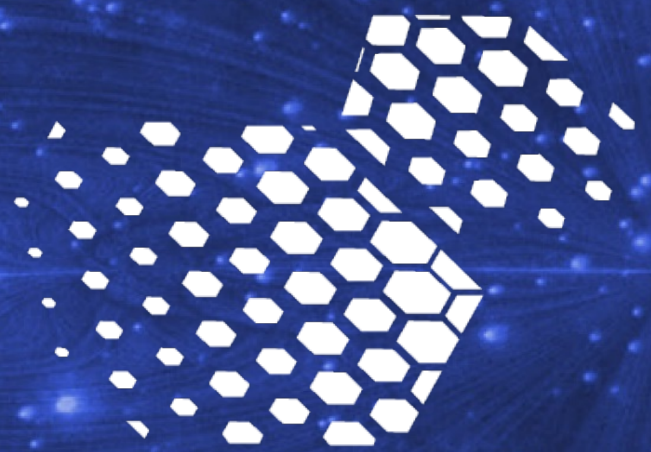




SST-1M

Single-Mirror
Small Size Telescope

Measuring the **Cosmic-Ray Proton Spectrum** with the **SST-1M** Stereoscopic Array

Jakub Juryšek

Institute of Physics of the Czech Academy of Sciences

TeV Particle Astrophysics 2026, Tendo, Japan



Co-funded by
the European Union

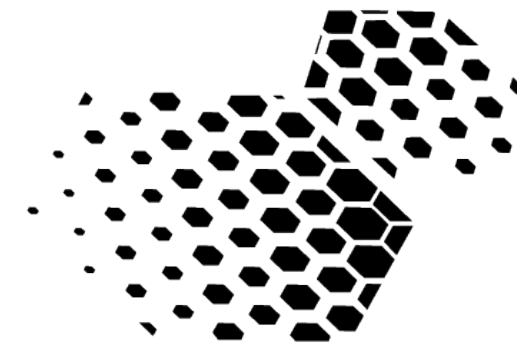


FZU

Institute of Physics
of the Czech
Academy of Sciences

SST-1M mini array

Imaging Atmospheric Cherenkov Telescopes



SST-1M

Single-Mirror
Small Size Telescope

- Two 4-m IACTs, **Ondrejov observatory (500 m a.s.l.), Czech Republic**
- Davies-Cotton optical design, **innovative SiPM camera with fully digital trigger and readout**
- **Stereo trigger** managed with **SWAT**, **White Rabbit** synchronisation of the timestamps



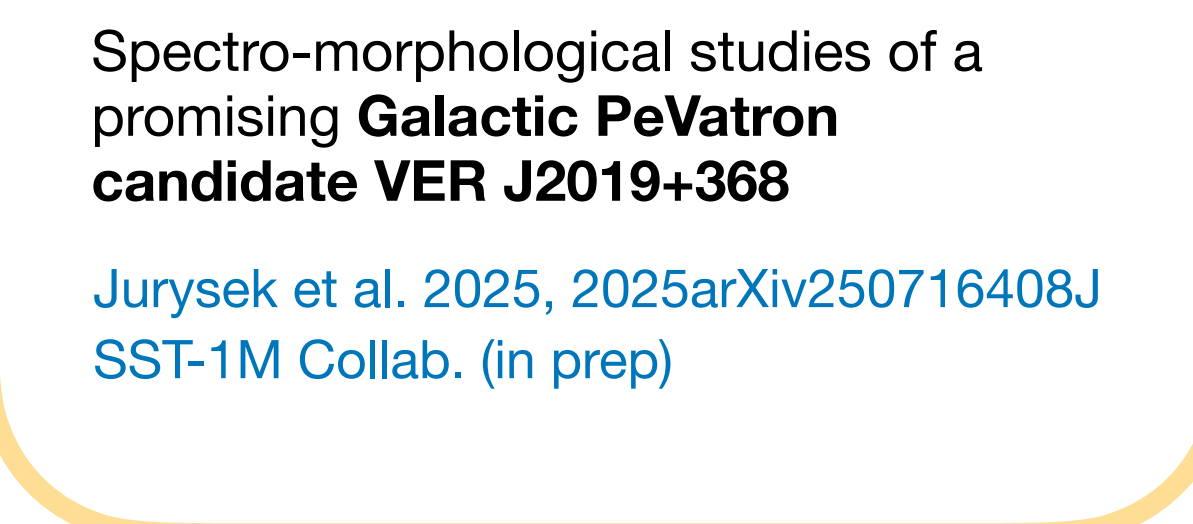
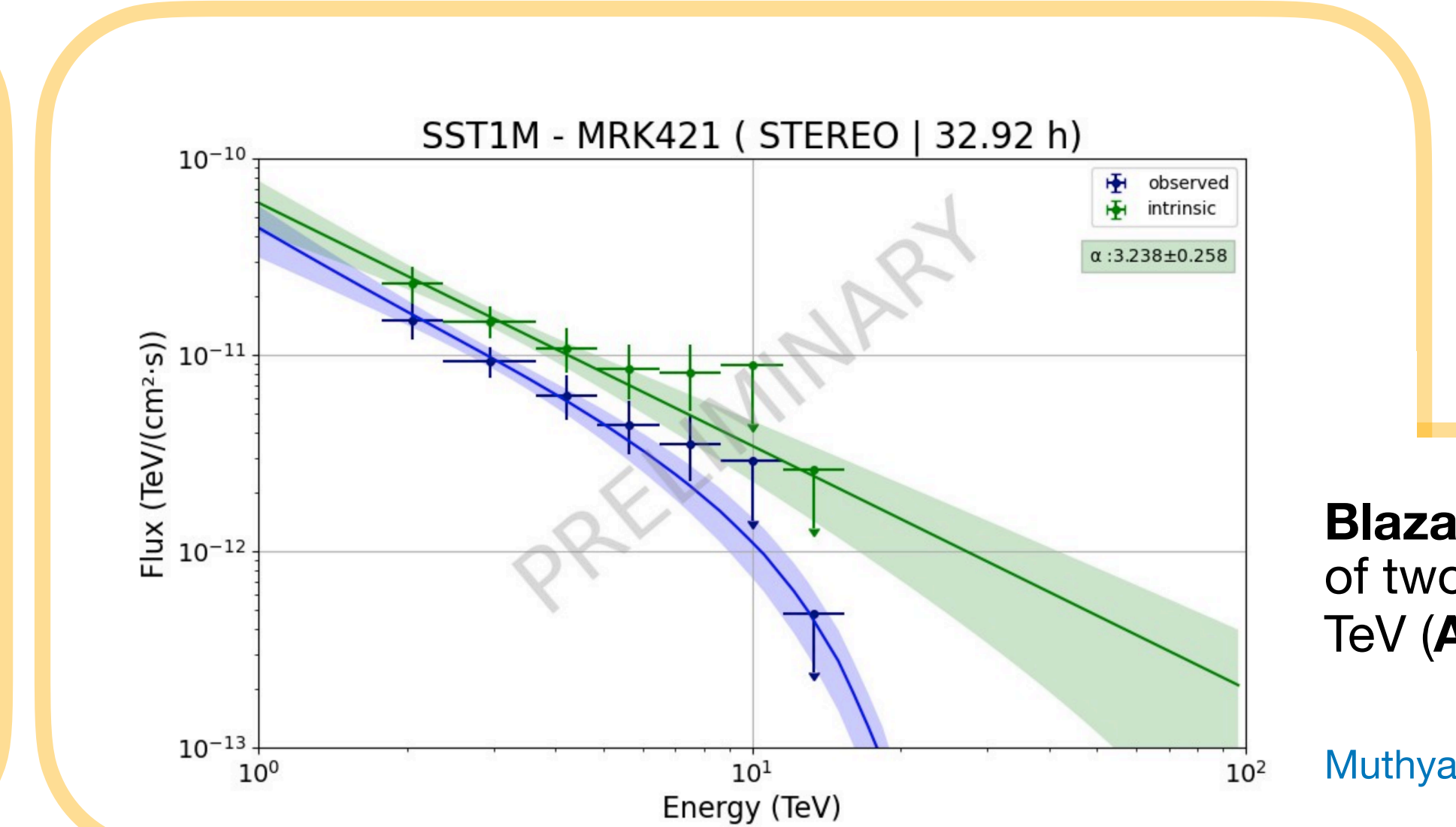
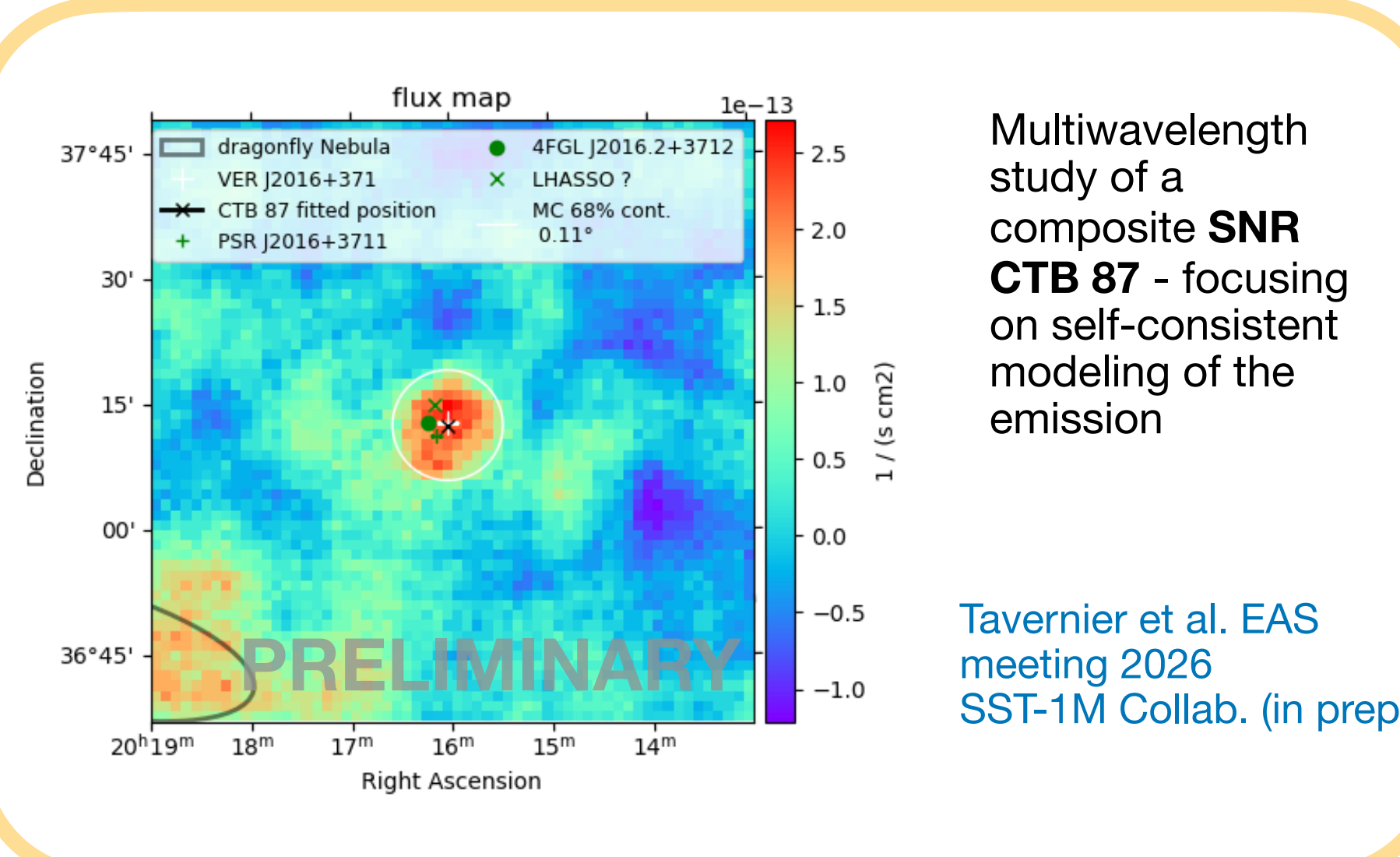
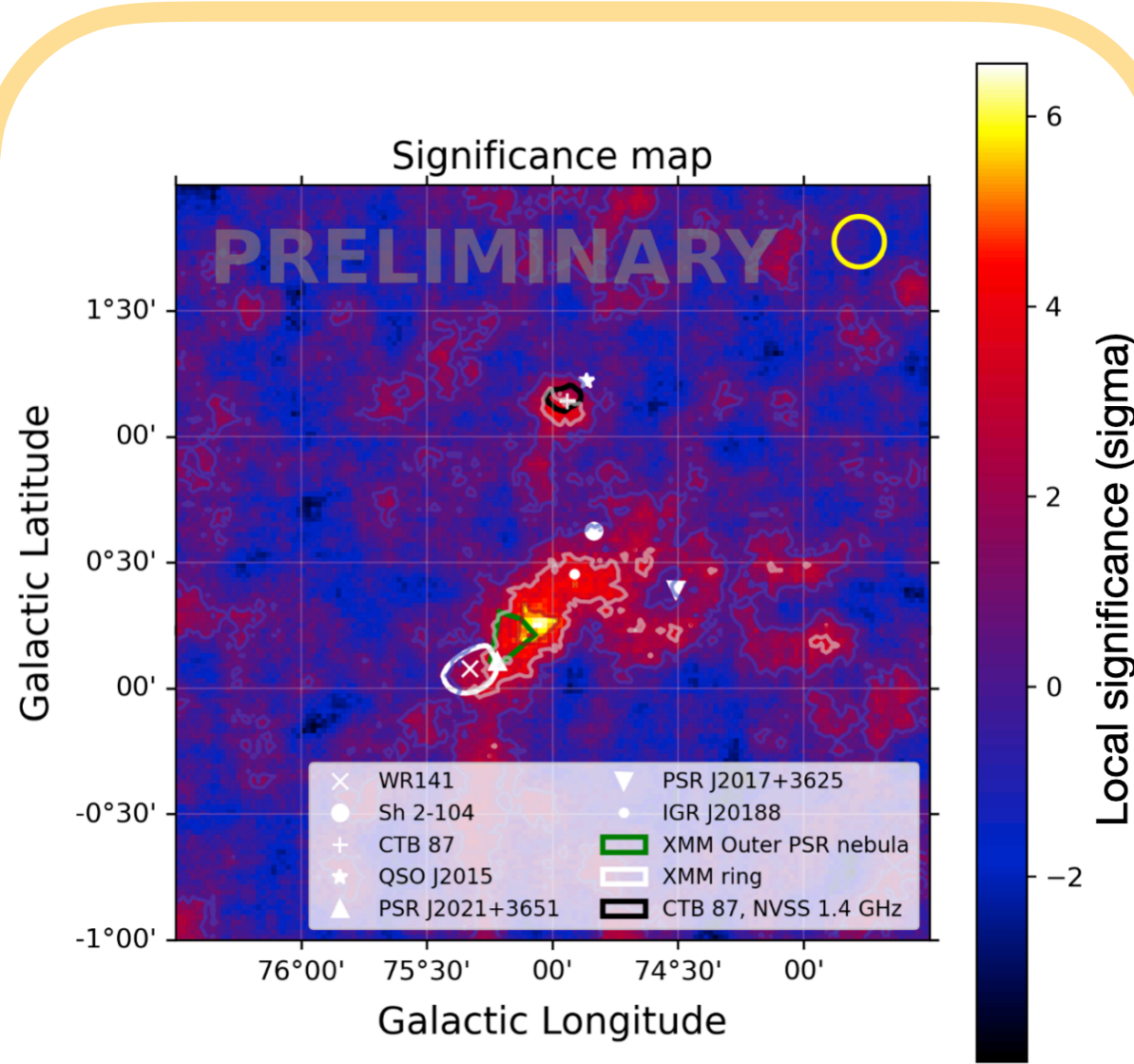
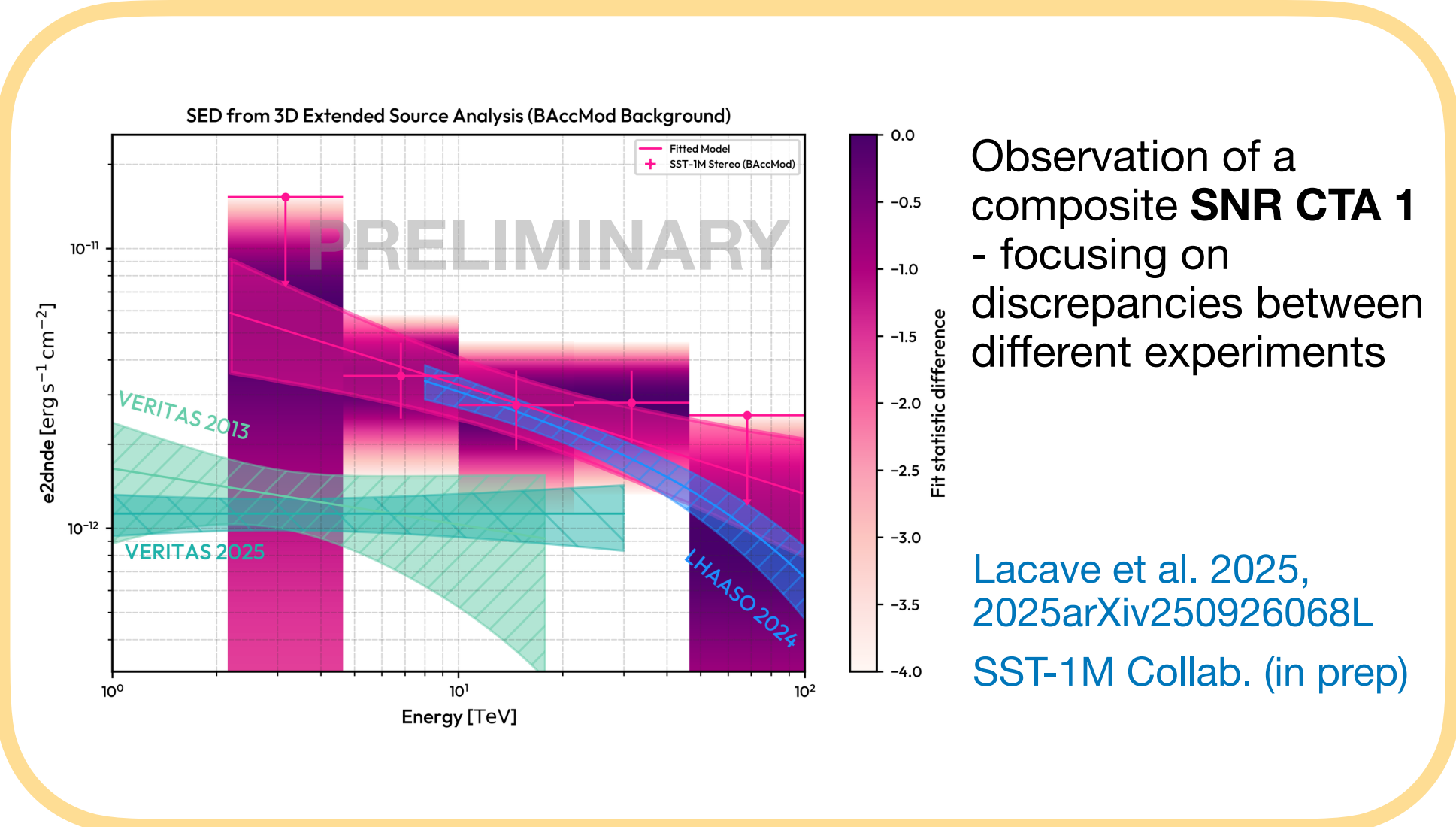
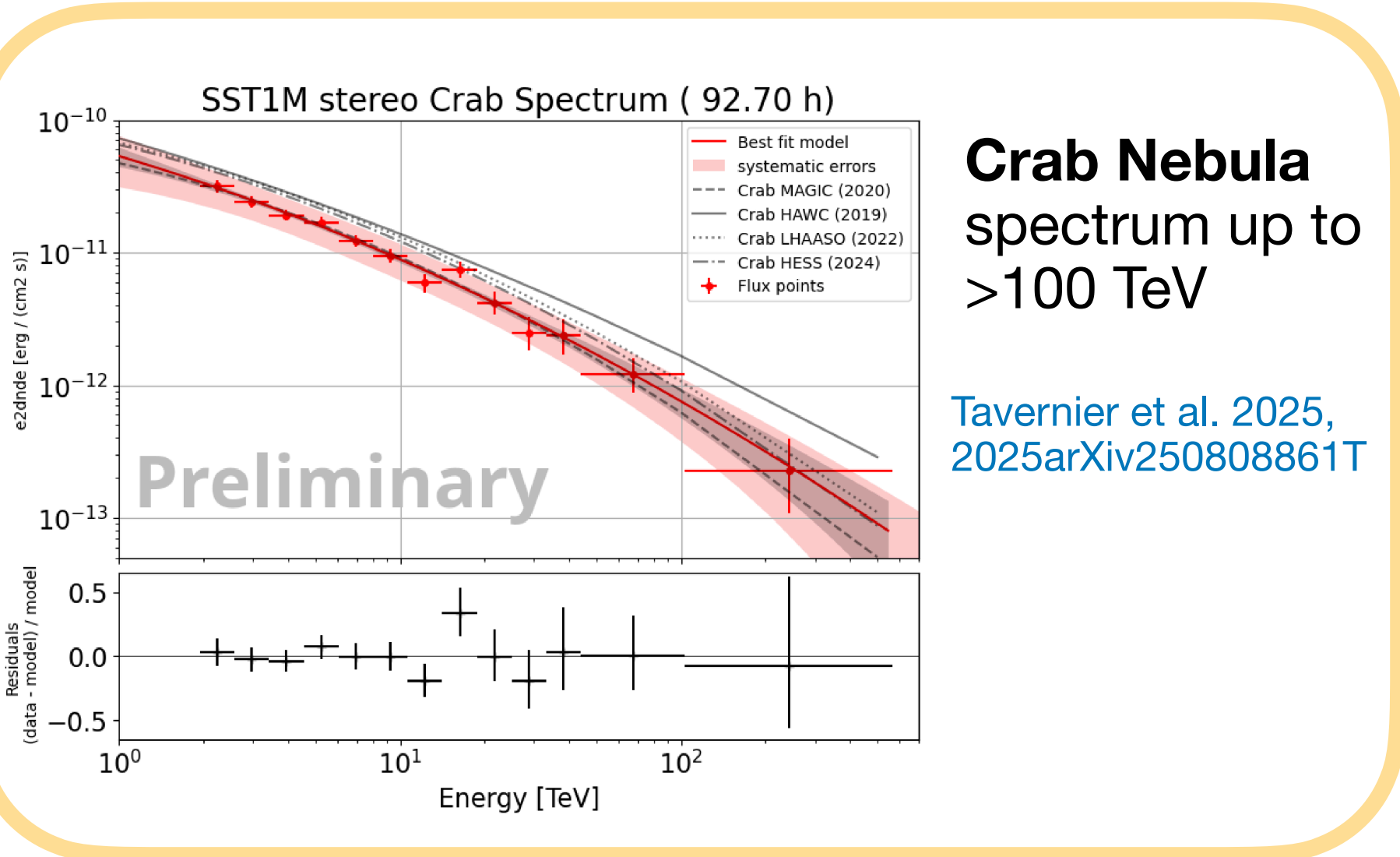
SST-1M HW paper -
[2025JCAP...02..047A](#)

