

Prompt Muon Forward Fit

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[wiki page](#)

Introduction

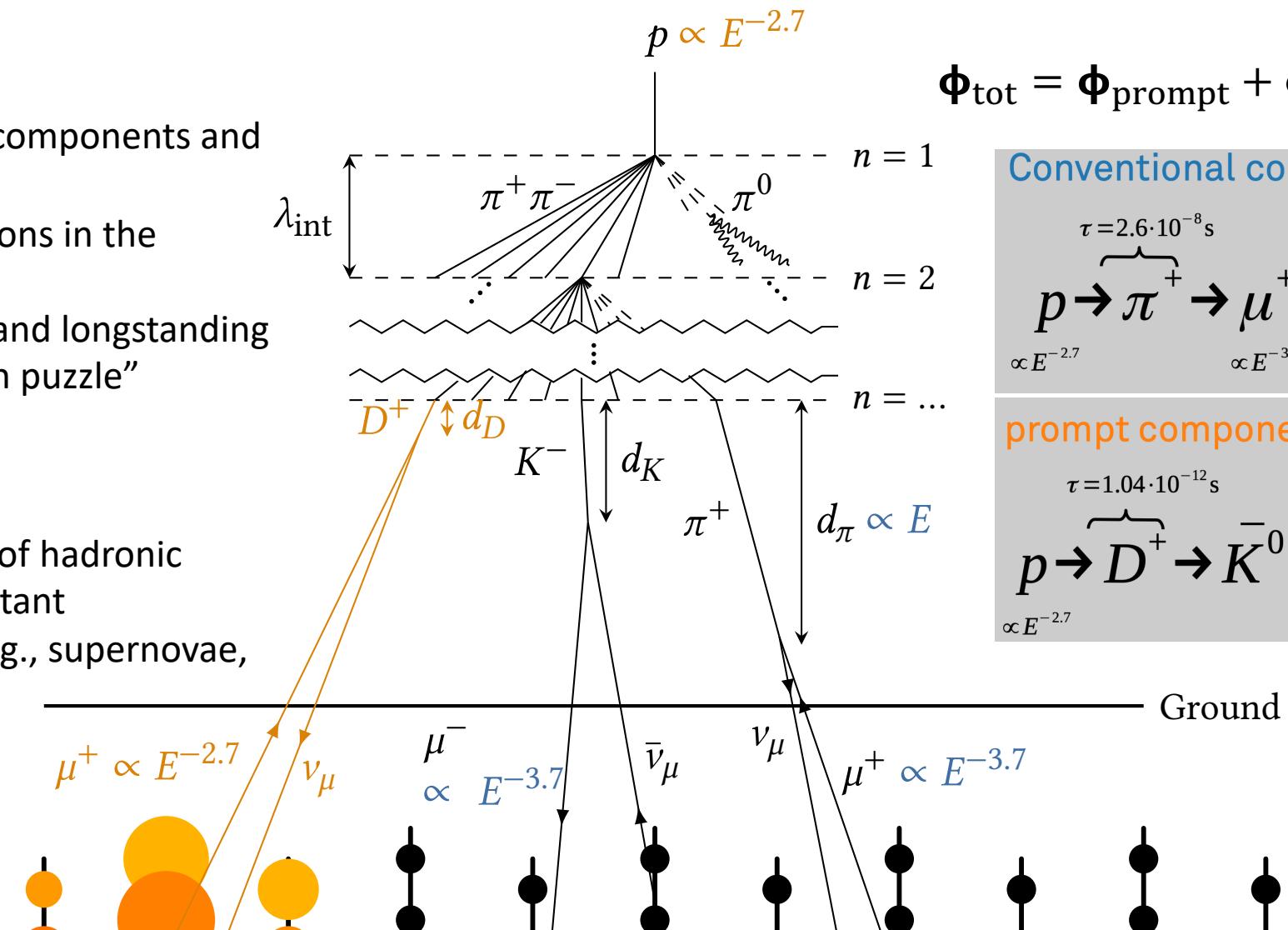
Motivation

- Characterize muon flux components and depth intensity
- Probe hadronic interactions in the atmosphere
- Constrain uncertainties and longstanding questions like the “muon puzzle”

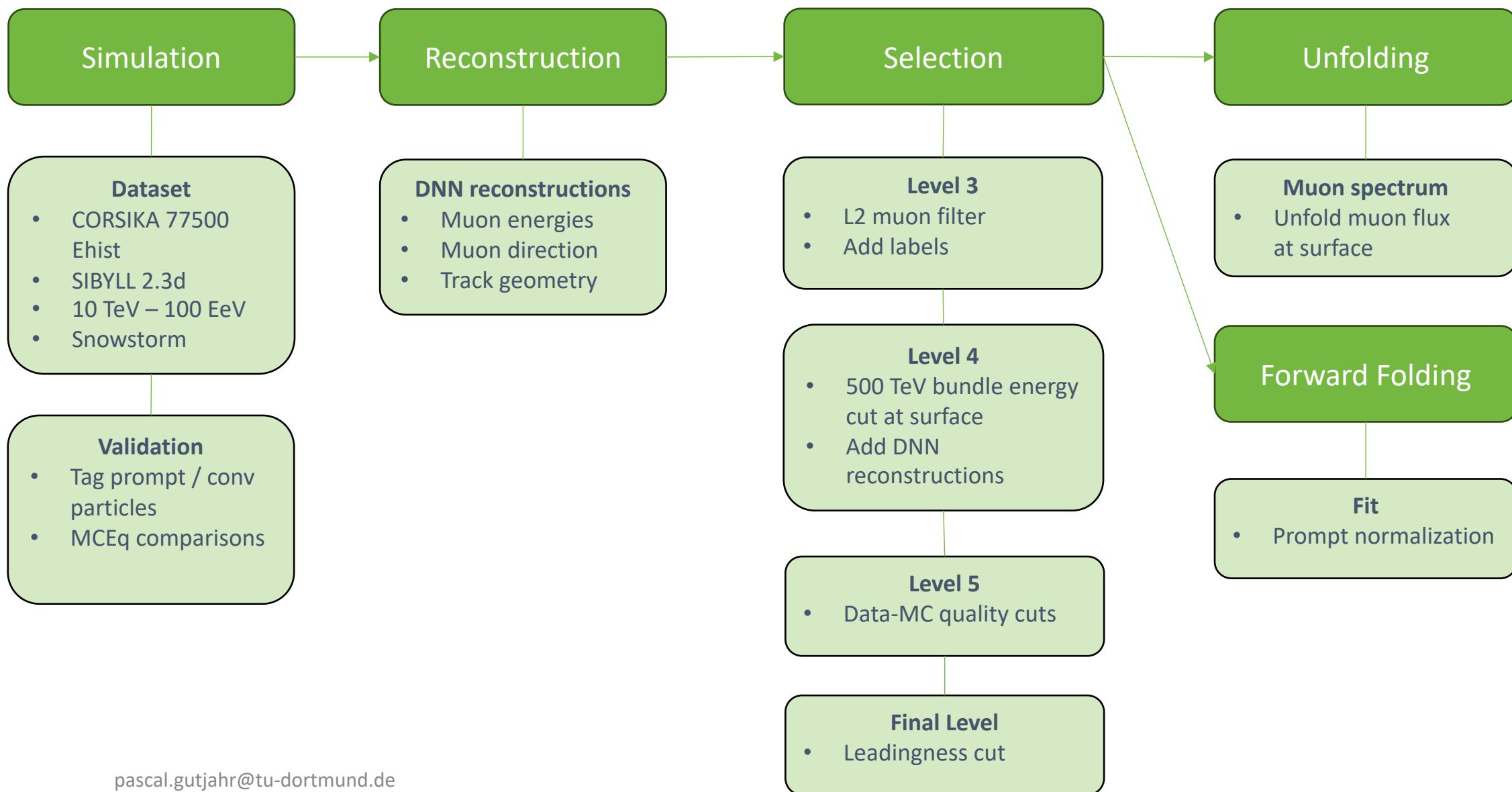
Long term

- Enhance understanding of hadronic processes relevant in distant astrophysical sources (e.g., supernovae, AGNs, ...)

Conventional Muon:
Parent is pion or kaon



Overview



NNMFit

- [NNMFit](#)
- Actively maintained python tool → diffuse group uses it
- Defines Likelihood (Poisson / SAY for limited MC statistics)
- Incorporates nuisance parameters
 - 5 in-ice detector systematics
 - CR-model interpolation
 - Spectral index shift
- 9 free fit parameter in total with
 - Conv norm
 - Prompt norm

- **Cosmic-ray model interpolation:** A linear interpolation between two flux models (H3a and GSF):

$$W_{\text{CR}} = W_{\text{H3a}} + \alpha_{\text{CR}} (W_{\text{GSF}} - W_{\text{H3a}}), \quad (4.6)$$

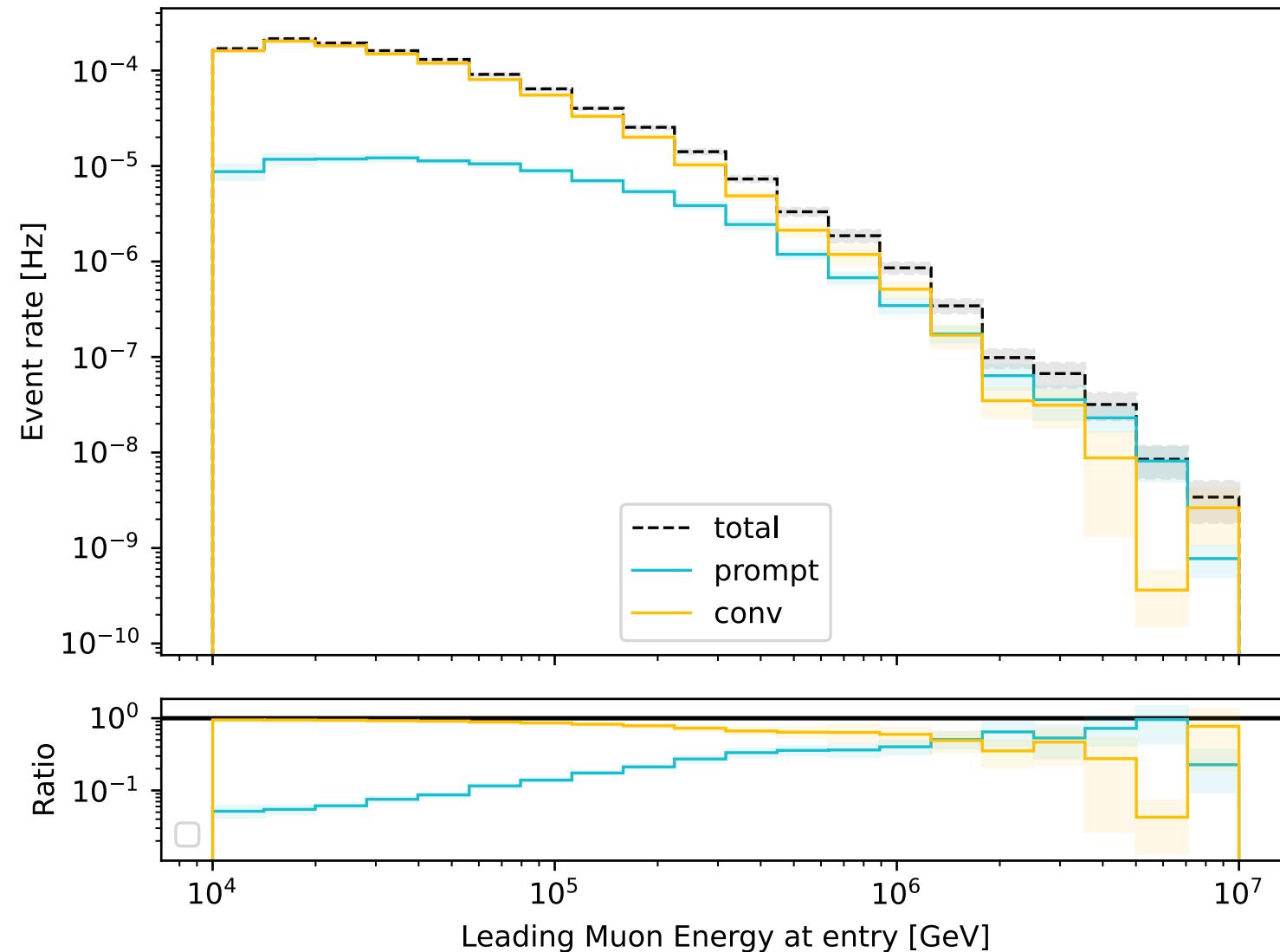
where $\alpha_{\text{CR}} = 0$ corresponds to H3a and $\alpha_{\text{CR}} = 1$ to GSF. This allows the fit to continuously explore differences between the two models without rerunning the analysis for each separately.

- **Spectral index shift:** A modification of the spectral slope of the primary flux:

$$W_{\Delta\gamma_{\text{CR}}} = \left(\frac{E_{\text{primary}}}{E_{\text{ref}}} \right)^{\Delta\gamma_{\text{CR}}}, \quad (4.7)$$

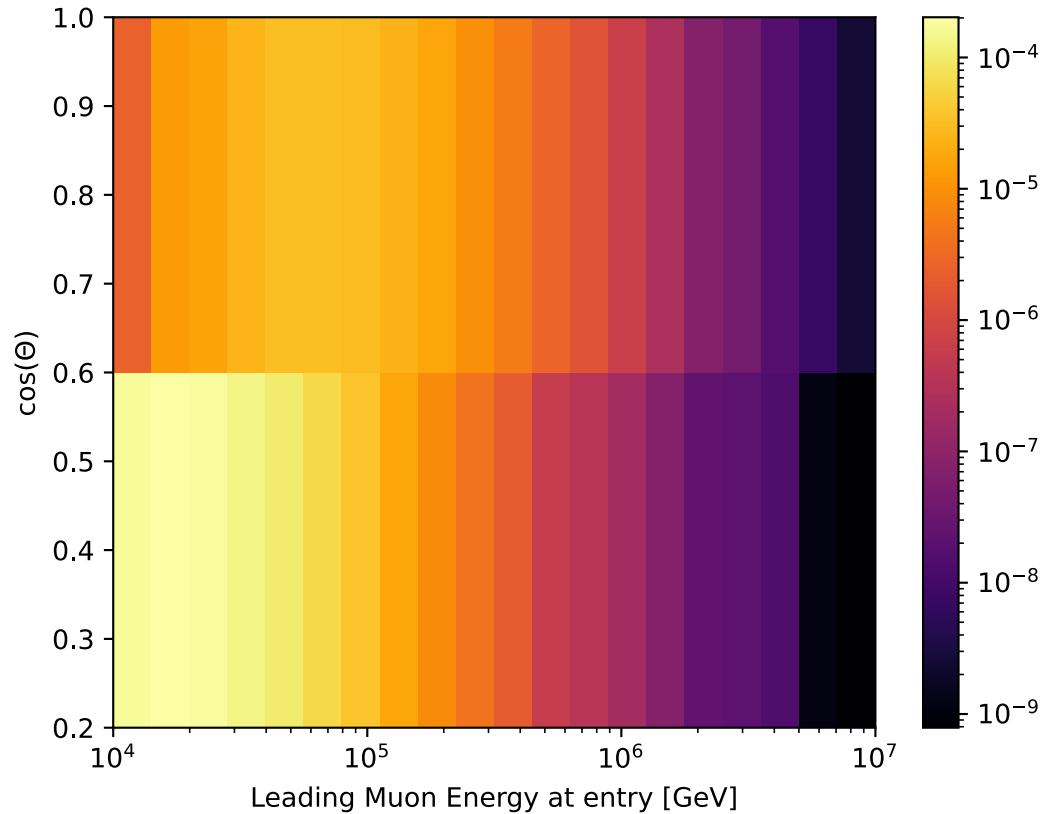
where E_{primary} is the energy of the primary cosmic ray and E_{ref} is the median primary energy in the dataset. A negative $\Delta\gamma_{\text{CR}}$ corresponds to a steeper spectrum, while a positive value corresponds to a flatter spectrum.

