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ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Massachusetts Institute of Technology

UNIVERSITY OF TEXAS ARLINGTON

MEOWS MEETING

MADISON COLLABORATION MEETING

SECRET MEETING 04/30/2019

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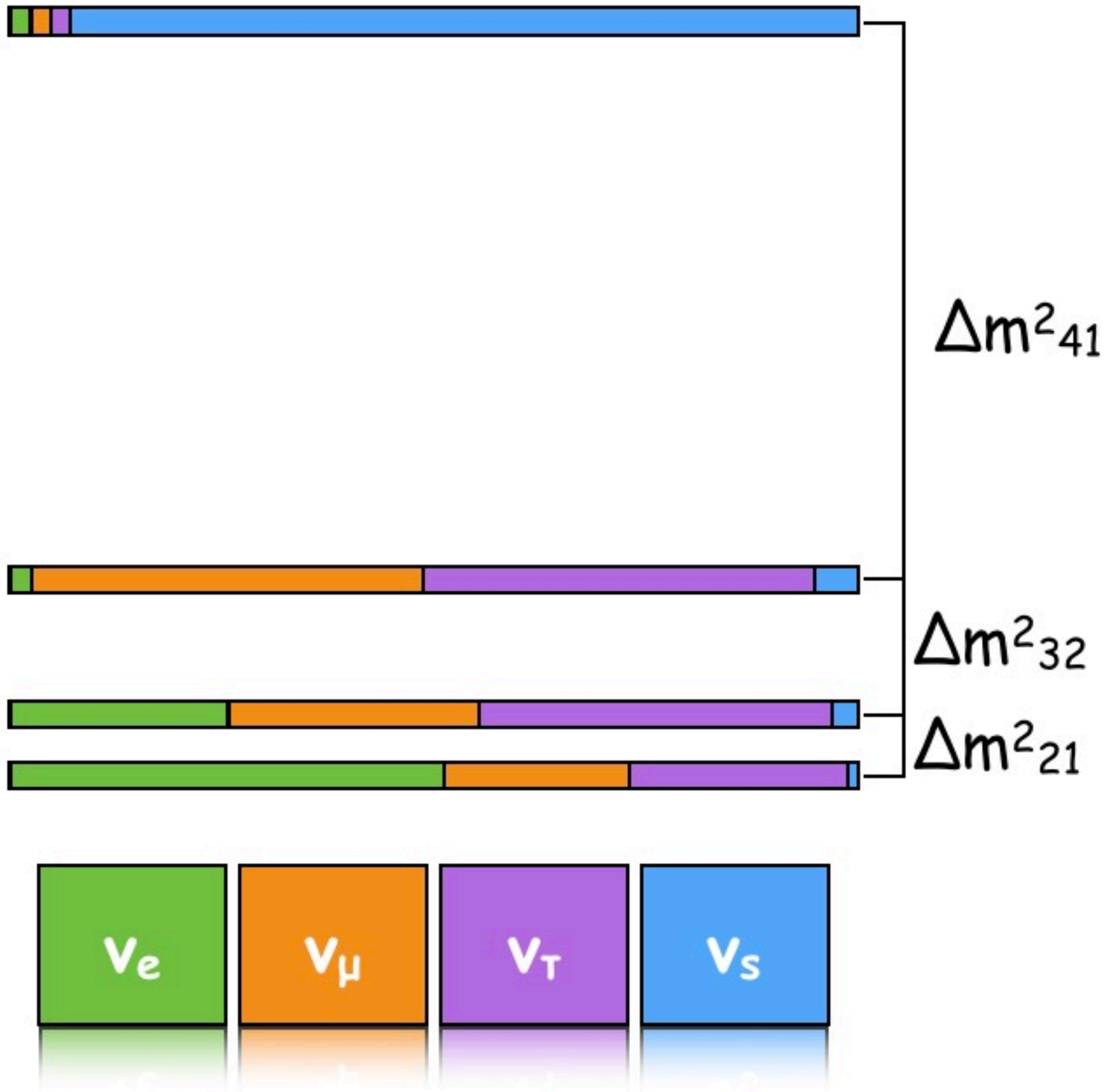
What are the parameters of interest?



In a **3+1 sterile neutrino model**, where there are 3 active neutrinos and 1 new sterile state ($m_{sterile} >> m_{active}$), the PNMS mixing matrix expands expands to 4x4.

The HE IC86.2011 Sterile Analysis chose to set the $|U_{\tau4}|^2$ mixing element to zero. This was a conservative choice.

MEOWS will perform scans in Δm^2_{41}, $|U_{\mu4}|^2$, and $|U_{\tau4}|^2$.

Standard PNMS matrix

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Not necessary for MEOWS since we assume the νPNMS matrix to be unitary.

$$|U_{e4}|^2 = 0$$

Justified since the neutrino sample is >99.9% ν_μ. The analysis is not sensitive to this parameter.

$$|U_{\mu4}|^2 = \sin^2\theta_{24}$$

The parameter of interest for IC86.2011

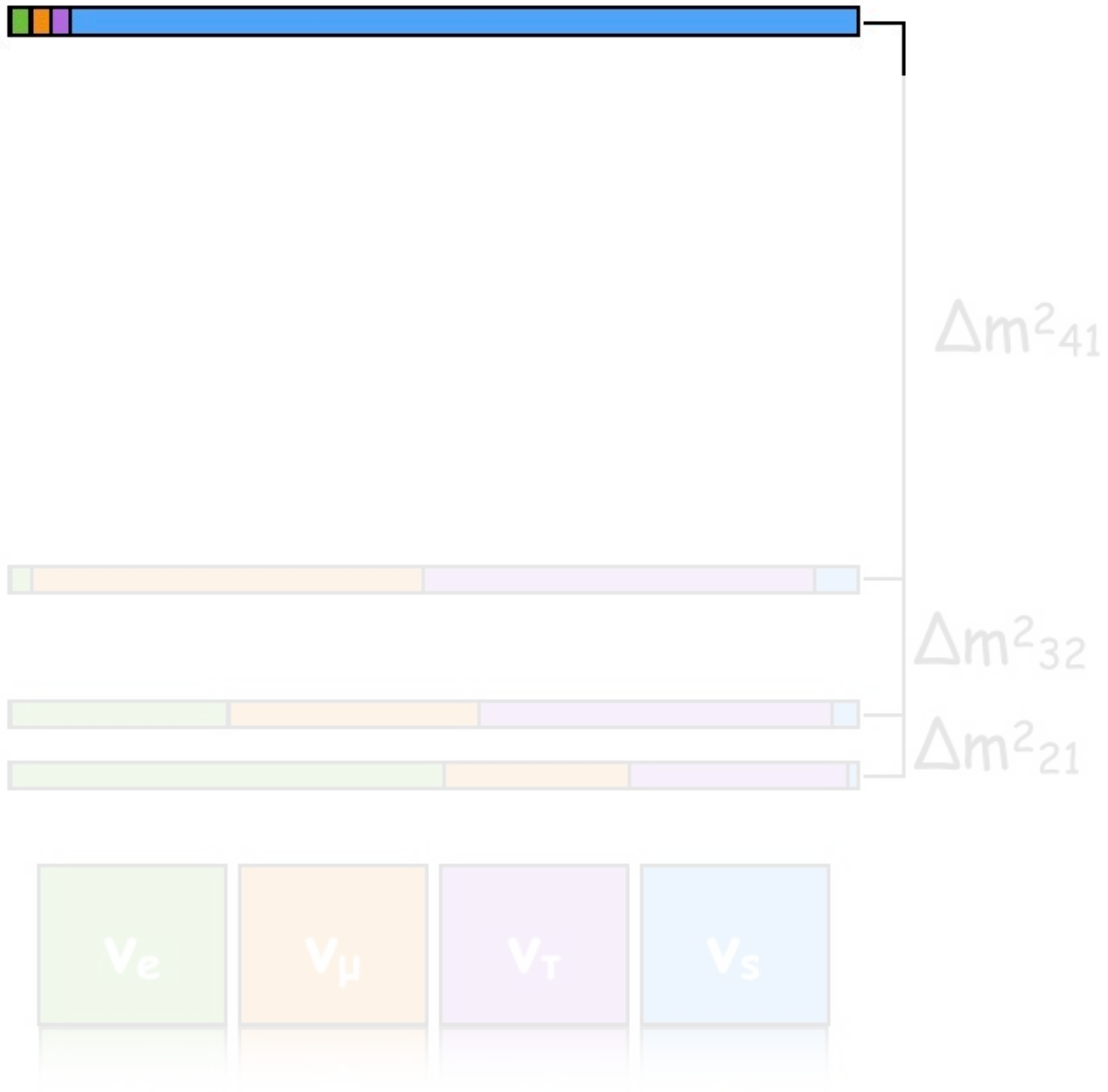
$$|U_{\tau4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$$

Choosing $|U_{\tau4}|^2 = 0$ was a conservative choice

What are the parameters of interest?

In a 3+1 sterile neutrino model, where there are 3 active neutrinos and 1 new sterile state ($m_{sterile} >> m_{active}$), the mixing matrix expands expands to 4x4.

The HE IC86.2011 Sterile Analysis chose to set the $|U_{\tau 4}|^2$ mixing element to zero. This was a conservative choice. MEOWS will scan over $|U_{\tau 4}|^2$.



$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Δm^2_{41} ← Mass splitting between Sterile and non-sterile states

$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$

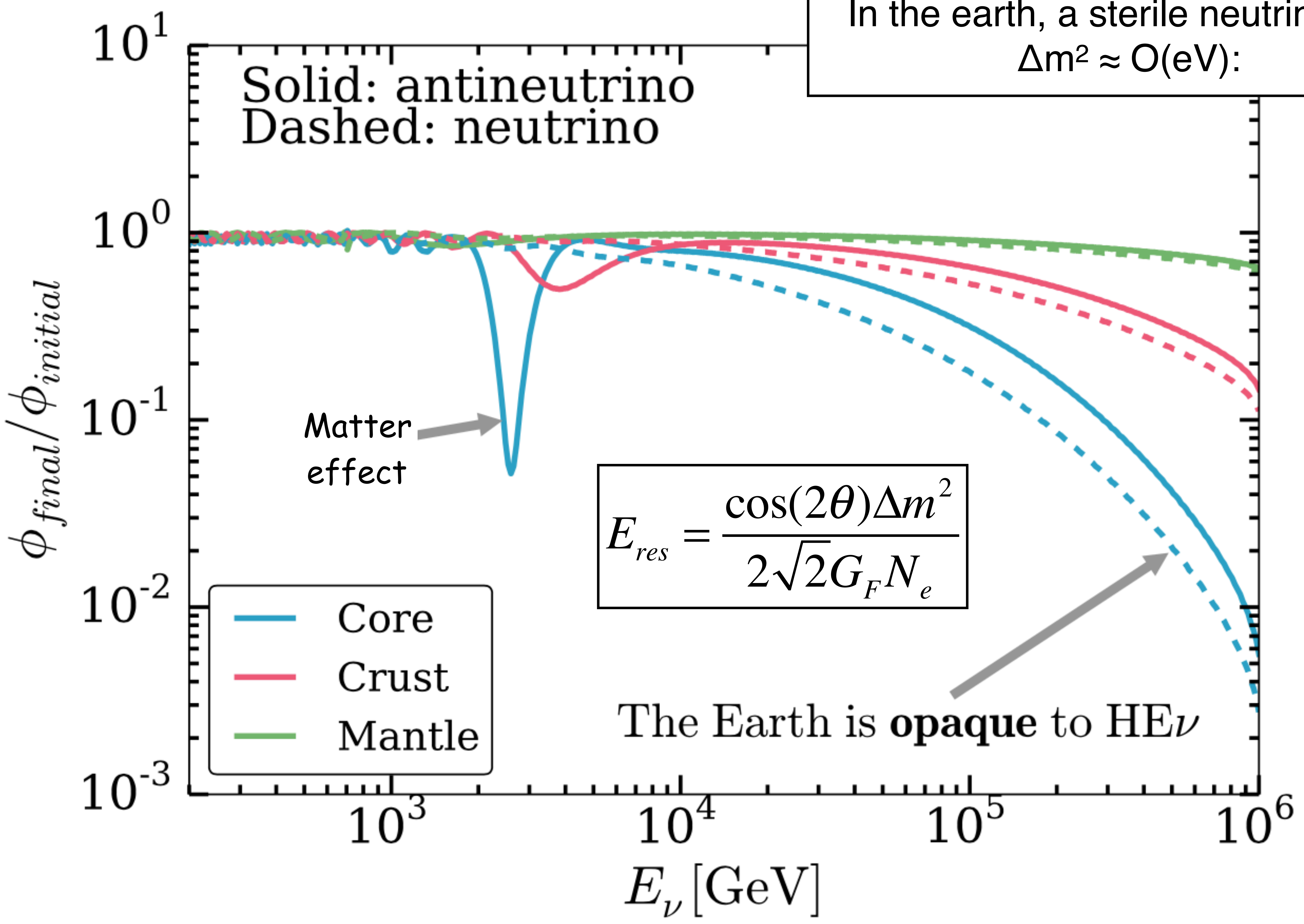
← We will use two variations of this: $\sin^2(2\theta)$, $|U_{\mu 4}|^2$

$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$$

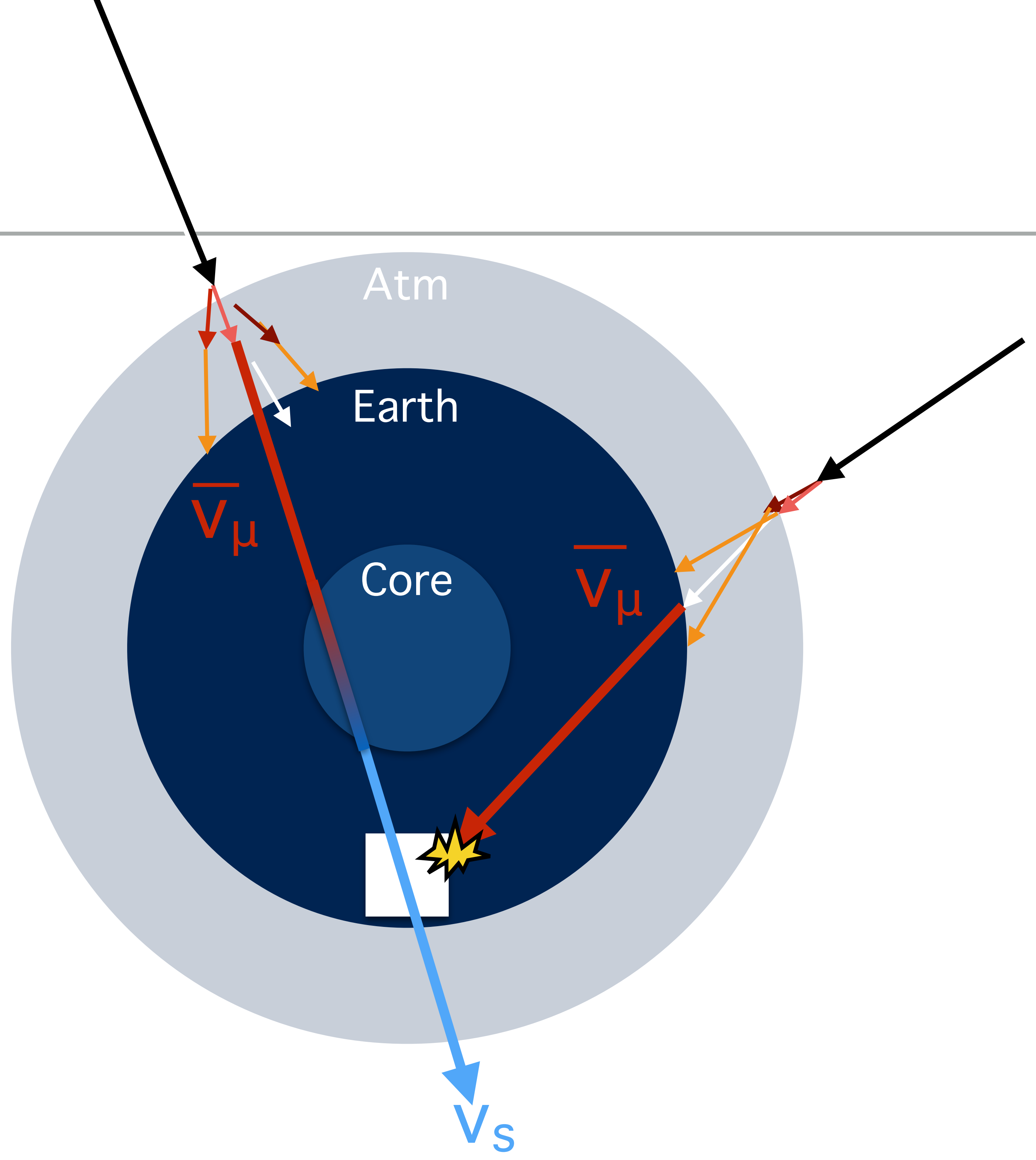
← This will be used with $U_{\mu 4}$

Matter enhanced resonance

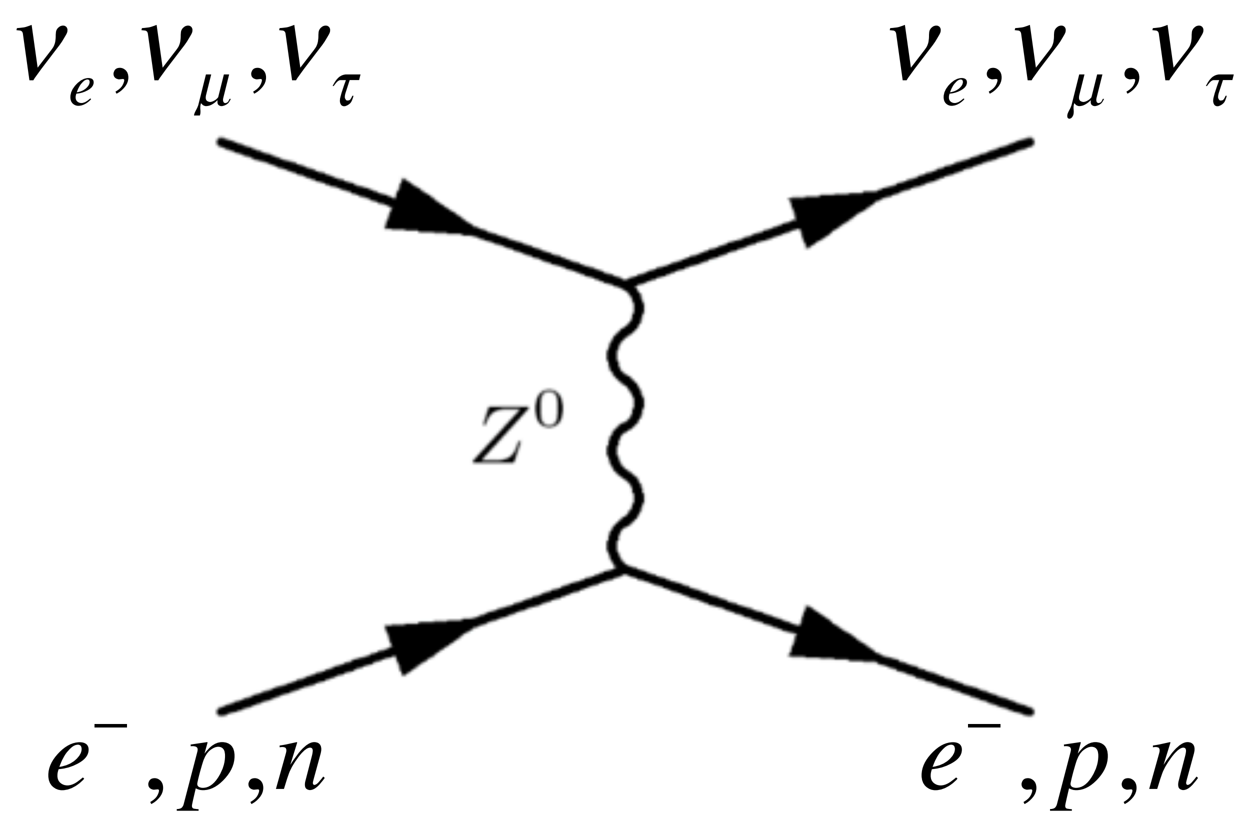
In the earth, a sterile neutrino with $\Delta m^2 \approx O(\text{eV})$:



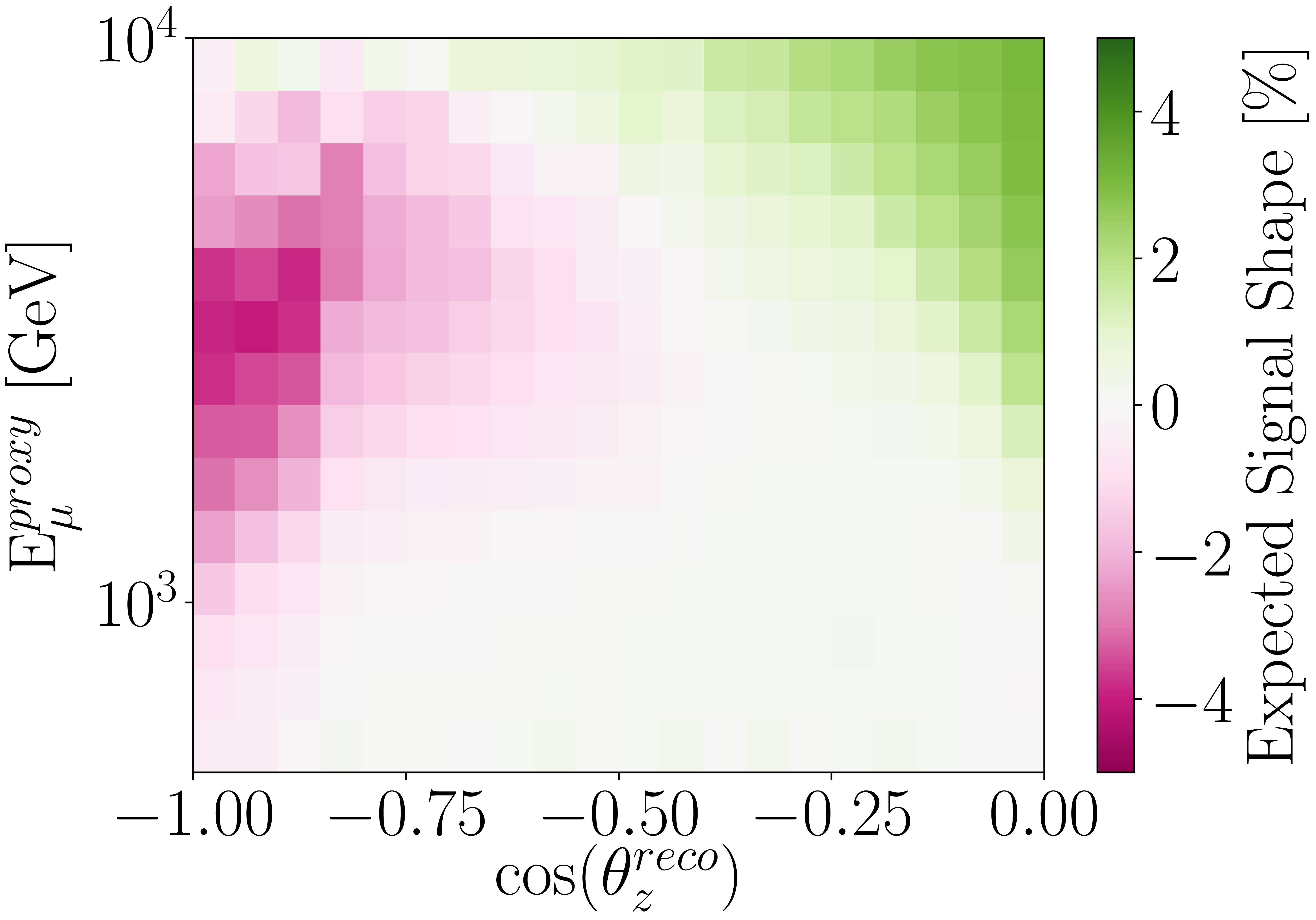
Argüelles, C. New Physics with Atmospheric Neutrinos

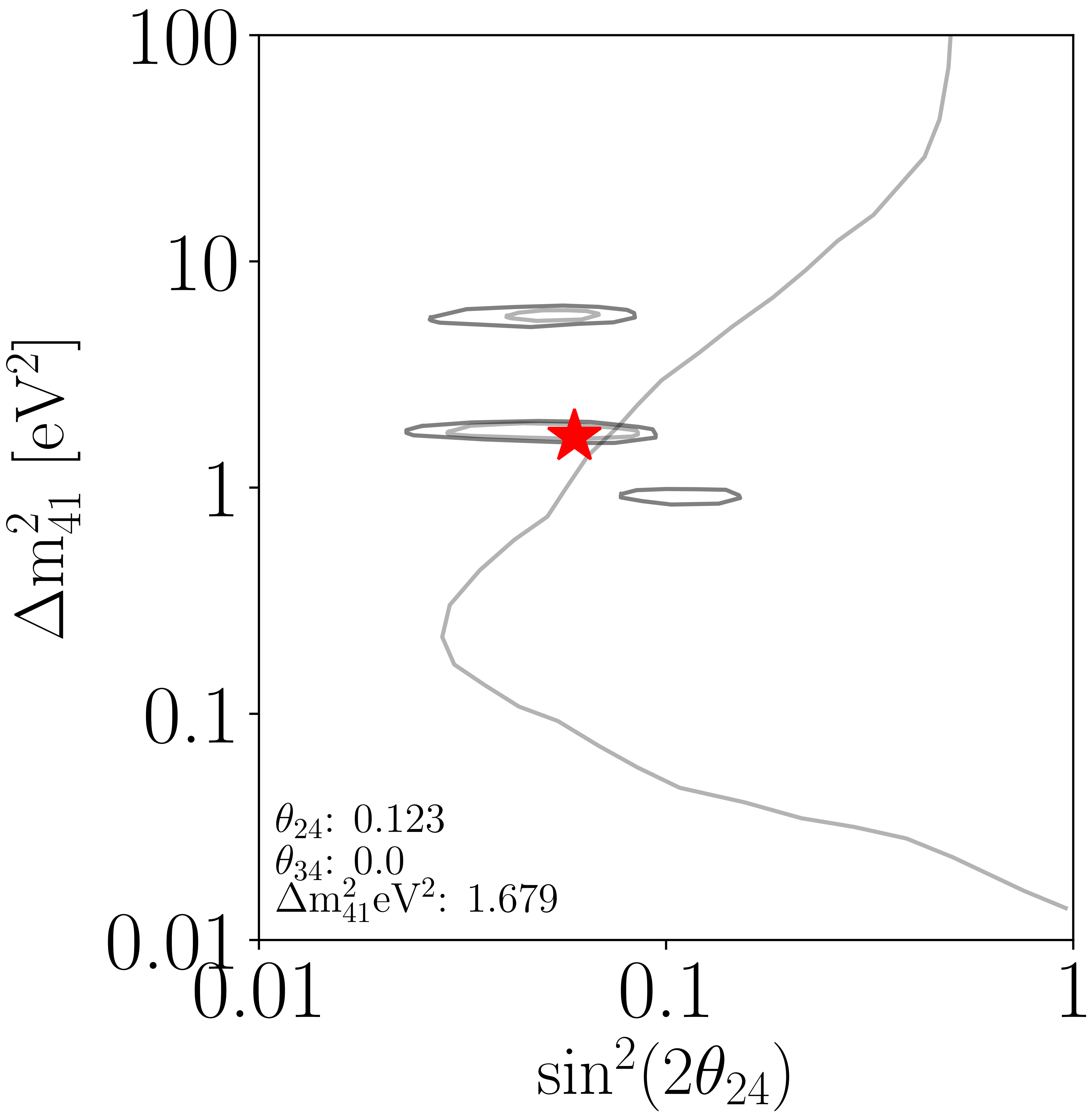


Resonance due to coherent forward scattering with NC.



Interesting areas of the parameter space

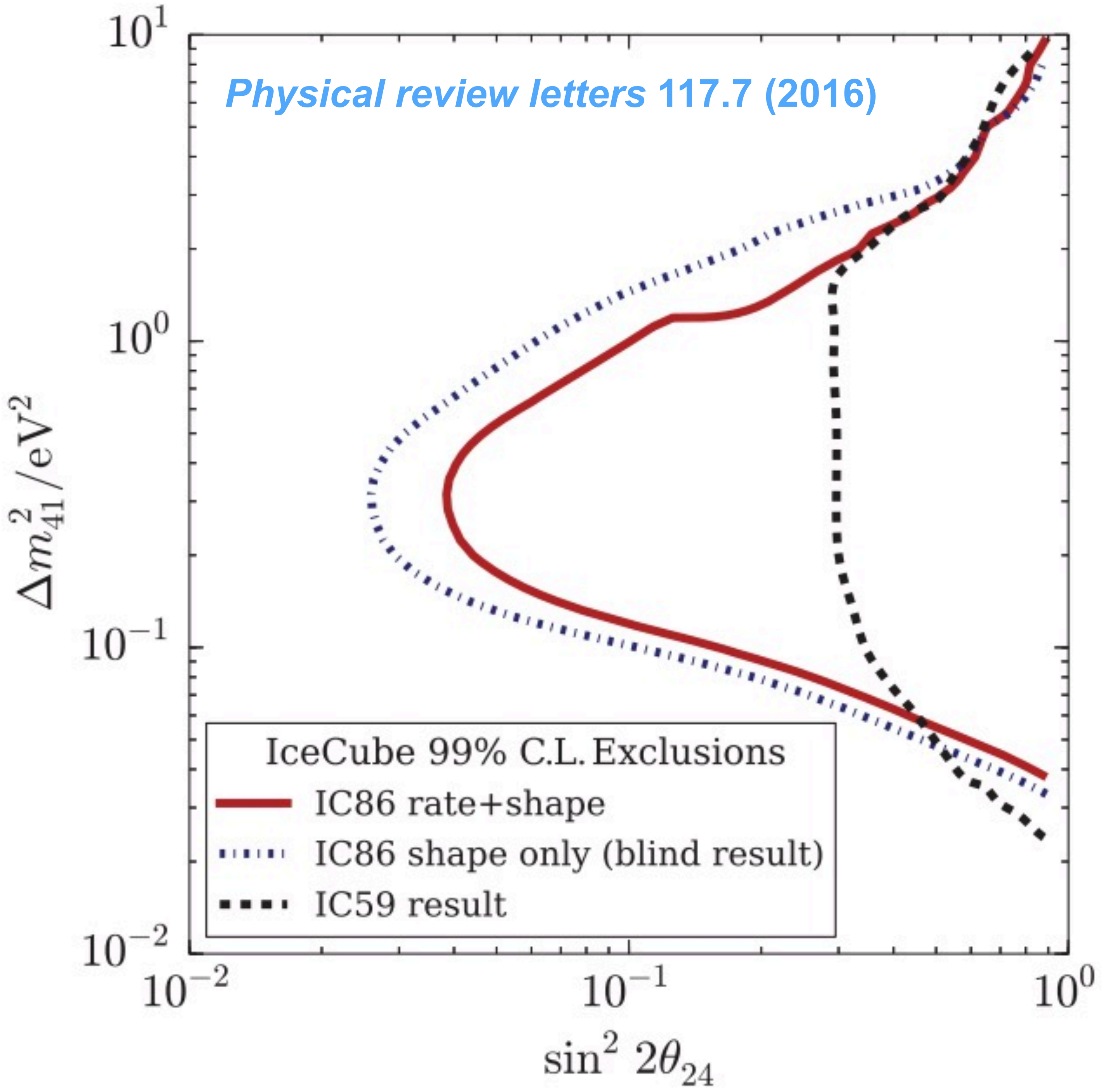




Previous IceCube results

IceCube has already released two sterile neutrino search results.

IC86.2011, 0.4-10TeV search for
a matter enhanced resonance.

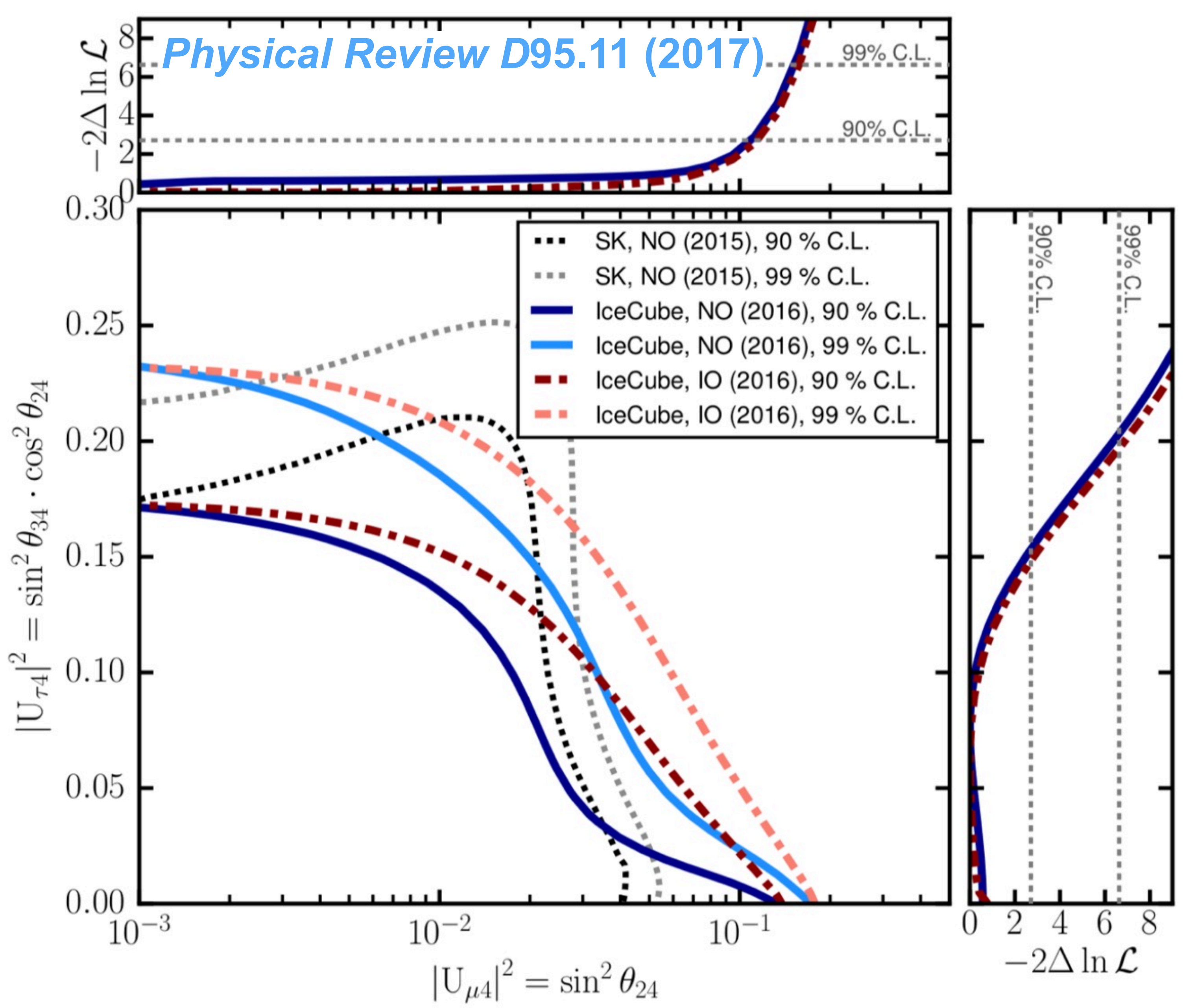


ANALYSIS I

[Δm^2, $\sin(2\theta_{24})^2$]

3-year DeepCore analysis.
10-100GeV oscillation search

$0.1\mathrm{eV}^2 > \Delta m^2 > 10\mathrm{eV}^2$



ANALYSIS II

[$|U_{\mu4}|^2$, $|U_{\tau4}|^2$]

13 applicable systematics

Ice Systematics:

- BulkIce (IceStorm)
- HoleIce (p_2-parameter splines)

Detector Systematics:

- DOM efficiency (6-spline support points)

Neutrino Flux Systematics:

- Atmospheric Density
- Cosmic Ray $\Delta\gamma$
- Hadronic interactions and cosmic ray flux (Barr parametrization)
- Normalization

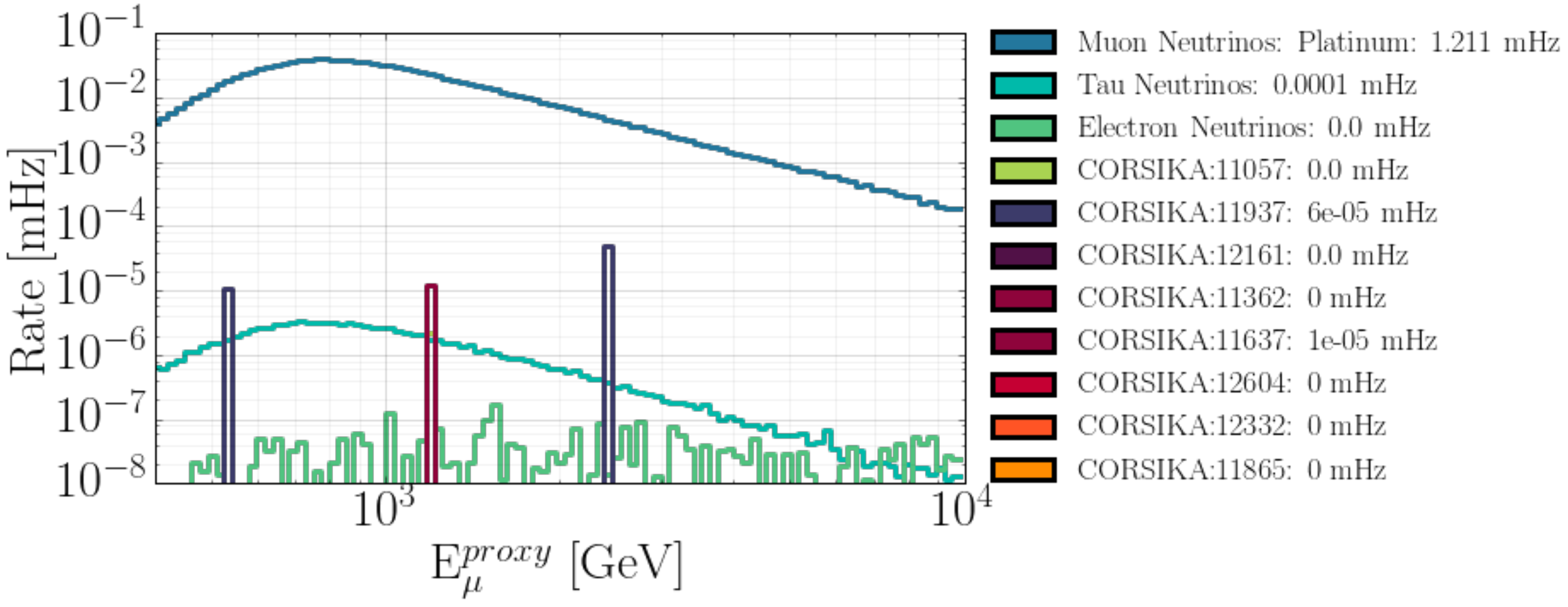
Systematic	Central Value	Prior Width (1σ)	Range
Forward Hole Ice	-1.0	+/-5	-5.0 to 2.0
IceGradient0	0	+/-1.0	NA
IceGradient1	0	+/-1.0	NA
DOM efficiency	1.27	+/-10%	1.23 to 1.35
Normalization	1.0	+/-0.4	NA
Atm. Density	0	+/-1.0	NA
CR spectral slope	0	+/-0.01	NA
Barr: WM	0	+/-0.40	-0.5 to 0.5
Barr: WP	0	+/-0.40	-0.5 to 0.5
Barr: YM	0	+/-0.30	-0.5 to 0.5
Barr: YP	0	+/-0.30	-0.5 to 0.5
Barr: ZM	0	+/-0.12	-0.2 to 0.5
Barr: ZP	0	+/-0.12	-0.2 to 0.5

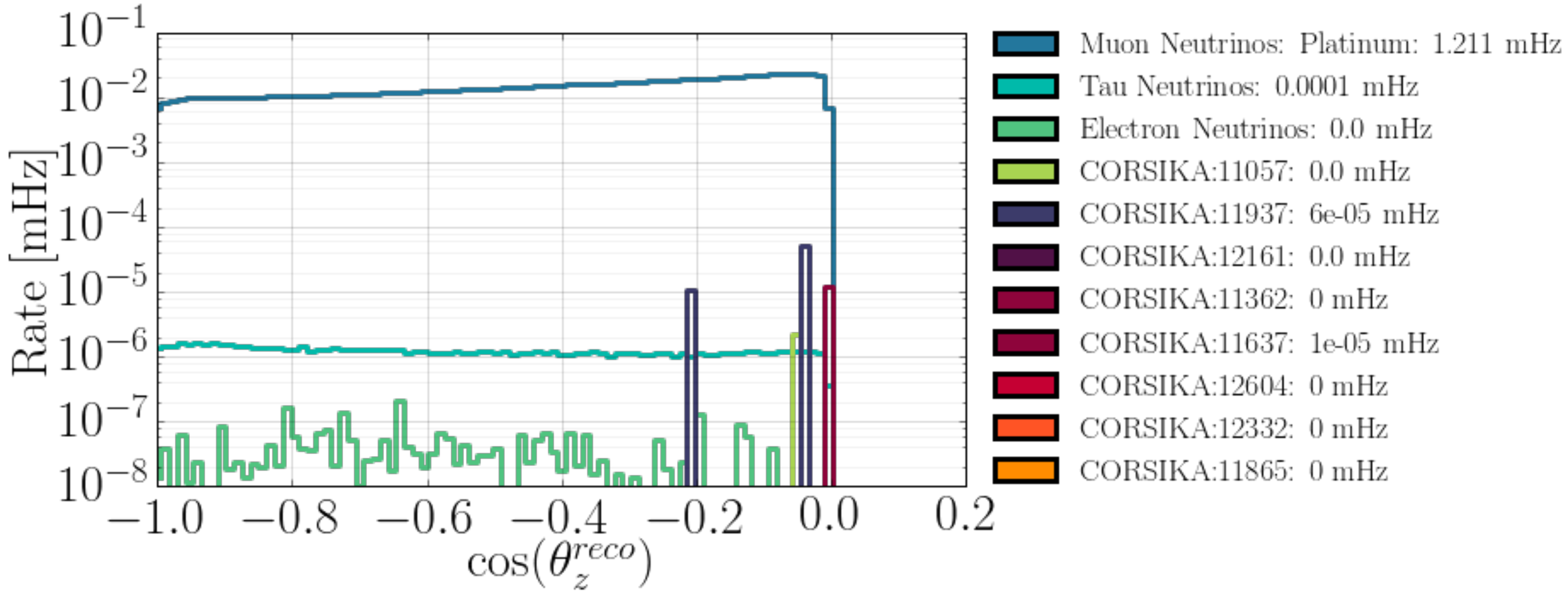
The **Platinum** event selection

If an event passes either the **Golden selection** or the **Diamond selection**, it is a 'good' event and makes it into the **Platinum selection**

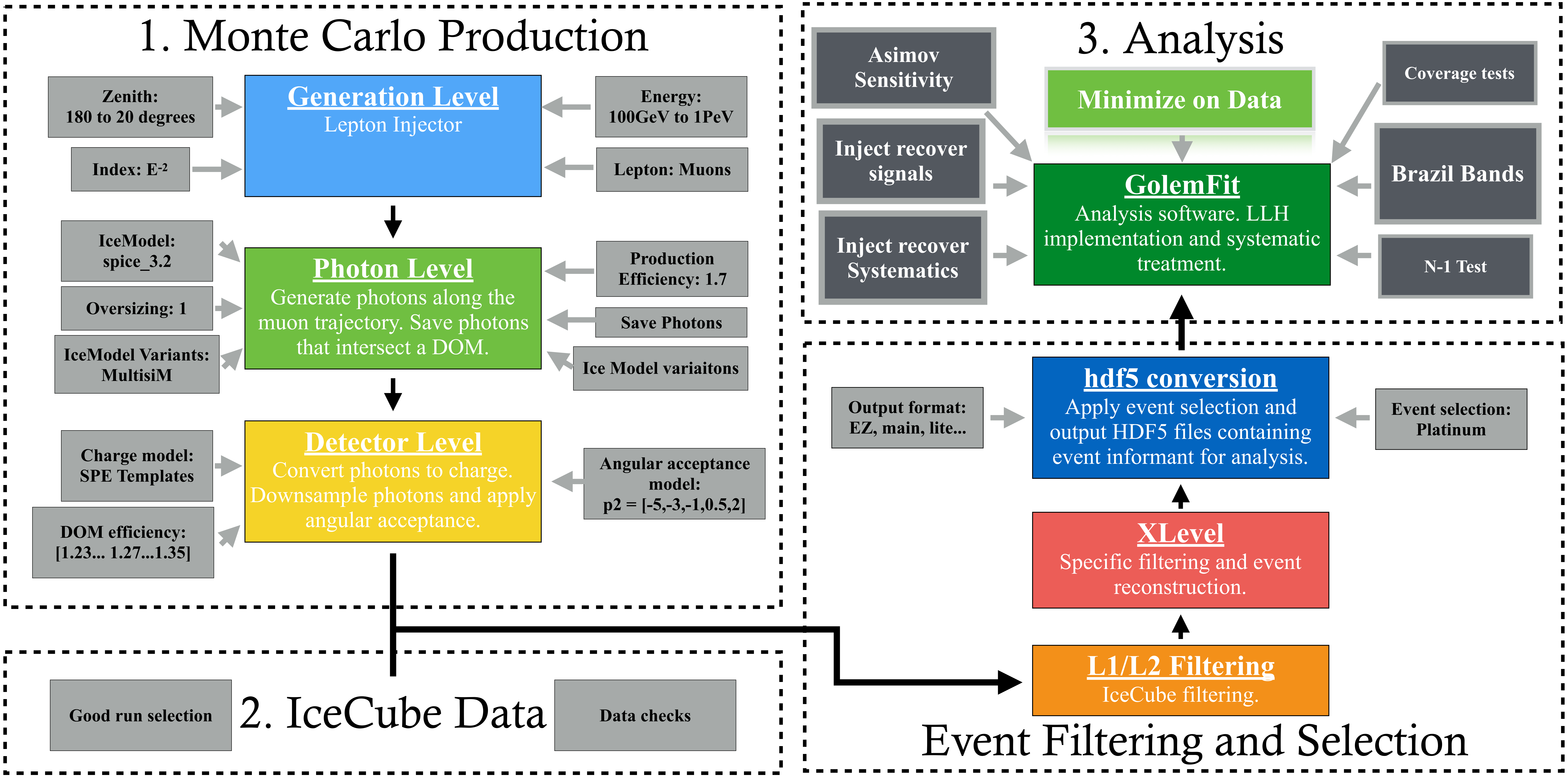
MC expectations of total events in 6.8 years:

Event Selection	Muon Neutrino	Tau Neutrino	Electron Neutrino	CR Muons	Selection Purity
Platinum	249,299 +/- 499	21 +/- 4	1 +/- 1	17 +/- 4	>99.9%





Analysis chain and overview of slides

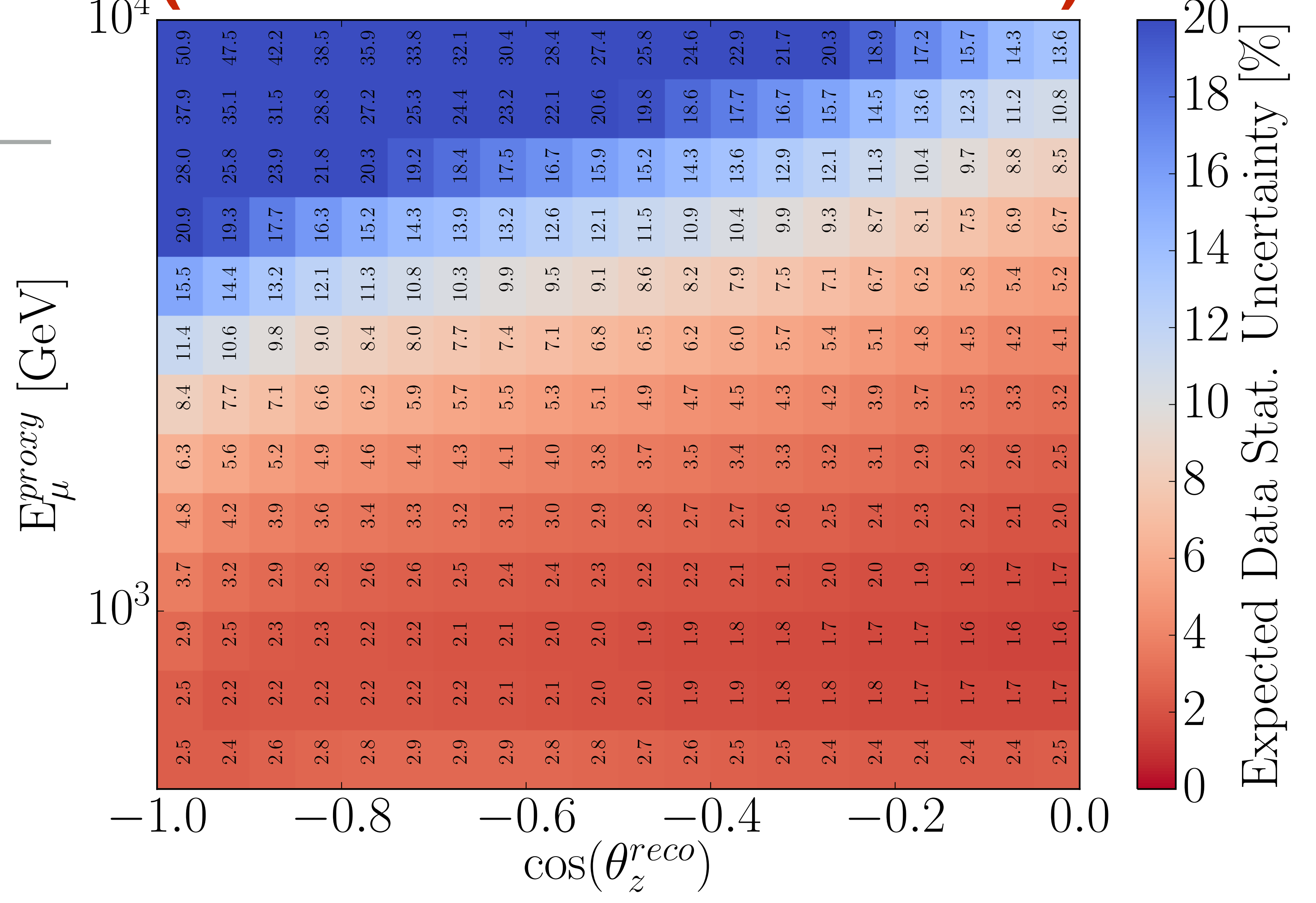


Binned LLH problem formulation

- 13 bins in energy from 500GeV to 9976GeV.
- 20 bins in zenith from Cos(θ_z) = -1.0 to 0.0.
- LLH values are reported relative to the minimum in the space.
- We will also report Bayesian Factor at each physics parameter point.
- MC ~1000 years of livetime.
- We also include a test statistic that accounts for finite MC.

Paper by Carlos, Tianlu, Austin: arXiv:1901.04645

(Total number of bins: 260)



$$LLH = \max_{\vec{\theta},d}\left(\sum_{i=1}^{N_{bins}}\left[x_i log\lambda_i(\vec{\theta},d) - \lambda_i(\vec{\theta},d)\right] - \sum_{\eta}\frac{(\theta_\eta - \Theta_\eta)^2}{2\sigma_\eta^2}\right)$$

Penalization factor determined by systematic priors (all Gaussian)

Probability of statistical observation using Poissonian statistics

We actually use a more complex statistical metric that takes into account finite MC uncertainty:

$$\left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1}\Gamma\left(k+\frac{\mu^2}{\sigma^2}+1\right)\left[k!\left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}+1}\Gamma\left(\frac{\mu^2}{\sigma^2}+1\right)\right]^{-1}$$

Analysis related tests and plots

Asimov: no statistical fluctuations.

- **Asimov Sensitivity**
- **N-1 tests:** removing one systematic at a time.
- **Systematic-Only Tests:** Only using groups of systematics
- **Inject Recover Systematics:** Inject a true value for a systematic, see if the minimizer recovers it.
- **Inject Recover Signal:** Inject a signal and see if the minimizer finds the correct minima

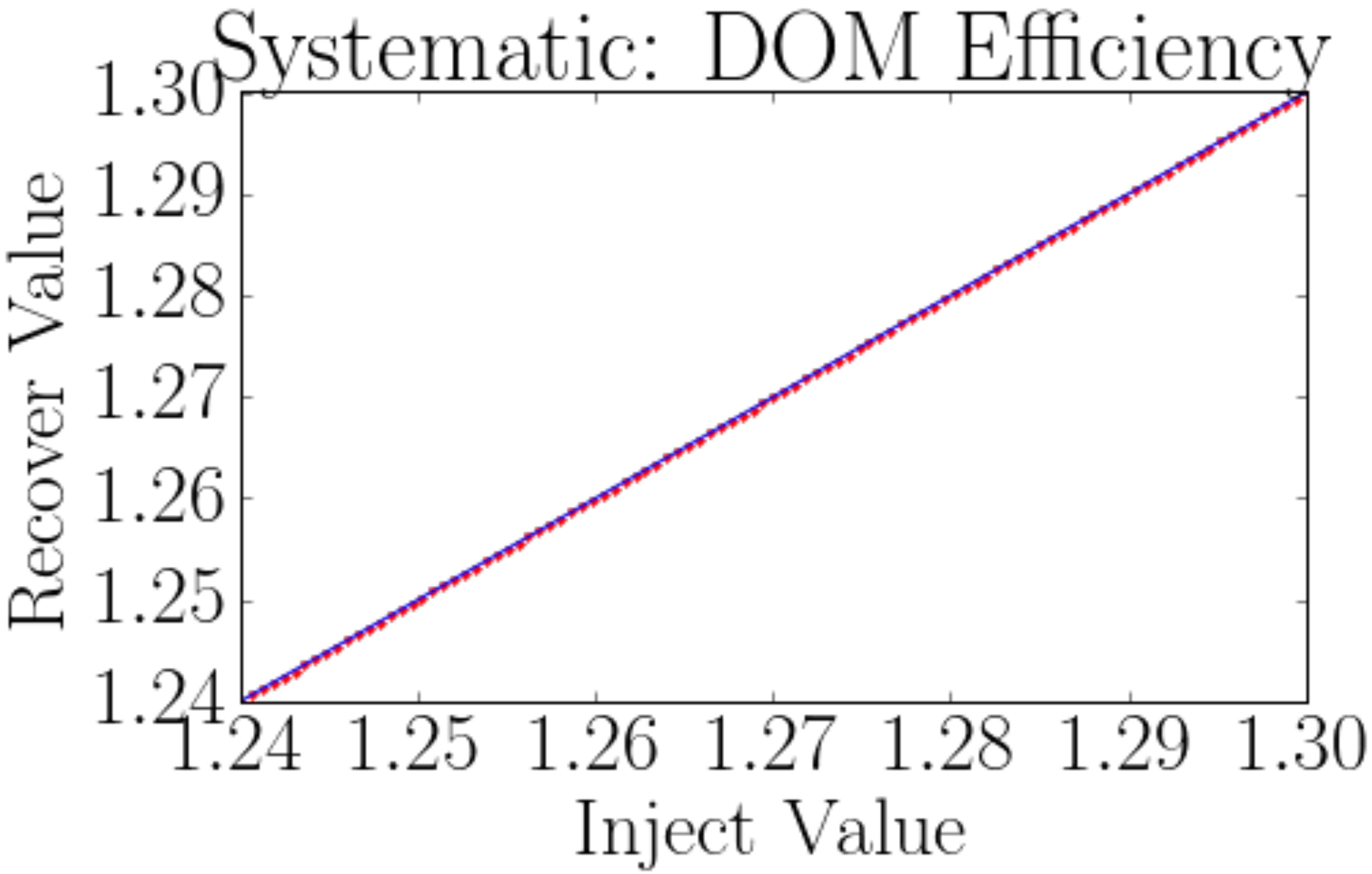
Ensemble tests: using many realizations (toy MC, fake datasets).

- **Expected best fit locations give the null:** where do we expect the best fit location given the null hypothesis
- **Brazil Bands:** estimating the range of expected 90% CL given the null hypothesis.
- **Coverage checks:** is Wilk's theorem valid? Do we require FC?

Checks: Inject-Recover Systematics Test

We inject a true value for a systematic and allow the minimizer to recover that value (the central value of the priors are also centered on the injected value).

Values are injected for each systematics at 100 different values, all of which are recovered (**red markers = blue line**).



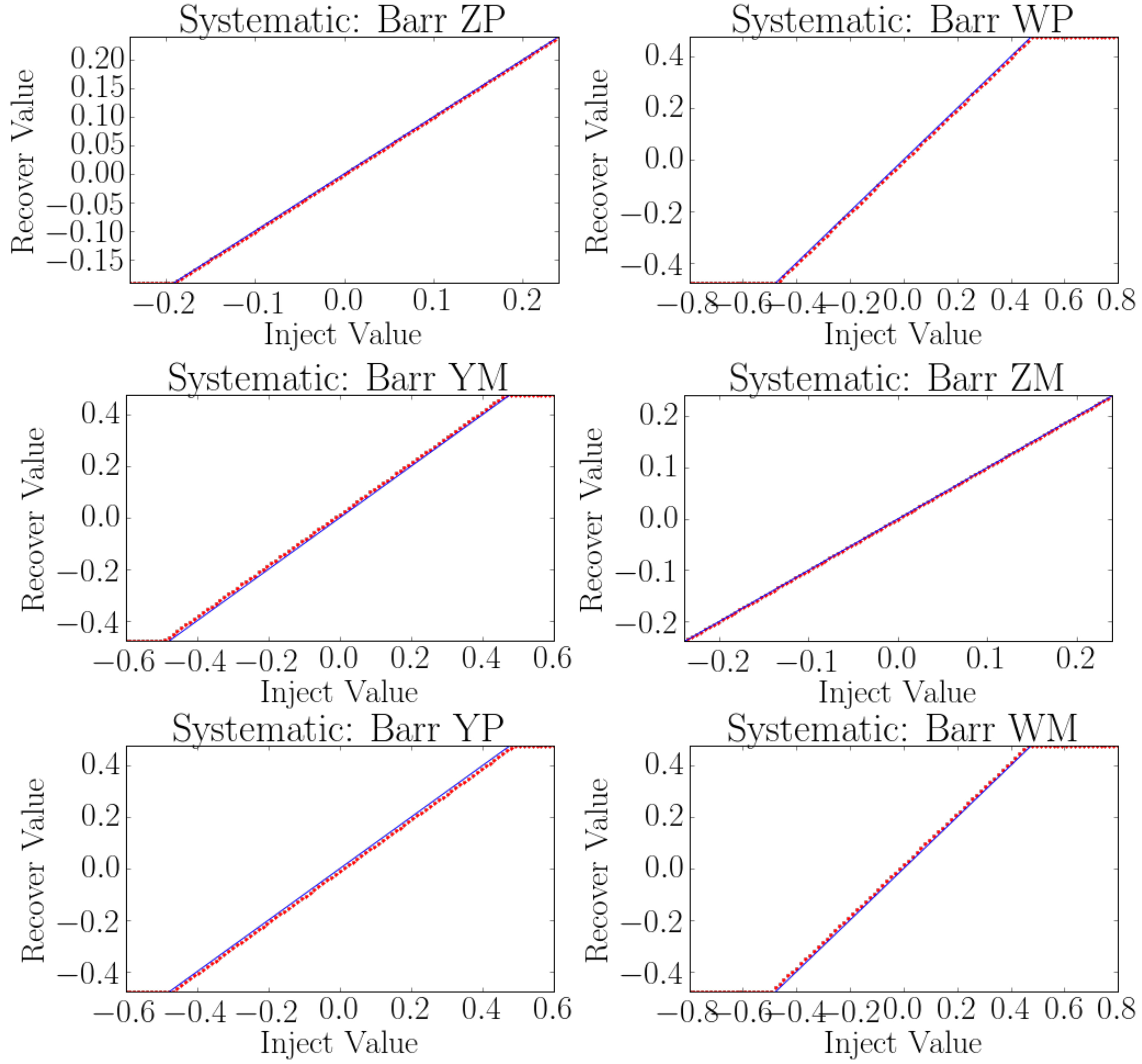
Example:

- **inject a true DOM efficiency at red markers**
- **Measure the minimized DOM efficiency recovered value.**

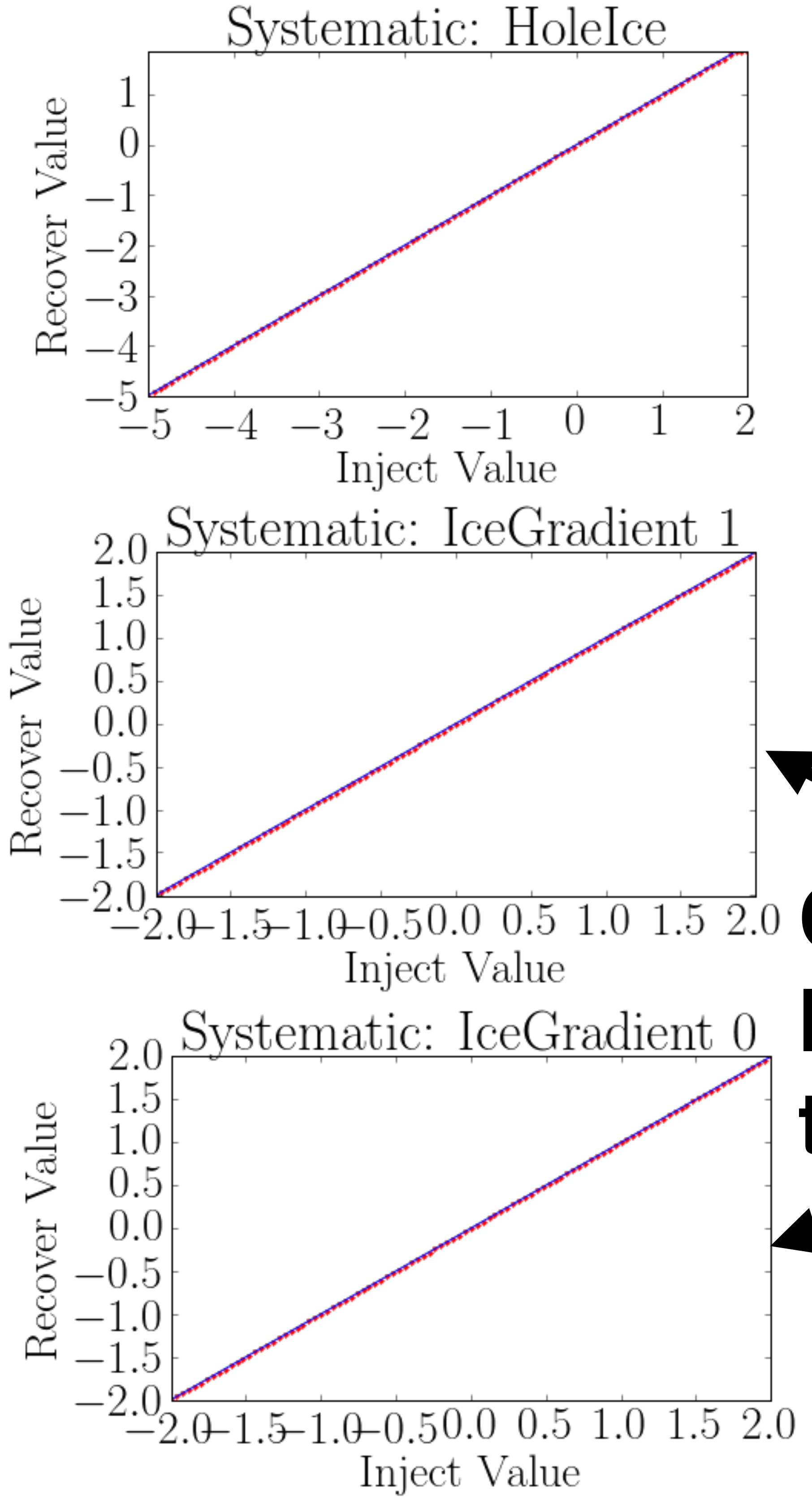
Tests passes if red markers == blue line.

Checks: Inject-Recover Systematics Test

Barr Systematics

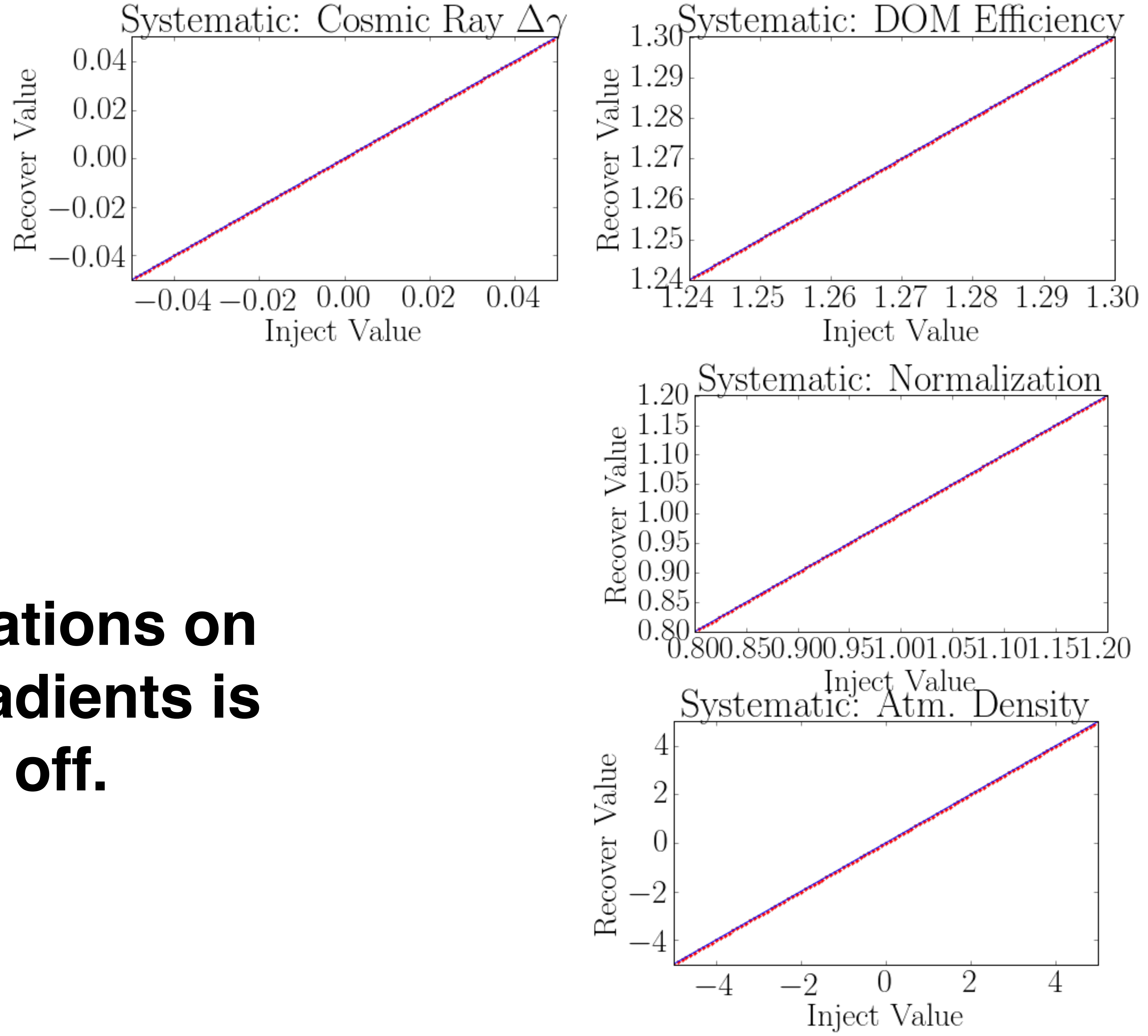


Ice Systematics

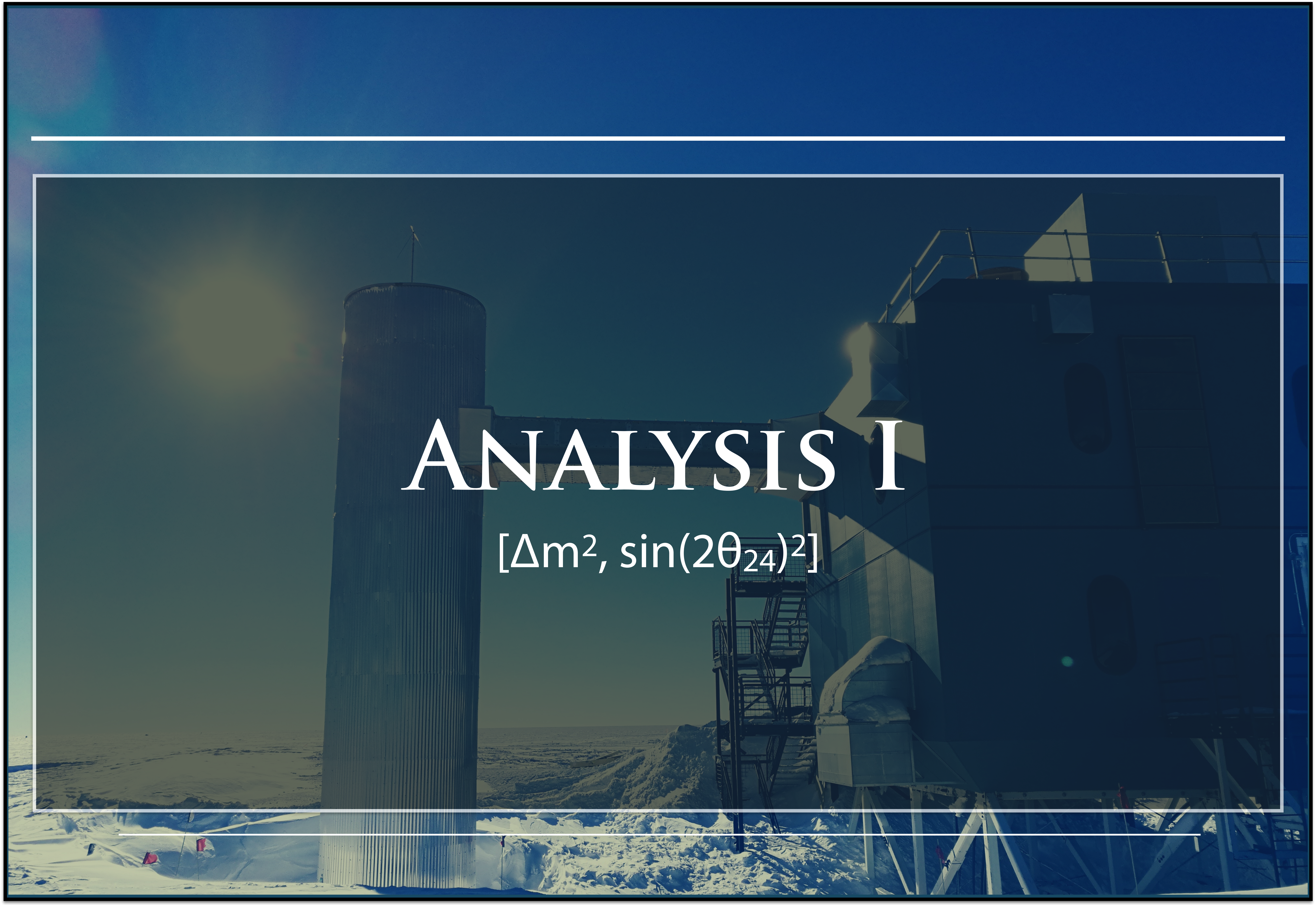


Correlations on Ice Gradients is turned off.

Other Systematics



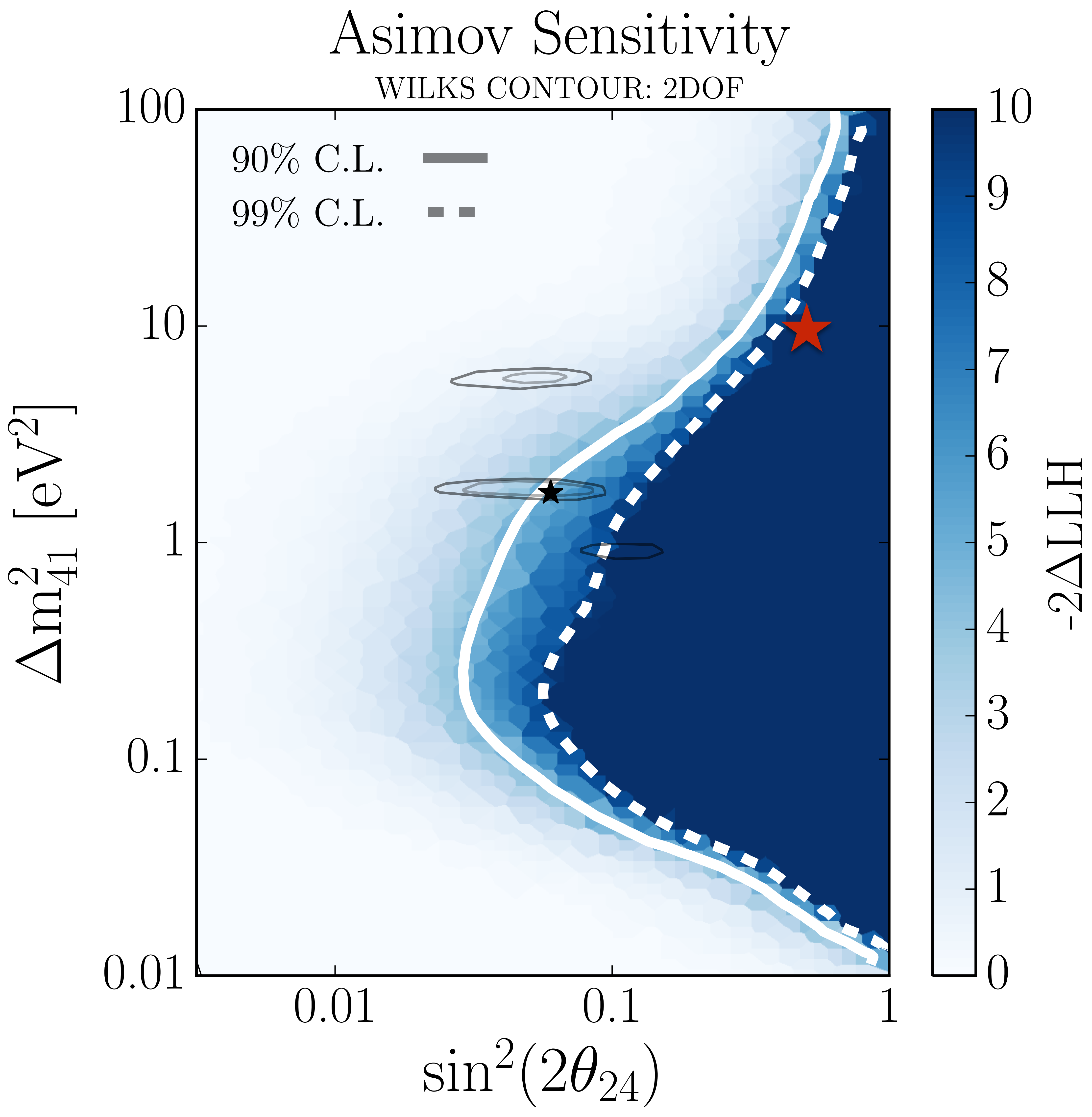
The take-away: Our systematic implementation looks good



Analysis I

$[\Delta m^2, \sin(2\theta_{24})^2]$

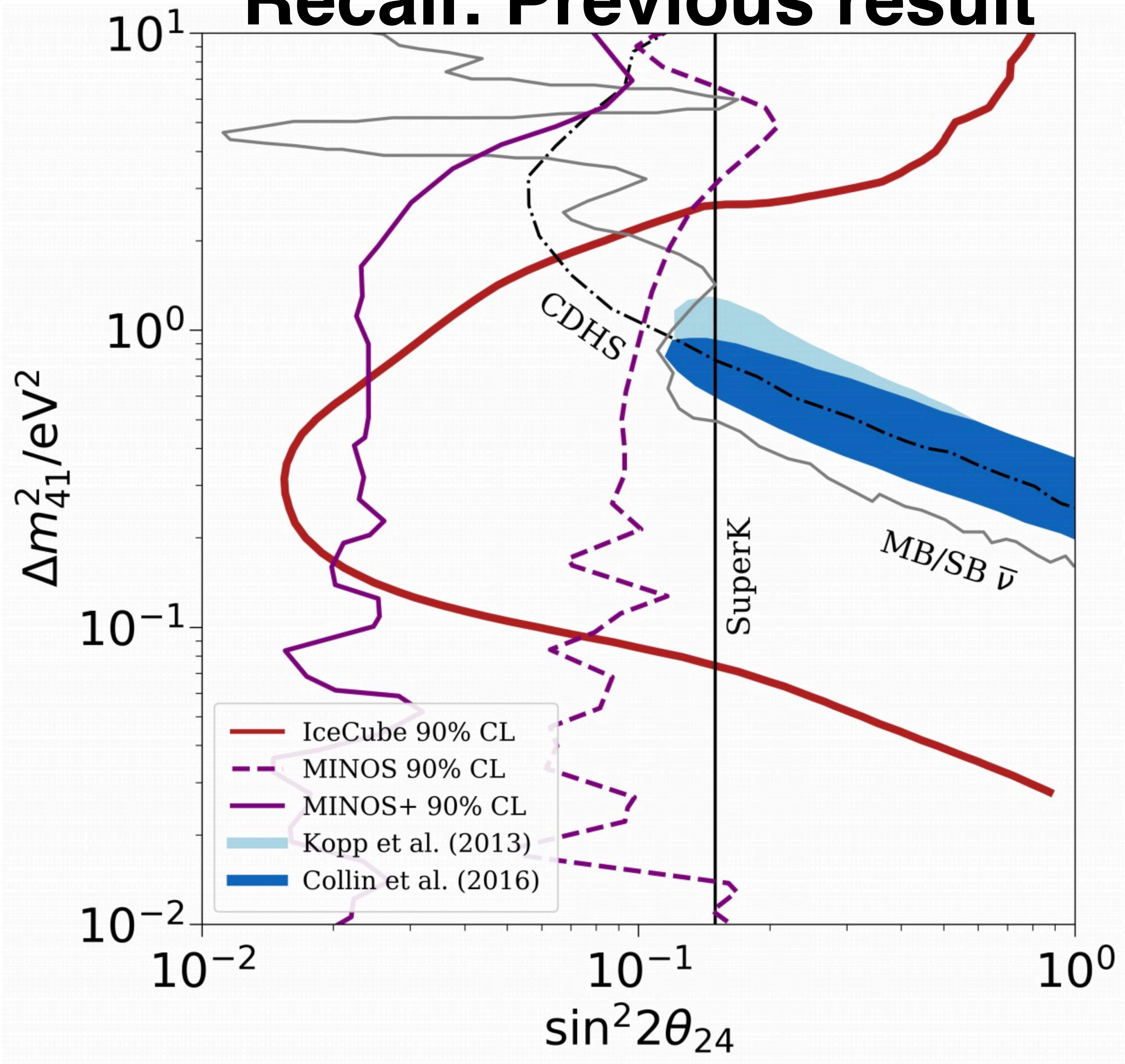
Asimov Sensitivity: [Δm², sin(2θ)²]



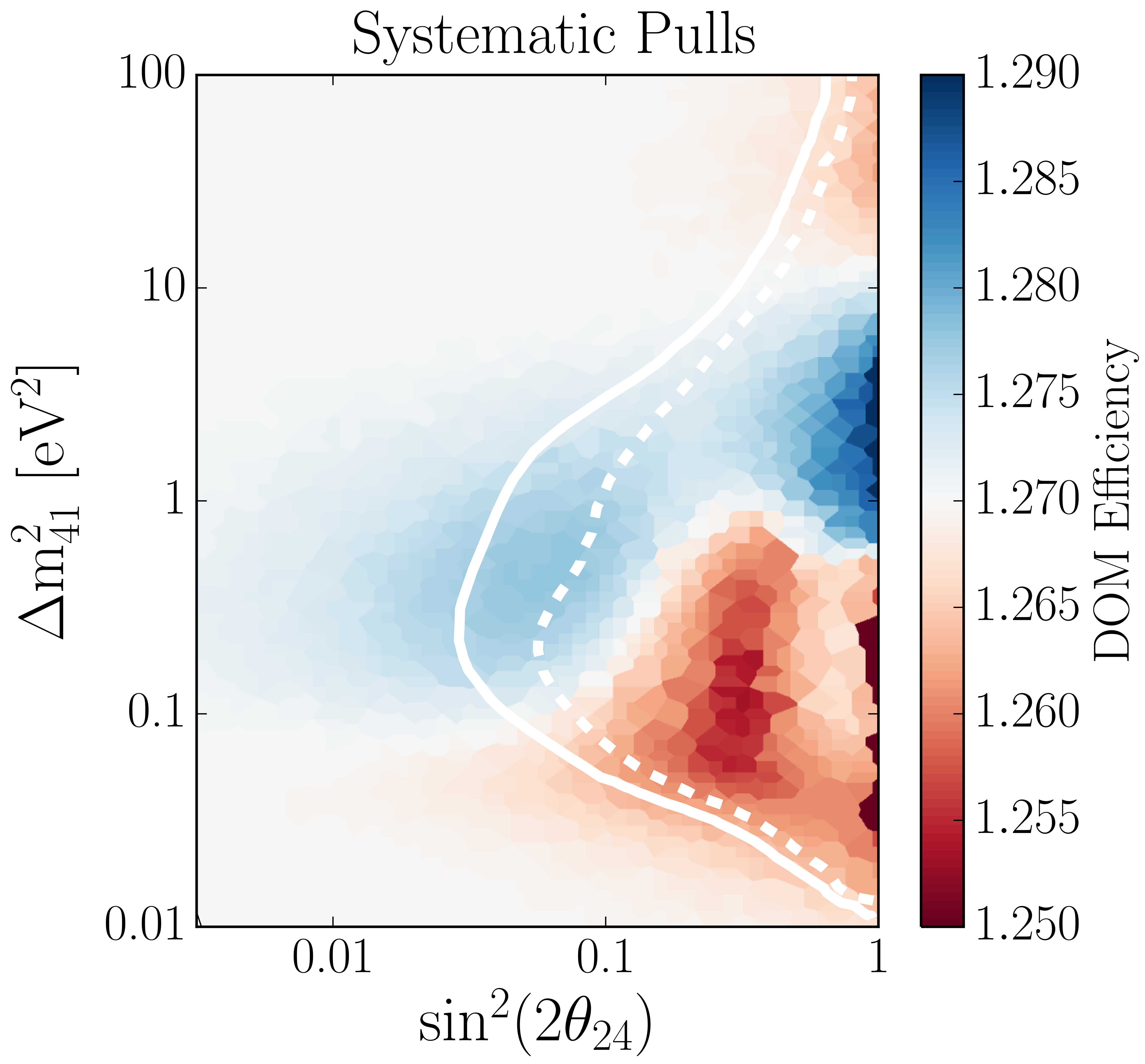
Asimov Sensitivity take-aways:

1. Our mean 90% CL probes the current sterile best fit.
2. We probe the previous best fit (★) point (IC86.2011) at high significance

Recall: Previous result



Asimov dataset: example systematic pull



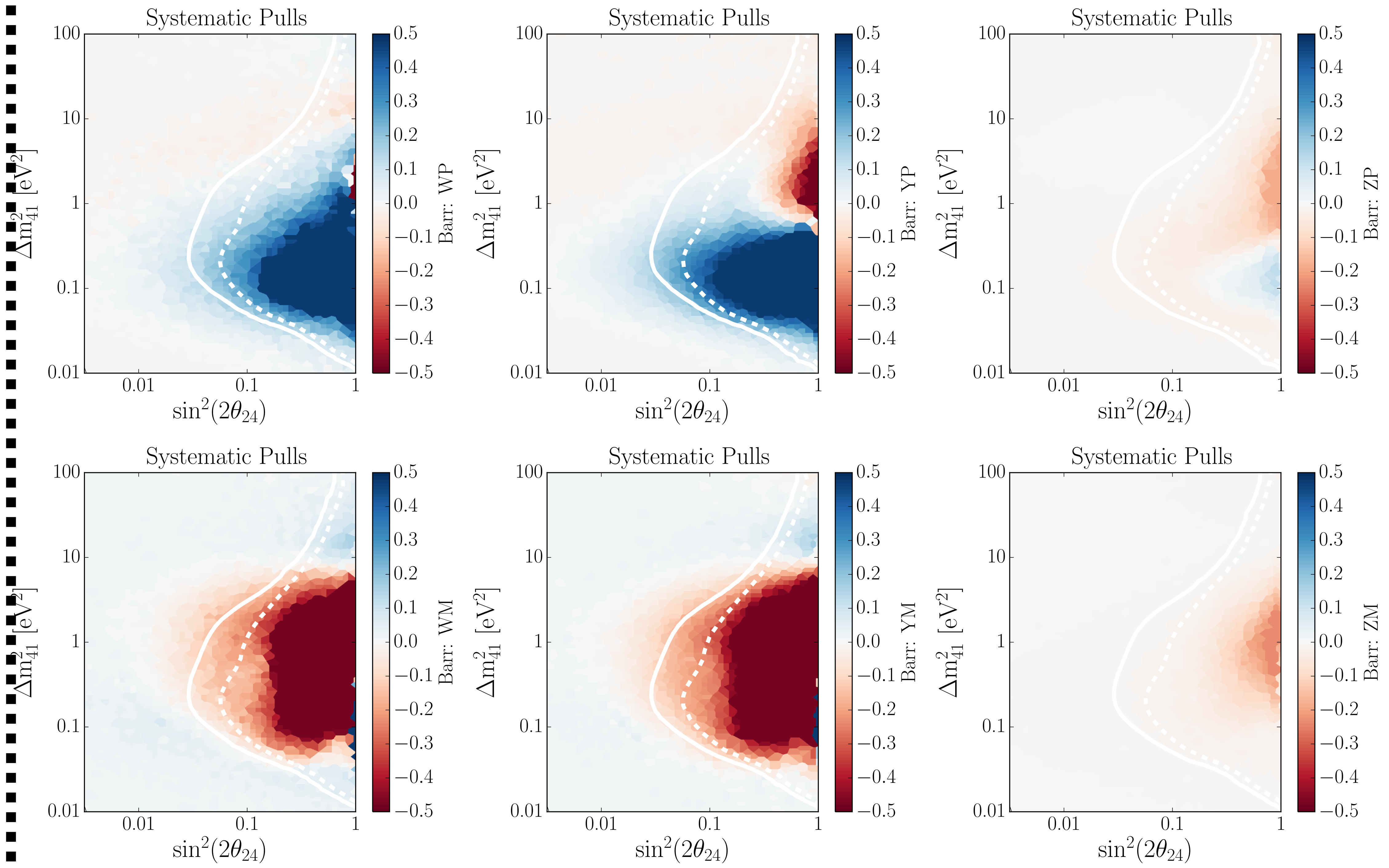
An example plot illustrating where in the parameter space the DOM efficiency systematic pulls, and in what direction.

This is for an Asimov dataset. But, they can be plotted for all realizations as well.

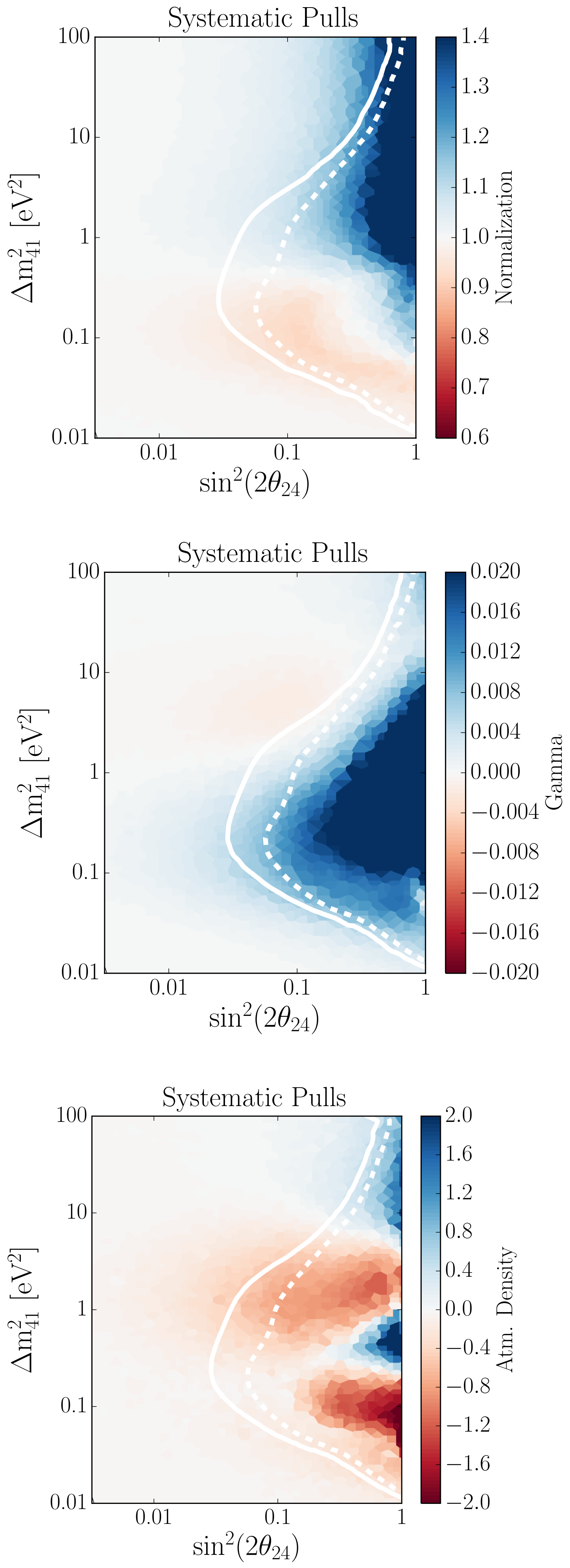
Note: Using my SPE Templates, a DOM efficiency of 1.27 is equivalent to 0.96.