Operation: Mandat et al. 2025,
[2025icrc.confE.746T](#)



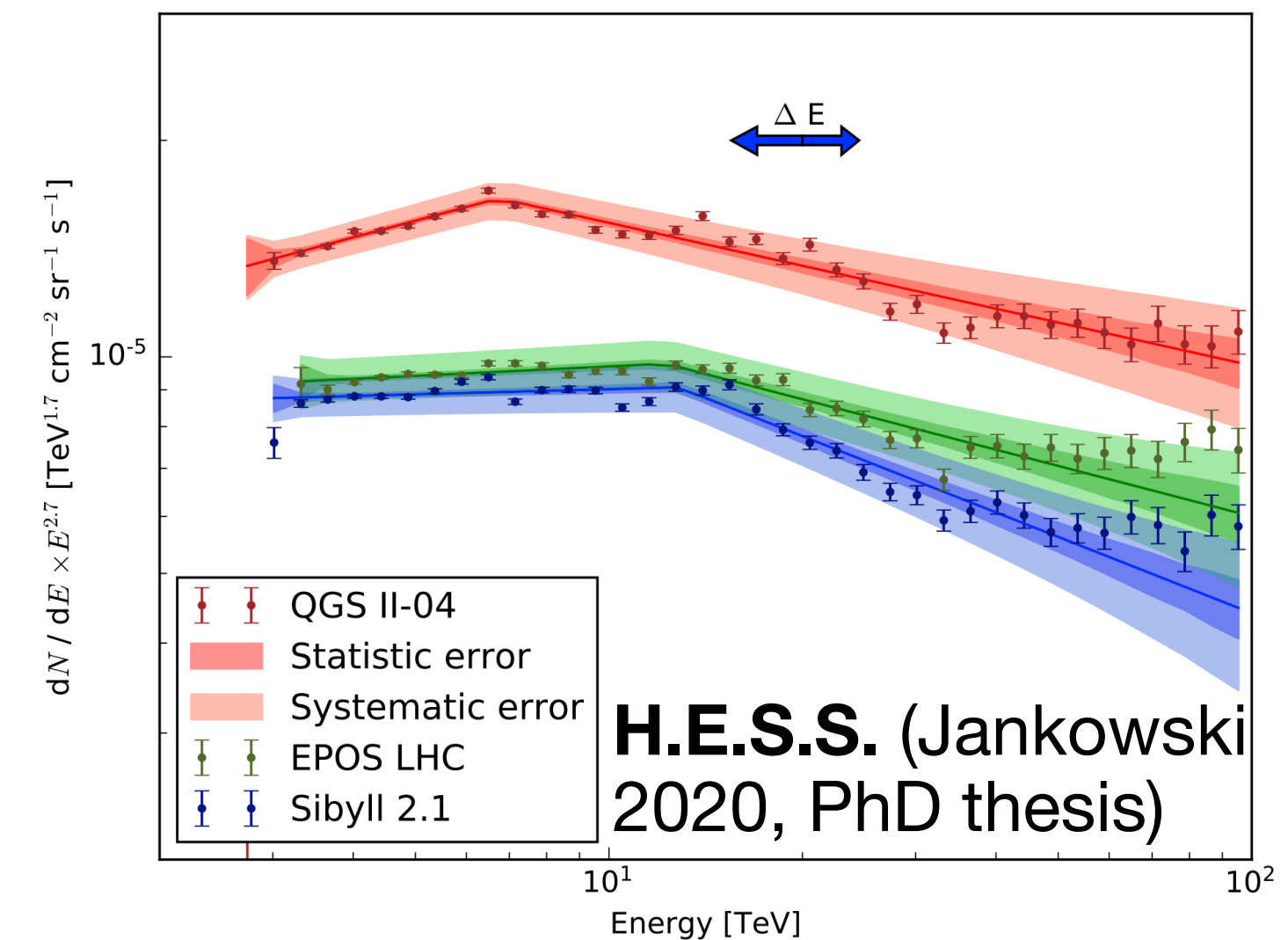
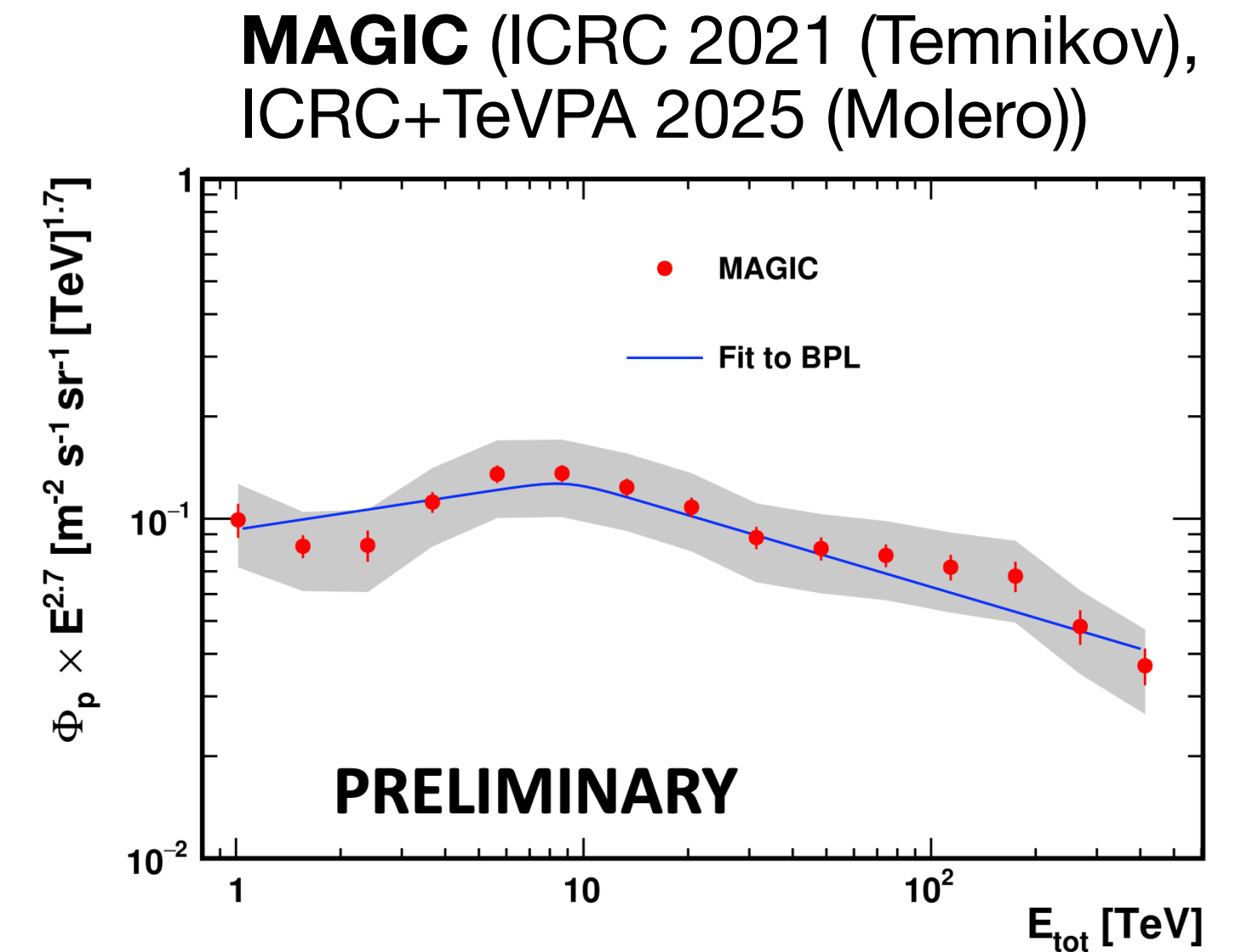
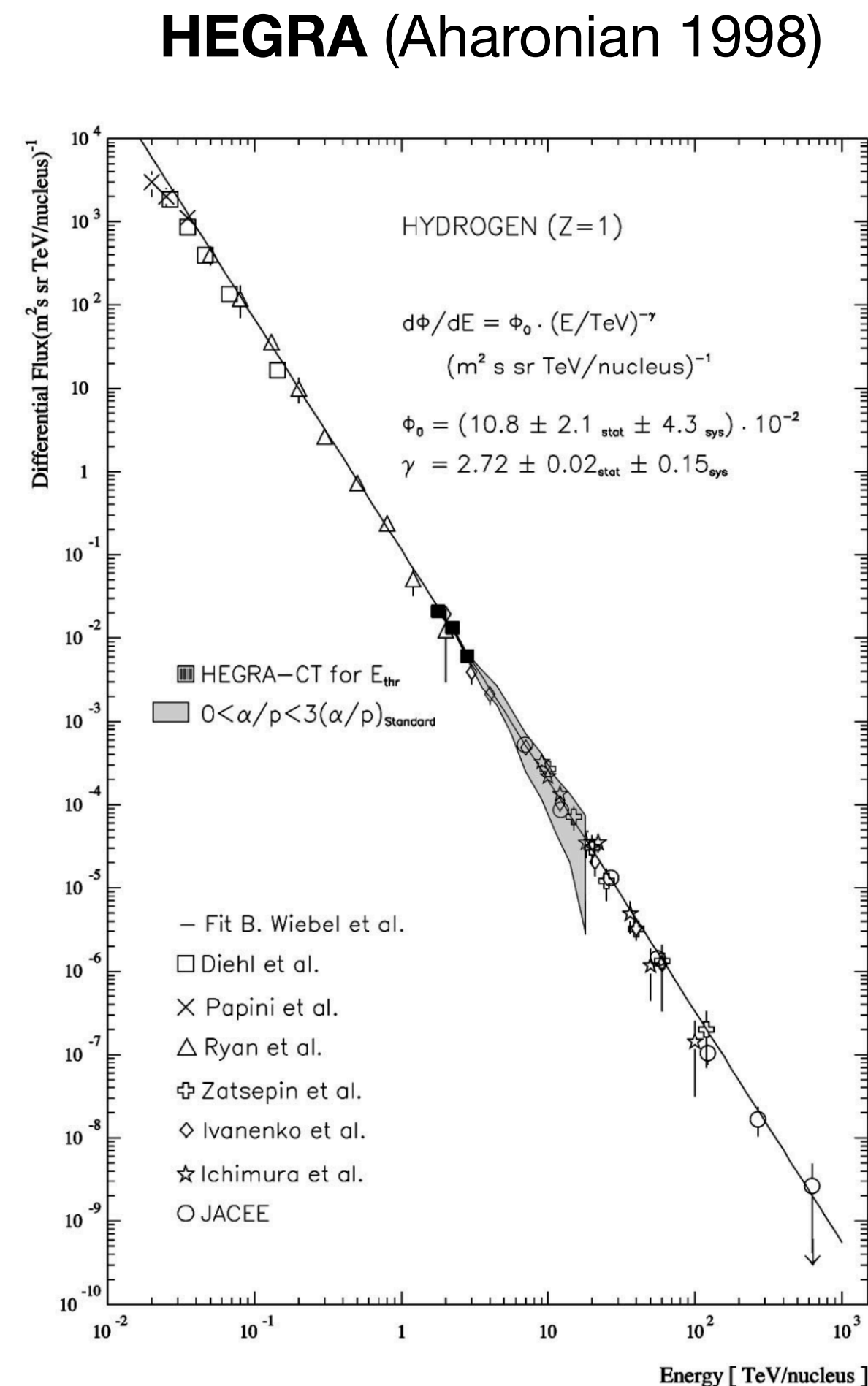
SST-1M: Recent scientific highlights

Gamma-ray observations



Proton spectrum with IACTs

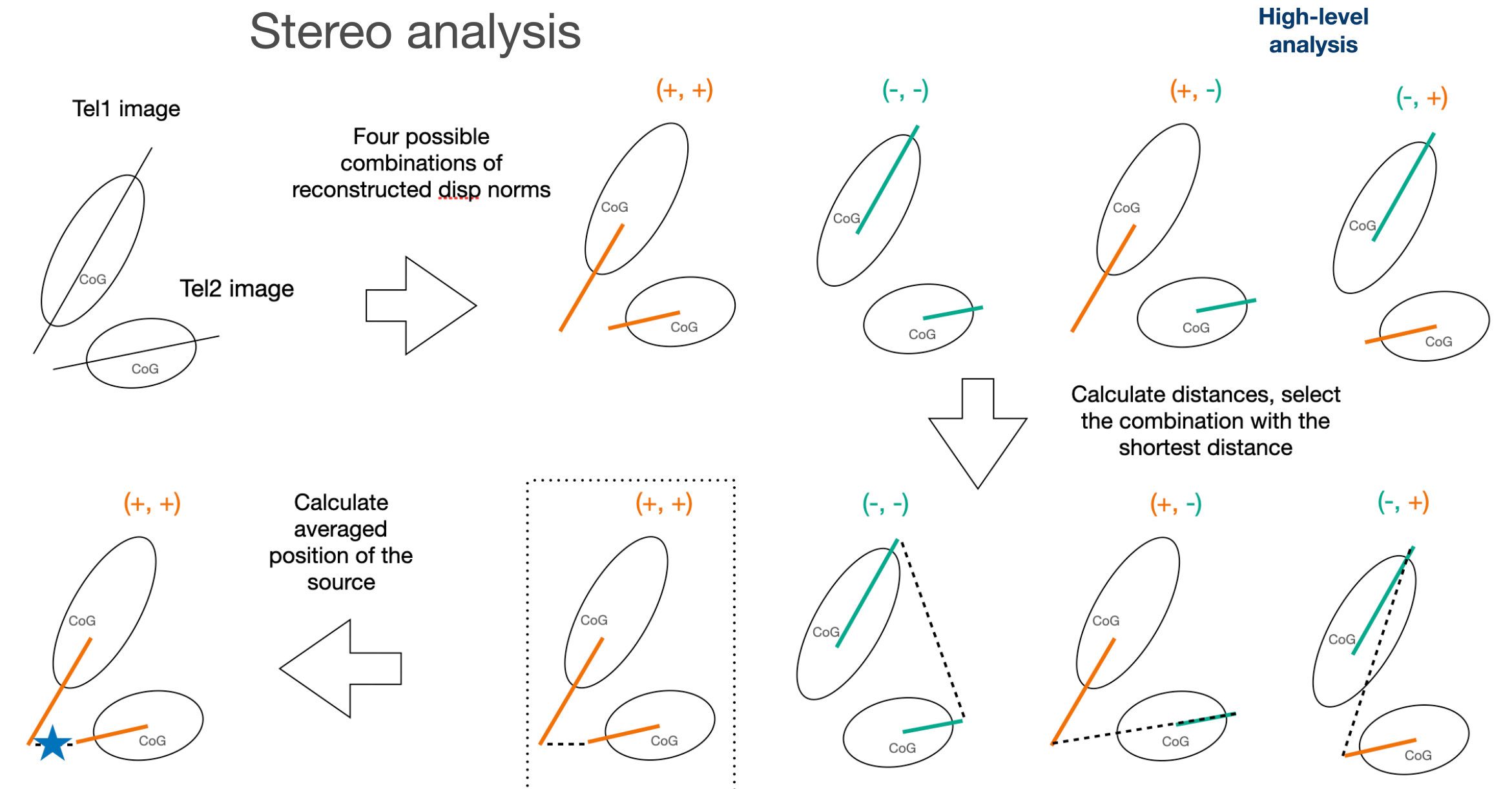
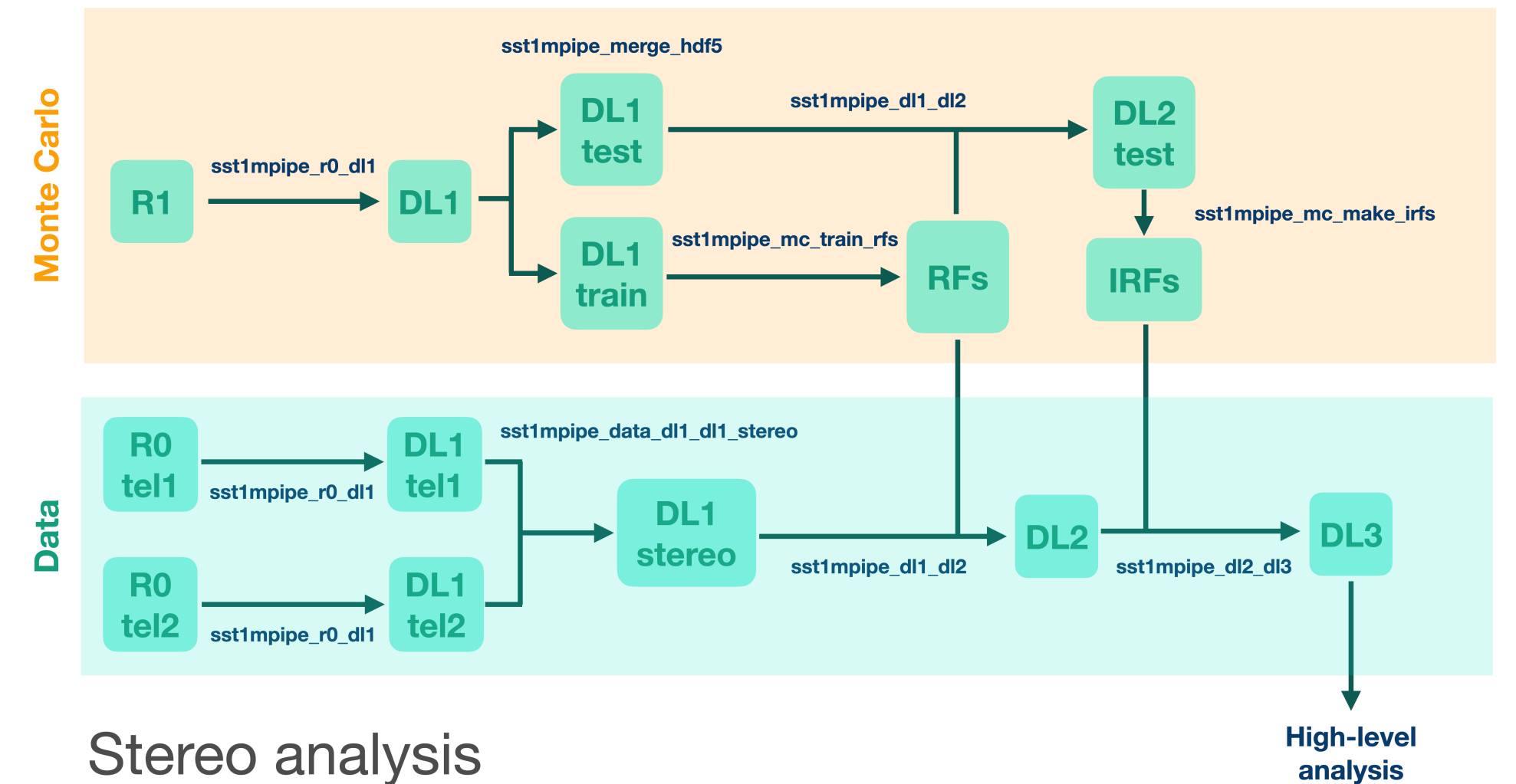
- Interesting spectral features detected by several experiments - softening at ~ 10 TeV (e.g. NUCLEON 2018, DAMPE 2019), hardening above ~ 100 TeV (DAMPE 2024, LHAASO 2025)
- **IACT data absolutely dominated with CR events**, but these are treated as a **background and thrown away** in standard gamma-ray analysis.
- **IACTs sensitivity to CRs** covers the most interesting range for the galactic science: **~ 1 TeV - ~ 1 PeV**
- Not so many attempts to reconstruct CR spectrum/composition from the IACT data so far.



