



IceCube Atmospheric Neutrino Measurements

Snowmass NF04 Topical Workshop
23 November, 2020

Carlos Argüelles



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

50 m

Ice Top

86 strings of DOMs,
set 125 meters apart

IceCube
detector

DeepCore

1450 m

2450 m

Antarctic bedrock

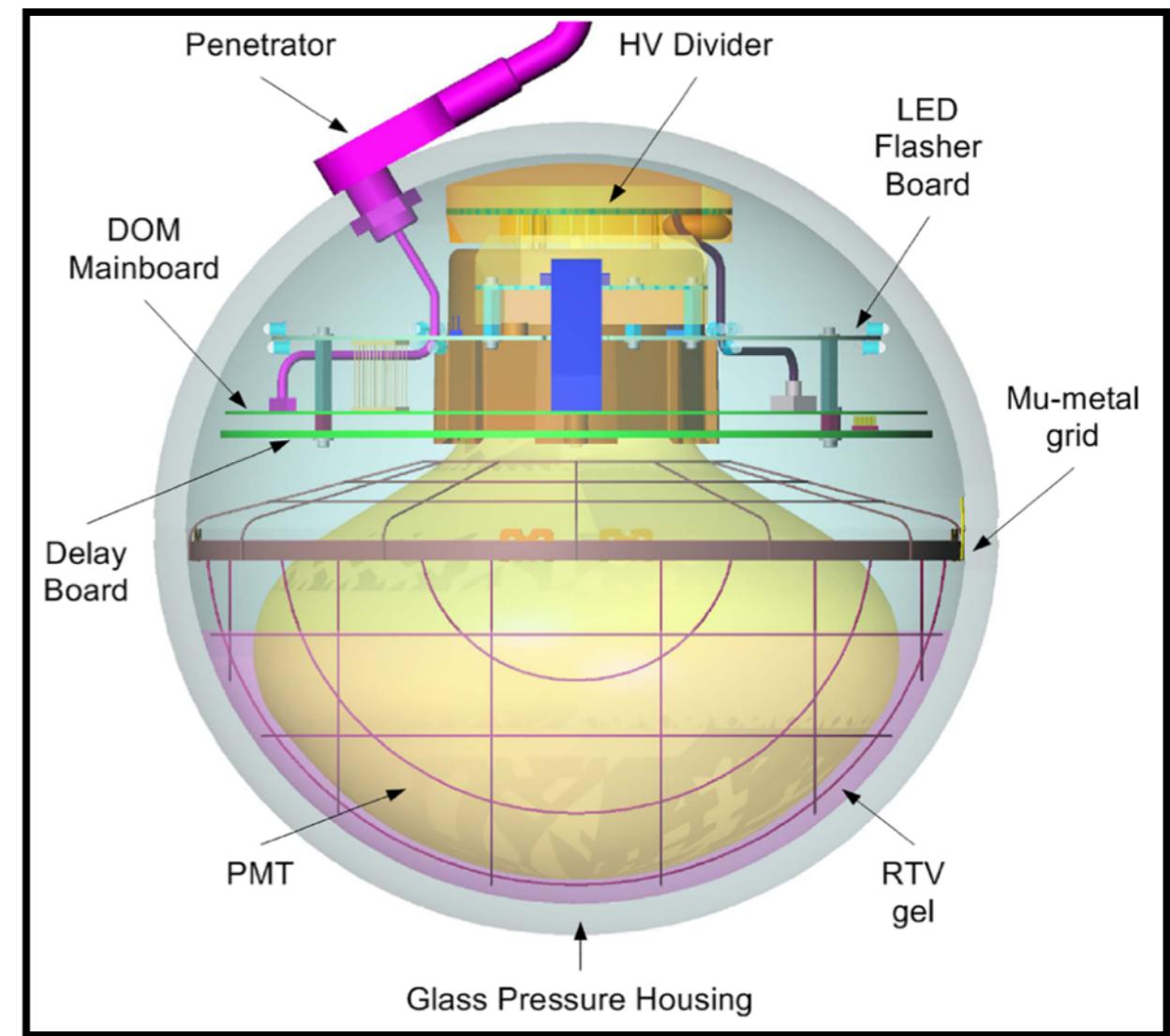
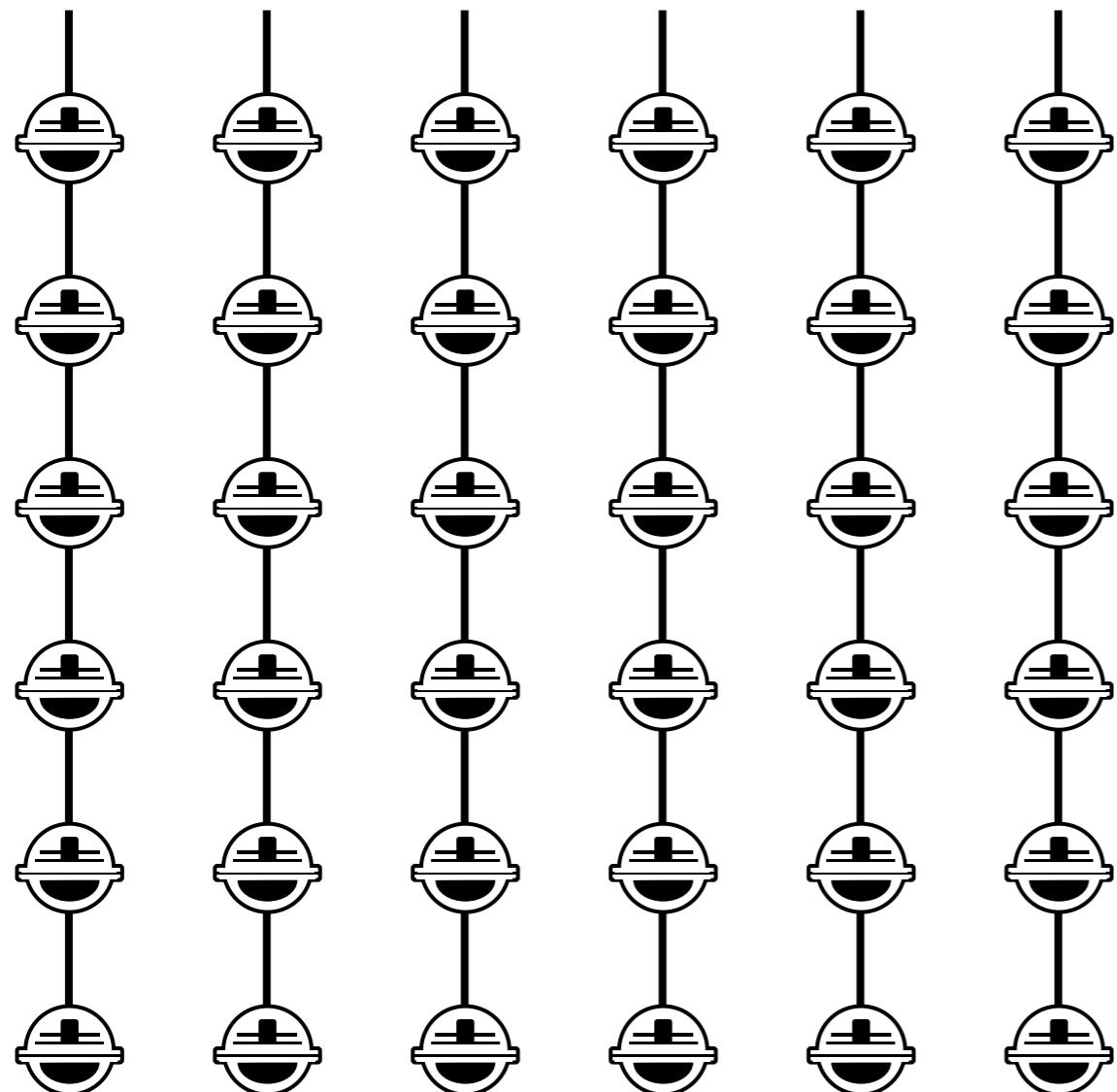
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

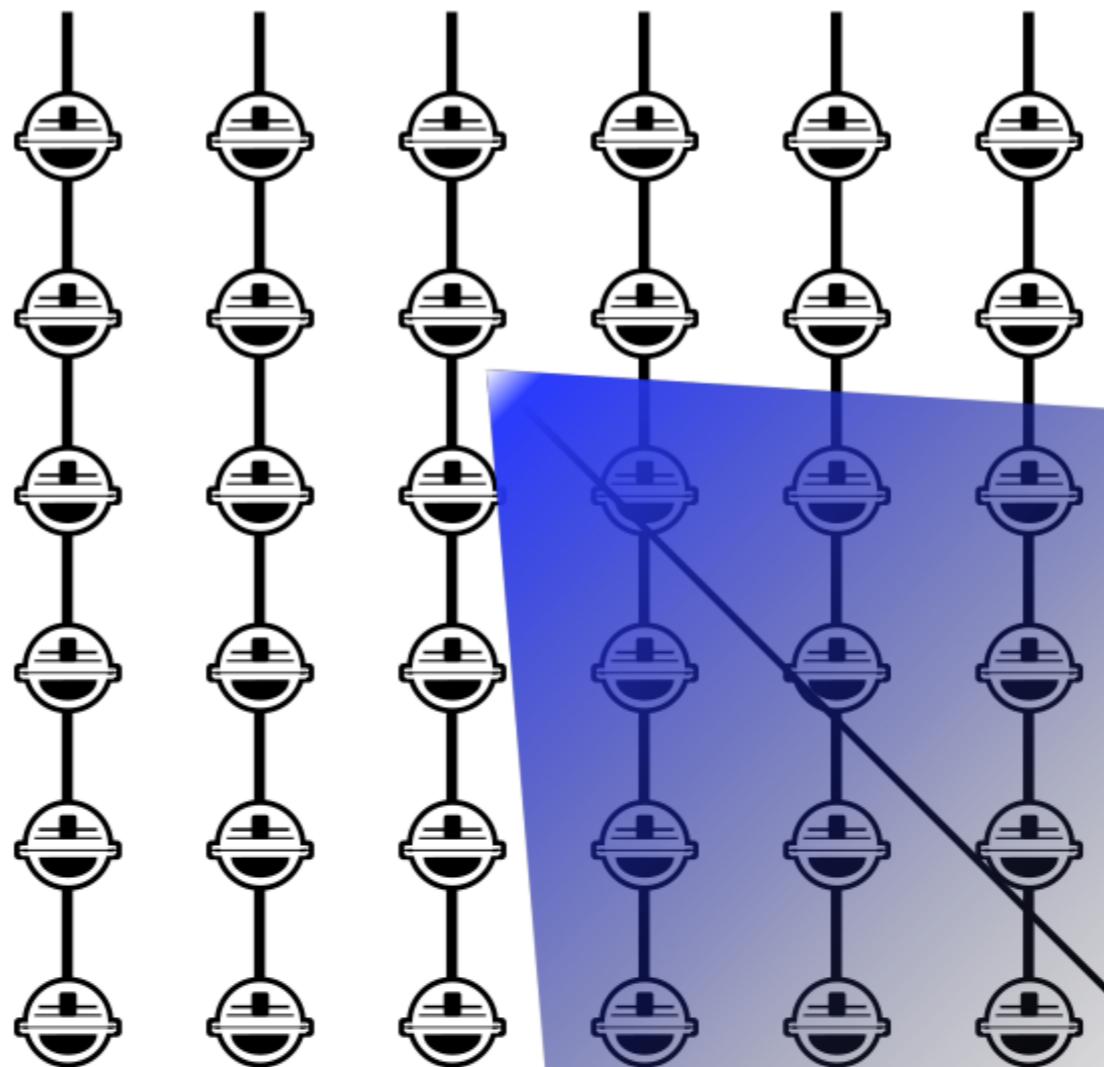
60 DOMs
on each string

DOMs
are 17
meters
apart

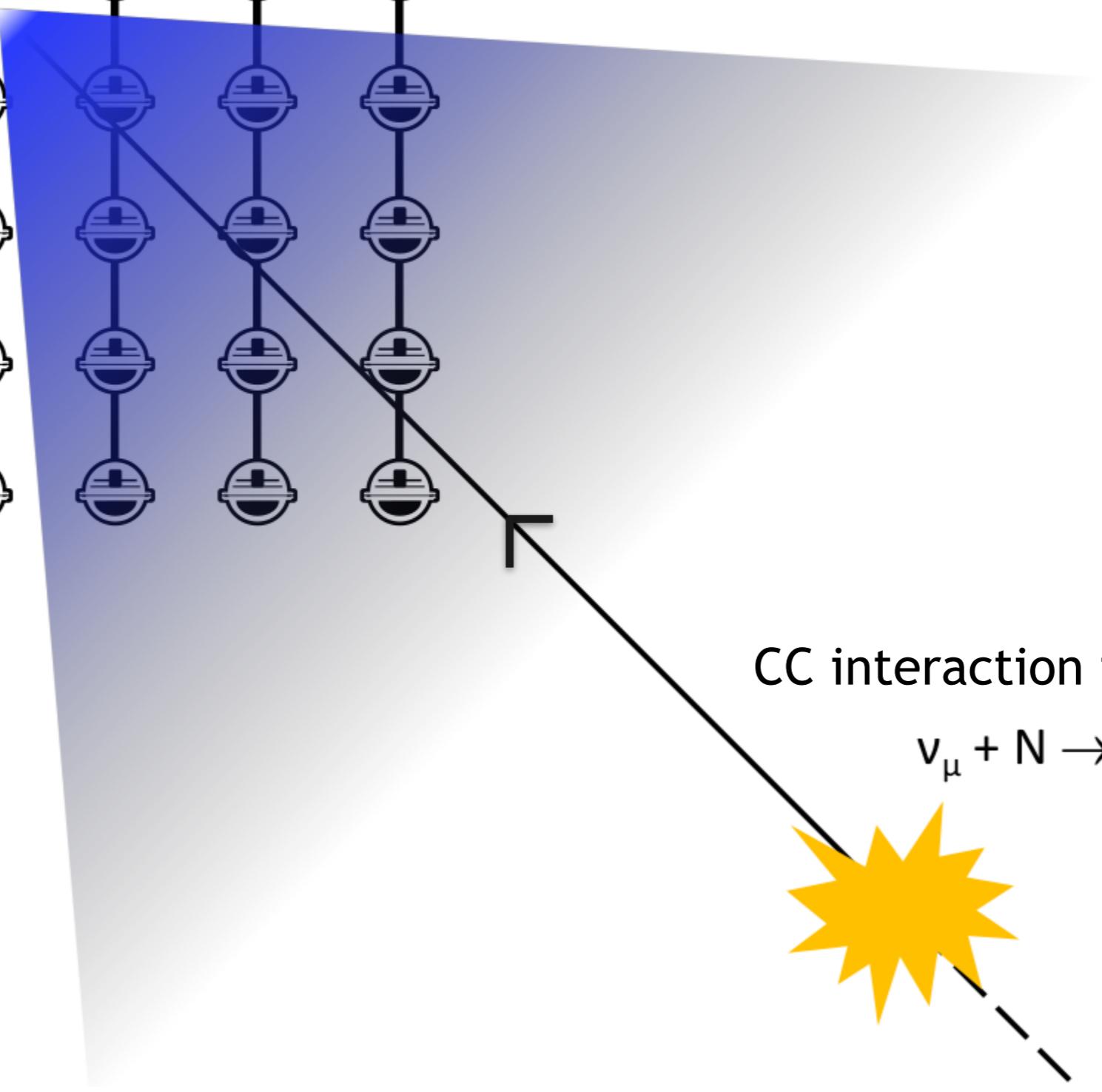


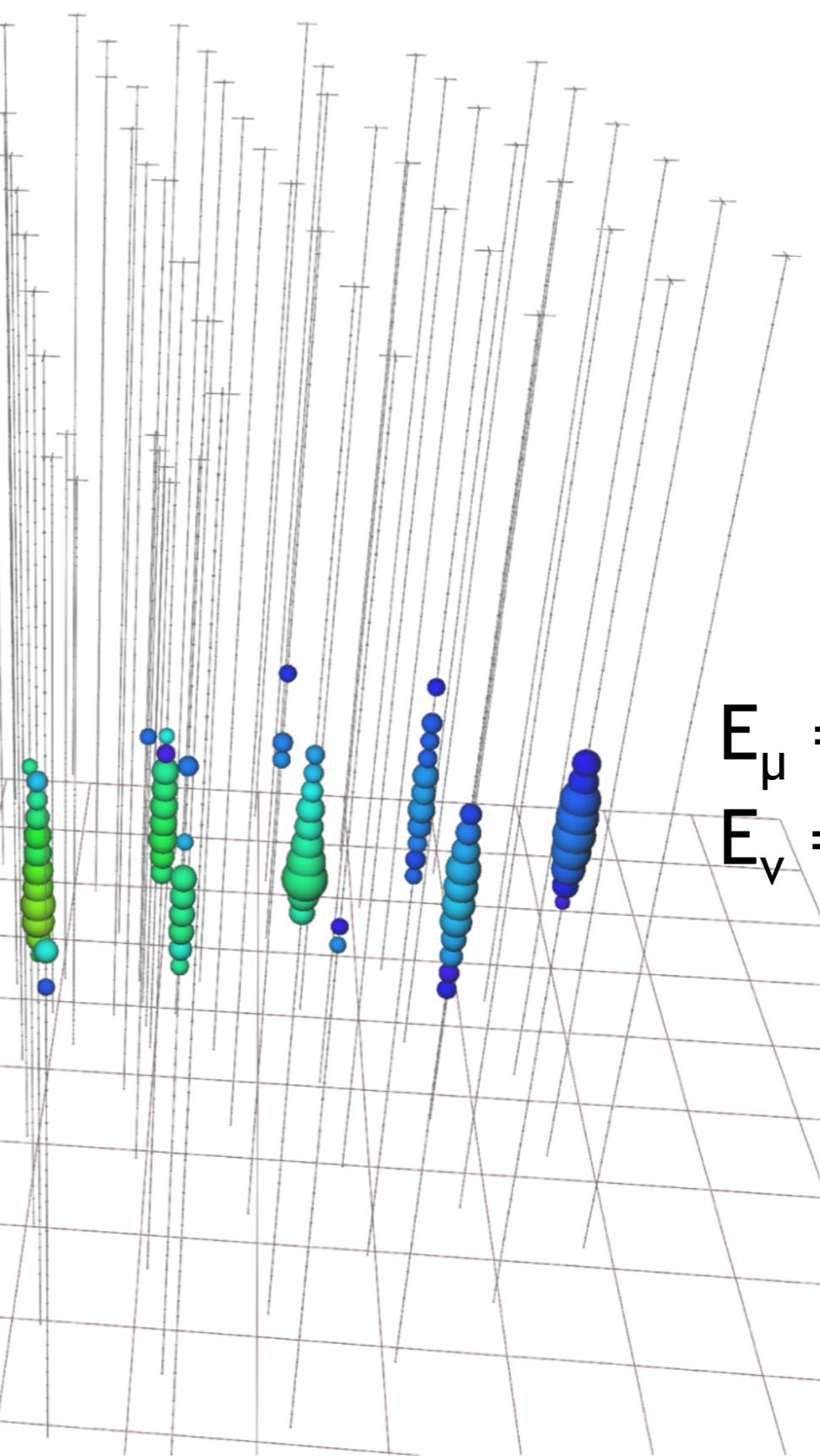
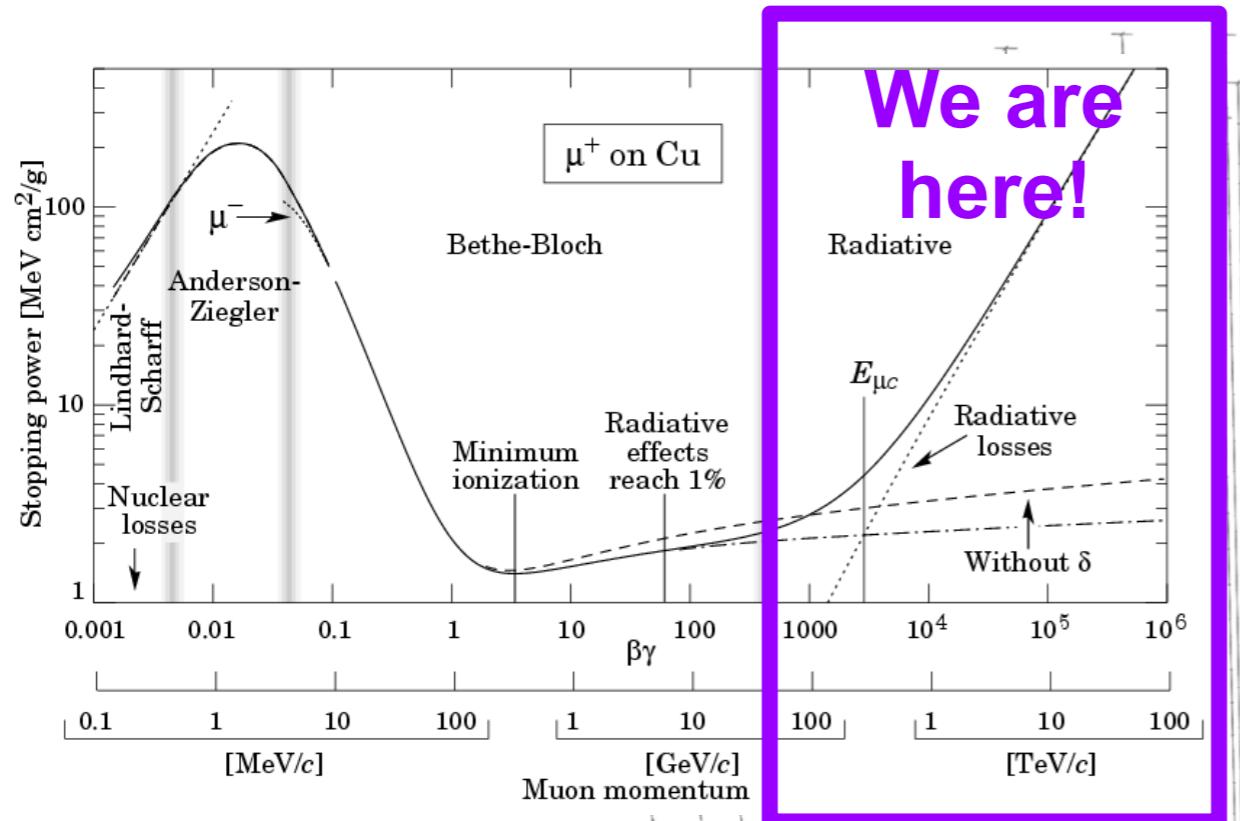
Digital Optical Module (DOM)