Asimov dataset: all of the systematic pulls

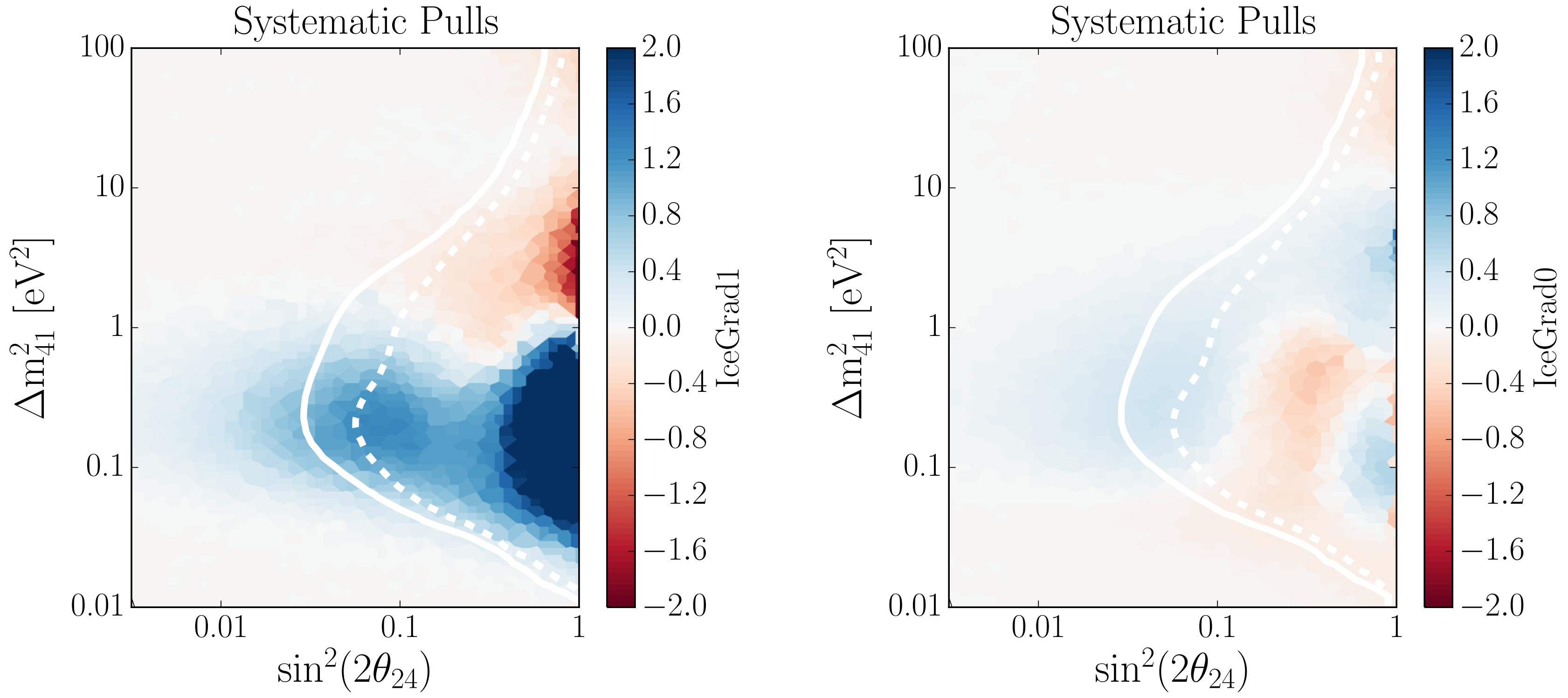
Flux Systematics

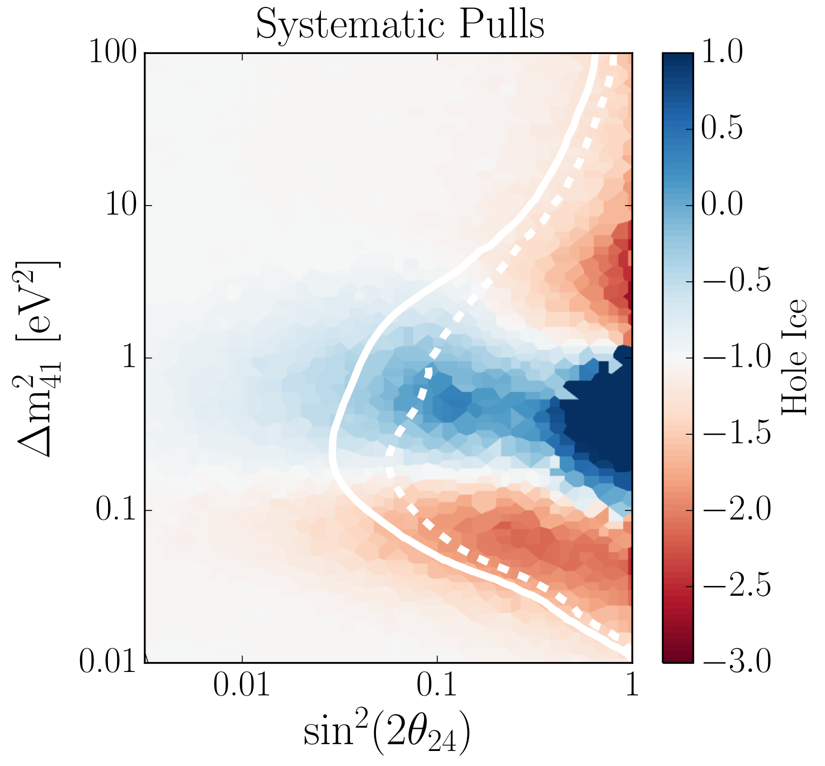


Barr Parameters

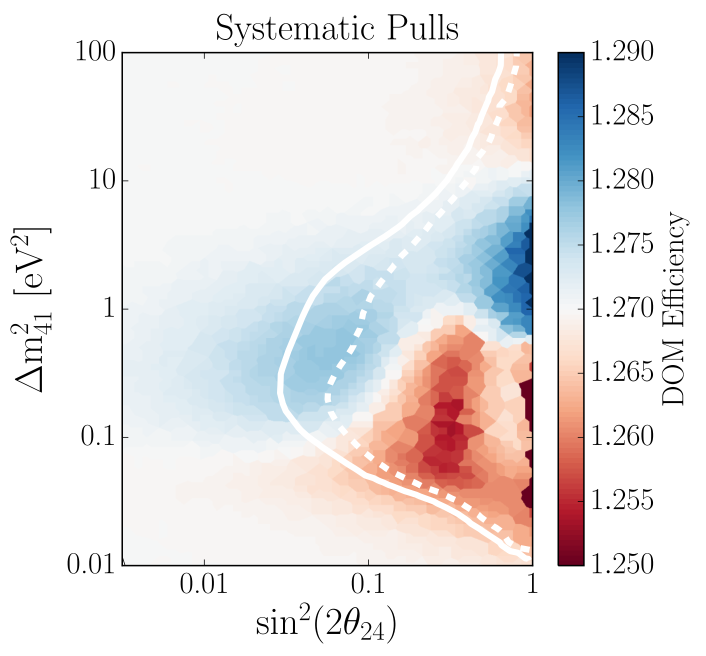


Ice Systematics





Detector systematics

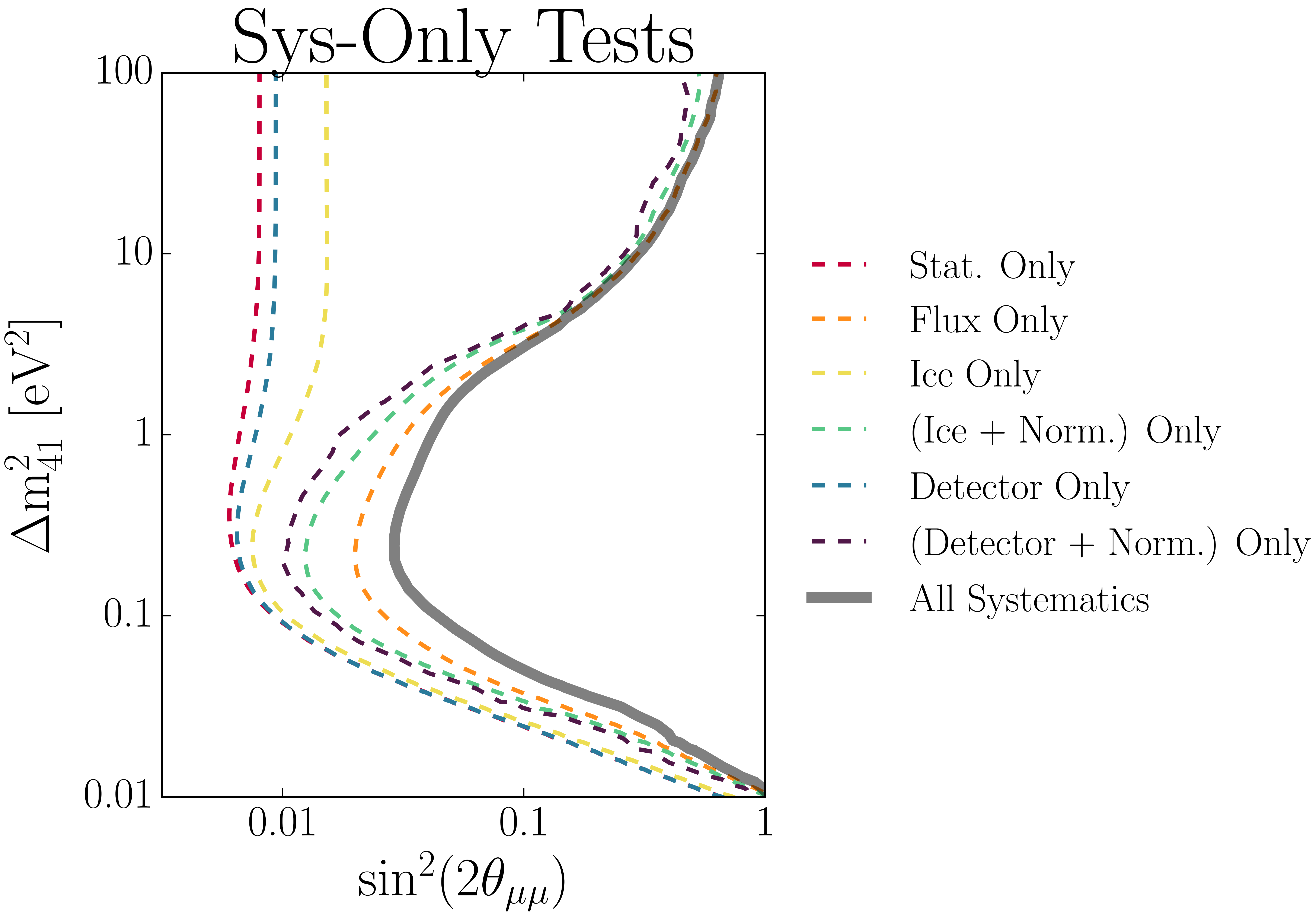


Asimov dataset: **Sys-only Test**

Systematics are grouped into:

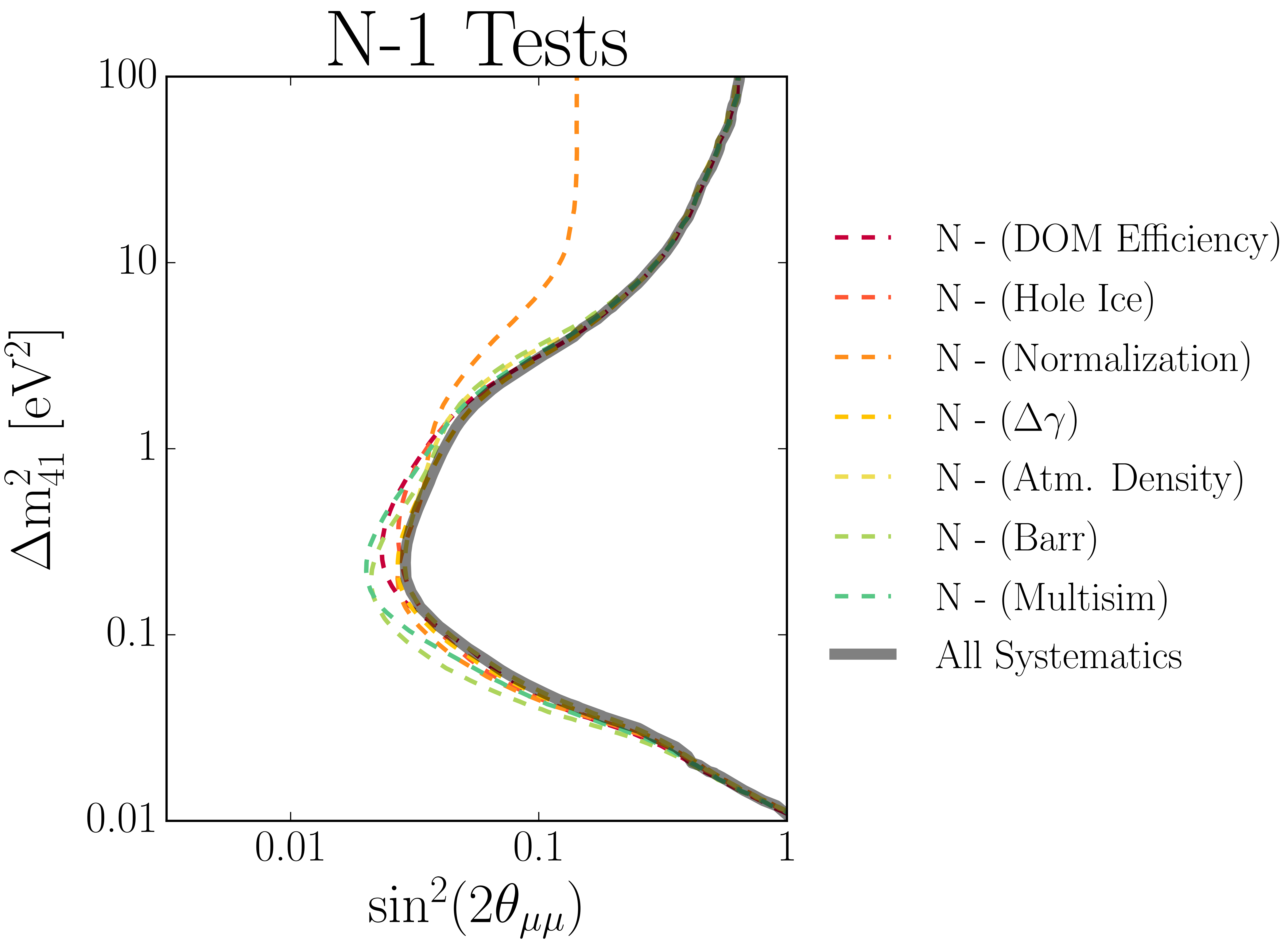
- Flux
  - Barr
  - CR spectral slope
  - Atm. Density
  - Normalization
- Detector
  - DOM efficiency
- Ice
  - IceStorm
  - HoleIce

The plot on the right holds all other systematics at the default value.

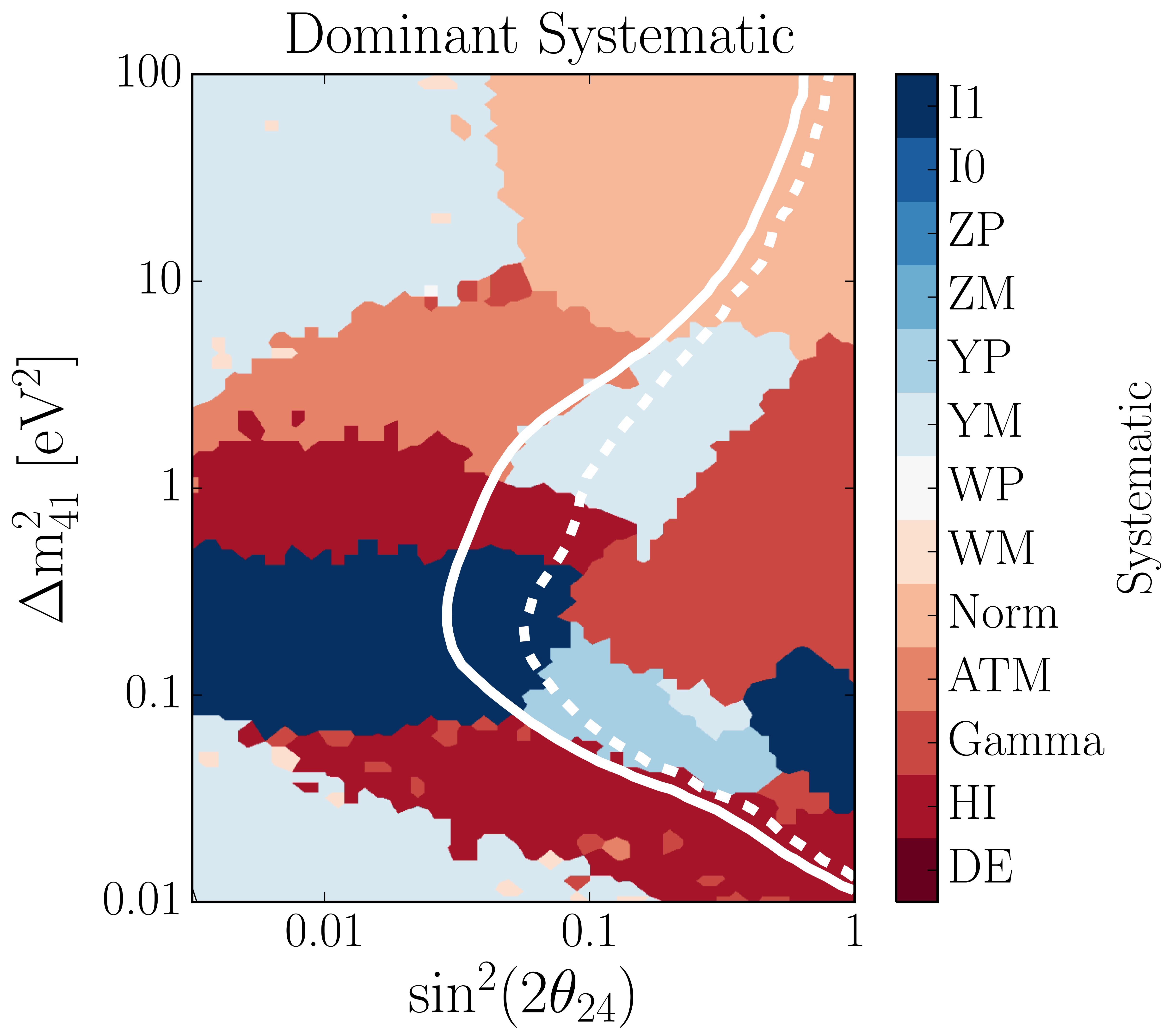


Asimov dataset: **N-1 Test**

This test minimizes the LLH using **all but one** of the systematics.



Dominant systematic pull in different regions



What are the dominant systematics at a particular sterile neutrino hypothesis?

I1 and I0 = IceGradient1 and IceGradient0

ZP, ZM, YP, YM, WP, WM = Barr parameters. Flux uncertainty.

Norm = Normalization of neutrinos.

ATM = The uncertainty of the atmospheric density.

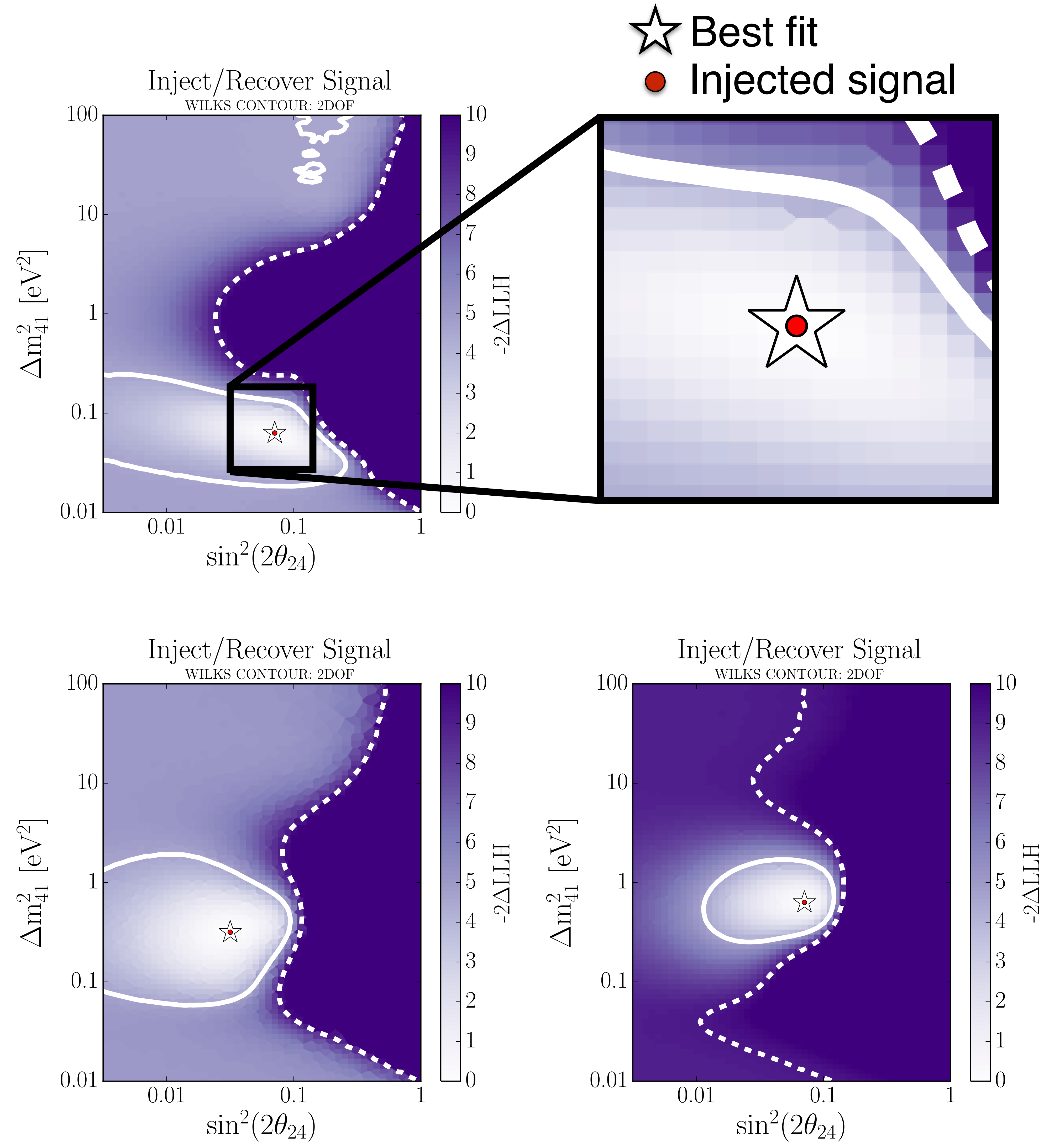
CR = The cosmic ray spectral slope.

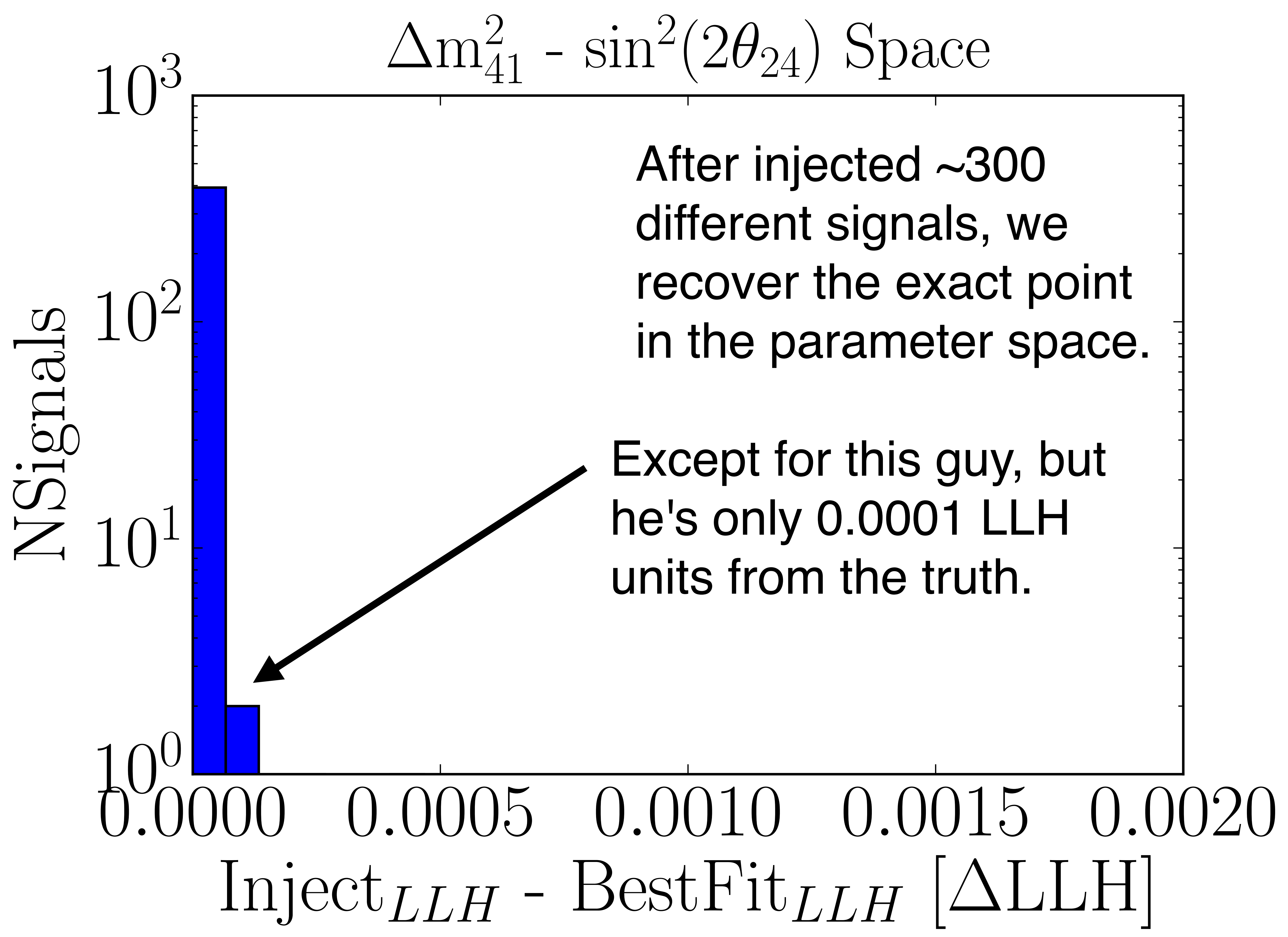
HI = The uncertainty in the hole ice.

DE = The uncertainty in the DOM efficiency.

BI = Bulk ice uncertainty.

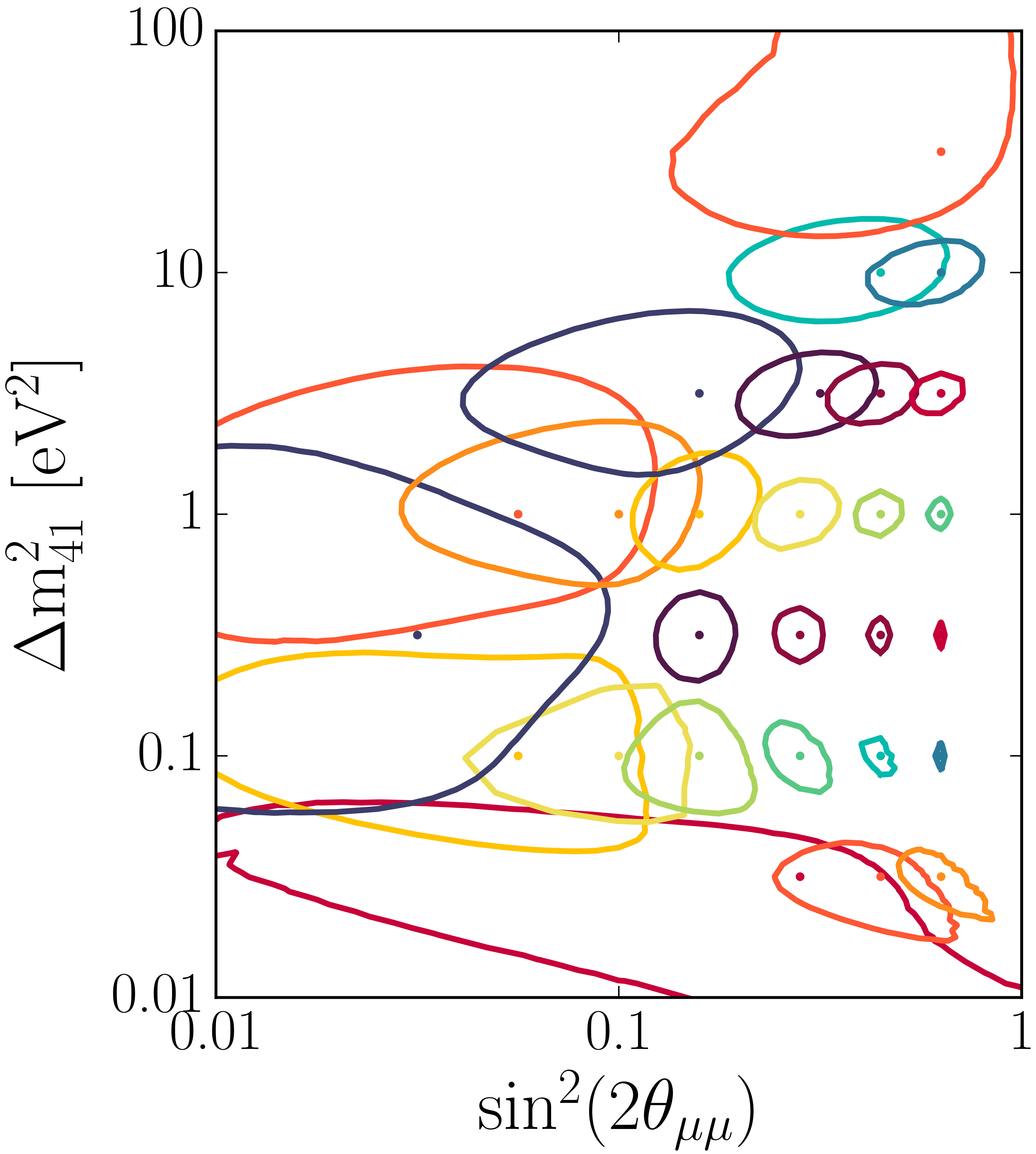
Asimov datasets: inject recover signals





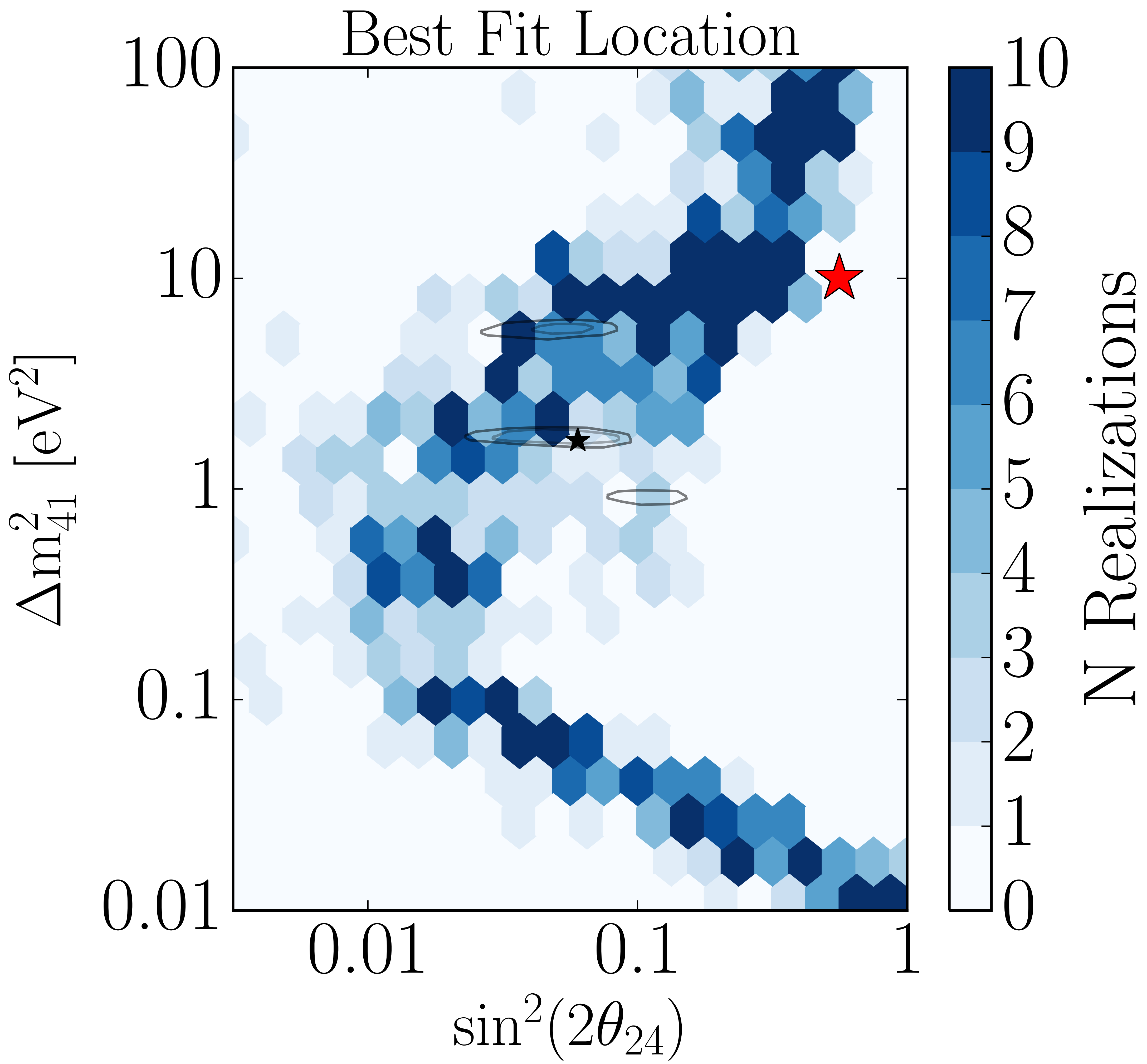
Asimov datasets: inject recover signals

The 90% contour given an injected point at "."

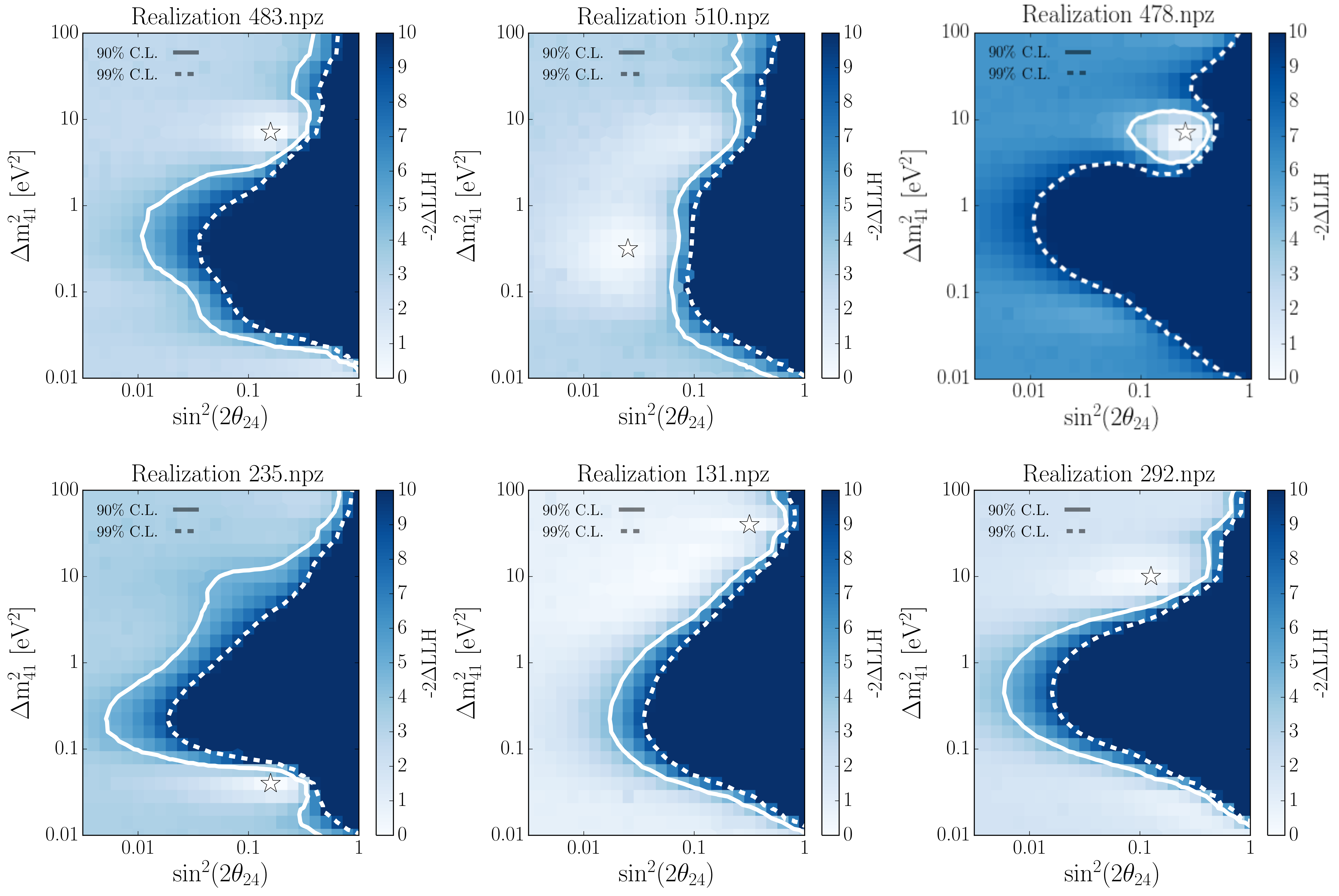


Ensemble tests: best fit location

Given 1000 realizations, where is the minima in the LLH space?

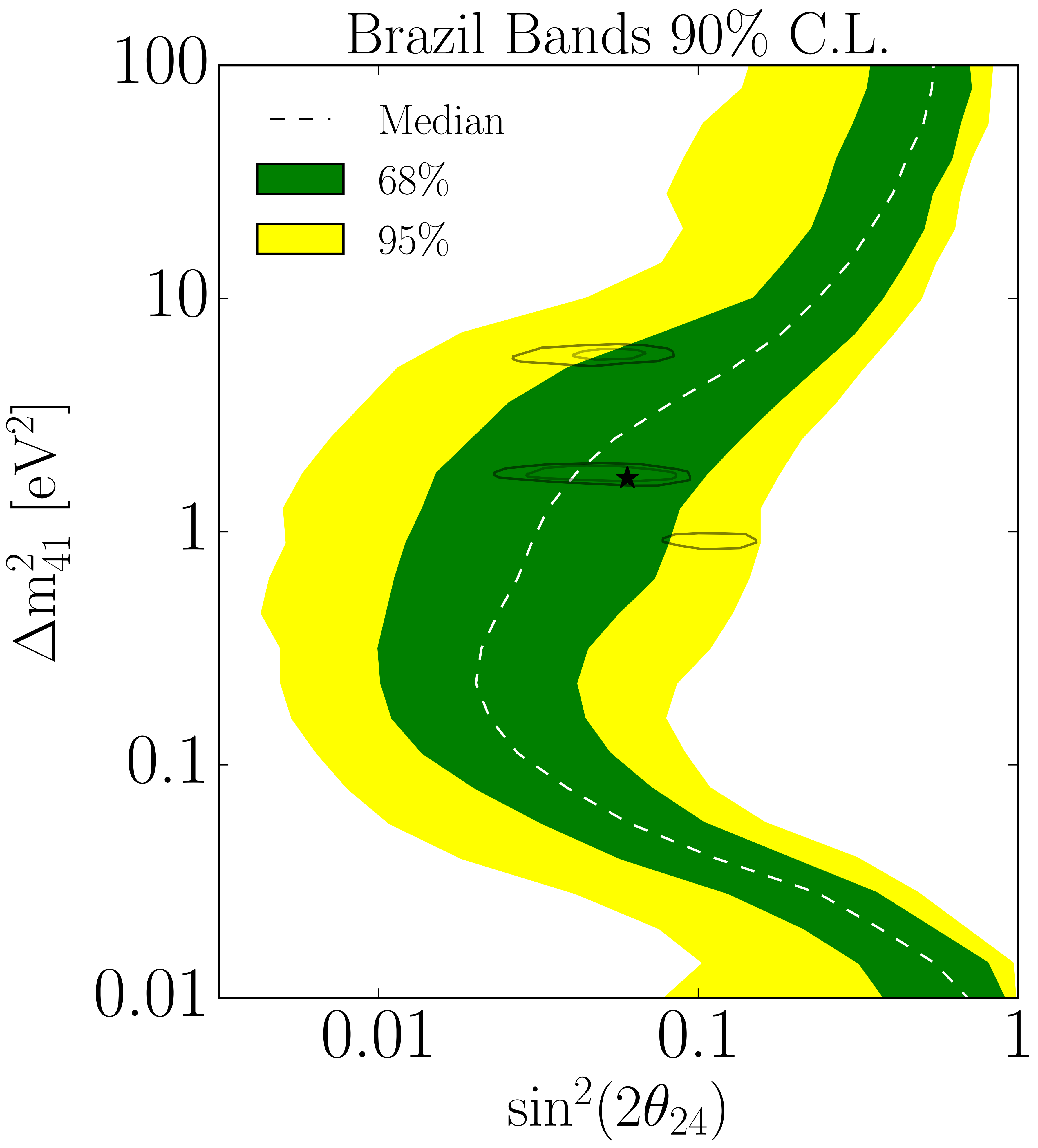


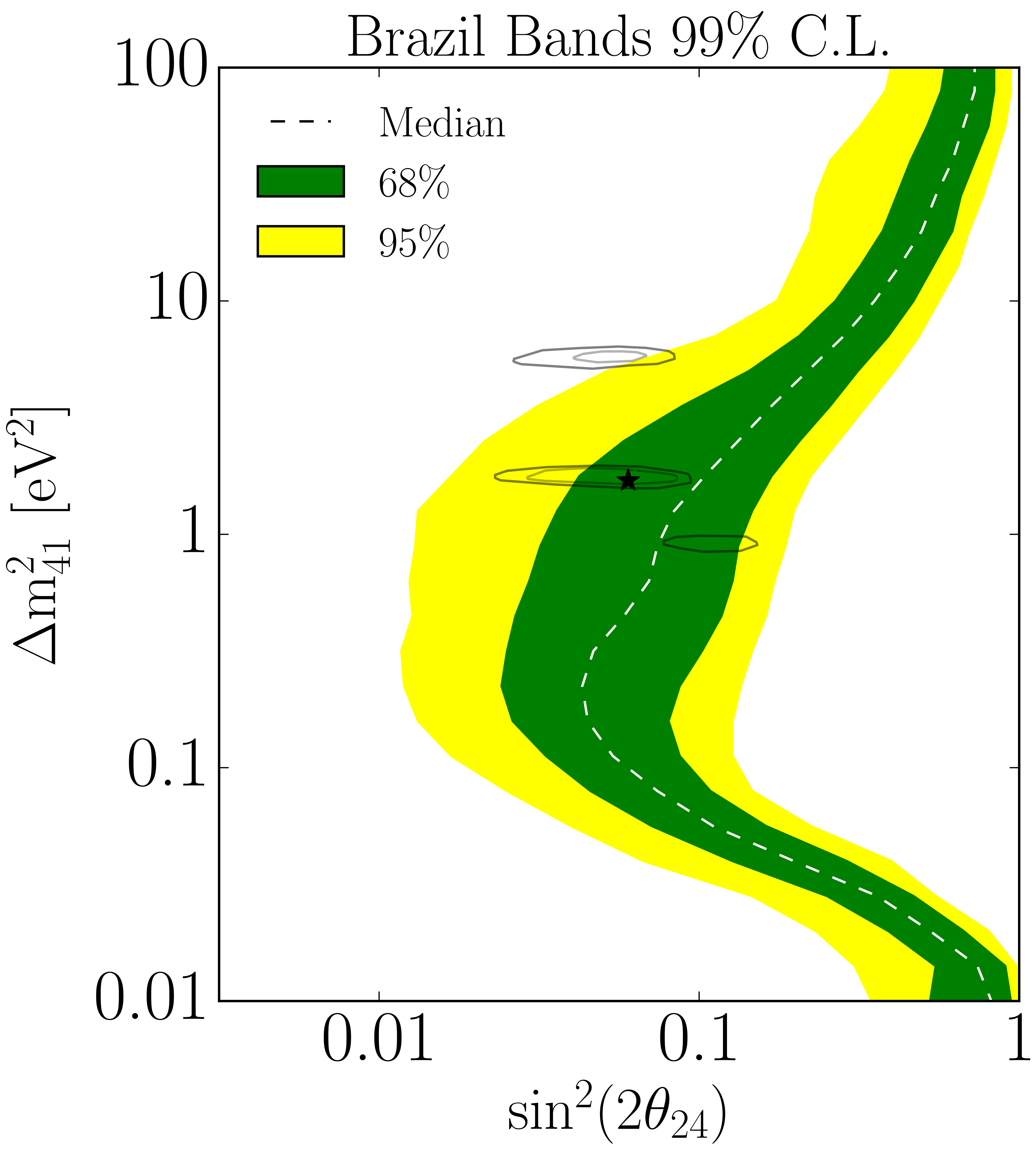
Example realizations



The Brazil Bands for the 90% and 99% CL

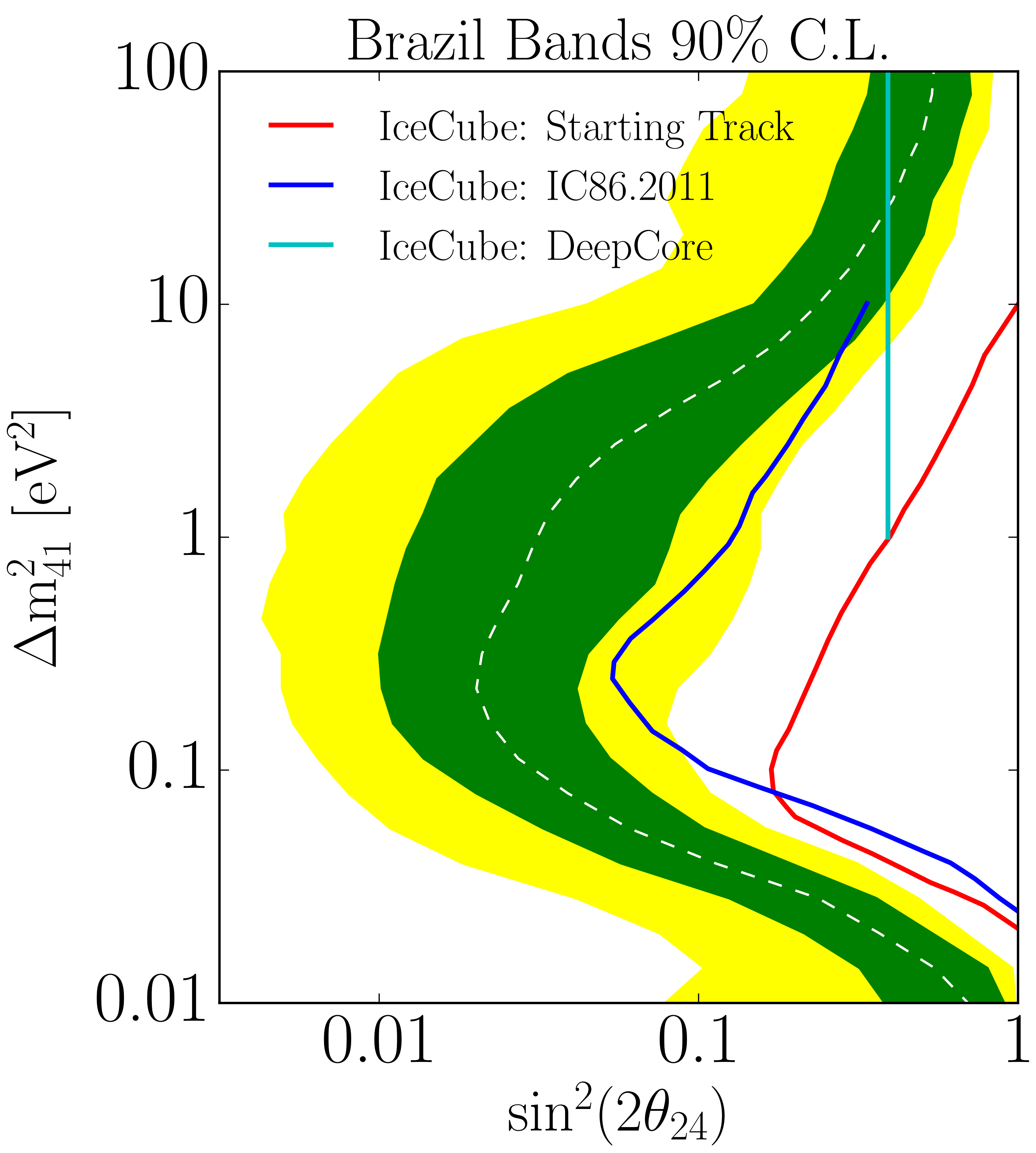
Describes the spread of the 90% and 99% contours from the realizations.



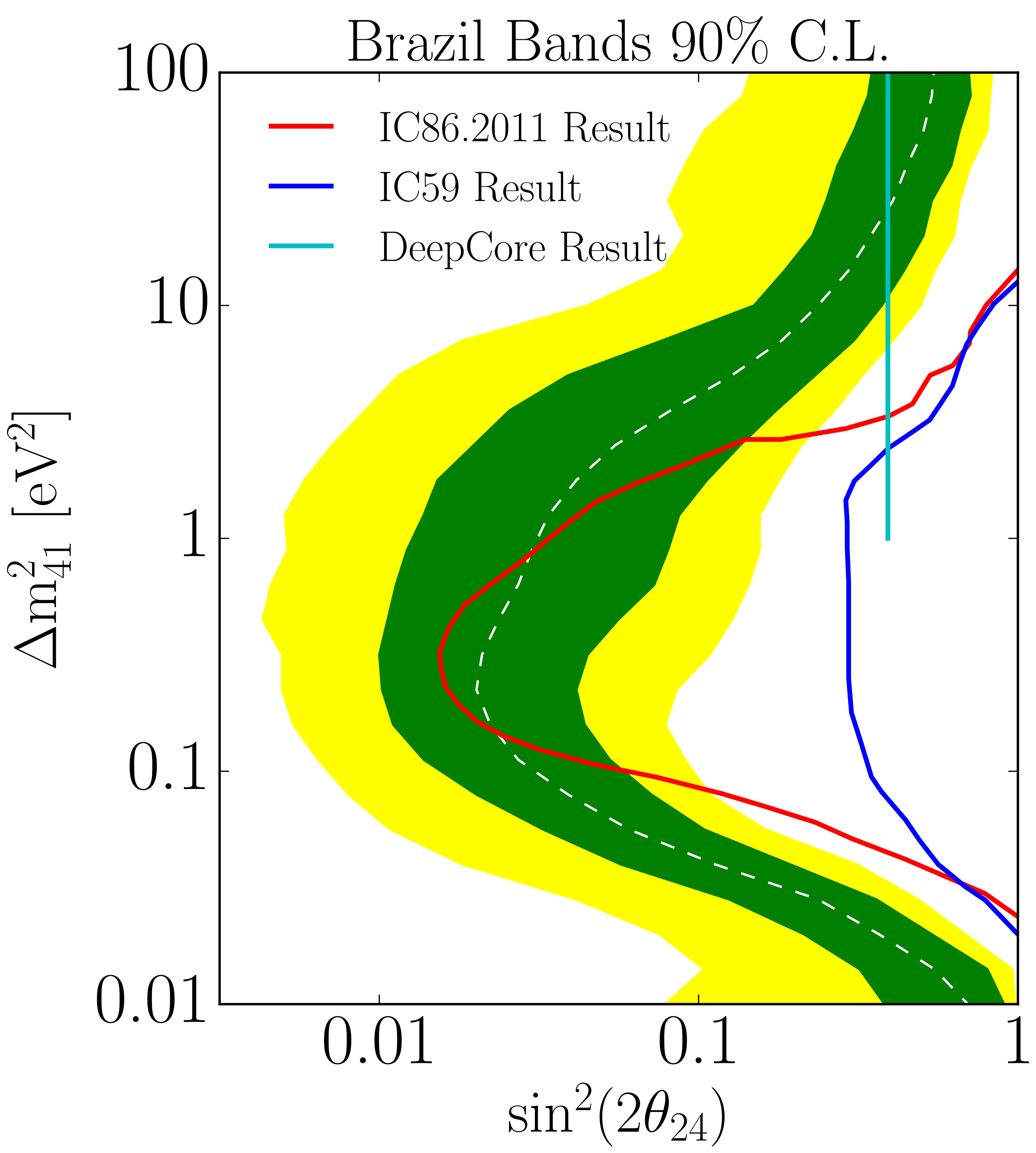


Brazil bands in context

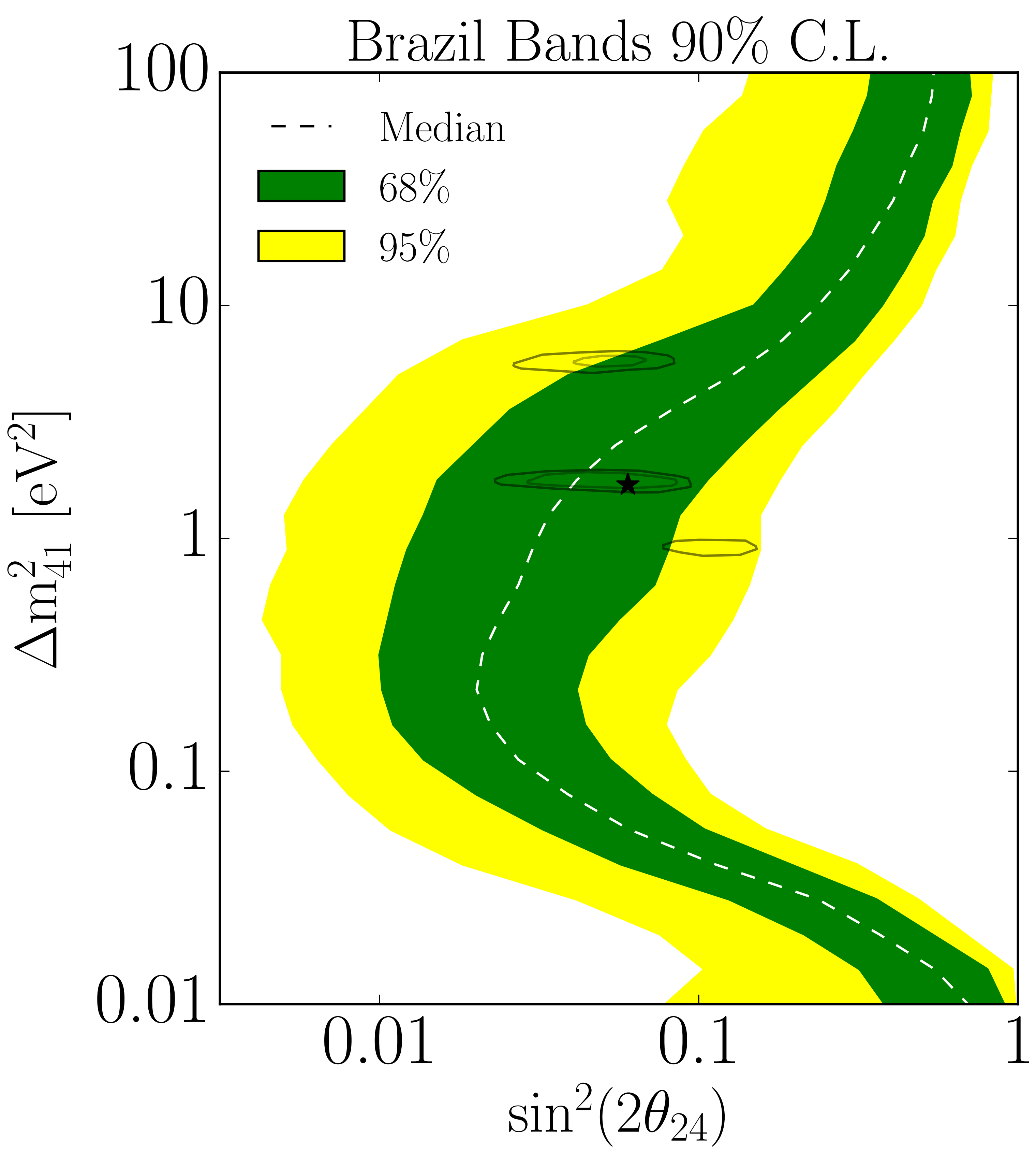
Comparing to IC **sensitivities**.



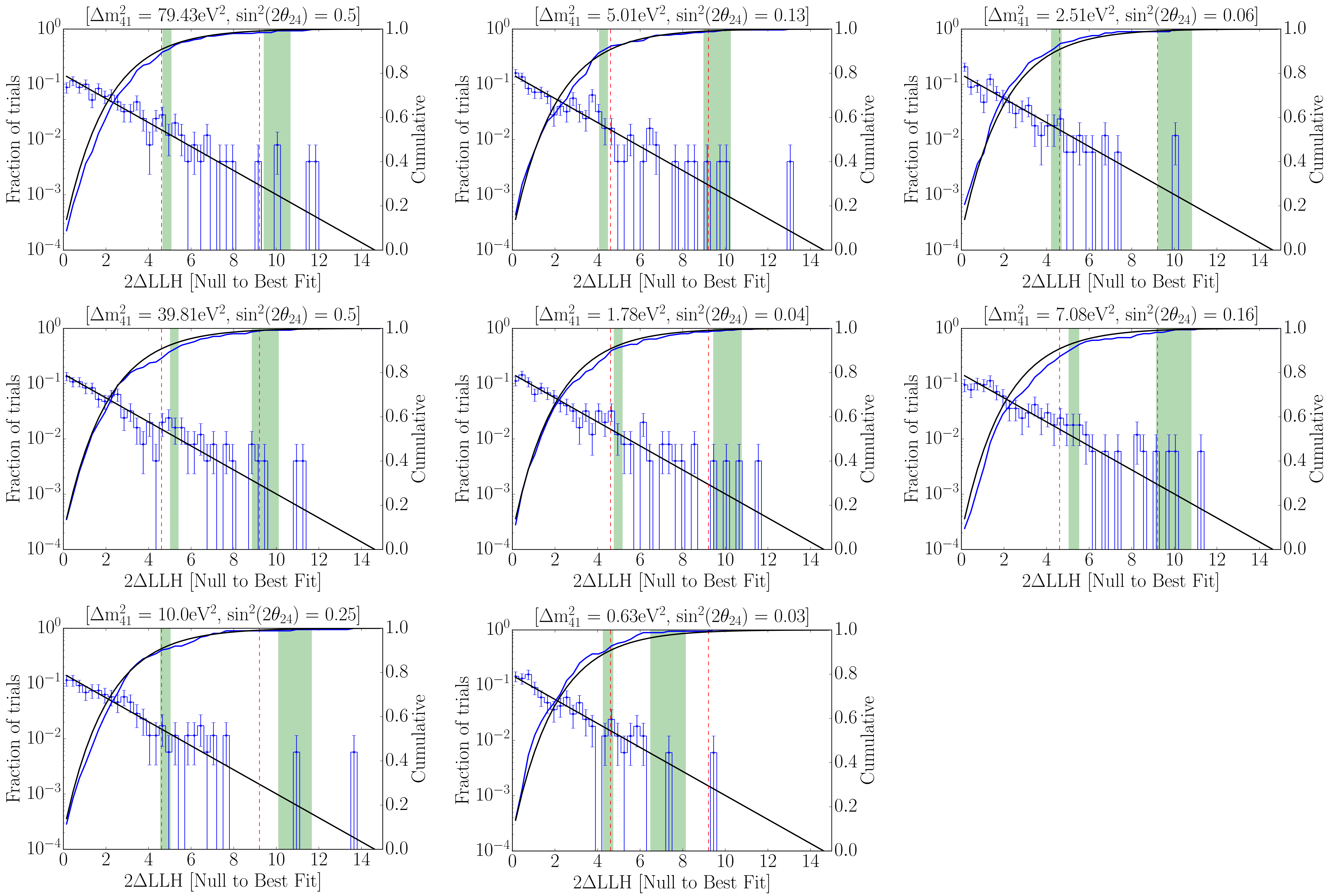
Comparing to IC **Results**.

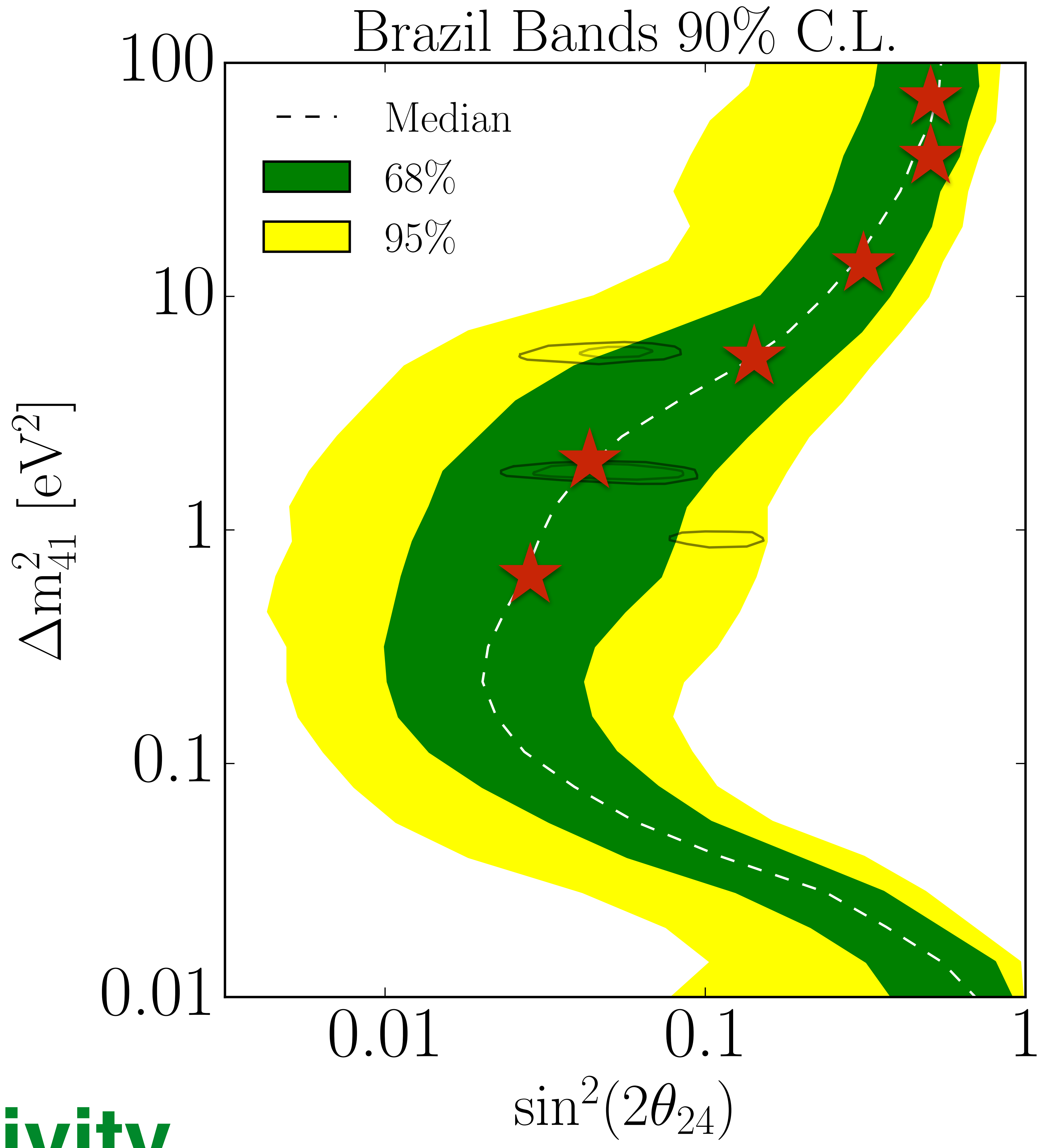


Comparing to **Global Best fit**.



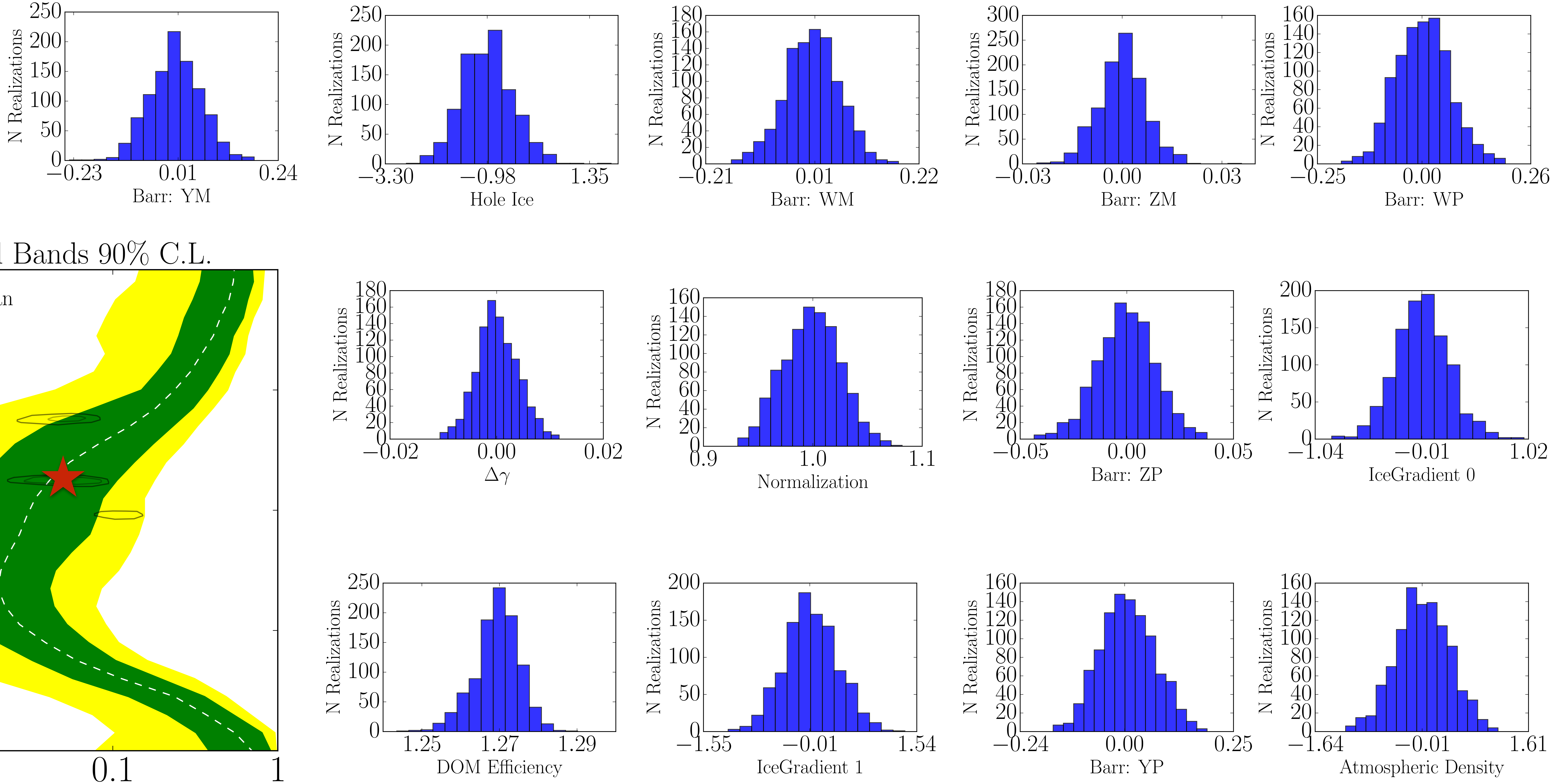
Coverage checks (2DOF)

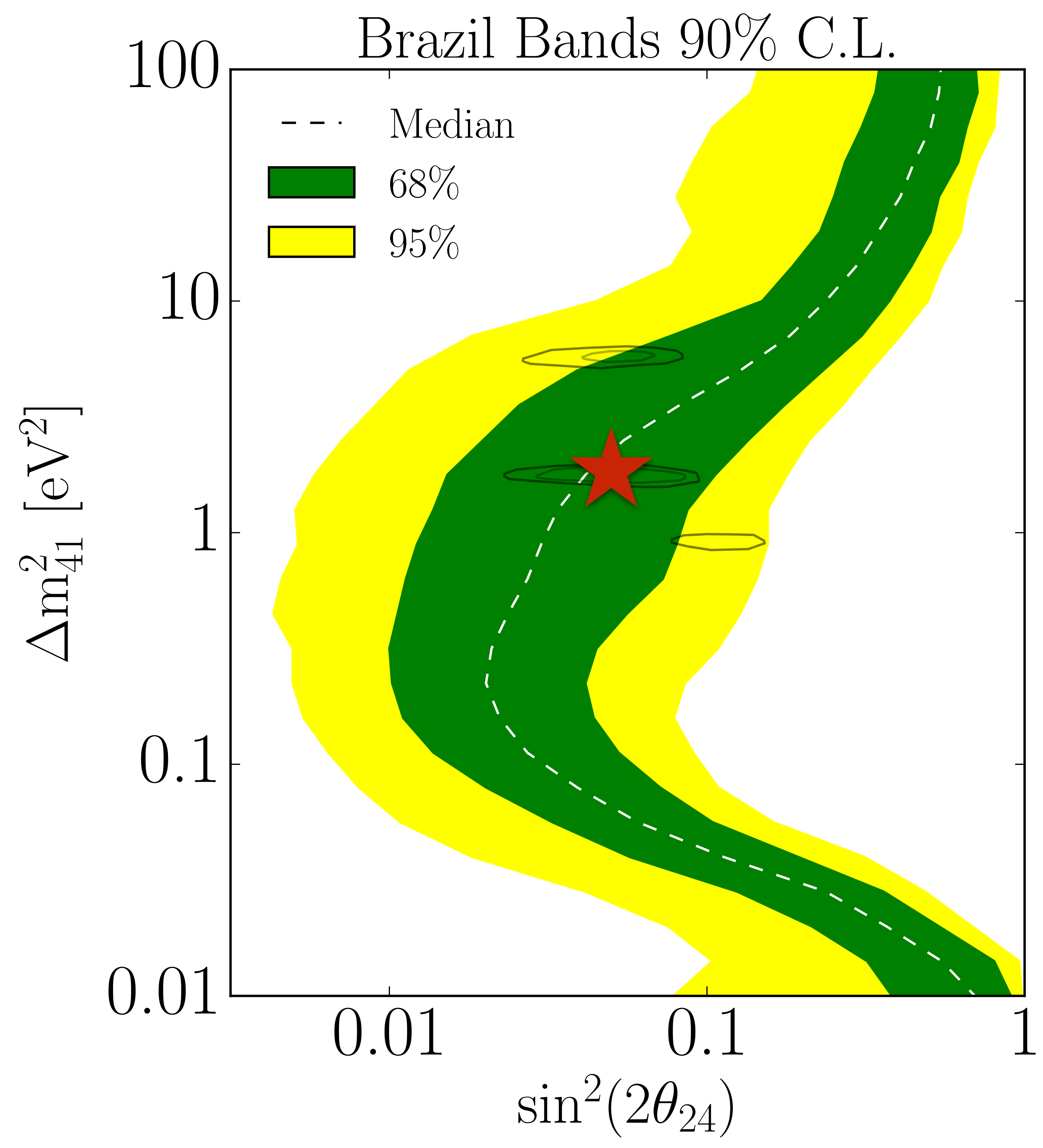




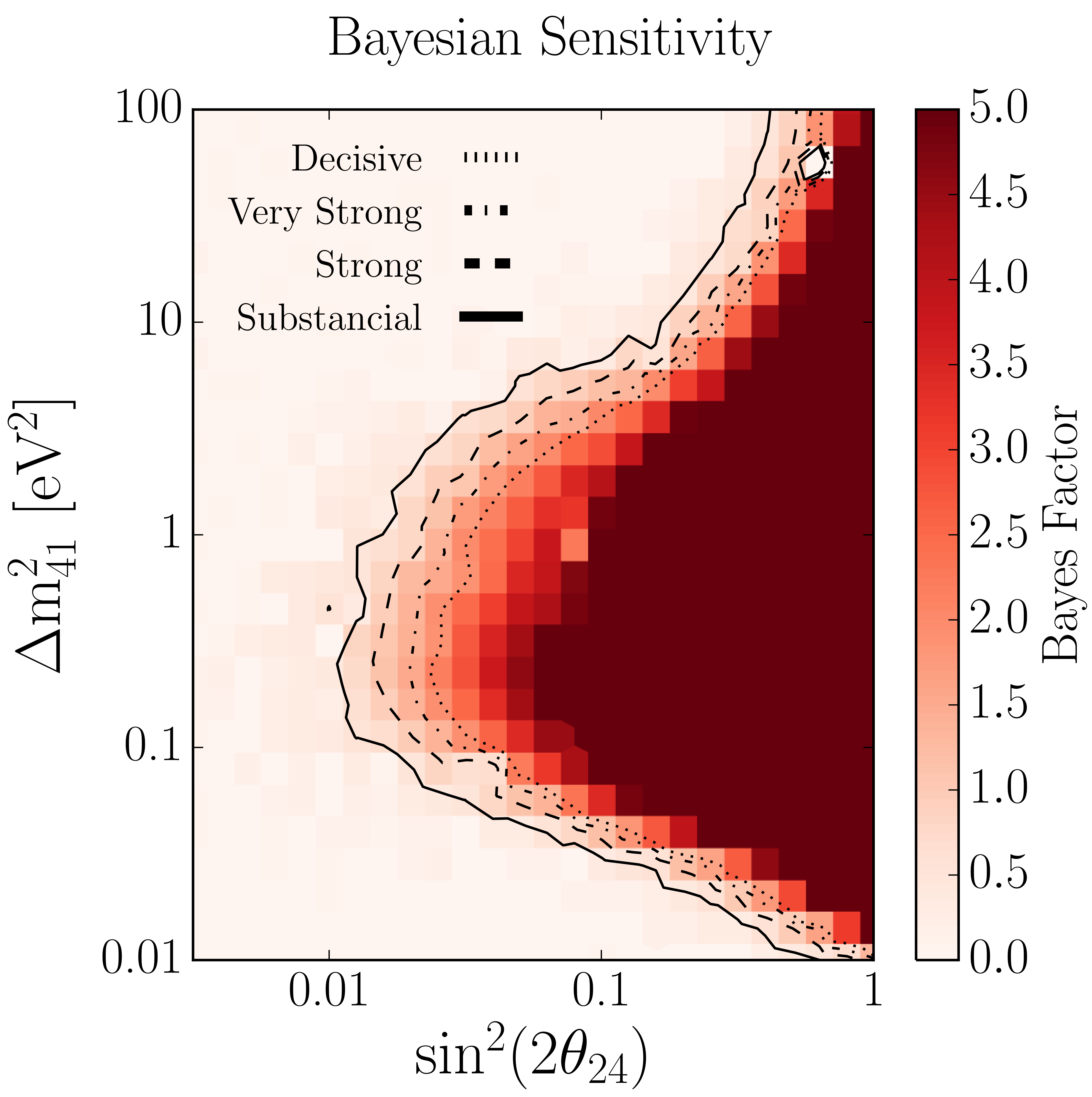
Good coverage across median sensitivity

Minimized systematic value from 1000 realizations





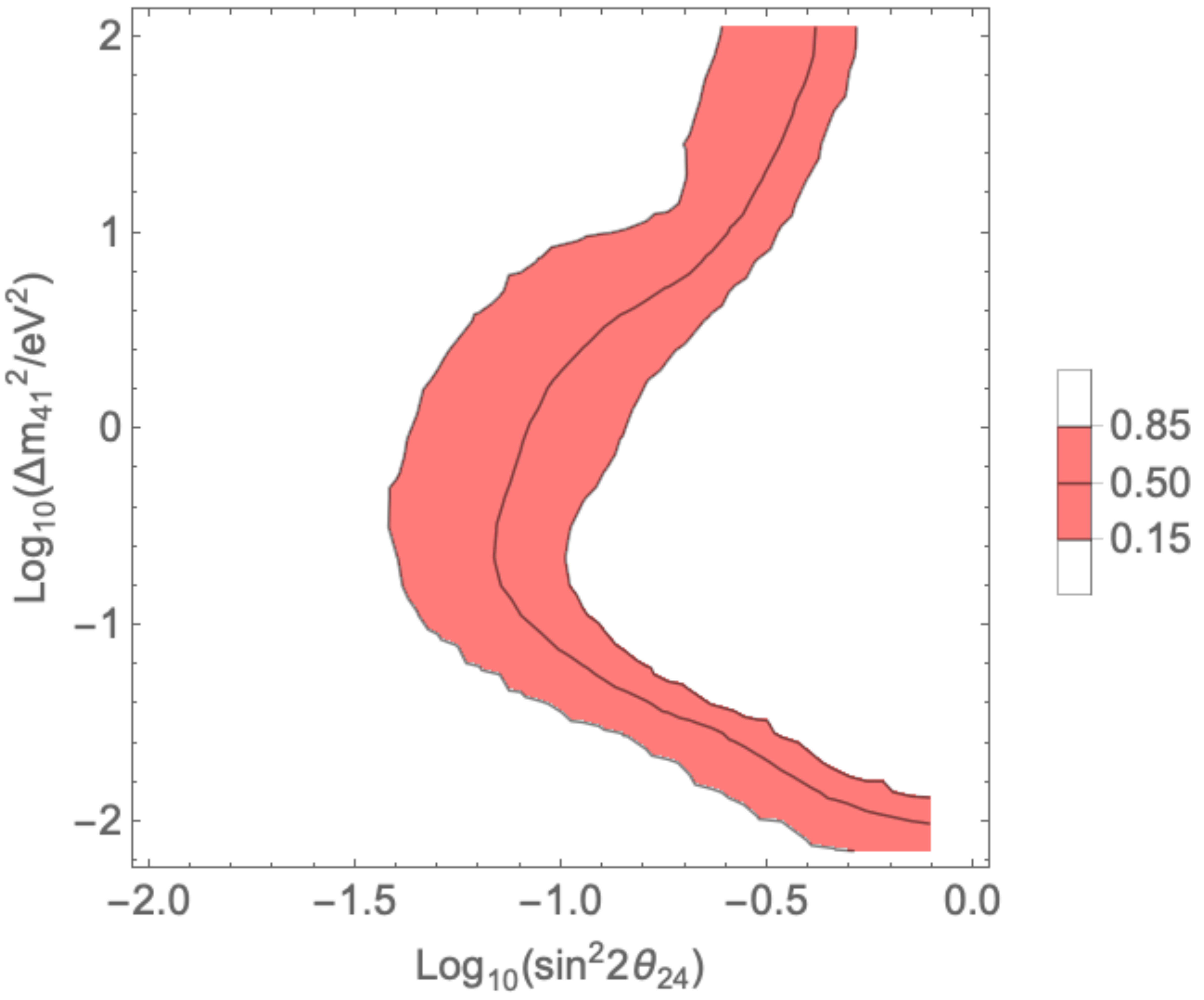
Bayesian sensitivity



- Contour insensitive to best fit.
- Comparing two models:
  - 3+1 hypothesis vs. No sterile hypothesis.
- "Decisive" contour is similar to the 90% Frequentist sensitivity.
- Procedure inseisitive to priors on sterile neutrino parameters

$$\mathcal{E}(\vec{\theta}) = \int d\vec{\eta}\mathcal{L}(\vec{\theta}, \vec{\eta})$$

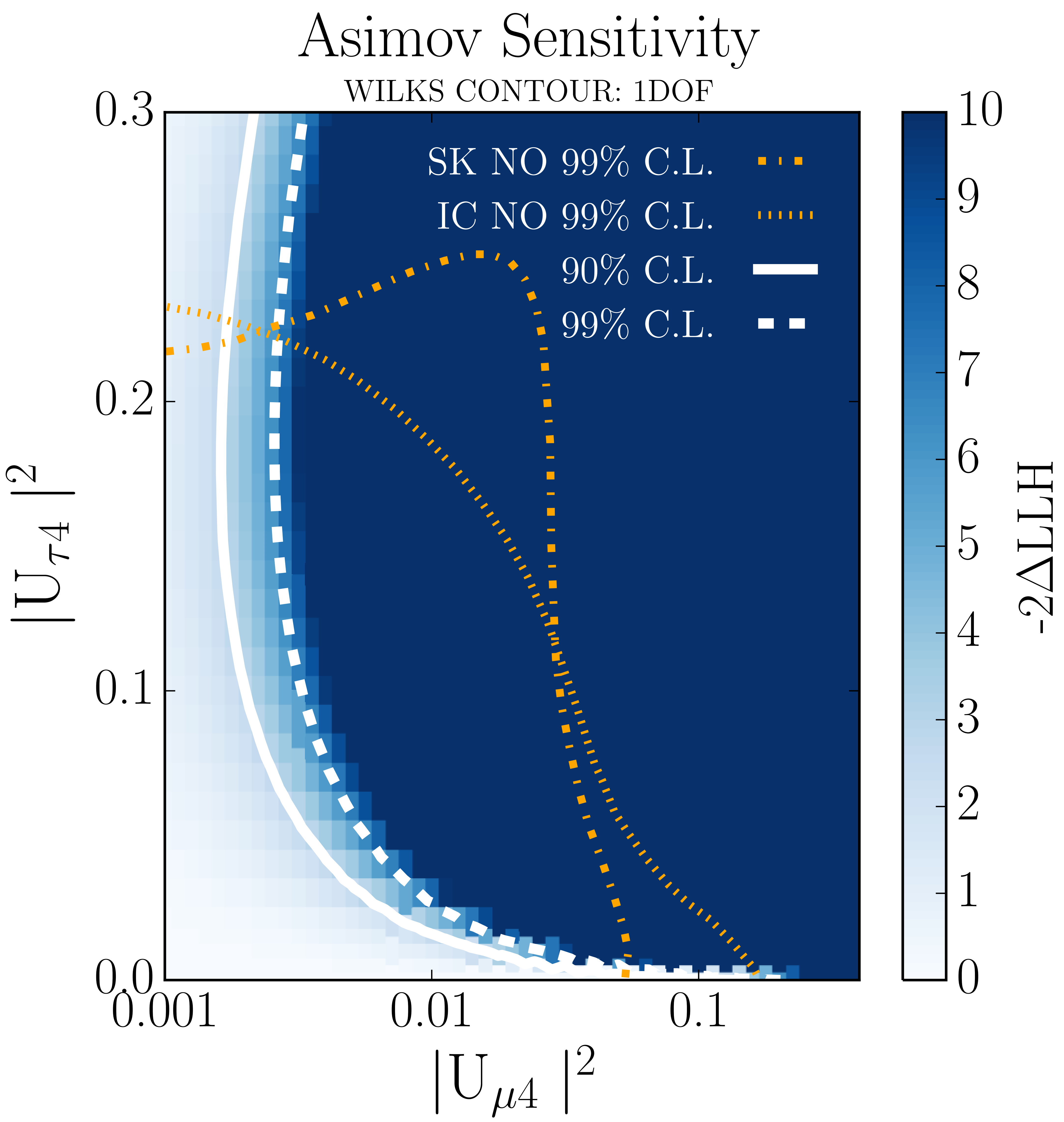
The Peru Plot



Analysis II

$[|U_{\mu 4}|^2, |U_{\tau 4}|^2]$

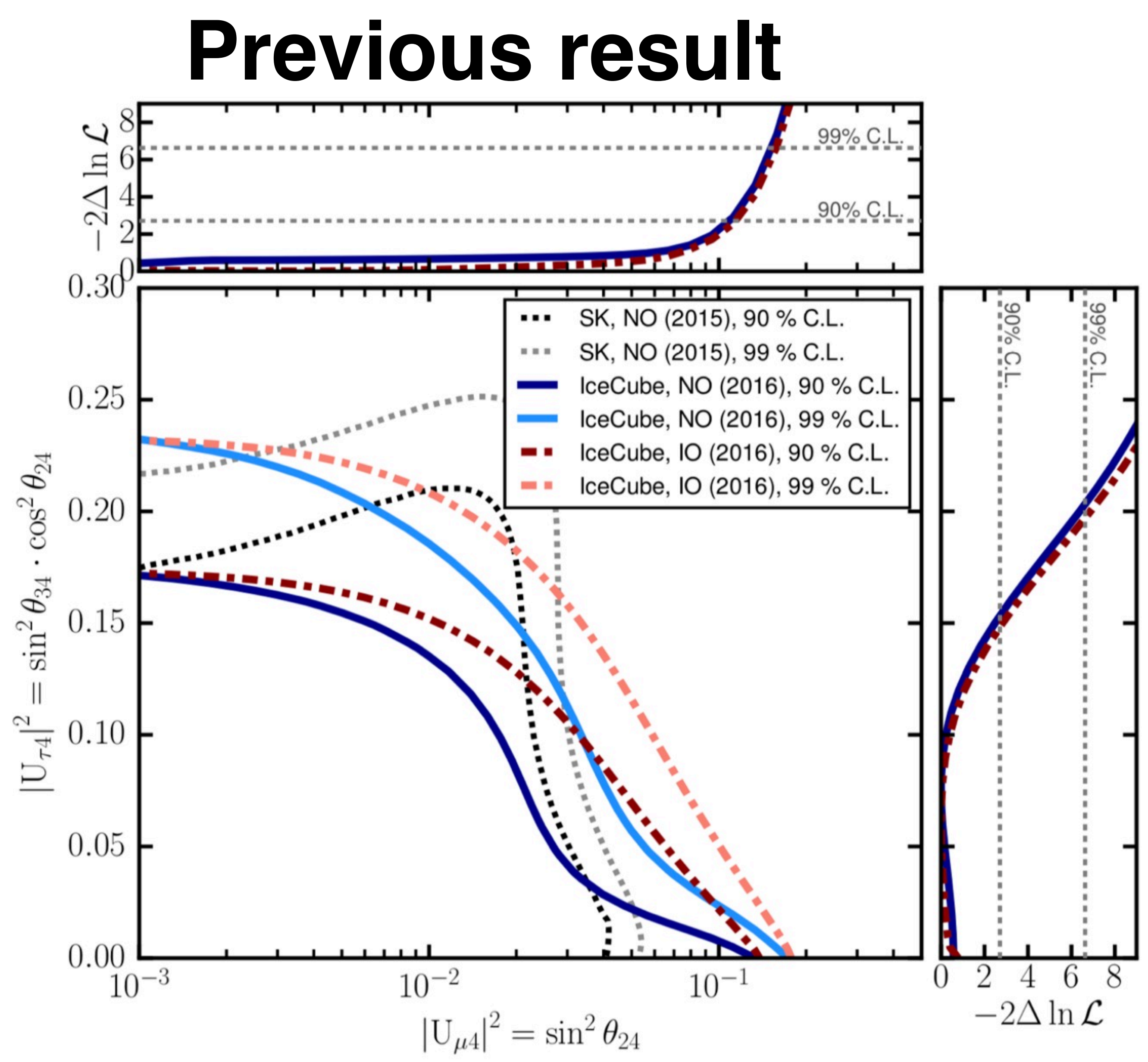
Asimov dataset: Asimov sensitivity



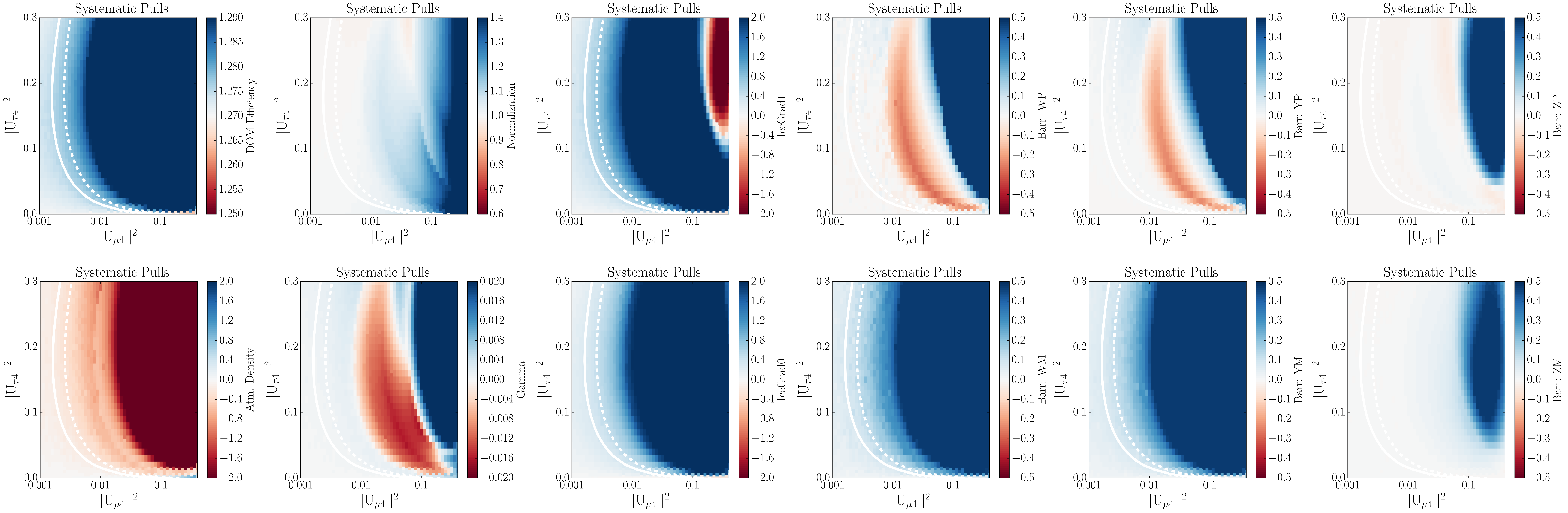
This plot is for $\Delta m_{41}^2 > 20 eV^2$.

It is a conservative limit that becomes stronger as we lower Δm^2 (down to approximate $0.01 eV^2$)

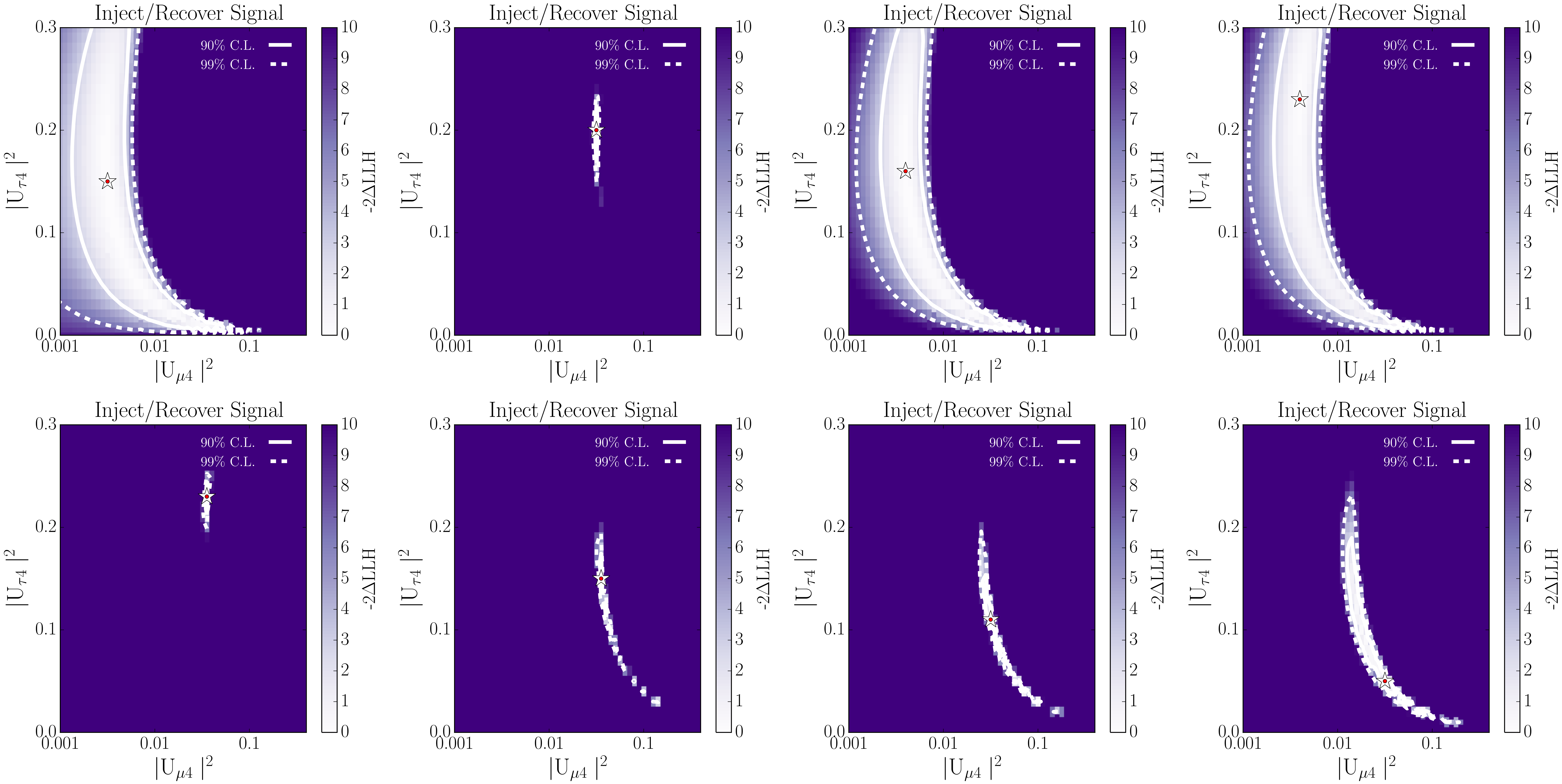
Previous results from IceCube and SK are shown.



Asimov dataset: systematic pulls

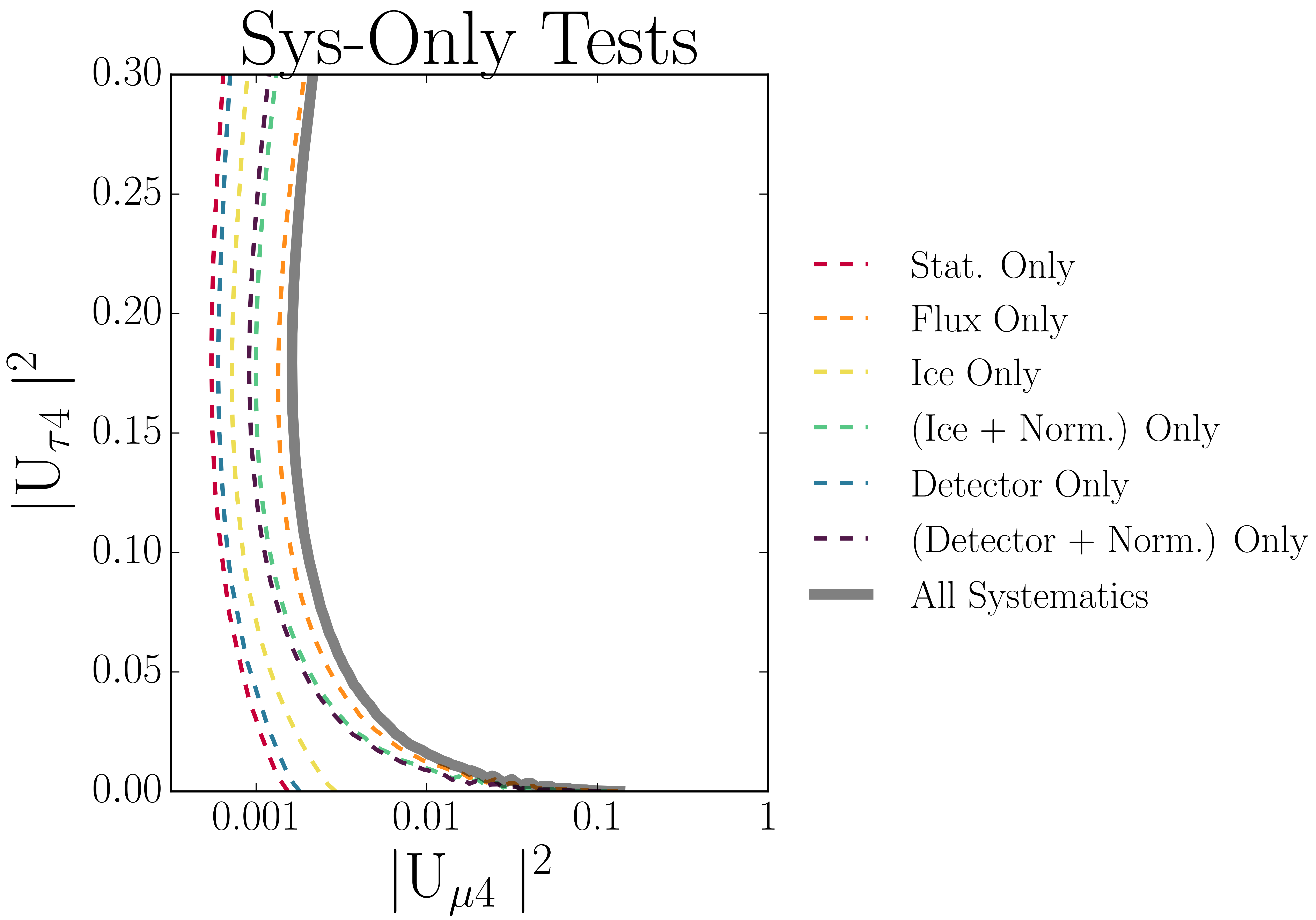


Asimov dataset: Inject recover signals



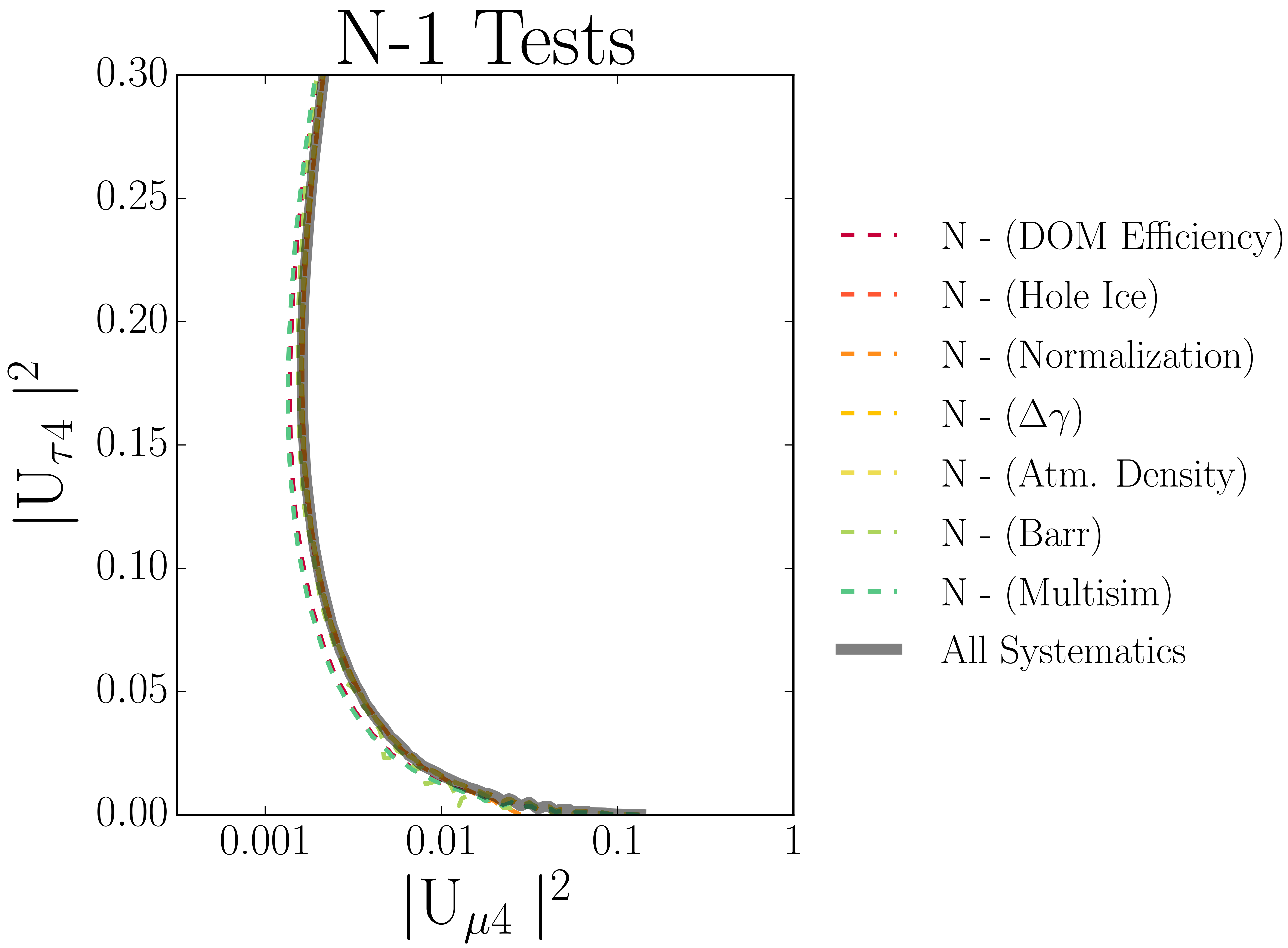
Asimov dataset: Systematic test (N-1)

Grouping the systematics into those related to the detector, ice, and flux.

