Monte Carlo generator tuning for cosmic-ray induced air shower simulations

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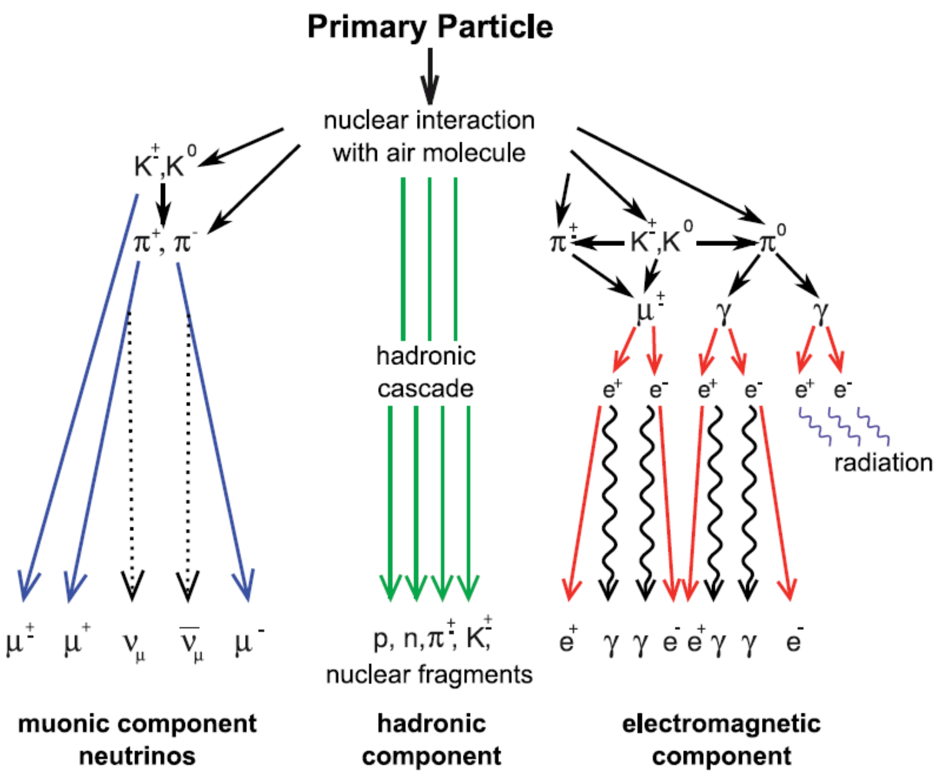
The need for MC generator tuning

Hadronization of process cannot be calculated from first principle
→ Need for hadronic models (MC generators)

Hadronization process has large impact on air shower features

Tuning essential to achieve high-quality simulations

→ Muon Puzzle



Tuning of Free Parameters

Adjust free parameters to achieve a good description of data

Manual or brute-force tuning difficult due to high computing cost

Systematic event generator tuning workflow: Professor tuning system

arXiv:0907.2973

Parameter based generator tuning

Optimize free parameters of MC generator using experimental data and Bayesian Methods

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A Bayesian tune of the Herwig Monte Carlo event generator

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Parameter based generator tuning

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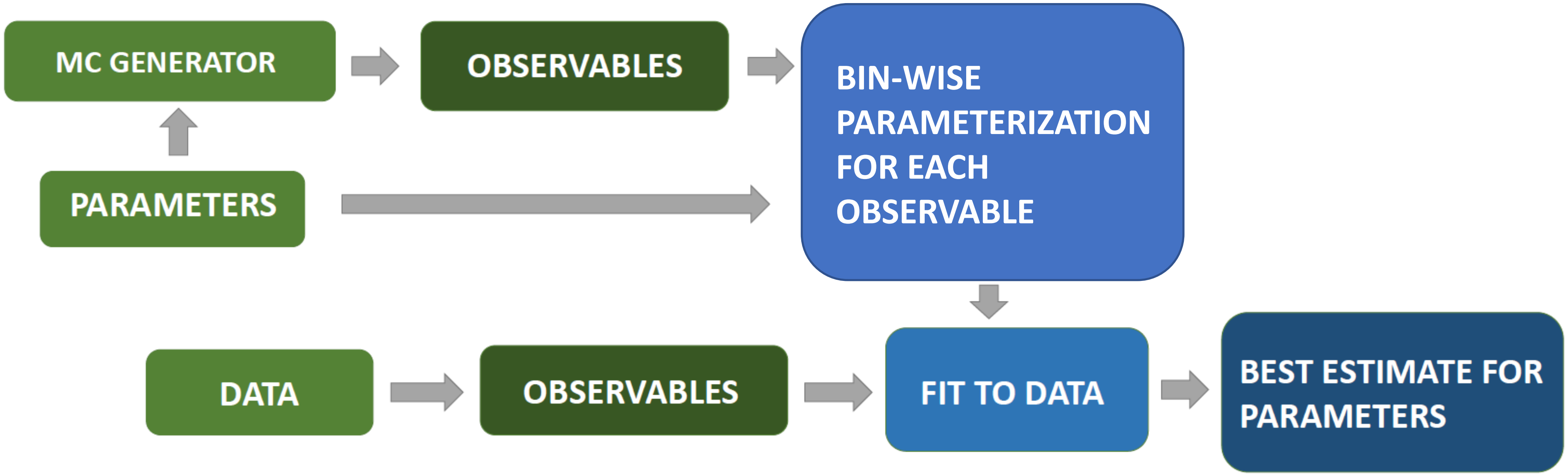
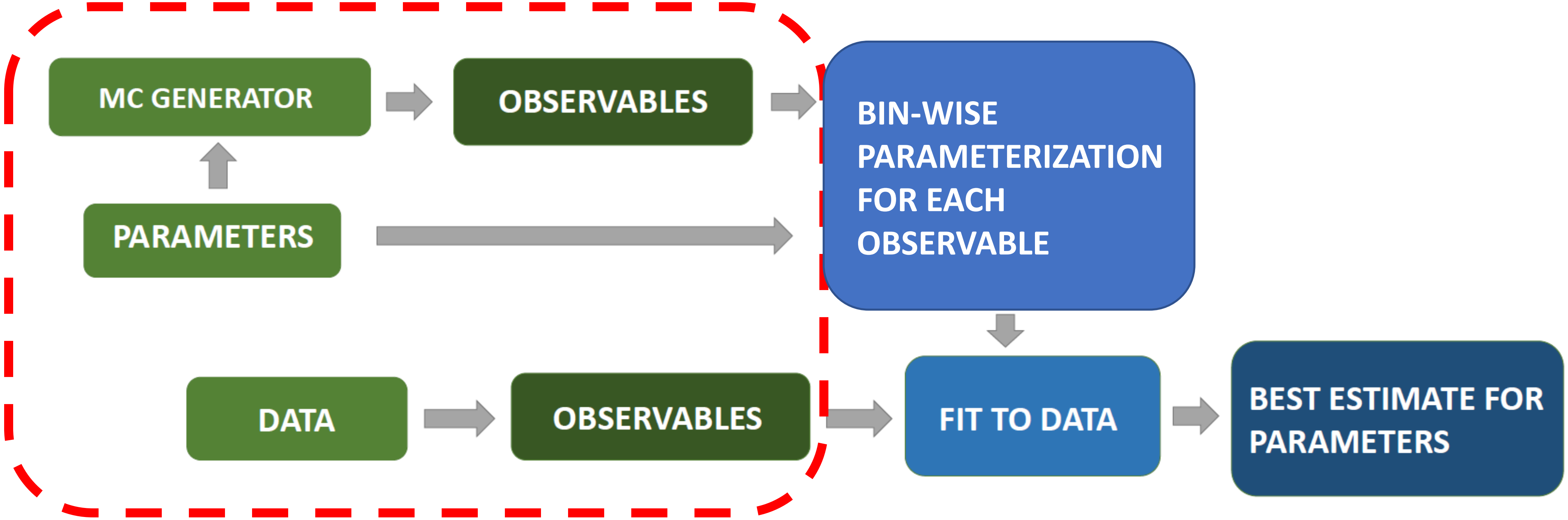