Reconstruction of protons with SST-1M

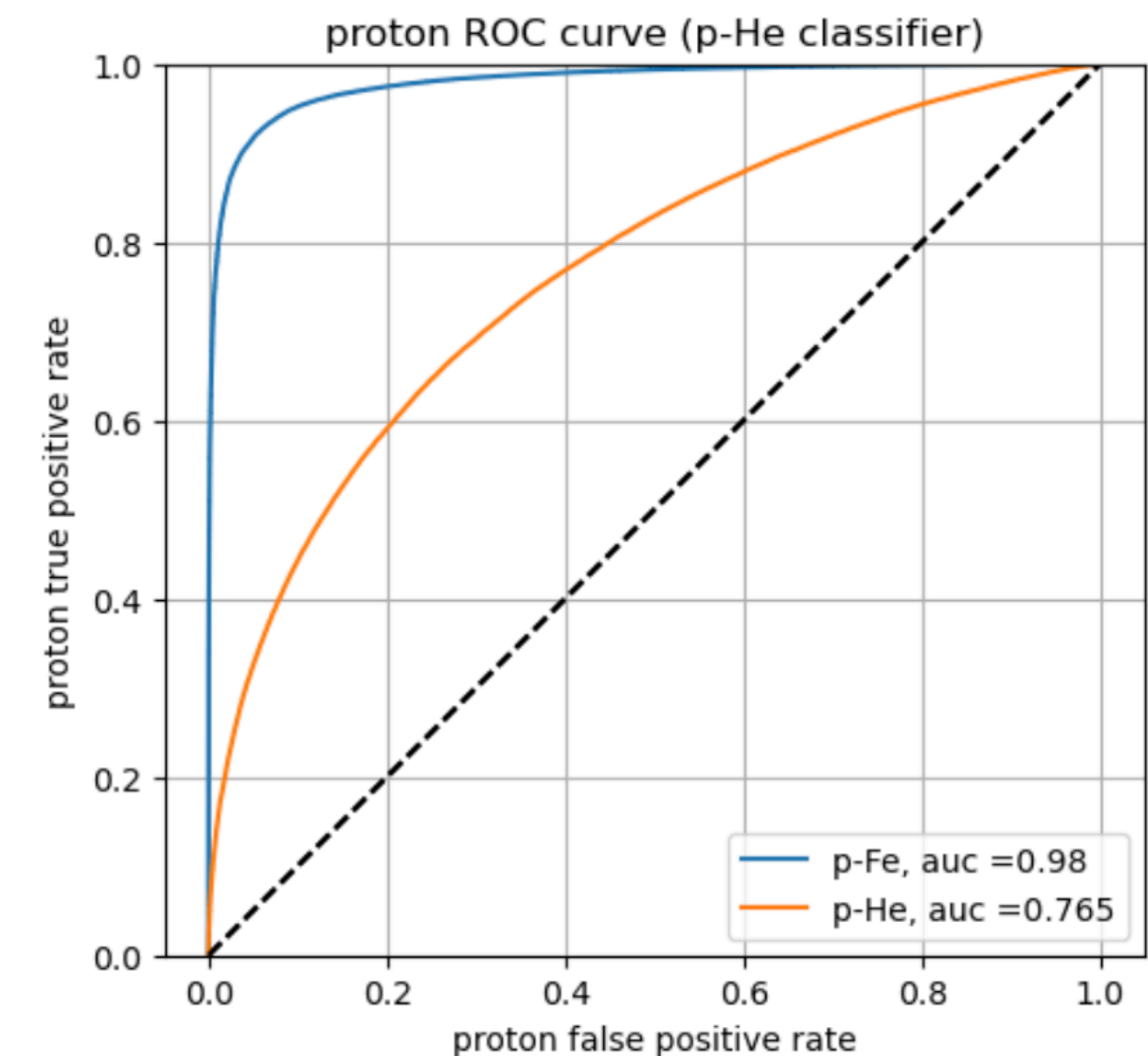
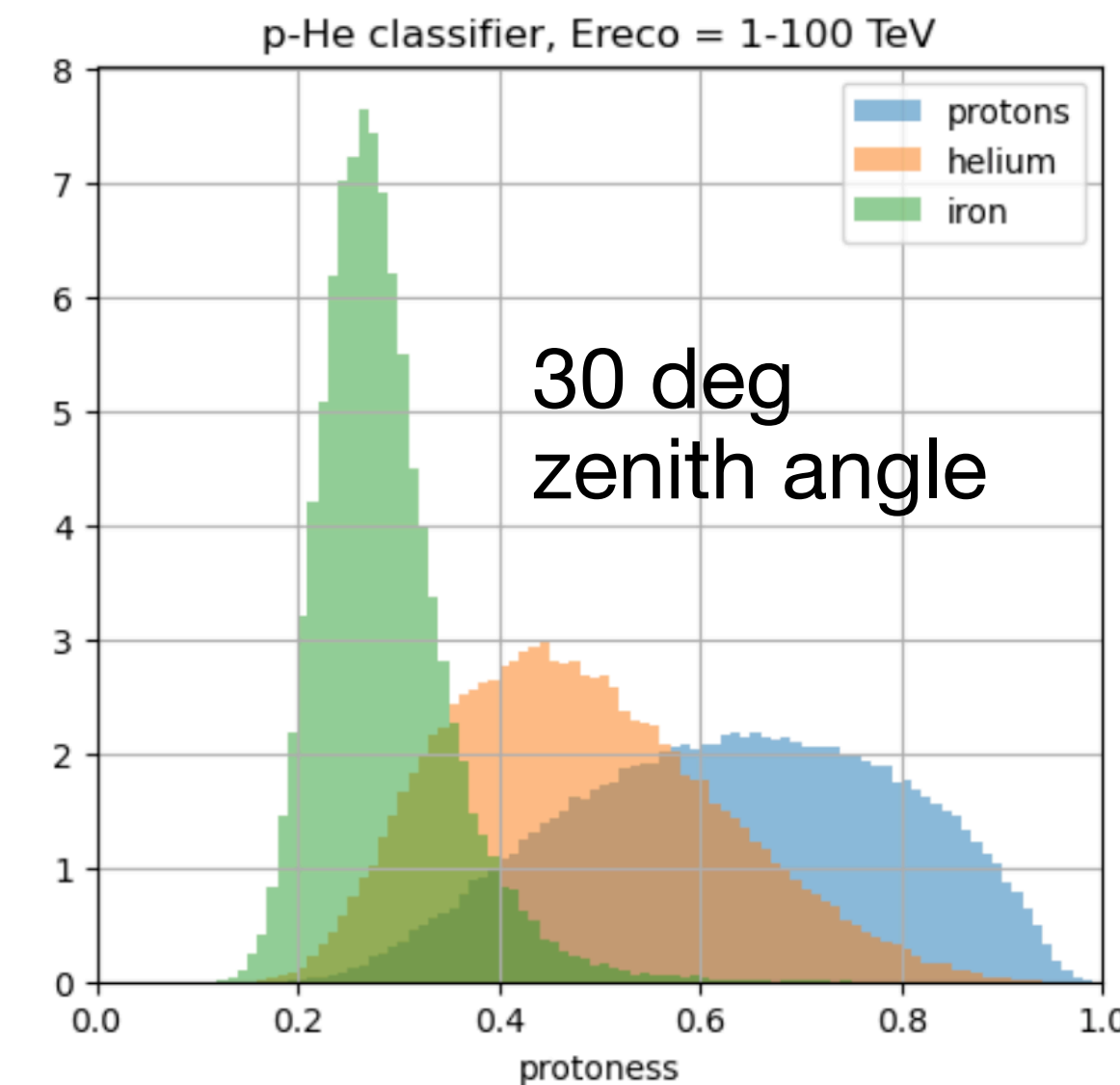
- Considering the expected cosmic-ray composition in the TeV range, **dedicated Random Forests trained on diffuse protons (signal) and helium nuclei (background) Monte Carlo**
- RF stereo reconstruction**
 - model training and IRF production very similar as in the standard gamma-ray analysis - `sst1mpipe` reconstruction pipeline
 - Energy reconstruction and particle classification** - RF per telescope using stereo geometry as additional features -> averaged predictions
 - Direction reconstruction** - DISP regressor per telescope, head/tail orientation providing the closest distance between the two predictions selected

Jurysek et al. (2025). `sst1mpipe`: v0.9.0. 13 Nov 2025. Zenodo

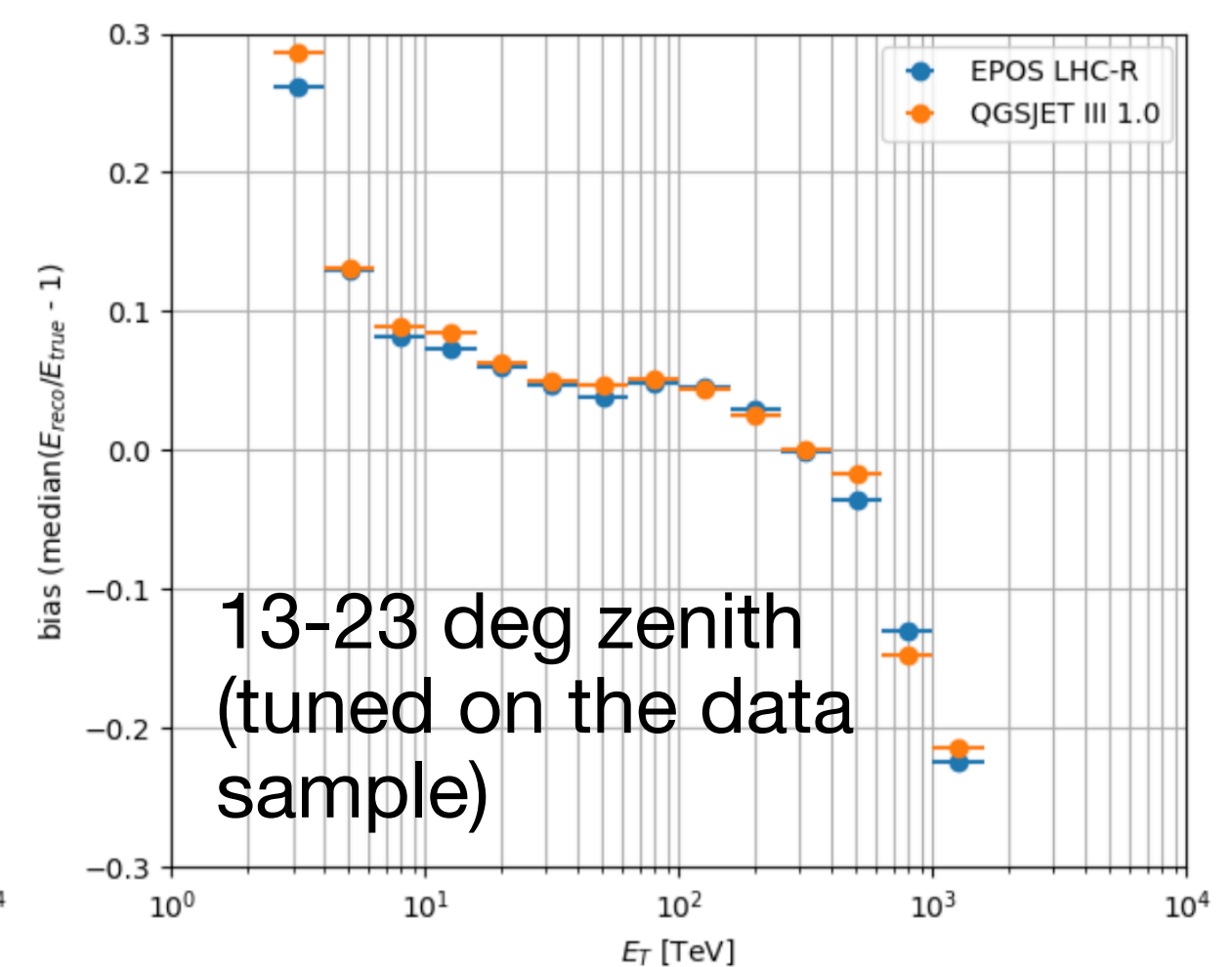
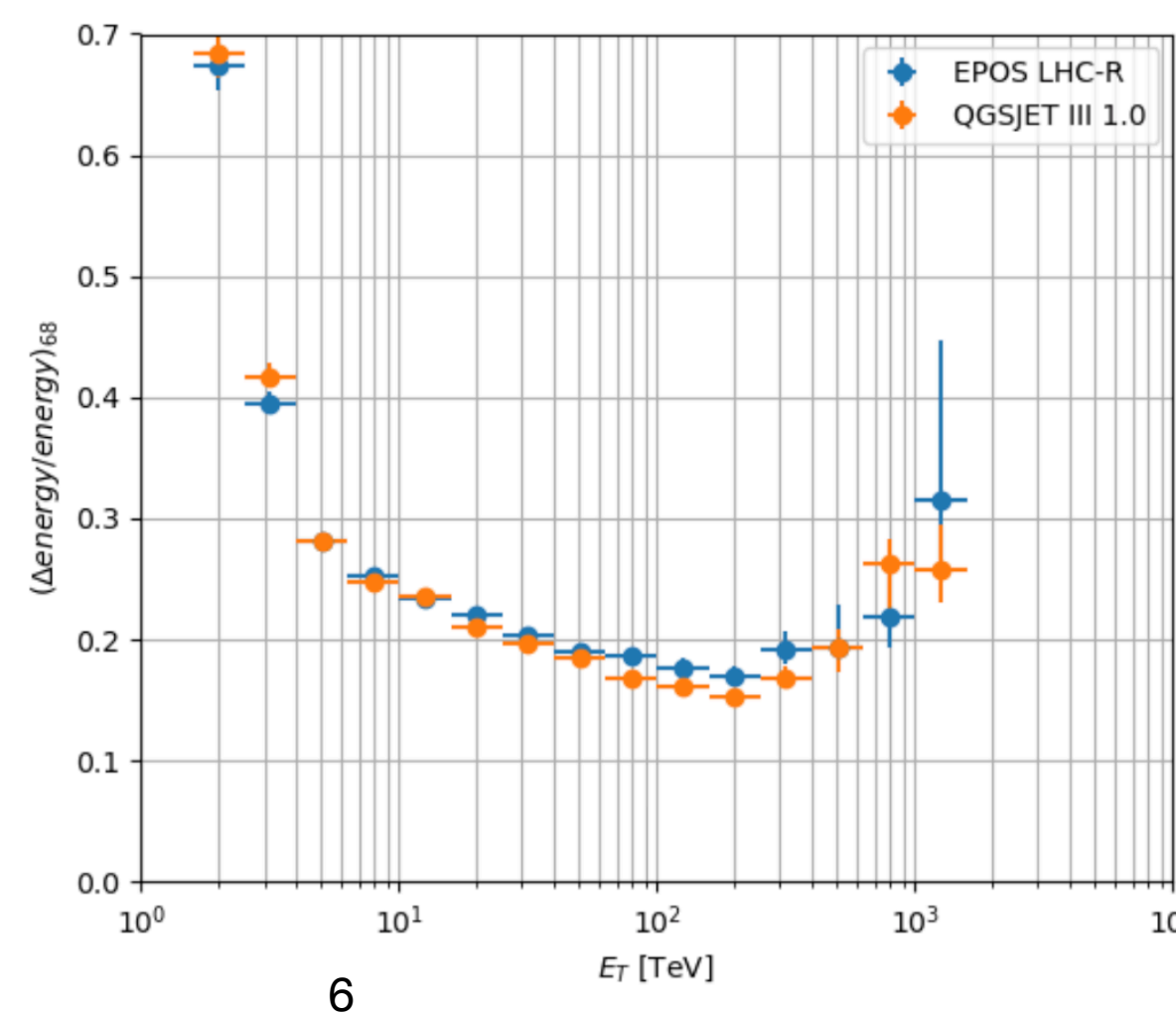


Performance for proton reconstruction

- Evaluated on testing diffuse protons, helium and iron MC
- **p/He classifier** rejects also heavier nuclei. protoness > 0.8 cut adopted for the proton spectrum analysis
- **Energy resolution ~20%, 5% energy bias** (migration matrix produced and forward-folded with the spectrum)