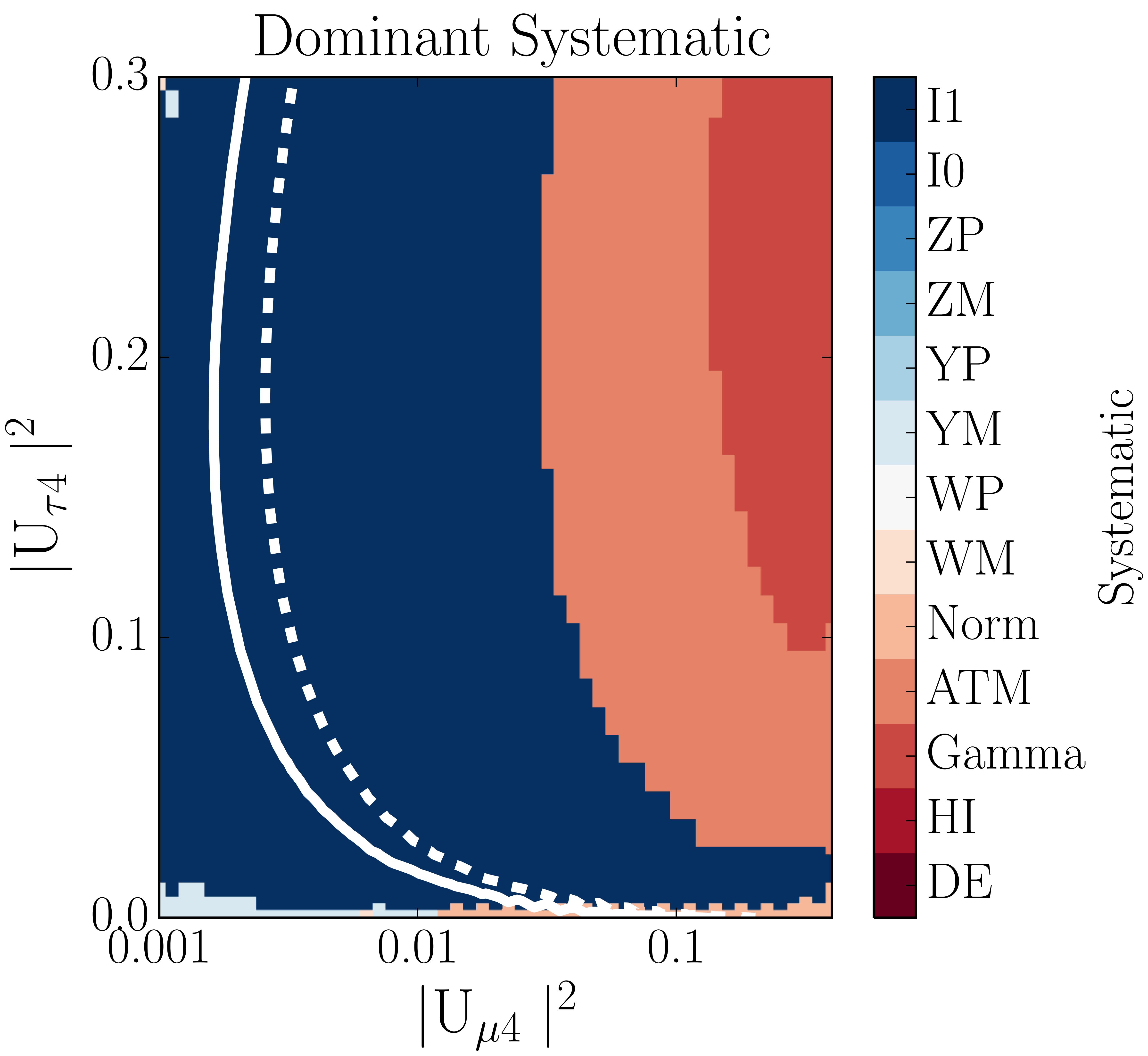


Asimov dataset: Systematic test (N-1)

This test removes one systematic at a time and then calculates the 90% CL sensitivity.



Dominant systematic pull in different regions



What are the dominant systematics at a particular sterile neutrino hypothesis?

I1 and I0 = IceGradient1 and IceGradient0

ZP, ZM, YP, YM, WP, WM = Barr parameters. Flux uncertainty.

Norm = Normalization of neutrinos.

ATM = The uncertainty of the atmospheric density.

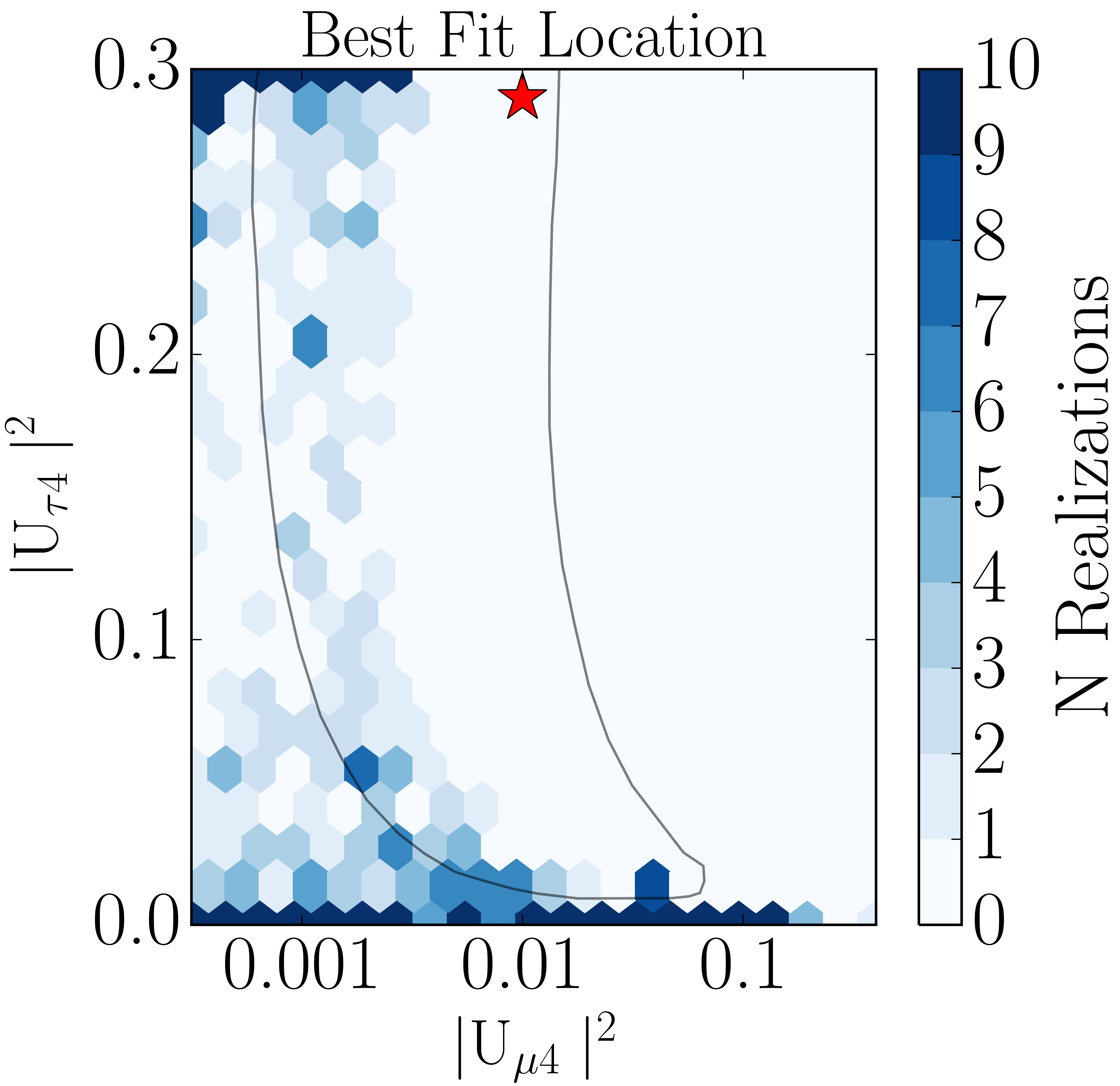
CR = The cosmic ray spectral slope.

HI = The uncertainty in the hole ice.

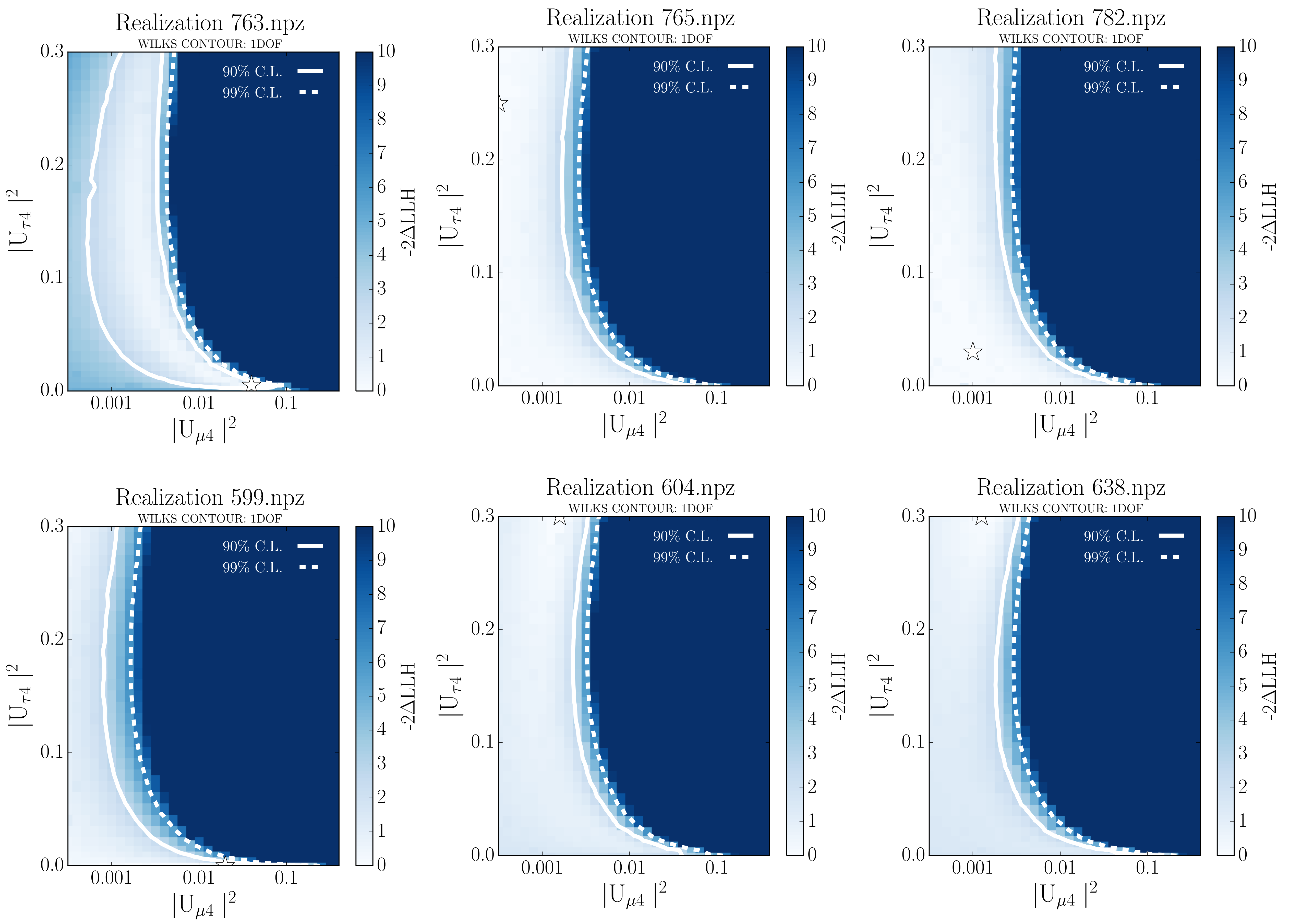
DE = The uncertainty in the DOM efficiency.

BI = Bulk ice uncertainty.

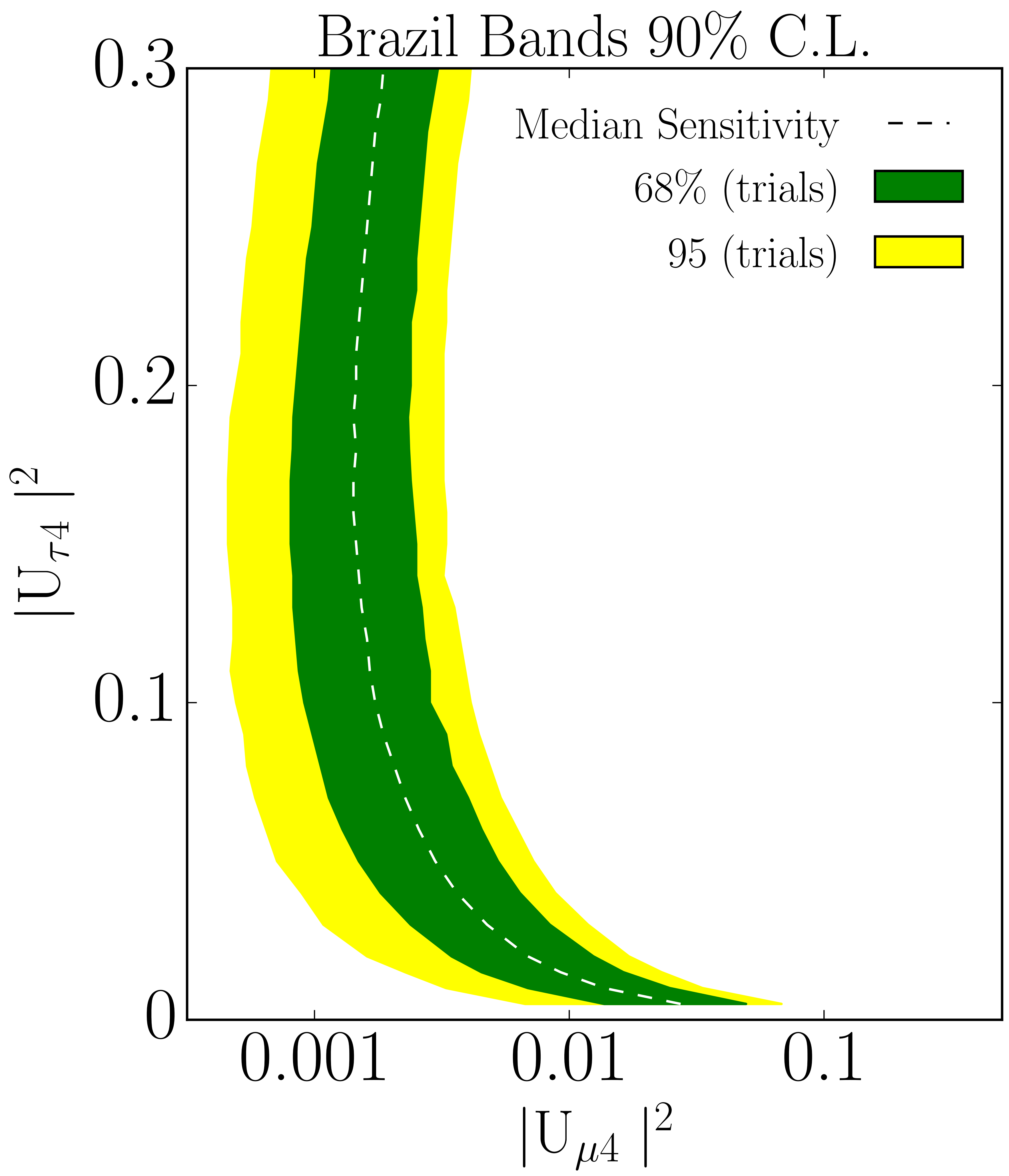
Best fit location

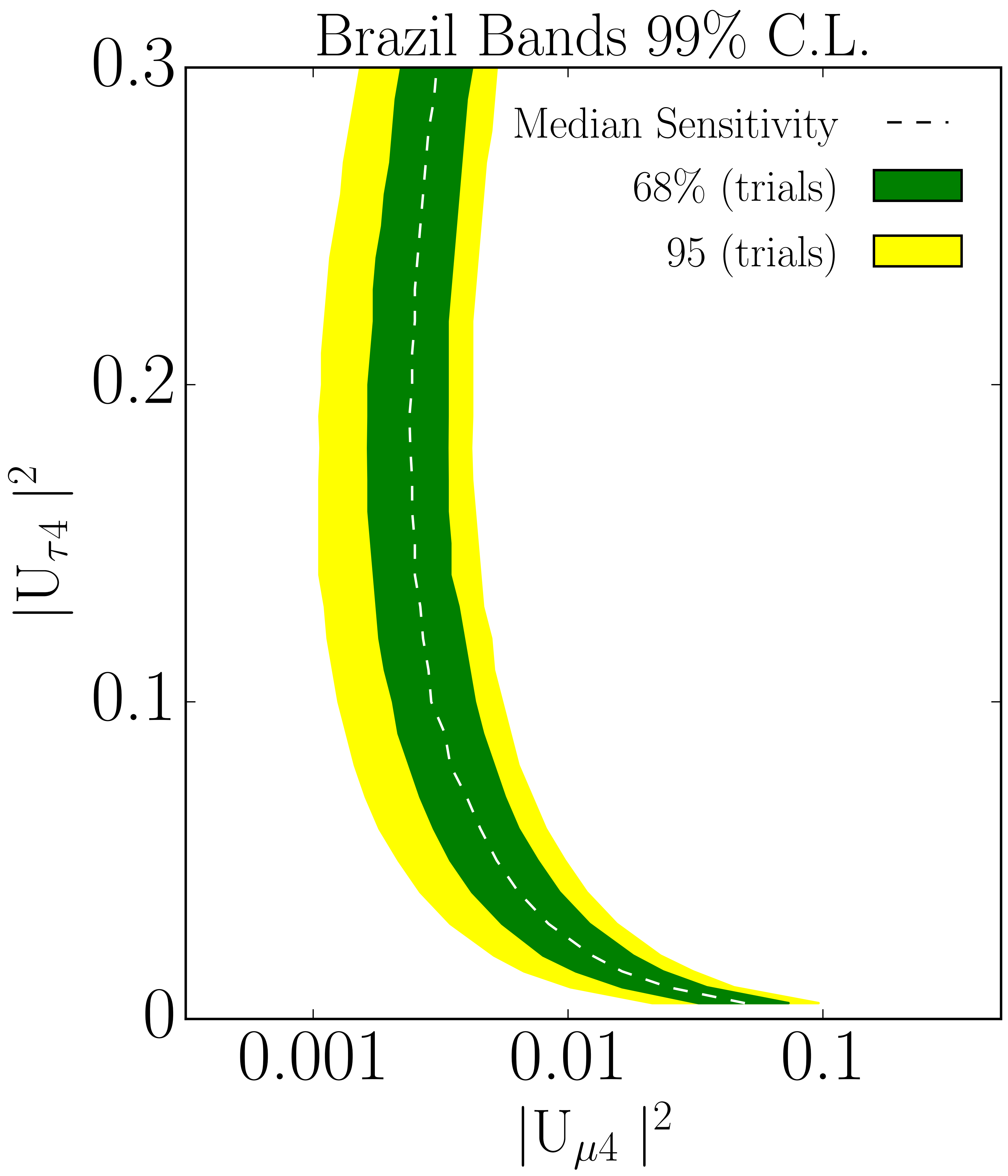


Example realizations



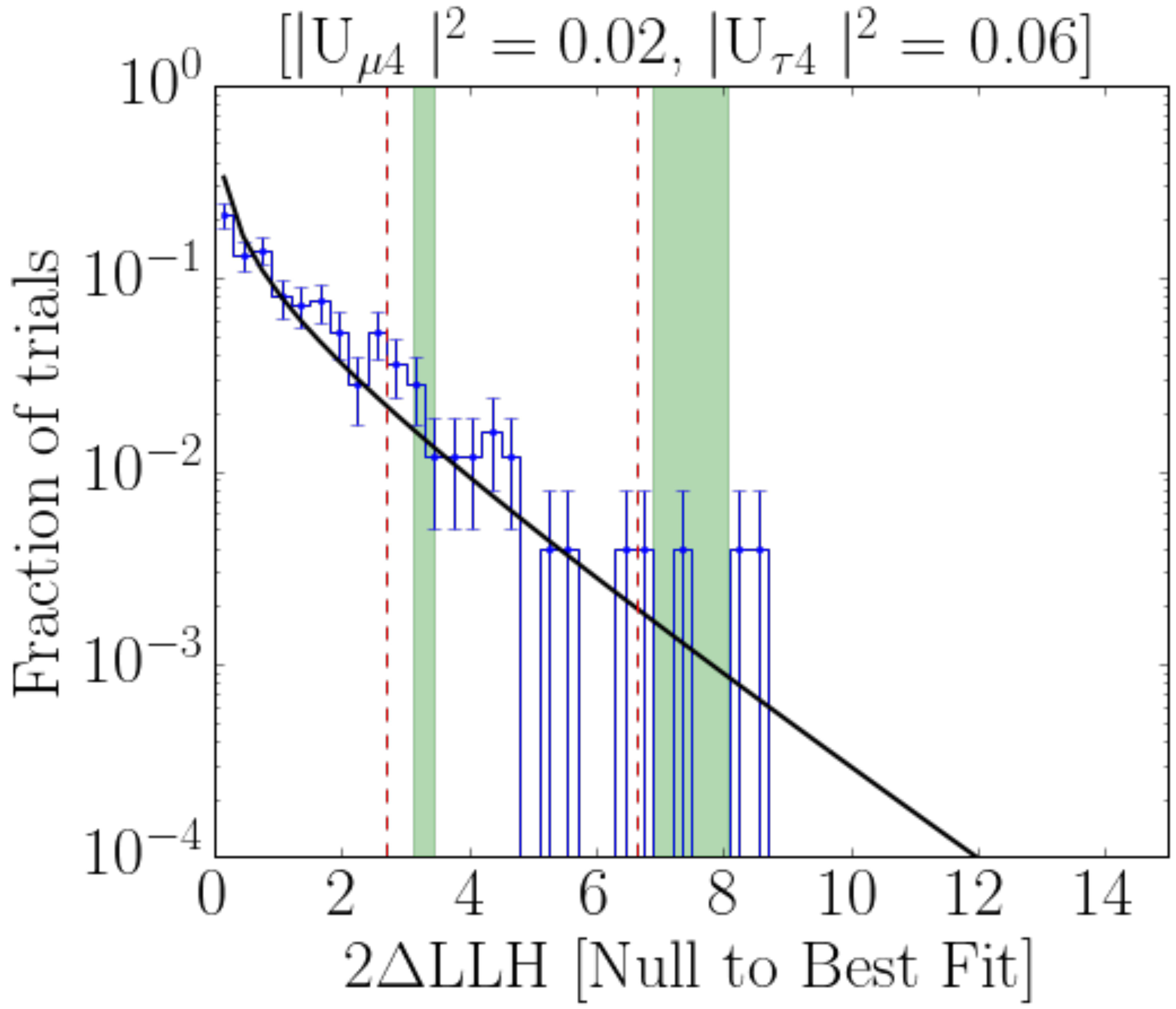
Brazil Bands. 1000 realizations

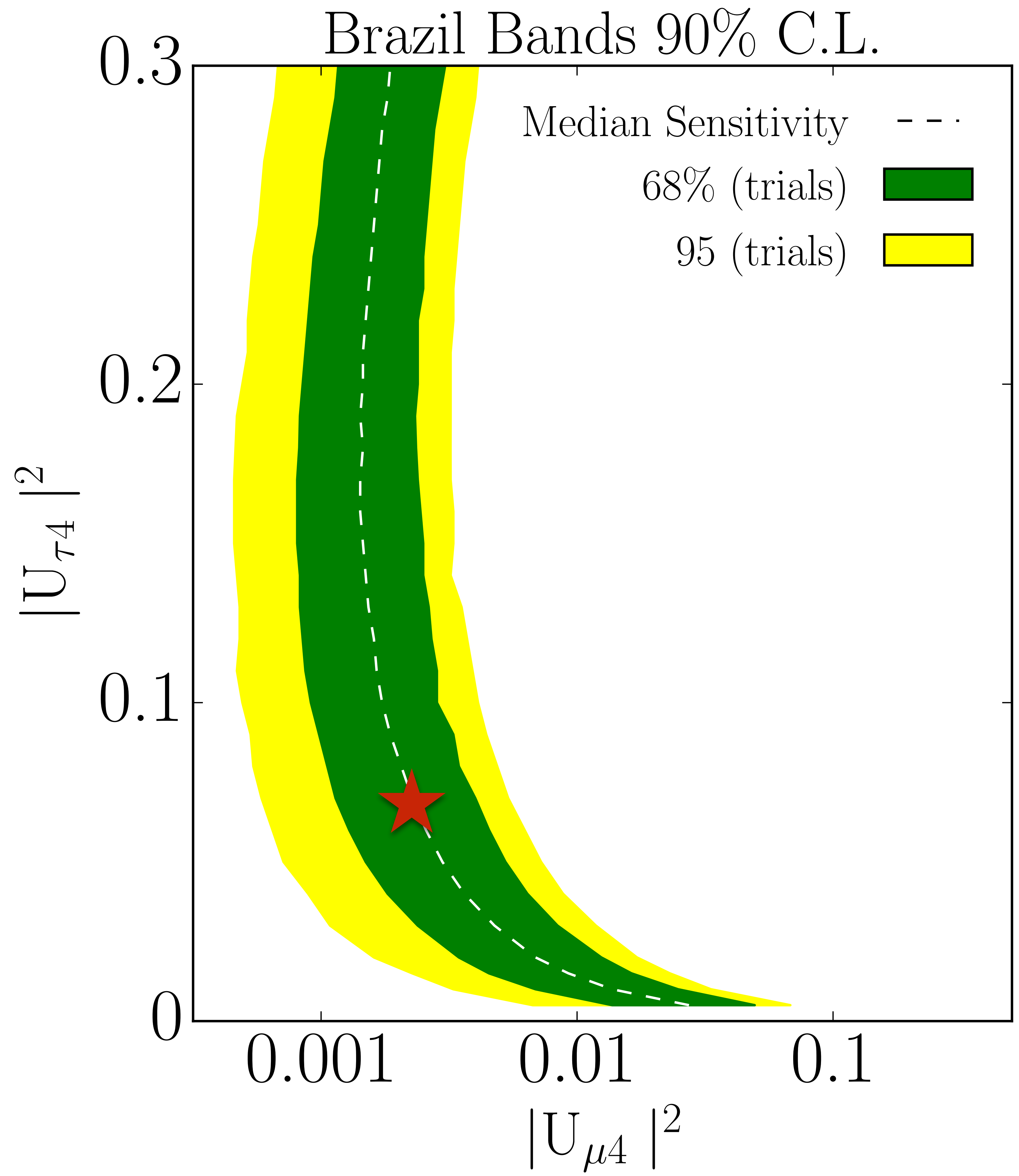




Coverage checks (1DOF)

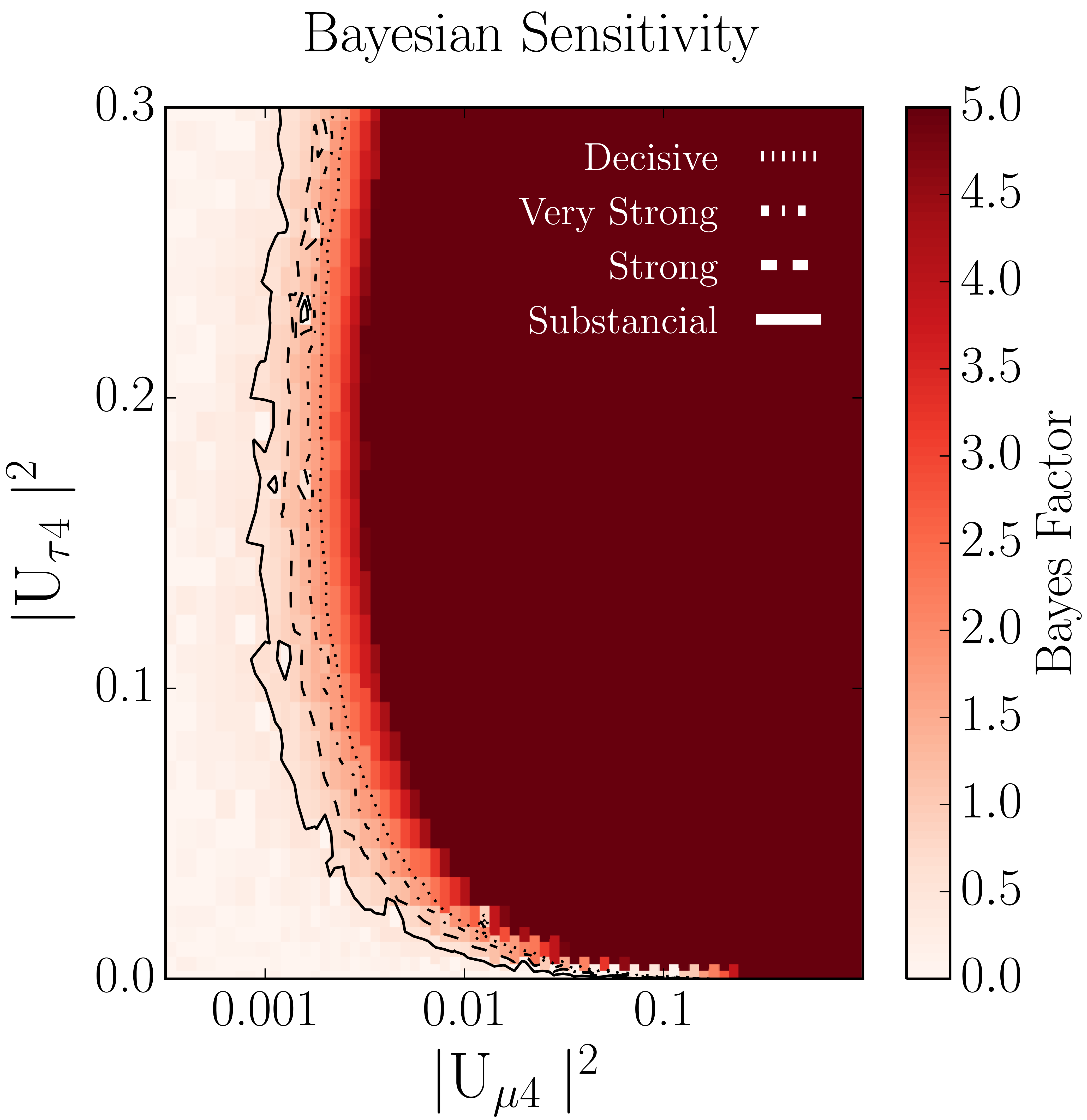
WORST Case , set to 2DOF.

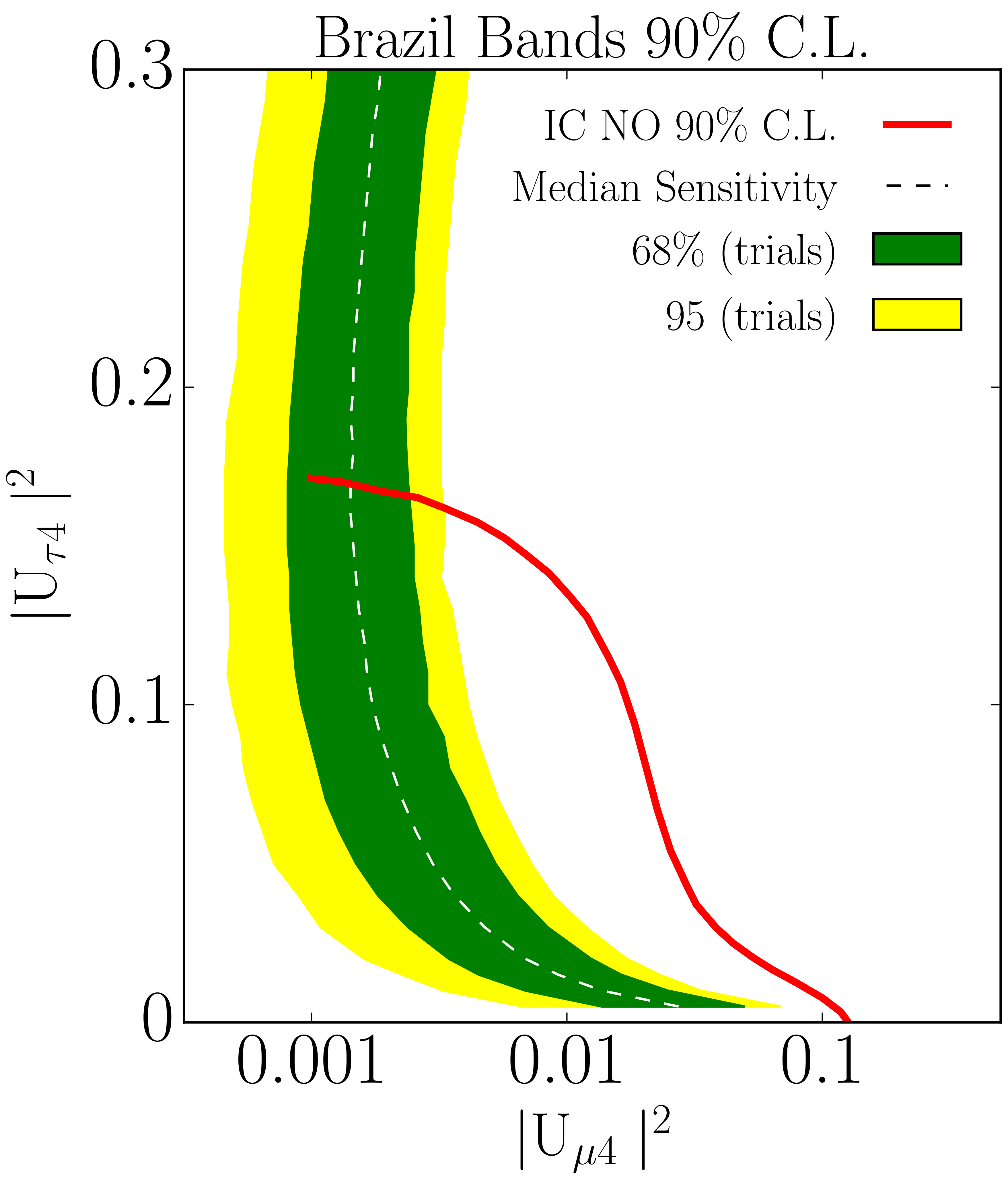




Perhaps slight under-coverage. More points to come.

Bayesian sensitivity and Brazils in context





DATA

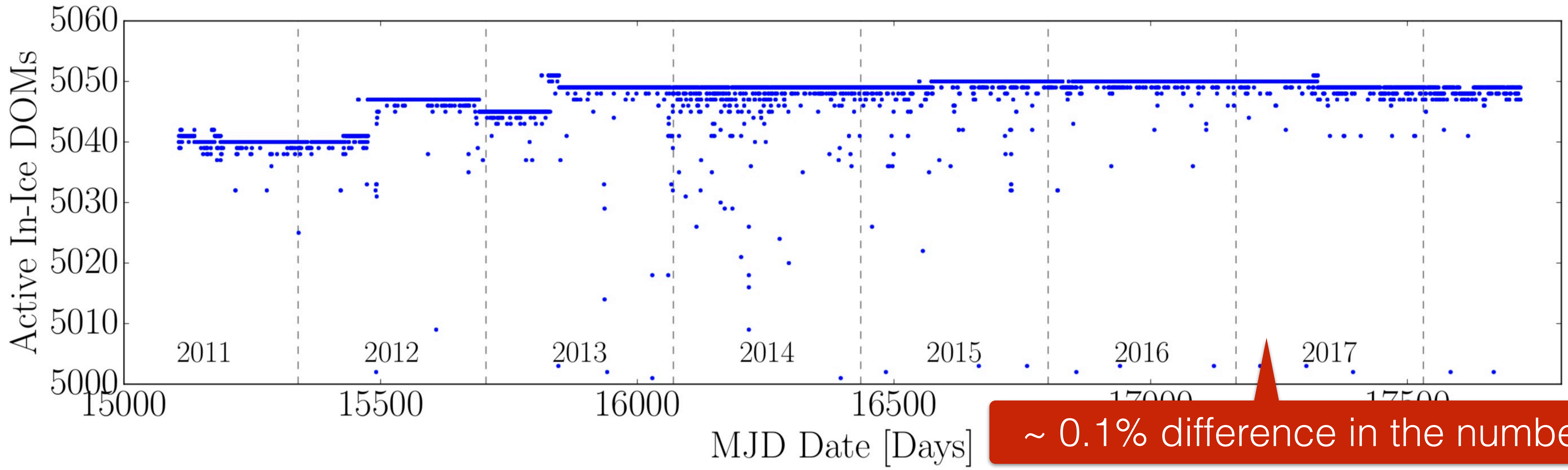
IceCube Data

Consistent rates between years

- 7 years of data (IC86.2011 - IC86.2017)
- Reconstructed energy range from 500GeV to 9.976TeV

- New event selection: ~**280,000** background-free atmospheric muon neutrinos over 7-years!
  - 14x the number of neutrinos as IC86.2011
  - Largest neutrino sample in IceCube (I think) -- ~80% new neutrinos!

Season	LiveTime [s]	Number of Neutrinos	Platinum Event Selection Rate [mHz]
2011	28368983	37525	1.388 +/-0.007
2012	27950931	37092	1.401 +/-0.007
2013	29801398	37964	1.399 +/-0.007
2014	30874229	40794	1.384 +/-0.007
2015	31325562	43088	1.402 +/-0.007
2016	30549531	41234	1.398 +/-0.007
2017	34733434	45228	1.403 +/-0.007



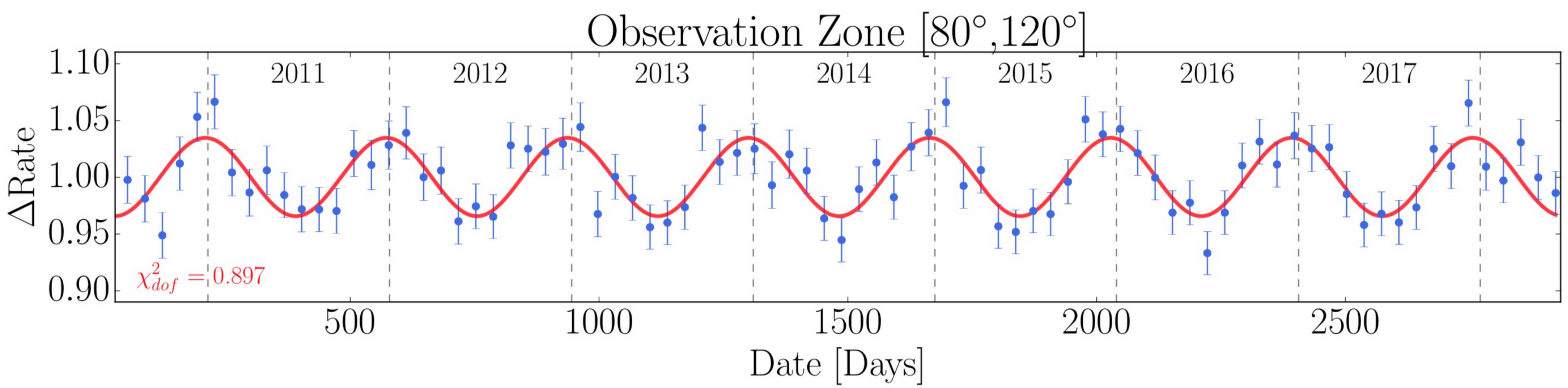
~ 0.1% difference in the number of active DOMs.

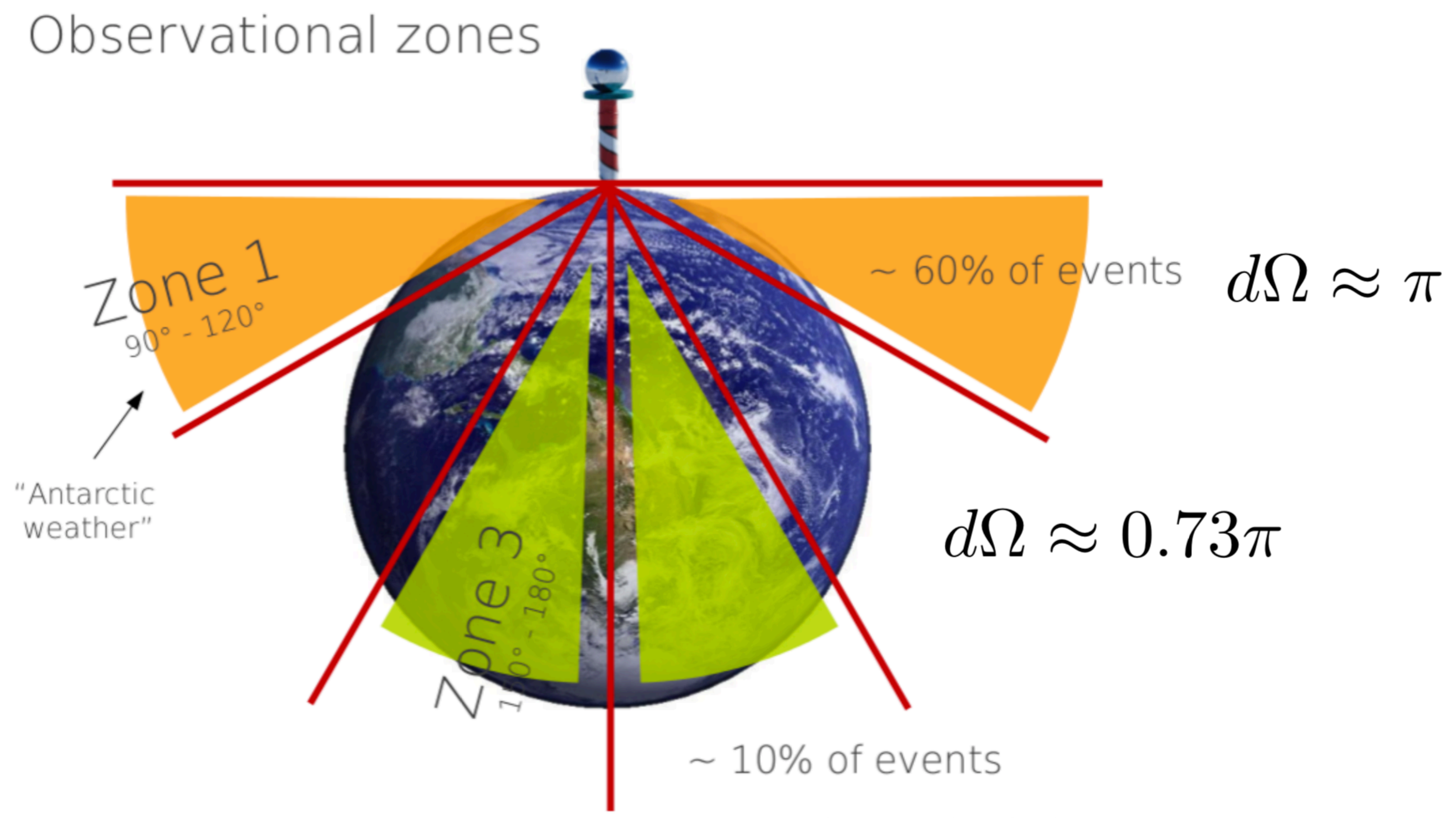
IceCube Data -- Stability checks

Consistent distributions between years

KS Test P-value, comparing the given season to all the other seasons						
	IC86.2011	IC86.2012	IC86.2013	IC86.2014	IC86.2015	IC86.2017
Qtot	0.22	0.59	0.46	0.99	0.63	0.91
Qtot NoDC	0.66	0.37	0.99	0.79	0.83	0.61
Nchan NoDC	1.00	0.26	0.97	0.77	0.91	1.00
NChan	1.00	0.99	0.34	0.94	0.91	0.95
MuEx Energy	0.66	0.90	0.84	0.85	0.81	0.92
MuEx Zenith	0.42	0.97	0.88	0.02	0.25	0.18

High statistic sample makes us sensitive to seasonal variations.





Burn sample proposed procedure

Burn Sample (5% burn sample)

Just shy of the amount of data as the IC86.2011 analysis (15k neutrinos).

Fit to Full space

↓

Get best fit

DO Not say where it is!

Plot nuisance parameter pulls at best fit

if > 3 sigma, stop.

Plotting EZ residuals. And histogram values of pulls

Plot 1D energy and zenith at best fit

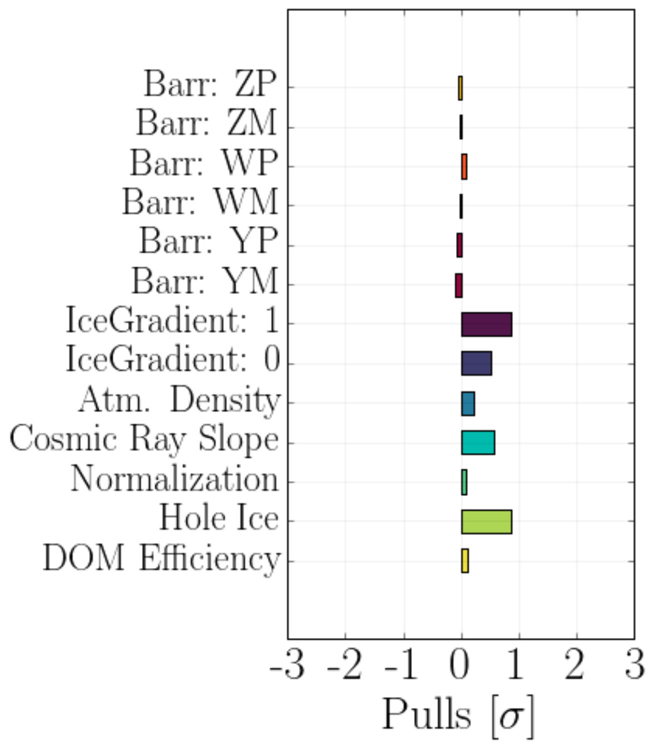
Do not look at 2D energy/zenith

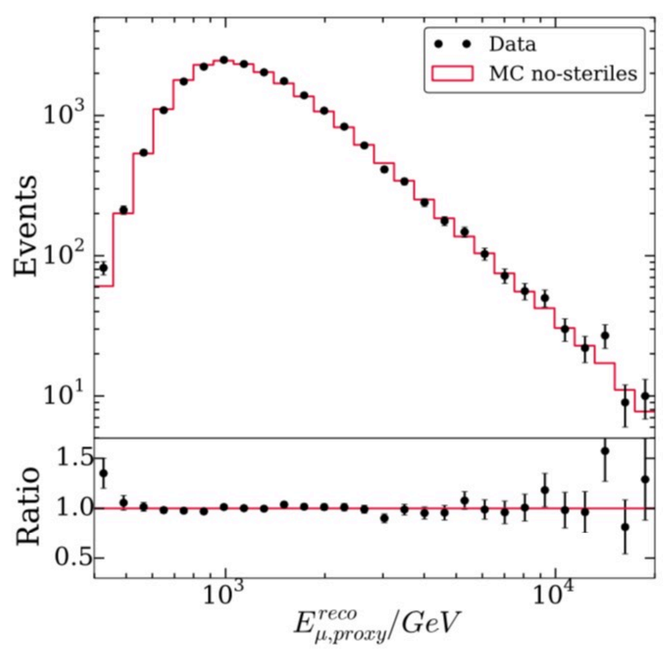
↓

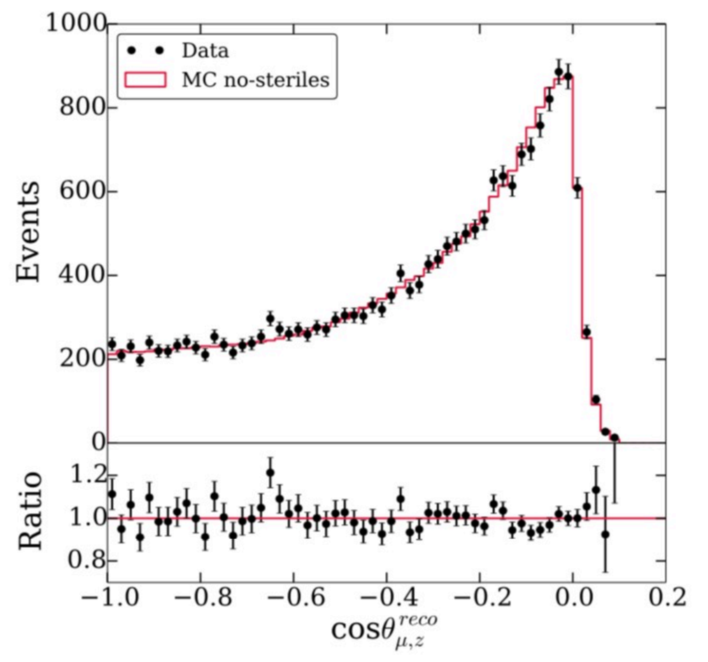
Use best fit and compare to compared to 5% of each year individually.

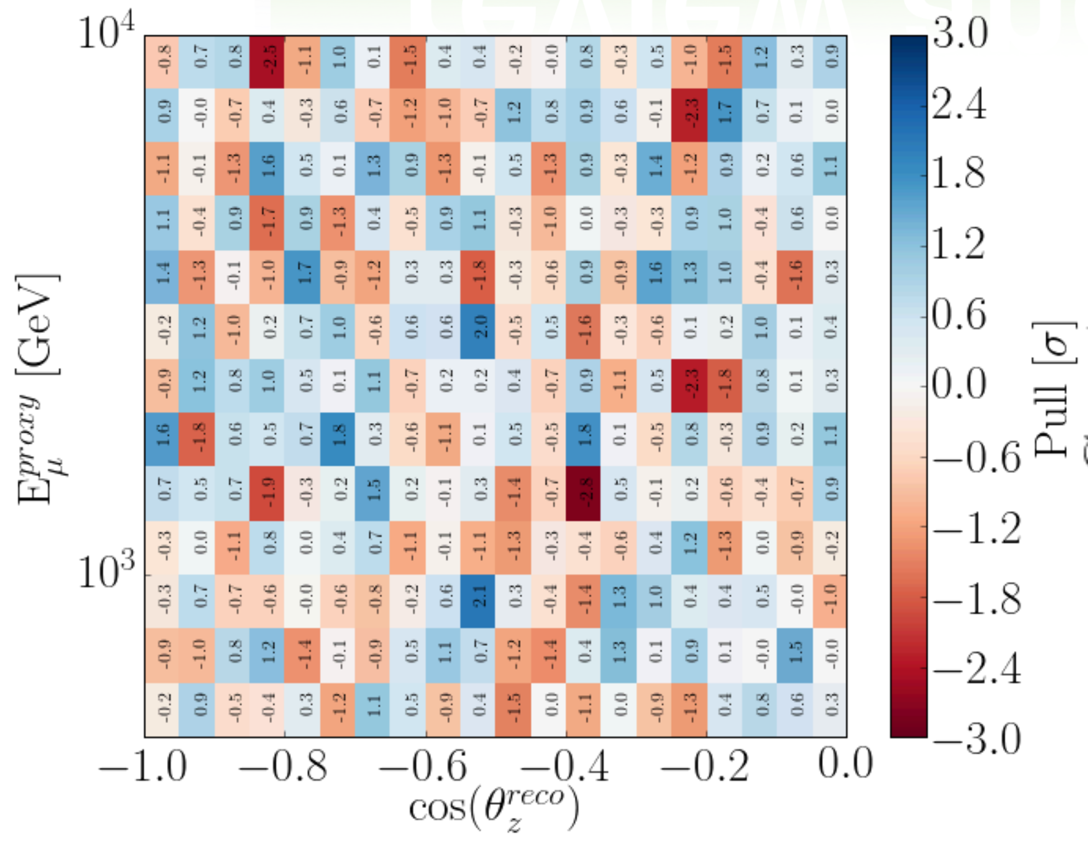
Stop if any of the years do not agree.

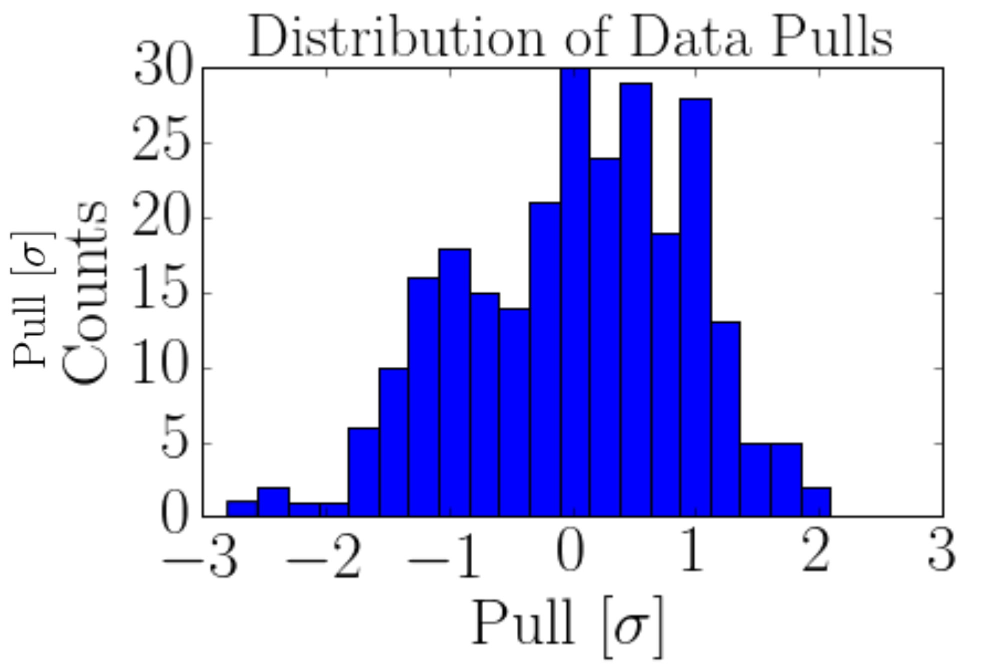
→ **Move to collaboration review and unblind!**











Unblinding proposed procedure

Unblinding procedure

Minimization full data over physics parameters	Do not report best fit
Look at 1D energy and zenith at best fit	Do not look at 2D projection
Look at systematic pulls at best fit point	**Stop** if best fit pull for any systematic > 3sigma
Plot 2d data pulls in energy and zenith	**Stop** if more than 3 bins have > 3 sigma pulls

Open Box!

Make all plots

If best fit is in tension with previous IceCube results, at 99%CL, then we investigate.

If best fit disagrees with world data, we proceed (we do not measure the same thing, we're unique).

Any circumstance

Split data:
first half versus last half.

Fin

Updating the analysis

MEOWS
MATTER ENHANCED OSCILLATIONS WITH STERILES

UPDATED SYSTEMATICS
- Flux parametrization
- Updated atm. density
- Ice systematic description
- HoleIce description/variants
- Spice3.2

FITTING IMPROVEMENTS
- NuSquids Improvements
- Bayesian Fitting
- Fitting θ_{34}
- SAY LLH
- Golem Fitter

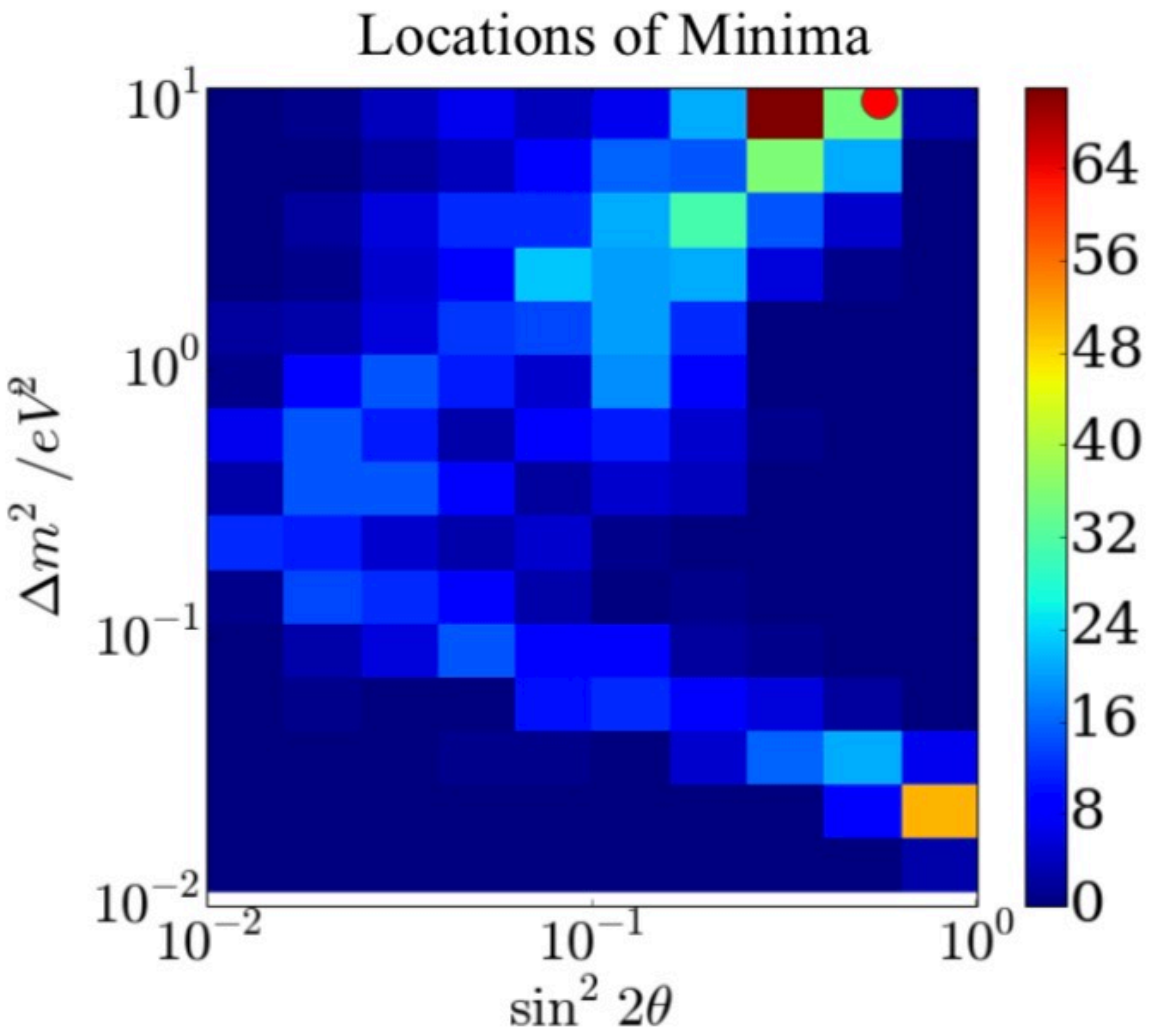
BUG FIXES
- EndCap fix
- Flux spline fixes
- Cross-section fix
- Kinematics fix

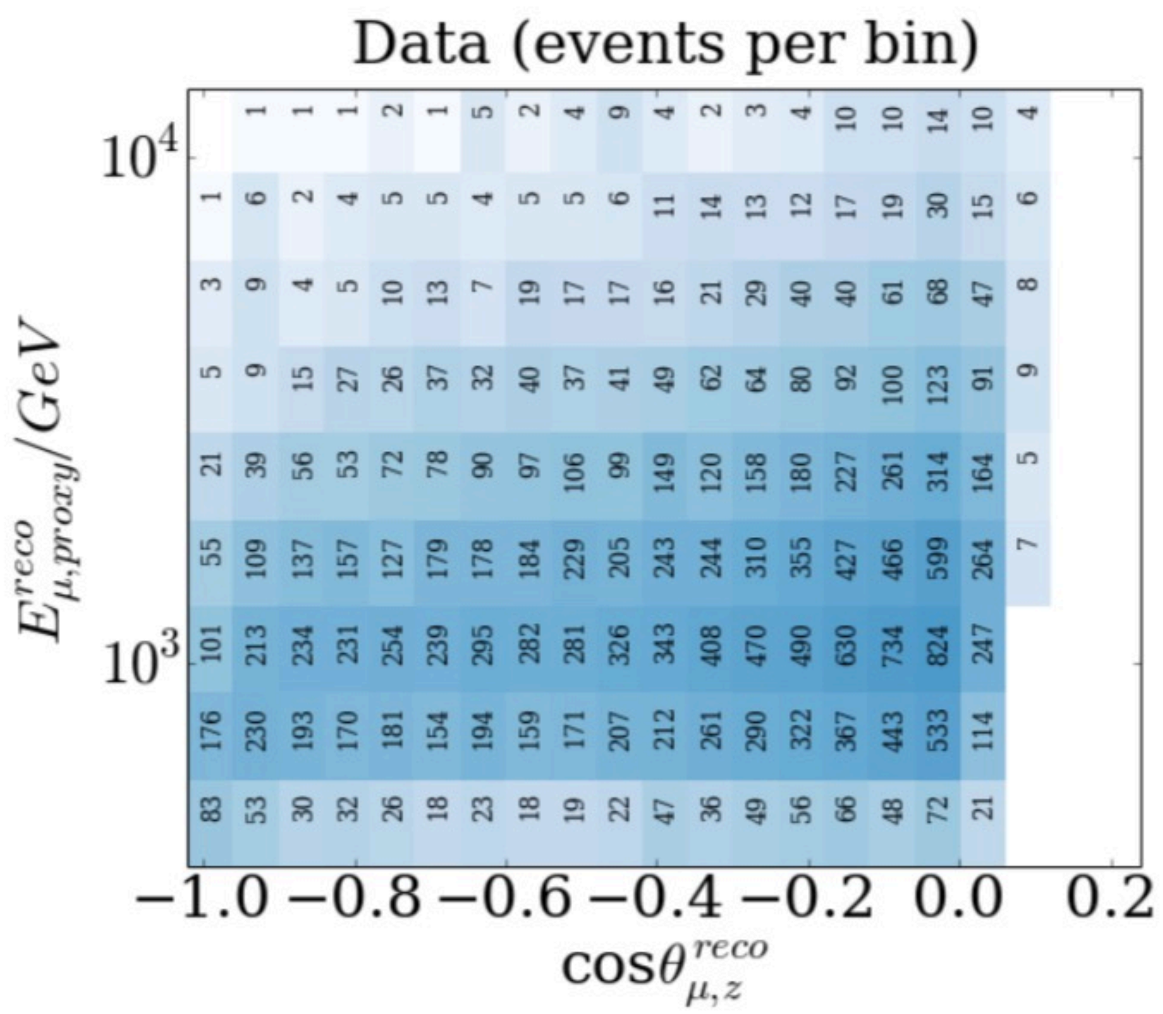
MC UPDATES
- SPE Templates
- Filters
- Double the amount of MC
- Updated Ice Model
- Updated software
- Lepton Weighter/Injector
- Updated topological splitter

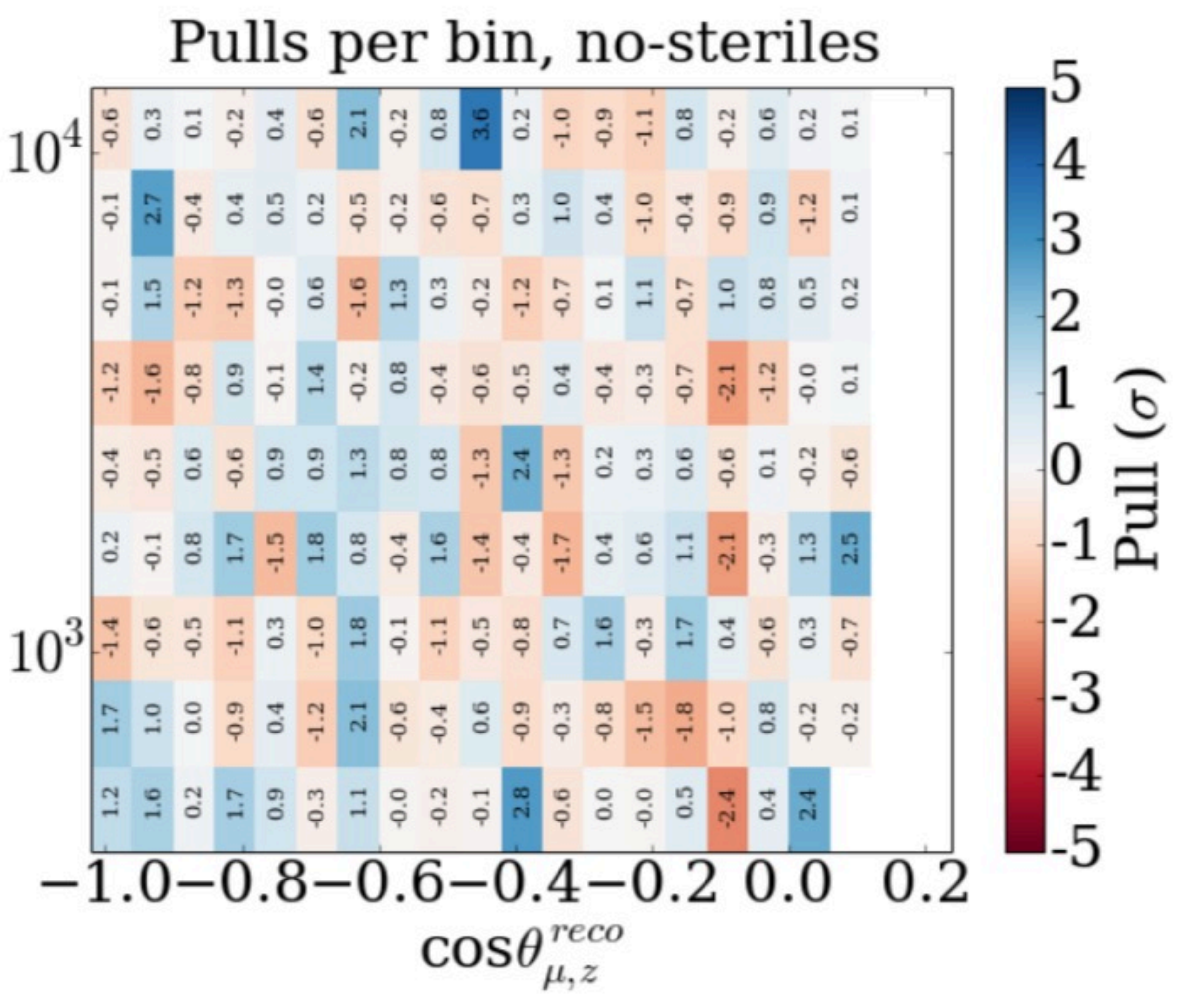
DATA UPDATES
- Unified Filters
- Pass2
- New cuts on data quality

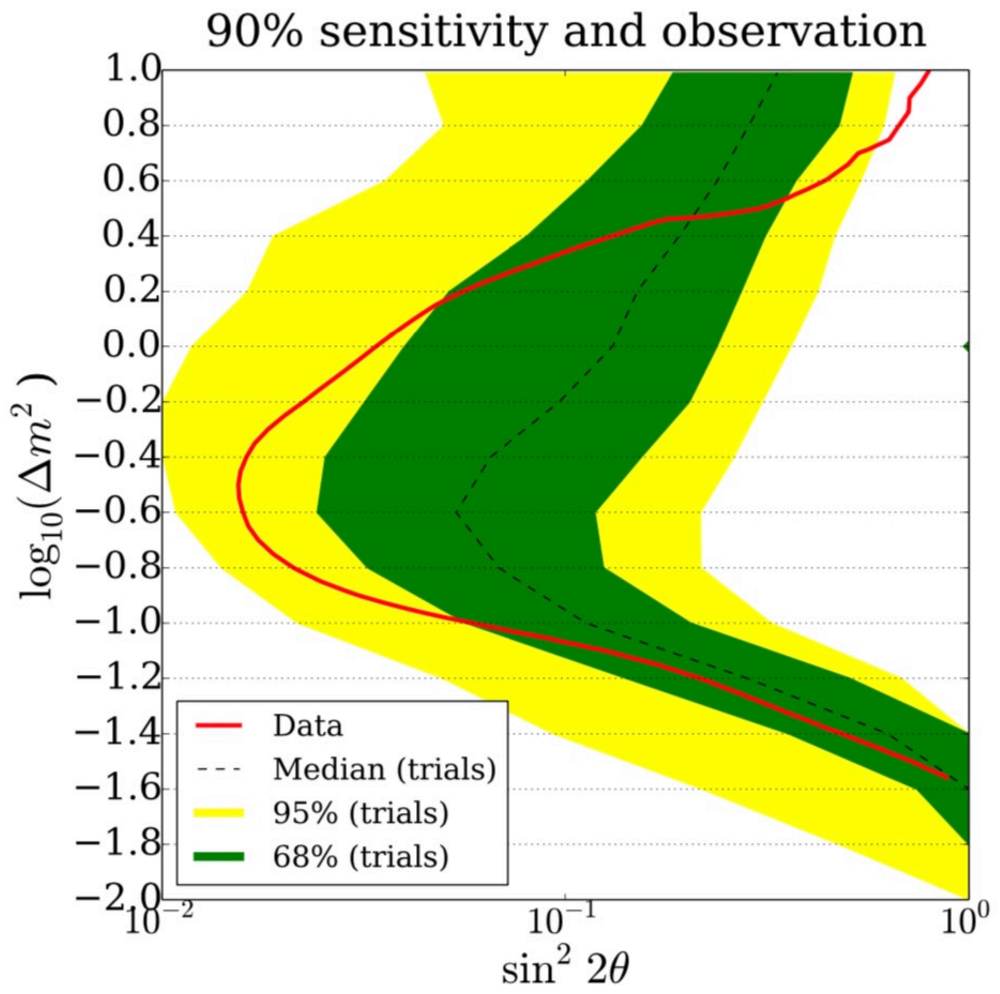
UPDATED STATISTICS
- 6.8 years lifetime of data
- Platinum Event selection
- 14x total data statistics
- Double MC statistics

Burn sample proposed procedure

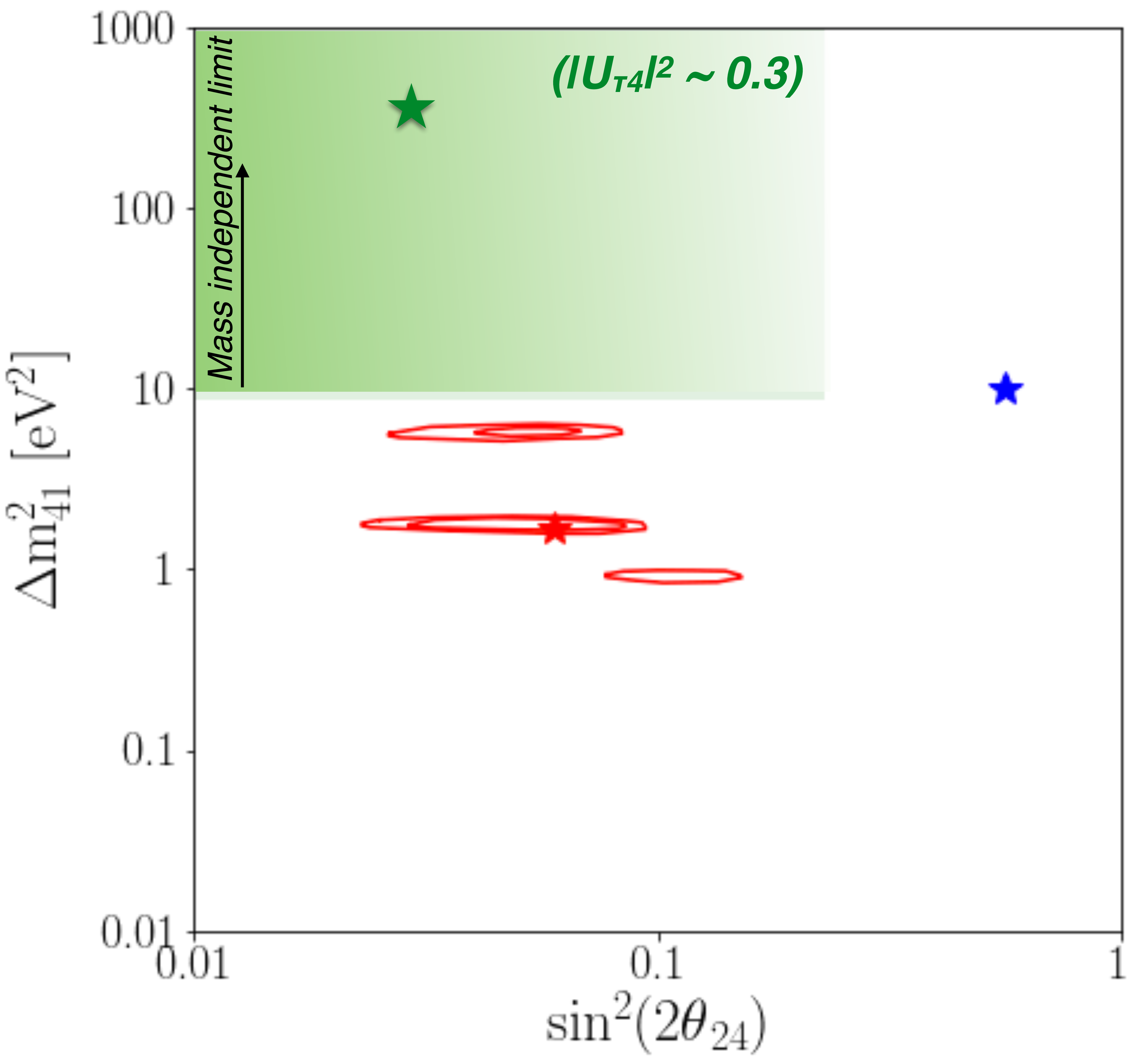








Interesting areas of the parameter space



- *Global Best Fit Regions ($|U_{\tau 4}|^2 = 0$)*
  - *Allowed regions at 90% and 99% [1]*
  - *expect 1.3 - 1.78 eV2 region to become more pronounced with the introduction of NEOS and DANSS results [2].*
- *Best fit of previous analysis ($|U_{\tau 4}|^2 = 0$) [3]*
- *Best fit of previous analysis while scanning over $|U_{\tau 4}|^2$ (in mass independent limit) [4]*
  - *Potentially relevant for the two anomalous ANITA events [5] (probably irrelevant, thanks Ibrahim...)*

[1] Collin, G. H., et al. "Sterile neutrino fits to short baseline data." Nuclear Physics B 908 (2016): 354-365.
[2] Dentler, Mona, et al. "Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos." arXiv preprint arXiv:1803.10661 (2018).
[3] Aartsen, M. G., et al. "Searches for sterile neutrinos with the IceCube detector." Physical review letters 117.7 (2016): 071801.
[4] Blennow, Mattias, et al. "IceCube bounds on sterile neutrinos above 10 eV." arXiv preprint arXiv:1803.02362 (2018).
[5] P. W. Gorham et al., "Characteristics of Four Upward-pointing Cosmic-ray-like Events Observed with ANITA", Phys. Rev. Lett. 117 no. 7, (2016) 071101, arXiv:1603.05218

Golem

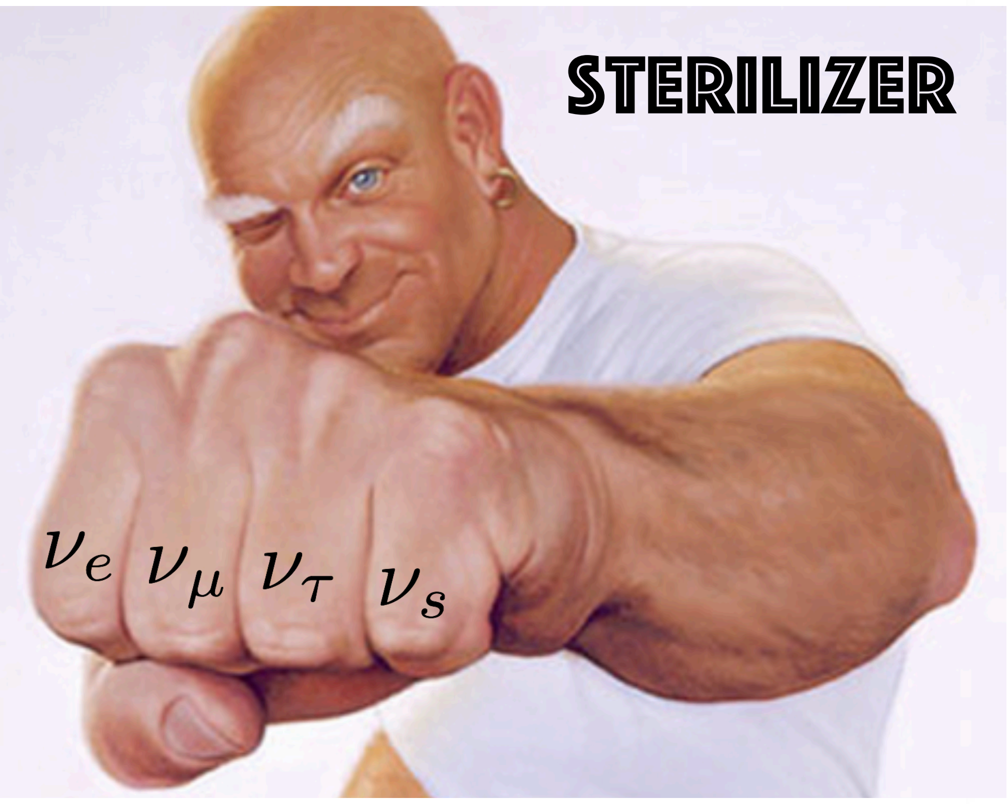
Sterilizer @ GolemFitter

Sterilizer (C++)
Used in MEOWS-1 year

GolemFit (C++)
Used in HESE-7.5 year

→ **Sterilizer@GolemFit**
Used in MEOWS-7 year

- **Build on top of Dr. C. Weaver analysis library PhysTools,**
- **Forward folding binned likelihood,**
- **C++ build with Python interface,**
- **Systematic uncertainties incorporated via nuisance parameters,**
- **Uses Leff to account for MC fluctuations,**
- **Oscillation physics implemented using nuSQuIDS,**
- **Same code base as HESE7.5, LVAtmo, and MEOWS-1year.**



We have been developing and learning from each iteration of our analysis framework. Our next iteration of these series of codes will be Golem:
https://github.com/austinschneider/Golem

Sterilizer @ GolemFitter -- FastMode

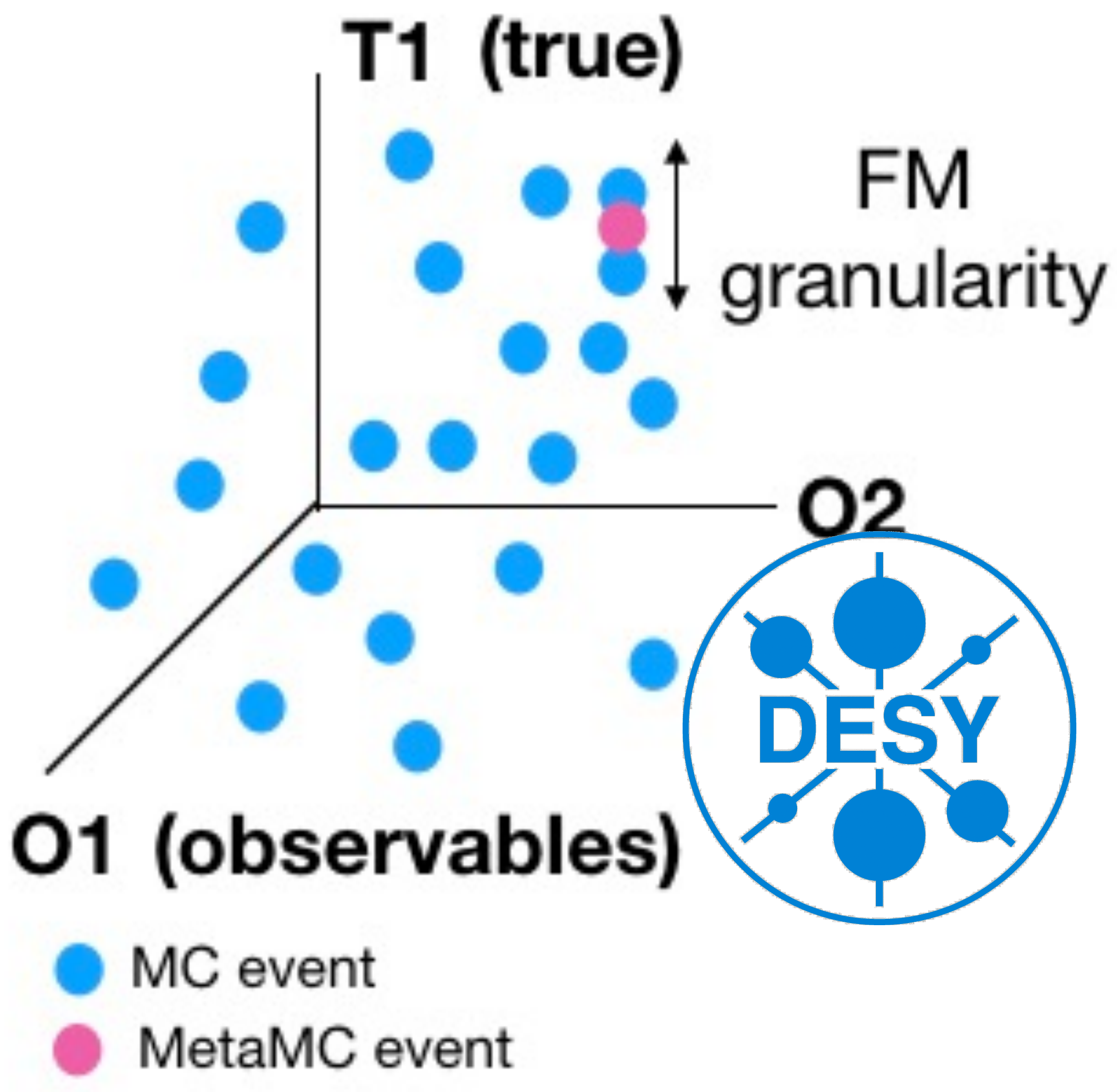
FastMode:
seamlessly changing from:

Event-by-event reweighing
(as used in diffuse analysis)
reweighing

to

Histogram-level-reweighing
(as used in PISA)

- FastMode parameter to move between the techniques.



MC events with the same reconstructed quantities, but same true within FM granularity merged into MetaMC events.

Effective reduction of MC size.

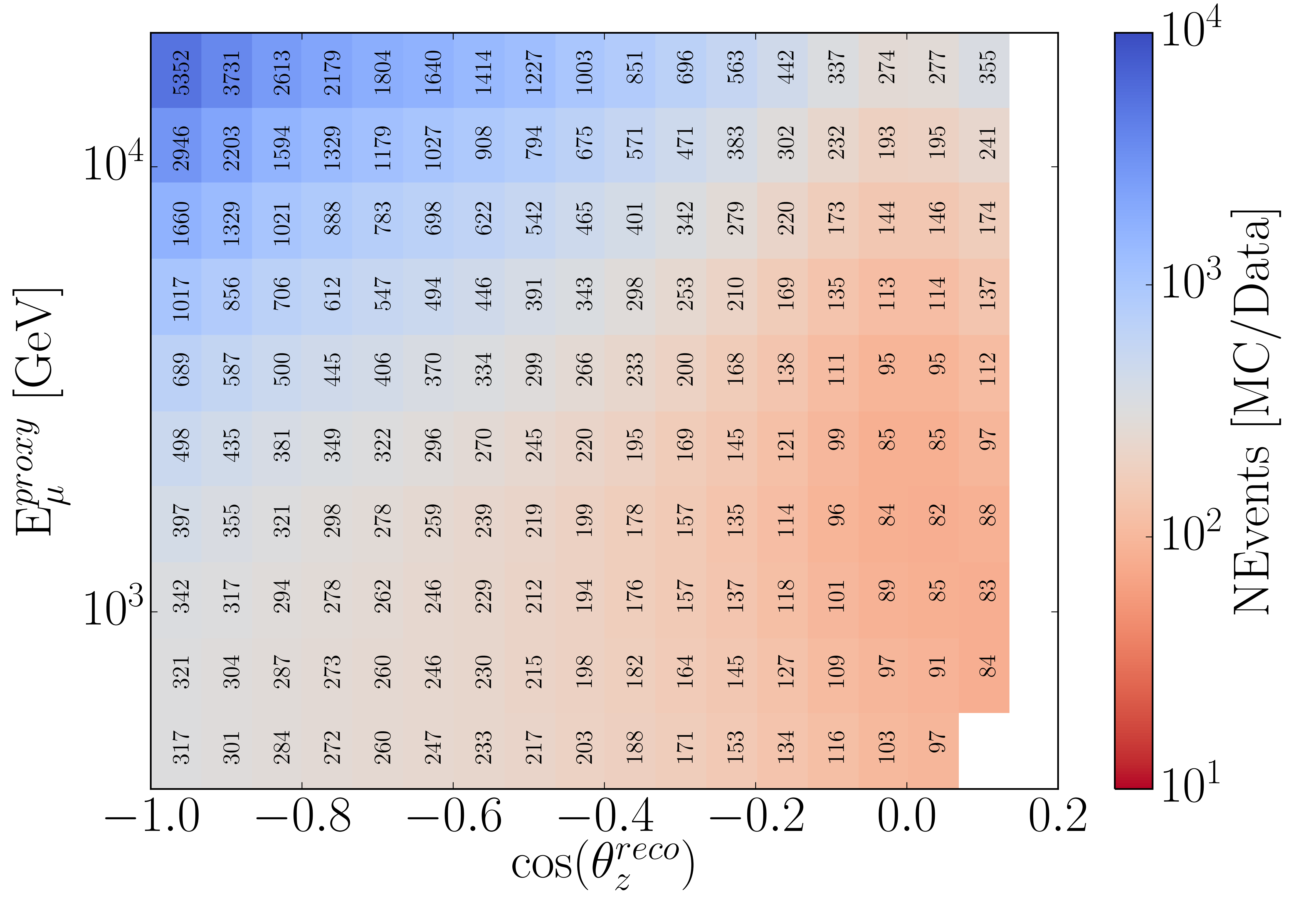
We have tested that fast mode gives us identical results, but it's much much faster.

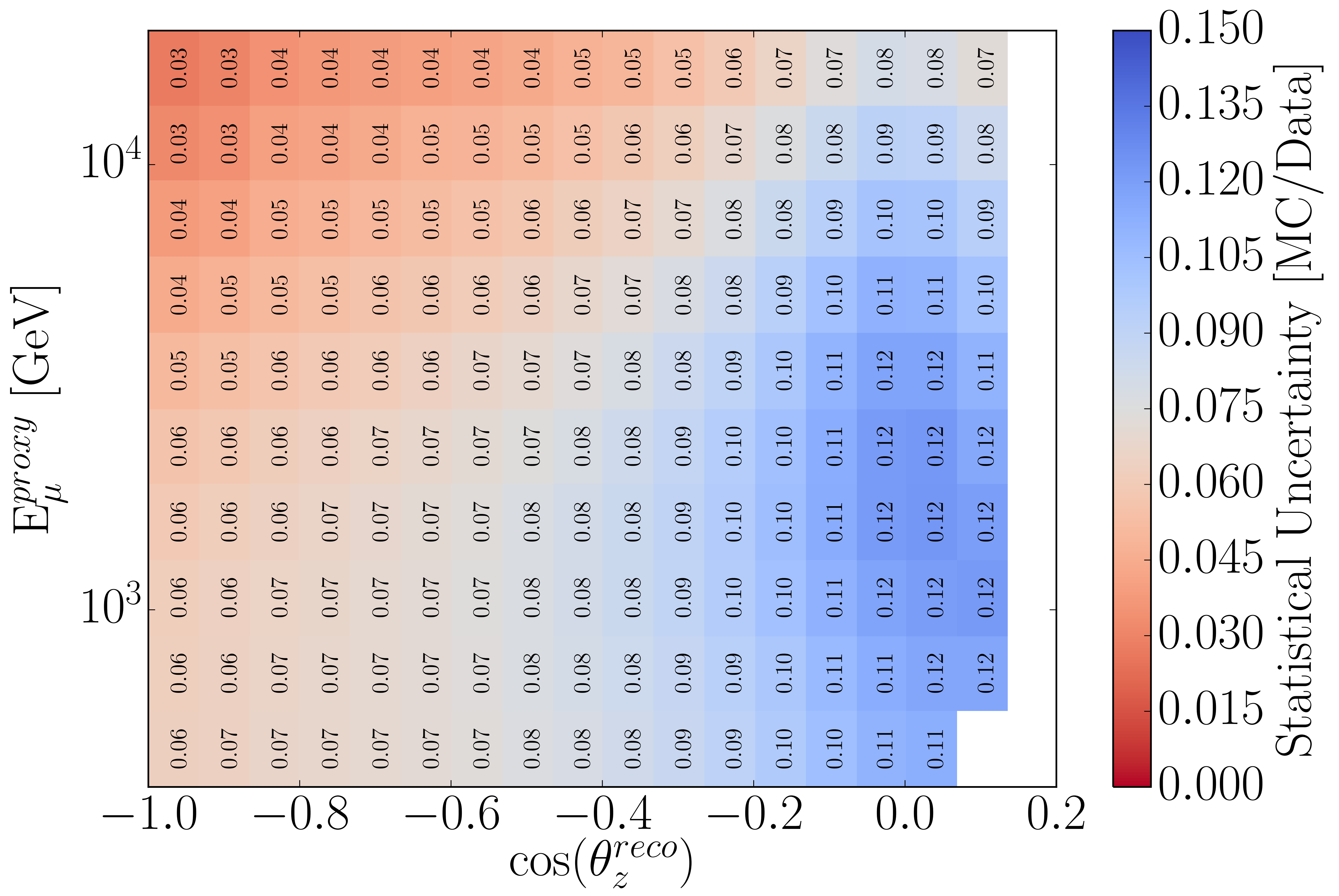
We have been developing and learning from each iteration of our analysis framework. Our next iteration of these series of codes will be Golem:
https://github.com/austinschneider/Golem


Monte
Carlo

MC Production -- Properties

~1000 years of equivalent livetime.
~1year of processing time, mostly OSG





MC Production -- full list of systematic datasets

Nominal MC Set:

Dataset	Location	DOM eff.	HoleIce parameters	Type	Spectrum	Energy Range	Ice Model	DOM Oversizing	IceModel	Events
Ares	MC/Systematics/Noise/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	Nominal MC	2e9
LE Ares	MC/Systematics/LE_Noise/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	1E2 to 2E2	Spice3.2	1	Nominal MC	5e8

Systematic Sets: There are also the corresponding LE sets for all those listed below.

Dataset	Location	DOM eff.	HoleIce parameters	Type	Spectrum	Energy Range [GeV]	IceModel	Oversizing	Used for	Events
Ares	MC/Nominal/Ares	1.23	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	DOMeff Splines	2e9
Ares	MC/Nominal/Ares	1.25	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	DOMeff Splines	2e9
Ares	MC/Nominal/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	DOMeff Splines	2e9
Ares	MC/Nominal/Ares	1.30	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	DOMeff Splines	2e9
Ares	MC/Nominal/Ares	1.33	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	DOMeff Splines	2e9
Ares	MC/Systematics/HoleIce1/Ares	1.27	p1 = 0.3, p2 = 2.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	HoleIce Splines	2e9
Ares	MC/Systematics/HoleIce3/Ares	1.27	p1 = 0.3, p2 = -5.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	HoleIce Splines	2e9
Ares	MC/Systematics/HoleIce4/Ares	1.27	p1 = 0.3, p2 = 0.05	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	HoleIce Splines	2e9
Ares	MC/Systematics/HoleIce5/Ares	1.27	p1 = 0.3, p2 = -3.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	HoleIce Splines	2e9
Ares	MC/Systematics/BulkIce1/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	BulkIce Variant	2e9
Ares	MC/Systematics/BulkIce2/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	BulkIce Variant	2e9
Ares	MC/Systematics/BulkIce3/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	BulkIce Variant	2e9
Ares	Multisim/Nominal/Ares	1.27	p1 = 0.3, p2 = -1.0	NuMu NuMuBar	E^{-2}	2E2 to 1E6	Spice3.2	1	MultiSim	2e9

MC Production -- full list of background datasets

CORSIKA background datasets:

Dataset	Location	DOM eff.	Spectrum	Energy Range [GeV]	Ice Model	DOM Oversizing	Used for
11637	CORSIKA/11637	0.99	$E^{-2.0}$	1E5 to 1E11	SpiceMie	5	Background MC
12332	CORSIKA/12332	0.99	$E^{-2.6}$	6E2 to 1E5	SpiceLea	5	Background MC
12604	CORSIKA/12604	0.99	$E^{-2.6}$	6E2 to 1E5	SpiceLea	5	Background MC
11057	CORSIKA/11057	0.99	$E^{-2.0}$	1E5 to 1E11	SpiceLea	5	Background MC
11865	CORSIKA/11865	0.99	$E^{-2.6}$	6E2 to 1E5	SpiceLea	5	Background MC
11937	CORSIKA/11937	0.99	$E^{-2.0}$	1E5 to 1E11	SpiceLea	5	Background MC
12161	CORSIKA/12161	0.99	$E^{-2.6}$	6E2 to 1E5	SpiceLea	5	Background MC
11362	CORSIKA/11362	0.99	$E^{-2.0}$	1E5 to 1E11	SpiceMie	5	Background MC

nu_e and nu_tau datasets:

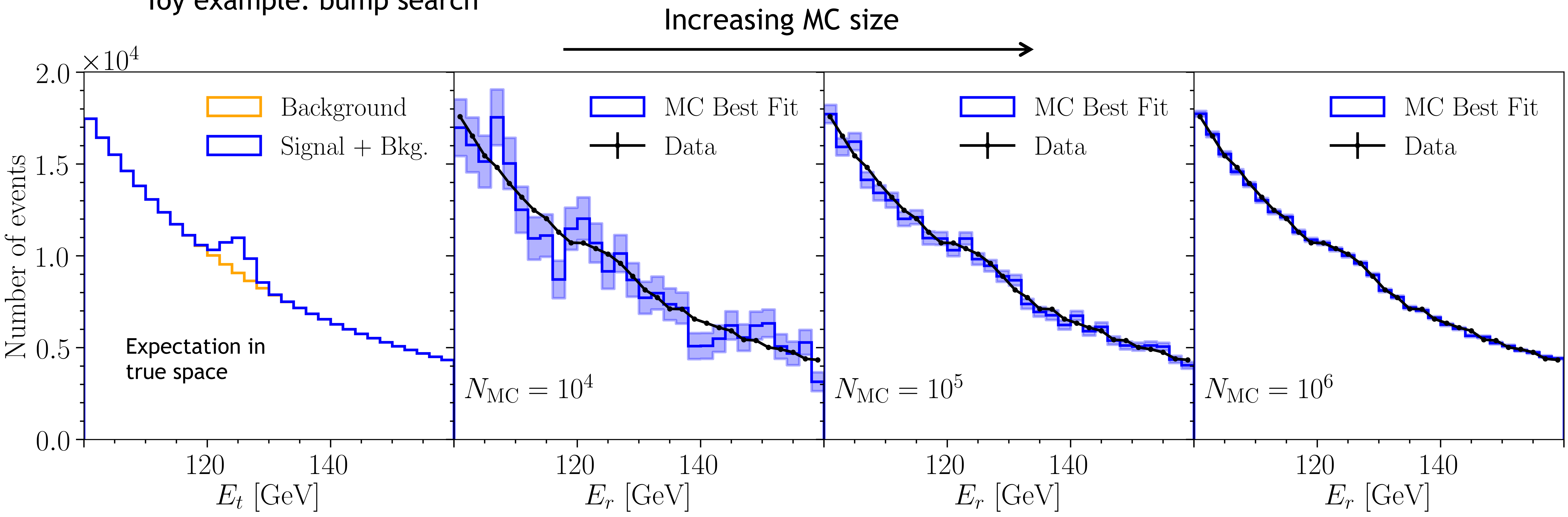
Dataset	Location	DOM eff.	HoleIce	Type	Spectrum	Energy Range [GeV]	Ice Model	DOM Oversizing	Used for	Events
Ares	MC/Systematics/Electron/Ares	1.27	p1 = 0.3, p2 = -1.0	NuE NuEBar	E^{-2}	2E2 to 1E6	Spice3.2	1	Background MC	2e9
Ares	MC/Systematics/Tau/Ares	1.27	p1 = 0.3, p2 = -1.0	NuTau NuTauBar	E^{-2}	2E2 to 1E6	Spice3.2	1	Nominal MC	2e9

Modified likelihood to account for Monte Carlo statistical uncertainties

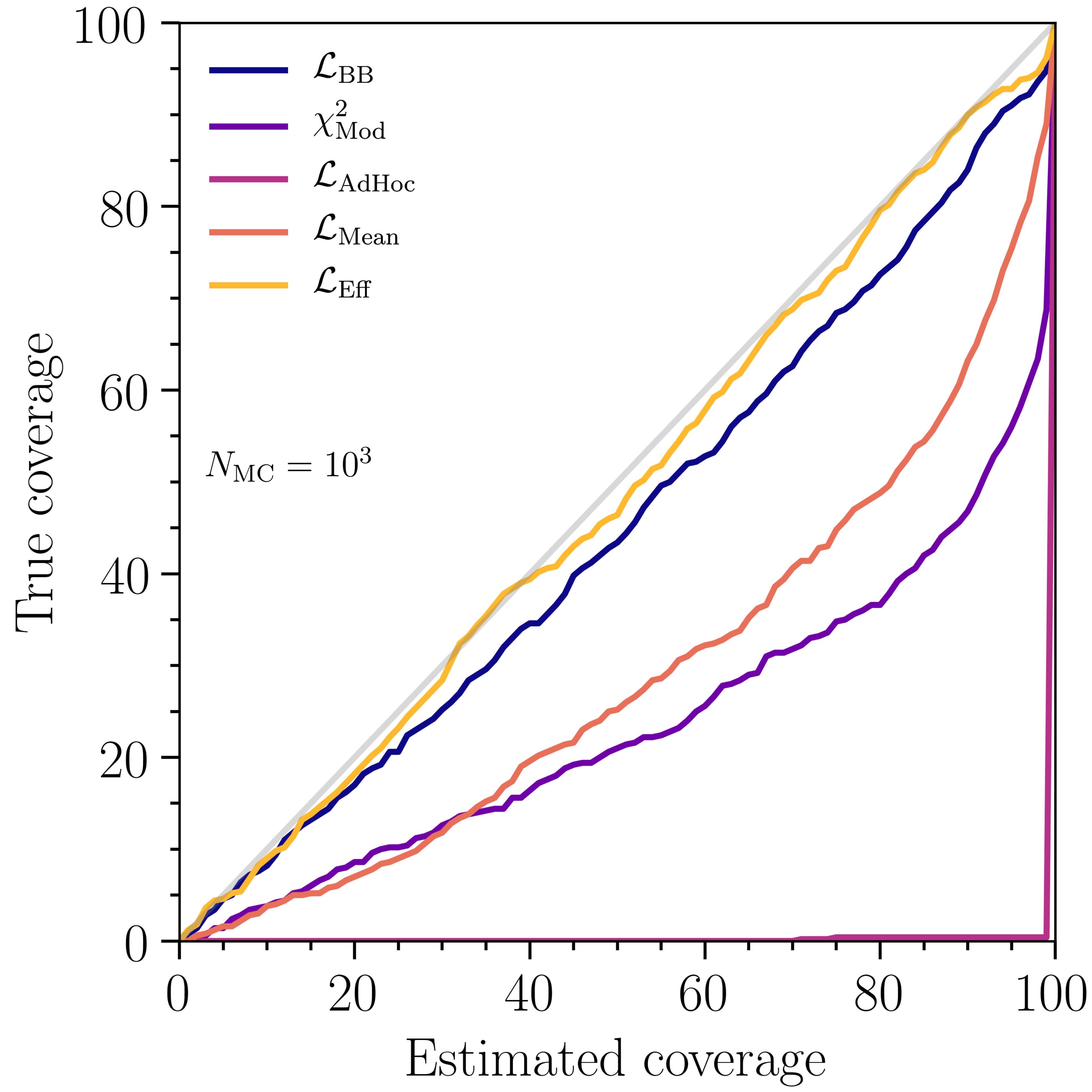
Need to account for the finite nature of Monte Carlo when comparing to data in order to avoid bias results.
We use a Leff given in arXiv:1901.04645 because:

it's fast, it's numerically stable, it's Wilks' theorem-friendly, and it does the job.

