

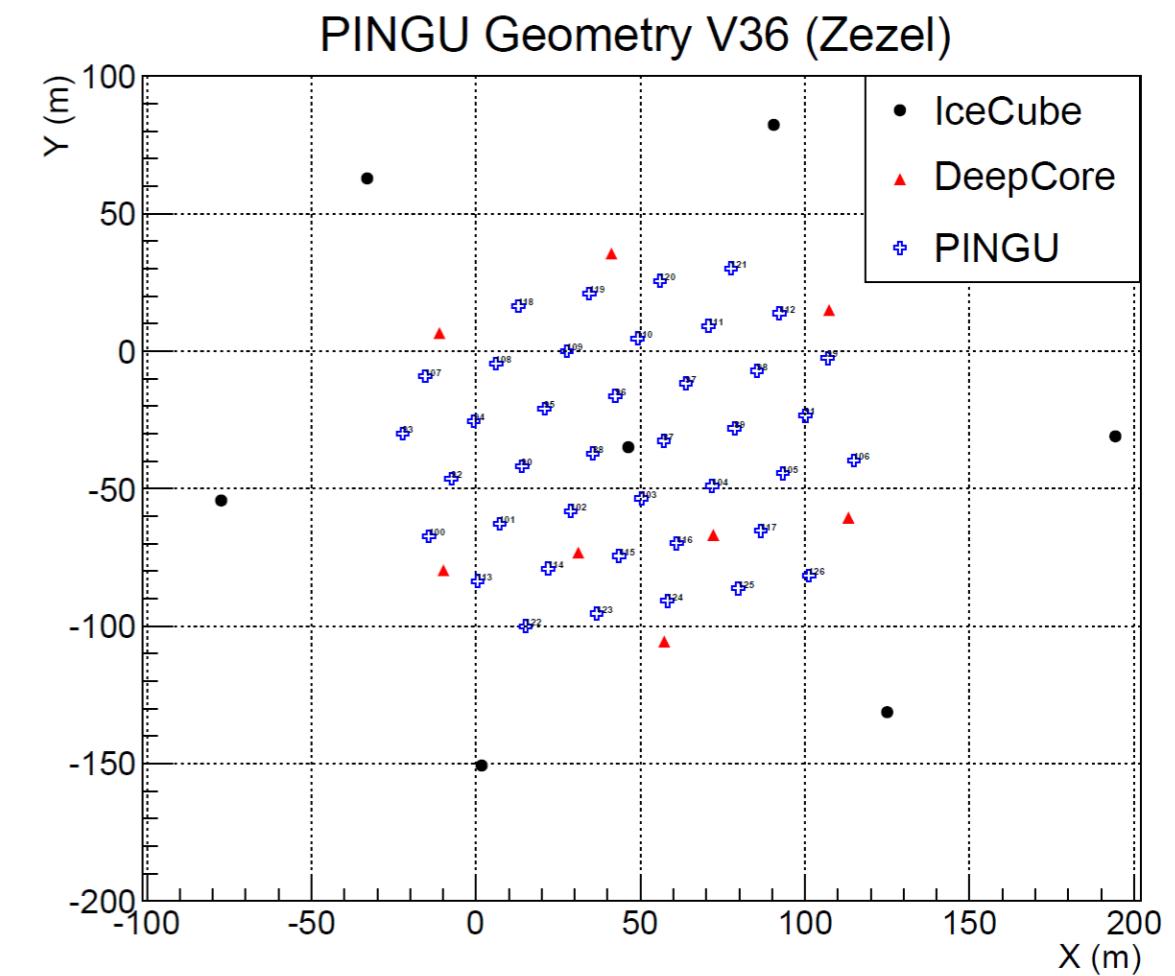
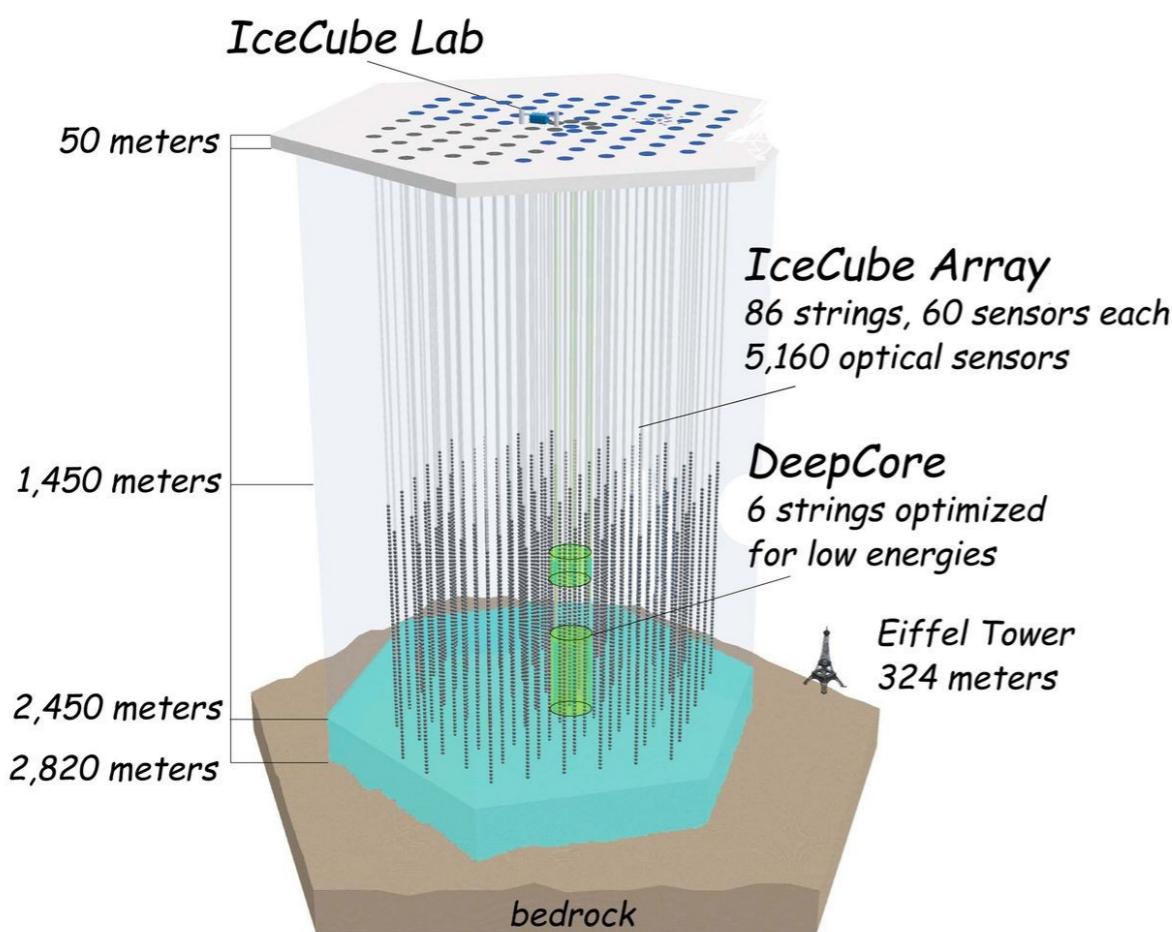
Atmospheric Flux Uncertainties and the Neutrino Mass Hierarchy

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VLVnT | Rome | 2015-09-15

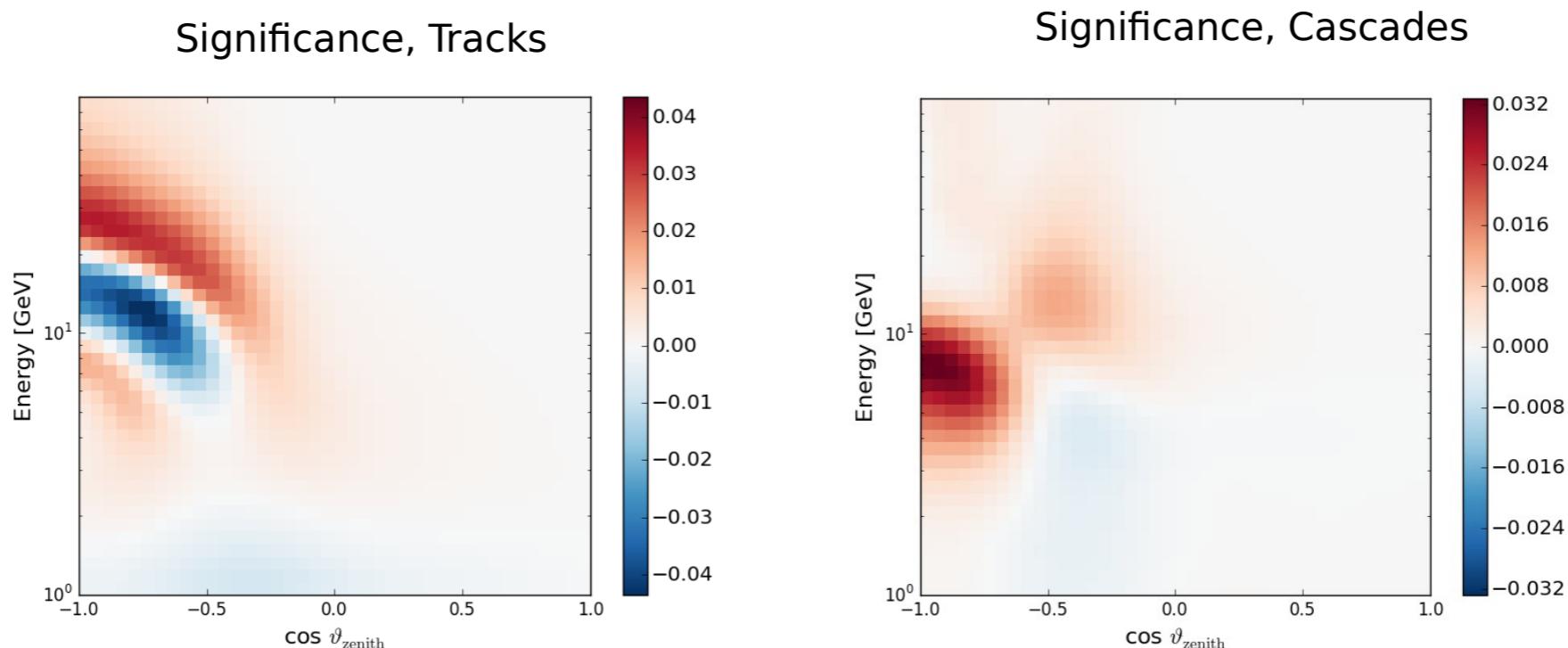


PINGU

- PINGU - Precision IceCube Next Generation Upgrade
- Proposed extension to IceCube at the geographic south pole
- 40 strings, 22m apart
- 96 optical modules pr string, 3m apart
- Dense instrumentation → Measure neutrinos with energies of a few GeV



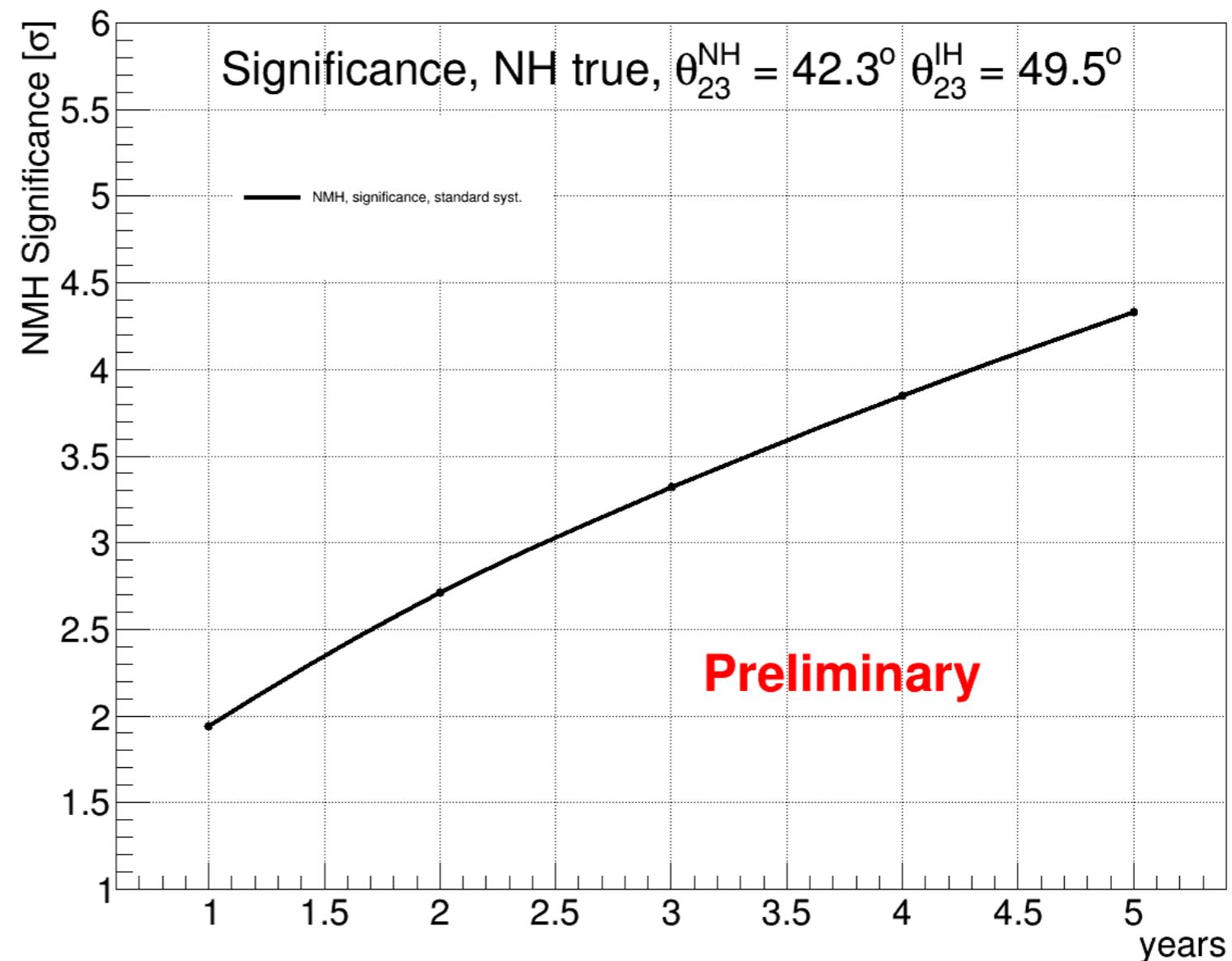
- PINGU Simulation and Analysis
- Not individual events but MC-data as input (eg. flux, effective area)
- Five step process: Flux, oscillation, effective area, reconstruction and PID.
- Uncertainties implemented as individual parameters
- Fast: Generate single expected event rate map in ~ 0.5 s
- → Generate maps in energy and zenith angle for NH and IH and evaluate neutrino mass hierarchy