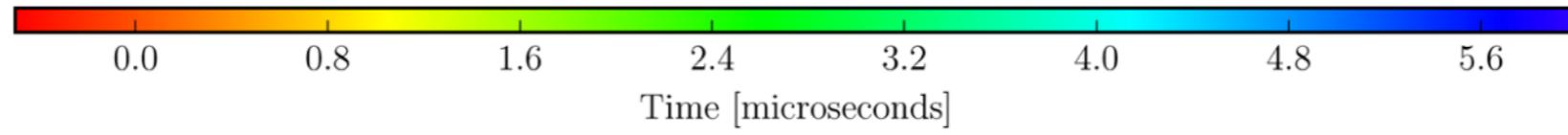


Cherenkov-light time and spatial
distribution
↳ muon direction



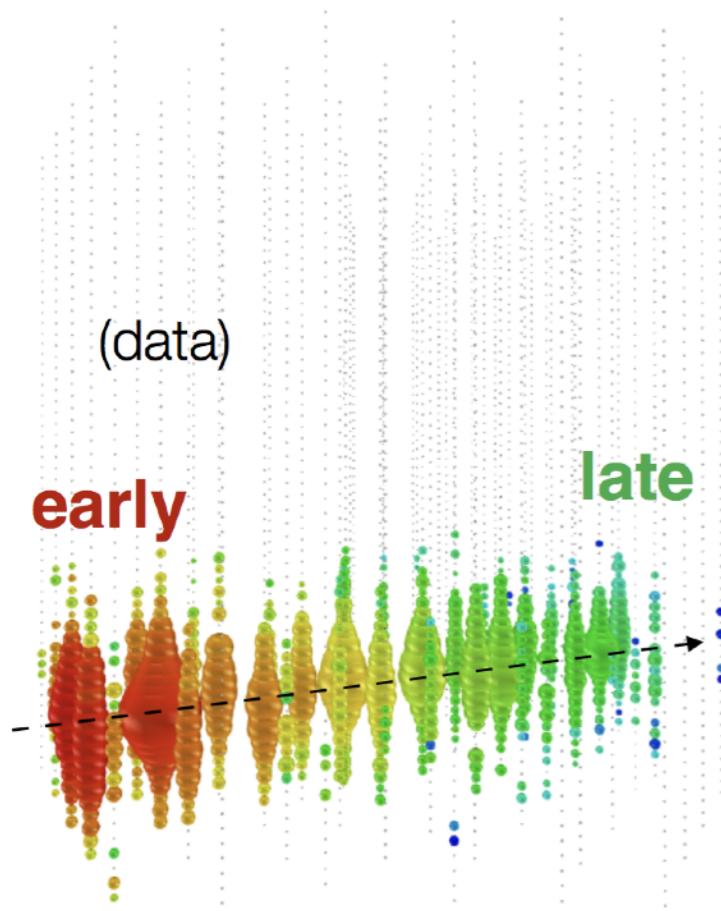


- Muon above critical energy
- Loses energy stochastically
- Resolution: $\sigma_{\log_{10}(E/\text{GeV})} \sim 0.4$



All event morphologies

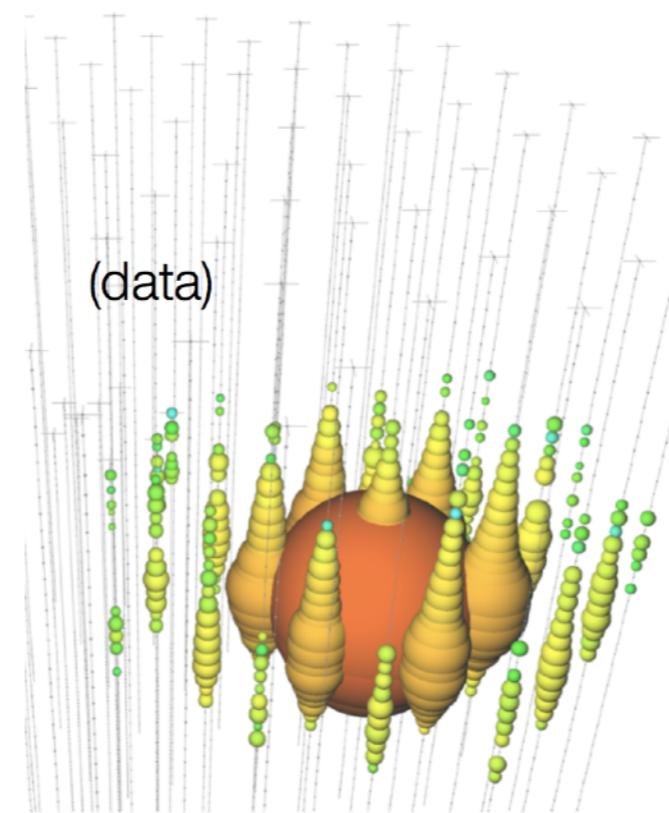
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

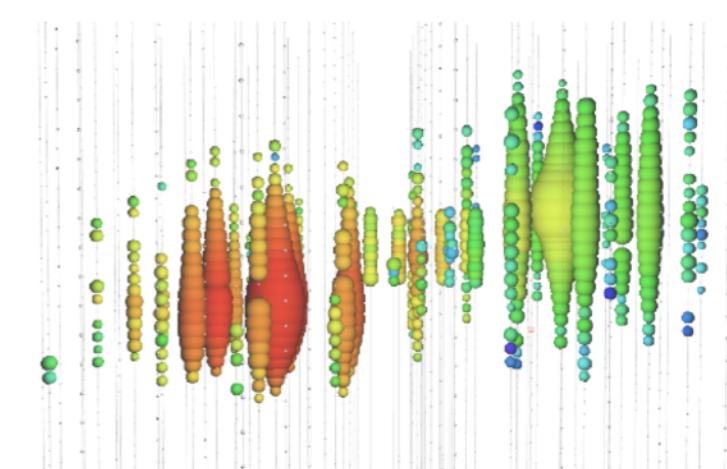
Neutral-current / ν_e



Isolated energy
deposition (cascade)
with no track

15% deposited energy resolution
10 degree angular resolution
(above 100 TeV)

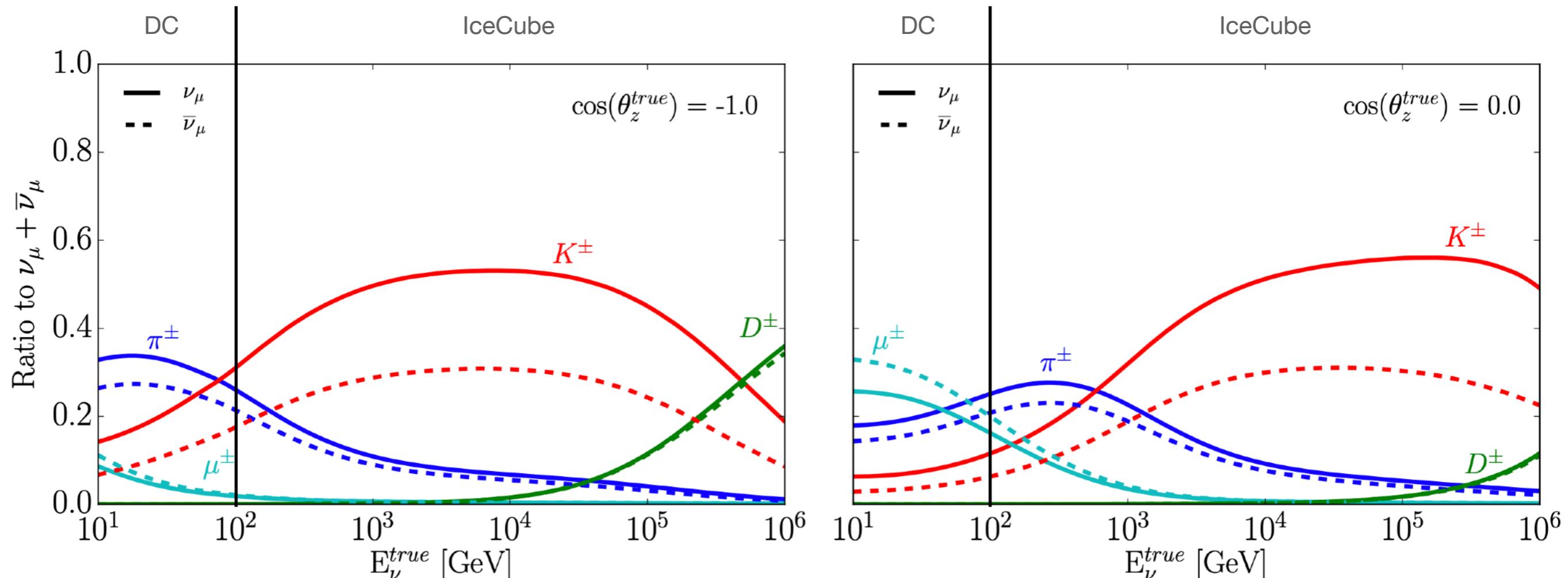
Charged-current ν_τ



Double cascade

(resolvable above ~ 100 TeV
deposited energy)

Atmospheric neutrinos in IceCube



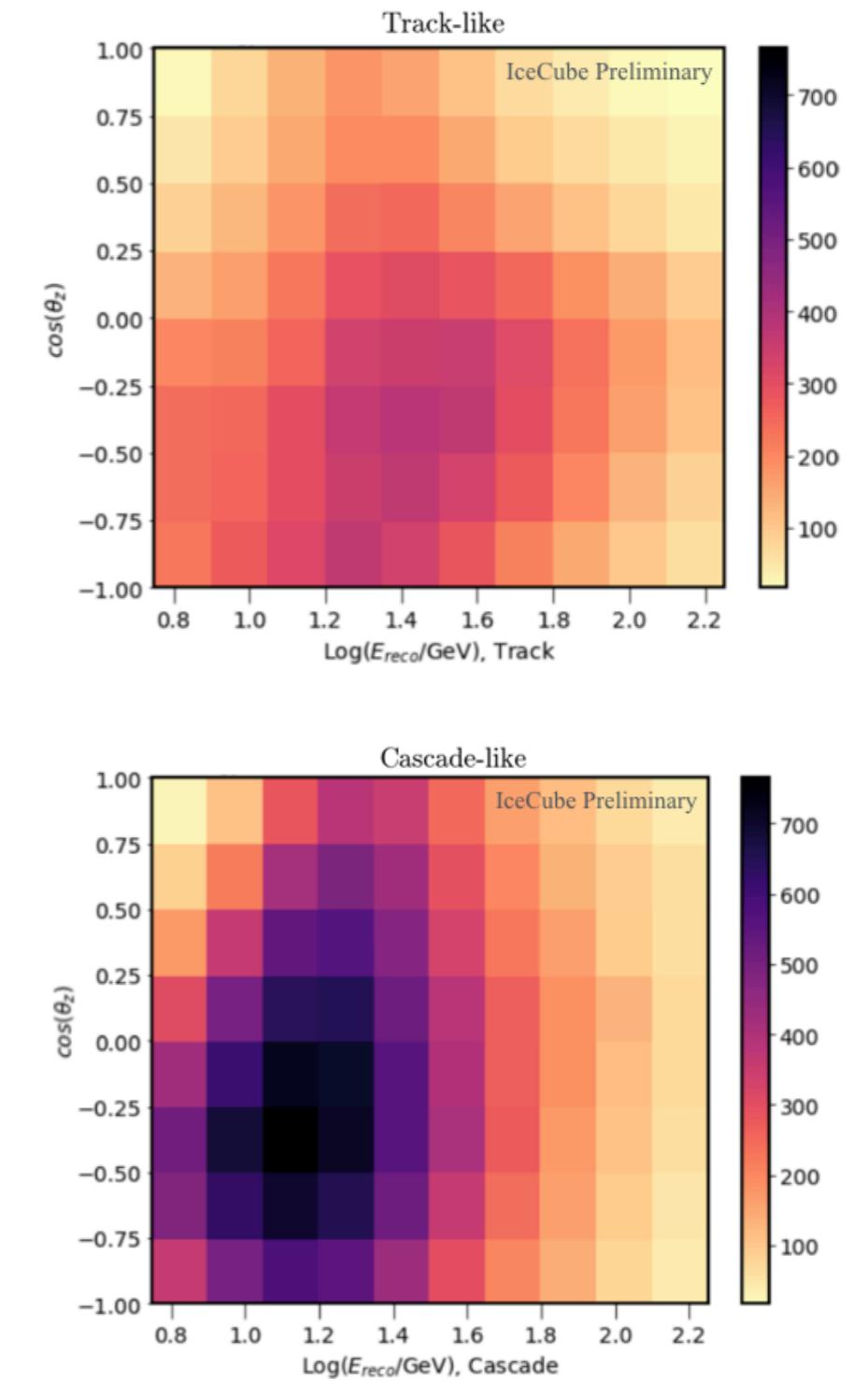
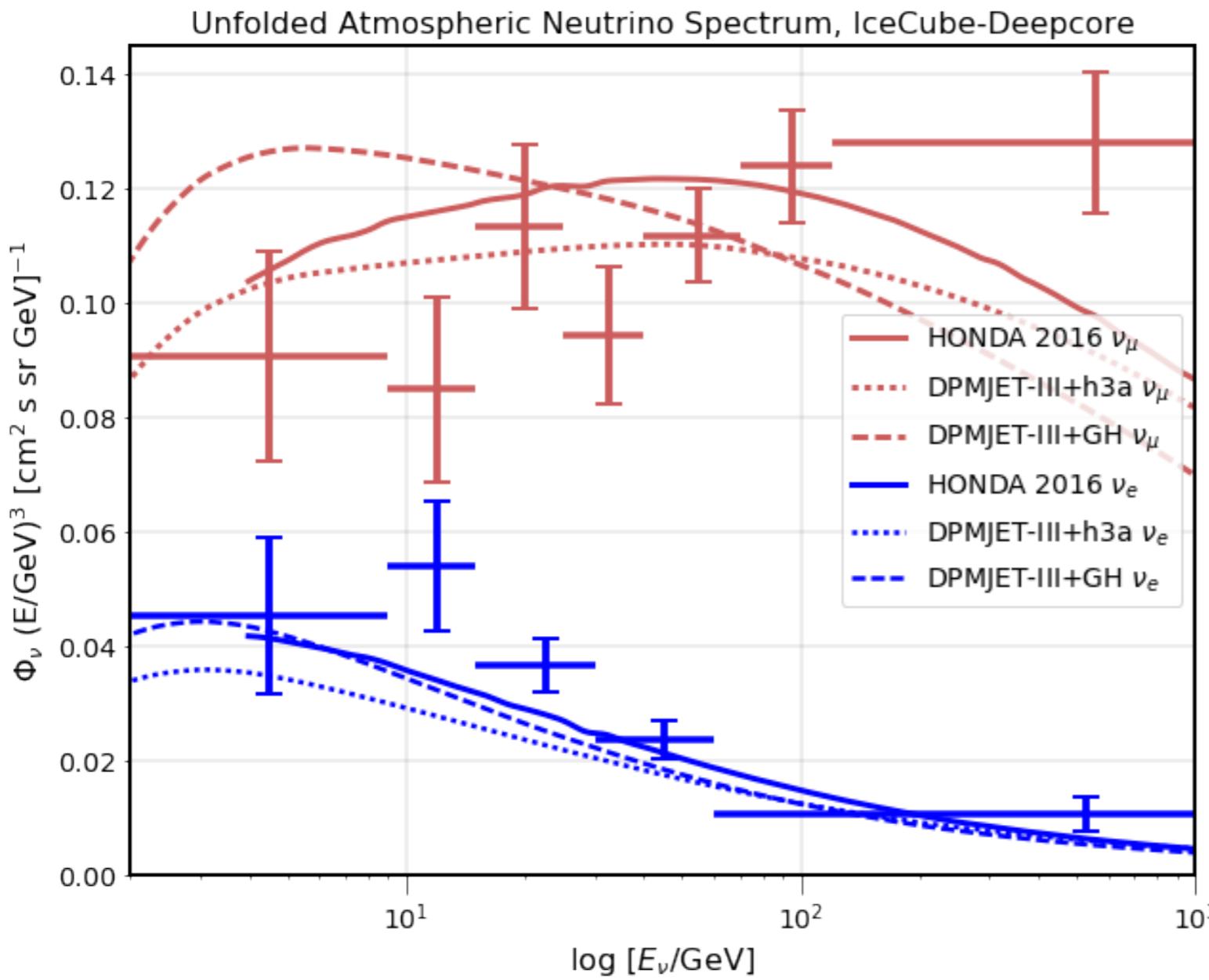
Three important observables:

- Energy
- Direction (zenith angle)
- Morphology: cascade, track, starting-track

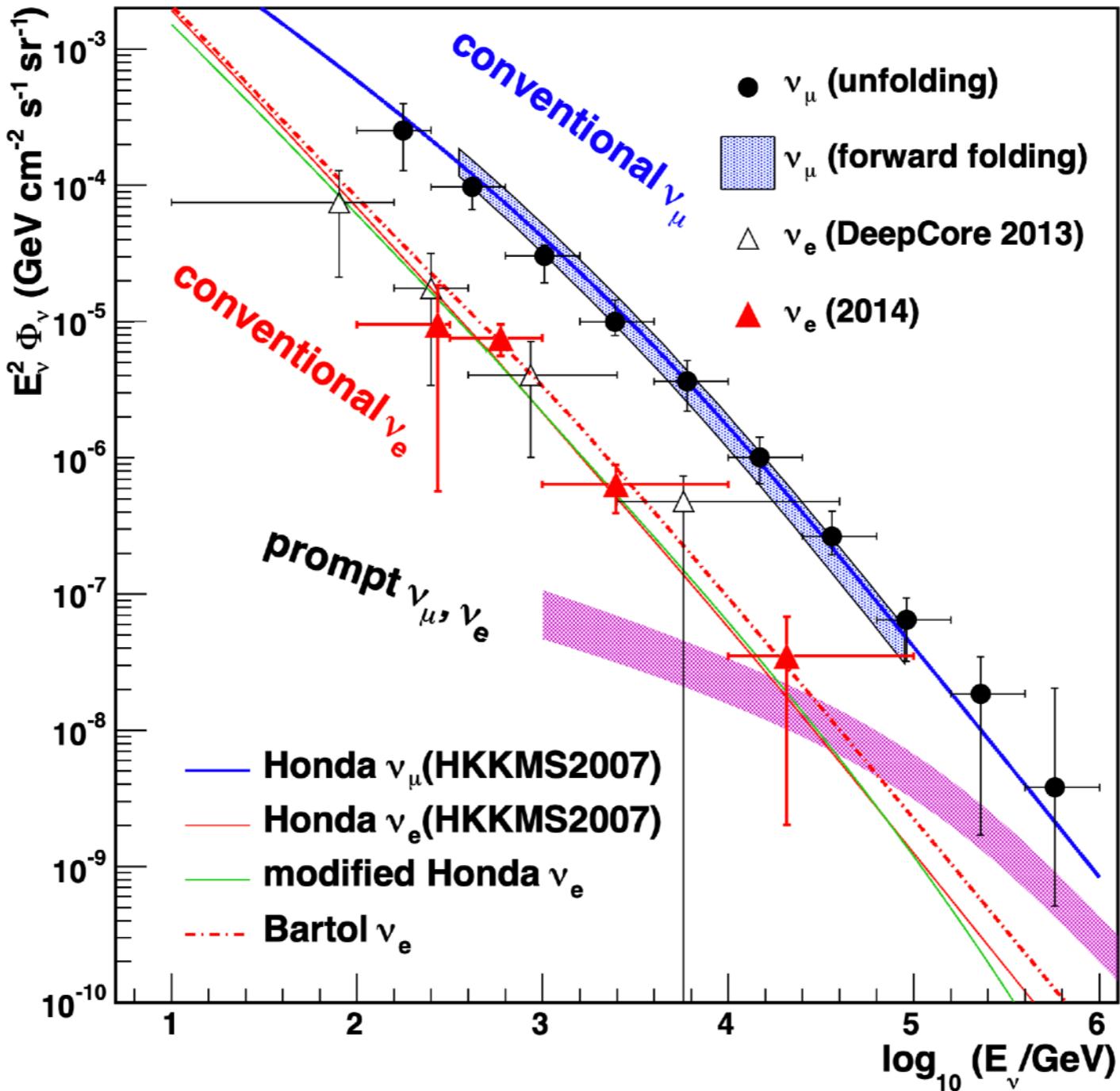
Neutrino Flux Unfoldings



IceCube-DeepCore 3yr Unfolding



IceCube 1yr unfolding



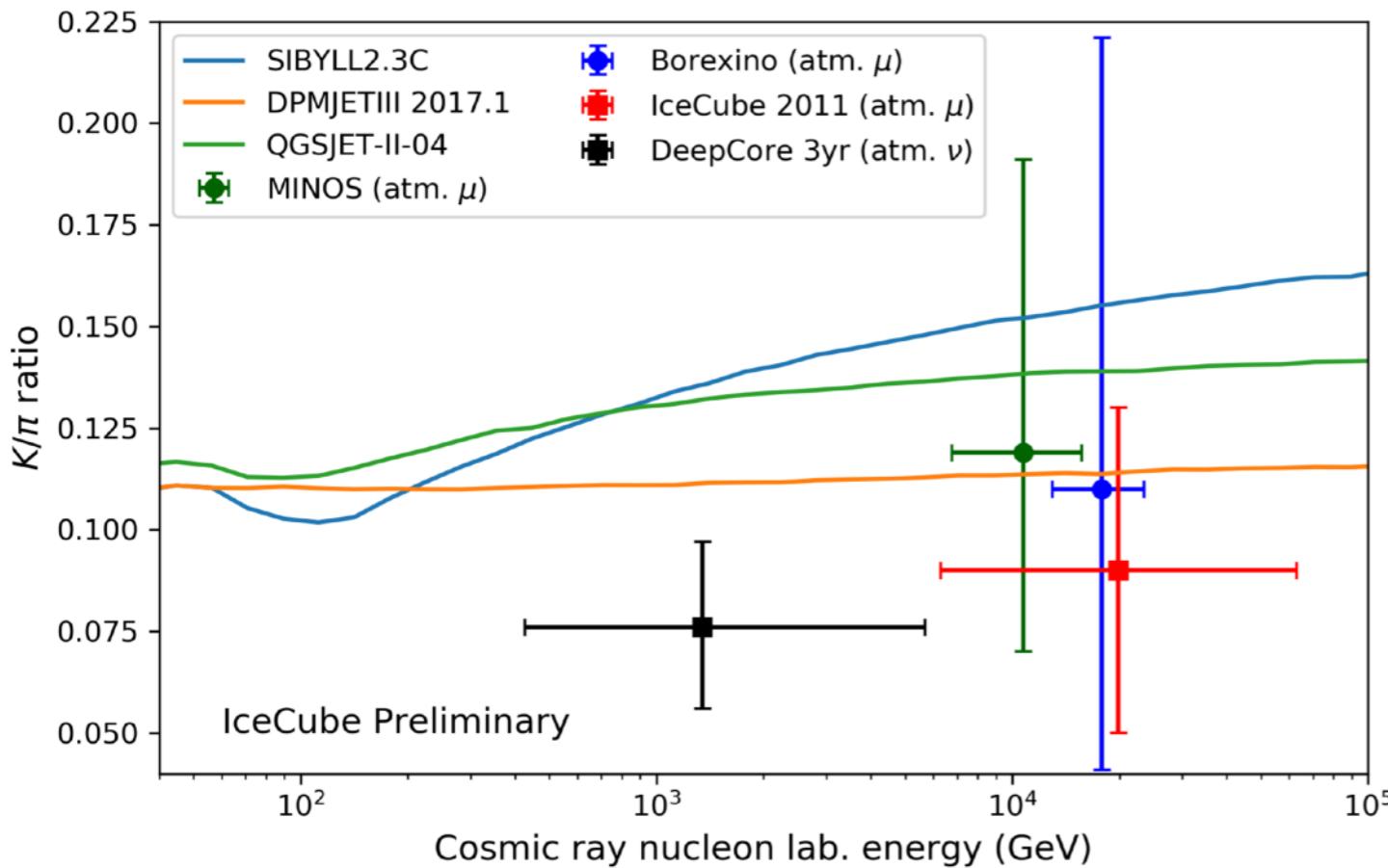
arXiv:<https://arxiv.org/abs/1607.08006>

Carlos A. Argüelles-Delgado - SnowMass NF04

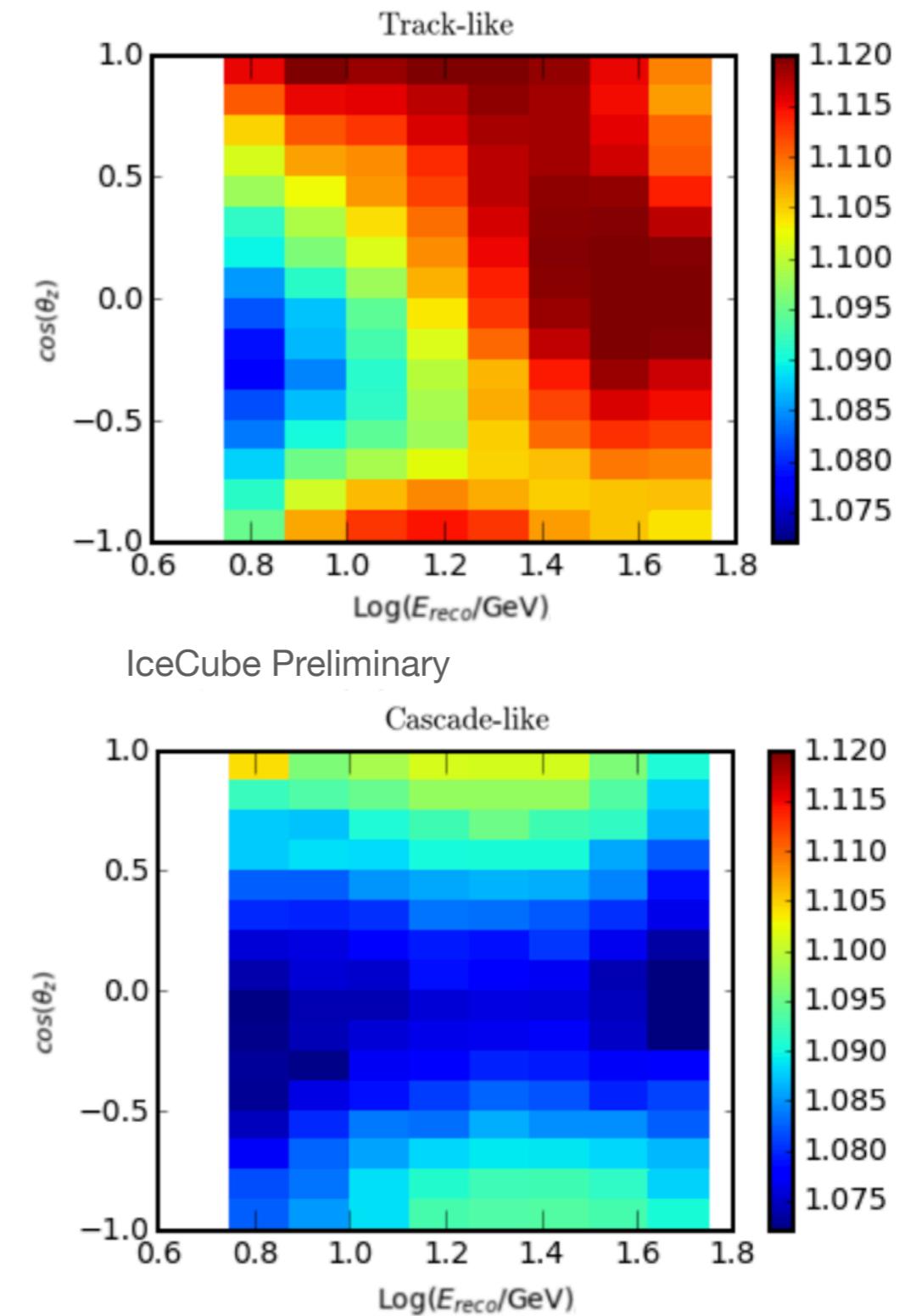
Forward-folding analyses

IceCube-DeepCore 3yr Pion-to-Kaon measurement

$$\Phi = N(\Phi_\pi + N_K \Phi_k)$$

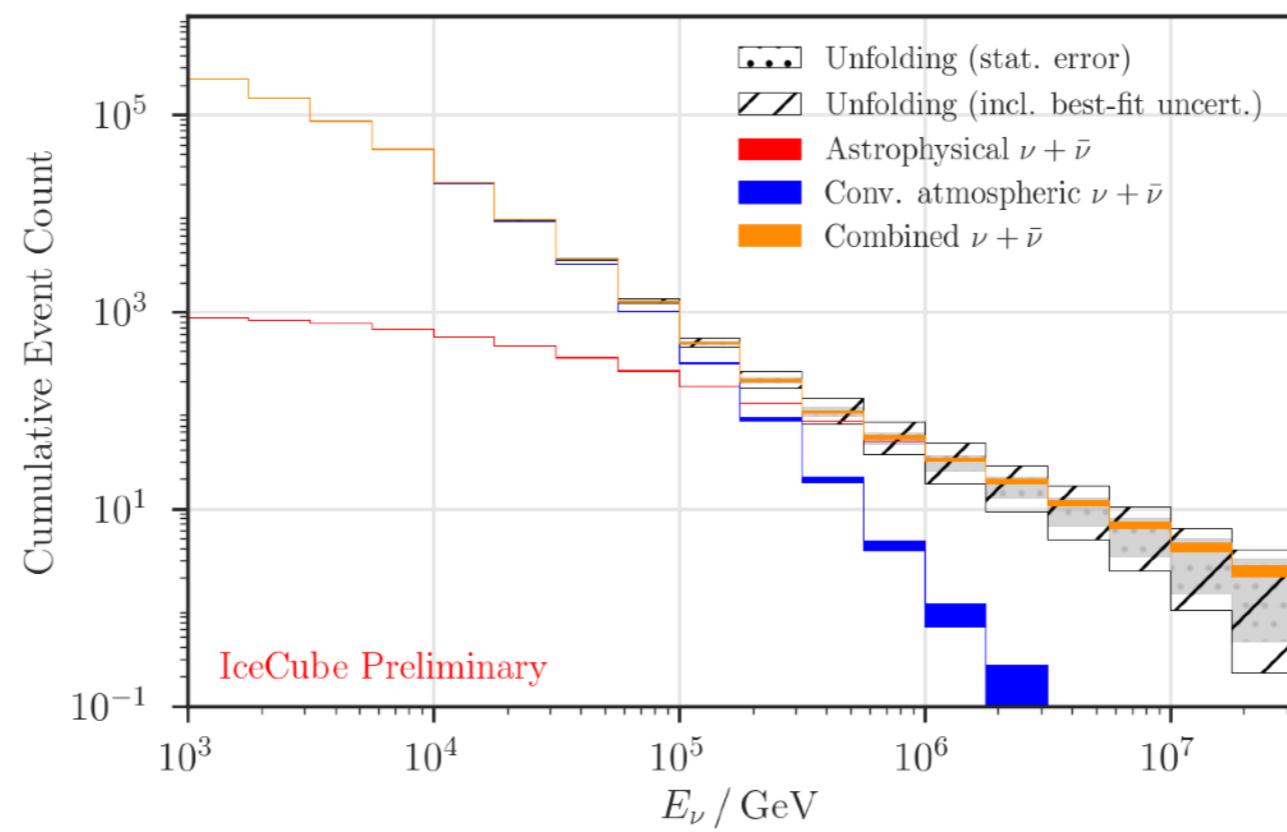
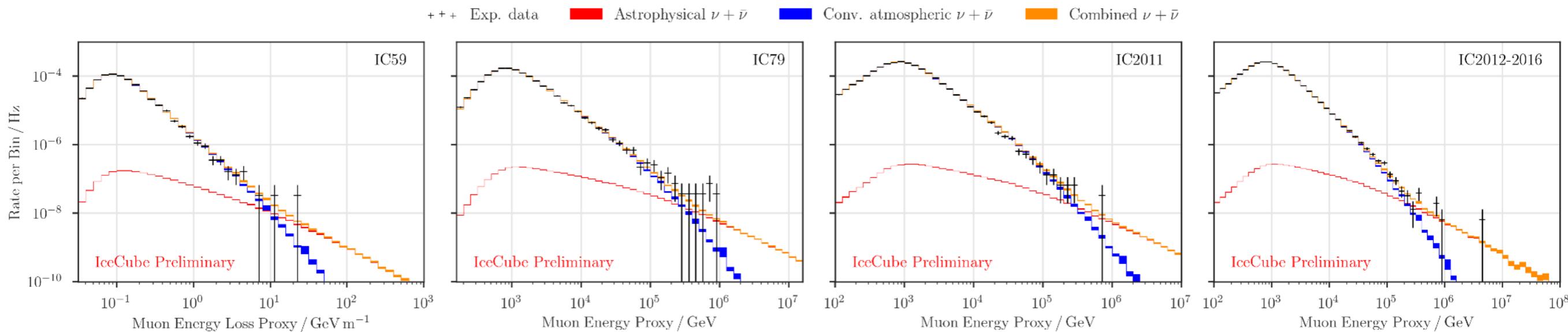


