Measuring total neutrino cross-section at intermediate energies (~100 GeV to a few TeV)

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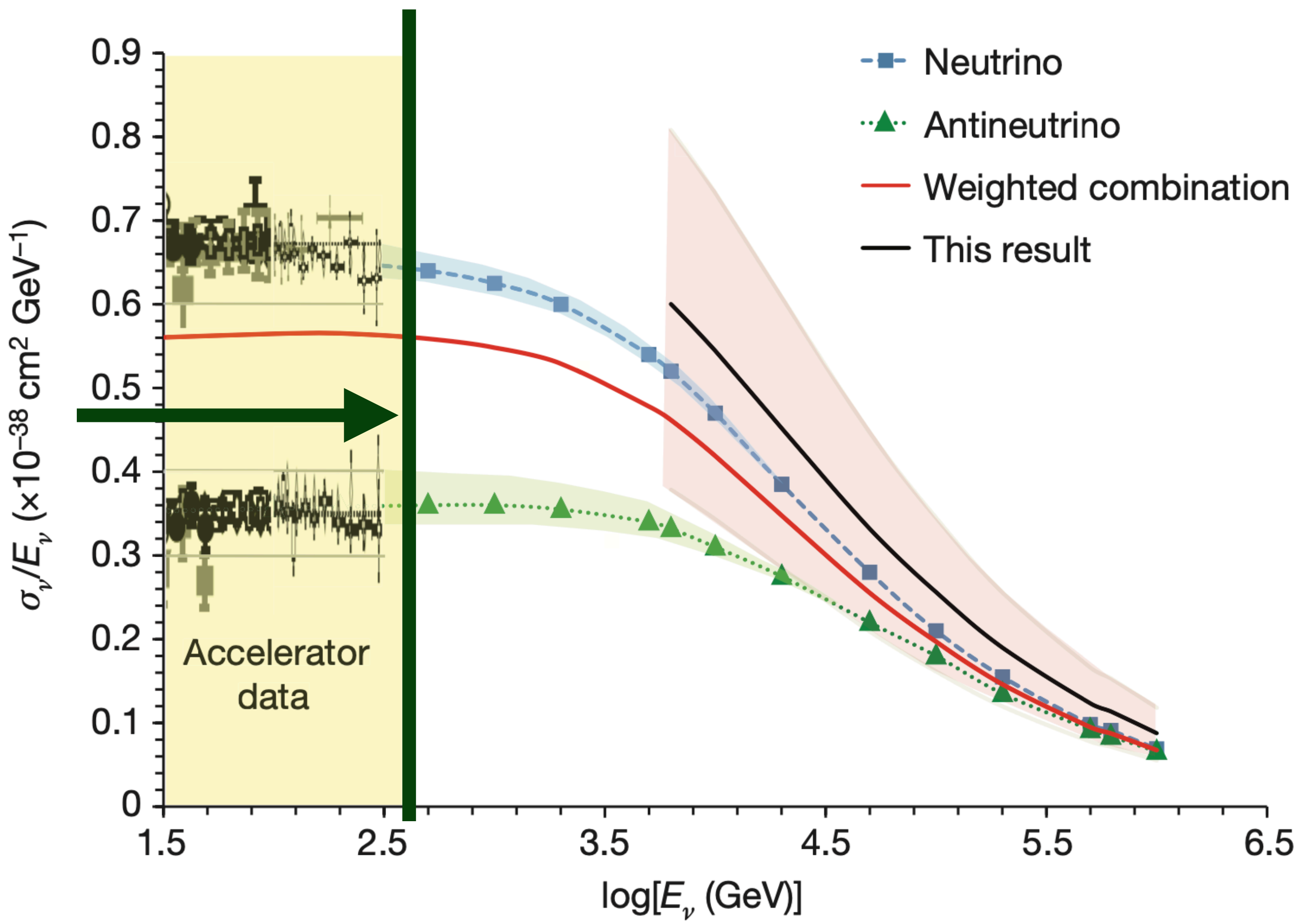
Cross-section measurement at TeV energy scale

- Target: ν_μ CC total cross-section
- Existing accelerators up to ~350 GeV



plot from [1]

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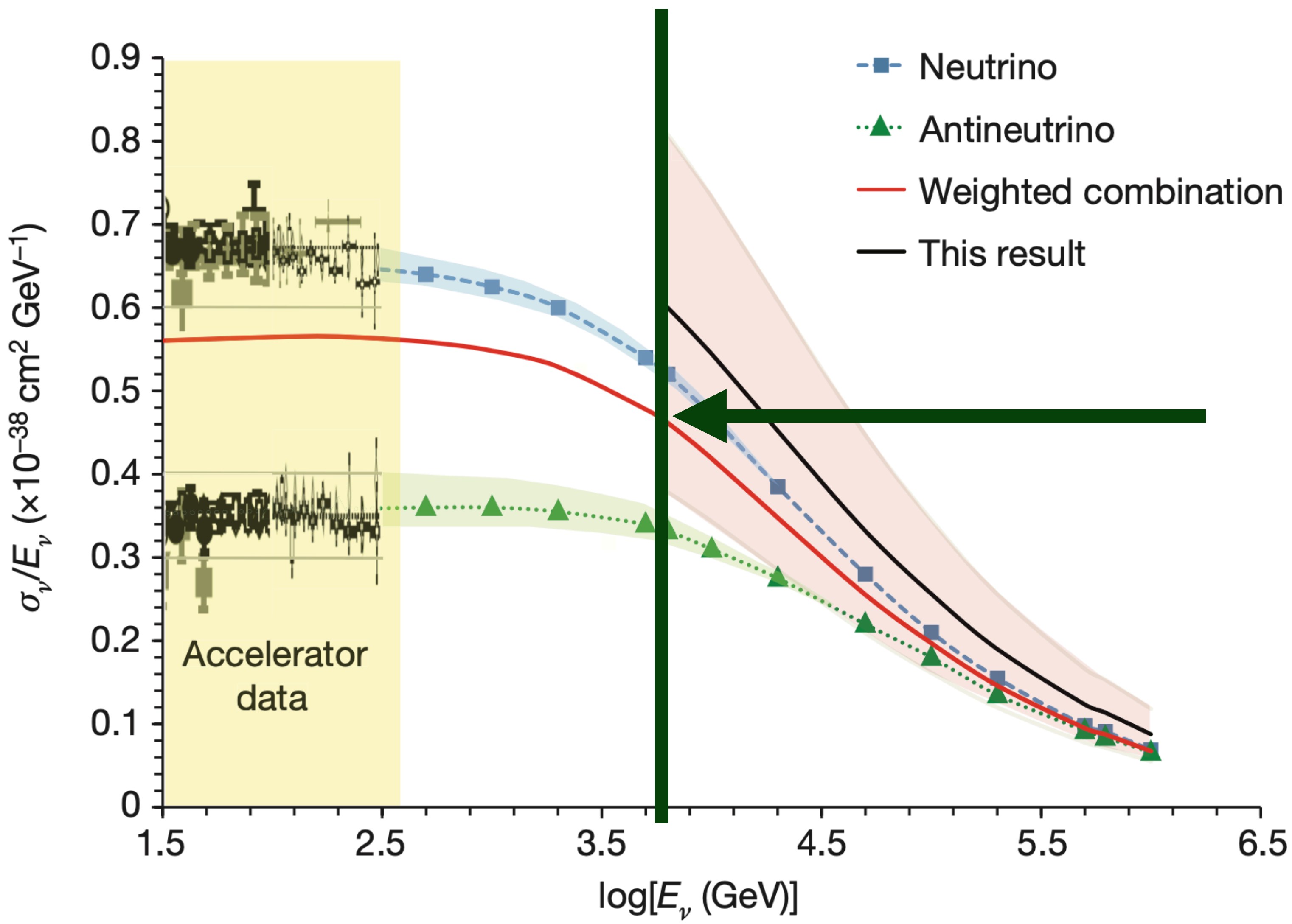
- IceCube measurements via neutrino-earth absorption - fades into very small effect by few TeV