Parameter based generator tuning

Generate MC samples for different sets of parameter configurations

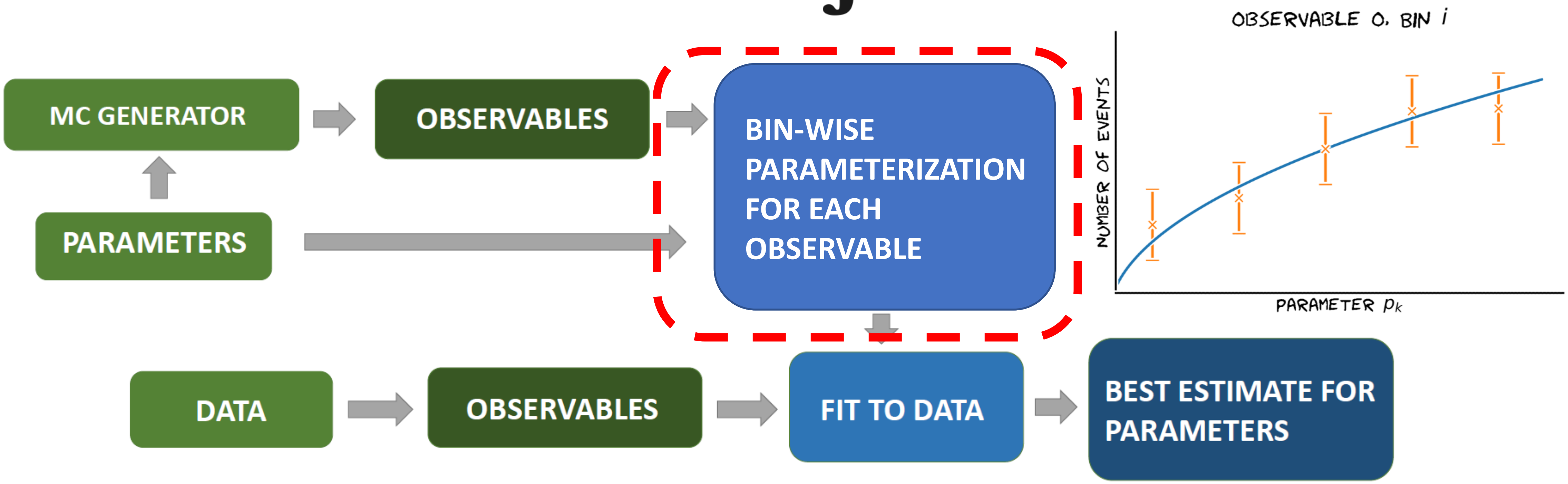
Reconstruct observables



Parameter based generator tuning

Create bin-wise parameterization of the observables as a function of the free parameters

