Observing the Prompt Component of the Atmospheric Muon Flux Using IceCube

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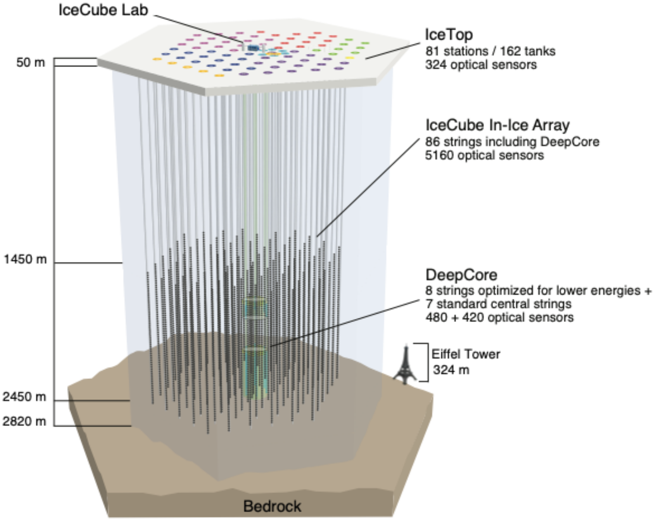
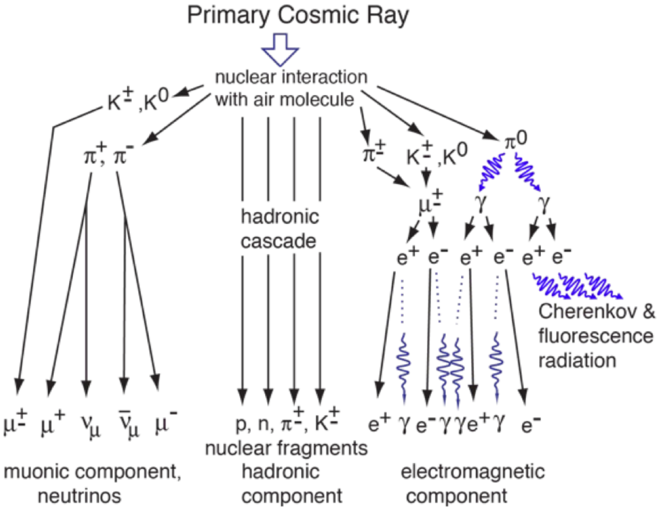
IceCube Neutrino Observatory

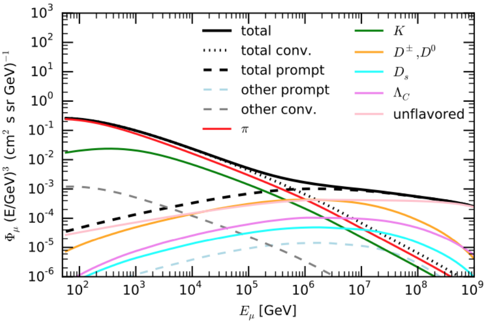


- Cubic kilometer scale cherenkov detector
- 5160 DOMs on 86 strings
- ≈ 3 kHz muon event rate

