Energy Reconstruction with the Radio Neutrino Observatory Greenland (RNO-G).

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RNO-G will be the first large-scale radio detector for neutrinos at energy > 10 PeV. 35 stations will detect radio signals from neutrino interactions in the ice sheet of Greenland [1].

Sensitivity to Neutrino Energy

Only part of the neutrino energy goes into the shower:

- Use Bayes' theorem to calculate neutrino energy posterior:

$$p(\lg(E_\nu)|\lg(E_r)) = \frac{p(\lg(E_r)|\lg(E_\nu))\cdot p(\lg(E_\nu))}{p(\lg(E_r))}$$

$p(\lg(E_\nu))$ Prior for neutrino energy

$p(\lg(E_r))$ Equal to integral over numerator

$p(\lg(E_r)|\lg(E_\nu))$ Reconstructed energy, given v energy

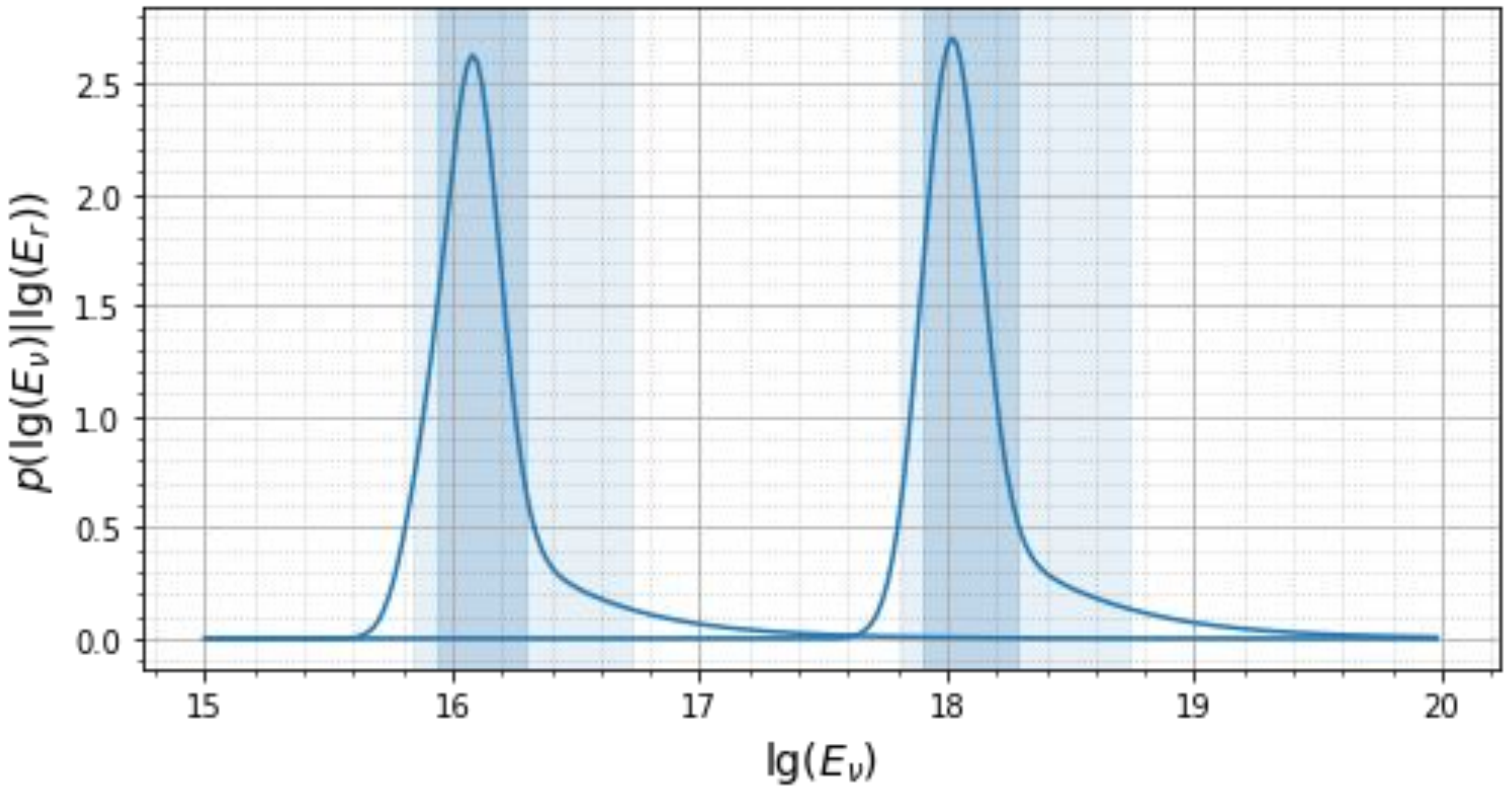


Fig3: Posterior distributions of neutrino energies for events with a reconstructed shower energy of 10^{16}eV and 10^{18}eV