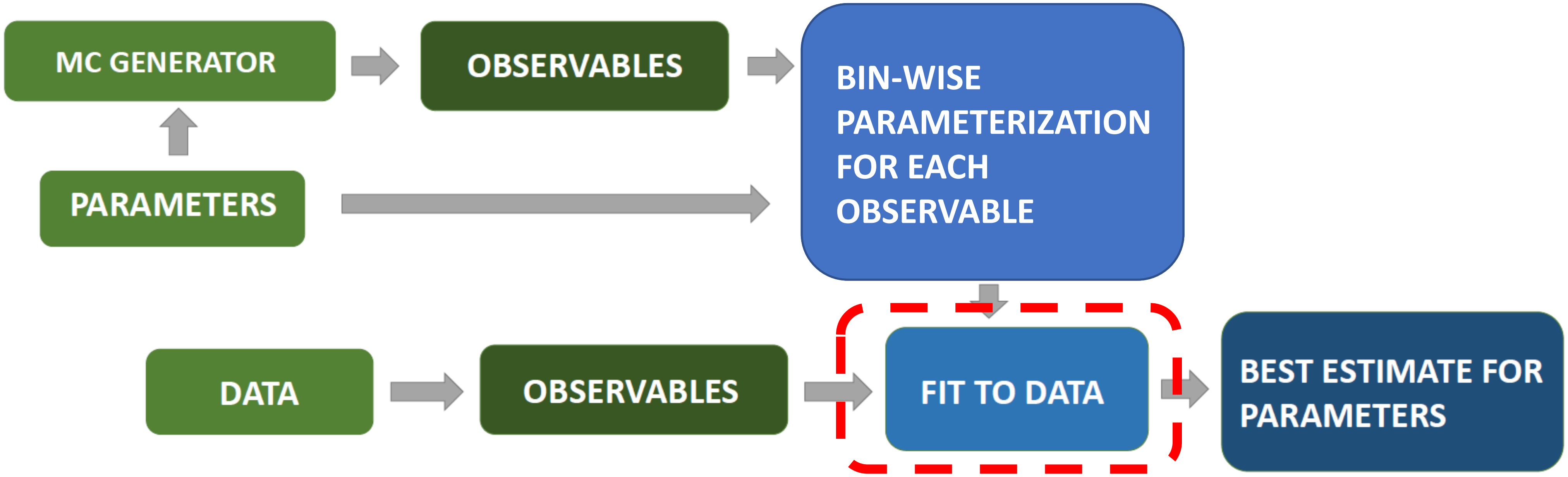
Written in julia



Parameter based generator tuning

Using the EFTfitter.jl tool a likelihood model is built from the parameterization and experimental data

N. Castro et al., *EFTfitter-A tool for interpreting measurements in the context of effective field theories,* Eur. Phys. J. C 76 (2016) 8, 432



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EFTfitter.jl:

Parameters

Data

$$\ln L(\vec{D}|\vec{\lambda}) = -\frac{1}{2}[\vec{D} - \vec{f}(\vec{\lambda})]^T \cdot M^{-1} \cdot [\vec{D} - \vec{f}(\vec{\lambda})]$$

Likelihood

Parameterization

Covariance Matrix

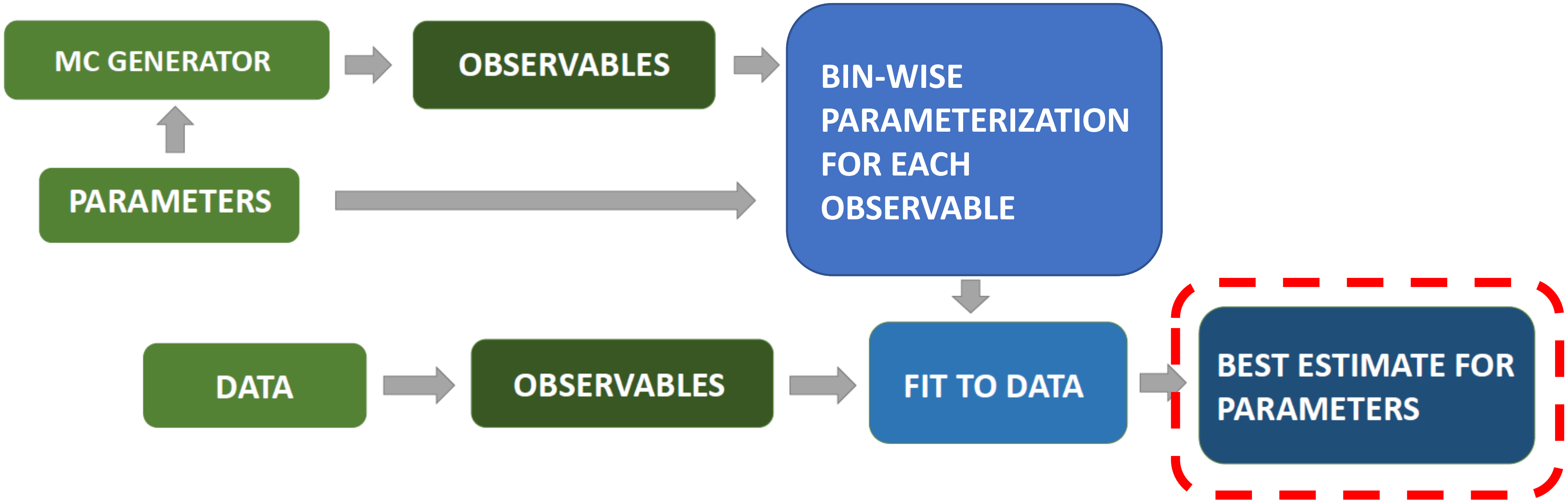
FOR

Parameter based generator tuning

Using the BAT.jl framework the posterior space of the free parameters is sampled to achieve a tuned parameter setting

O. Schulz et al., *BAT.jl:A Julia-Based Tool for Bayesian Inference,* SNCS (2021)

Bayesian Analysis Toolkit

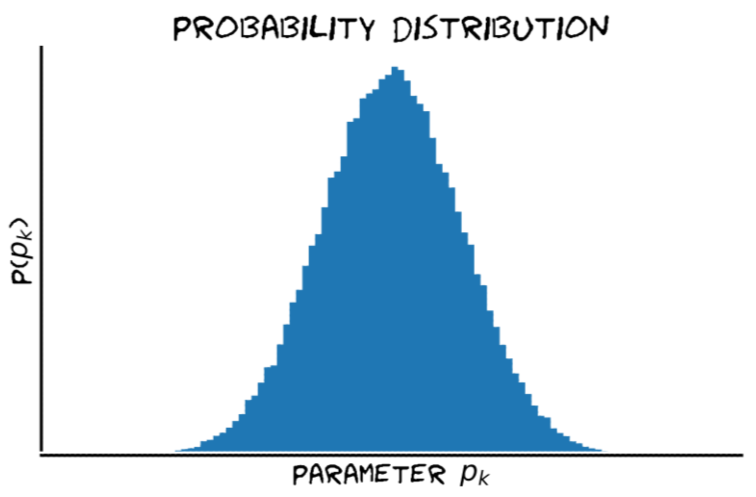


Sampling Posterior Space

Posterior *Likelihood* *Prior*

Bayes' Theorem : $$p(\vec{\lambda}|\vec{D}) \propto L(\vec{D}|\vec{\lambda}) \cdot p(\vec{\lambda})$$

Markov Chain Monte Carlo
→ Metropolis-Hastings Algorithm (as default)



Air Shower Simulation and MC Generator

Choice of MC generator for tuning
→ PYTHIA: Collider background and convenient access to tuning

C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3.* (2022). arXiv:2203.11601