Toy example: bump search



Modified likelihood to account for Monte Carlo statistical uncertainties



Accurate coverage with varying amounts of mc.

Event Selection

Platinum event selection

We have two event selections that are > 99.9% pure ν_μ events. If an event passes either of these event selections, we include it in the **Platinum selection**.

Diamond:

Data Reduction:

1. Qtot NoDC < 20 PE
2. NChan NoDC < 15 DOMs
3. NDirDoms < 12 DOMs
4. Cos(MuExZenith) > 0.0
5. Average Charge Weighted Distance > 89 m/PE

Coincident Events Reduction:

1. BayesLLHR < 30
2. log10(Overburden) < 0.6 * log10(ParaboloidSigma-0.03)+7.5
3. log10(Overburden) < 2.5 * (RLogL-7.1) +3.0
4. log10(Overburden) < 10.0/(BayesLLHR-30.0) +4.0

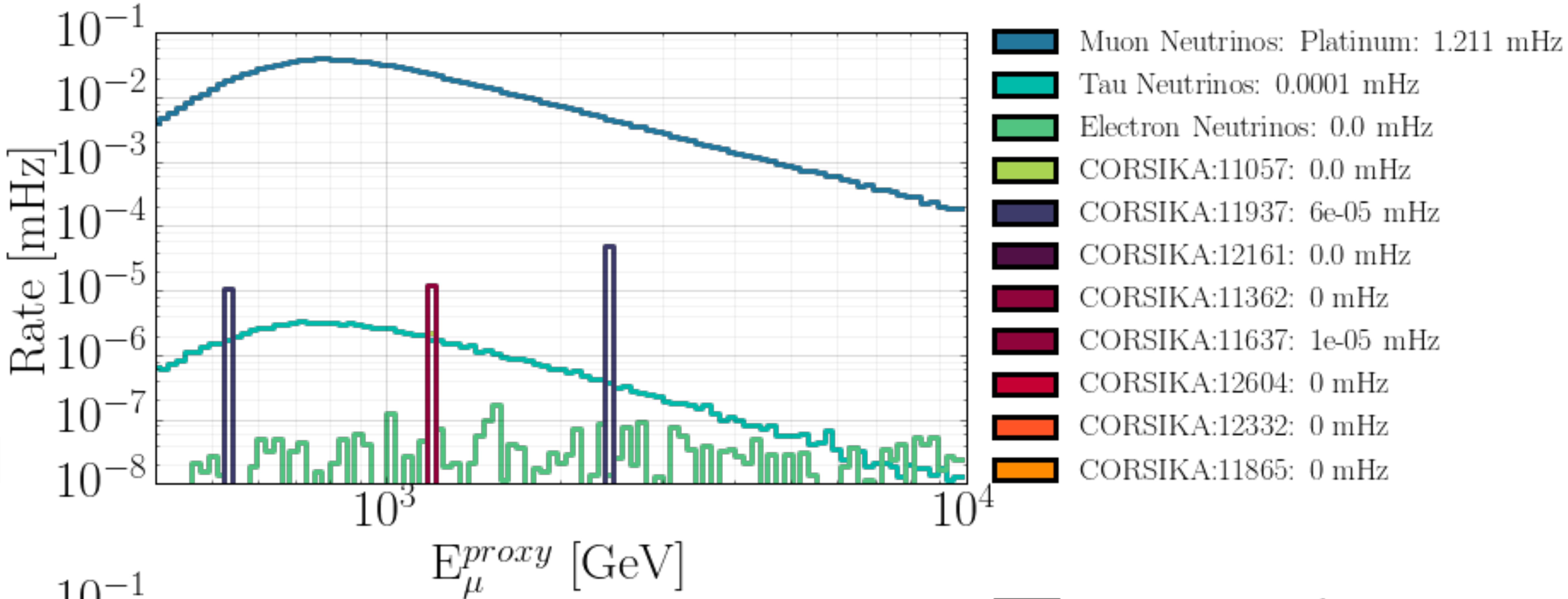
Cleanup:

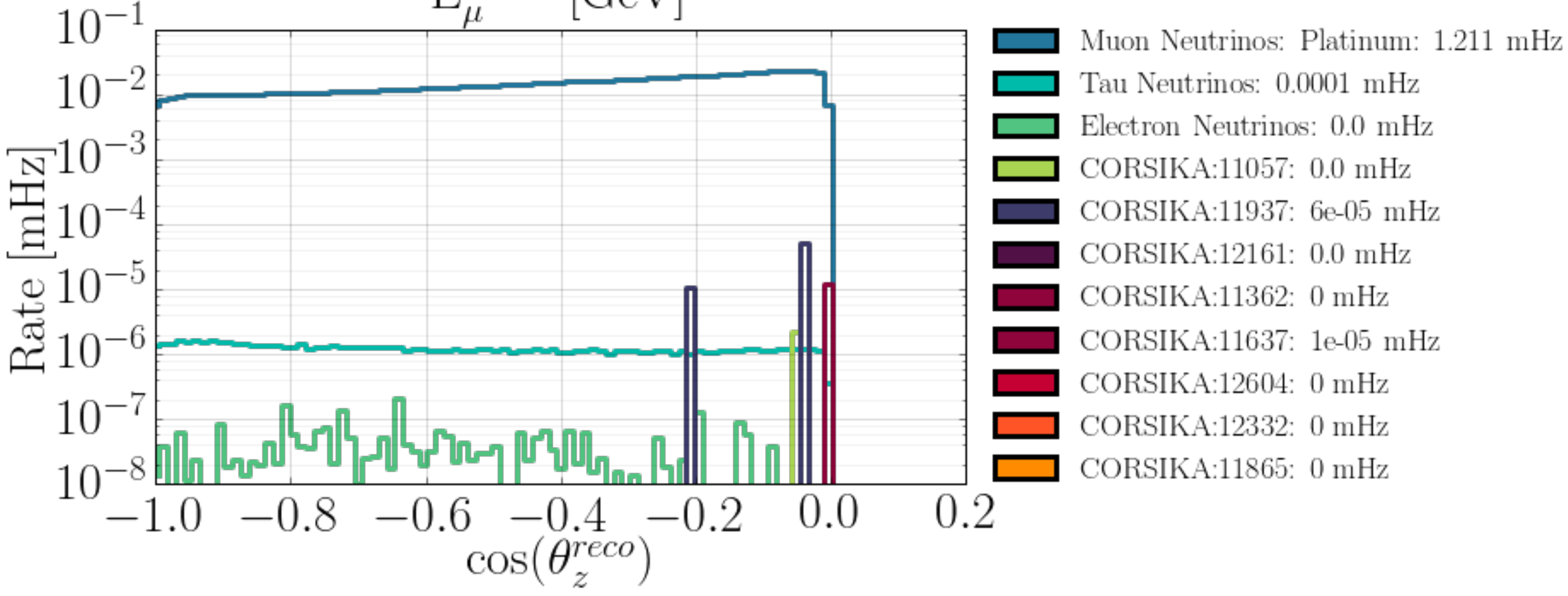
1. DirL < 350 m
2. abs(DirS) > 0.45
3. abs(MuEx COGZ) > 450 m
4. MuEx COGR > 650 m
5. RLogL > (3./18.)*(DirNDoms) + 5.7

Golden:

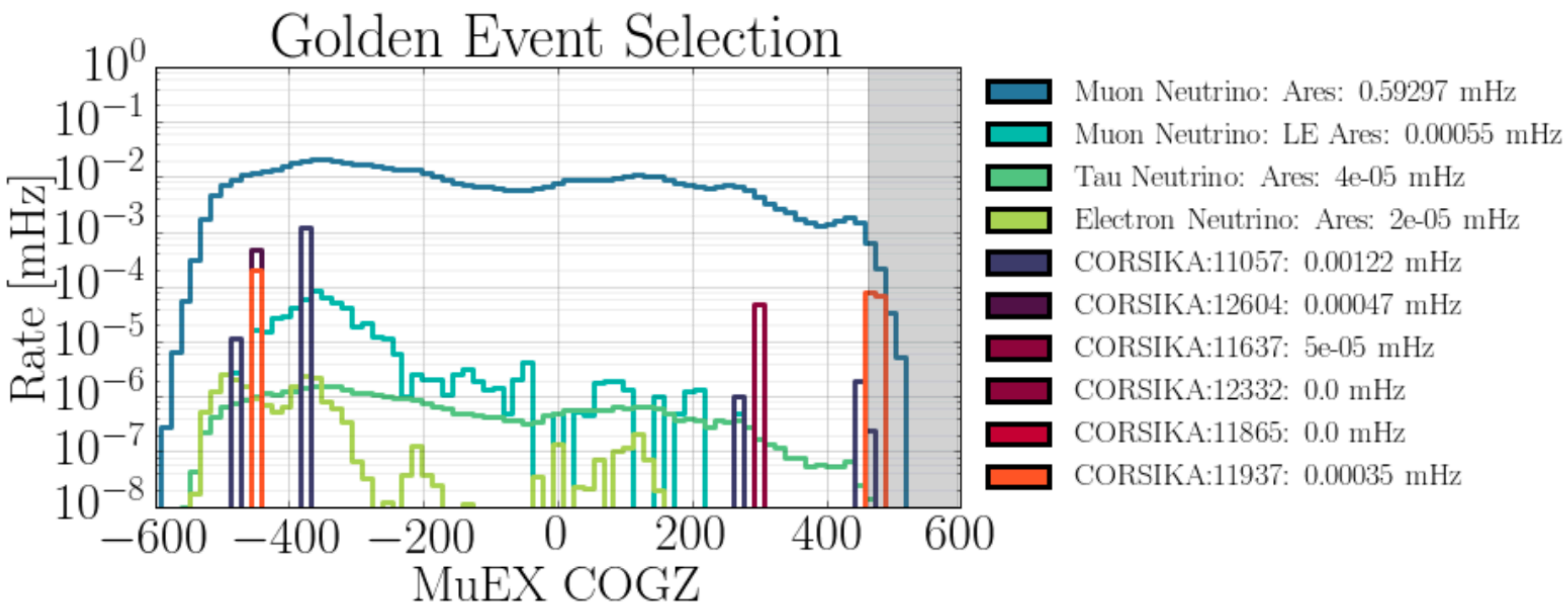
IC86 diffuse analysis and the IC86 Sterile analysis, plus:

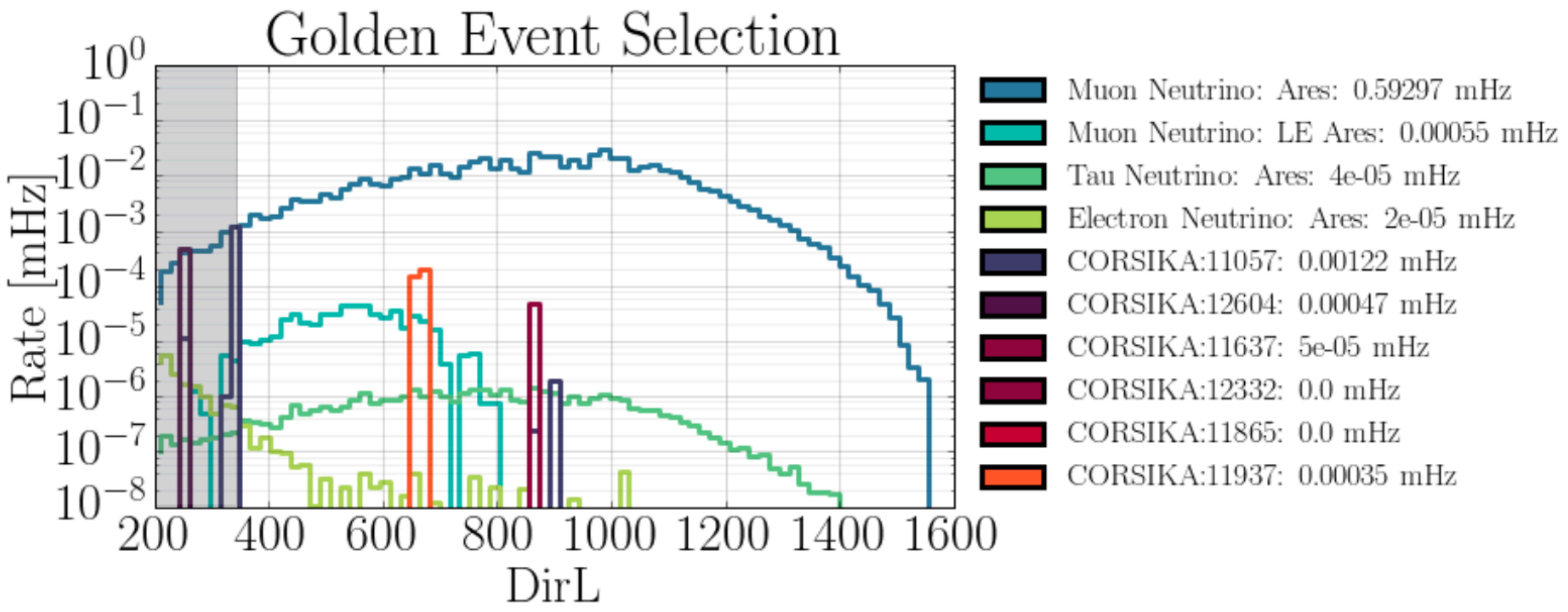
1. MuEx COGZ > 450 m
2. DirL < 350m
3. AQWD > 90m/PE
4. Cos(MuExZenith) > 0.0





Update to the Diffuse selection (Golden selection)



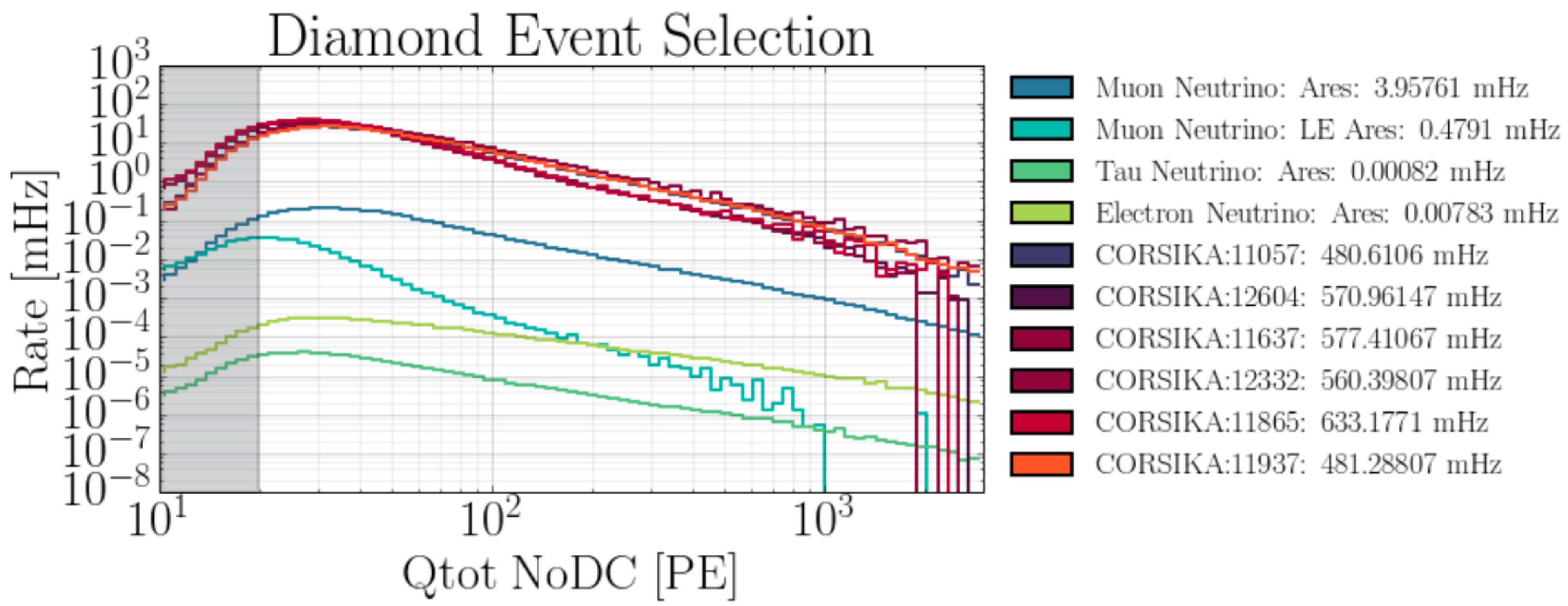


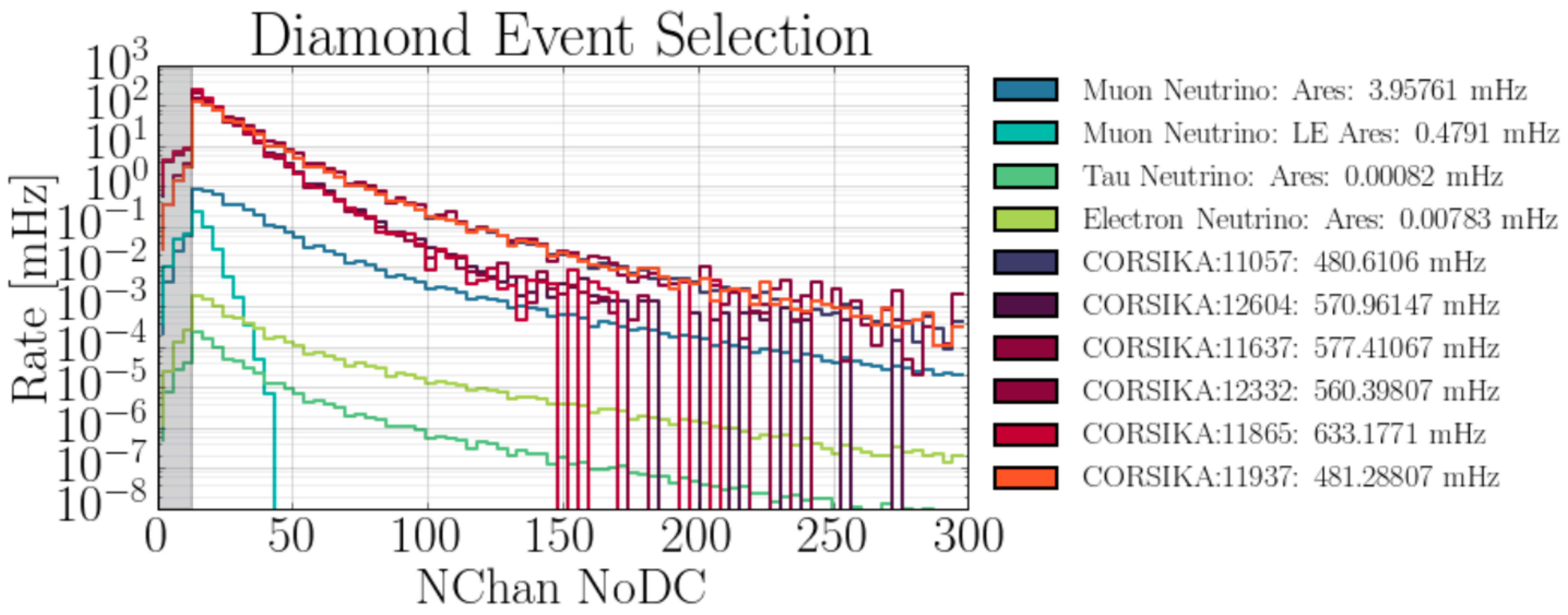
The IC86.2011 analysis found that approximately 1% (consistent with a hand-scan of the events) of their events were due to coincidence muons and had a high AQWD (~90% of them had an AQWD > 100m/PE).

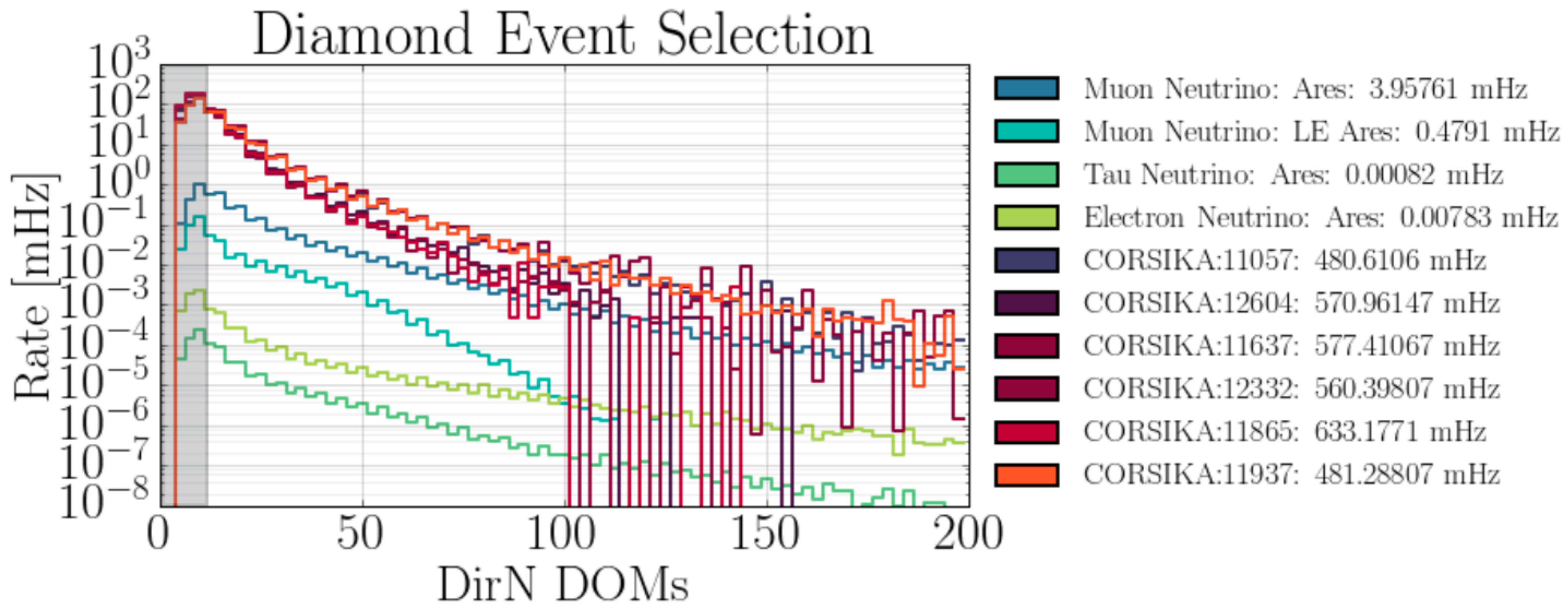
We implement a new cut on the AQWD at 90m/PE, and introduce an updated TopologicalSplitter, which was found to further reduce the background by a factor of 1.7.

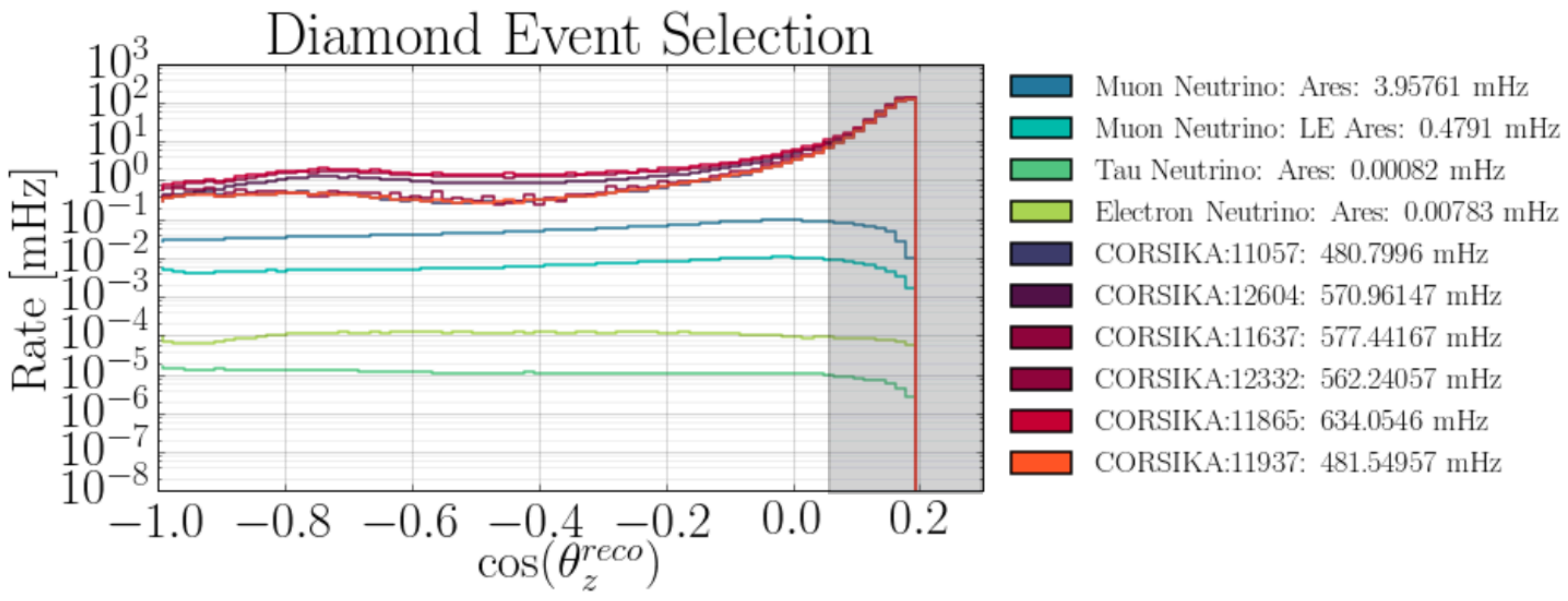
We have also checked the event selection against 8 independent sets of CORSIKA, which pushed us to also include a further cut on the COGZ and DirL. The culmination of these modifications led to a decrease in the event rate by roughly 5%, however, we eliminate roughly 95% of the remaining contamination, bringing the Golden selection to >99% purity.

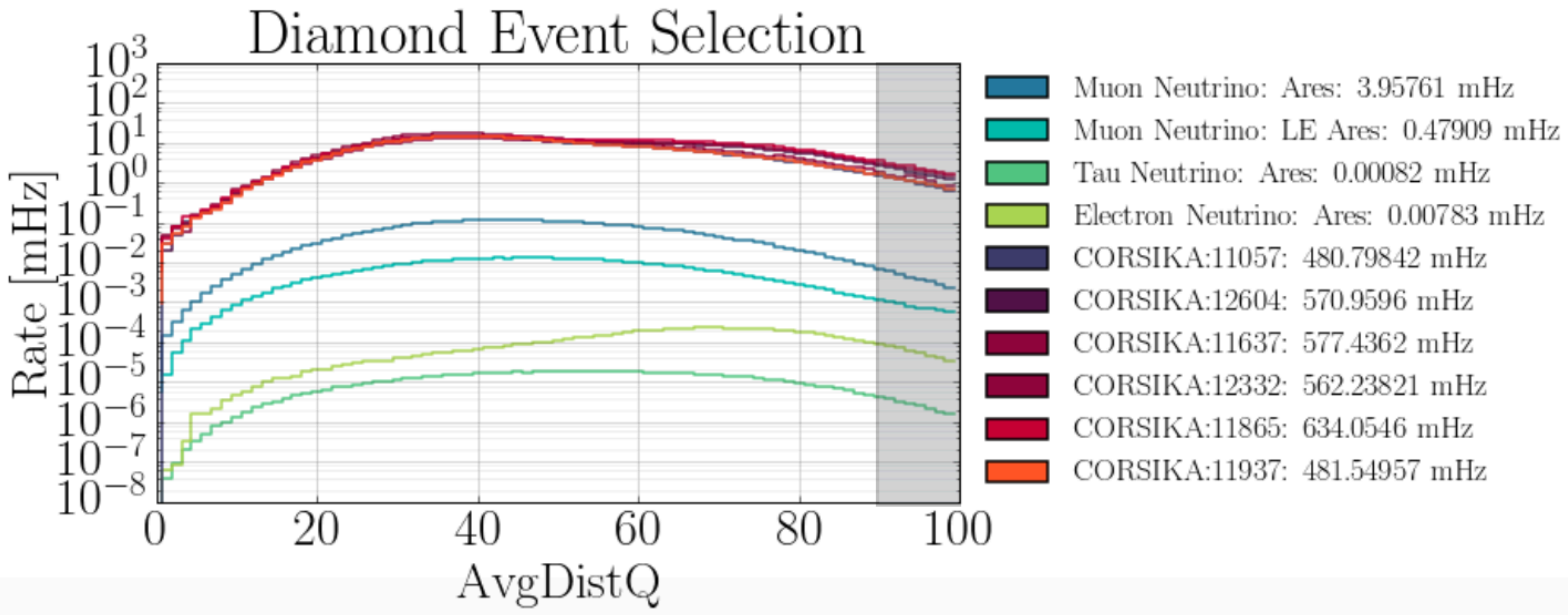
Diamond event selection: data reduction





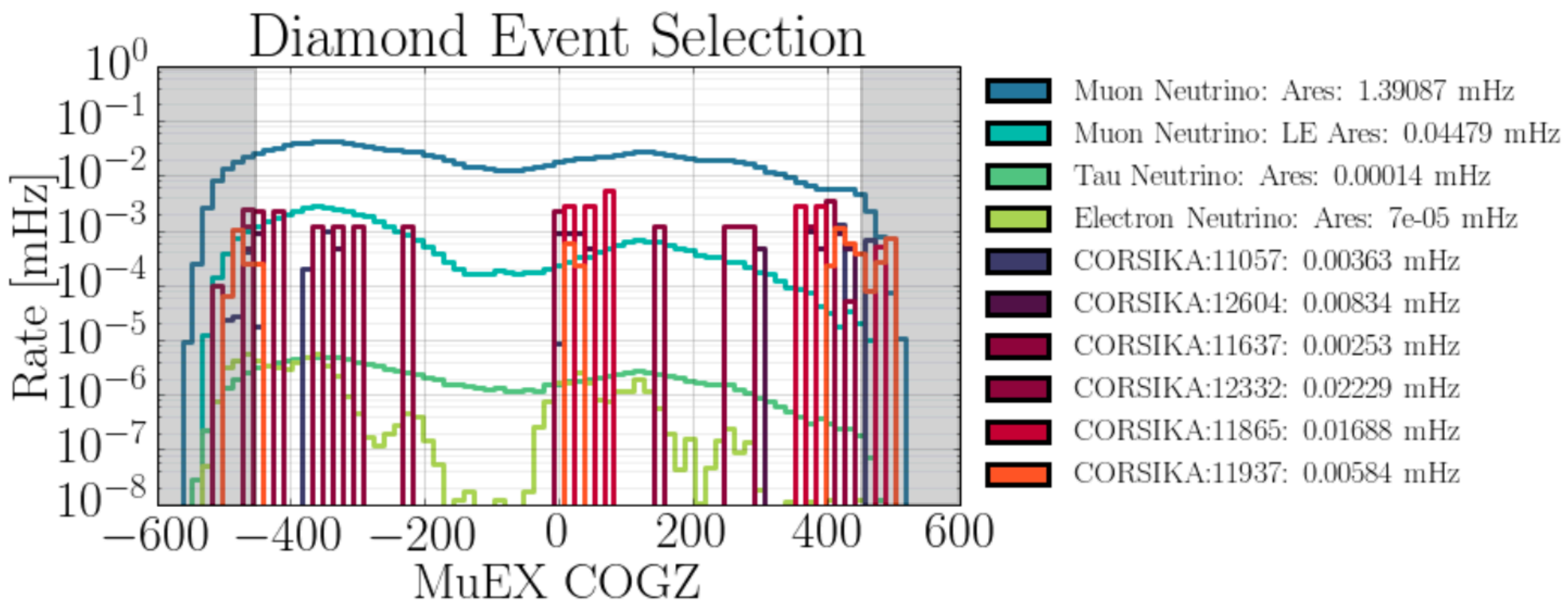


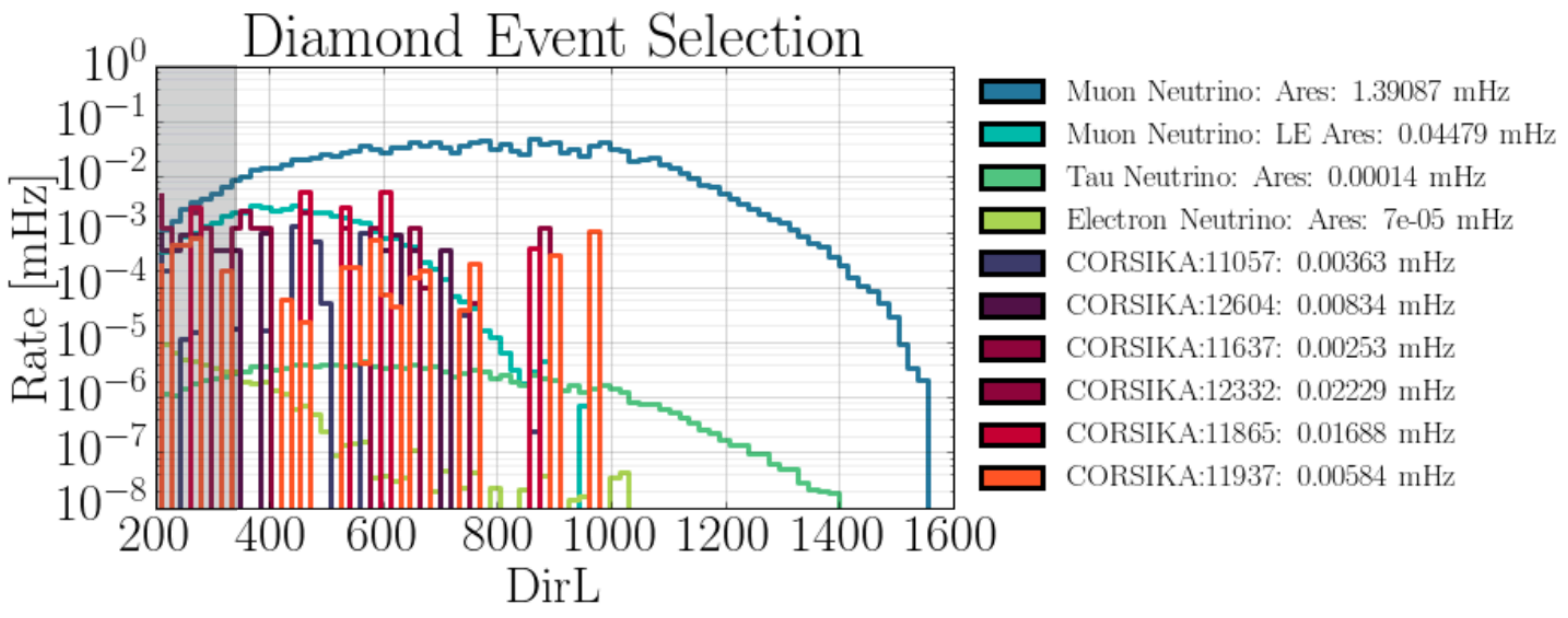


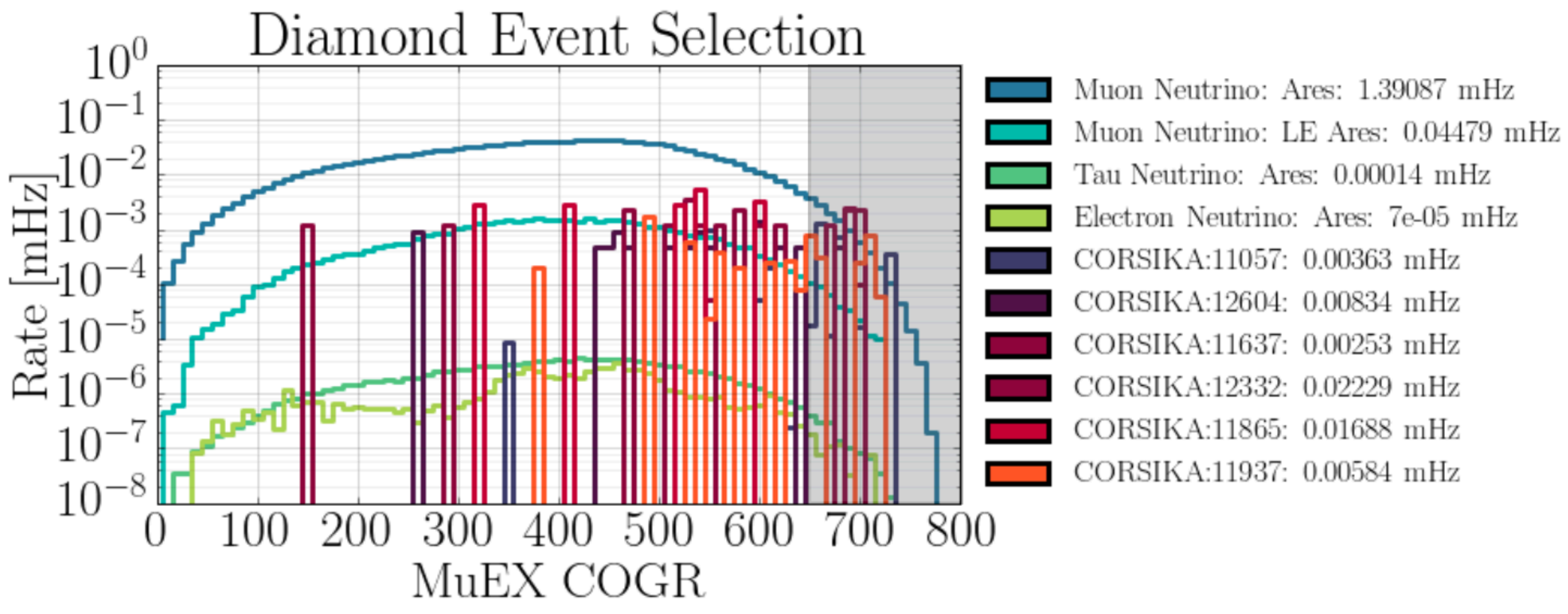


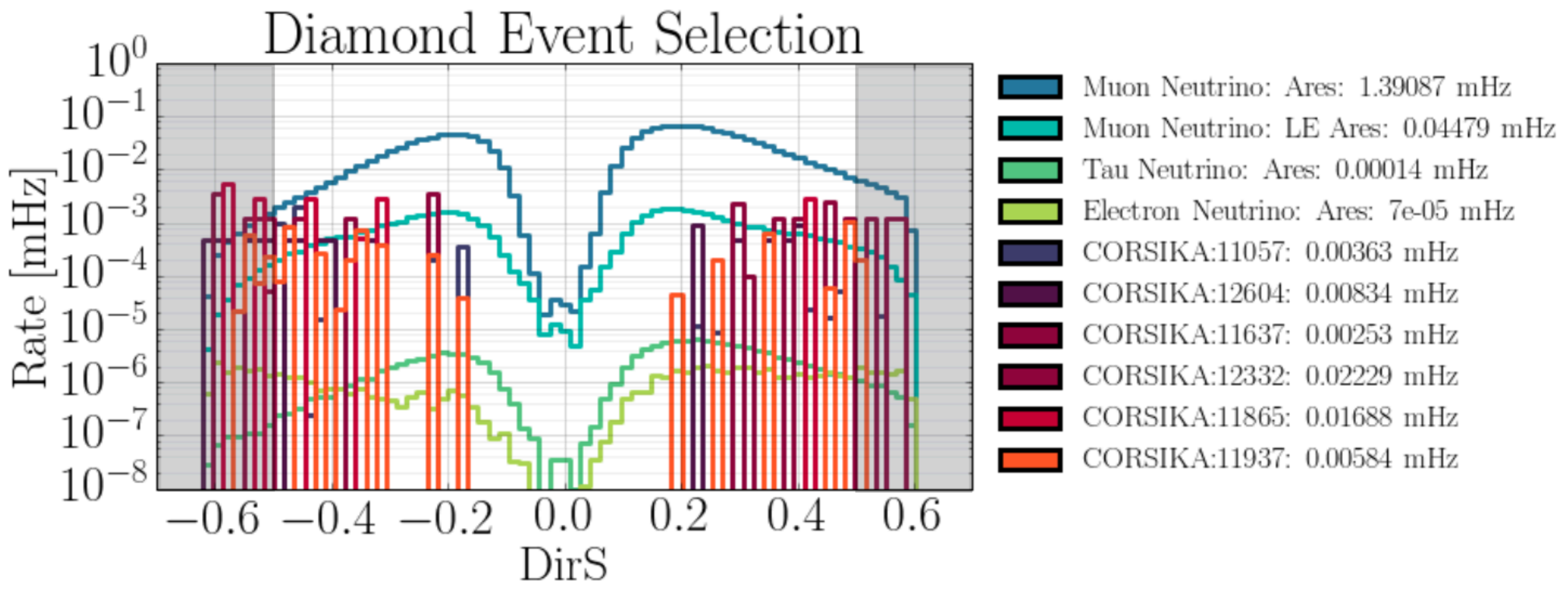
Diamond event selection: Coincidence reduction

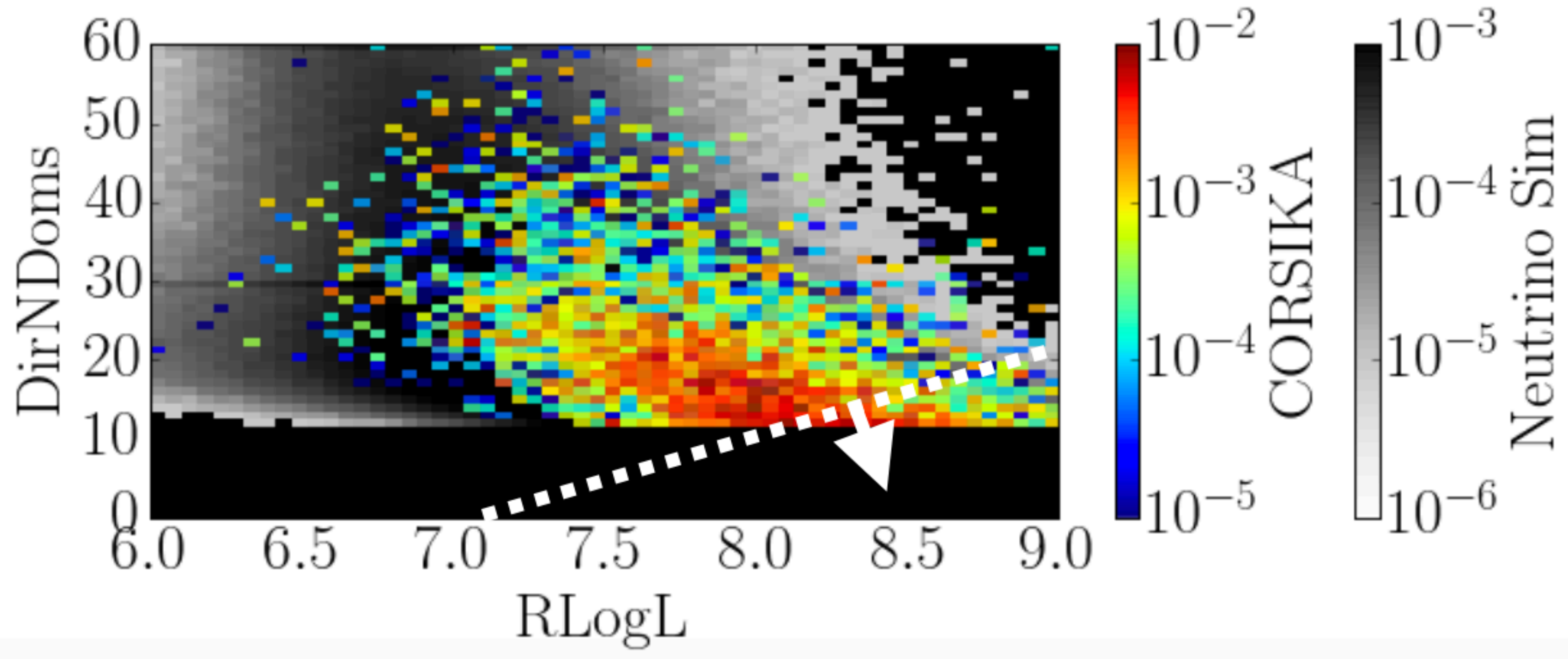
Diamond event selection: Cleanup



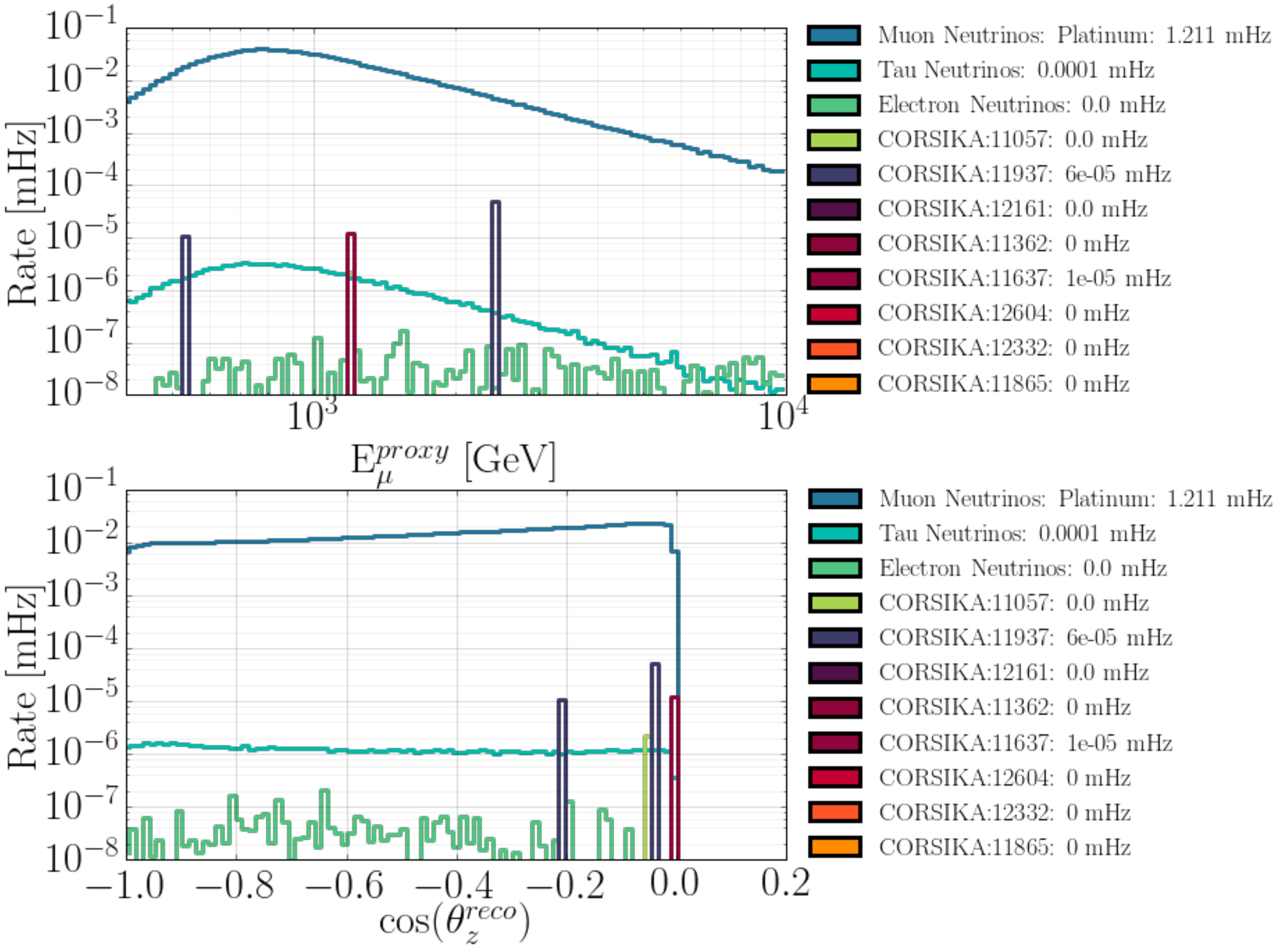






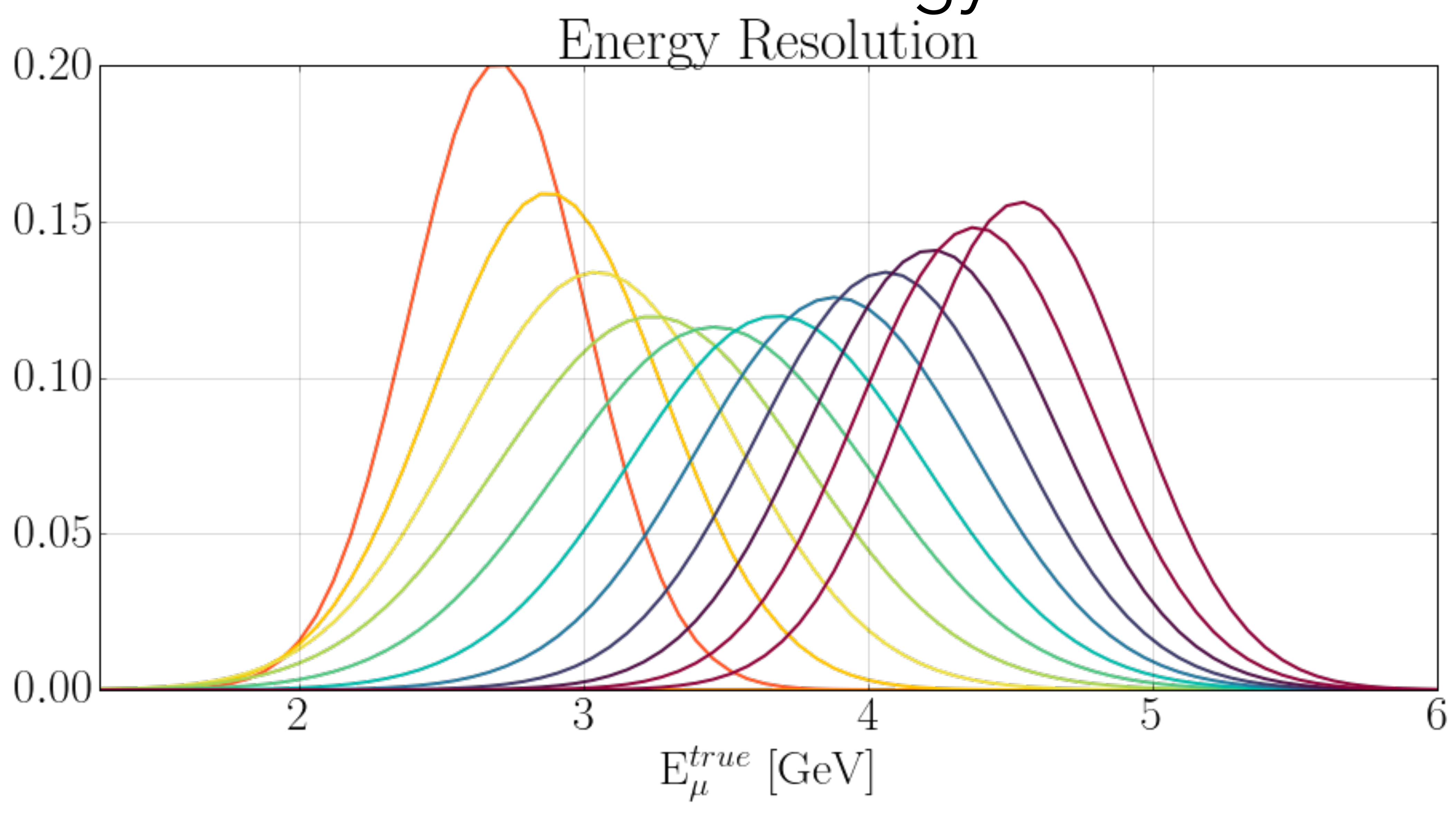


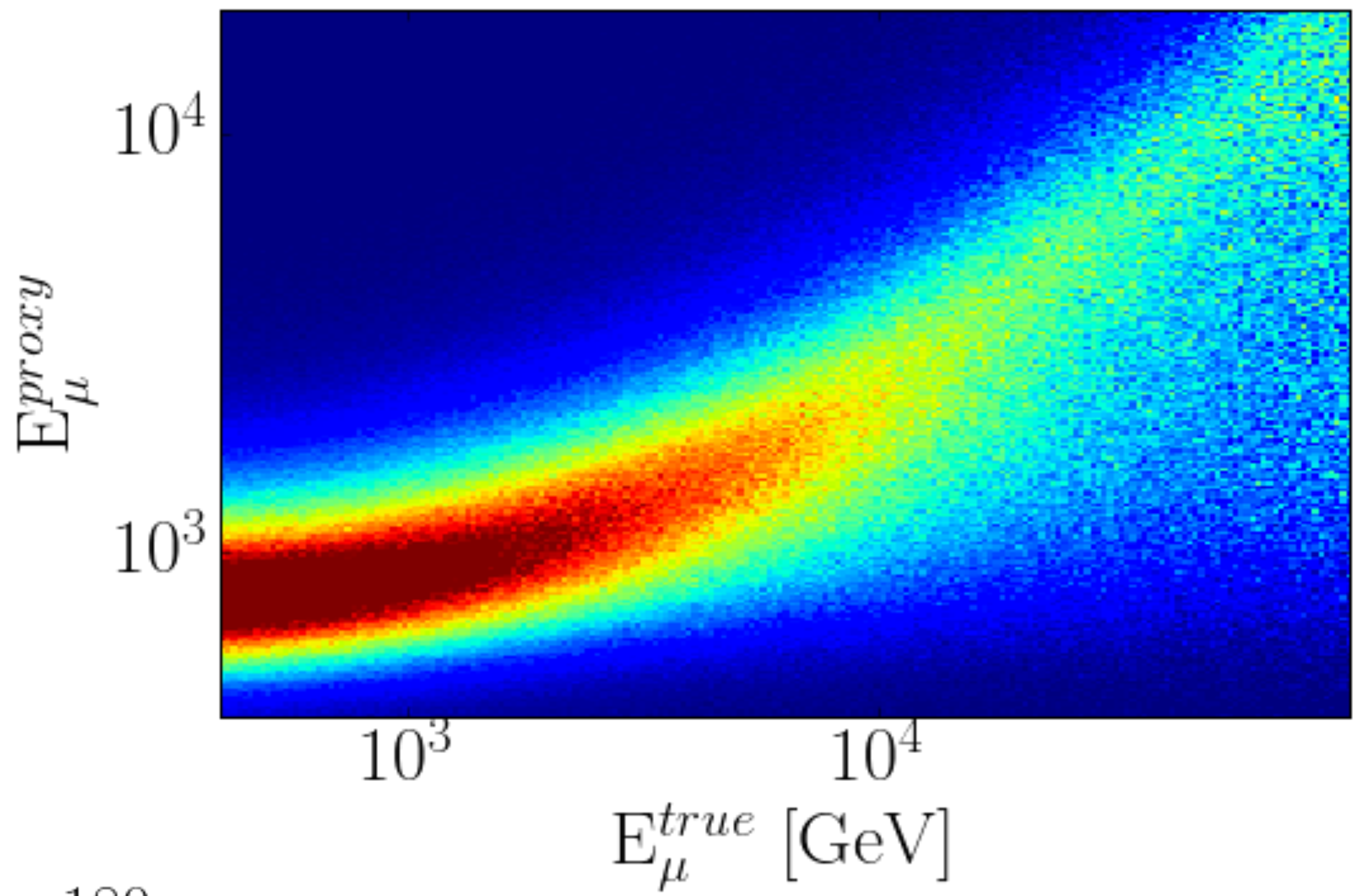
Final distributions

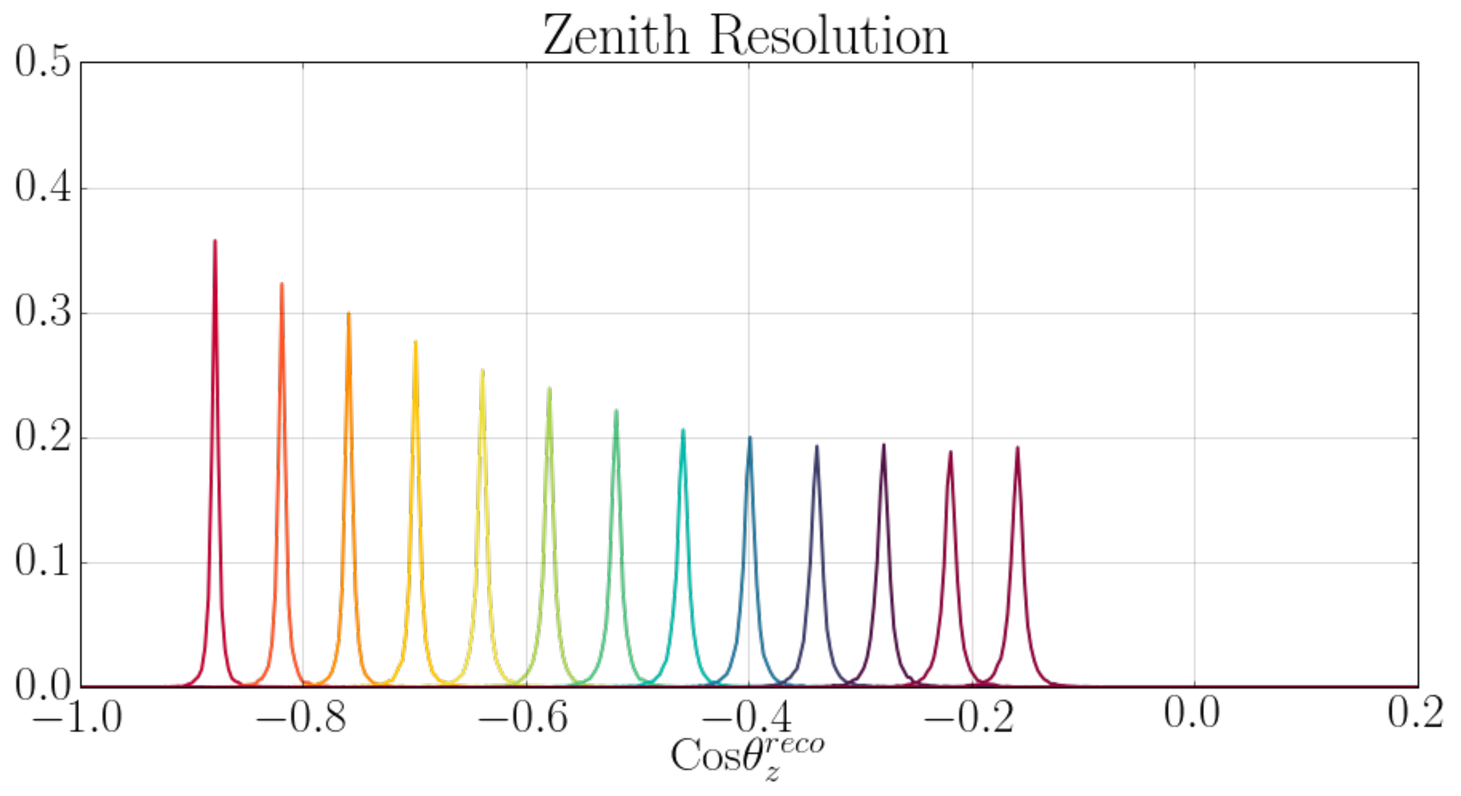


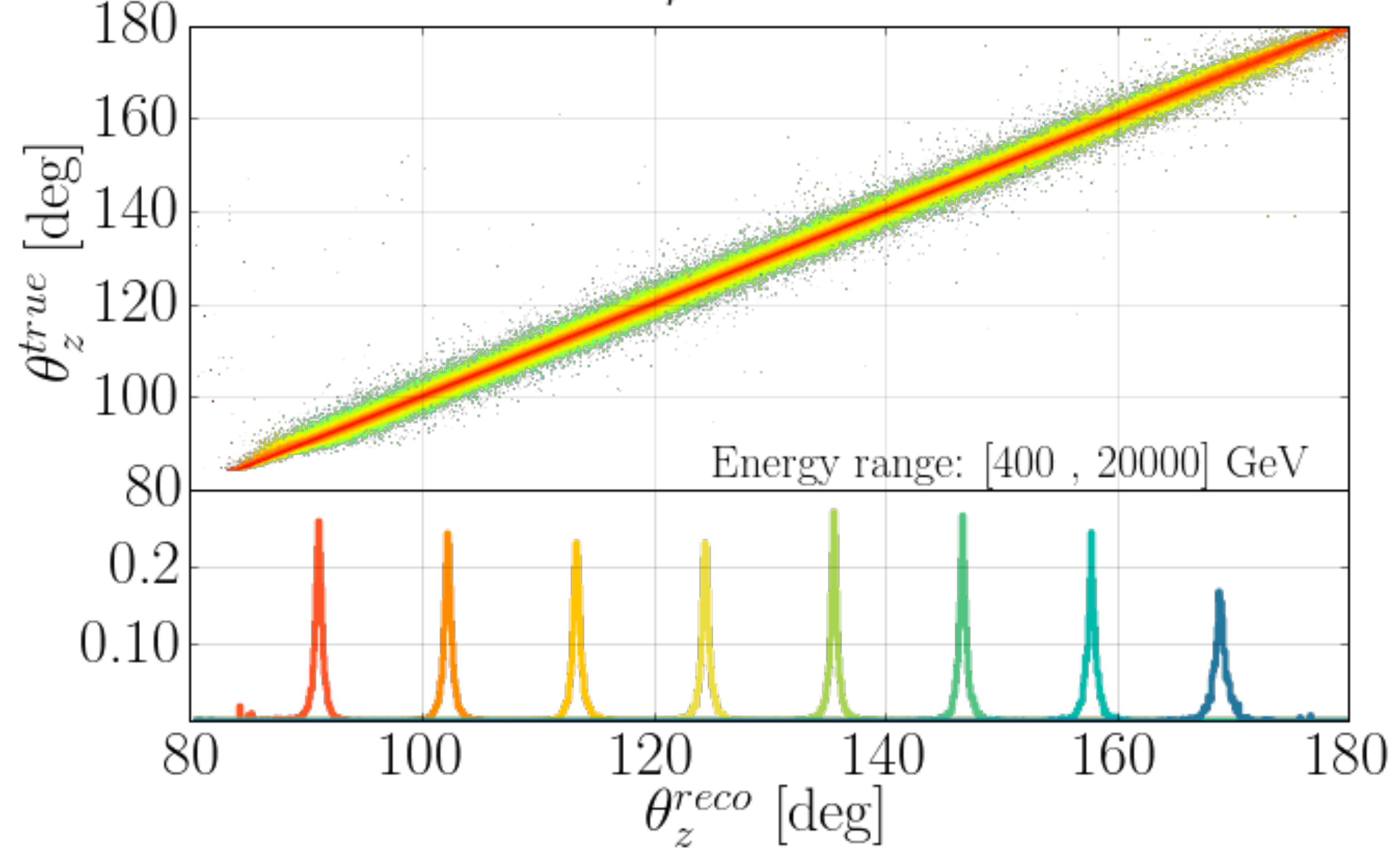
Energy and angular resolution

Energy and zenith resolution using MuEX.







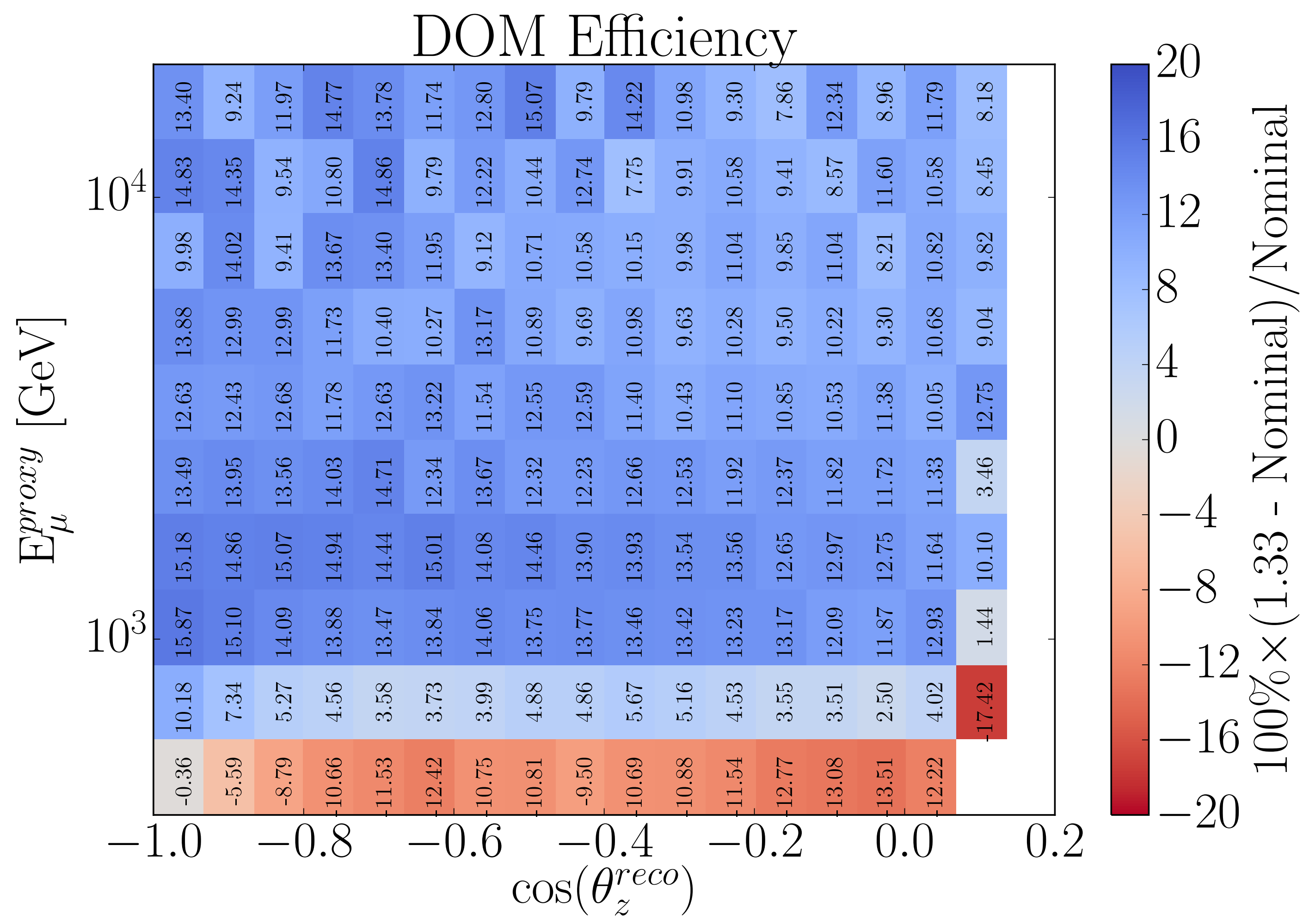


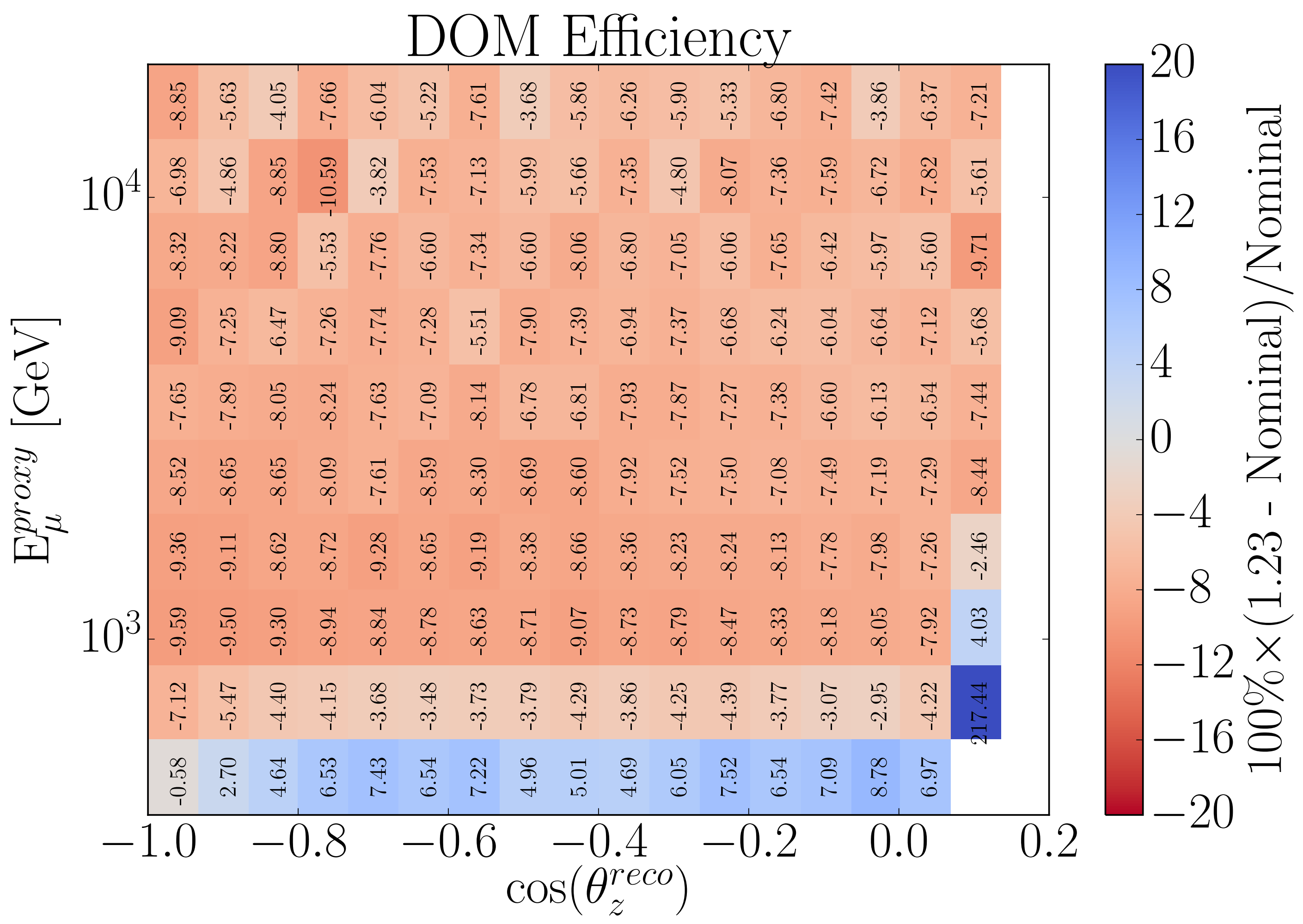
Systematics

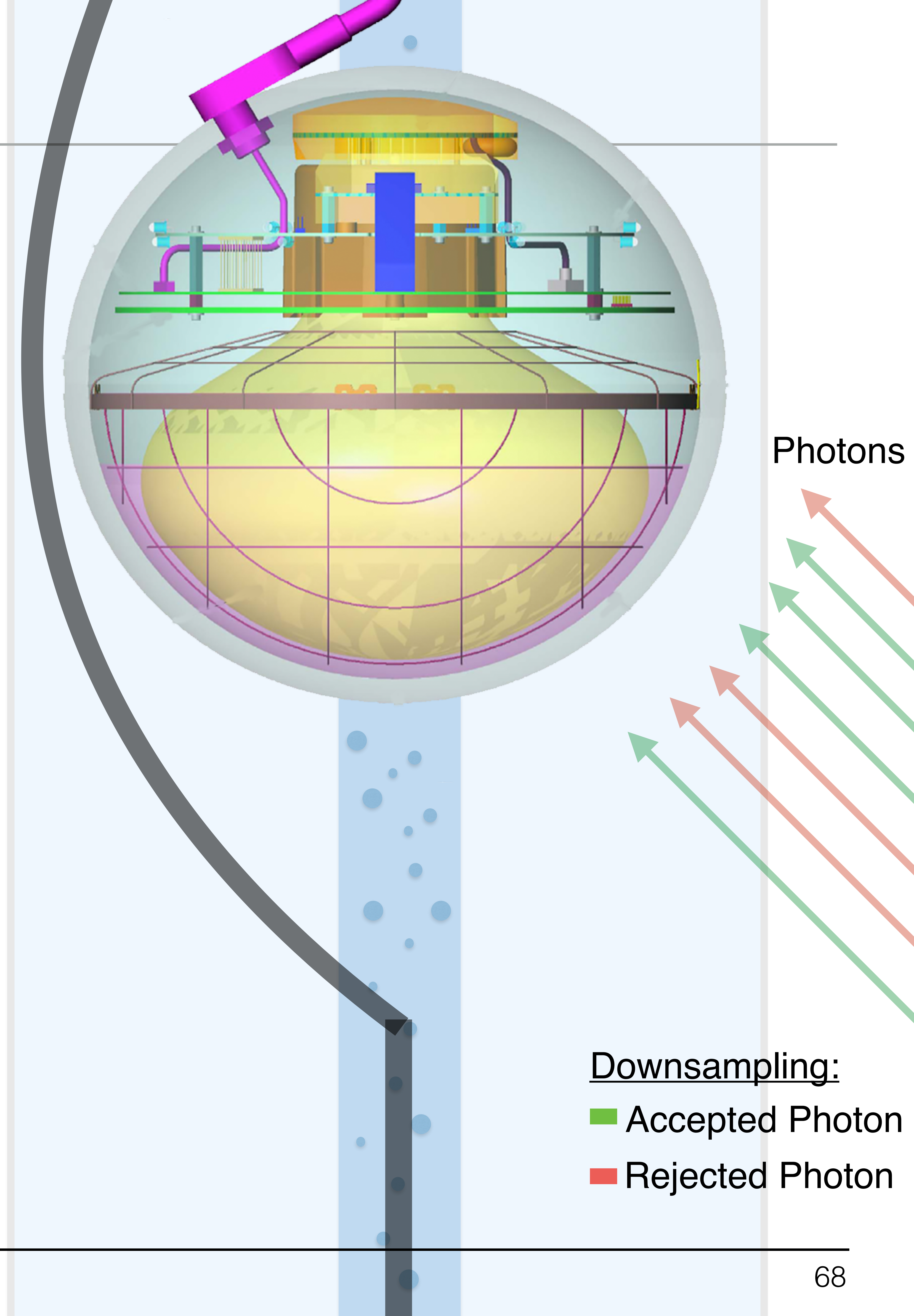
Detector Systematics: DOM efficiency

A generic systematic is included that scales the number of photons incident on the DOM. The scale factor is typically quoted a DOM efficiency of 0.94 (for Spice 3.2), however we use SPE Templates which further scales this to 1.27.

- 6 MC sets are generated with different DOM efficiencies.
- We spline between the curves in Energy and Zenith.



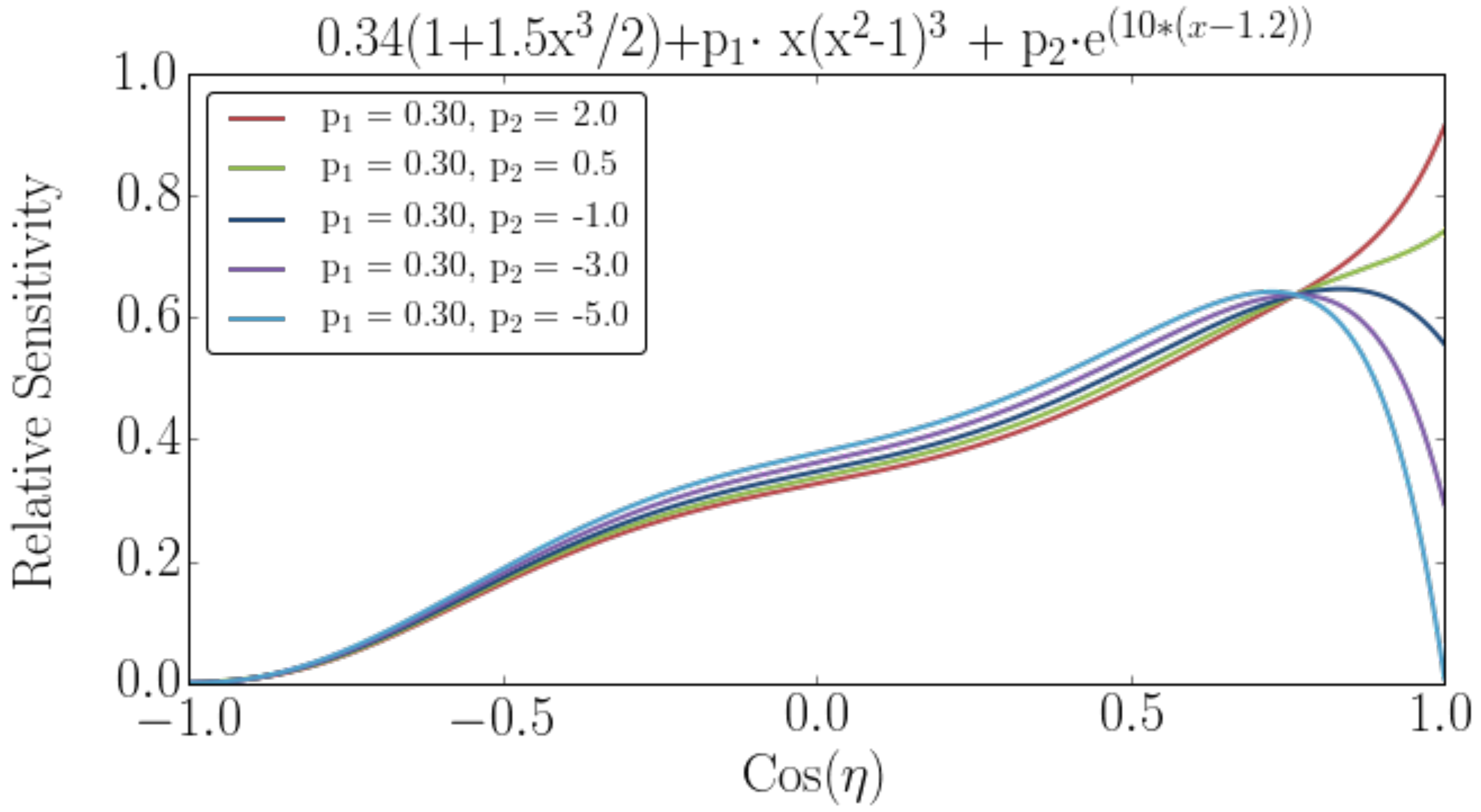


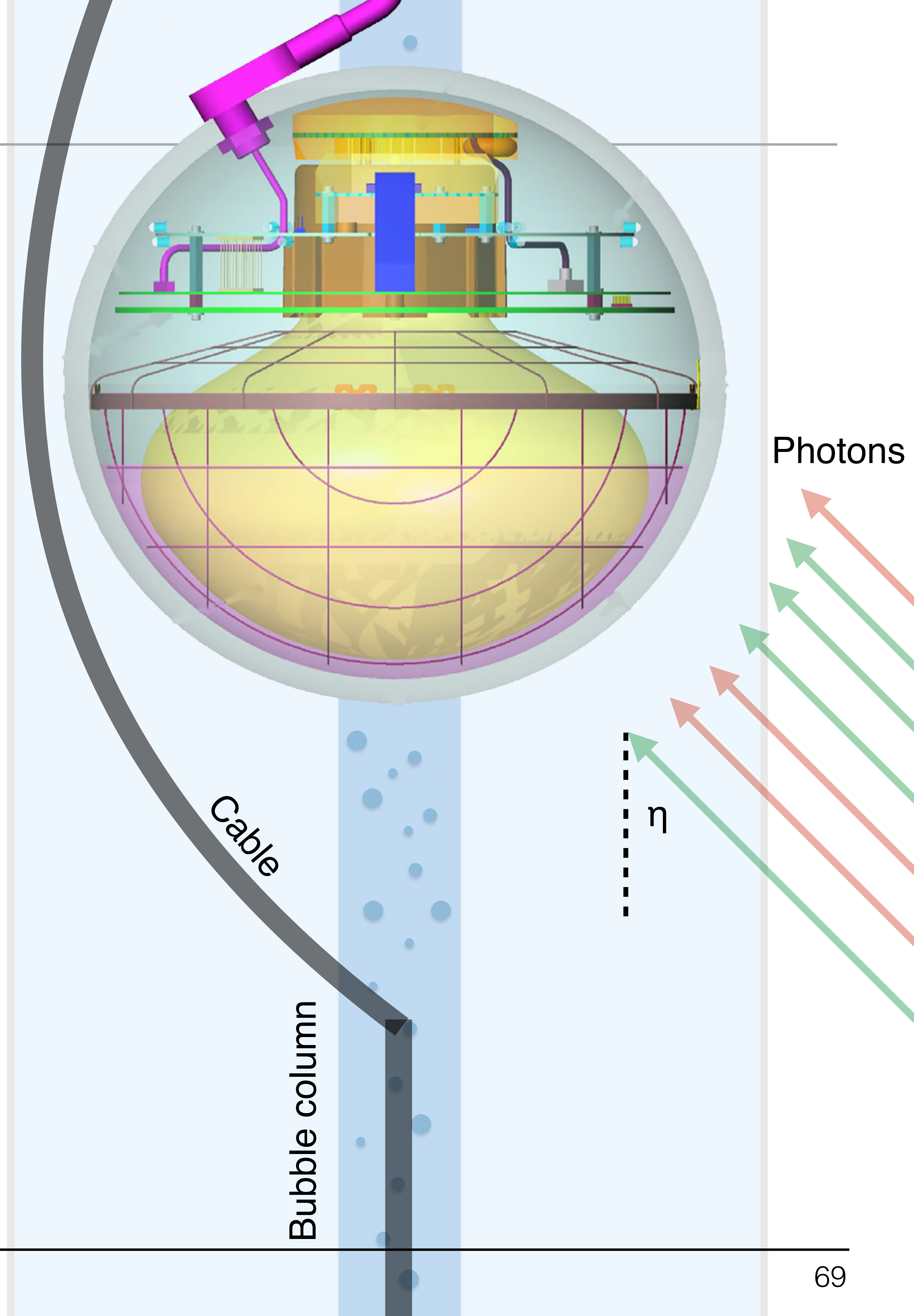


Ice Systematics: Hole Ice

When the holes for the DOMs were drilled, the ice refroze around the DOM creating ice with different optical properties. Leads to a modification in the relative sensitivity as a function of incident angle.

- 5 MC sets are generated with the **Relative Sensitivity** curves below.
- We spline between the curves in Energy and Zenith.





Ice Systematics: Hole Ice files

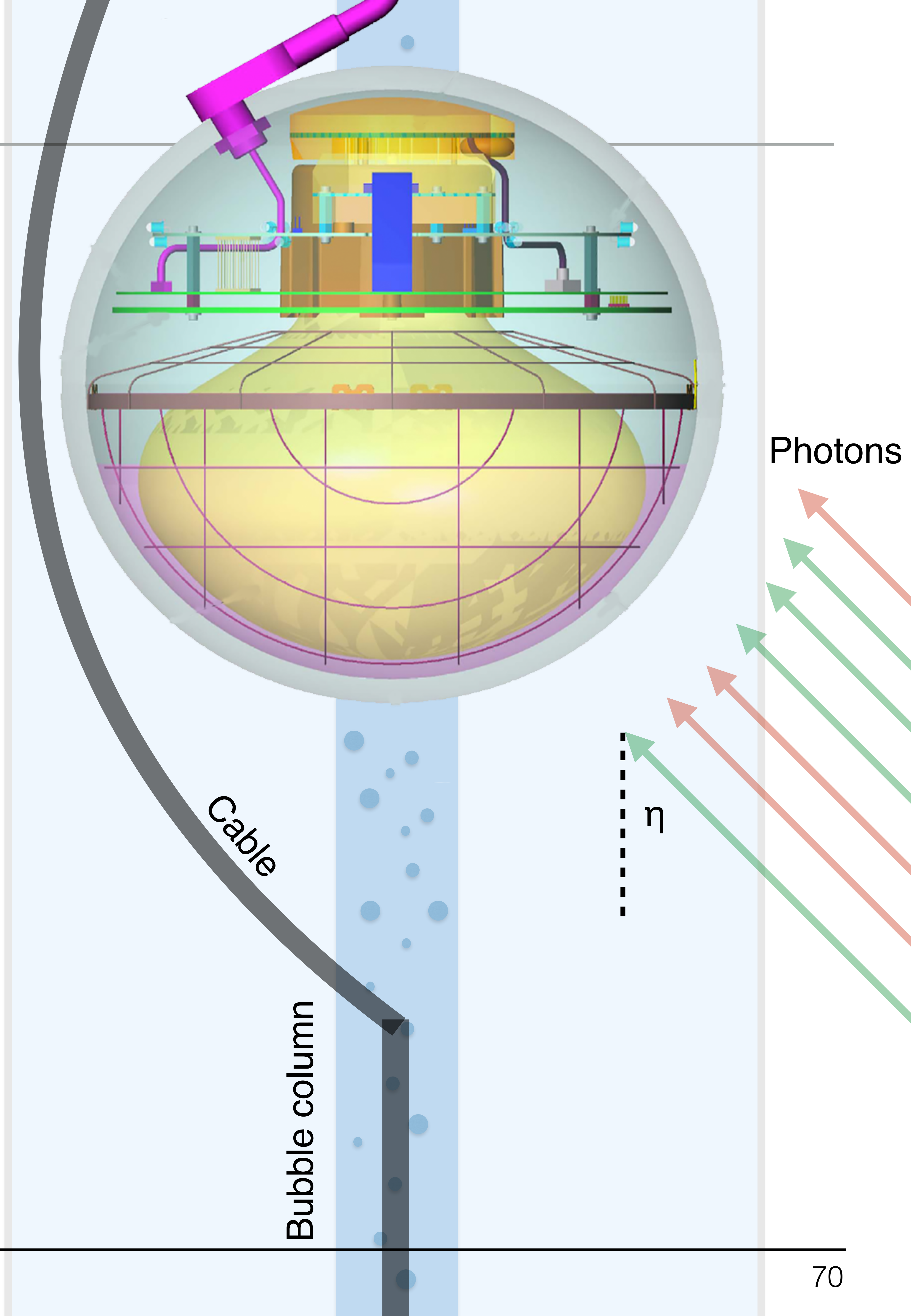
$$0.34(1+1.5x^3/2)+p_1 \cdot x(x^2-1)^3 + p_2 \cdot e^{(10*(x-1.2))}$$

Example file for hole ice:

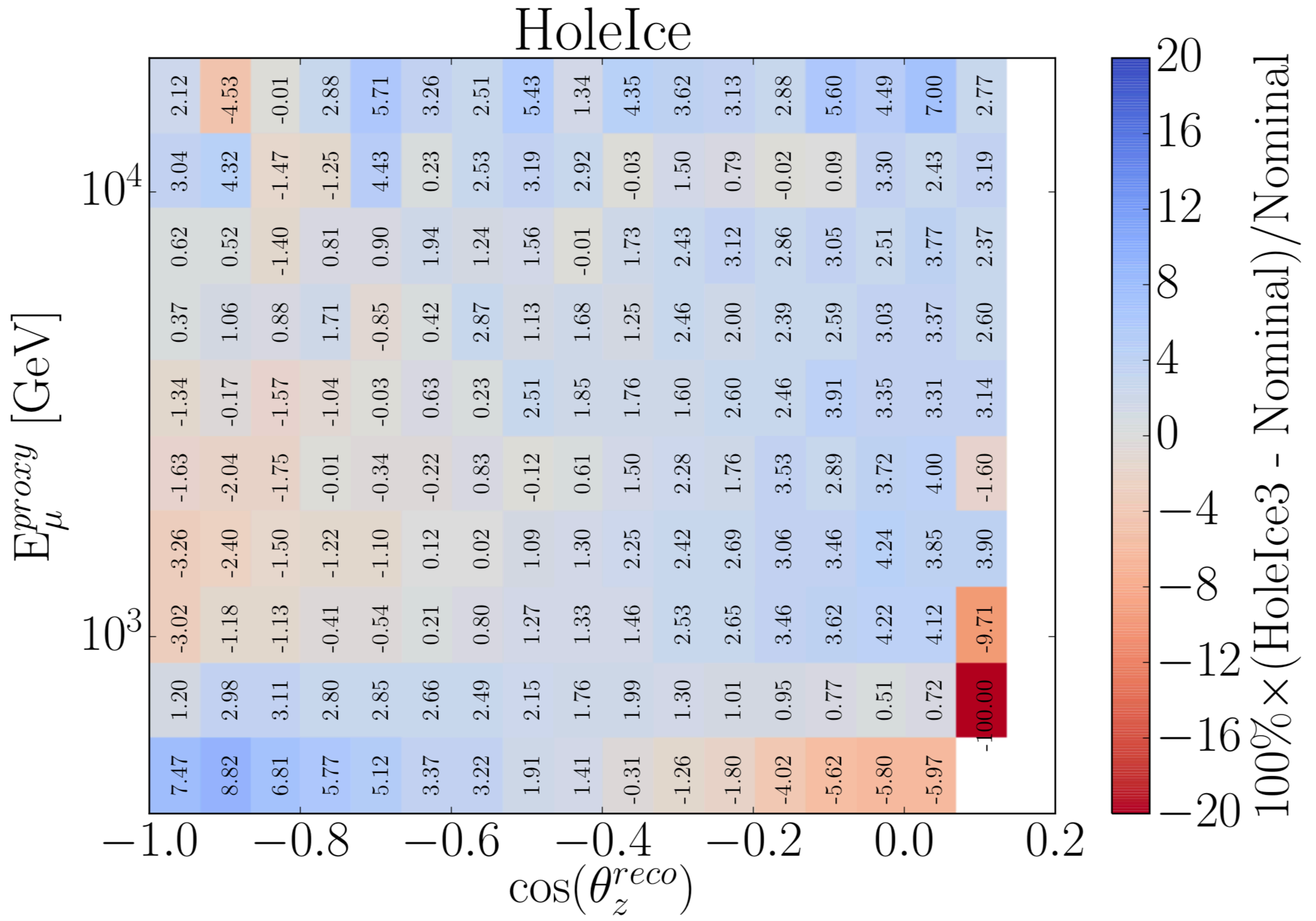
location: Simulation metaproject:
ice-models/resources/models/angsens_flasher

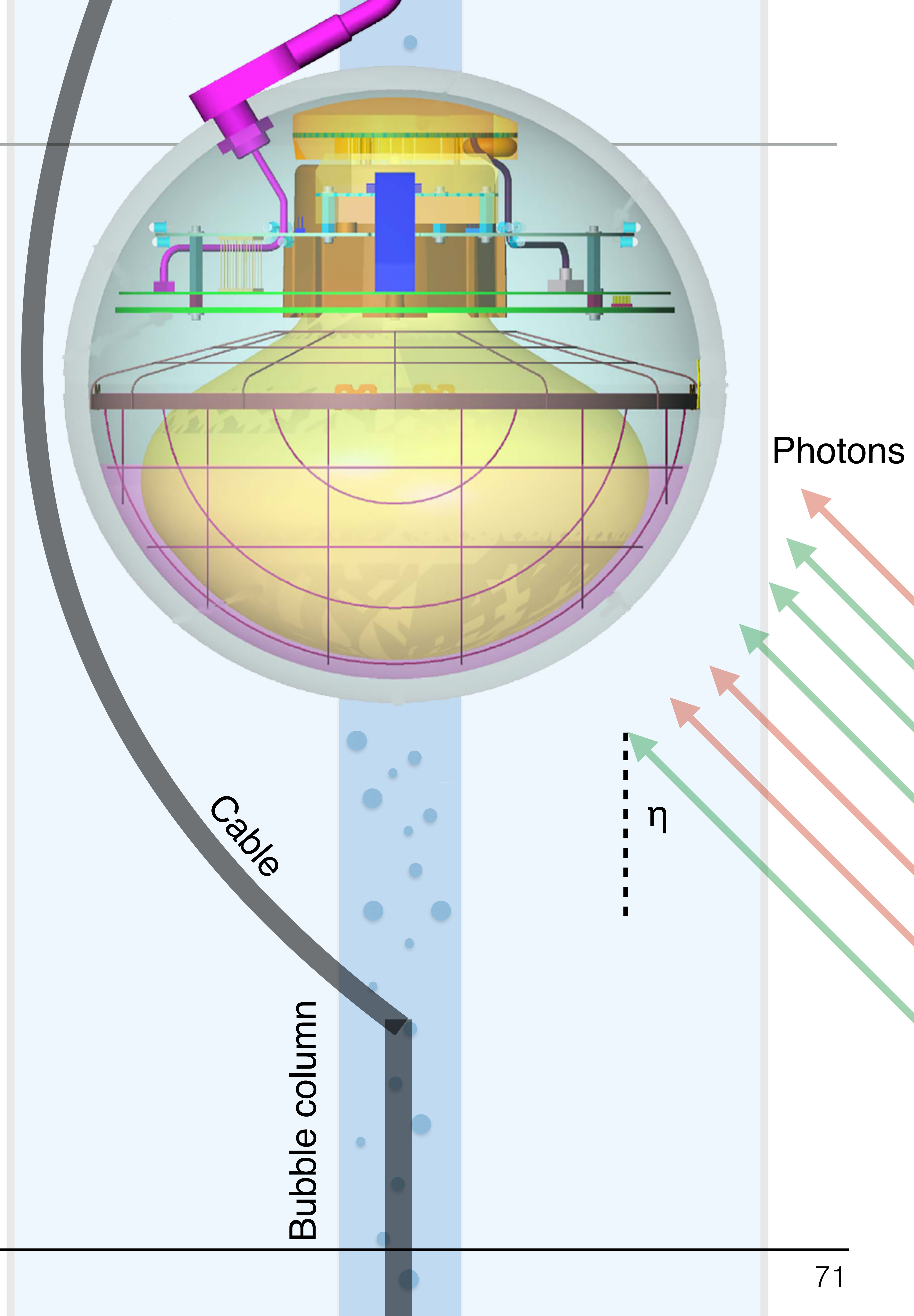
Point: p1 = 0.3, p2 = 0.5
Note: there should be 12 lines in the file!!!