Atmospheric Air Showers

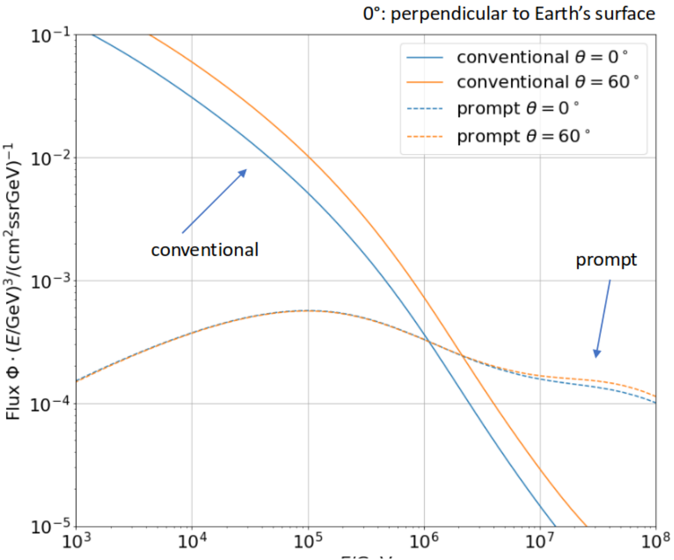


The Prompt Component



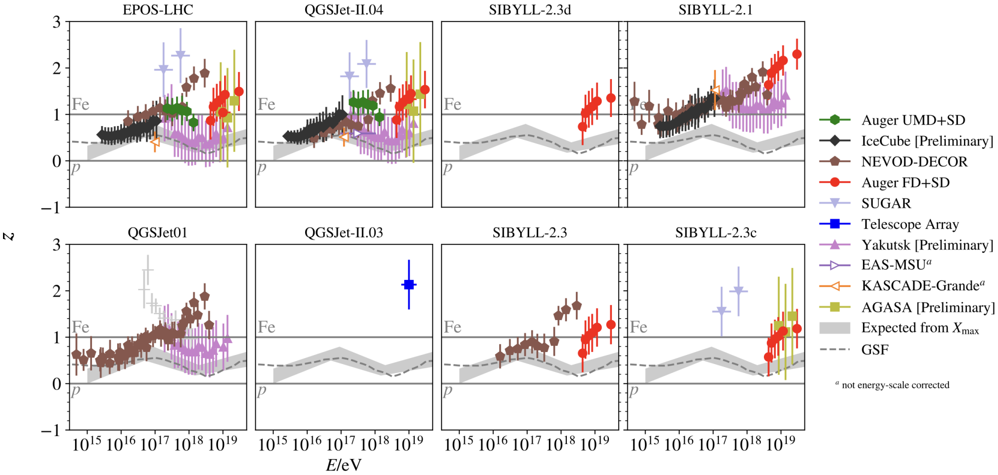
- Conventional: produced by $K^{\pm}/\pi^{\pm}$
- Prompt: produced by short-lived particles
- Prompt dominant at high energies

Prompt sensitivity

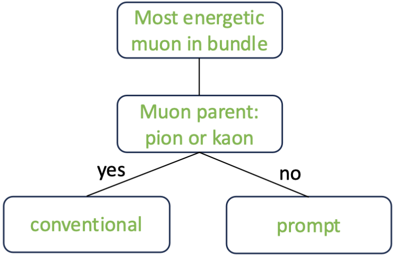


- Sensitivity increases at high energies
- Prompt less impacted by the zenith angle

The Muon-Puzzle

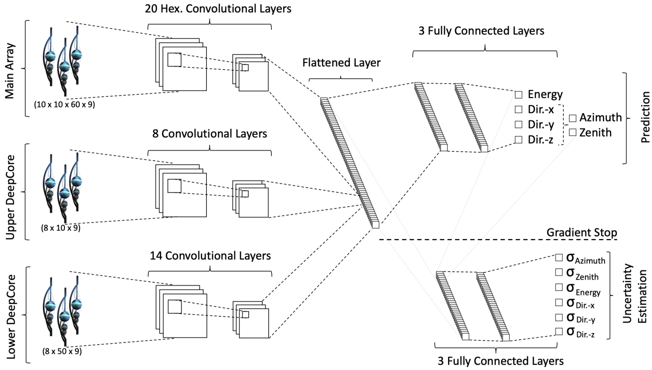


Simulations and tagging



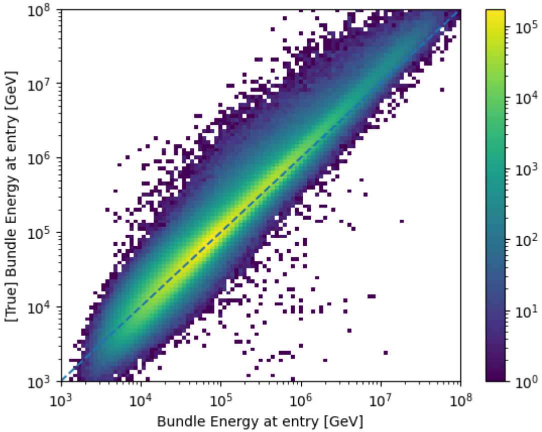
- Tagging of parent particles in CORSIKA simulations
- Prompt definition based on parent of leading muon
- Simulation up to extremely high energies