PISA & NMH

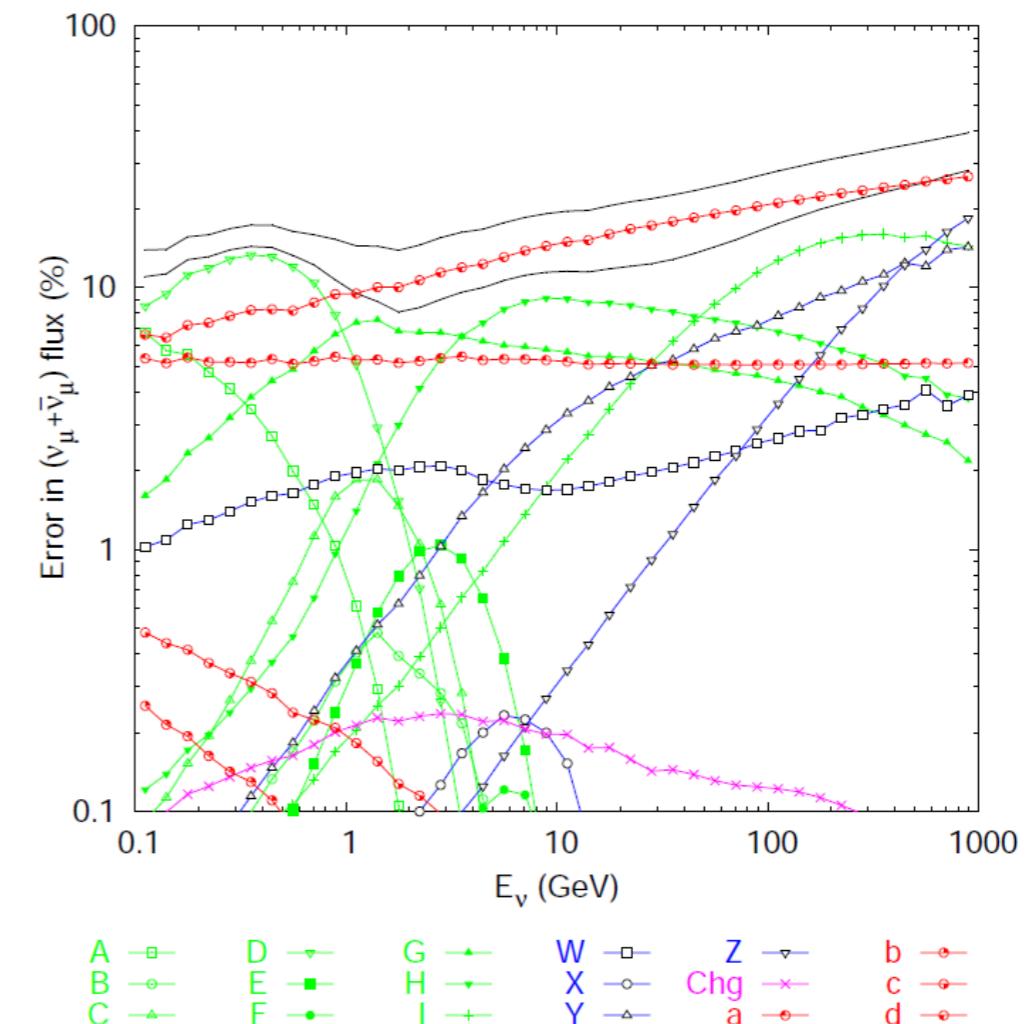
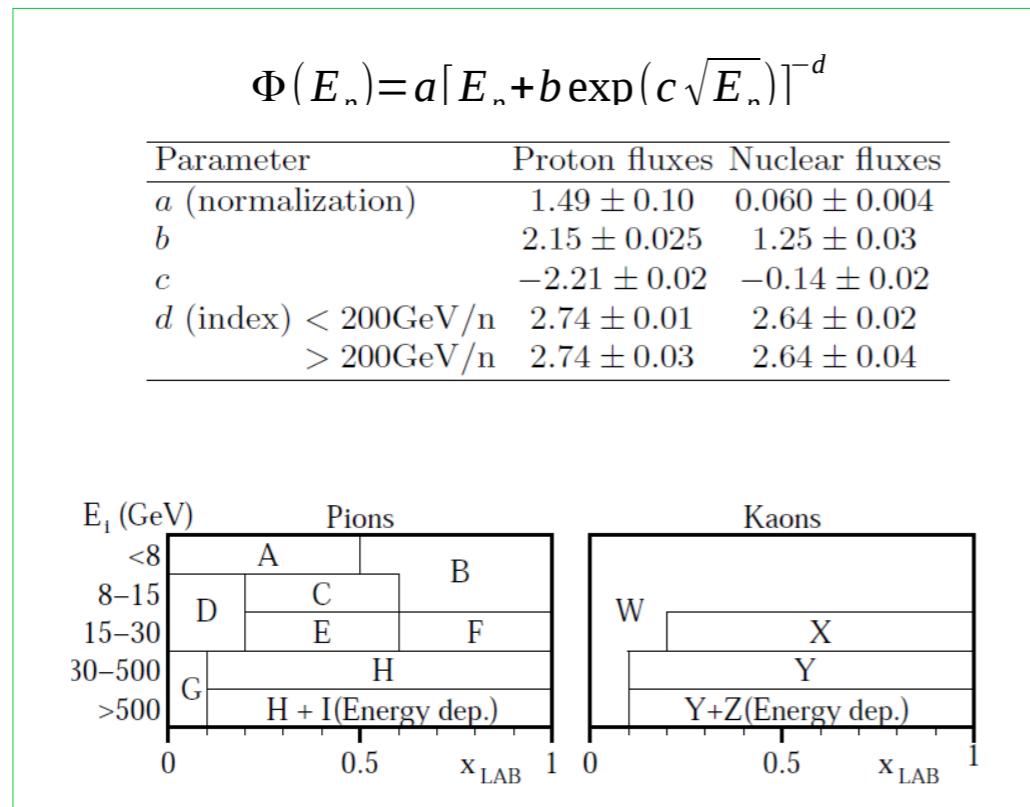
- Standard: 7 Systematics
- Run $\Delta\chi^2$ analysis (pull and fisher methods) with the systematics as free parameters with gaussian priors
(Find IH plot in the backup slides) (Mixing angles from 2014 global fit [1])
- Are these 7 enough?

Systematic
v/\bar{v}
v_e/v_μ
θ_{13}
θ_{23}
Δm_{31}^2
Aeff (inc. cross section)
Energy Scale



Implementing Flux Uncertainties

- Barr. Et al. Investigates the flux uncertainties (arXiv: 0611266v1)
- Uncertainties expressed as 18 functions of energy: $F_i(E)$

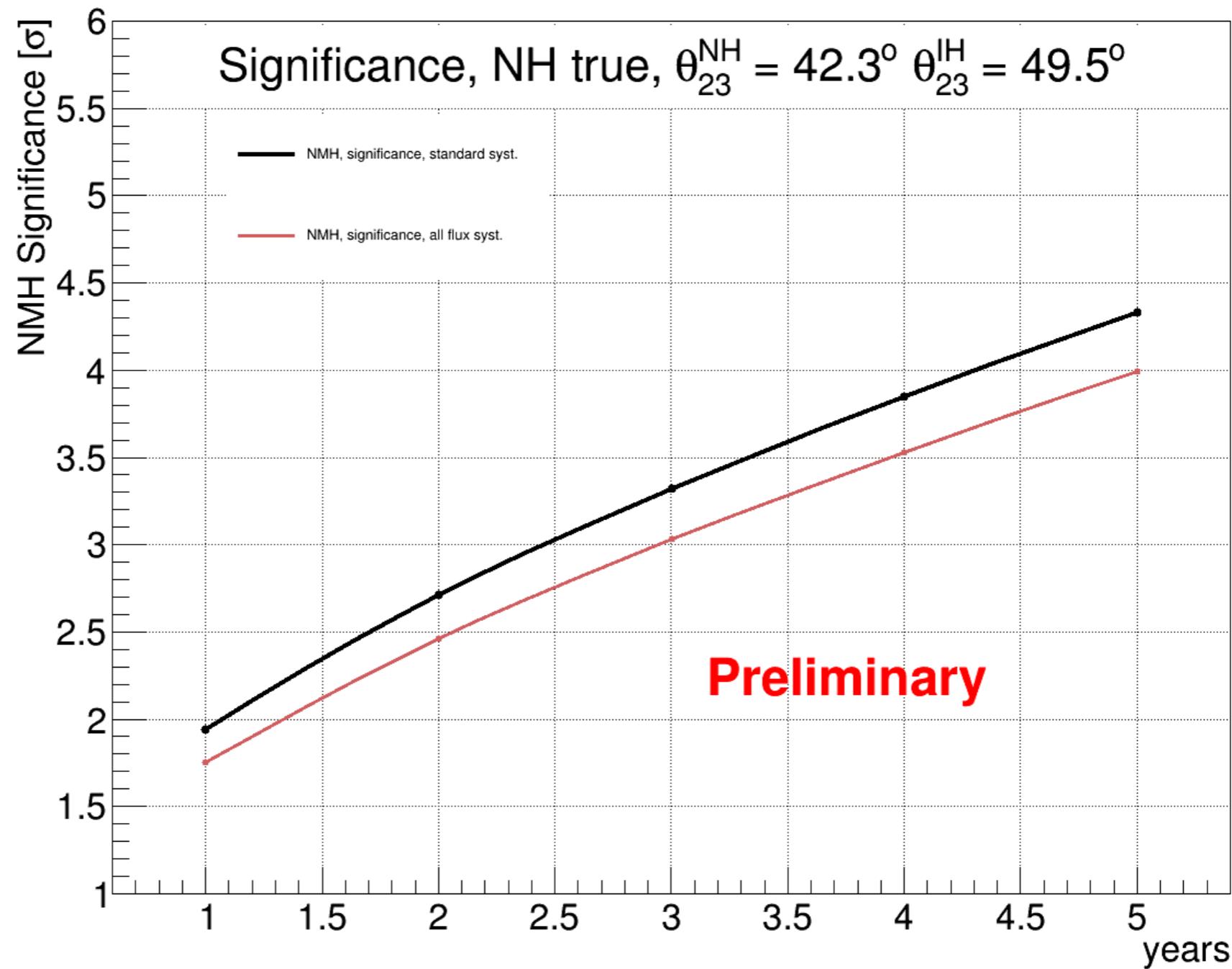


- We implement 18 independent normalization parameters A_i
- Implemented in PISA, as a modification of the flux: $\Phi'(E) = \Phi(E)(1 + \sum_i A_i F_i(E))$

Including the Flux Systematics

- Significance drops from 3.85σ to 3.53σ for 4 years of livetime

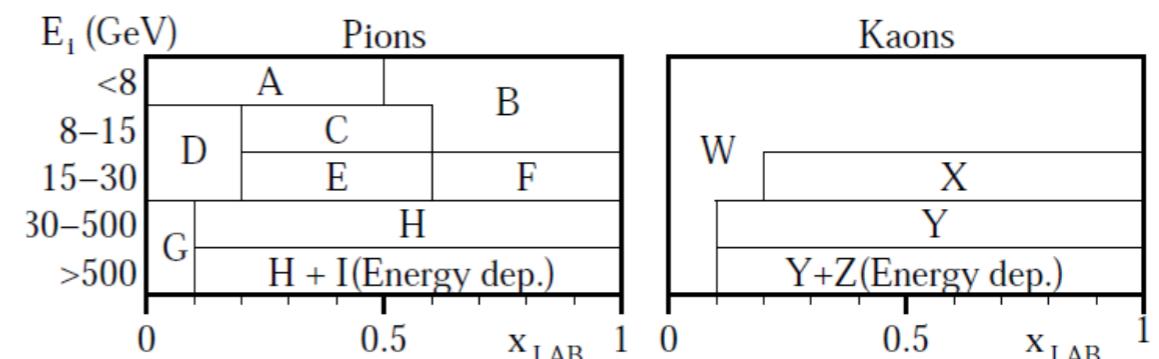
(from 3.23σ to 2.85σ for the inverted hierarchy, find the plot in the backup slides)



