Friedrich-Alexander-Universität
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A joint-likelihood analysis of CTAO and KM3NeT data in Gammapy to constrain hadronic gamma-ray contributions

Tim Unbehaun, Lars Mohrmann, Stefan Funk
08.09.2025

A **Python** package for **gamma-ray** astronomy

Project idea

“Are there Galactic gamma-ray sources for which the combined analysis of data from KM3NeT and CTAO would help us to discriminate between hadronic and leptonic emission scenarios?“

Outline:

- Focus is on individual sources (Galactic ones)
- Simulation study that might serve as blueprint for future analyses
- Demonstrates how Gammapy can be used to analyze neutrino data

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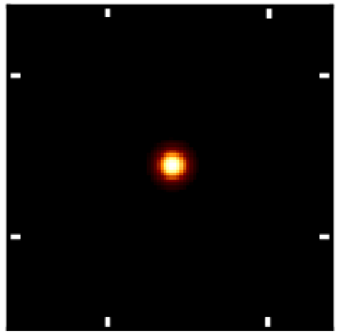
Regular Article - Experimental Physics

Prospects for combined analyses of hadronic emission from γ-ray sources in the Milky Way with CTA and KM3NeT

T. Unbehaun, L. Mohrmann, S. Funk (members of the CTA Consortium) and the KM3NeT Collaboration*,[a]

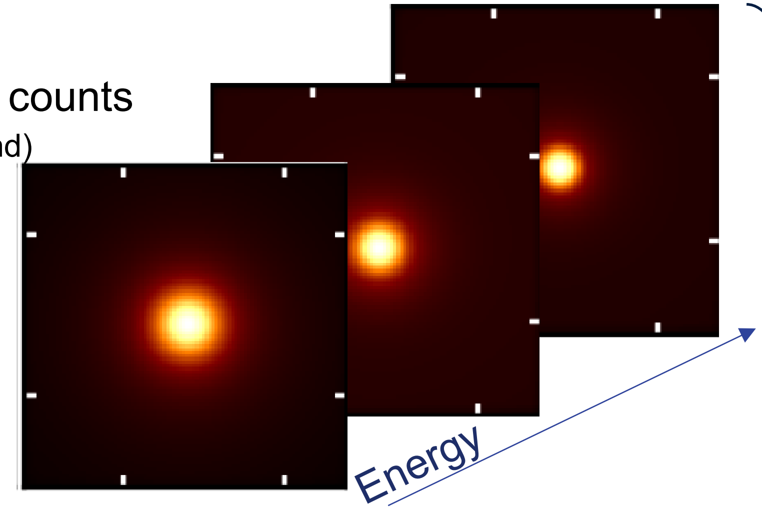
Binned likelihood analyses

True source model

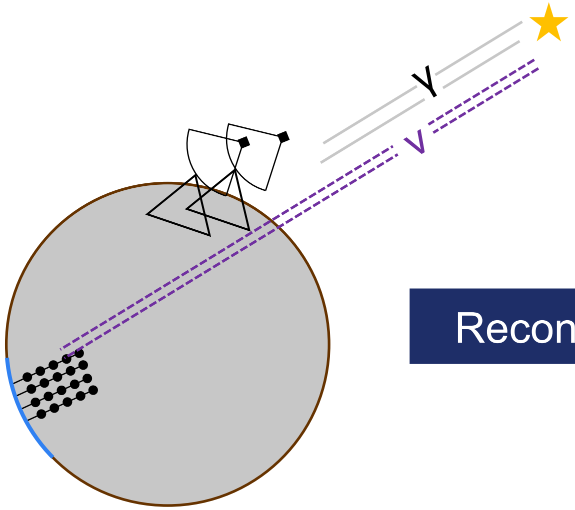


Forward-folding with IRFs

Predicted counts
(+ background)

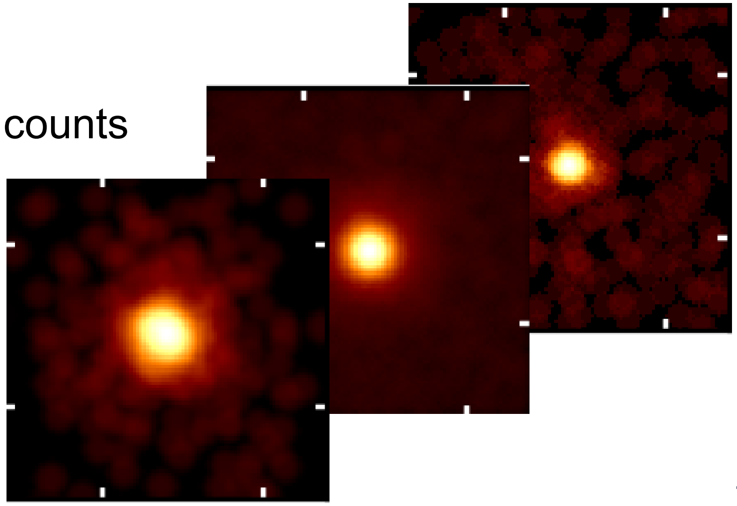


Statistical comparison



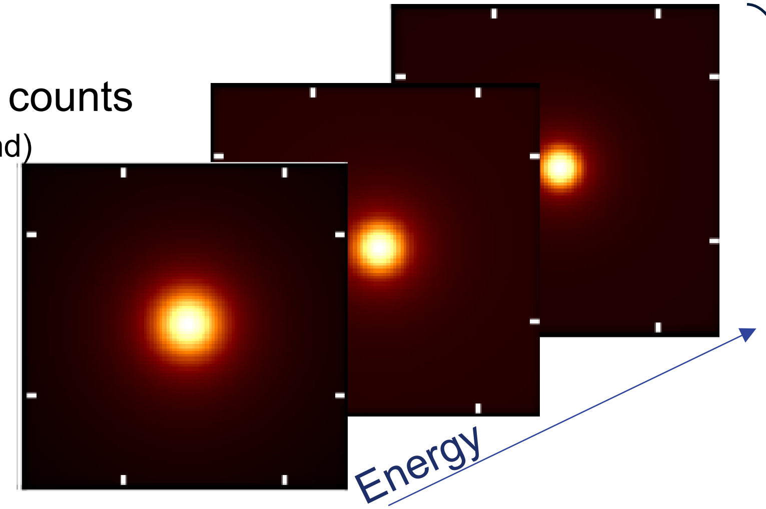
Reconstruction + Binning

Observed counts



Binned likelihood analyses

Predicted counts
(+ background)



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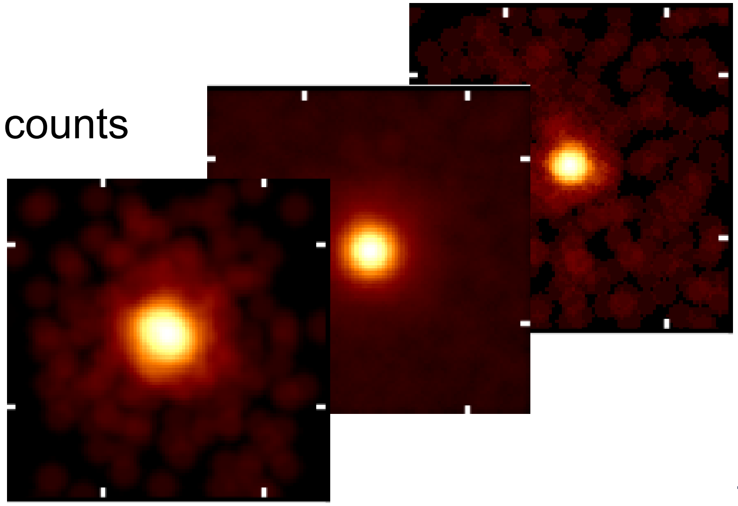


<u>Statistical comparison:</u>

- Poisson probability in pixel *i* to measure *n* counts given the model prediction $\nu(\xi)$ for parameters ξ

$$P\left(n_i \,\middle|\, \nu_i(\xi)\right) = \frac{\nu_i(\xi)^{n_i}}{n_i!} \times \exp(-\nu_i(\xi))$$

- Log-Likelihood:

$$-\ln \mathcal{L}(\xi) = -\sum_{i=1}^{N} \ln\left[\frac{\nu_i(\xi)^{n_i}}{n_i!} \times \exp(-\nu_i(\xi))\right]$$

