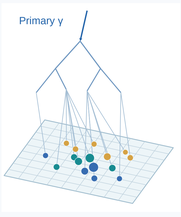
Energy Reconstruction with ParticleNet for LHAASO-WCDA

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1. Motivation



WCDA detection plane

Beyond $N_{\rm hit}$: One hit count misses spatial, charge and timing patterns.

Hit-level AI: ParticleNet learns from positions, charges and times.

Goal: Reduce energy mixing and strengthen spectral constraints.

2. Model and performance on simulation data

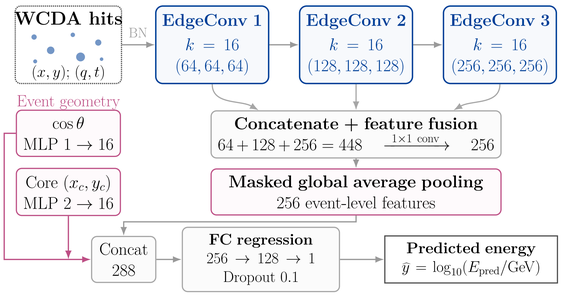


Figure 1. ParticleNet with zenith and core embeddings.

Training: charge-weighted sampling of up to 500 hits; event normalization; Huber loss ($\delta = 0.2$).

MC selection:

- $E_{\rm true} > 100$ GeV
- $\theta < 50°$
- pincness < 1.1
- fitstat $= 0$
- direction error $< 3°$
- $d_{\rm edge} > 0$

3. MC performance

29.3% **Gaussian core width near 6 TeV**

$5 \le E_{\rm true}/\text{TeV} < 7$; fit $-0.5 \le r \le 0.5$.

$r = E_{\rm pred}/E_{\rm true} - 1$. WCDA-1 $N_{\rm hit}$ reference: $\sim 33\%$ (contextual comparison).

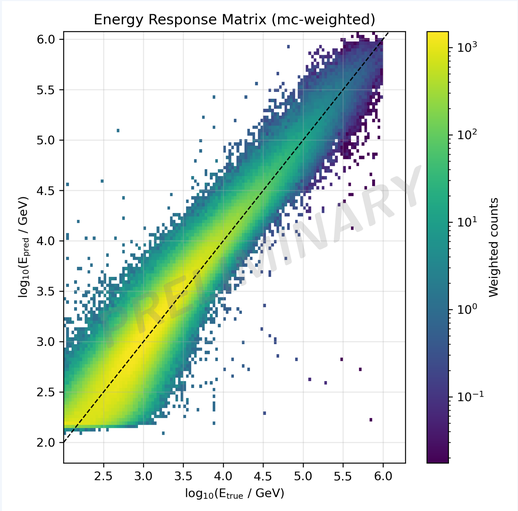


Figure 2. Weighted MC counts; dashed: $E_{\rm pred} = E_{\rm true}$.

0.020 dex	0.200 dex	0.201 dex
bias	scatter	RMSE

857,926 weighted MC events; log residual $\Delta = \log_{10}(E_{\rm pred}/E_{\rm true})$.

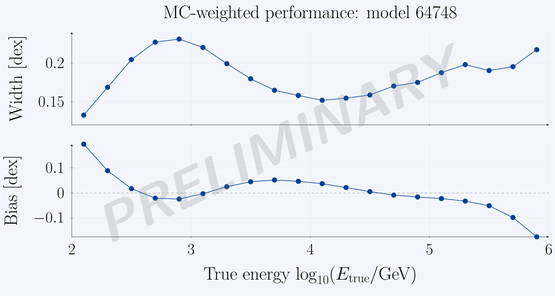


Figure 3. Width $\mathrm{std}_w(\log_{10} E_{\rm pred})$ (top) and bias (bottom) in true-energy bins.

