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IceCube
Neutrino Observatory

Observing the Prompt Component of the Atmospheric Muon Flux Using IceCube

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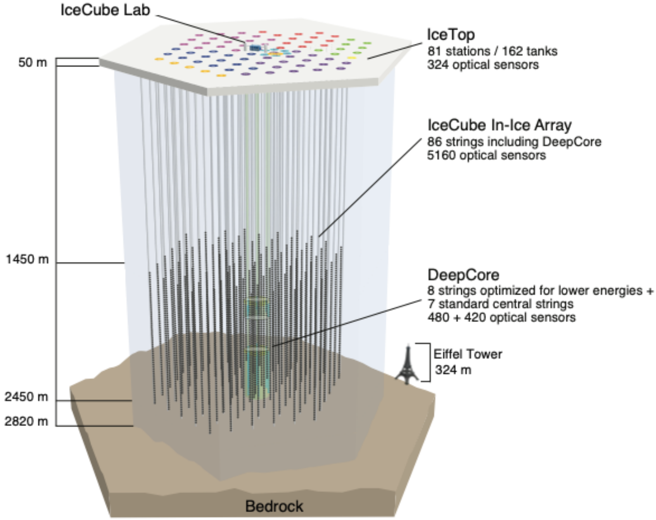
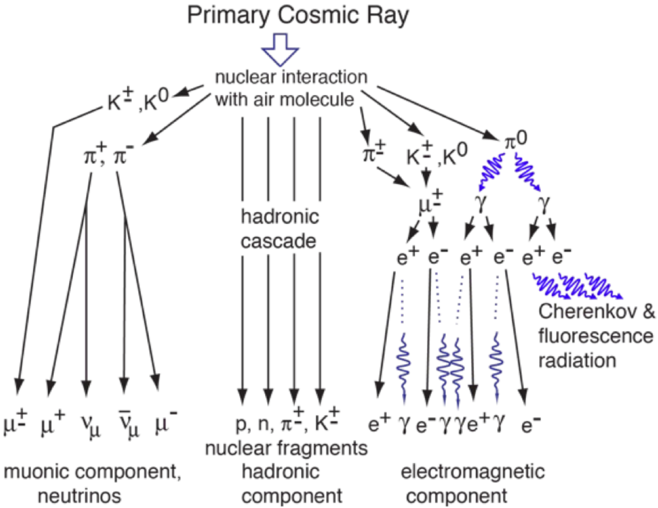
3 April 2025

IceCube Neutrino Observatory

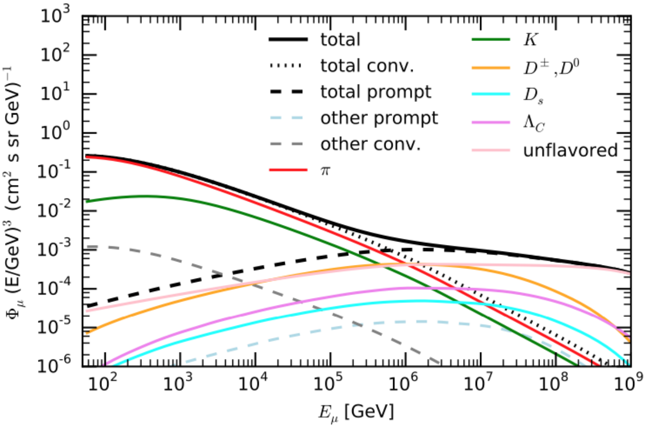


- Cubic kilometer scale cherenkov detector
- 5160 DOMs on 86 strings
- ≈ 3 kHz muon event rate