Particle classification
performance

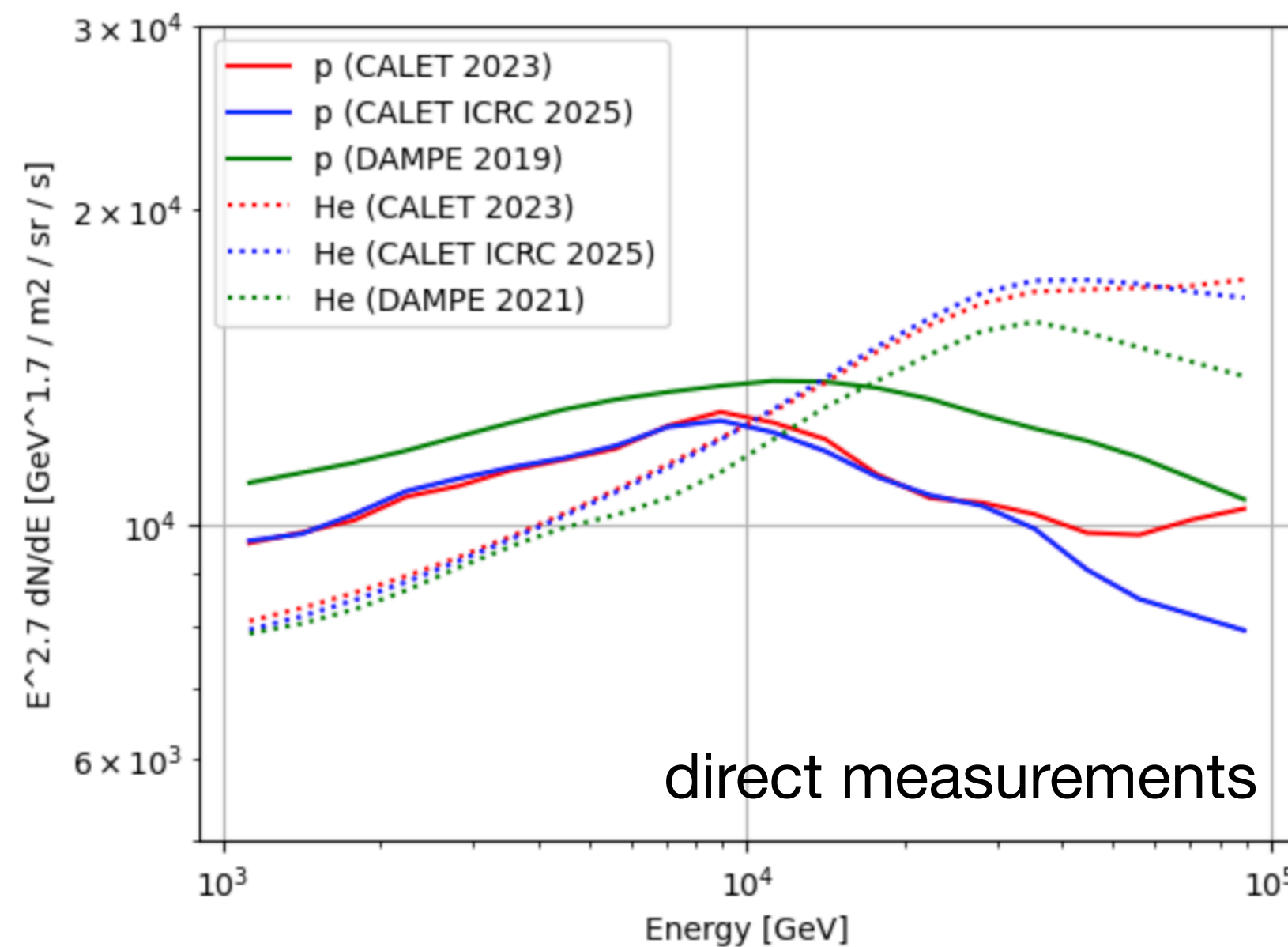


Energy reconstruction
performance

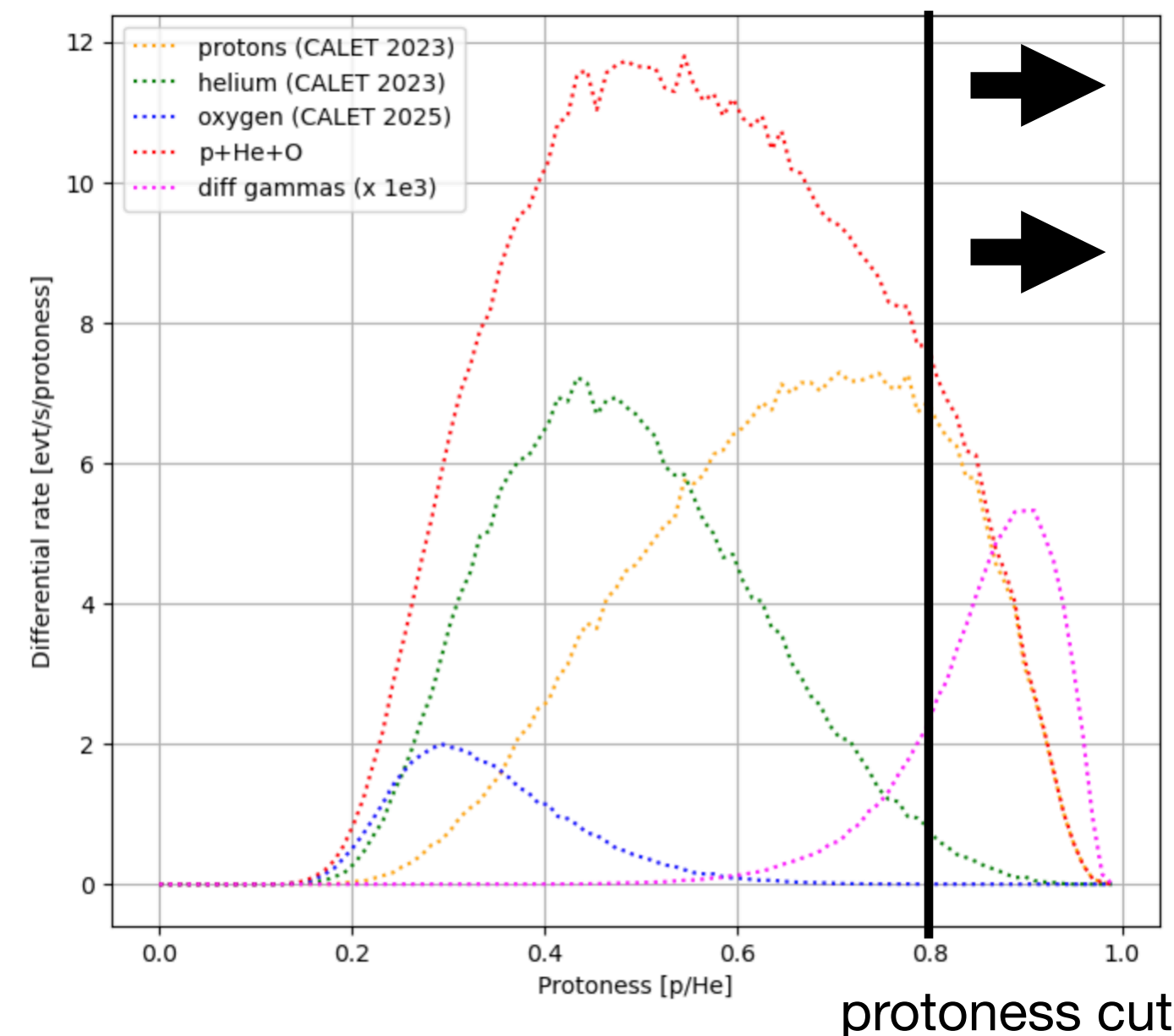
Contamination with heavier nuclei

- Additional MC simulations of **Fe** and **O** to evaluate contamination in the final sample after the cuts
- **Contamination with huclei heavier than helium is negligible**
- Helium contamination can be estimated from direct measurements up to ~ 200 TeV, and with models of composition above that energy
- **Expected helium contamination $< 10\%$ up to 100 TeV**
- Systematic differences between different experiments/models up to $\sim 3\%$ (< 100 TeV) $\sim 10\%$ (> 100 TeV) - **included in our systematic uncertainty**

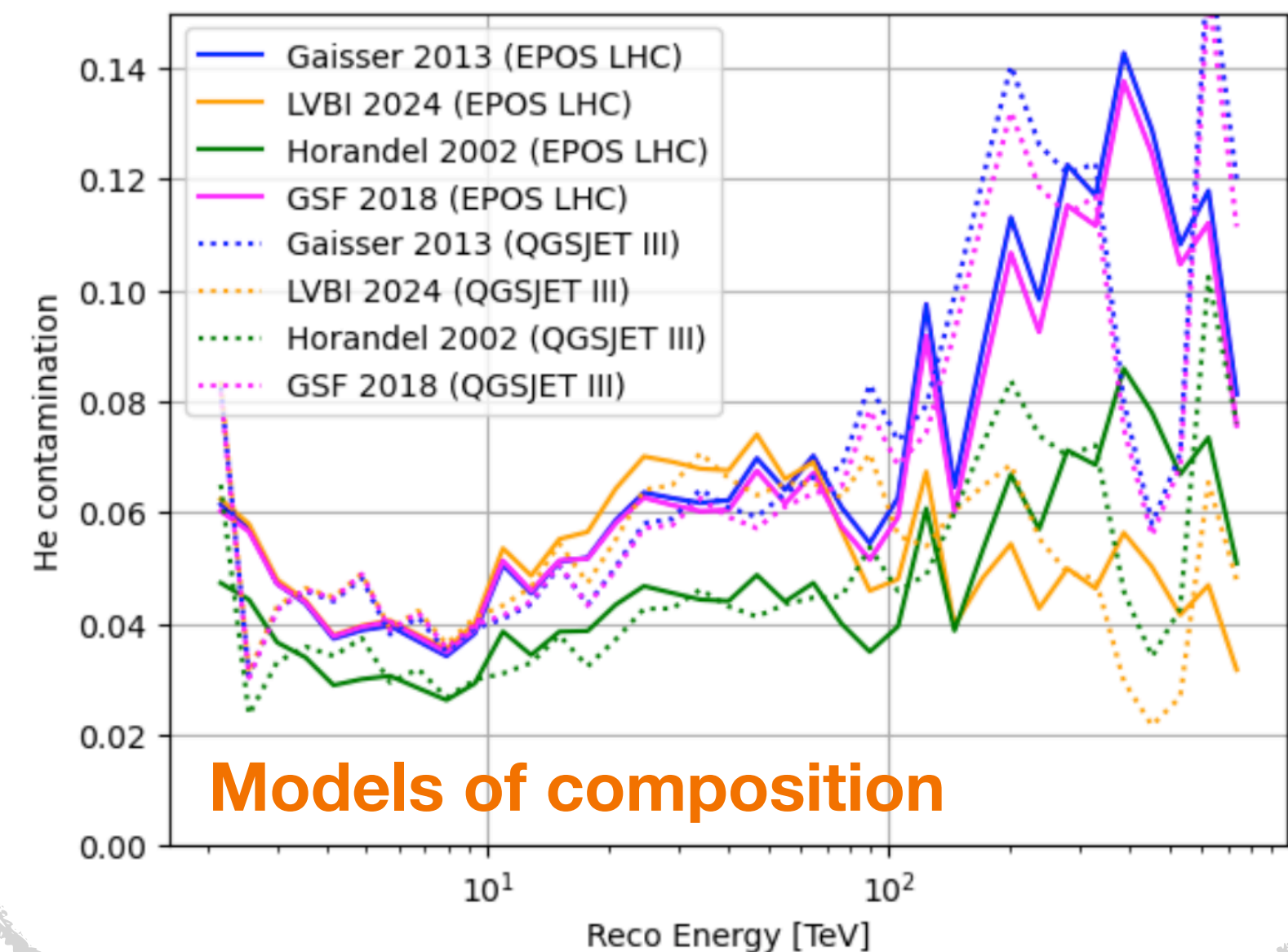
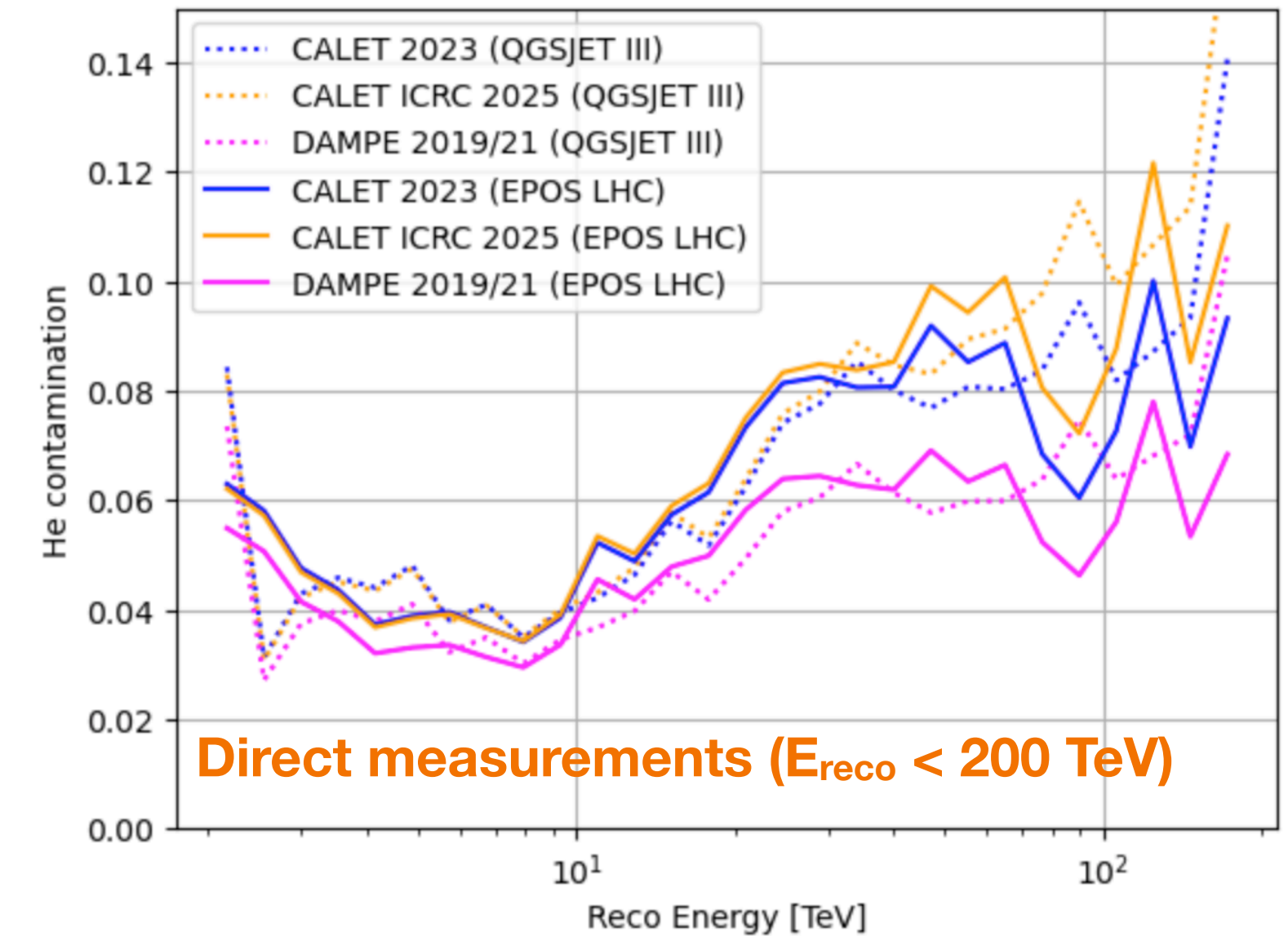
proton and helium CR flux



