Gamma-ray point source search with IceTop and IceCube

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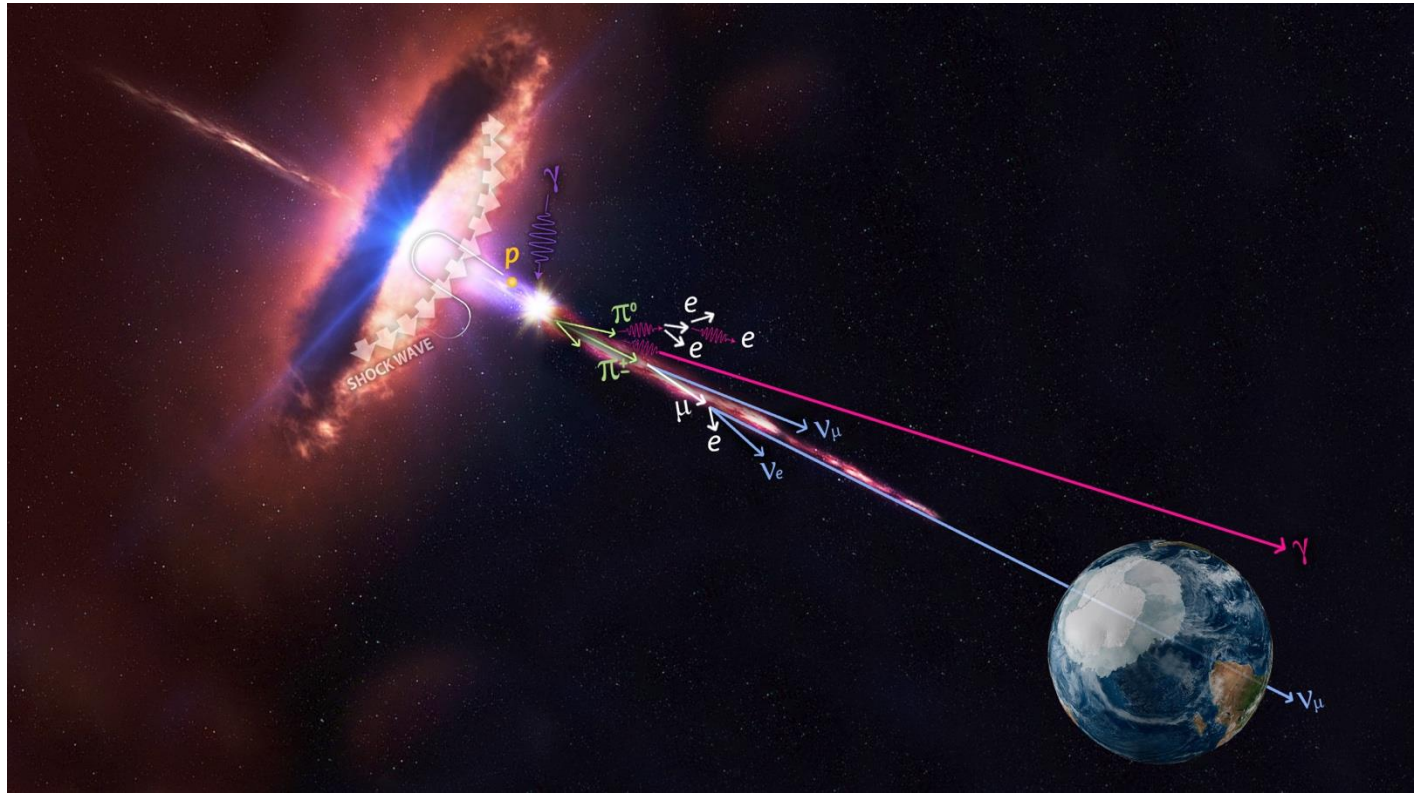
- CosPA 2026

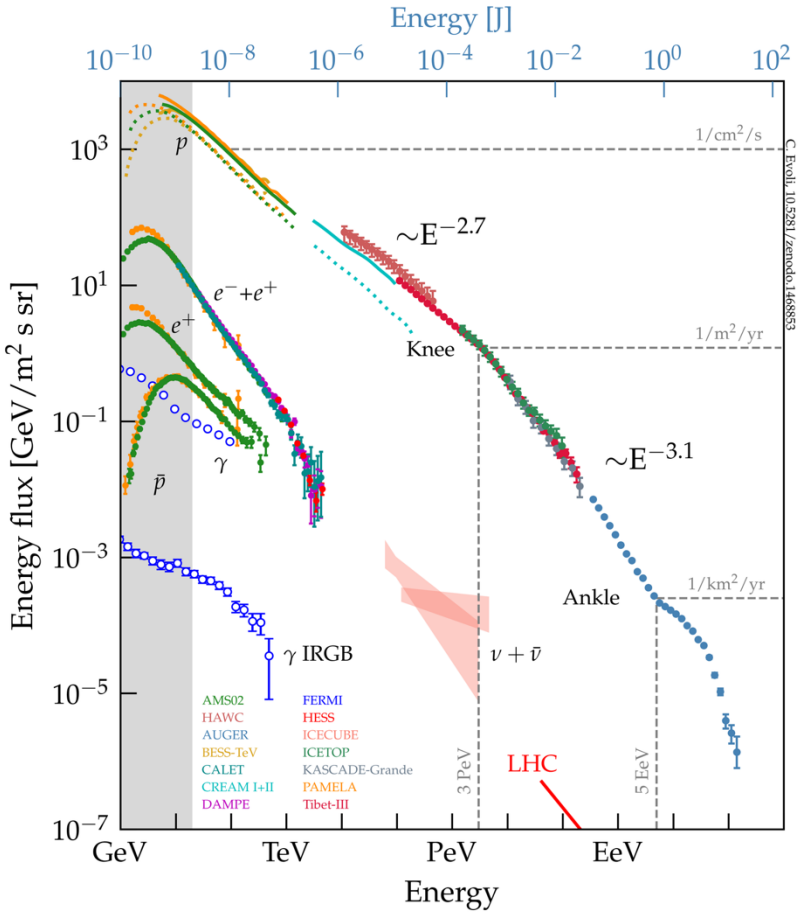
Main question

- What and where are the highest energy accelerators within our galaxy? What is the limit?



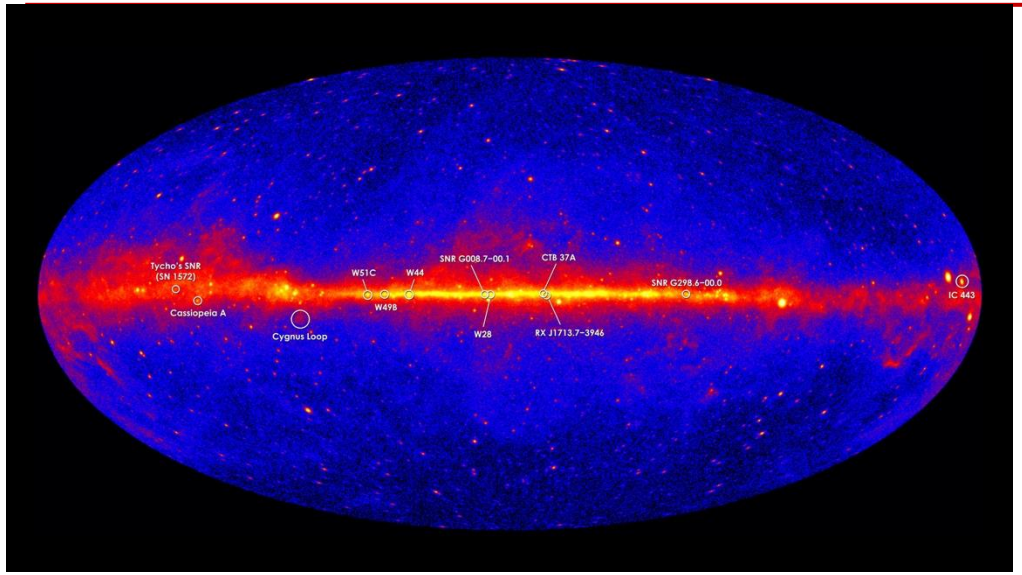
Main question

- What and where are the highest energy accelerators within our galaxy? What is the limit?
- The knee in the spectrum is believed to be related to a change in cosmic-ray sources.
- Below this point, cosmic rays are thought to originate from sources within the Milky Way galaxy, hinting at the presence of PeV hadron accelerators within the galaxy known as Galactic PeVatrons.
- LHAASO has reported the detection of multiple PeV gamma ray sources, maybe IceCube can too!

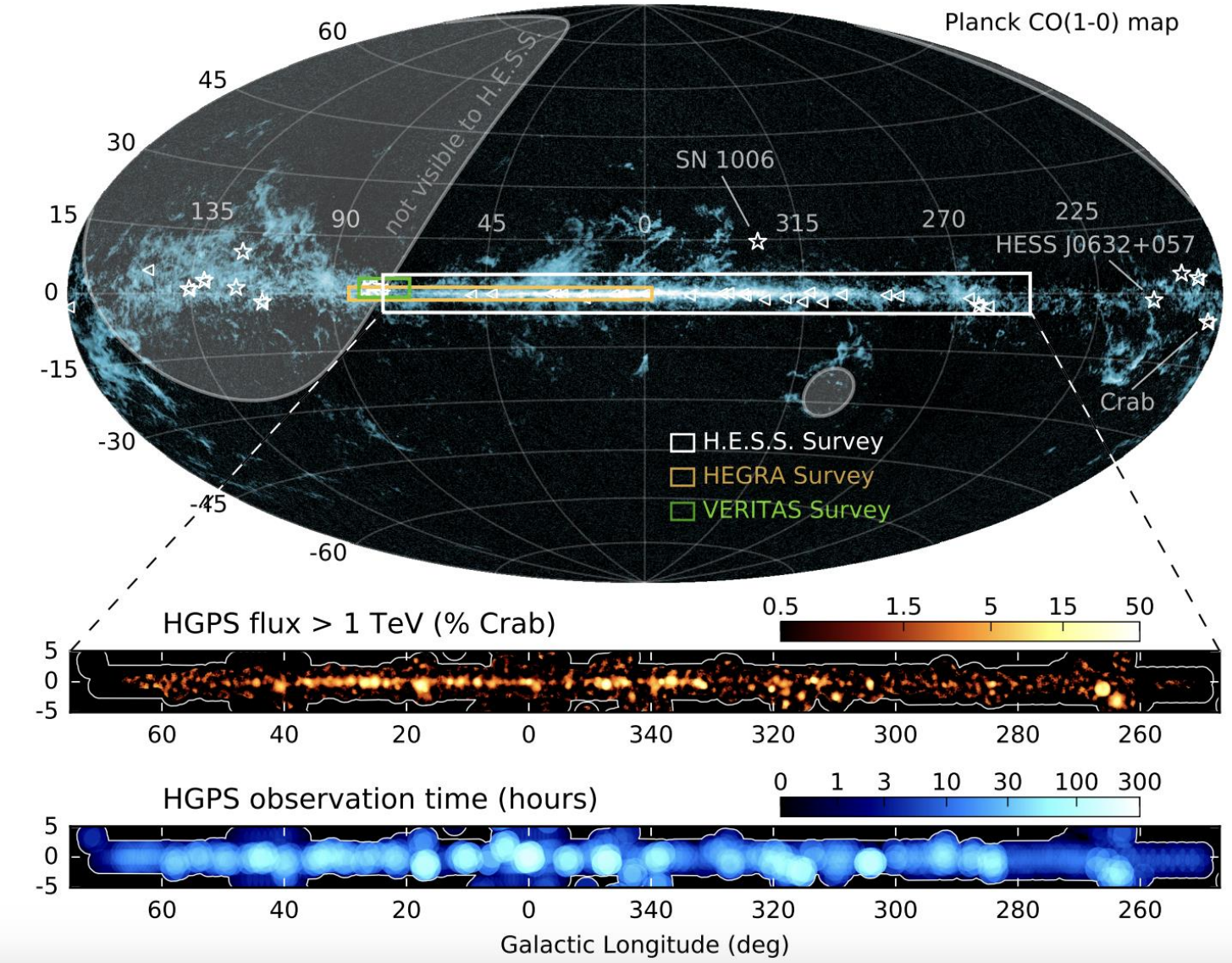


Ref: C. Evoli, The Cosmic-Ray Energy Spectrum, Dec. 2020, 10.5281/zenodo.4396125.