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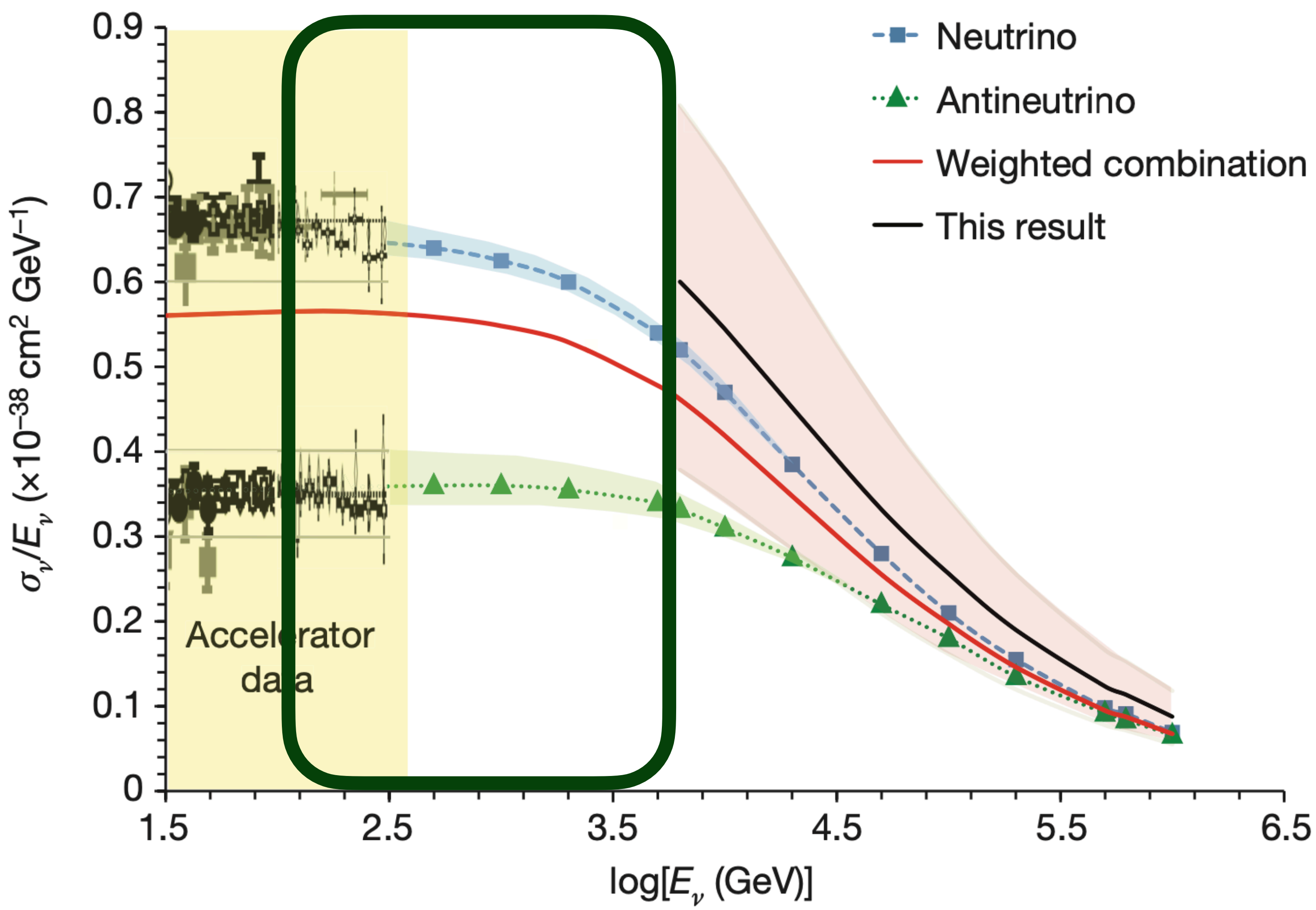
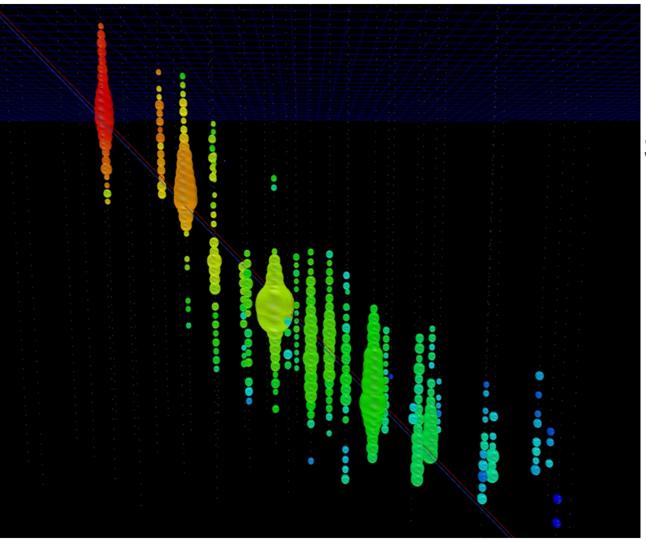


plot from [1]

IceCube Neutrino Observatory

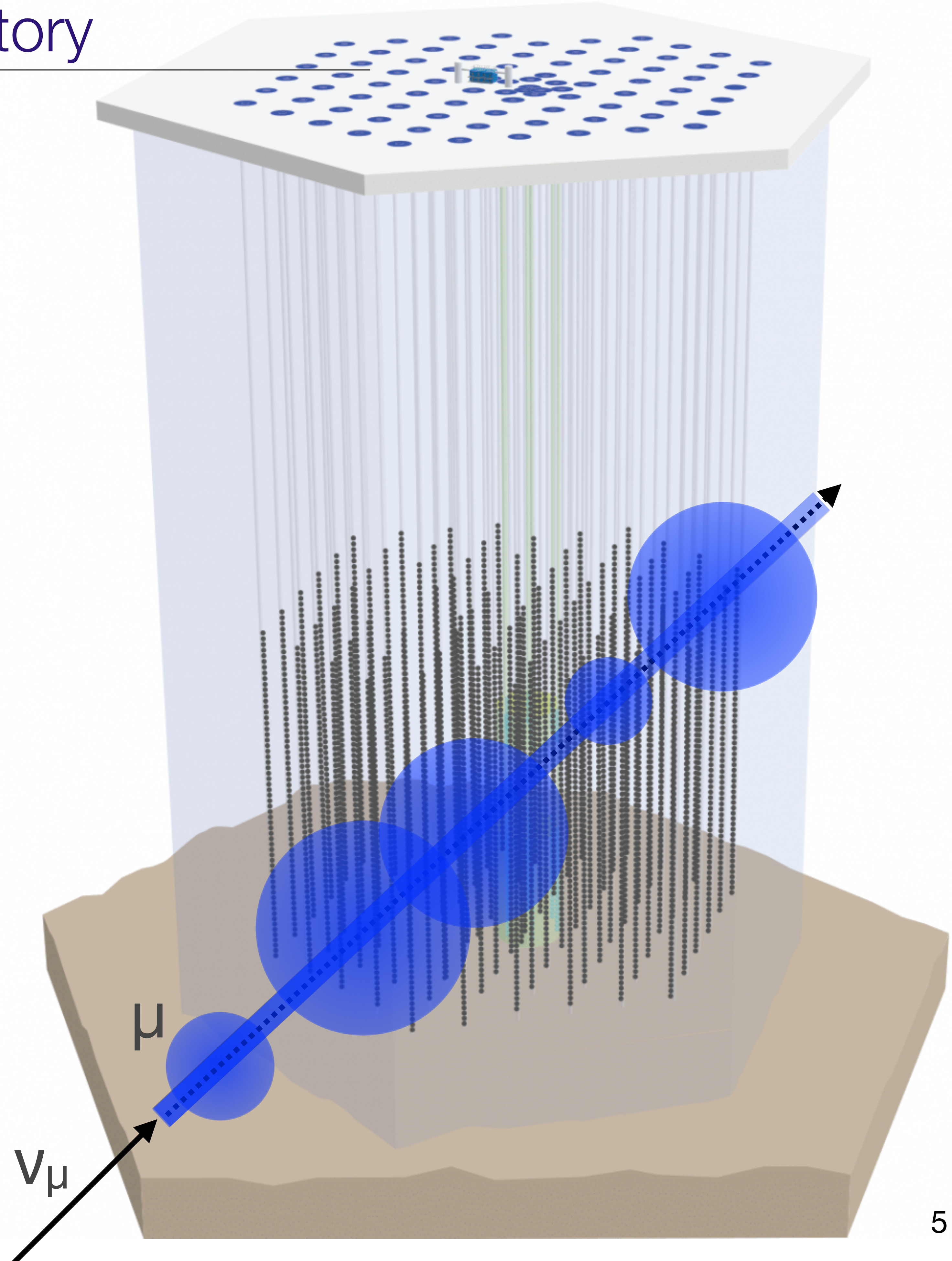
- Instruments ~1 km^3 of the deep Antarctic glacier with optical sensors at South Pole Station
- Detects Cherenkov radiation emitted from charged particles produced by ν interactions in or near detector volume
- Use amount & timing of deposited charge to reconstruct particle properties