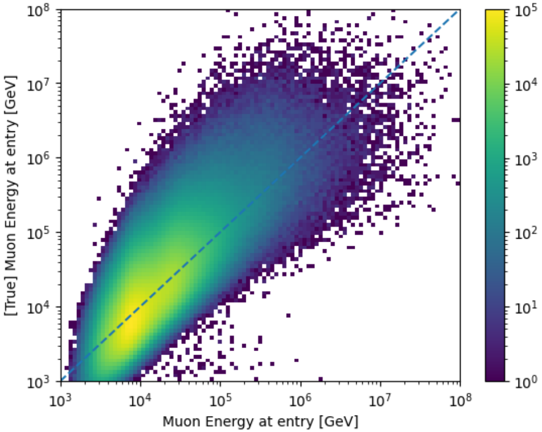
Reconstructions



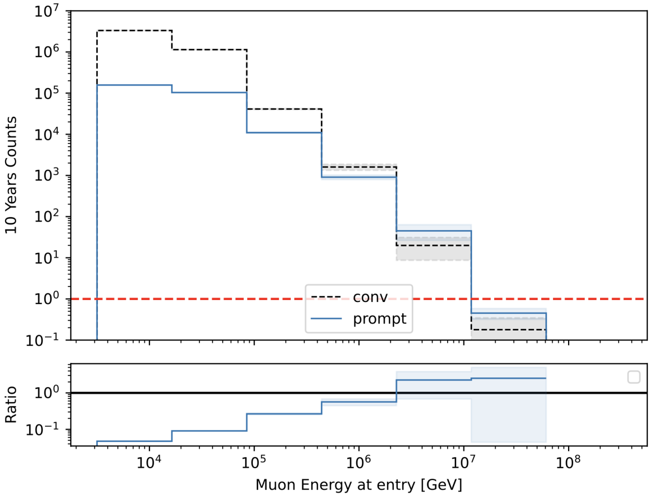
- Neural network based
- Zenith angle, bundle energy and leading muon energy

Reconstructions



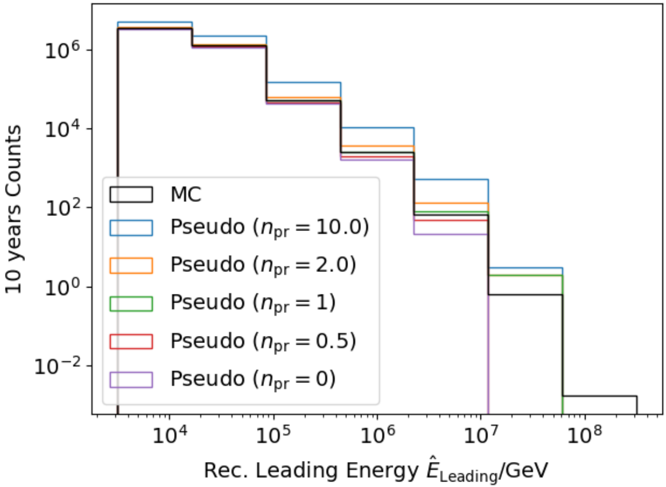


Forward Folding



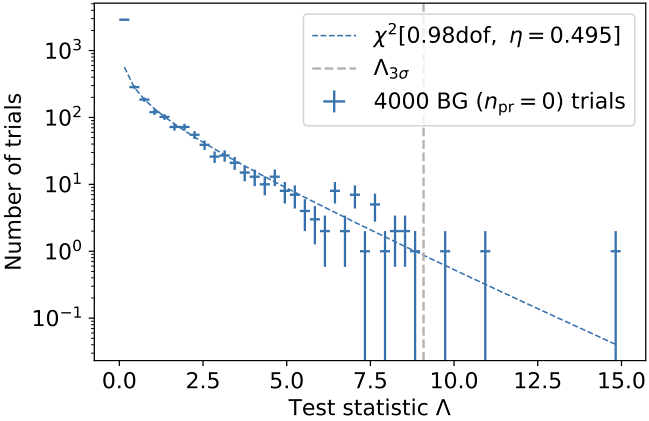
- Prompt normalization: fraction of prompt component relative to current MC-simulation n_{pr}
- Poisson likelihood in each histogram bin
- Rescale with normalization factors
- Strong model dependency

Pseudo experiments and asimov tests



- Testing method based on simulations
- Asimov: Toy data resembling the MC expectation given the injected input parameters
- Pseudoexperiments: Sampled based on weights