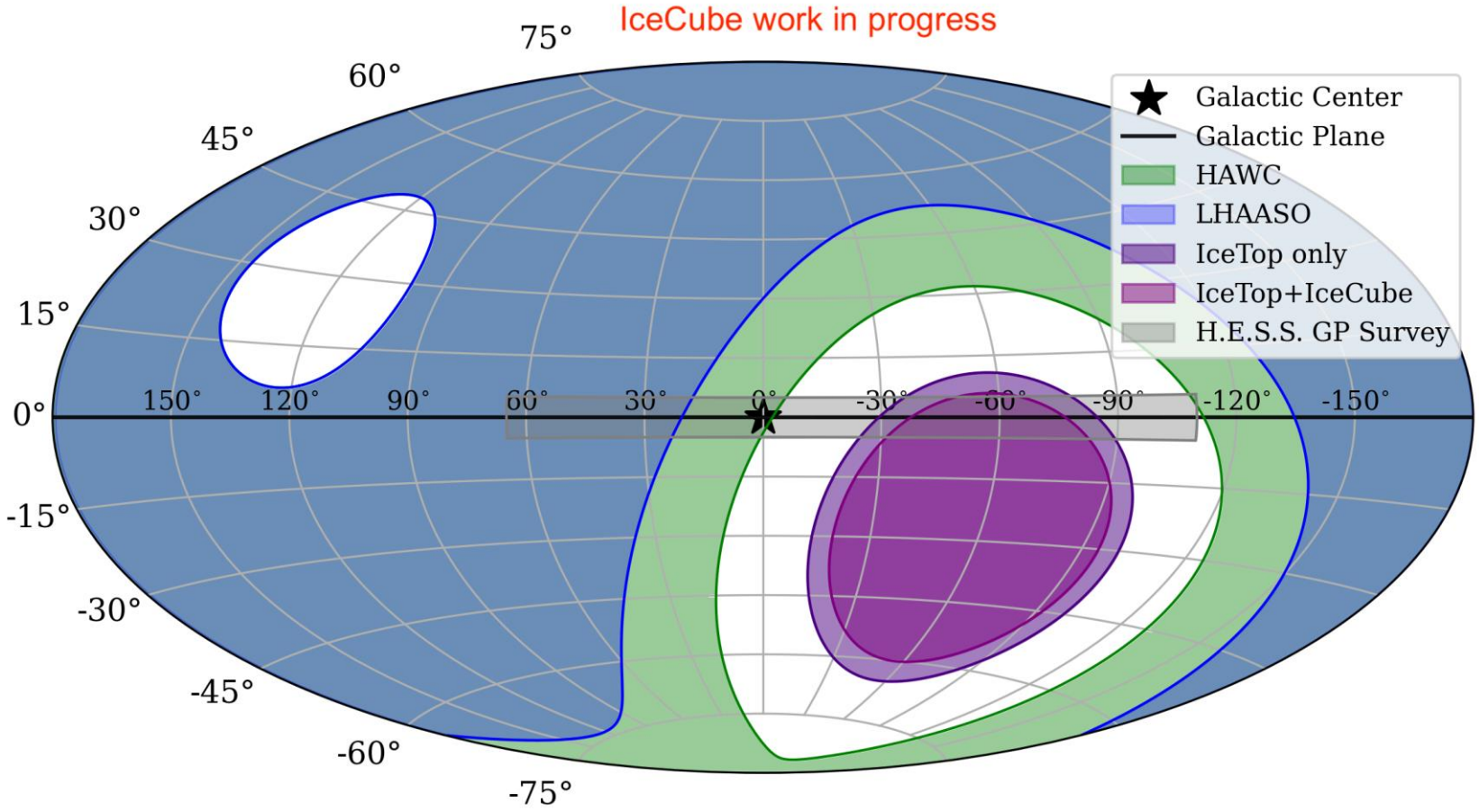
Our Gamma-ray sky



- Fermi-LAT energy limit approximately 20 MeV to 300 GeV
- H.E.S.S. galactic plane survey only reaching up to 100 TeV.
- What about higher energy?

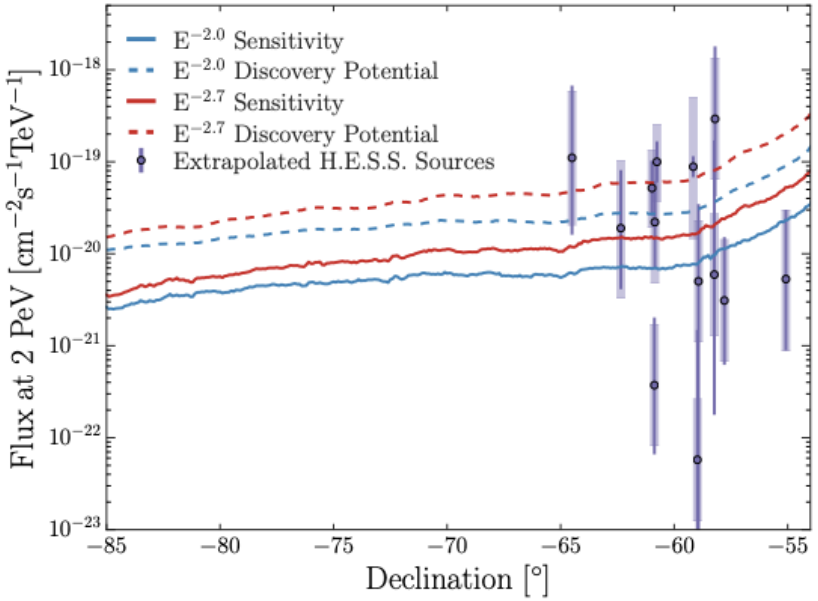


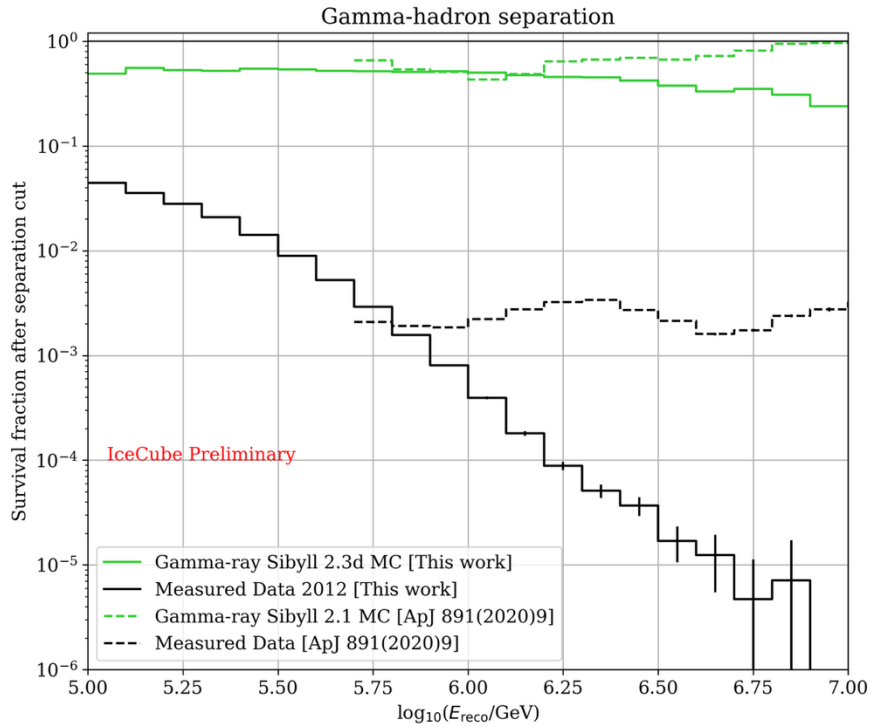
IceCube is in a unique position



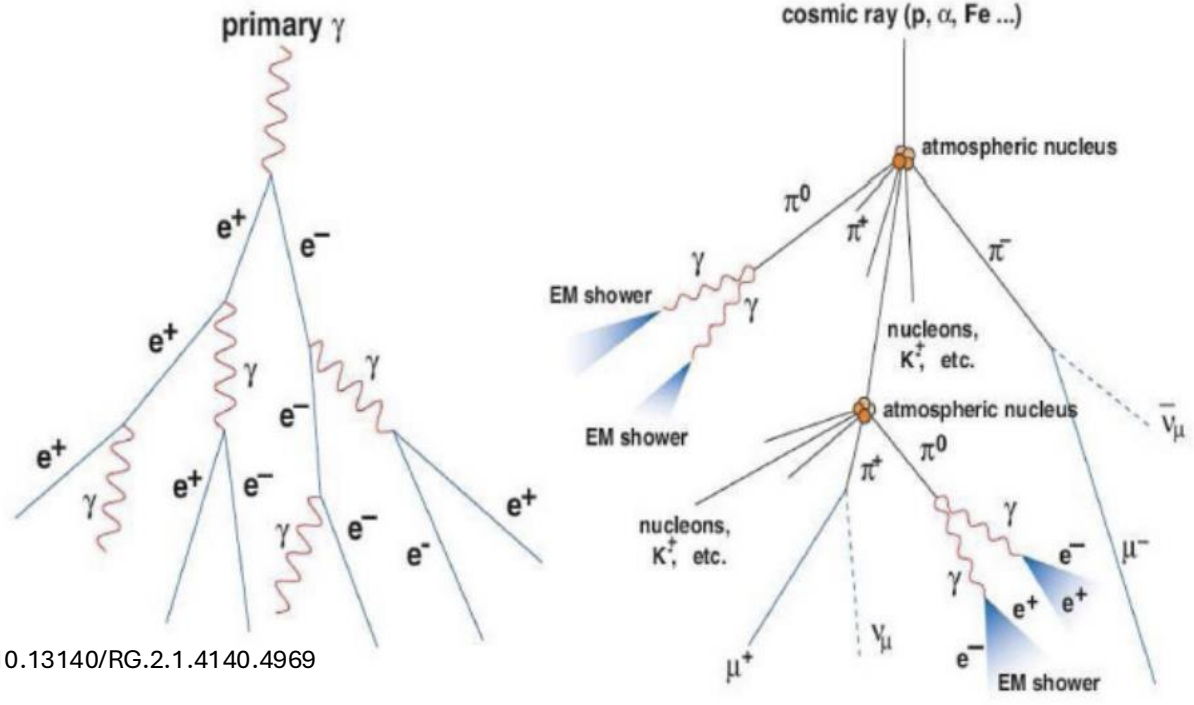
Search status

- Initial search (Aartsen et al. 2013) used only 40 strings in-ice and one year of data. Found no sources.
- Previous analysis (Aartsen et al. 2020) used in-ice and surface array with 5 years of data. Used machine learning for event selection – found no significant gamma-ray emission.
- Was able to place upper limits on high energy emission of H.E.S.S sources and 90% confidence level upper limit on point sources.
- Recent studies (Schröder & Bontempo 2025) improved background rejection power by approximately an order of magnitude at 1 PeV.