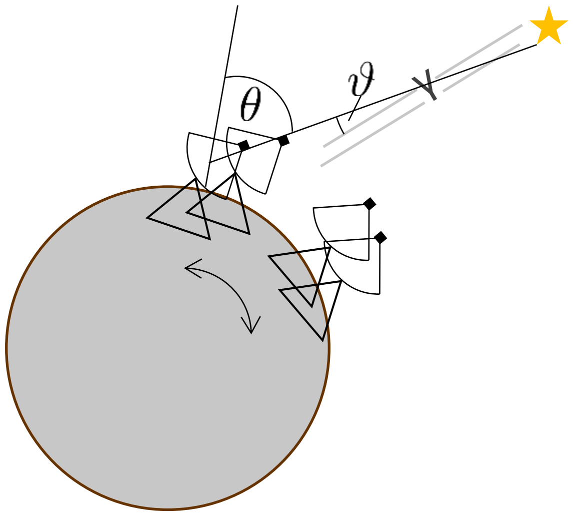
- Minimizing $\mathrm{TS} \equiv -2 \ln \mathcal{L}$ maximizes the Likelihood

Generation of IRFs

Pointed instruments (CTAO)

IRFs depend on:

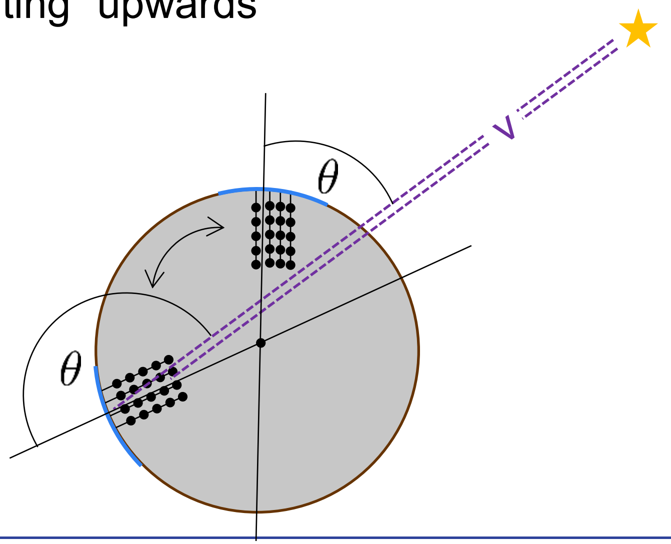
- True energy
- Zenith angle θ (averaged per observation)
- Offset angle ϑ (fixed per observation)
  (angle between source and pointing position)



Stationary instruments (KM3NeT)

IRFs depend on:

- True energy
- Zenith angle θ, changing with Earth's rotation
  (angle between source and detector orientation)
- Interpret θ as offset with the telescope
  "pointing" upwards



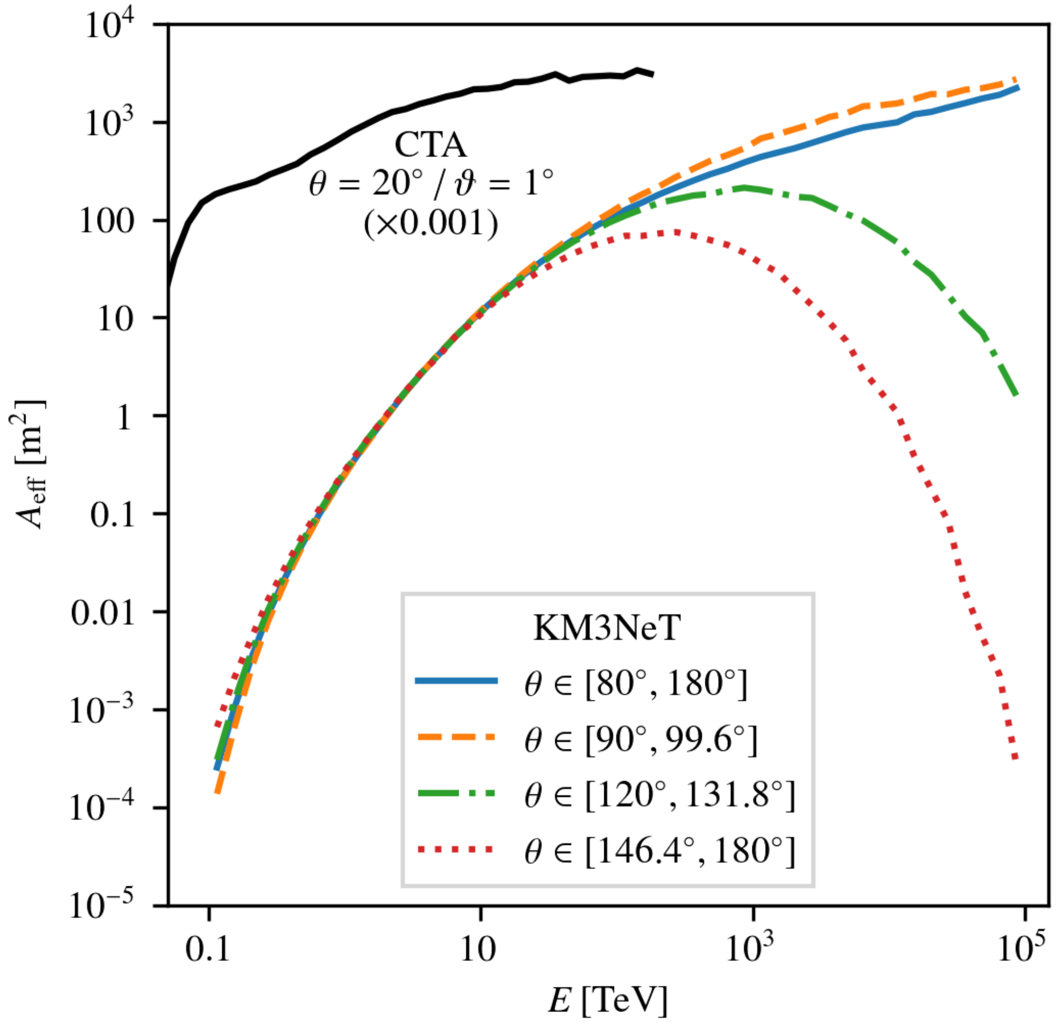
Generation of IRFs

IRFs are publicly available in the 'GADF'[1] format

- CTA: https://www.ctao.org/for-scientists/performance/
- KM3NeT: https://zenodo.org/records/8298464

1. Effective area

$$\Phi(E_{\text{true}}, \vec{r}_{\text{true}}) \times A_{\text{eff}} \times T = N_{\text{pred}}(E_{\text{true}}, \vec{r}_{\text{true}})$$



[1] https://gamma-astro-data-formats.readthedocs.io/en/v0.3/

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1. Effective area

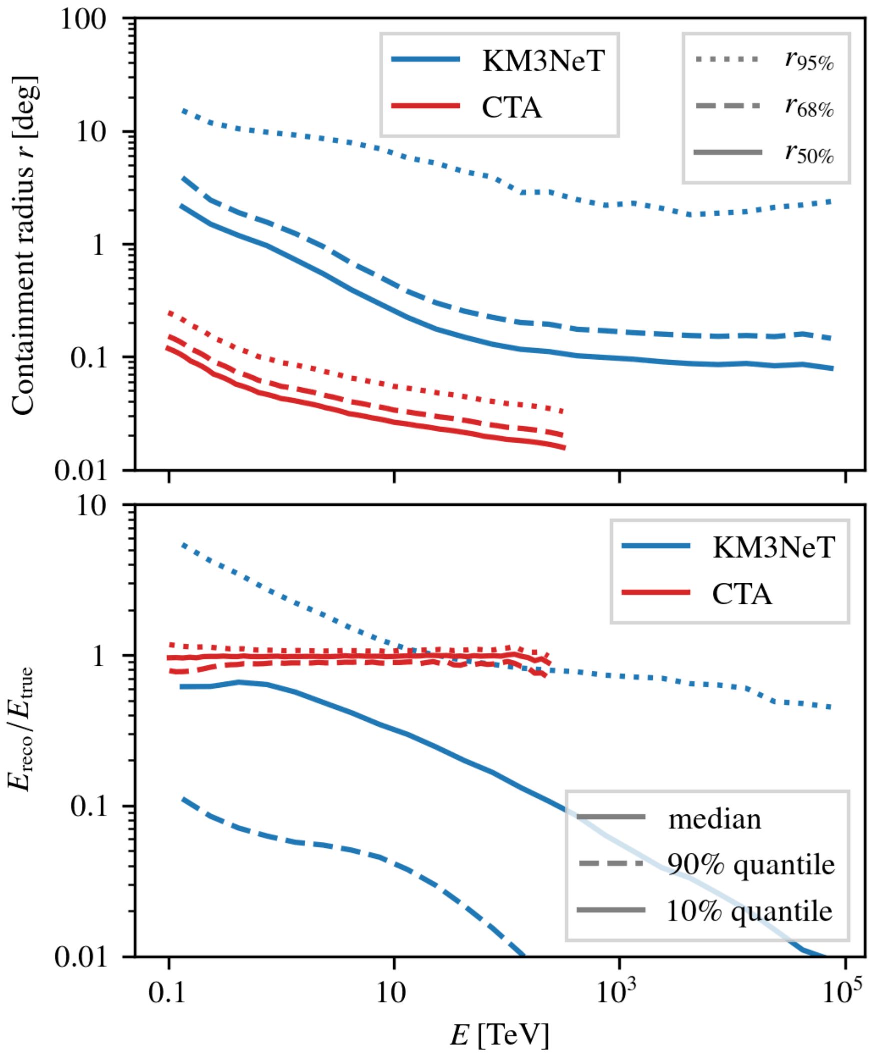
$$\Phi(E_{\mathrm{true}}, \vec{r}_{\mathrm{true}}) \times A_{\mathrm{eff}} \times T = N_{\mathrm{pred}}(E_{\mathrm{true}}, \vec{r}_{\mathrm{true}})$$