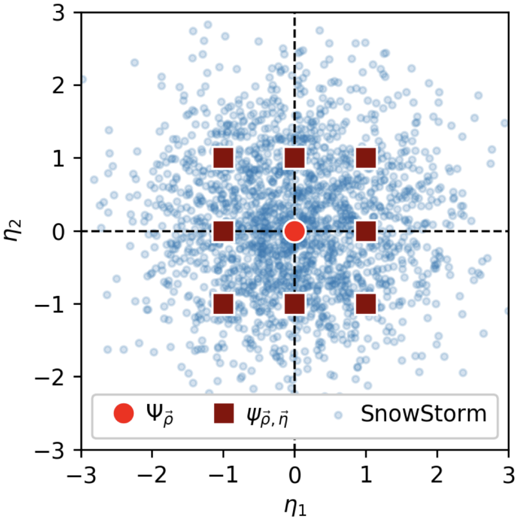
Background Estimation



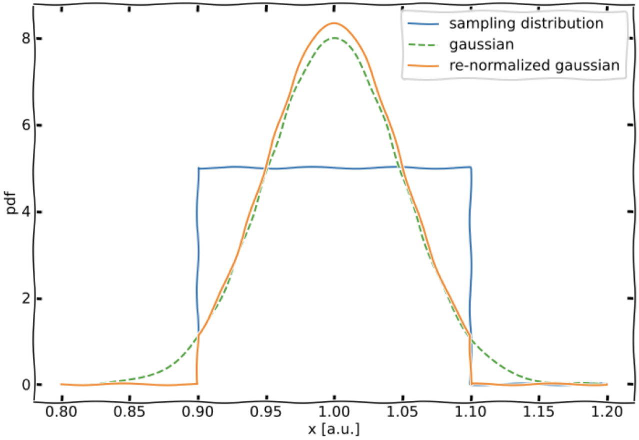
- Likelihood ratio test: $\lambda = -2(llh(\Theta_0) - llh(\Theta))$
- Draw background samples with $n_{pr} = 0$
- Wilks' theorem: fit χ^2-distribution

Systematic Parameters: SnowStorm

- Detector parameters regarding the ice and DOMs
- 5-Parameters: Absorption, Scattering, DOM-Efficiency, 2 hole-ice models
- SnowStorm Ensemble: Individual systematics sampled each event
- Drawn from uniform distribution

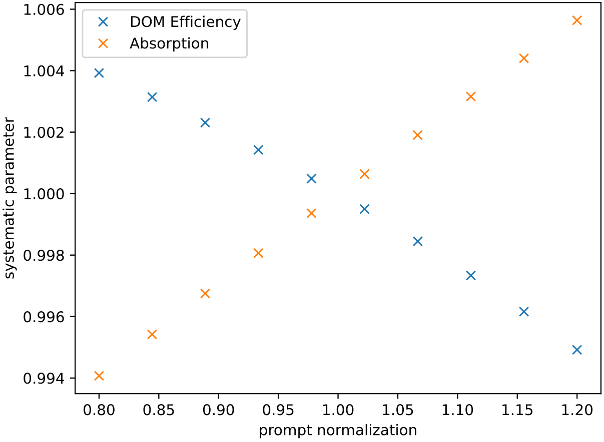


Systematics: Reweighting



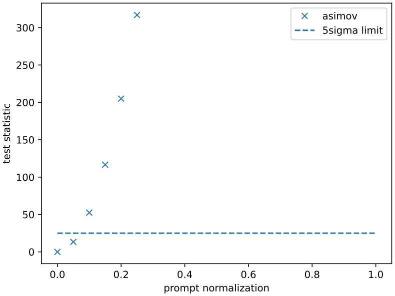
- How do the parameters impact the bincount?
- Reweighting
- ”Inject” hypothesis for parameter by reweighting
- Fit mean of reweighting distribution as nuisance parameter

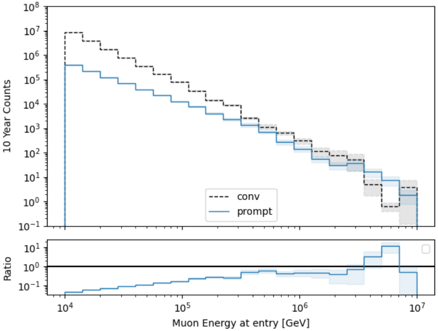
Detector Parameters



- How do these parameters impact the likelihood?
- Test: How do the fitted systematics change when fixing the prompt normalization in the fit
- Systematics partially absorb the changed expectation

Discovery Potential including systematics





- Fitting of high Number of parameters requires good resolution → more bins
- Tests show extremely high significance
- What about the uncertainties?

The SAY-likelihood

- Poisson likelihood:

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

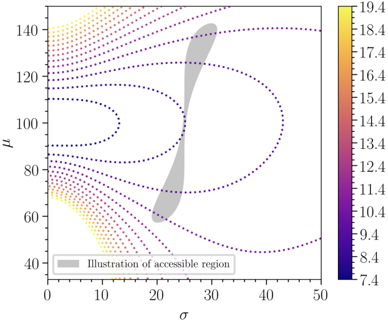
- Assumption: Expectation exactly known
- For a limited number of sampled MC events this assumption is unrealistic
- Better: Consider distribution of weights based on MC truth:

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

- This leads to:

$$L_{Eff}(\vec{\Theta}|k) = (\frac{\mu}{\sigma^2})^{\frac{\mu^2}{\sigma^2}+1}\Gamma(k + \frac{\mu^2}{\sigma^2} + 1)(k!(1 + \frac{\mu}{\sigma^2})^{k+\frac{\mu^2}{\sigma^2}+1}\Gamma(\frac{\mu^2}{\sigma^2} + 1))^{-1} \tag{3}$$