0.77 <- First line describes the peak relative sensitivity.
0.336576
0.215372
0.0018322
0.617527
-0.00232271
-0.477028 <- This describes a polynomial fit to the distribution.
0.000481457
-0.299339
0.0101417
0.315676
0.0228995



Ice Systematics: Hole Ice shapes





Flux Systematics: Atmospheric Density Uncertainties

Big thanks to Gabriel

The density of the atmosphere effects the production of the neutrinos.
Atmospheric density change leads to changes in the:

- Interaction region
- Energy loss of mesons, capture versus decay of mesons

Interaction Model

1.QGSJET-II-04
2.SIBYLL 2.3 RC1
3.SIBYLL 2.3 RC1 Point-like

+

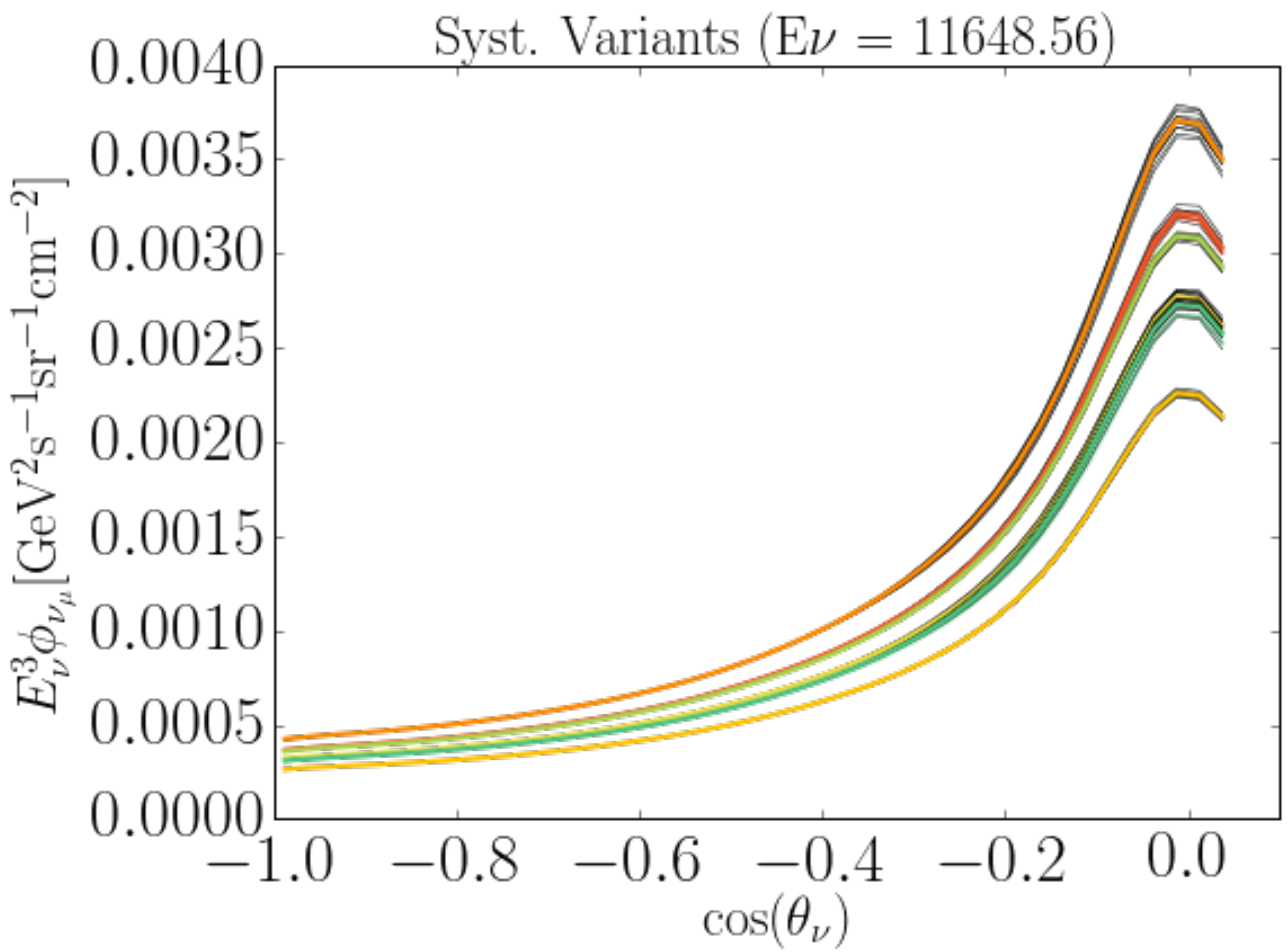
CR Flux Model

1. Poly-gonato
2. Zatsepin-Sokolskaya/PAMELA
3. Hillas-Gaisser/Gaisser-Honda

+

AIRS systematic variations

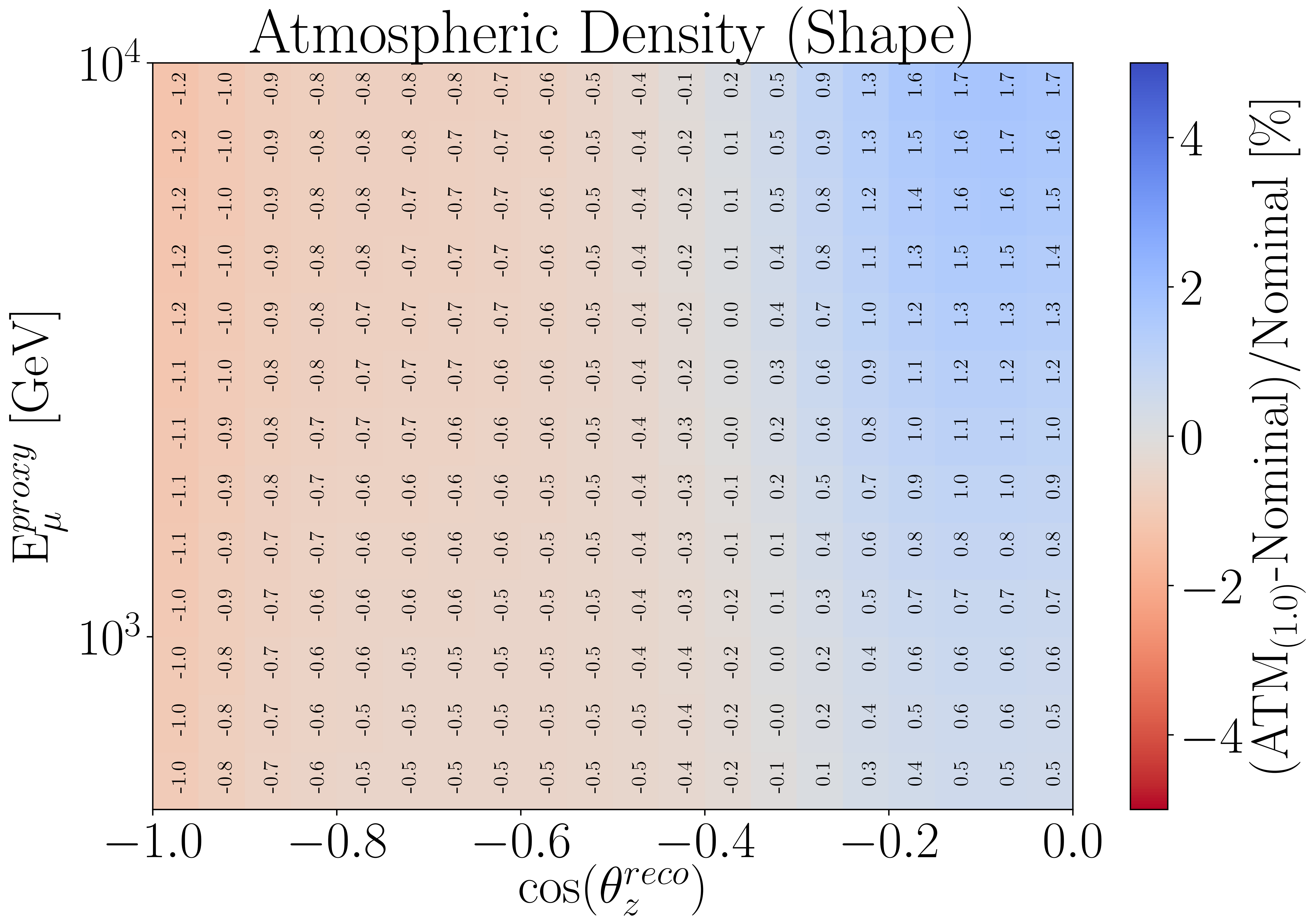
1. Monthly averages per year
2. Temperature variations
3. Height up to ~45km
4. 1° x 1° area of Earth coverage
5. 24 fixed level pressure measurements



[1] A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and T. Stanev, "Calculation of conventional and prompt lepton fluxes at very high energy," arXiv:1503.00544 [hep-ph].

Flux Systematics: Atmospheric Density Uncertainties

Big thanks to Gabriel



Flux Systematics: Cosmic ray spectral index

Change in CR spectral slope

$$\phi(E) \rightarrow \phi(E)\left(\frac{E}{E_0}\right)^{-\Delta\gamma}$$

The cosmic ray spectral index systematic represents a hardening or softening of the energy spectrum.

In the energy range of the MEOWS analysis (TeV to 100TeV), there are three relevant cosmic ray experiments which report an uncertainty on the slope of approximately $\Delta\gamma = 0.01$.

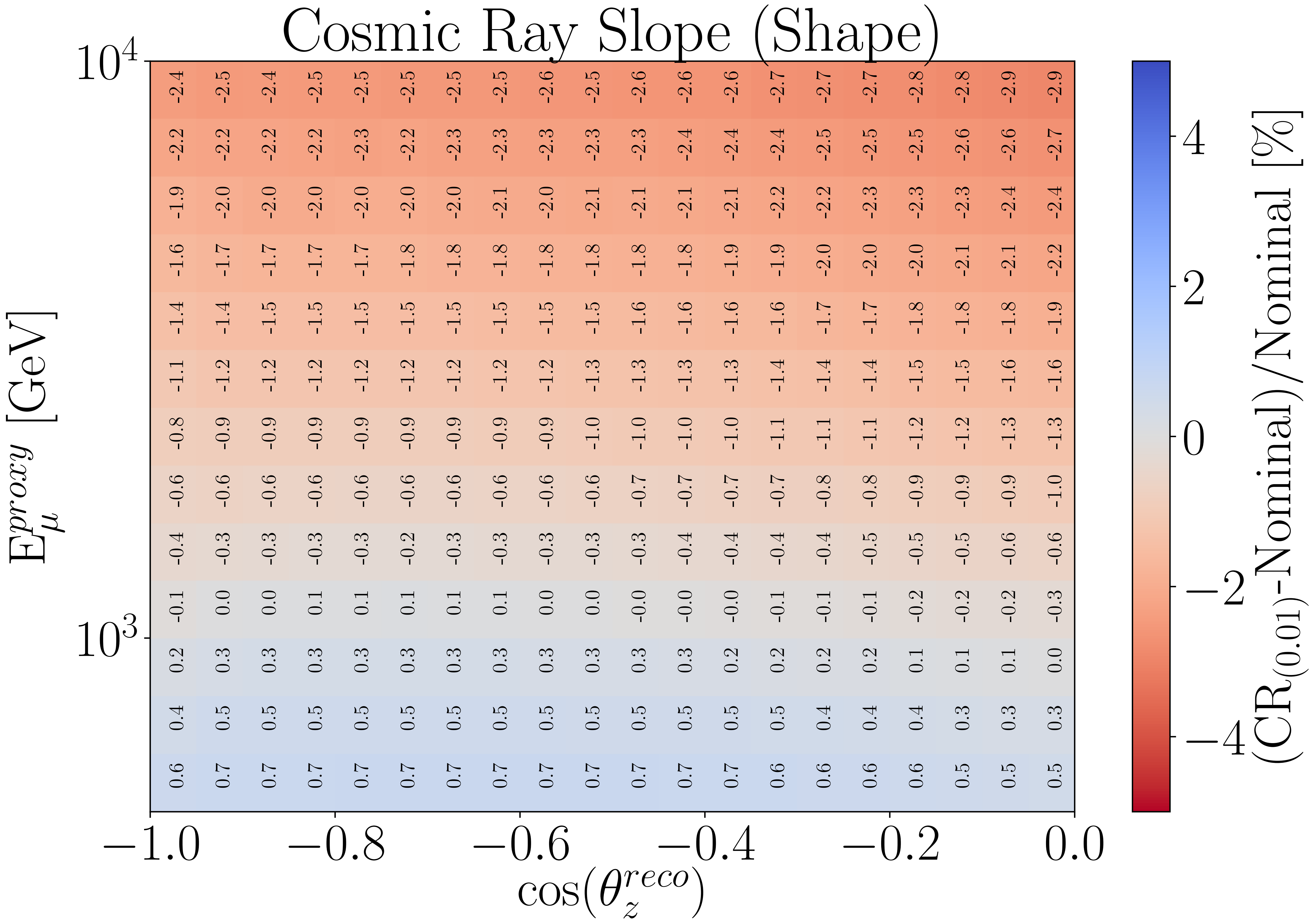
The characteristic energy, E_0, we use is at 2.2TeV.

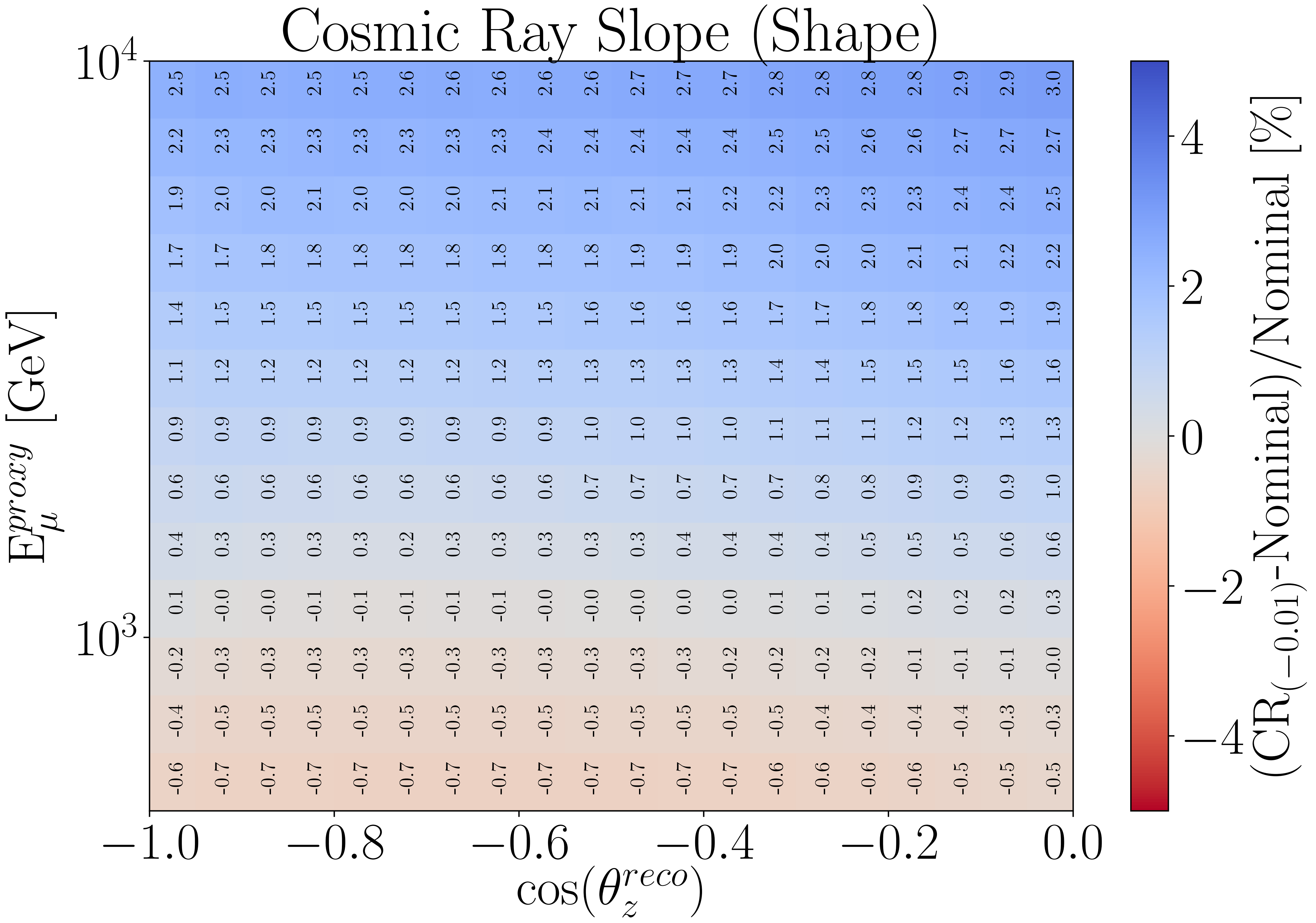
Experiment	Year	Energy range	Measured CR Slope	Note
CREAM-III	2017	1TeV - 200TeV	-2.65 +/- 0.03	Interesting steepening above 10TeV link
HAWC	2017	10TeV - 500TeV	–2.63 +/- 0.01	Also sees a steepening at 45TeV link
Argo-YBJ	2016	3TeV - 300TeV	-2.64 +/- 0.01	link
Pamela	2011	50GeV - 15TeV	-2.70 +/- 0.05	Too low energy link
NUCLEON	2017	1TeV - 200TeV	NA	Waiting for publication link
ATIC-2	2009	50GeV - 200TeV	NA	They note a steepening at 10TeV, but not the fit link

Flux Systematics: Cosmic ray spectral index shape

$$\phi(E) \to \phi(E)\left(\frac{E}{E_0}\right)^{-\Delta\gamma}$$

Change in CR spectral slope





Ice Systematics -- Bulk ice (IceStorm)

1. Coverage

   The MultiSim provides a more representative systematic coverage of the systematics

2. Efficiency

   Monte Carlo is expensive, both temporally and computationally.

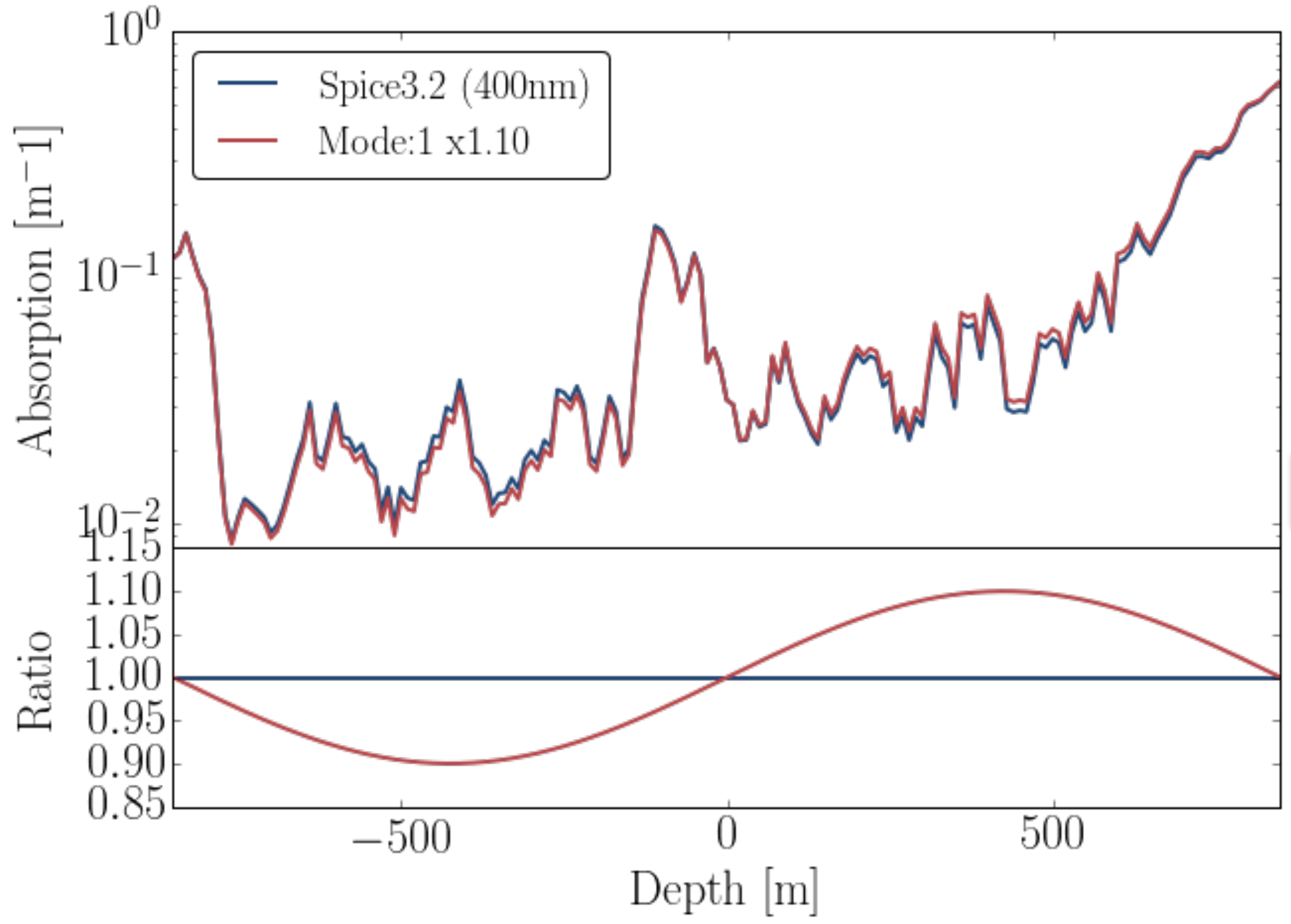
   The MultiSim allows for the many nuisance parameters to be explored using a single set of Monte Carlo.

3. Scalability

   Incorporating more comprehensive systematic treatments (depth dependance ice uncertainties, detailed DOM angular acceptance, etc.) presents scaling problems for discrete shifts.

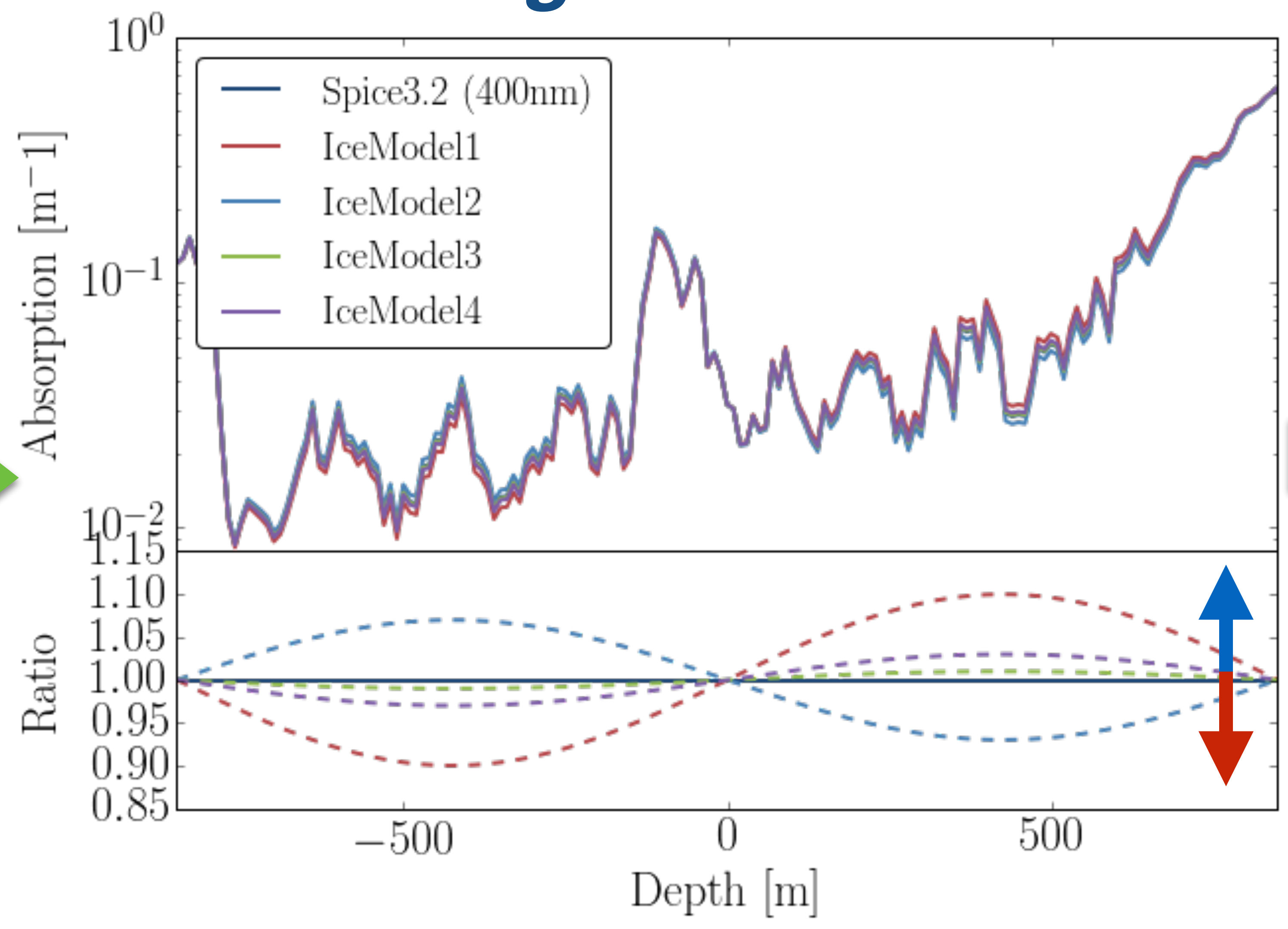
Ice Systematics -- Bulk ice (IceStorm)

Fourier Mode1 example:



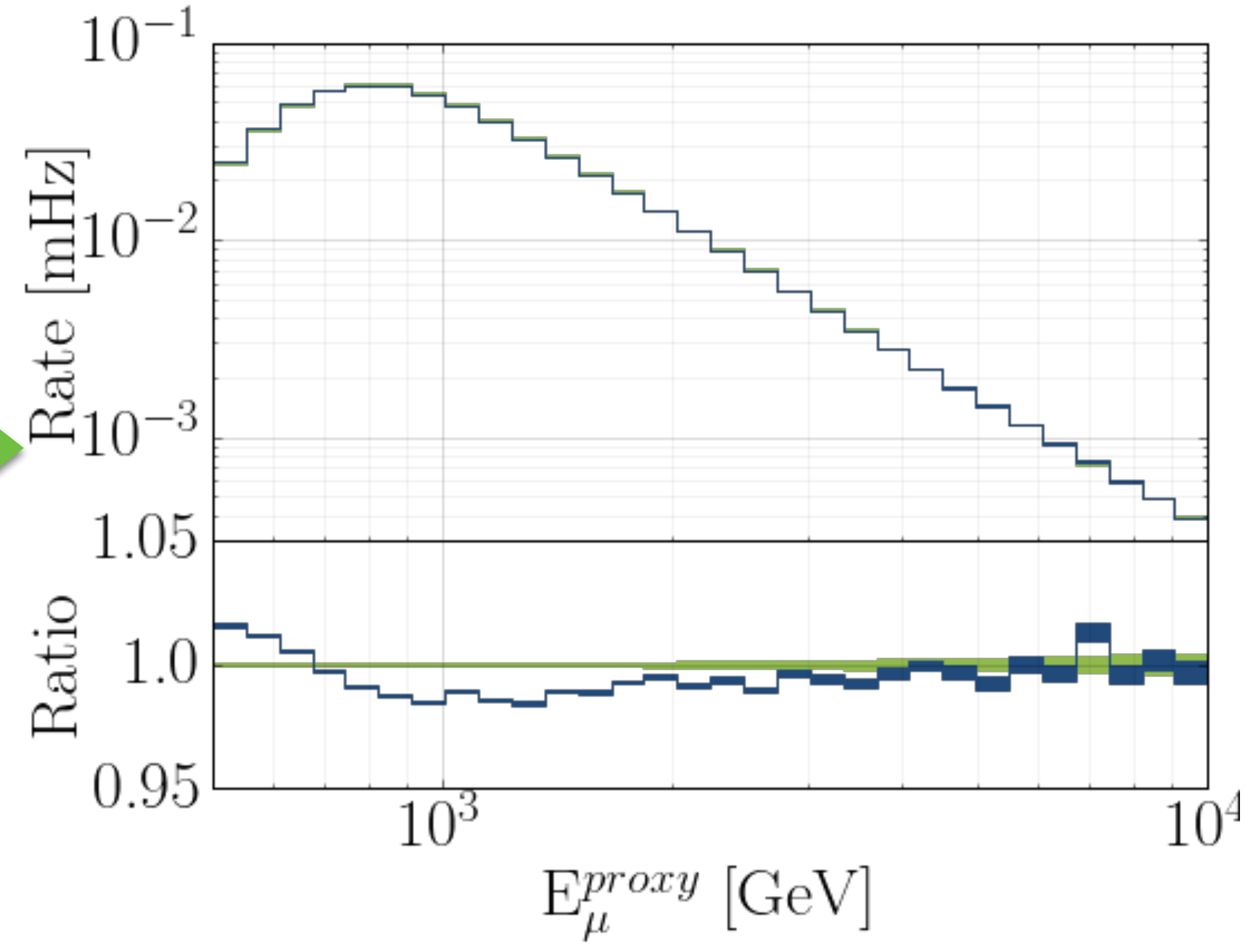
Flasher data tell us the allowed spread in the amplitude and phase.

Every 100 events, change the model:



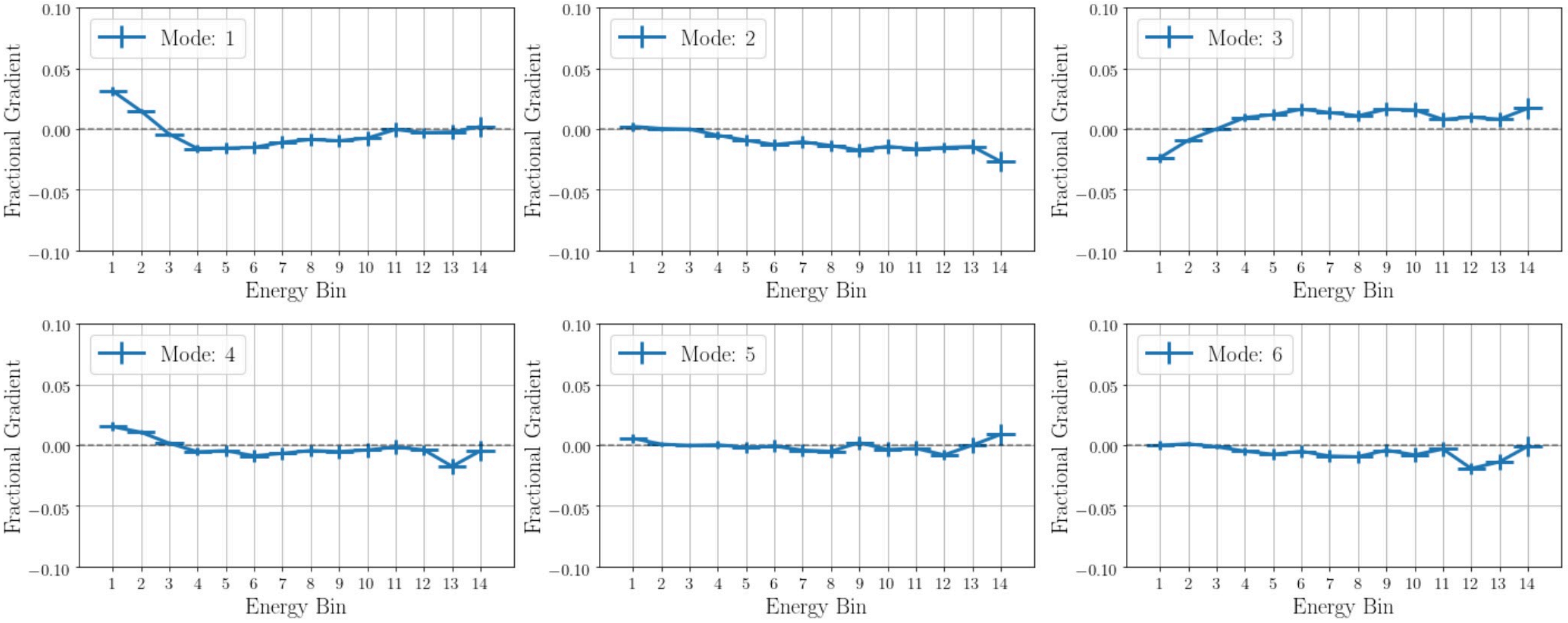
We now have $O(10^7)$ ice models in our MC set.

Split the full MC to get the 'Gradient'



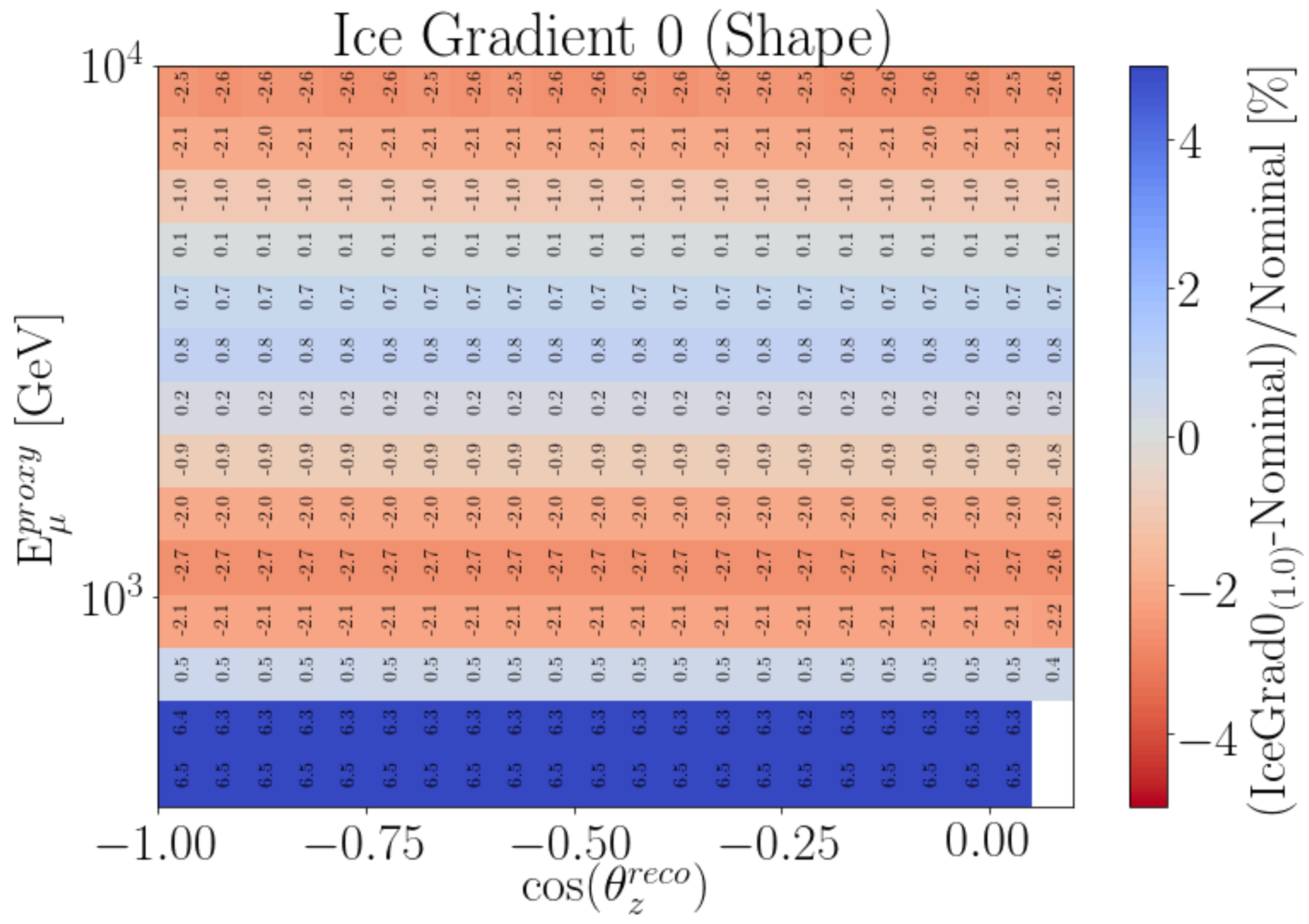
The change from **positive perturbed models** to the **negative perturbed models** gives the **Gradient**. (with some scale factor)

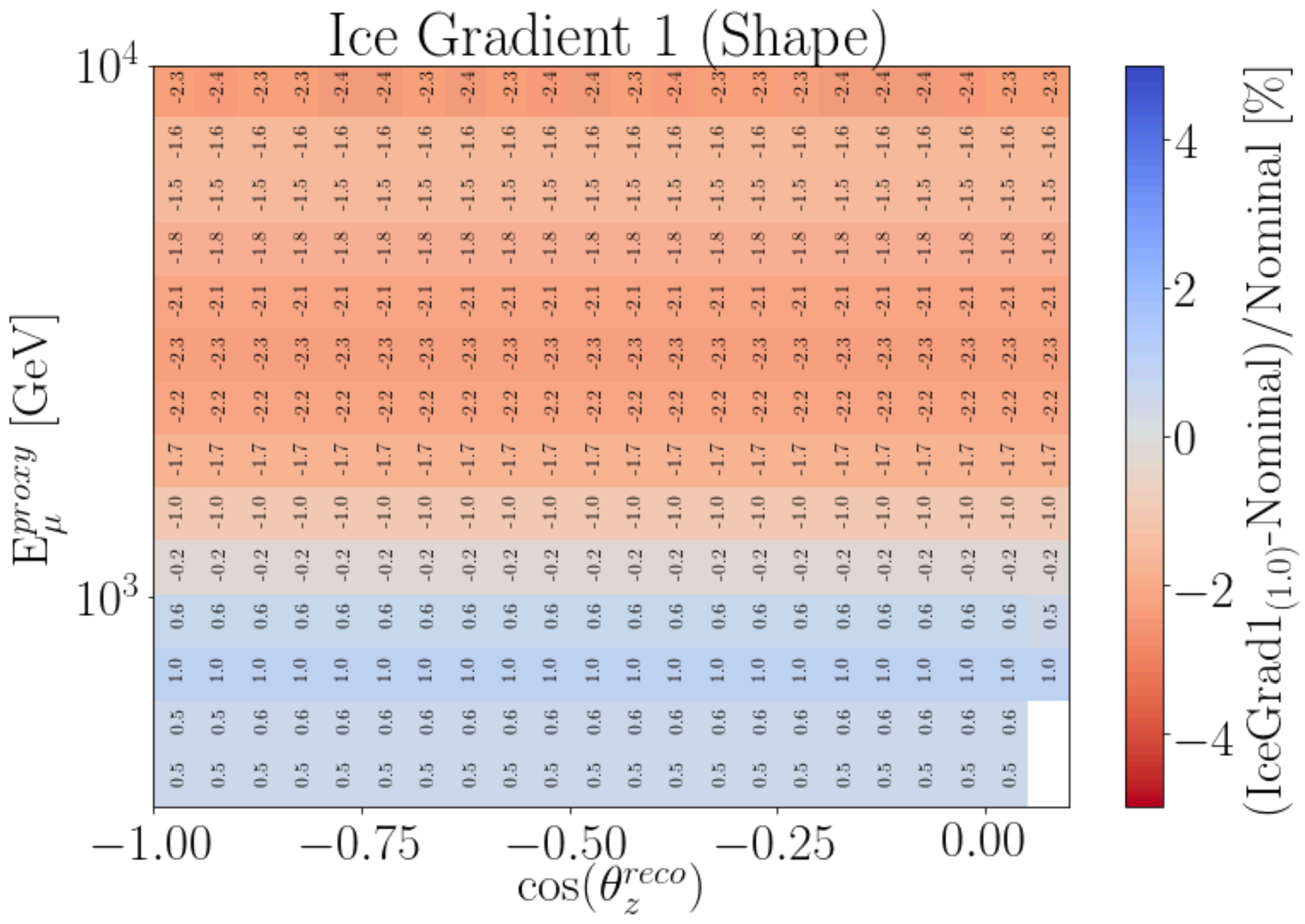
Ice Systematics -- Bulk ice (IceStorm)



MultiSim systematic shape

A linear combination of two shapes can describe the shapes associated with the the first 6 modes. They do not vary independently.





Description is available in the Technote.

https://www.dropbox.com/s/u7zxwdpuch62evw/MultiSim-12.pdf?dl=0

Flux Systematics: Barr scheme

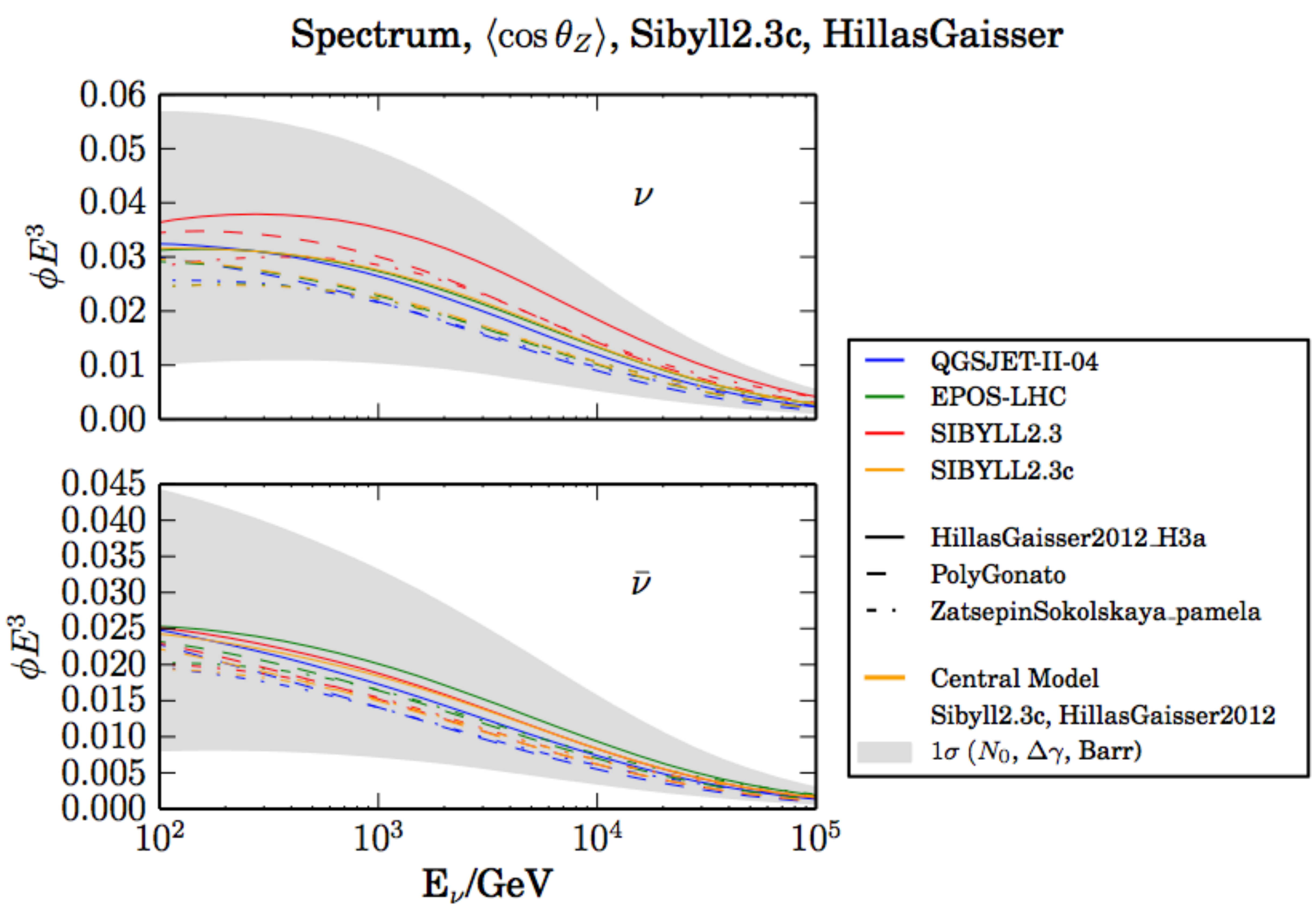
Marjon + Carlos

Previous flux systematic treatment: discrete variant of a few models.
New flux systematic treatment: continuous variations that describe the pion/kaon uncertainties

More physical description of the uncertainty.

Parameter	x_{LAB}	Energy / GeV	Uncertainty	π±/K±
H±	0.1 – 1.0	30 – 1e11	15%	π±
W±	0.0 – 0.1	30 – 1e11	40%	K±
Y±	0.1 – 1.0	30 – 1e11	30%	K±
Z±	0.1 – 1.0	500 – 1e11	12.2% × $\log_{10}$(E/500 GeV)	K±

The continuous variation is shown to span the discrete flux systematics.

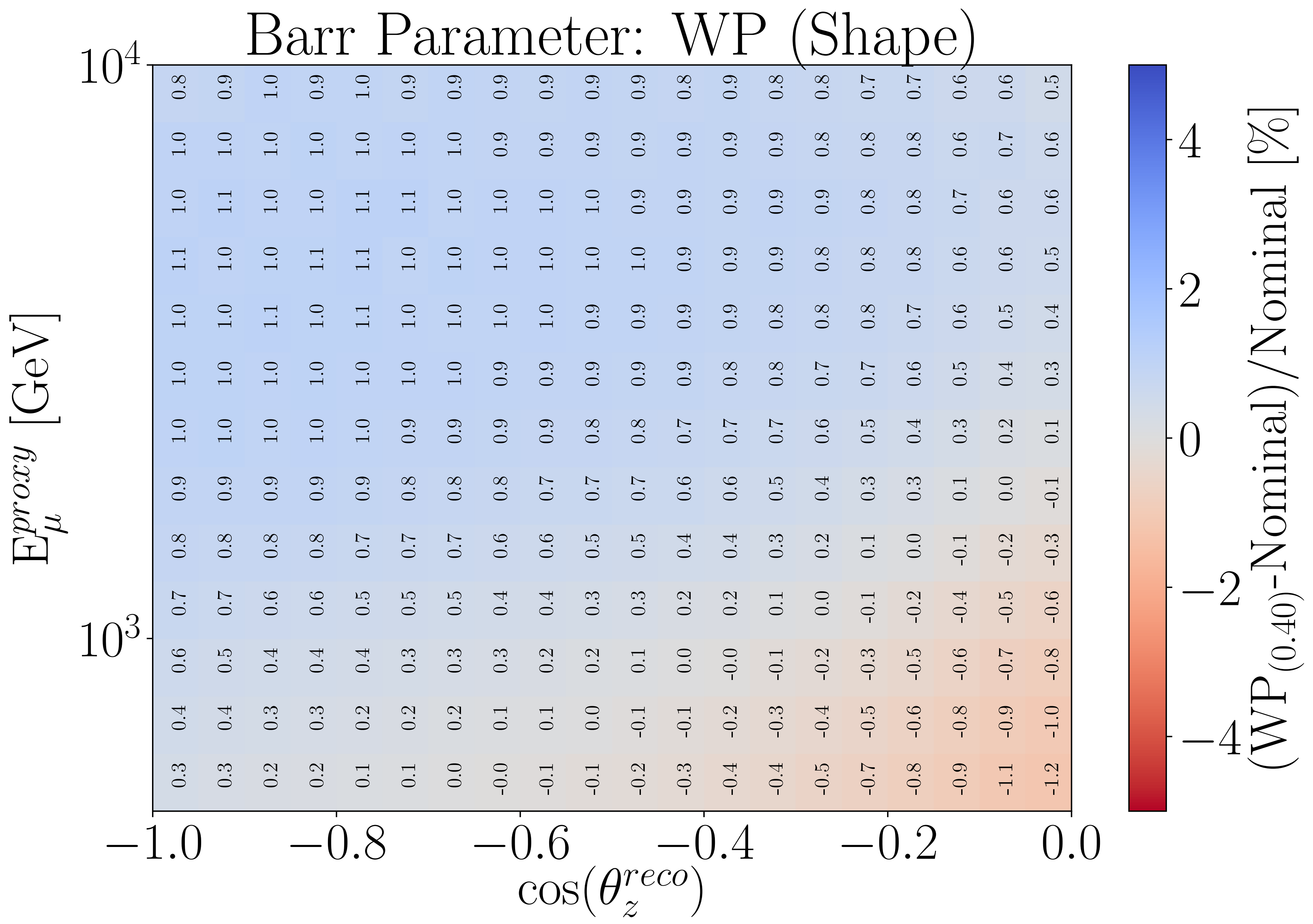


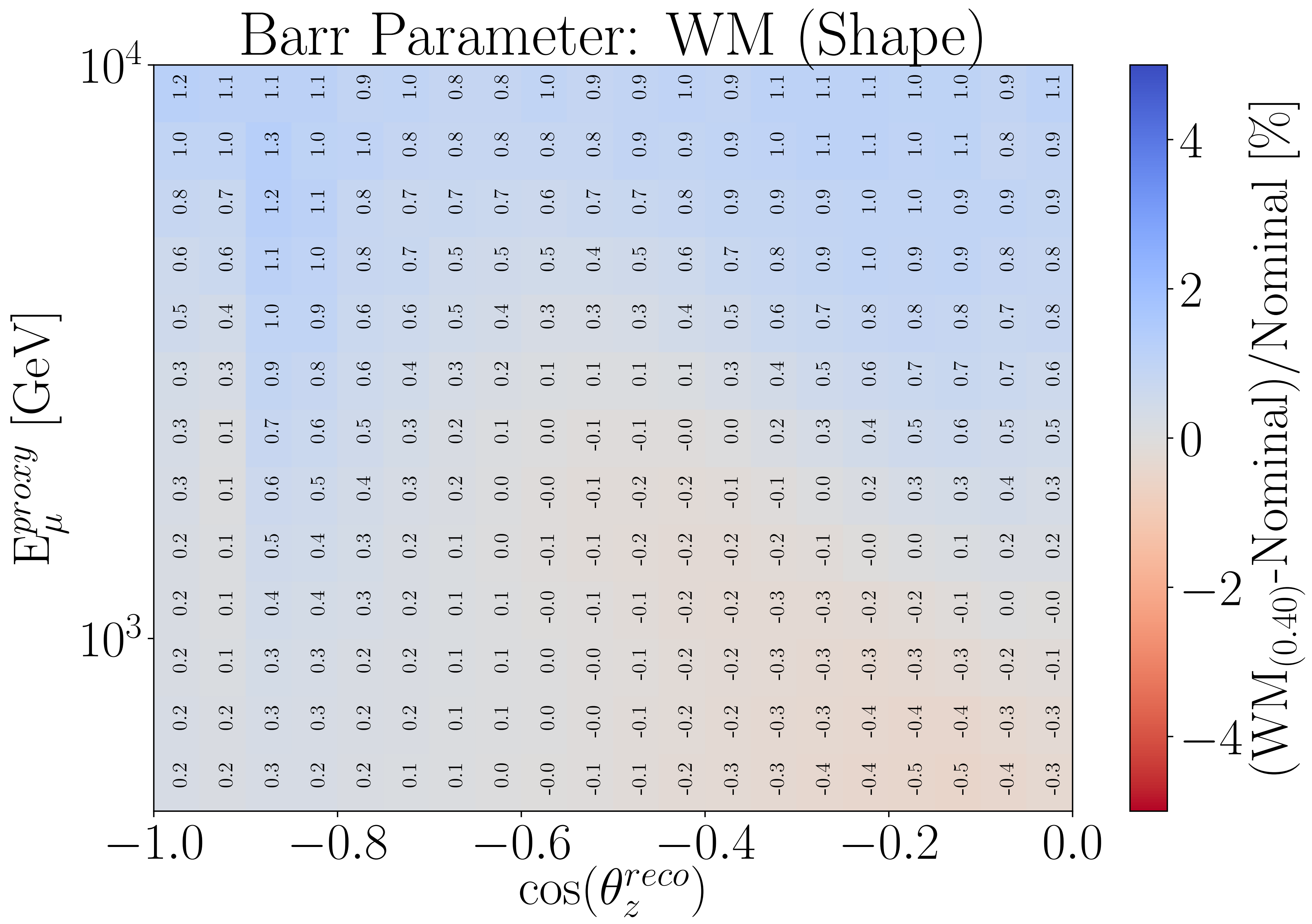
Flux Systematics: Barr shapes: WP/WM

The WP and WM:
Contribution from positive (P) and negative (M) charged kaons with low Bjorken X.

Parameter	x_{LAB}	Energy / GeV	Uncertainty	π±/K±
H±	0.1 – 1.0	30 – 1e11	15%	π±
W±	0.0 – 0.1	30 – 1e11	40%	K±
Y±	0.1 – 1.0	30 – 1e11	30%	K±
Z±	0.1 – 1.0	500 – 1e11	12.2% × $\log_{10}$(E/500 GeV)	K±

Kaons dominate the muon neutrino contributor above ~80GeV. The shape at Null:



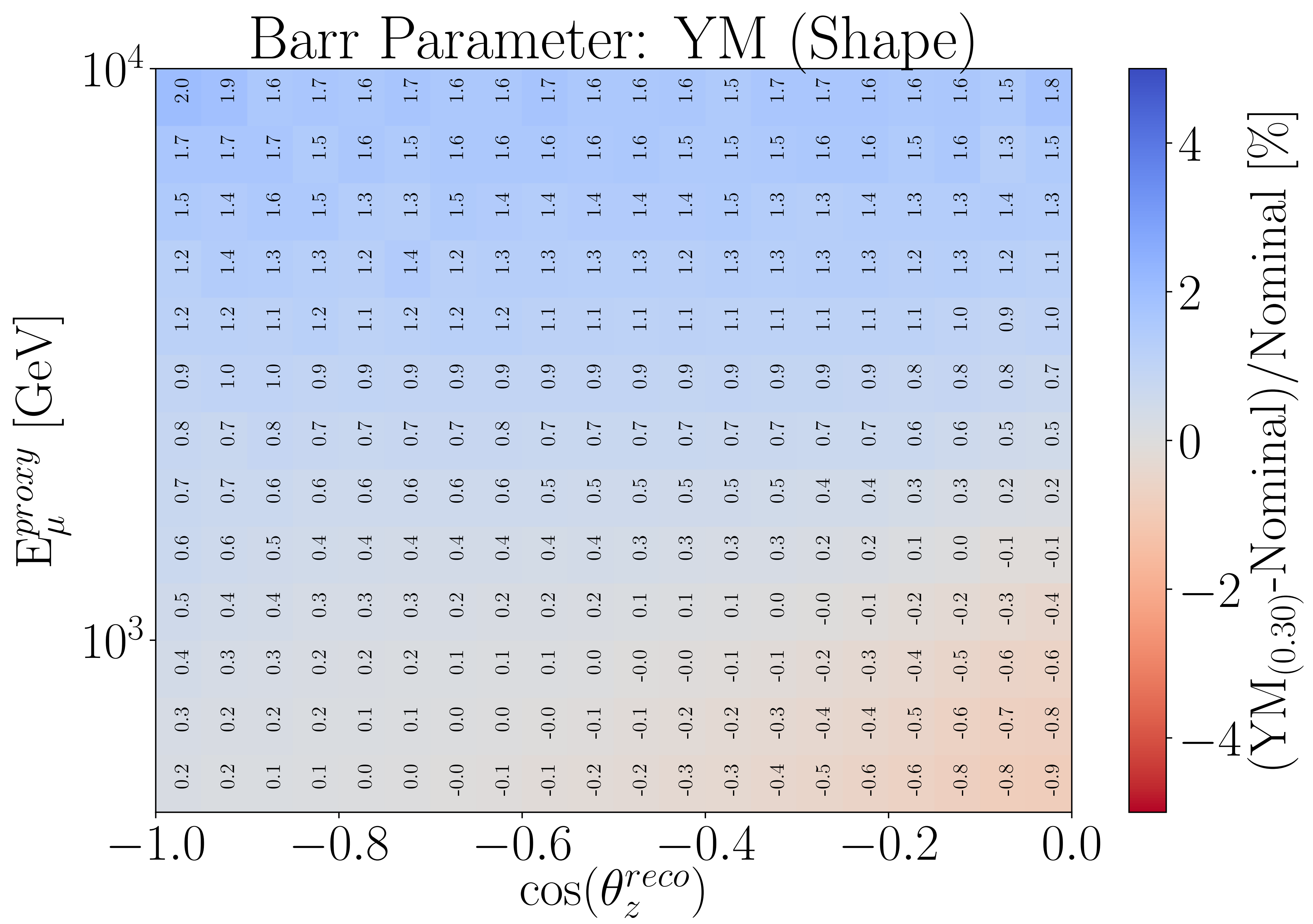


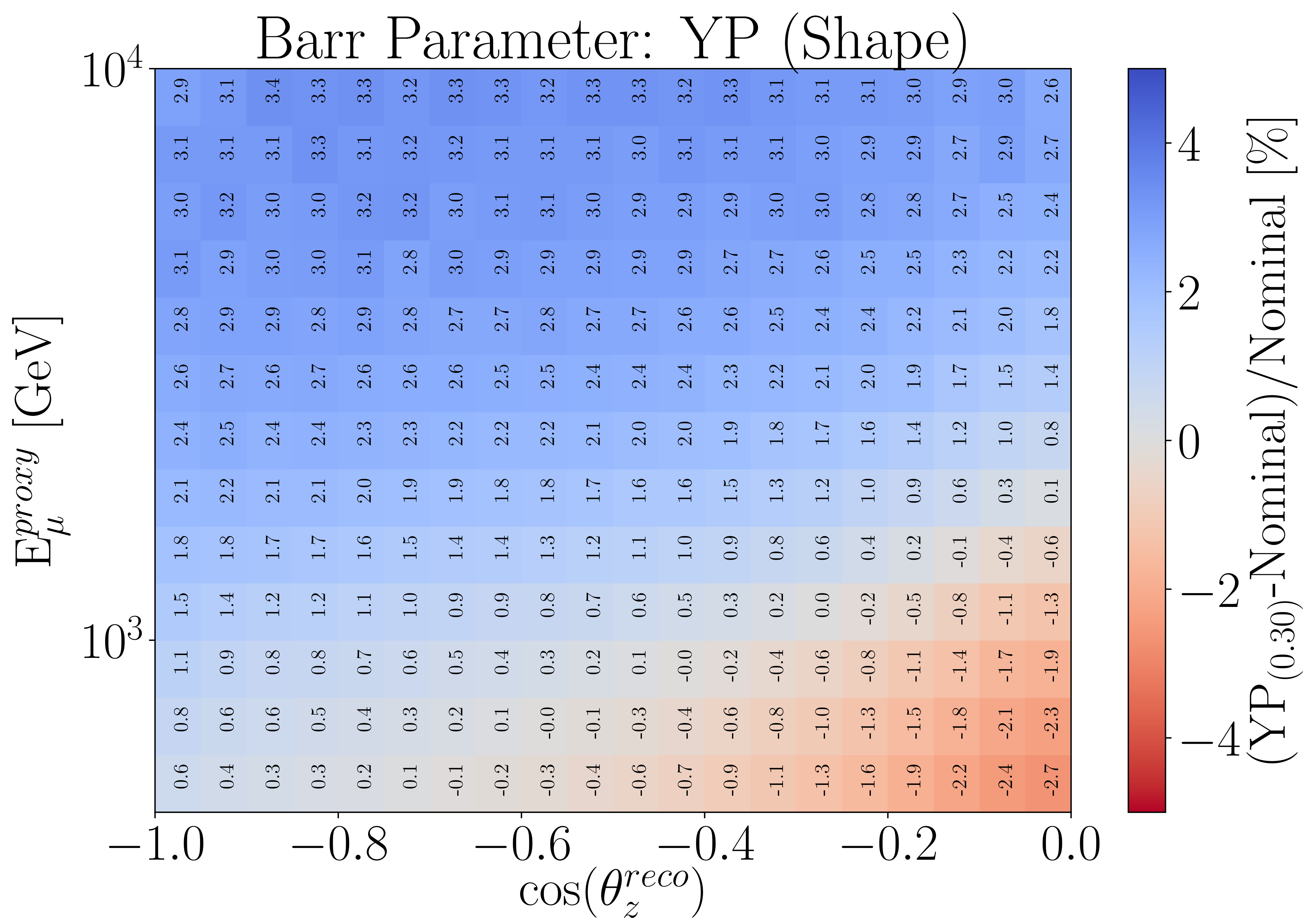
Flux Systematics: Barr shapes: YP/YM

The YP and YM:
Contribution from positive (P) and negative (M) charged kaons with low Bjorken X.

Parameter	x_{LAB}	Energy / GeV	Uncertainty	π±/K±
H±	0.1 – 1.0	30 – 1e11	15%	π±
W±	0.0 – 0.1	30 – 1e11	40%	K±
Y±	0.1 – 1.0	30 – 1e11	30%	K±
Z±	0.1 – 1.0	500 – 1e11	12.2% × $\log_{10}$(E/500 GeV)	K±

Kaons dominate the muon neutrino contributor above ~80GeV. The shape at Null:



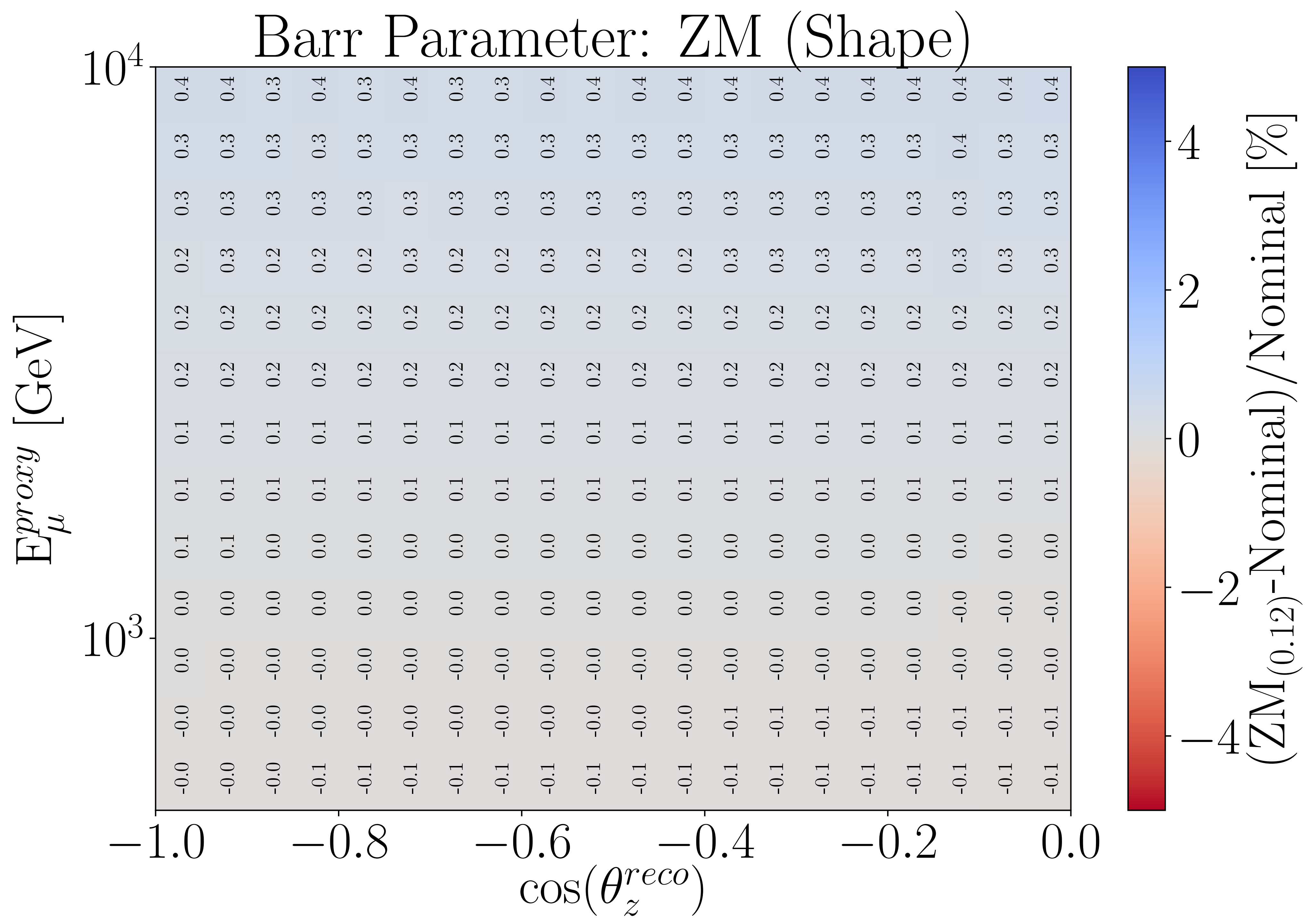


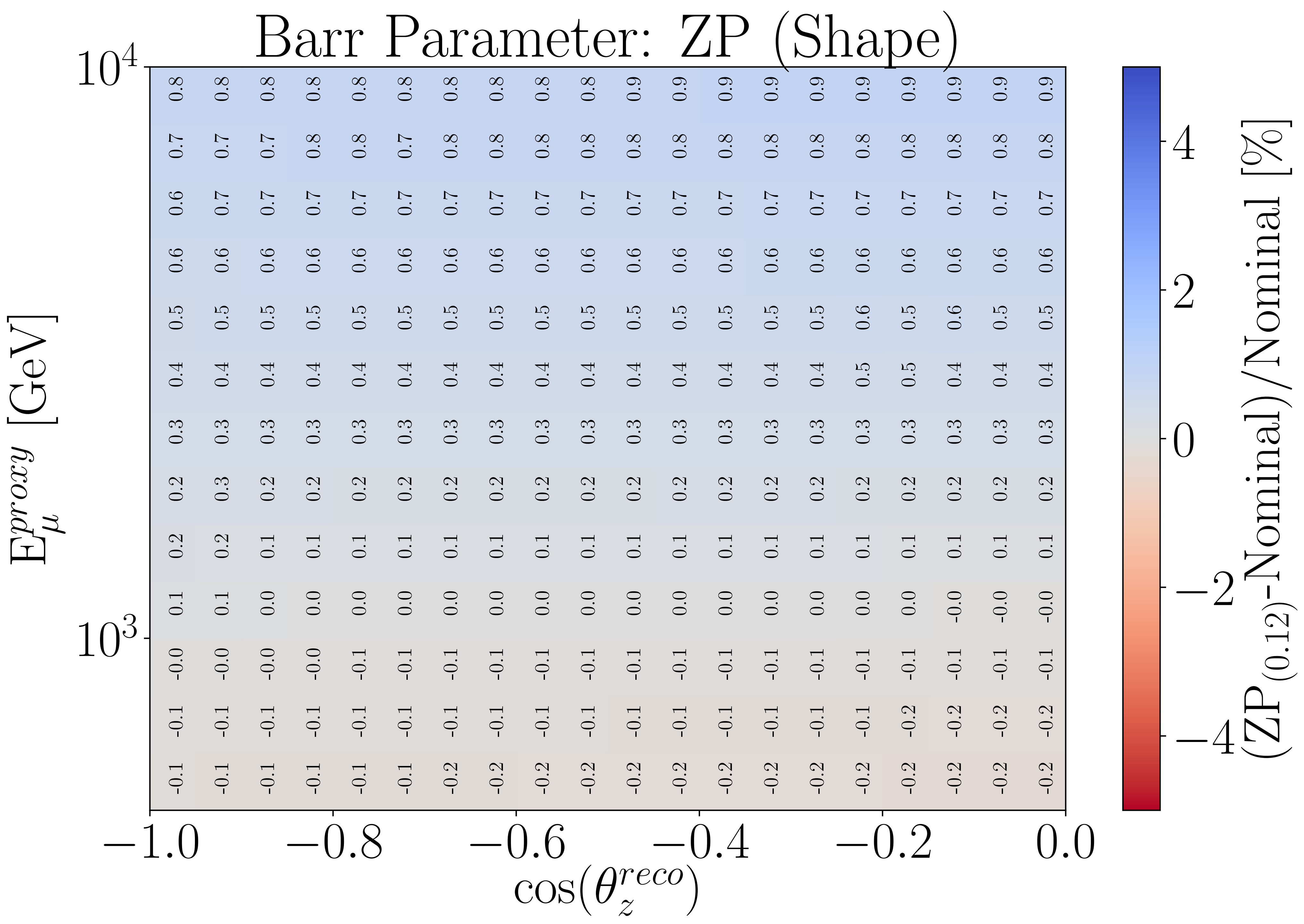
Flux Systematics: Barr shapes: ZP/ZM

The ZP and ZM:
Contribution from positive (P) and negative (M) charged kaons with an energy dependent uncertainty.

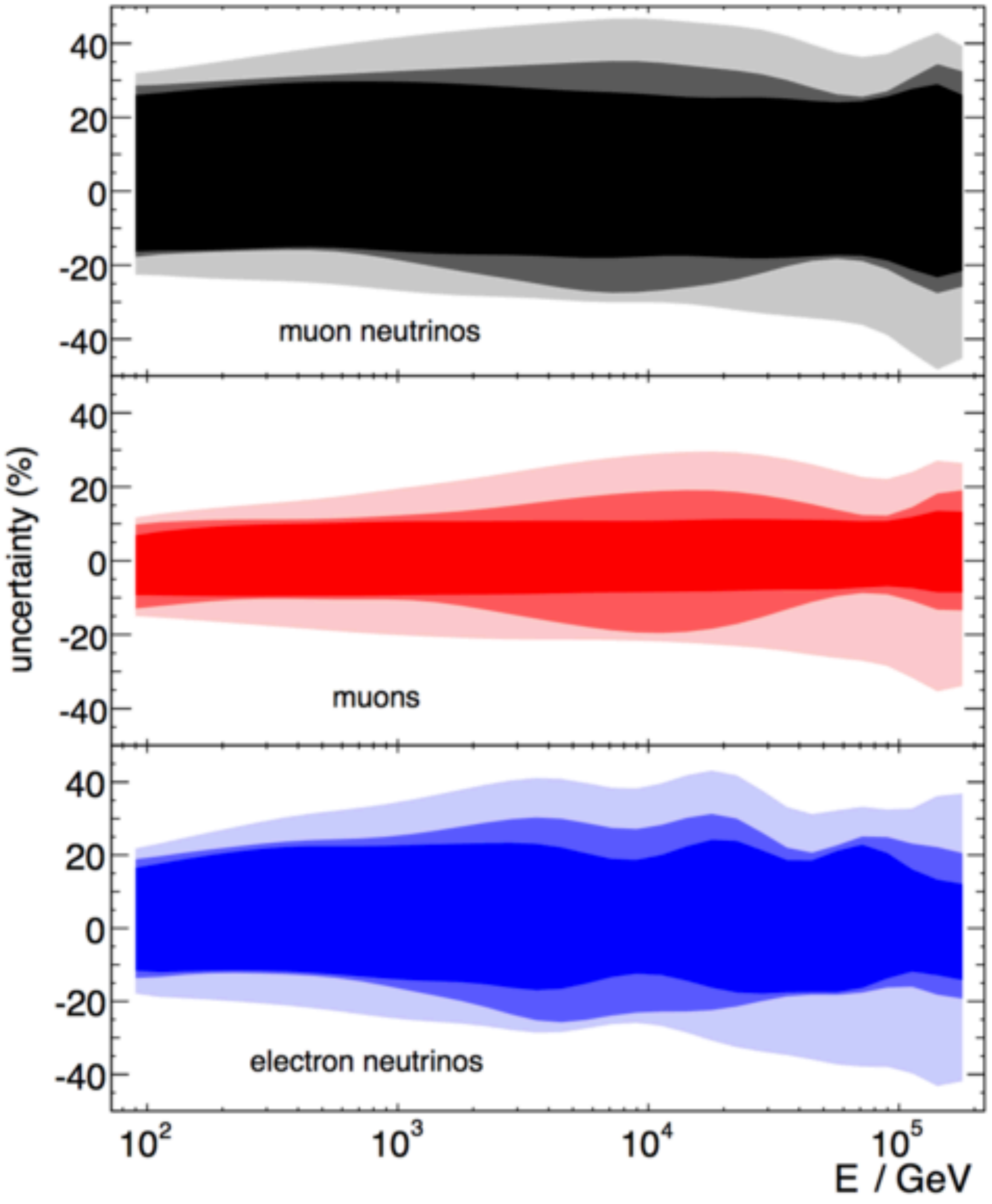
Parameter	x_{LAB}	Energy / GeV	Uncertainty	π±/K±
H±	0.1 – 1.0	30 – 1e11	15%	π±
W±	0.0 – 0.1	30 – 1e11	40%	K±
Y±	0.1 – 1.0	30 – 1e11	30%	K±
Z±	0.1 – 1.0	500 – 1e11	12.2% × $\log_{10}$(E/500 GeV)	K±

Kaons dominate the muon neutrino contributor above ~80GeV. The shape at Null:



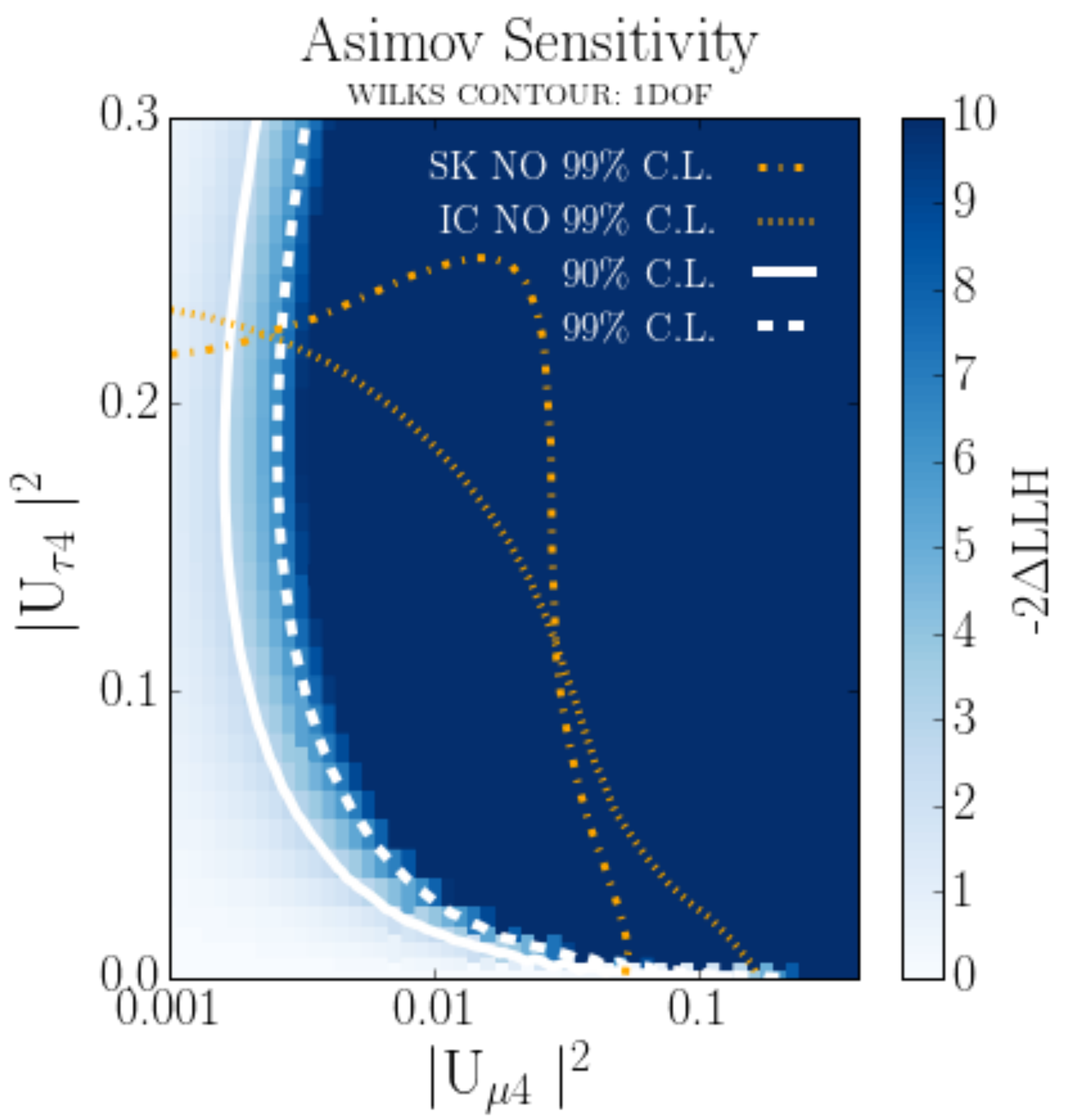


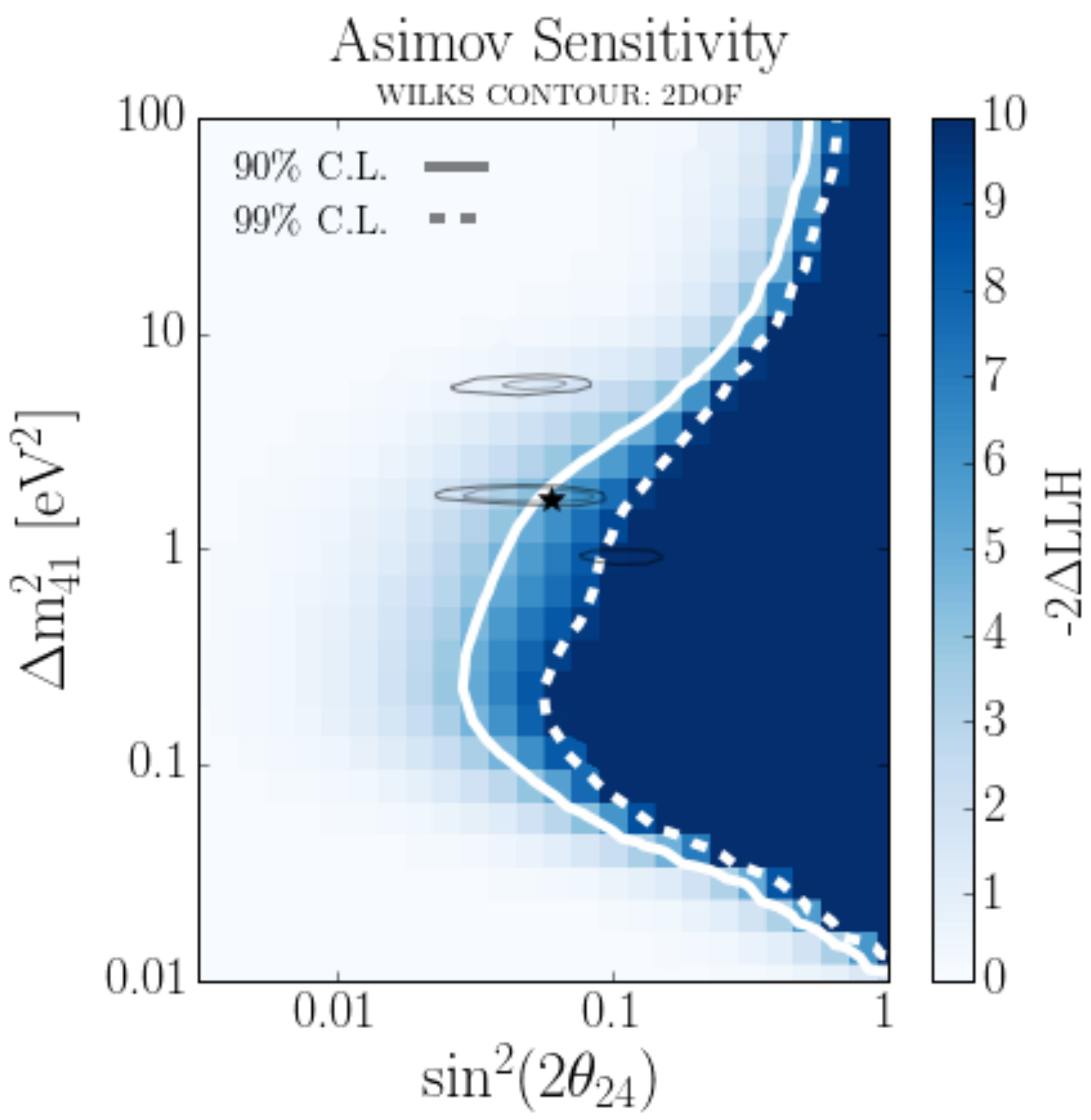
Flux Systematics: Normalization



We place an uncertainty on the flux normalization of 40%.

While this is rather extreme, going to 20% does not improve our sensitivity (plots below). Even decreasing the prior width of the normalization to 5%, doesn't help too much.

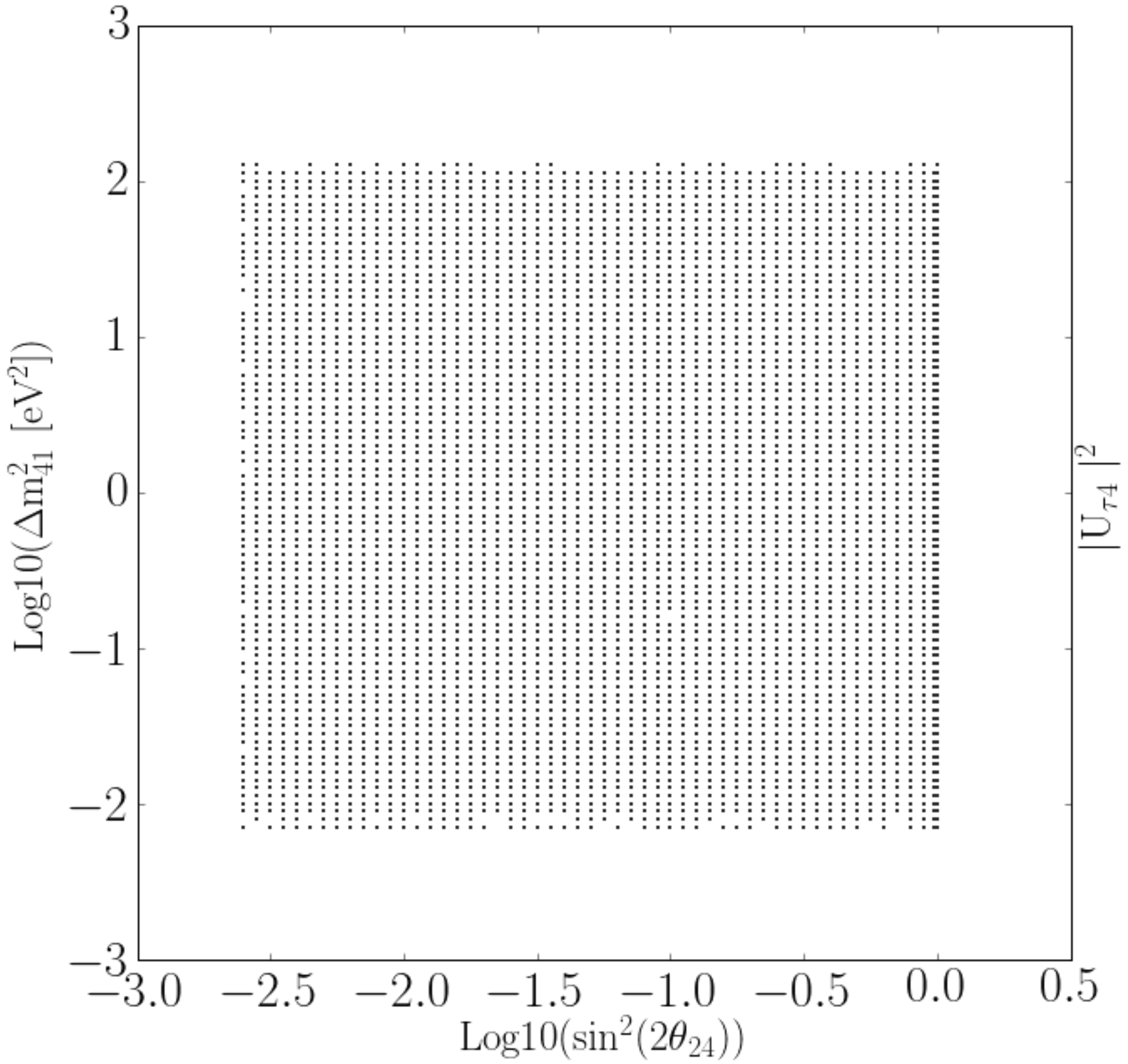


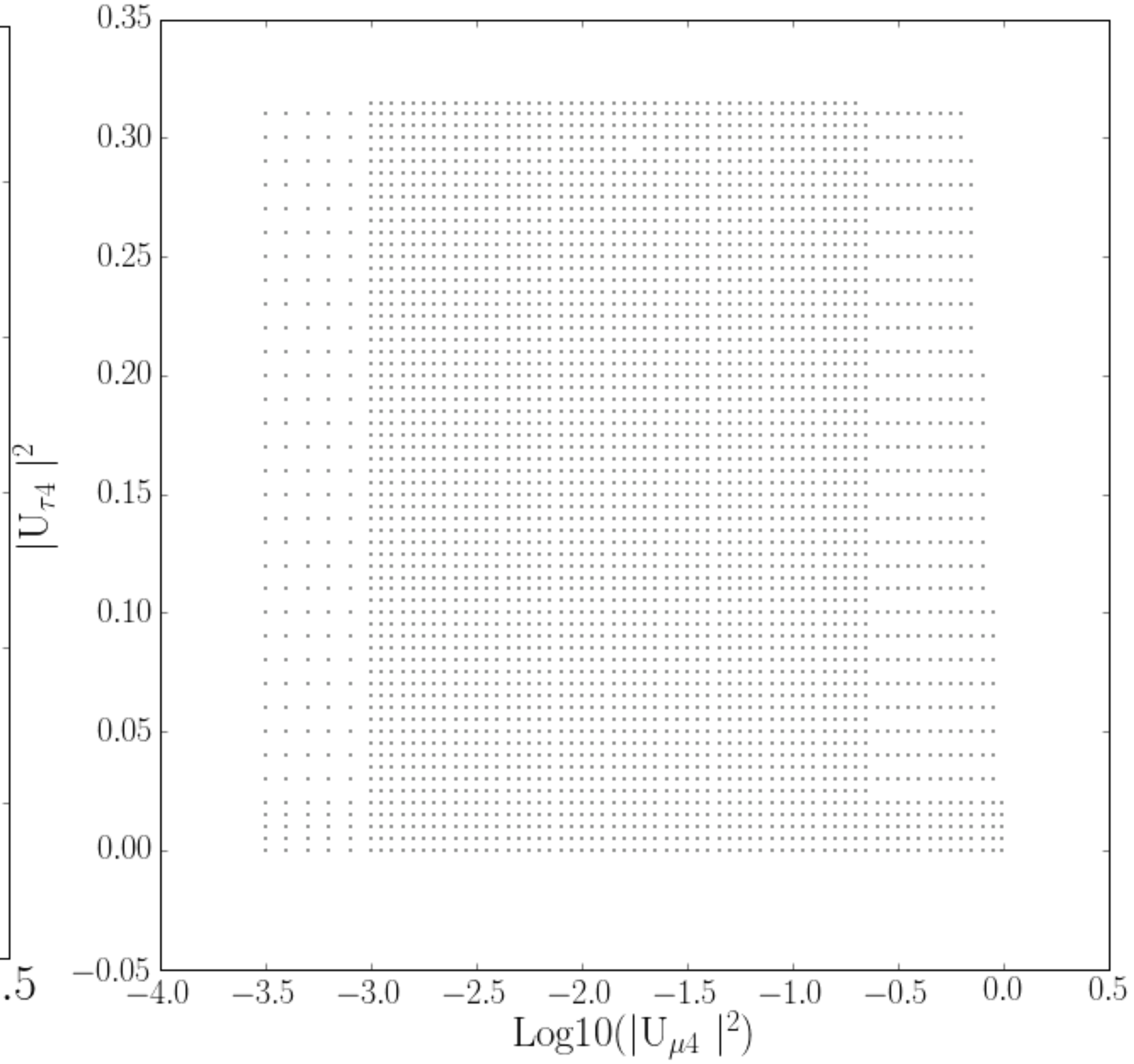


Analysis

Generated Neutrino Fluxes

The following points indicate where we have generated fluxes. All points are used for Asimov tests. Toy MC tests are performed with a subset of the points.





Emin	500 GeV
Emax	9976GeV
Log_{10}(E)bin	0.1
NEnergy Bins	13
$cos(Z)_{max}$	0.0
$cos(Z)_{min}$	-1.0
$cos(Z)_{bin}$	0.05
NZenith Bins	20

Resolution of parameter scans

Computationally taxing realization (toy MC) scans are performed on a coarse grid. All Asimov tests are performed at the highest resolution.