Reconstructed protoness

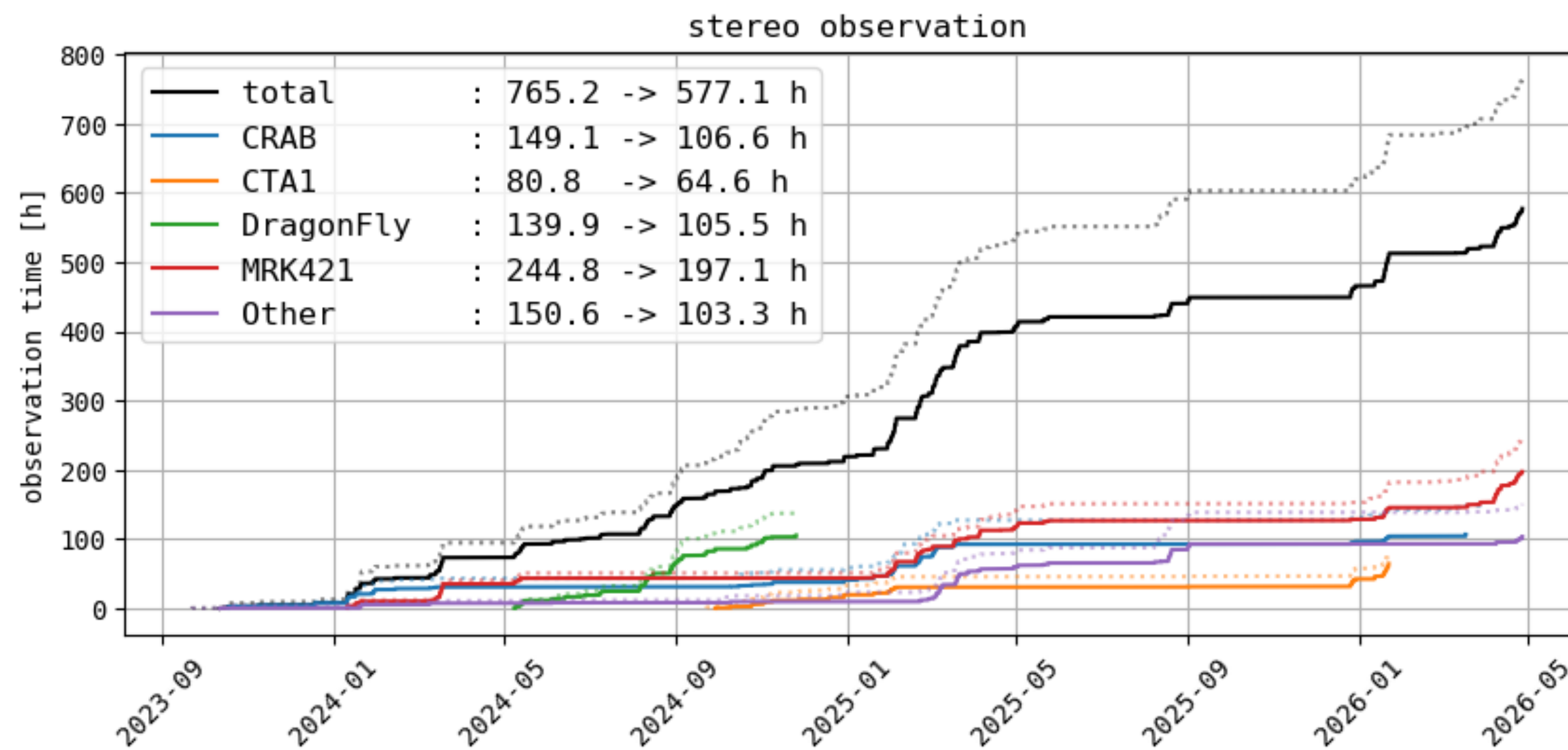


Expected He contamination

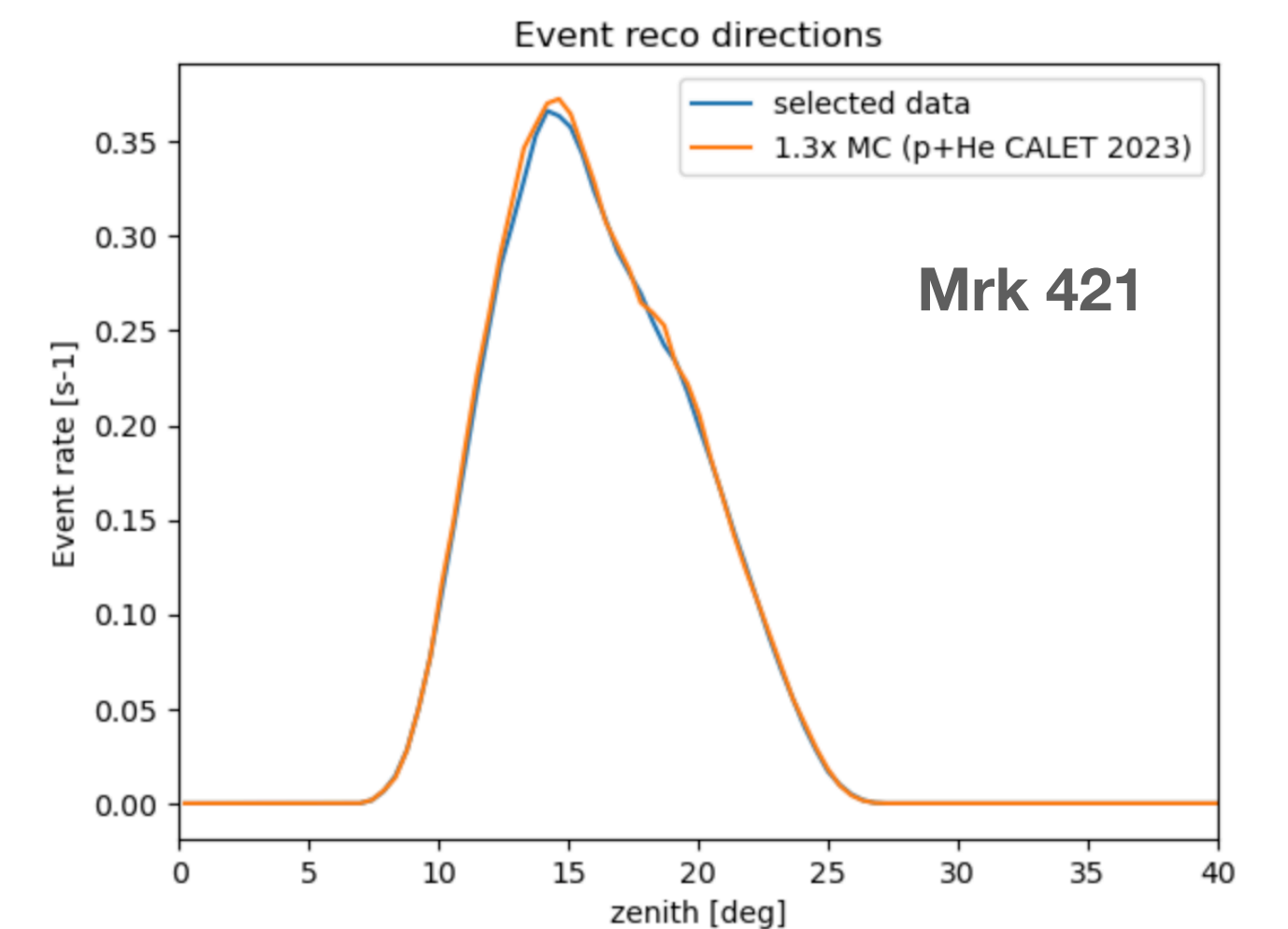
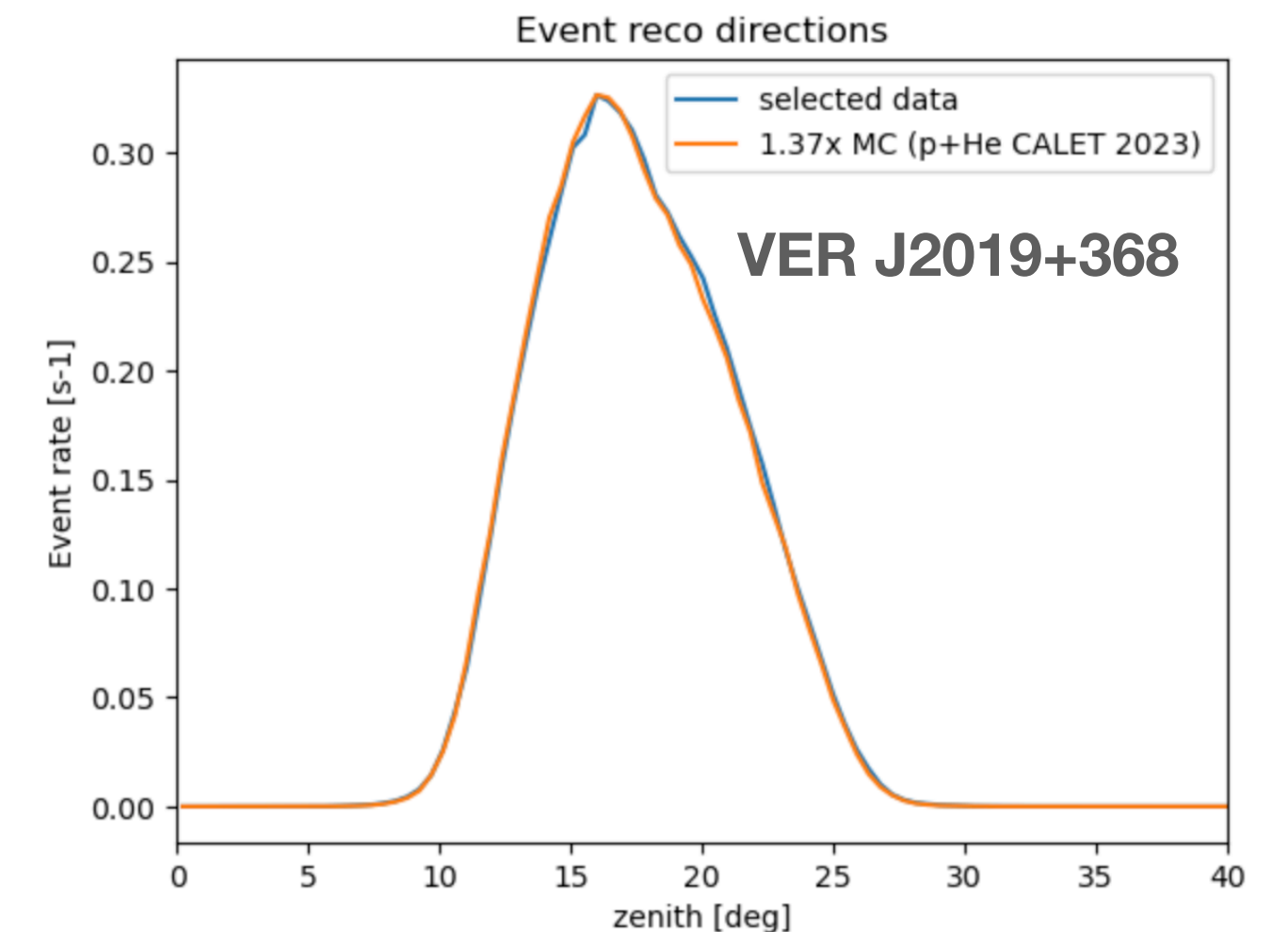


Dataset selection and dedicated MC

- SST-1M conducts deep stereoscopic observations of selected galactic gamma-ray sources, nearby blazars monitoring, and transient follow ups. All data samples are dominated with CR events, which are usually rejected in standard gamma-ray analysis.
- Two large datasets from 2024-2025, **VER J2019+368** (13-23 deg zenith) and **Mrk 421** (12-22 deg zenith), were used for the proton spectrum analysis, selecting only low zenith angle pointings, which resulted in **60 hours of good quality data**
- **Dedicated proton and helium MC** were produced (different interaction models, see slide 10) with precisely tuned distribution of telescope pointing directions



MC with data-tuned pointing

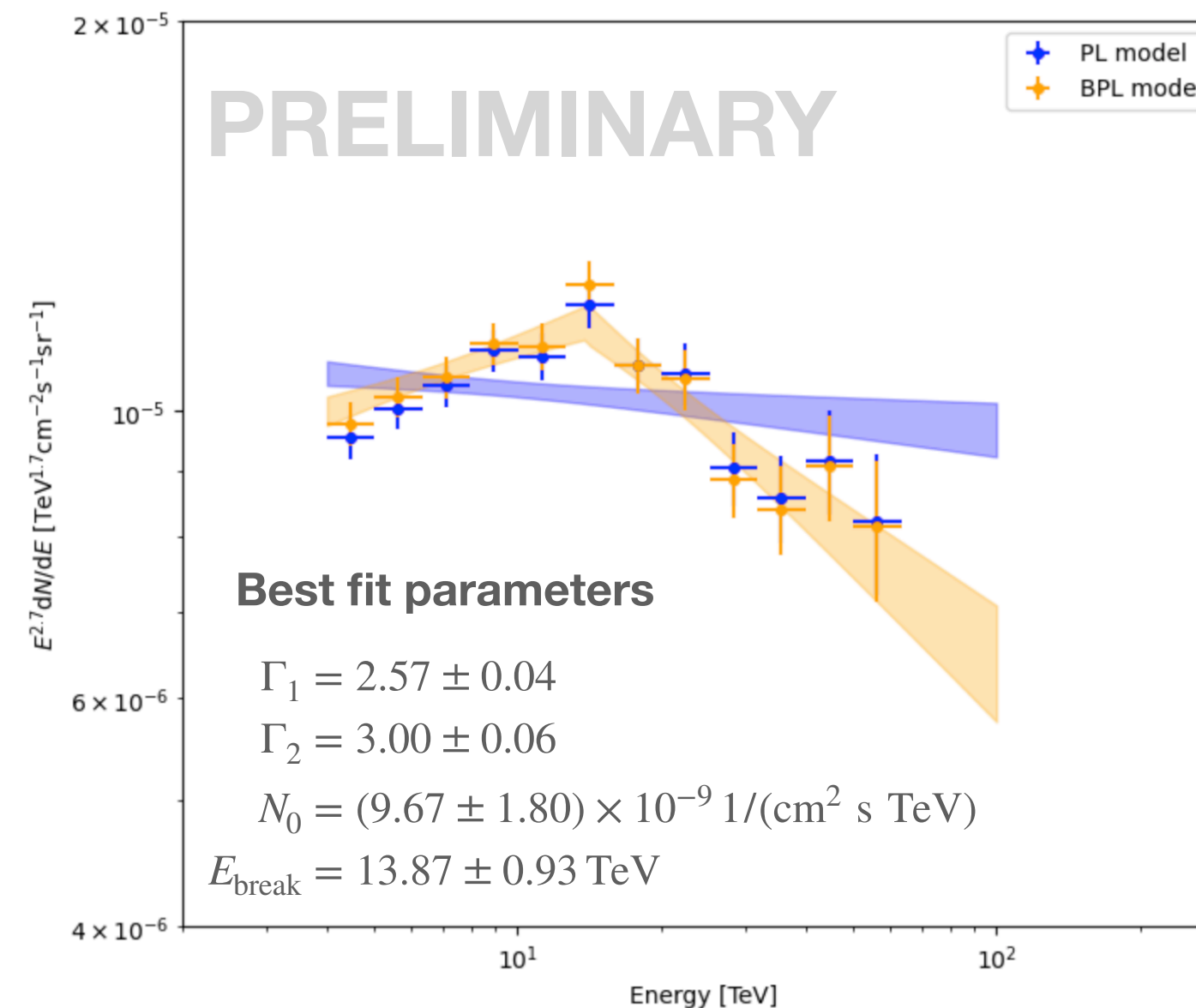
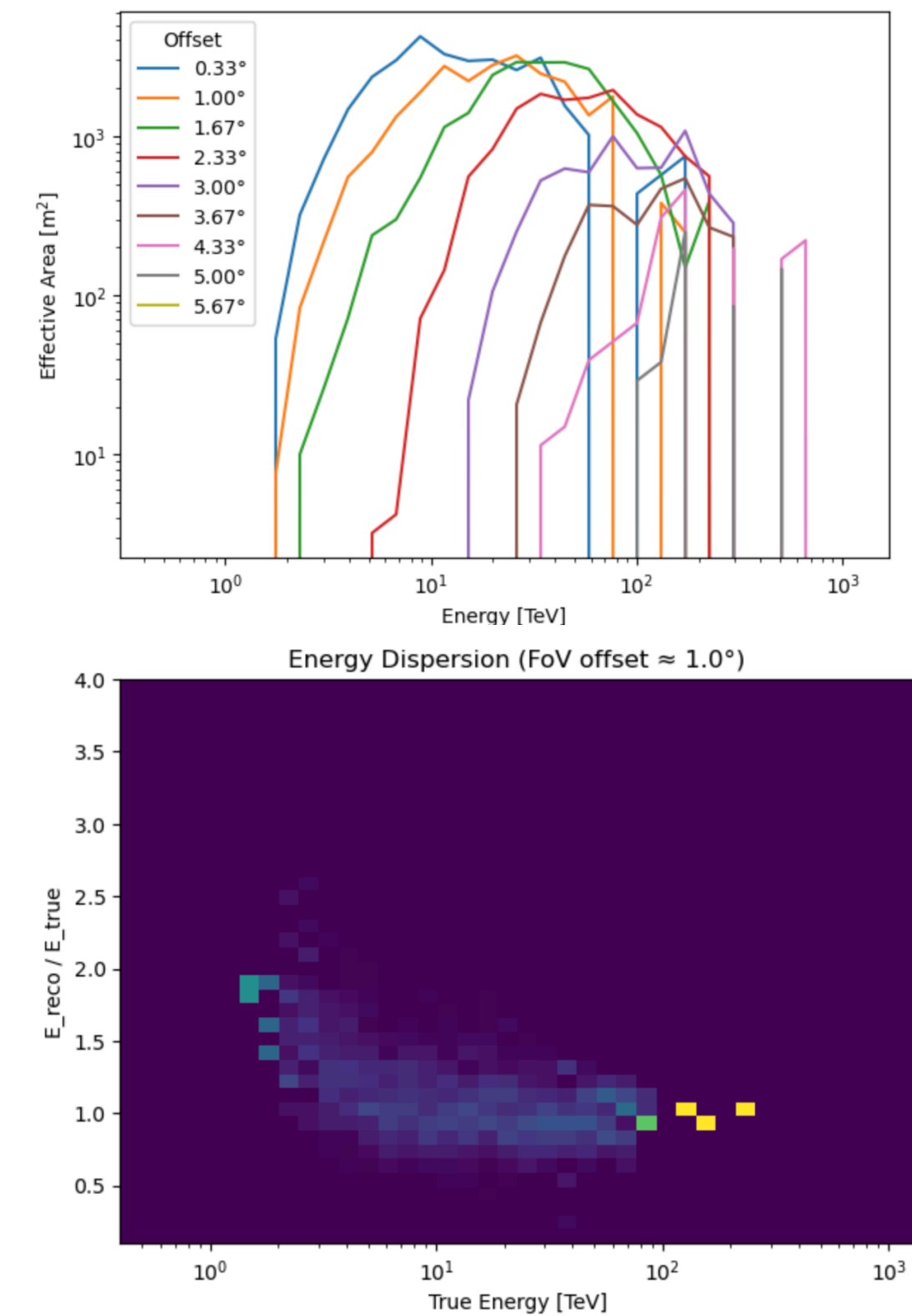


Proton spectrum reconstruction

- Joint analysis of both stacked datasets in gammapy
- Limited MC statistics in IRFs -> energy range of the analysis (2, 60) TeV
- Known gamma-ray sources masked (VER J2019+368, CTB 87, Mrk 421) to avoid gamma-ray contamination
- Fixed helium background in the model (differences between models go to systematics, see slide 10)
- Likelihood ratio test of Broken power-law vs power-law spectral shapes => BPL with **spectral break at 13.87 +/- 0.93 TeV strongly preferred**

IRFs

- proton (Aeff, migration matrix and PSF) and helium (bkg) MC
- GSF (Dembinski 2025) spectrum assumed for the helium bkg
- EPOS LHC-R model of hadronic interactions in MC



BPL vs. PL

$$\Delta\text{TS} = 2(\ln \mathcal{L}_{\text{BPL}} - \ln \mathcal{L}_{\text{PL}}) = 26.0$$

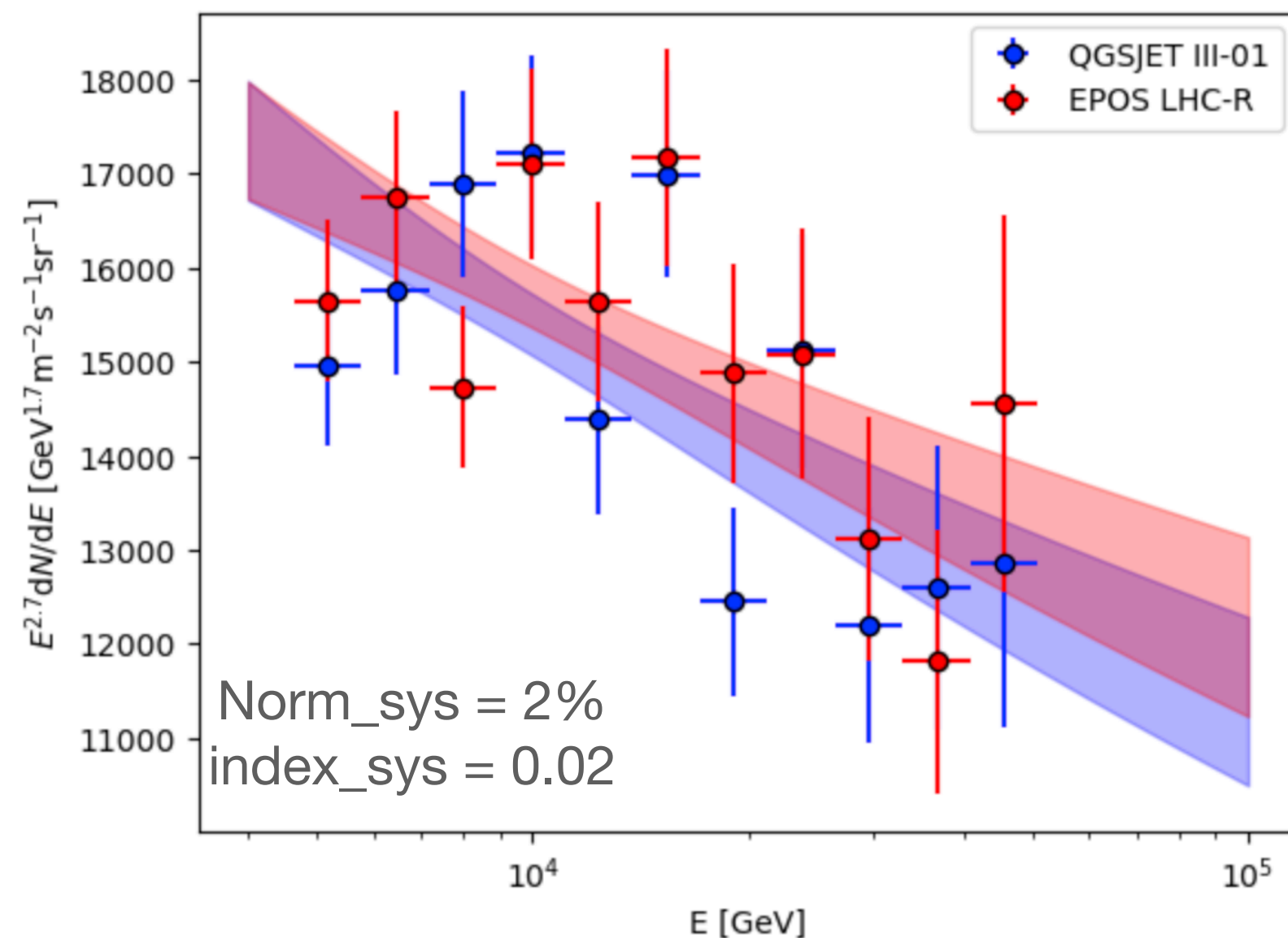
Corresponding to **4.7 σ** under Wilks' theorem with 2 d.o.f.