Track-like event



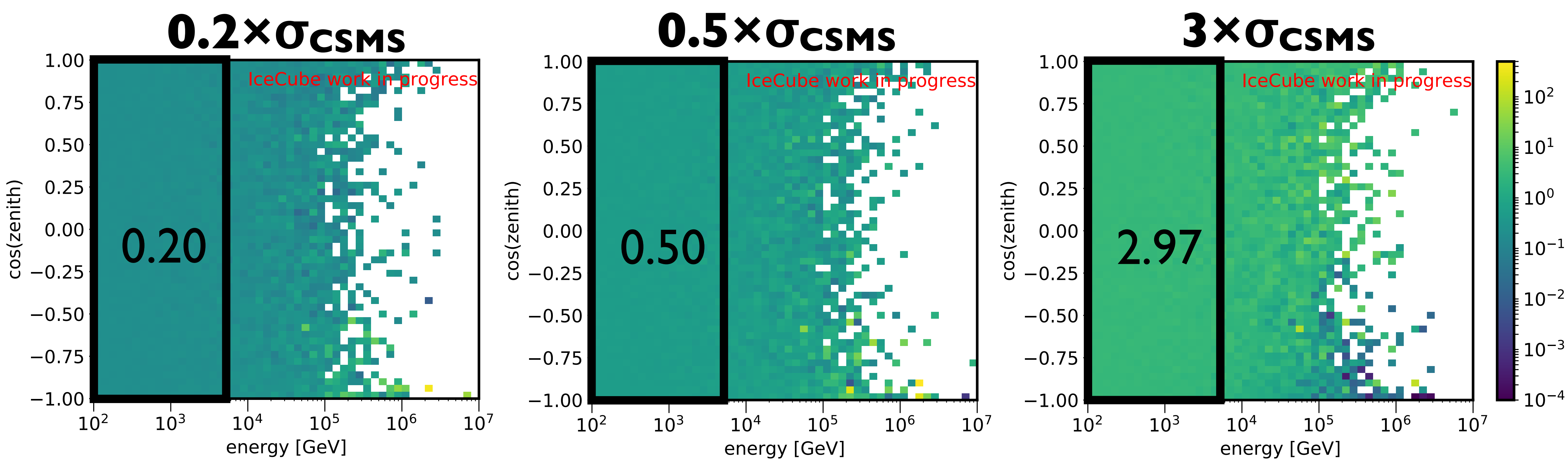
size of sphere: amount of charge deposited

colour: timing (red is early, blue is late)



Cross-section measurement at TeV energy scale

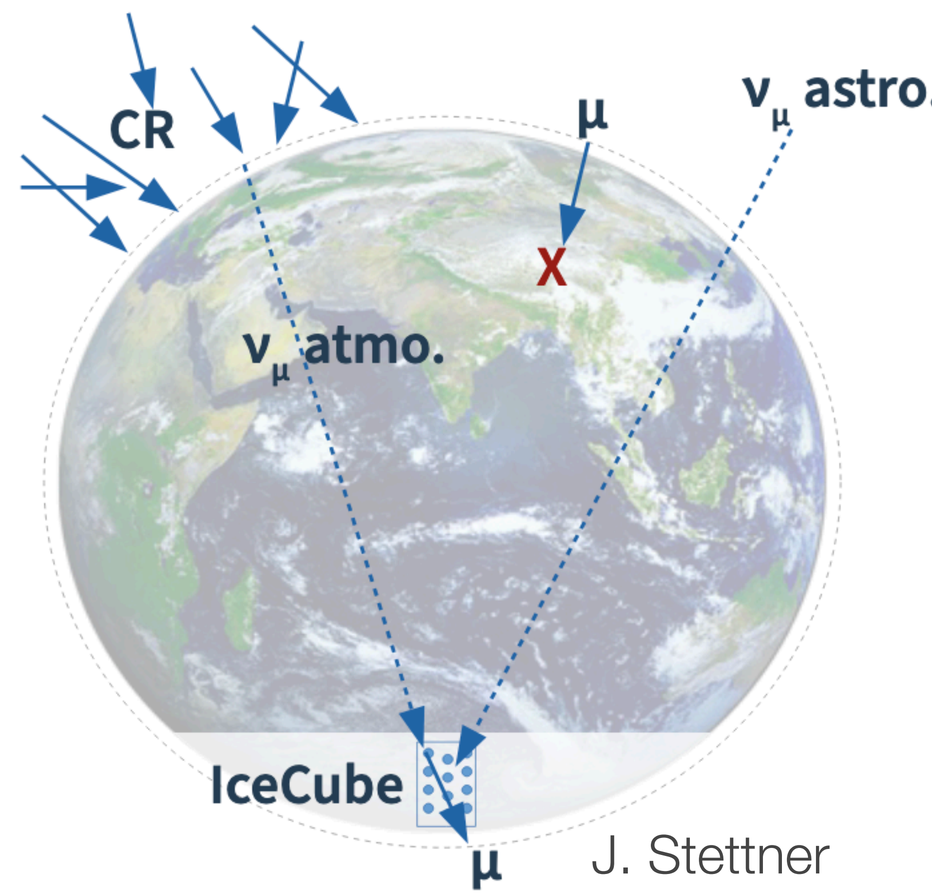
- Expected that the event rate scales linearly with cross-section and can be measured with normalization of the predicted flux
- Check assumption of linearity with neutrino generator simulation - success!



ratio of expected events for modified σ_{CSMS} over standard σ_{CSMS}

Use existing event sample and analysis software

- Required: high statistics, clean, well-understood sample of ν_μ CC
- Use diffuse astrophysical flux through-going ν_μ event selection [2]
    - zenith > 85° to remove atmospheric μ
    - select high-quality, ν_μ-induced muon tracks
    - 8.5 years of data*
- Perform a forward folding fit of reconstructed energy and zenith using a binned Poisson likelihood