Effect of increasing the pion fraction by 20%



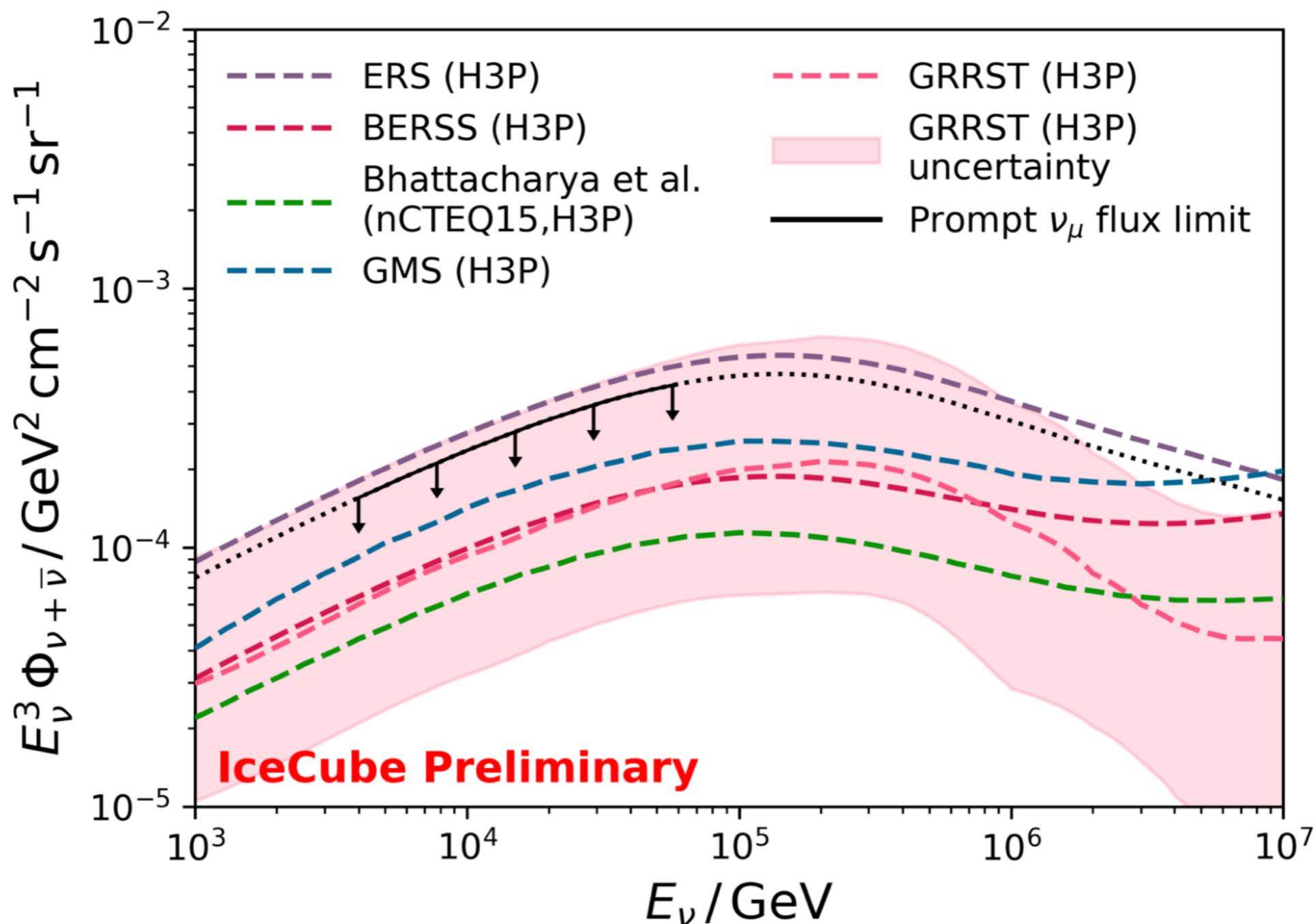
High-energy track measurements

8 years of northern track muon-neutrino



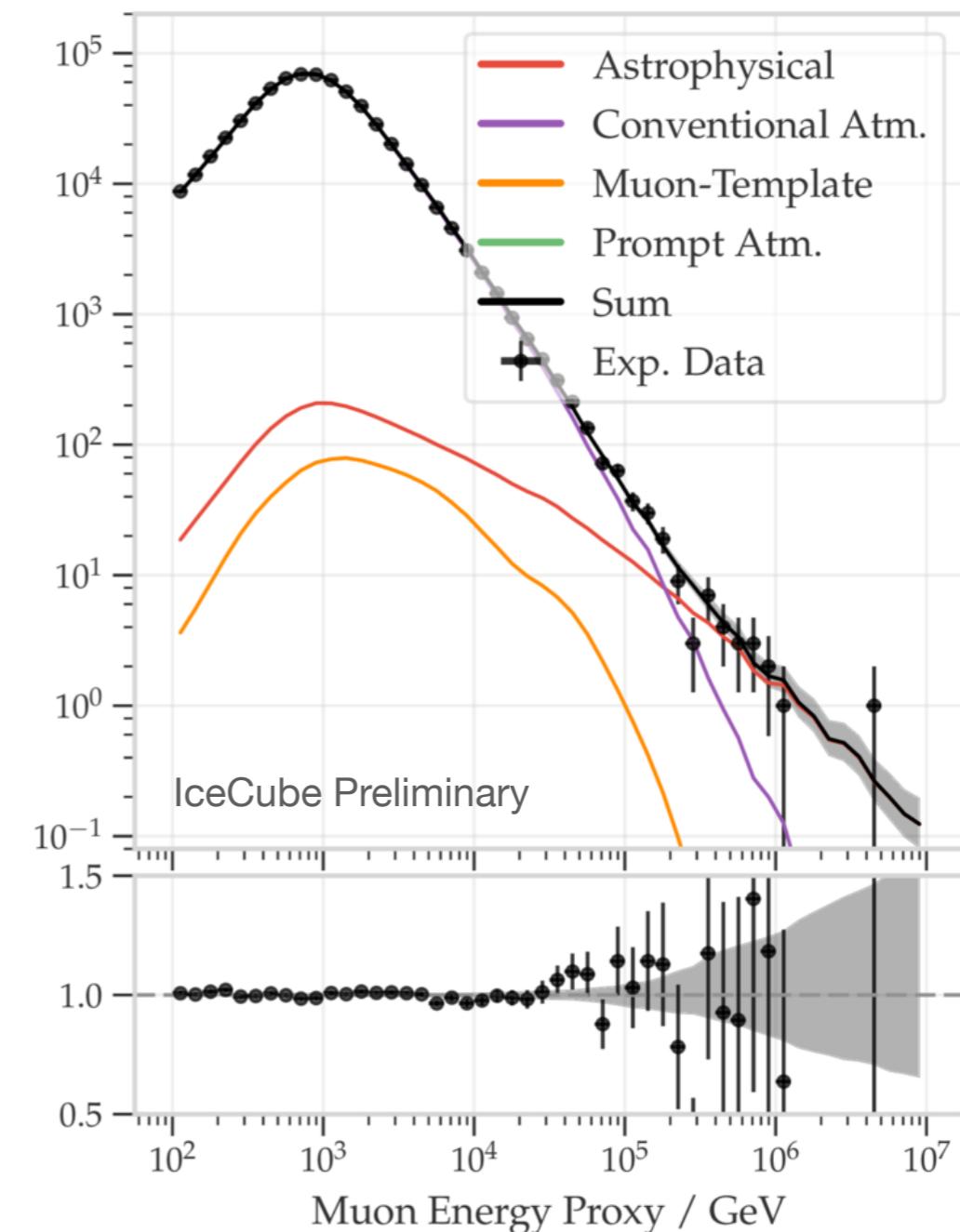
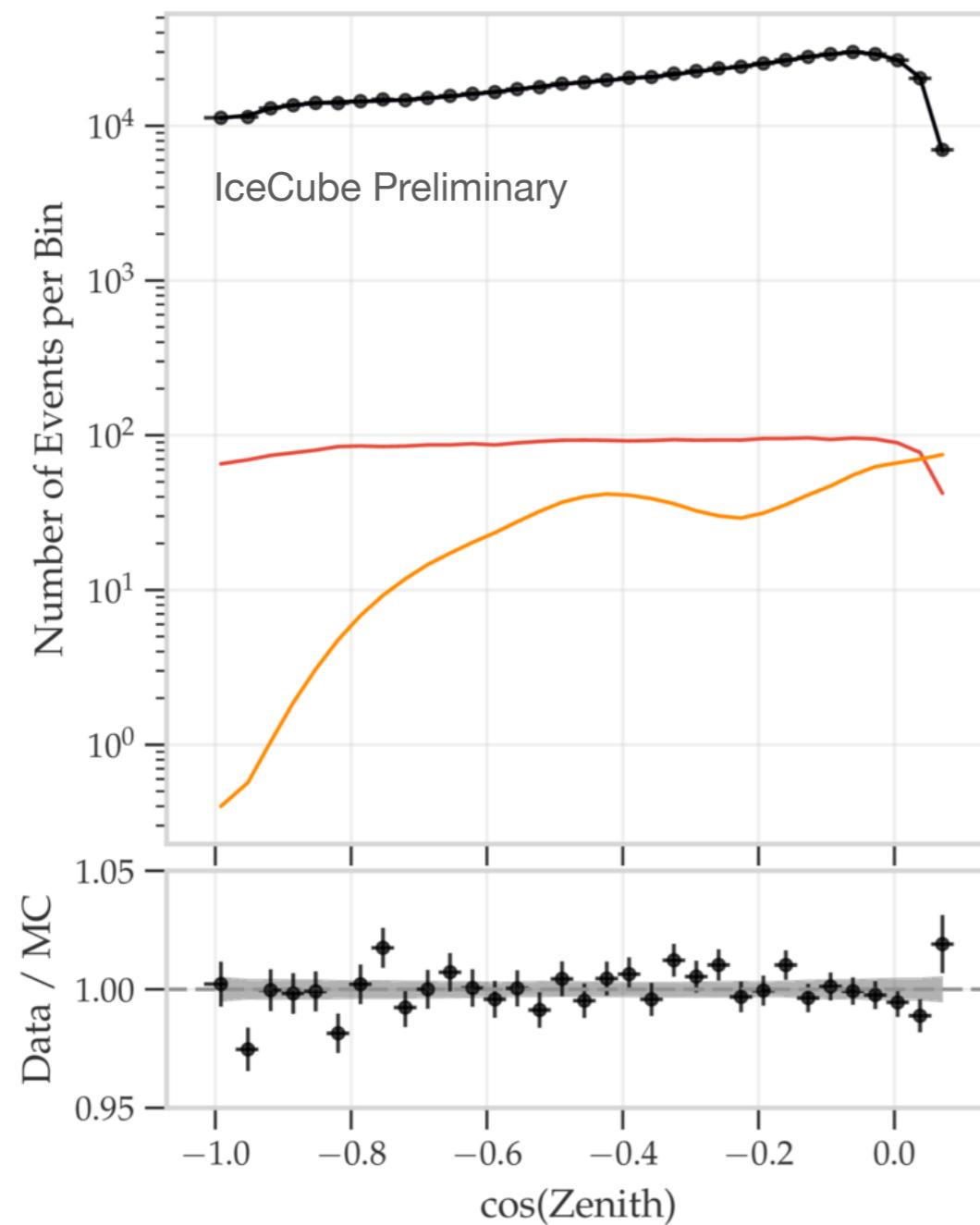
High-energy track measurements

8 years of northern track muon-neutrino

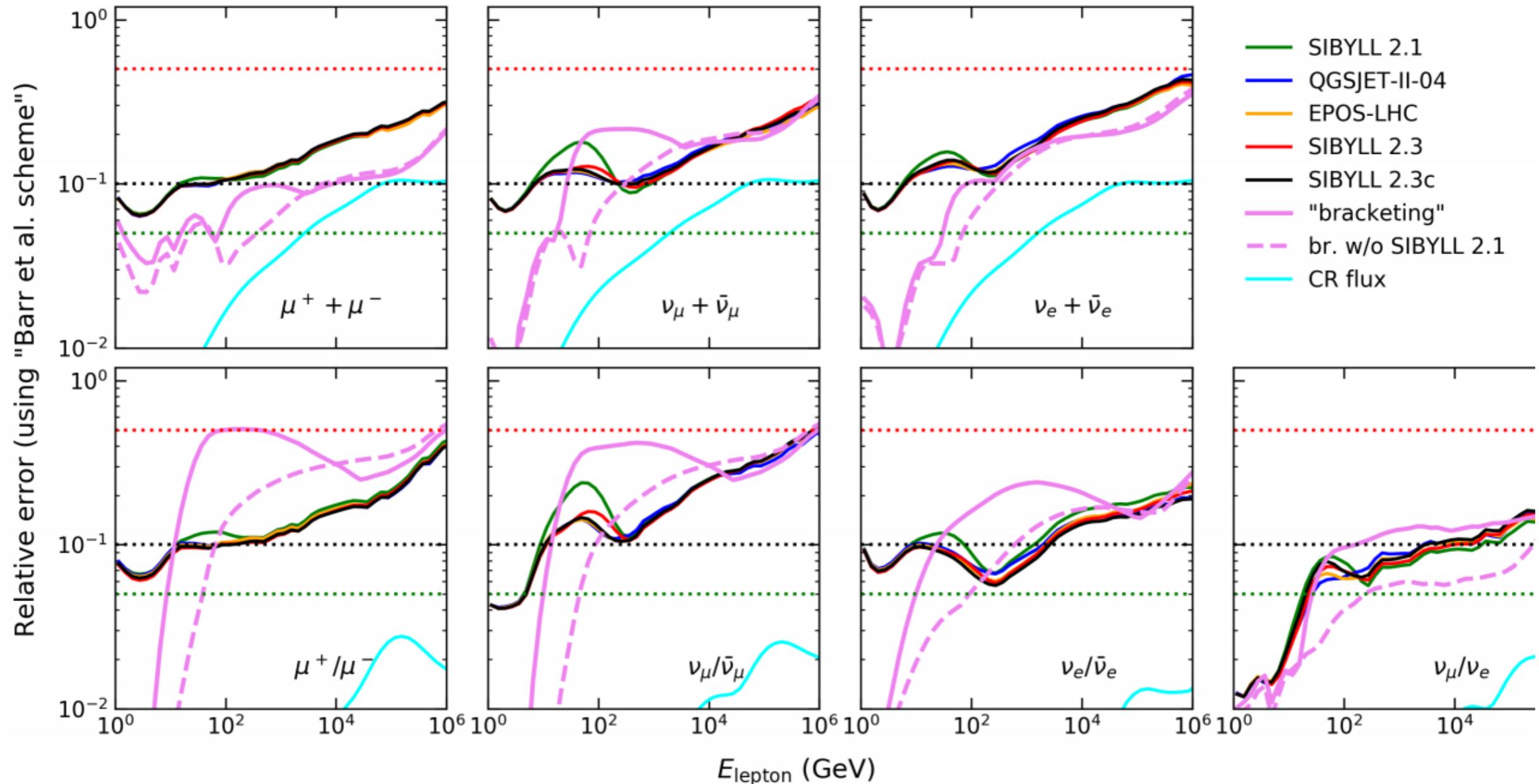


High-energy track measurements

Upcoming 9.5 years of northern track muon-neutrino



Improved treatment of atmospheric flux uncertainties

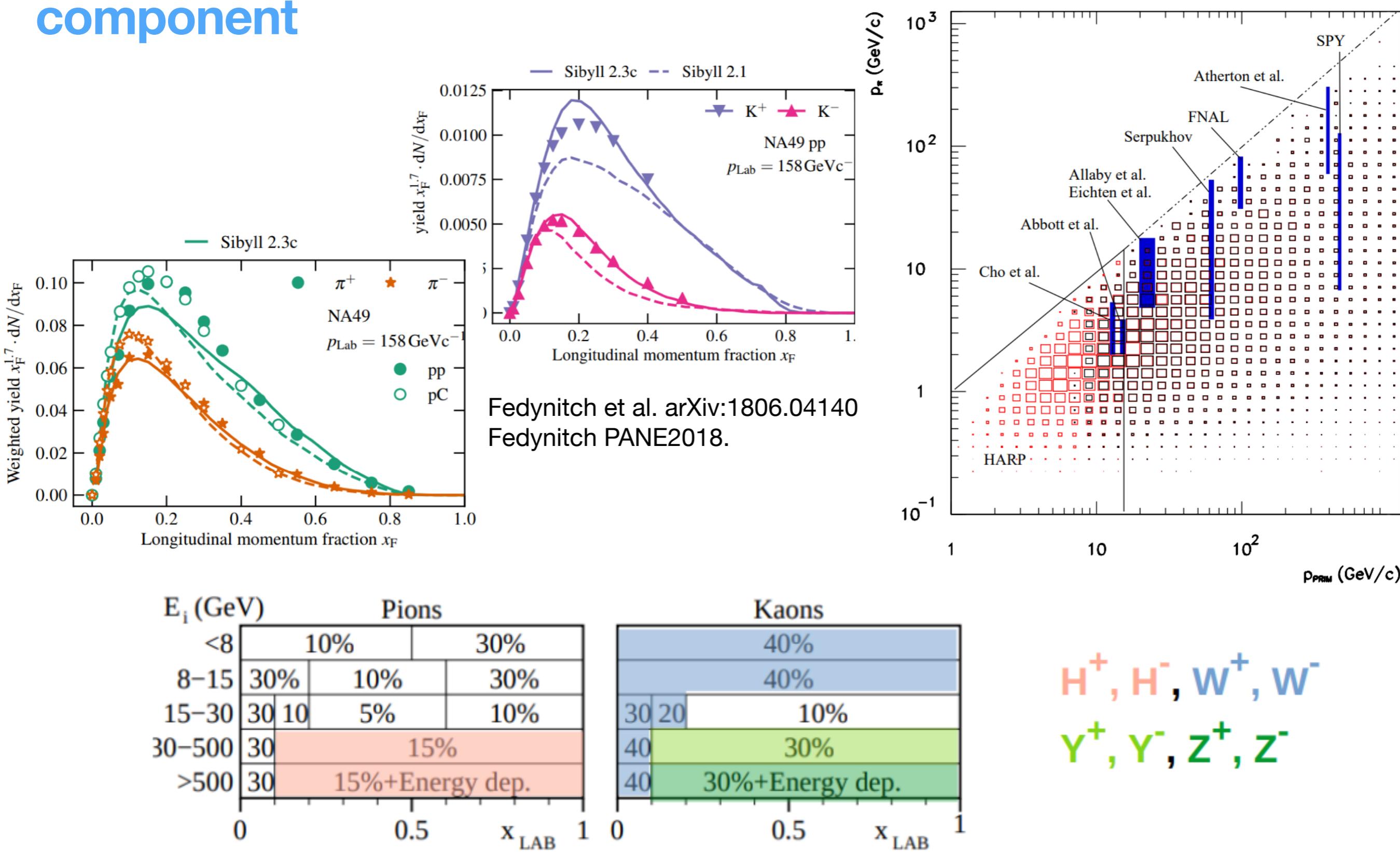


Fedynitch et al. arXiv:1806.04140
Fedynitch PANE2018.