$$\Delta\text{AIC} = 22, \Delta\text{BIC} = 19$$

Evaluation of systematic uncertainties

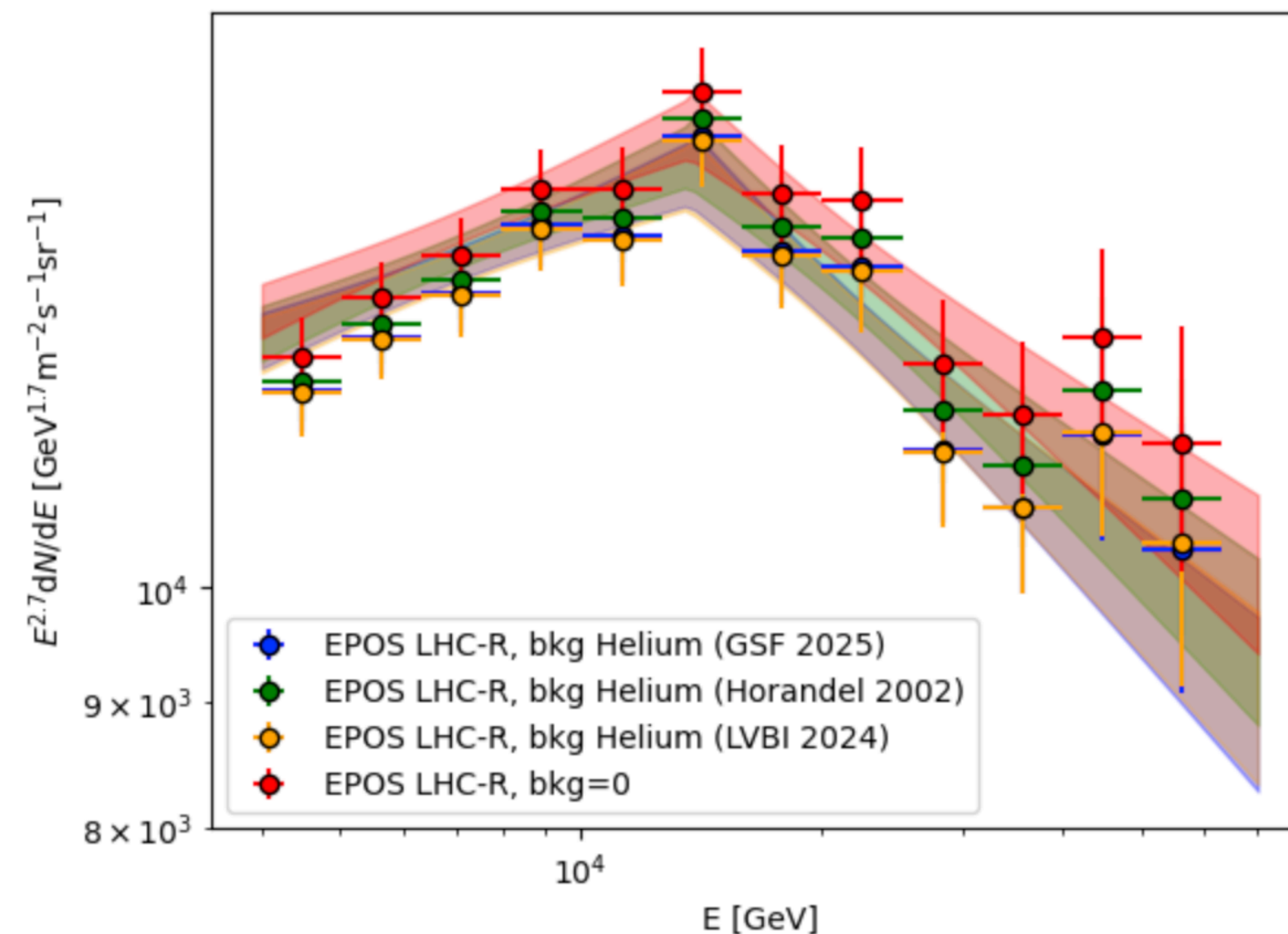
Interaction models: EPOS LHC-R / QGSJET III 1.0

- Full analysis (including the RF training) repeated for two interaction models
- Tuned MC with QGSJET III 1.0 only available for the VER J2019 dataset -> smaller sample, only comparison of PLs



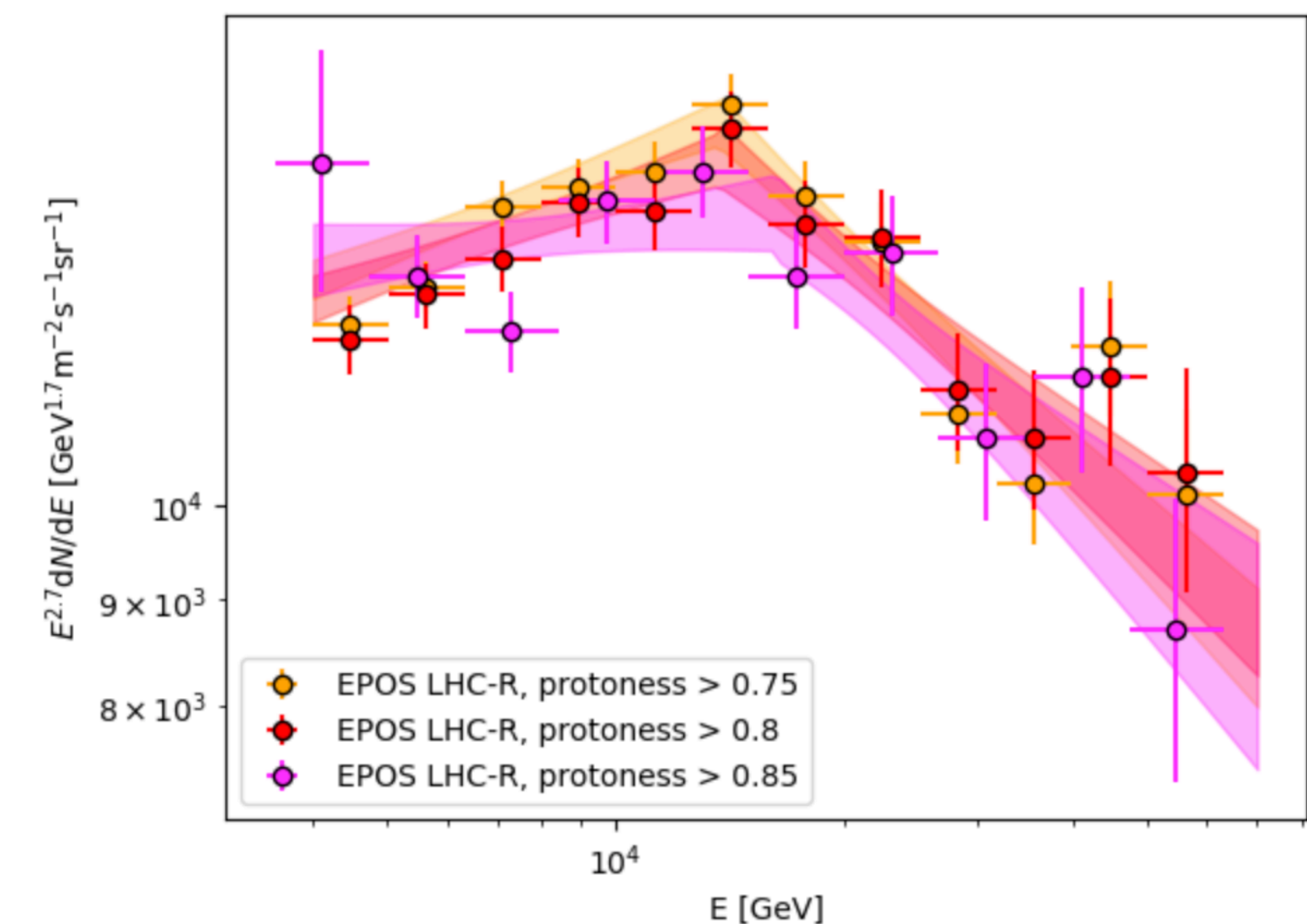
Residual bkg from different models

- Full analysis with different bkg models in the IRFs (all fixed in the gammapy analysis)
- Both data samples, EPOS LHC-R only



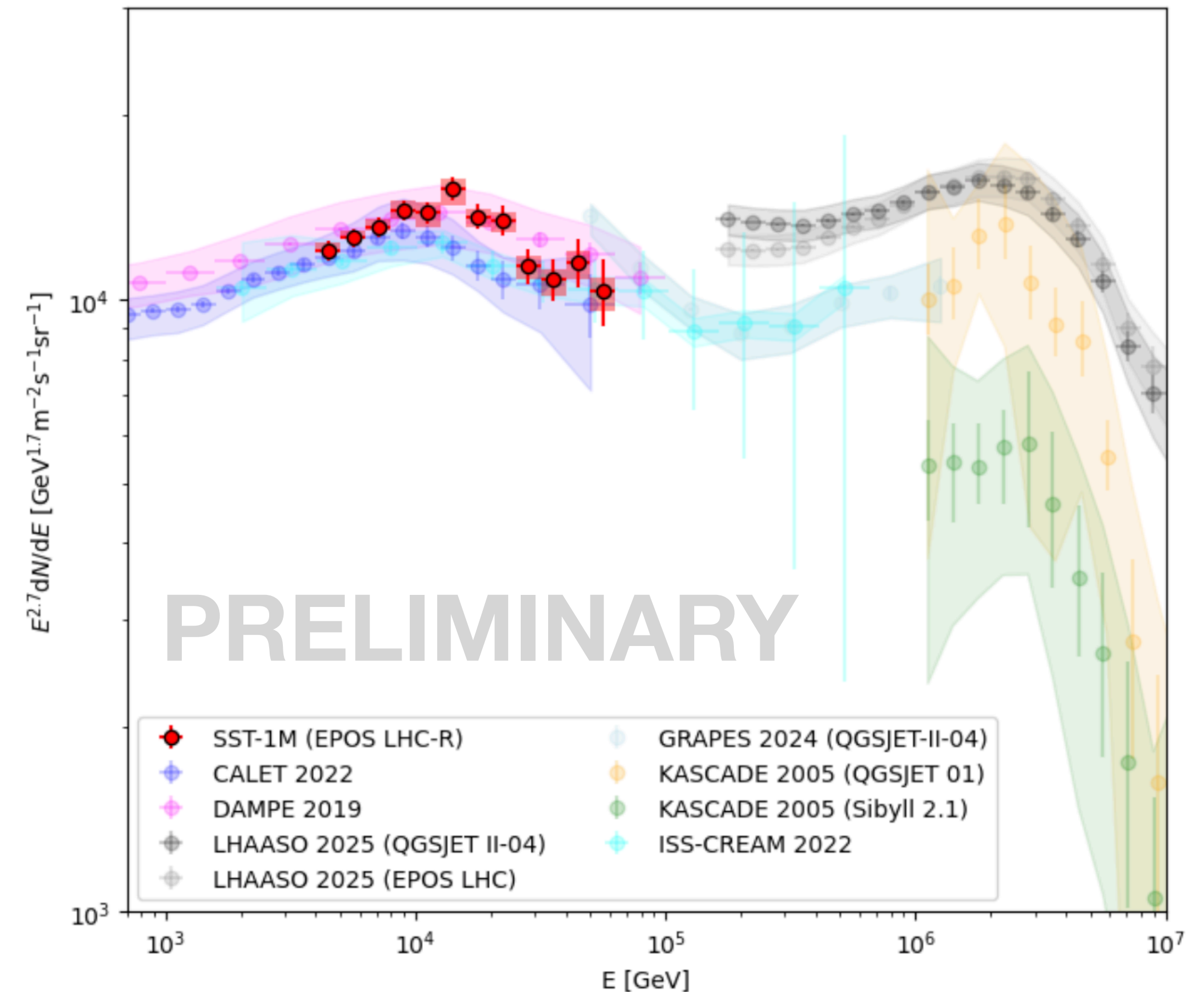
Sensitivity to the protoness cut

- Full analysis with different protoness cut - the fixed bkg model compensates reasonably well the Helium contamination (heavier nuclei contribute to the remaining differences, but they are small) in a reasonable range of protoness
- Both data samples, EPOS LHC-R only



Summary

- The first proton spectrum derived from the SST-1M data looks promising
- **Broken power-law spectrum with a spectral break at 13.87 ± 0.93 TeV strongly preferred**
- Results so far limited by statistics (in both data and MC) - joint analysis of more SST-1M data samples to be considered (**only about 10% of the total SST-1M good quality data in the sample presented**). Extension to 100 TeV and beyond can be expected.
- SST-1M proton spectrum consistent with the other instruments within the uncertainties



Thank you

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Registration number: CZ.02.01.01/00/22_010/0008598



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Back up slides

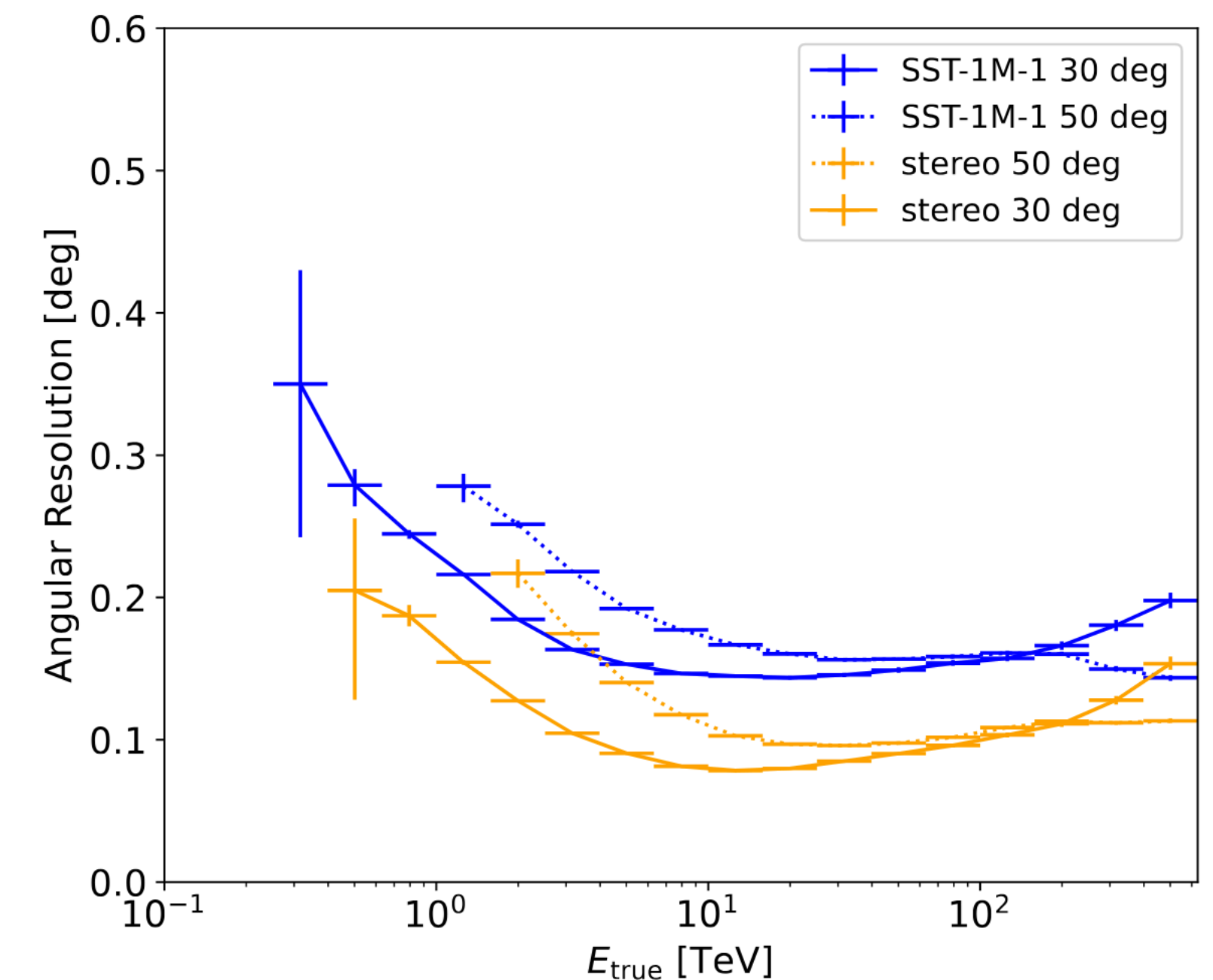
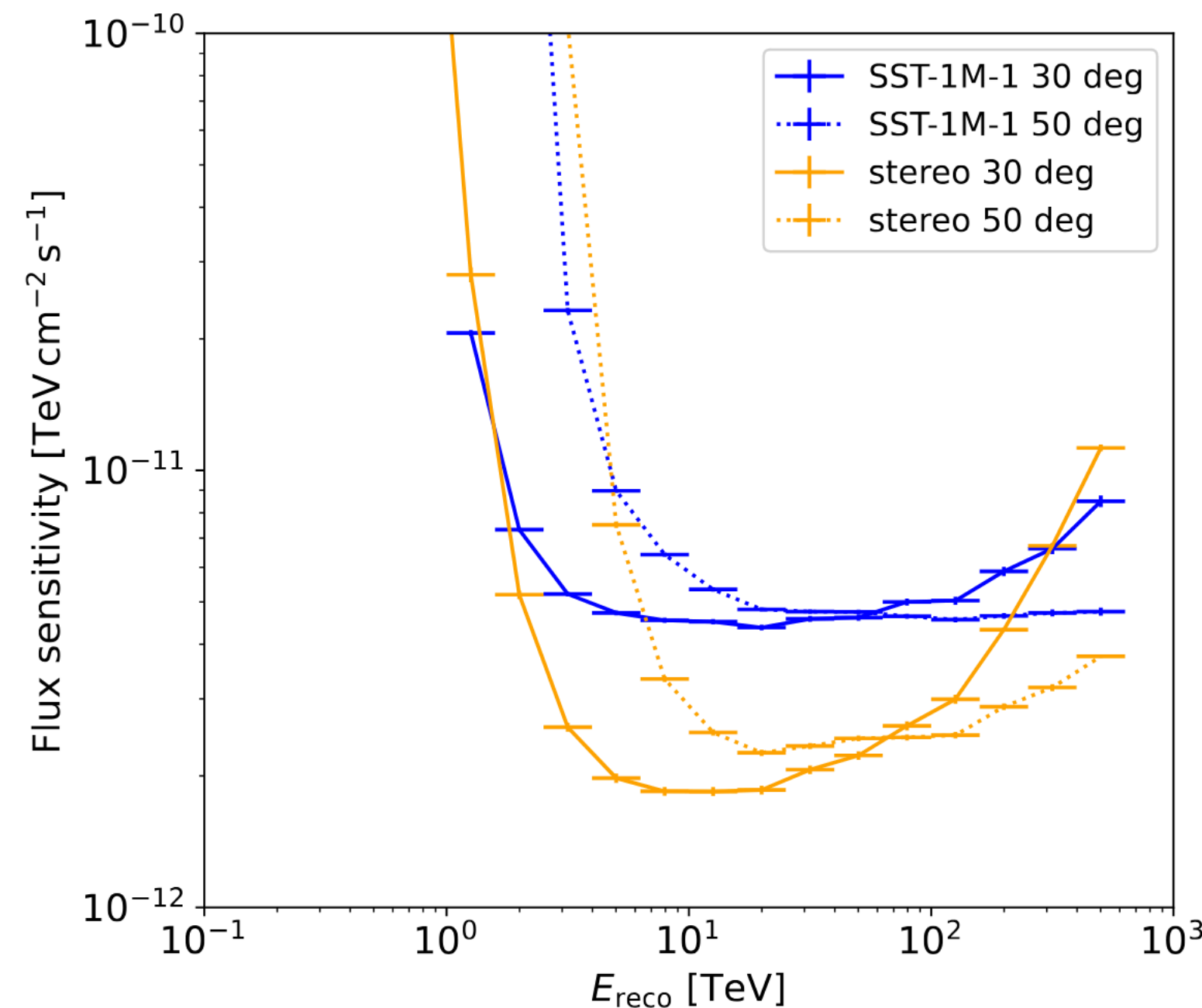
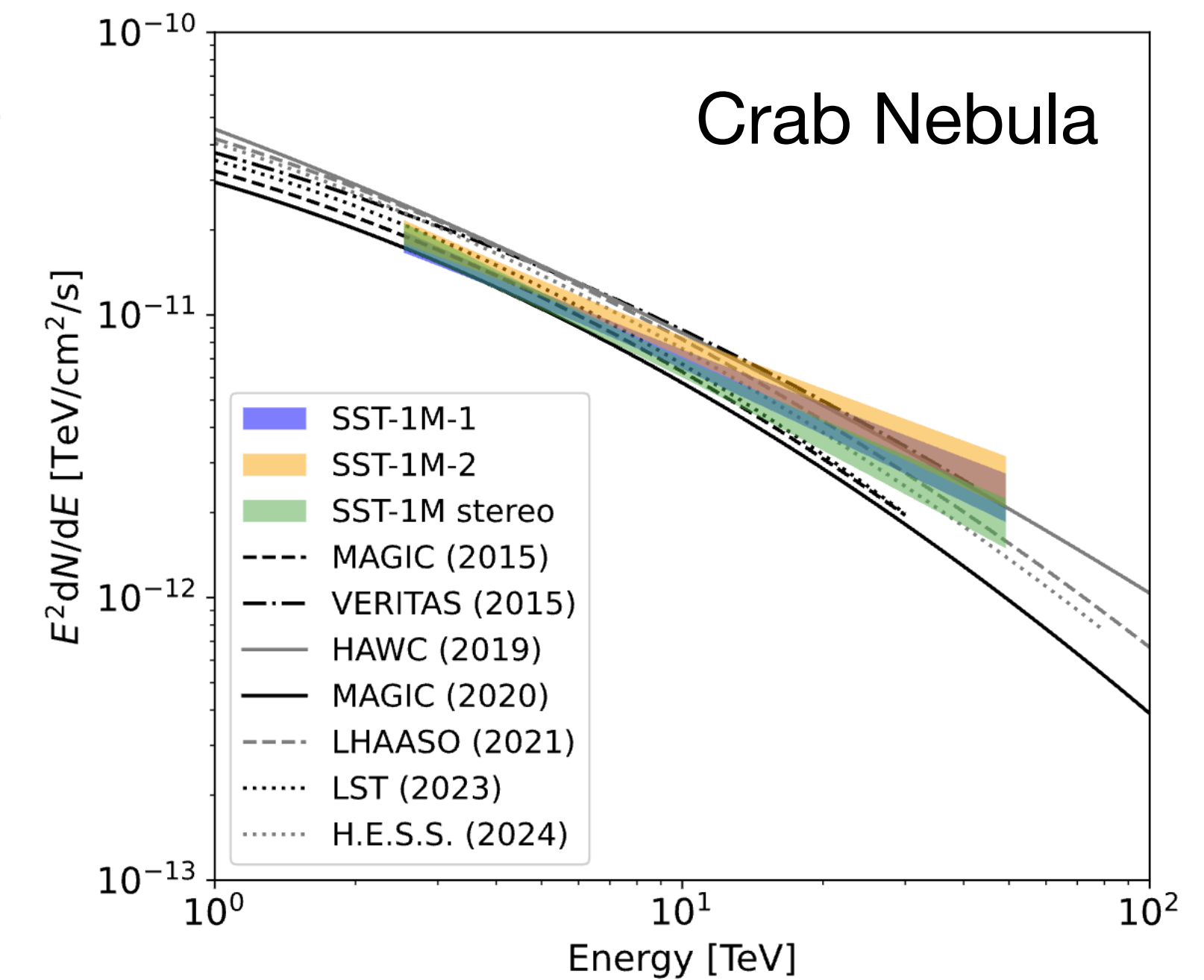
SST1-M performance at low altitude