Constraints and Impacts

- Certain parameters impact our measurements more than others, from the Fisher analysis:

parameter	impact [%]	best fit	full
hierarchy	100.0	0.000e+00	3.179e-01
deltam31	19.4	-2.370e-03	3.991e-05
energy_scale	3.5	1.000e+00	1.296e-02
flux_hadronic_H	3.1	0.000e+00	2.879e-01
theta23	2.7	6.745e-01	8.932e-03
aeff_scale	1.4	1.000e+00	6.289e-02
flux_hadronic_I	0.8	0.000e+00	4.413e-01
theta13	0.4	1.484e-01	3.488e-03
flux_hadronic_E	0.1	0.000e+00	9.058e-01
nue_numu_ratio	0.1	1.000e+00	1.813e-02
flux_hadronic_Y	0.0	0.000e+00	6.977e-01
flux_spectral_index_d	0.0	0.000e+00	6.372e-01
nu_nubar_ratio	0.0	1.000e+00	1.000e-01



arXiv: 0611266v1

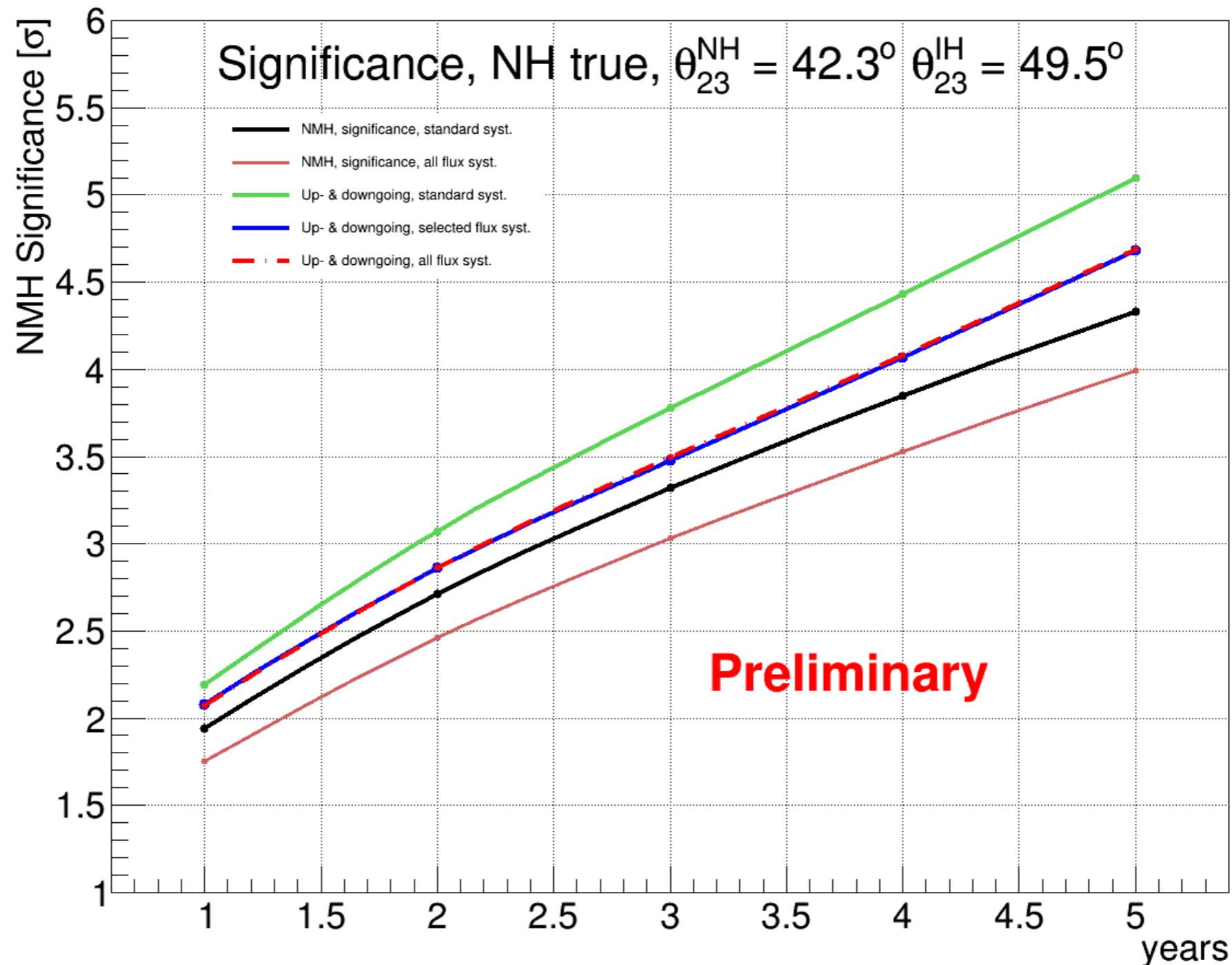
- Perhaps those can be constrained in a region without oscillations?
- Include downgoing region?

Downgoing region: Overview

- Proof of concept
- Hypothesis: We can constrain the uncertainty parameters in the down going region, where there should be little to no oscillation effects.
- For now: We assume same A_{eff} for up and down going regions
- For now: We ignore background effects
- → Run analysis including the flux uncertainties as free parameters with a gaussian prior
- → Constrain parameters (and increase significance)

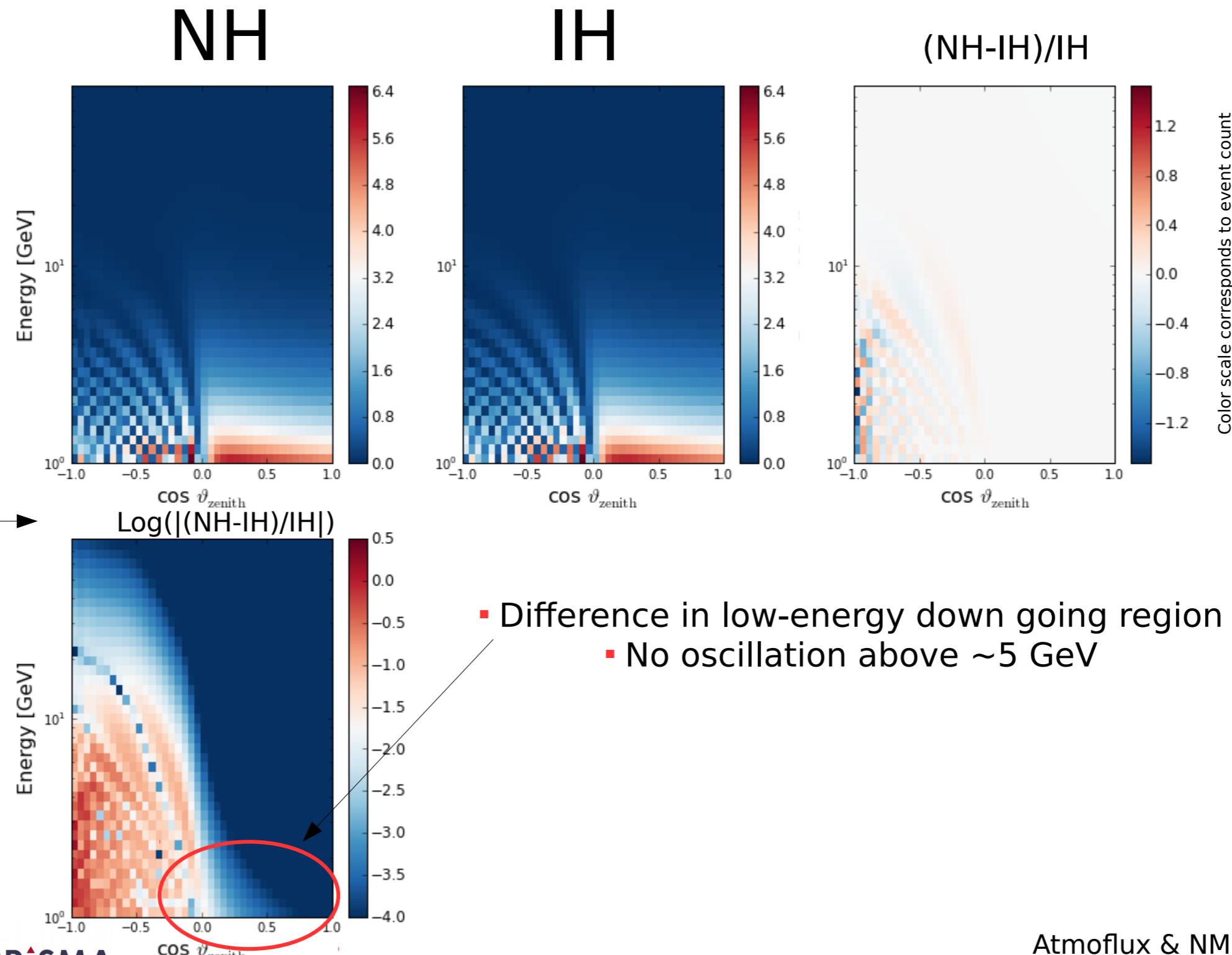
Up- and Downgoing region

- Normal Hierarchy, Pull method
- Increases 4-year significance up to $\sim 4.0\sigma$ including the systematics



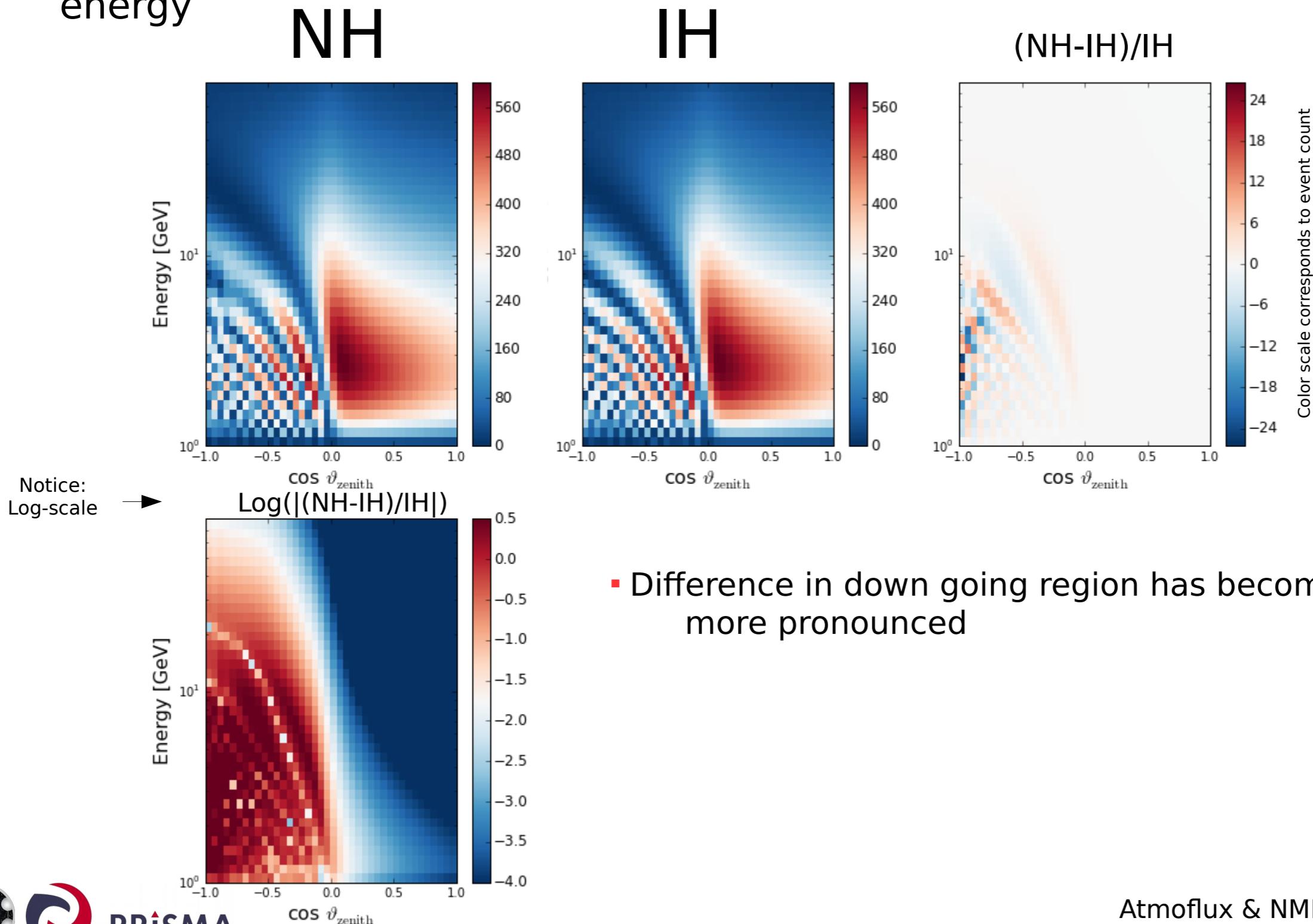
PISA: Oscillation Stage

- Expectation: Only upgoing region is oscillated



PISA: Aeff Stage

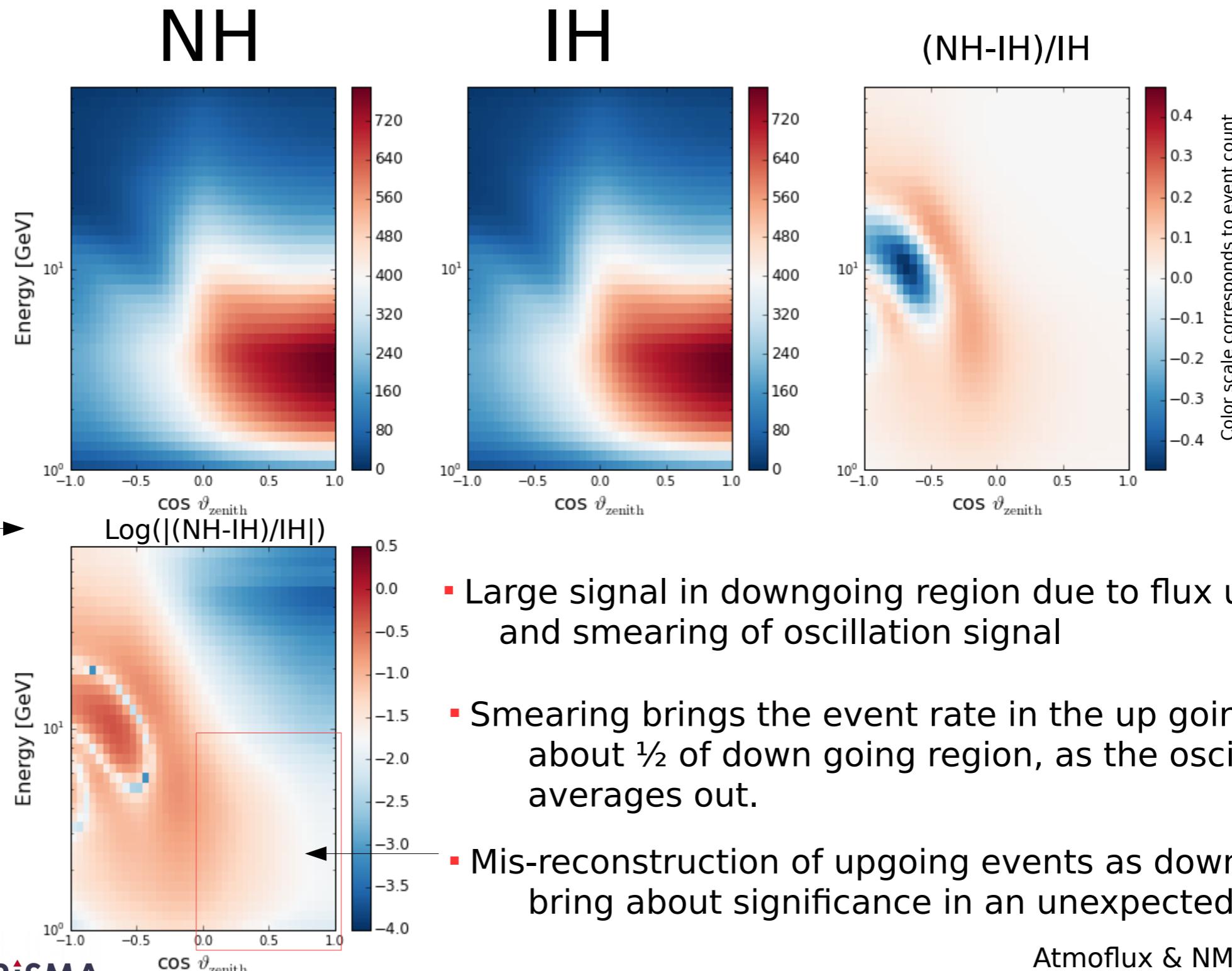
- Expectation: Signal region to move up in energy as cross section goes with energy