Atmospheric Air Showers

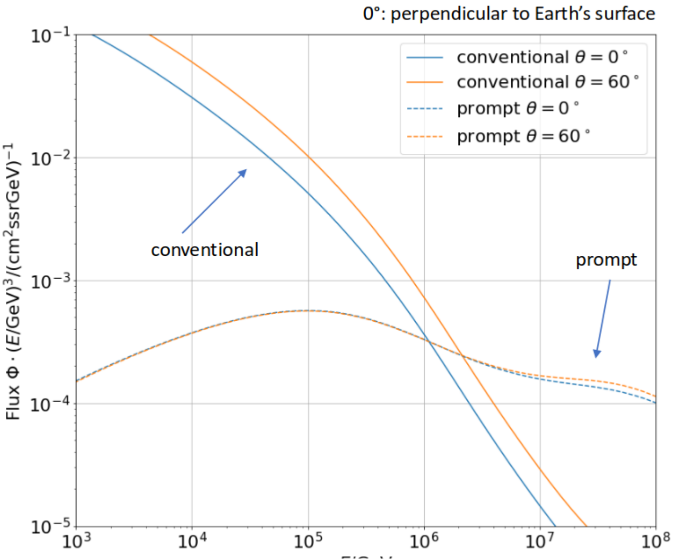


The Prompt Component



- Conventional: produced by $K^{\pm}/\pi^{\pm}$
- Prompt: produced by short-lived particles
- Prompt dominant at high energies

Prompt sensitivity



- Sensitivity increases at high energies
- Prompt less impacted by the zenith angle

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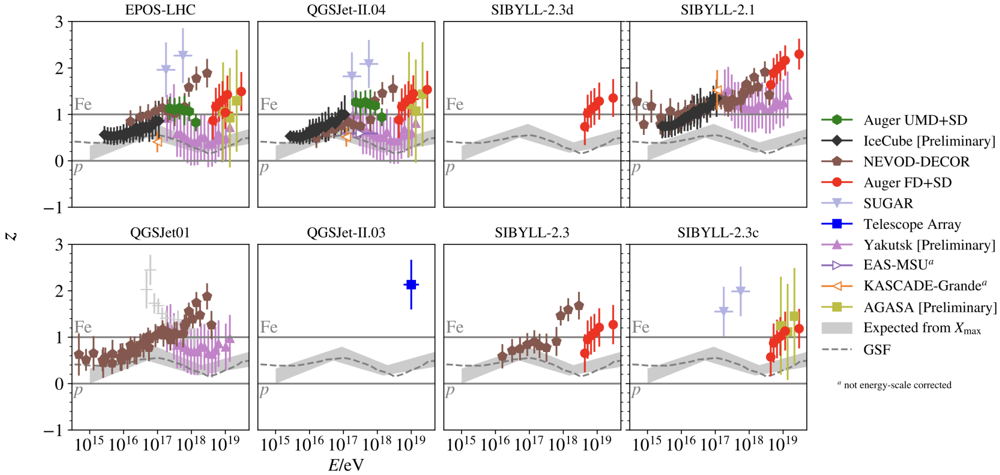
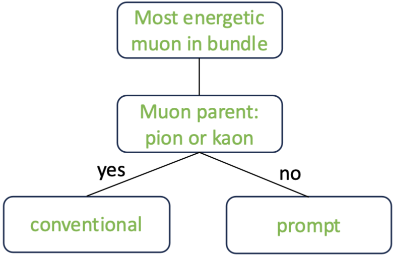
The Muon-Puzzle



Simulations and tagging



- Tagging of parent particles in CORSIKA simulations
- Prompt definition based on parent of leading muon
- Simulation up to extremely high energies