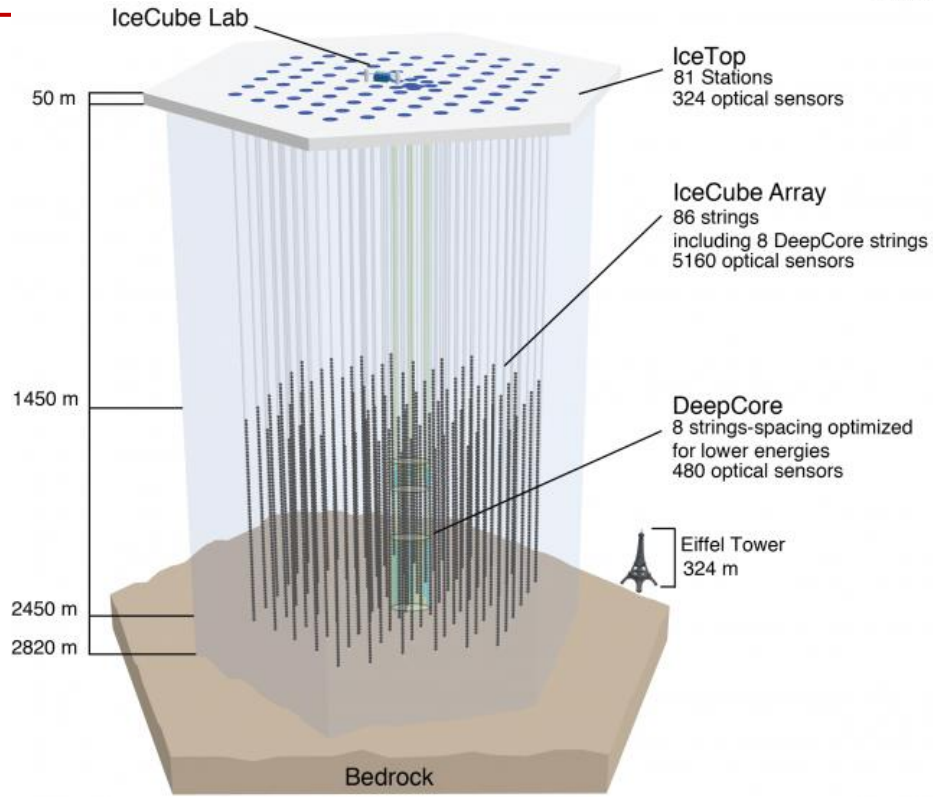




How do we detect?



doi: 10.13140/RG.2.1.4140.4969

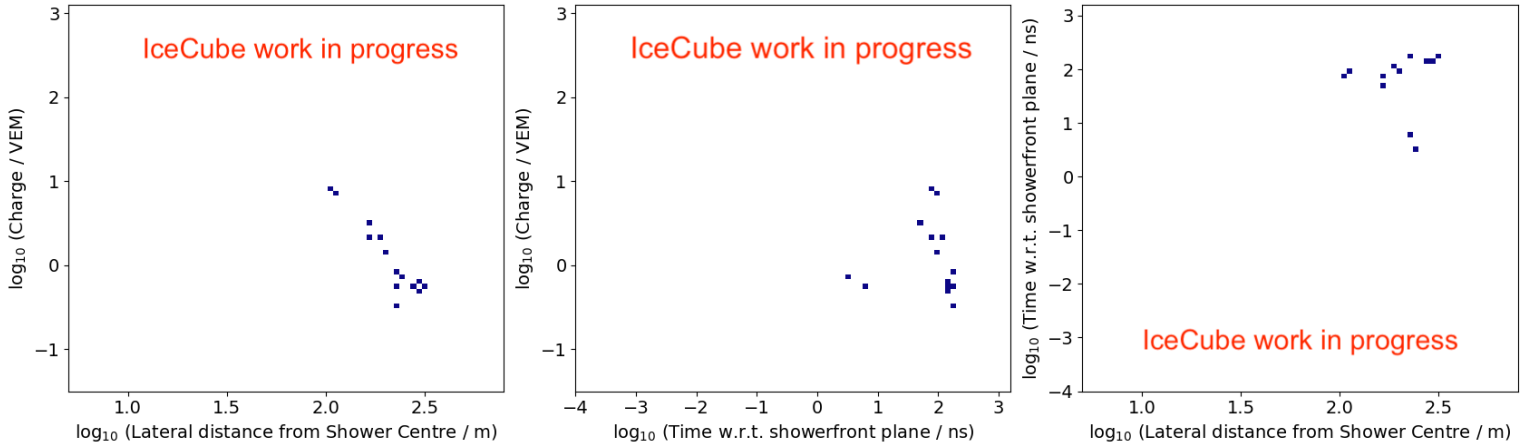


- Air-shower geometry and CR energy proxy are reconstructed using IceTop pulses
- Separate step needed to distinguish gamma air-showers from hadronic ones

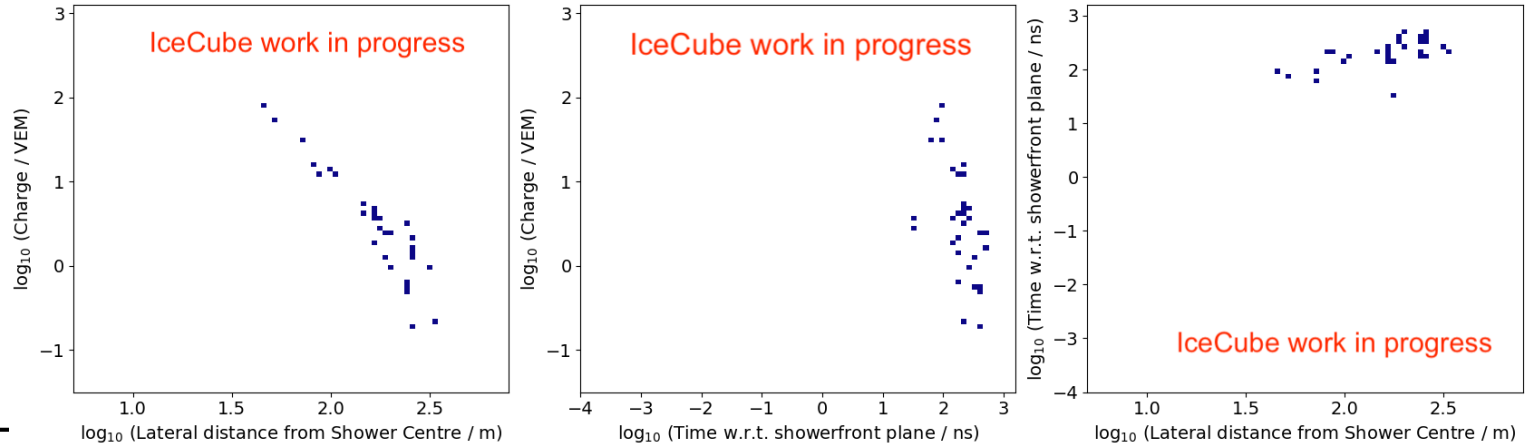
Gamma/Hadron separation - IceTop

- Using CNN optimized in recent study (Hewett, 2025), inputs are 2-D distributions. In the final fully connected layer are other IceTop parameters.