2. Point spread function (PSF)

$$N_{\mathrm{pred}}(E_{\mathrm{true}}, \vec{r}_{\mathrm{true}}) * \mathrm{PSF} = N_{\mathrm{pred}}(E_{\mathrm{true}}, \vec{r}_{\mathrm{reco}})$$

3. Energy dispersion (Edisp)

$$N_{\mathrm{pred}}(E_{\mathrm{true}}, \vec{r}_{\mathrm{reco}}) * \mathrm{Edisp} = N_{\mathrm{pred}}(E_{\mathrm{reco}}, \vec{r}_{\mathrm{reco}})$$



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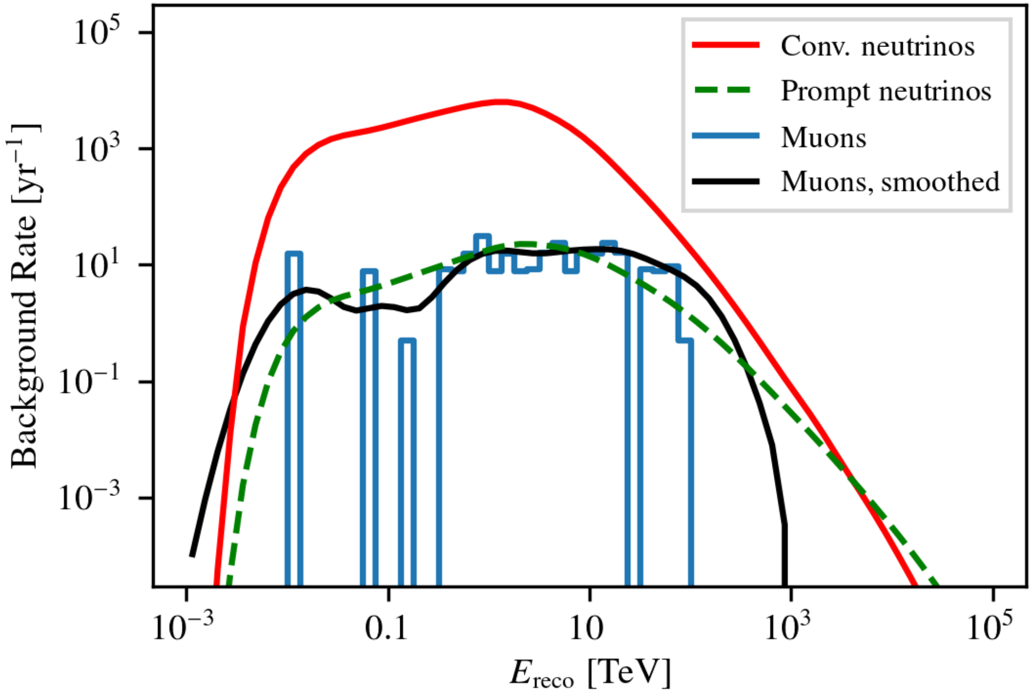
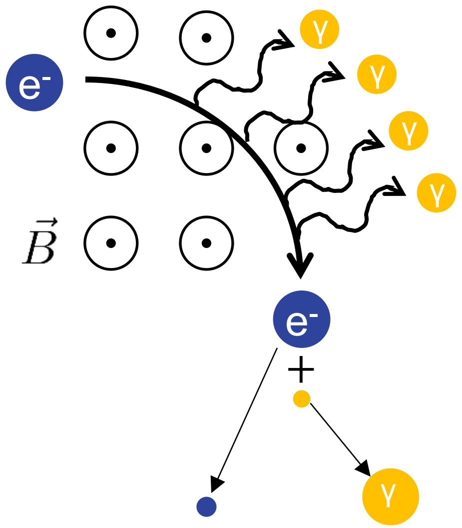
$$N_{\mathrm{pred}}(E_{\mathrm{true}}, \vec{r}_{\mathrm{reco}}) * \mathrm{Edisp} = N_{\mathrm{pred}}(E_{\mathrm{reco}}, \vec{r}_{\mathrm{reco}})$$

4. Background from simulations of CR induced air showers



Production of gamma rays

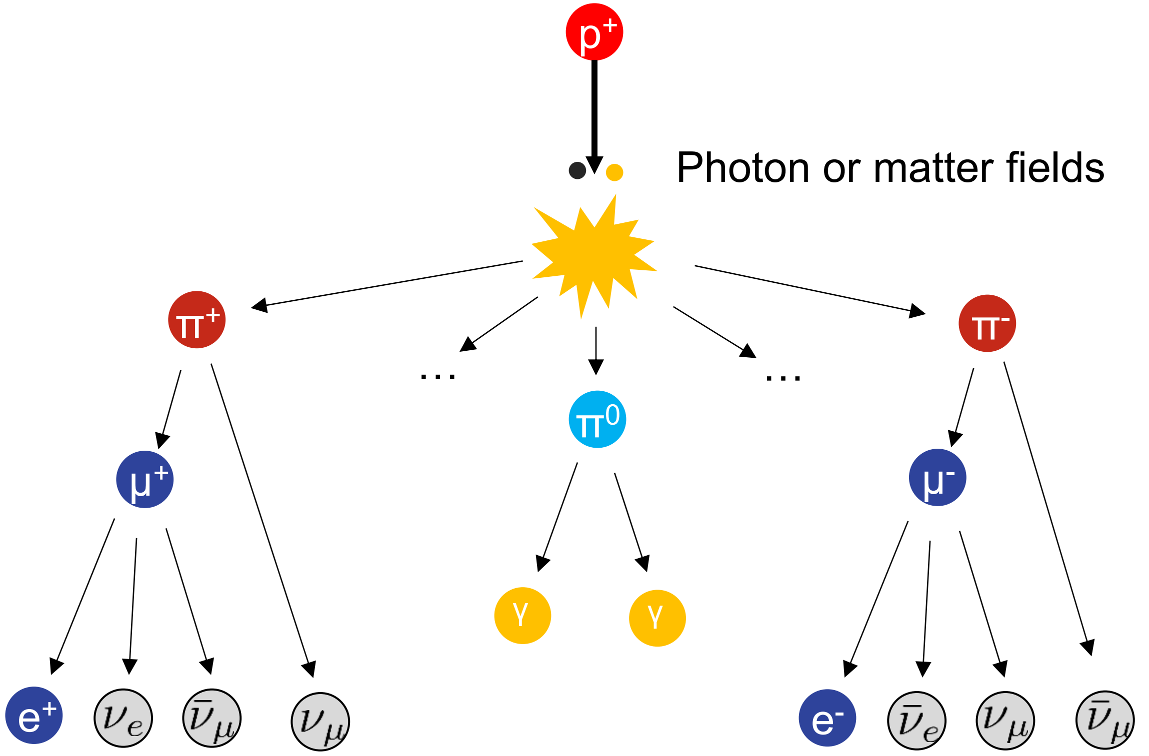
Leptonic production – IC model



Synchrotron emission
(radio – soft gamma rays)