Leading Energy Spectrum Final Level

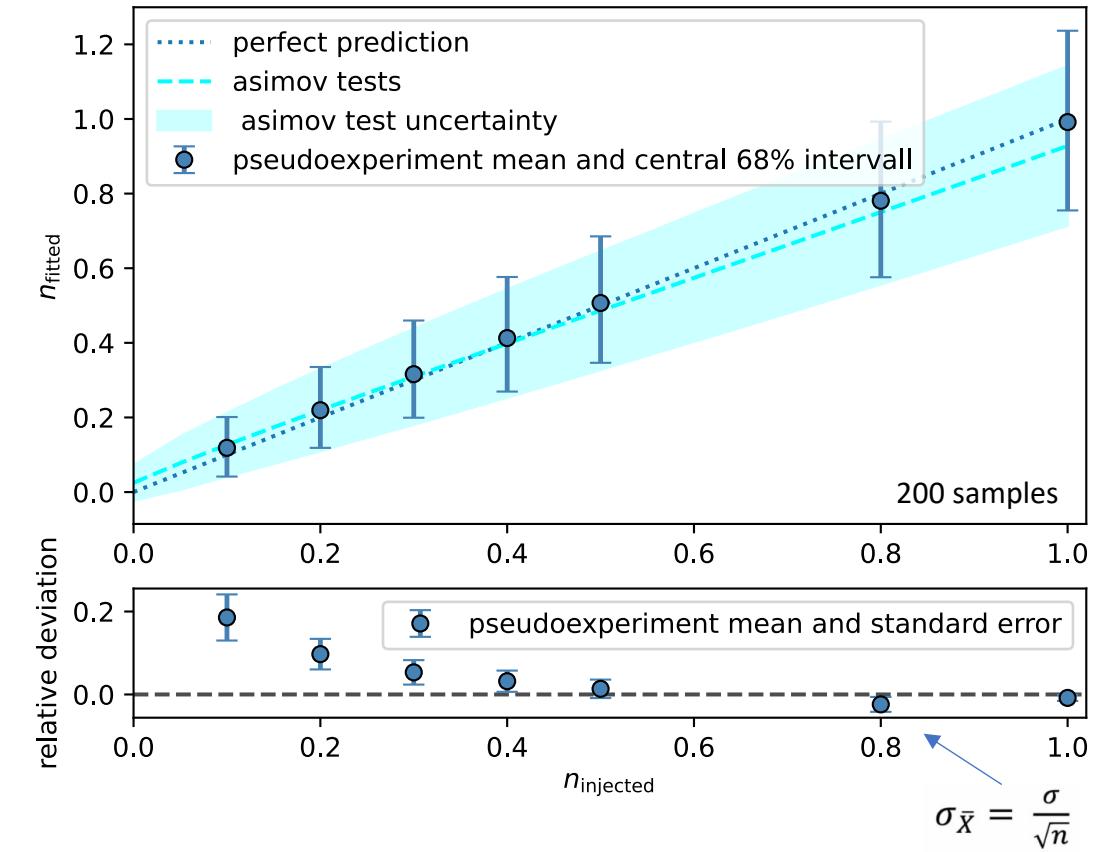


12 years Prediction

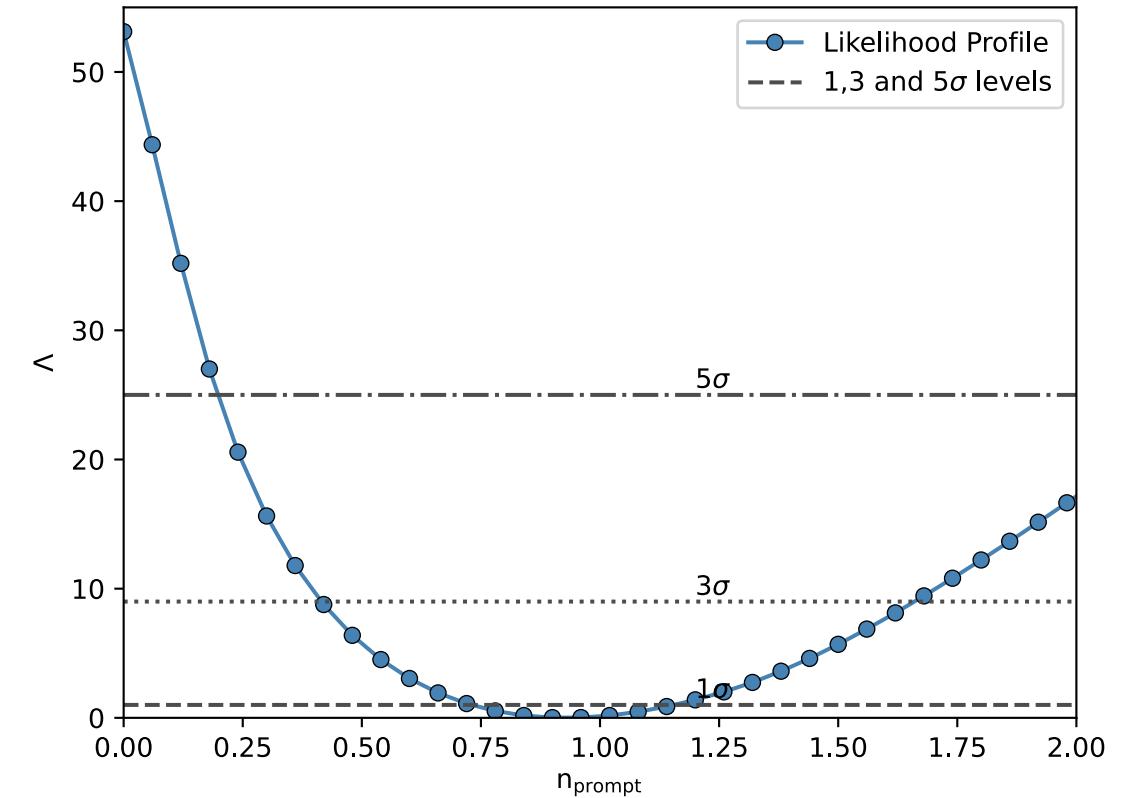
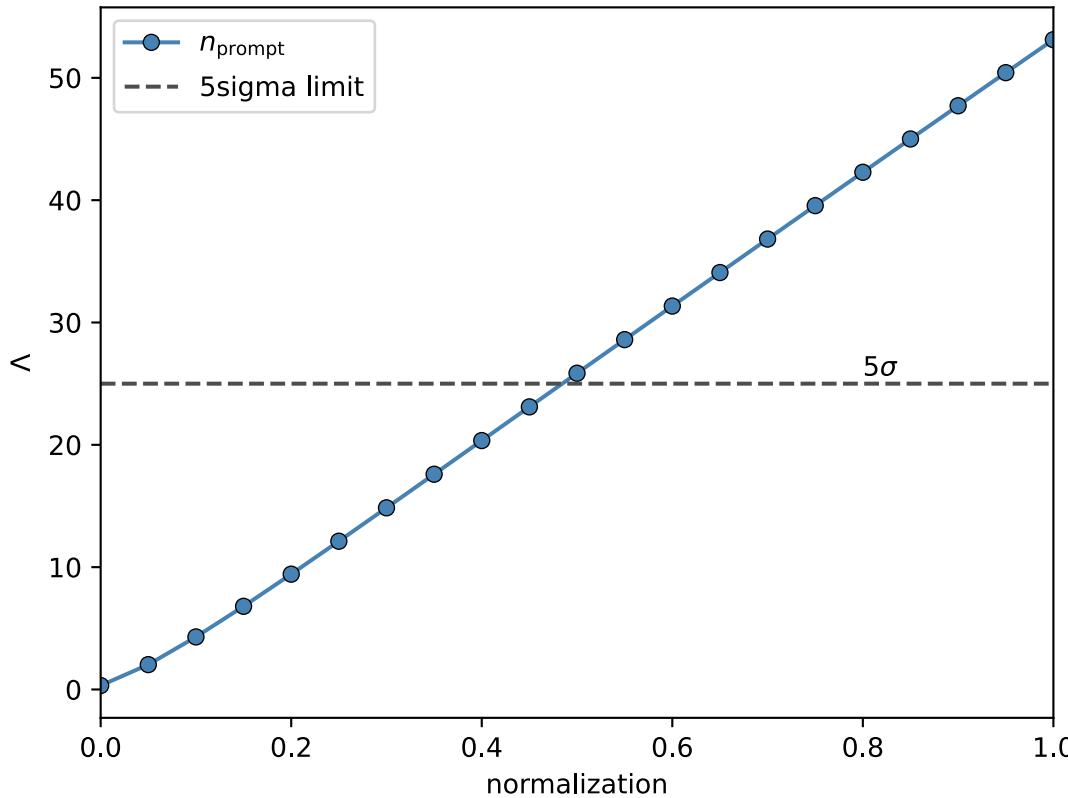
Binning



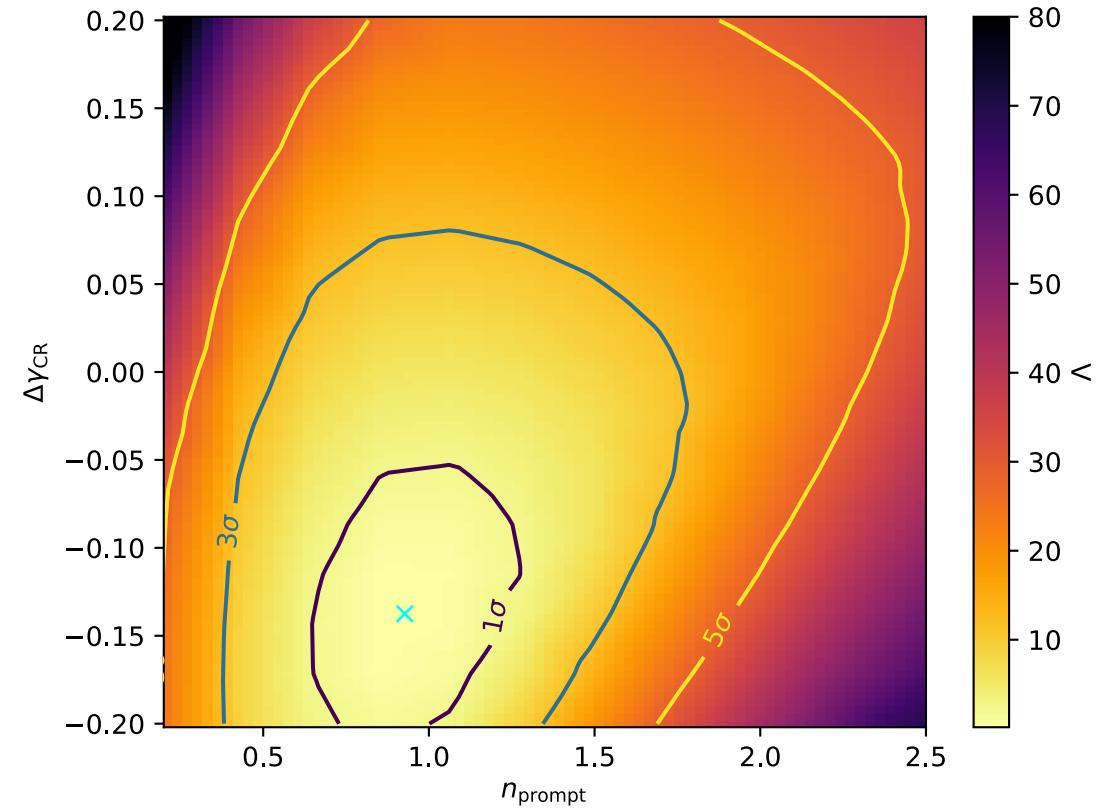
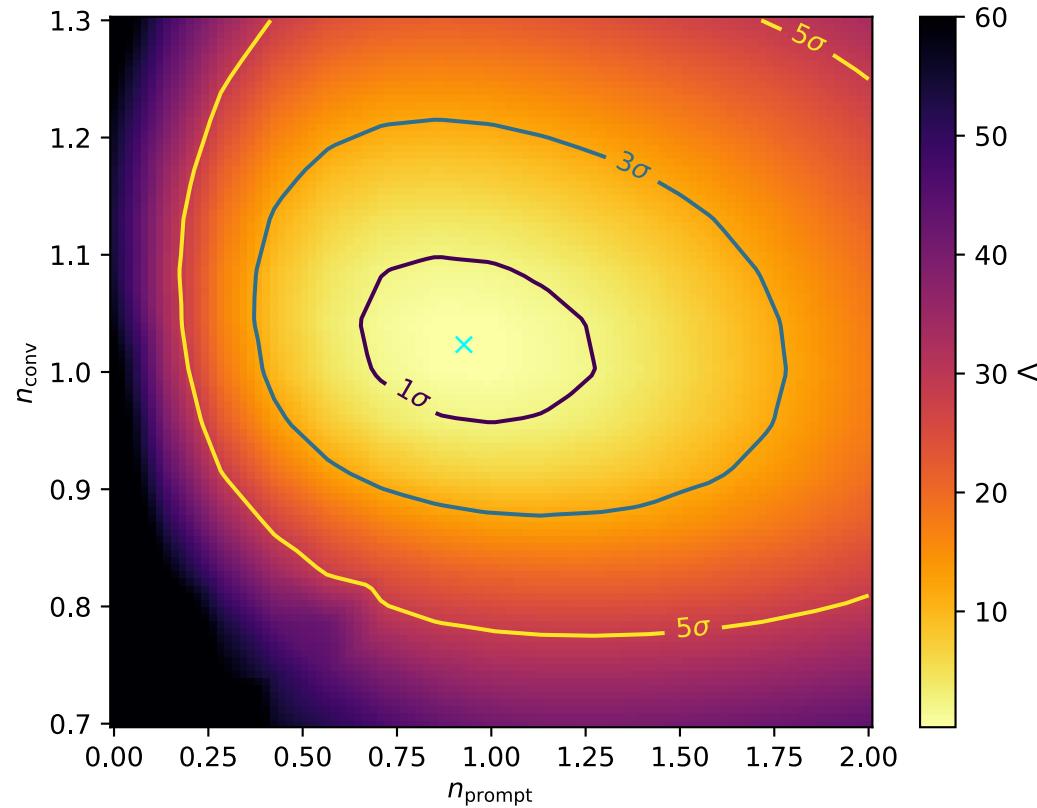
Bias Plot



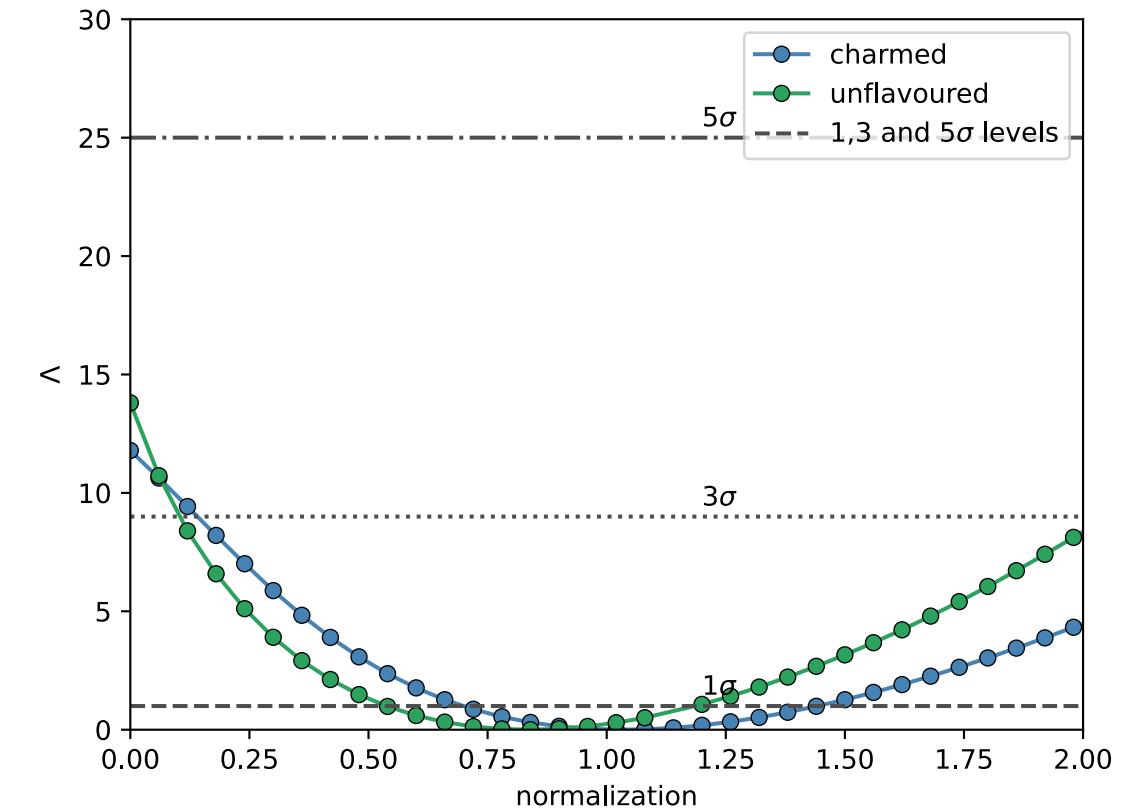
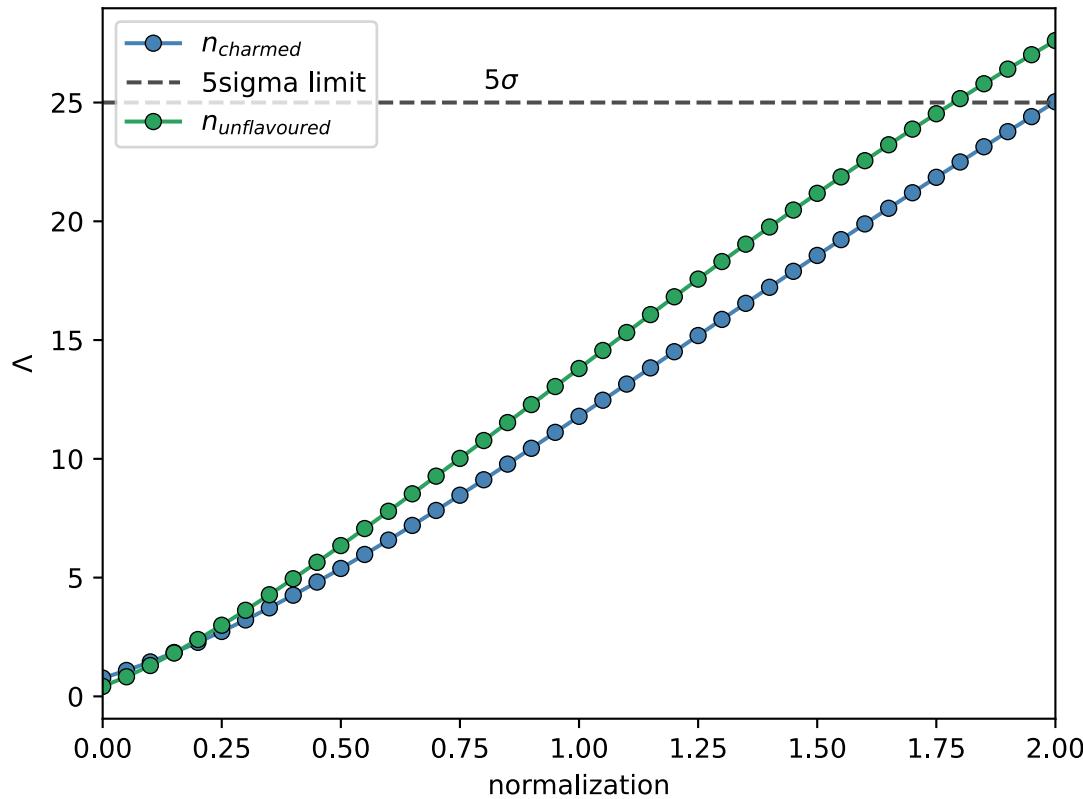
Discovery Scan: Prompt Norm