Single gamma event →



Single proton event →

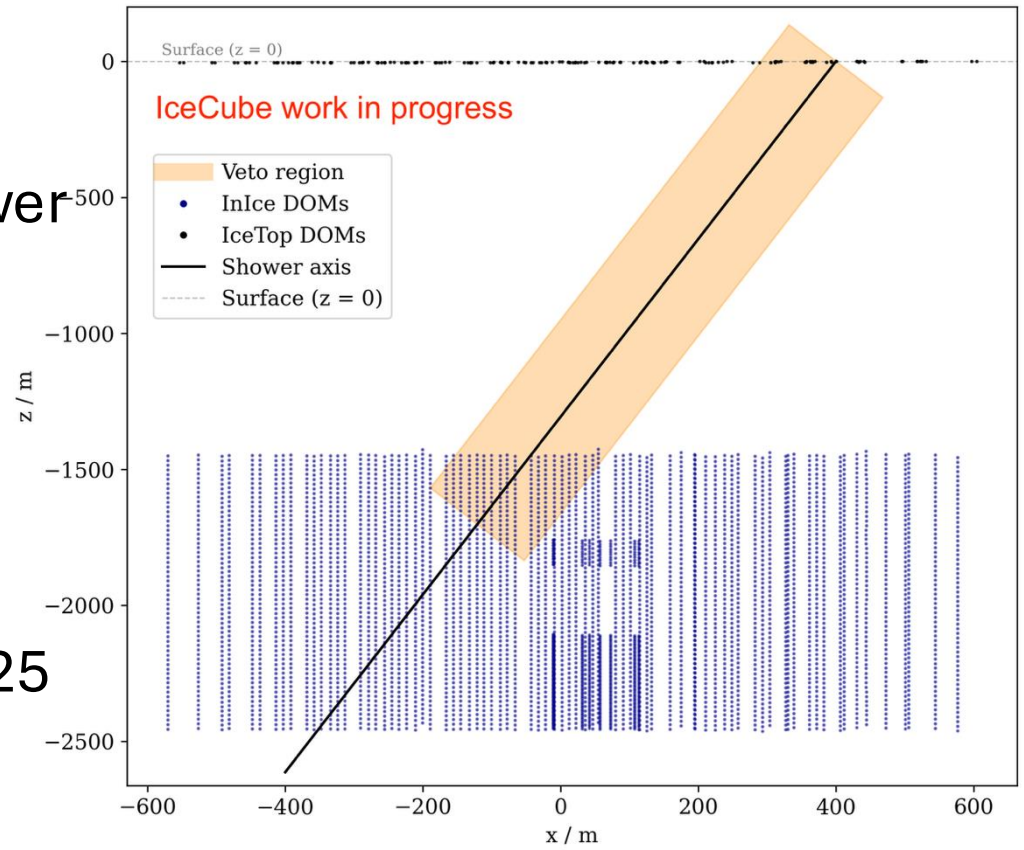


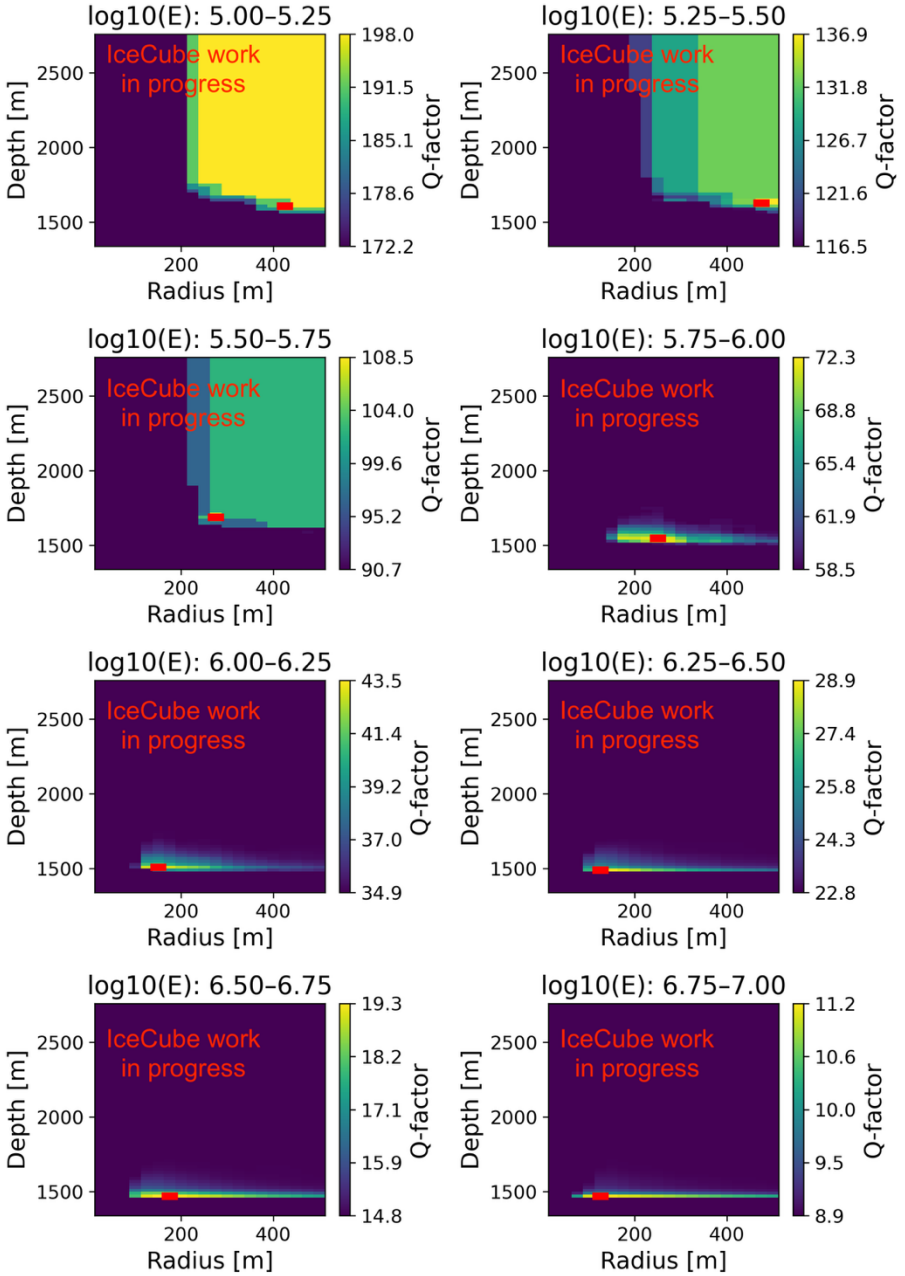
Gamma/Hadron separation– in ice

Can we separate showers that produce muons along the air-shower axis?

Optimized via Q factor in energy bands of log10(E/GeV) = 0.25

$$Q = \frac{\zeta_\gamma}{\sqrt{\zeta_{CR}}}$$

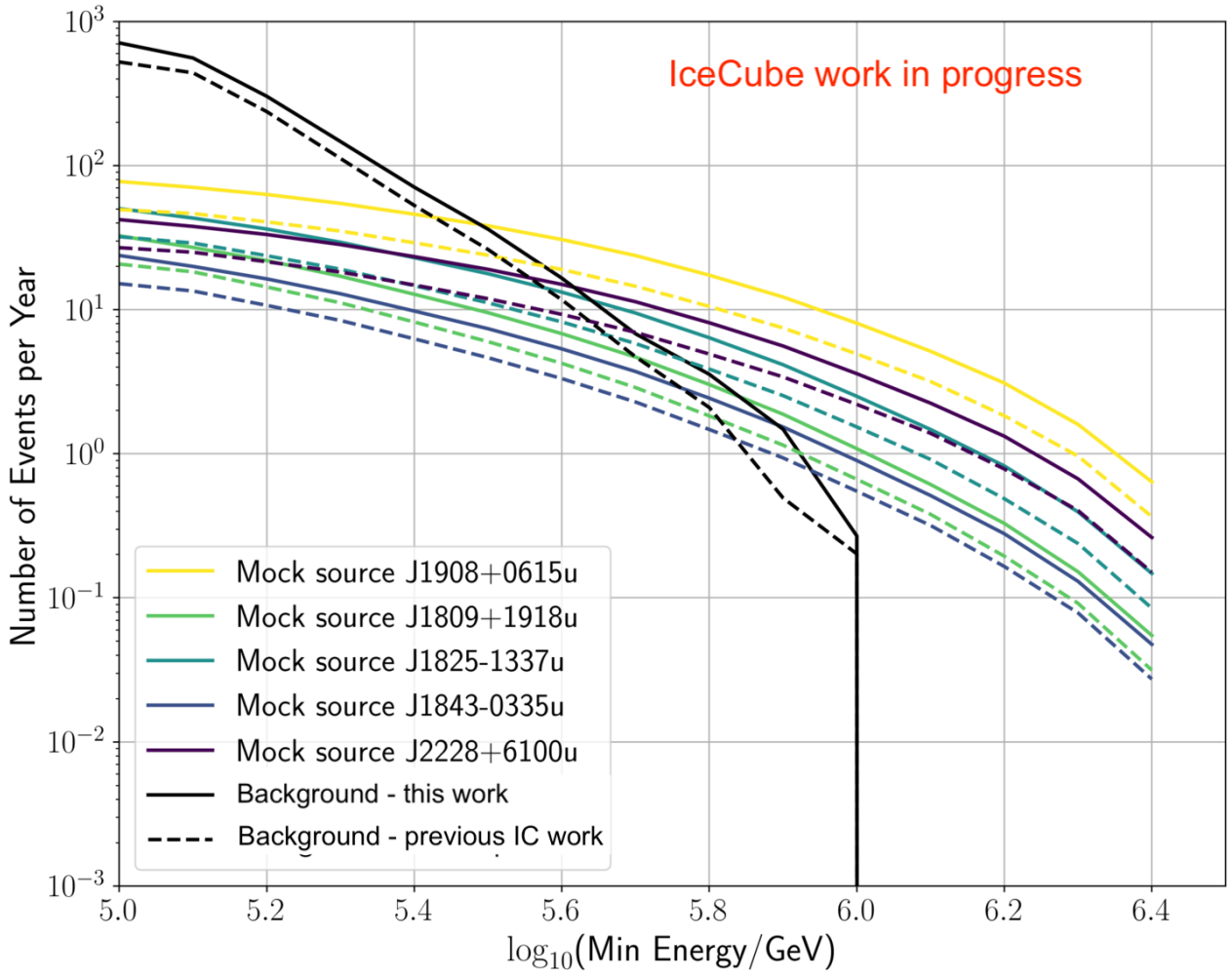




Estimated number of events

- Integrated number of events as a function of starting energy after ML selection cuts for mock LHAASO-like sources and background.

- All dashed lines show previous event selection, solid lines are improved selection.



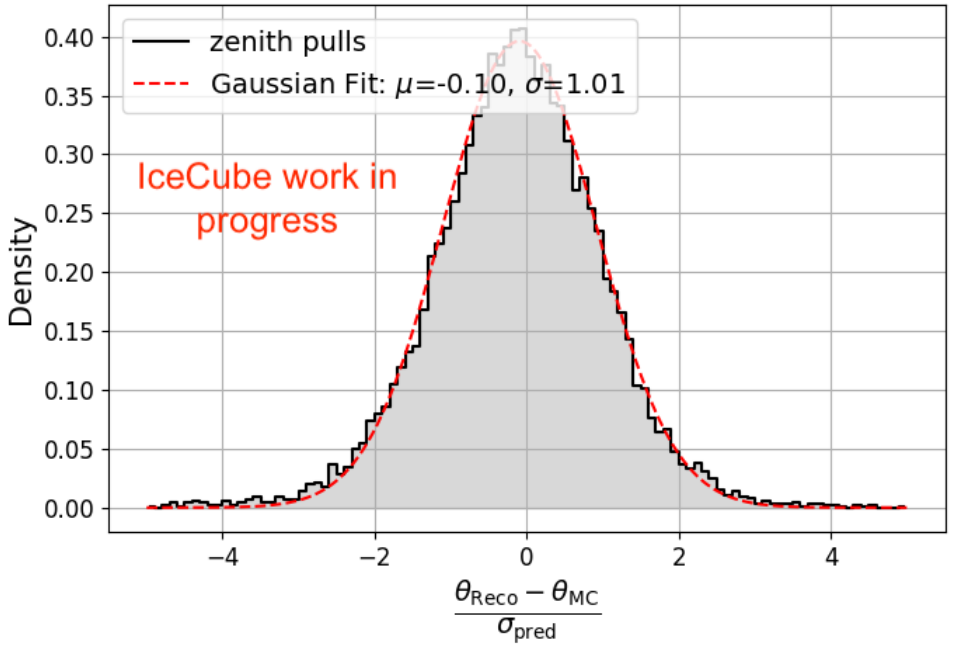
Angular error estimation

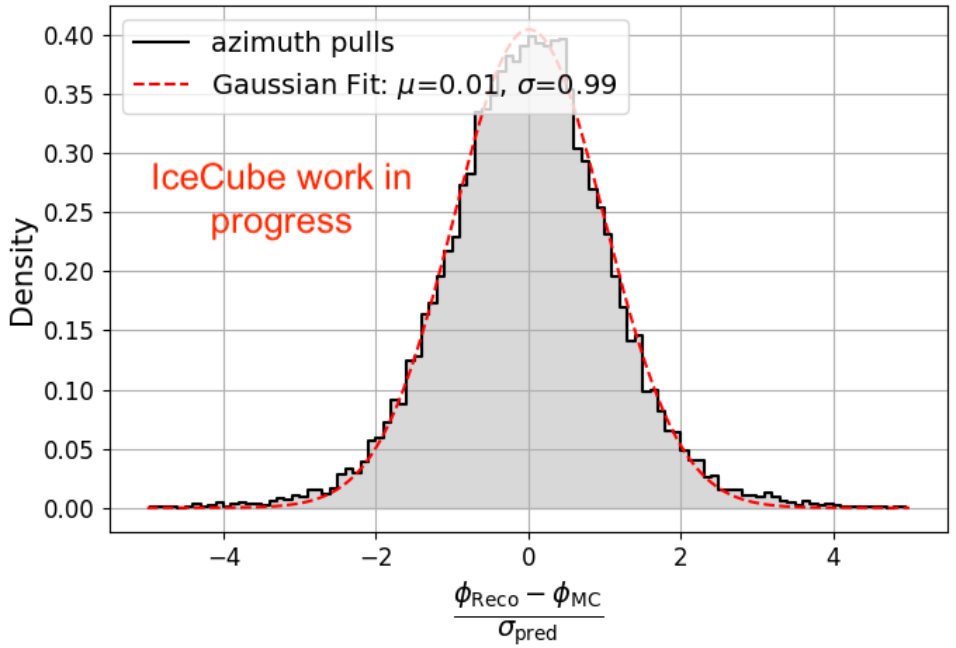
- Can we estimate angular error on an event-by-event basis? Important for point source searches! (**Note NOT estimating direction**)

