Methods for a consistent treatment of systematic uncertainties in a combined analysis of IceCube's high energy neutrino data

Richard Naab[1*], **Erik Ganster**[2] for the IceCube collaboration

[1]DESY Zeuthen, [2]RWTH Aachen University

[*]Speaker

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ICECUBE

DESY.

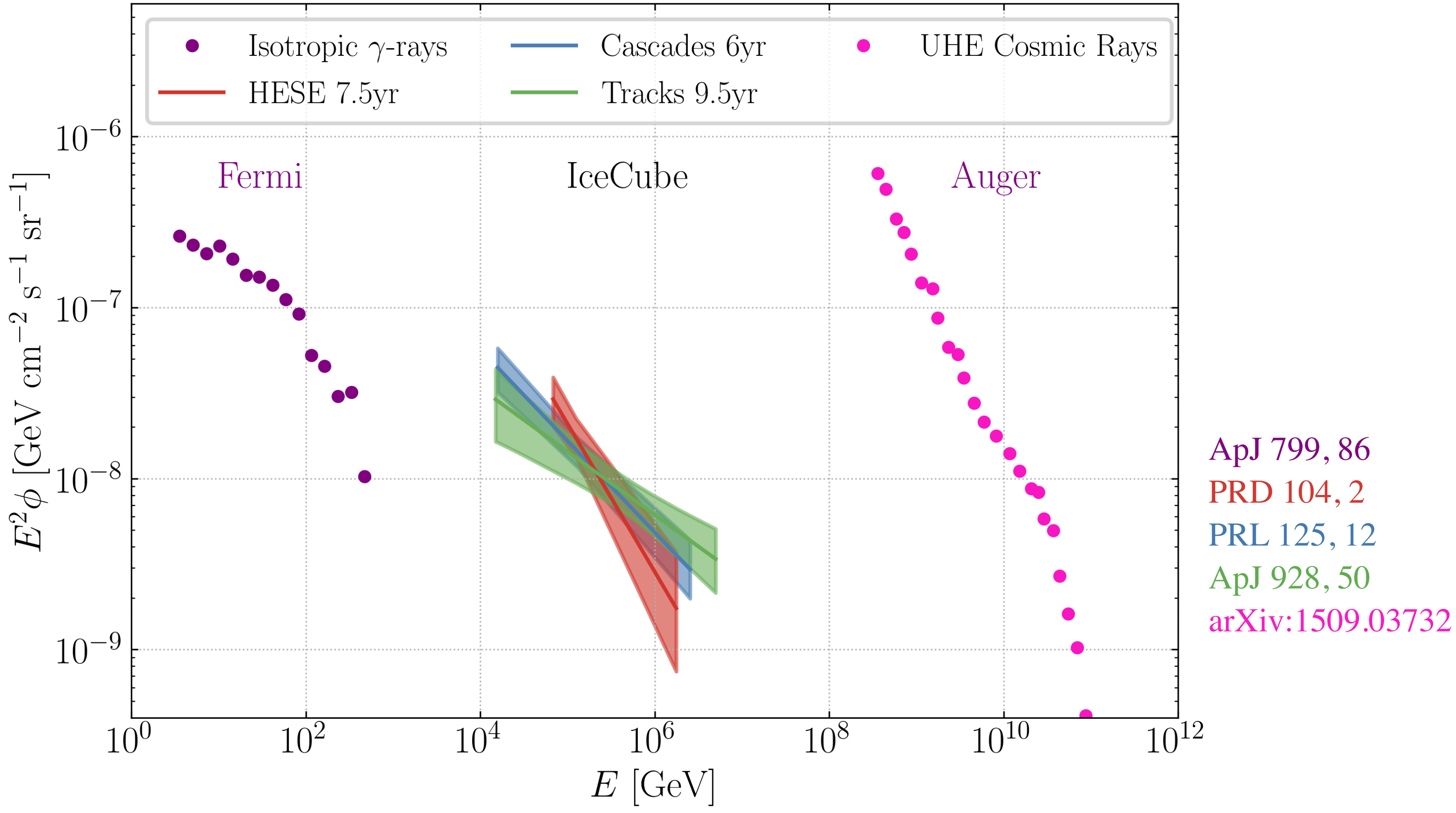
Motivation

Neutrinos and other messengers from the high energy universe

Multi-messenger picture:

- Tight relations between diffuse fluxes of cosmic rays, gamma rays and neutrinos

Energy spectra connected to underlying population of sources

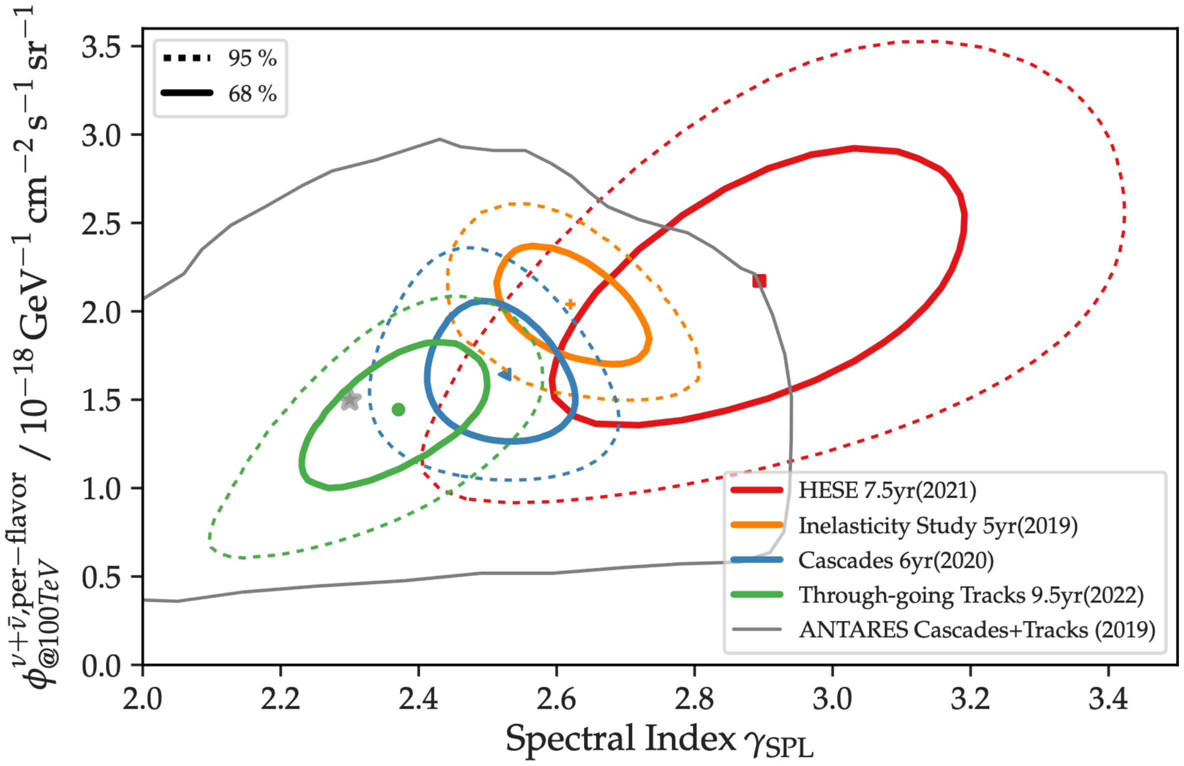


Motivation

The astrophysical neutrino energy spectrum

- Most simple model for the astrophysical neutrino flux:
  - Single power law with normalisation and spectral index as free parameters
  - No statistical preference for models with more structure, so far
- IceCube measures neutrinos in different detection channels (event selections)
  - Probe different neutrino flavours as well as different energy ranges of the diffuse spectrum
- Our goal: Want to combine multiple samples in a **Combined Fit**, in order to get a more complete picture & probe structure in spectrum