Use of air shower simulations

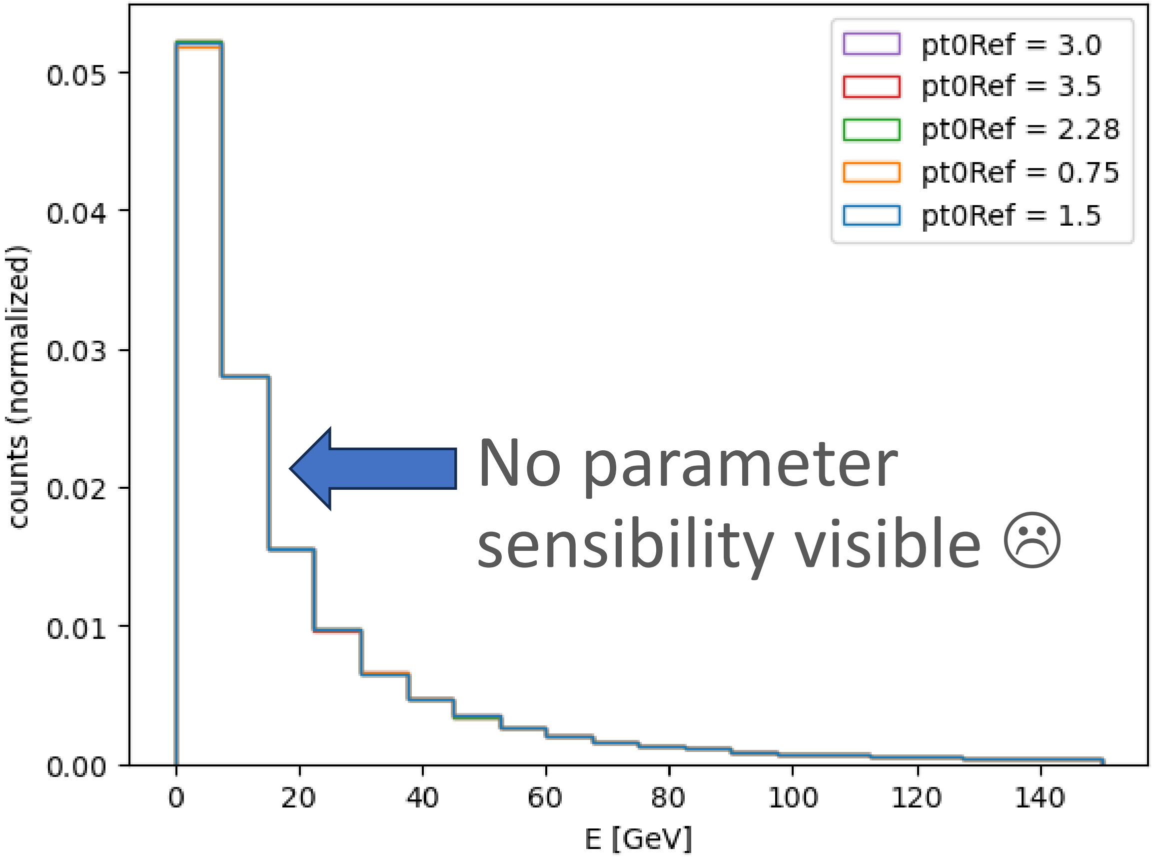
→CORSIKA8

→ Currently in development

→ PYTHIA as event generator

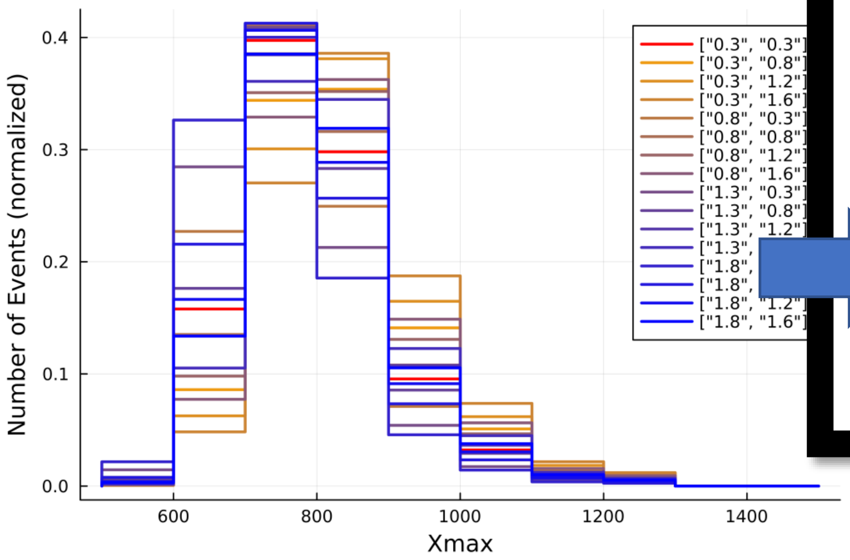
Current Problem

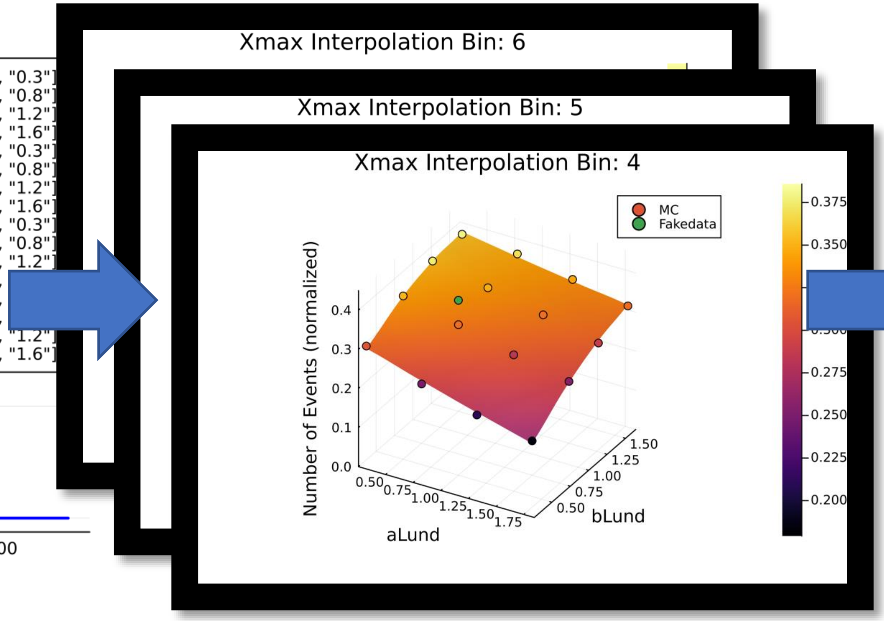
At the moment… CORSIKA8 is still in development