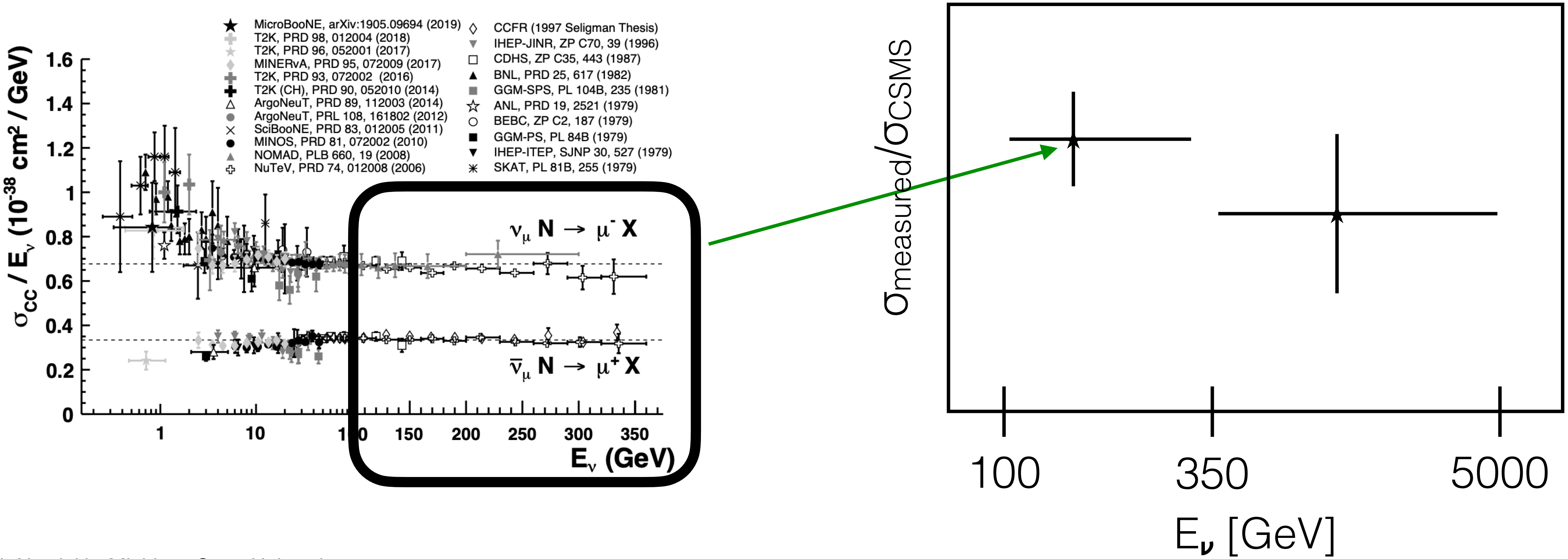
J. Stettner

*full event selection contains 9.5 years, but 1st year is calibrated differently & will be dropped for this analysis

Physics parameters

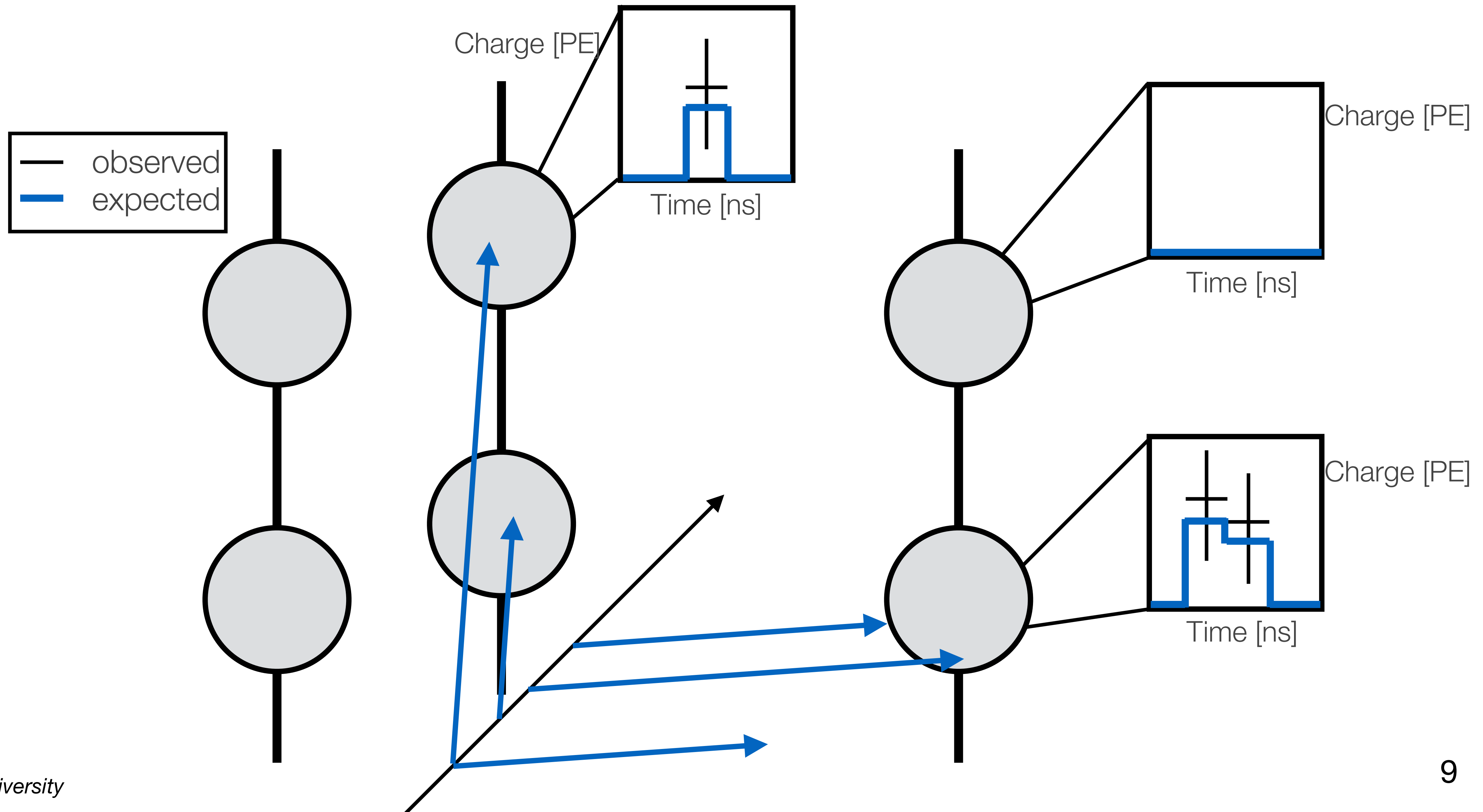
- Break up energy range into multiple bins, measuring a scaling factor relative to the CSMS model [3] for each
  - scaling applies to $\nu + \overline{\nu}$, since IceCube has no mechanism to distinguish ν and $\overline{\nu}$
- Use accelerator measurements as a prior to partially break correlation with atmospheric flux normalization
- Replace existing energy estimator with one tailor-made for the region of interest

conceptual figure



Reconstruction - DirectReco

- Provides a prediction of expected light at each photo-sensor for event hypothesis
- Utilizes a GPU-based algorithm to parallelize the direct propagation of photons. This permits using complete ice model descriptions
- Replaces the previous use of lookup tables to estimate the detector response, which limited complexity of ice modelling