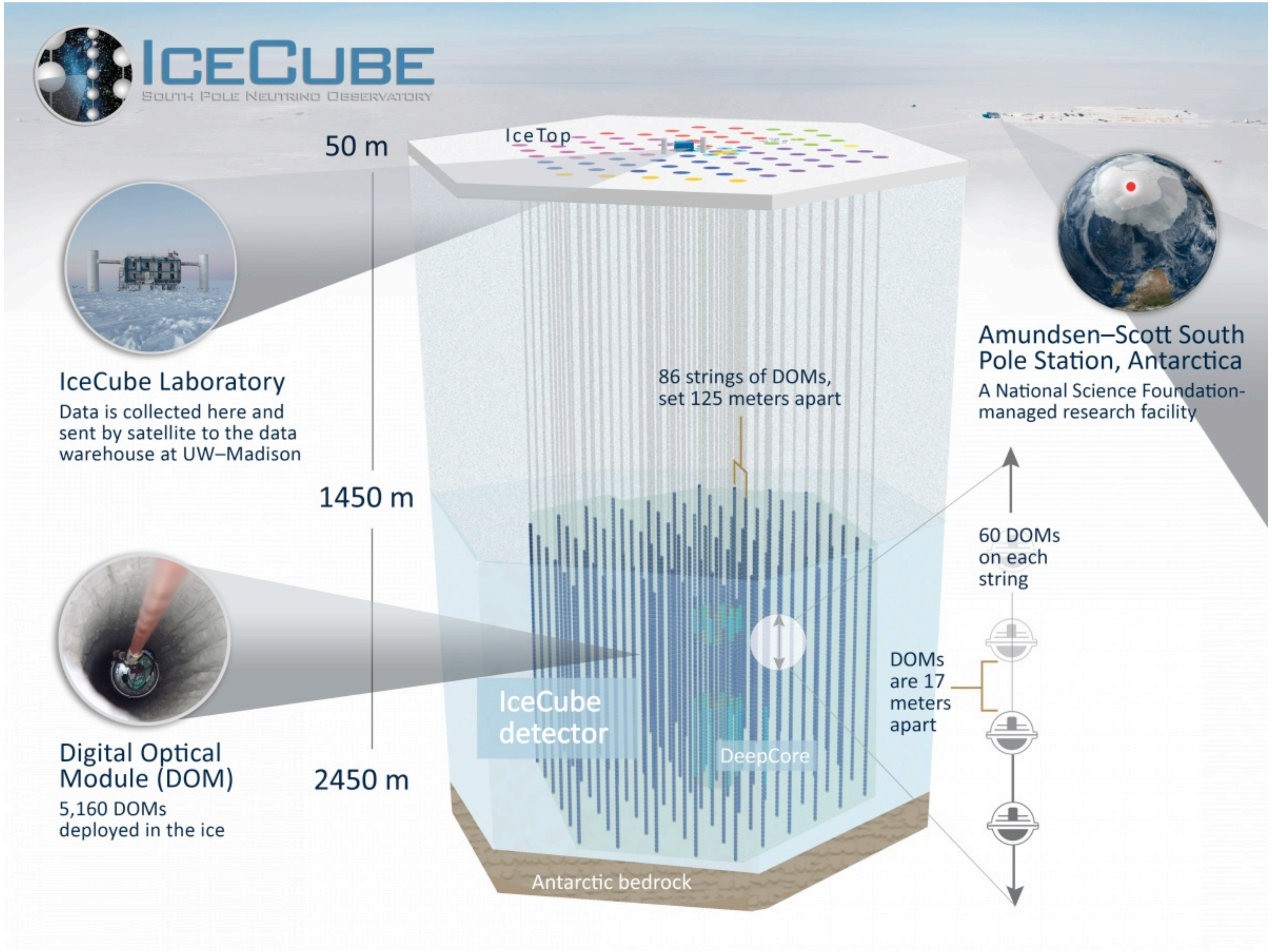
arXiv:2203.08096



IceCube

Detecting neutrino interactions in ice

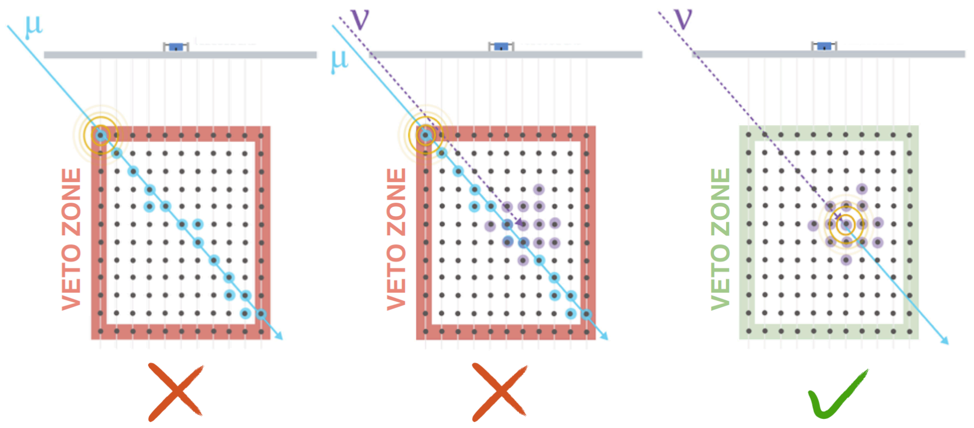
- Instrumented 1km^3 of ice, deep in Antarctic glacier where ice has highest transparency
J. Geophys.Res., 111, D13
- Digital Optical Modules (DOMs) detect Cherenkov radiation from secondary particles of ν-interactions



Neutrino fluxes in IceCube

Atmospheric backgrounds

- Background for measurement of astrophysical ν flux: atmospheric μ and ν produced in cosmic ray air-showers
- 2.3 kHz event rate at trigger level dominated by μ, reduce by
  - Restricting sample to up-going events (northern sky)
  - Veto-techniques (southern sky)
- Atmospheric ν flux potentially reduced in veto, otherwise indistinguishable