- Difference in down going region has become more pronounced

PISA: Reco Stage

- Expectation: Smearing evens out oscillation signal over neighborhood bins

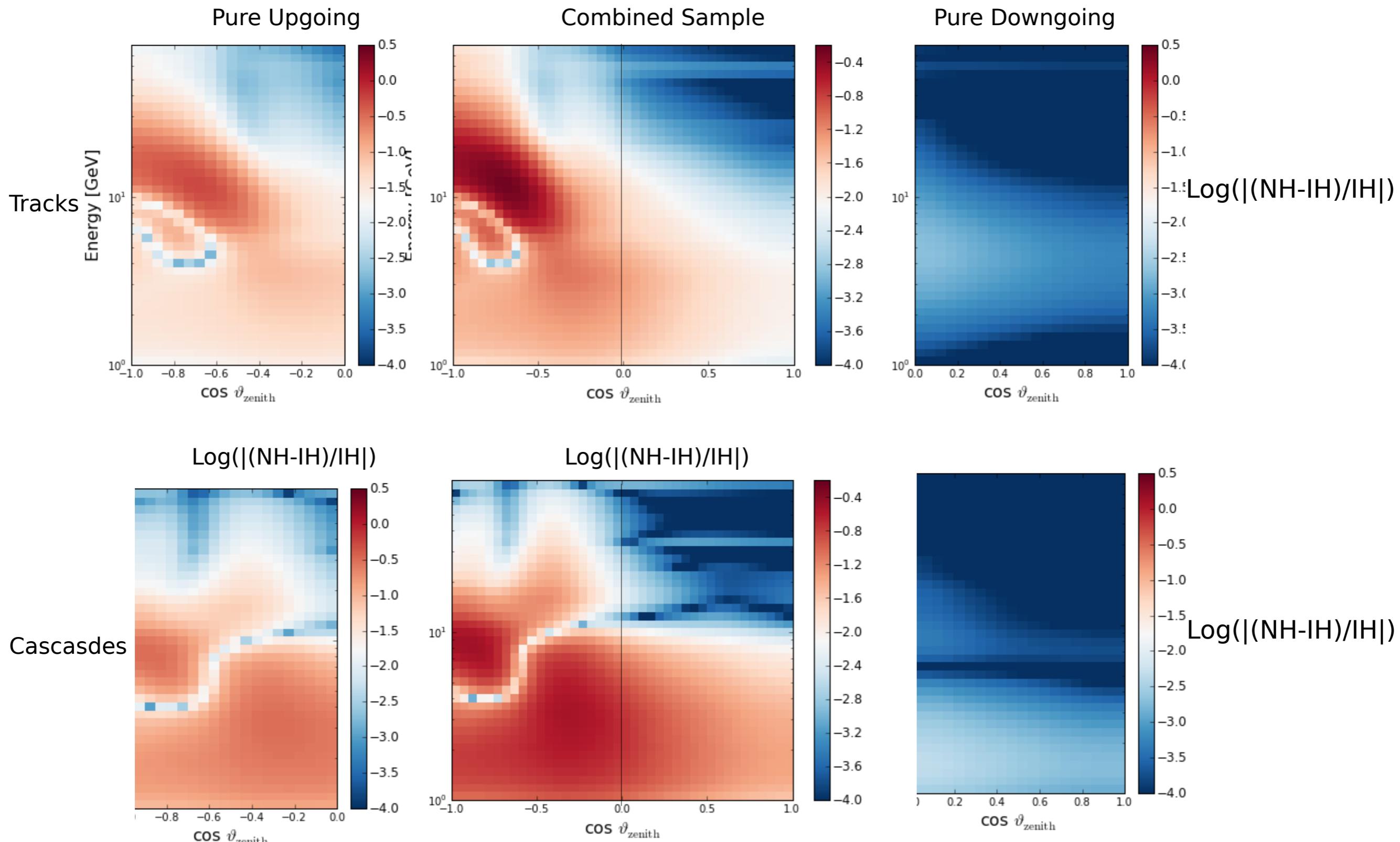


- Large signal in downgoing region due to flux un-oscillated and smearing of oscillation signal
- Smearing brings the event rate in the up going region to about $\frac{1}{2}$ of down going region, as the oscillation averages out.
- Mis-reconstruction of upgoing events as downgoing may bring about significance in an unexpected region

Smearing Consistency Check

- Can we trust the smearing? (Currently using VBKDE, under further development in Uni. Mainz)
- Question: How does the smearing impact the up/down going regions?
- Check: Split data in two independent sets: one for each region.
- → Run analysis again.

Pure Up/Down vs Combined - plots



NOTE: No Uncertainties
Included!

Pure Up/Down vs Combined - stats

- Significance in regions and channels

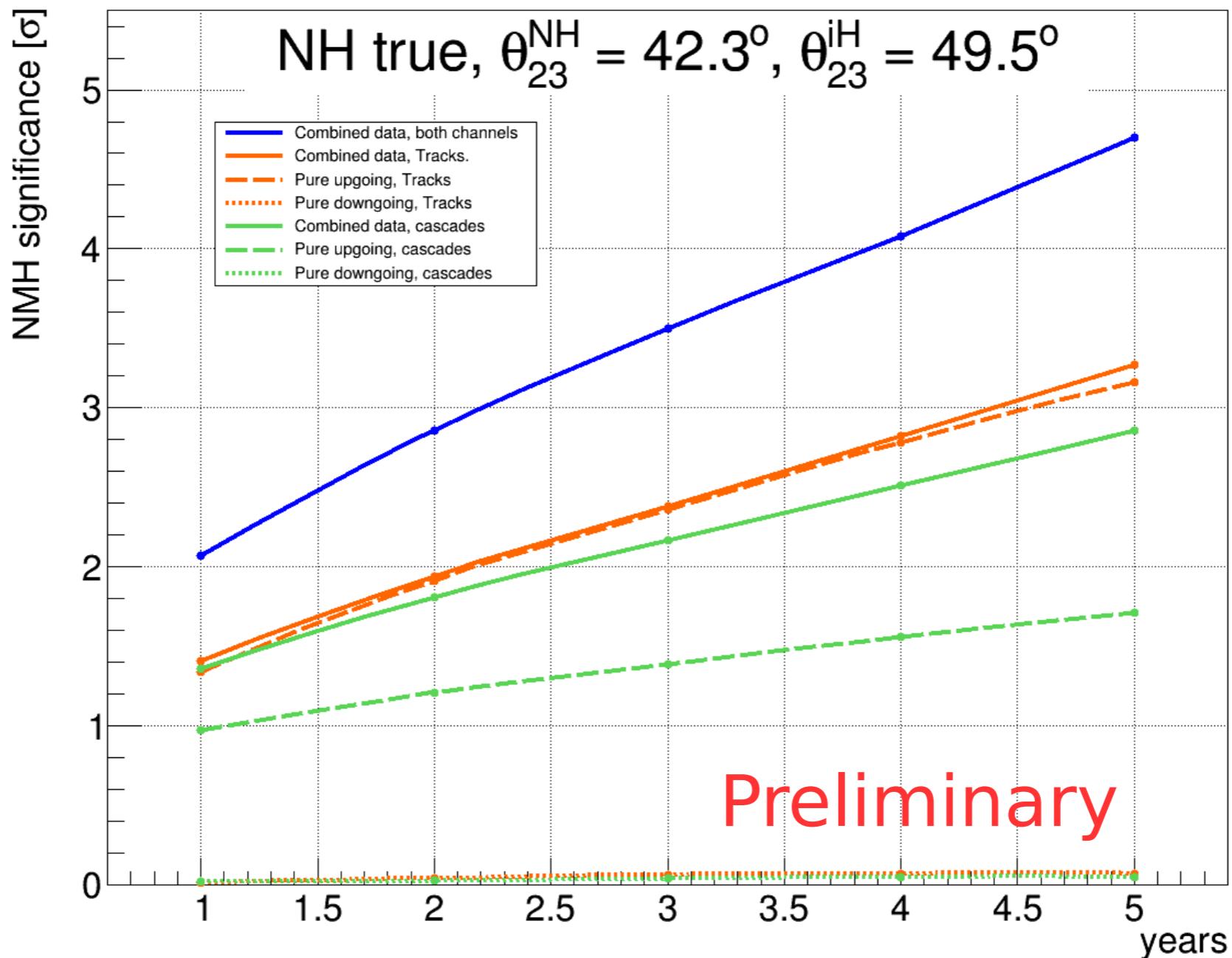
	Tracks	Cascades
Pure Up	7.67	9.11
Pure Down	0.55	0.75
Pure total	7.68	9.14
Comb. Up	7.48	8.60
Comb. Down	2.24	5.04
Comb. total	7.97	10.1

- Smearing seem to have diverse effects in different channels
- This effect depends on mixing angle (see similar slide in backups)
- Question: What if we include the uncertainties?

NOTE: No Uncertainties Included!

Pure Up/Down vs Combined + Uncertainties

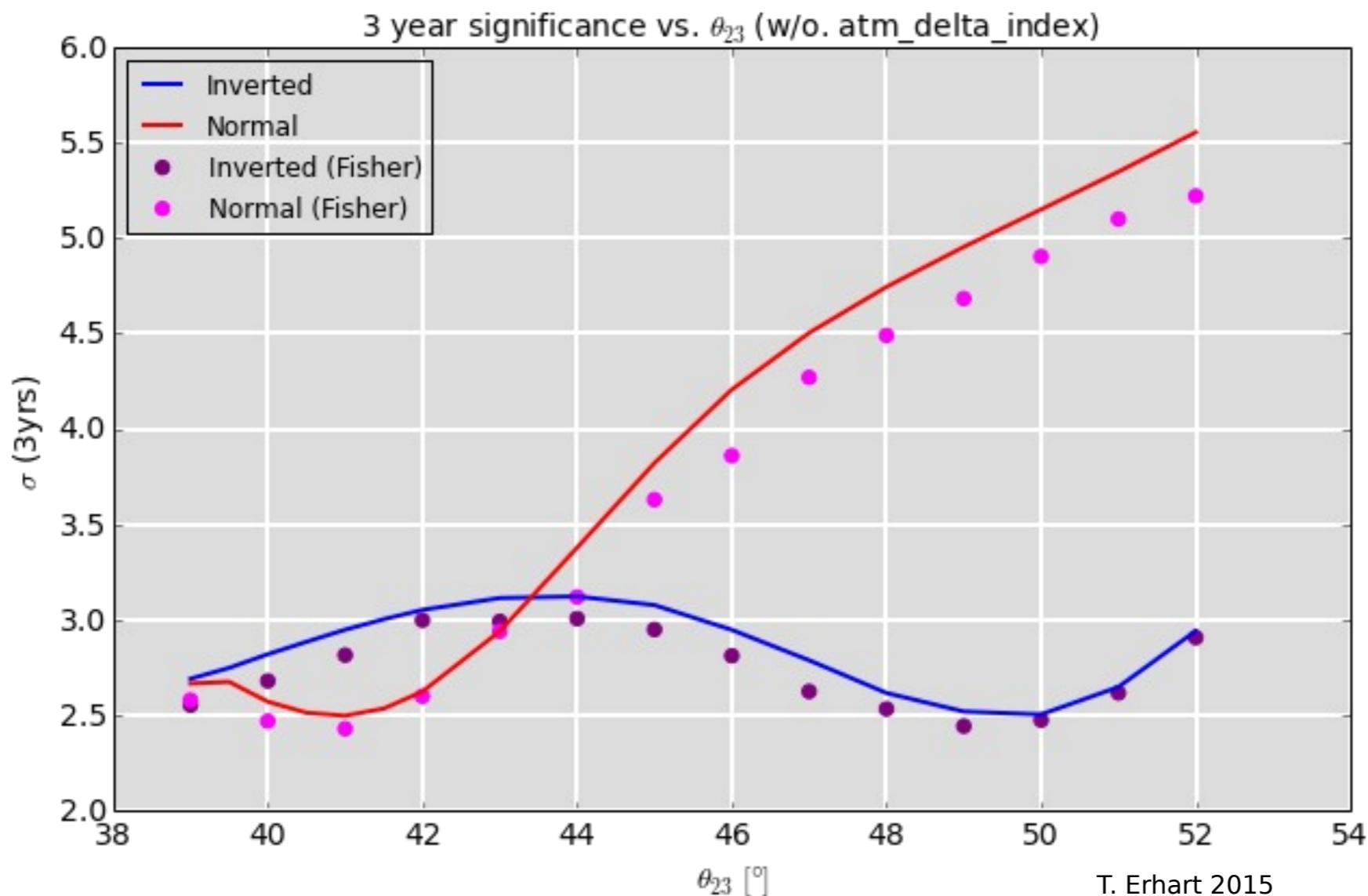
- Channel gain by sample region, pull method:



- Significance comes from smearing and constrains on uncertainties
(not from oscillation in downgoing region)

Method and Octant

- Octant dependence of the NMH sensitivity
- Pull- vs Fisher methods
- Evaluating Fisher matrix at best-fit point in opposite hierarchy



Closing remarks

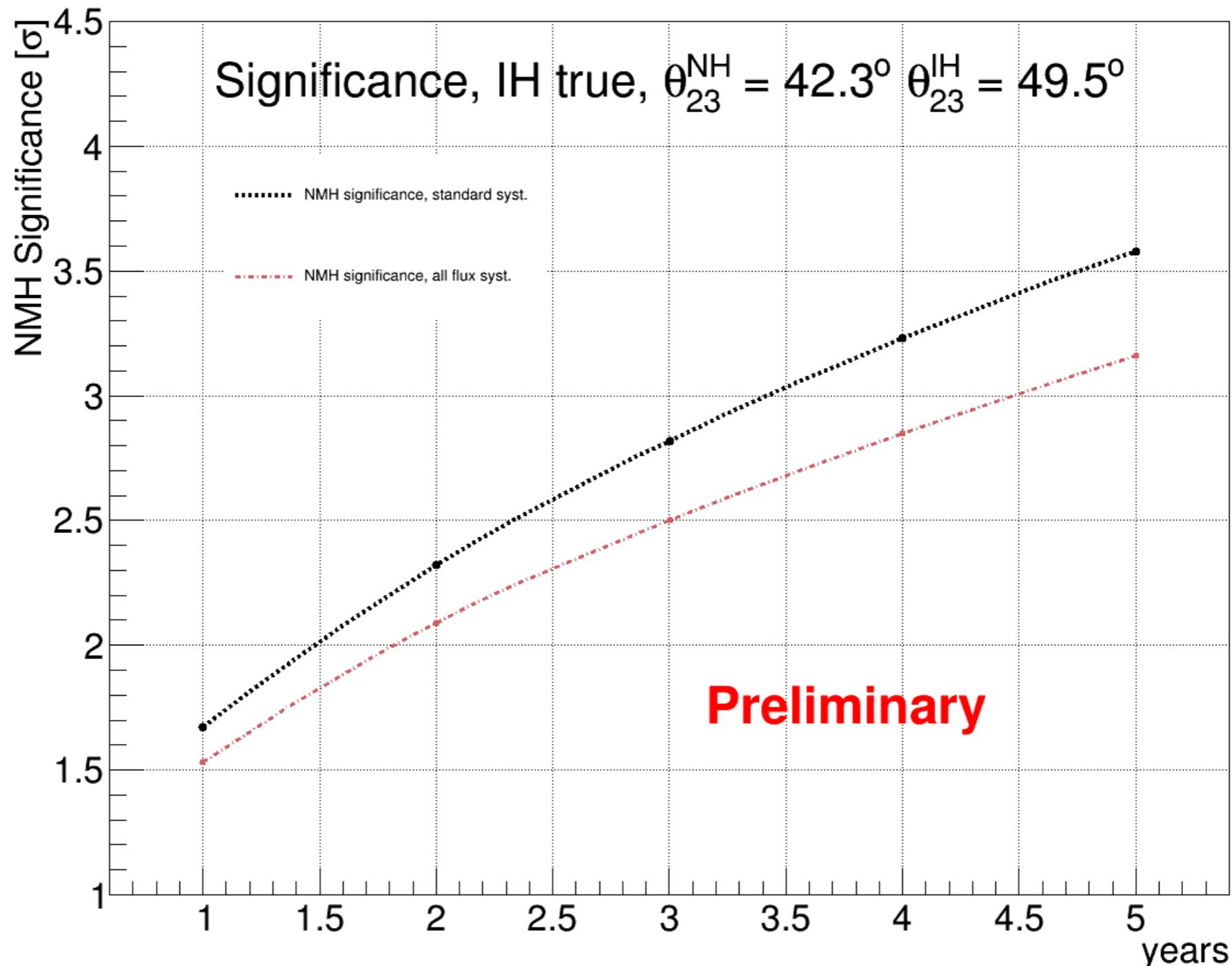
- PINGU is now quantifying the specific impacts of systematics on our NMH significance.
- In a best-case scenario: Including the downgoing region can result in increased significance, due to smearing and constraints on uncertainties
- Proof of concept (eg: add background and change effective area)

Backup

- Backup slides from here on out

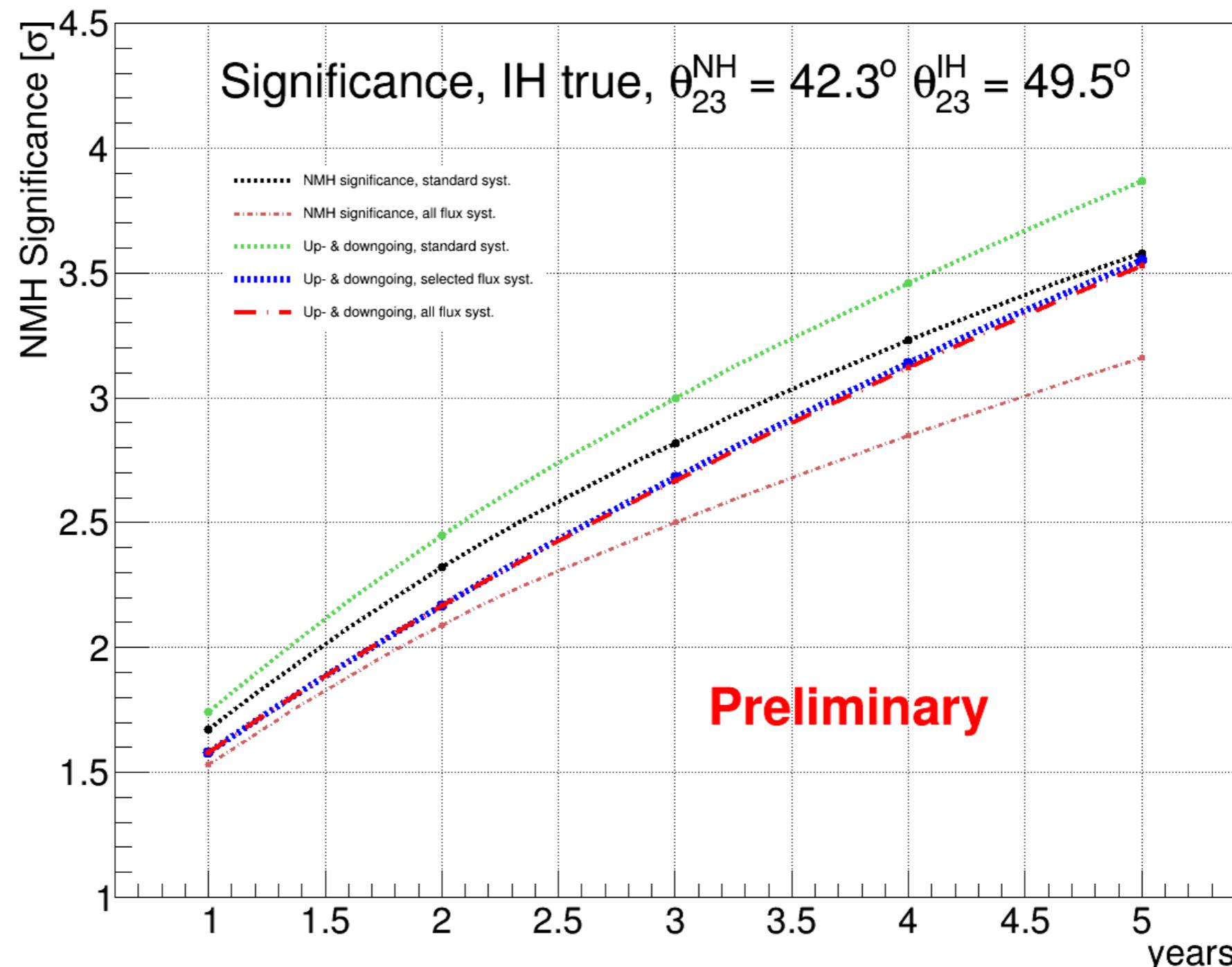
Including the systematic

- Inverted Hierarchy



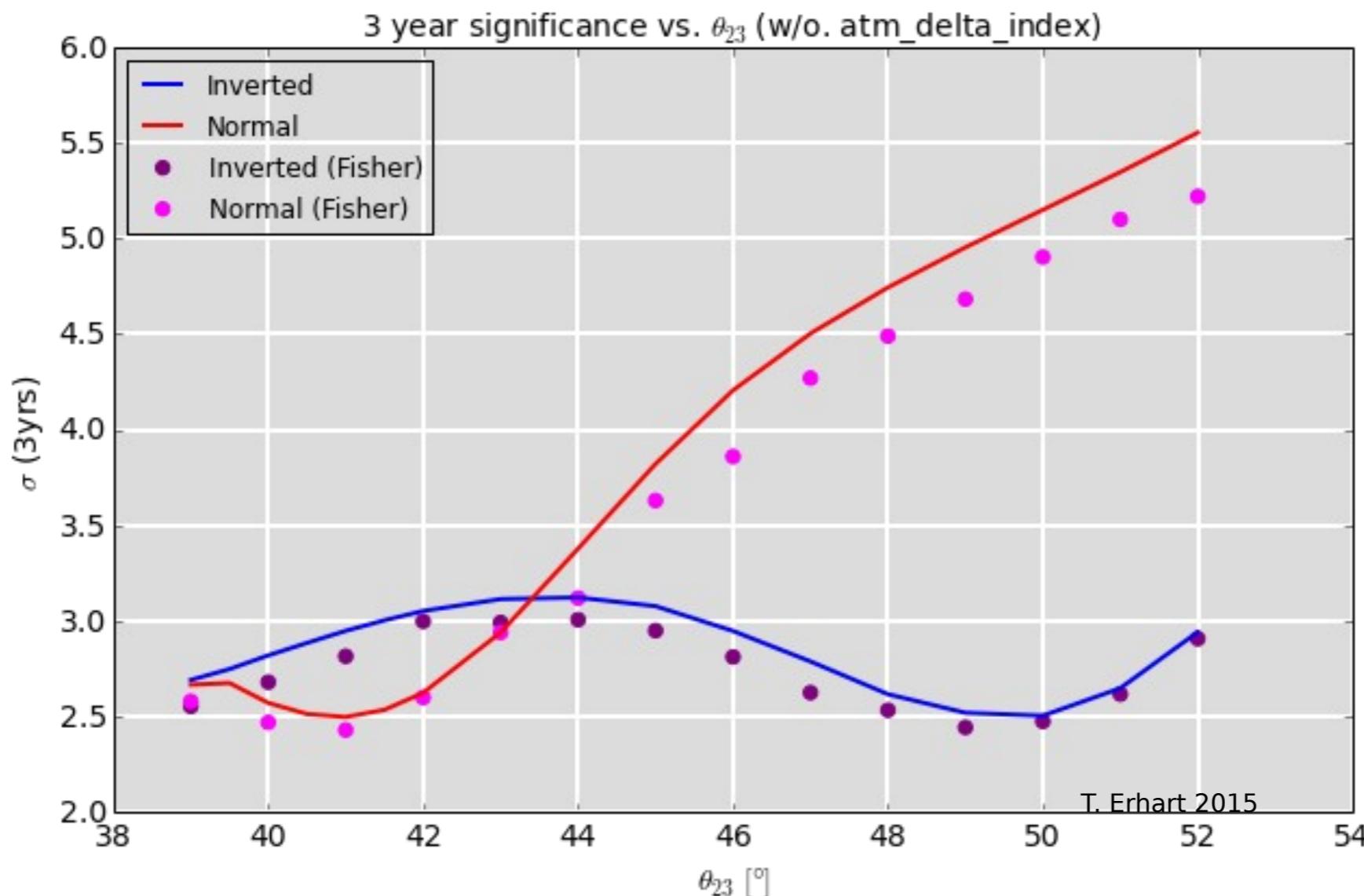
Up- and Downgoing Region

- Inverted Hierarchy, pull method
- Increases 4-year significance back up to $\sim 3.14\sigma$ including the systematics

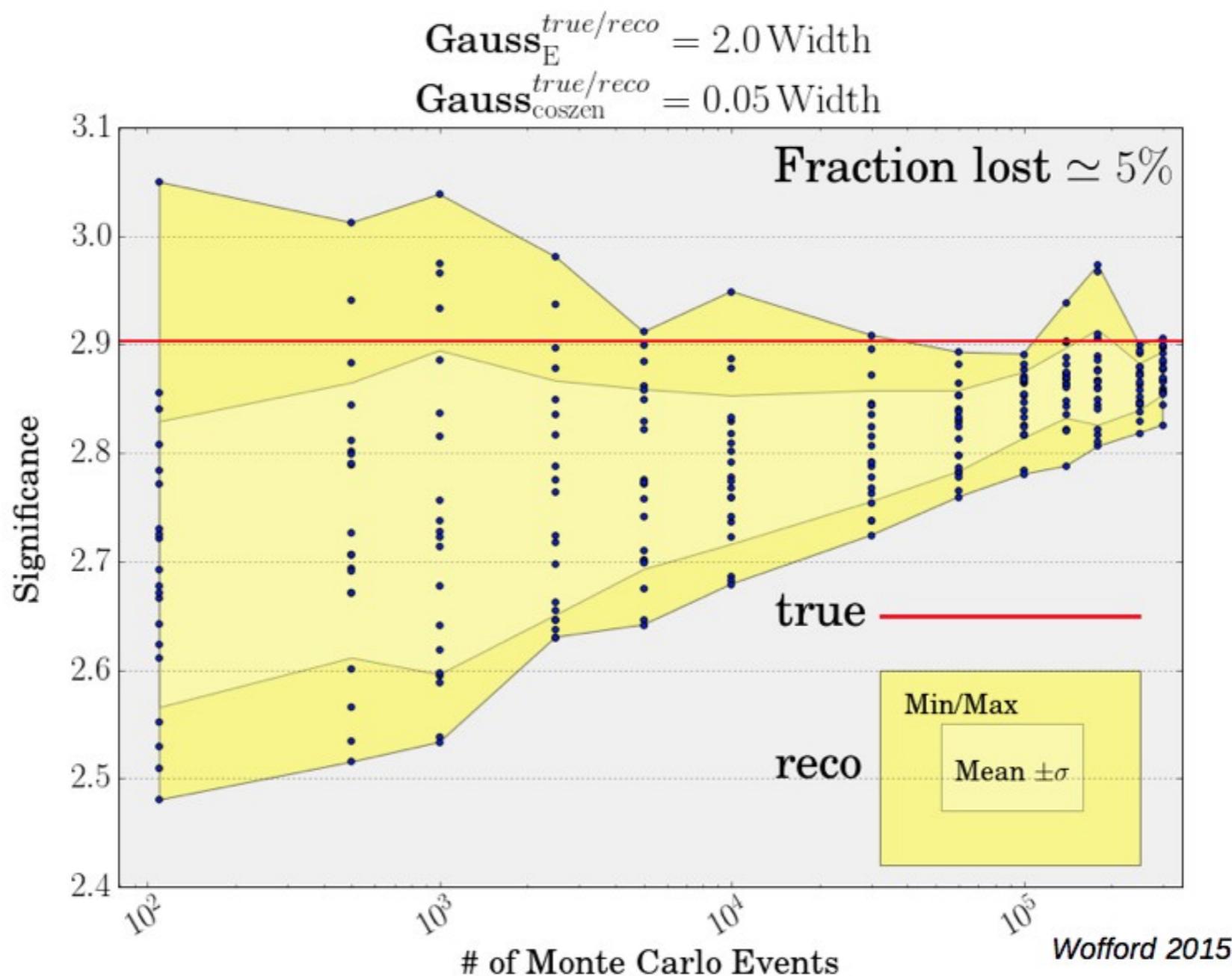


Pull method vs Fisher Method

- Evaluating Fisher matrix at best-fit point in opposite hierarchy
- Pull vs Fisher