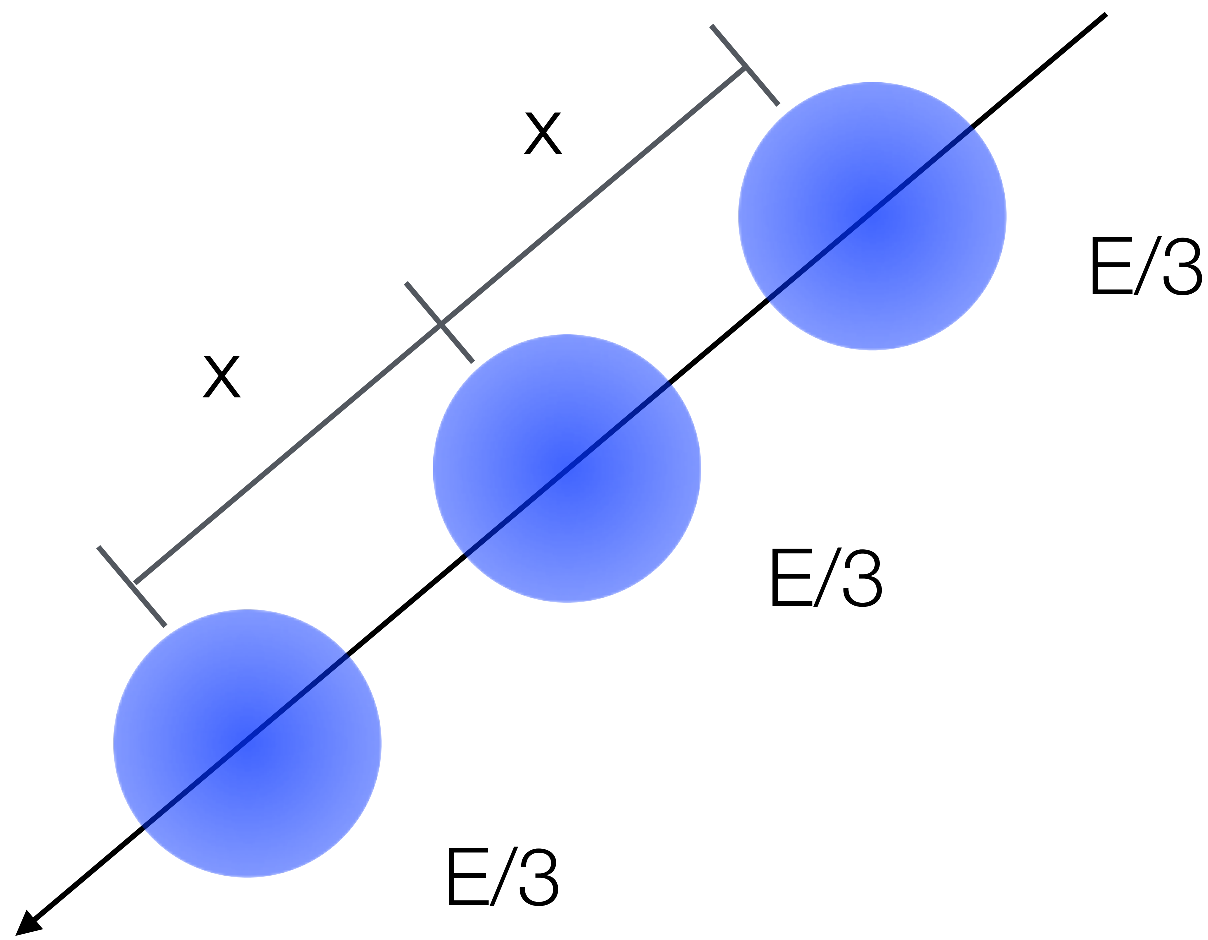


Reconstruction - DirectReco

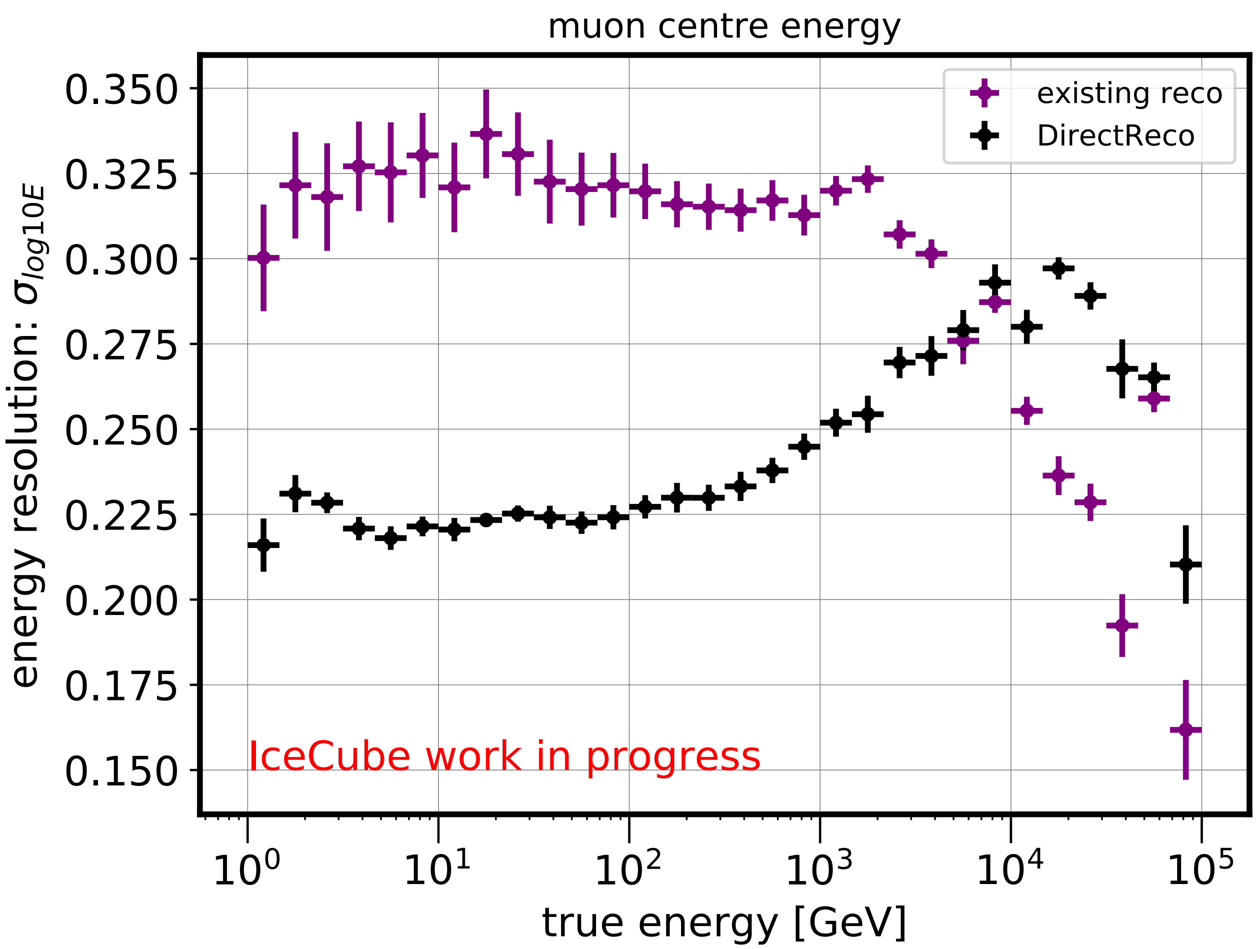
- Goal: hypothesis tailored to the unique properties of the event type, i.e. through-going muon track, ~100 GeV to ~TeV

- Approximate track as a series of point-like emissions, with
  - equidistant spacing along the track
  - an equal fraction of total track energy

e.g. a muon with energy of E GeV and x m cascade spacing



Reconstruction update - resolution



- Improvement observed in the energy resolution for a common event sample for muon energies up to ~5 TeV (where stochastic losses start to dominate)