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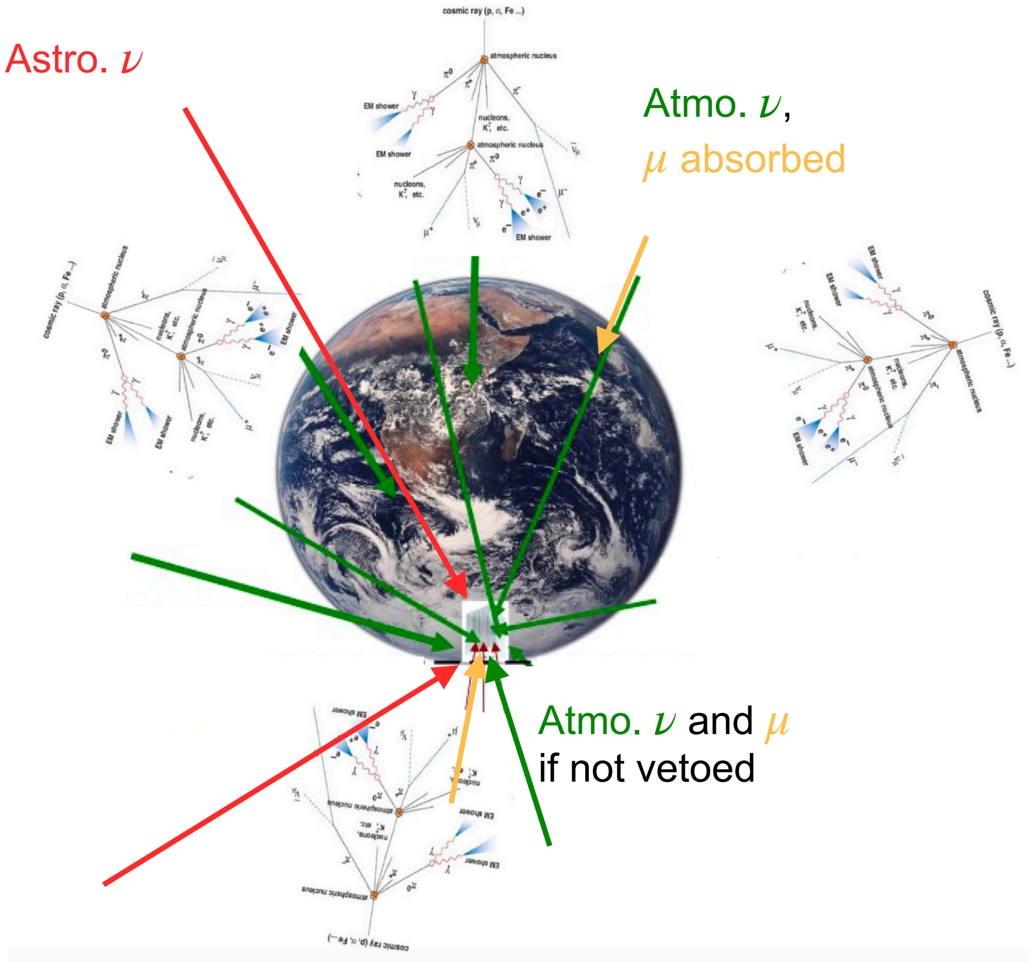


Event samples and analysis method

Event topologies in IceCube

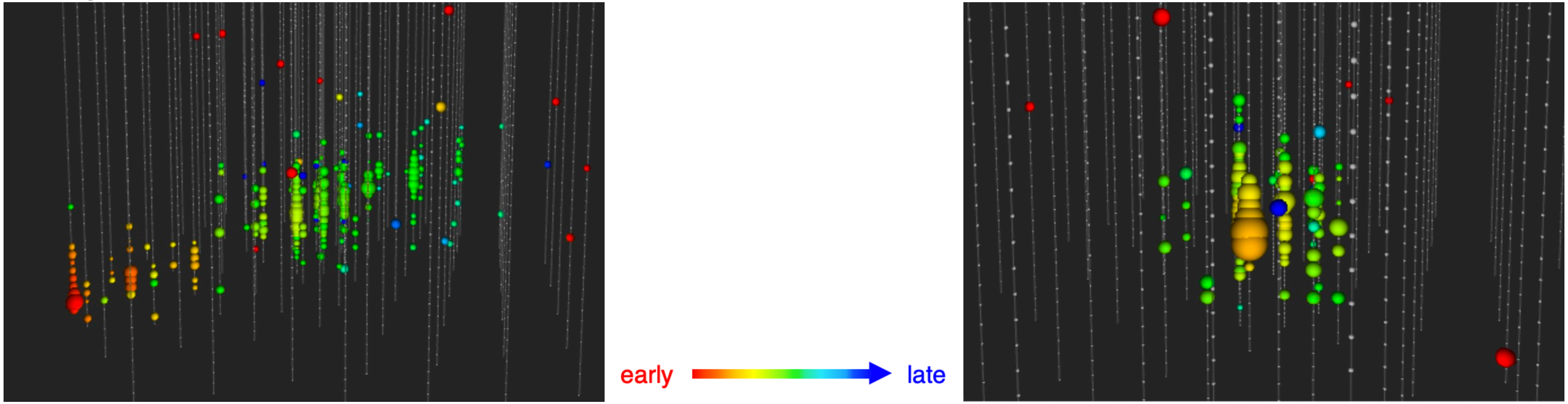
Targeted in combined fit: Tracks and Cascades

Track-like events

- μ produced in ν_μ-CC interaction
- Large lever arm: good angular resolution (<1°)
- Energy of μ at detector entry
- μ produced far outside still reach the detector: large effective area

Cascade-like events

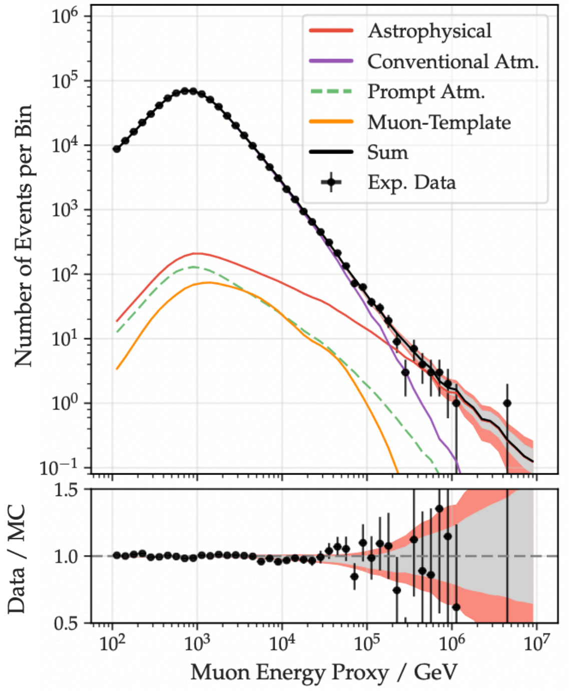
- ν_e/ν_τ-CC & all-flavour NC interaction
- Poorer angular resolution (<10°)
- Visible energy deposited within instrumented volume
- Interaction vertex ~within detector



Combined fit of tracks and cascade data

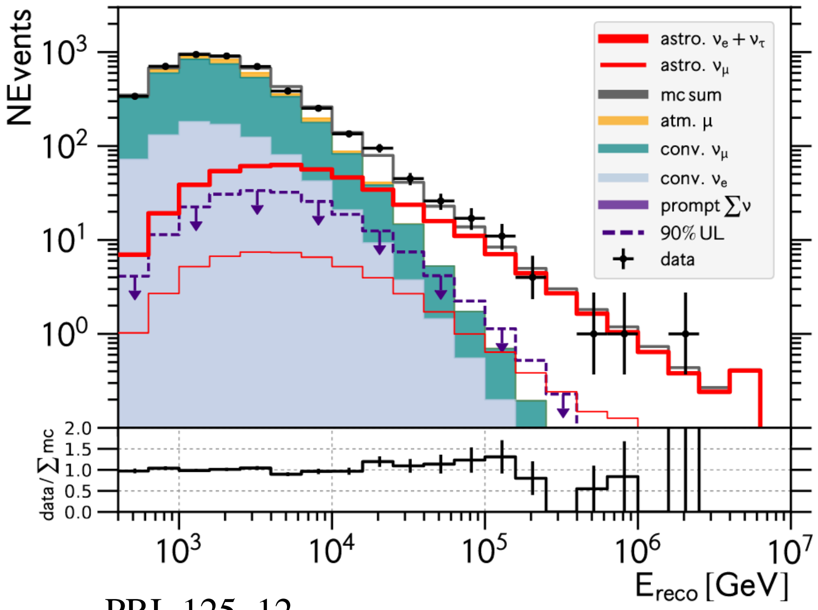
Event selections

- Tracks selection:
  - Restricted to northern sky (θ > 85deg)
  - Track quality cuts and BDT to discriminate cosmic ray backgrounds and cascade events
  - 650k Events / 9.5 years



ApJ 928, 50

- Cascade selection:
  - Cascade filter, reduce cosmic ray background
  - Fiducial volume cuts and BDT classification of events
  - 4.3k Events / 6 years