Carlos A. Argüelles-Delgado - SnowMass NF04

Improved uncertainty in conventional component

RECENT PAPER: arXiv:2005.12943



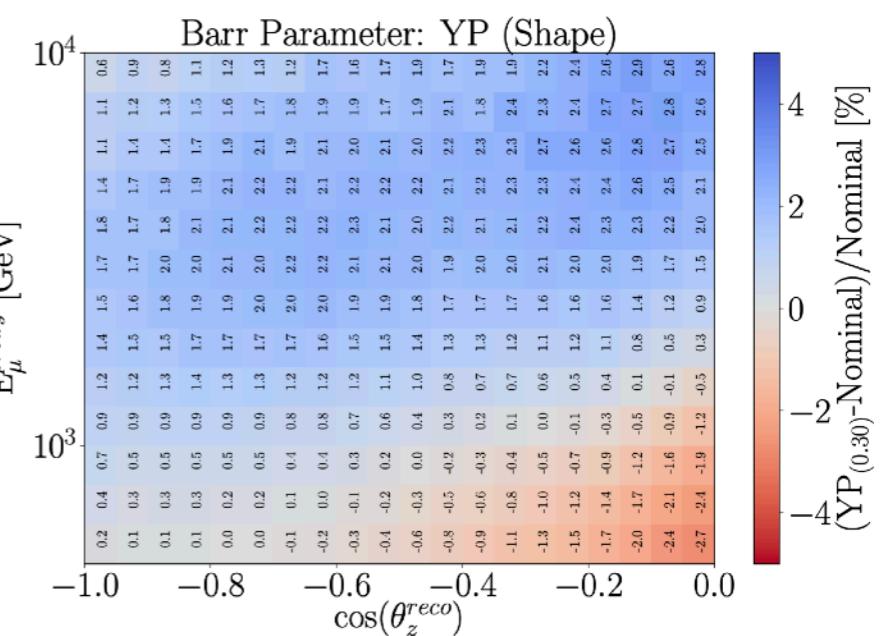
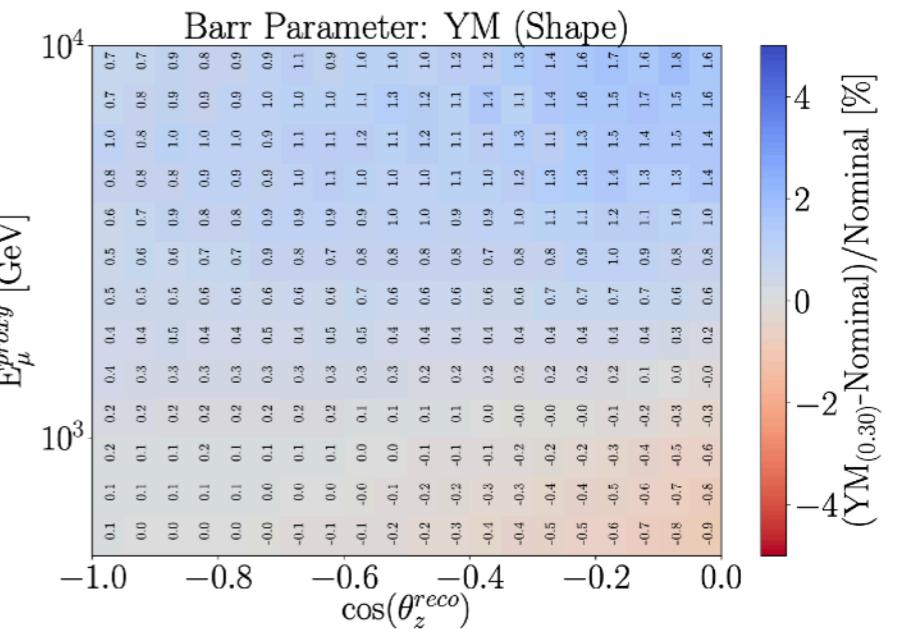
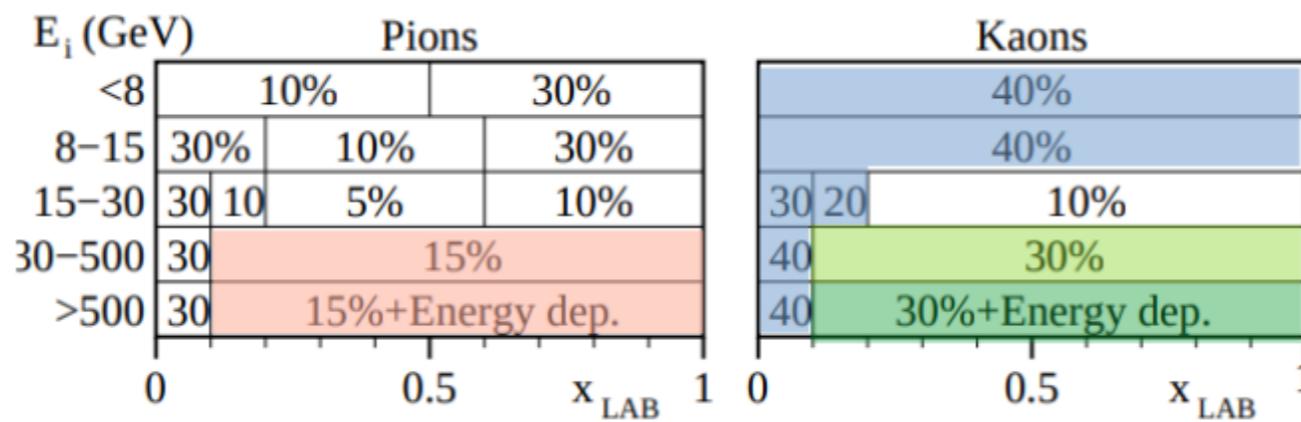
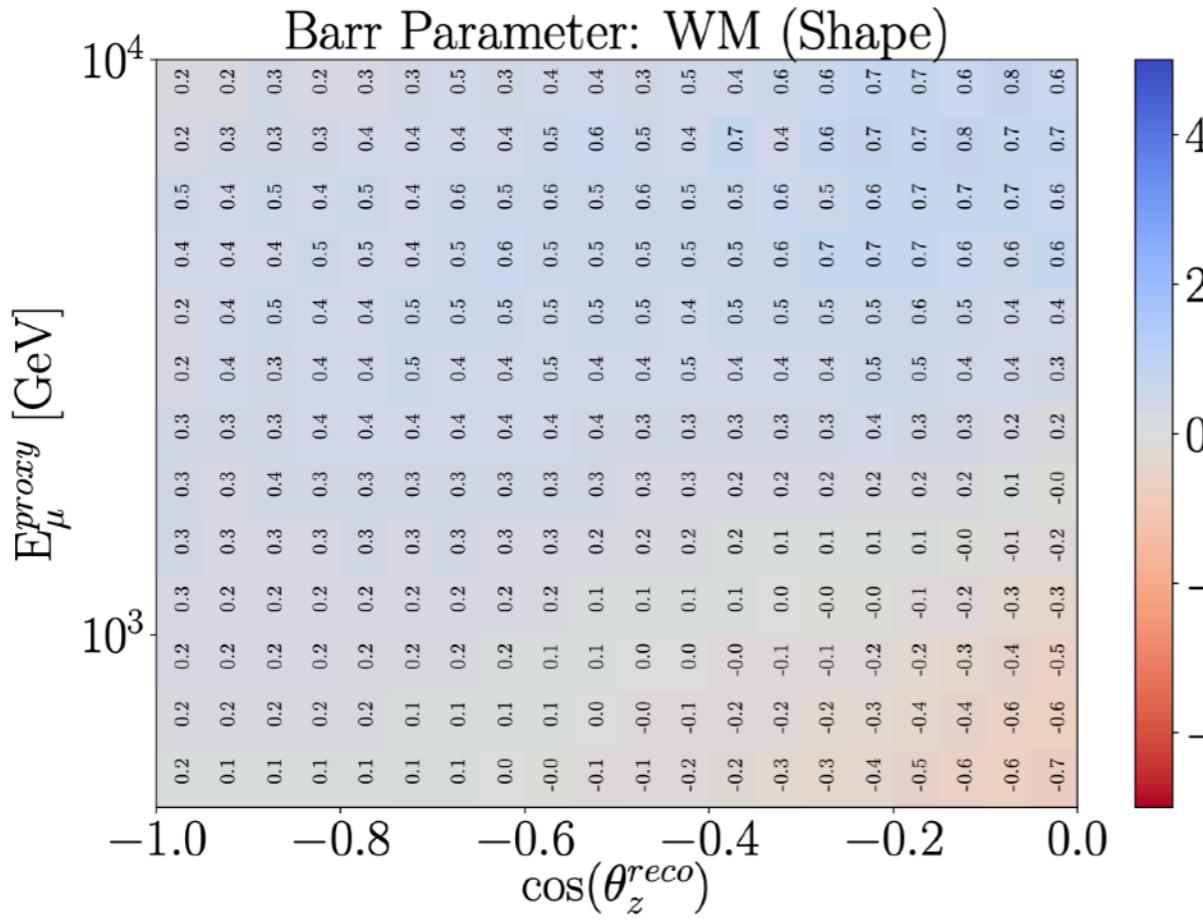
G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev,
Phys. Rev. D 74 (Nov, 2006) 094009

Carlos A. Argüelles-Delgado - SnowMass NF04

H^+, H^-, W^+, W^-
 Y^+, Y^-, Z^+, Z^-

“Barr templates” for high-energy muon-neutrinos

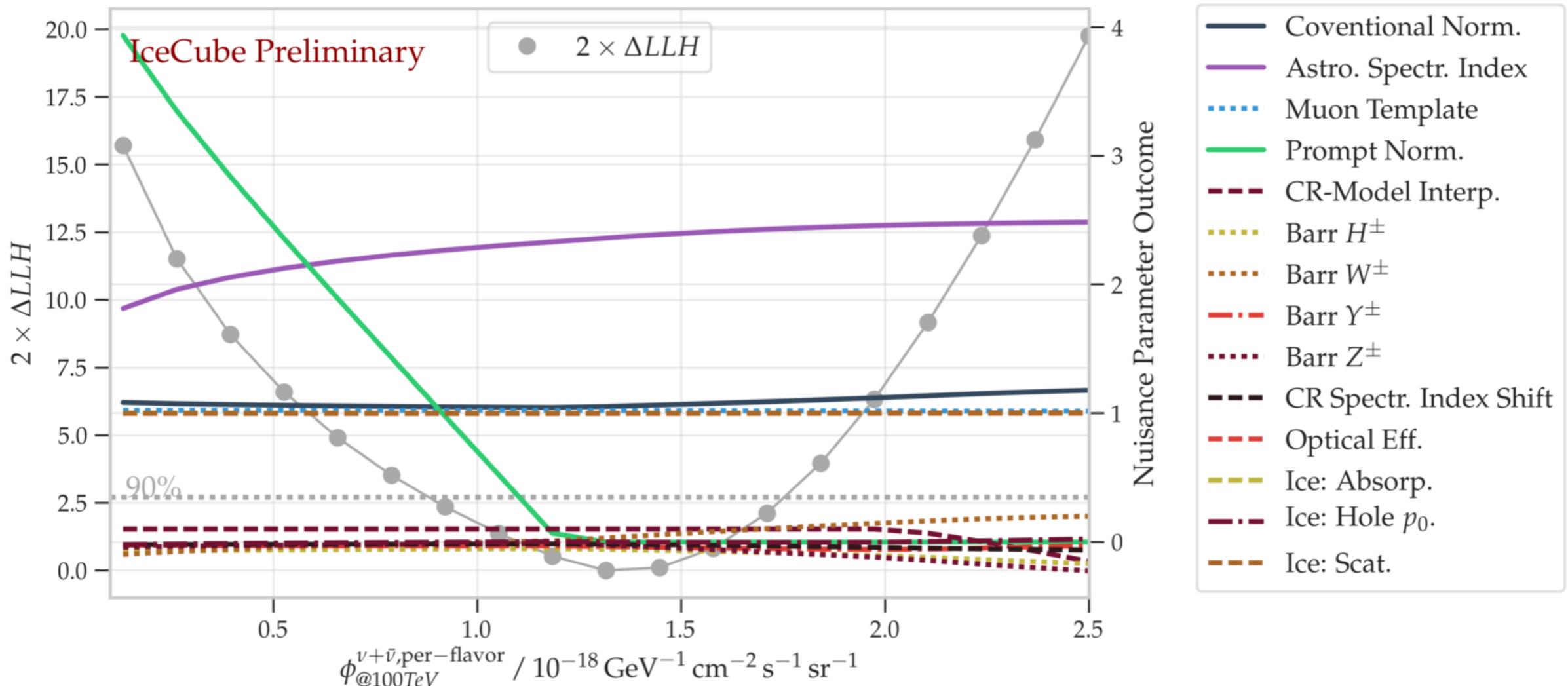
RECENT PAPER: arXiv:2005.12943



H^+, H^-, W^+, W^-
 Y^+, Y^-, Z^+, Z^-

High-energy track measurements

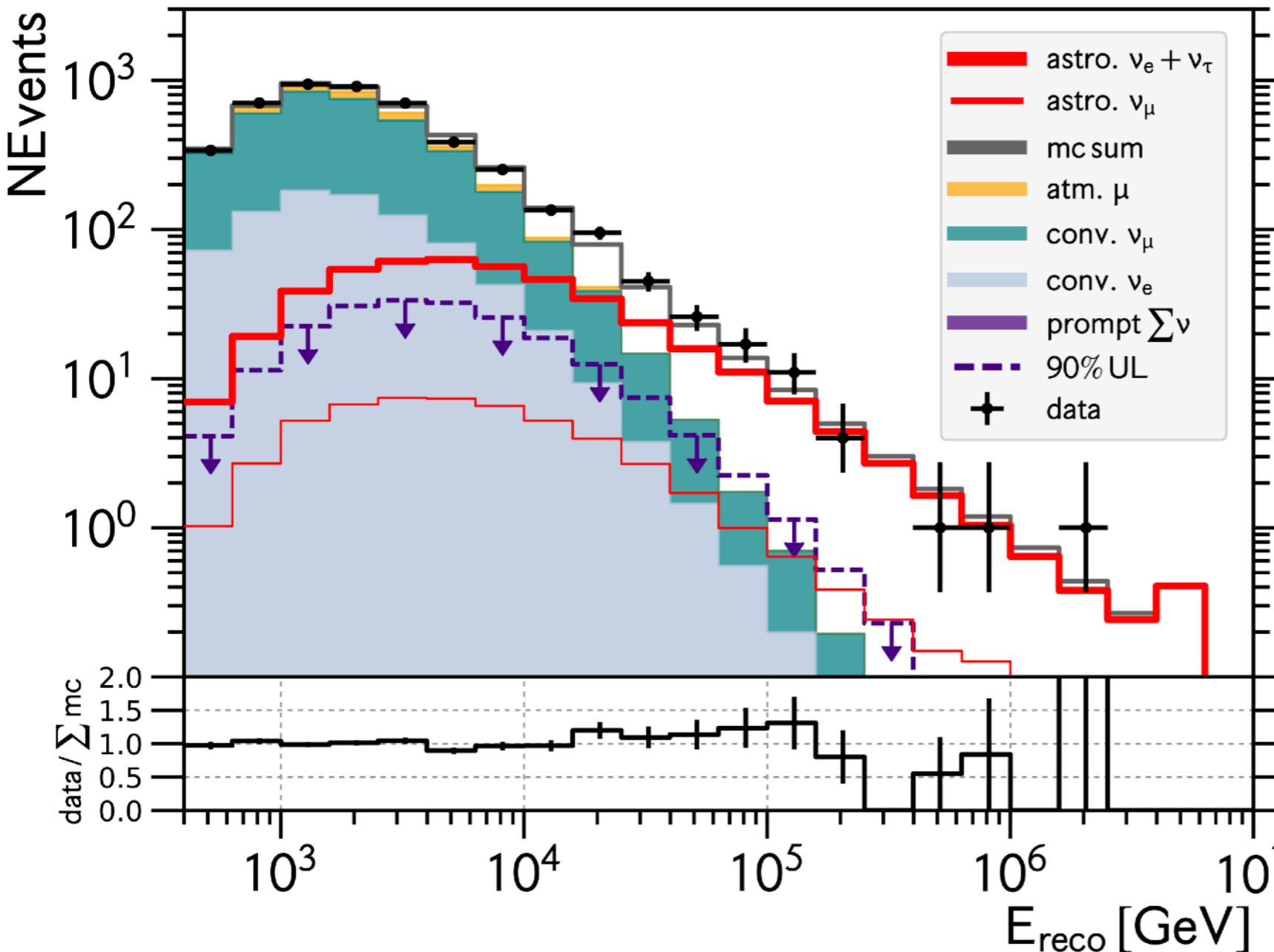
Upcoming 9.5 years of northern track muon-neutrino



Prompt component best-fit point is still zero with improved analysis.
Constraints from improved analysis coming soon!