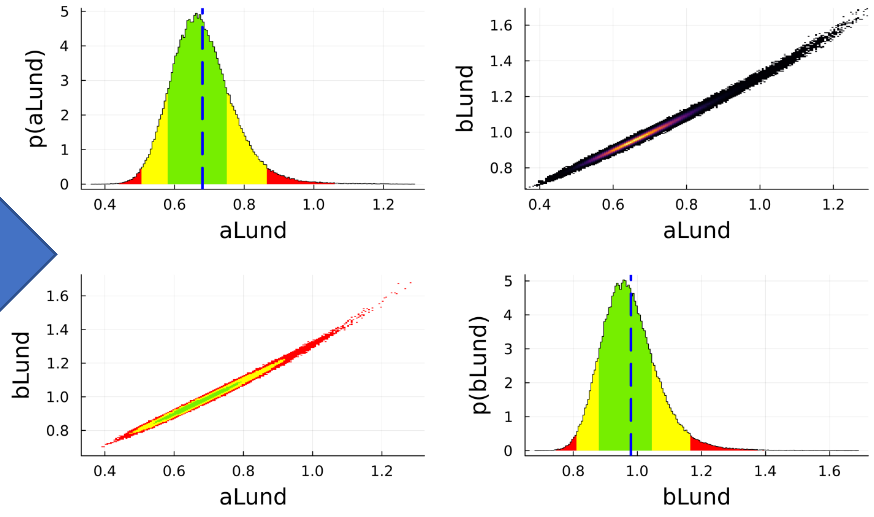


Toy Model For Pythia Tuning

Test Pythia tuning in toy model using only the Pythia 8 event generator

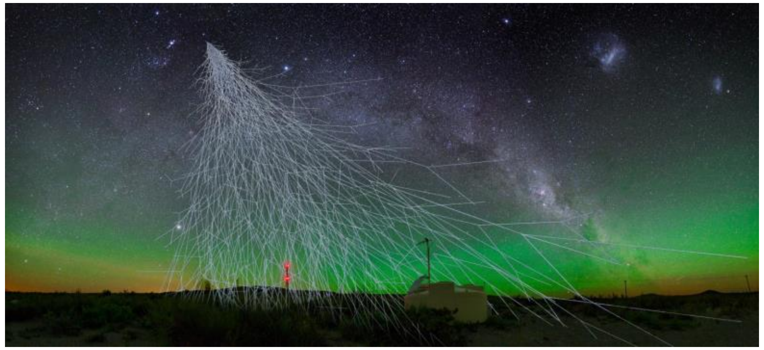






Combining F3 & F4 Efforts

Collider Physics **Astro Particle Physics**



Project combines expertise from Collider, IceCube and Pierre Auger Observatory physicists by providing data and methods

Conclusion

Monte Carlo tuning using a Bayesian approach is possible

Tested on collider data for particle physics and in toy studies

Outlook

Use of air shower data and CORSIKA8 for MC generator tuning

Combine collider and air shower data for simultaneous tune

Backup

Verify Tuning Algorithm

Simple toy study to test and demonstrate potential usefulness of tuning algorithm

Toy study based on PYTHIA example *main183*
→ Example includes simple study on air shower evolution in the atmosphere

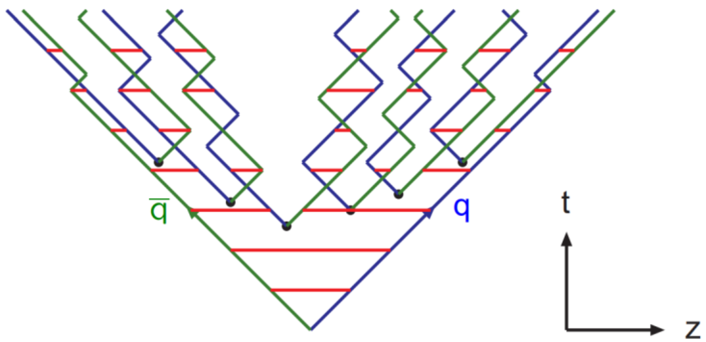
T. Sjöstrand, M. Utheim, Hadron interactions for arbitrary energies and species, with applications to cosmic rays. Eur. Phys. J. C 82, 21 (2022)

→ Provides quick and convenient generation of air shower observables for testing of tuning algorithm

Toy Study

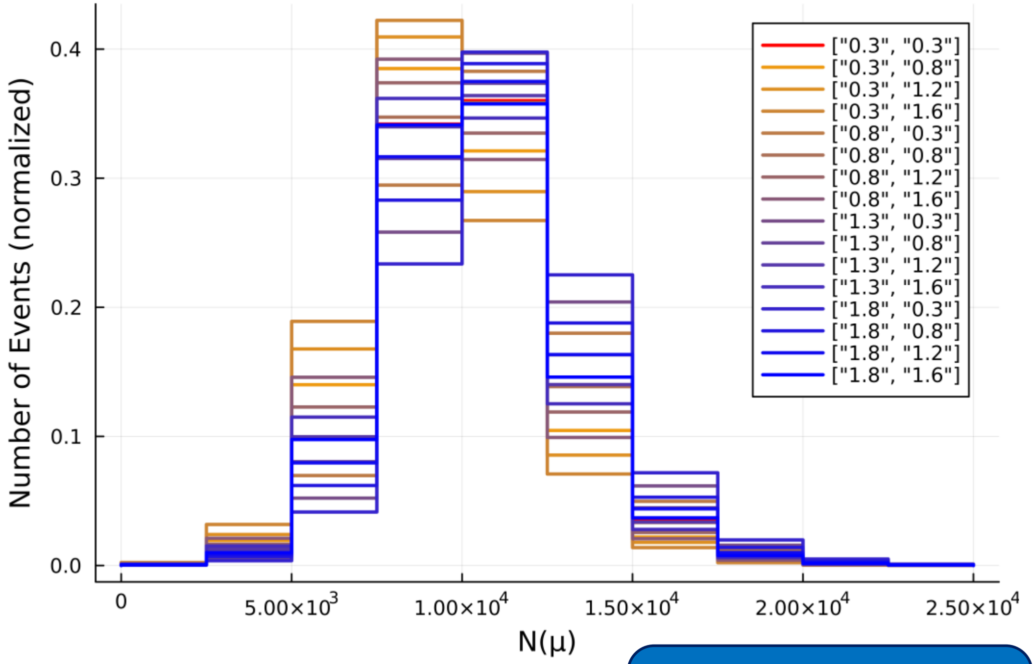
Study and test tuning method
→ Generate muon number and shower maximum observable
for different aLund and bLund parameter settings