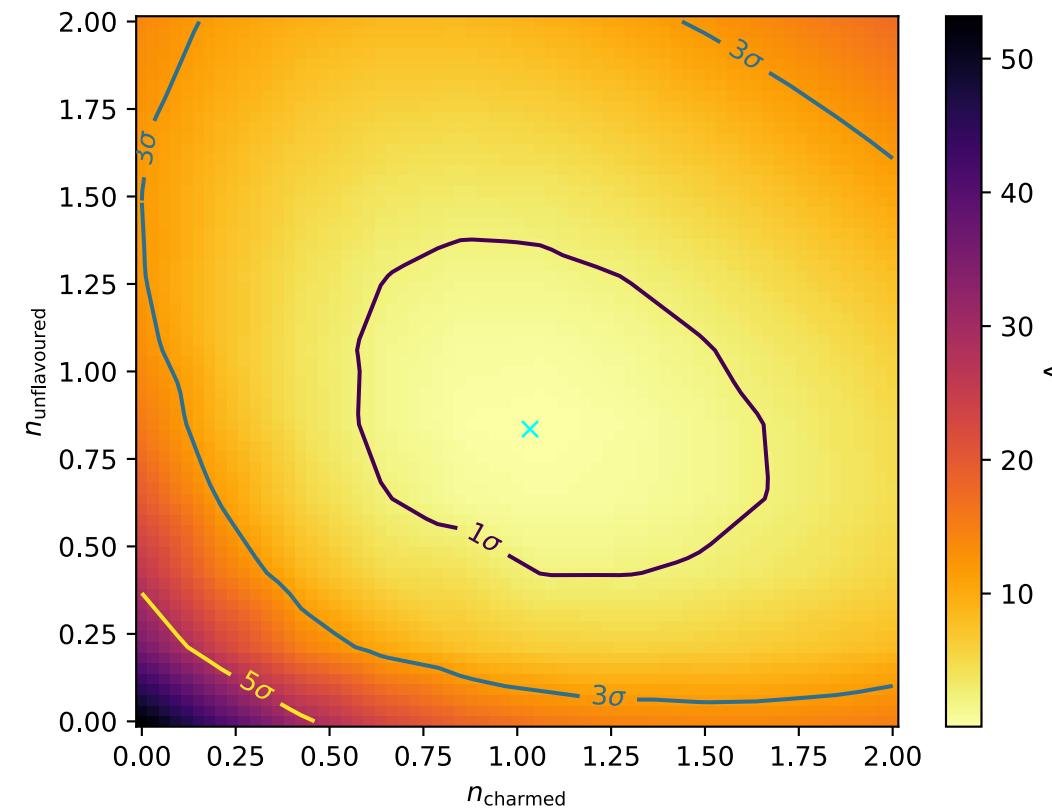
2D Scans: Prompt Norm



Discovery Scan: Charmed & Unflavored



2D Scan: Charmed & Unflavored

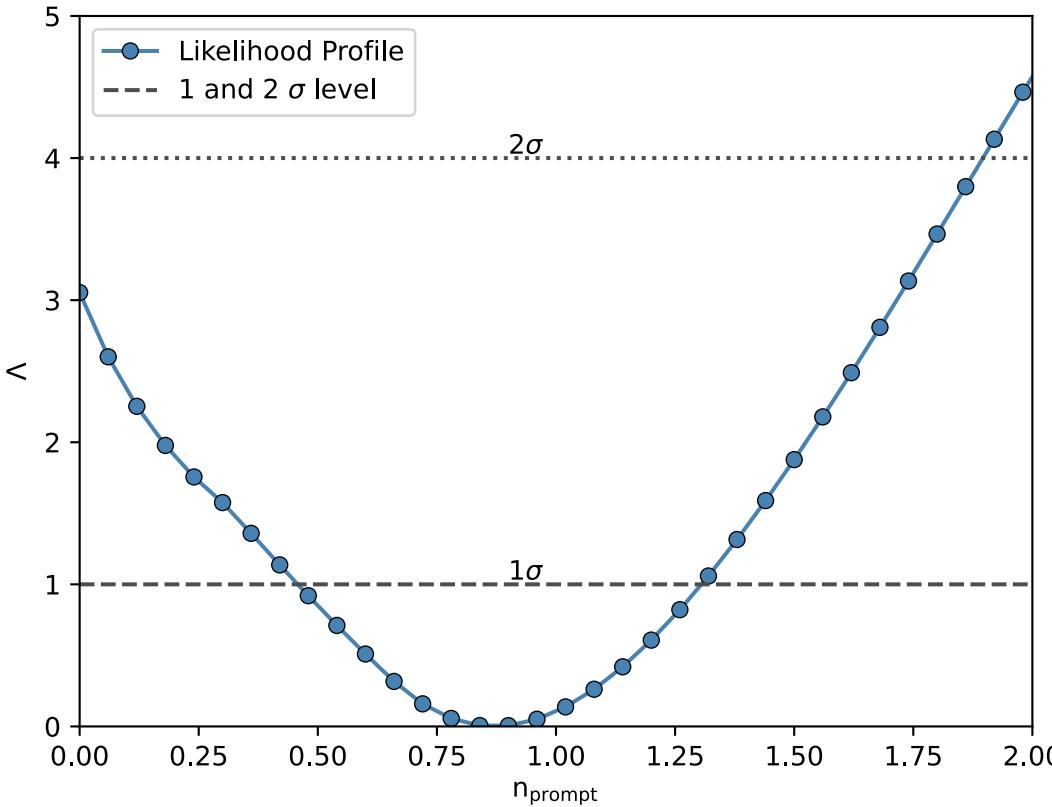


Burnsample

Burnsample Normalization Fits

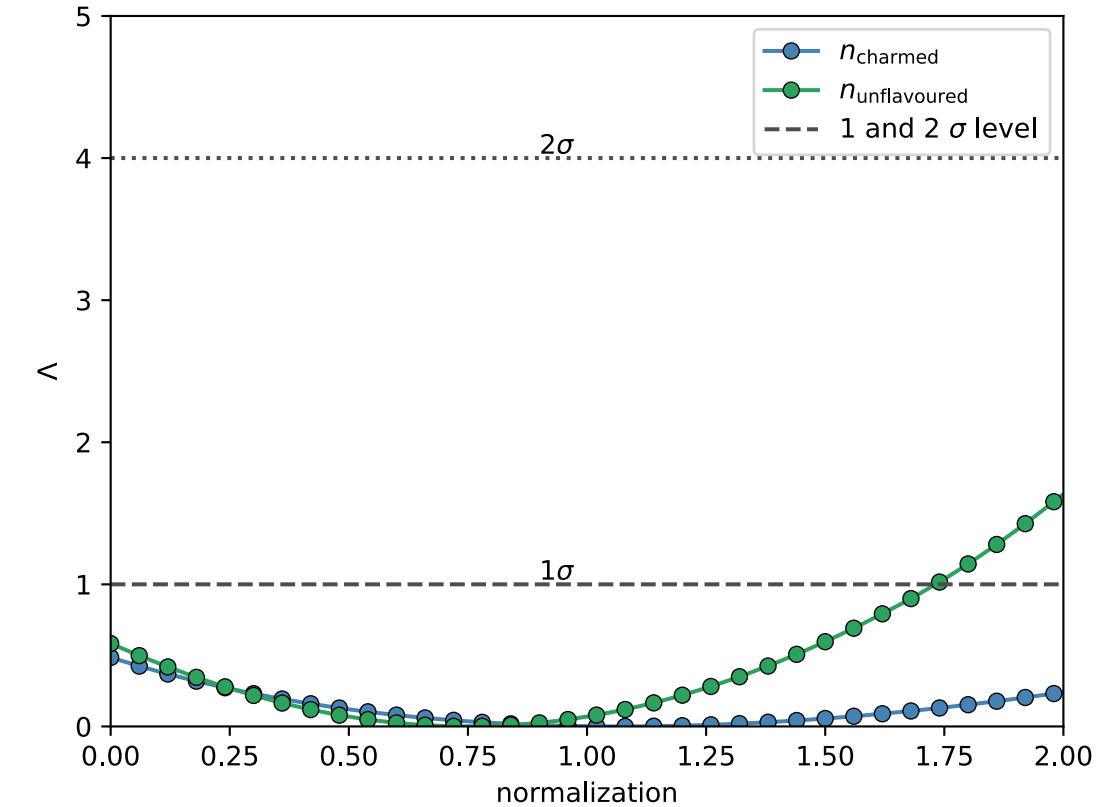
Bins
10 energy
2 zenith

Prompt

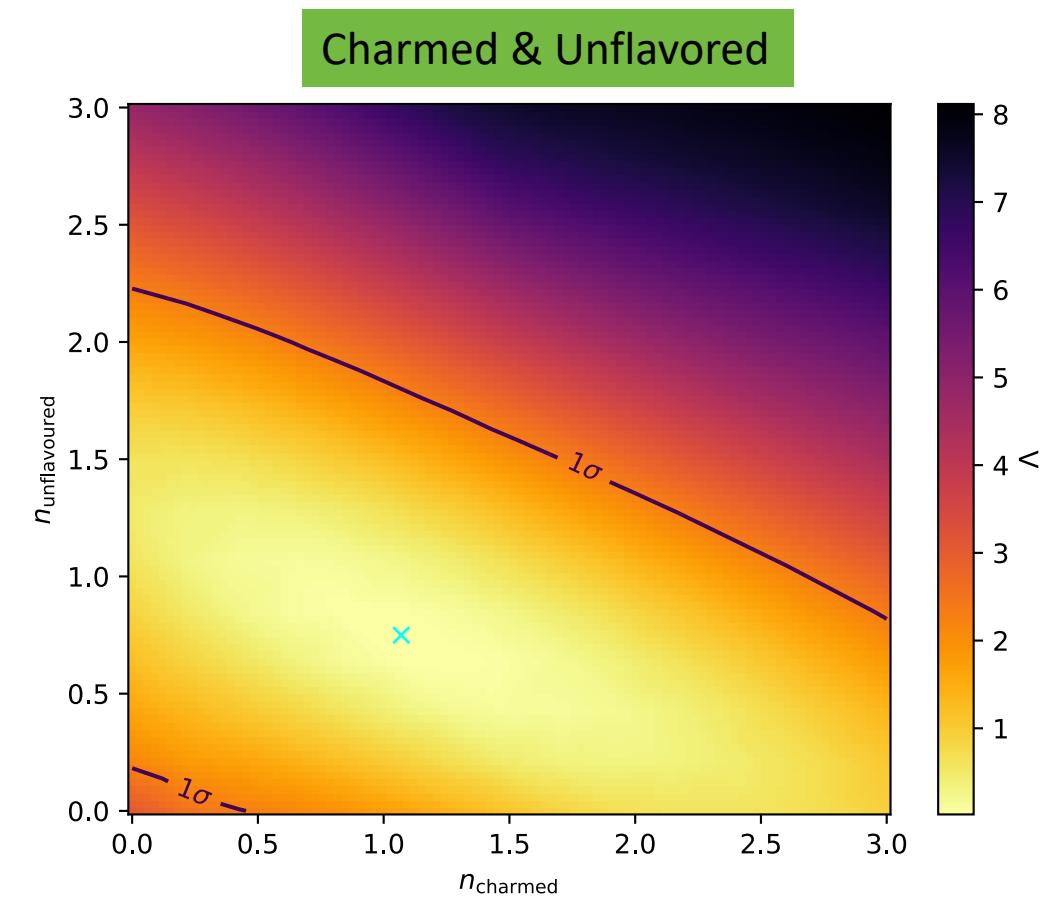
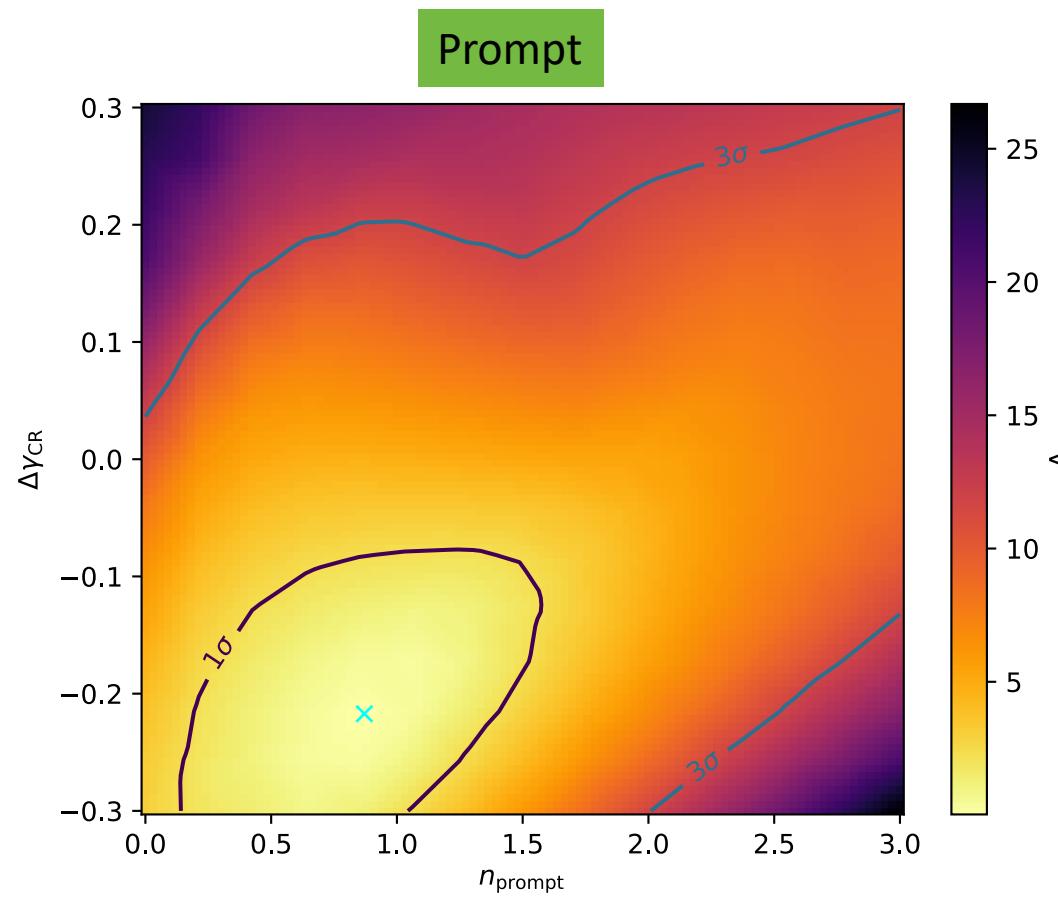