High-energy cascade measurements

6 years all-sky cascade analysis



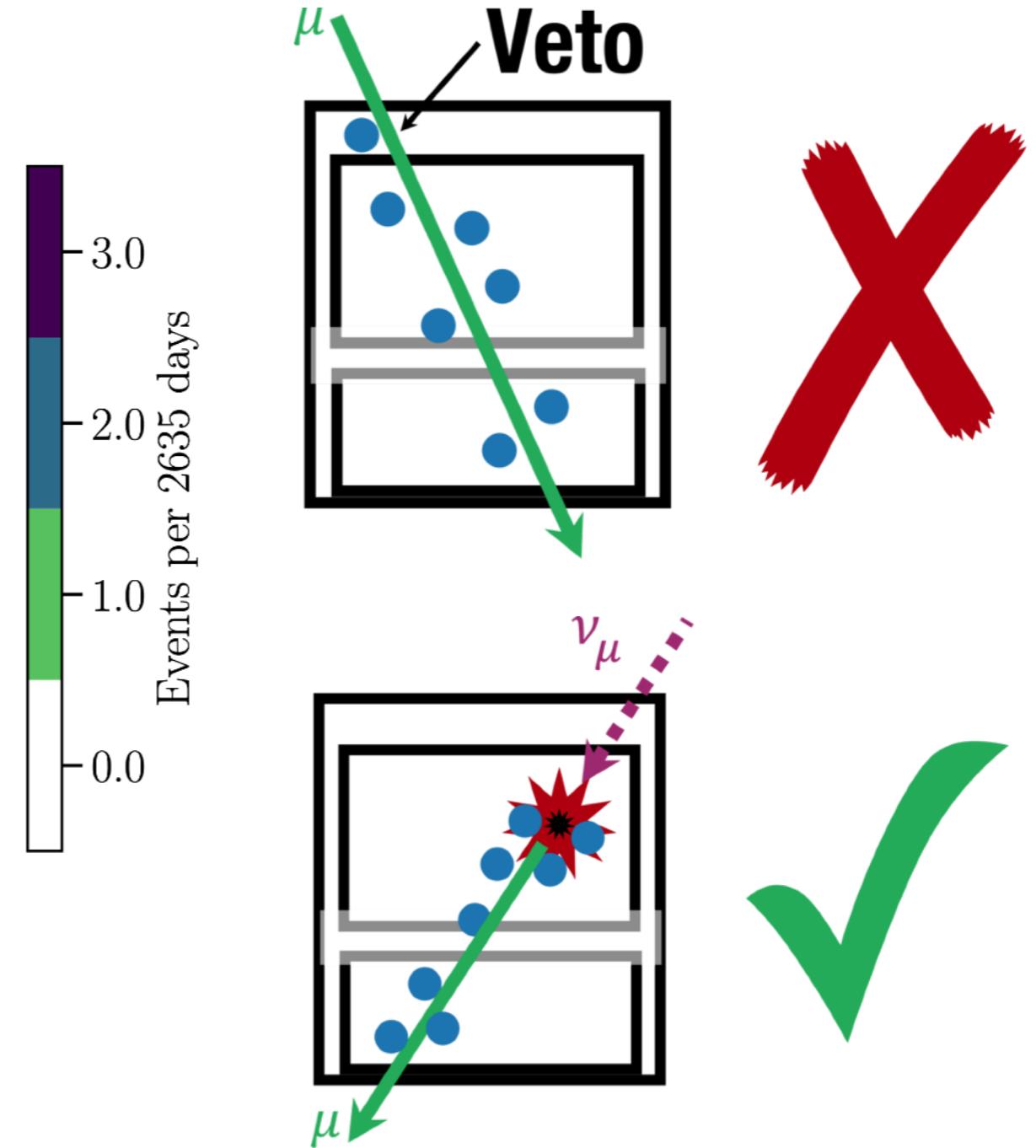
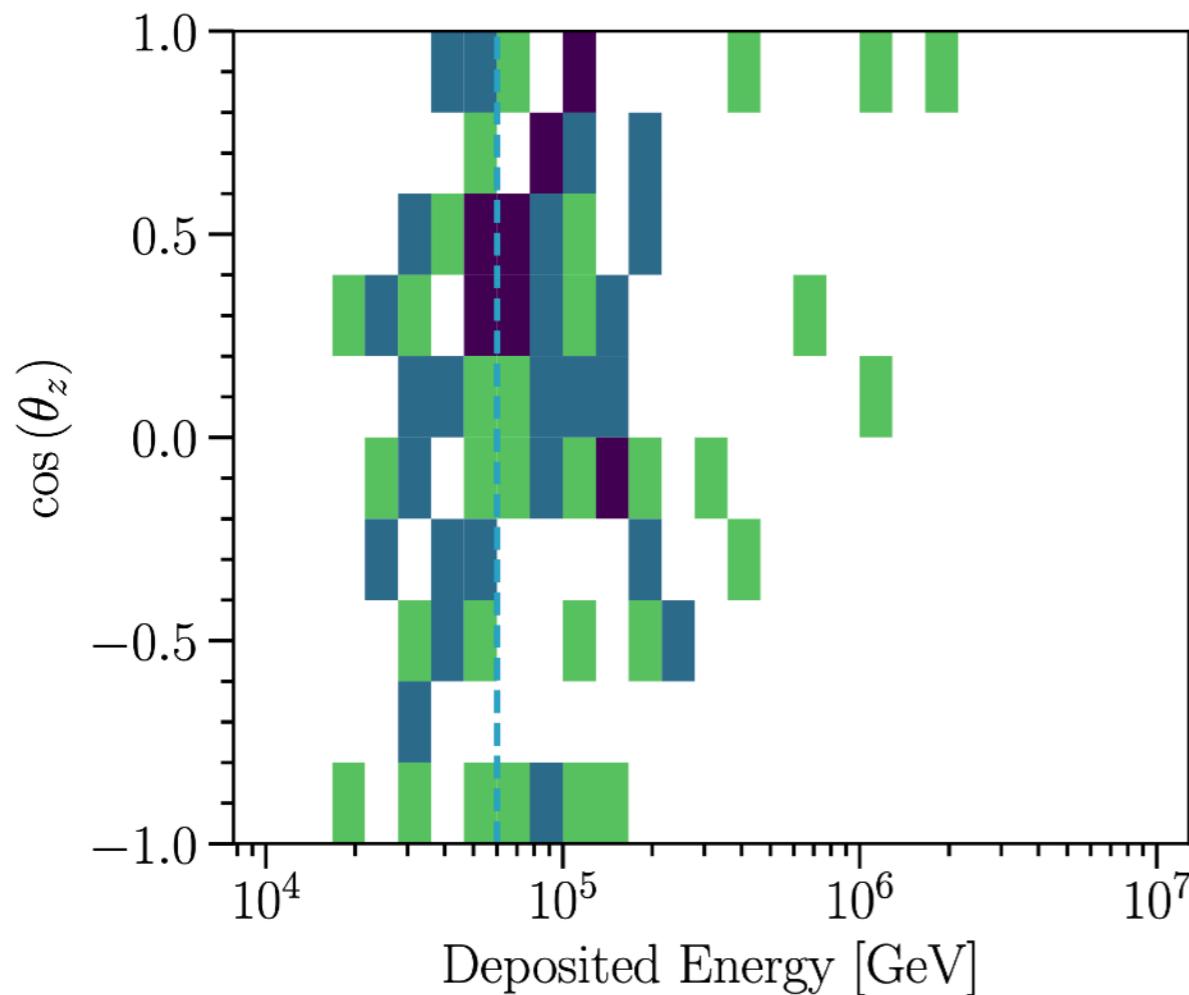
Number of Events	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
astro.	303^{+46}_{-45} (127 $^{+12}_{-12}$)	59^{+8}_{-7} (22 $^{+2}_{-2}$)	204^{+28}_{-27} (80 $^{+7}_{-7}$)
astro. GR	$0.73^{+0.31}_{-0.22}$	-	-
atmo. conv.	851^{+23}_{-23} (50 $^{+3}_{-3}$)	2901^{+64}_{-65} (143 $^{+8}_{-8}$)	-
atmo. prompt	< 192 (< 57)	< 32 (< 7)	-

Parameter	Prior constraint	Result $\pm 1\sigma$ (< 90% upper limit)
γ	-	2.53 ± 0.07
ϕ_{astro}	-	$1.66^{+0.25}_{-0.27}$
ϕ_{conv}	-	$(1.07^{+0.13}_{-0.12}) \times \Phi_{HKKMS06}$
ϕ_{prompt}	-	$< 5.0 \times \Phi_{BERSS}$
ϕ_{muon}	-	1.45 ± 0.04
$\Delta\gamma_{CR}$	0.00 ± 0.05	0.02 ± 0.03
ϵ_{scat}^{BI}	1.00 ± 0.07	1.02 ± 0.03
ϵ_{abs}^{BI}	1.00 ± 0.07	$1.03^{+0.05}_{-0.04}$
ϵ_{scat}^{HI}	-	1.72 ± 0.19
ϵ_{eff}^{DOM}	0.99 ± 0.10	$1.03^{+0.08}_{-0.07}$

Parameter	Prior constraint	Result $\pm 1\sigma$ (< 90% upper limit)
γ	-	2.53 ± 0.07
ϕ_{astro}	-	$1.66^{+0.25}_{-0.27}$
ϕ_{conv}	-	$(1.07^{+0.13}_{-0.12}) \times \Phi_{HKKMS06}$
ϕ_{prompt}	-	$< 5.0 \times \Phi_{BERSS}$
ϕ_{muon}	-	1.45 ± 0.04
$\Delta\gamma_{CR}$	0.00 ± 0.05	0.02 ± 0.03
ϵ_{scat}^{BI}	1.00 ± 0.07	1.02 ± 0.03
ϵ_{abs}^{BI}	1.00 ± 0.07	$1.03^{+0.05}_{-0.04}$
ϵ_{scat}^{HI}	-	1.72 ± 0.19
ϵ_{eff}^{DOM}	0.99 ± 0.10	$1.03^{+0.08}_{-0.07}$

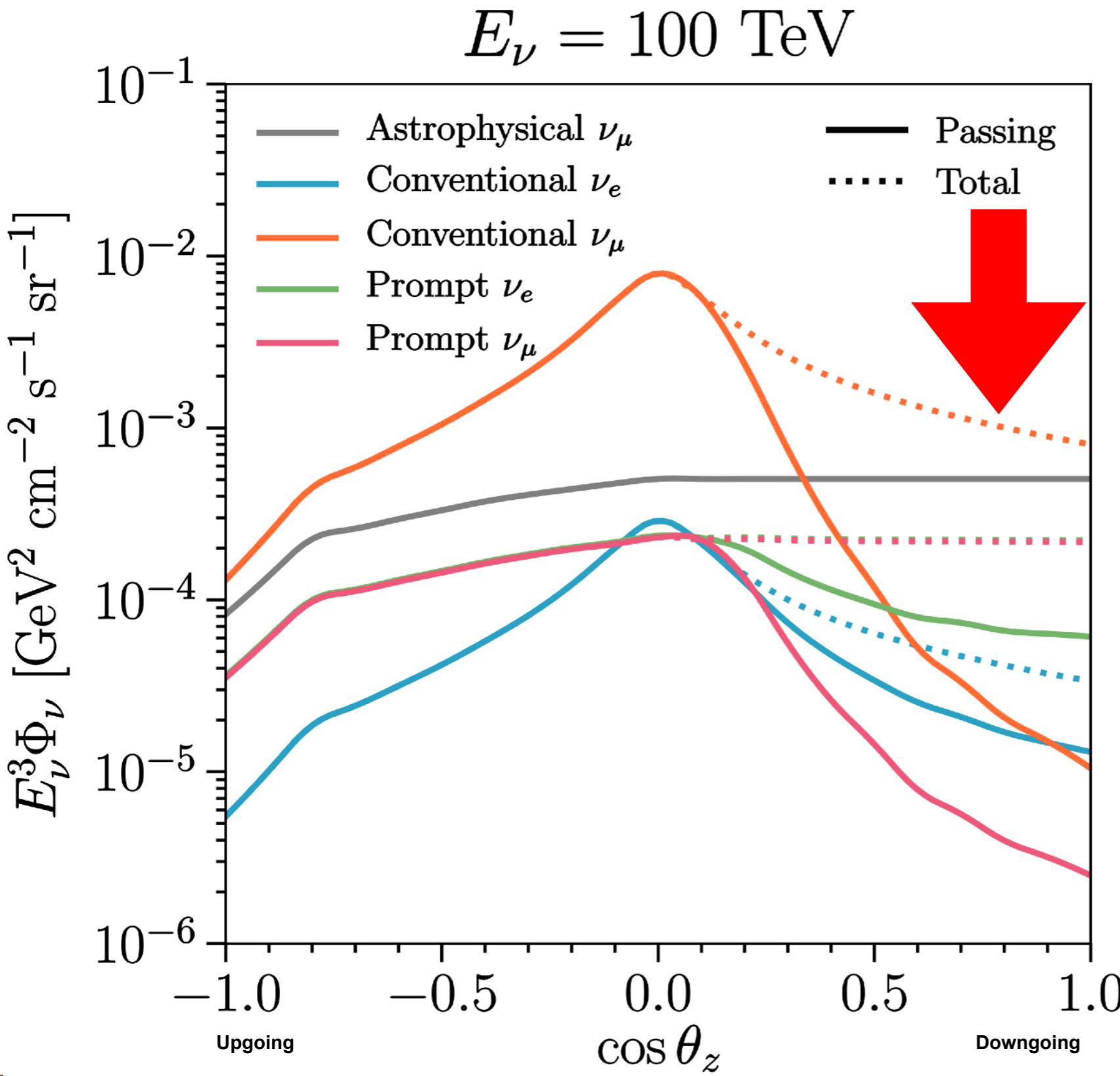
RECENT PAPER: arXiv:2001.09520

High-energy starting-events measurements

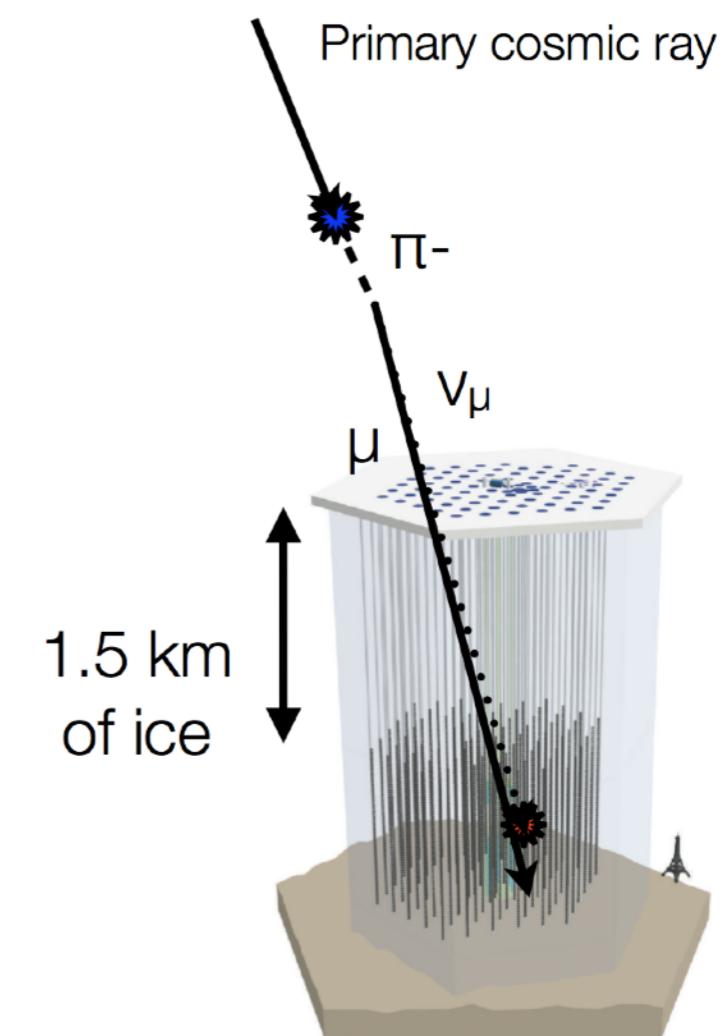


NEW PAPER: arXiv:2011.03545

Effect of coincident-muon rejection

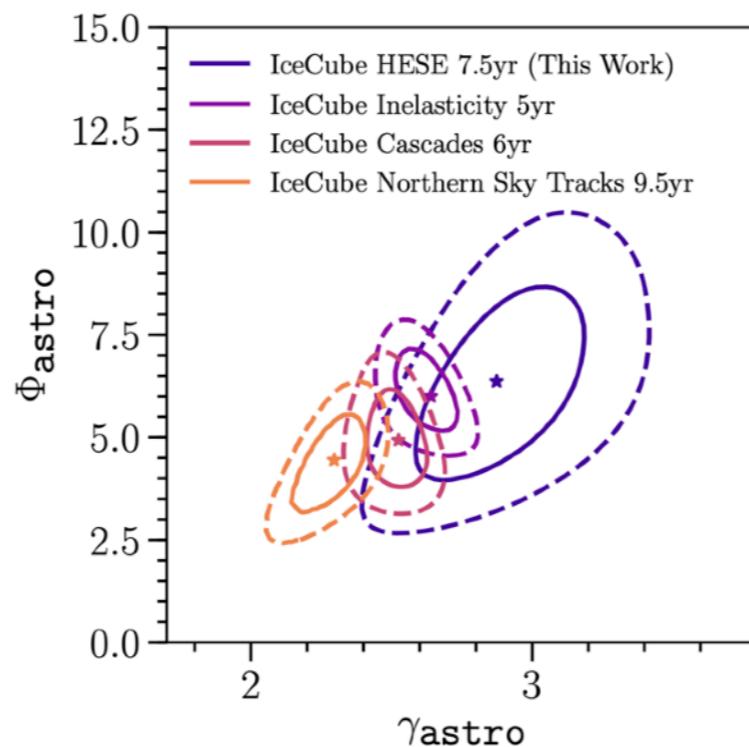
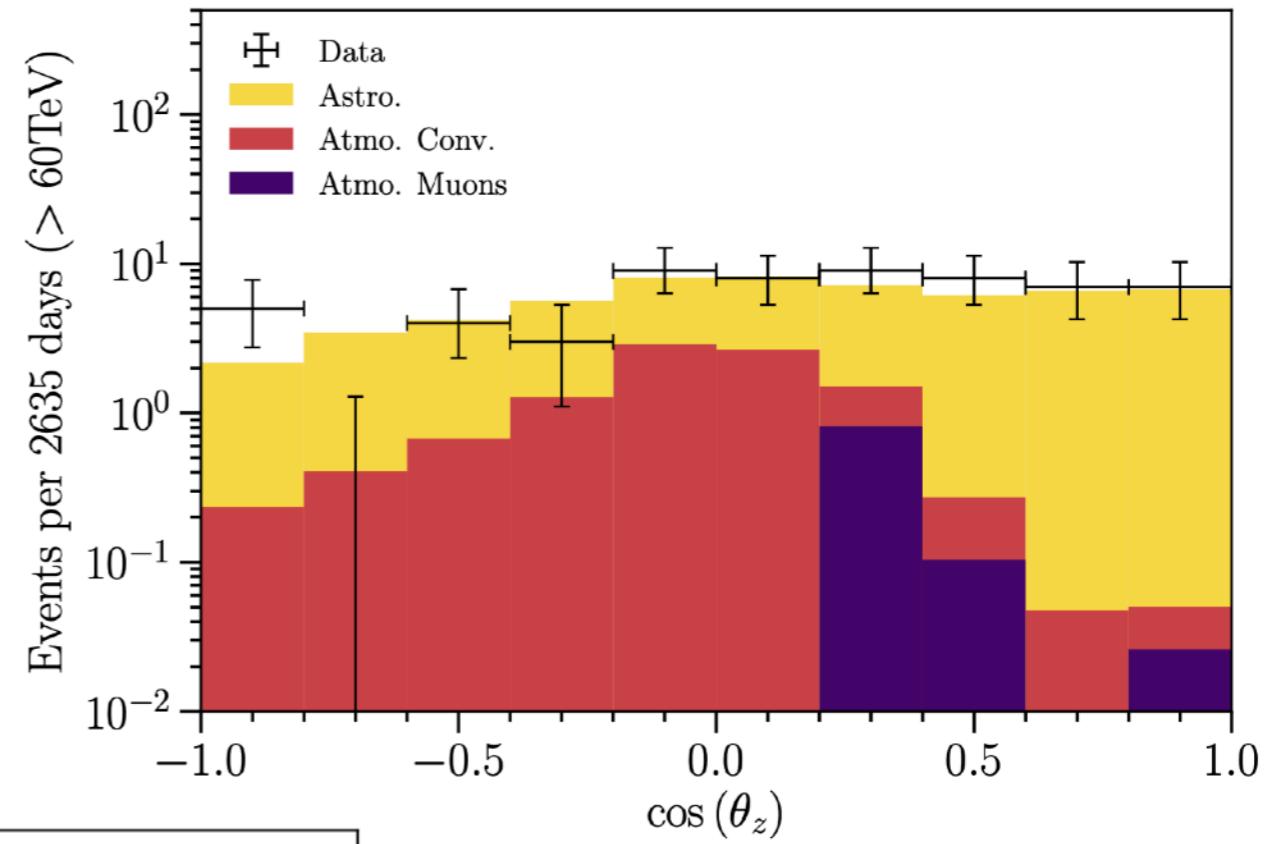
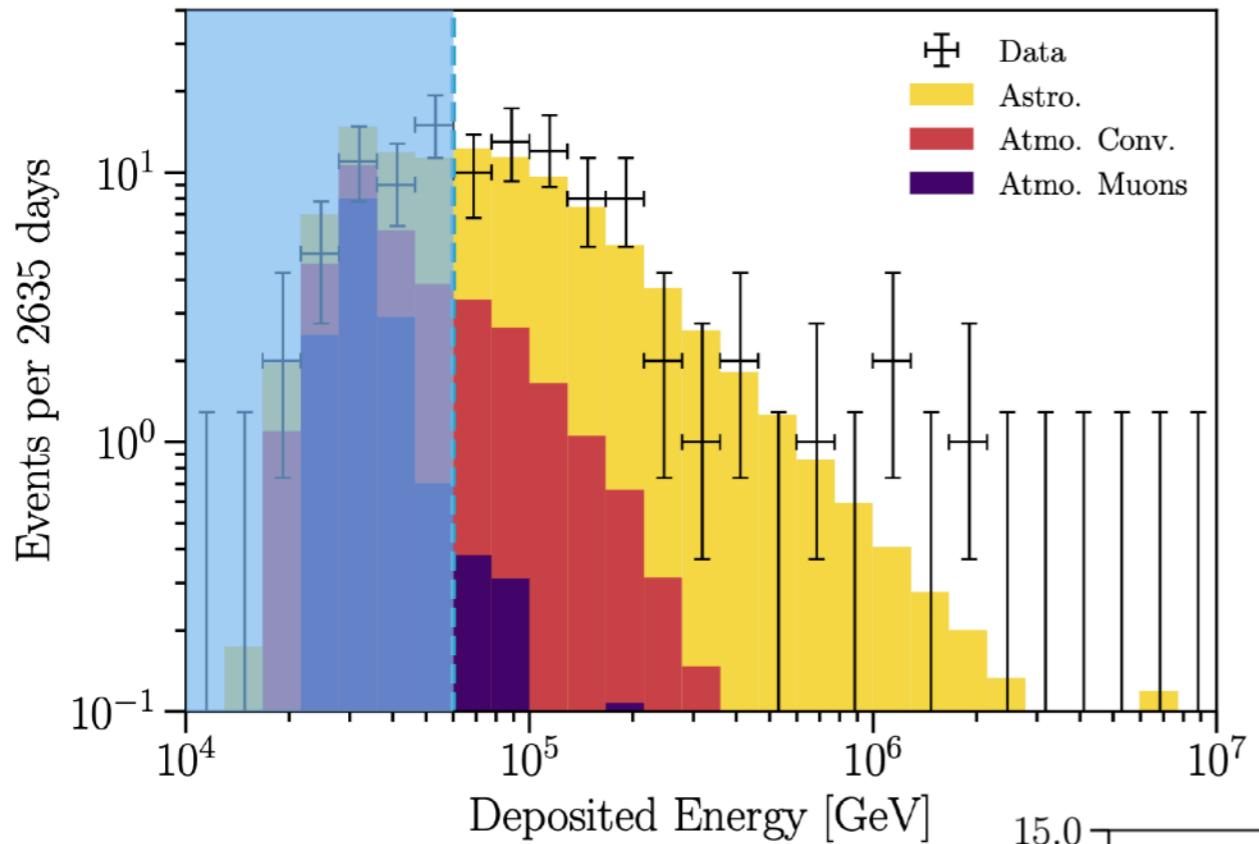


An active muon veto removes down-going atmospheric neutrinos.