$$\boldsymbol{n} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \sin(\theta) \cdot \cos(\phi) \\ \sin(\theta) \cdot \sin(\phi) \\ \cos(\theta) \end{bmatrix}, \qquad \theta_{\text{res}} = \cos^{-1}\left(\boldsymbol{n}_{\text{true}} \cdot \boldsymbol{n}_{\text{reco}}\right) \cdot \frac{180}{\pi}.$$

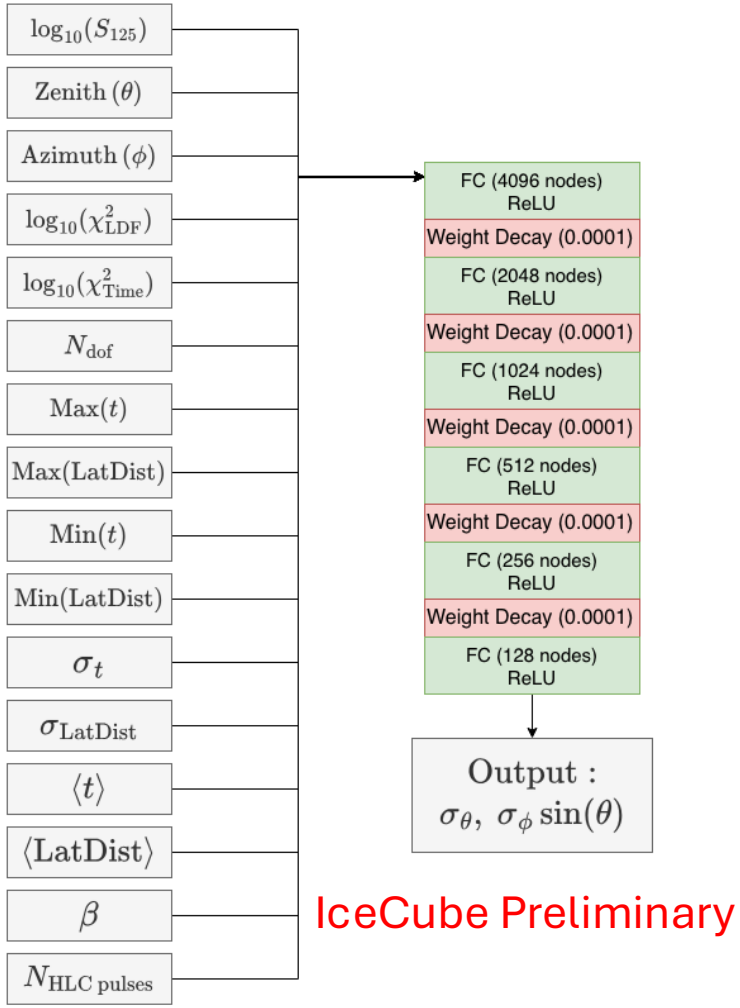
- Previously tried a BDT to directly estimate opening angle (didn't work well ☹)
- Now optimized a NN to estimate zenith and azimuth error separately, then circularize

$$\sigma_{\Delta\Psi} = \sqrt{\frac{\sigma_\theta^2 + \left(\sigma_\phi \cdot \sin(\theta_{reco})\right)^2}{2}}$$