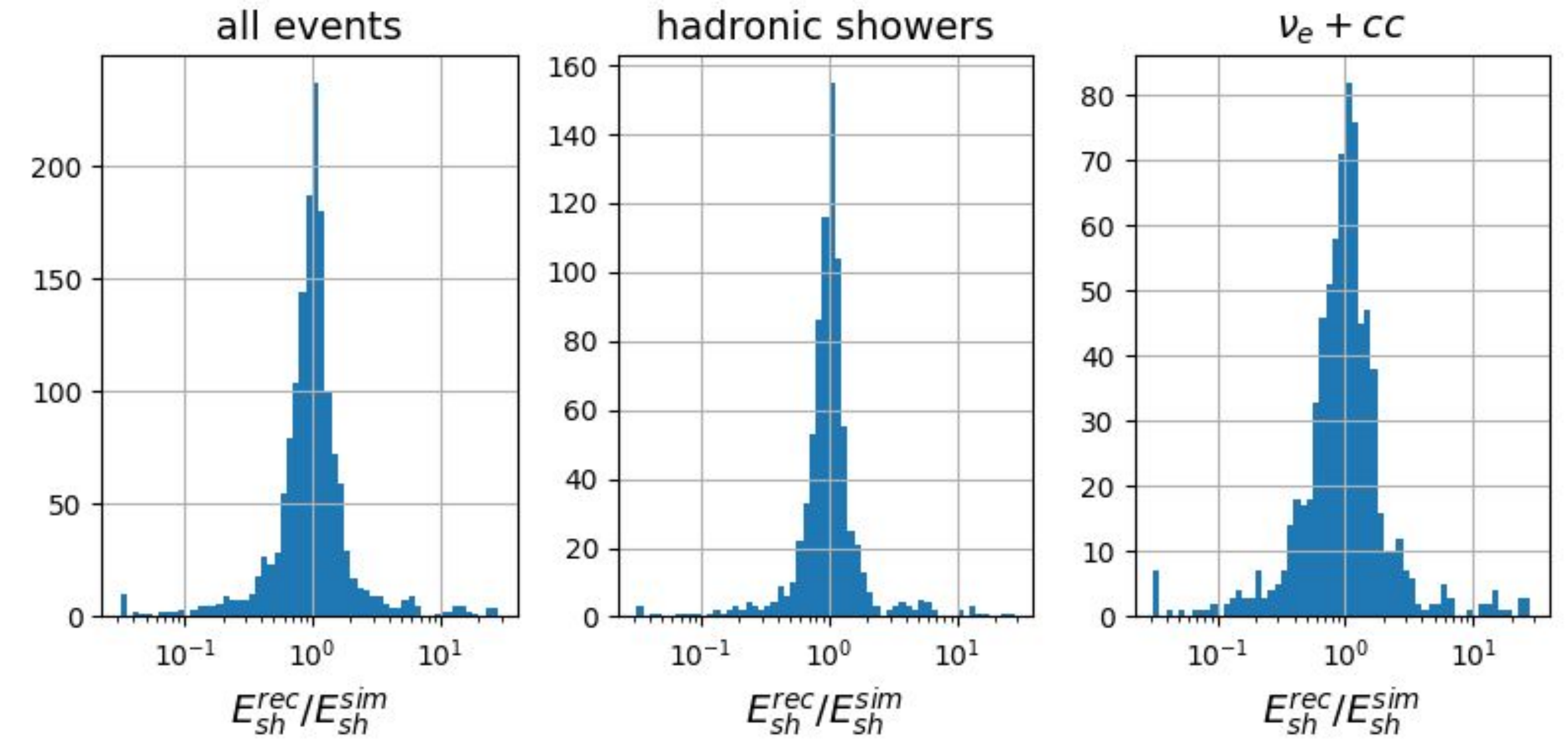


Fig4: Histogram of the ratios between reconstructed and actual shower energies for all event types (left), for events only producing a hadronic shower (middle) and for electron neutrinos undergoing charged current interactions (right)