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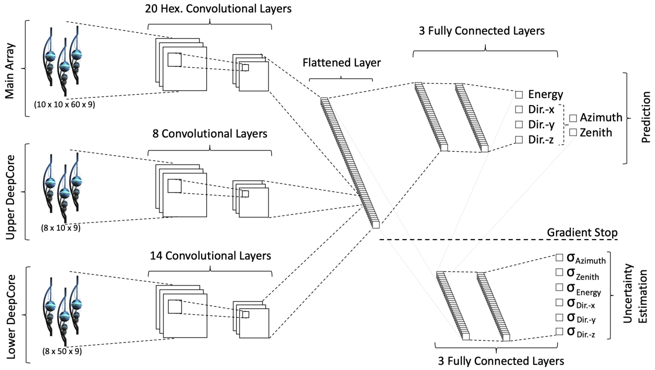
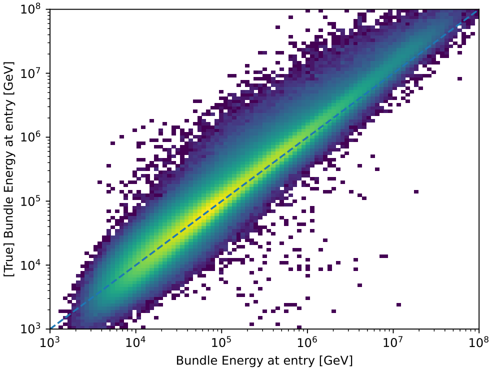
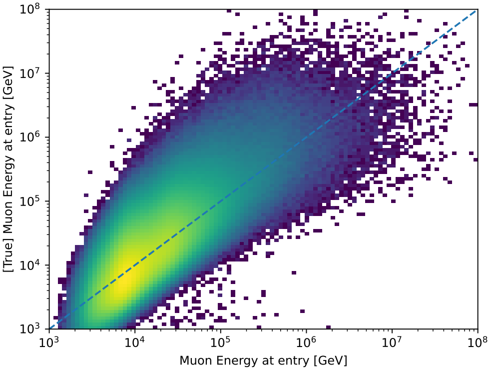
Reconstructions



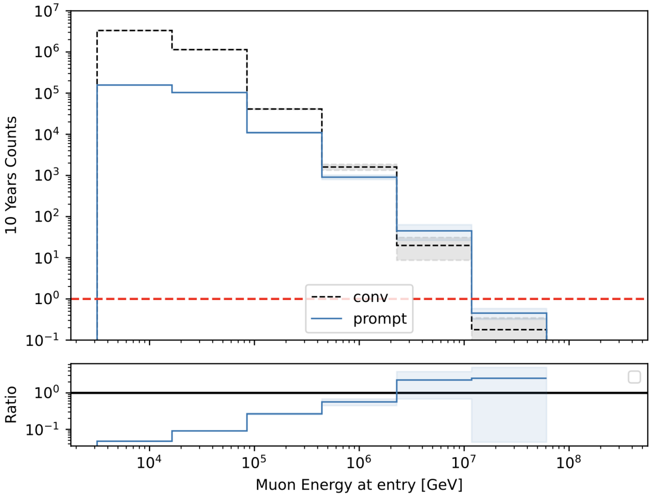
- Neural network based
- Zenith angle, bundle energy and leading muon energy

Reconstructions



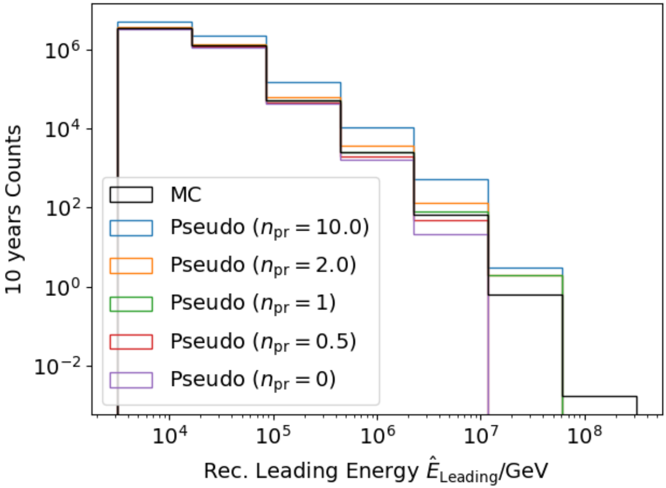


Forward Folding



- Prompt normalization: fraction of prompt component relative to current MC-simulation n_{pr}
- Poisson likelihood in each histogram bin
- Rescale with normalization factors
- Strong model dependency

Pseudo experiments



- Testing method based on simulations
- Events drawn based on primary model and normalizations
- Inject normalization