$$\text{Prompt norm} = 0.87 \pm 0.42$$

Charmed & Unflavored

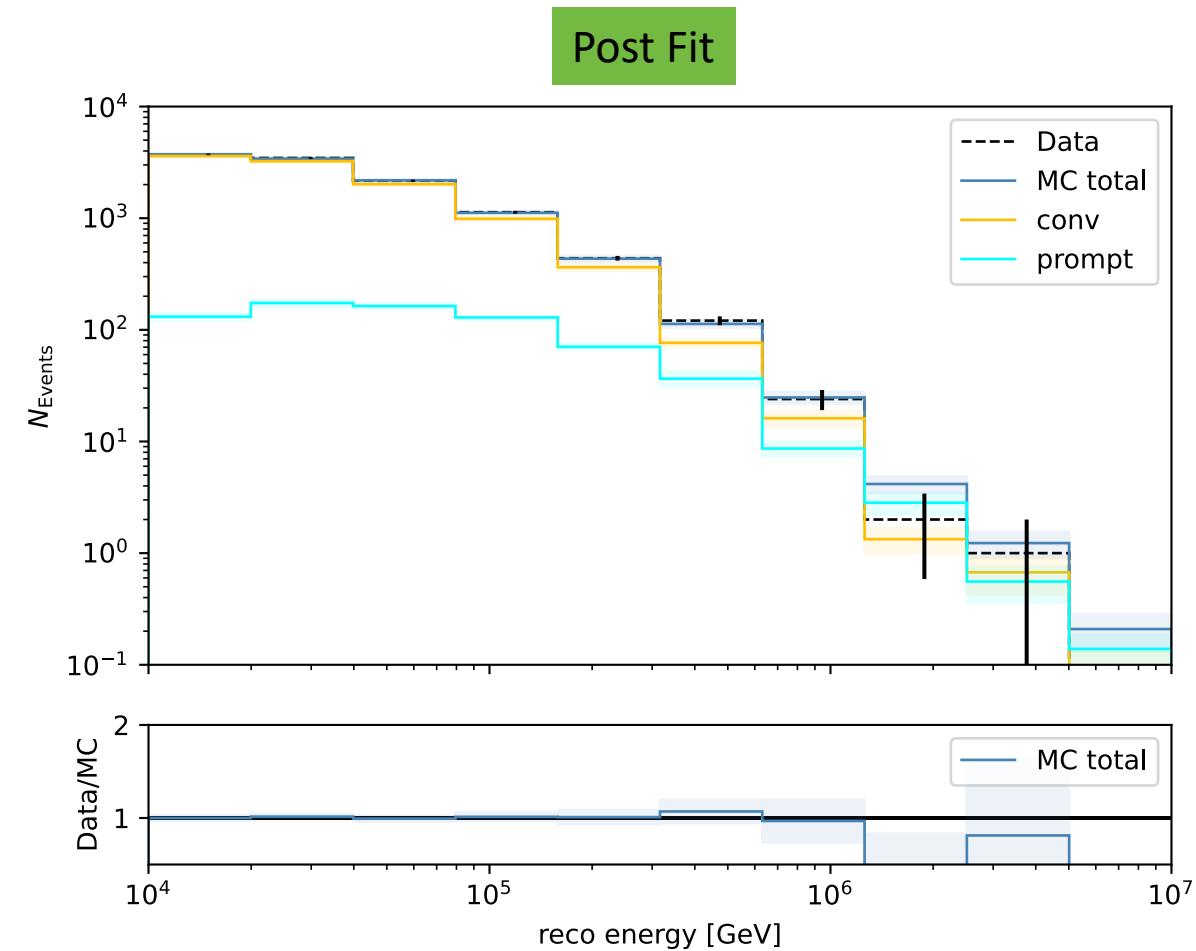
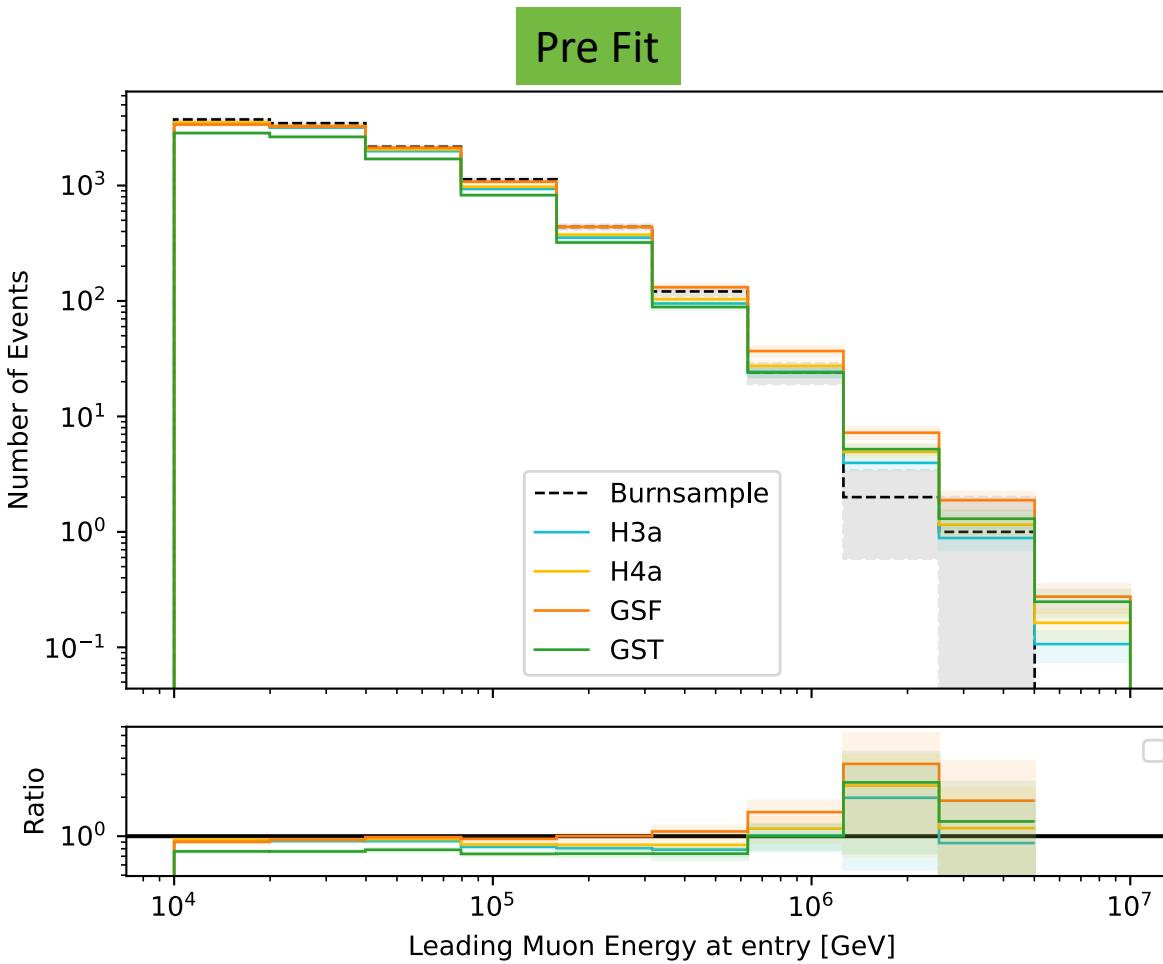


2D Scans Burnsample



Data—MC: Pre & Post Fit

CR_gamma	CR_grad	corsika_conv_norm	corsika_prompt_norm	dom_eff	fit_success	ice_abs	ice_holep0	ice_holep1	ice_scat
-0.217154	0.0	1.188847	0.870507	0.944079	True	0.998045	0.003604	-0.034653	0.97671

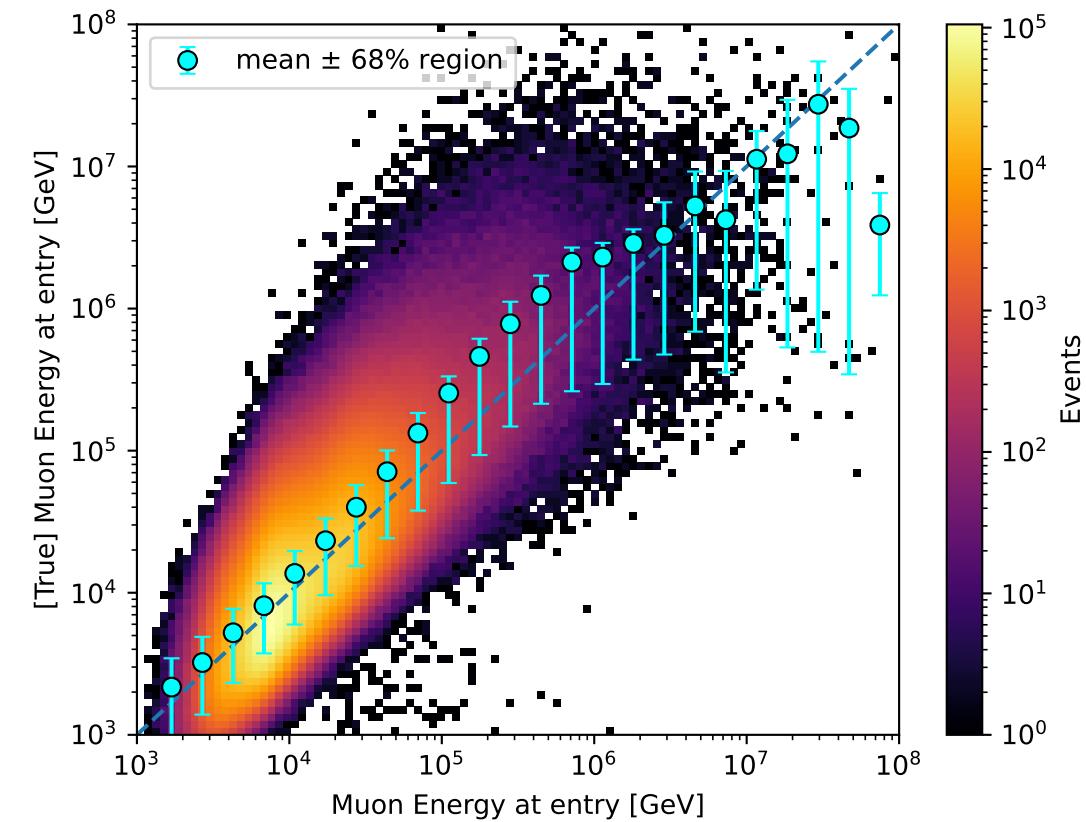
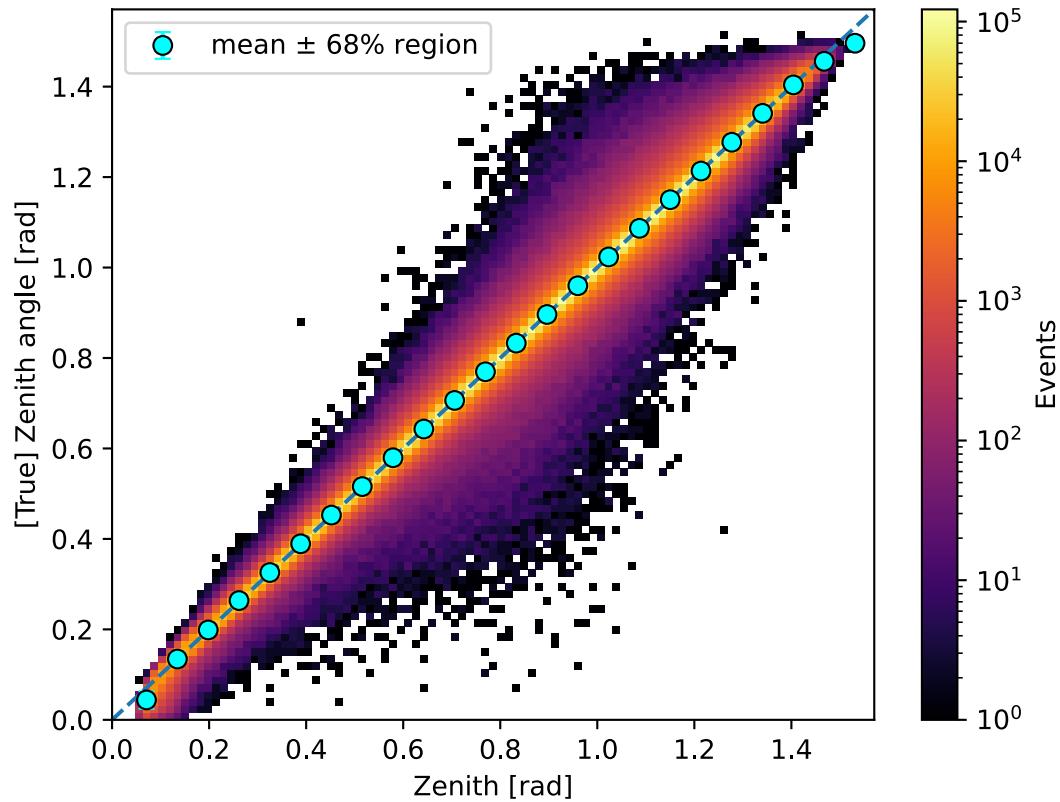


Summary

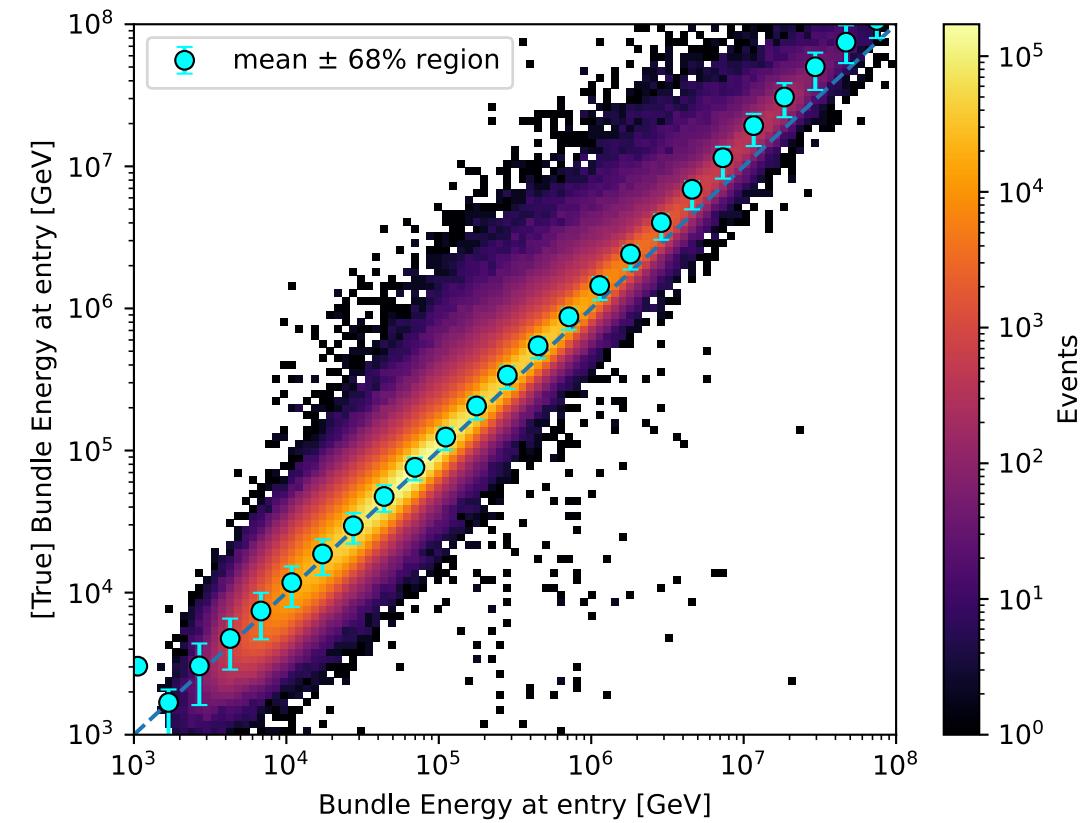
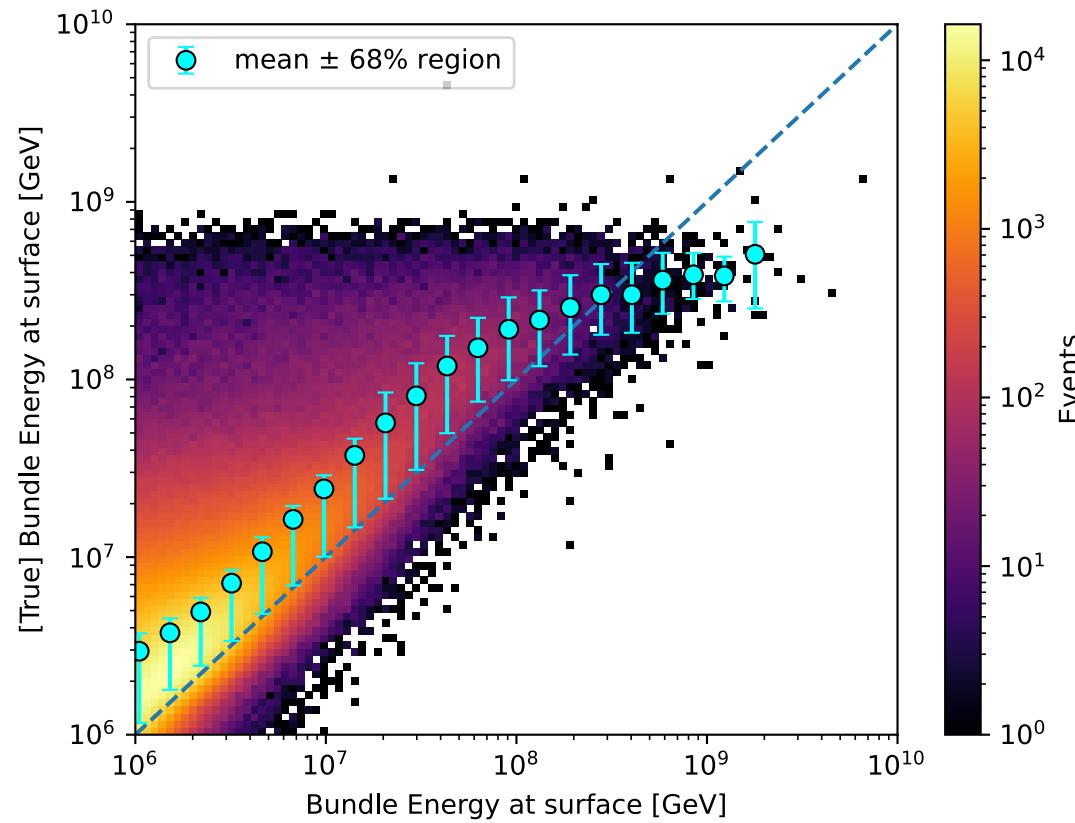
- Use SAY likelihood in NNMFit to fit prompt (charm/unflavored) normalization
- 9 (10) free parameters
 - 5 ice systematics
 - CR interpolation
 - Spectral index shift
 - Prompt (charm/unflavored) norm
- 12 years prediction for prompt norm > 7 sigma
- Burnsample (~ 100 days) fit
 - Good data—mc agreement with fitted nuisance parameters
 - ~ 1.7 sigma for prompt
 - Prompt norm = 0.87 ± 0.42