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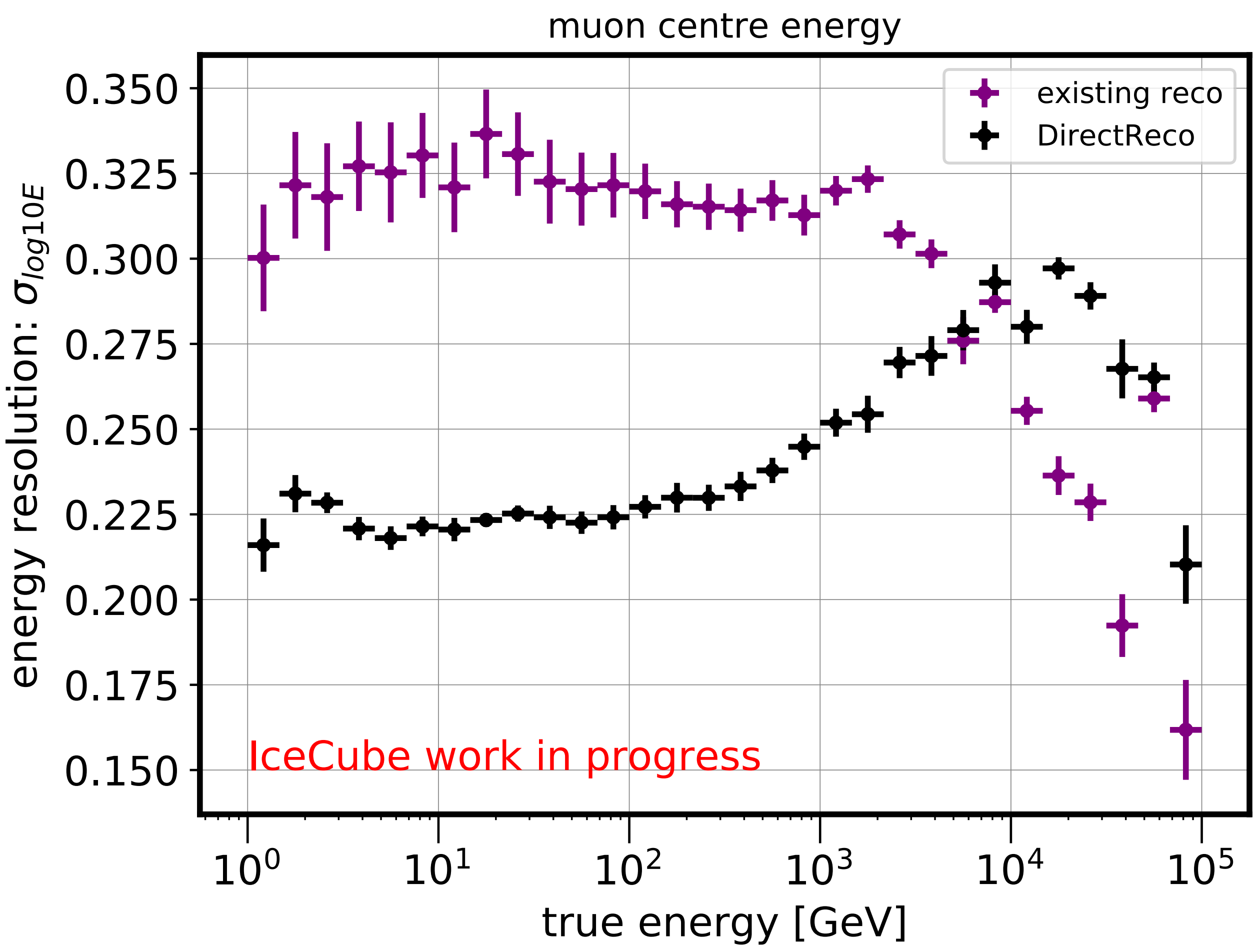
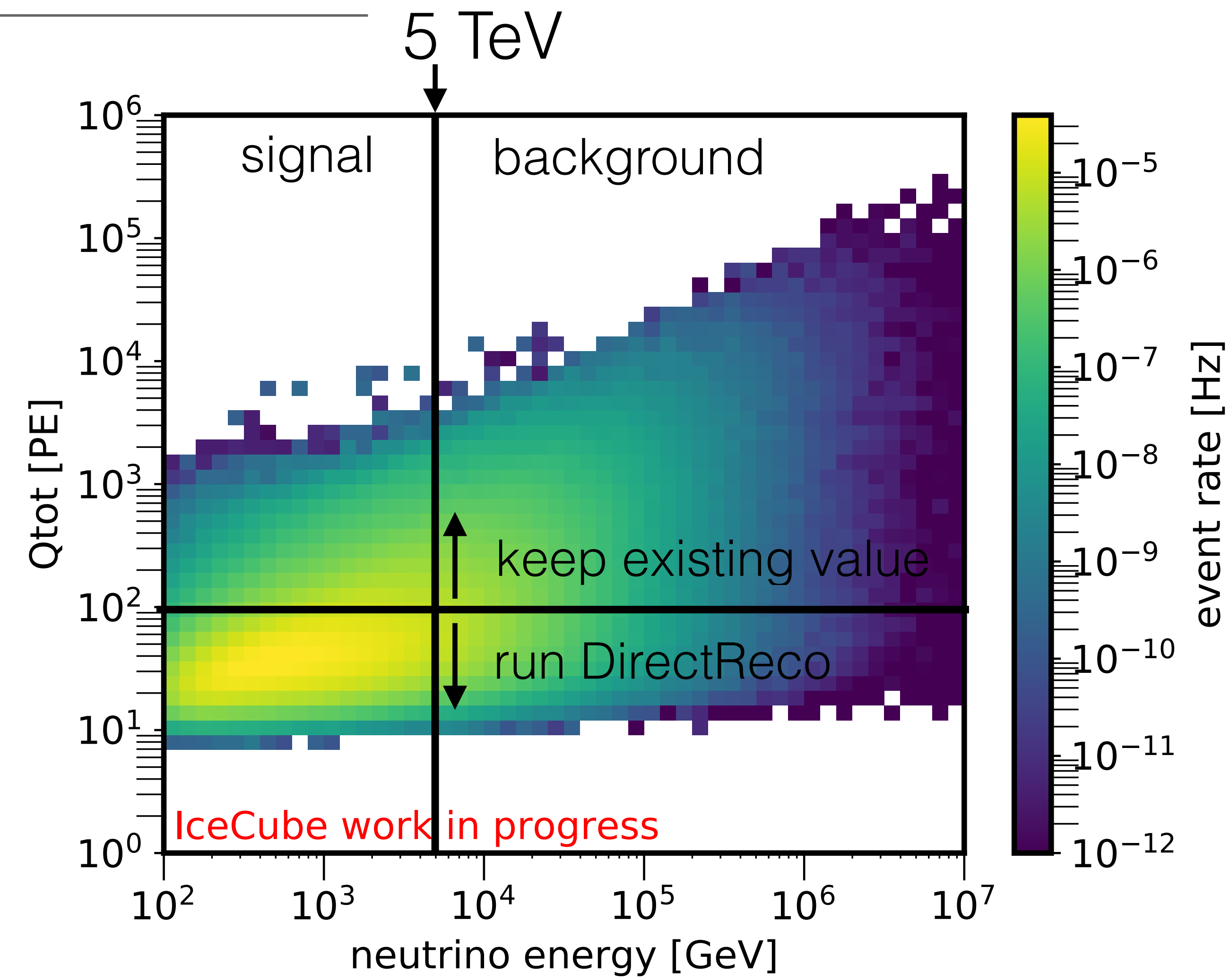