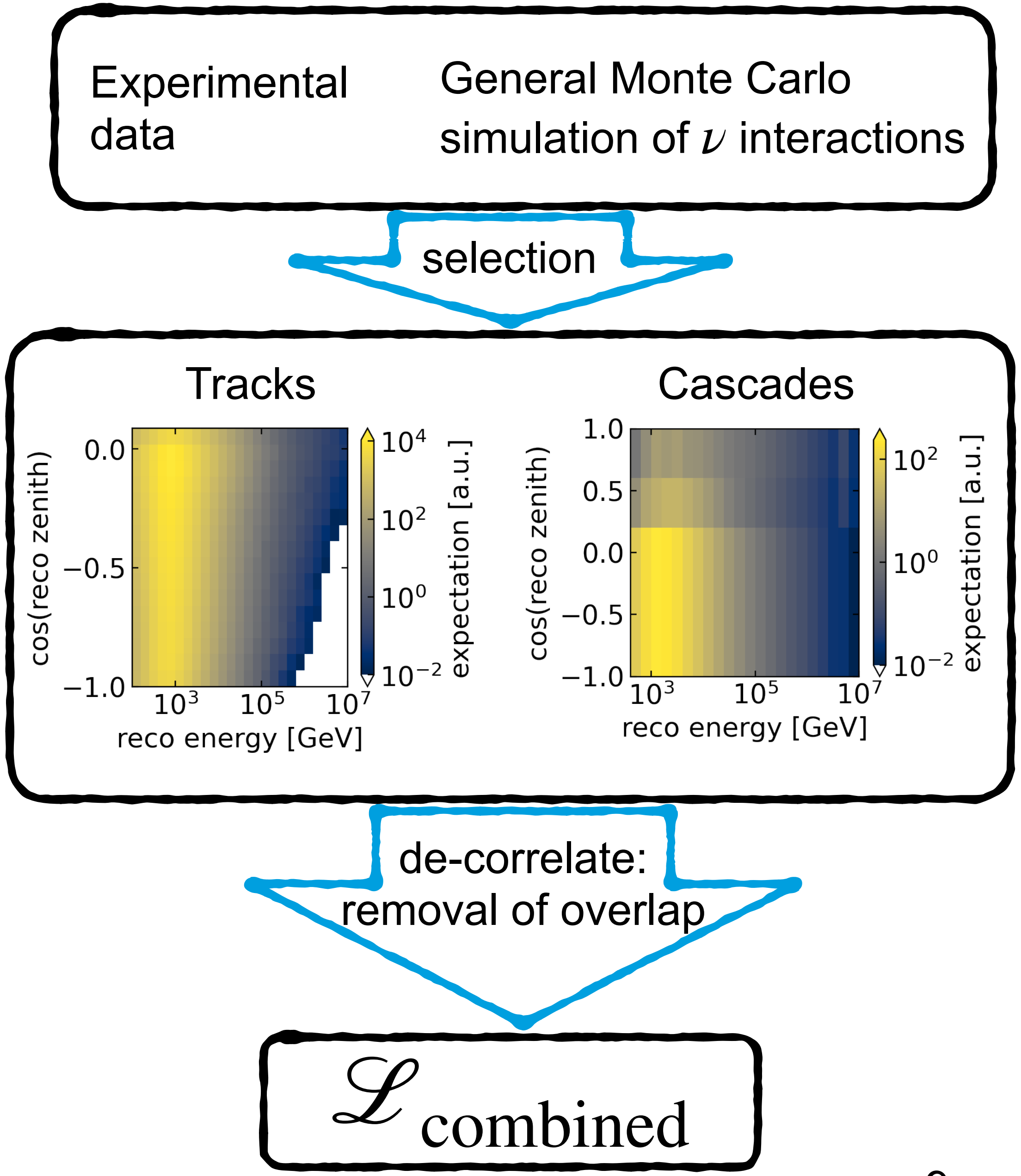


PRL 125, 12

Analysis Concept

Combining event selections

- Binned likelihood analysis, with reconstructed energy and zenith angle observables
- de-correlate analysis bins so that $\mathscr{L}_{\text{combined}} = \mathscr{L}_{\text{tracks}} \times \mathscr{L}_{\text{cascades}}$
- Consistent Monte Carlo simulation necessary in order to correctly account for this event overlap:
  - Minor fraction (0.1% of signal), expected since selected topologies very different
  - Mostly short muon tracks starting in the detector, do not constitute signal events of either selection
  - Removal of overlapping events from either of the two selections does not affect sensitivity

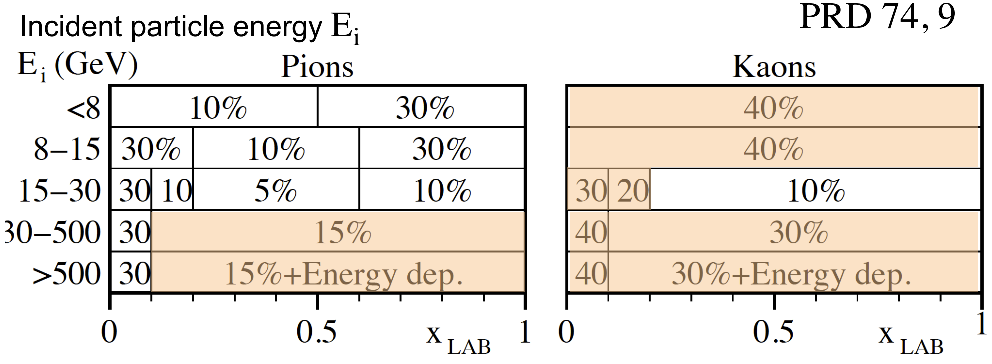


Analysis concept

Sources of uncertainties

- Atmospheric ν flux modelled with MCEq, with nuisance parameters:
  - Overall yield, spectral index shift, hadronic interaction model interpolation
  - Barr-scheme: variation of ν yields from π/K decays
- Atmospheric μ modelled with CORSIKA/MuonGun: overall flux yield uncertainty
- Detector response
  - Uncertainty to great extend dominated by optical properties of ice and optical efficiency of photosensors
  - Need dedicated simulation modelling within the according uncertainty: SnowStorm technique - continuous variation of detector response during simulation, method verification successful in fit of Tracks sample
  - Self-veto effect