Backup

Reconstructions Level 4

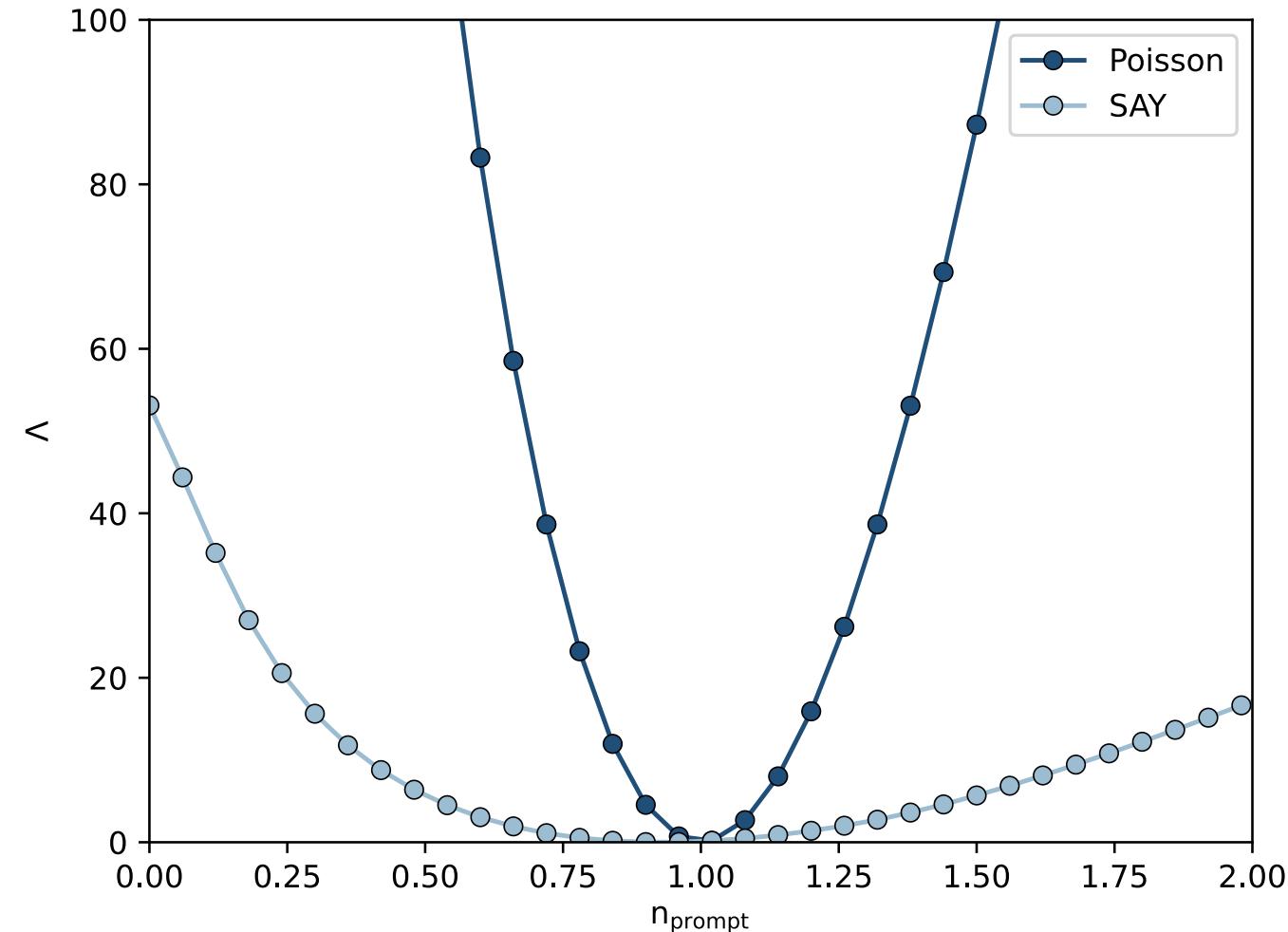


Reconstructions Level 4

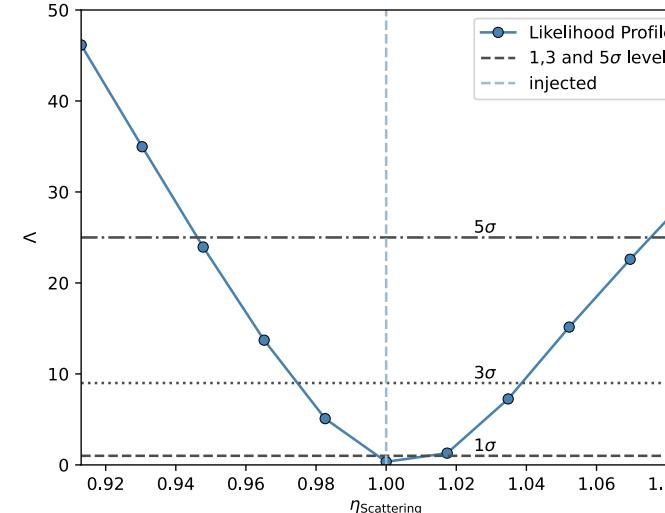
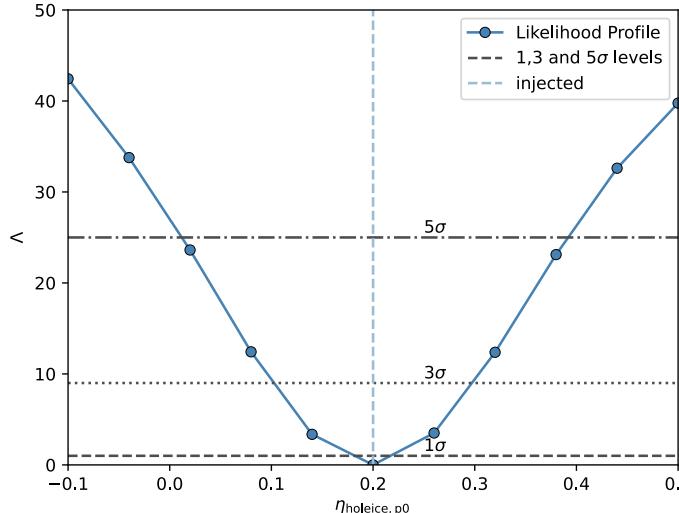
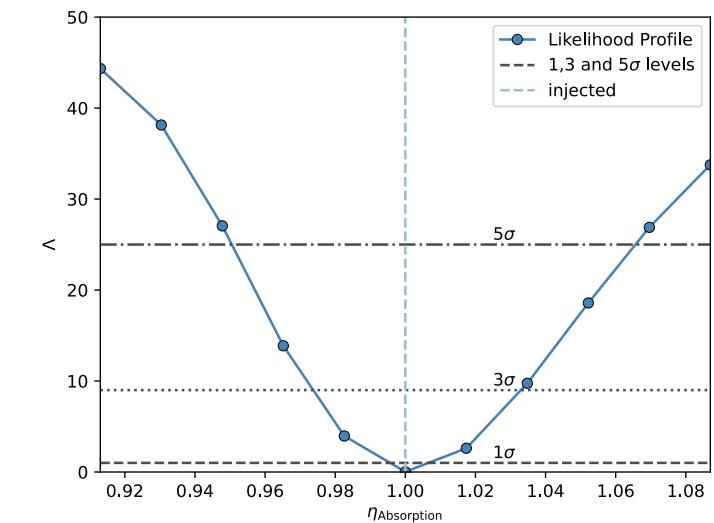
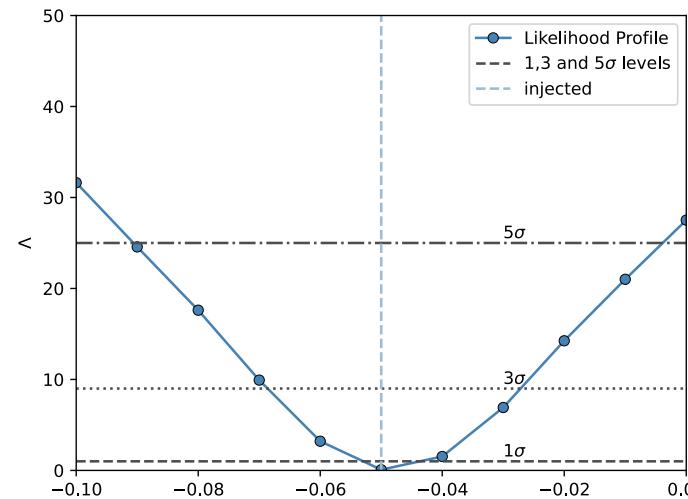
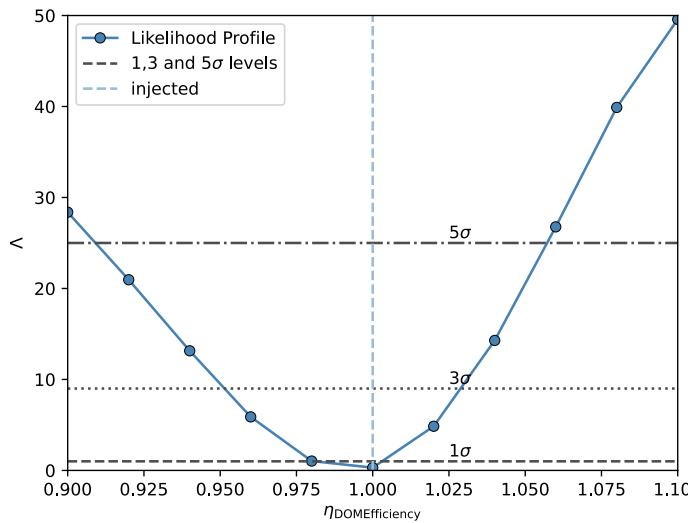


Poisson vs SAY

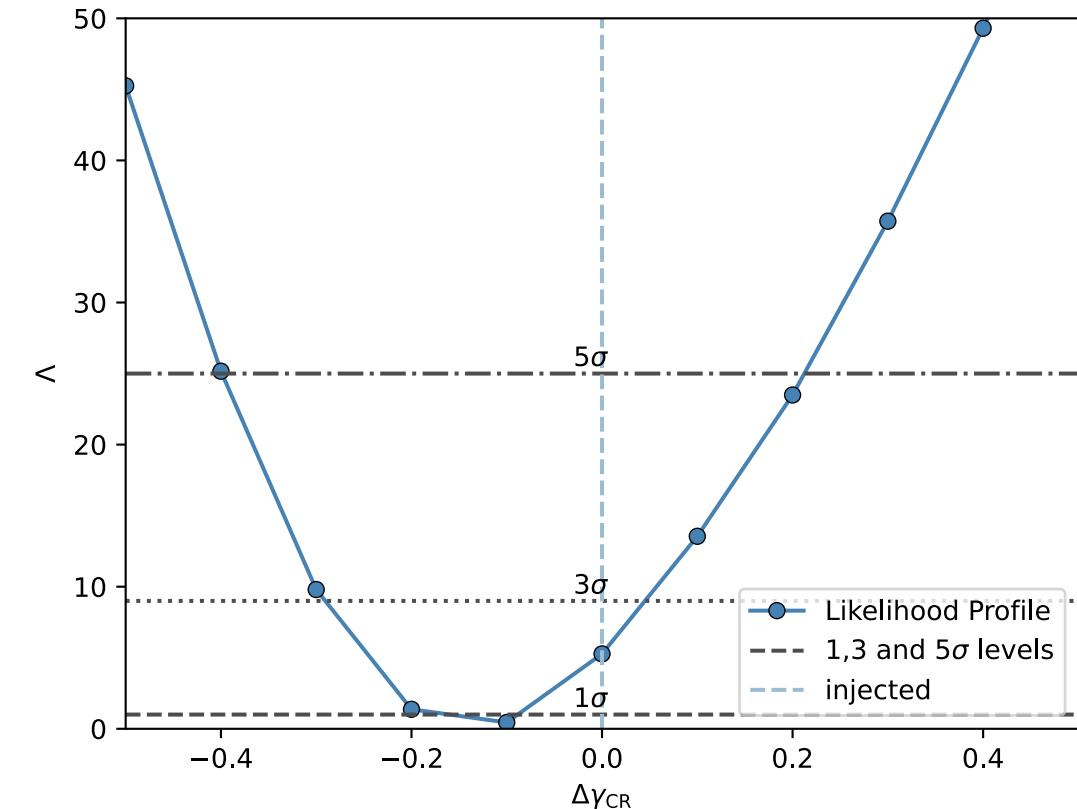
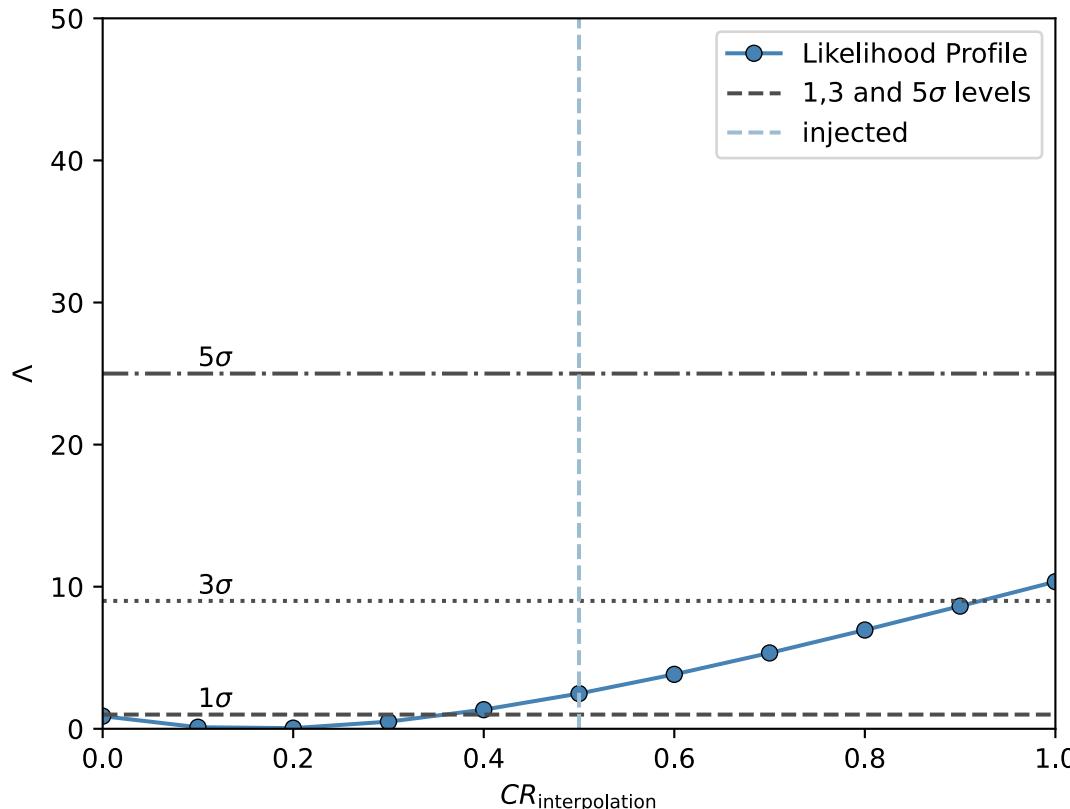
- 12 years lifetime
- Final Level



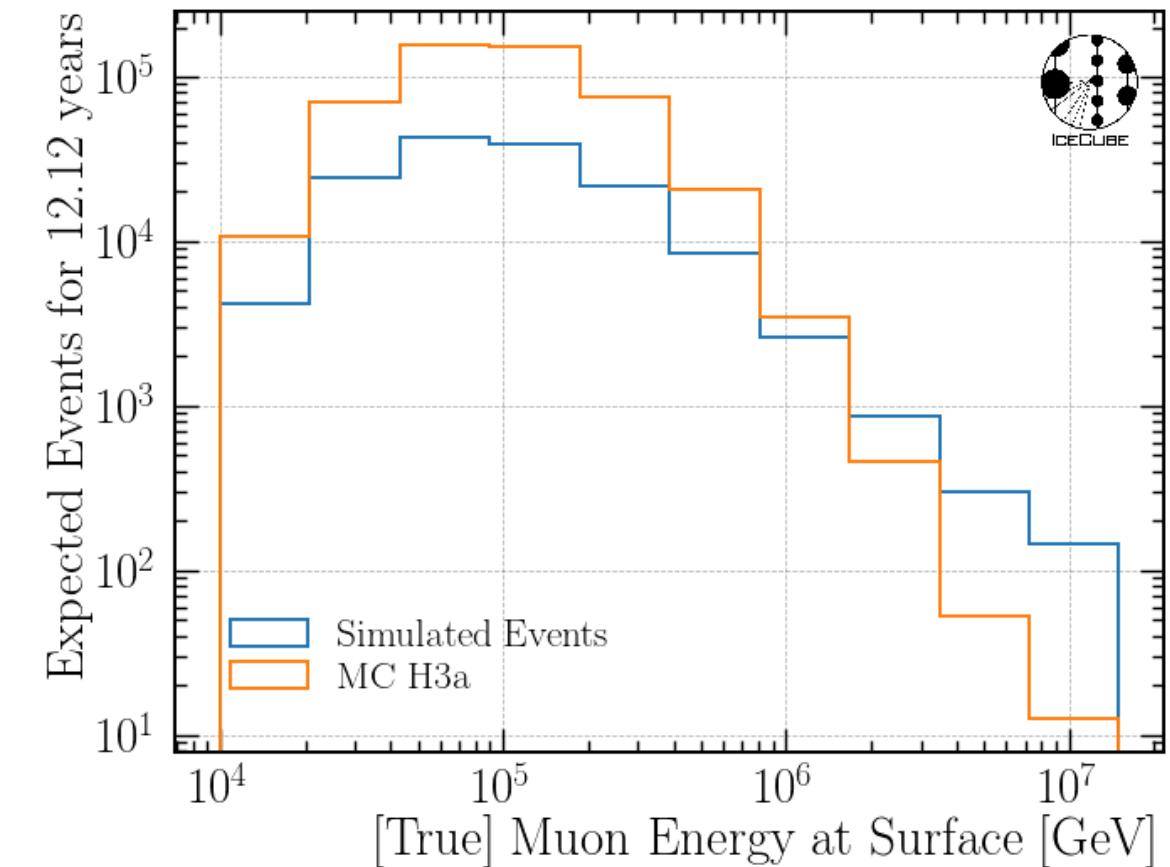
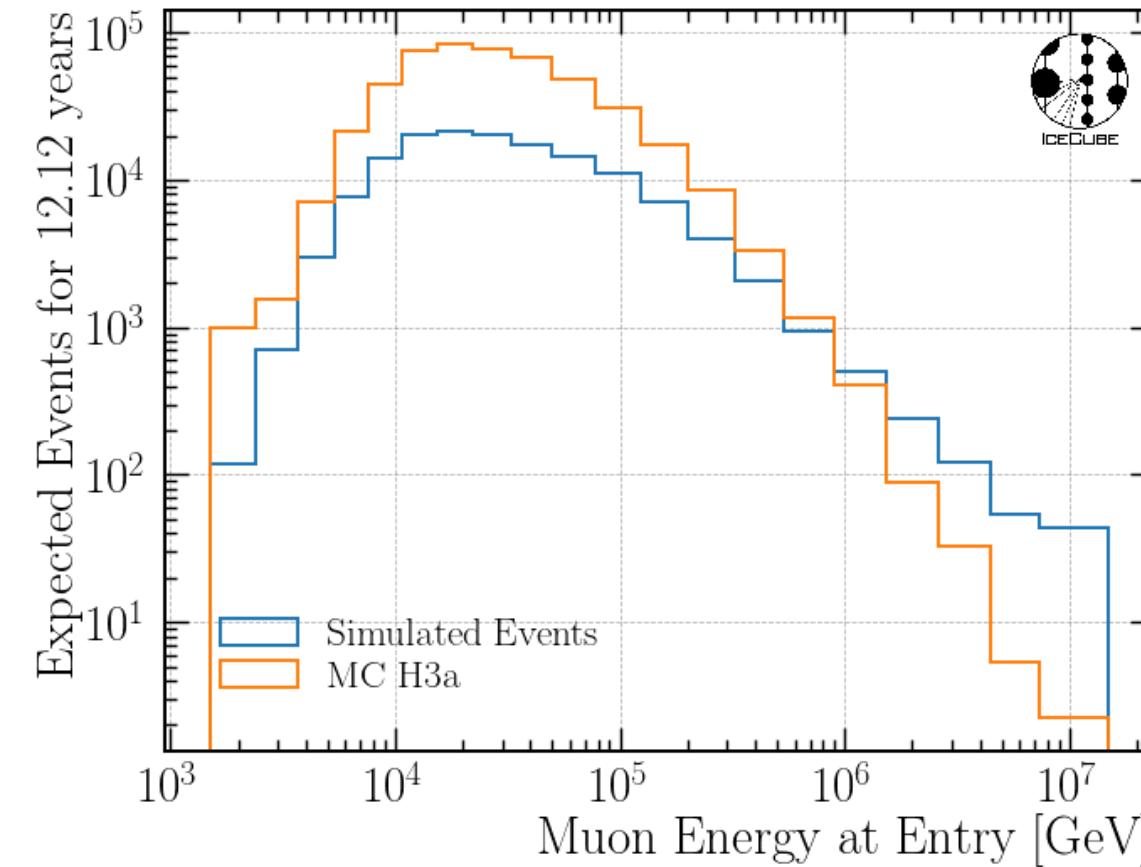
LLH Scan Ice Systematics