Gamma-ray performance

- Given **large FoV** and **low altitude**, SST-1M probes the highest gamma-ray energies among existing IACTs
- Significant improvement of stereo over mono reconstruction
- Systematics effects well understood:
 - Energy scale: $< 10\%$
 - Flux normalisation $\approx 23\%$
 - Spectral index $\approx 3\%$

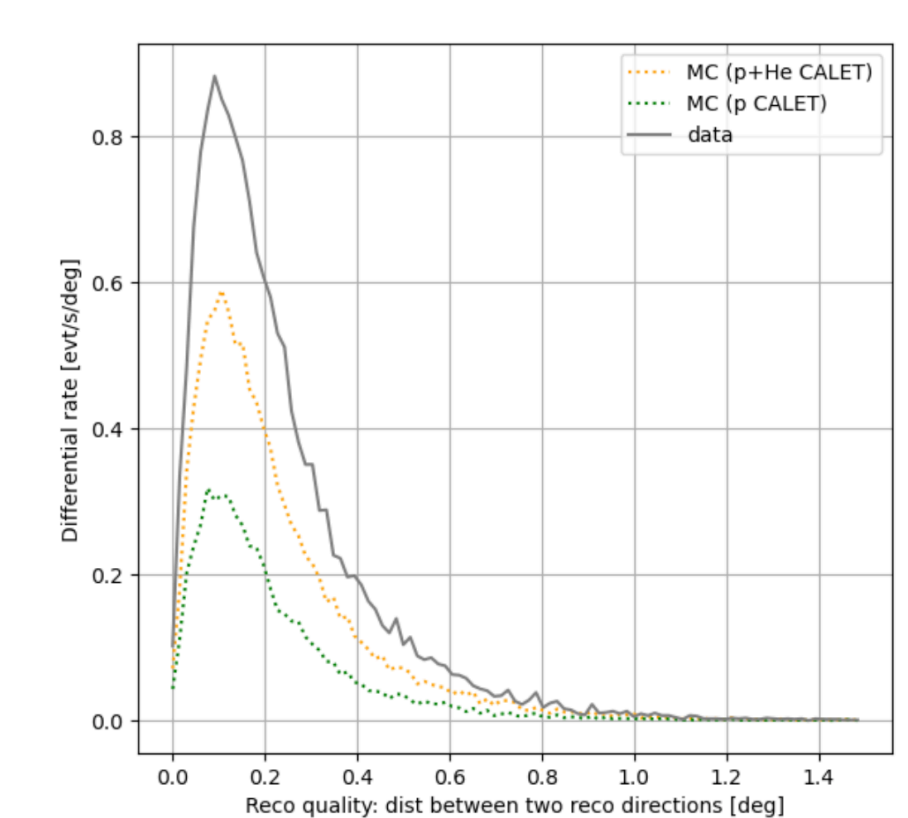
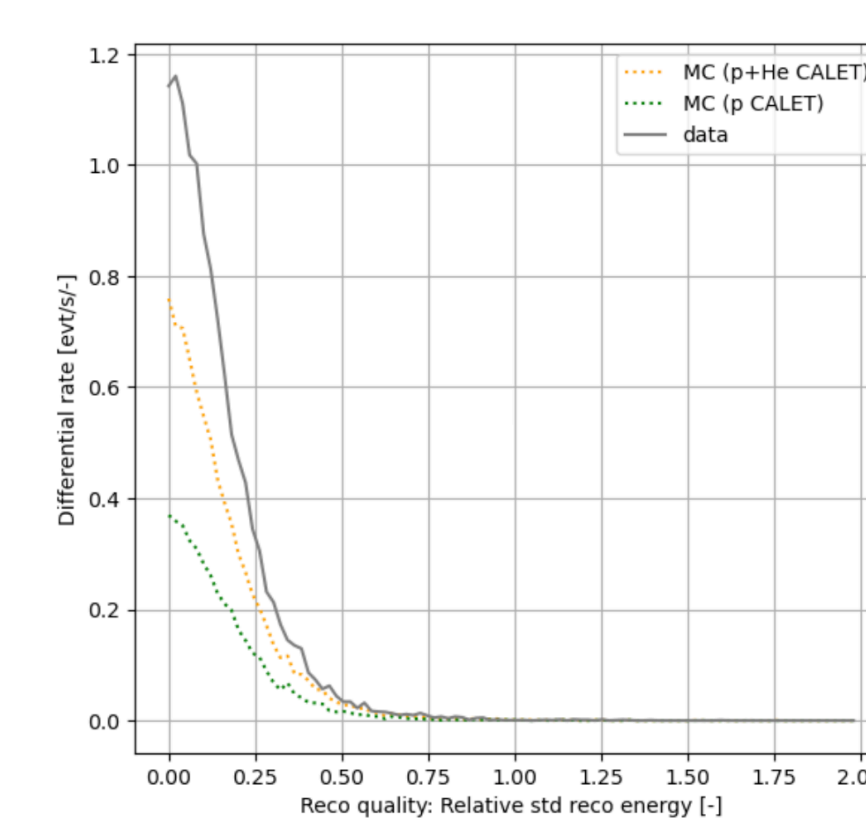
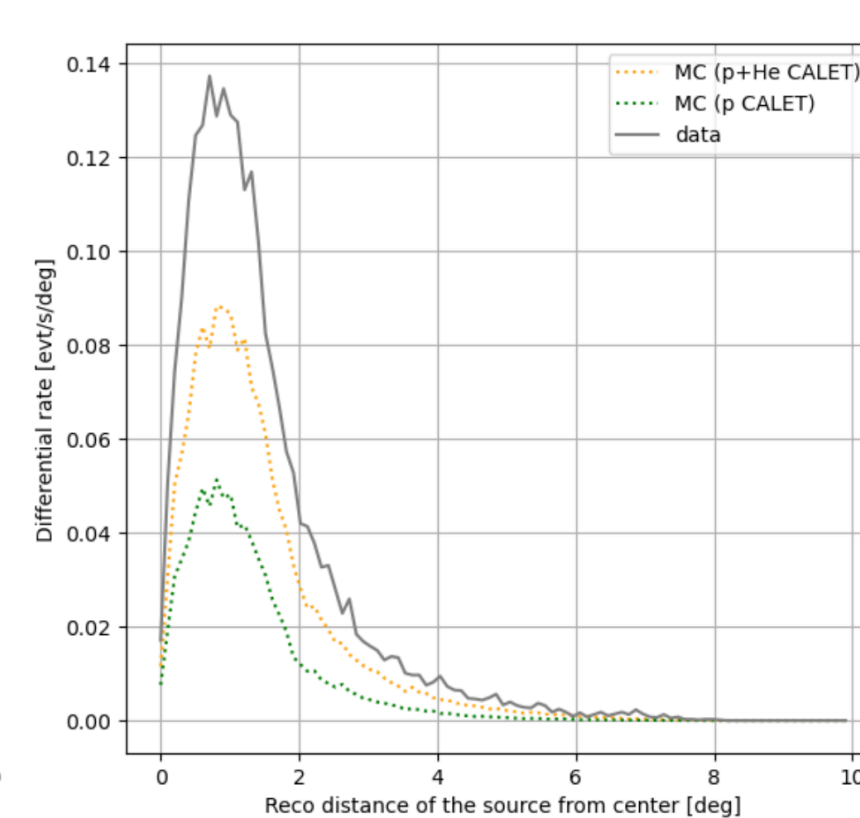
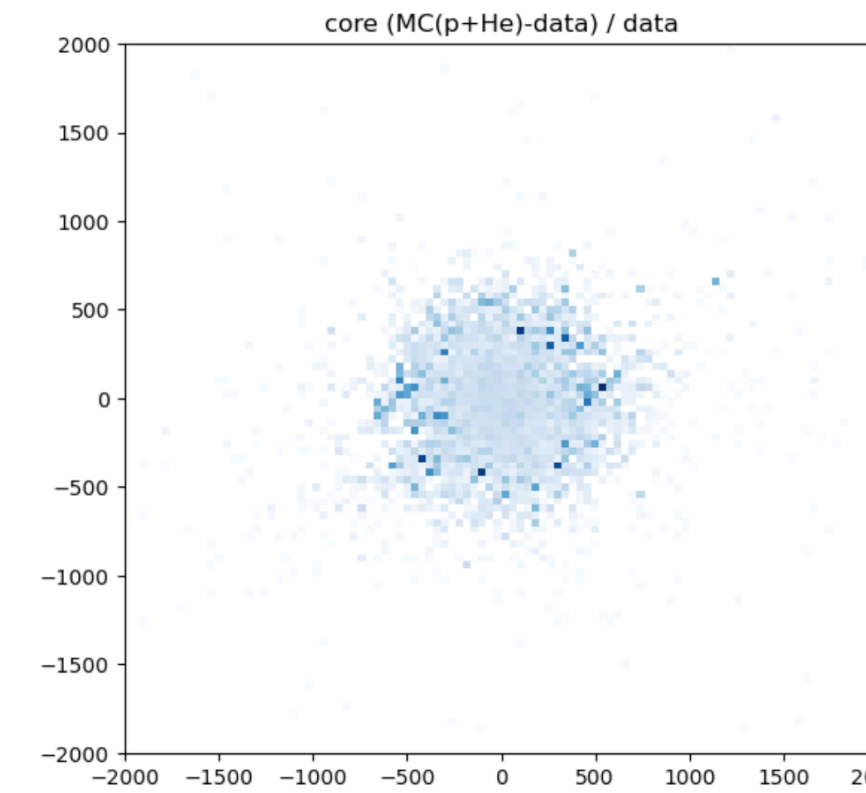
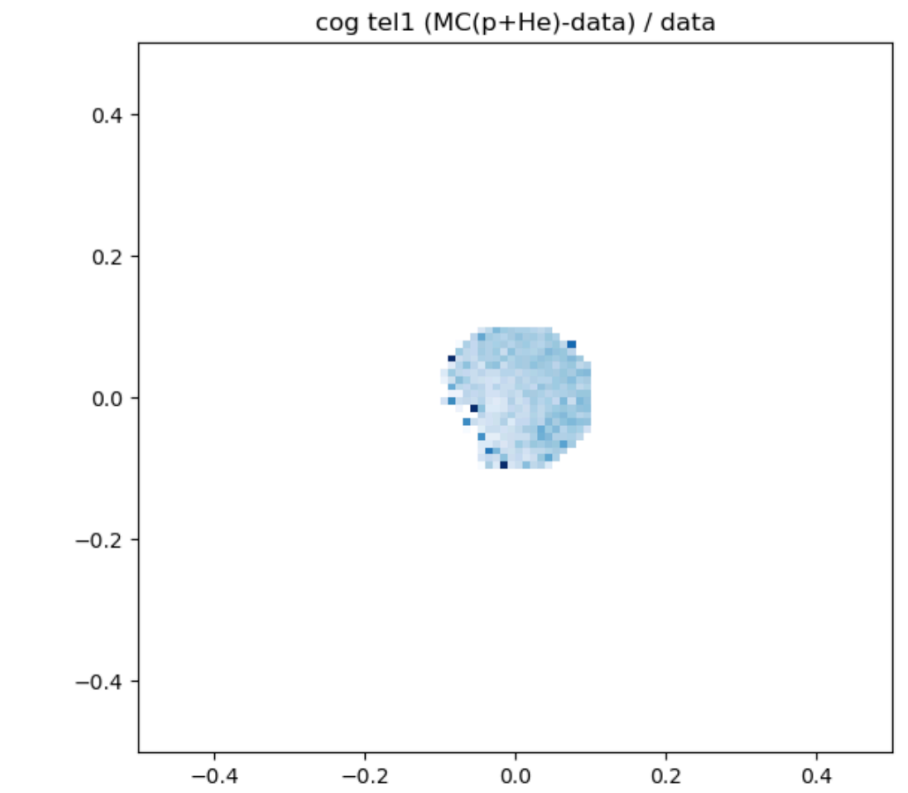
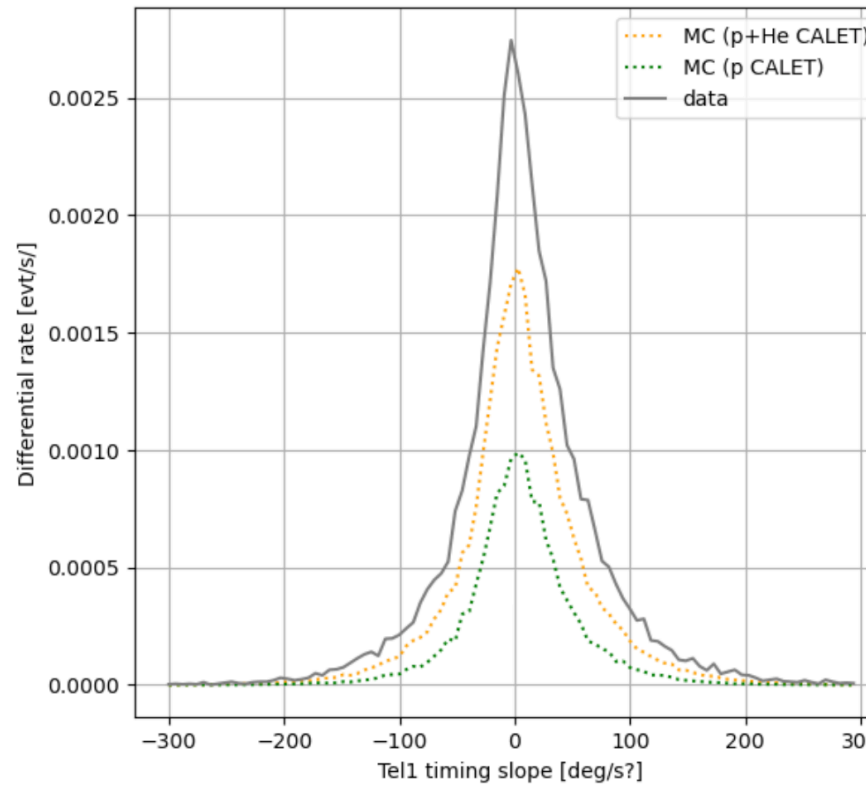
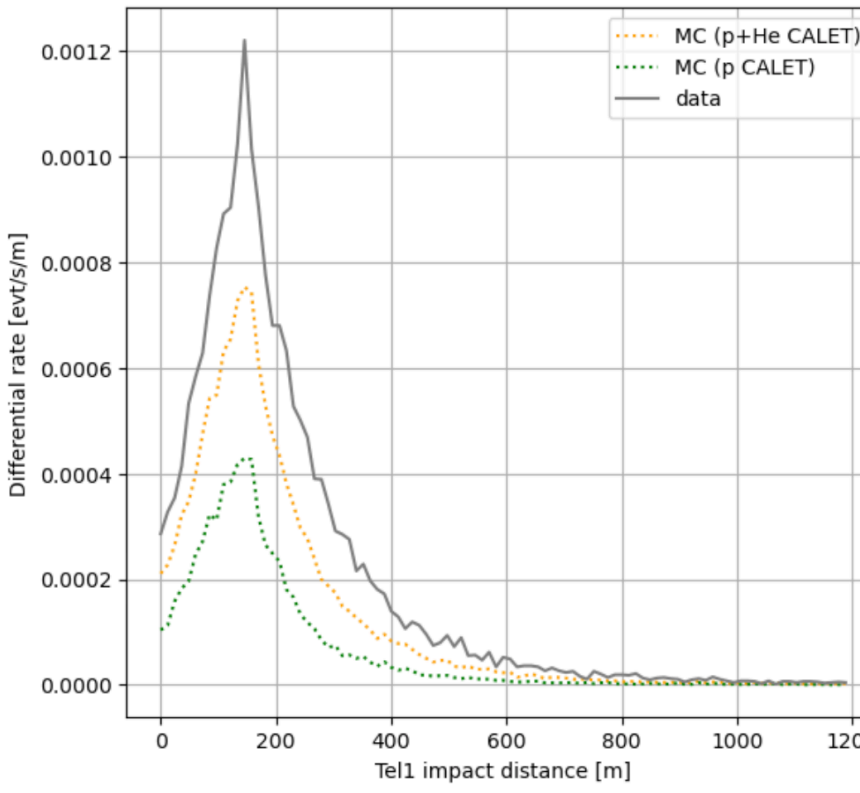
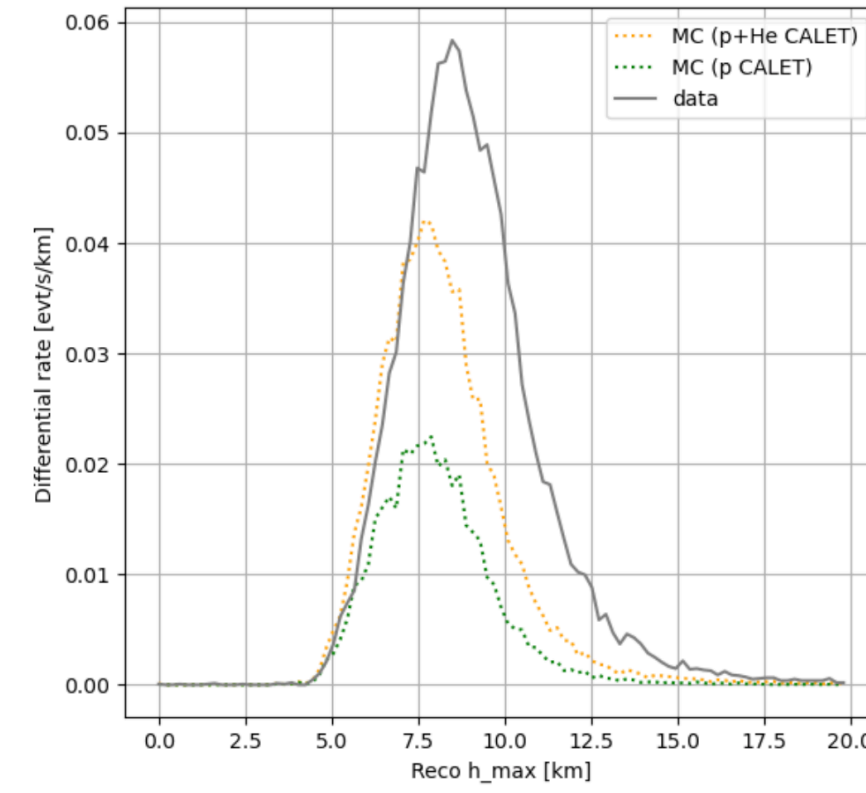
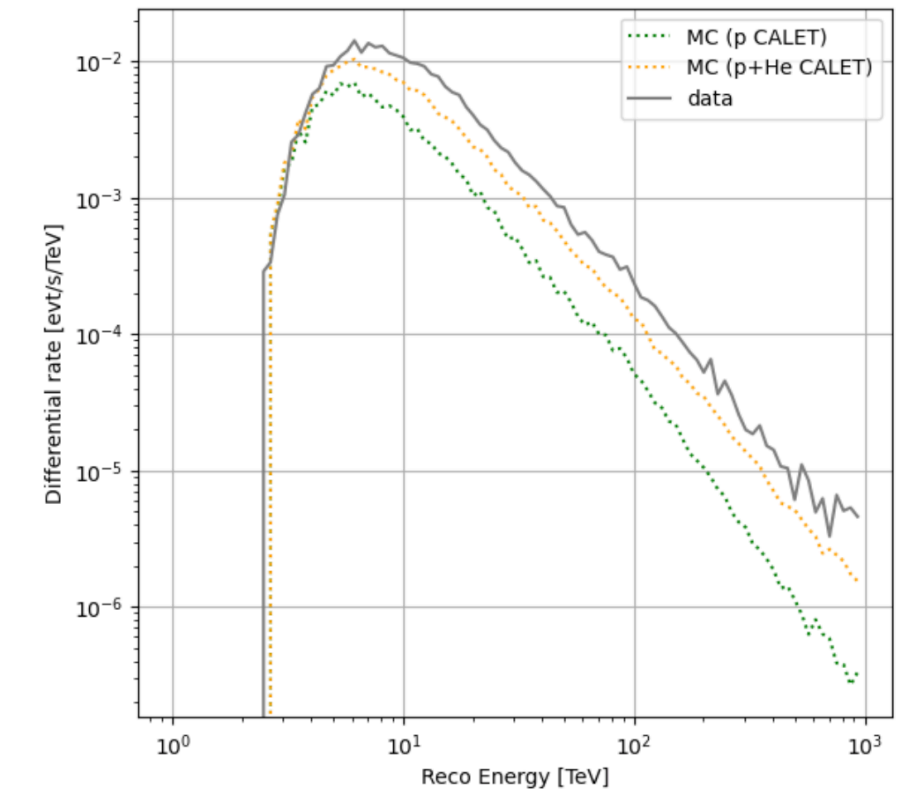
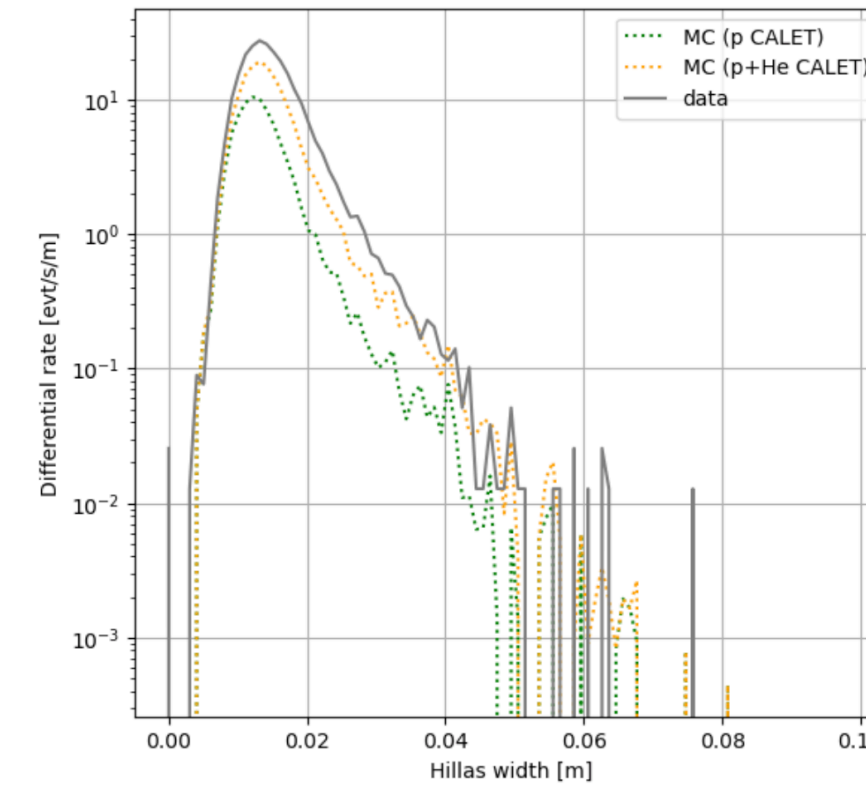
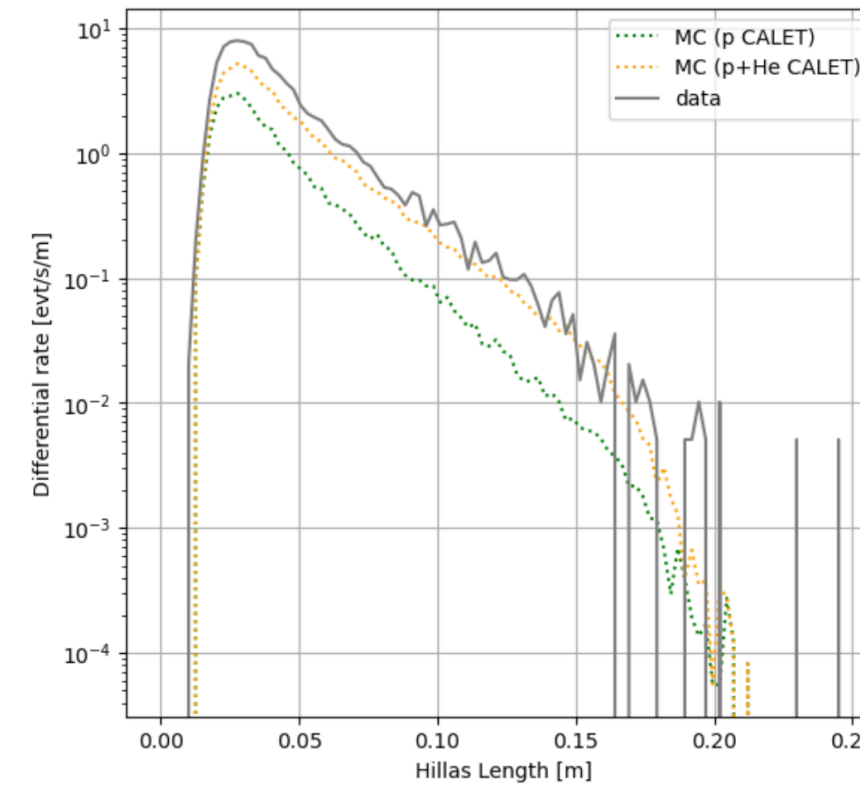
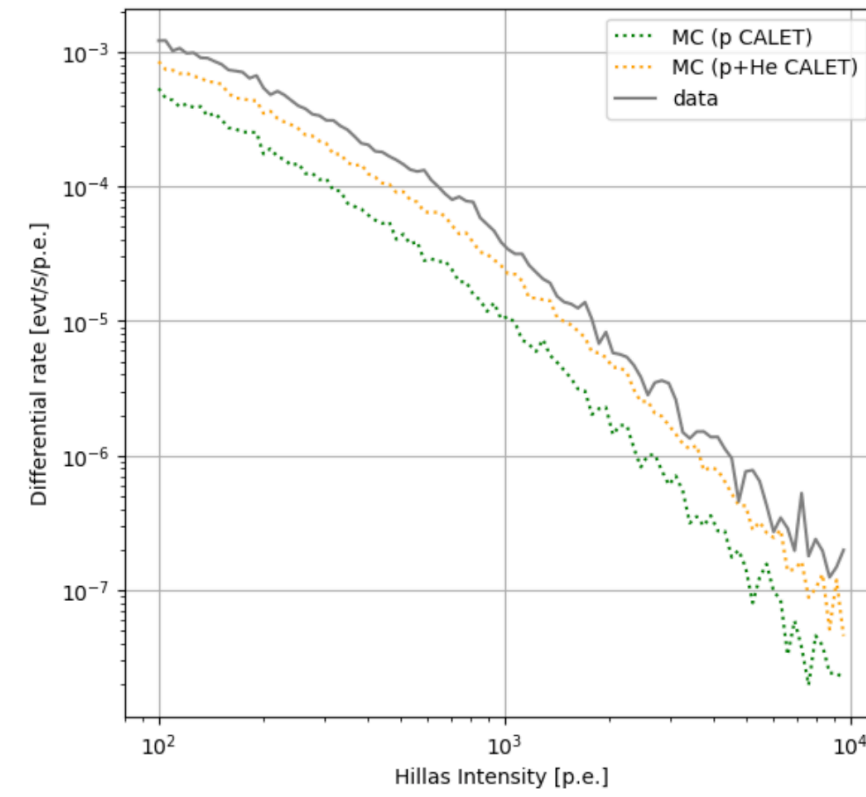
SST-1M performance paper -
[2025A&A...699A.255A](#)