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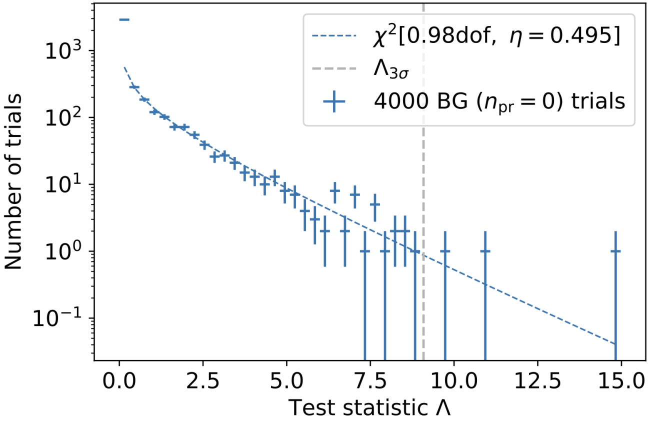
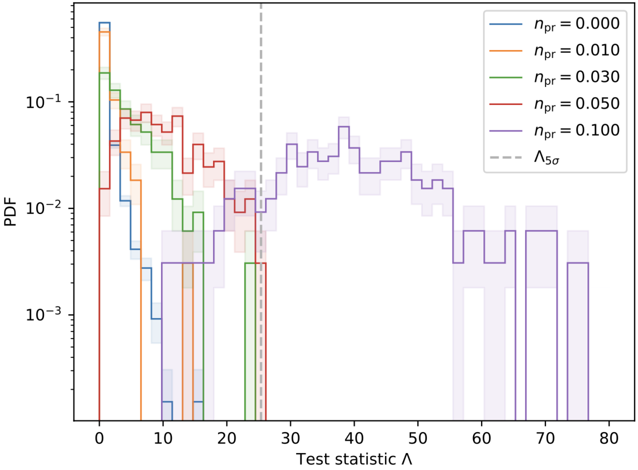
Background Estimation



- Likelihood ratio test
- Draw background samples with $n_{pr} = 0$
- Wilks' theorem: fit χ^2-distribution

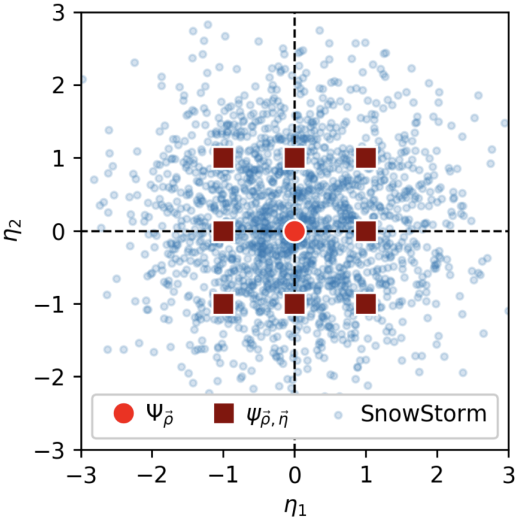
Discovery Potential: First Estimate



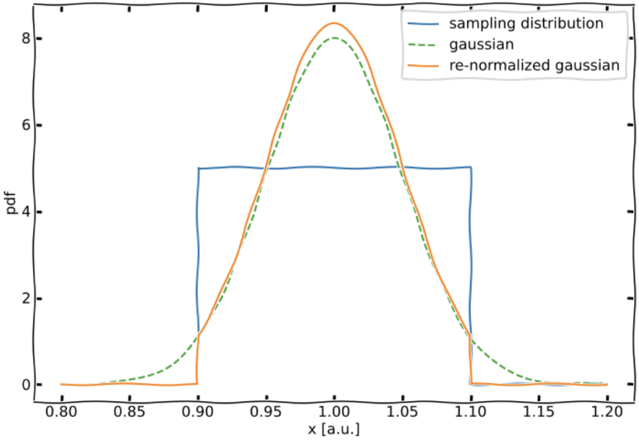
- Prompt norm required to detect it with the current method?
- Discovery potential: Norm at which half the generated trials yield 5σ significance in the likelihood ratio test
- Caution: Systematics are not yet included
- Switch to NNMFit

Systematic Parameters: SnowStorm

- Detector parameters regarding the ice and DOMs
- SnowStorm Ensemble: Individual systematics sampled each event
- Drawn from uniform distribution