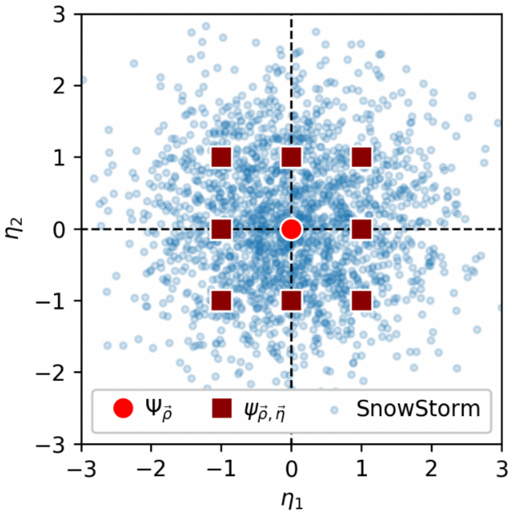
PRD 74, 9



Ratio of secondary to incident particle energy x_{LAB}

Shaded orange: Phase-space considered here

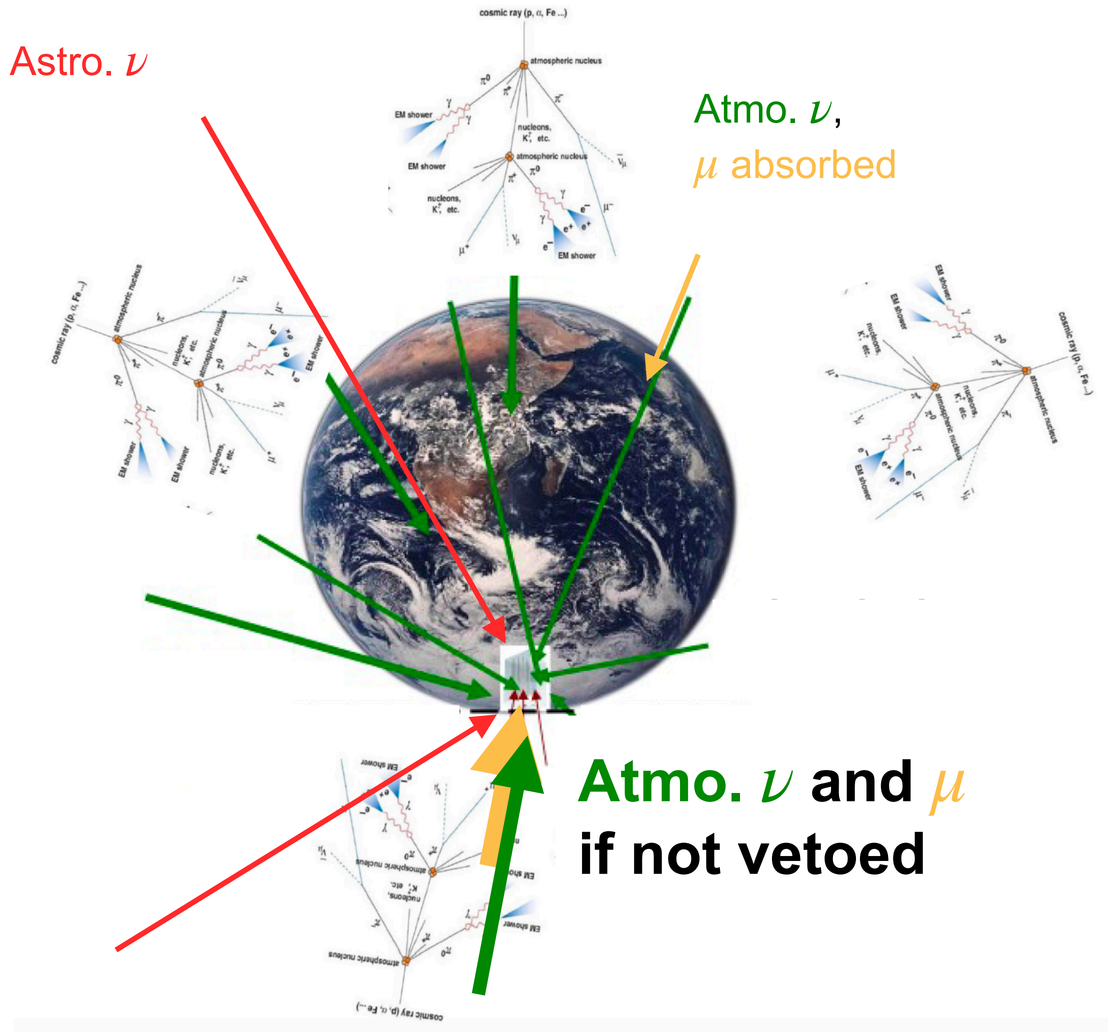
JCAP10 (2019) 048



Atmospheric flux modelling

Self-veto uncertainty for Cascade selection

- Event selection removes track-like events, mainly coming from atmospheric μ
  - Atmospheric ν might be rejected as well if coming from same air-shower as μ
- Full air-shower simulation with corresponding μ and ν not feasible to sufficient statistics, use ν only simulation and correct with ν*Veto* (JCAP07(2018)047)
  - Selection-specific response to μ arriving at the detector uncertain due to same computational limits $\rightarrow$ effective energy threshold as additional source of uncertainty
- Disclaimer: Variation not yet accounted for in sensitivities shown below



Sensitivities

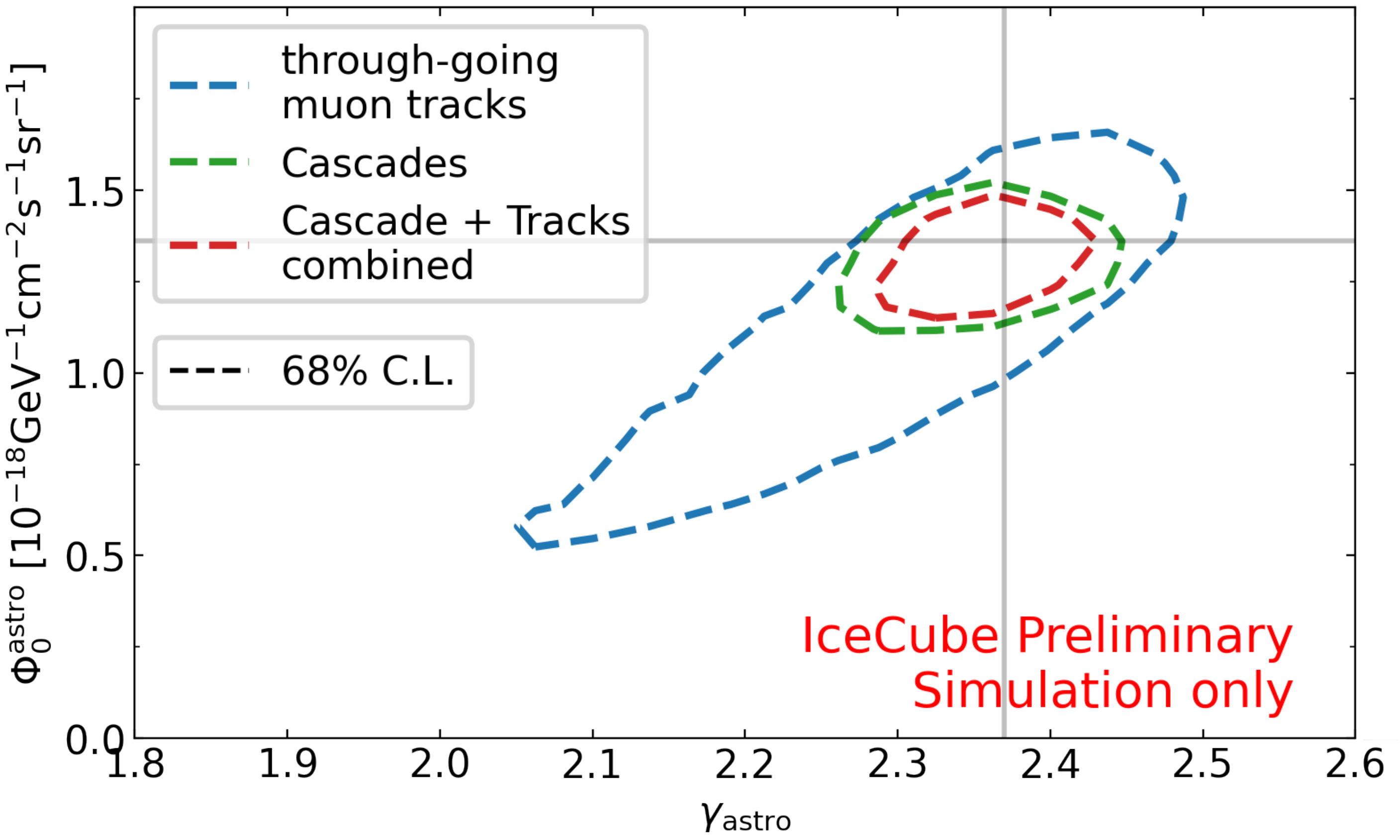
Sensitivities

Astrophysical single power law

- 10 years of data assumed
- Energy resolution of cascade channel has more power to constrain energy spectrum
- High statistics tracks channel helps in the combination by constraining atmospheric fluxes and detector systematics

	through-going tracks	cascades	combined fit
flux normalization Φ_0^{astro}	$1.36^{+0.21}_{-0.65}$	$1.36^{+0.11}_{-0.17}$	$1.36^{+0.09}_{-0.15}$
spectral index γ_{astro}	$2.37^{+0.08}_{-0.23}$	$2.37^{+0.05}_{-0.07}$	$2.37^{+0.04}_{-0.05}$