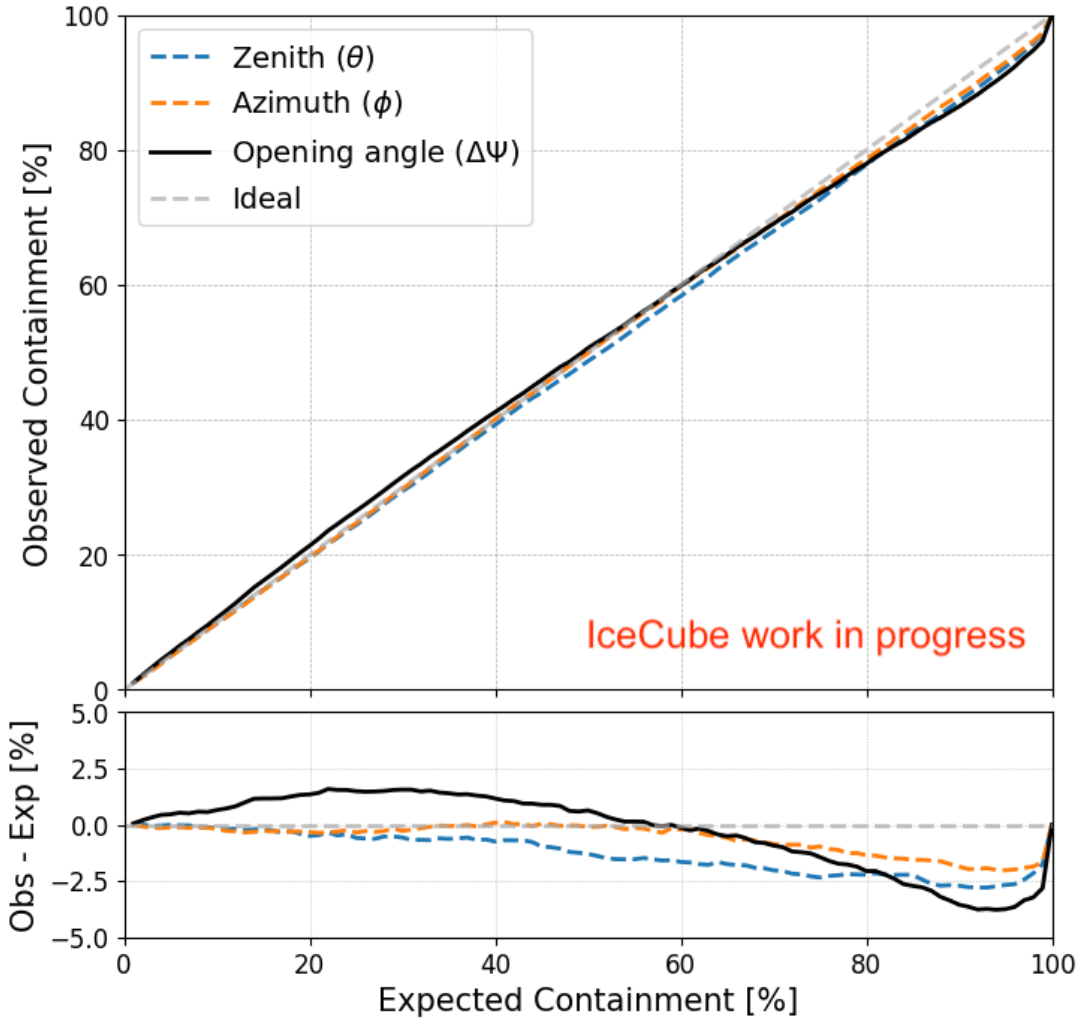




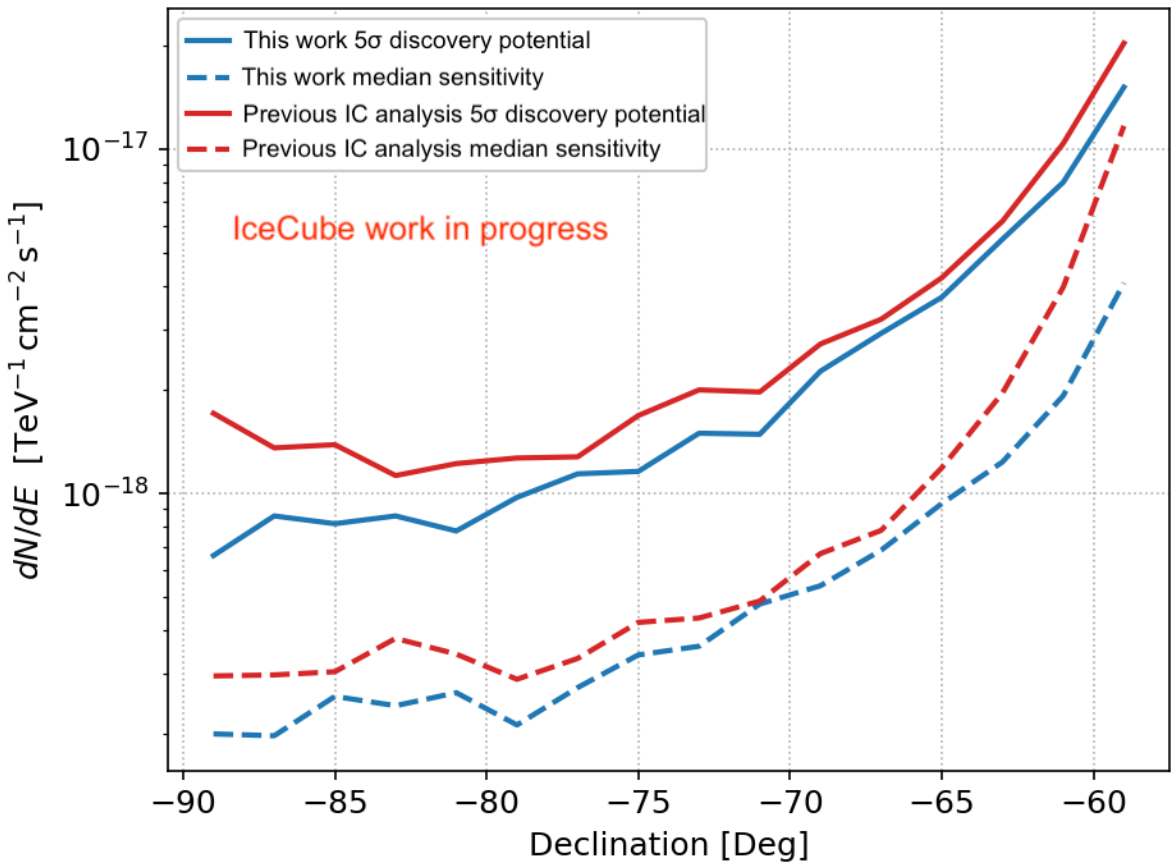
Coverage of pull distributions

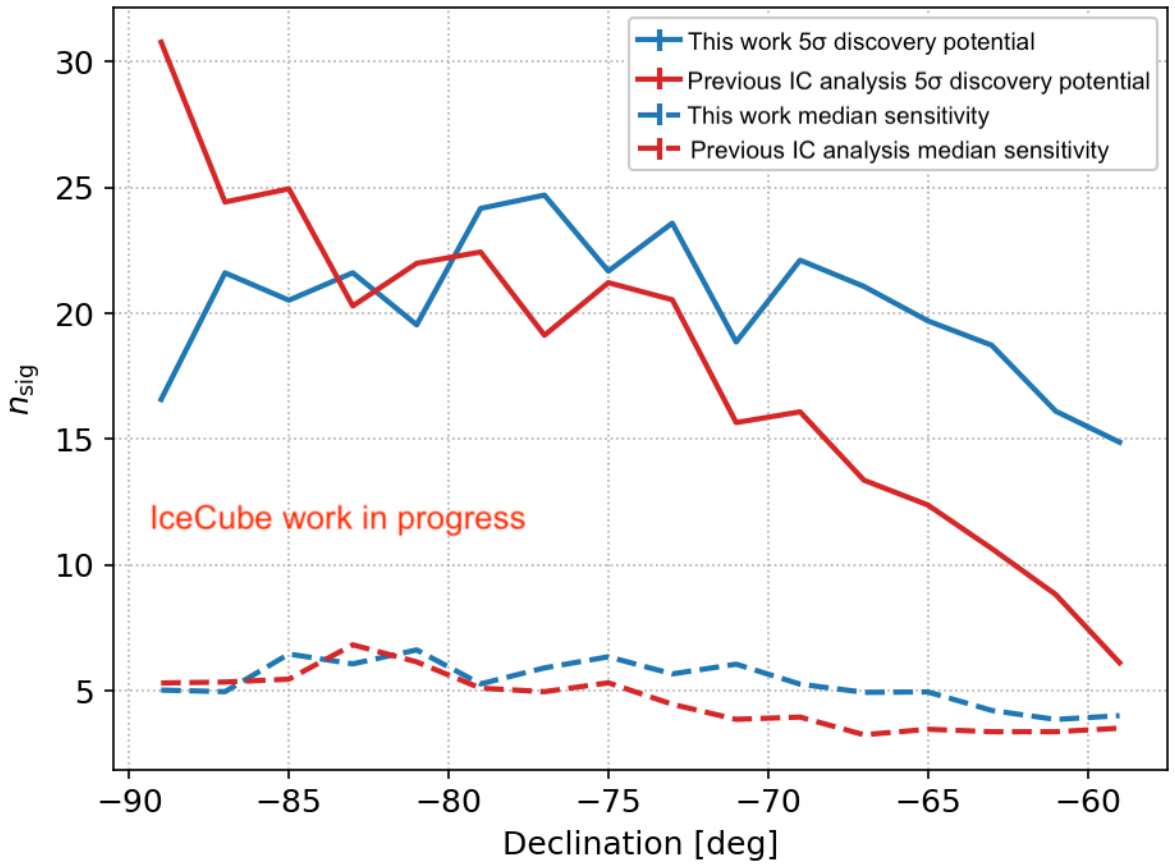


IceCube Preliminary



Sensitivity estimates





Summary

- Defined a new event selection combining ML techniques with IceTop data and an energy dependent veto region for the in-ice volume.
- Working off previous improvements (Schröder & Bontempo 2025) , only currently using testing for the year 2012.
- Created a neural network to estimate angular error on an event-by-event basis, results are promising and have provided improvements in coverage.
- Sensitivity estimates show improvements over previous methods, in both sensitivity and source injection bias.
- Results show possible interpolation between multiple years of data, accounting for snow on tanks. Simulations are computationally expensive, train a new model every 3 years?

Thank you!

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Questions?

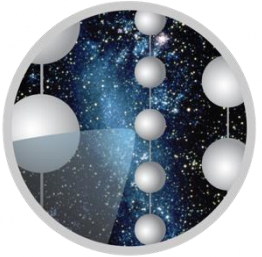
References:

- Aartsen, M. G., et al. (IceCube Collaboration) 2013, "Search for Galactic PeV Gamma Rays with the IceCube Neutrino Observatory," *Phys. Rev. D*, 87, 062002. doi:10.1103/PhysRevD.87.062002

- Aartsen, M. G., et al. (IceCube Collaboration) 2020, "Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Yr of Data from the IceCube Observatory," *ApJ*, 891, 9. doi:10.3847/1538-4357/ab6d67

- Schröder, F. G. & Bontempo, F. (for the IceCube Collaboration) 2025, "Improved Gamma-Hadron Separation for PeV Photon Searches with IceCube," *arXiv:2507.05833*, presented at ICRC 2025. doi:10.48550/arXiv.2507.05833

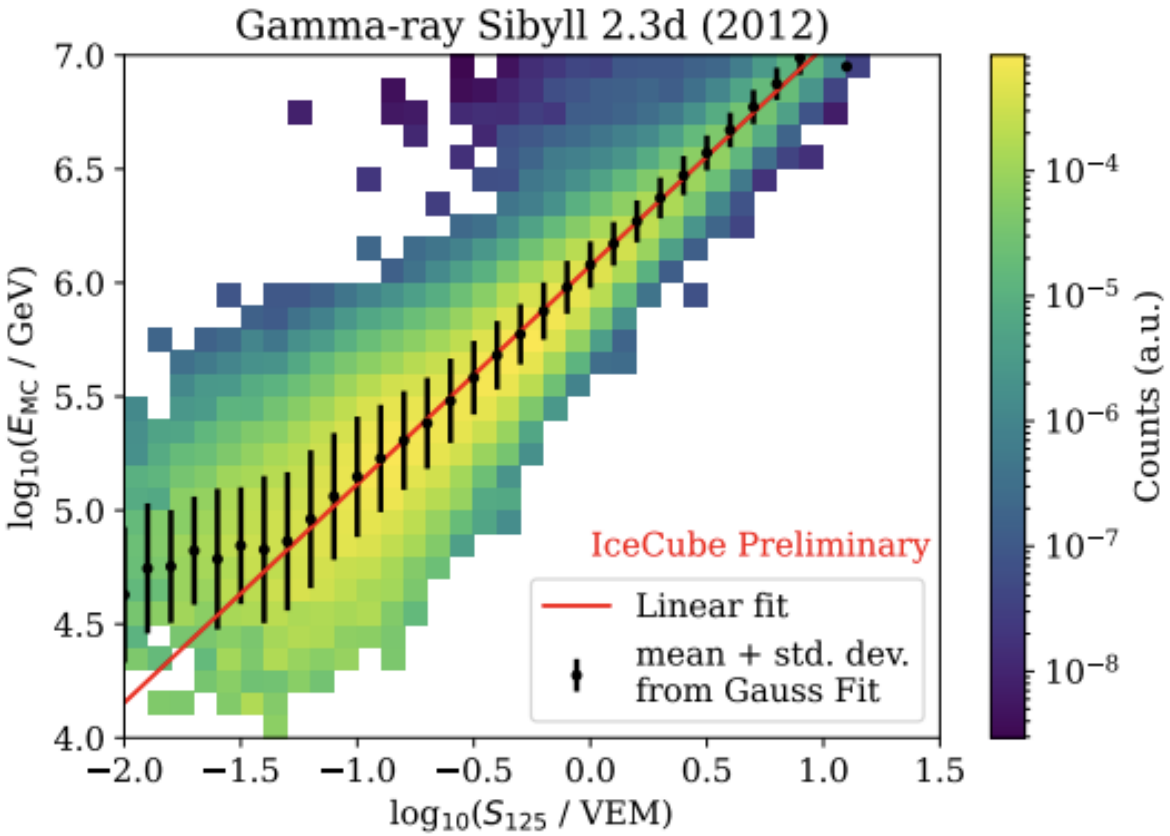
- Hewett, R. 2025, "Machine Learning Techniques for Gamma-Hadron Separation with IceCube," MSc thesis, University of Canterbury. doi:10.26021/16083