4. Spectral analysis

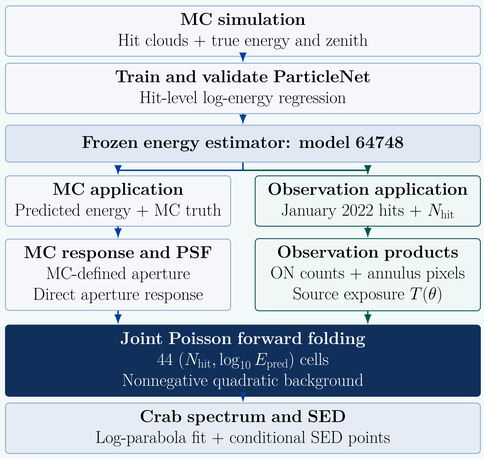


Figure 4. Workflow from MC training to the 44-cell spectral fit.

Forward folding predicts source counts per cell:

$$S_c(\boldsymbol{\eta}) = \int dE\, d\theta\, \phi(E;\boldsymbol{\eta})\, A_c^{\rm ap}(E,\theta)\, T(\theta).$$

$A_c^{\rm ap}$: MC aperture response; $T(\theta)$: source exposure.

Log-parabola spectrum: ϕ_0 normalization, α index, β curvature.

$$\phi(E) = \phi_0 \exp\left[-\alpha \ln(E/E_0) - \beta \ln^2(E/E_0)\right], \quad E_0 = 3 \text{ TeV}.$$

MC/data cuts: pincness < 1.1, fitstat $= 0$, $\theta < 50°$ and $d_{\rm edge} > 20$ m.

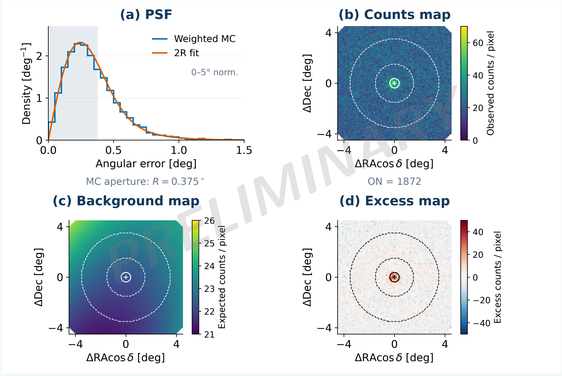


Figure 5. Example cell: $100 \le N_{\rm hit} < 200$, $1 \le E_{\rm pred}/\text{TeV} < 1.78$. Annulus 1.5°–3.5°; excess is diagnostic only; color scales differ.

5. Crab spectrum reconstruction

January 2022: **44 independent cells** across 7 $N_{\rm hit}$ bands ($30 \le N_{\rm hit} < 2000$) and 11 predicted-energy bins.

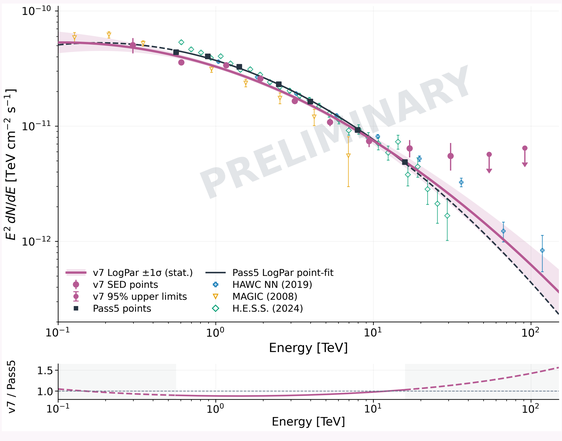


Figure 6. Crab SED and v7/Pass5 ratio (same Pass5 fit). Band: conditional 1σ; arrows: $2\Delta\text{NLL} = 2.71$ endpoints.

Best-fit log-parabola parameters ($E_0 = 3$ TeV):

$$\phi_0 = 2.044 \times 10^{-12}\ \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}, \quad \alpha = 2.633, \quad \beta = 0.0942 \pm 0.0236.$$

Conditional errors (fixed cells, apertures, response); systematics under study.

6. Summary and next steps

Result: We reconstructed the Crab spectrum through forward folding using ParticleNet energy estimates from WCDA hits.

Next: Validate the method using the Mrk 421 spectral cutoff and integrate the workflow into the WCDA analysis pipeline.

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