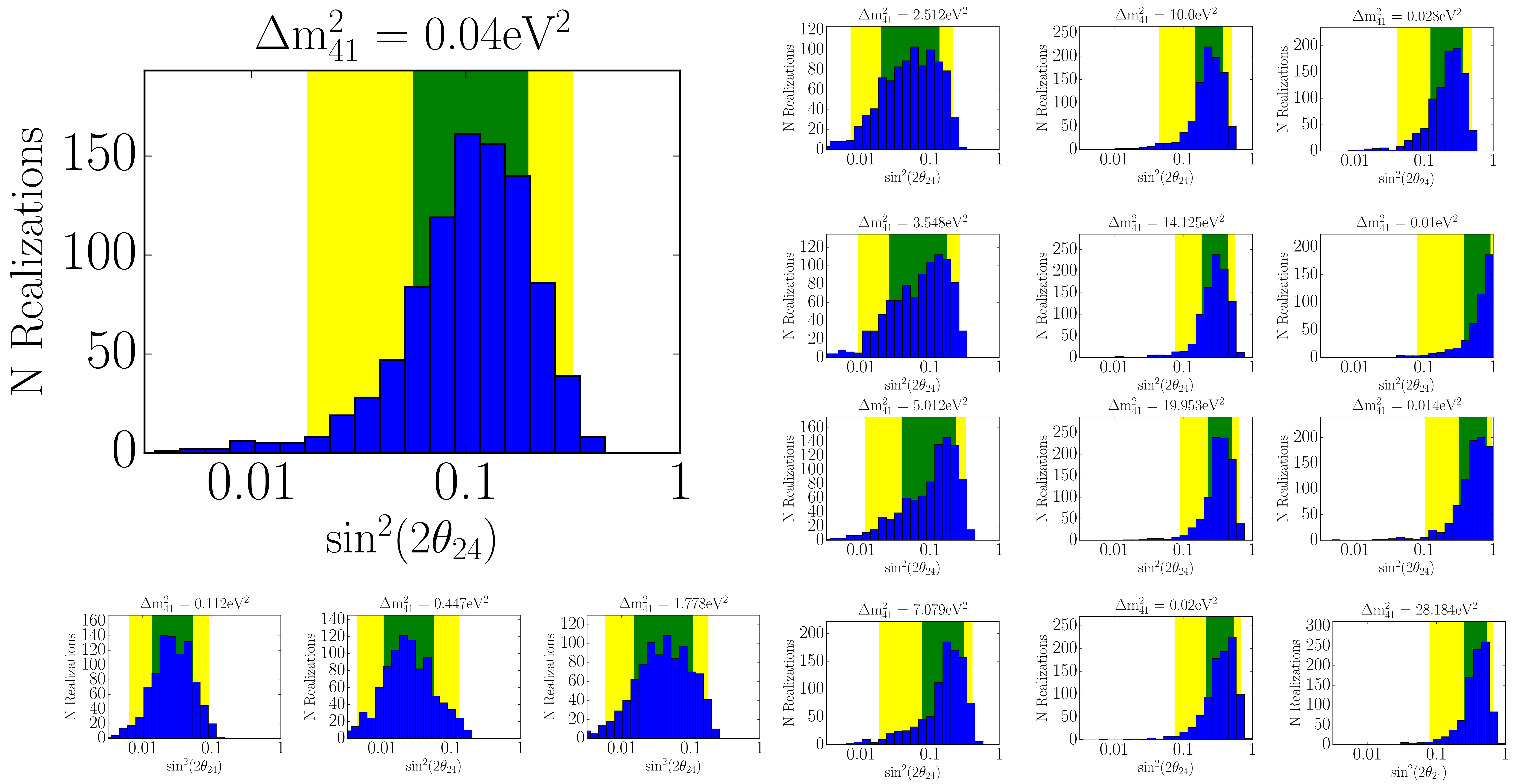
Analysis		Realizations	Asimov
[Δm^2, $\sin(2\theta)^2$]	$\mathrm{Log}_{10}(\Delta m^2)$ scan range	[-2.0 to 2.0eV^2]	[-2.0 to 2.0eV^2]
	$\mathrm{Log}_{10}(\sin(2\theta)^2)$ range	[-2.5 to 0]	[-2.5 to 0]
	$\mathrm{Log}_{10}(\Delta m^2)$ step size	0.15	0.05
	$\mathrm{Log}_{10}(\sin(2\theta)^2)$ step size	0.10	0.05
	Total Number of points:	**748**	**4649**
[$\lvert U_{\mu 4}\rvert^2$, $\lvert U_{\tau 4}\rvert^2$]	$\mathrm{Log}_{10}(\lvert U_{\mu 4}\rvert^2)$ scan range	[-2.0 to 2.0eV^2]	[-2.0 to 2.0eV^2]
	$\lvert U_{\tau 4}\rvert^2$ range	[-2.5 to 0]	[-2.5 to 0]
	$\mathrm{Log}_{10}(\lvert U_{\mu 4}\rvert^2)$ step size	0.01	0.01
	$\lvert U_{\tau 4}\rvert^2$ step size	0.10	0.05
	Total Number of points:	**1118**	**2047**

Analysis 1

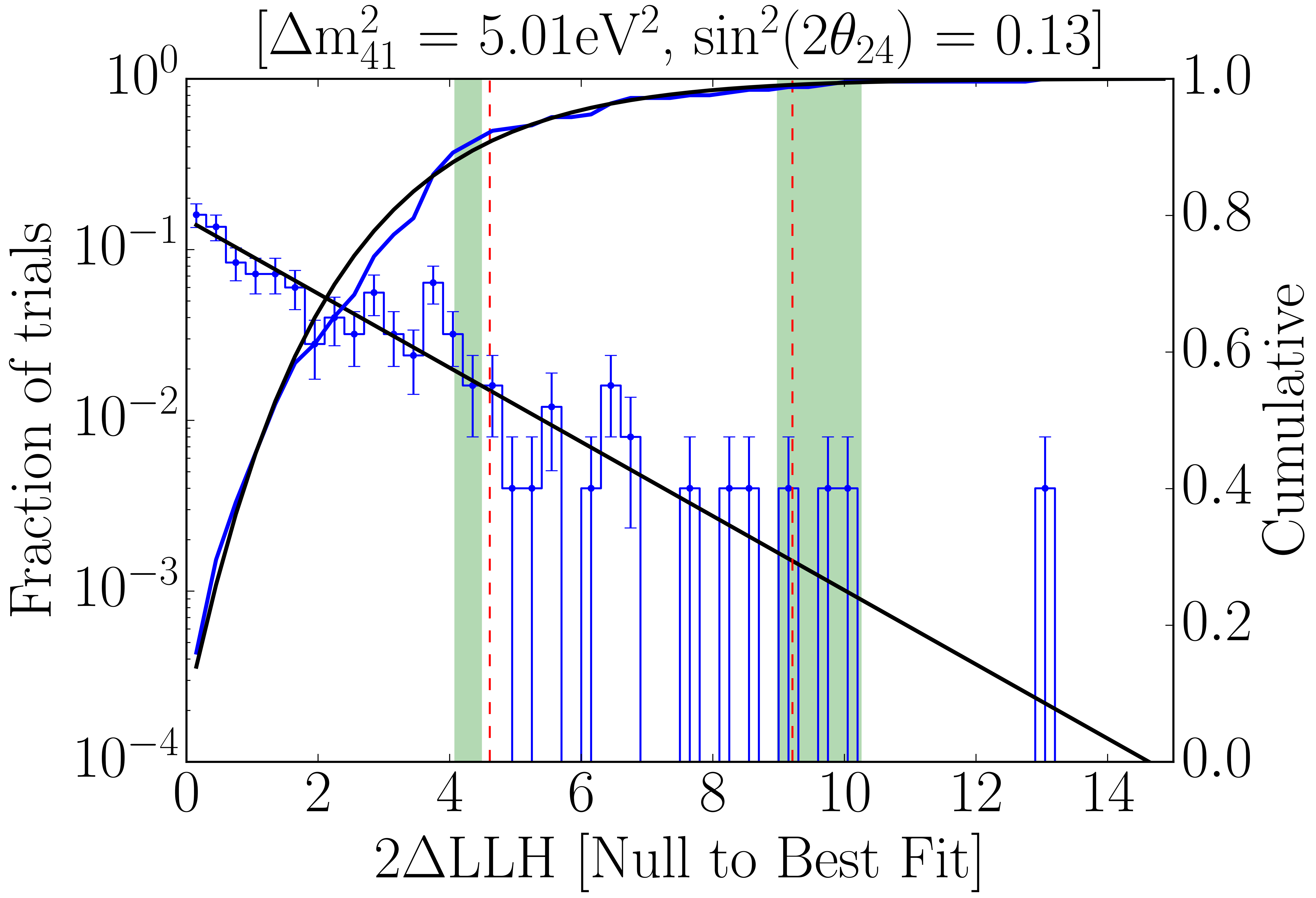
[Δm^2, $\sin(2\theta)^2$]

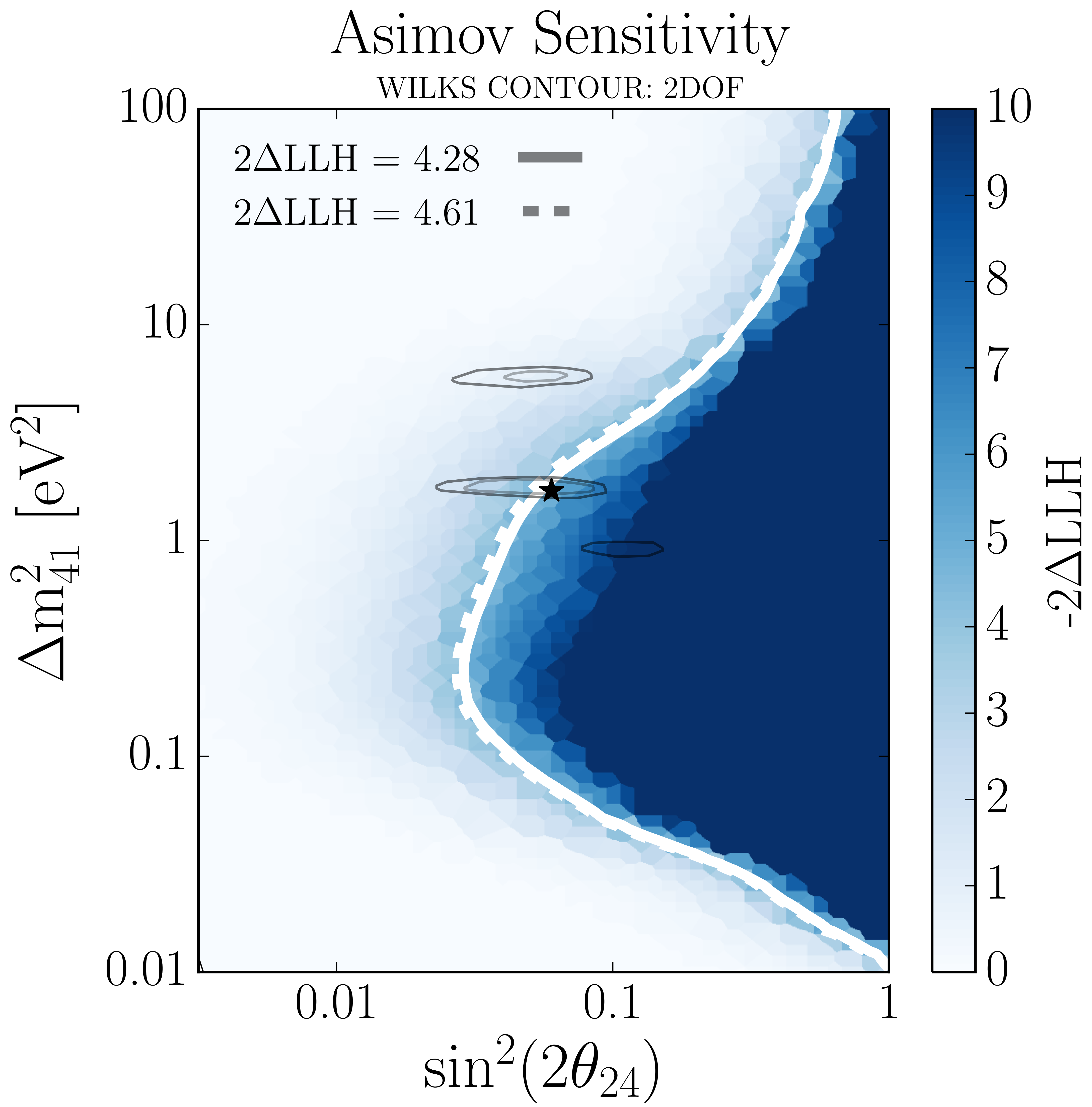
Inject Recover Signals

Brazil plots slices



Asimov Systematic Pulls

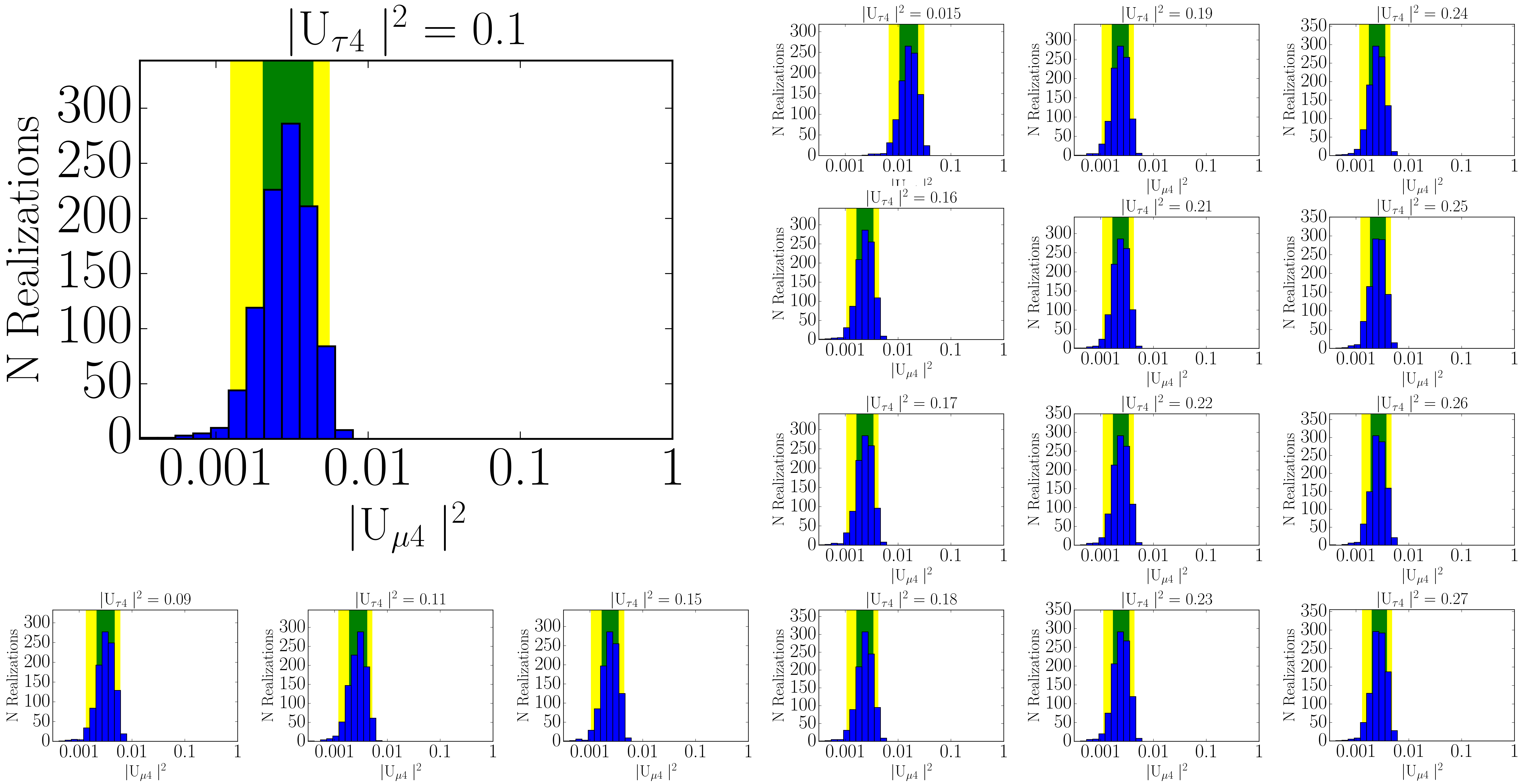




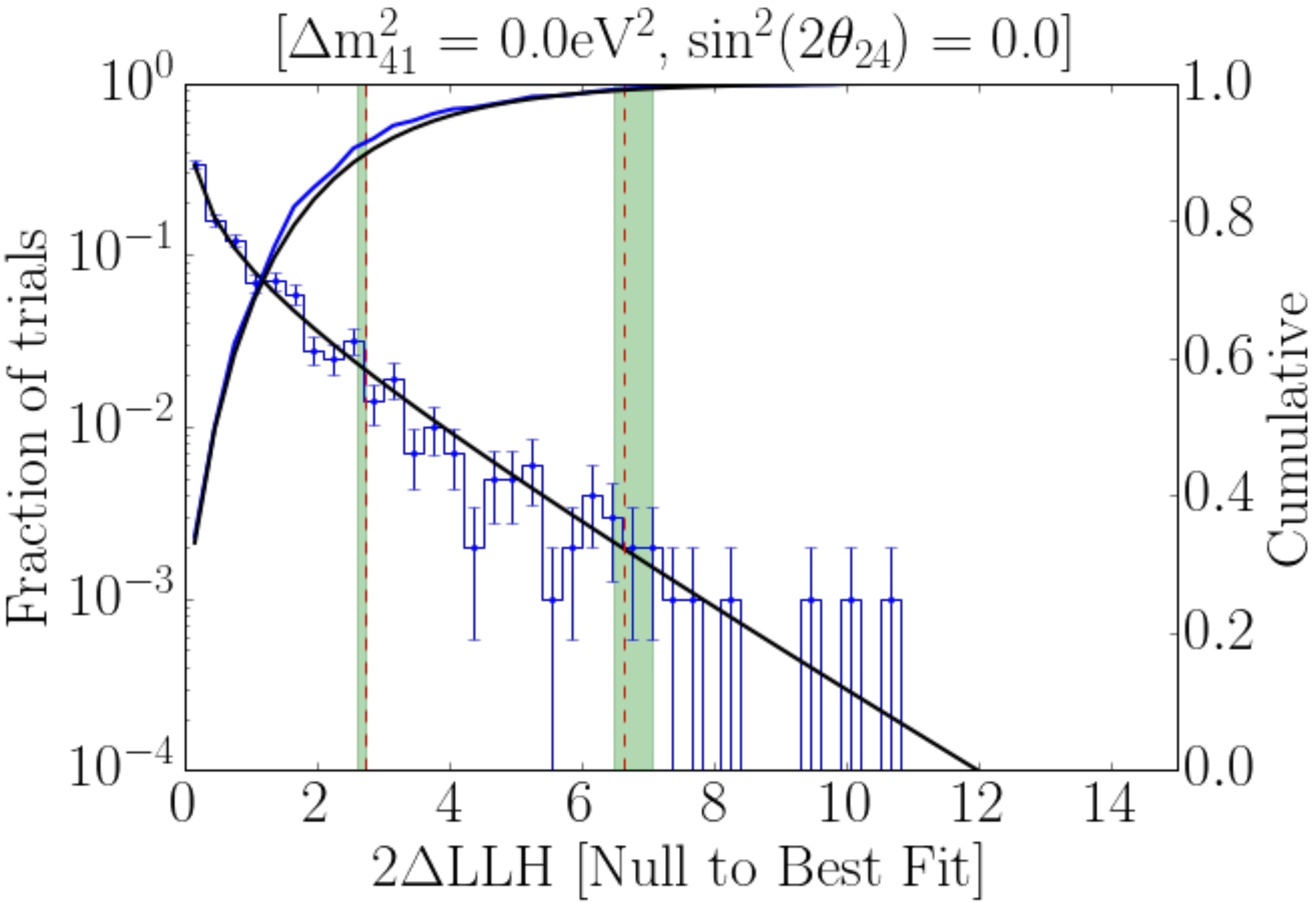
Analysis 2

$[|U_{\mu 4}|^2, |U_{\tau 4}|^2]$

Brazil plots slices



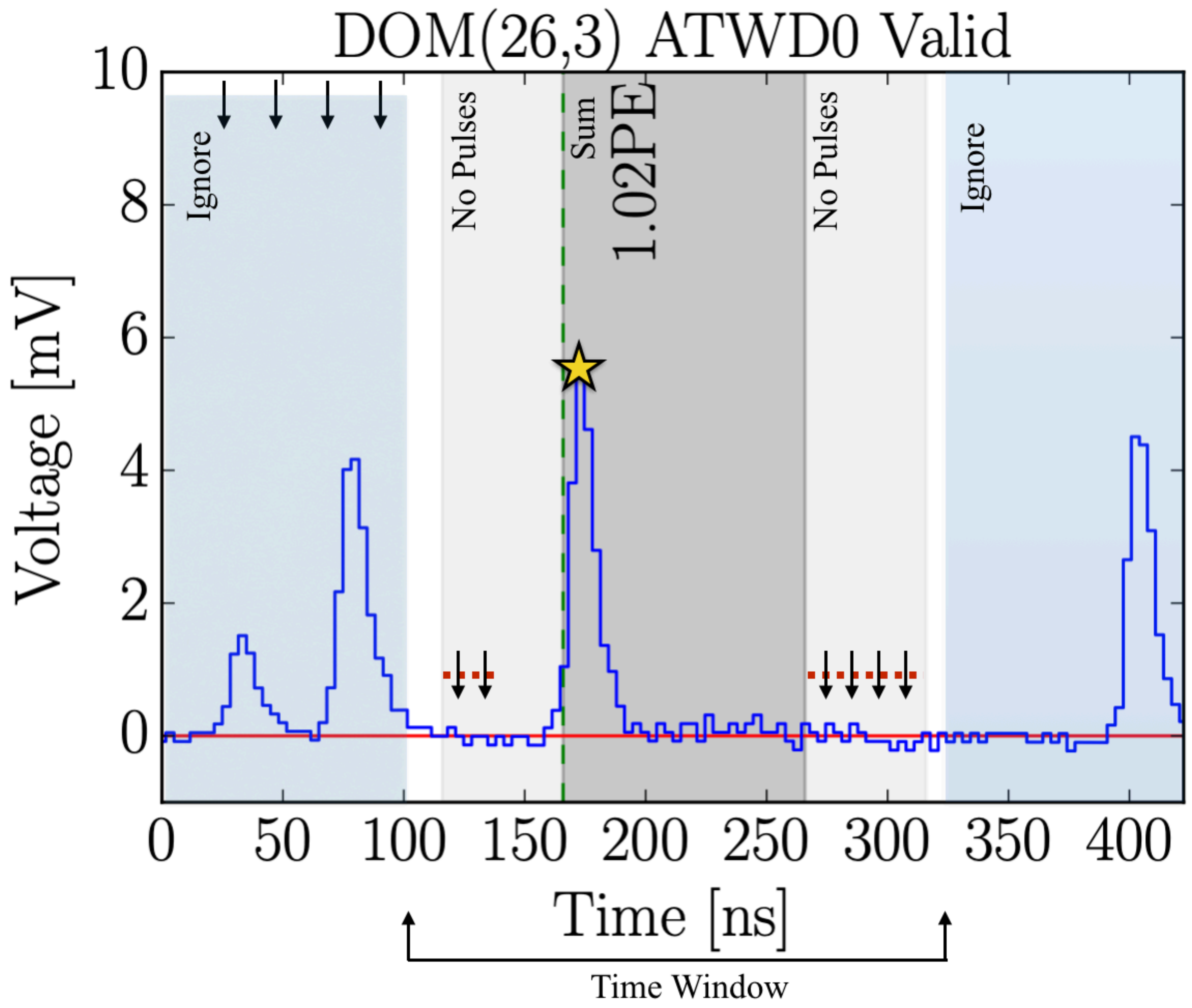
Coverage checks (1DOF)

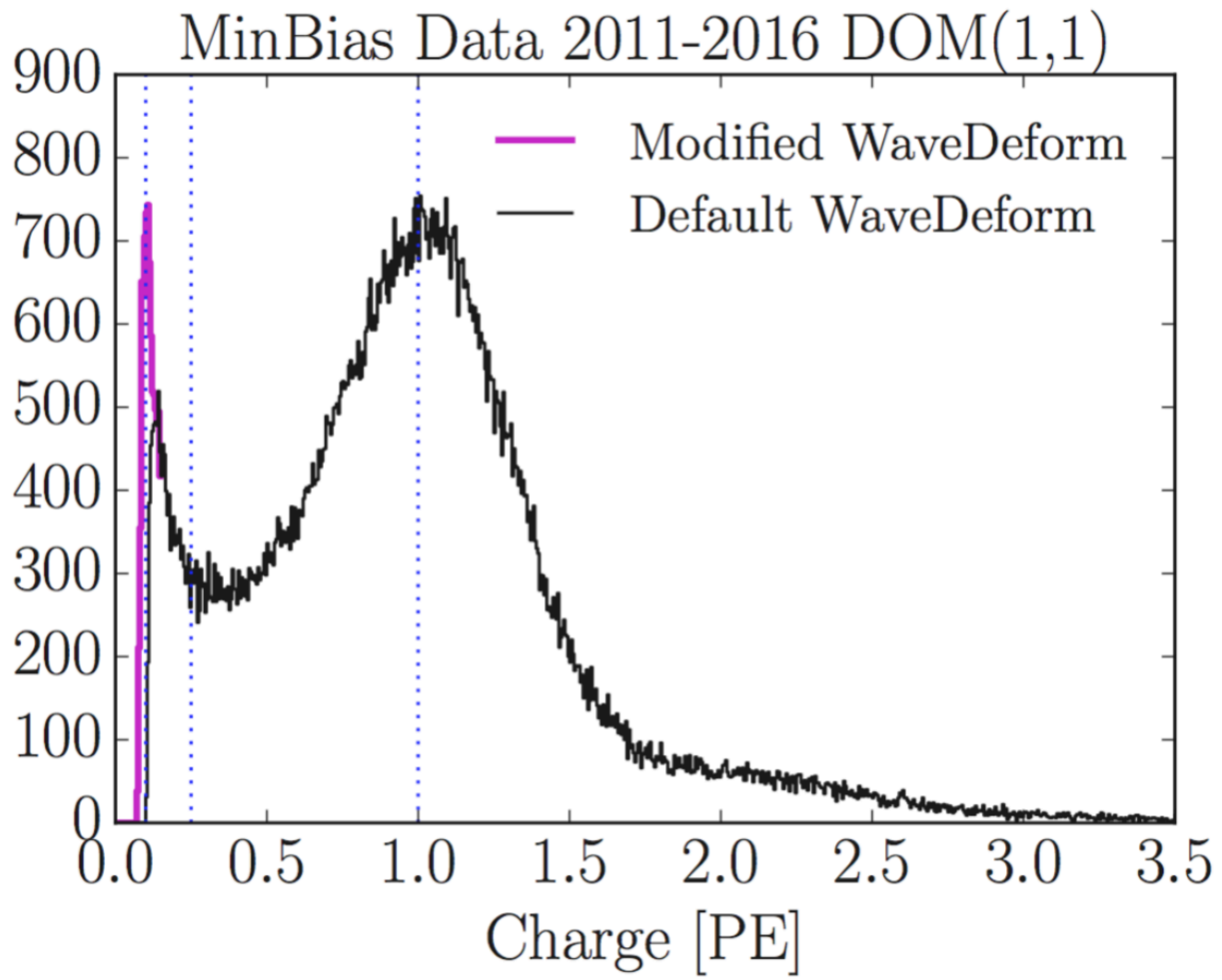


SPE Templates

Analysis level SPE Templates w/wo Pass2

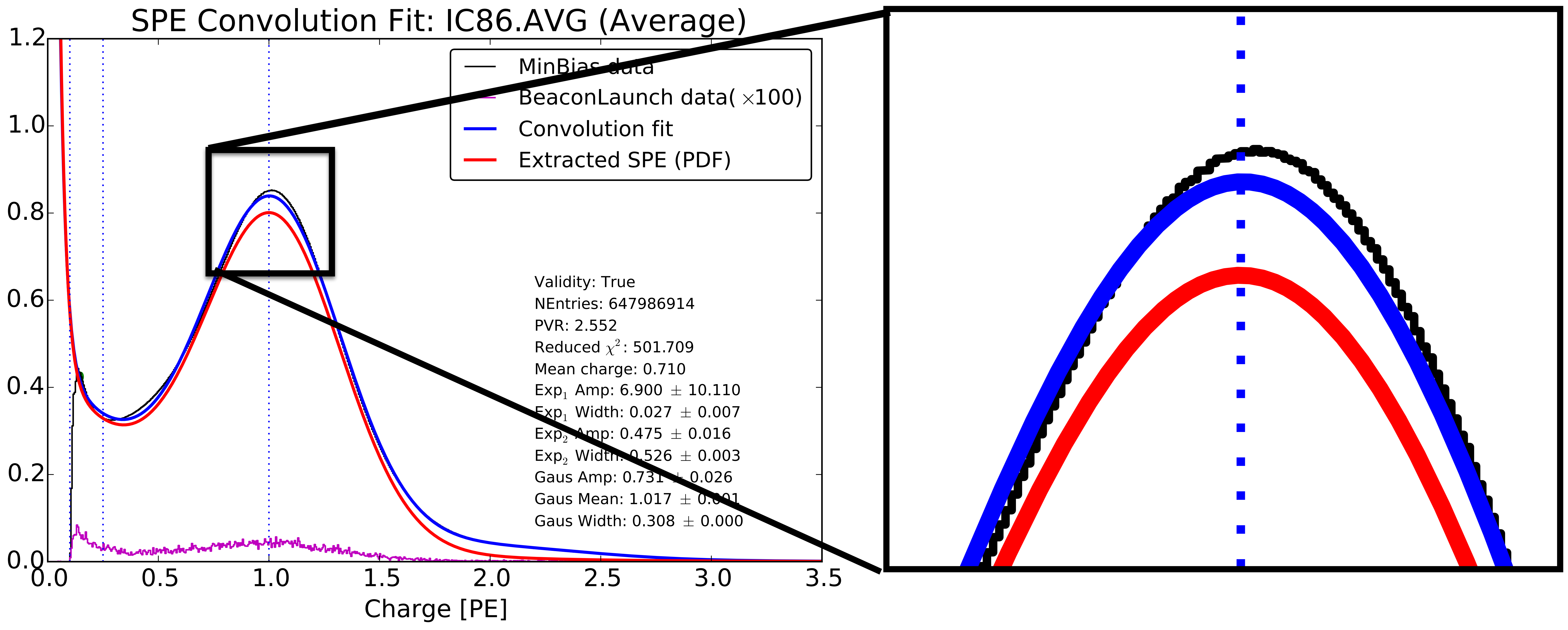
We have a well developed procedure for extracting good candidate single photo electrons from the MinBias and BeaconLaunch datasets.





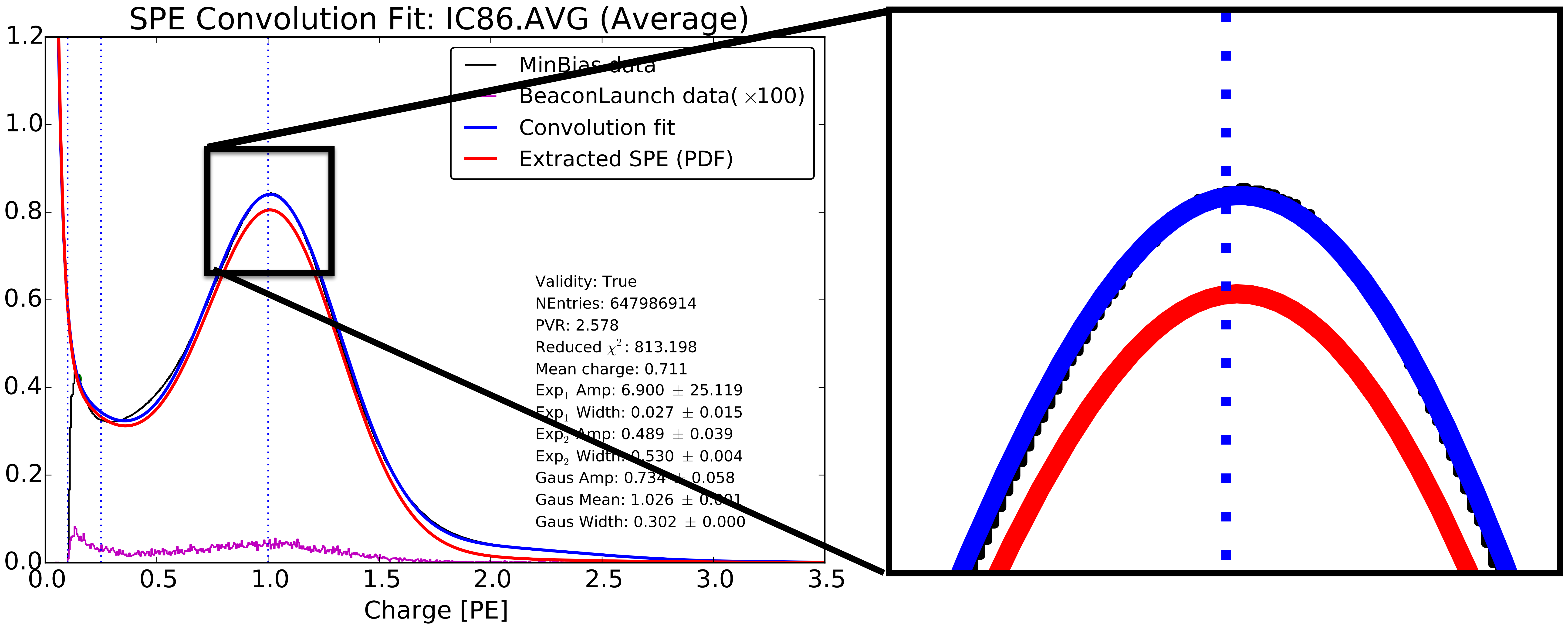
Analysis level SPE Templates w/wo Pass2

The convolutional fitter extracts the shape of the SPE distribution, accounting for multi-PE contamination.



However, we see that the fit (**blue**) isn't perfect (compare to **black**).
It's especially important to get the peak correct, since we will use it to calibrate the DOMs.

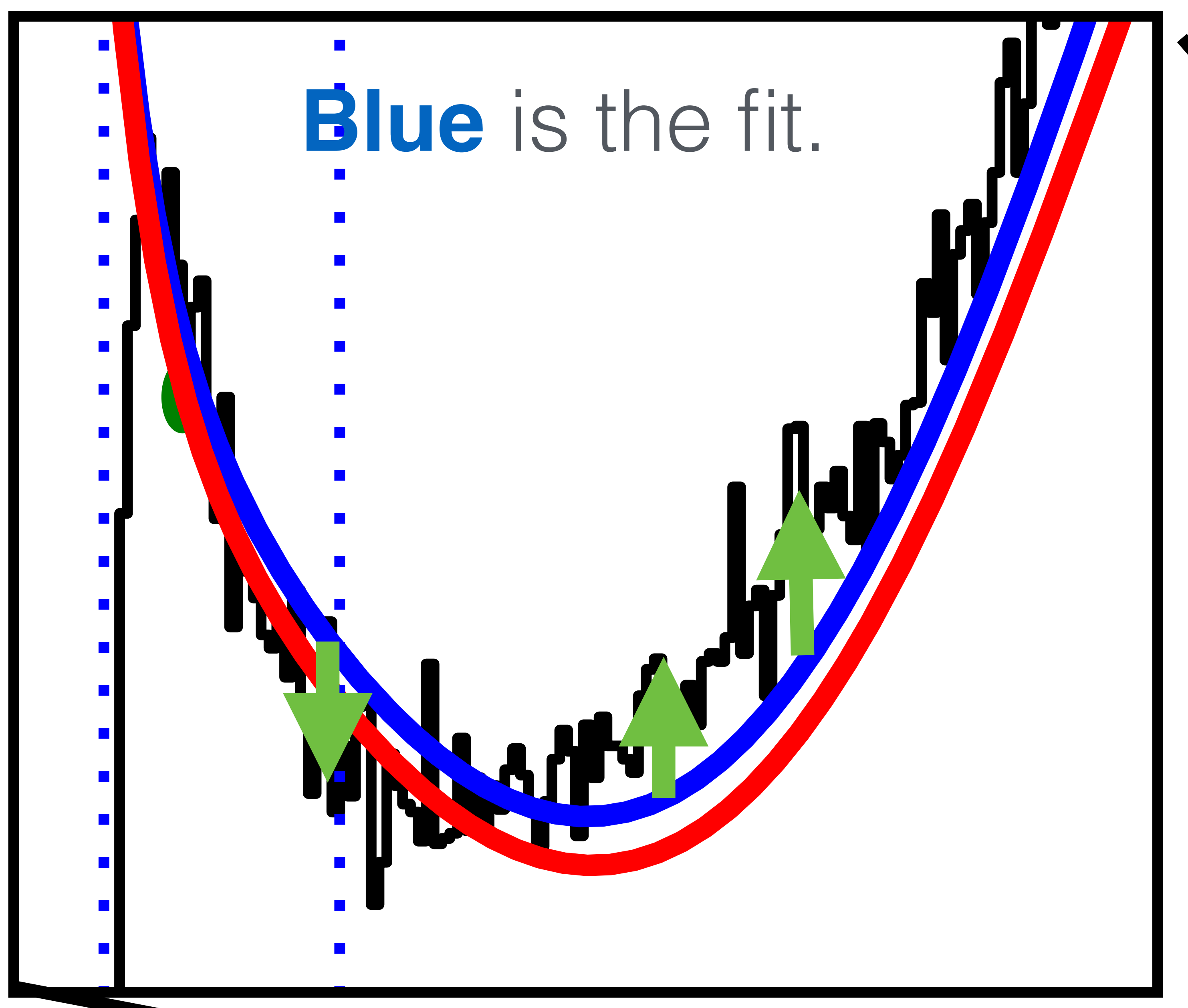
Analysis level SPE Templates w/wo Pass2

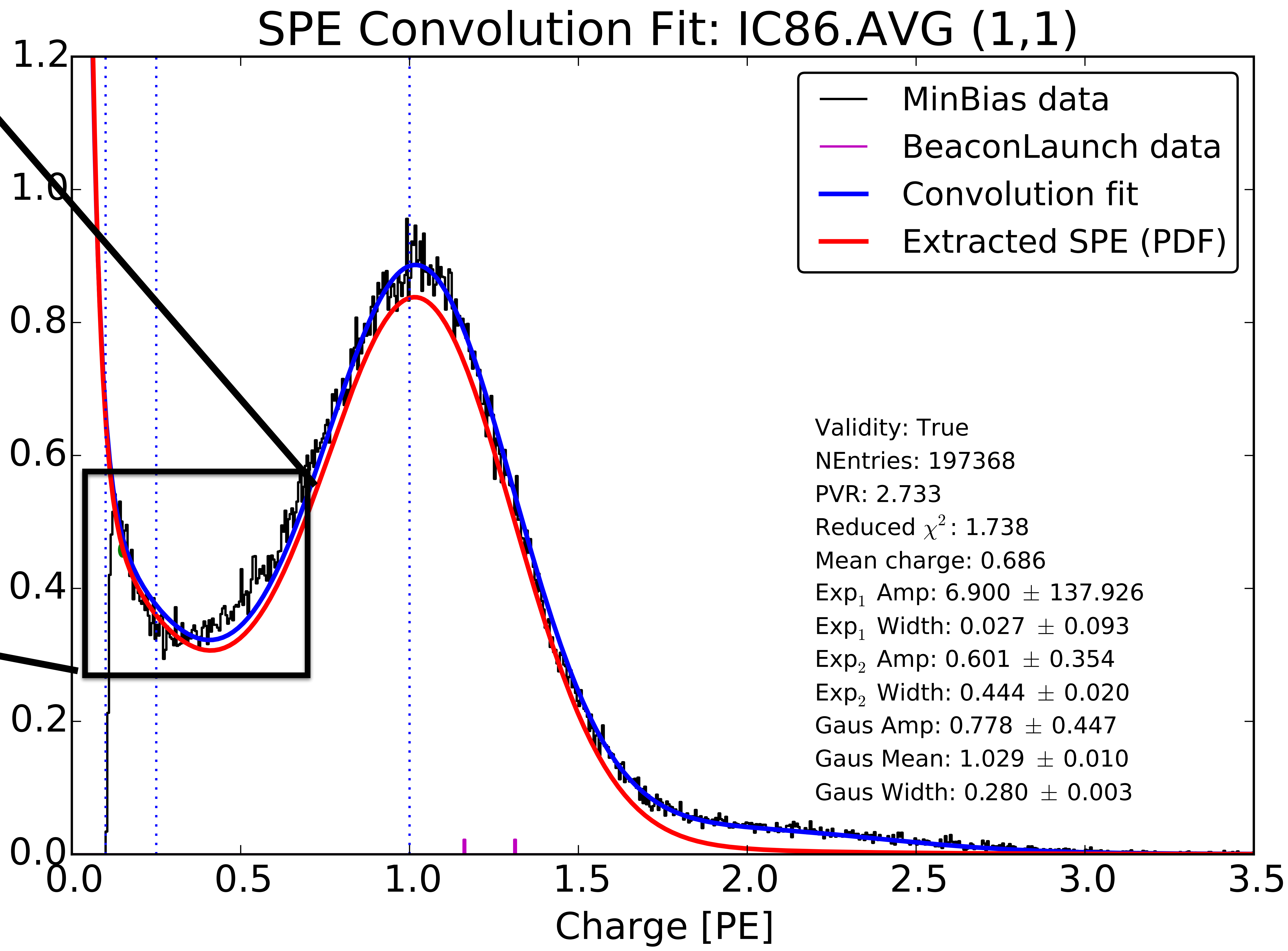


We can force the fitter to prioritize getting this peak correct by decreasing the uncertainty near the peak.

But this obviously hurts the overall fit quality.

Analysis level SPE Templates w/wo Pass2



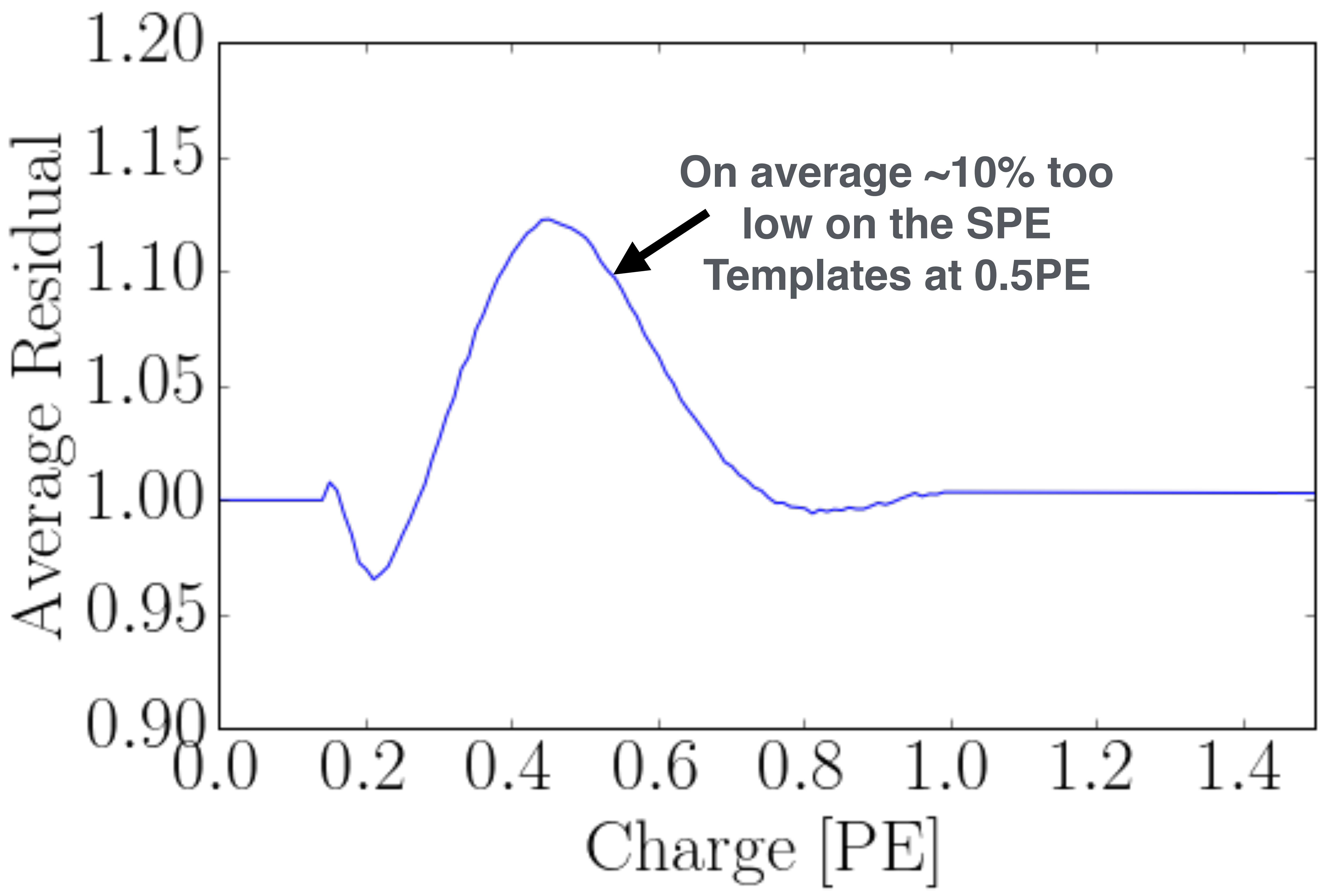


The **red line** is the SPE Template for this DOM.

The **green arrows** represent the residual in a bin, of the fit.

Analysis level SPE Templates w/wo Pass2

After calculating the residual for all DOMs, we calculate the **average residual** (how far off each fit is on average).

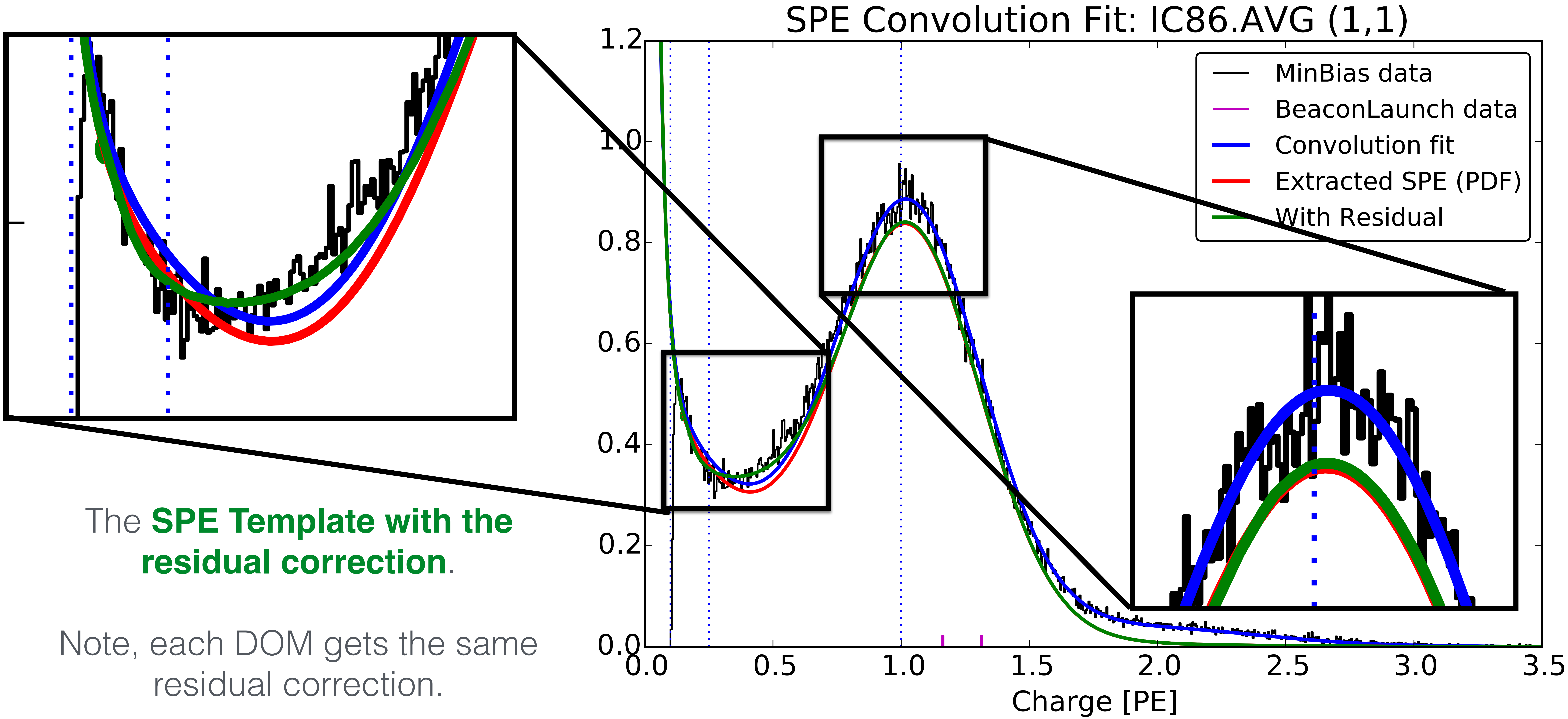


This correction is an overall correction to all the SPE Templates.

We model the SPE distribution as:
Exp1 + Exp2 + Gaussian

However, this is likely not the shape of the true distribution. The **average residual** accounts for this.

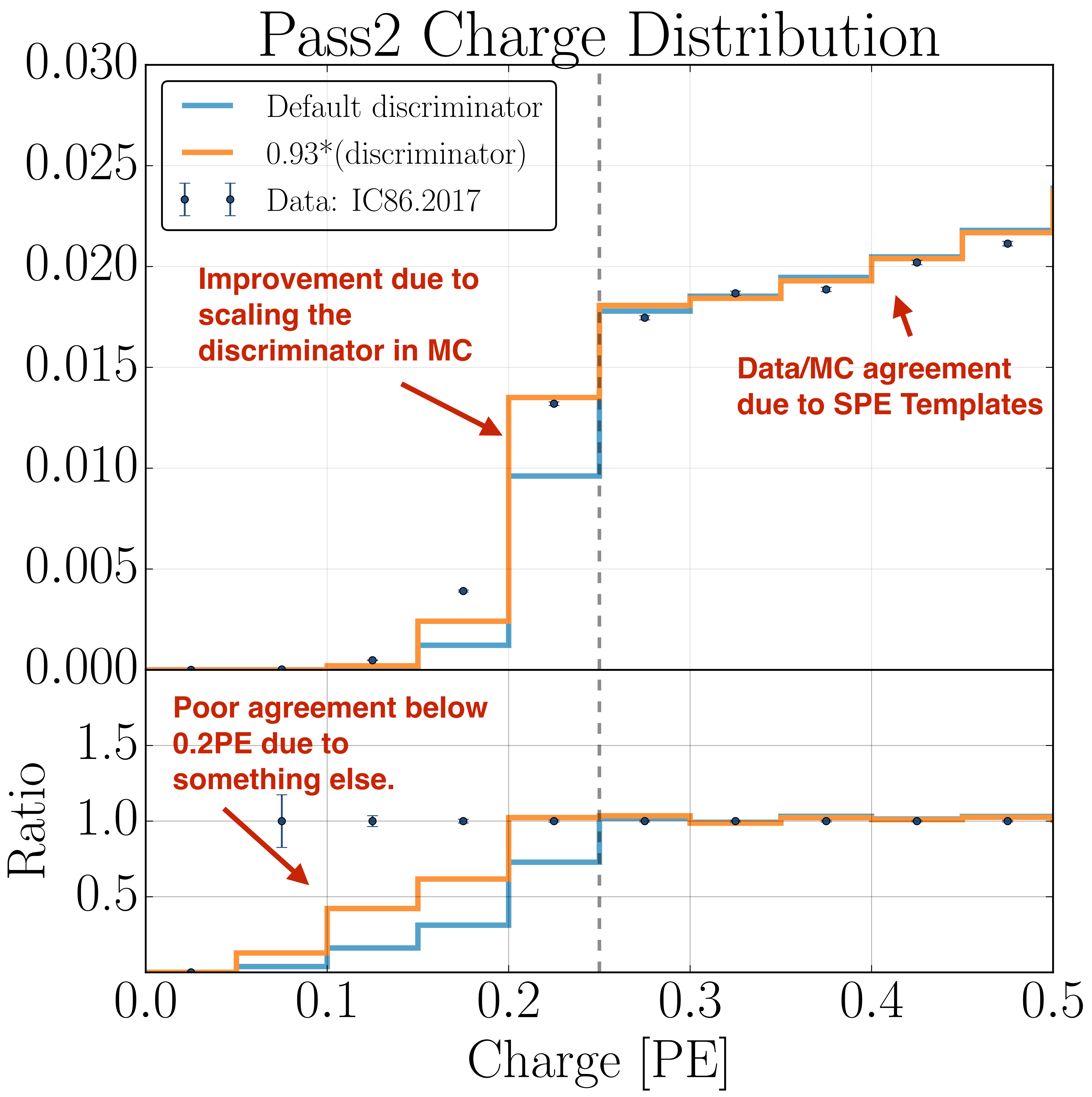
Analysis level SPE Templates w/wo Pass2



The **SPE Template with the residual correction**.

Note, each DOM gets the same residual correction.

Another correction: modification to the discriminator threshold



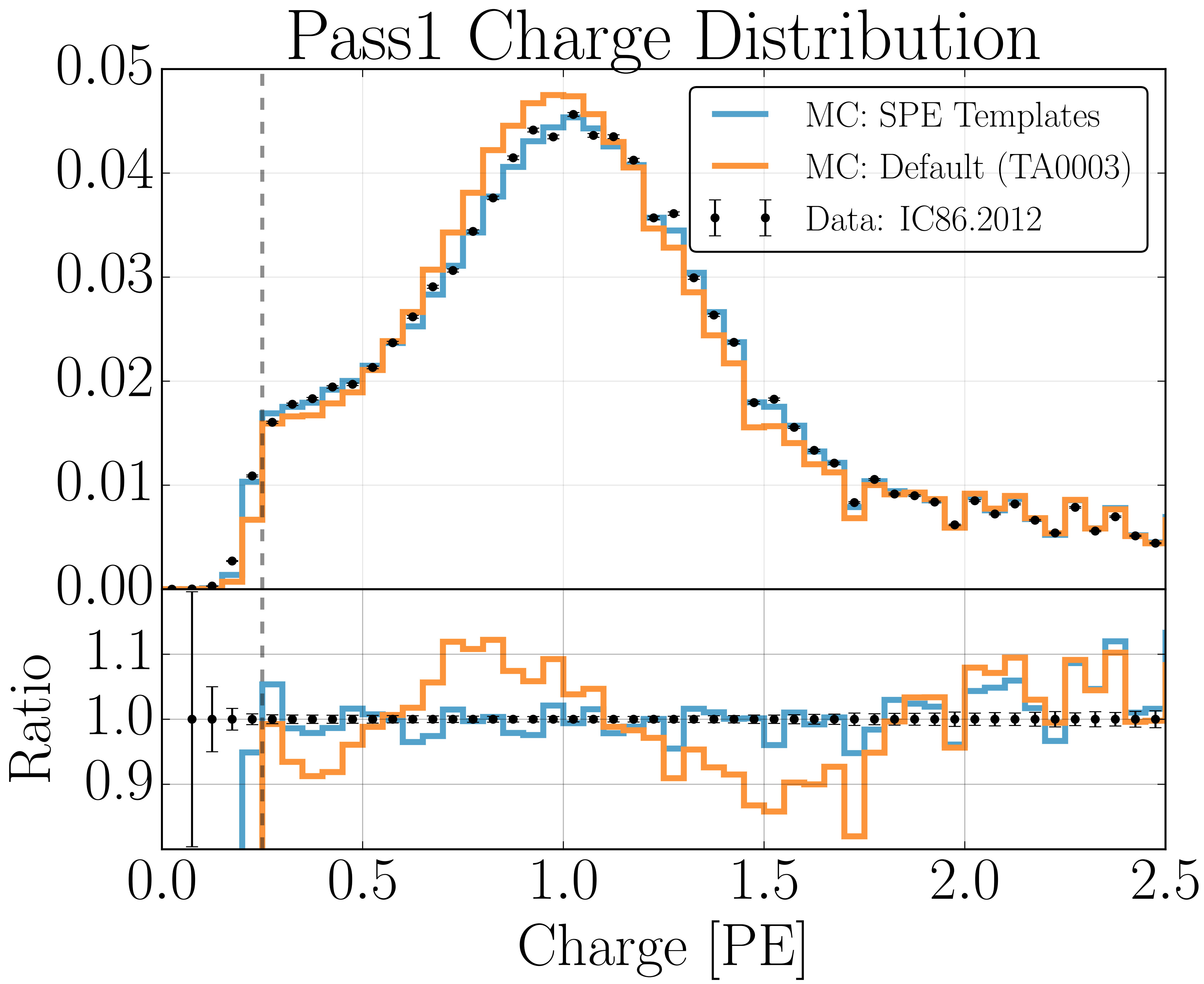
Mismatch shown between Data and MC below ~0.25PE.

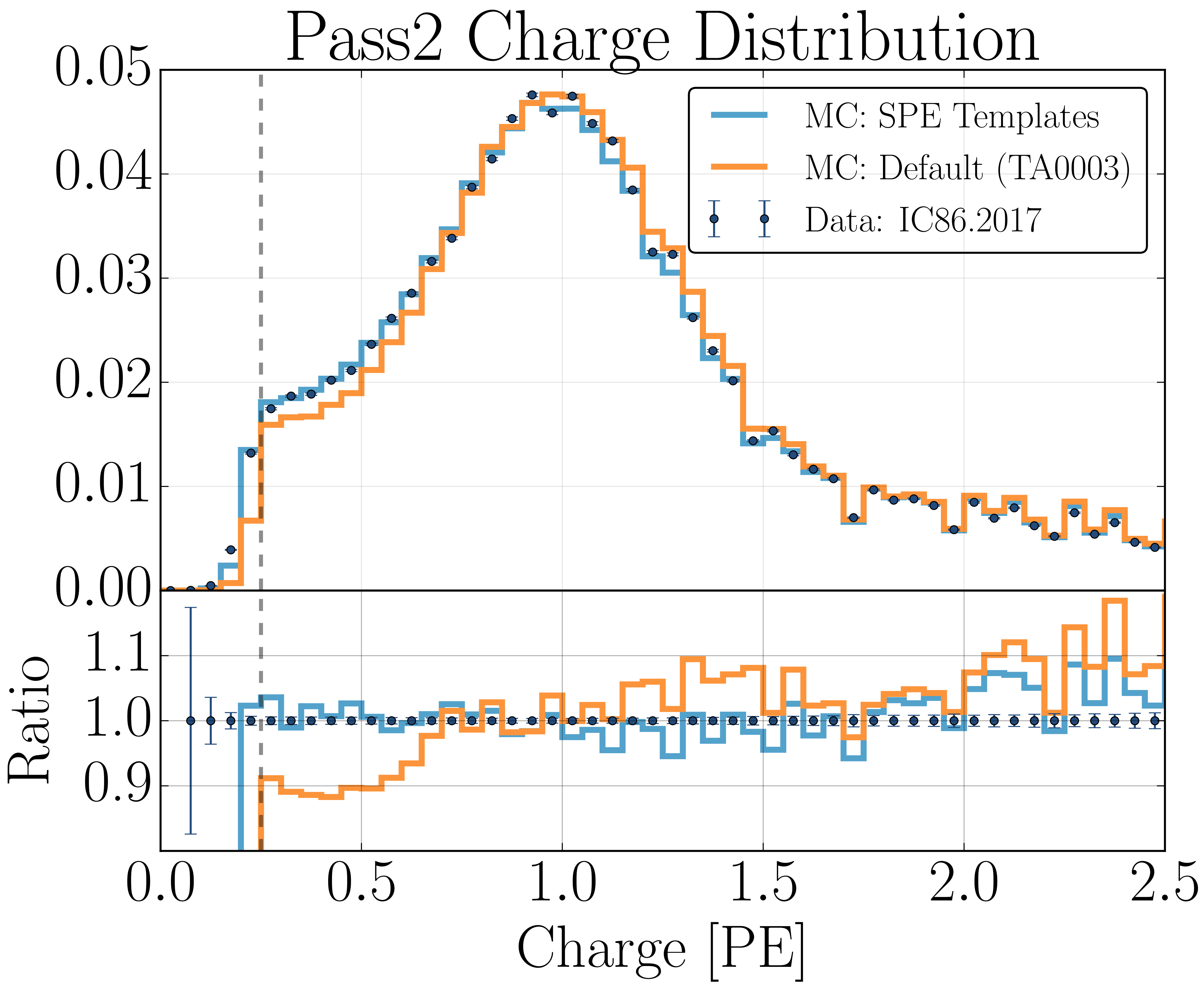
Discrepancy is not due to the charge template (TA0003 vs. SPE Templates behave the same)

Issue is likely due to the discriminator setting in MC.

Decreasing the discriminator setting in MC by 7% shows a large improvement (Orange vs. Blue).

MC/Data comparison results… Awesome

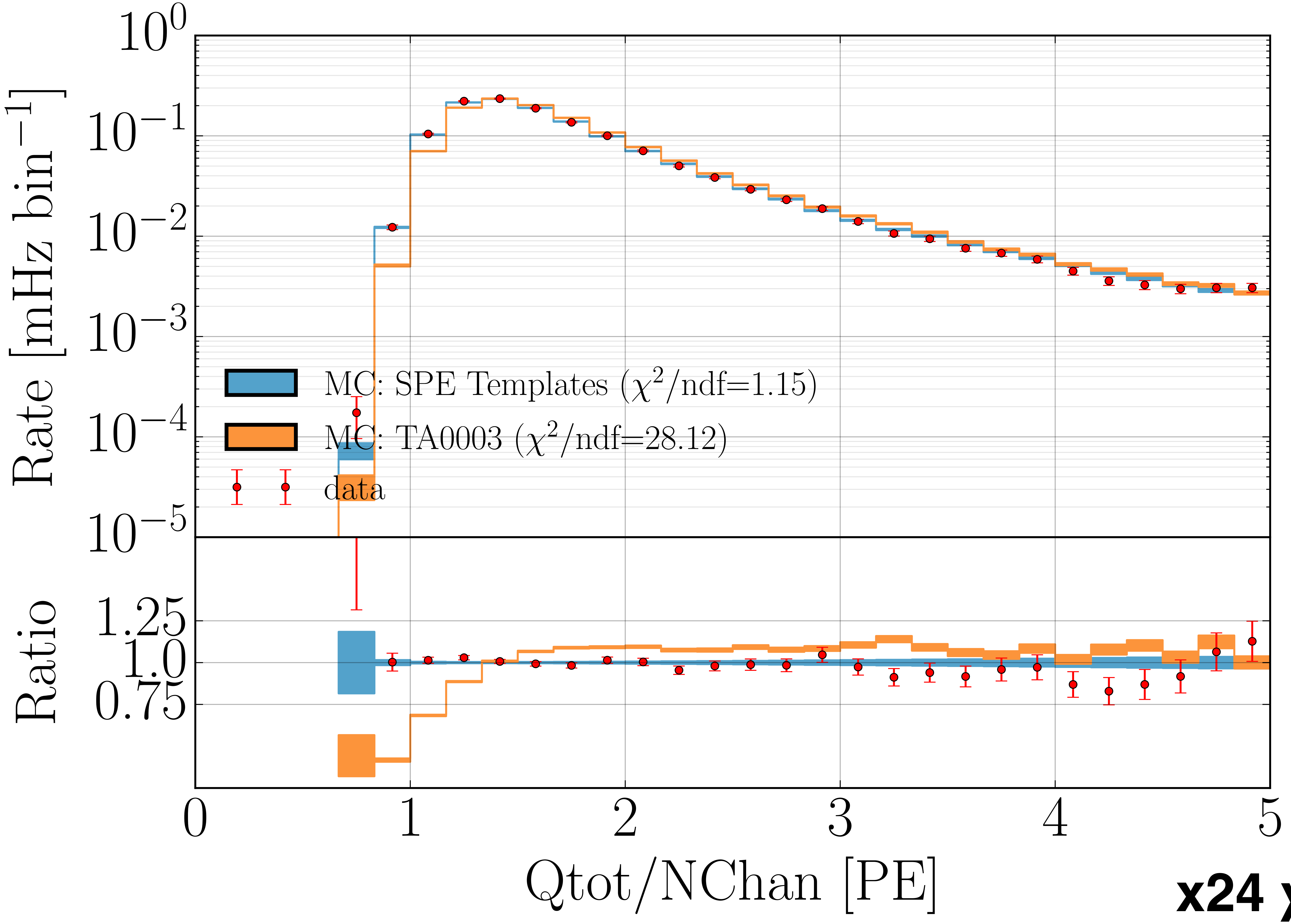




x4.62 χ^2 improvement!

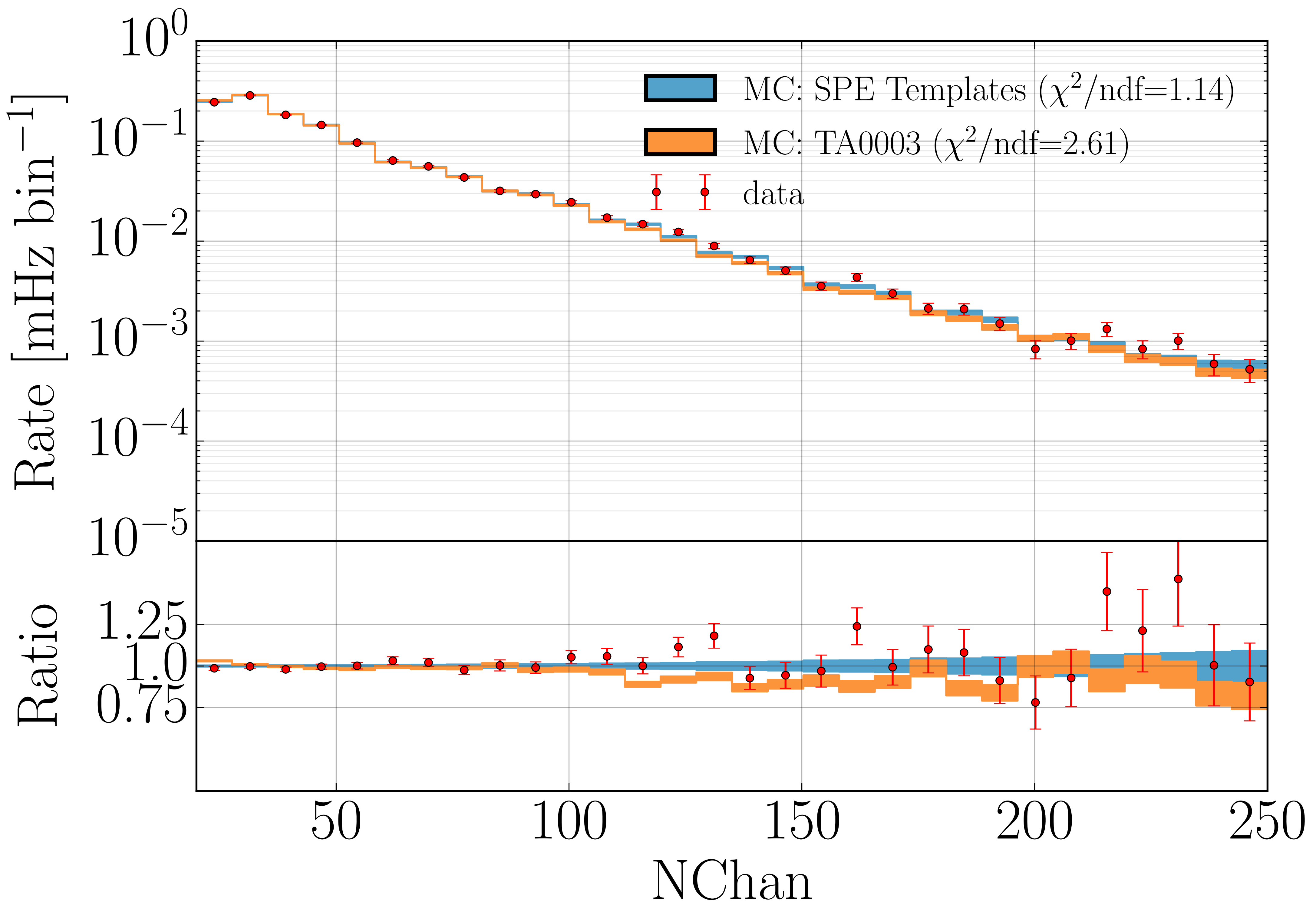
x6.15 χ^2 improvement!

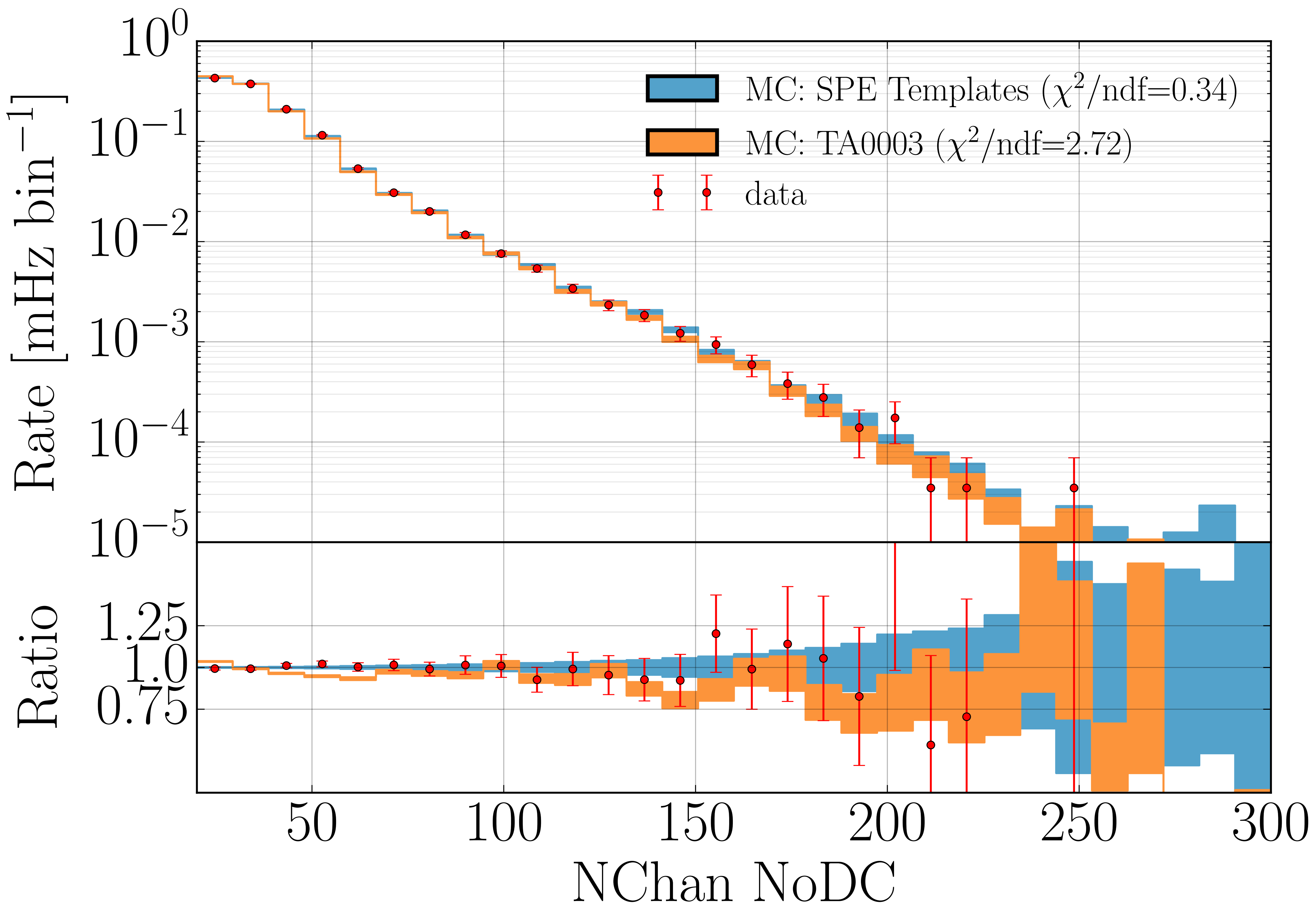
MC/Data comparison results… Awesome



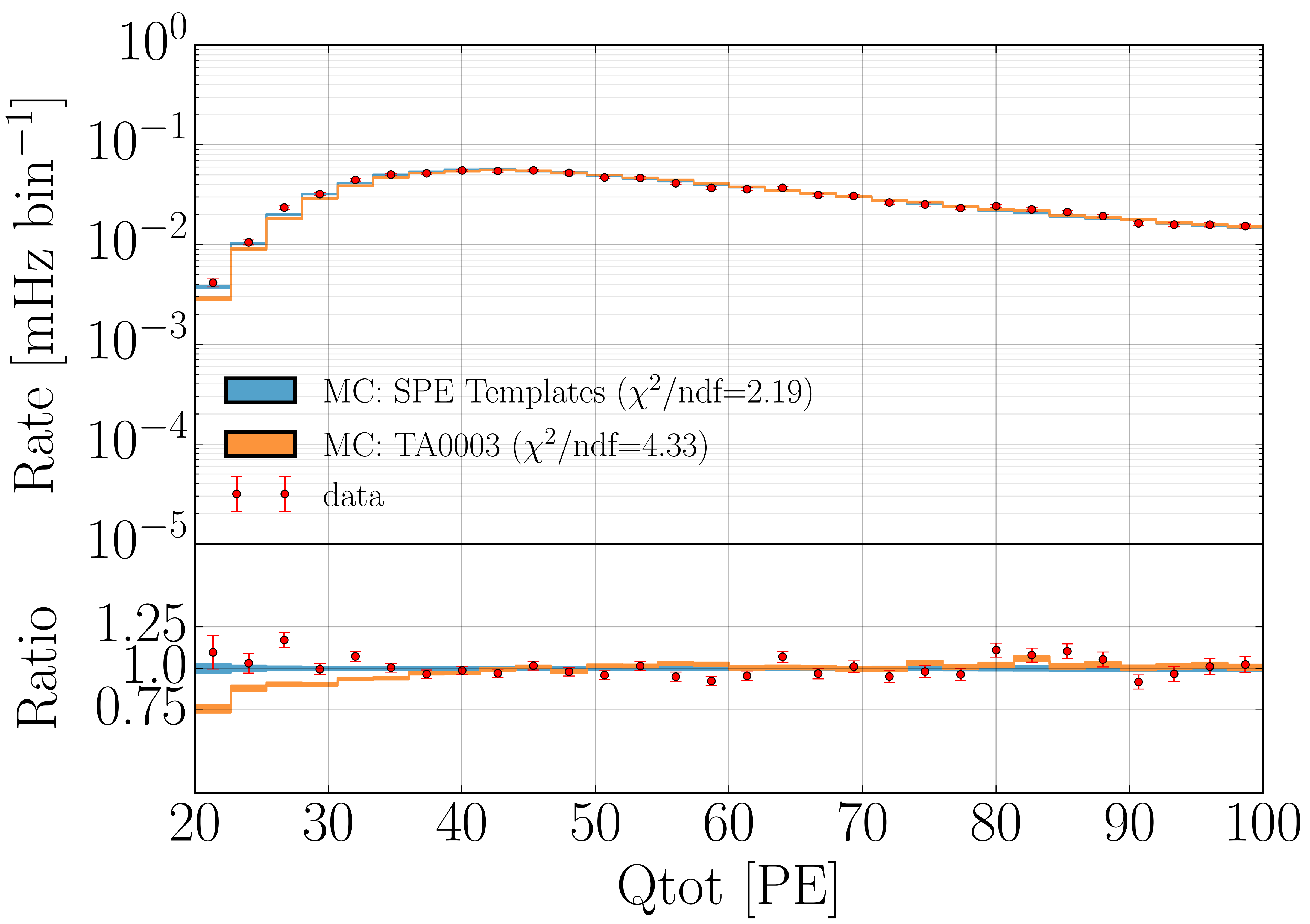
x24 χ^2 improvement!

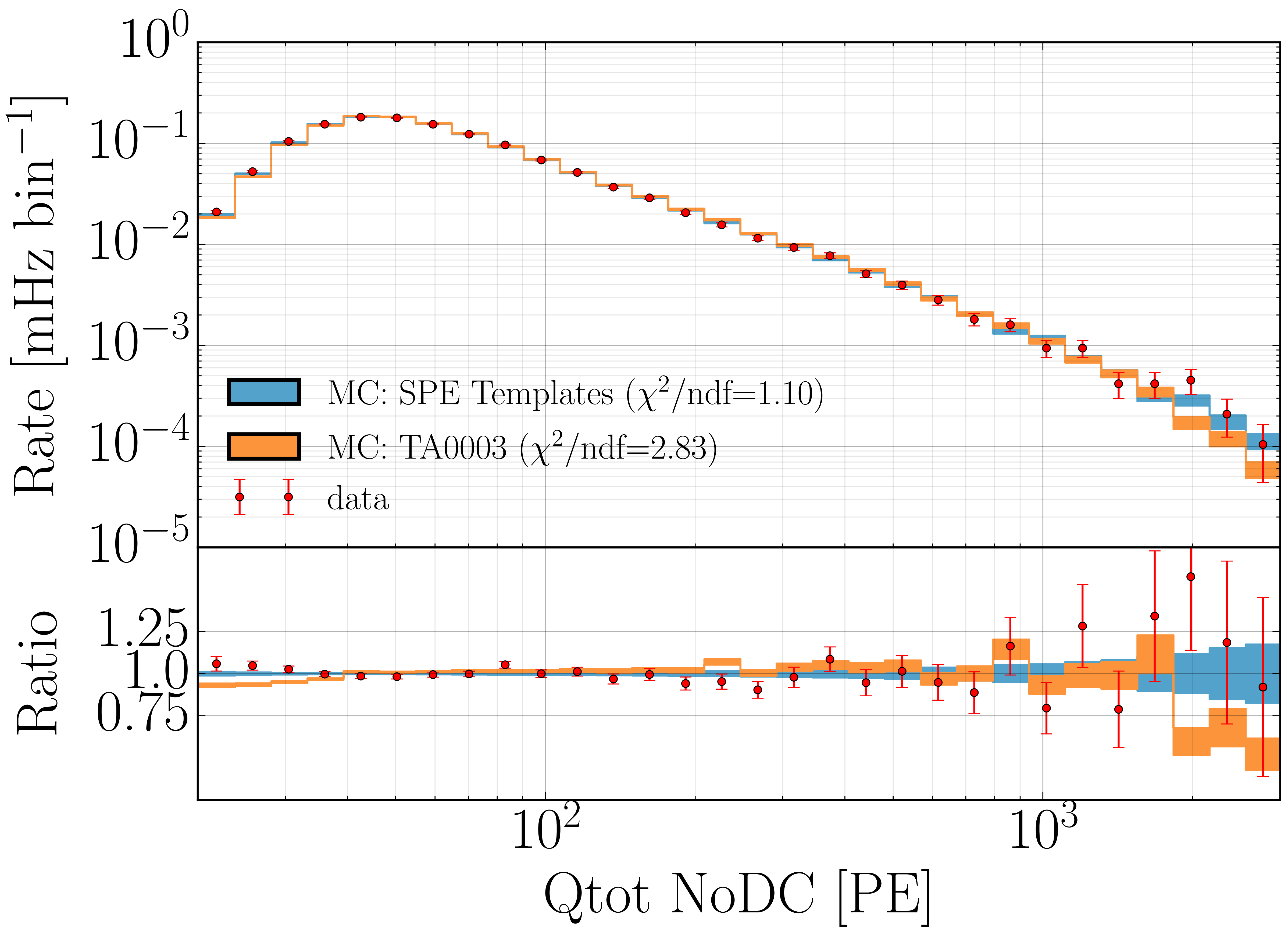
MC/Data comparison results… Awesome





MC/Data comparison results… Awesome





How to use the SPE Templates with the latest updates

This update only requires slight updates to the existing code.

1. **DOMLauncher:**
    - used to get the SPE distribution from the GCD, then add in the residual.
    - scales the discriminator threshold by 0.93
2. **WaveDeform**:
    - applies the scaling factor on the measured charge to match the data of interest.
        - ie. if you want to compare to Pass2, then WaveDeform applies the Pass2 correction to the charges.

3. **An updated GCD**, which will have the label Pass1, Pass2, Pass3, indicating what the generated MC should be used for.

The other modifications are already in place and work.

1. compensation factor -- working great.
2. dataclasses update to incorporate the new GCD format
3. DOMLauncher to get the SPE distribution from Data.
4. SPE fit injector to make the GCD files from my JSON files.

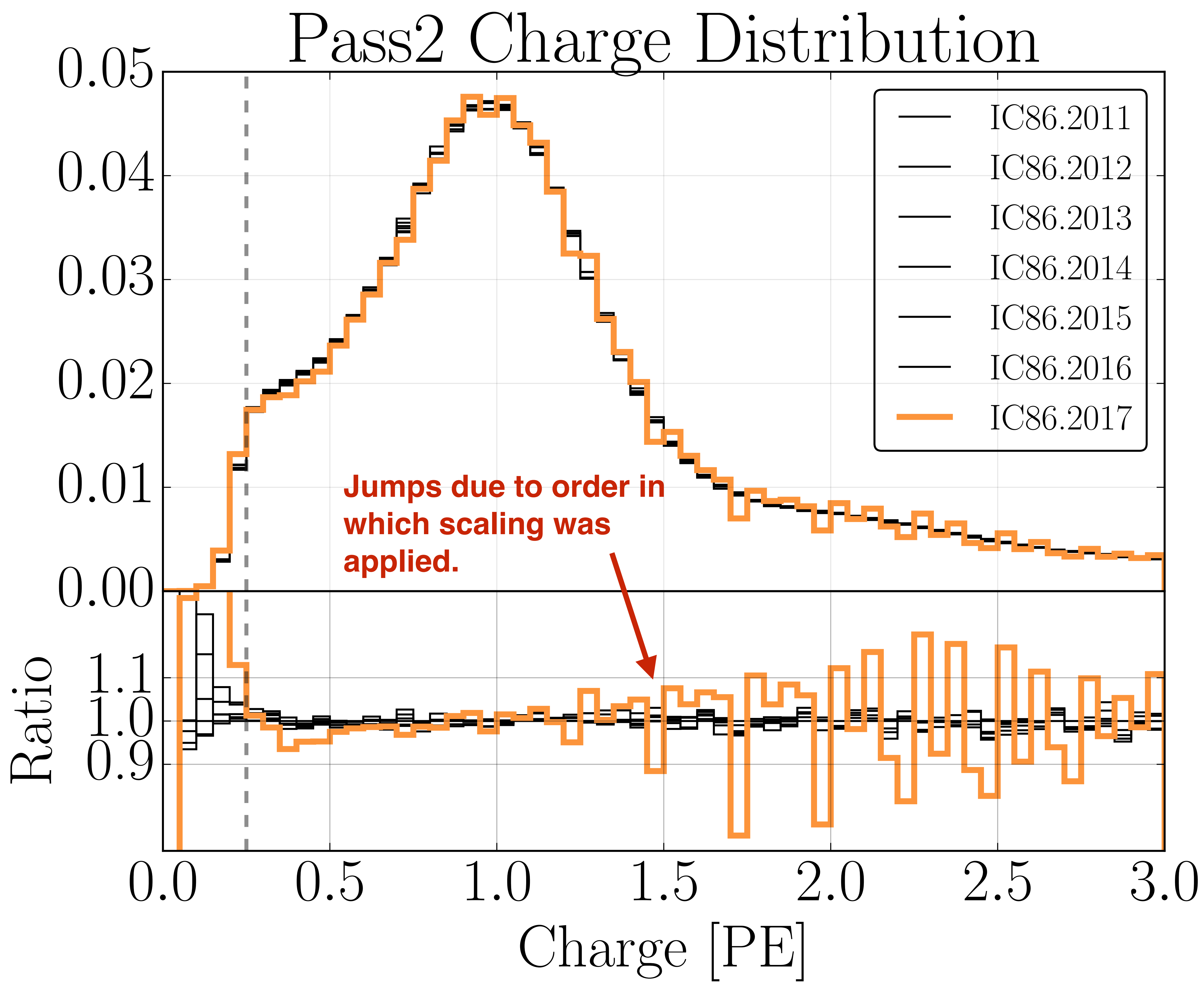
How to incorporate the SPE Templates as a systematic

With this new procedure, one can check the effect of the SPE Templates as a systematic uncertainty.

You have:

1. SPE Template MC: simply scale the mean_atwd_charge and mean_fadc_charge by +/-1%.
2. Defat MC: run SPE Template MC.

Pass2 IC86.2017+ charge distributions



Mismatch shown in **Data** between pass2 years.

Binning effect.

Reason: The order in which the charge scaling factor was applied to Pass2.

IC86.2011-2016:

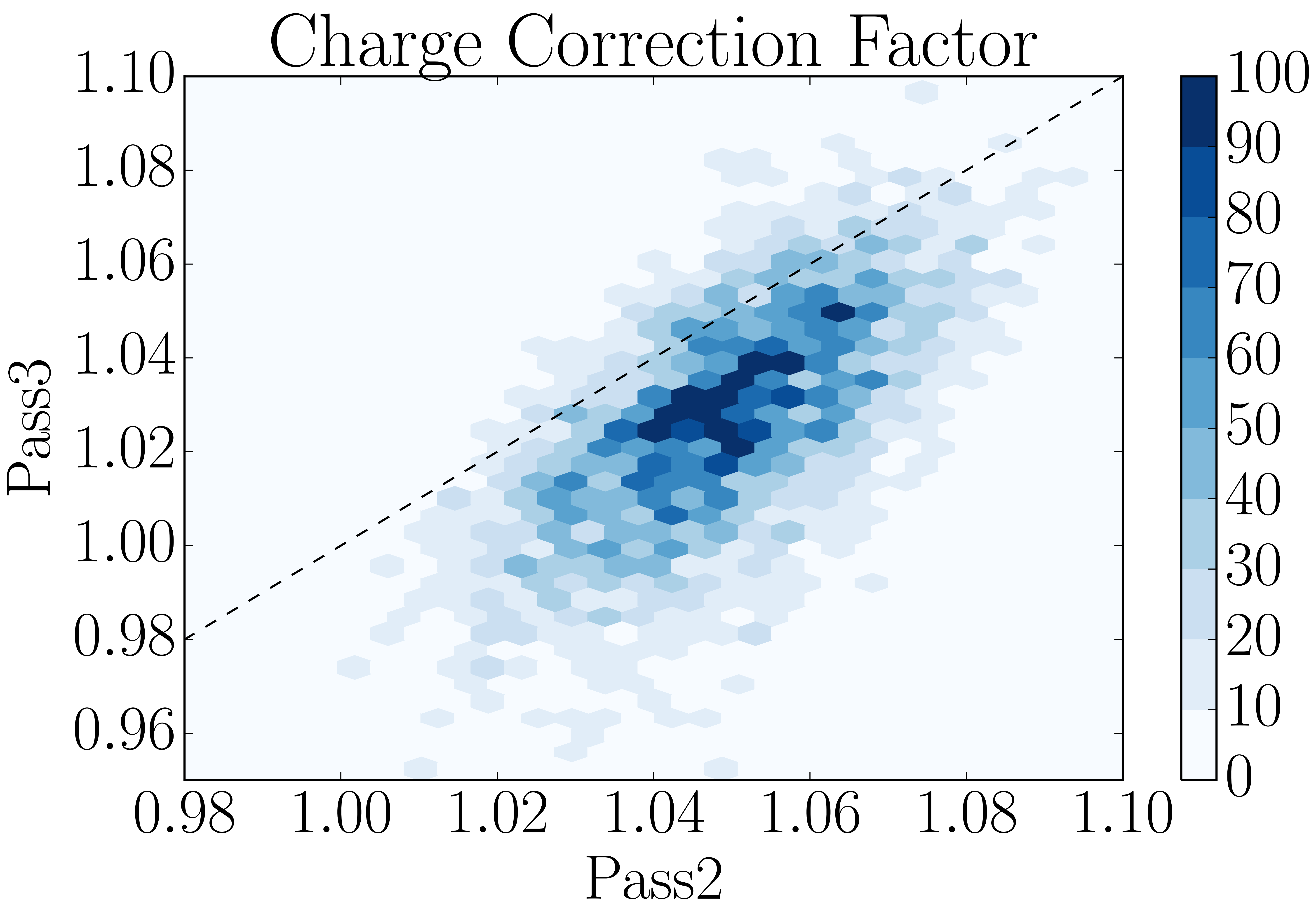
- sDST then scaling of charge

IC86.2017+:

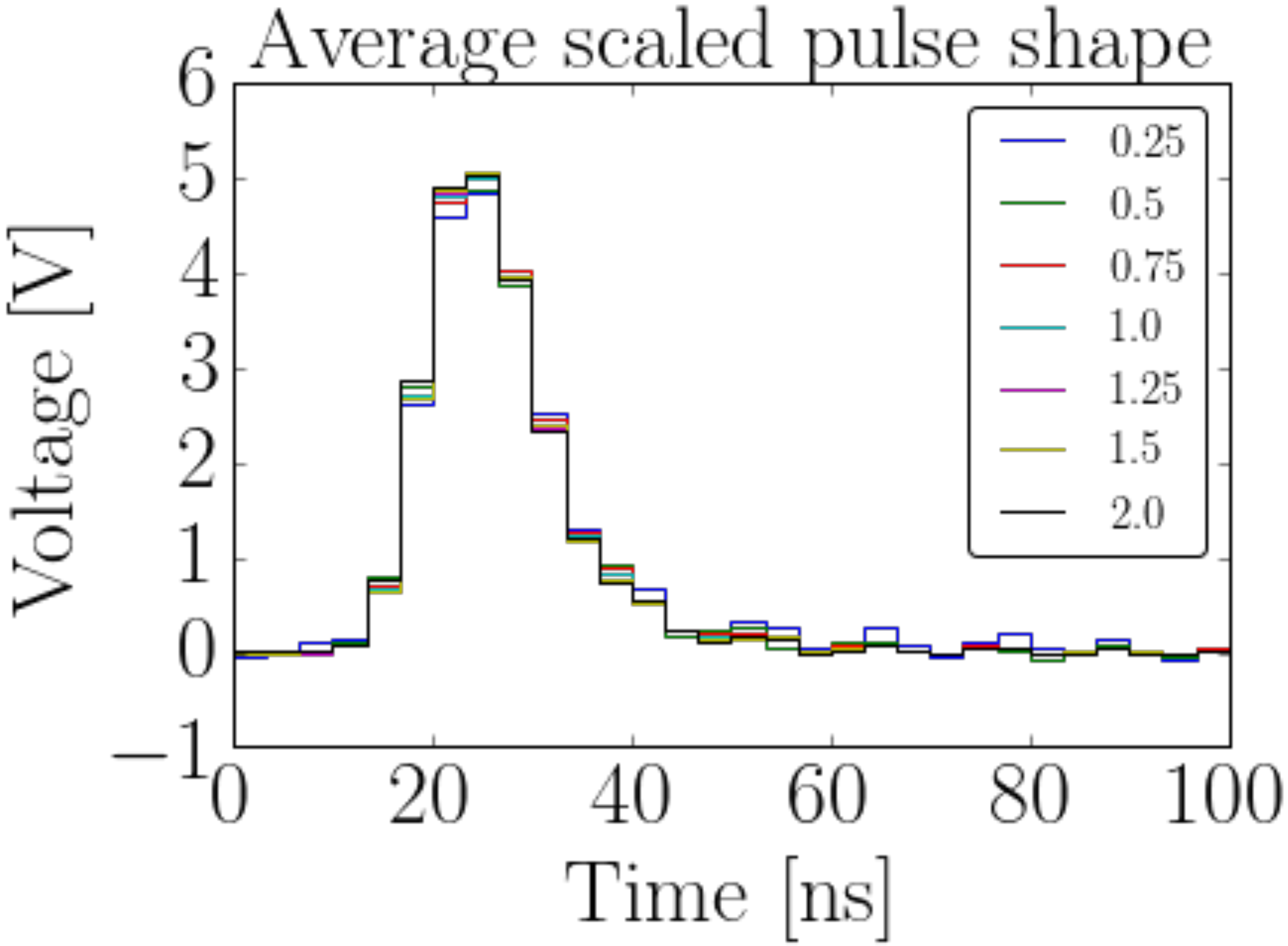
- scaling of charge then sDST

Pass3 would fix this. All data would look like IC86.2017 in the plot.

Pass2 IC86.2017+ charge distributions



Do pulse shapes scale with charge



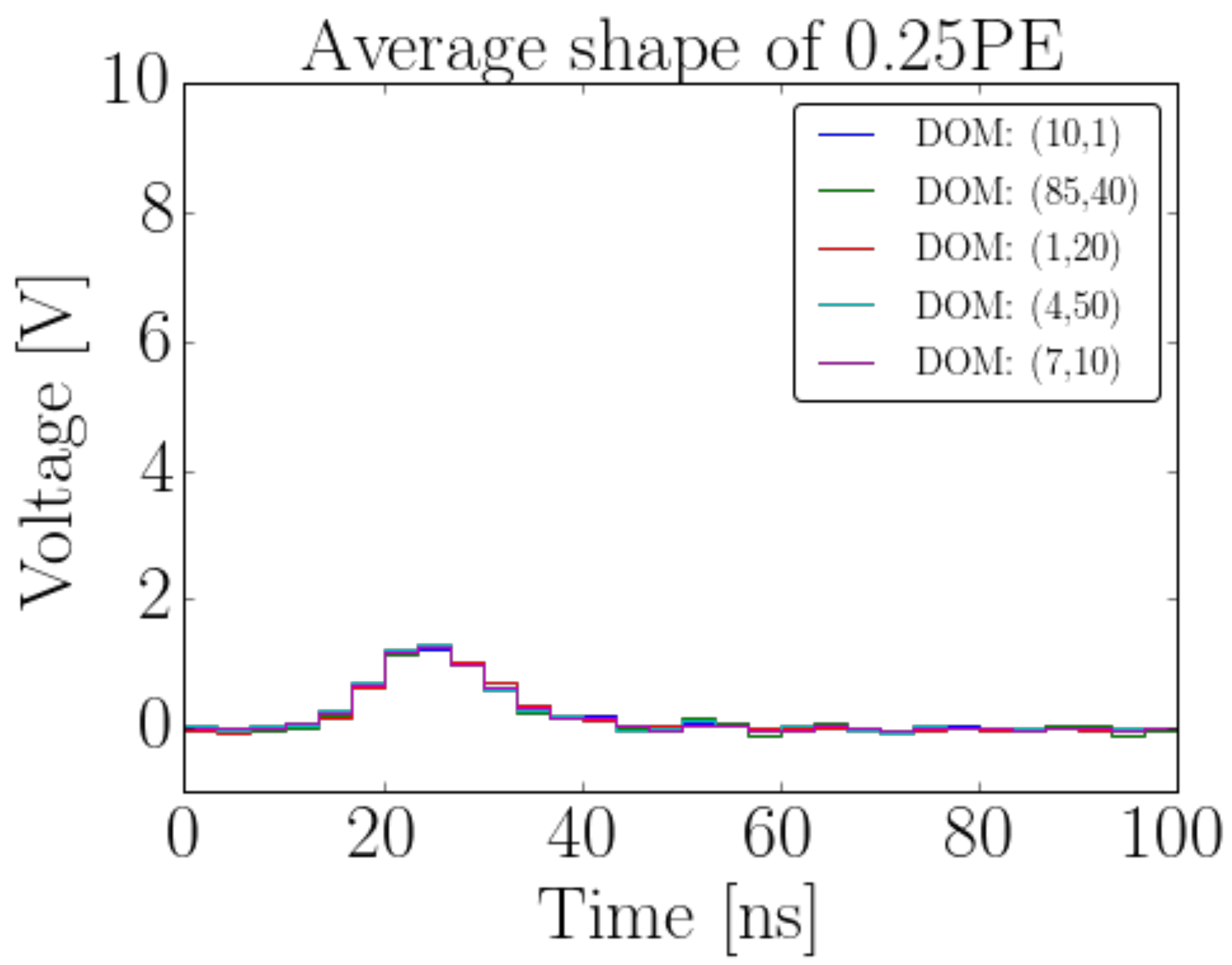
WaveDeform assumes that the shape of a pulse scales linearly with charge.

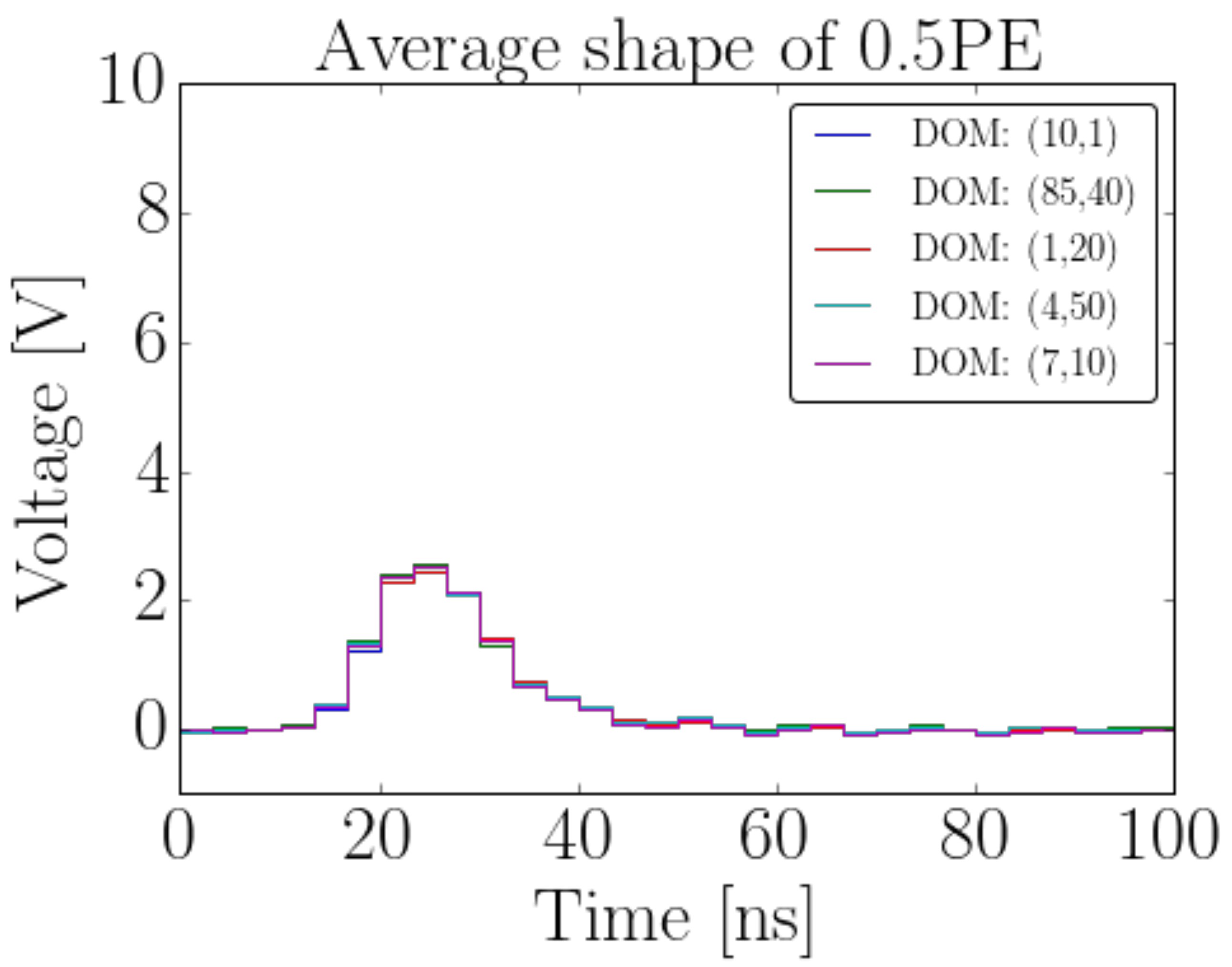
e.g. The shape of a 0.25PE pulse, looks like a 1PE pulse scaled by 0.25.

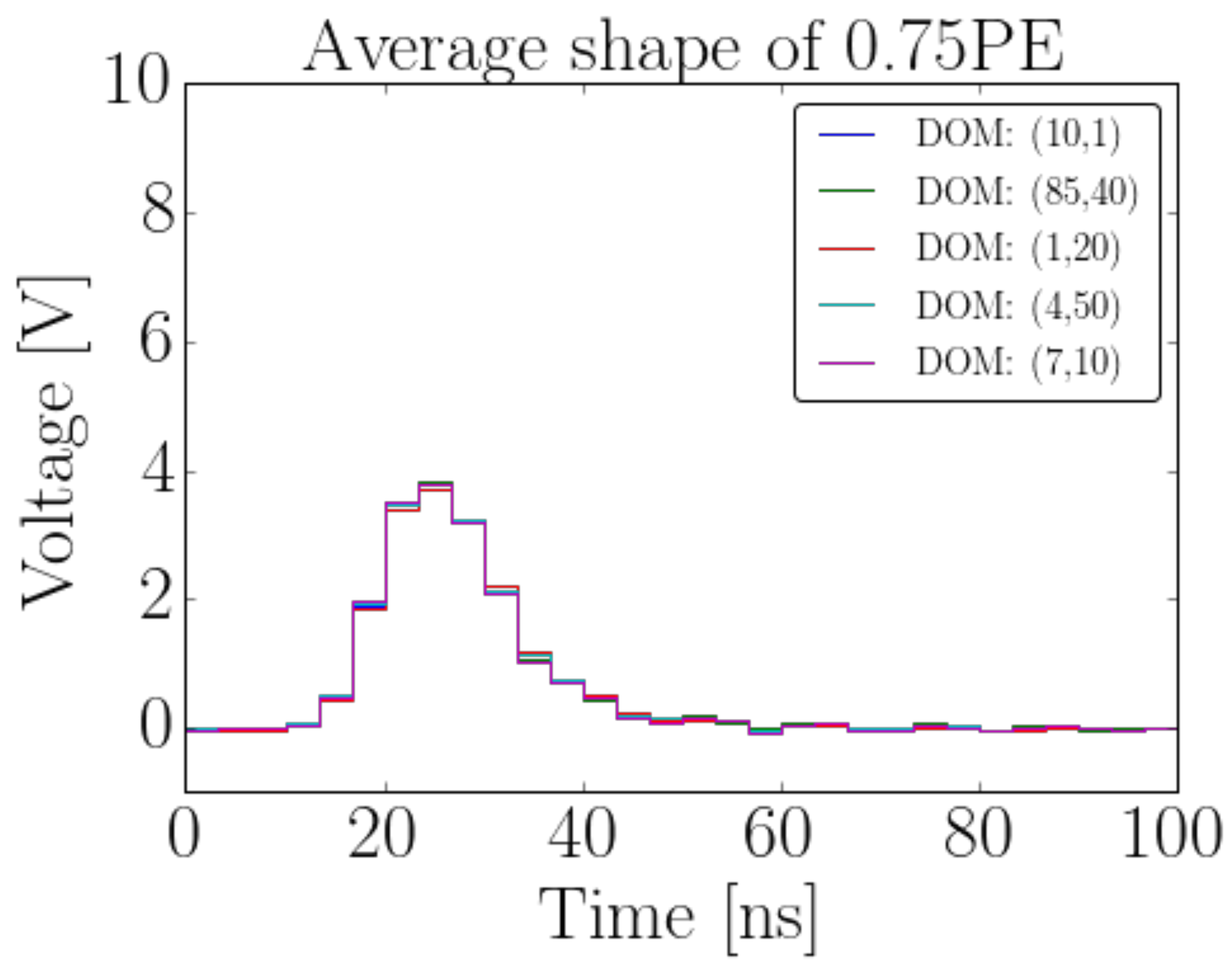
This appears to be a good approximation.