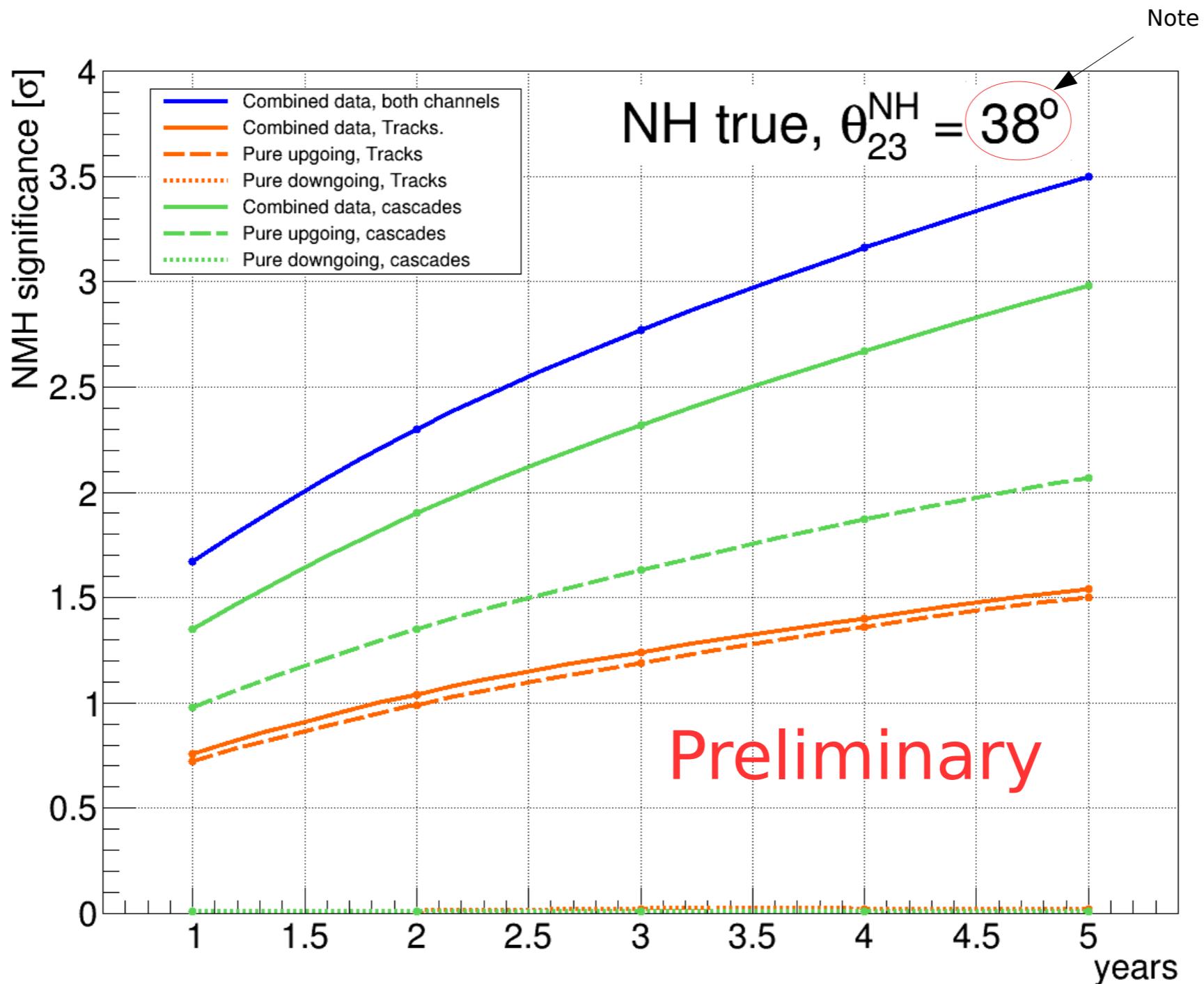


- Precision of the VKBDE



Pure Up/Down vs Combined + Uncertainties

- Output from the Fisher analysis



- Question: Where does the significance come from? Smearing?
Constraining Uncertainties?



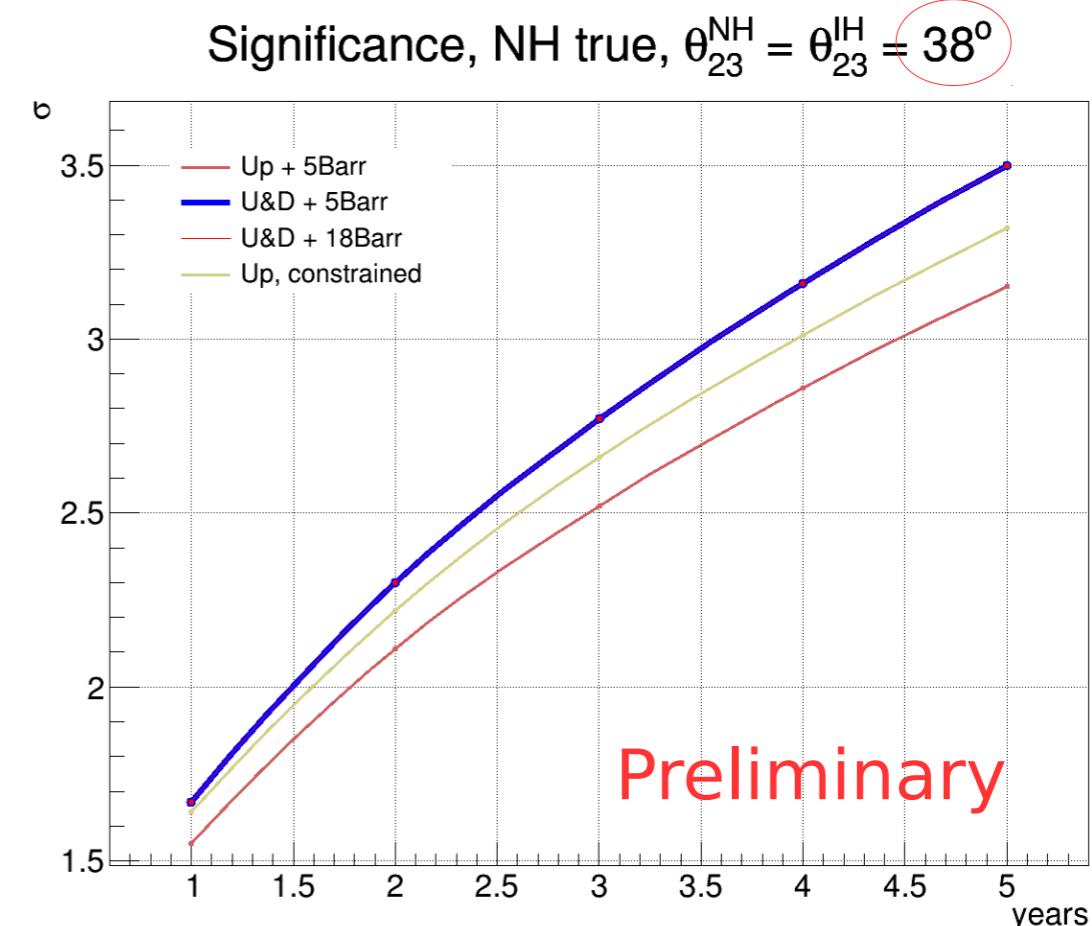
Check: Constraints vs. Smearing - 38 deg

- Check: Use constraints from the pure down going sample as input for the pure up going sample, and check the significance improvement.

Up going only, uncertainty parameters constrained by down going region

NMH, comb: hierarchy significance (sigma): 3.32

parameter	impact [%]	best fit	full
Hierarchy	100.0	0.000e+00	3.012e-01
theta23	31.3	8.639e-01	1.655e-02
deltam31	16.1	-2.370e-03	3.911e-05
energy_scale	2.8	1.000e+00	1.266e-02
flux_hadronic_H	2.6	0.000e+00	1.778e-01
aeff_scale	1.6	1.000e+00	4.312e-02
flux_hadronic_I	1.5	0.000e+00	2.676e-01
theta13	0.5	1.484e-01	3.472e-03
flux_hadronic_E	0.4	0.000e+00	7.799e-01
flux_hadronic_Y	0.1	0.000e+00	4.938e-01
nue_numu_ratio	0.0	1.000e+00	1.668e-02
flux_spectral_index_d	0.0	0.000e+00	4.053e-01
nu_nubar_ratio	0.0	1.000e+00	1.000e-01



- The added constraints boost our significance from 3.15σ to 3.32σ
- Using statistics and smearing in the downgoing region as well will bring it to 3.50σ

Constraint on Parameters (5yrs)

Upgoing only

NMH, comb: hierarchy significance (sigma): 3.15

parameter	impact [%]	best fit	full
Hierarchy	100.0	0.000e+00	3.179e-01
deltam31	19.4	-2.370e-03	3.991e-05
energy_scale	3.5	1.000e+00	1.296e-02
flux_hadronic_H	3.1	0.000e+00	2.879e-01
theta23	2.7	6.745e-01	8.932e-03
aeff_scale	1.4	1.000e+00	6.289e-02
flux_hadronic_I	0.8	0.000e+00	4.413e-01
theta13	0.4	1.484e-01	3.488e-03
flux_hadronic_E	0.1	0.000e+00	9.058e-01
nue_numu_ratio	0.1	1.000e+00	1.813e-02
flux_hadronic_Y	0.0	0.000e+00	6.977e-01
flux_spectral_index_d	0.0	0.000e+00	6.372e-01
nu_nubar_ratio	0.0	1.000e+00	1.000e-01

Down going only

NMH, comb: hierarchy significance (sigma): 0.03

parameter	impact [%]	best fit	full
Hierarchy	100.0	0.000e+00	3.109e+01
theta23	80.5	6.745e-01	8.020e-01
nue_numu_ratio	36.2	1.000e+00	2.118e-02
energy_scale	9.3	1.000e+00	3.627e-02
aeff_scale	8.4	1.000e+00	8.666e-02
flux_hadronic_E	0.4	0.000e+00	8.567e-01
flux_hadronic_Y	0.4	0.000e+00	6.535e-01
flux_hadronic_H	0.4	0.000e+00	2.497e-01
deltam31	0.0	-2.370e-03	5.000e-05
flux_hadronic_I	0.0	0.000e+00	4.017e-01
flux_spectral_index_d	0.0	0.000e+00	5.628e-01
theta13	0.0	1.484e-01	3.491e-03
nu_nubar_ratio	0.0	1.000e+00	1.000e-01