Inverse Compton scattering
(gamma rays)

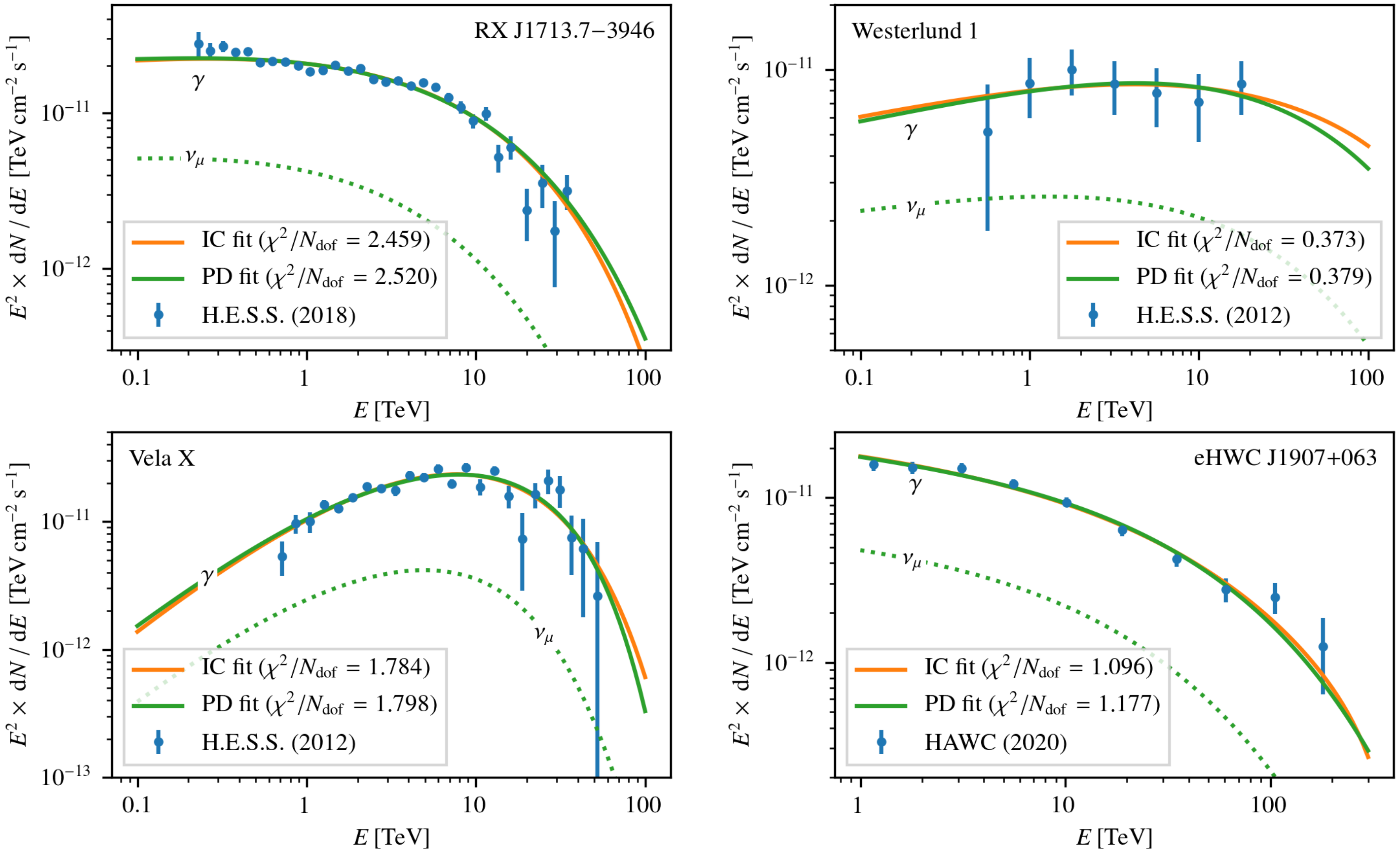
Hadronic production – PD model



Generation of input models

$\Phi(E_{\mathrm{true}}, \vec{r}_{\mathrm{true}})$?

- Input models from pion decay (PD) and inverse Compton (IC) fits to flux points from the literature
- Primary particle distribution parametrized as a power law with exponential cutoff
- Neutrino prediction follows from the parametrization by Kelner et al. 2006

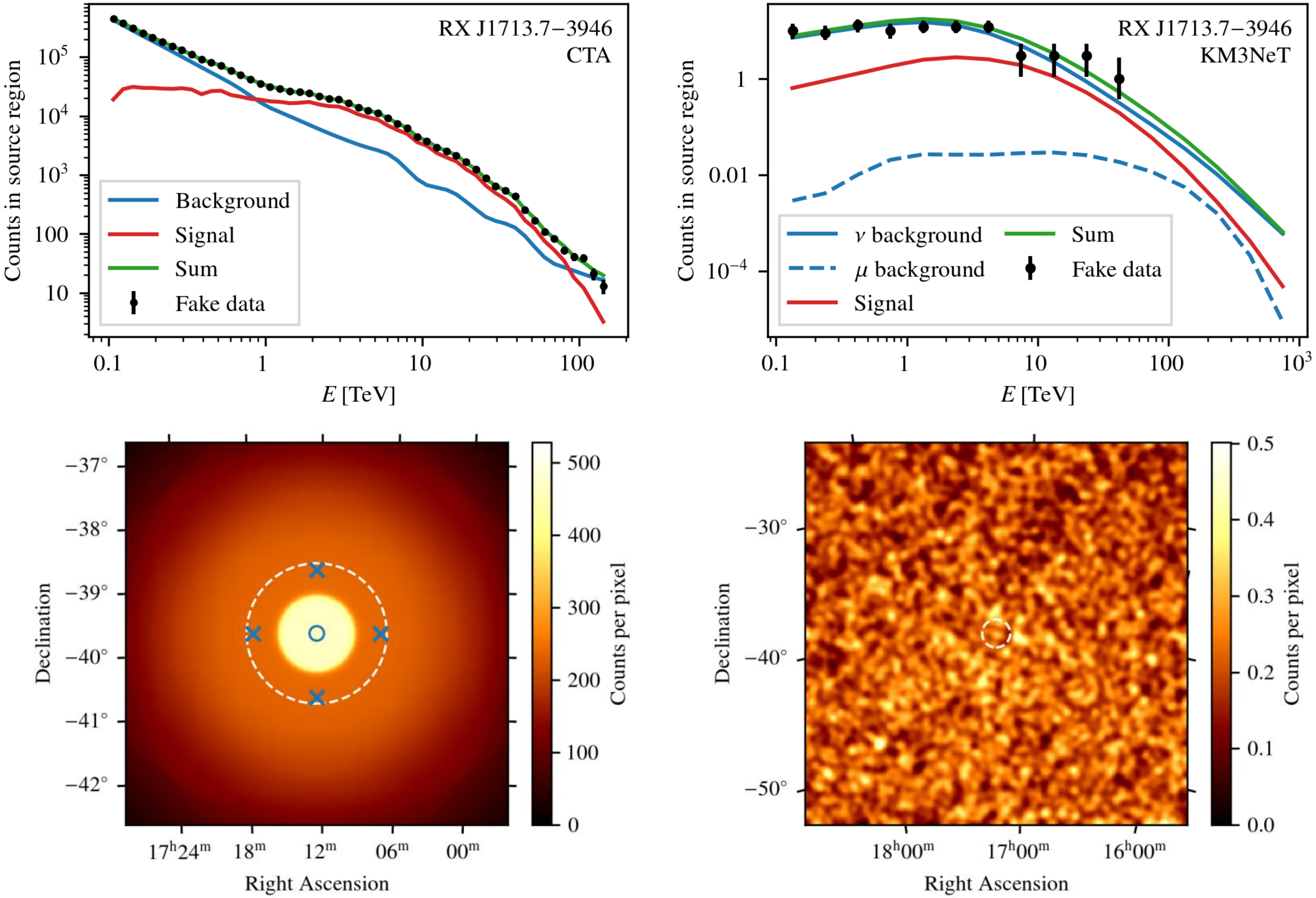


Generation of datasets

Combining the IRFs and the models in Gammapy's `MapDataset` class allows for drawing random pseudo-observations

- Spectrum and morphology constrained by the CTA dataset (200h)

- Barely visible signal in the KM3NeT dataset (10yr), only in the hadronic scenario