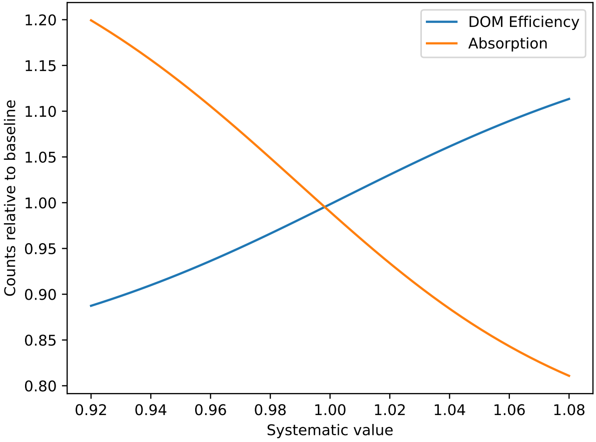


Systematics: Reweighting



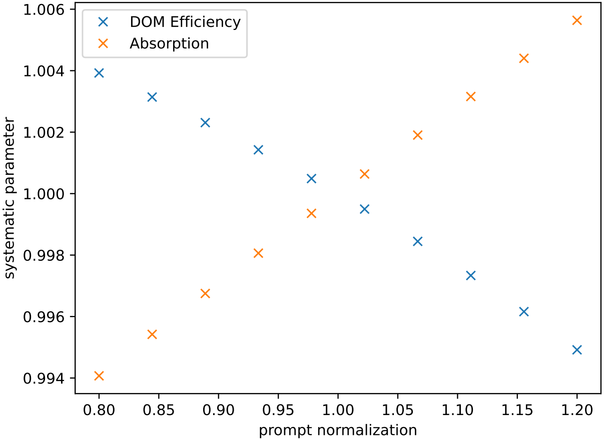
- How do the parameters impact the bincount?
- Splitting or reweighting
- ”Inject” hypothesis for parameter by reweighting

Detector Parameters



- DOM efficiency
- Absorption of the ice
- Scattering in the ice
- Hole-ice models

Detector Parameters



- Likelihood Scan: Fix parameters in the fit
- Systematics partially absorb the changed expectation

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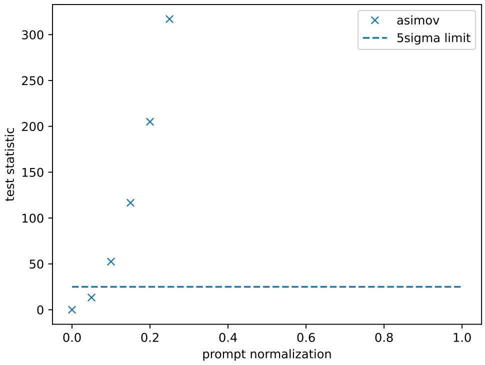
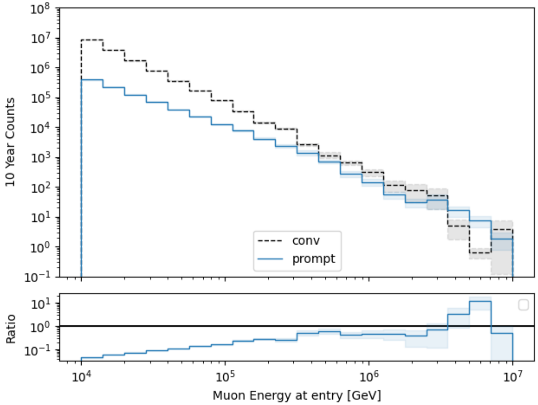
Discovery Potential including systematics





The SAY-likelihood

- Poisson likelihood:

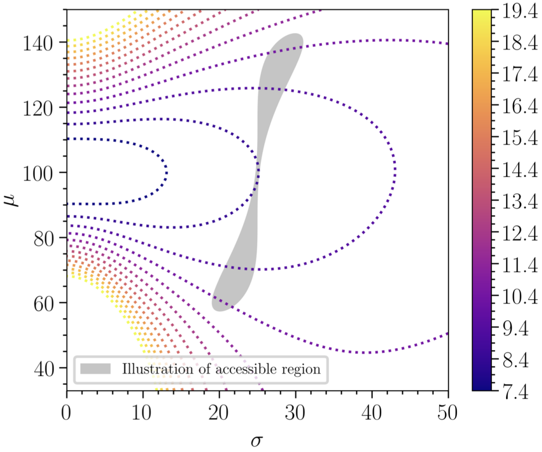
$$L(\vec{\Theta}|k) = \frac{\lambda(\vec{\Theta})^k e^{-\lambda(\vec{\Theta})}}{k!} \tag{1}$$