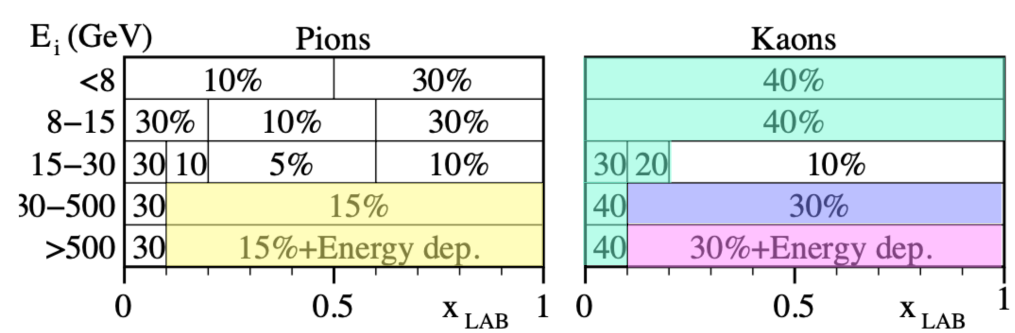
- Improvement observed in the energy resolution for a common event sample for muon energies up to ~5 TeV (where stochastic losses start to dominate)

- Save computing time by re-processing only events with deposited charge (Qtot) < 100 photo-electrons

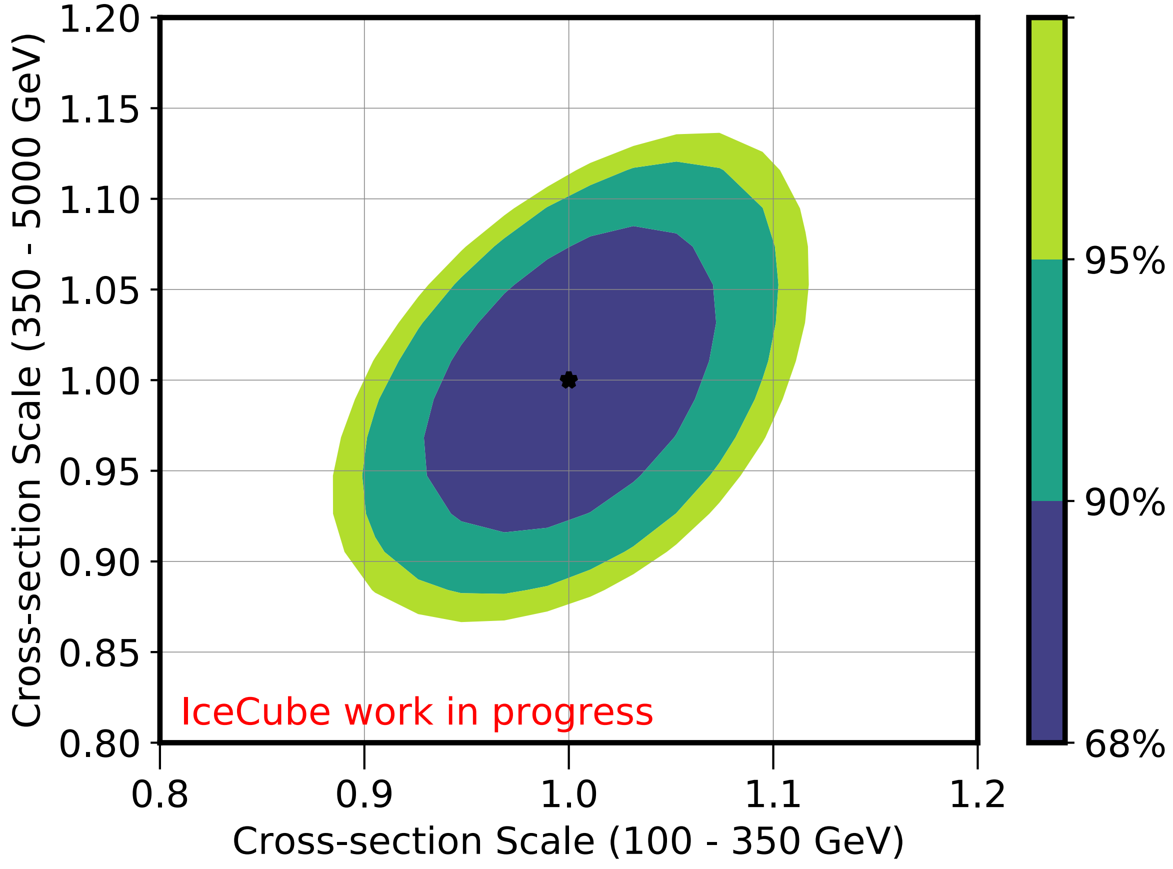
Sources and modelling

- Neutrino flux is modelled with four components:
  - ‘Conventional’ atmospheric neutrinos
  - ‘Prompt’ atmospheric neutrinos
  - Isotropic astrophysical neutrinos, single power-law energy spectrum
  - Mis-reconstructed atmospheric muons (sub-dominant)
- Atmospheric neutrino fluxes are computed using MCEq [4], using H4a cosmic ray model and Sibyll2.3c hadronic model
- Cosmic ray uncertainty modelled via nuisance parameters (interpolate between H4a & GST4, Δ spectral index)
- Hadronic interaction model uncertainties are described using Barr parameters [5] as nuisance parameters, with priors widths from paper

$H^{+/-}$, $W^{+/-}$, $Y^{+/-}$, $Z^{+/-}$



Profile likelihood scans



- Potential measurement looks promising!
- 100 - 350 GeV scale parameter includes prior calculated from overlapping accelerator-based measurements
- Nuisance parameters describing detector modelling effects are not yet included, but their effect is expected to be small

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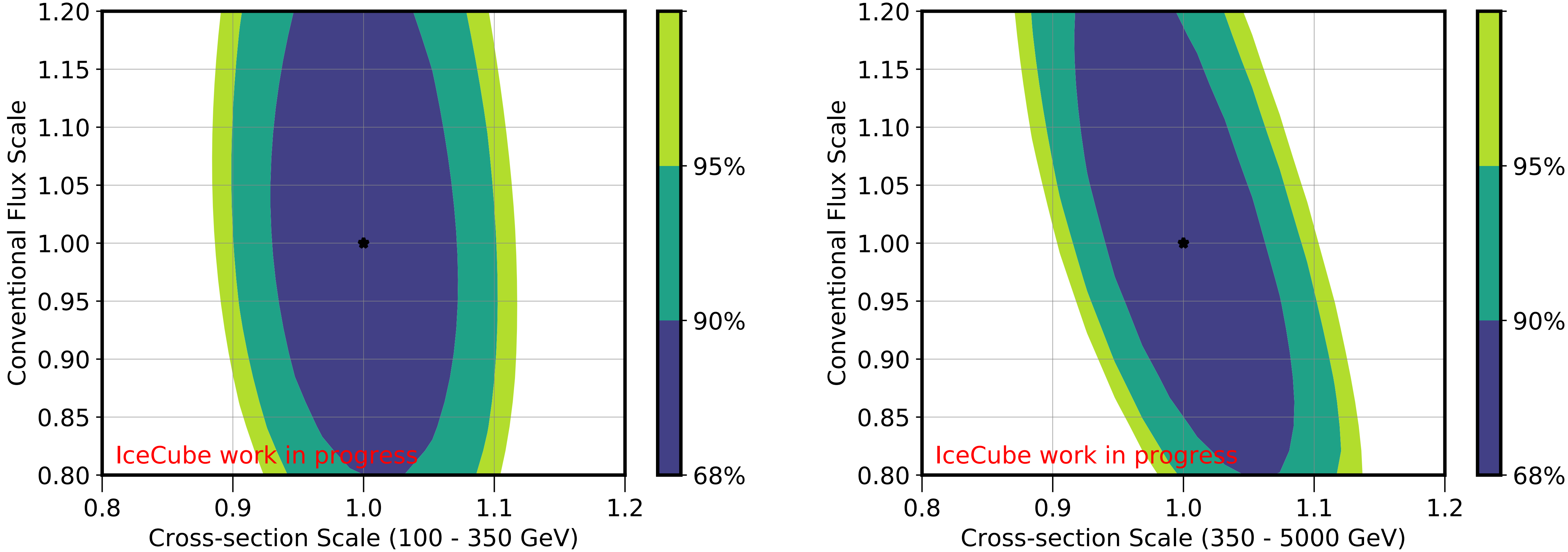