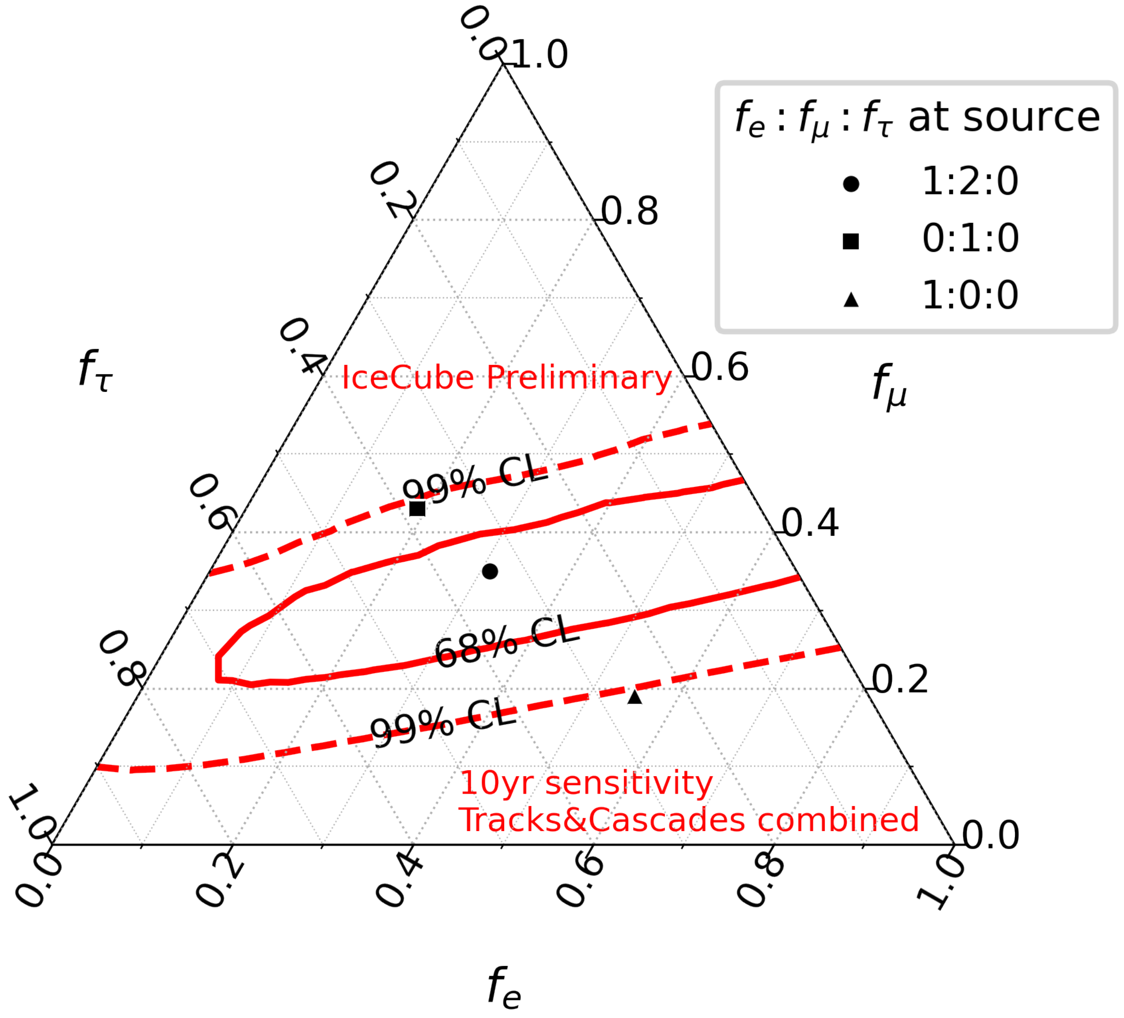
PoS(ICRC2021)1129



Sensitivities

Astrophysical flavour ratio

- Combination of tracks and cascades provides sensitivity to flavour content of the astrophysical flux
- ν_μ fraction relatively well constrained by tracks sample, ν_e/ν_τ fraction degenerate in cascade sample
- no dedicated ν_τ selection here, but 10-15% contribution to tracks selection provides constraint
- Can possibly distinguish between different emission mechanisms at idealised sources
  - 1:2:0 from π- and subsequent μ decay
  - 0:1:0 from sources with dampened μ
  - 1:0:0 from neutron decay

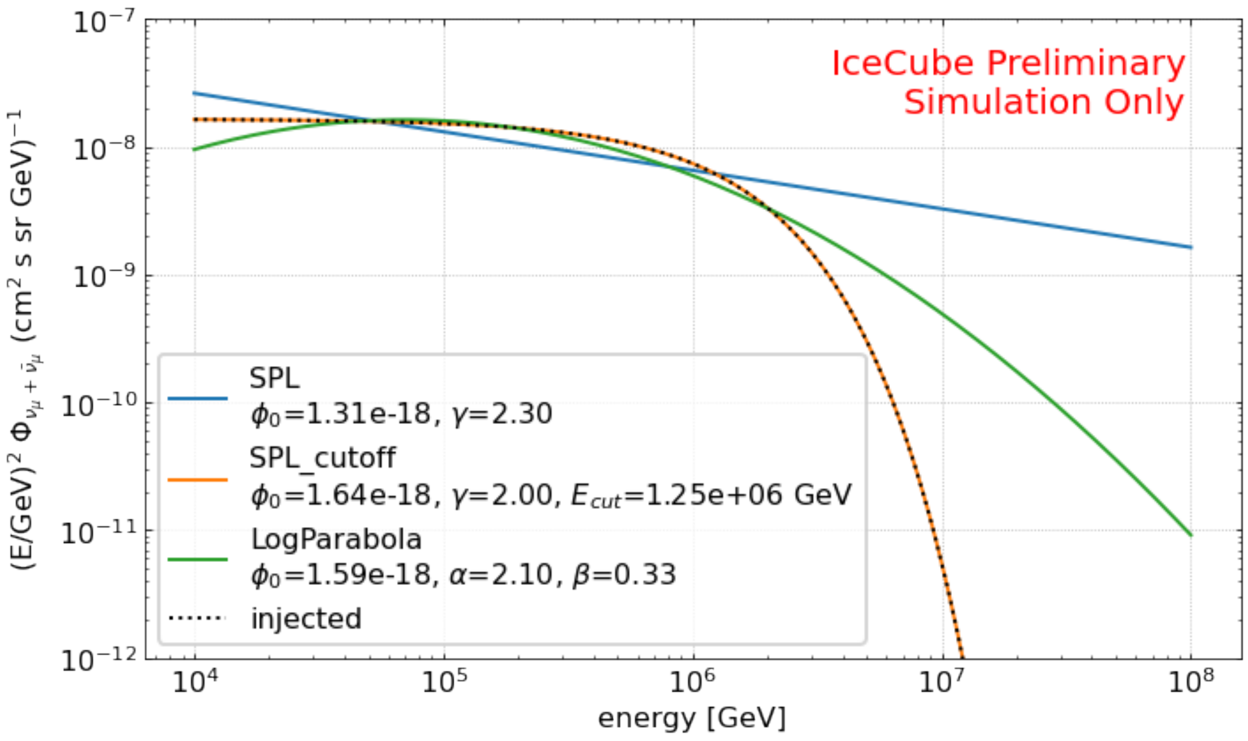


Models beyond the single power law

Testing for curvature in astrophysical ν spectrum

- Assume cutoff model[1], test compatibility of alternative model: single power law (SPL), cutoff or LogParabola flux
- Combination provides additional constraints: Improvement larger than simple combination of two independent measurements!