Analysis Scenarios

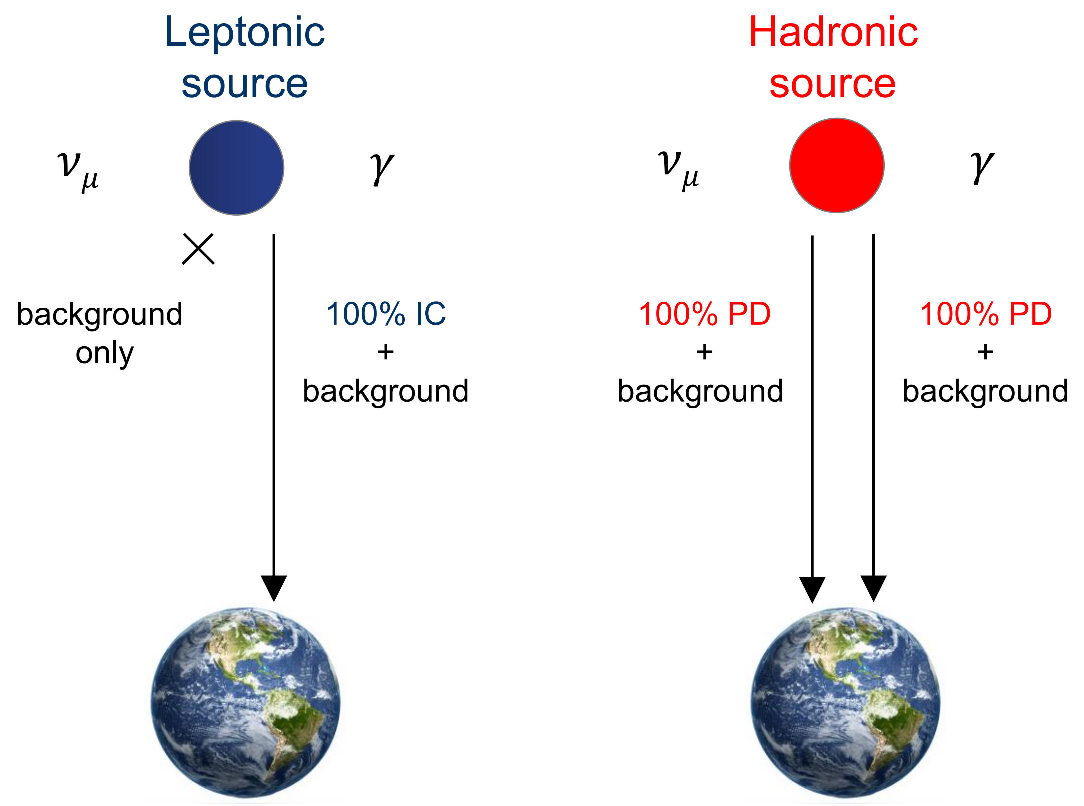
Compare three analysis scenarios

1) **CTA alone:**
How well can CTA differentiate between the emission scenarios on its own, not considering any neutrino data

2) **KM3NeT with CTA spectrum:**
How well can KM3NeT differentiate between the emission scenarios when knowing the CTA spectrum and its uncertainties

3) **KM3NeT + CTA combined fit:**
What can we gain by simultaneously fitting the source models to gamma-ray and neutrino data

Two emission scenarios



Results

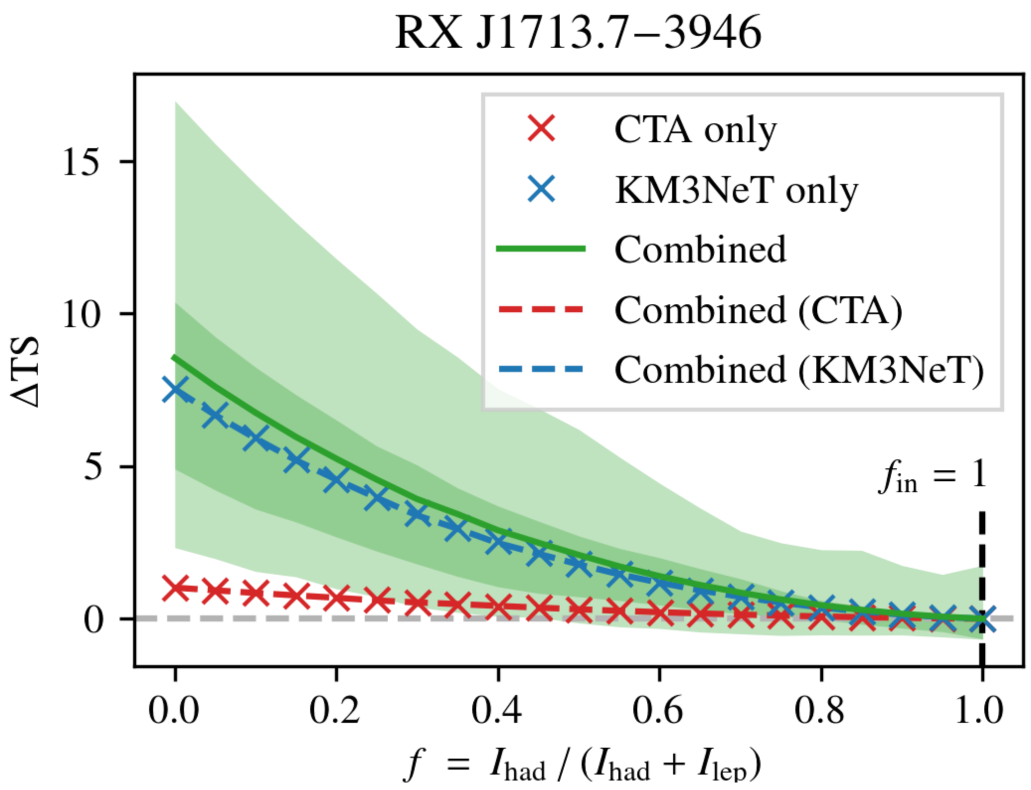
4 sources x 2 emission scenarios x 100 pseudo experiments

On each:

- Perform likelihood-profile scans of the hadronic contribution *f* to the total gamma-ray flux
- Constrain *f* using a penalty term for each scan point f_{scan}

$$-2\ln\mathcal{L}_{tot} = -2\ln(\mathcal{L}_{\text{CTA}}\cdot\mathcal{L}_{\text{KM3}}) + \frac{(f - f_{scan})^2}{0.01^2}$$

- Larger TS values correspond to stronger rejection of that hadronic fraction
- The contributions of the CTA/KM3NeT datasets in the combined analysis agree with the analysis scenarios 1 + 2



Results

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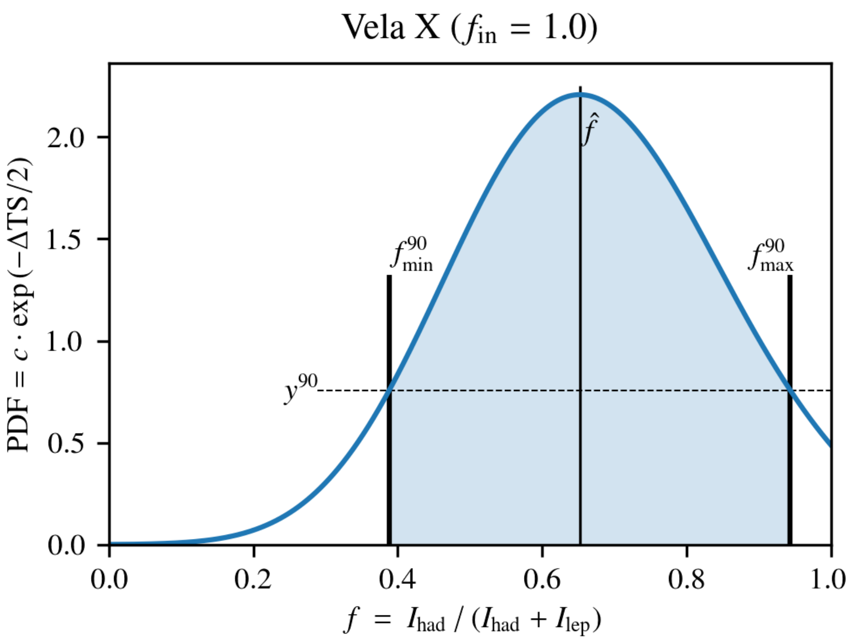
On each:

- Calculate credible intervals by integrating

$$\frac{\mathcal{L}_{M1}}{\mathcal{L}_{M2}} = e^{-\Delta TS/2}$$



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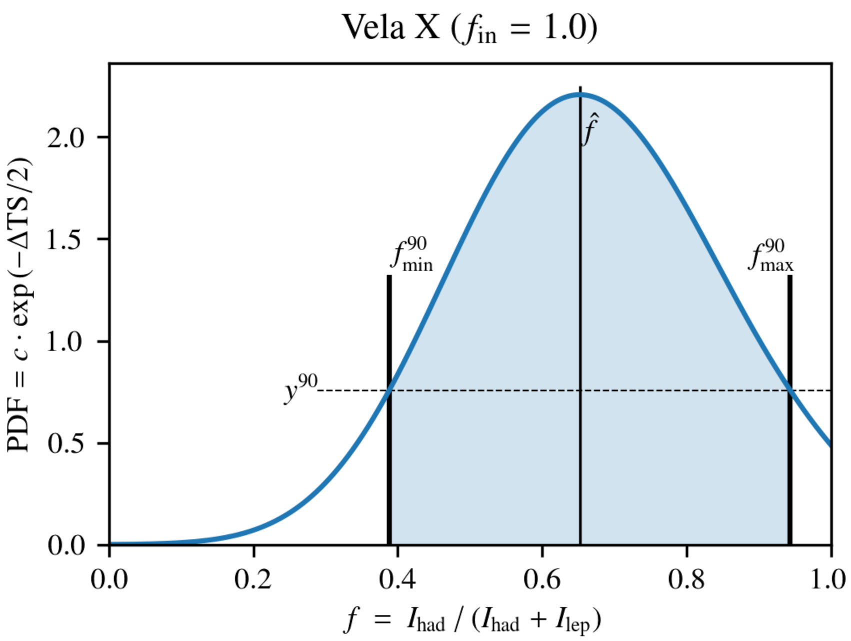
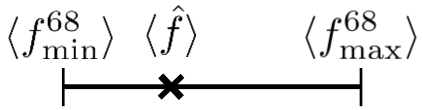
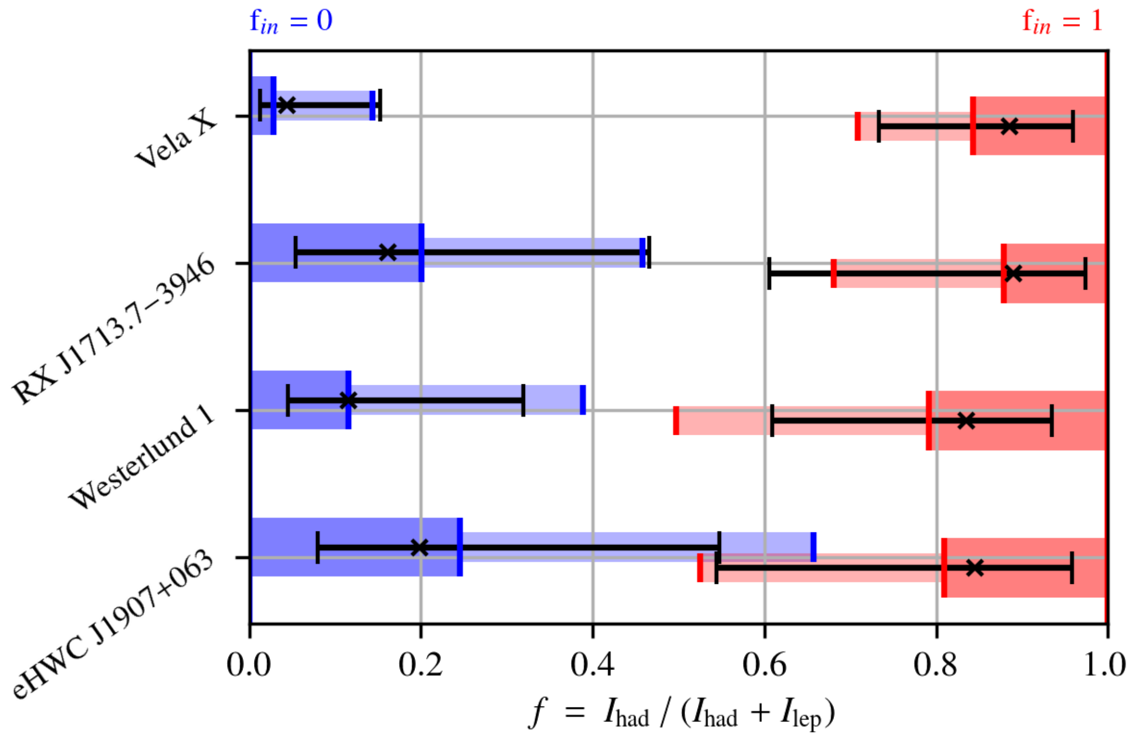
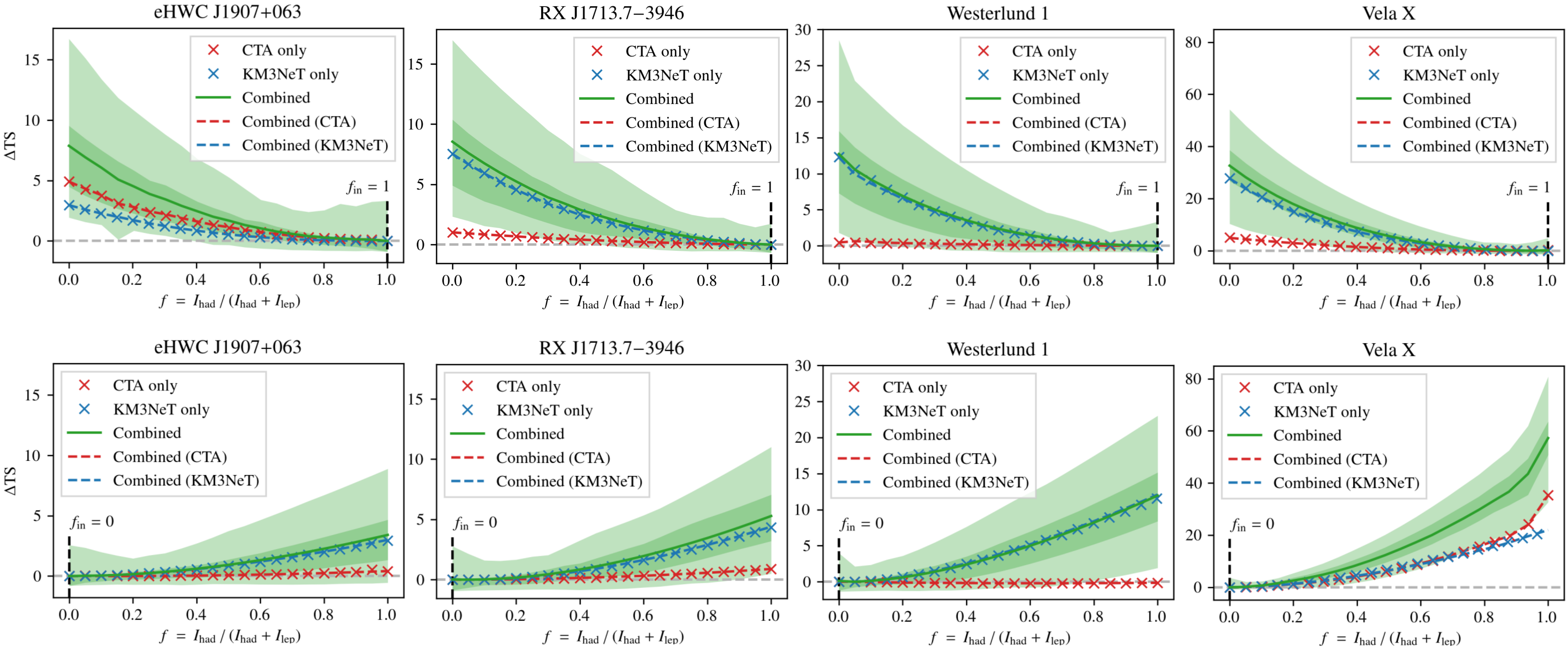




68% and 90% quantiles of the best-fit $\hat{f}$



Likelihood scans



Conclusion

- Gammapy can be used to analyze neutrino data (from DL3 onwards)

- Convenient framework for joint gamma-ray–neutrino analyses
(custom models can be implemented, continuously developed with new features, etc…)

- Combining gamma-ray and neutrino data at the event level yields results consistent with combining constraints from separate analyses. However, only if the emission region, spectrum, convergence of the fitting algorithm, etc, are consistent! This is best ensured within a single framework.