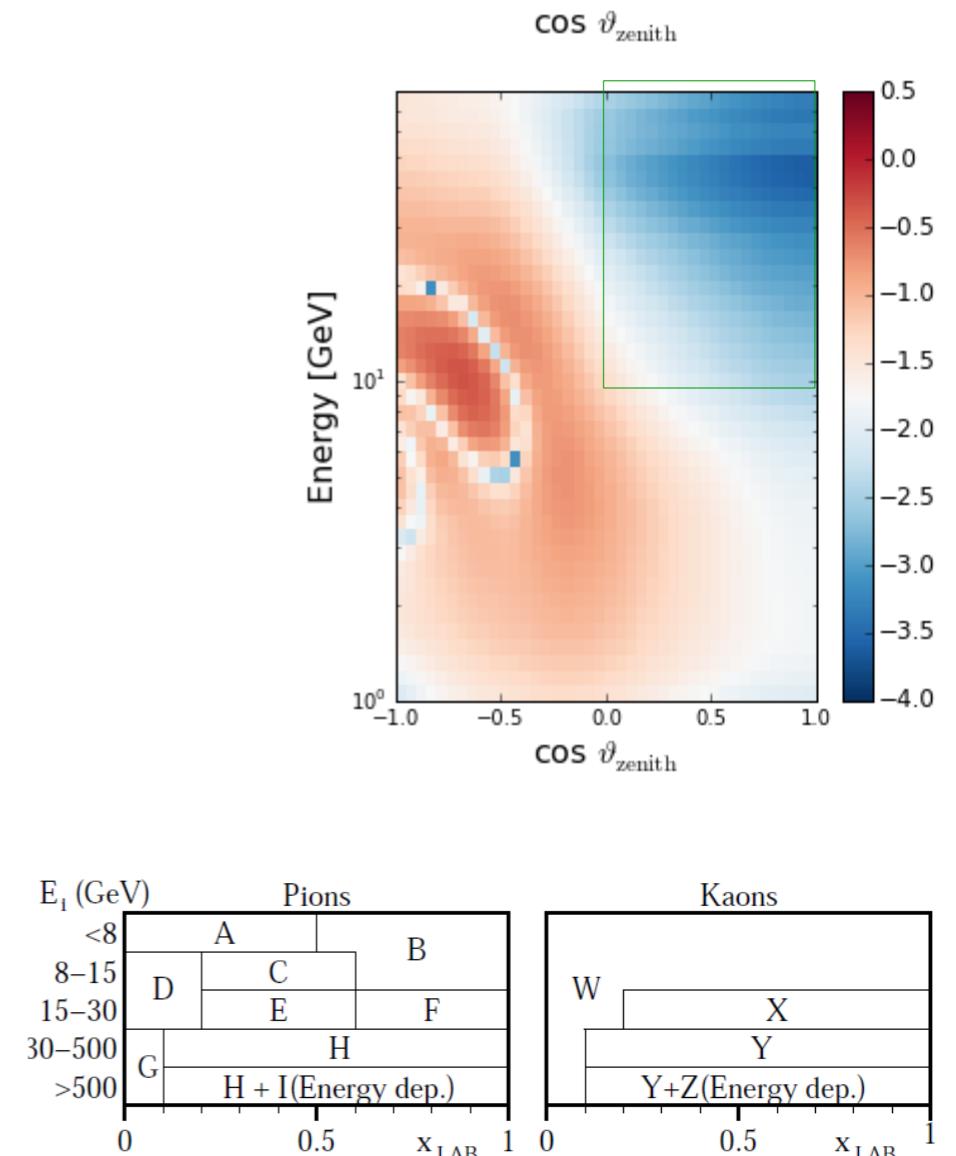
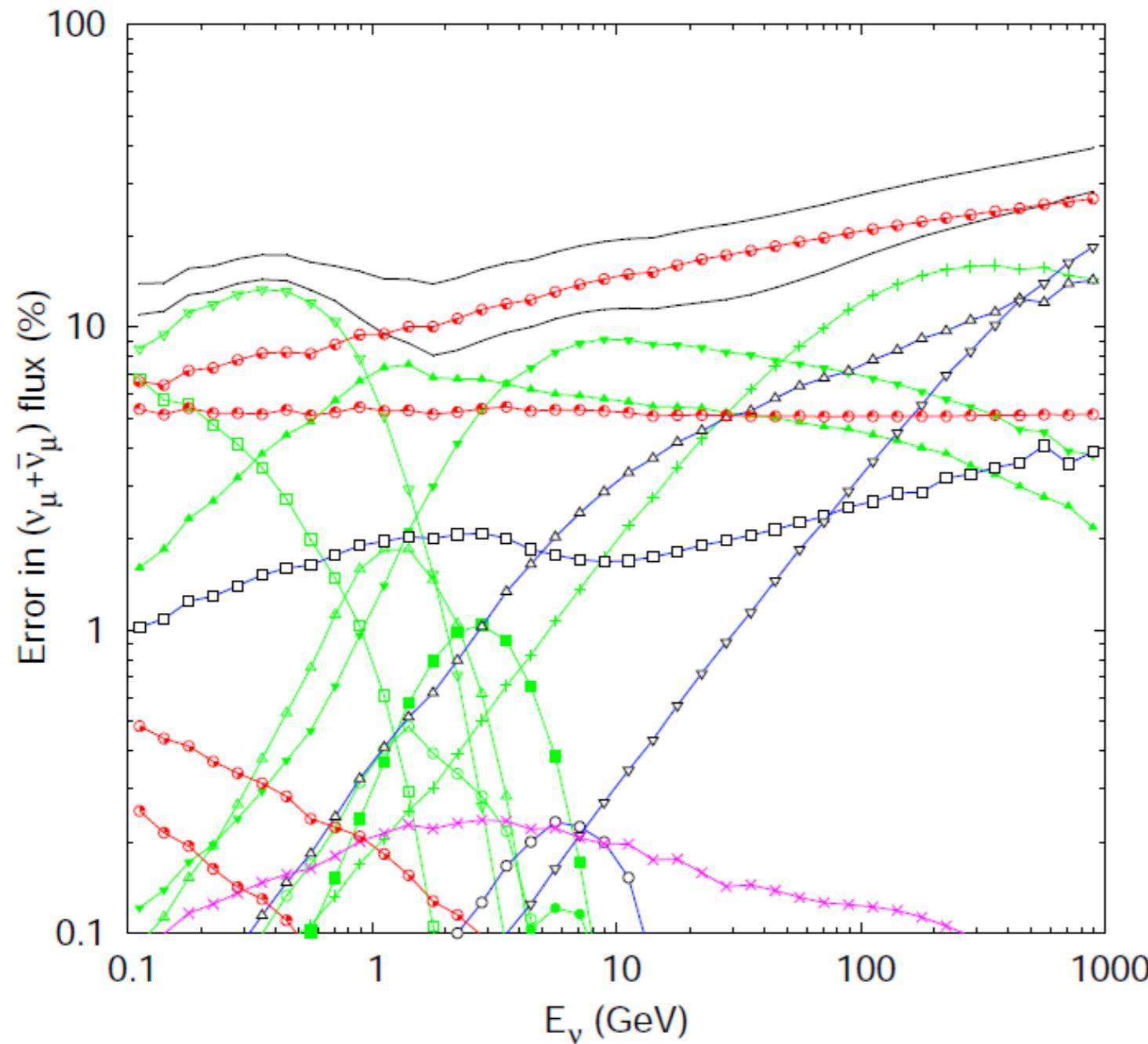
Up and Down going

NMH, comb: hierarchy significance (sigma): 3.50

full	parameter	impact [%]	best fit
	hierarchy	100.0	0.000e+00
2.859e-01	deltam31	16.3	-2.370e-03
3.447e-05	energy_scale	2.6	1.000e+00
1.056e-02	aeff_scale	0.9	1.000e+00
4.719e-02	nue_numu_ratio	0.7	1.000e+00
8.512e-03	theta13	0.5	1.484e-01
3.488e-03	flux_hadronic_I	0.3	0.000e+00
2.105e-01			

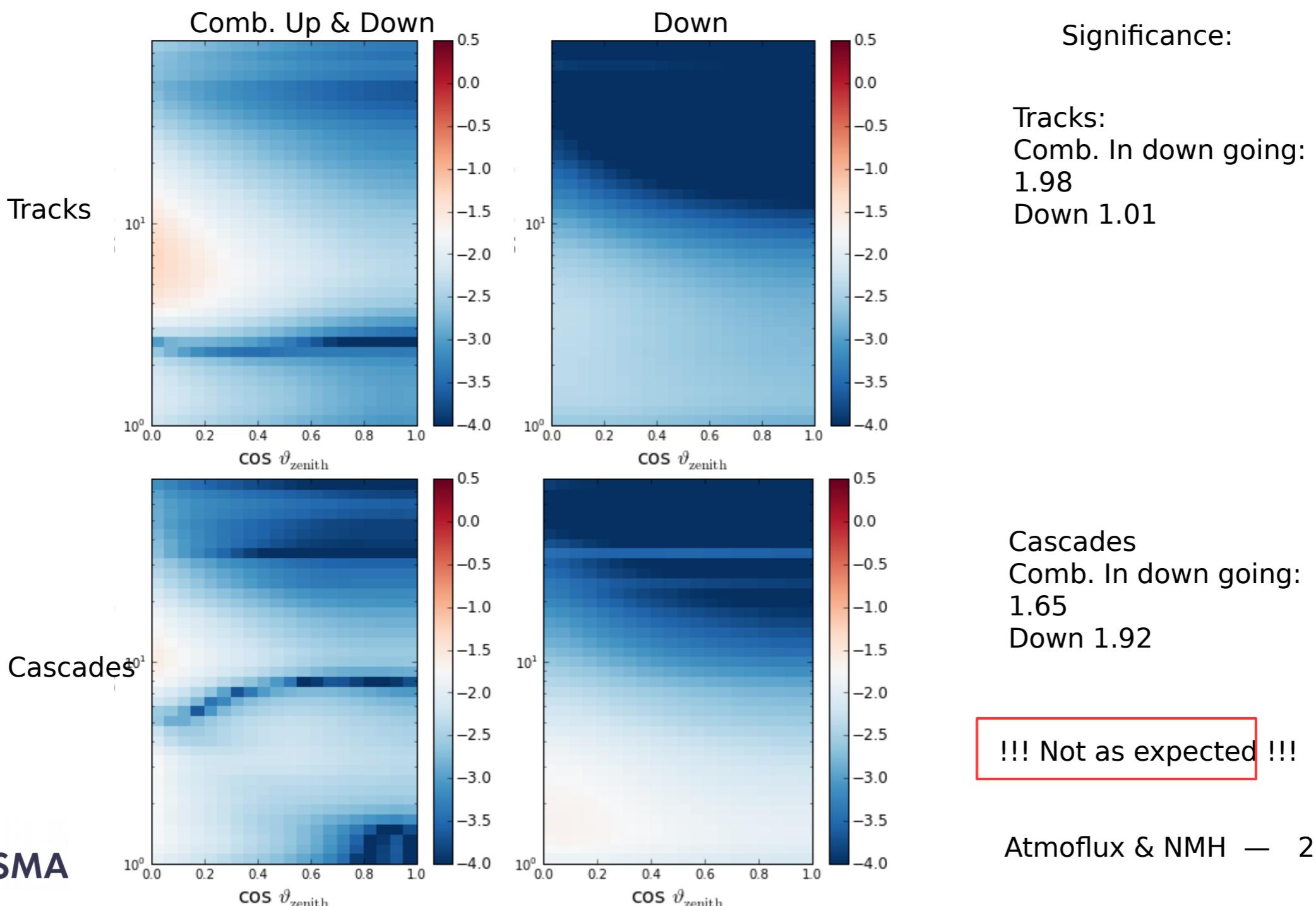
Constraining the uncertainties

■ Barr uncertainty overview

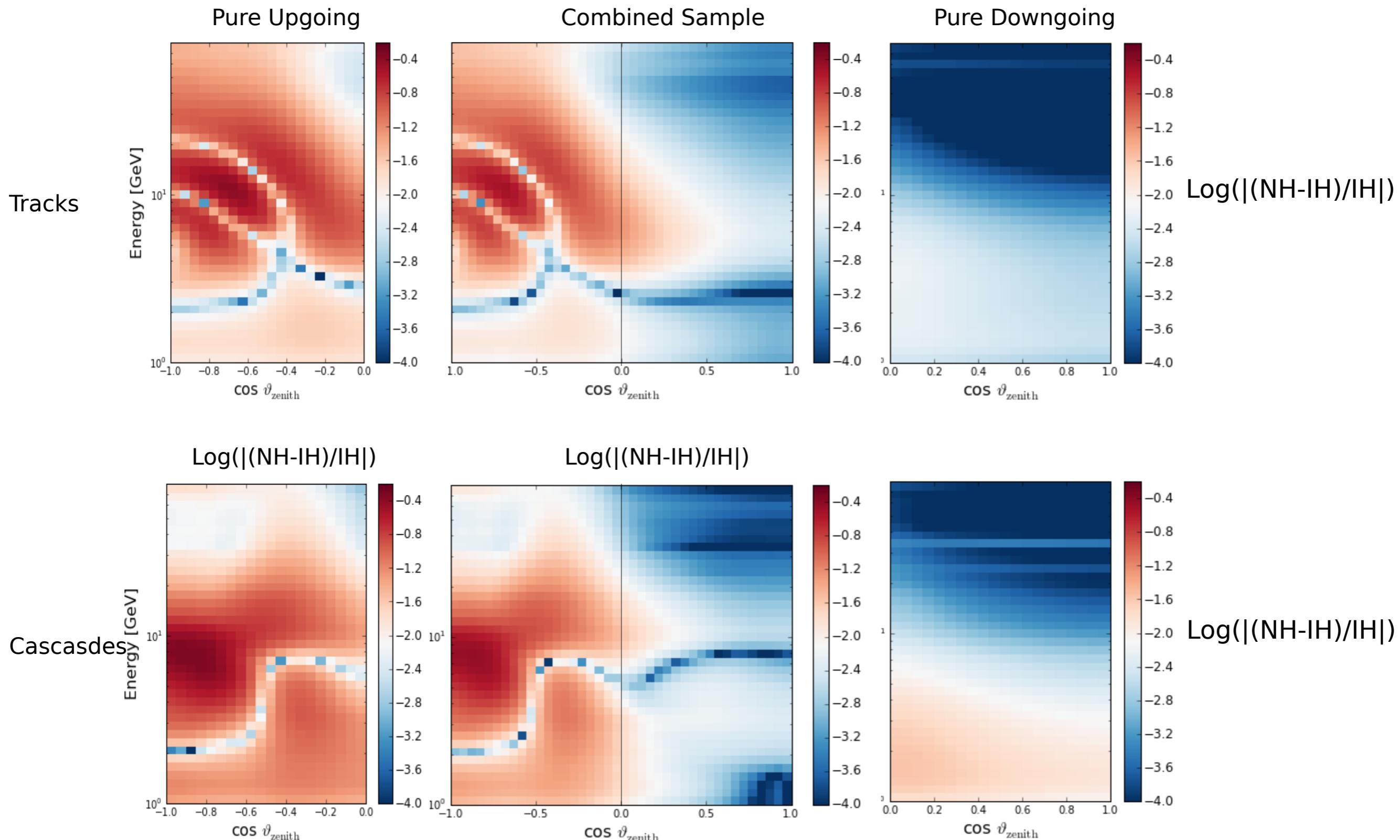


Further Sanity-check: Downgoing Only (38 deg)

- Hypothesis: Significance in down going region is caused by smearing.
- Running the analysis only using the down going flux, we expect very little to no significance.
- Plot again in $\log(|(\text{NH-IH})/\text{IH}|)$, for 3 years