Event selection	SPL	LogParabola
Through-going muon tracks	p=0.16 (1.4σ)	p=0.84 (0.2σ)
Cascades	p=0.011 (2.5σ)	p=0.32 (1.0σ)
Combined	p=0.002 (3.1σ)	p=0.26 (1.1σ)



[1]Flux assumption: *ApJ 928, 50* best fit model flux

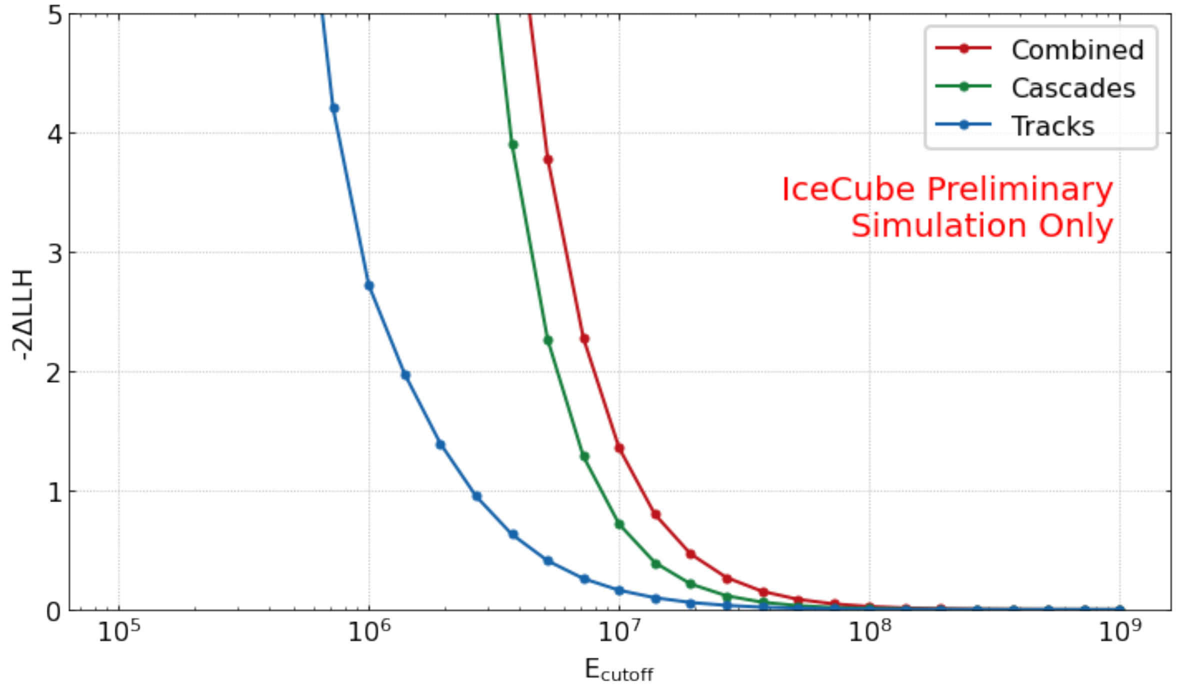
Models beyond the single power law

Testing for curvature in astrophysical ν spectrum

- Assume LogParabola model[1], test compatibility of alternative model: single power law (SPL), cutoff or LogParabola flux
- Combination provides additional constraints: Improvement larger than simple combination of two independent measurements!

Event selection	SPL	Cutoff
Through-going muon tracks	p=0.13 (1.5σ)	p=0.68 (0.4σ)
Cascades	p=0.001 (3.2σ)	p=0.21 (1.2σ)
Combined	p=9e-5 (3.9σ)	p=0.16 (1.3σ)

- Assume un-broken single power law[1]: Expected lower limit on exponential cutoff E_{cutoff}

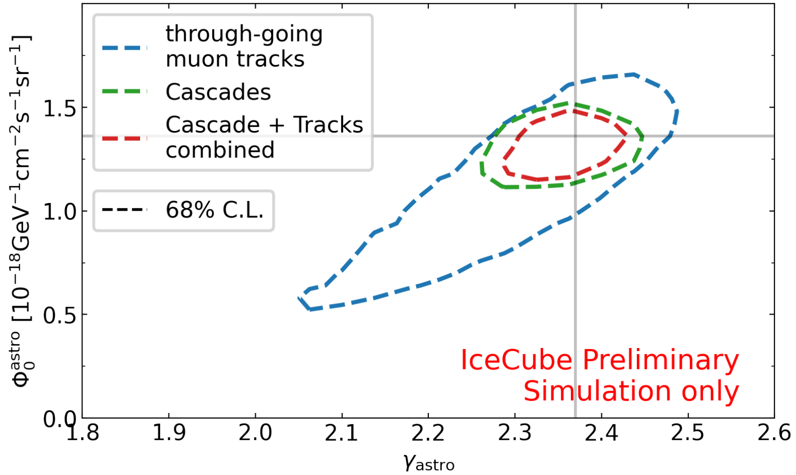


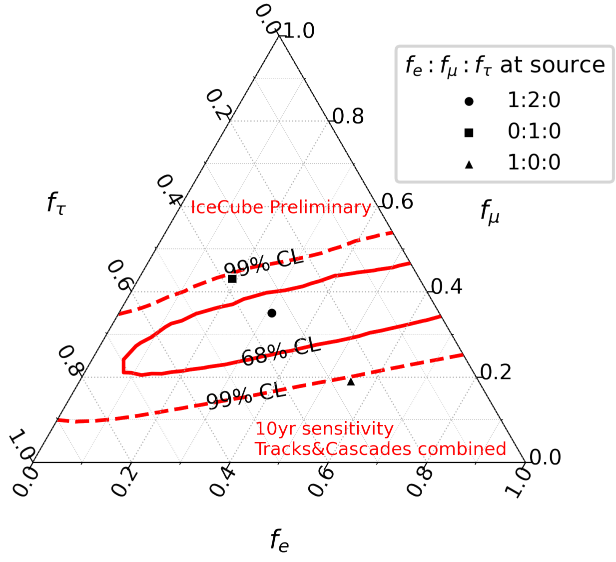
[1]Flux assumption: *ApJ 928, 50* best fit model flux

Outlook

Results coming up soon

- Toolkit for measuring the diffuse ν spectrum using the combination of event selections
    - SnowStorm Monte Carlo technique for consistent treatment of detector systematics, successfully verified on Tracks sample
    - General Monte Carlo simulation to fully de-correlate events samples
    - Combined likelihood with common nuisance parameters
- Performing combined fit on data soon, using IceCube's high-energy cascade (11 years, to be unblinded) and track data
    - Probing energy spectrum and flavour composition with unprecedented precision