LLH Scan CR Gradient & Spectral Index Shift

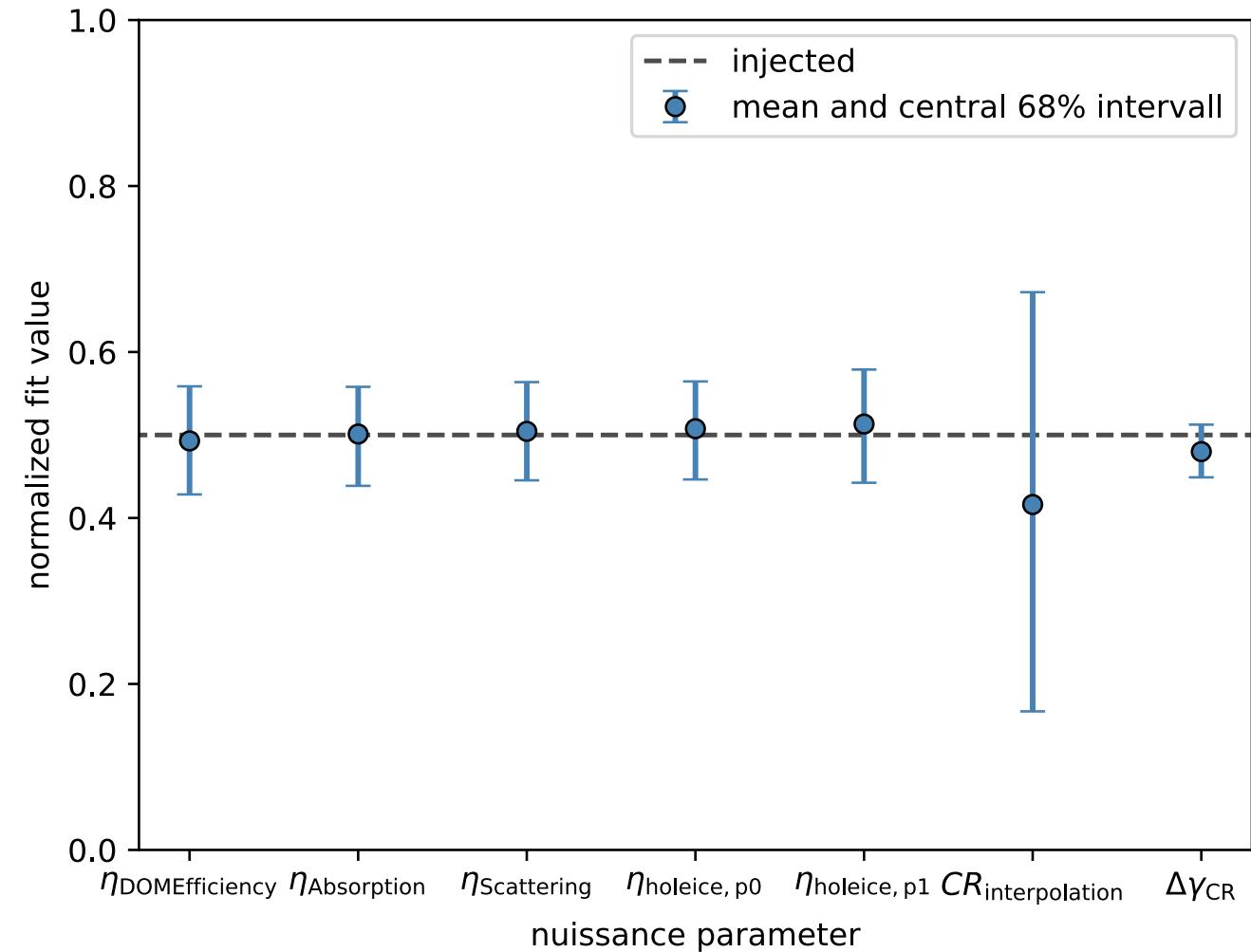


MC Statistics

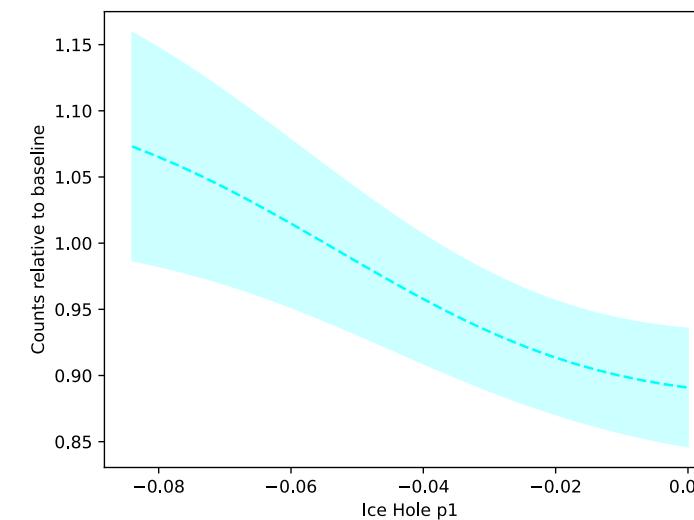
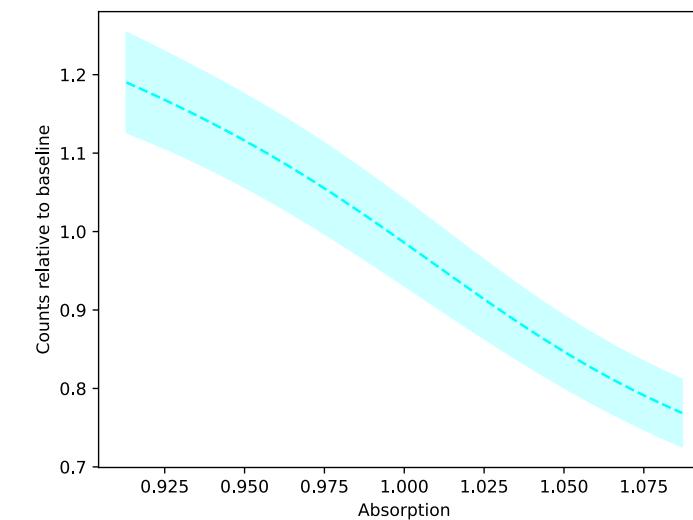
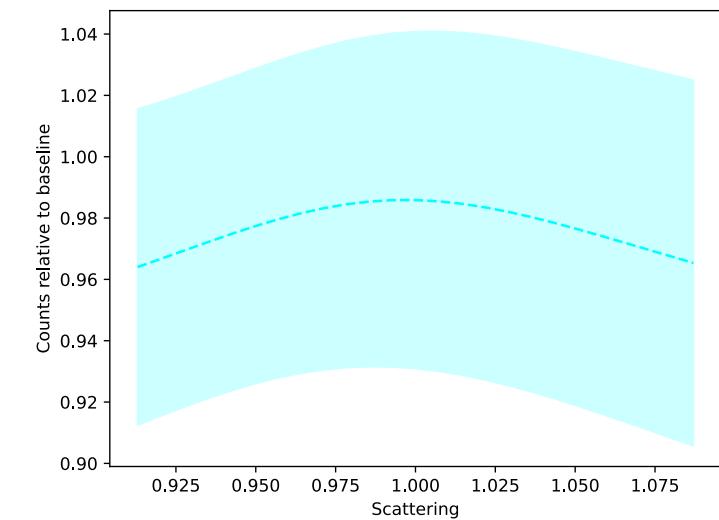
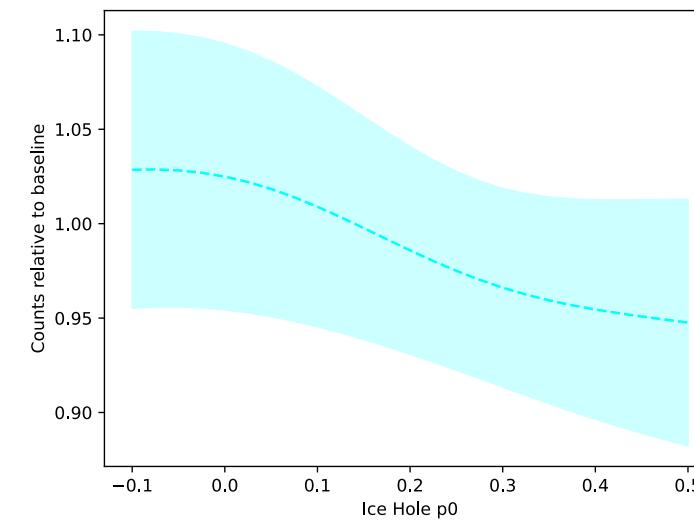
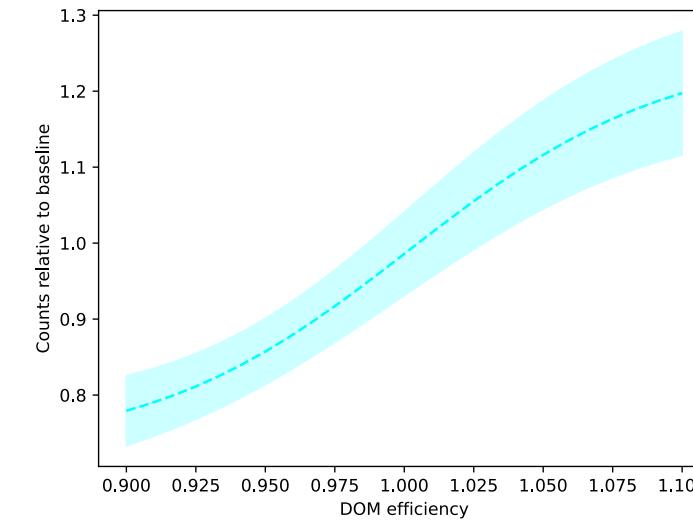