SST-1M performance studies:
Jurysek et al., 2019, arXiv:1907.08061
Jurysek, et al., 2023, arXiv:2307.09799



Detailed comparison of DL2s in MC/data

- Dragonfly sample, MC QGJSJET III
- All events (after basic quality cuts)
- Except for hmax, the agreement in the rest is fine
- Relatively strong cut on CoG is required to reach good agreement in h_max (not yet understood)



Galactic diffuse gamma-ray flux

How important is the diffuse galactic background in the VER J2019 sample?

=> should be negligible

$l \sim 77$ deg, $b \sim 1$ deg

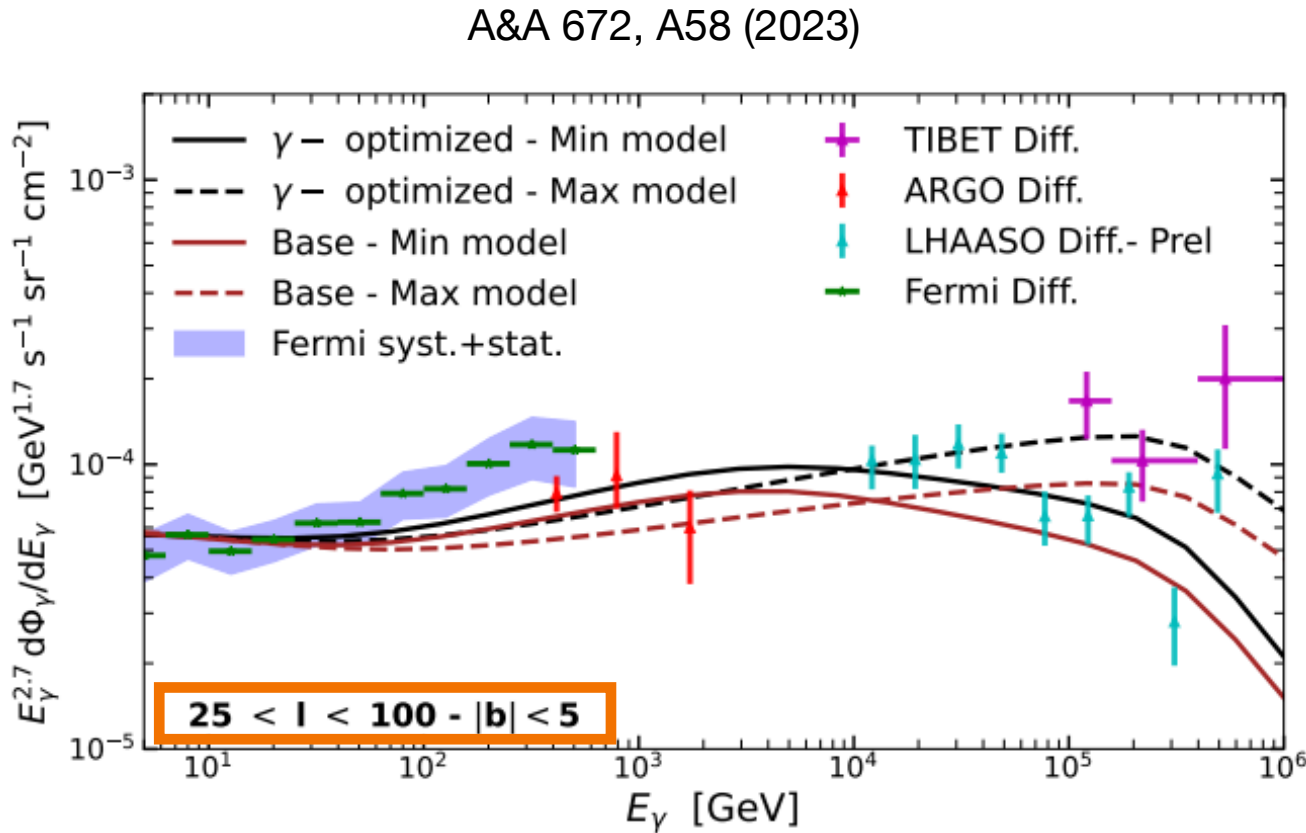
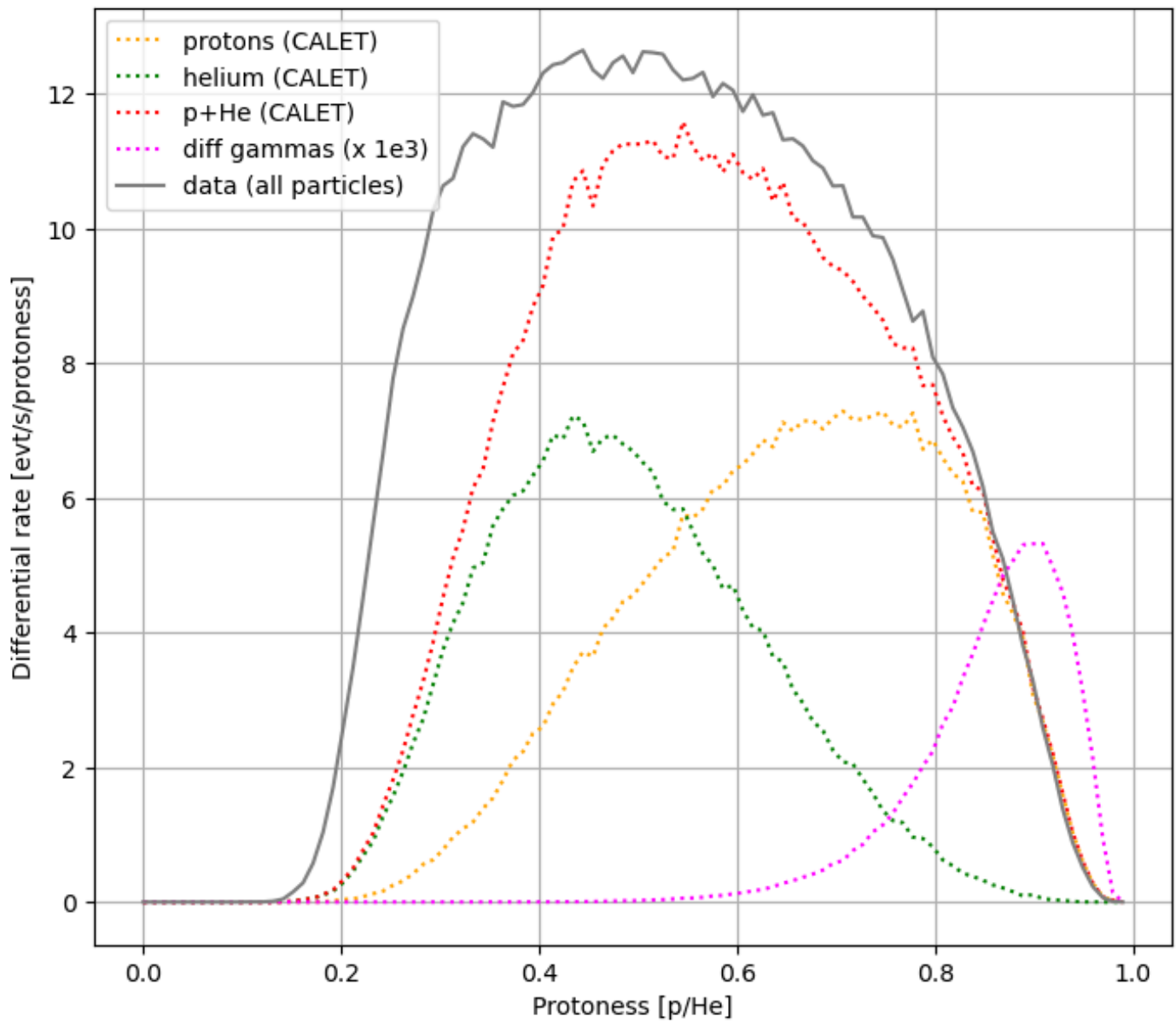


Fig. 4. Gamma-ray spectra computed within the conventional (Base) and γ -optimized scenarios compared to Tibet AS γ (Amenomori et al. 2021) and LHAASO (Zhao et al. 2021; preliminary) data in the window $|b| < 5^\circ$, $25^\circ < l < 100^\circ$. The Galactic diffusion emission spectrum measured by *Fermi*-LAT and extracted as discussed in Sect. 2.2, and the ARGO-YBJ data (Bartoli et al. 2015) in the same region, are also shown. The contribution of unresolved sources, which may be significant at the highest energies, is not shown. The models account for the effect of γ -ray absorption onto the CMB photons (see Sect. 3.2).

Distribution of protoness, including diff gammas classified with p/He classifier (multiplied with 1e3)

Expected DL2 stereo event rate after all cuts (protoness > 0.8)



Comparison of the spectra (not folded with SST-1M IRFs)