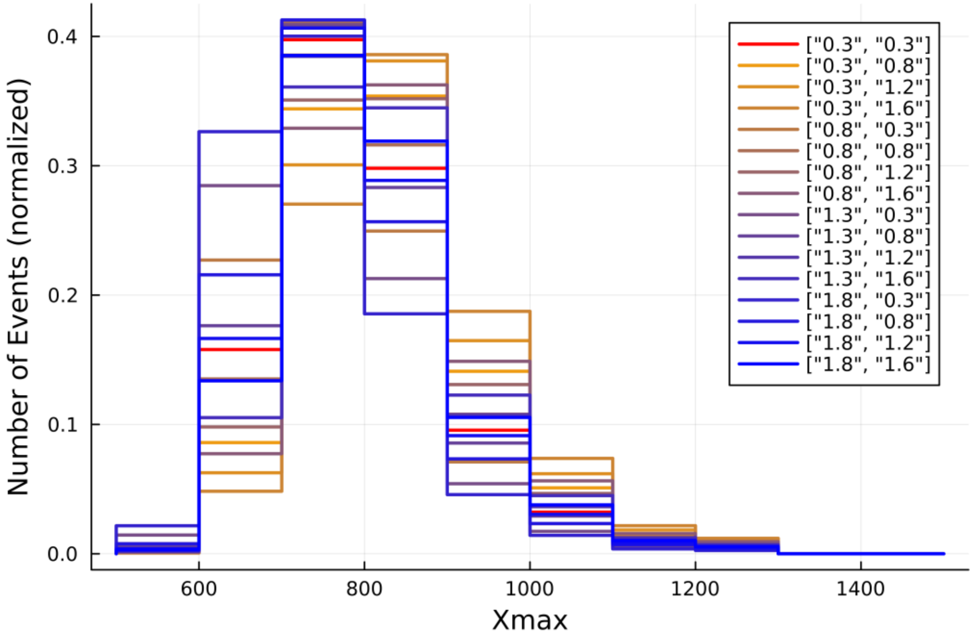
$$f(z) \propto z^{-1}(1-z)^a exp\left(\frac{-bm_\perp^2}{z}\right)$$