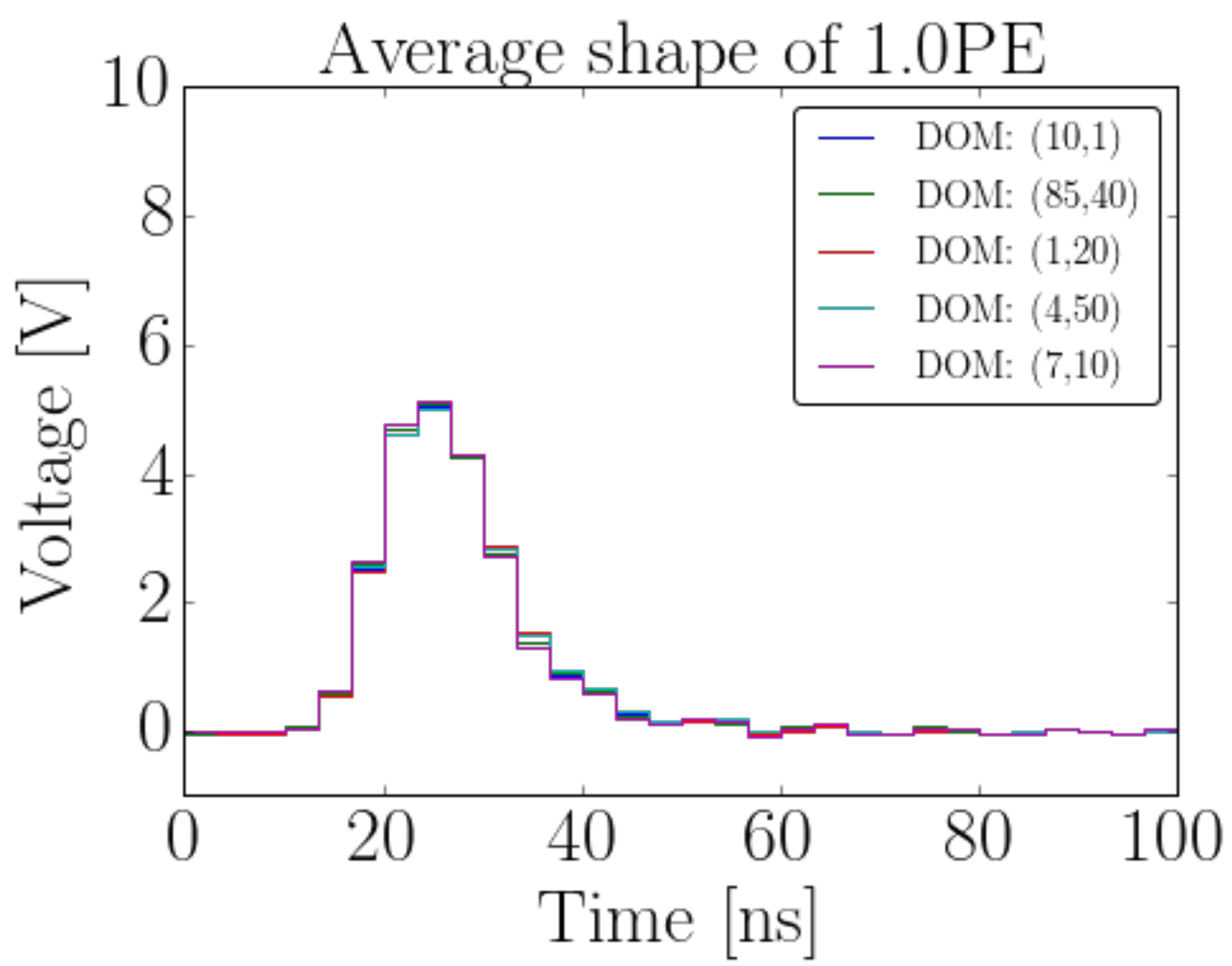
The plot on the left shows the average shape of a charge, scaled by the charge.

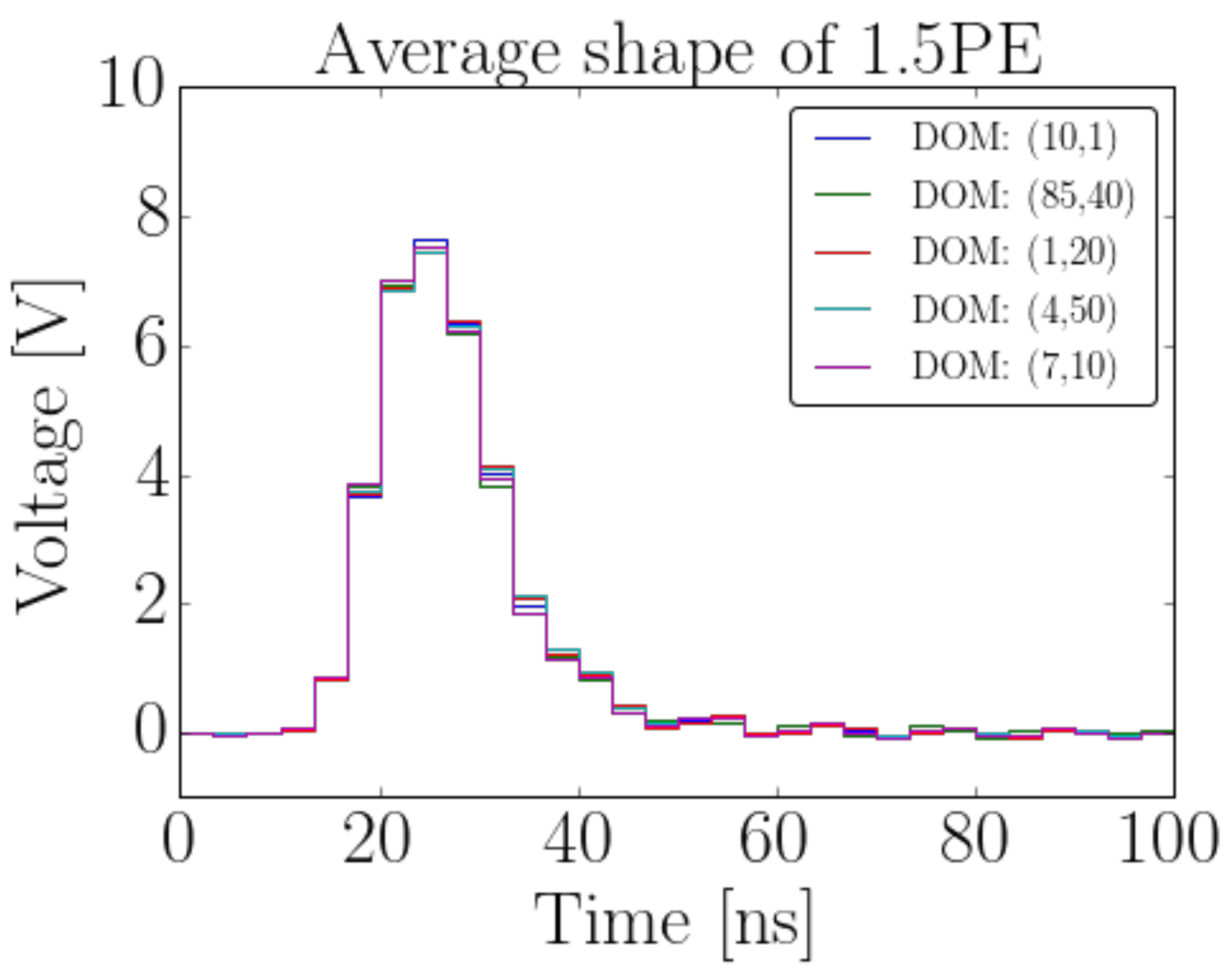
Does the shape of a pules change from DOM to DOM?







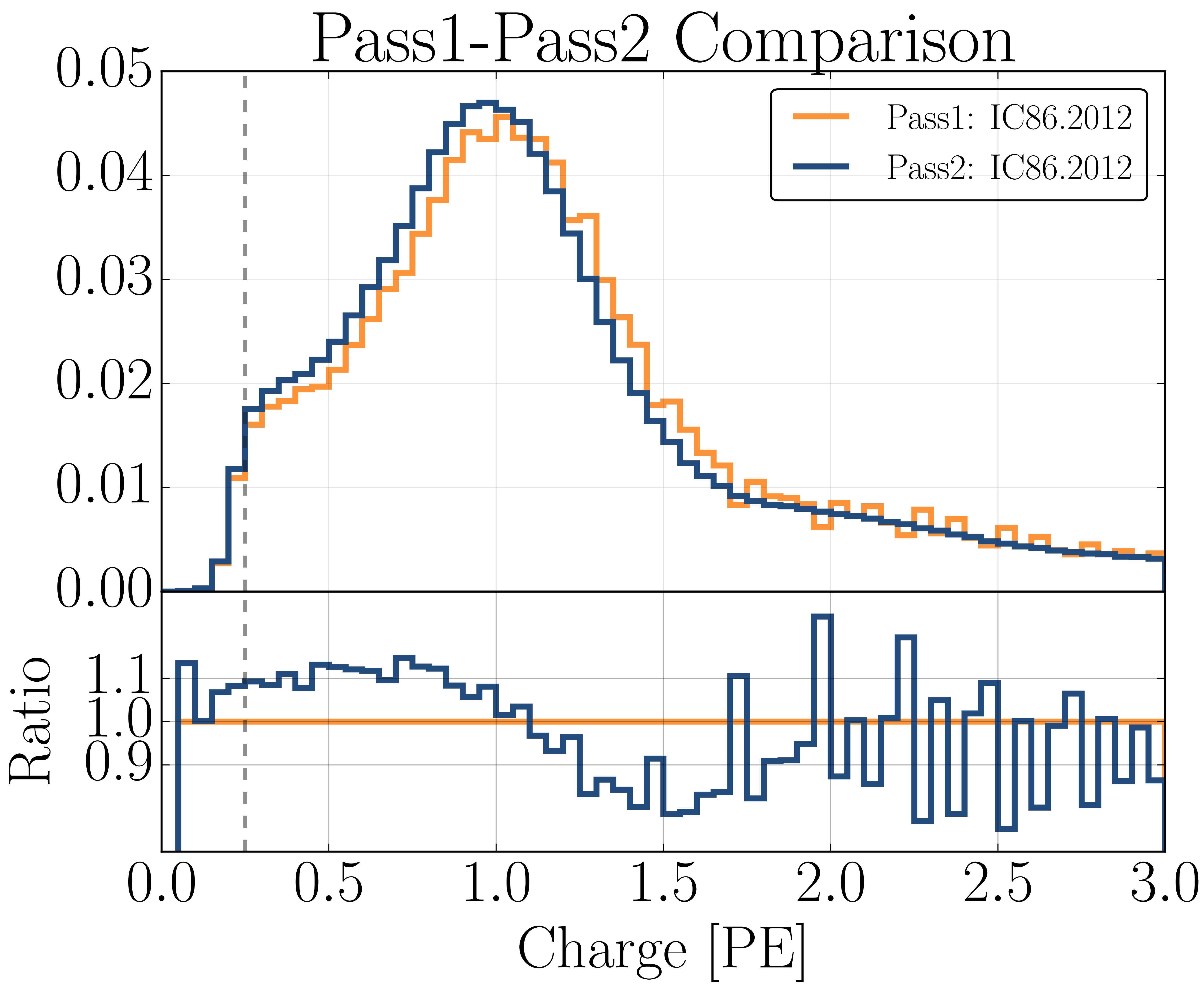




The shape of pulses seems to be consistent between DOMs.

These are averaged over 100s of pulses.

Inject Recover Signals

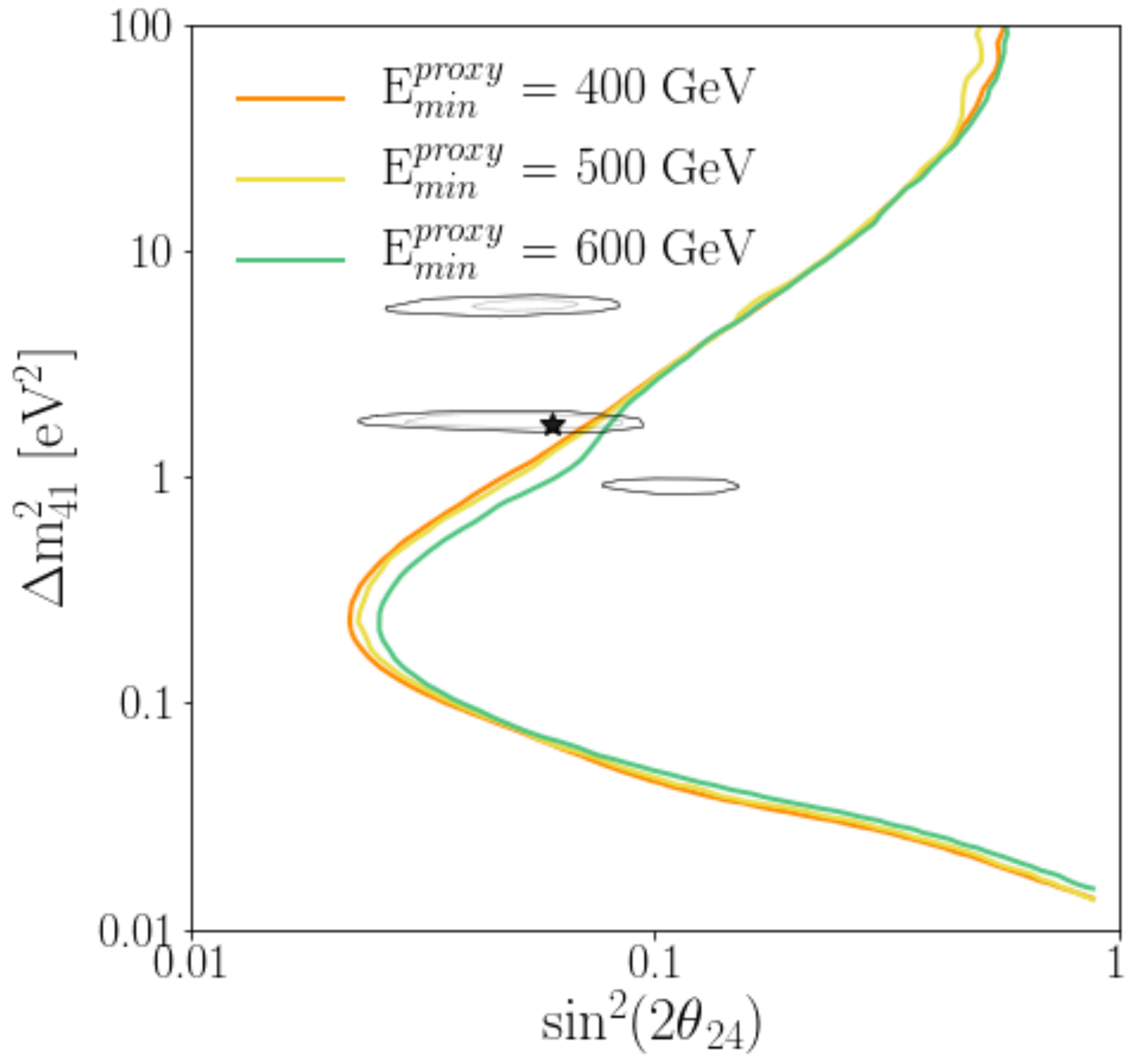


IceCube
SOUTH POLE NEUTRINO OBSERVATORY

Next steps

Thanks for your attention!

Low energy cut-off



The current state of the analysis introduces a cut at 400GeV reconstructed energy.

We investigated whether we gain anything from keeping these low energy events.

There appears to be minimal improvement using events sub-500 GeV.

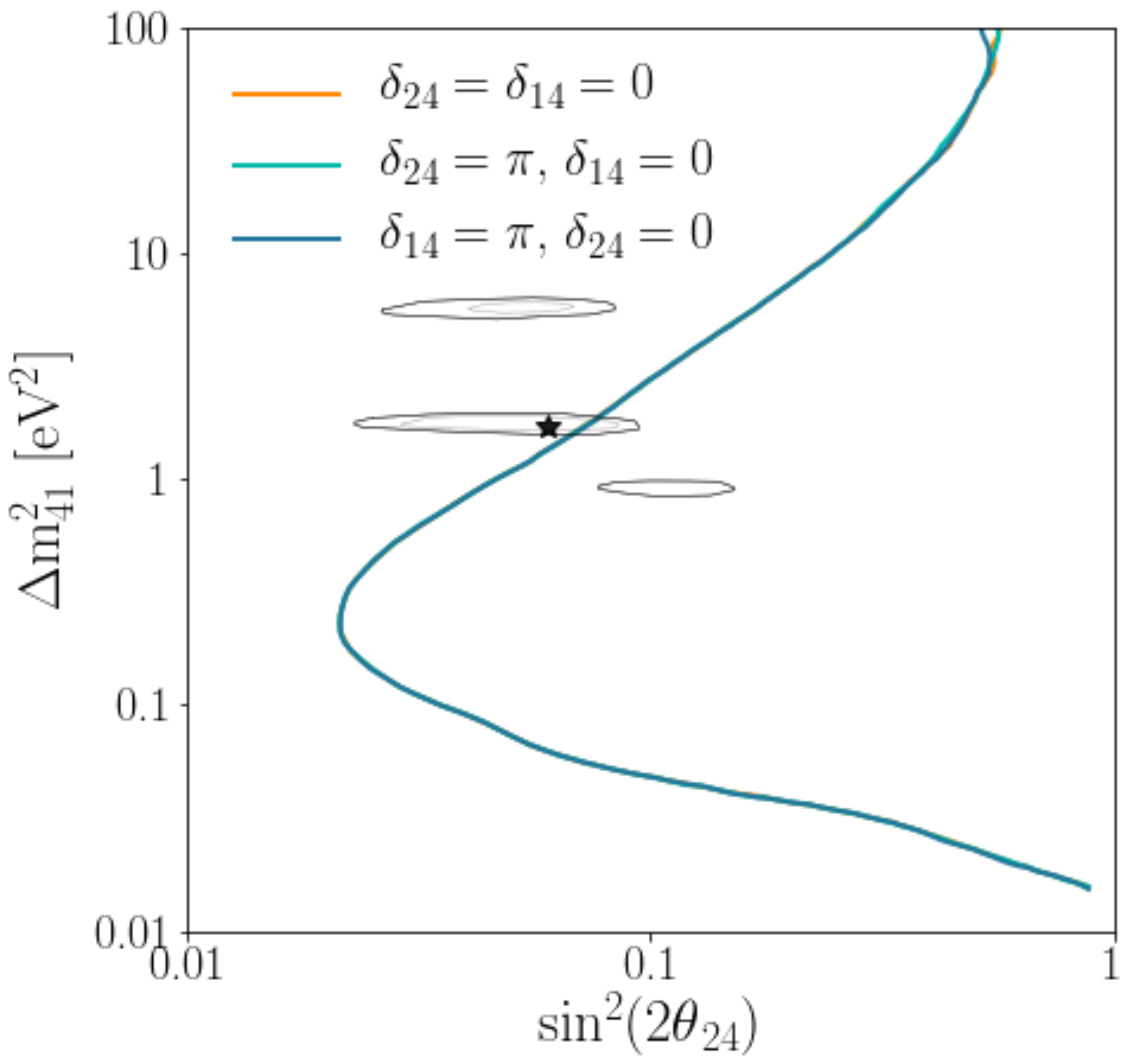
Prior to implementing a cut at 500GeV, we'll first check if this holds when all systematics are included.

Sterile CP-violating phase

Including a single sterile state introduces two new cp-phases, d24 and d14, in the extended PNMS matrix.

The sensitivity was generated using three different combinations of cp-phases.

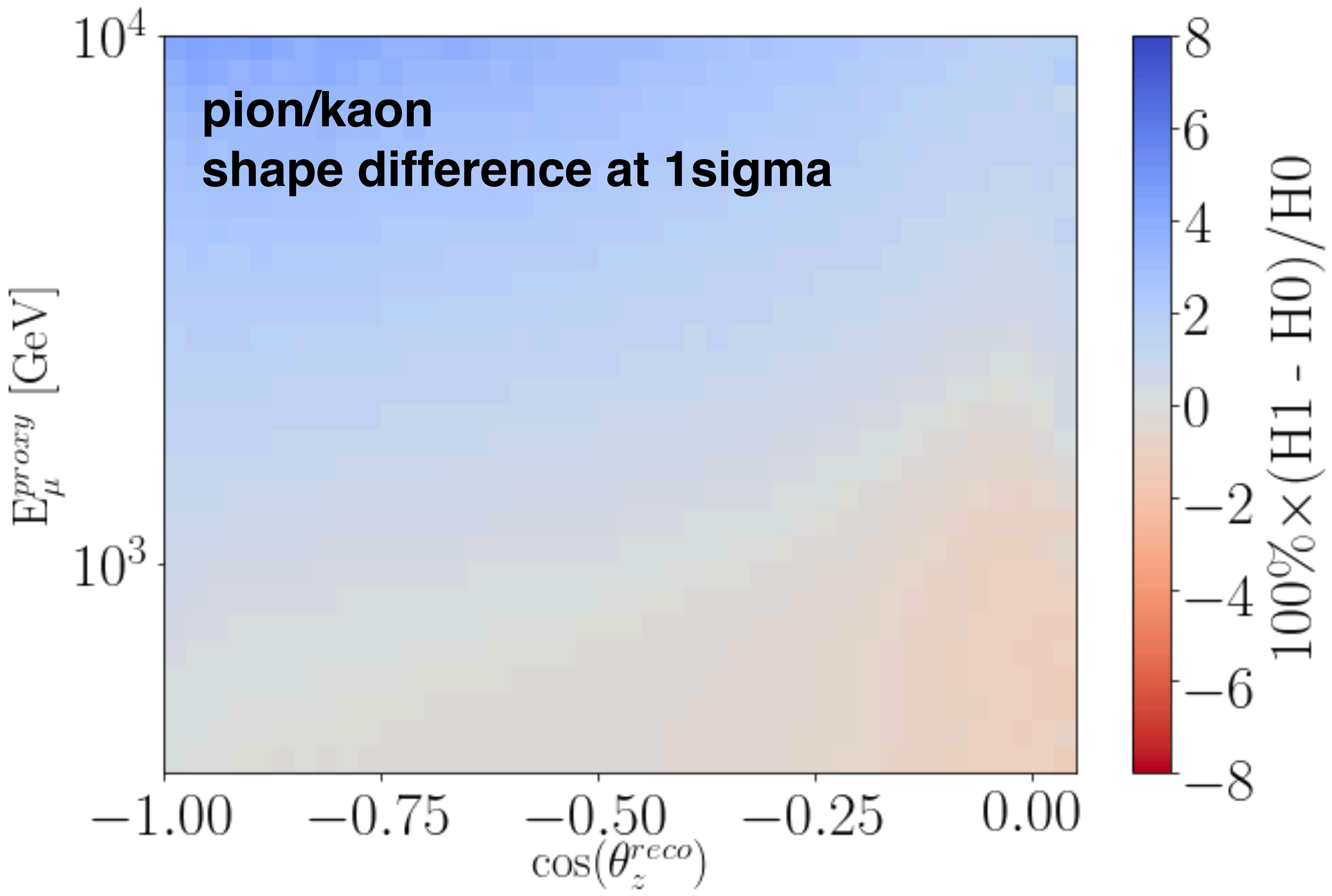
We find that we are not sensitive to the cp-phases.

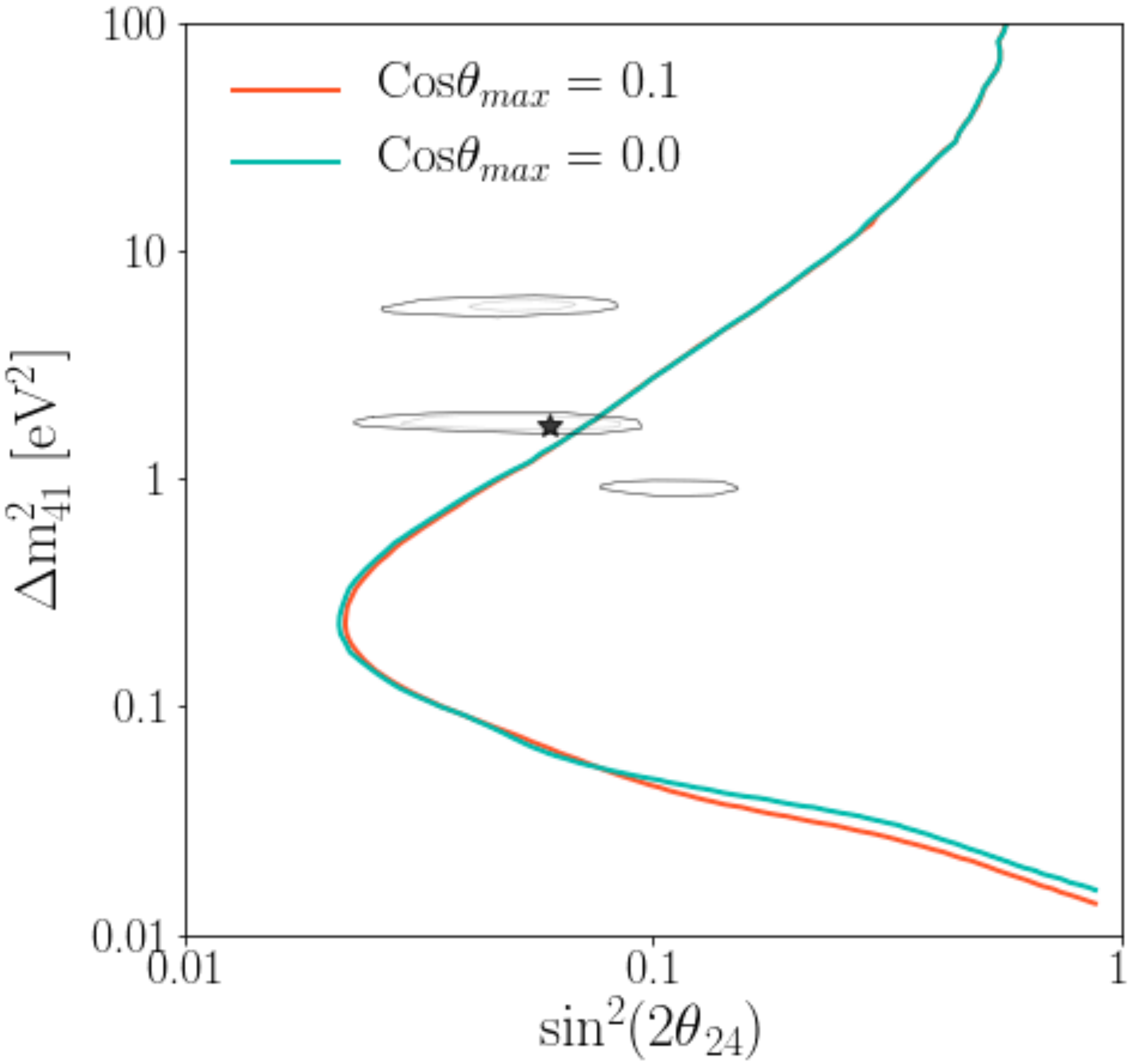


Maximum zenith cut-off

The low energy events (sub-TeV) near the horizon help constrain the pion/kaon ratio.

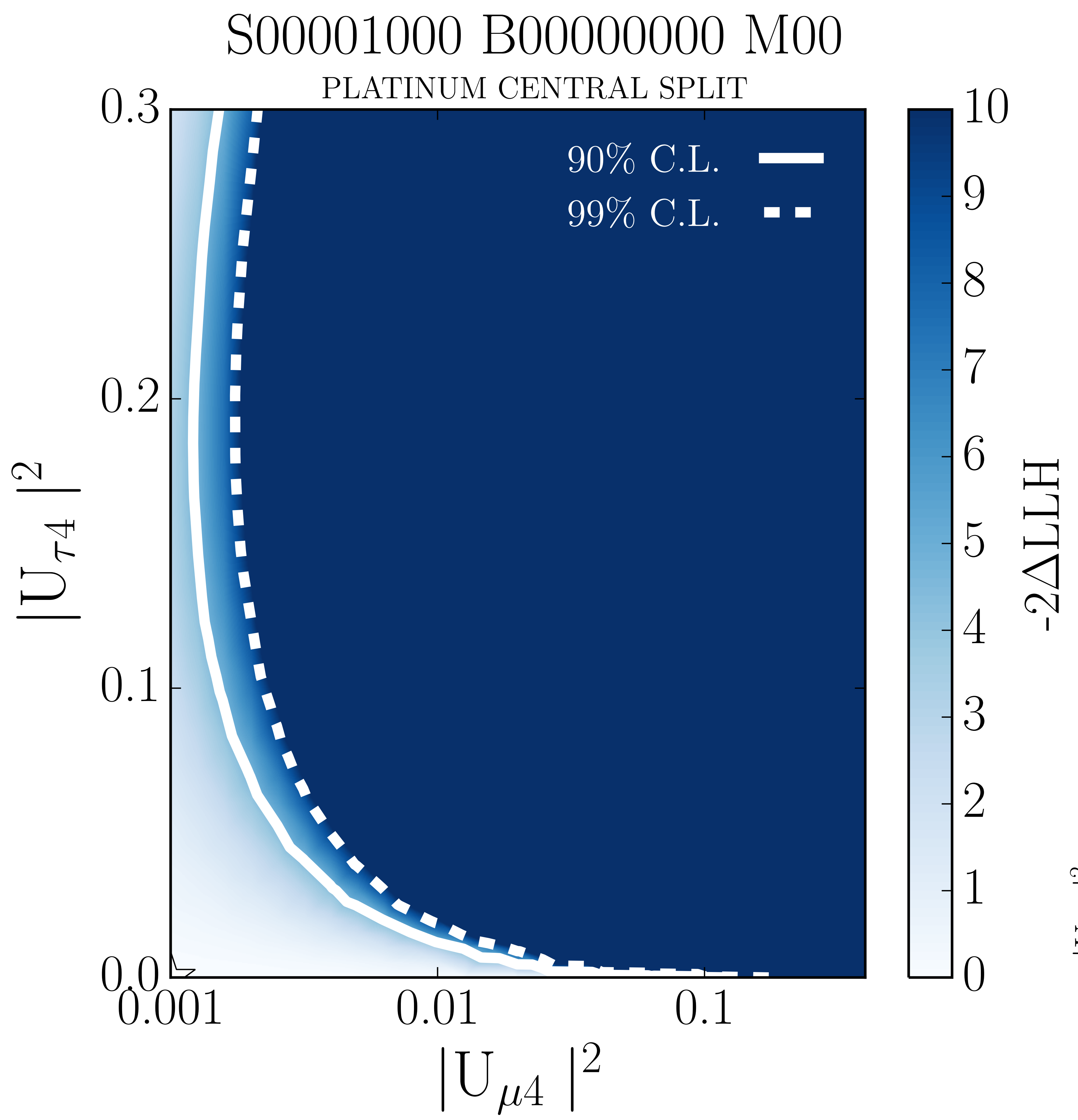
However, we do not appear to gain much looking above the horizon.

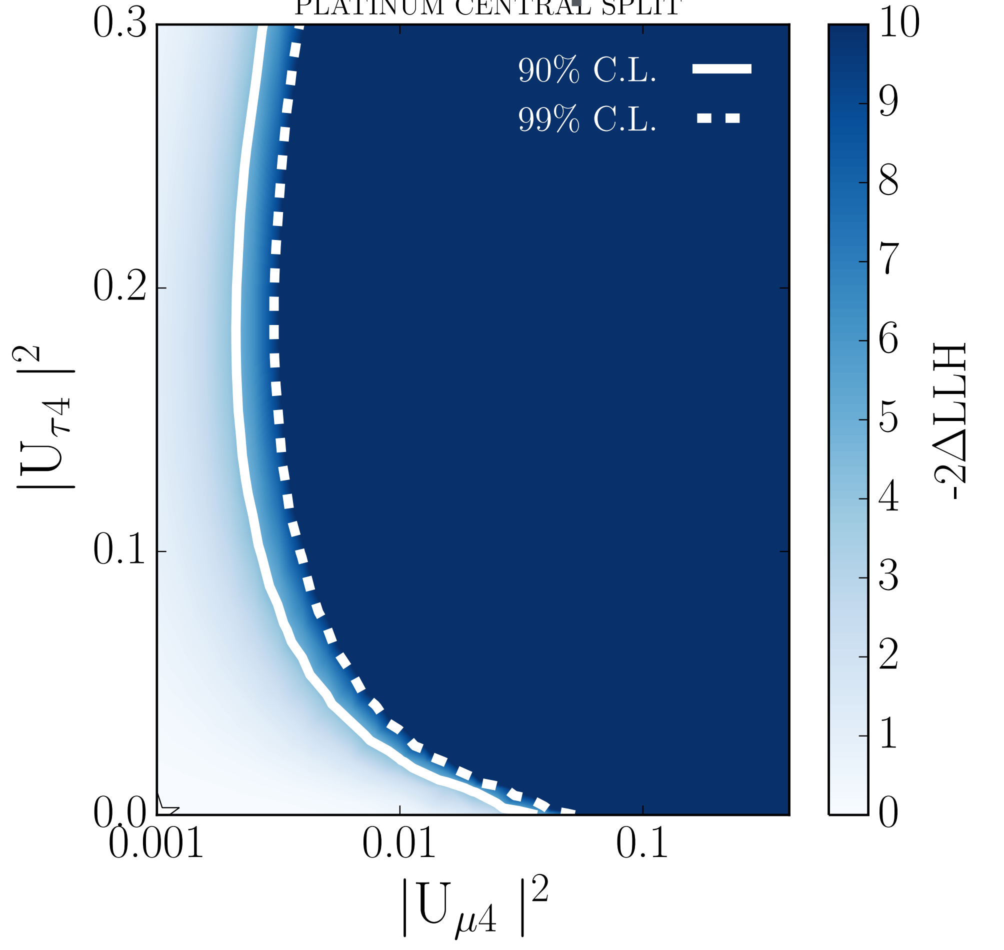


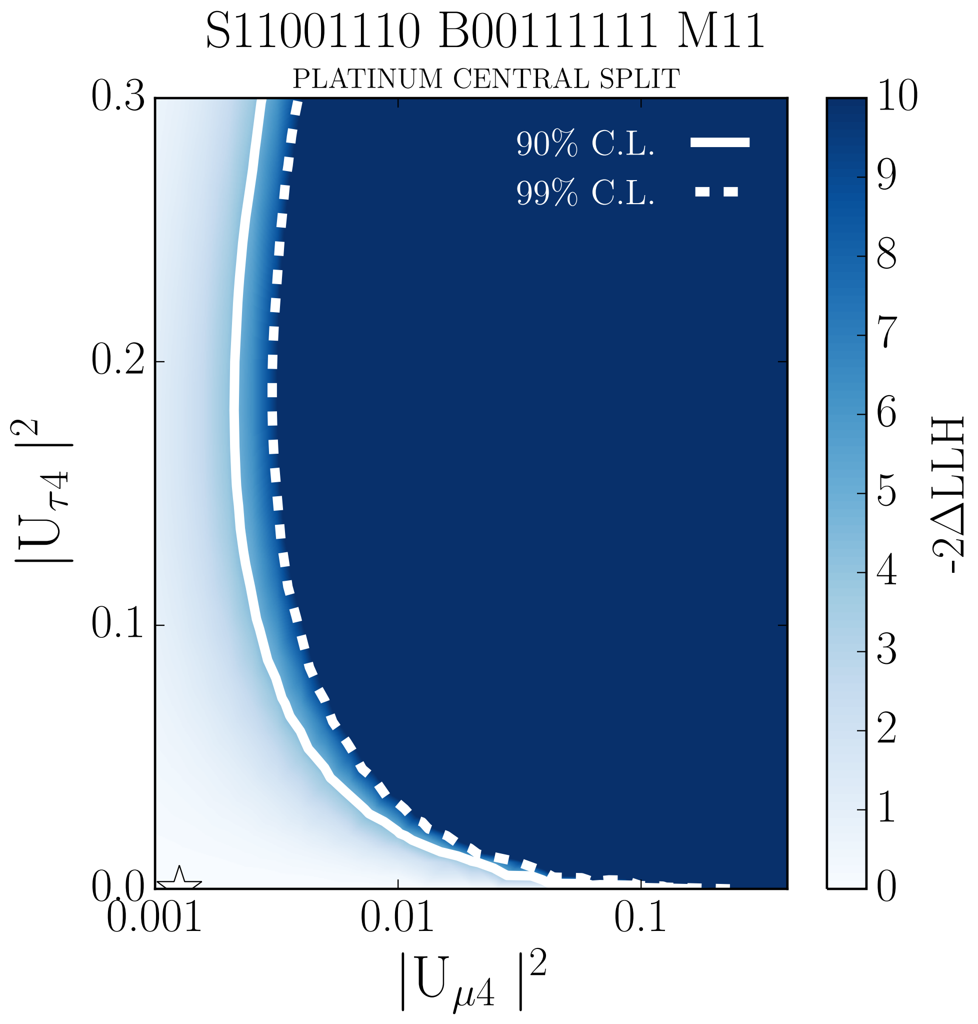


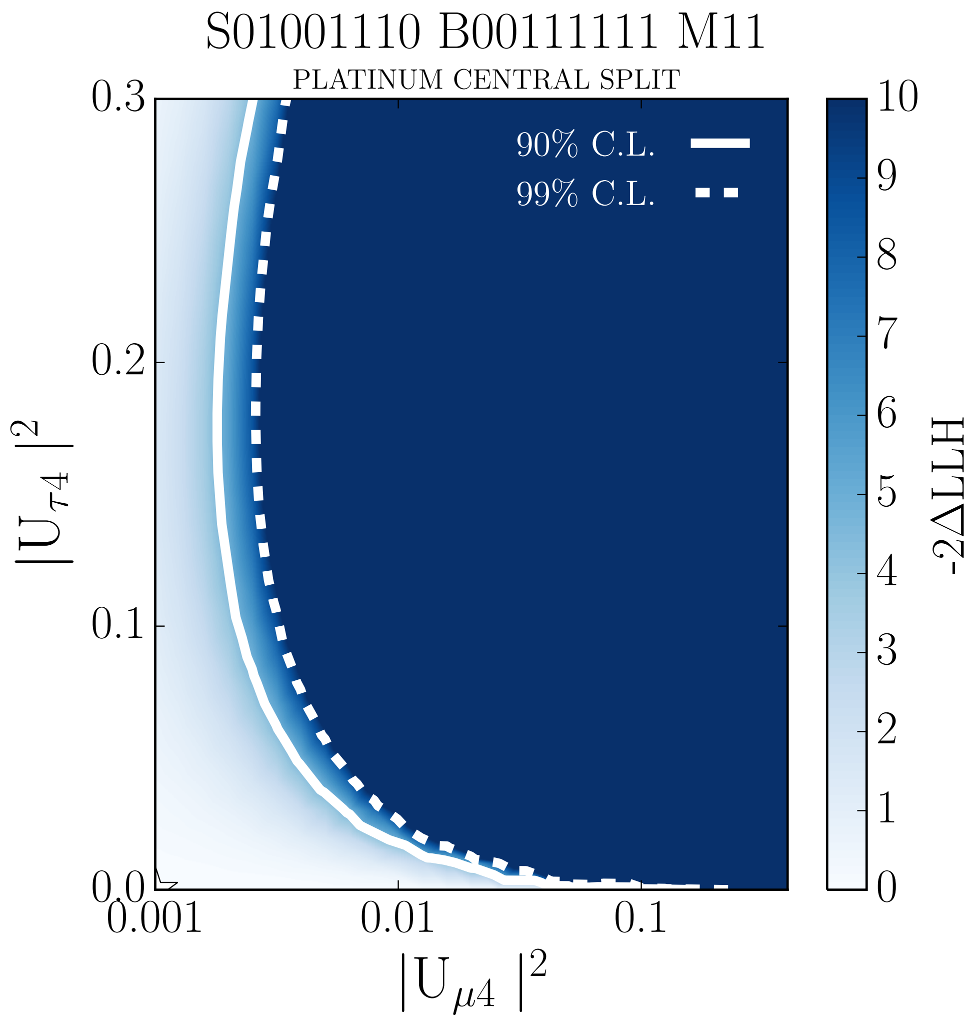
N-1 Test

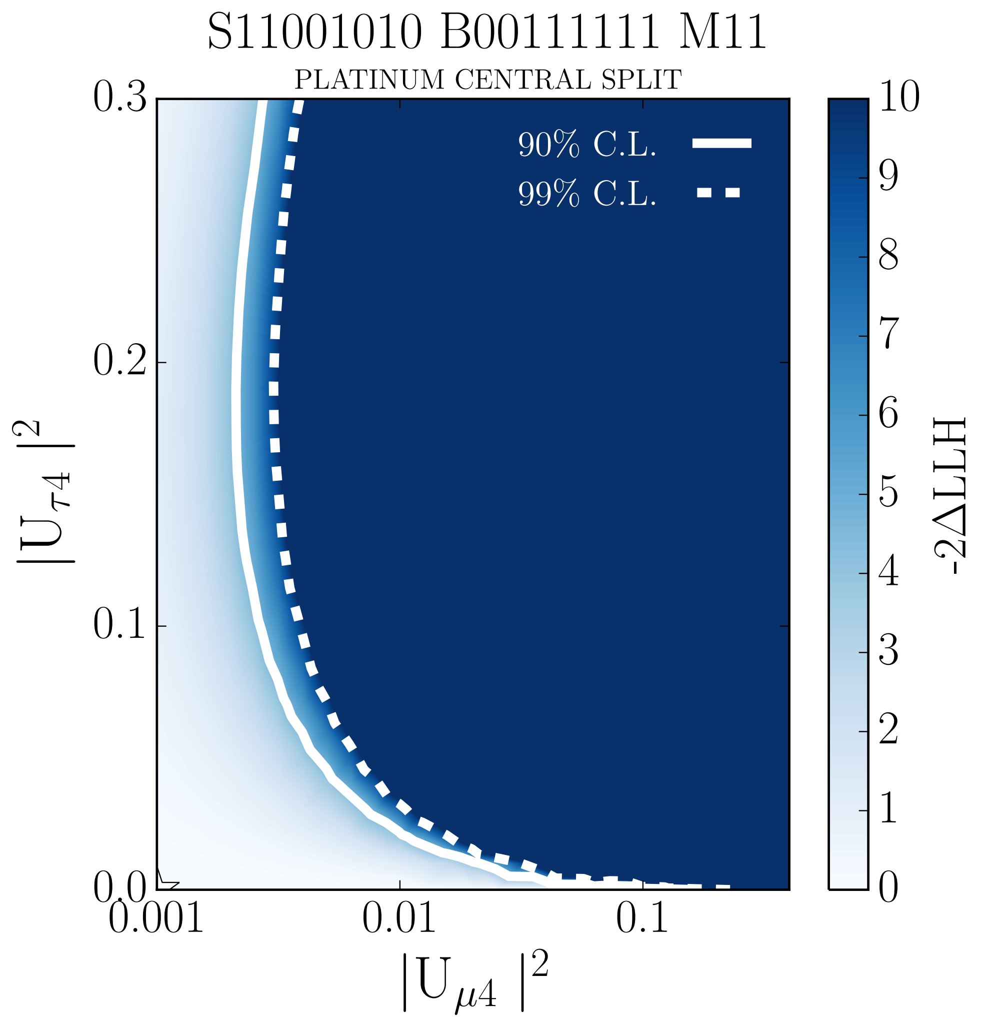
Show systematic pulls distributions at best fit points.

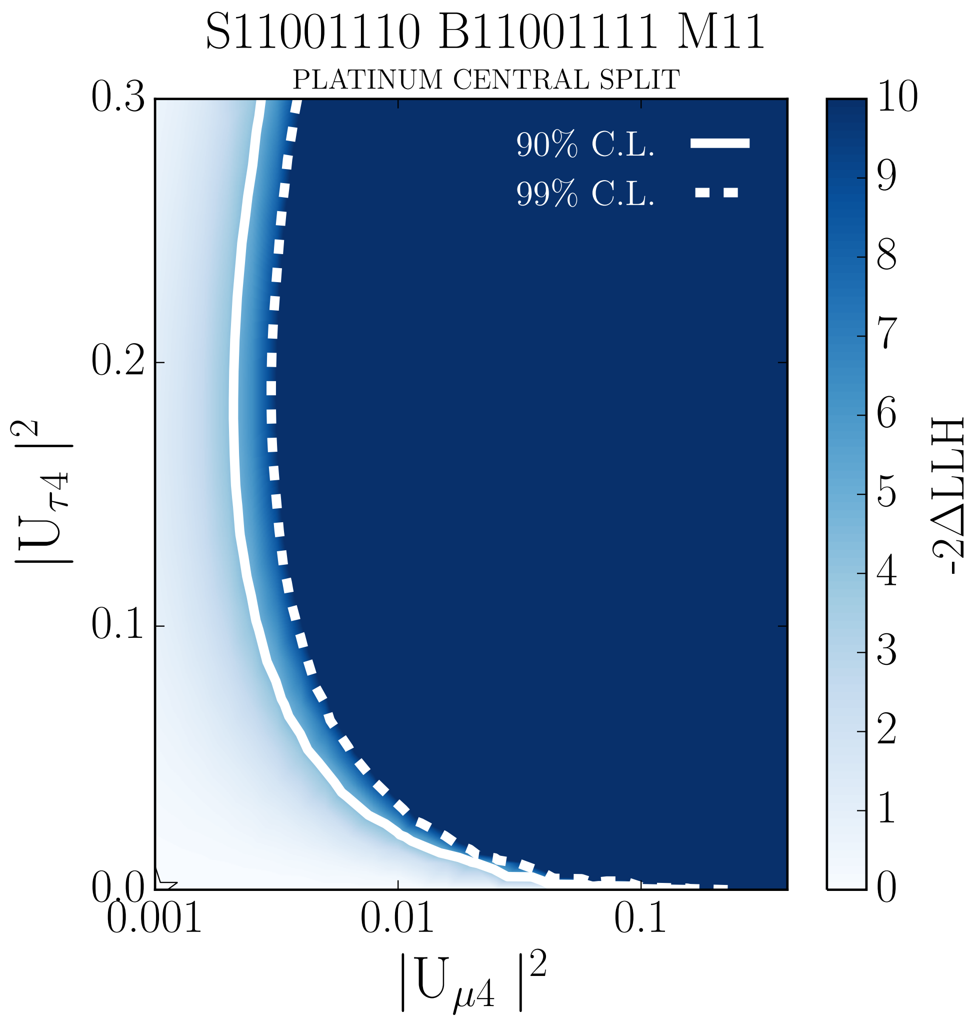






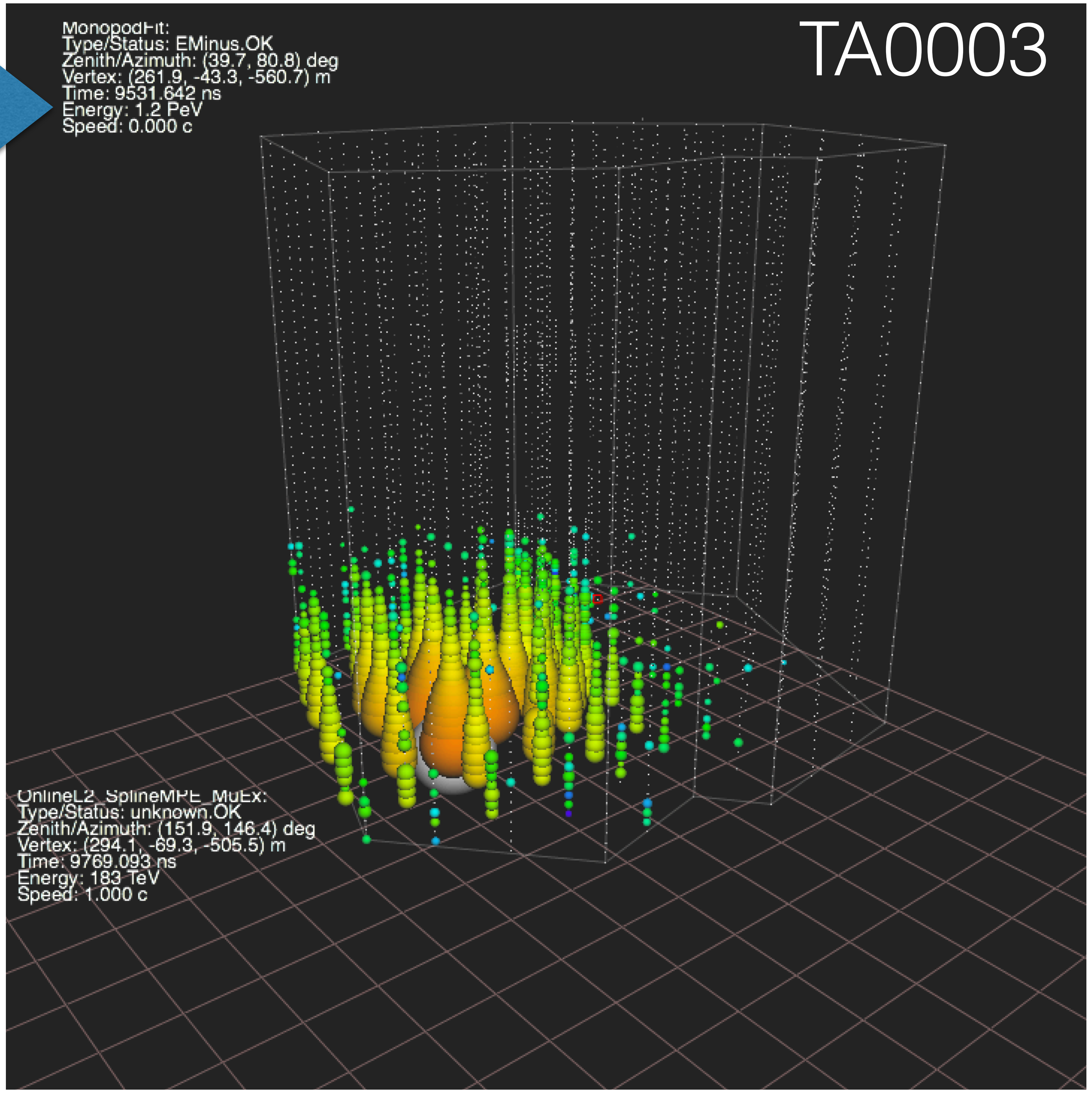


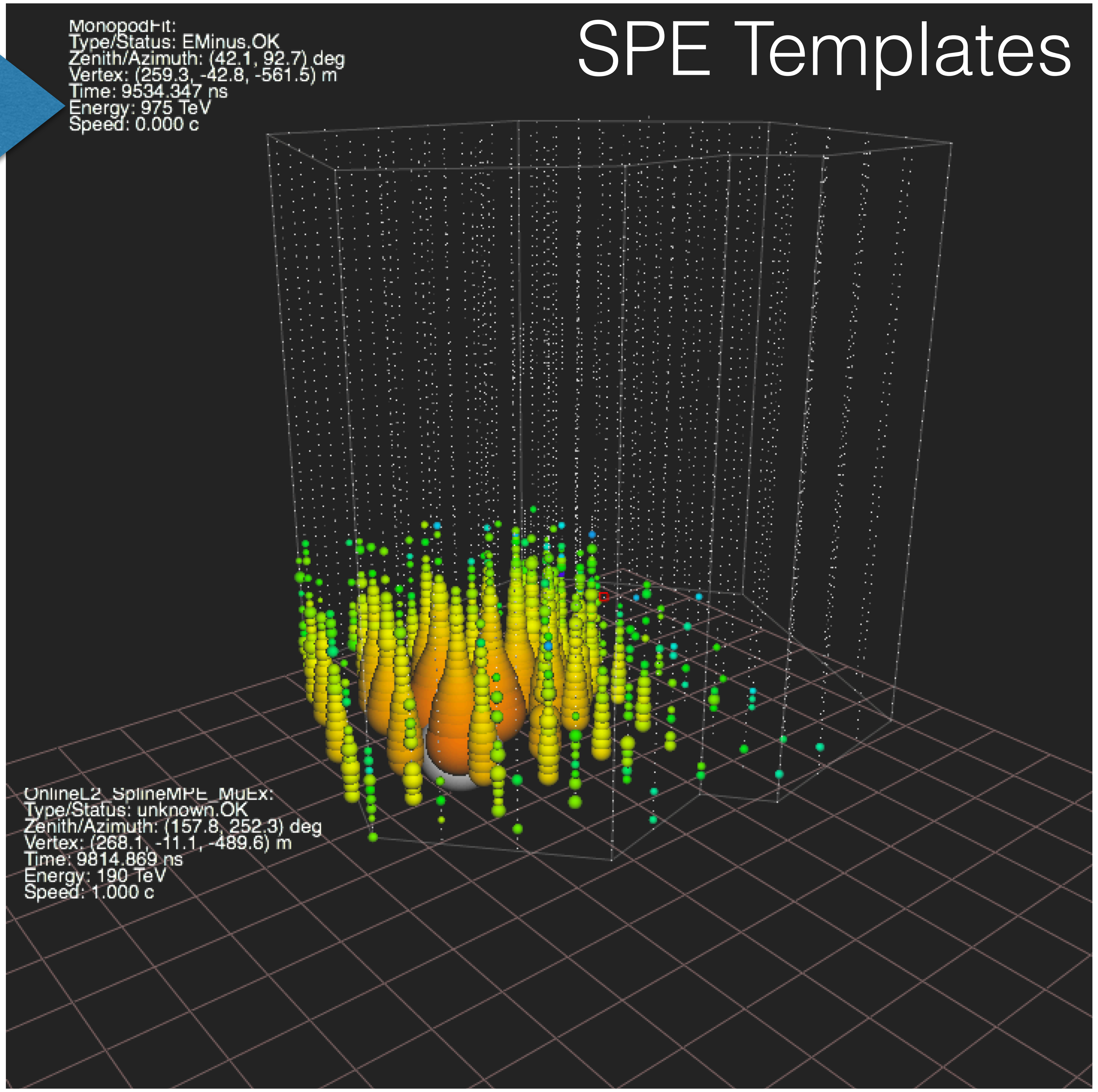




Energy estimators with the new SPE Templates

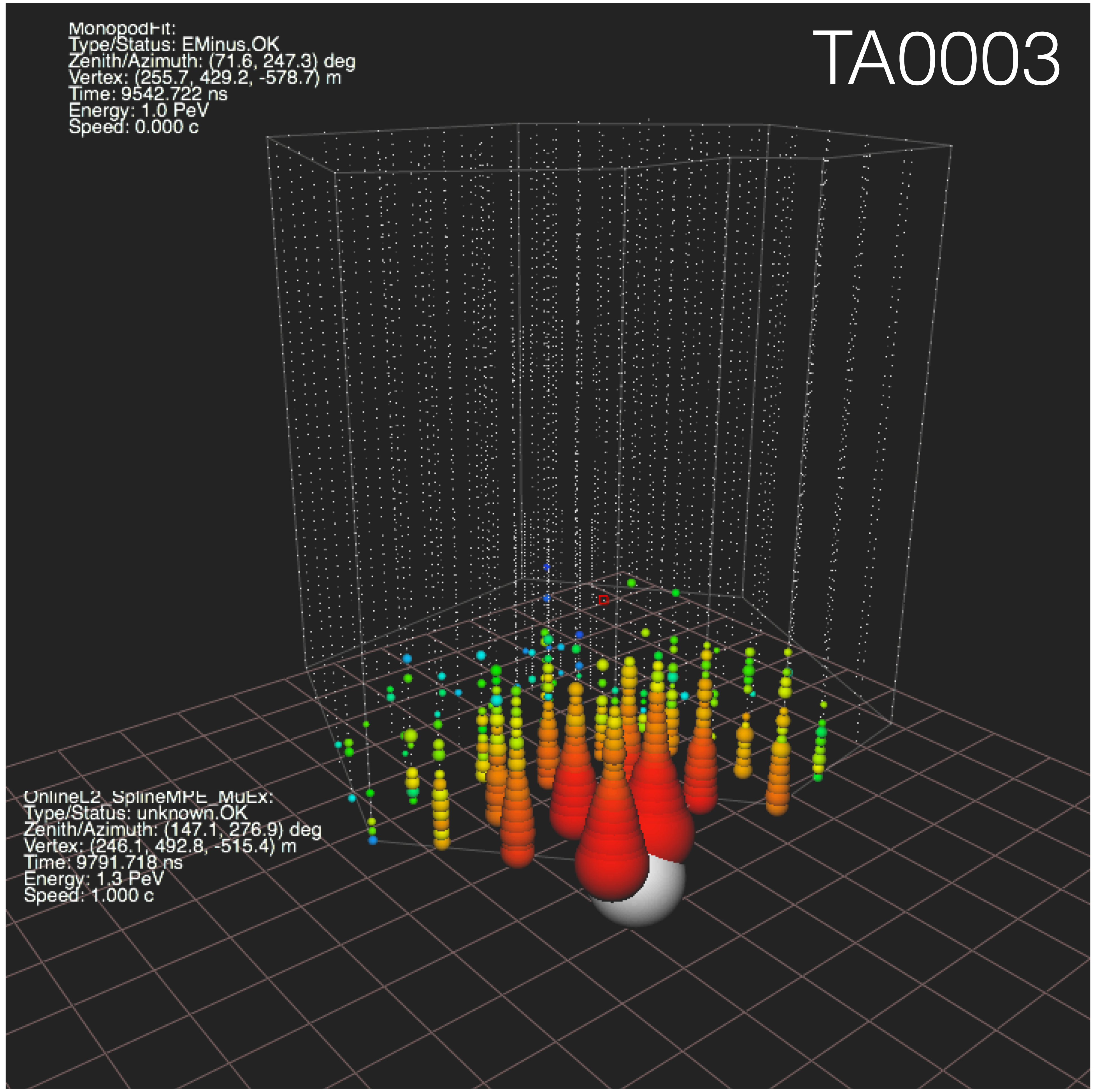
Reassuring news for some:

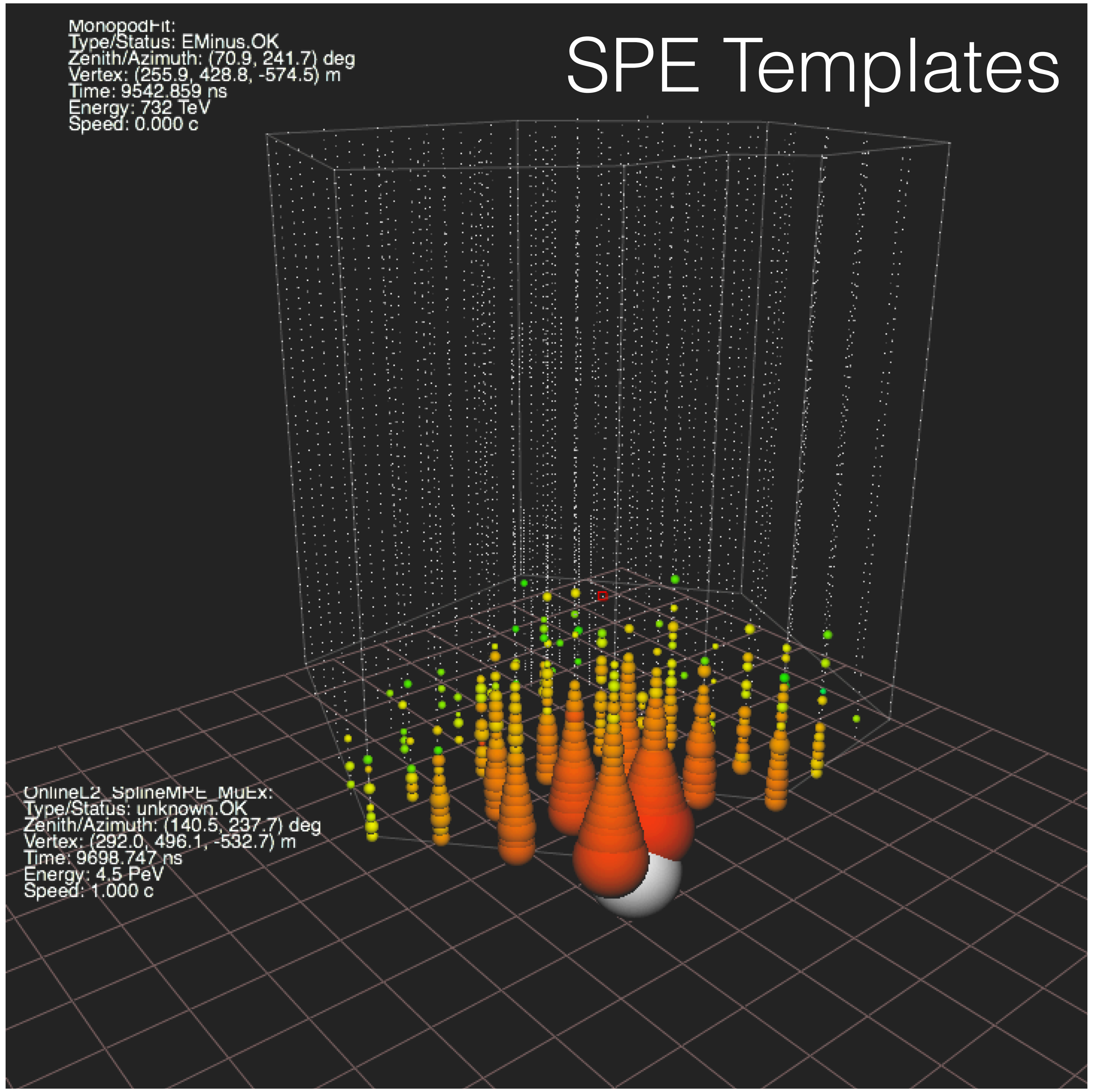




No significant change observed in the energy estimators (sub 30%)

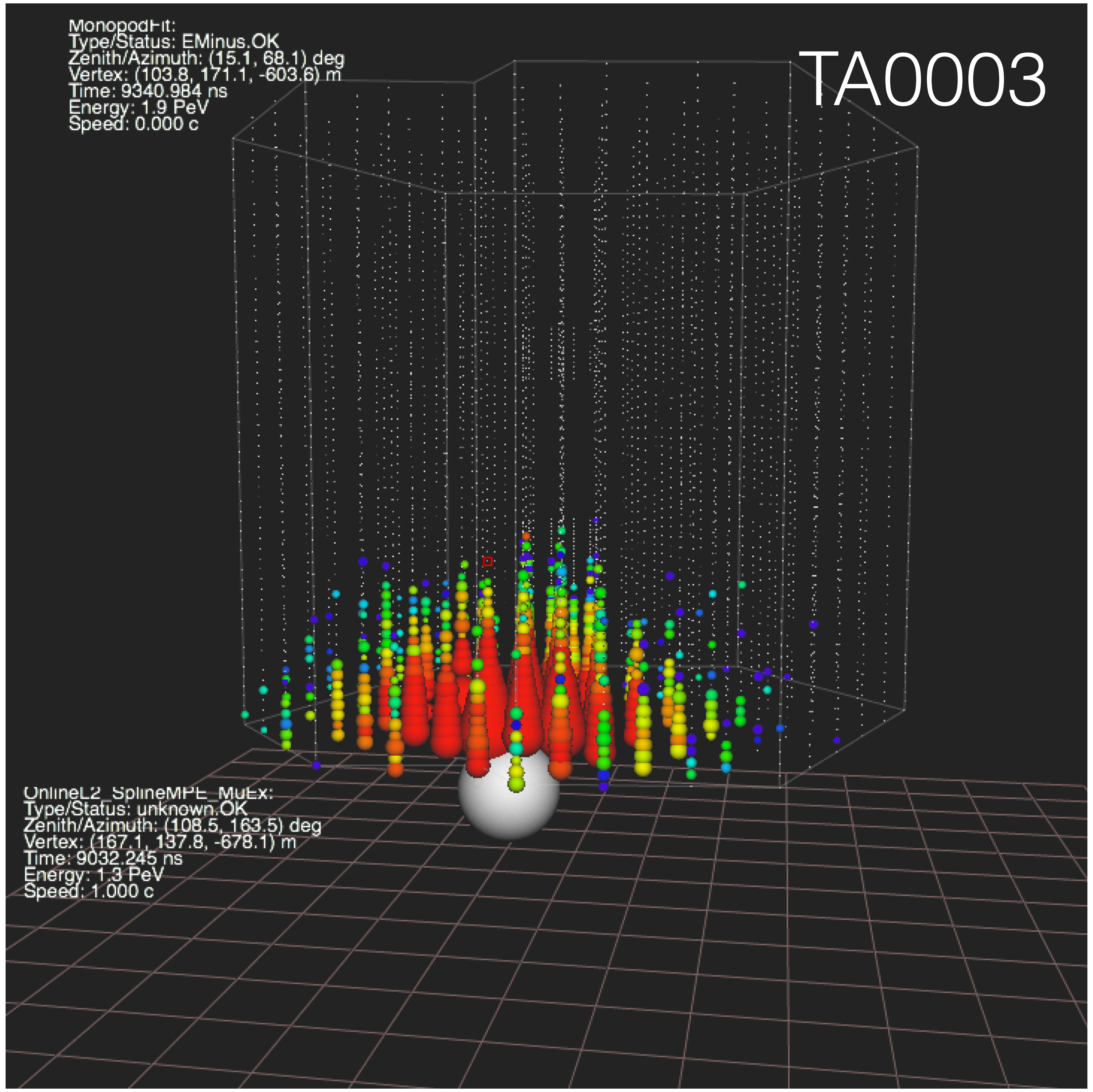
Energy estimators with the new SPE Templates

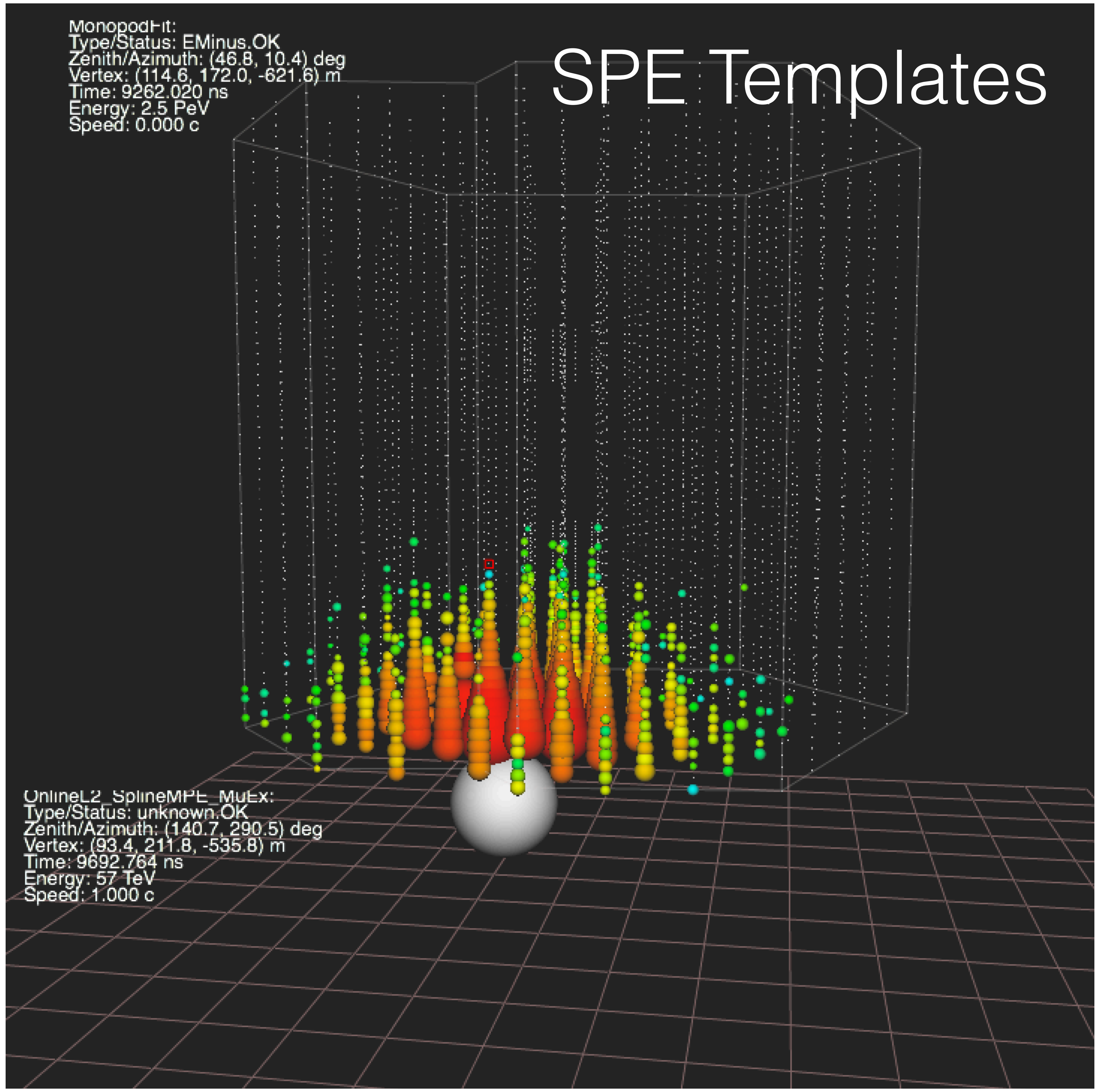




No significant change observed in the energy estimators (sub 30%)

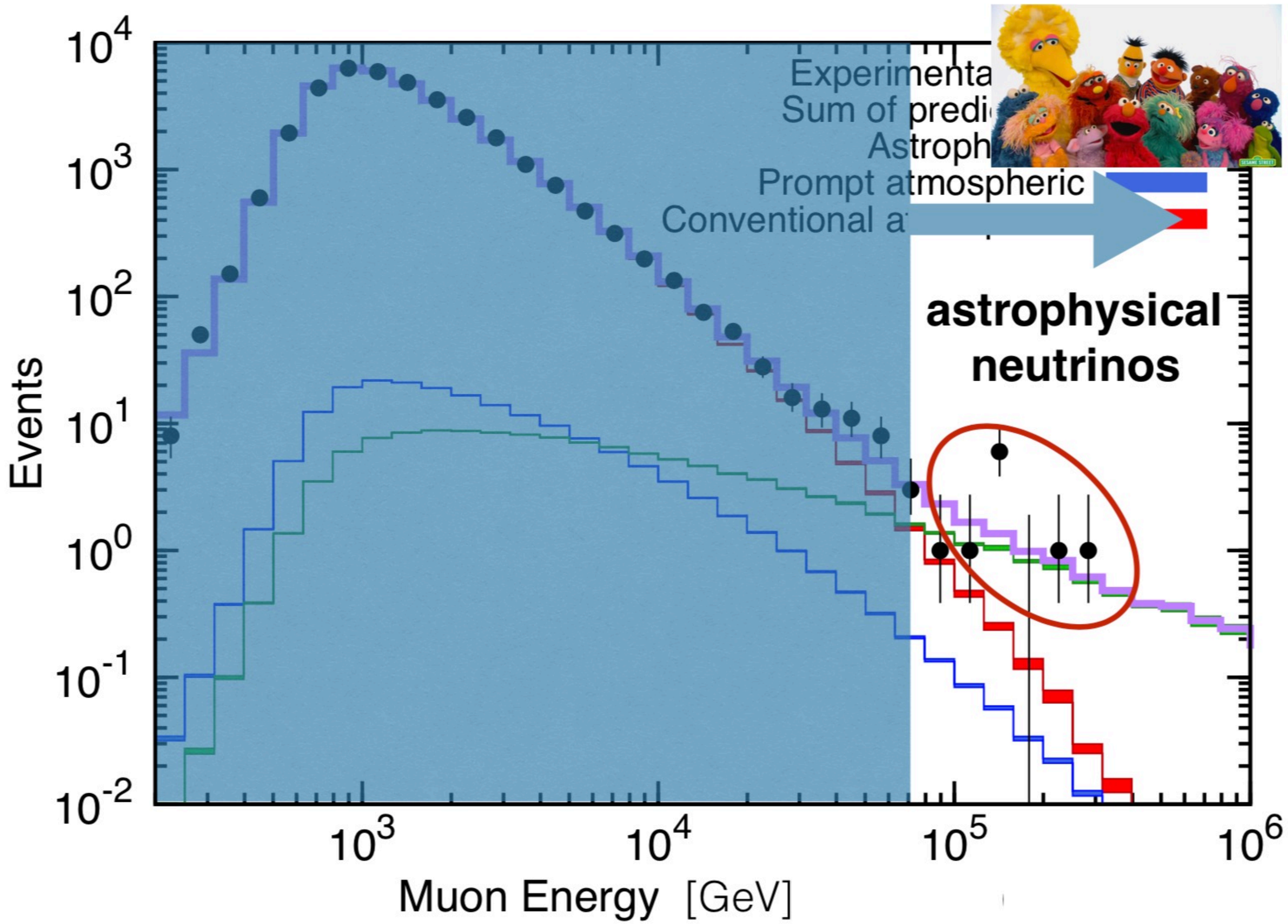
Energy estimators with the new SPE Templates



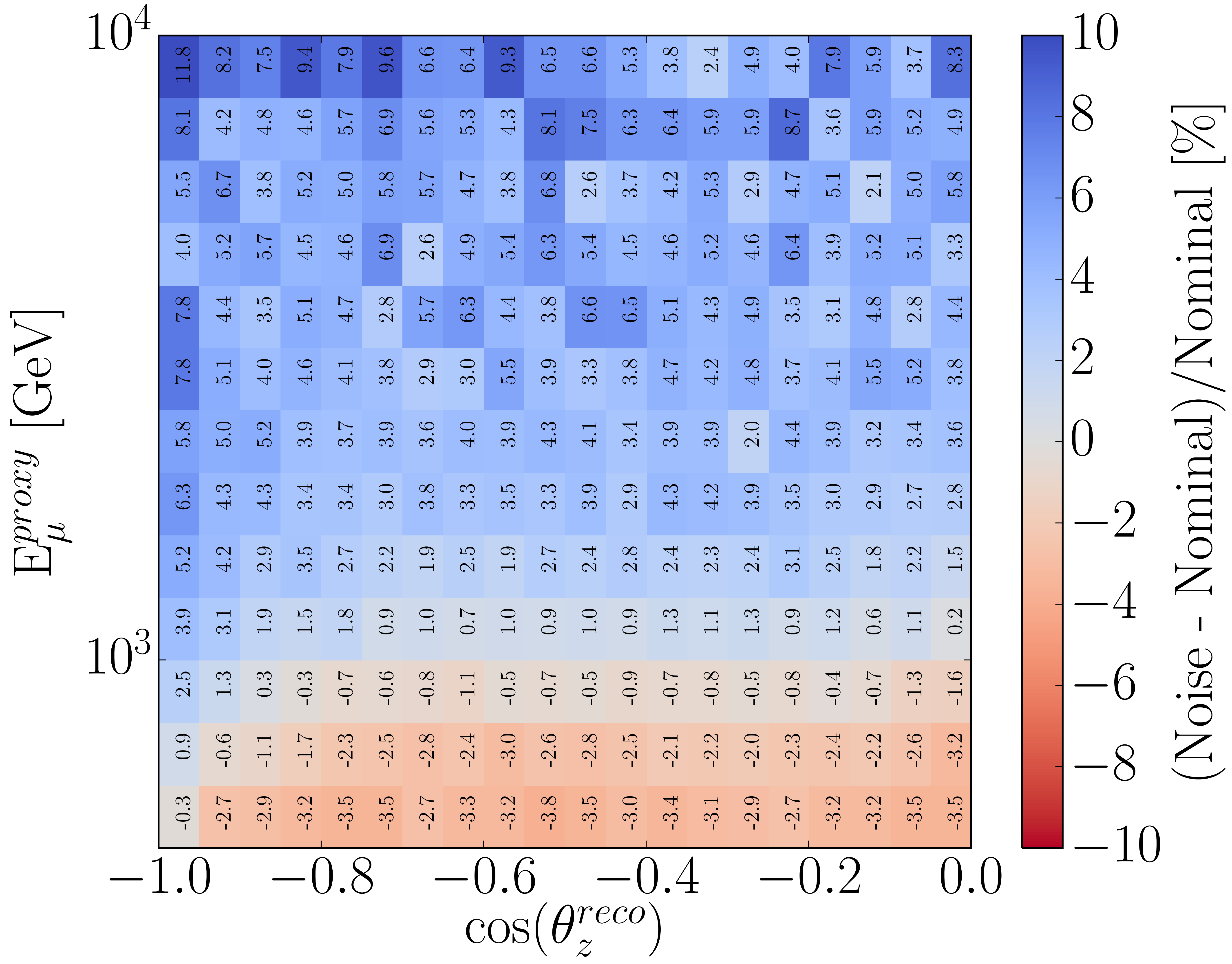


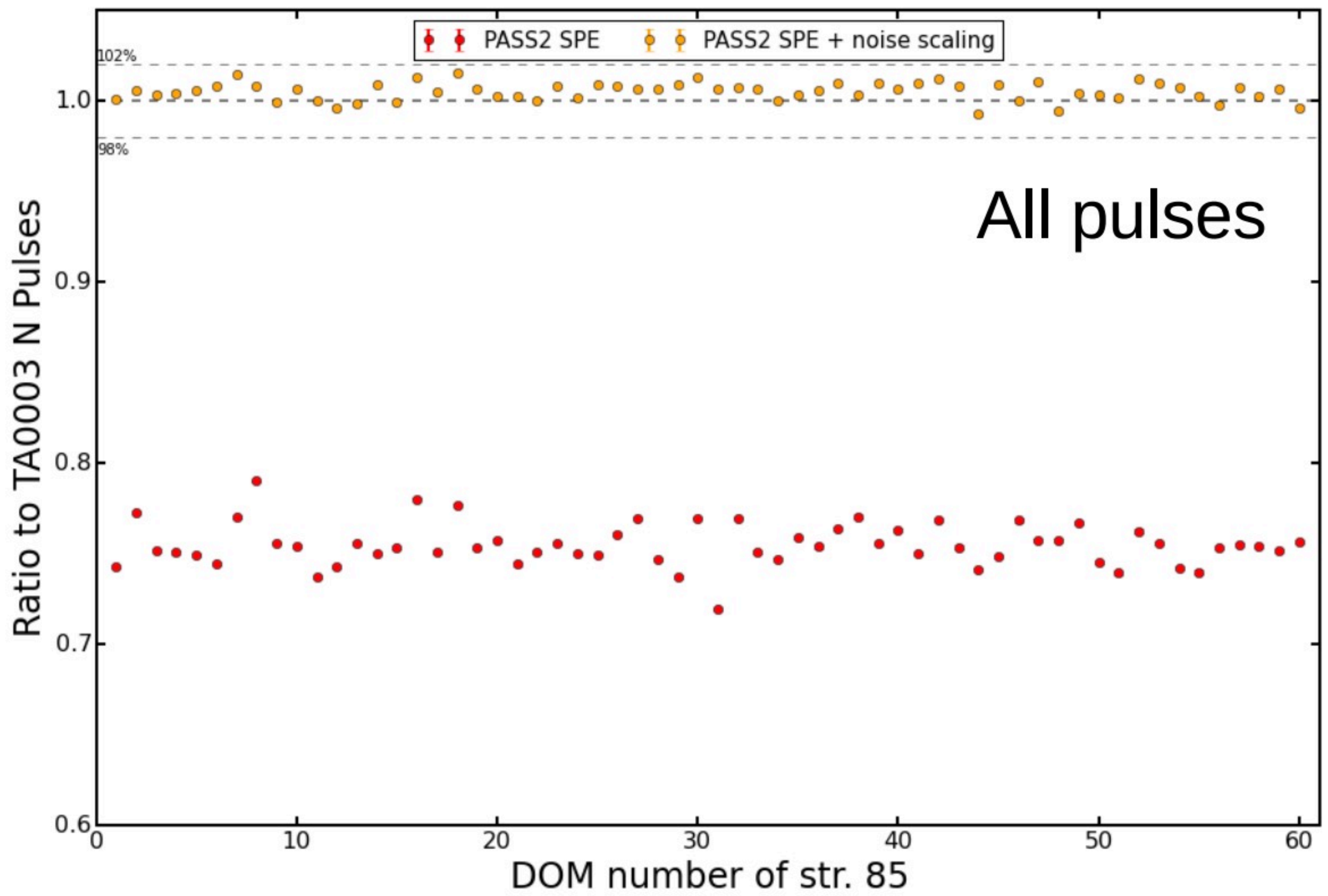
No significant change observed in the energy estimators (sub 30%)

Astrophysical Neutrinos



Noise update due to SPE Templates



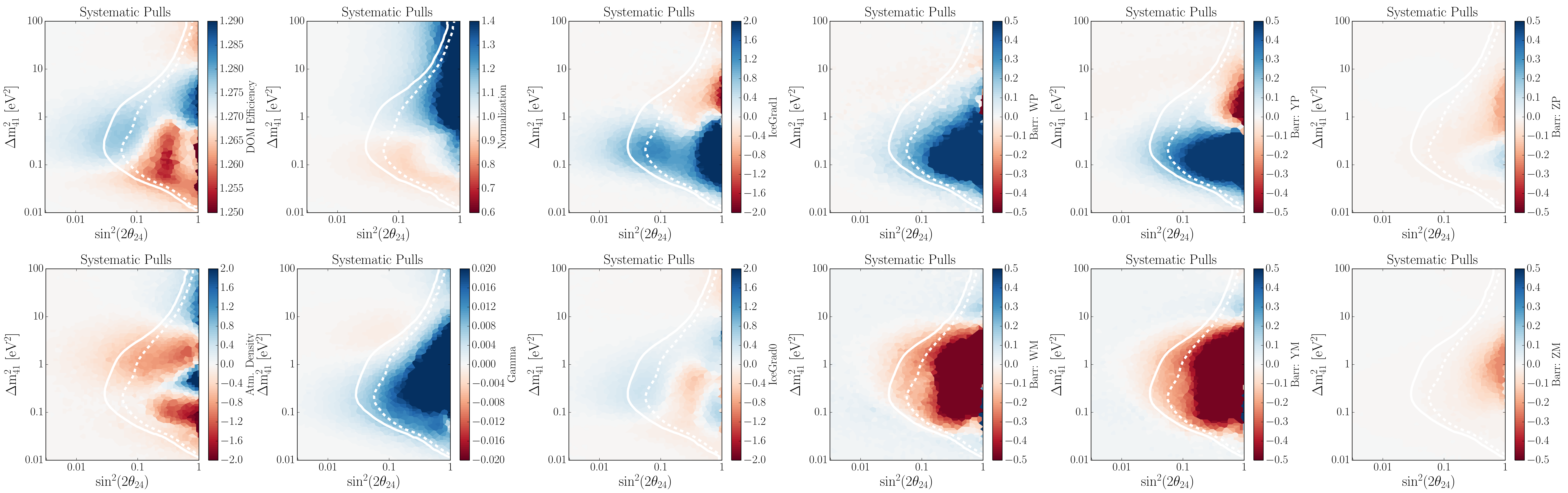


It was recently shown that the shapes of the SPE Templates modify the expected noise.

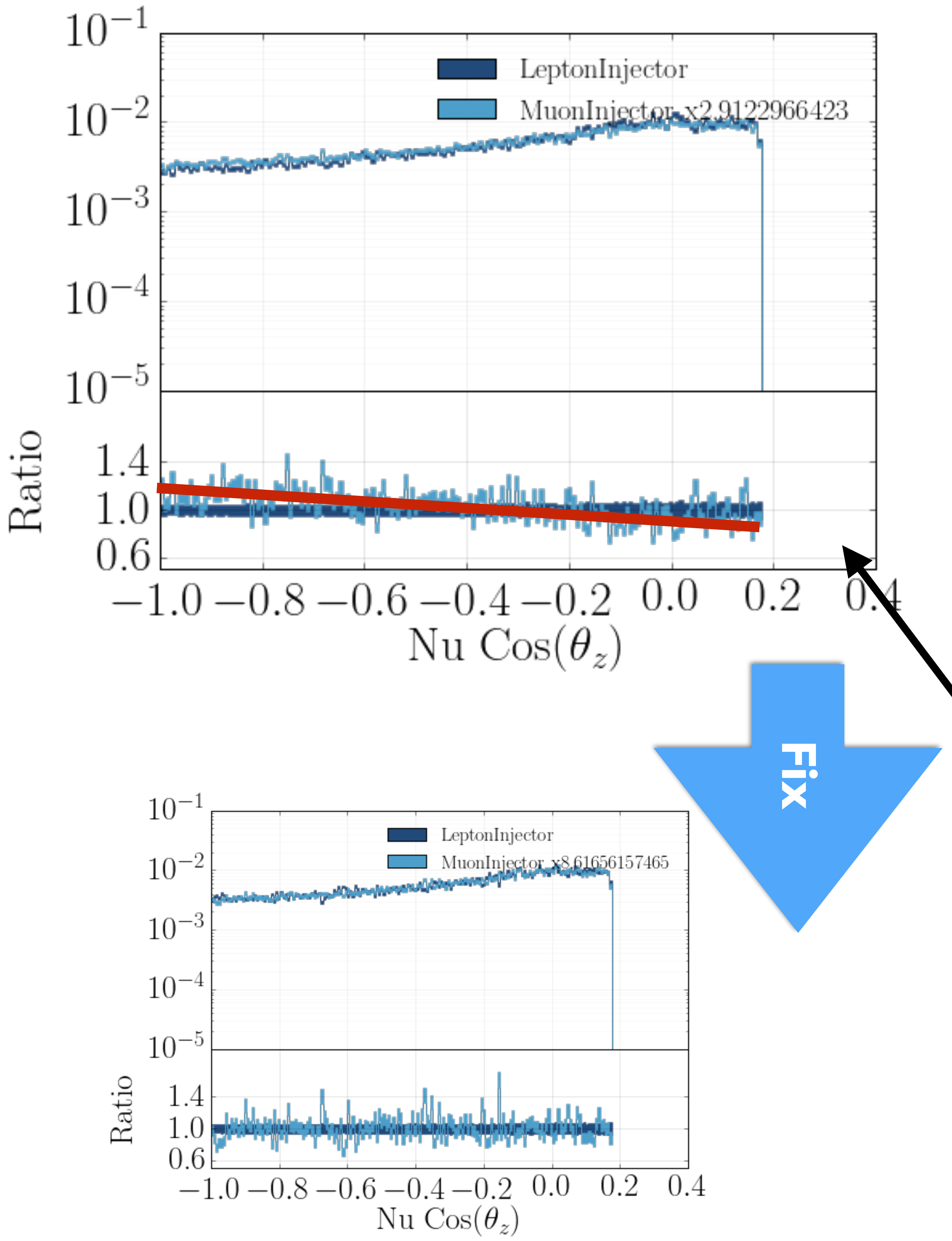
Andrii's presentation:
https://drive.google.com/file/d/1snvZRyFL2zYhAoxsgRuP6eK5IKrkPA0R/view

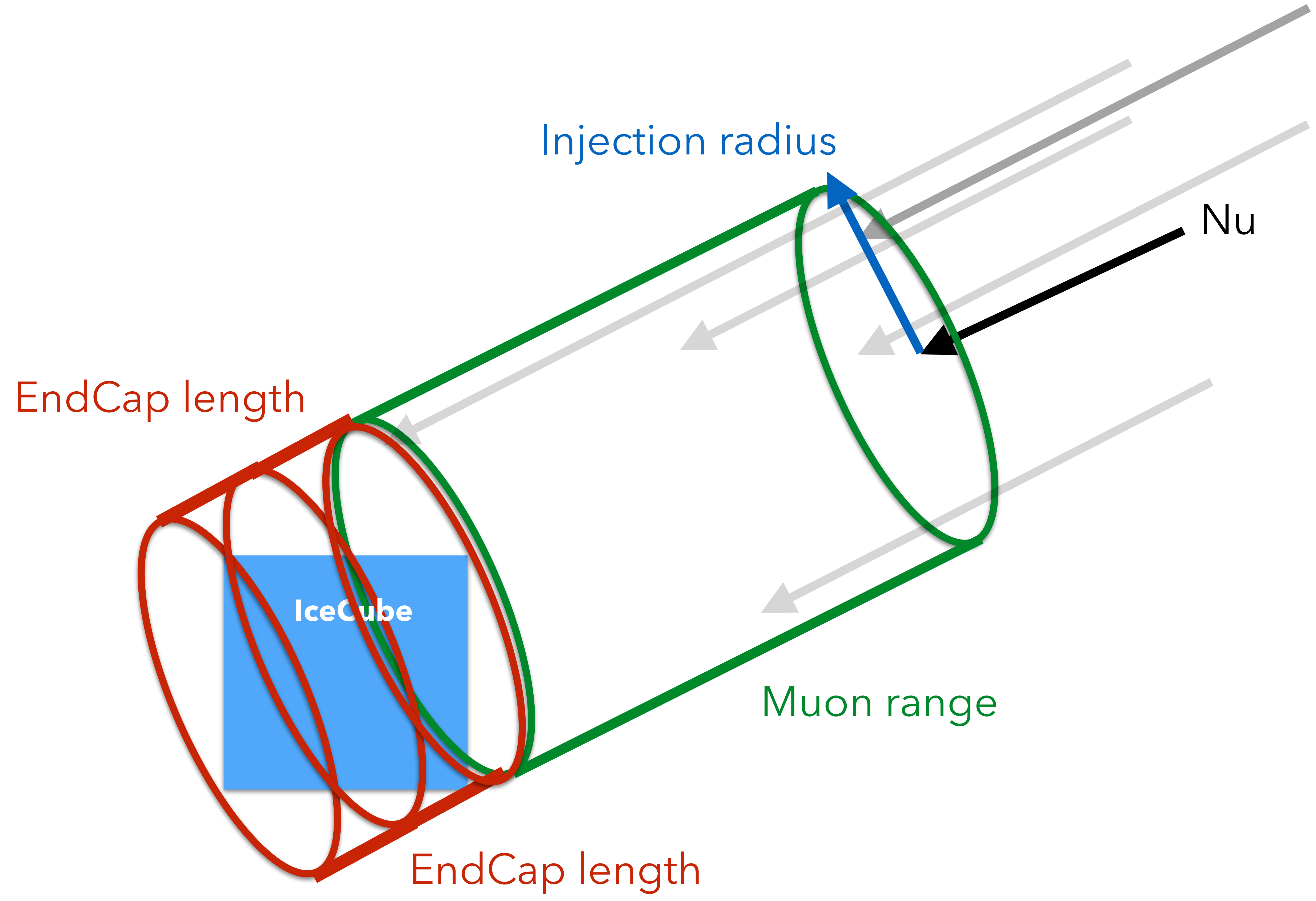
BIG THANKS TO ANDRII AND TOM

Asimov Systematic Pulls: [Δm², sin(2θ)²]



Expected change in Zenith dependance

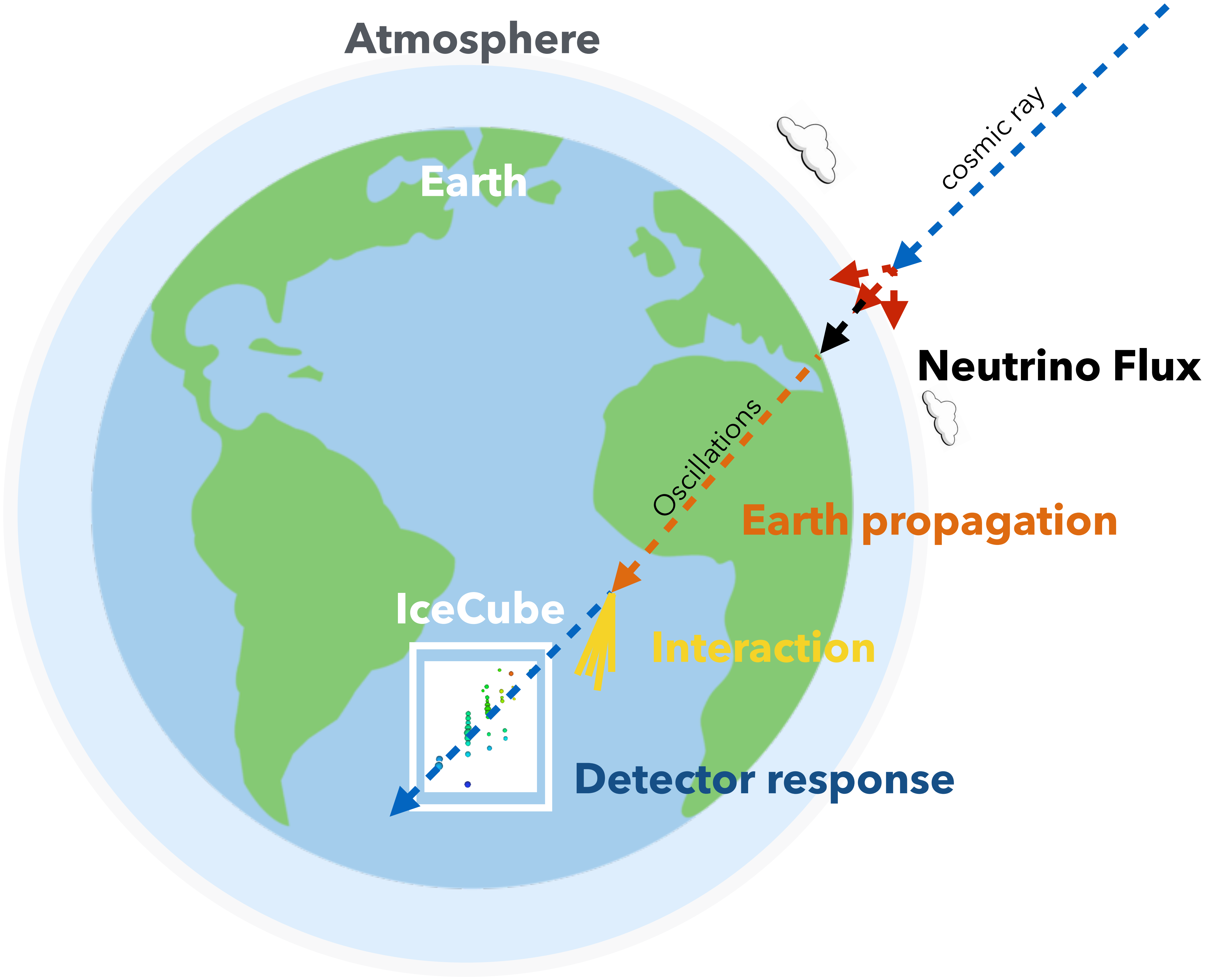




The EndCap was not included on the previous analysis.

Introduces a Zenith shift.

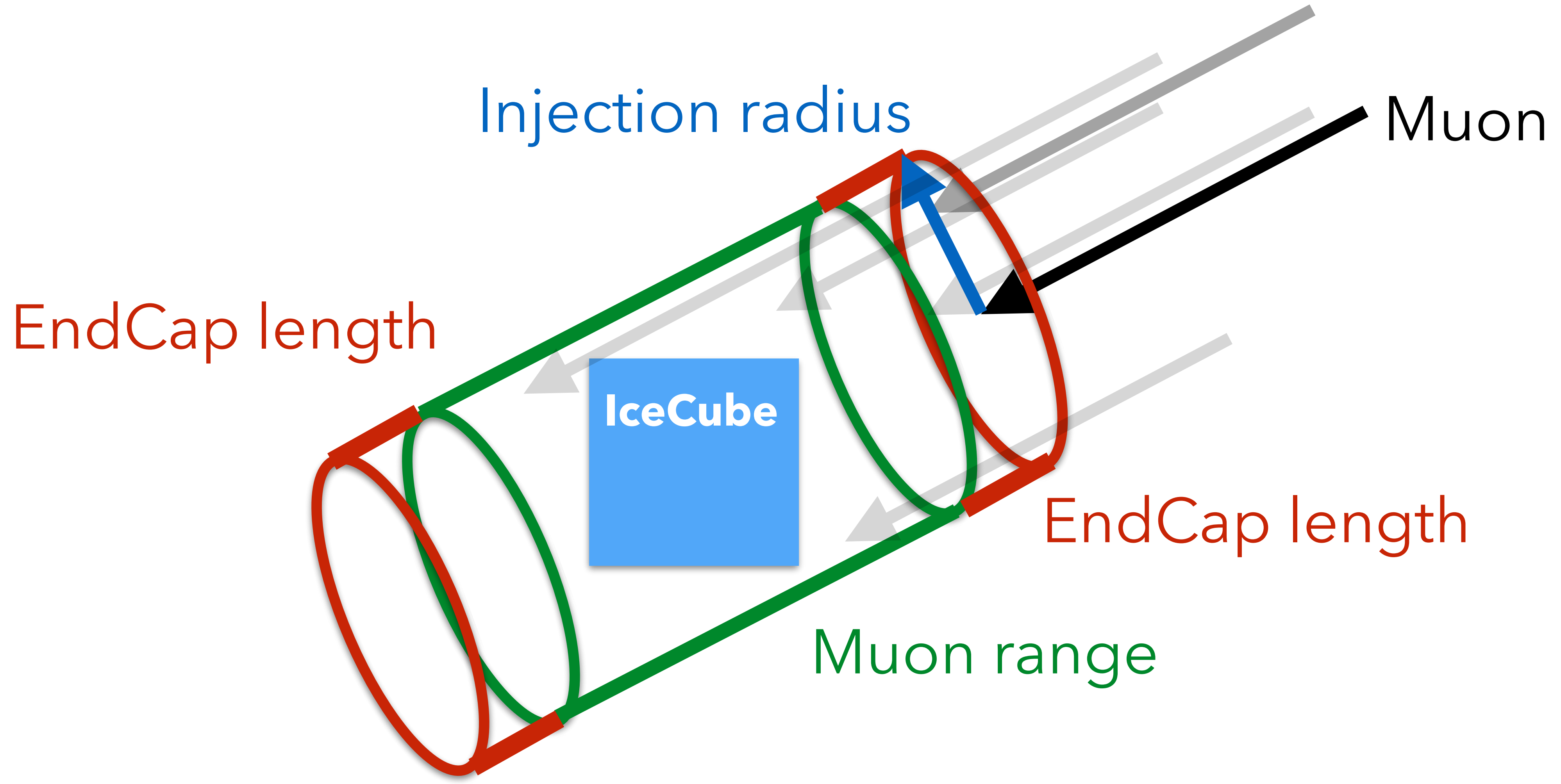
Generation level



Two principle ideas:

Goal: you want to get to the interaction point.