ICECUBE

Backup

Energy Reconstruction



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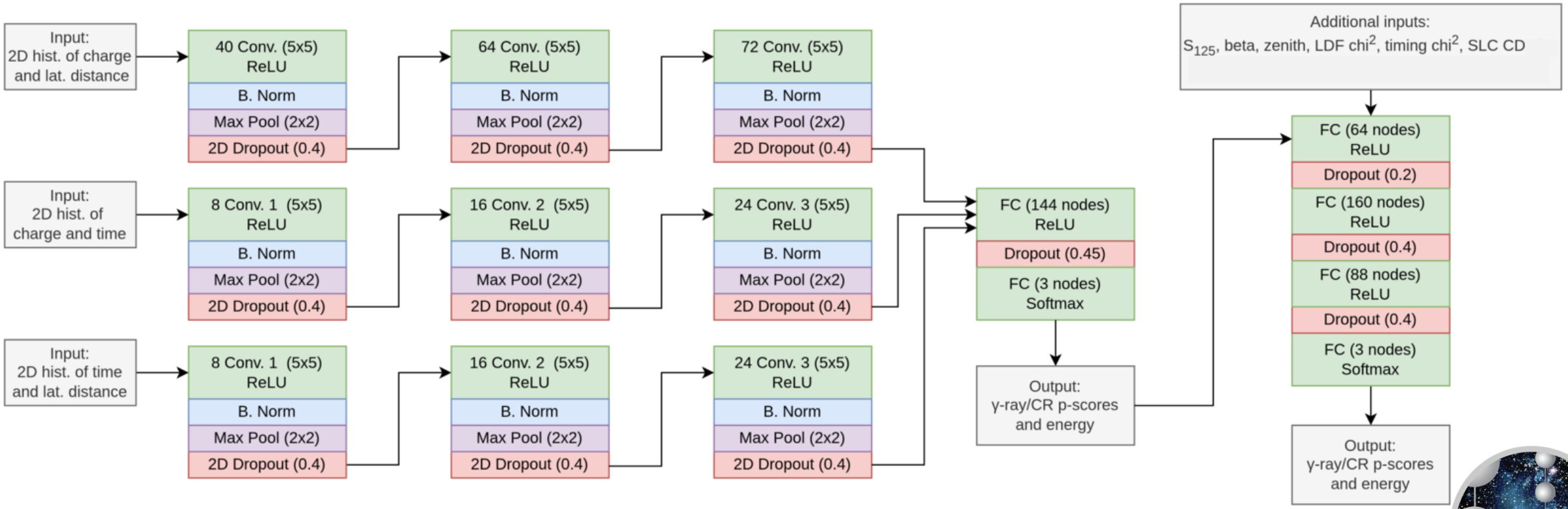
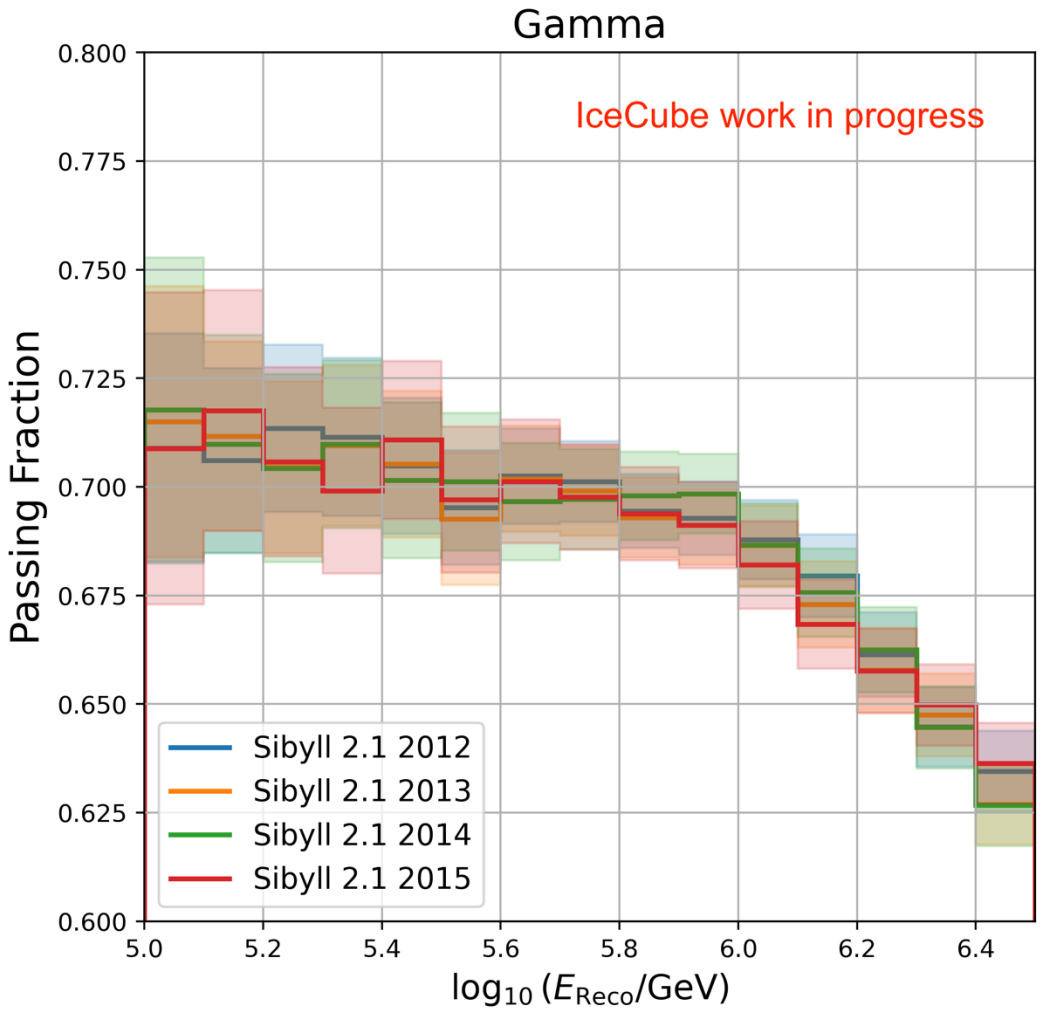
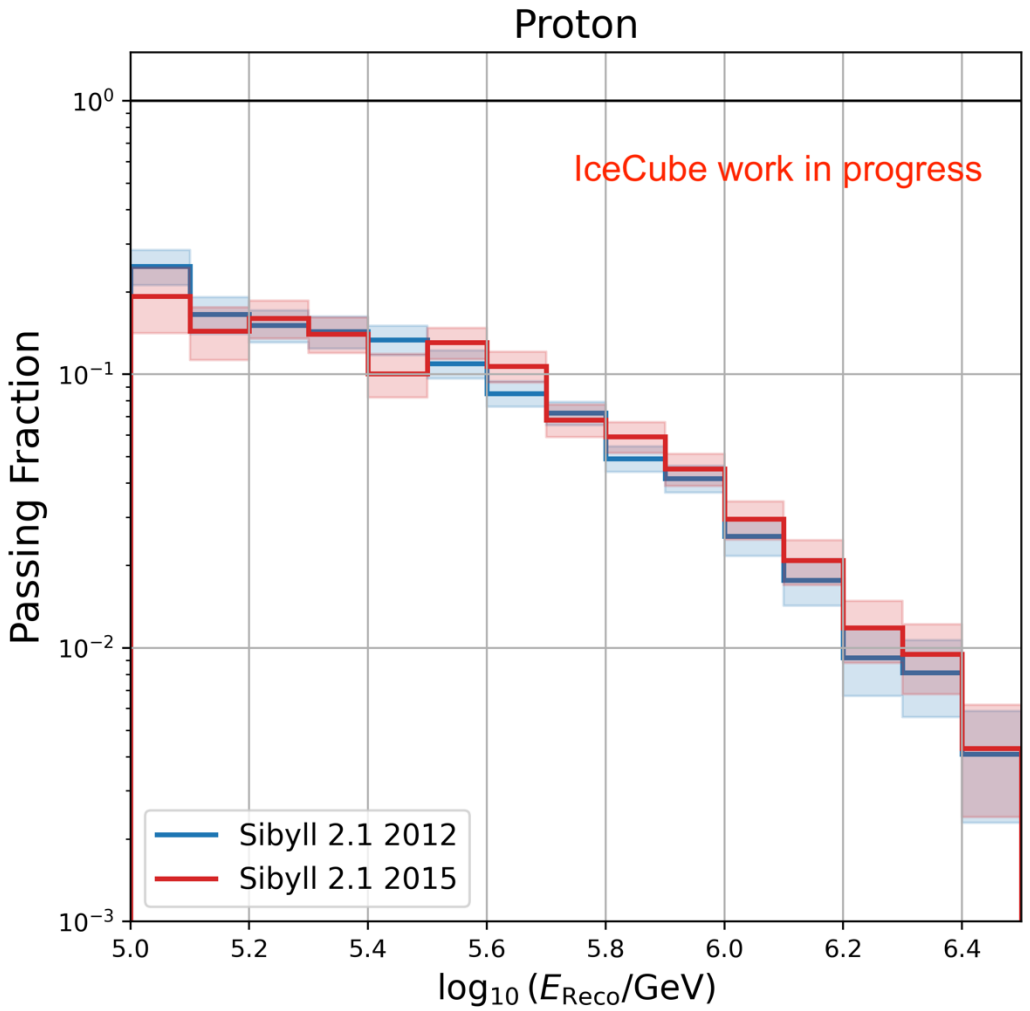
CNN architecture



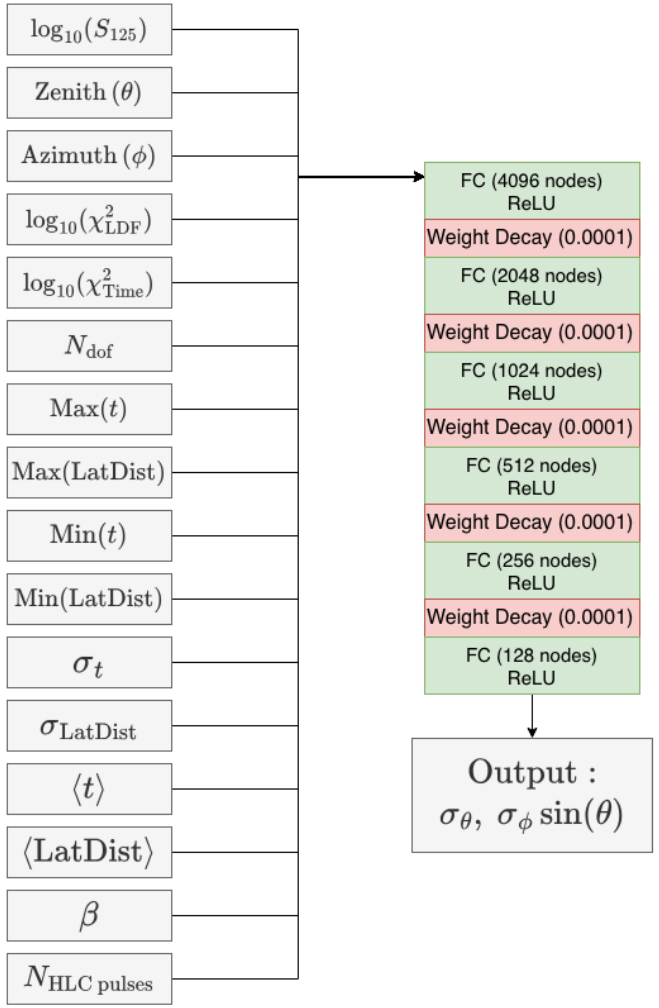
- Note energy is not used! Just helps the ML algorithm