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Summary and outlook

- Analysis goal: measure total neutrino-nucleon cross-section from 100 GeV to 5 TeV
- Use existing IceCube diffuse ν_μ event selection and associated analysis tools as the foundation
- Reconstruction - reprocess events with specifically tailored energy reconstruction (DirectReco) for improved resolution in the region of interest
- First tests look promising! Updates soon
- Remaining work: incorporate detector modelling nuisance parameters into fits & run a few tests (add charge observable, investigate $\nu/\bar{\nu}$ effects)

References

[1] IceCube Collaboration, M. G. Aartsen et al. Nature 551 (2017) 596–600

[2] IceCube Collaboration, J. Stettner, PoS ICRC 2019 (2020) 1017

[3] A. Cooper-Sarkar, P. Mertsch, and S. Sarkar JHEP 08 (2011) 042

[4] Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, and T. Stanev, EPJ Web Conf.99 (2015) 08001

[5] G. D. Barr, T. K. Gaisser, S. Robbins, and T. Stanev, Phys. Rev. D74 (2006) 094009

Backup slides

Fit parameters

neutrino cross-section - apply to conventional, prompt and astrophysical fluxes

atmospheric neutrino a.k.a. conventional flux parameters

charmed atmospheric neutrino a.k.a. prompt flux parameters

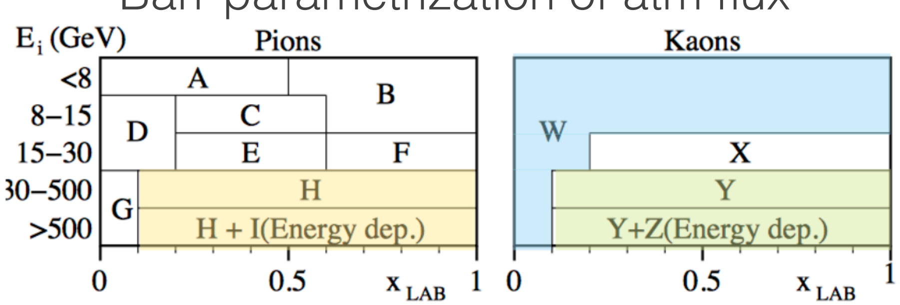
astrophysical neutrino flux parameters**

muon background parameter

detector (ice) related parameters

parameter	description	type
x-sec scale 1	scale x-sec* (100 - 350 GeV)	**physics**
x-sec scale 2	scale x-sec* (350 - 5000 GeV)	**physics**
conventional norm	normalization	nuisance
barr H	modify pion contribution	nuisance
barr W	modify kaon contribution	nuisance
barr Y	modify kaon contribution	nuisance
barr Z	modify kaon contribution	nuisance
delta gamma	Δ cosmic ray spectral index	nuisance
CR grad	interpolation bt primary CR models	nuisance
prompt norm	normalization	nuisance
astro norm	normalization	nuisance
astro gamma	astrophysical spectral index	nuisance
muon template norm	normalization	nuisance
dom efficiency	standard light-yield scaling	nuisance
ice absorption	absorption coeff (bulk ice)	nuisance
ice scattering	scattering coeff (bulk ice)	nuisance
ice hole p0	unified hole ice model	nuisance

Barr parametrization of atm flux



* relative to CSMS

**single power-law hypothesis

Correlation matrix (previous test with existing reconstruction)

IceCube work in progress

neutrino cross-section* - apply to conventional, prompt and astrophysical fluxes

atmospheric neutrino a.k.a. conventional flux parameters

charmed atmospheric neutrino a.k.a. prompt flux parameters

astrophysical neutrino flux parameters**

muon background parameter

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	xsec_piece1	xsec_piece2	conv_norm	barr_h	barr_w	barr_y	barr_z	delta_gamma	CR_grad	prompt_norm	astro_norm	gamma_astro	muon_norm	dom_eff	ice_abs	ice_scat	ice_holep0
xsec_piece1	1.00	0.81	-0.72	0.00	0.09	0.06	-0.11	-0.77	0.04	-0.08	-0.45	-0.37	0.09	-0.05	-0.02	0.00	0.11
xsec_piece2	0.81	1.00	-0.95	-0.35	0.26	0.37	0.05	-0.50	-0.29	-0.12	-0.33	-0.26	0.13	-0.20	-0.08	-0.02	0.03
conv_norm	-0.72	-0.95	1.00	0.46	-0.31	-0.46	-0.13	0.33	0.46	0.15	0.27	0.22	-0.10	0.10	0.01	0.12	0.03
barr_h	0.00	-0.35	0.46	1.00	-0.28	-0.45	-0.27	-0.29	0.58	0.29	-0.14	-0.14	-0.09	-0.01	-0.10	0.15	0.07
barr_w	0.09	0.26	-0.31	-0.28	1.00	0.17	-0.29	-0.03	-0.28	-0.01	-0.07	-0.06	0.12	-0.05	0.03	0.02	0.04
barr_y	0.06	0.37	-0.46	-0.45	0.17	1.00	-0.24	-0.05	-0.26	-0.28	0.07	0.04	0.08	0.11	0.28	-0.00	0.08
barr_z	-0.11	0.05	-0.13	-0.27	-0.29	-0.24	1.00	0.37	-0.17	-0.06	0.04	0.05	-0.09	0.05	0.04	-0.12	-0.11
delta_gamma	-0.77	-0.50	0.33	-0.29	-0.03	-0.05	0.37	1.00	-0.60	0.07	0.45	0.37	-0.07	0.01	-0.08	-0.04	-0.19
CR_grad	0.04	-0.29	0.46	0.58	-0.28	-0.26	-0.17	-0.60	1.00	0.03	-0.18	-0.14	-0.06	0.14	0.17	0.04	0.12
prompt_norm	-0.08	-0.12	0.15	0.29	-0.01	-0.28	-0.06	0.07	0.03	1.00	-0.44	-0.42	-0.02	0.05	0.01	0.03	-0.14
astro_norm	-0.45	-0.33	0.27	-0.14	-0.07	0.07	0.04	0.45	-0.18	-0.44	1.00	0.91	-0.02	0.02	-0.02	-0.01	-0.10
gamma_astro	-0.37	-0.26	0.22	-0.14	-0.06	0.04	0.05	0.37	-0.14	-0.42	0.91	1.00	-0.06	-0.00	-0.03	0.02	-0.10
muon_norm	0.09	0.13	-0.10	-0.09	0.12	0.08	-0.09	-0.07	-0.06	-0.02	-0.02	-0.06	1.00	-0.03	-0.01	0.04	0.05
dom_eff	-0.05	-0.20	0.10	-0.01	-0.05	0.11	0.05	0.01	0.14	0.05	0.02	-0.00	-0.03	1.00	0.93	-0.16	-0.01
ice_abs	-0.02	-0.08	0.01	-0.10	0.03	0.28	0.04	-0.08	0.17	0.01	-0.02	-0.03	-0.01	0.93	1.00	0.02	0.18
ice_scat	0.00	-0.02	0.12	0.15	0.02	-0.00	-0.12	-0.04	0.04	0.03	-0.01	0.02	0.04	-0.16	0.02	1.00	0.59
ice_holep0	0.11	0.03	0.03	0.07	0.04	0.08	-0.11	-0.19	0.12	-0.14	-0.10	-0.10	0.05	-0.01	0.18	0.59	1.00

* scale relative to CSMS

**single power-law hypothesis