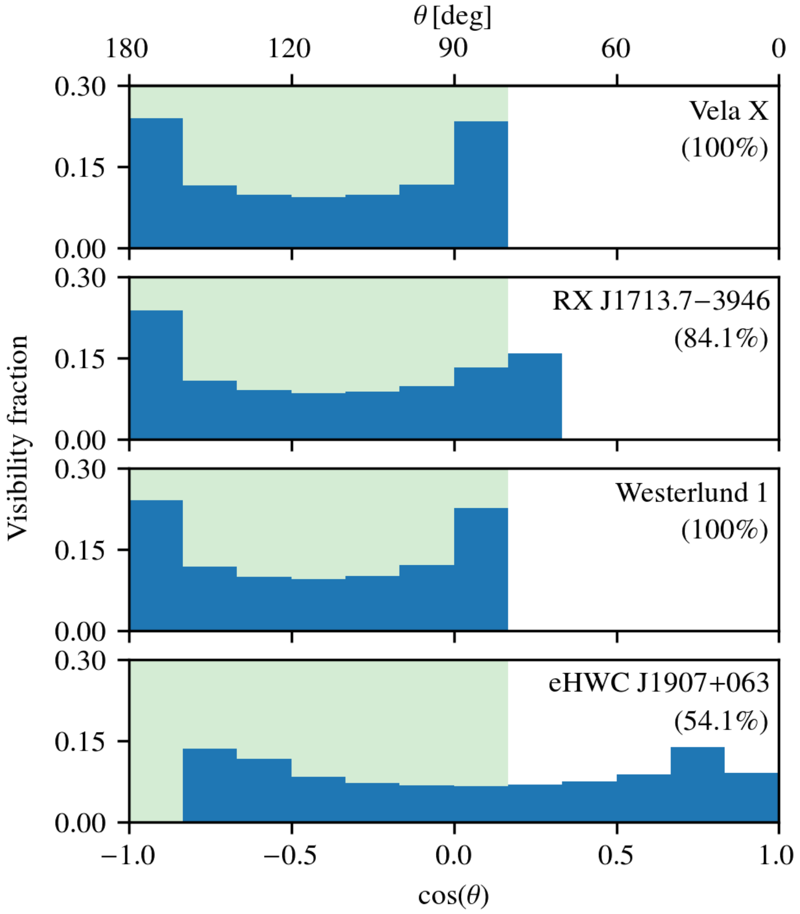
- Neutrino emission provides valuable additional information to the gamma-ray spectrum when distinguishing between emission scenarios.

Thanks
for your attention!