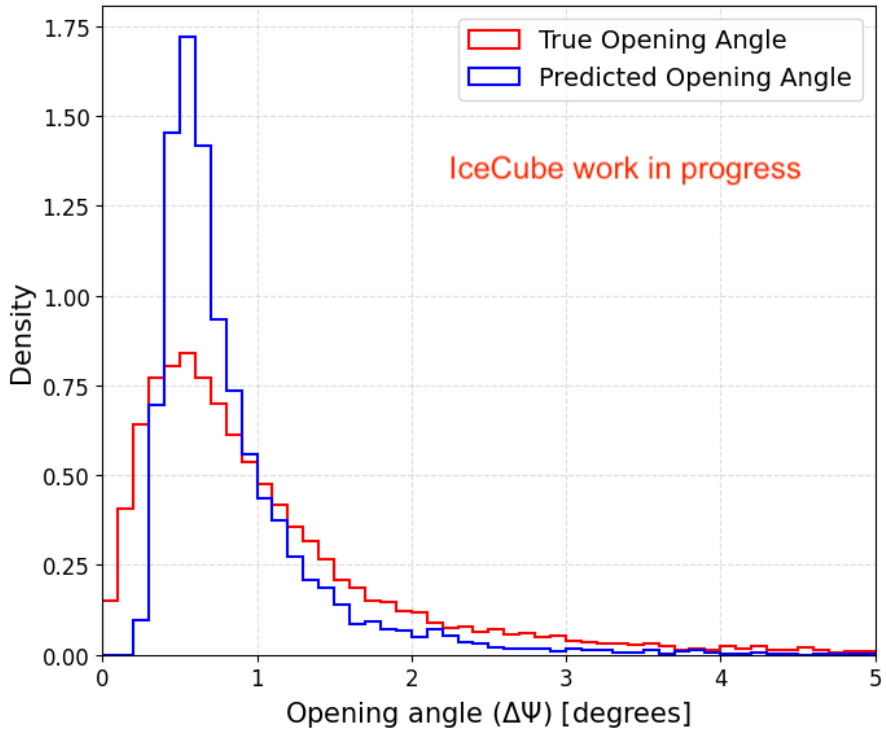
Event selection on further years

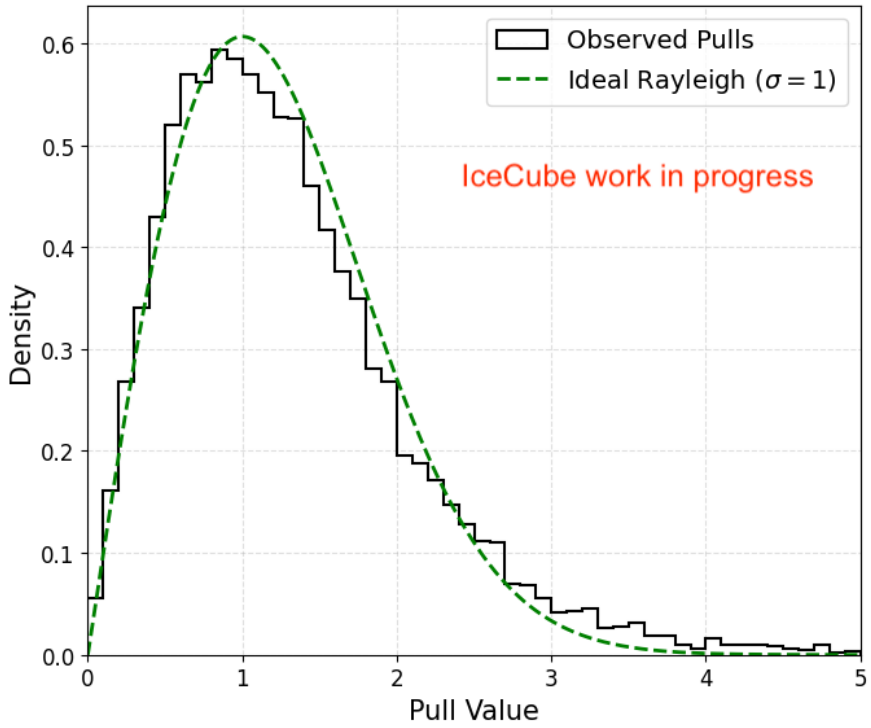




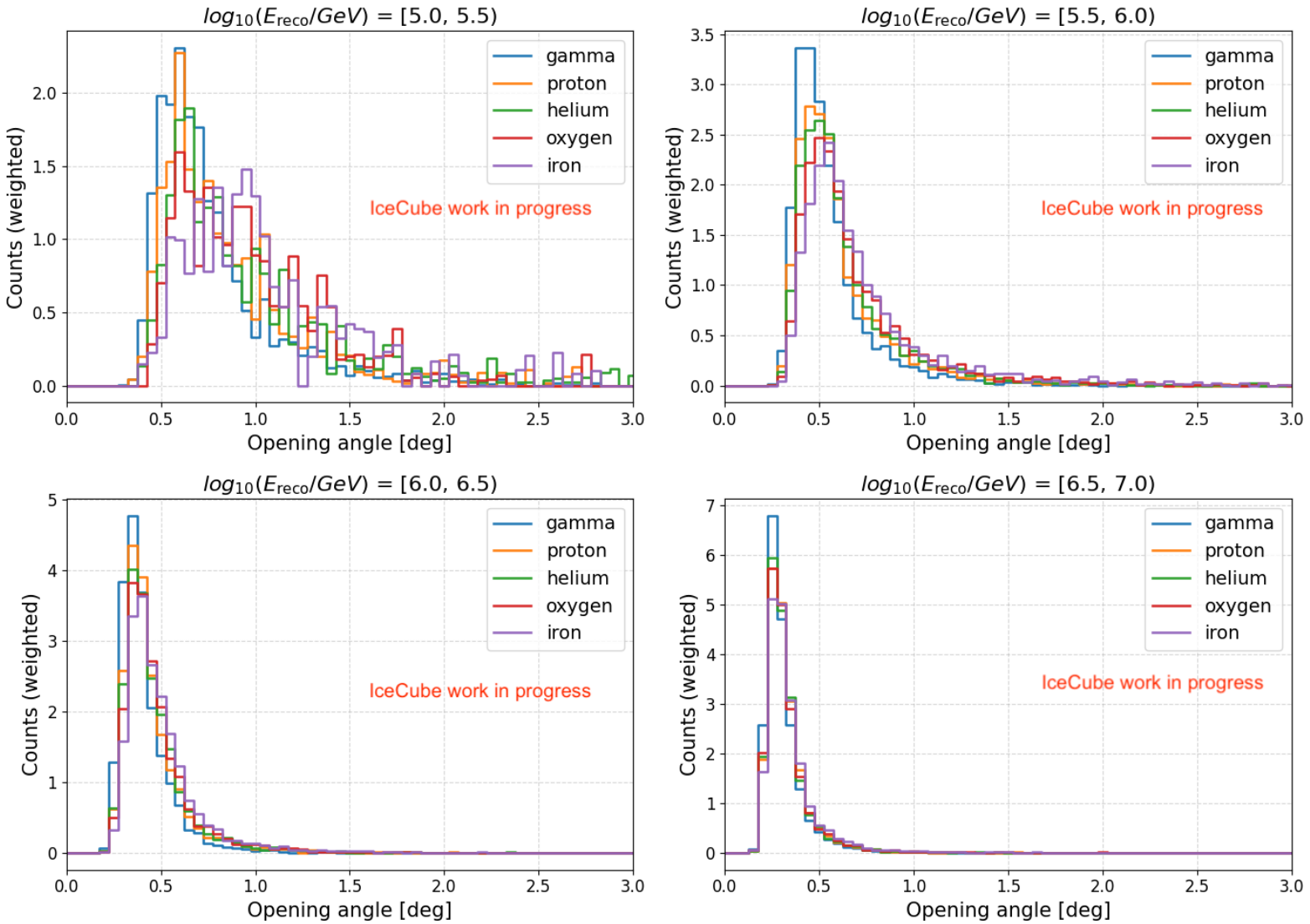
NN model


$\log_{10}(S_{125})$
Zenith (θ)
Azimuth (ϕ)
$\log_{10}(\chi^2_{\mathrm{LDF}})$
$\log_{10}(\chi^2_{\mathrm{Time}})$
N_{dof}
Max(t)
Max(LatDist)
Min(t)
Min(LatDist)
σ_t
$\sigma_{\mathrm{LatDist}}$
$\langle t \rangle$
$\langle \mathrm{LatDist} \rangle$
β
$N_{\mathrm{HLC\ pulses}}$
FC (4096 nodes)
ReLU
Weight Decay (0.0001)
FC (2048 nodes)
ReLU
Weight Decay (0.0001)
FC (1024 nodes)
ReLU
Weight Decay (0.0001)
FC (512 nodes)
ReLU
Weight Decay (0.0001)
FC (256 nodes)
ReLU
Weight Decay (0.0001)
FC (128 nodes)
ReLU
Output :
$\sigma_\theta,\ \sigma_\phi \sin(\theta)$


True Opening Angle
Predicted Opening Angle
IceCube work in progress
Density
Opening angle (ΔΨ) [degrees]


Observed Pulls
Ideal Rayleigh ($\sigma = 1$)
IceCube work in progress
Density
Pull Value

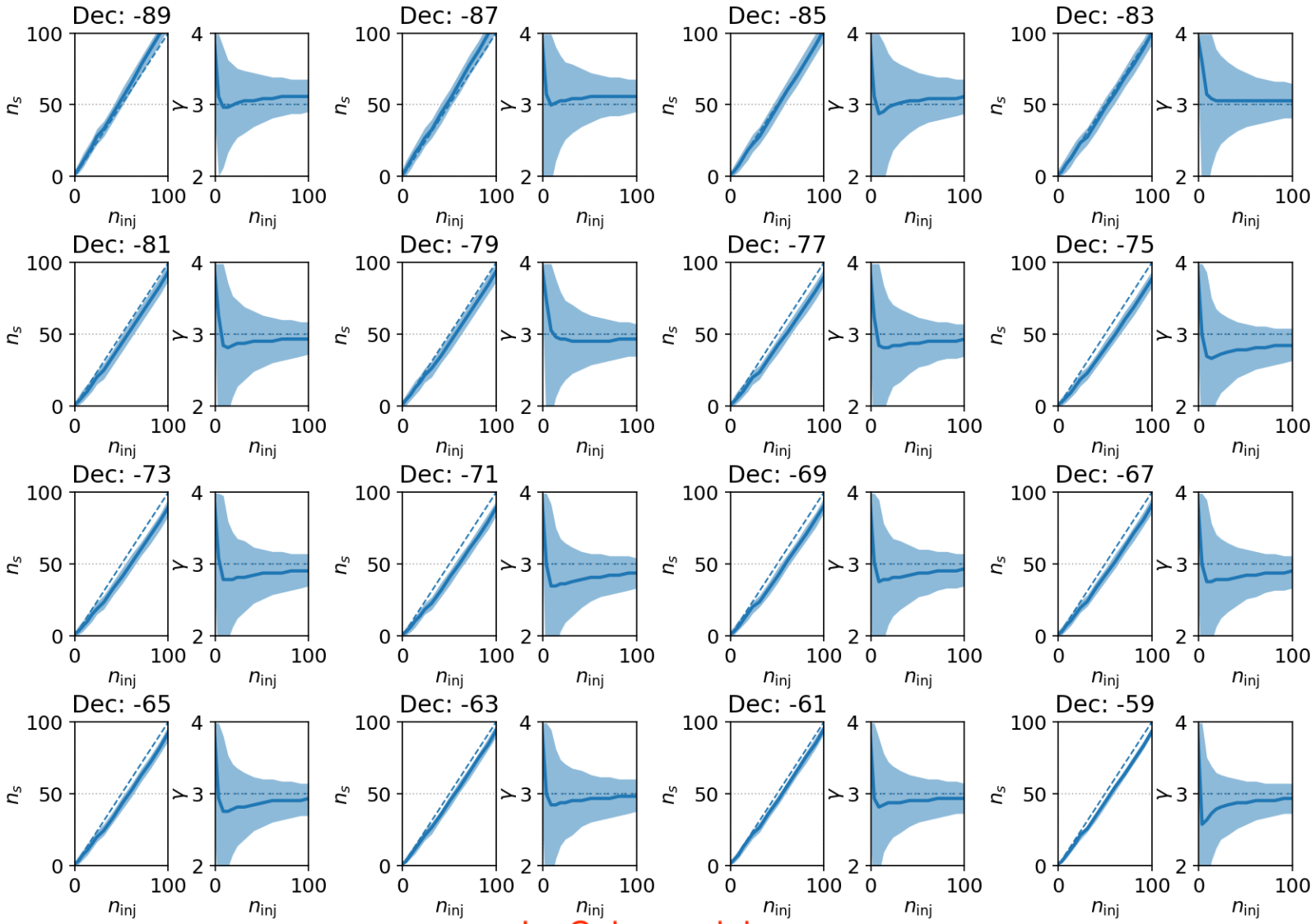
Other primaries in NN



Source injection bias

- Using 10% of 2012 scrambled data to estimate background (approx. 9000 events remain after event selection)
- 50,000 trials per dec. band
- No changes to general likelihood

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \frac{n_s}{N} S(x_i) + \left(1 - \frac{n_s}{N}\right) B(x_i).$$



IceCube work in progress