SAY vs Poisson



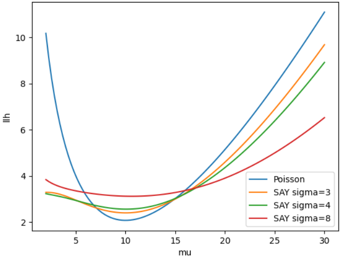


Abbildung: Left: Contours of negative SAY log likelihood for k = 100. Right: Poisson likelihood and SAY likelihood for k = 10 for three different uncertainties

- SAY likelihood is broader for higher uncertainties!
- Allows for konservative estimate when dealing with high MC-uncertainties

SAY vs Poisson: Likelihood scan

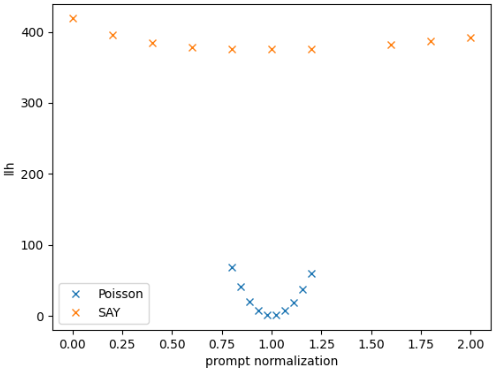
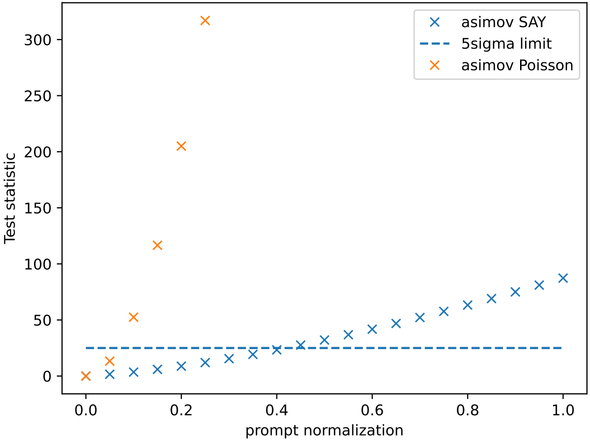


Abbildung: 1D likelihood scans of the prompt component for both likelihoods

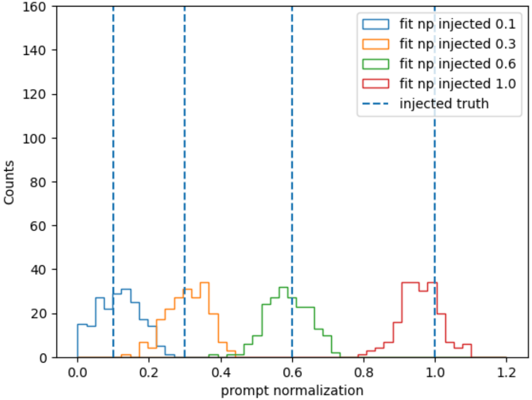
- Likelihood scans reflect this: SAY likelihood has a much broader profile resulting in less significance

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

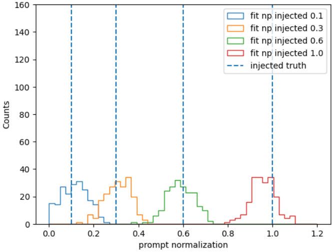


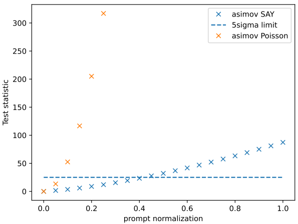
- Generated using Pseudoexperiments
- Unresolved bias!

Outlook

- Include quality cuts (data level 5) → Increase data-mc agreement
- Make control fit of conv in low energy region where you dont expect prompt events → Cross check for conventional fit
- Try to test on Burnsample
- Problem: Low lifetime of a few months compared to ten years
- Include new Parameters:
  - $n_{charmed}$,$n_{unflavoured}$: Contribution of charmed and unflavoured particles. Can these components be measured individually?
  - $\Delta\gamma$: Potential shift in spectral indices of the components, softer or harder spectrum
  - γ_{CR}: Cosmic ray gradient
  - Use interpolation between primary models

Summary





- Generate prompt tag in simulation
- Simulate up to high energies
- Use NNMFit to include systematics
- Estimate significance from

Backup: 2D histogram