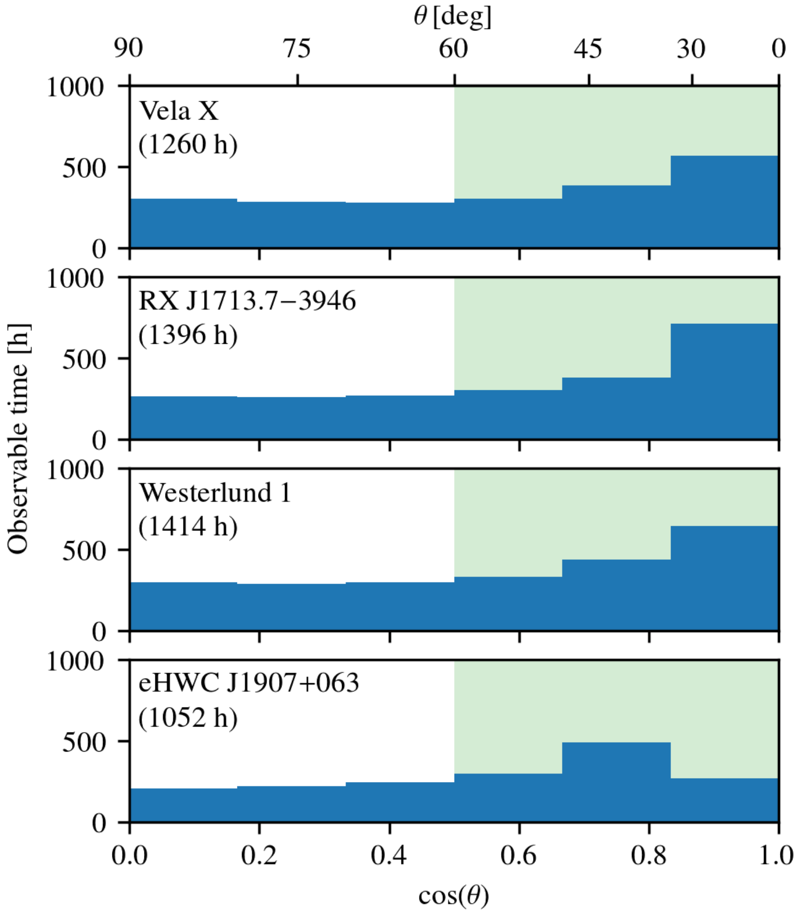
Backup

Visibilities

KM3NeT

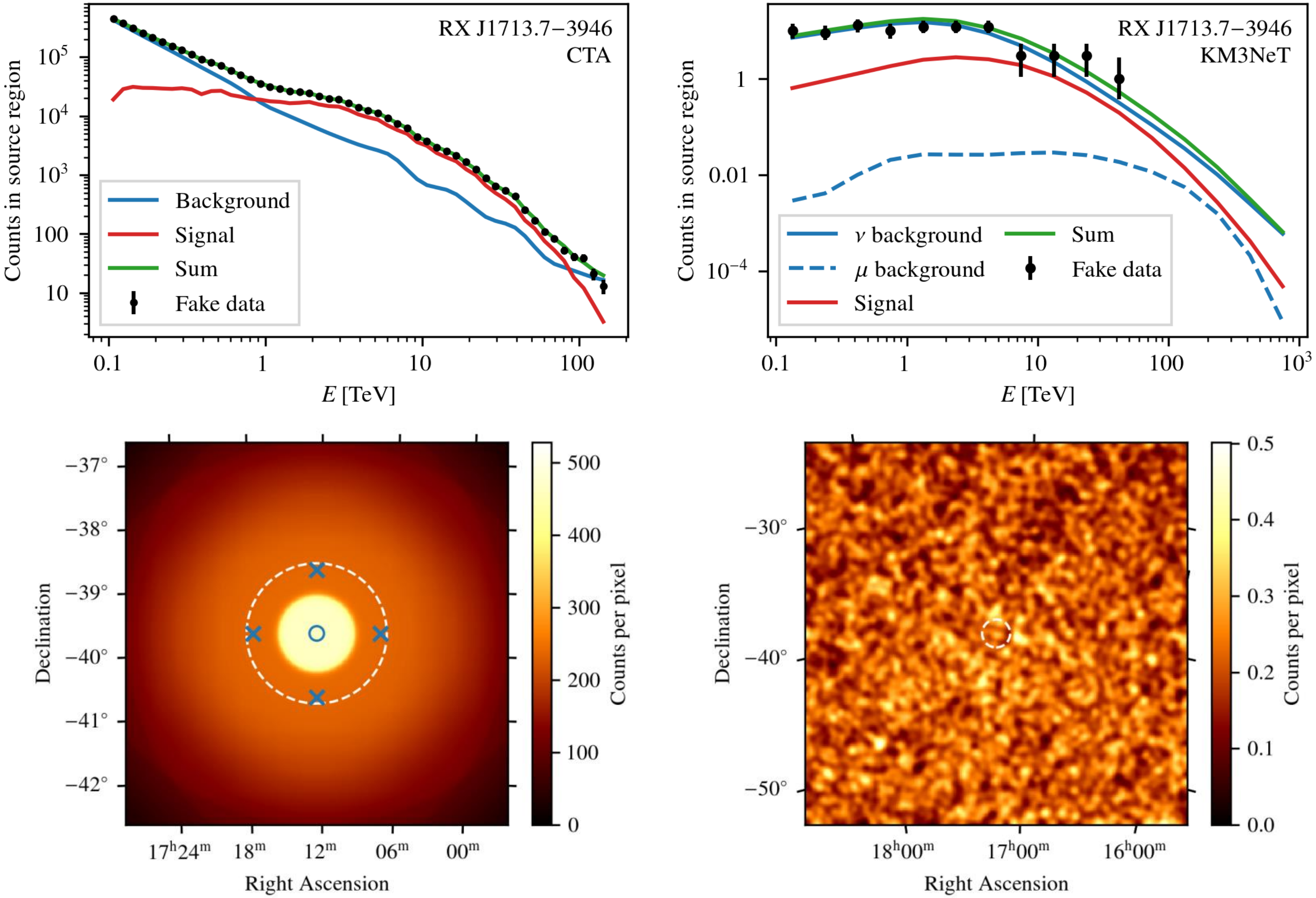


CTA South



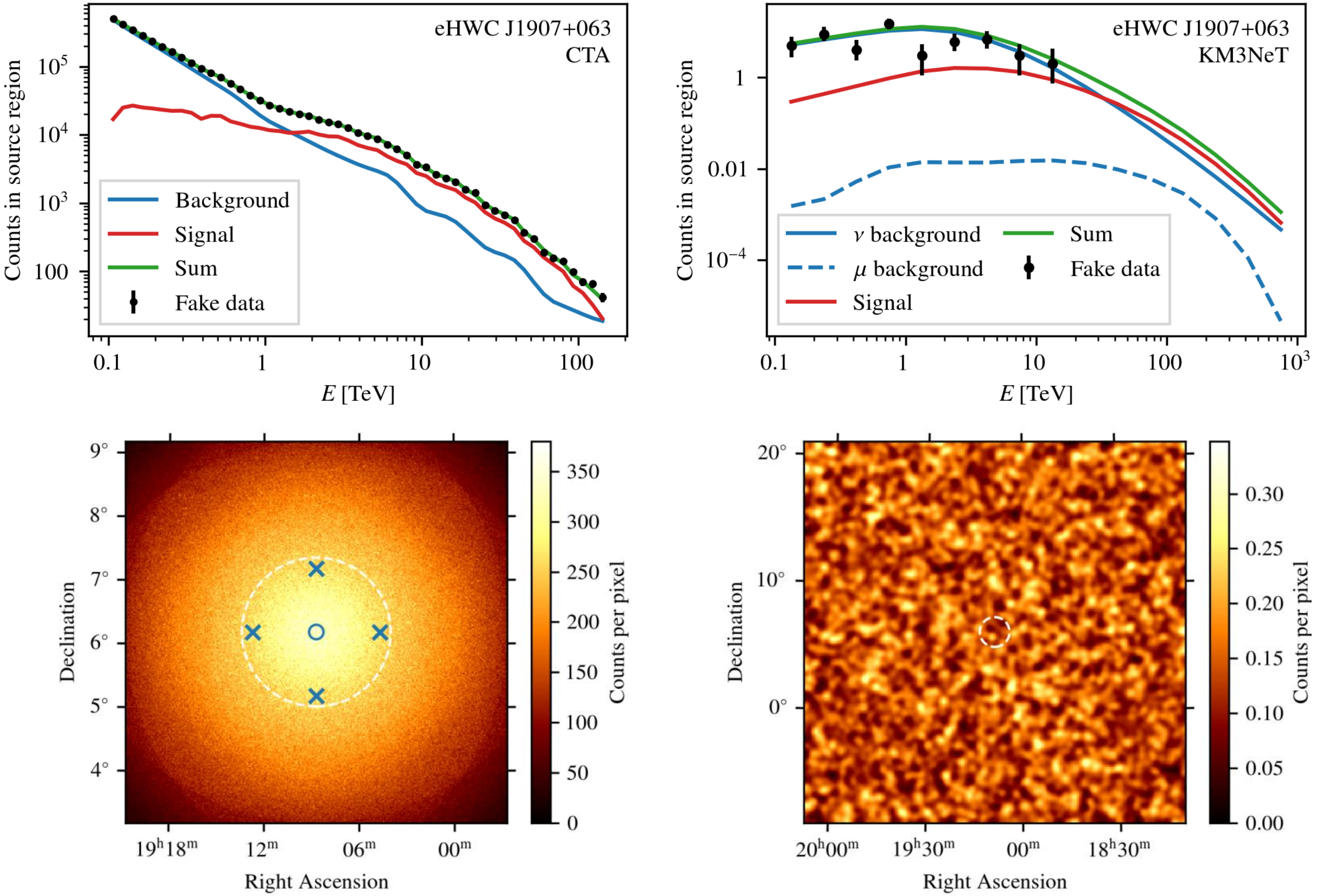
Generation of datasets

RX J1713.7-3946



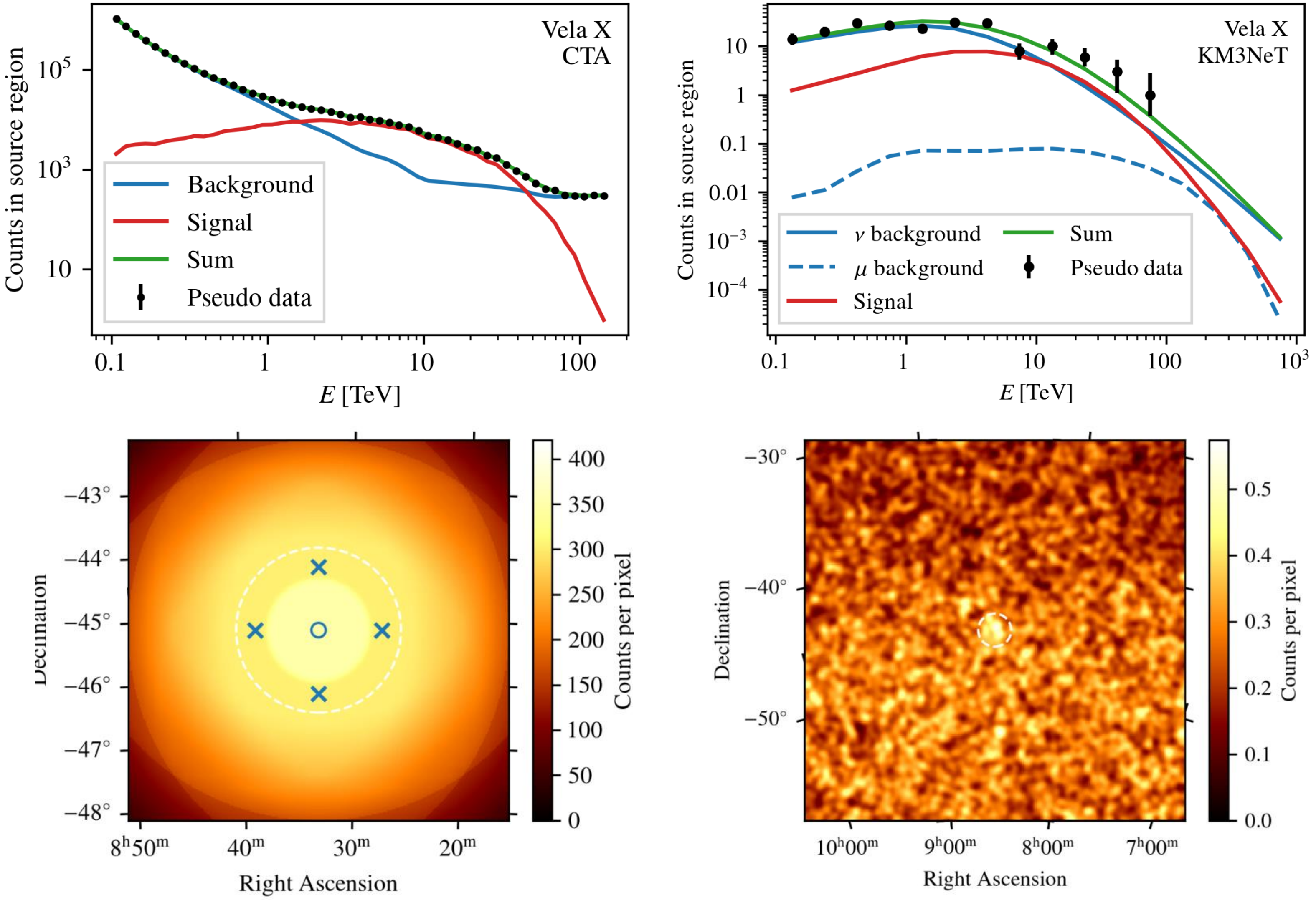
Generation of datasets

eHWC J1907+063



Generation of datasets

Vela X



Generation of datasets

Westerlund 1