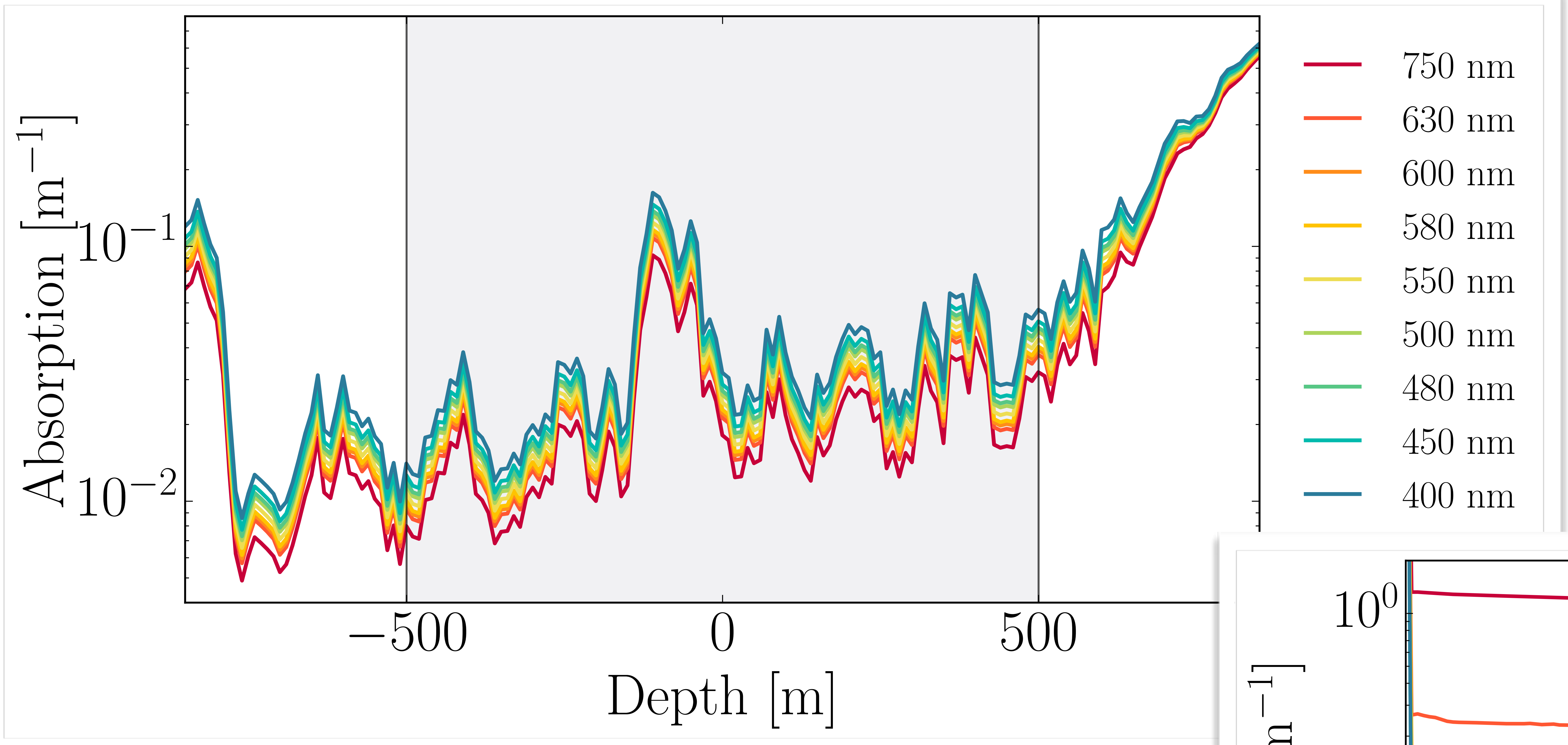
1. **The old IceCube way:**
   - Generate neutrinos at the atm. production point.
   - Propagate through the earth.
   - Force interactions around IceCube. (XS)
   - This is **NuGen Full Mode**.
2. **The new IceCube way:**
   - Generate Leptons+Hadrons around detector
   - Connect these to some flux and XS.
   - This is **Lepton Injector** and **NuGen Detector Mode**

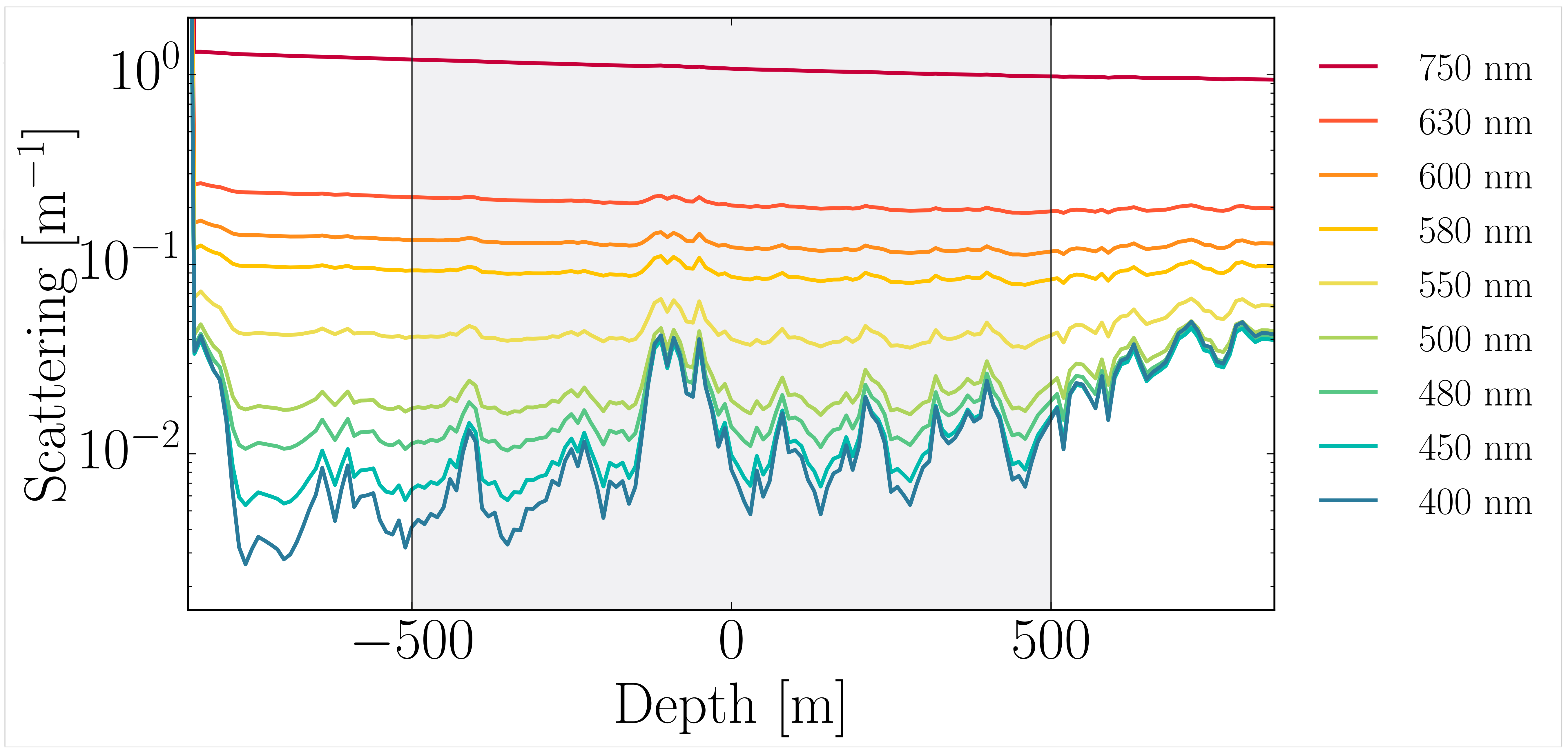


LeptonInjector improvements over NuGEN

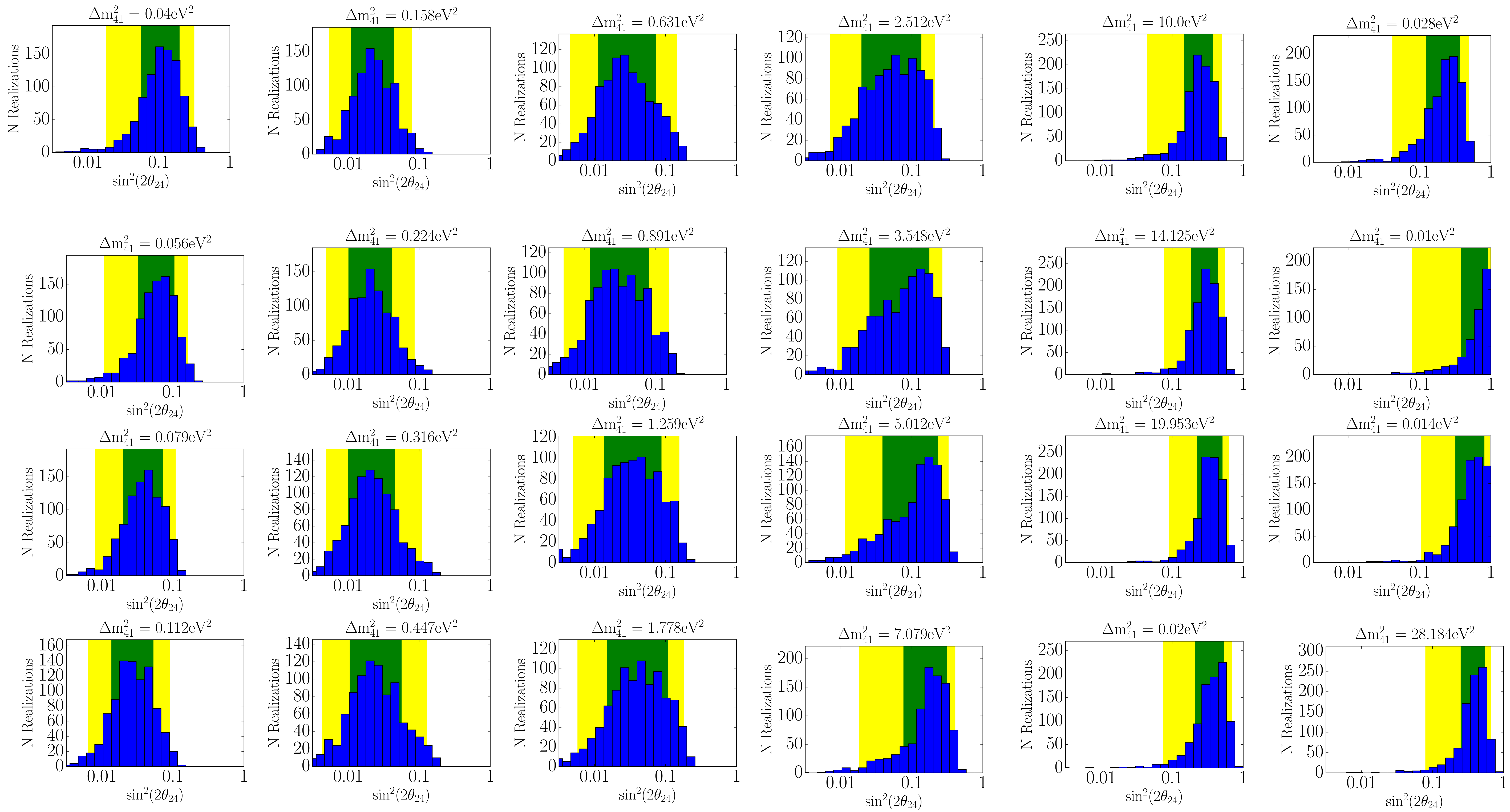
Difference	NuGen Former production	LeptonInjector / LeptonWeighter	NuGen Detector Mode
Muon Kinematics	Massless Muon (by default)	Proper kinematics	Proper kinematics
Hadron Kinematics	Hadron collinear with neutrino.	Proper kinematics	Kinematics will be updated
Low energy muons	Sets the kinetic energy to the total energy	Properly deals with LE muons	Will be fixed
High energy muons	Strange disagreement with seed 1234.		
Atmospheric air	No air interactions	Allows for in-air interactions. PeV scale affected.	No air propagation. World volume is earth. Inject at Earth surface.
Matter effects	Fixed cross-sections. Required to re-run MC.	Density profile decoupled from event generation. Allows re-weighting.	Density profile decoupled from event generation. Allows re-weighting.
Neutrino Oscillations	Need to re-run MC for oscillations	Oscillations are decoupled from event generation. Allows re-weighting.	Oscillations are decoupled from event generation. Allows re-weighting.
Cross-sections	Cross-section tables, 111 bins.	High fidelity splines	does same LI splines.

Bulk ice characteristics

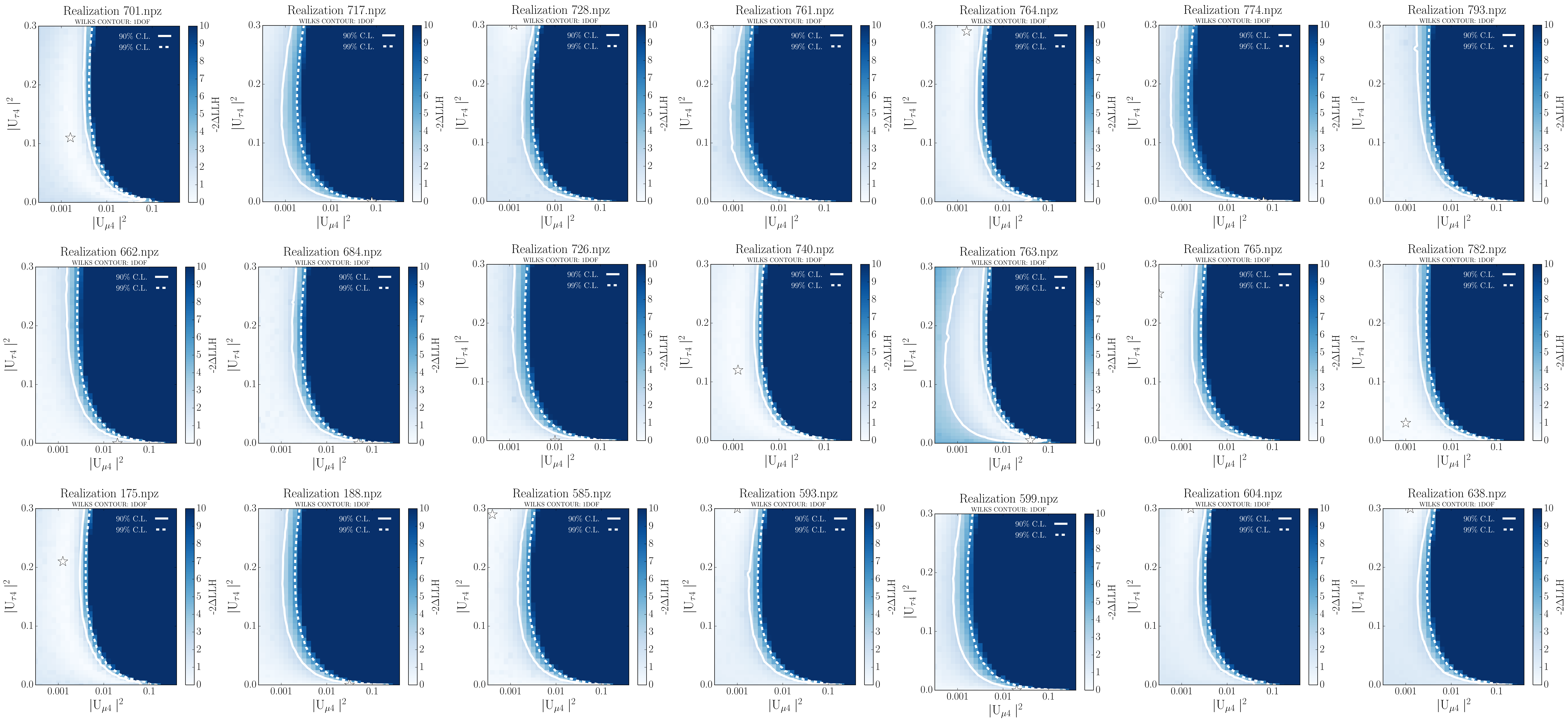




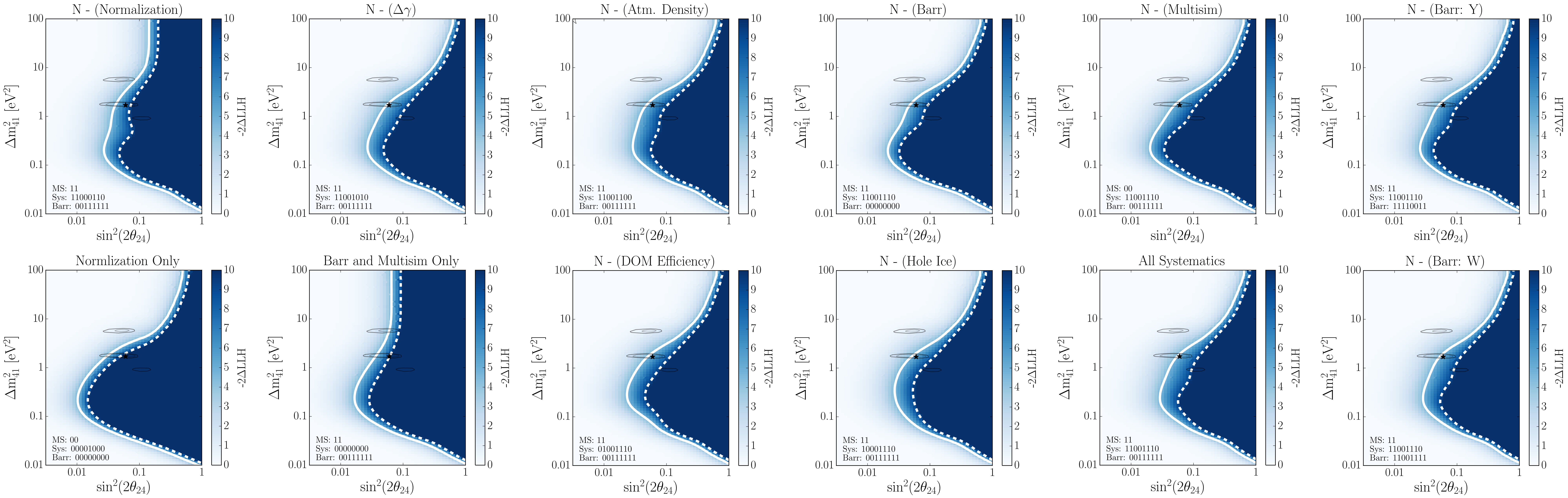
Brazil plots slices



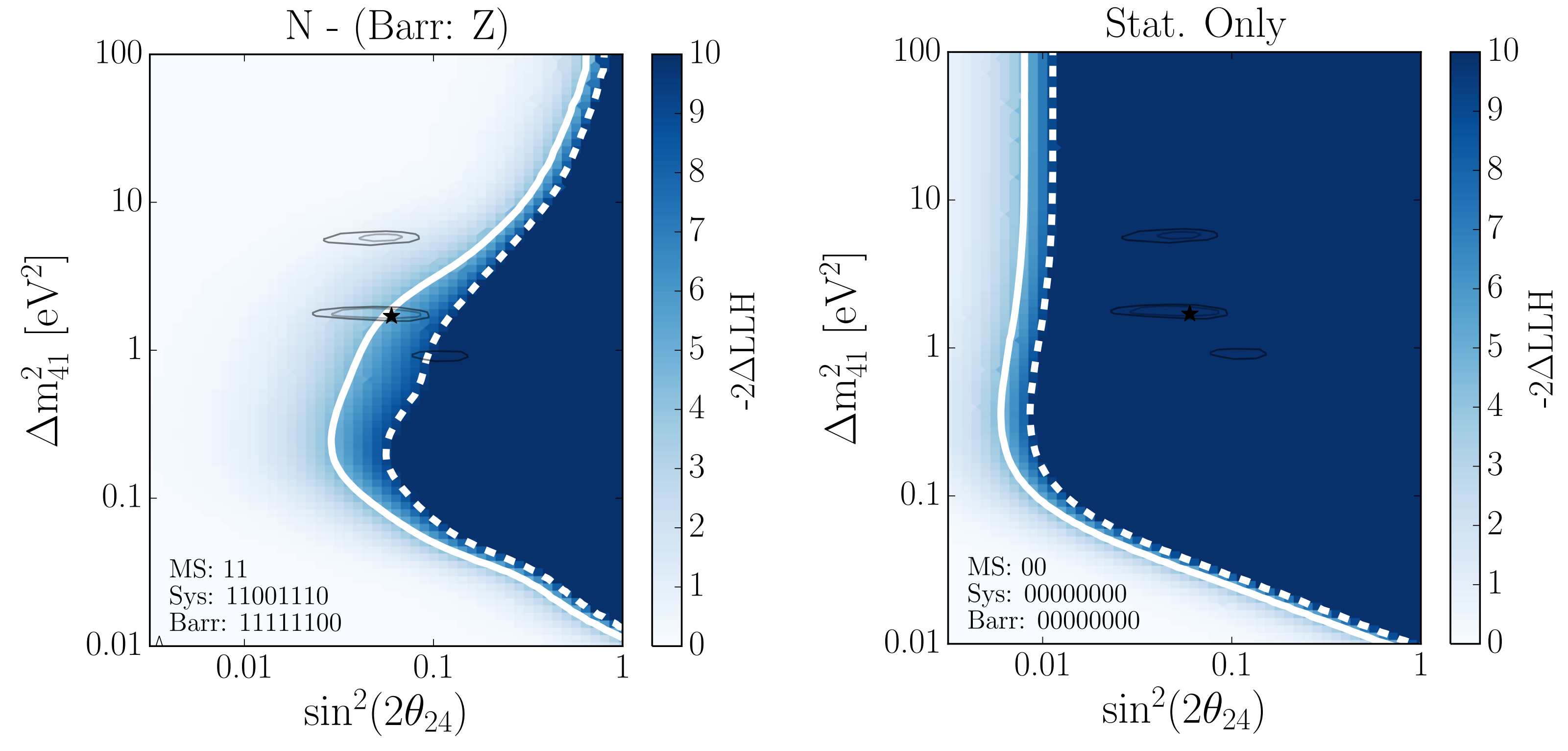
21 example Toy MC (Realizations)



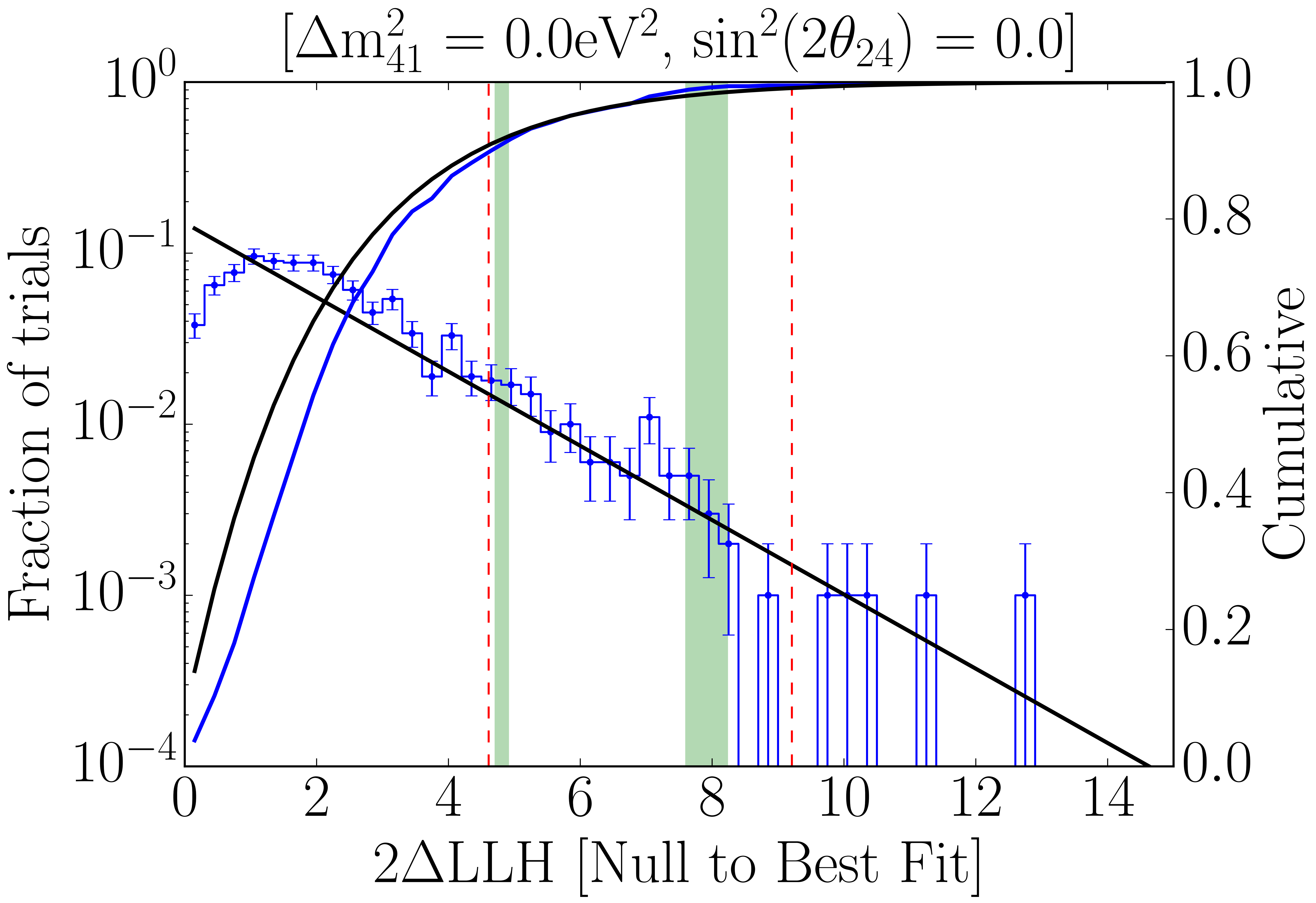
Asimov (N - 1) Systematic: [Δm², sin(2θ)²]



This test removes one systematic at a time and then calculates the 90%CL sensitivity.



Checking coverage at null hypothesis



Flux Systematics: Barr shapes: HP/HM

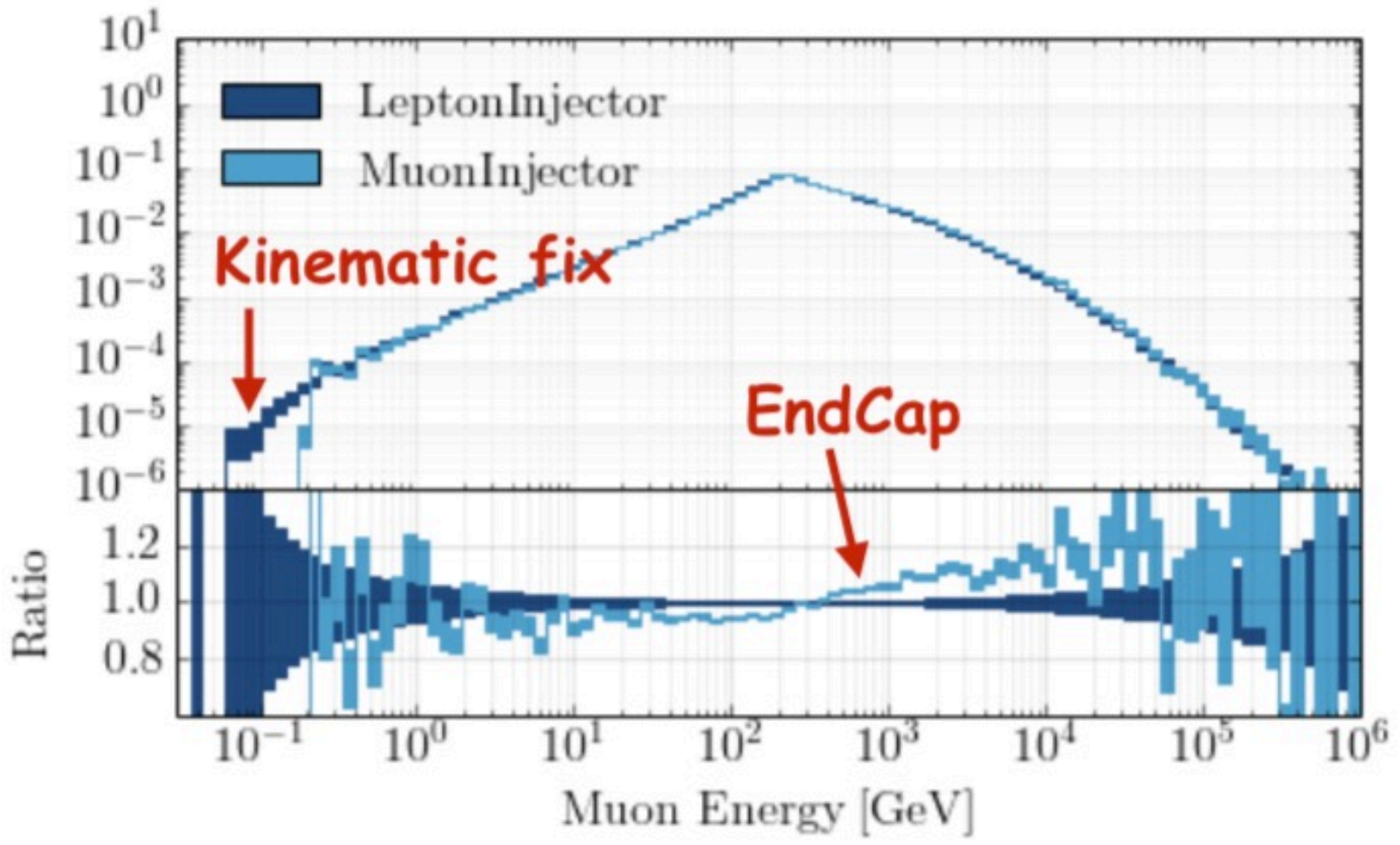
The HP and HM:
Contribution from positive (P) and negative (M) charged pions.

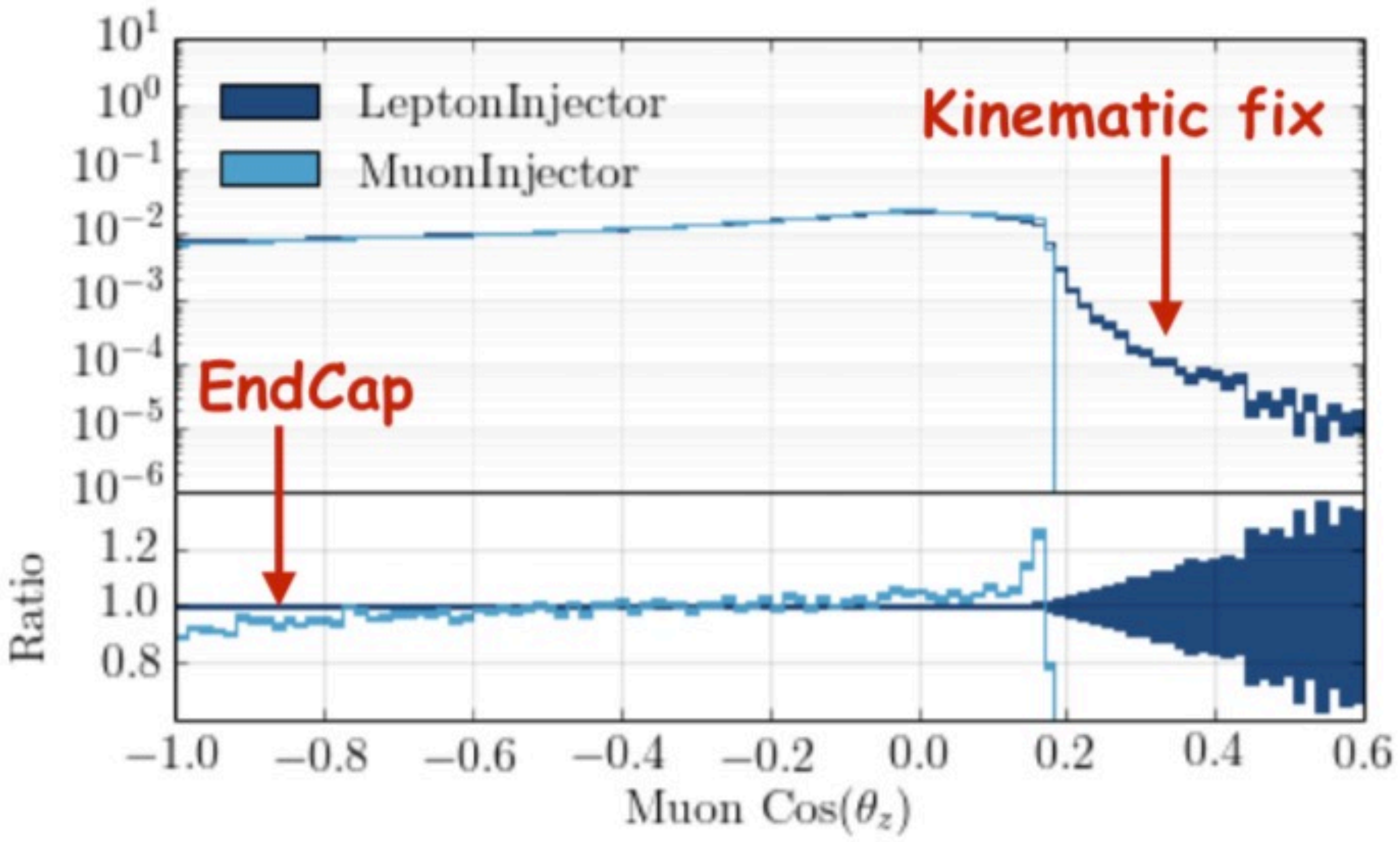
Parameter	x_{LAB}	Energy / GeV	Uncertainty	π±/K±
H±	0.1 – 1.0	30 – 1e11	15%	π±
W±	0.0 – 0.1	30 – 1e11	40%	K±
Y±	0.1 – 1.0	30 – 1e11	30%	K±
Z±	0.1 – 1.0	500 – 1e11	12.2% × $\log_{10}$(E/500 GeV)	K±

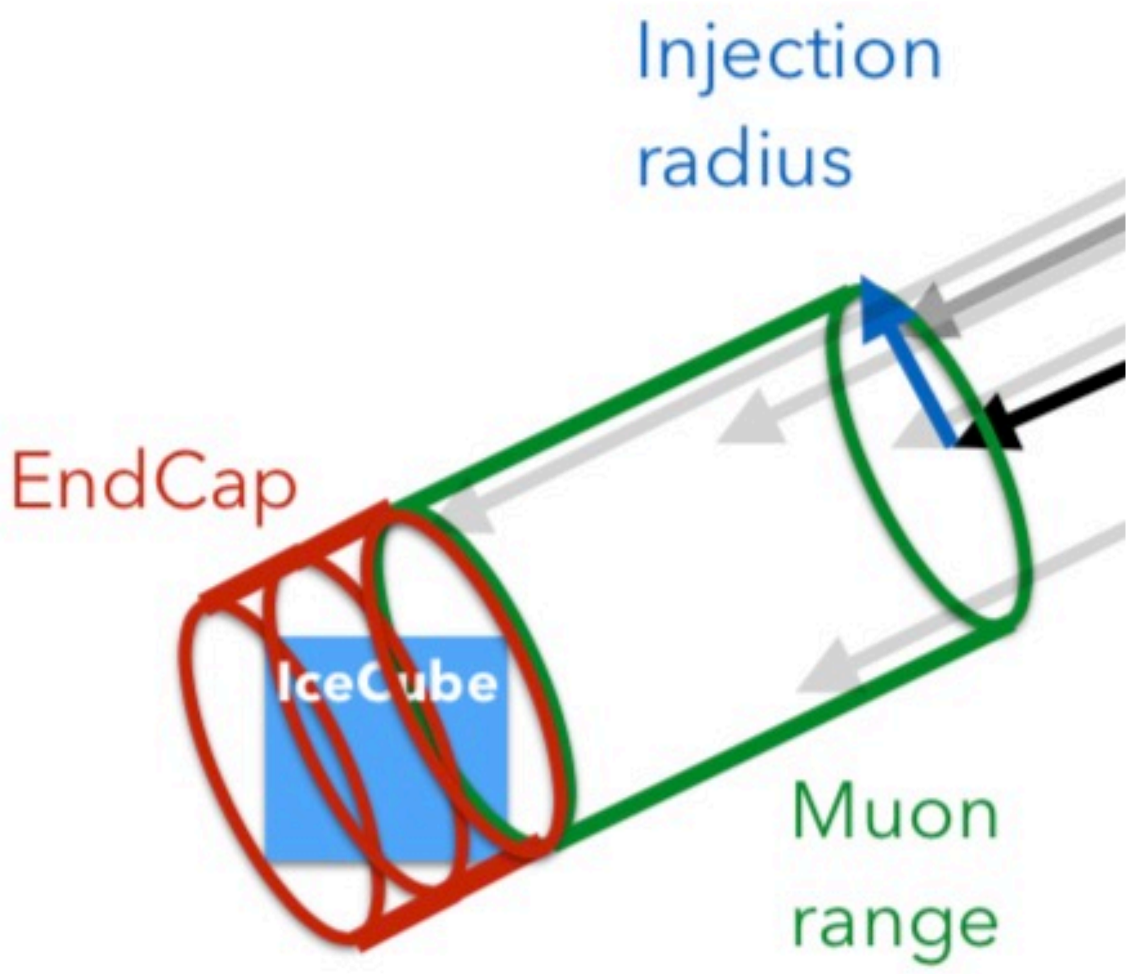
Pions are a subdominant contributor to the muon neutrino flux above ~80GeV.

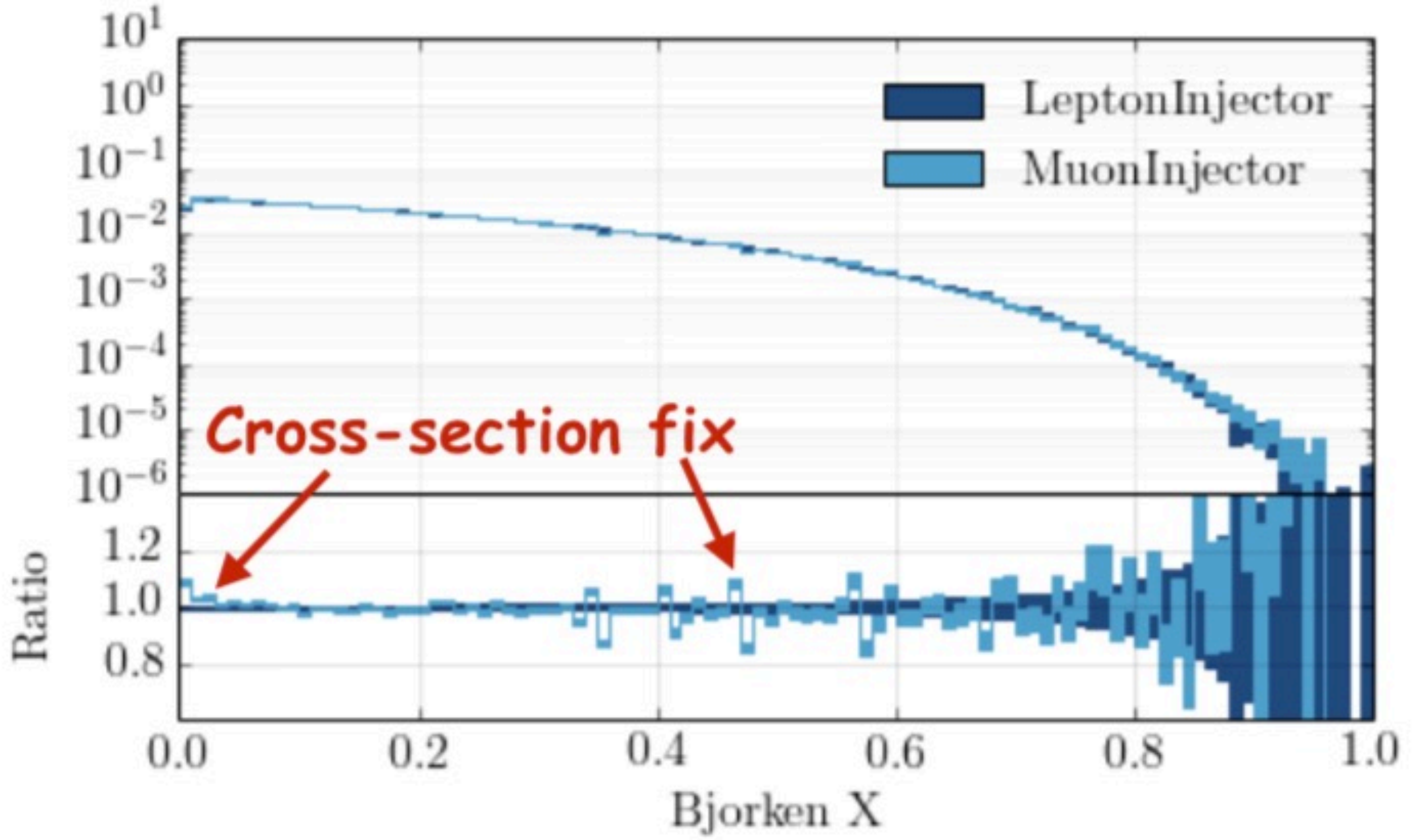
Shapes are small enough that we do not include HP/HM as a systematic.

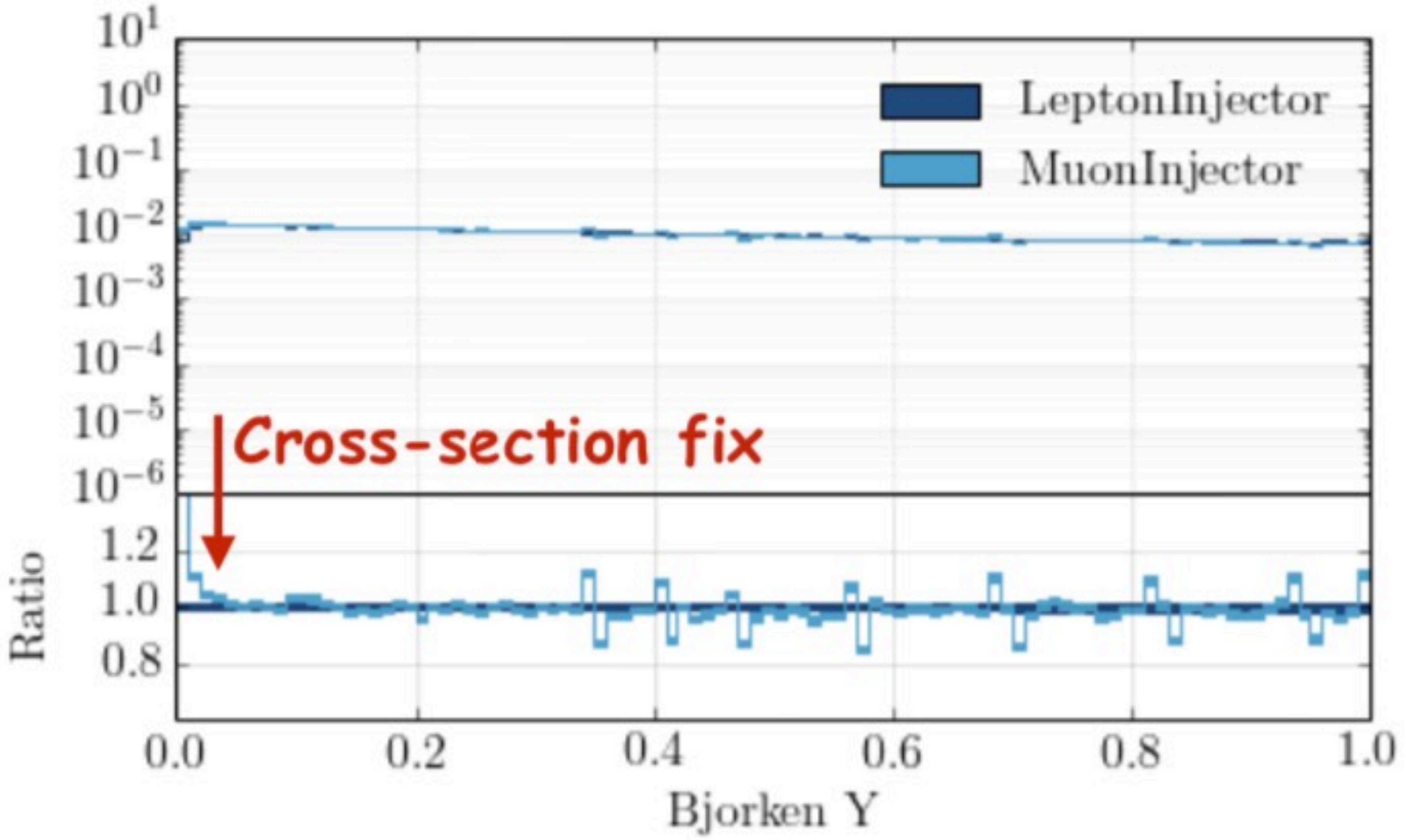
Flux Systematics: Barr shapes: HP/HM



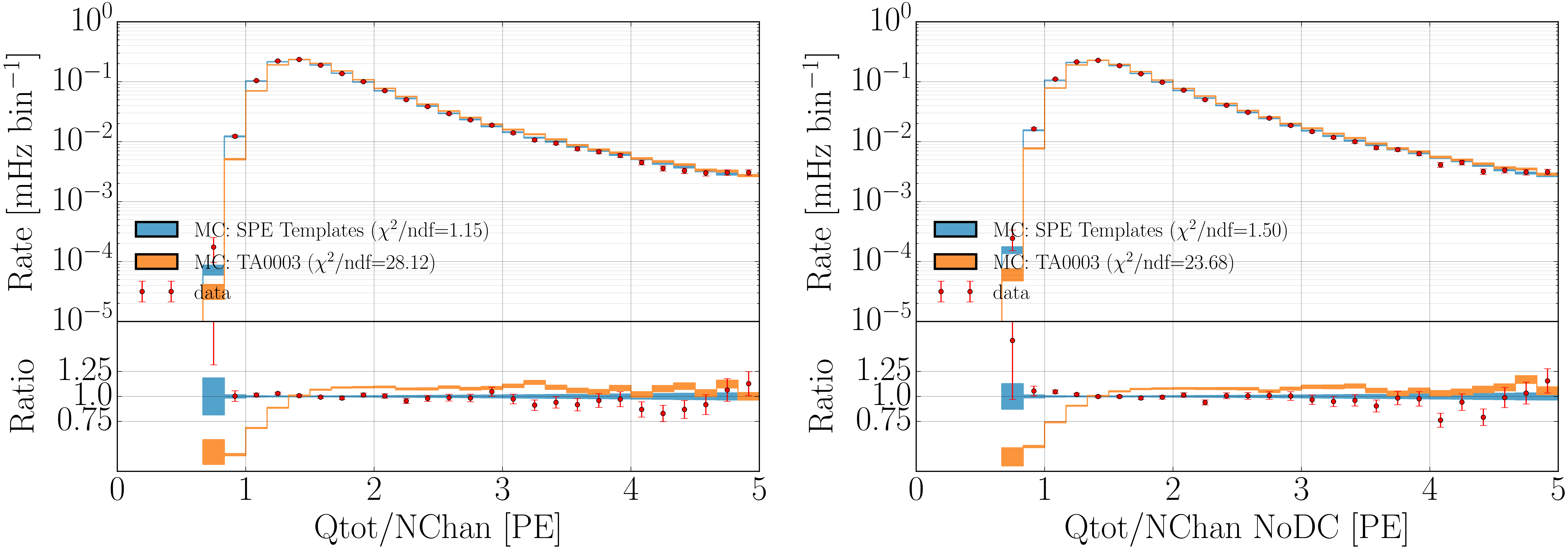






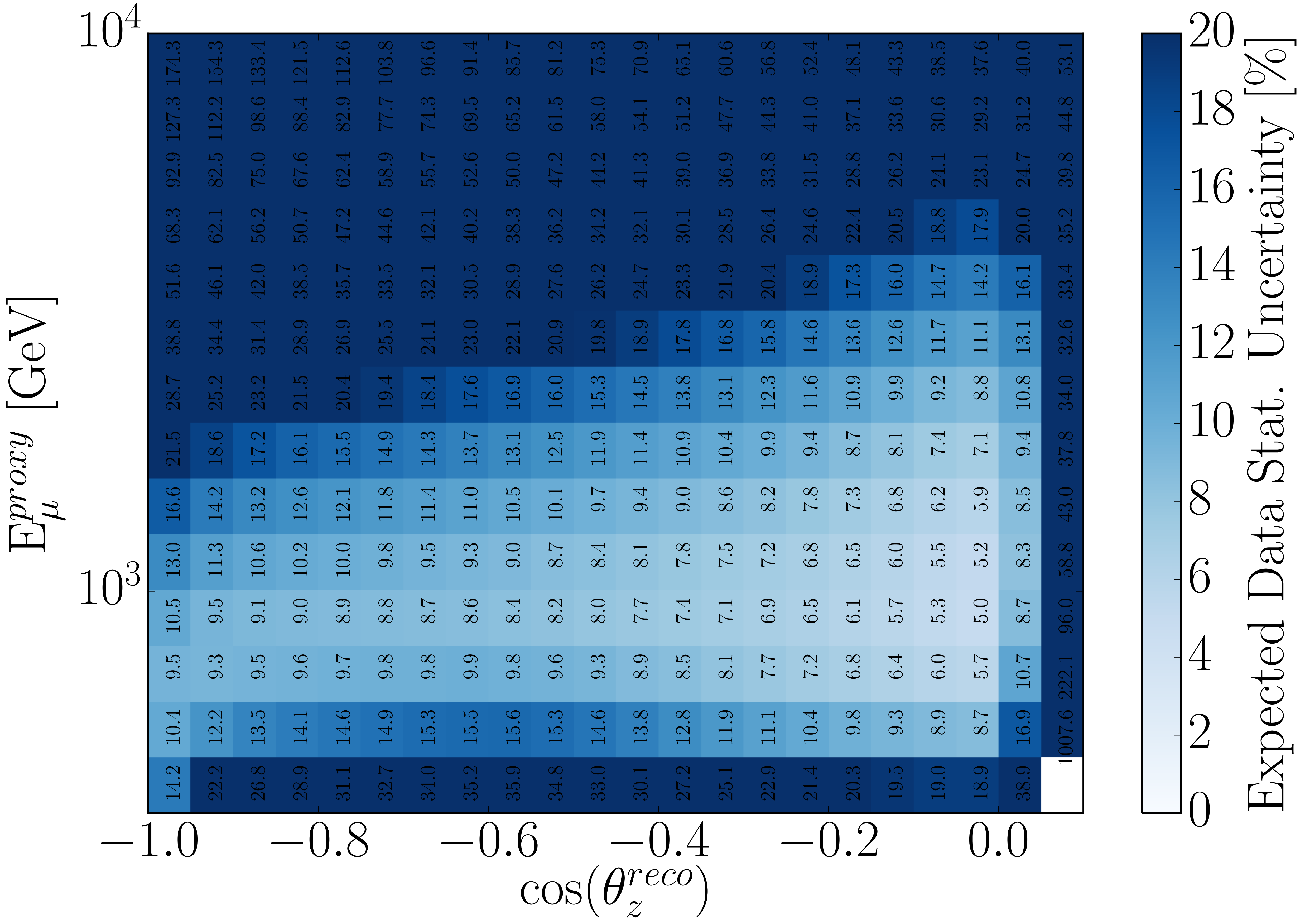


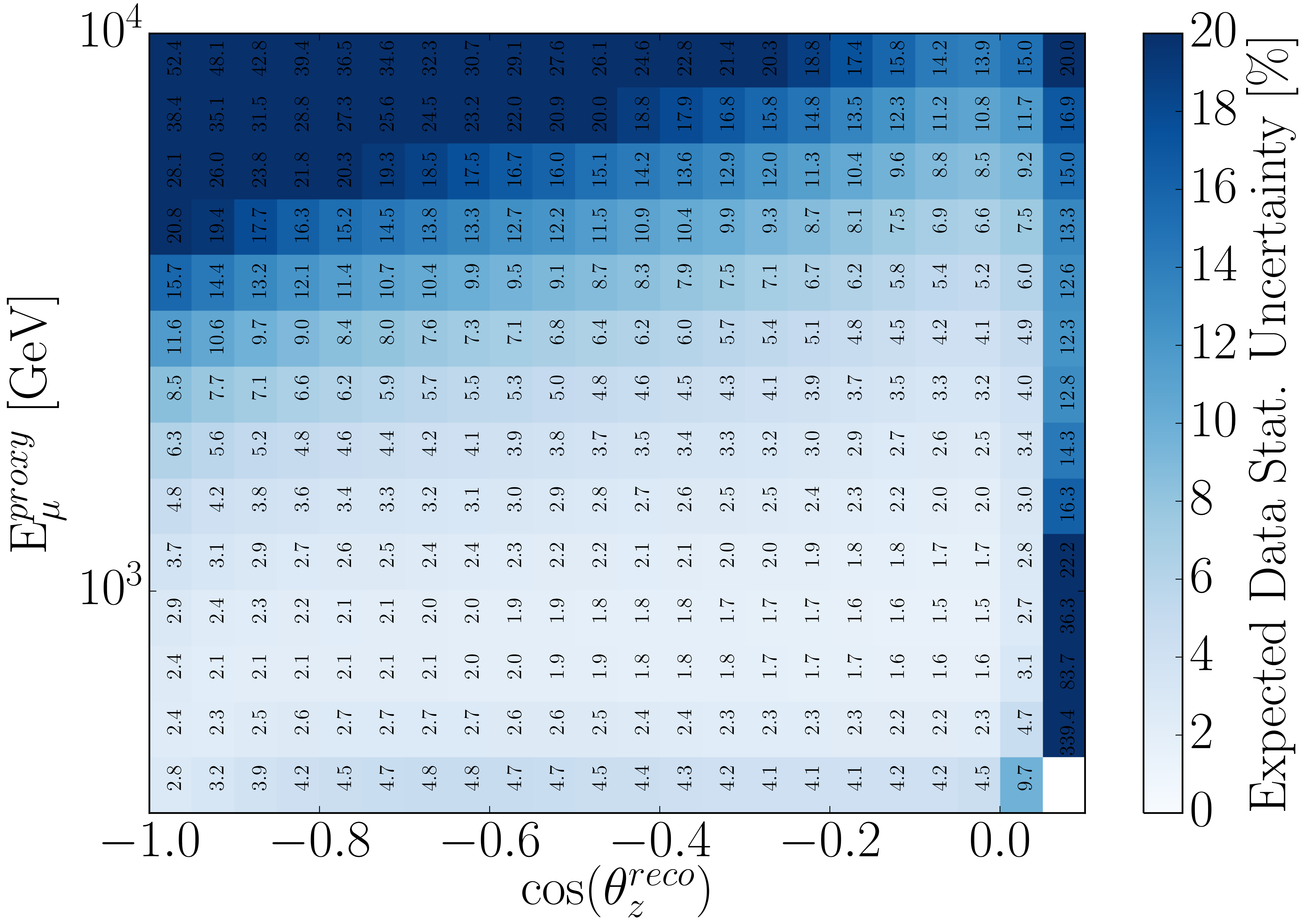
MC/Data comparison results… Awesome



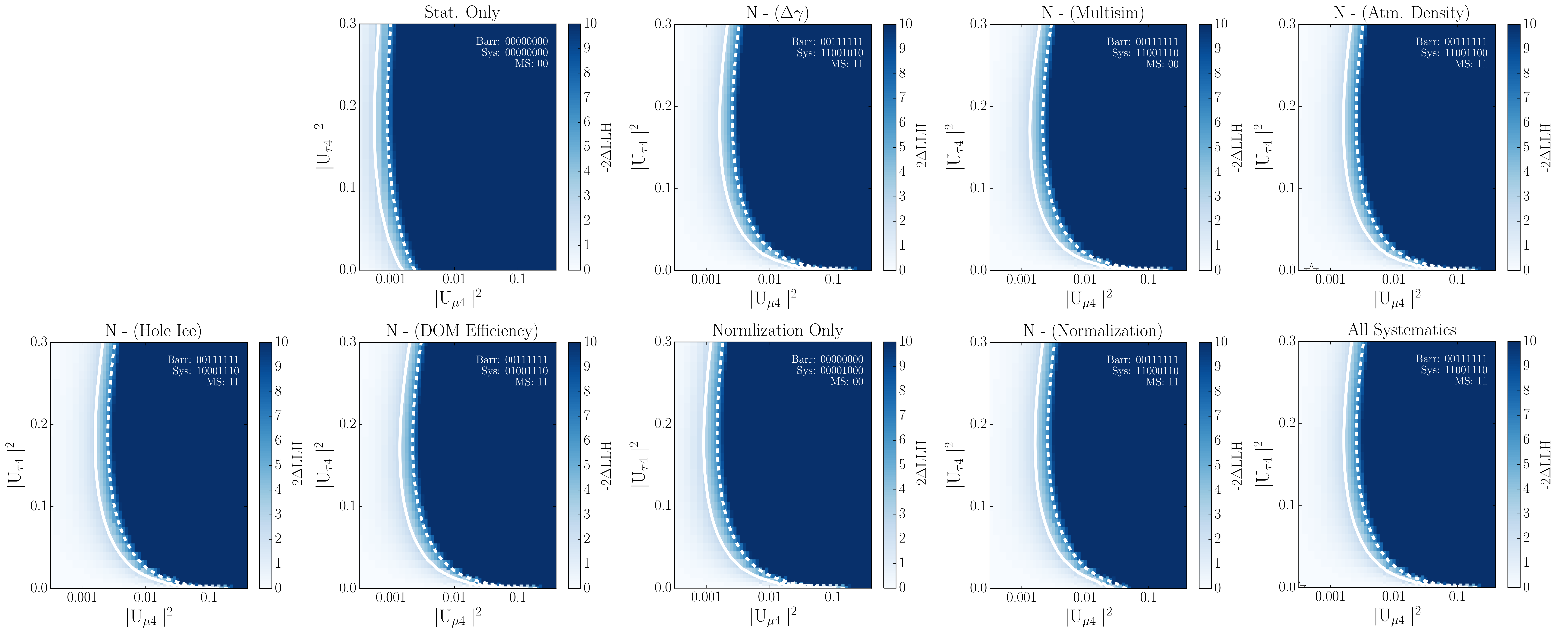
Interesting areas of the parameter space

If an event passes either the **Golden selection** or the **Diamond selection**, it is a 'good' event and makes it into the **Platinum selection**





Asimov dataset: Asimov N-1 systematics test



Binning information

A binned maximum log-likelihood algorithm with nuisance parameters to account for systematic uncertainties is used to determine the sterile neutrino mixing parameters.

Probability of statistical observation using Poissonian statistics

Penalization factor determined by systematic priors (all Gaussian)

$$LLH = \max_{\vec{\theta},d}\left(\sum_{i=1}^{N_{bins}}\left[x_i log\lambda_i(\vec{\theta},d) - \lambda_i(\vec{\theta},d)\right] - \sum_{\eta}\frac{(\theta_\eta - \Theta_\eta)^2}{2\sigma_\eta^2}\right)$$

Emin	500 GeV
Emax	9976GeV
$Log_{10}(E)$bin	0.1
NEnergy Bins	14
$cos(Z)_{max}$	0.0
$cos(Z)_{min}$	-1.0
$cos(Z)_{bin}$	0.05
NZenith Bins	21


```
"E_Edges": [
        2.6989700043360187,
        2.798970004336019,
        2.898970004336019,
        2.998970004336019,
        3.098970004336019,
        3.1989700043360187,
        3.298970004336019,
        3.398970004336019,
        3.498970004336019,
        3.598970004336019,
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        3.798970004336019,
        3.898970004336019,
        3.998956440470486
],
```
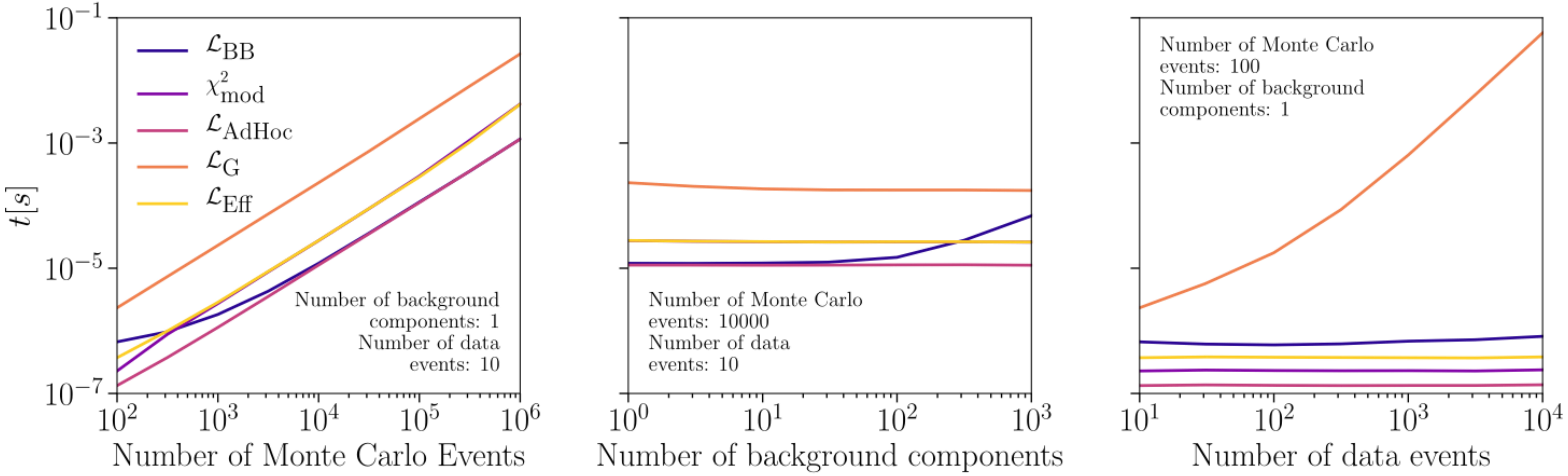
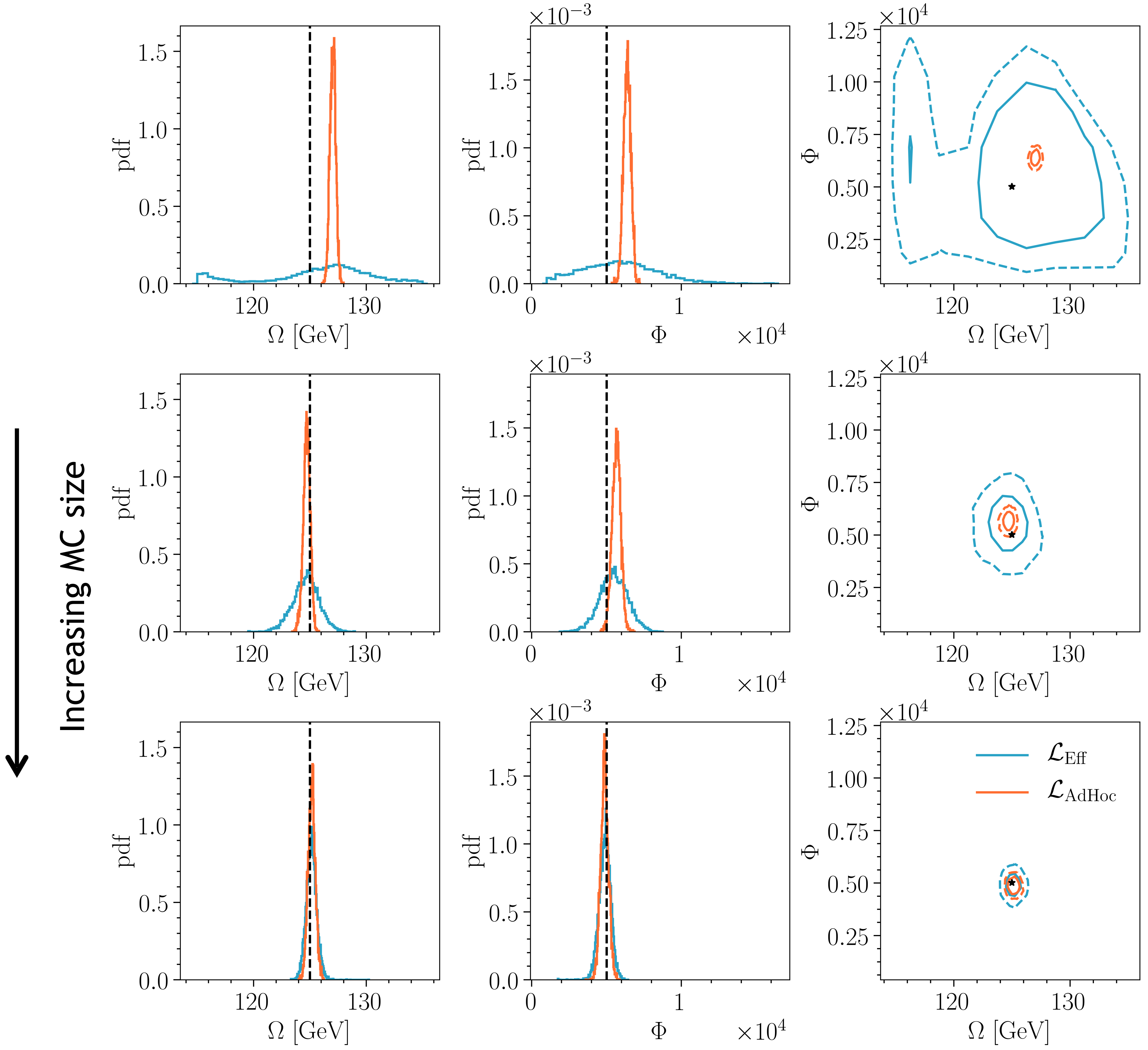

```
"Z_Edges": [
        -1.0,
        -0.9500000000000001,
        -0.9,
        -0.8500000000000001,
        -0.8,
        -0.75,
        -0.7000000000000001,
        -0.65,
        -0.6000000000000001,
        -0.55,
        -0.5,
        -0.45,
        -0.4,
        -0.35000000000000003,
        -0.30000000000000004,
        -0.25,
        -0.2,
        -0.15000000000000002,
        -0.1,
        -0.05,
        0.0
],
```

Modified likelihood to account for Monte Carlo statistical uncertainties





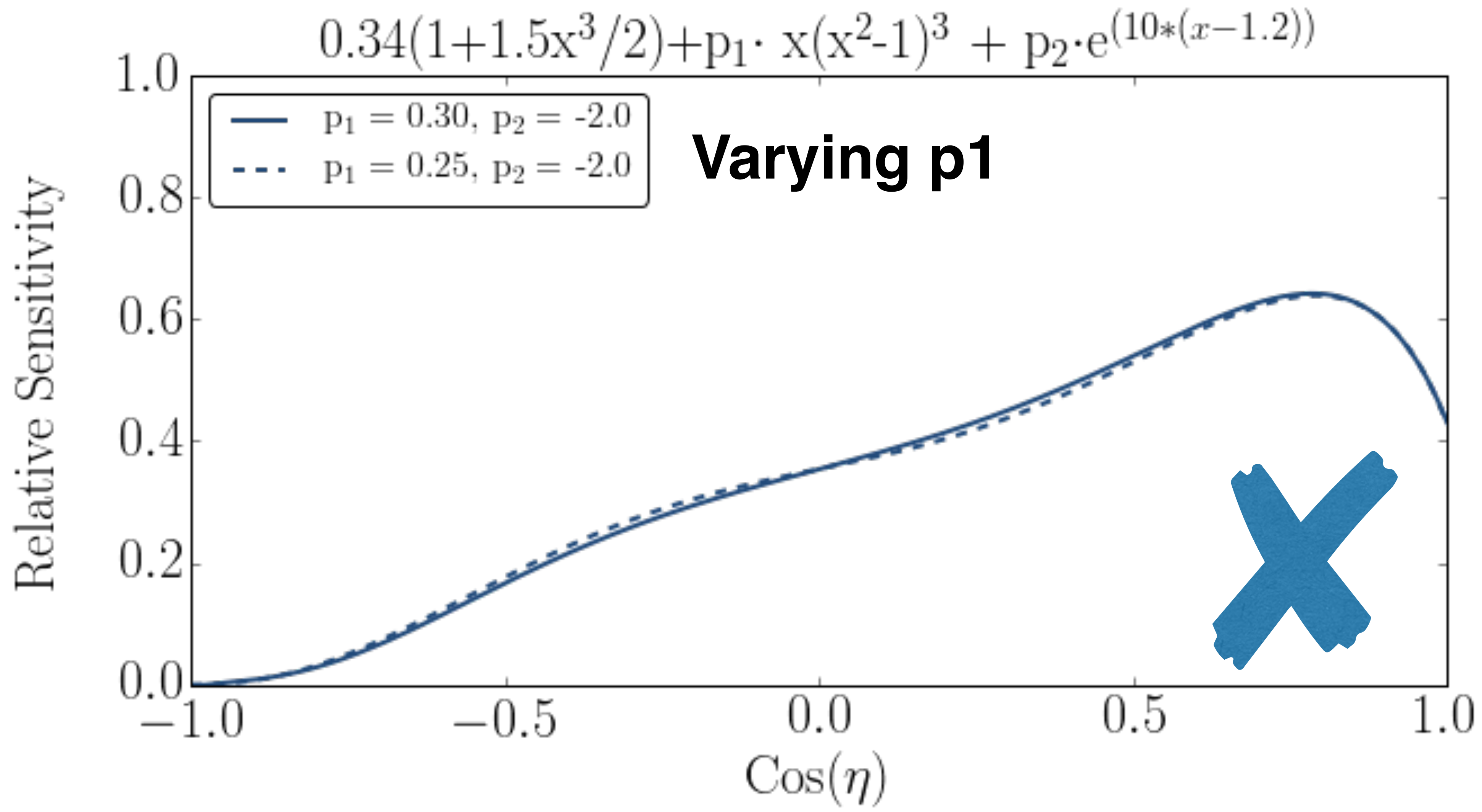
Black dot: true
Blue: Leff
Orange: Poisson LLH

$$\mathcal{L}_{\rm Eff} \quad \left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1}\Gamma\left(k+\frac{\mu^2}{\sigma^2}+1\right)\left[k!\left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}+1}\Gamma\left(\frac{\mu^2}{\sigma^2}+1\right)\right]^{-1}$$

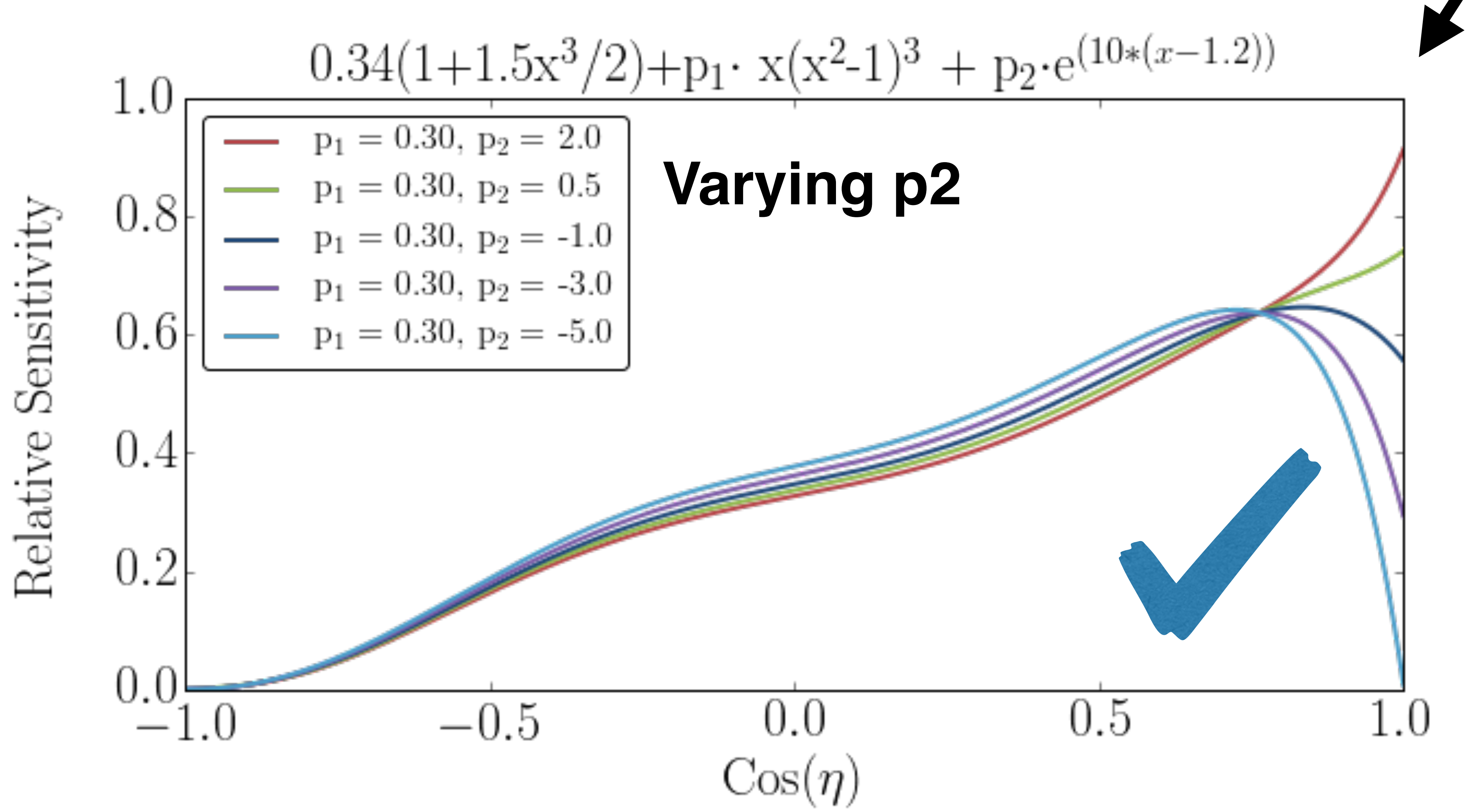
$$\mu(\theta) \equiv \sum w_i(\theta) \ , \sigma(\theta)^2 \equiv \sum w_i^2(\theta)$$

See talk by Tianlu Yuan this meeting also see paper by C. A. Argüelles, A. Schneider, and T. Yuan arXiv:1901.04645. Python and C+
https://github.com/austinschneider/MCLLH

Ice Systematics: Hole Ice

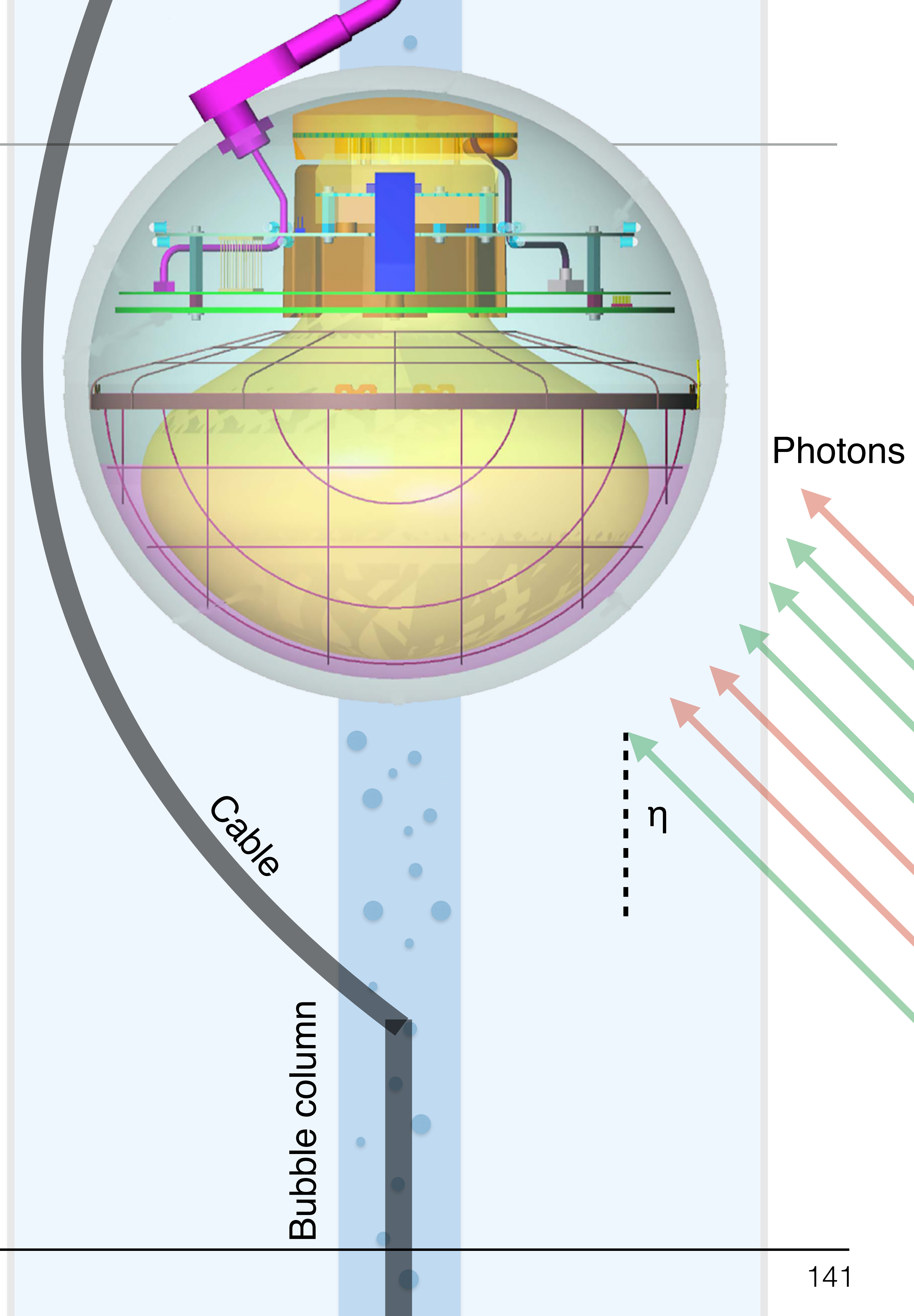


P1 has a small effect on the HoleIce angular acceptance curves. Instead, we concentrate on the p2 parameter.

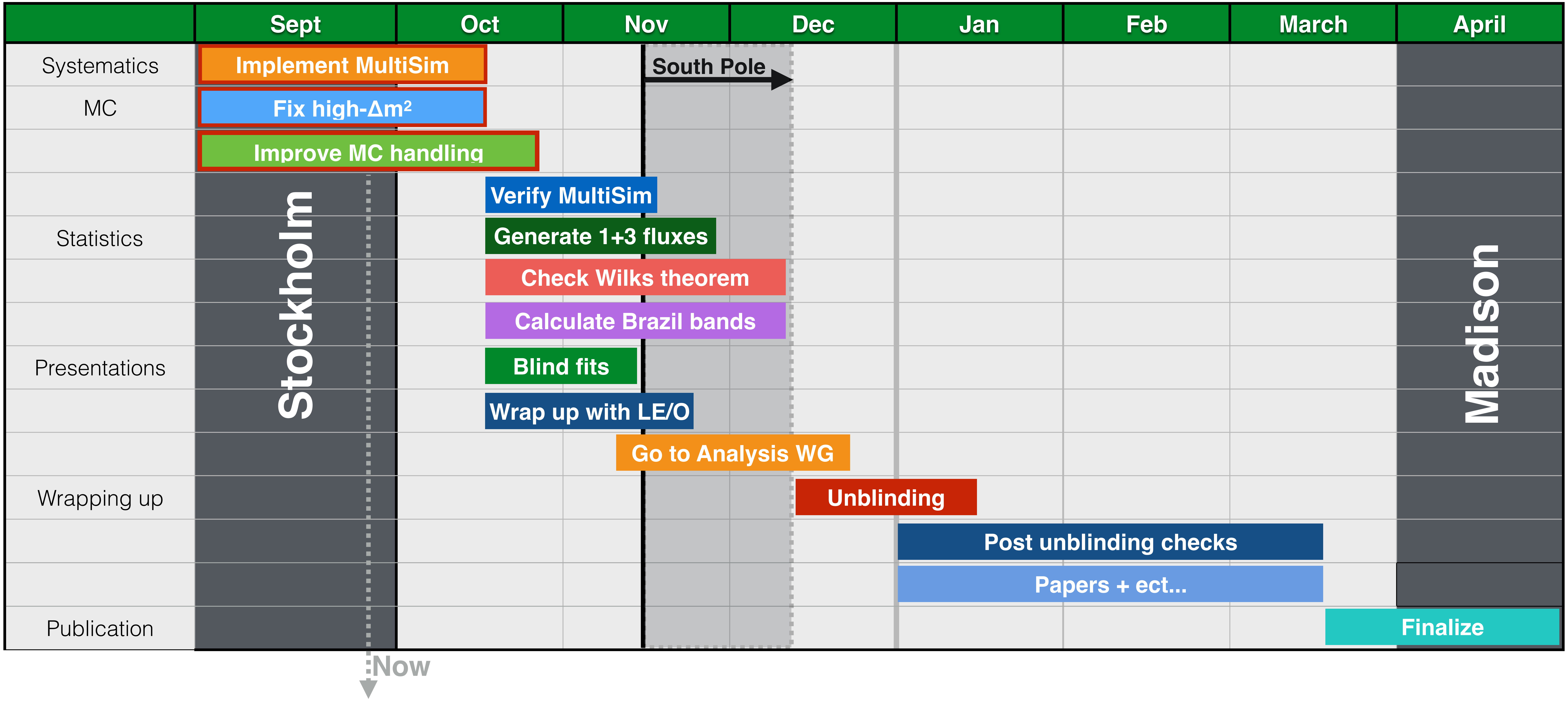


We spline between 5 different values of the p2 parameter.

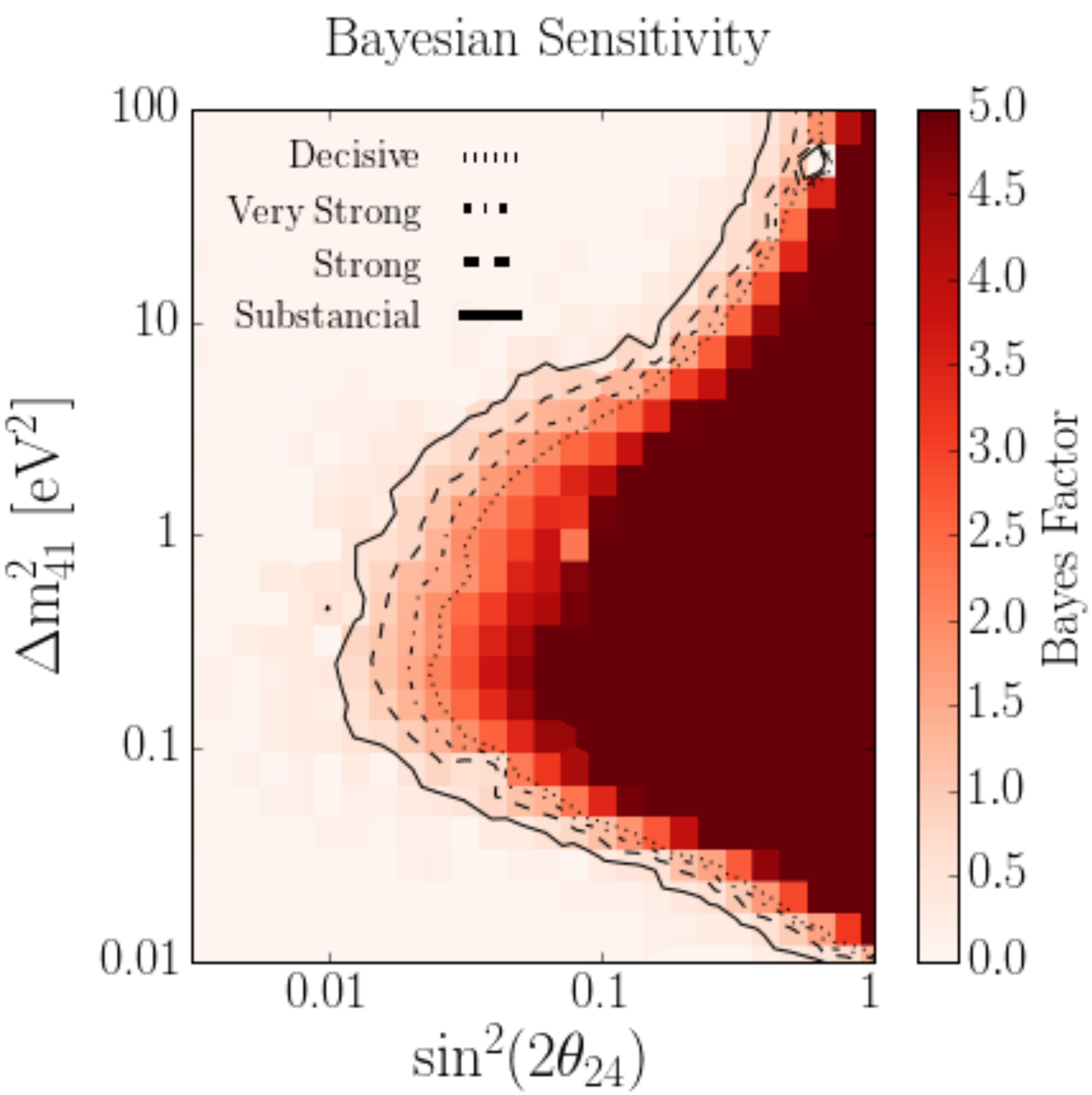
Flat prior.

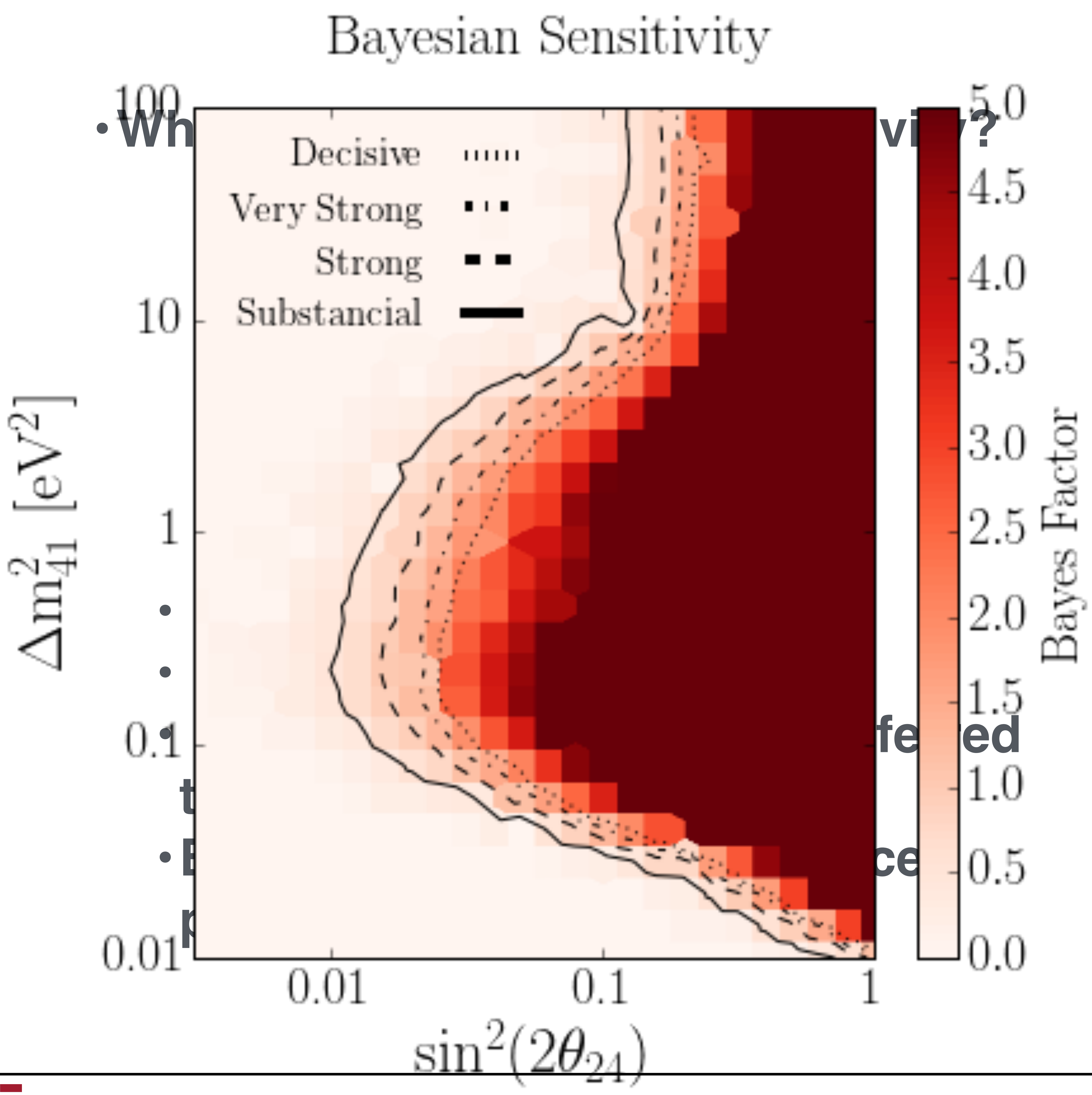


Timeline, and to-do list

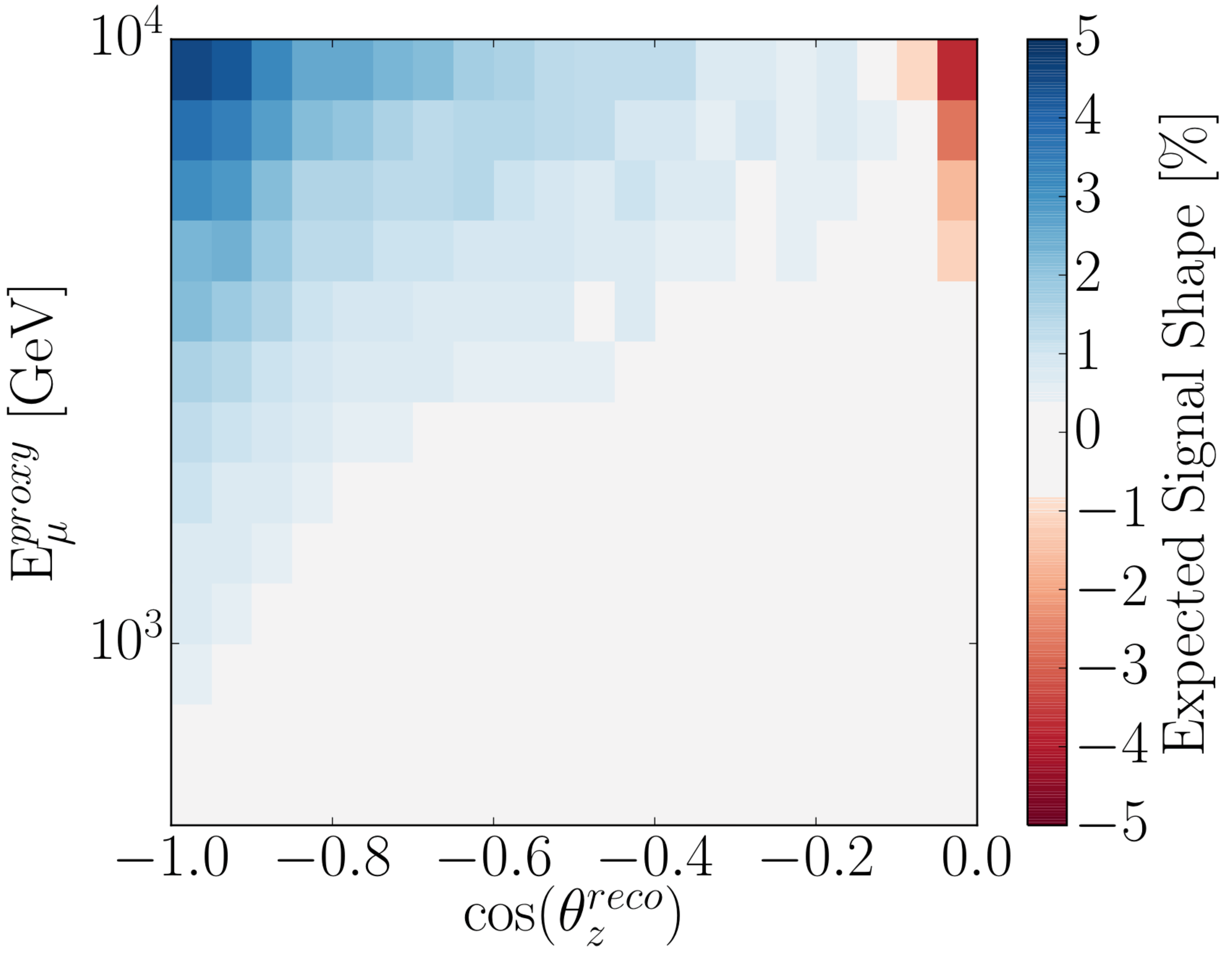


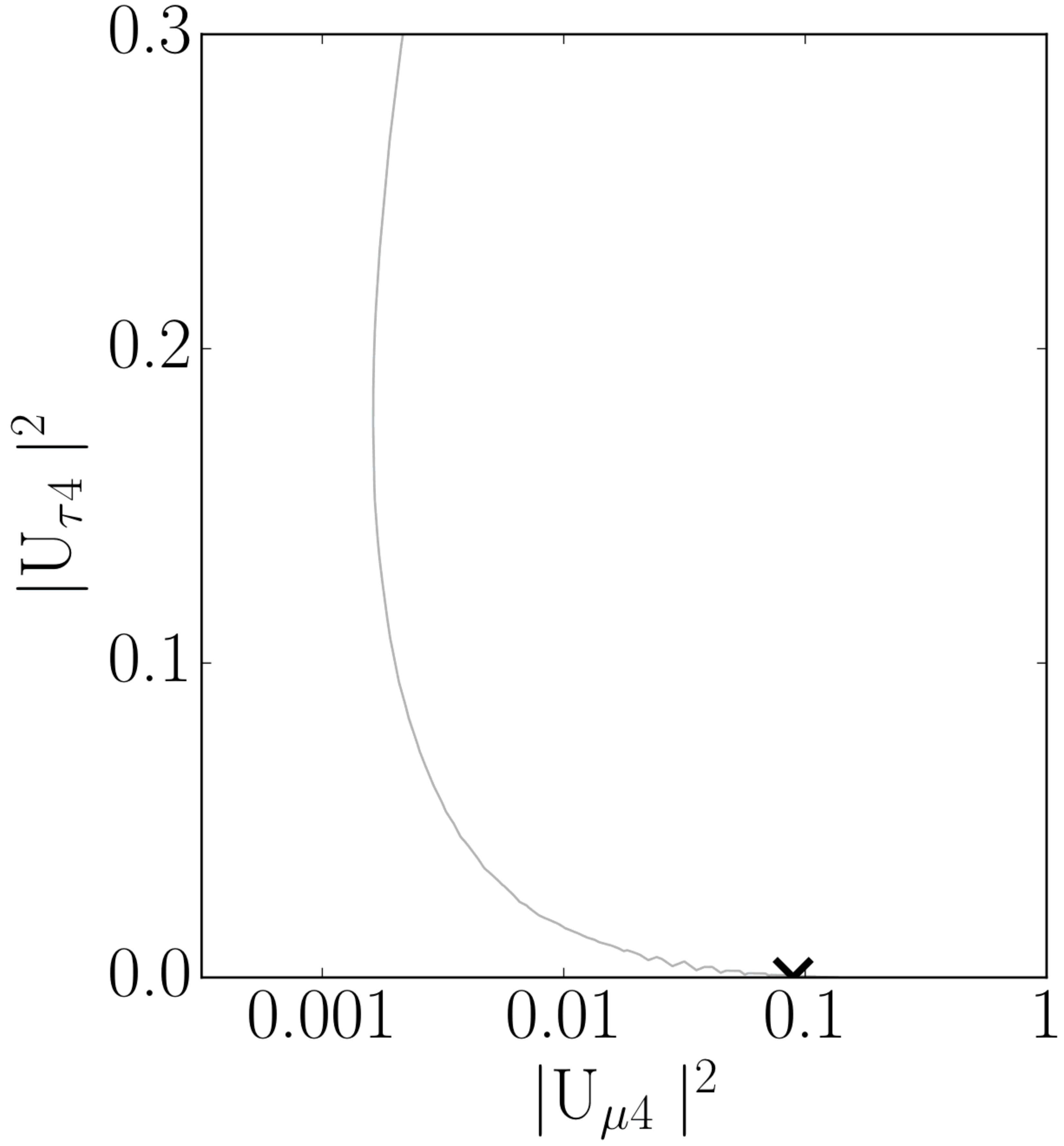
Bayesian sensitivity





Coverage checks (1DOF)





Interesting areas of the parameter space