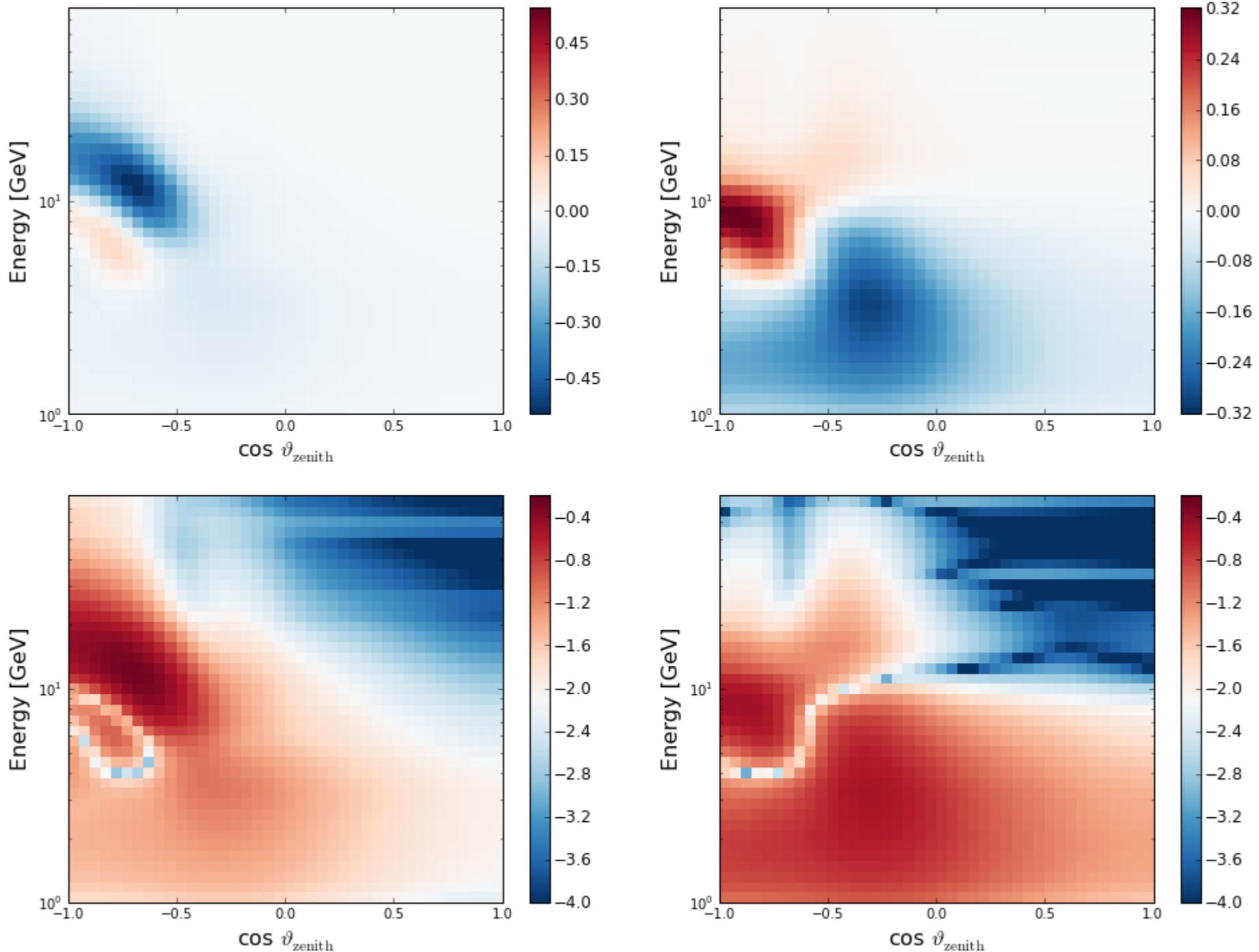
Pure Up/Down vs Combined - 38 deg



NOTE: No Uncertainties
Included!

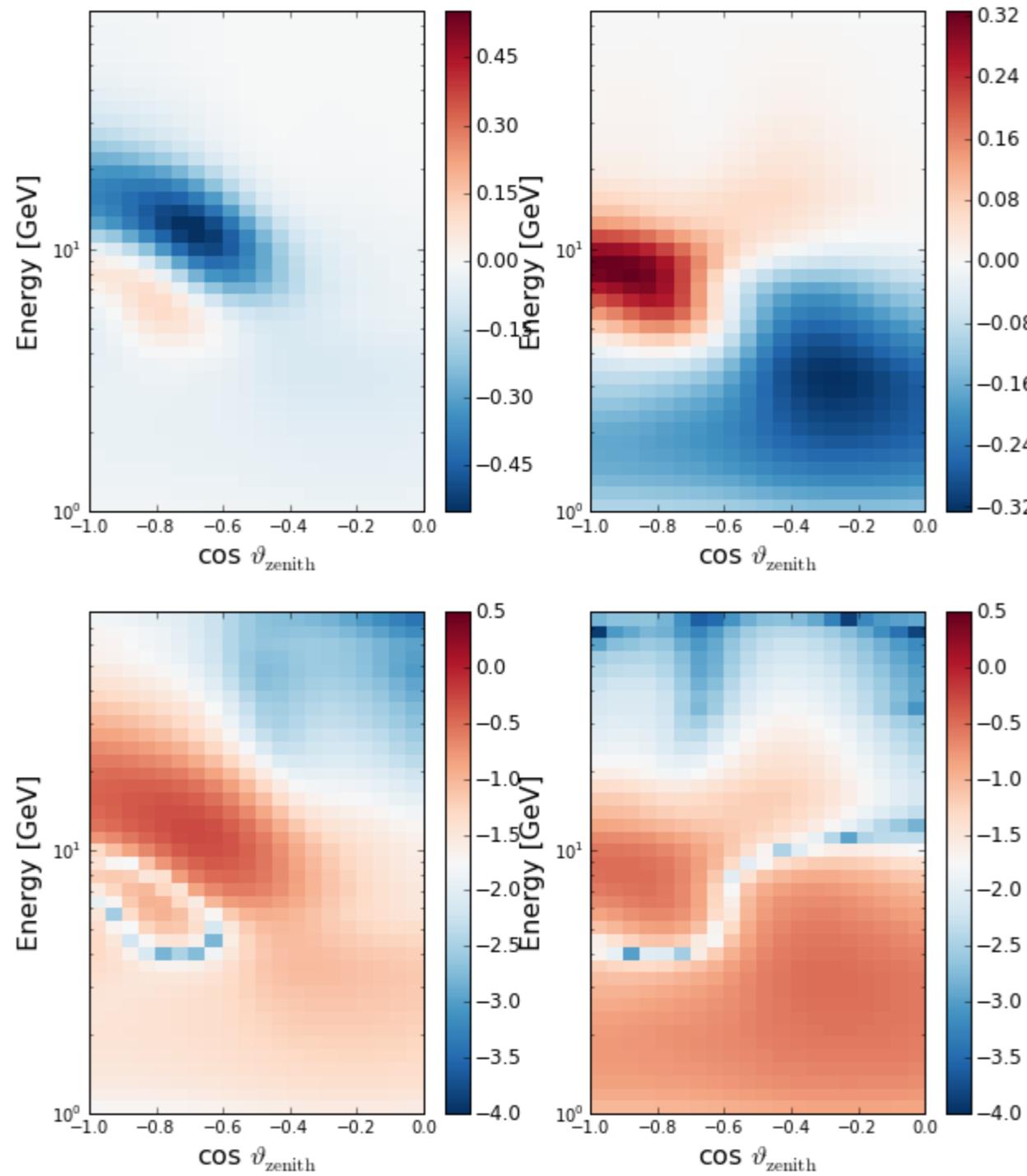
Combined Sample Templates

- Mixing Angles: NH = 42.3 deg. IH = 49.5 deg.



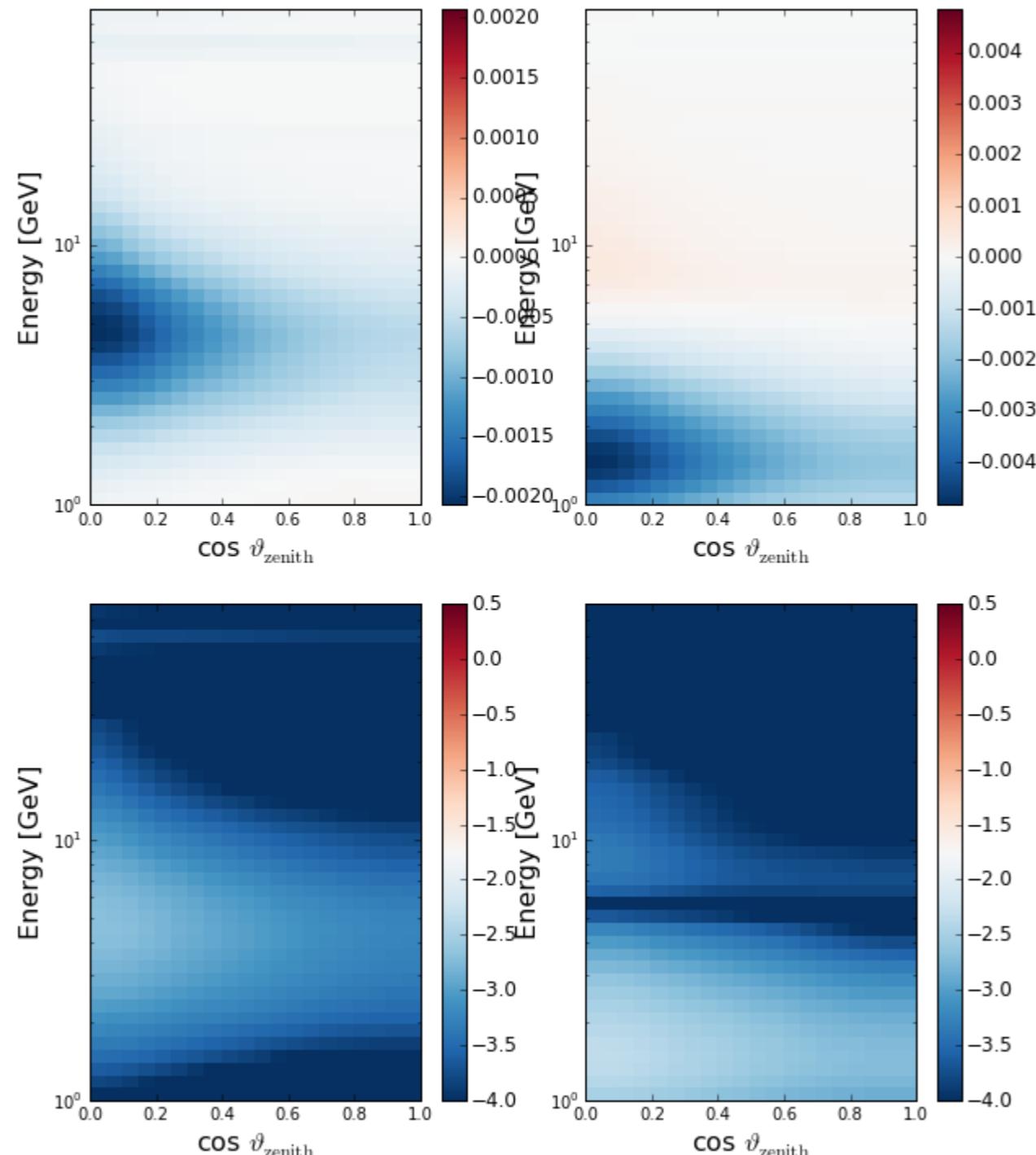
Upgoing Sample Templates

- Mixing Angles: NH = 42.3 deg. IH = 49.5 deg.



Downgoing Templates

- Mixing Angles: NH = 42.3 deg. IH = 49.5 deg.



Pure Up/Down vs Combined - stats - 38 deg.

- Significance in regions and channels

	Tracks	Cascades
Pure Up	7.25	7.78
Pure Down	1.14	2.18
Pure total	7.33	8.07
Comb. Up	7.11	7.56
Comb. Down	2.24	1.87
Comb. total	7.45	6.86

- Smearing seem to have diverse effects in different channels
- Particularly the cascade channel suffers from this
- Question: What if we include the uncertainties?

NOTE: No Uncertainties
Included!

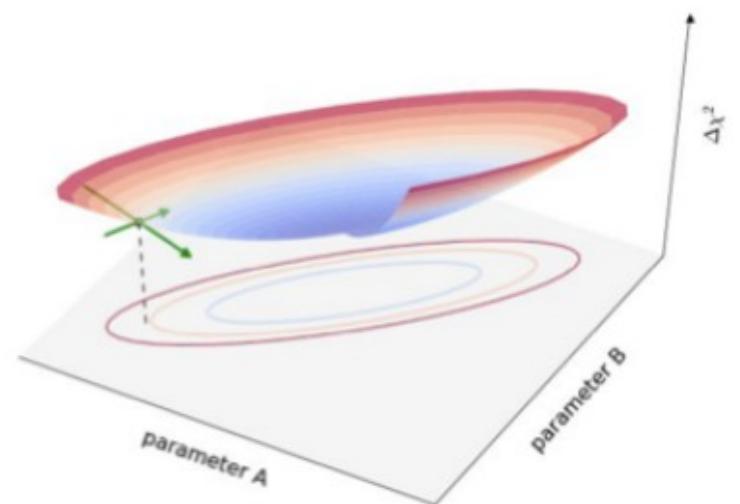
The Fisher Method

- Instead of typical i-parameter Likelihood (which must be evaluated at each grid point giving i^i points), we can approximate the full likelihood with a:
- Multivariate Gaussian Distribution:

$$L \approx N \exp \left[-\frac{1}{2} (\theta_i - \hat{\theta}_i) F_{ij} (\theta_j - \hat{\theta}_j) \right]$$

- With: $\hat{\theta}_i$ being the maximum likelihood estimators
 F_{ij} the Fisher matrix for the parameters evaluated

$$F_{ij} \equiv \left. \frac{-\partial^2 \ln L(x_o; \theta)}{\partial \theta_i \partial \theta_j} \right|_{ML}$$



- Caveat: Estimators must be gaussian \rightarrow data AND estimators gaussian \rightarrow estimators are linear. This is not the case for certain values of θ_{23}