Bias All Systematics

- 12 years lifetime
- Final Level



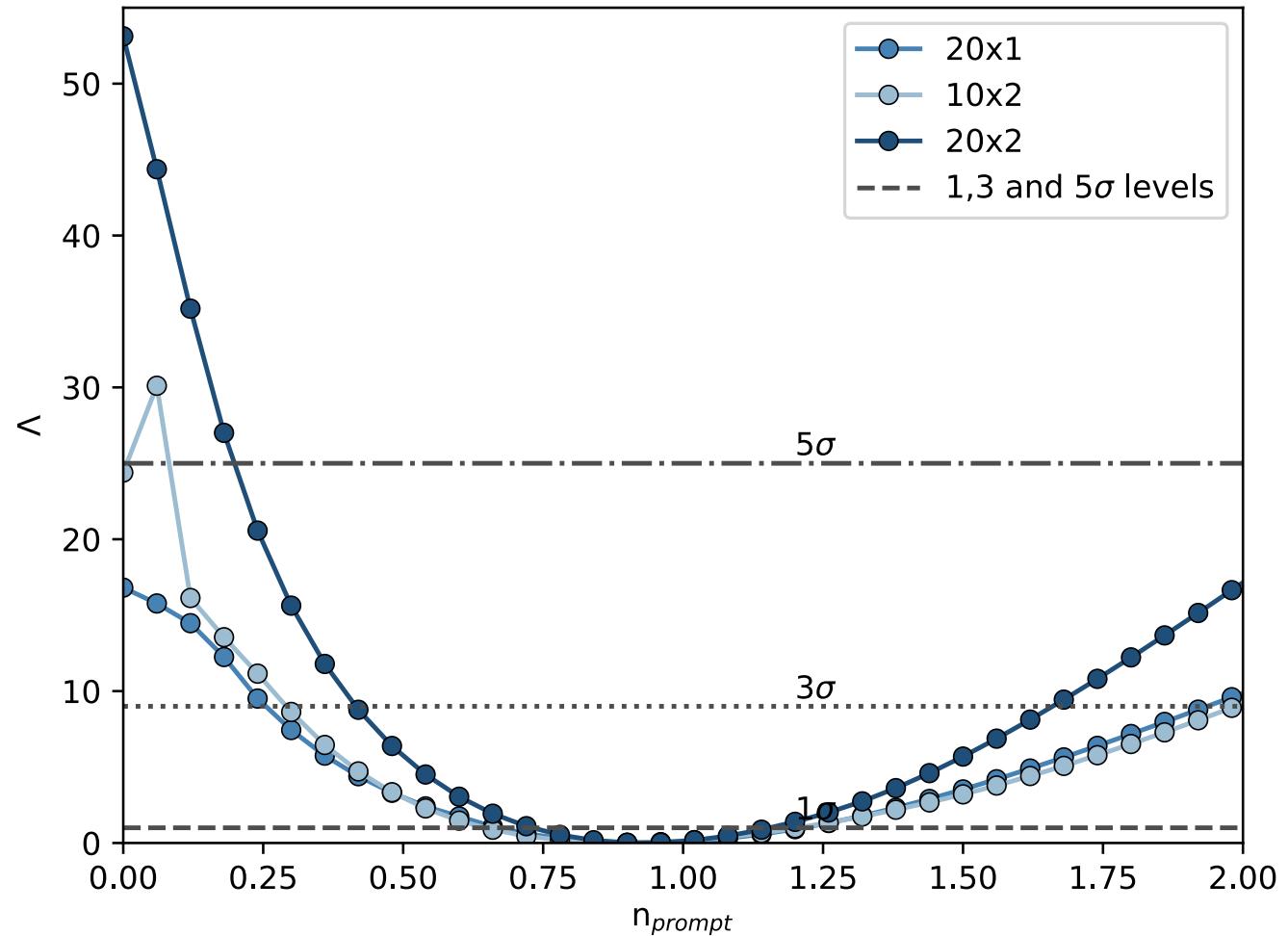
Ice Systematics Impact on Bin 0



- Baseline = entire snowstorm set

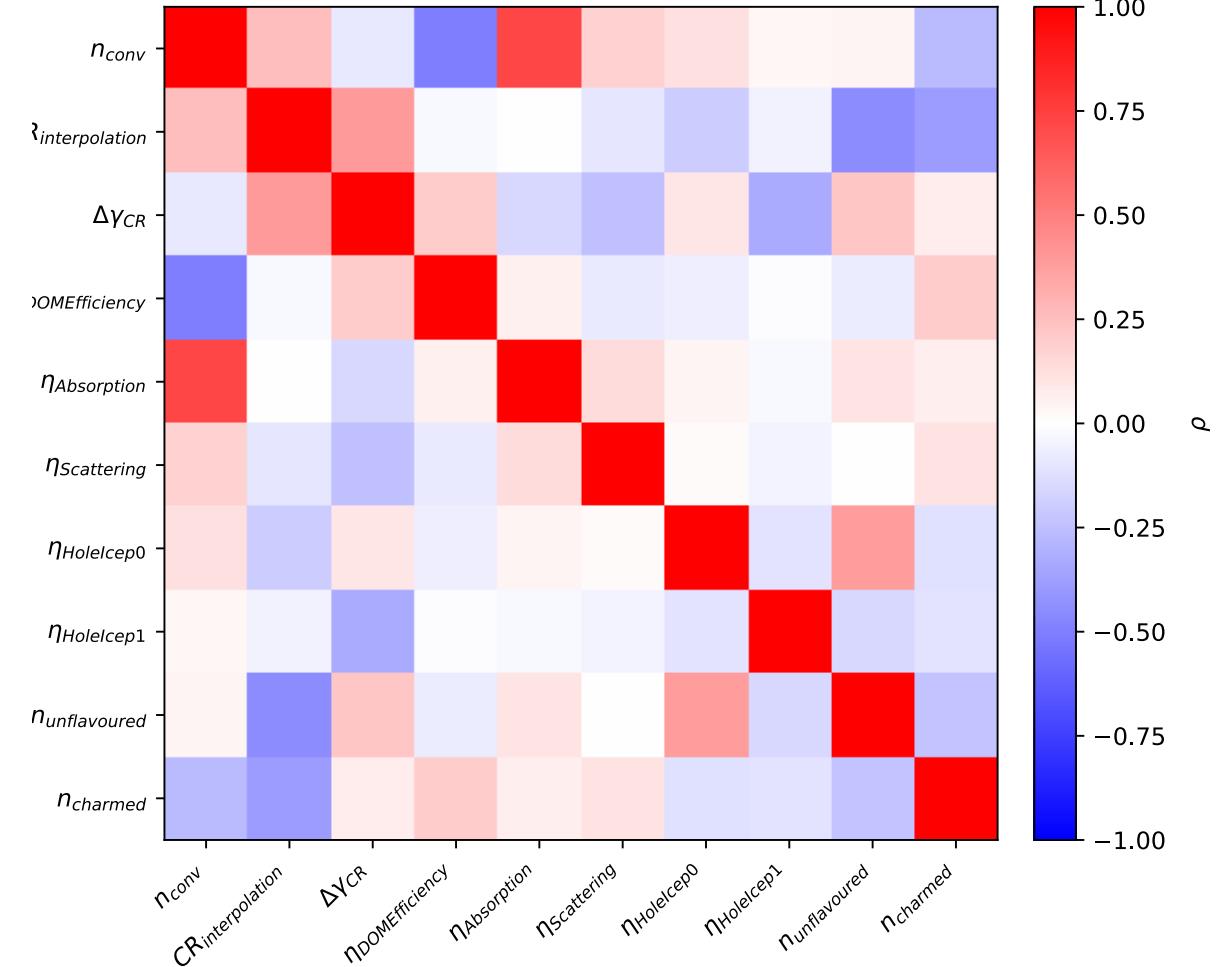
Test Different Binnings

- 12 years lifetime
- Final Level

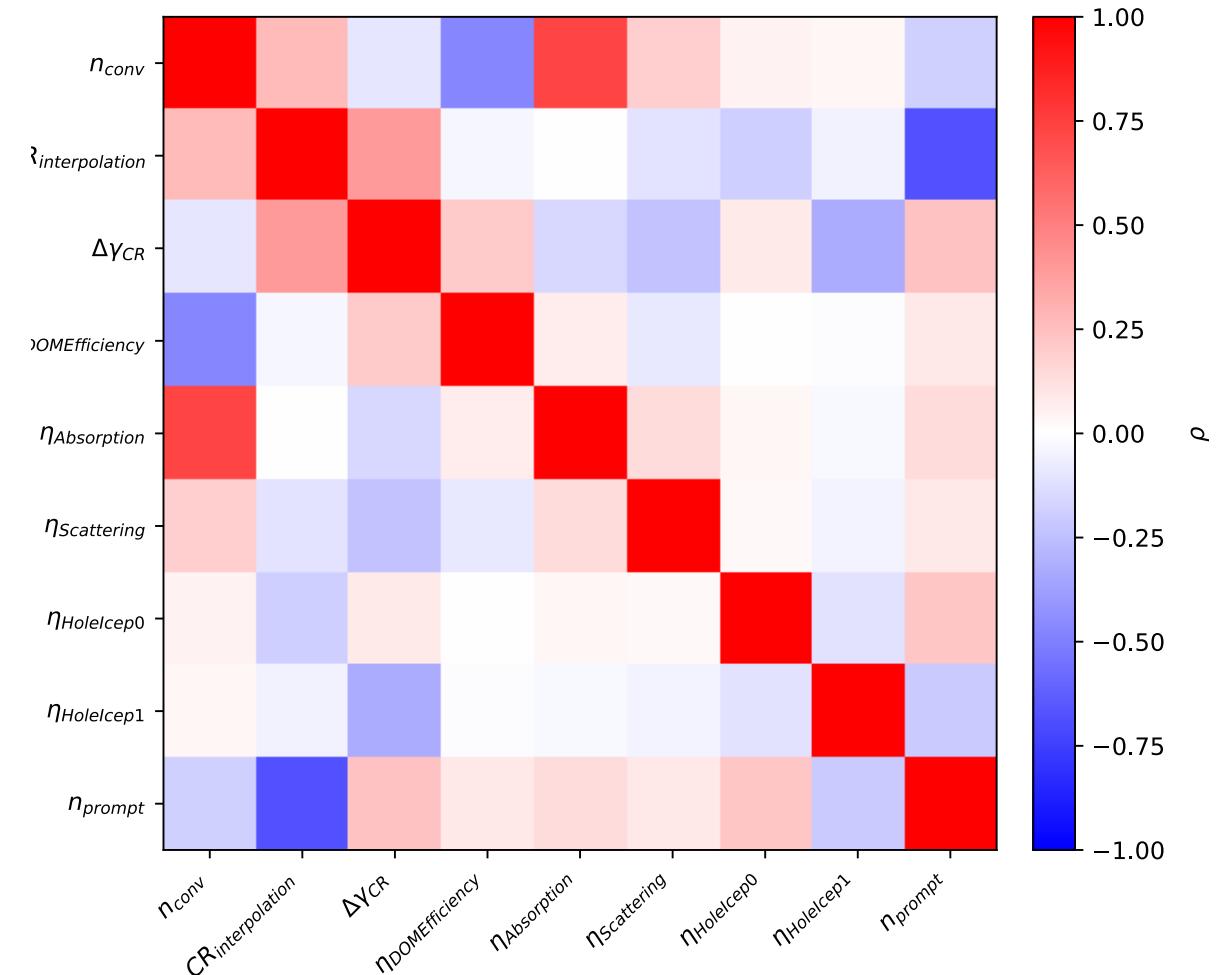


Parameter Correlations

Fit charmed & unflavored norm

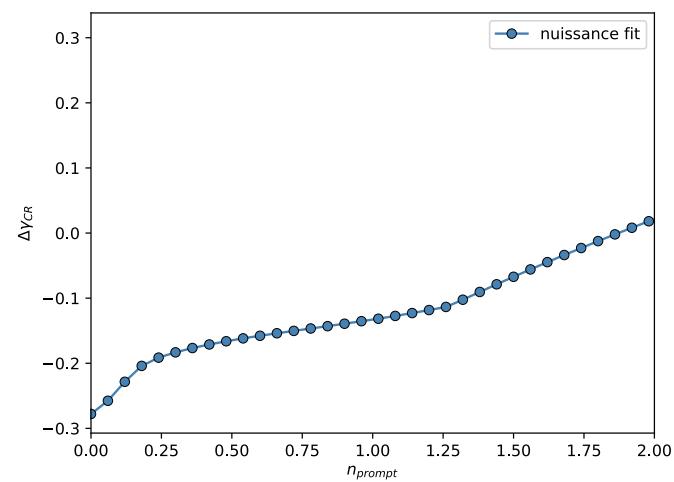
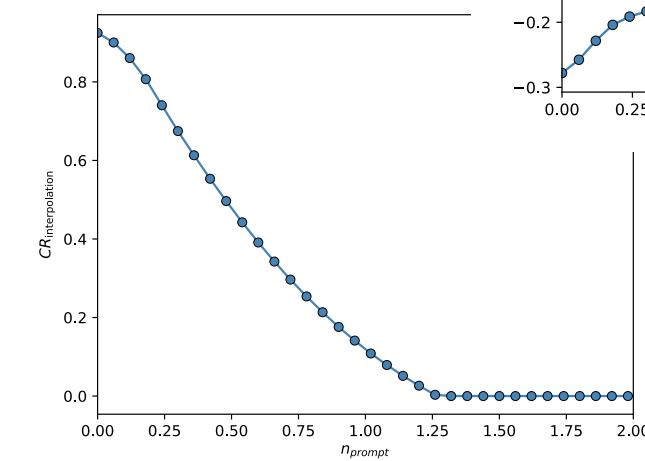
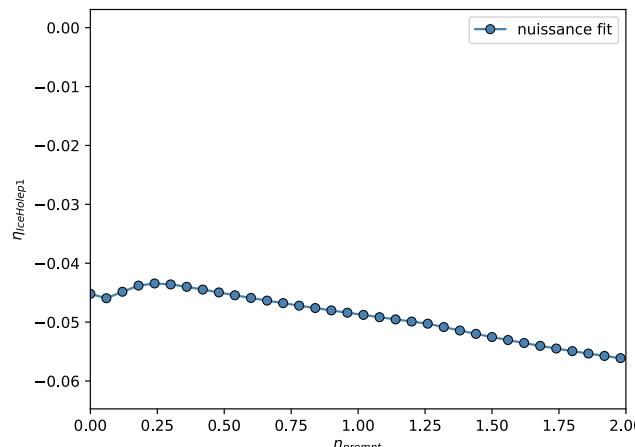
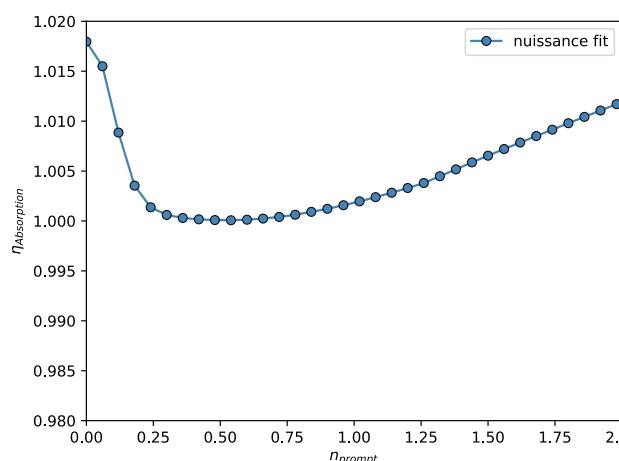
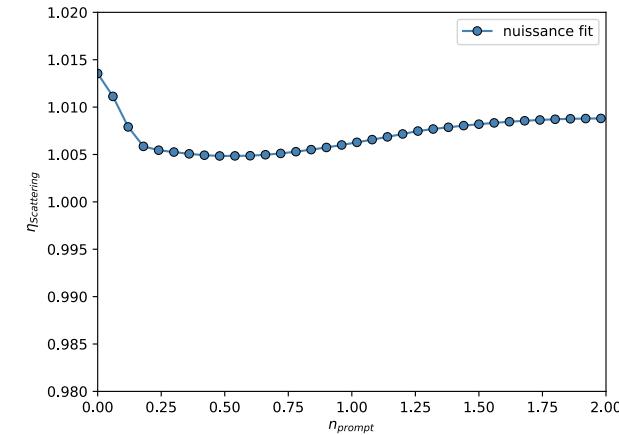
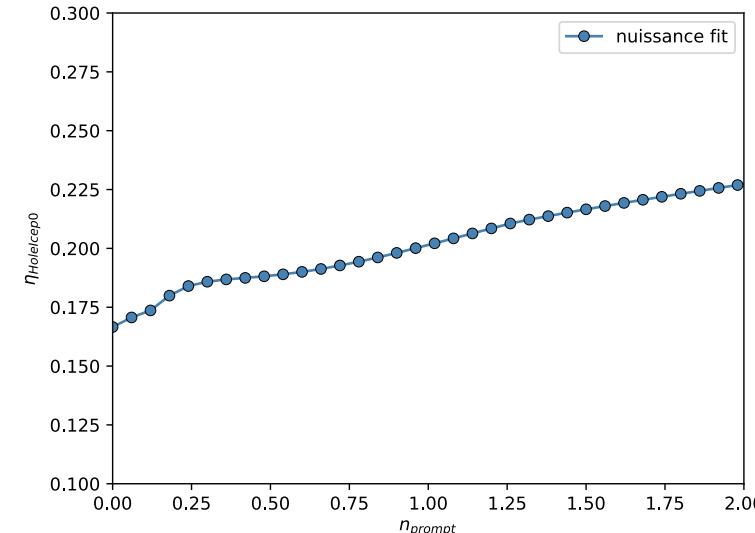
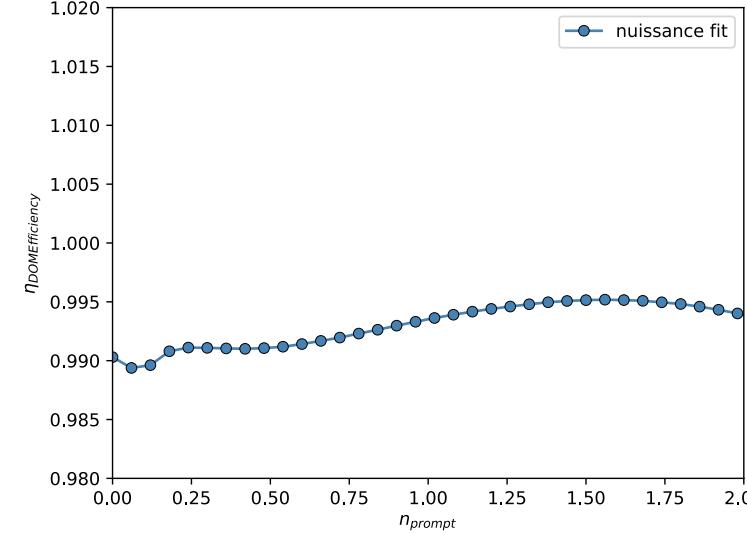


Fit prompt norm

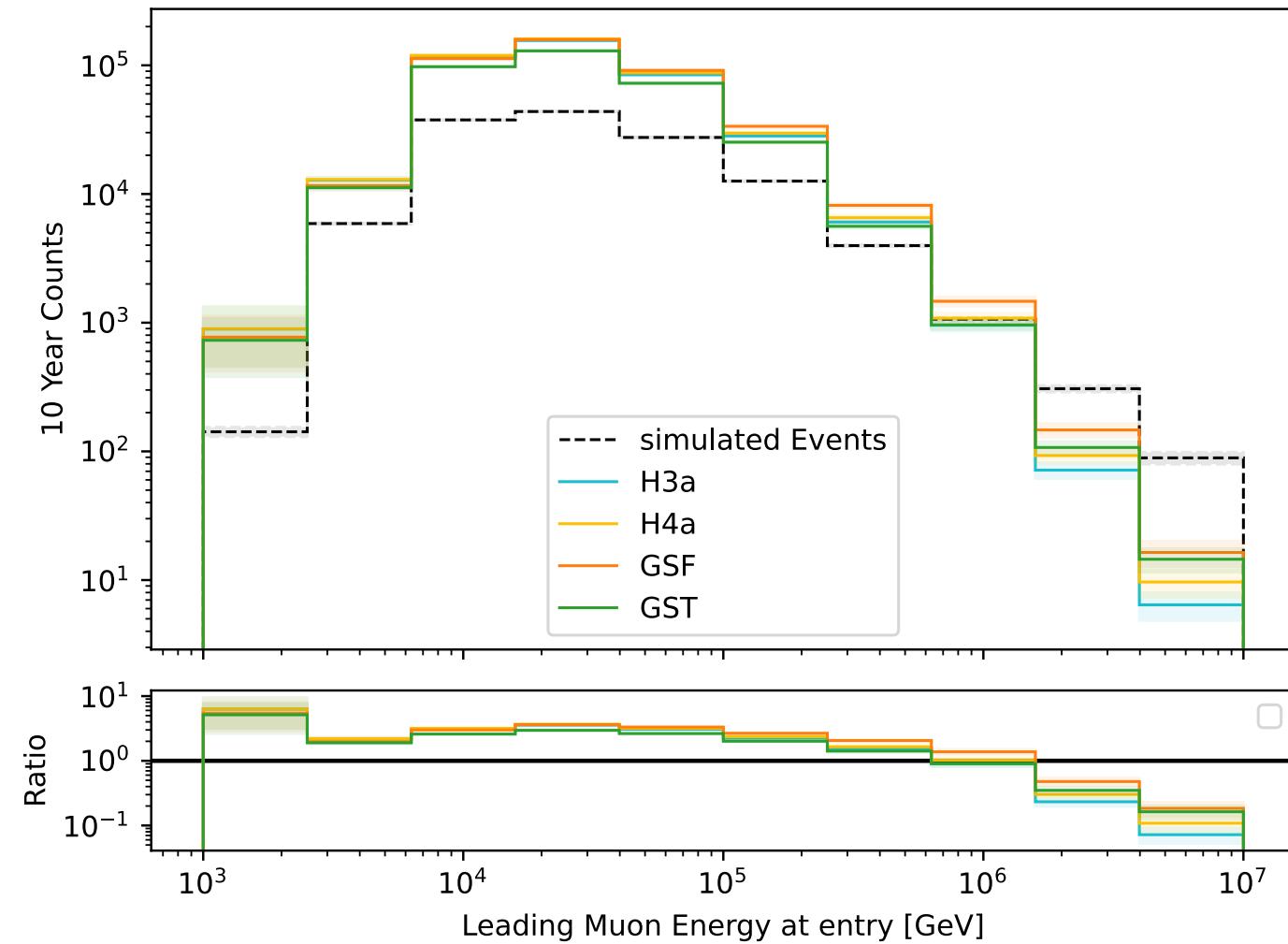


- Most nuisance parameters fitted within the boundaries
- CR interpolation = 0 for prompt > 1.25