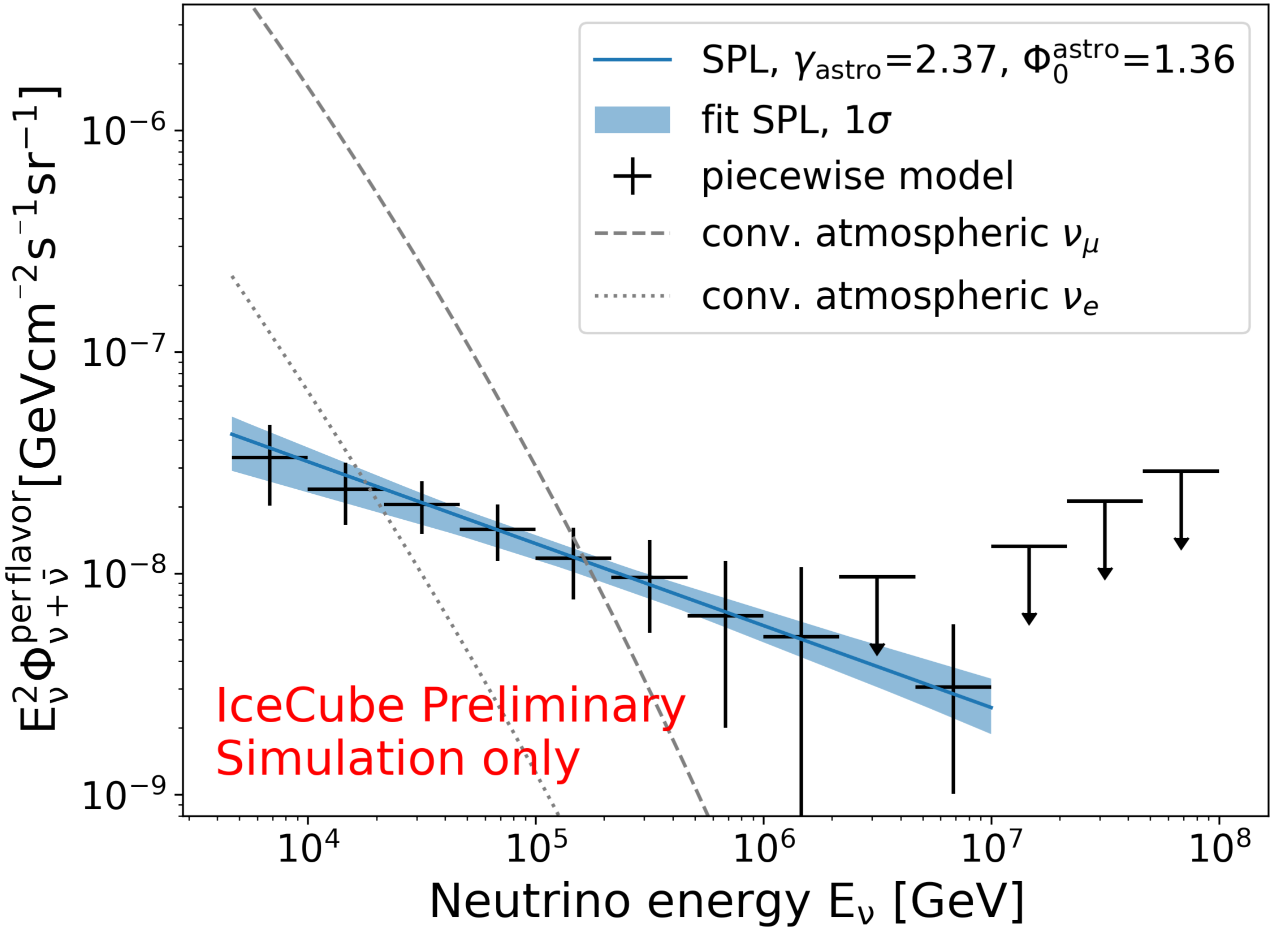
Backup

Sensitivities

Astrophysical segmented flux

PoS(ICRC2021)1129

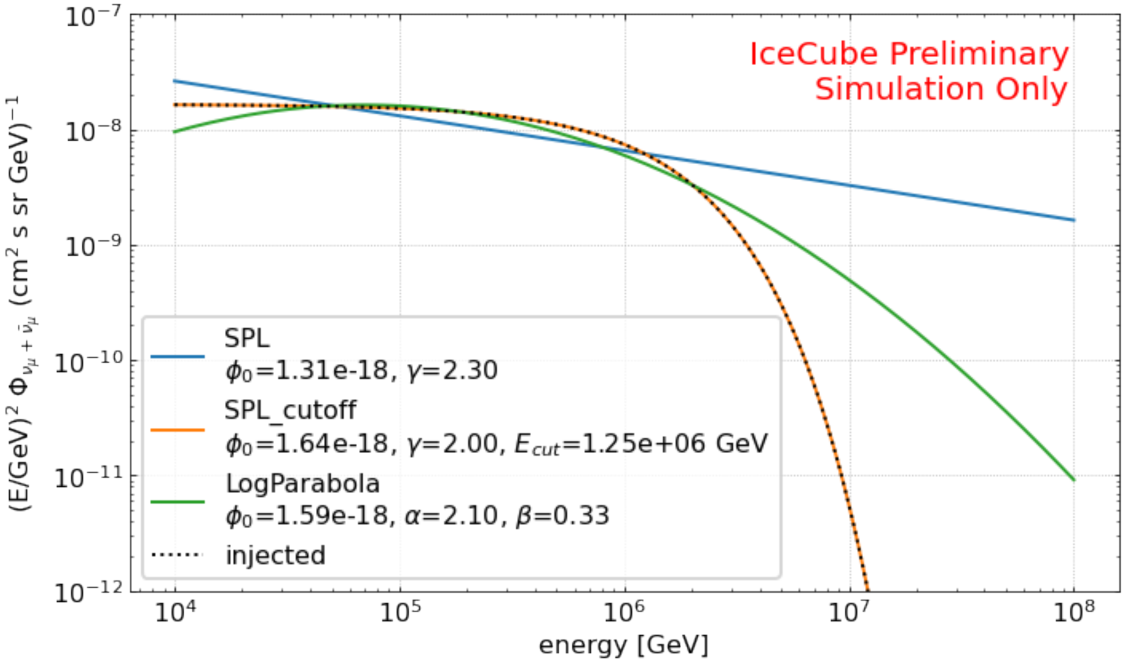
- 10 years of data assumed
- Highest energies: Low atmospheric background, but also astrophysical spectrum falls off
- Lower energies: astrophysical component subdominant, self-veto for down-going cascade events still provides sensitivity
- Glashow resonance at 6.3 PeV enhances sensitivity



Models beyond the single power law

Testing for curvature in astrophysical ν spectrum

- Isotropic single power law (SPL) model
  - $$\Phi_{\text{astro}}^{\nu+\bar{\nu}}(E_\nu) = \Phi_0^{\nu+\bar{\nu}} \left(\frac{E_\nu}{100\text{TeV}}\right)^{-\gamma}$$
- Isotropic cutoff model
  - $$\Phi_{\text{astro}}^{\nu+\bar{\nu}}(E_\nu) = \Phi_0^{\nu+\bar{\nu}} \left(\frac{E_\nu}{100\text{TeV}}\right)^{-\gamma} e^{\left(\frac{-E_\nu}{E_{\text{cutoff}}}\right)}$$
- Isotropic LogParabola model
  - $$\Phi_{\text{astro}}^{\nu+\bar{\nu}}(E_\nu) = \Phi_0^{\nu+\bar{\nu}} \left(\frac{E_\nu}{100\text{TeV}}\right)^{-\alpha_{\text{LP}}-\beta_{\text{LP}}\log\left(\frac{E_\nu}{100\text{TeV}}\right)}$$



Analysis tool NNMFit

Statistical modelling for combined analyses

- **Binned likelihood**, using e.g. reconstructed energy and reconstructed zenith as observables:
  $$\mathscr{L}(\mu_j) = \prod_j \mathscr{L}^j_{\text{bin}}(\mu_j; d_j)$$
  with bin expectations μ_j and data counts d_j

- Test different **flux models** by re-computing bin expectations μ_j from event weights
  $$\mu_j(\vec{\theta}) = \sum_i w^j_i(\vec{\theta}) :$$ **forward folding**

- Millions of MC events, O(20) parameters $\vec{\theta}$: need fast computations
  - **theano** package (continued as **aesara**) for optimising and evaluating tensor operations, including automatic differentiation