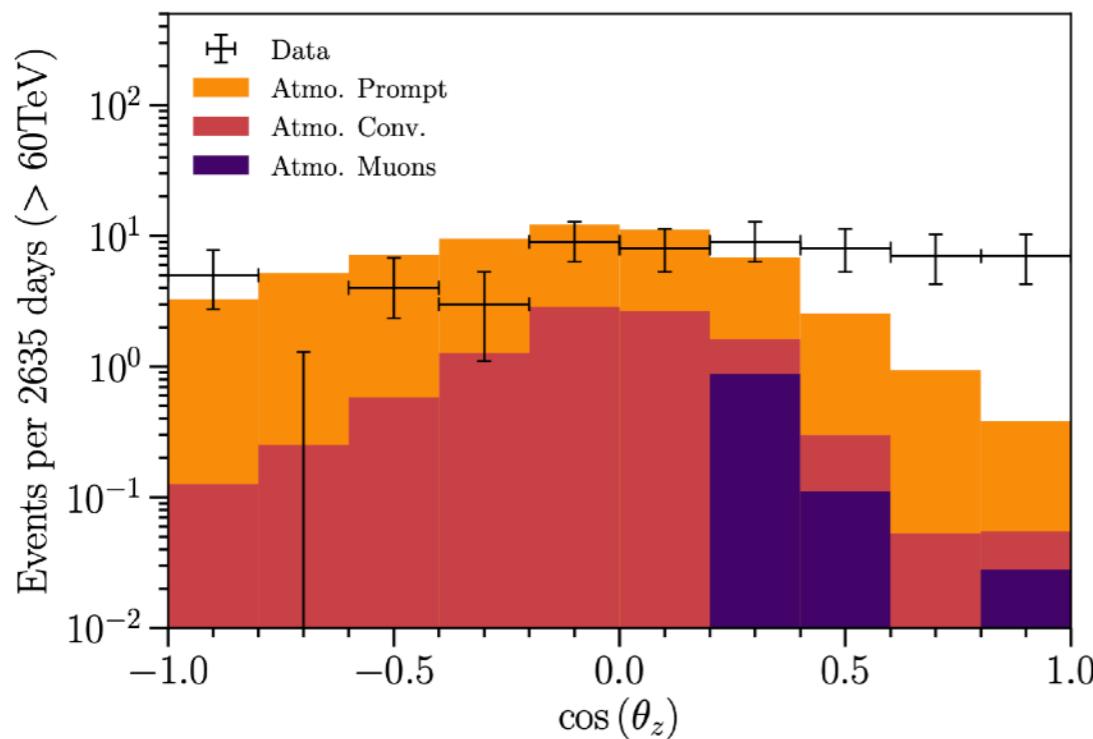
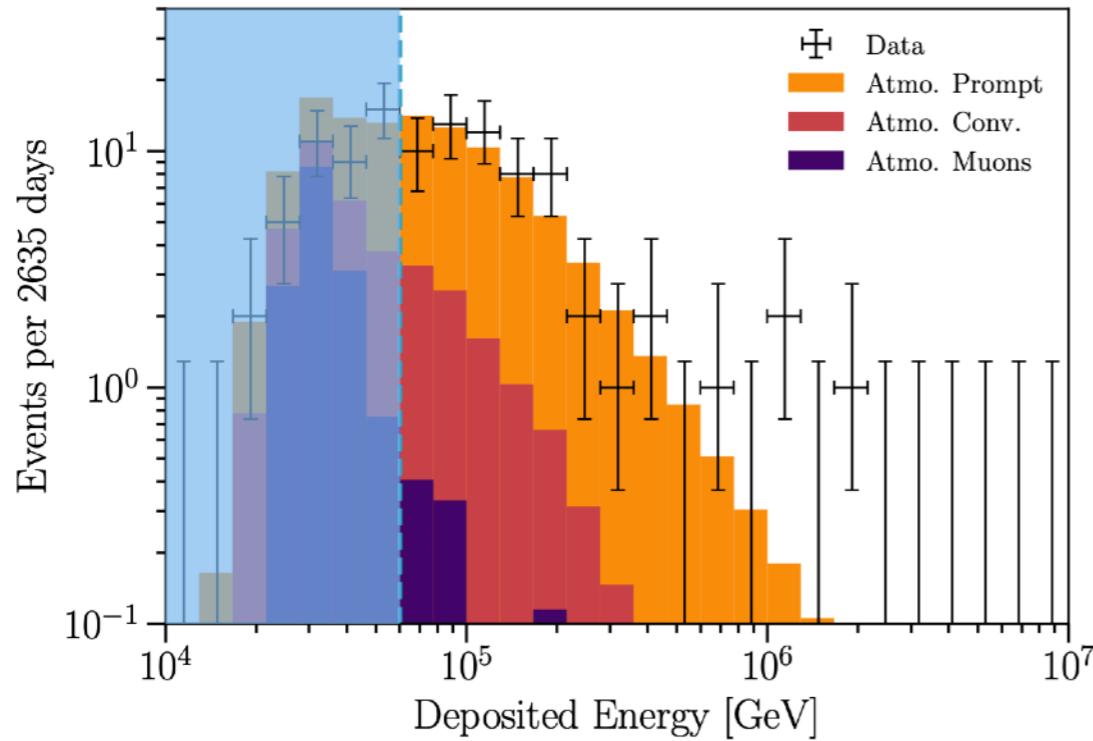
Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
CA, Palomares-Ruiz, Austin Schneider,
Wille, Yuan
JCAP 1807 (2018) no.07, 047

High-energy starting event data fit



NEW PAPER: arXiv:2011.03545

Prompt on High-energy starting sample

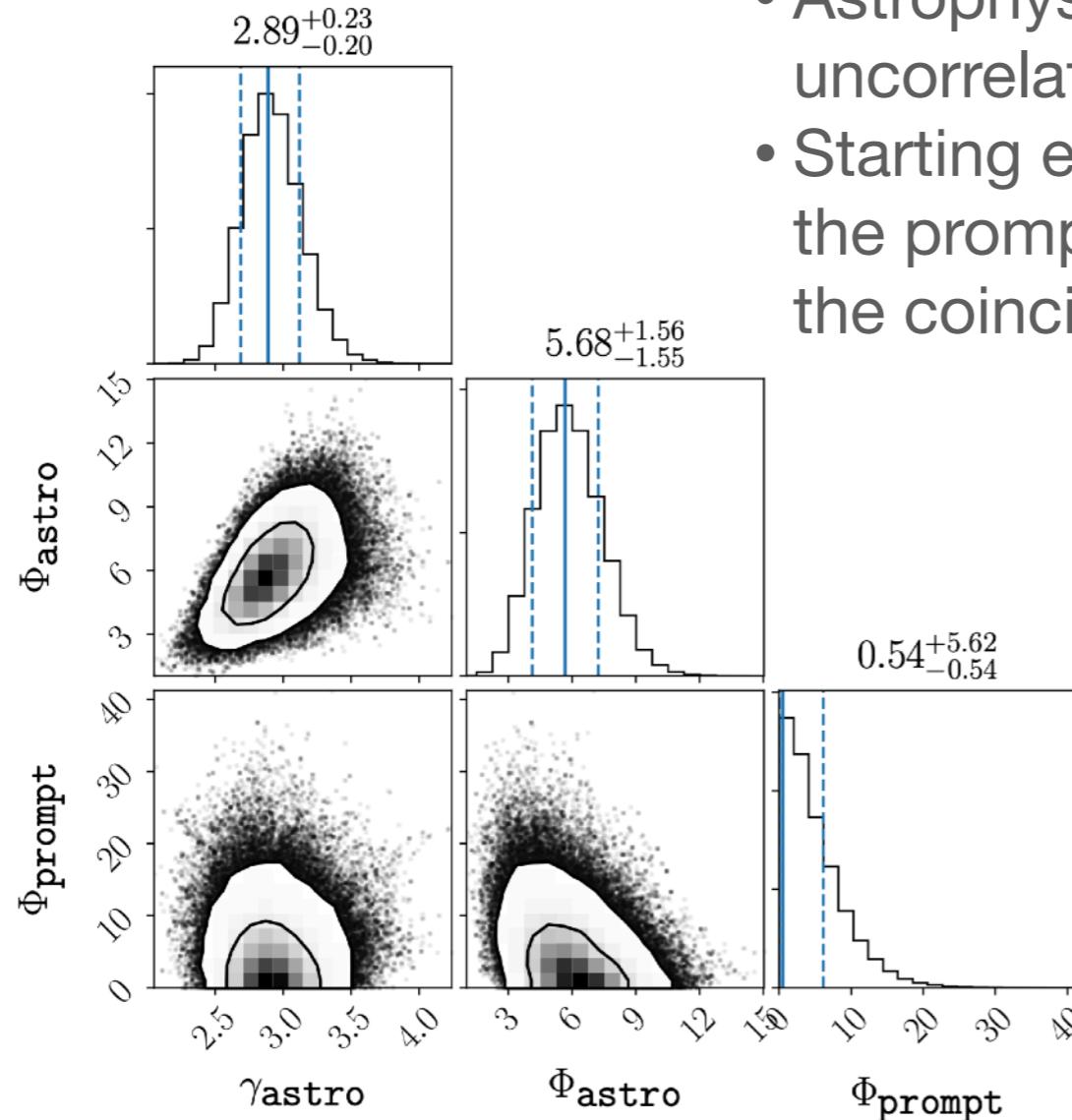


- Atmospheric-only fit results in a very poor fit to the angular distribution.
- Requires extremely large prompt flux ~ 20 times larger than baseline model. Ruled out by all of our prompt constraints.

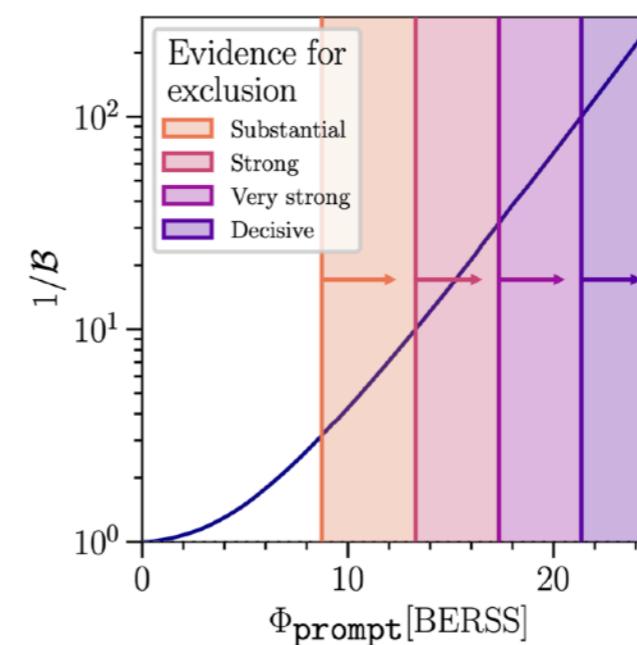
NEW PAPER: arXiv:2011.03545

Prompt on High-energy starting sample

NEW PAPER: arXiv:2011.03545



- Astrophysical power-law parameters mostly uncorrelated with prompt flux normalization.
- Starting event sample results in a poor constraint to the prompt flux, compare to other samples, due to the coincident-muon suppression.



	Frequentist upper limit (90 % C.L.)	Bayesian model rejection (strong)
Northern sky muons IC59 [193]	$3.80 \times \phi_{ERS}$	—
Northern sky muons IC86 [57]	$1.06 \times \phi_{ERS}$	—
All-sky medium-energy starting cascades [62]	$1.52 \times \phi_{ERS}$	—
HESE 7.5 years (this work)	$9.82 \times \phi_{BERSS}$	$13.29 \times \phi_{BERSS}$

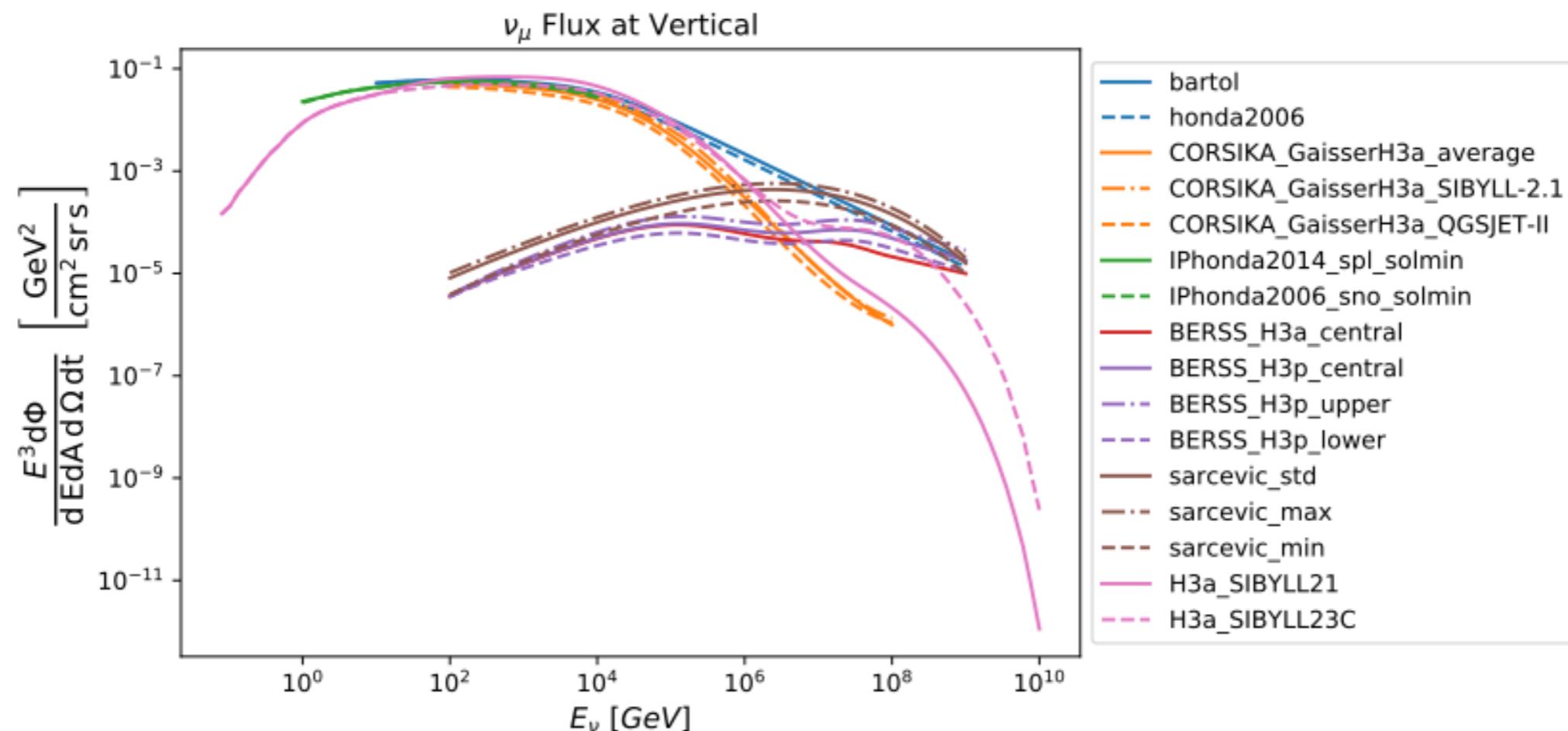
$$\phi_{ERS}(100 \text{ TeV}) \approx 2.5 \cdot \phi_{BERSS}(100 \text{ TeV})$$

Carlos A. Argüelles-Delgado - SnowMass NF04

Atmospheric neutrino public repository

vflux

<https://github.com/IceCubeOpenSource/nuflux>



From python:

```
import nuflux
flux = nuflux.makeFlux('honda2006')
nu_type=nuflux.NuMu
nu_energy=1e3 # in GeV
nu_cos_zenith = 0.5
print(flux.getFlux(nu_type,nu_energy,nu_cos_zenith))
```

from c++:

```
#include <nuflux/nuflux.h>

int main(){
    boost::shared_ptr<nuflux::FluxFunction> flux;
    flux=nuflux::makeFlux("honda2006");
    double f=flux->getFlux(nuflux::NuMu,1e3,0);
    std::cout << f << '\n';
}
```



Take home message

- High-energy and low-energy unfoldings.
- Measurement of the pion-to-kaon contribution at sub-TeV energies.
- Search for prompt neutrinos using cascades, tracks, and starting tracks: so far no prompt component observed.
- Improved treatment of the conventional component by means of Barr-gradients. Data can constrain parameters to be smaller than priors.
- Strongest prompt constraints still come from the northern sky tracks at ~ 2.5 BERSS. Cascade constraints at a similar level.
- New open source neutrino flux repository! Try it out!