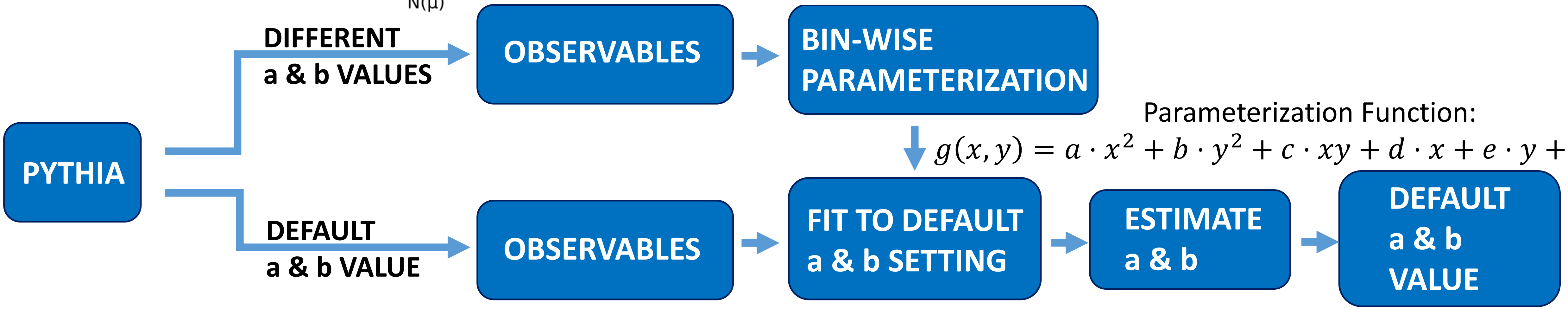


→ Use PYTHIAs default value for a- and bLund as *fake data* to tune against

Generate air shower simulations



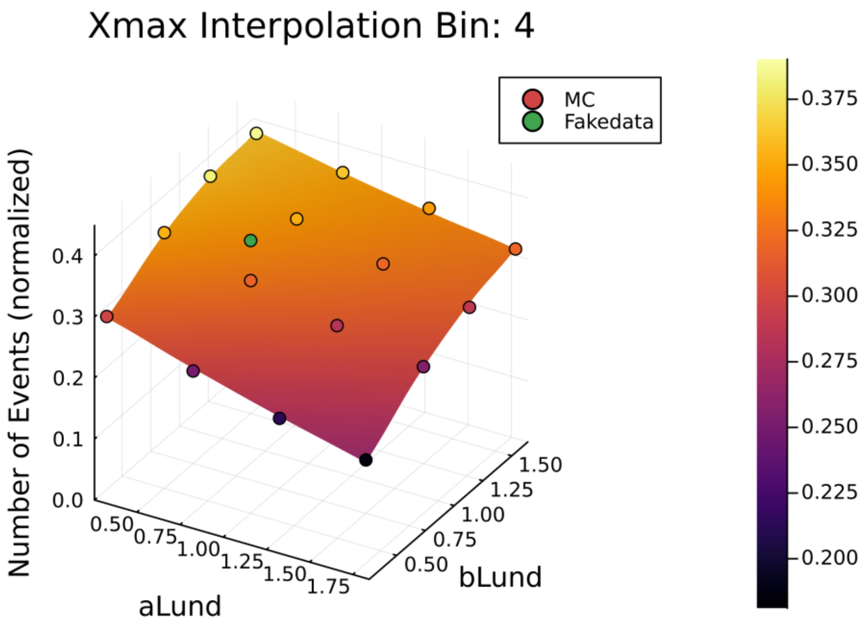


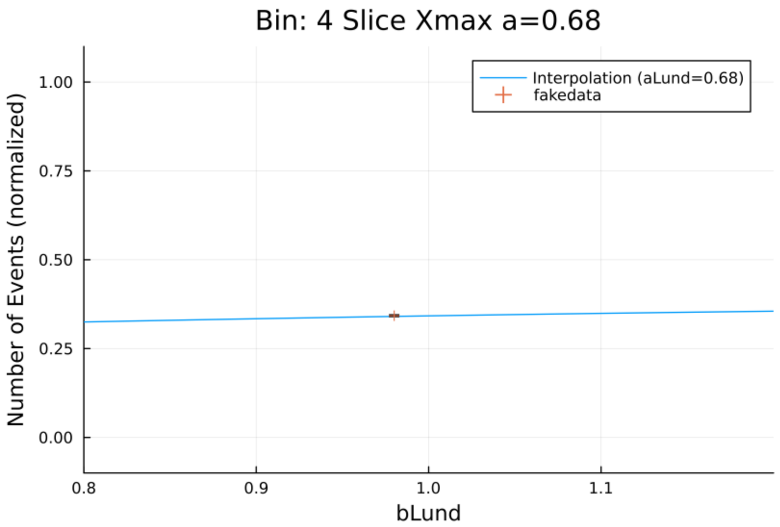


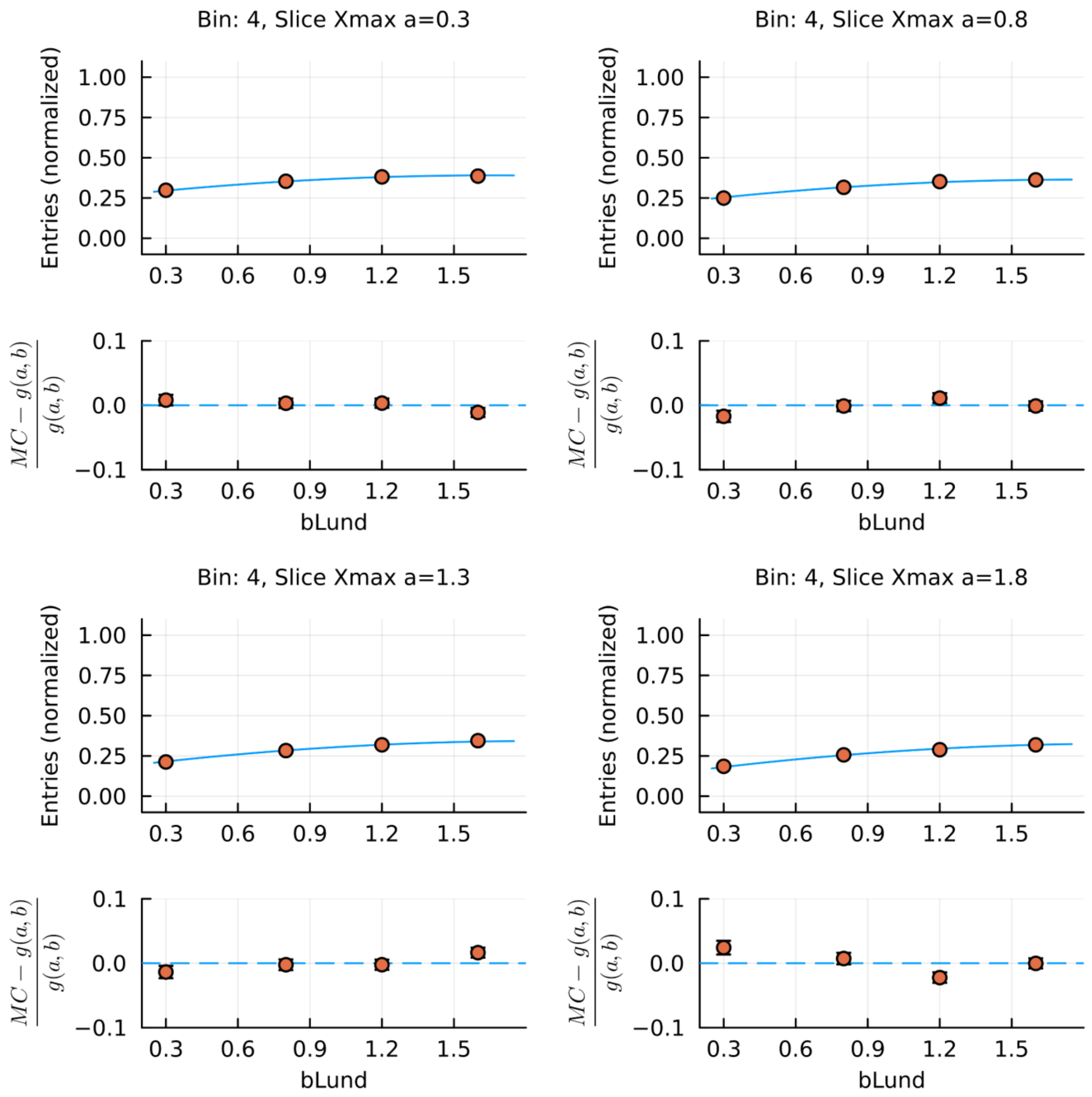
Parameterization Function:

$$g(x,y) = a \cdot x^2 + b \cdot y^2 + c \cdot xy + d \cdot x + e \cdot y + f$$

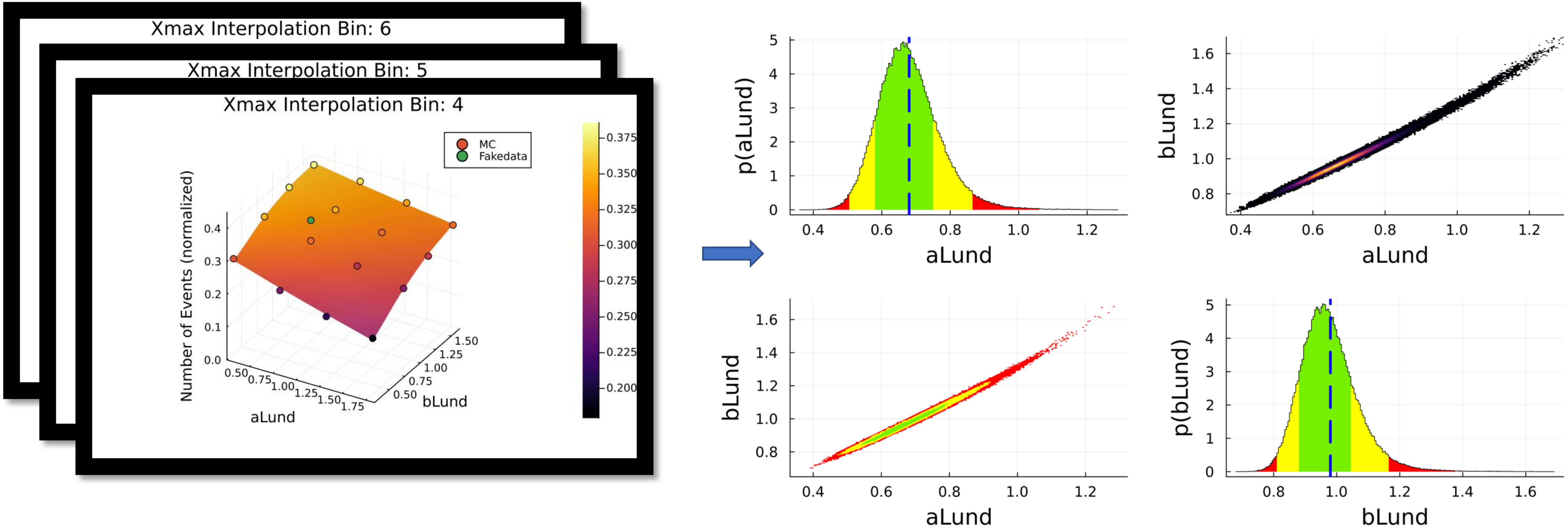
Parameterization







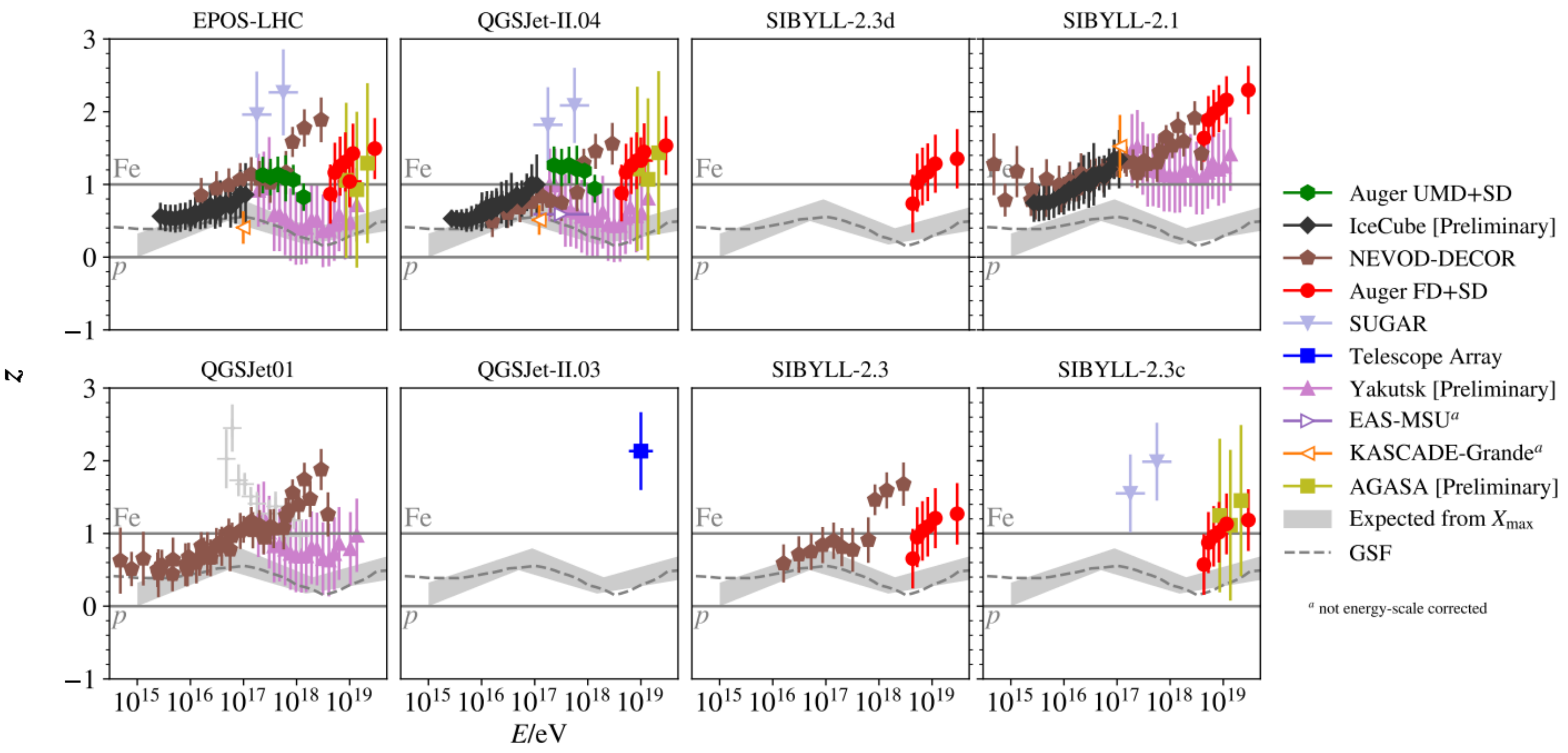
Sampling the posterior space



Muon Puzzle

High energies: Muon excess in observations compared to simulations

$$z = \frac{\ln\left(N_{\mu}^{\mathrm{det}}\right) - \ln\left(N_{\mu,p-\mathrm{sim}}^{\mathrm{det}}\right)}{\ln\left(N_{\mu,\mathrm{Fe-sim}}^{\mathrm{det}}\right) - \ln\left(N_{\mu,p-\mathrm{sim}}^{\mathrm{det}}\right)}$$



J. Albrecht et al., *The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider,* Astrophys.Space Sci. 367 (2022) 3, 27