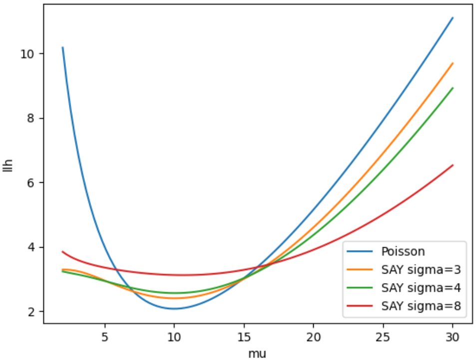
- Assumption: Expectation exactly known
- For a limited number of sampled MC events this assumption is unrealistic
- Better: Consider distribution of weights based on MC truth:

$$L(\vec{\Theta}|k) = \int_0^{\text{inf}} \frac{\lambda^k e^{-\lambda}}{k!} P(\lambda|\vec{w}(\vec{\Theta})) d\lambda \tag{2}$$

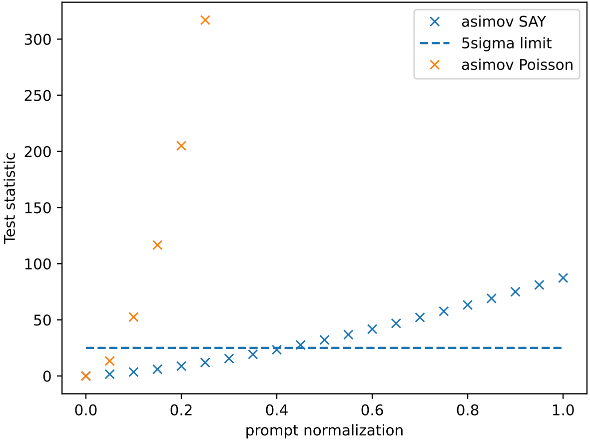
- This leads to:

SAY vs Poisson



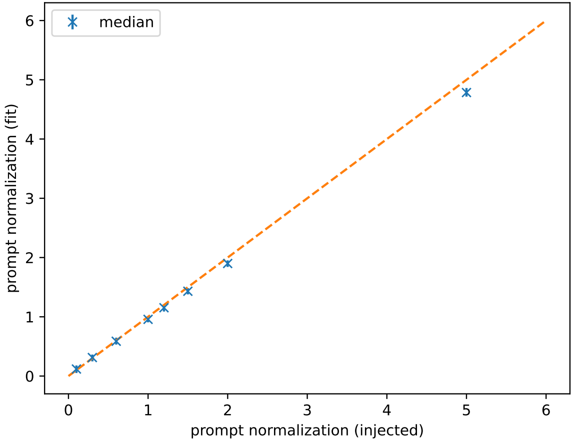


Impact of SAY on the fit



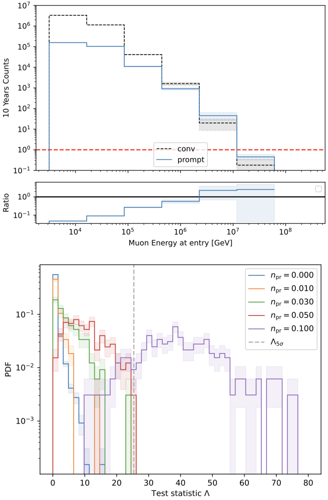
- SAY likelihood significantly reduces the discovery potential
- This reflects the high MC uncertainties in the high energy region
- SAY converges to Poisson for perfect MC statistic → no disadvantage in using it

Bias test and fit precision



- Generated using Pseudoexperiments
- Generally good prediction
- Slight bias at high norms

Summary



- Generate prompt tag in simulation
- Simulate up to high energies
- Forward fit of prompt normalization
- Use MC to estimate significance