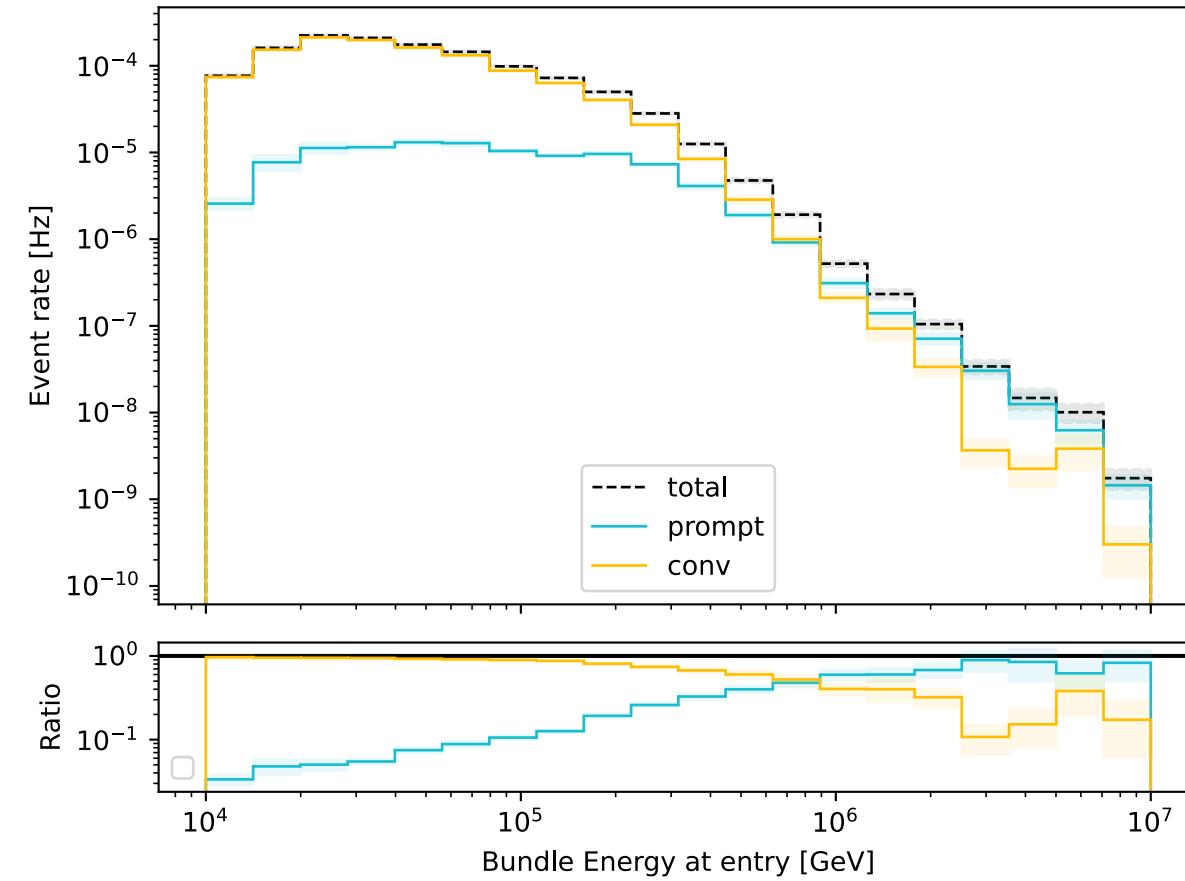
Fitted Systematics in Prompt Scan



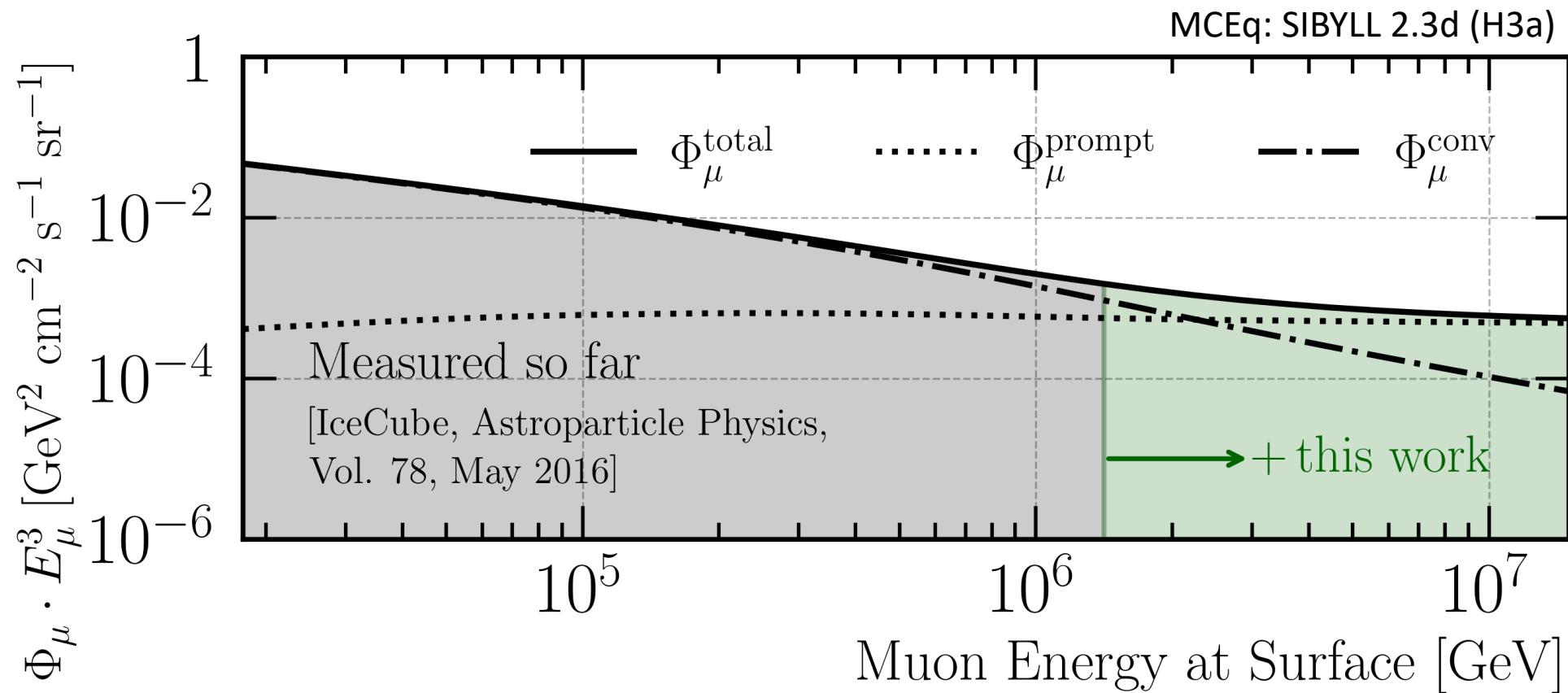
MC Statistics Final Level



Bundle Spectrum Final Level



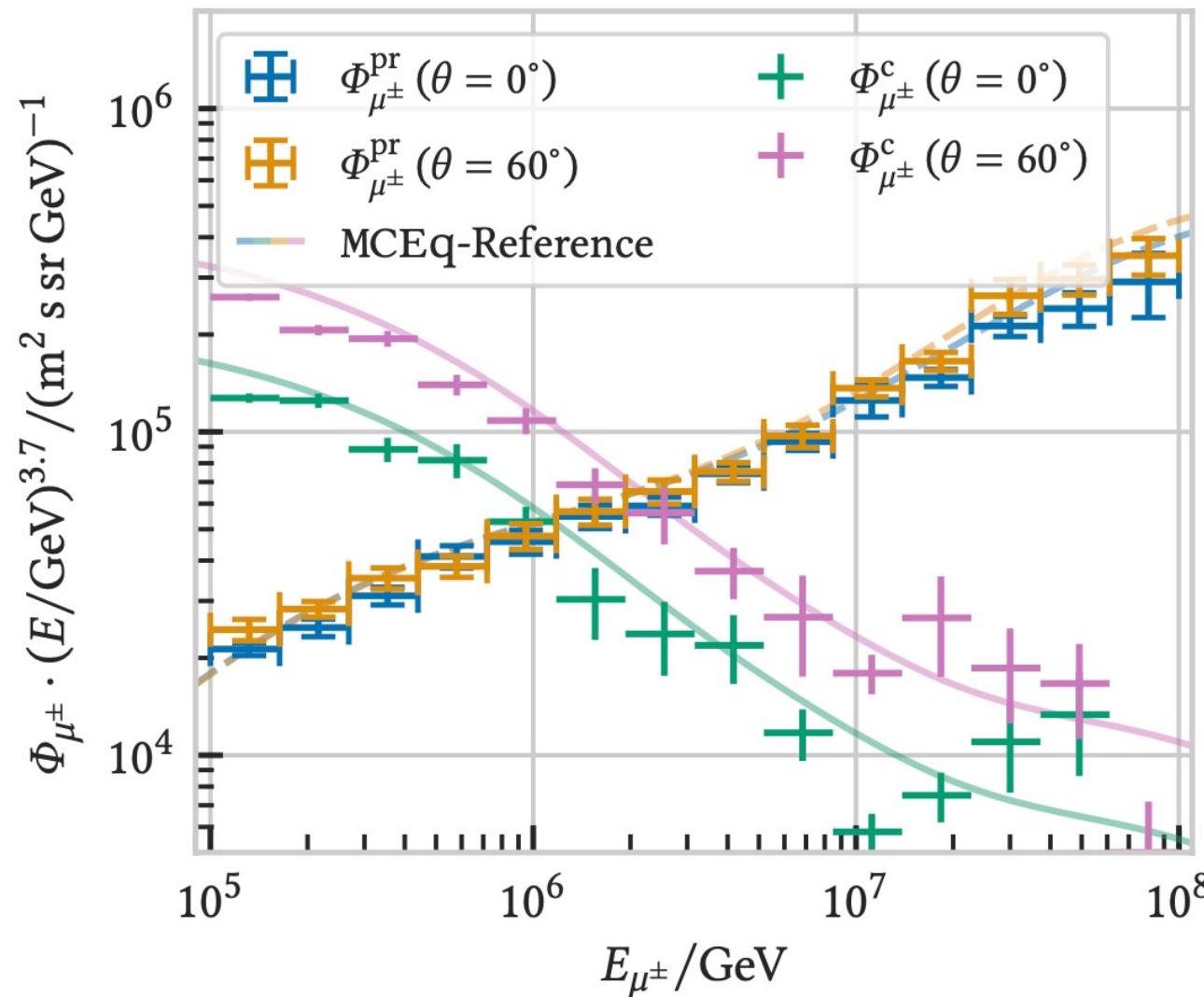
Goal: Measure Muon Flux at Surface



New CORSIKA simulation

with extended history option for information about the parent particles

CORSIKA 7 vs. MCEq

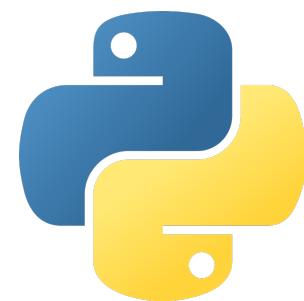


MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
<https://github.com/mceq-project/MCEq>

➤ Good agreement for inclusive flux

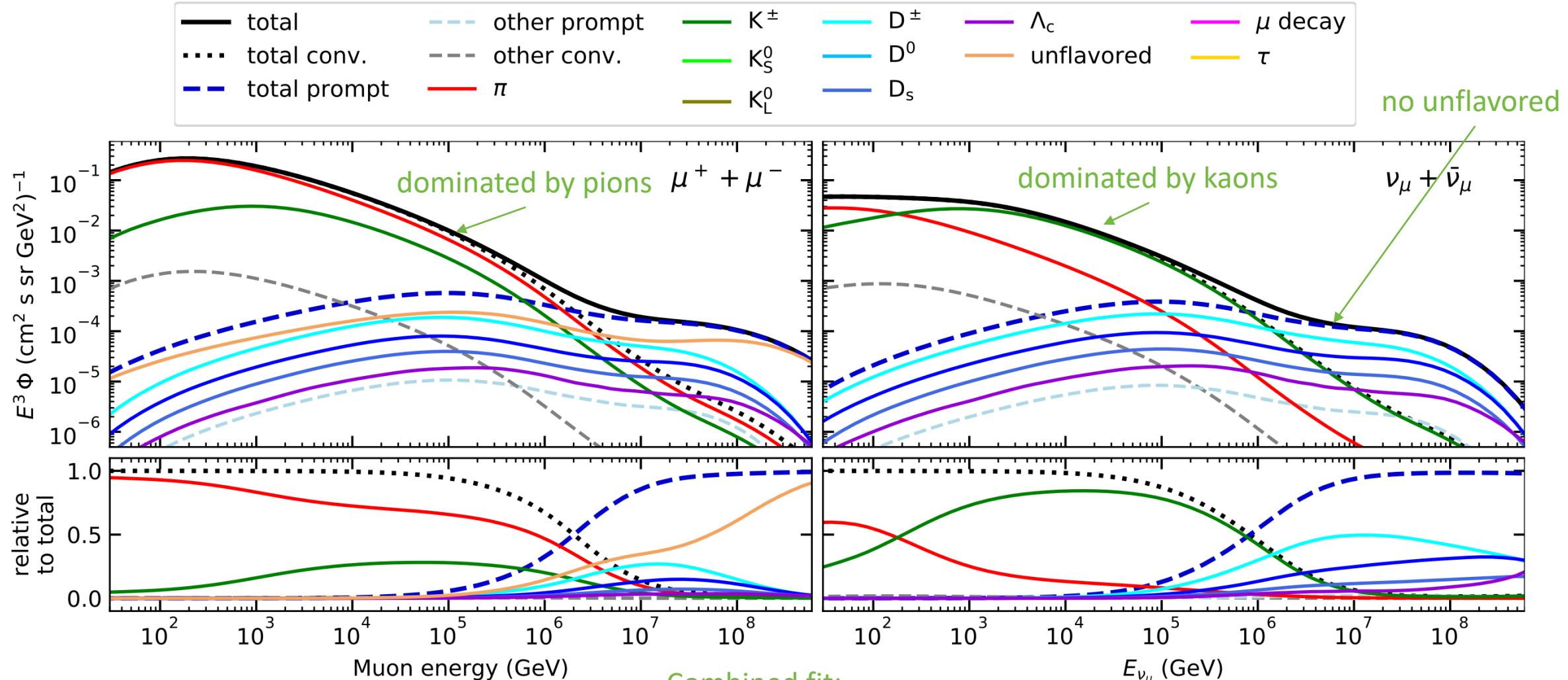
Python package developed – PANAMA

- Execute CORSIKA 7 (multi core)
- Read DAT files → pandas DataFrames
- Parse EHIST option
- Calculate primary weightings



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

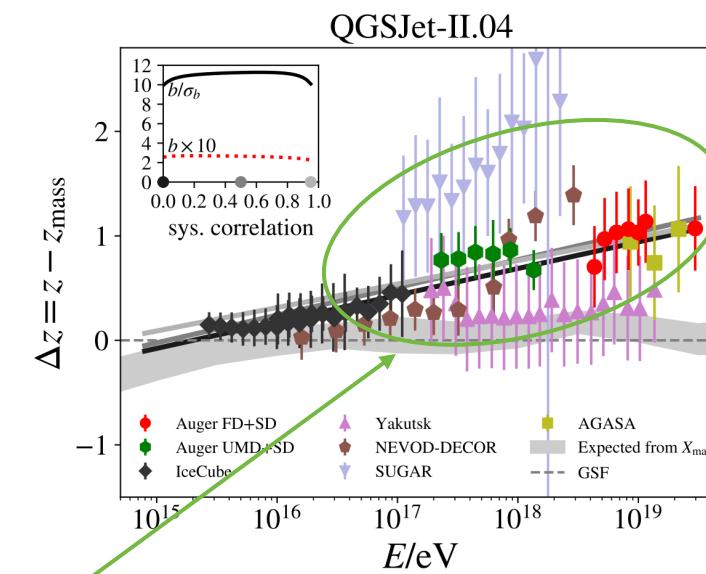
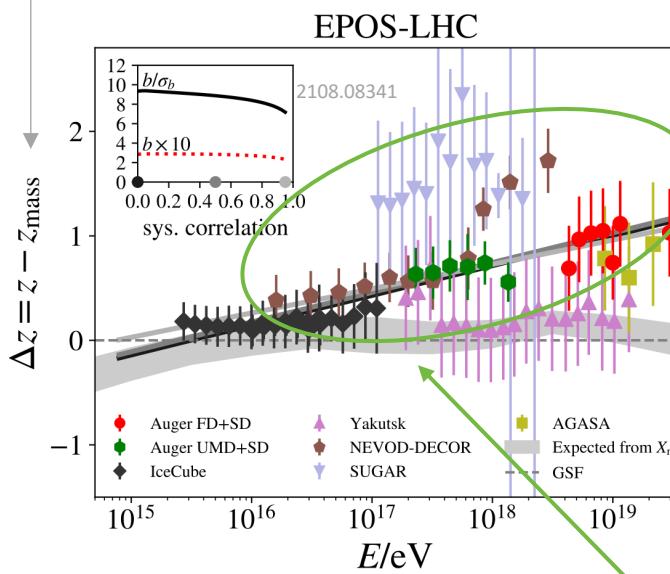
- handle on pion/kaon ratio
- handle on charmed mesons

Muon puzzle and model uncertainties

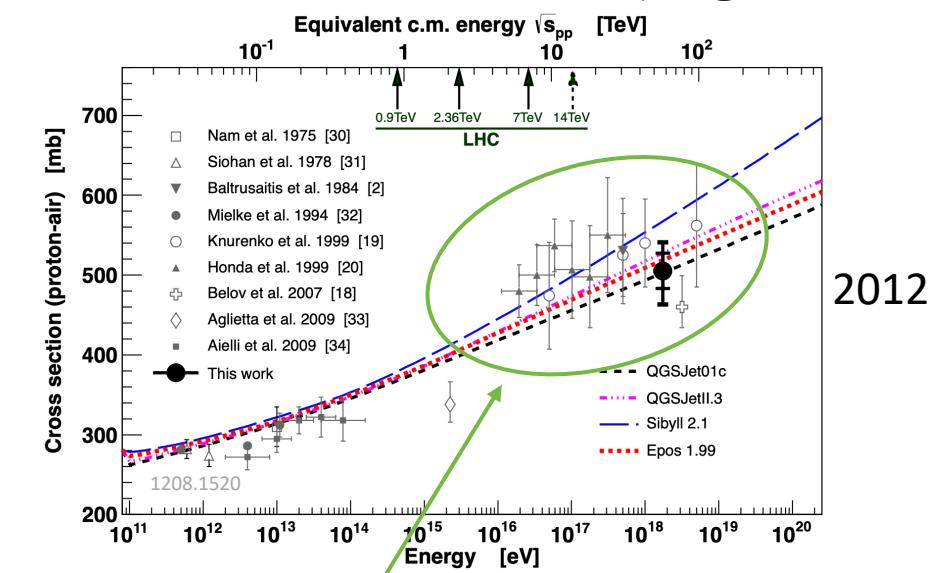
"muon number"

$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$

Expected z
("muon number")



➤ More muons measured than simulated for $E > 40 \text{ PeV} \sim \text{ cms } 8 \text{ TeV}$



➤ Uncertainties at $E > 10 \text{ PeV}$