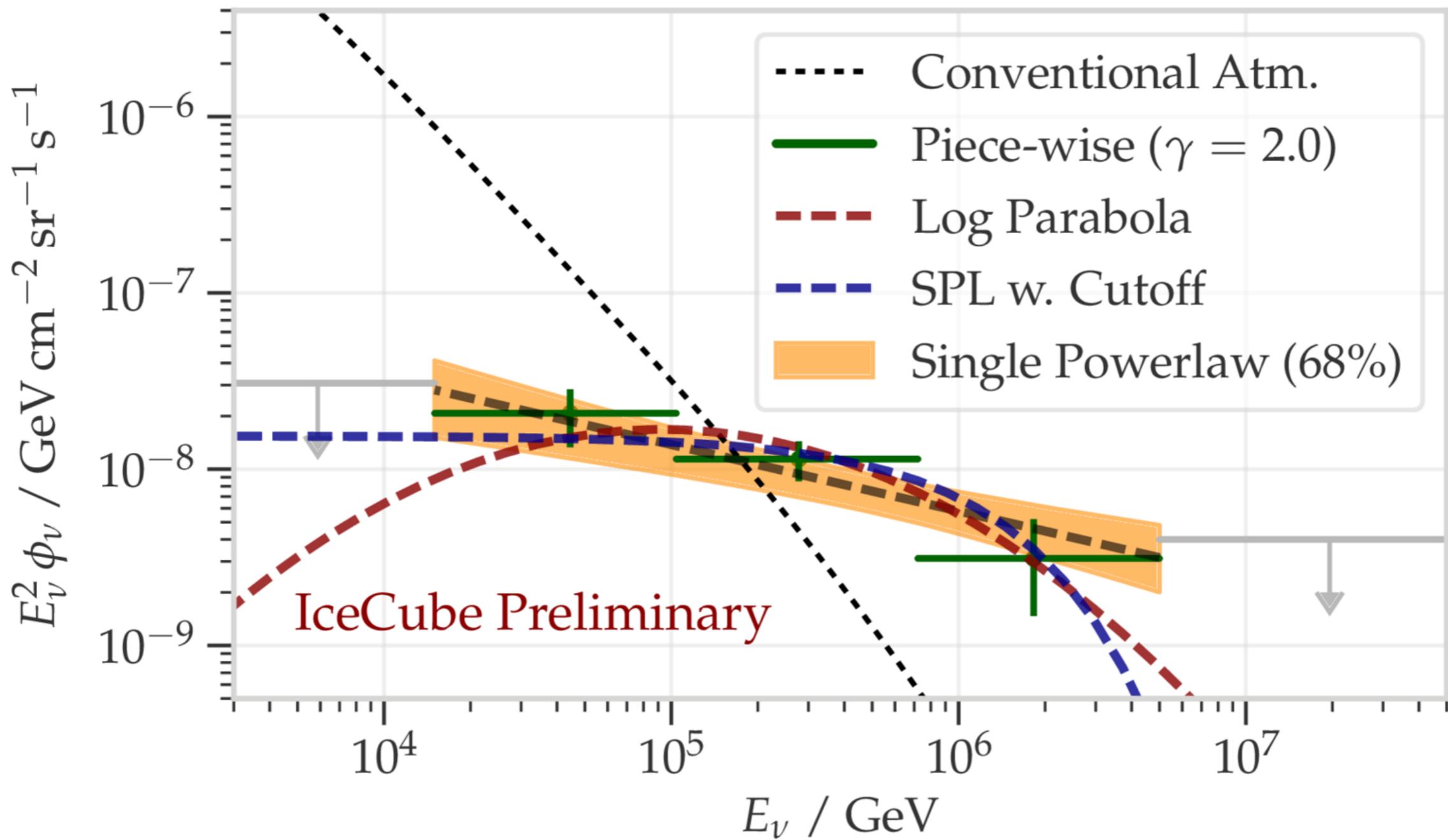
Gracias!



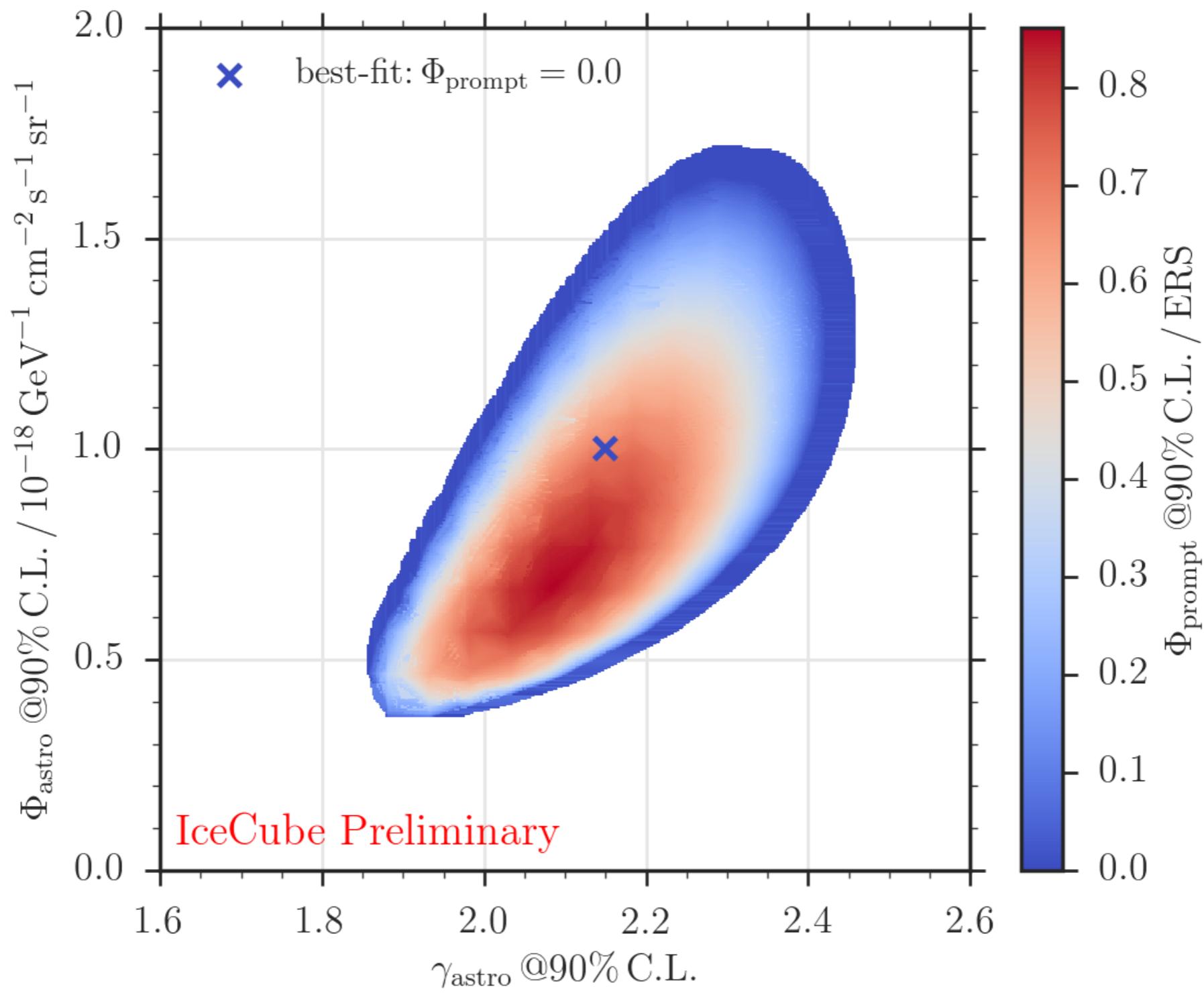
Bonus Slides



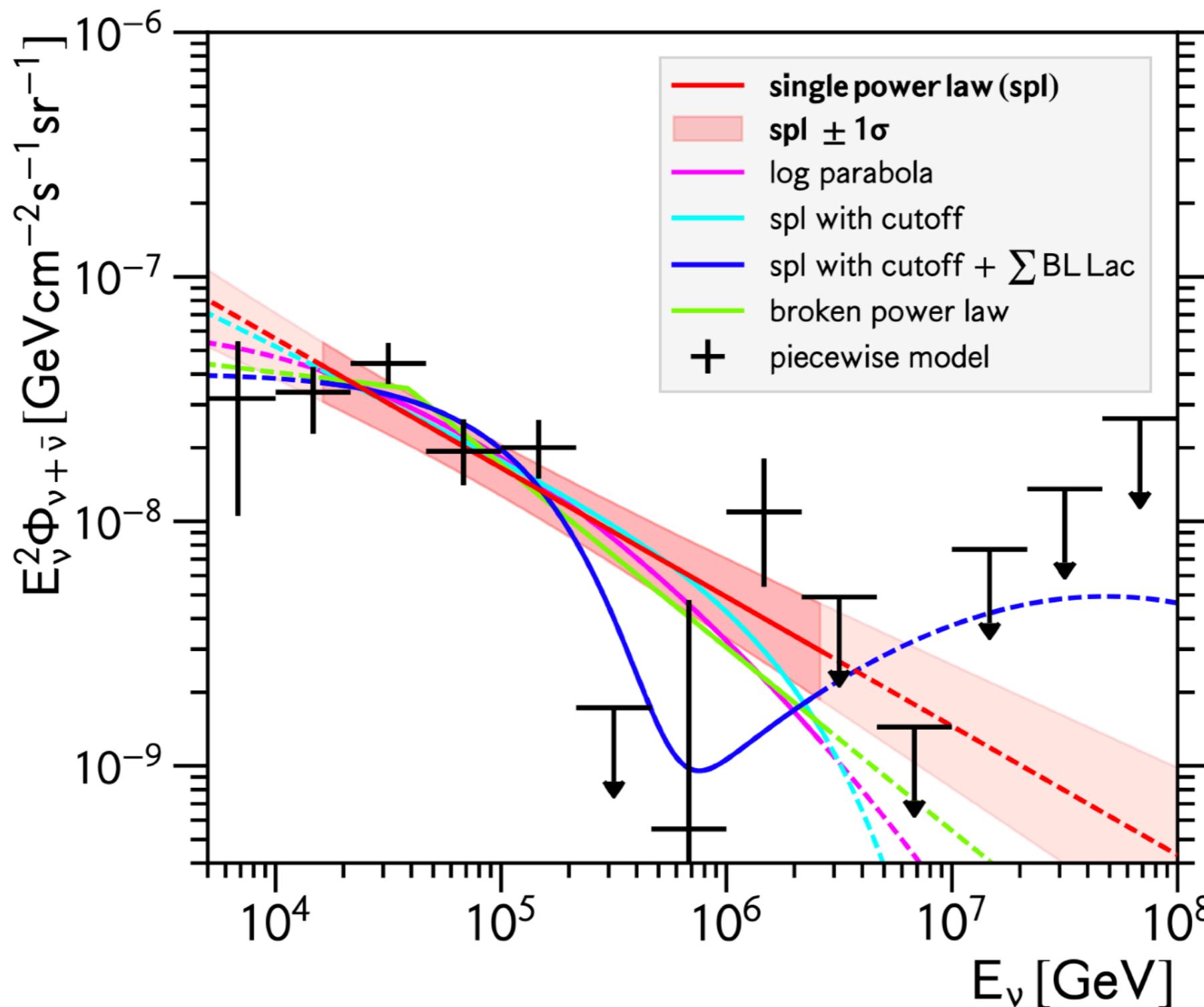
Upcoming 9.5 years of northern track muon-neutrino



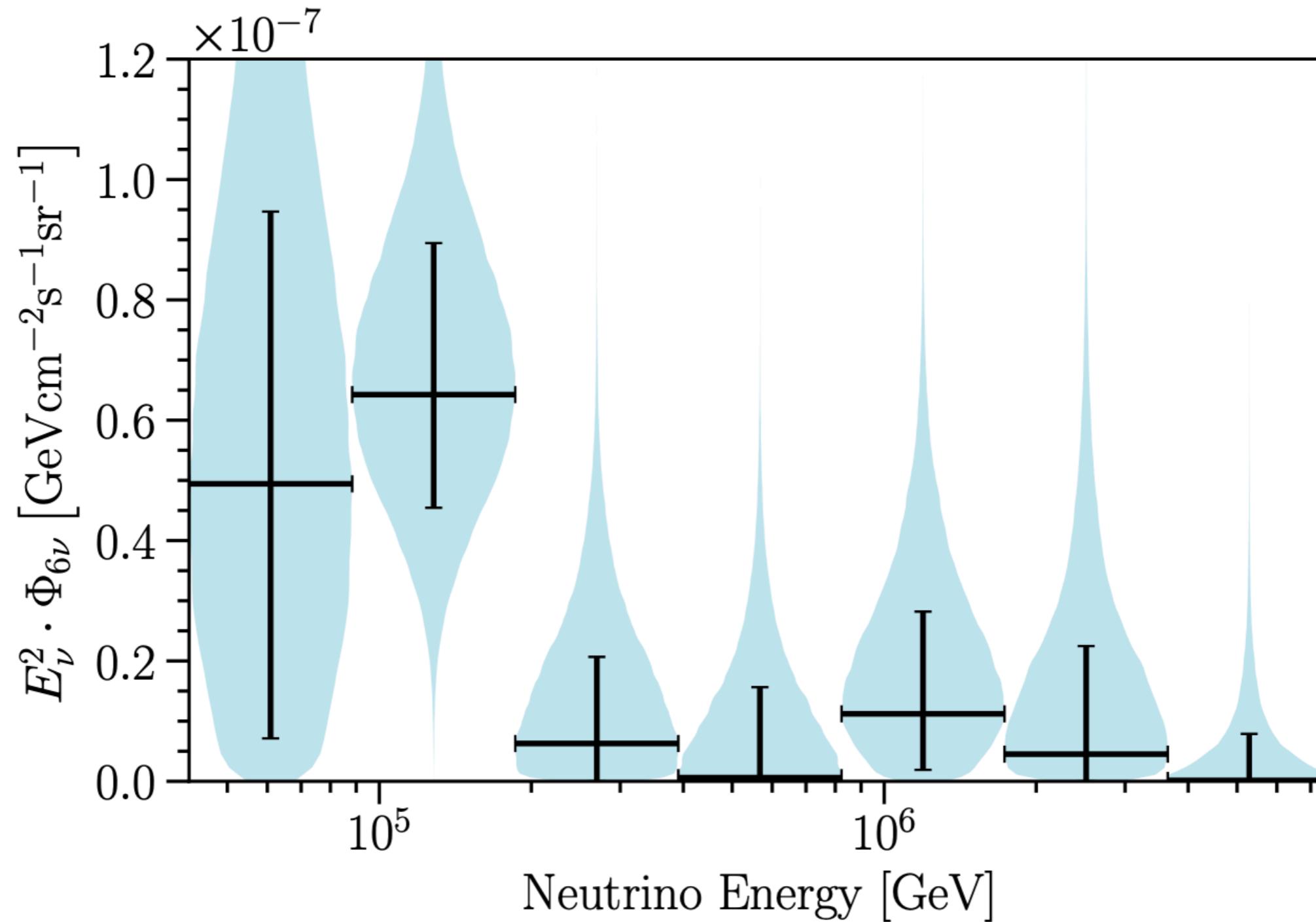
8 years of northern track muon-neutrino



6 yr cascade segmented fit result



7.5 yr HESE segmented astro fit result



RECENT PAPER: arXiv:2005.12943

Parameter	Central	Prior (Constraint)	Boundary
Physics Mixing Parameters			
Δm_{41}^2	none	flat log prior	[0.01, 100] eV ²
$\sin^2(\theta_{24})$	none	flat log prior	[$10^{-2.6}$, 1.0]
$\sin^2(\theta_{34})$	none	flat log prior	[$10^{-3.1}$, 1.0]
Detector parameters			
DOM efficiency	0.97	0.97 ± 0.10	[0.94, 1.03]
Bulk Ice Gradient 0	0.0	$0 \pm 1.0^*$	NA
Bulk Ice Gradient 1	0.0	$0 \pm 1.0^*$	NA
Forward Hole Ice (p_2)	-1.0	-1.0 ± 10.0	[-5, 3]
Conventional Flux parameters			
Normalization ($\Phi_{\text{conv.}}$)	1.0	1.0 ± 0.4	NA
Spectral shift ($\Delta\gamma_{\text{conv.}}$)	0.00	0.00 ± 0.03	NA
Atm. Density	0.0	0.0 ± 1.0	NA
Barr WM	0.0	0.0 ± 0.40	[-0.5, 0.5]
Barr WP	0.0	0.0 ± 0.40	[-0.5, 0.5]
Barr YM	0.0	0.0 ± 0.30	[-0.5, 0.5]
Barr YP	0.0	0.0 ± 0.30	[-0.5, 0.5]
Barr ZM	0.0	0.0 ± 0.12	[-0.25, 0.5]
Barr ZP	0.0	0.0 ± 0.12	[-0.2, 0.5]
Astrophysical Flux parameters			
Normalization ($\Phi_{\text{astro.}}$)	0.787	$0.0 \pm 0.36^*$	NA
Spectral shift ($\Delta\gamma_{\text{astro.}}$)	0	$0.0 \pm 0.36^*$	NA
Cross sections			
Cross section σ_{ν_μ}	1.00	1.00 ± 0.03	[0.5, 1.5]
Cross section $\sigma_{\bar{\nu}_\mu}$	1.000	1.000 ± 0.075	[0.5, 1.5]
Kaon energy loss σ_{KA}	0.0	0.0 ± 1.0	NA

Parameter	Analysis I	Analysis II
Physics Mixing Parameters		
Δm_{41}^2	4.47 eV^2	$> 10 \text{ eV}^2$
$\sin^2(2\theta_{24})$	0.10	0.006
$\sin^2(2\theta_{34})$	0.0	0.40
Detector parameters		
DOM Efficiency	0.961 ± 0.005	0.965 ± 0.005
Ice Gradient 0	-0.15 ± 0.25	0.05 ± 0.24
Ice Gradient 1	0.36 ± 0.53	0.89 ± 0.54
Hole Ice (p_2)	-3.44 ± 0.44	-3.23 ± 0.44
Conventional Flux parameters		
Normalization ($\Phi_{\text{conv.}}$)	1.19 ± 0.05	1.11 ± 0.05
Spectral shift ($\Delta\gamma_{\text{conv.}}$)	0.068 ± 0.012	0.066 ± 0.012
Atm. Density	-0.16 ± 0.71	-0.17 ± 0.68
Barr WM	-0.02 ± 0.28	0.00 ± 0.29
Barr WP	0.00 ± 0.28	0.01 ± 0.29
Barr YM	-0.06 ± 0.24	-0.03 ± 0.25
Barr YP	-0.10 ± 0.15	-0.05 ± 0.15
Barr ZM	-0.00 ± 0.11	-0.00 ± 0.11
Barr ZP	0.01 ± 0.09	0.016 ± 0.089
Astrophysical Flux parameters		
Normalization ($\Phi_{\text{astro.}}$)	0.95 ± 0.21	0.80 ± 0.21
Spectral shift ($\Delta\gamma_{\text{astro.}}$)	0.11 ± 0.19	-0.06 ± 0.21
Cross sections		
Cross section σ_{ν_μ}	1.00 ± 0.03	1.000 ± 0.03
Cross section $\sigma_{\bar{\nu}_\mu}$	1.003 ± 0.075	1.004 ± 0.074
Hadronic energy loss σ_{KA}	-0.35 ± 0.93	-0.06 ± 0.90

8 yr muons with the MEOWS sample