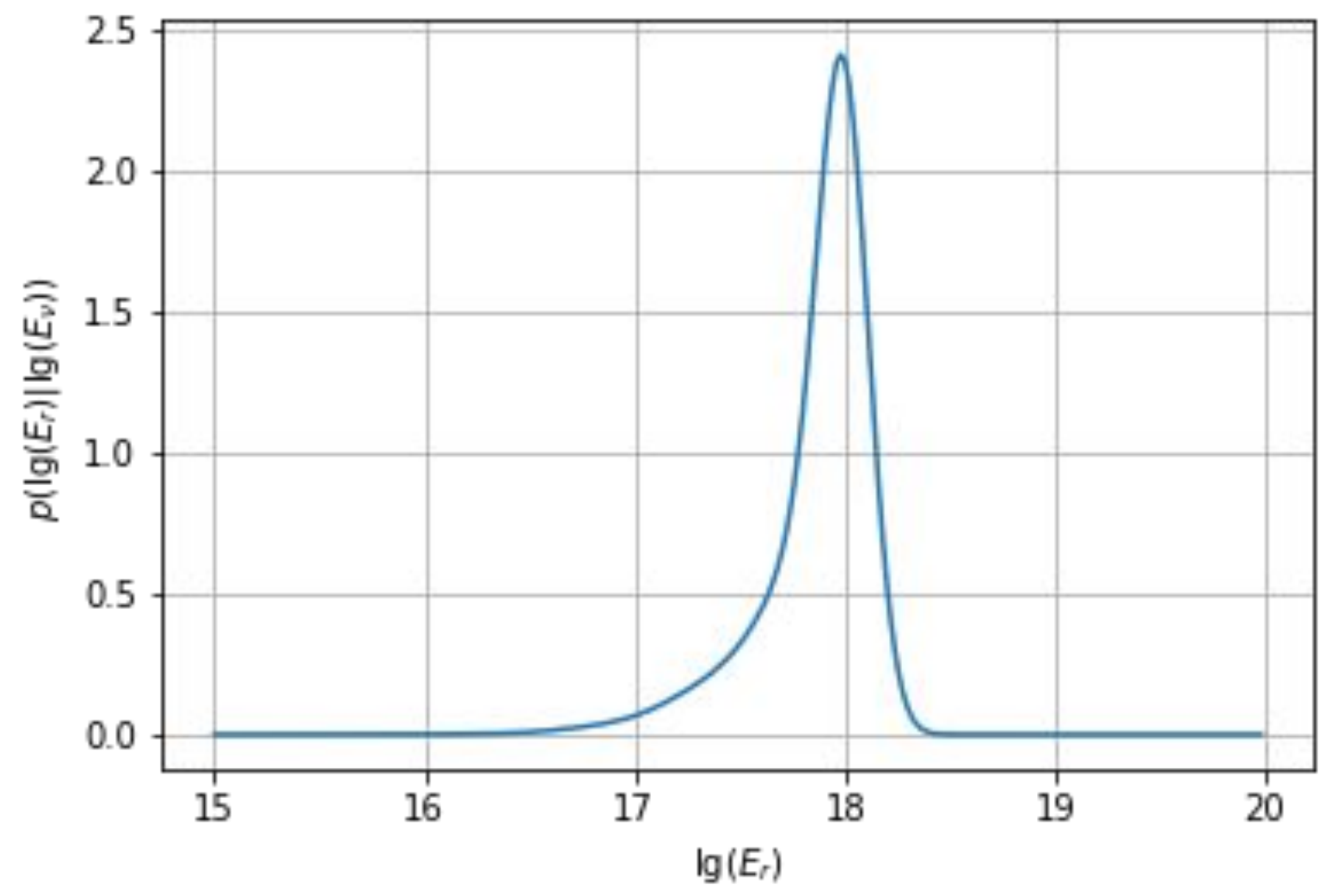


Fig5: Probability distribution of reconstructed energies for a neutrino with an energy of 10^{18}eV.

- Reconstruct interaction vertex from time differences between channels
- Electric field reconstruction using Information Field Theory [2]
- Shower energy reconstruction from electric field amplitude and spectrum shape
- 68% quantile of [-0.13, 0.12] on $\lg(E_r/E_s)$

- Ignoring energy of flavor dependence of uncertainties $\mathcal{N}(\lg(E_r/E_s)|0,\sigma_{\lg(E)})$
- Approcimate uncertainties with normal distribution
- Then distribution of reconstructed shower energies for given neutrino energy is:

$$p(\lg(E_r)|\lg(E_\nu)) = \int d\lg(E_s) \quad \mathcal{N}(\lg(E_r/E_s)|0,\sigma_{\lg(E)})\cdot p(\lg(E_s)|\lg(E_\nu))$$

Neutrino Spectrum

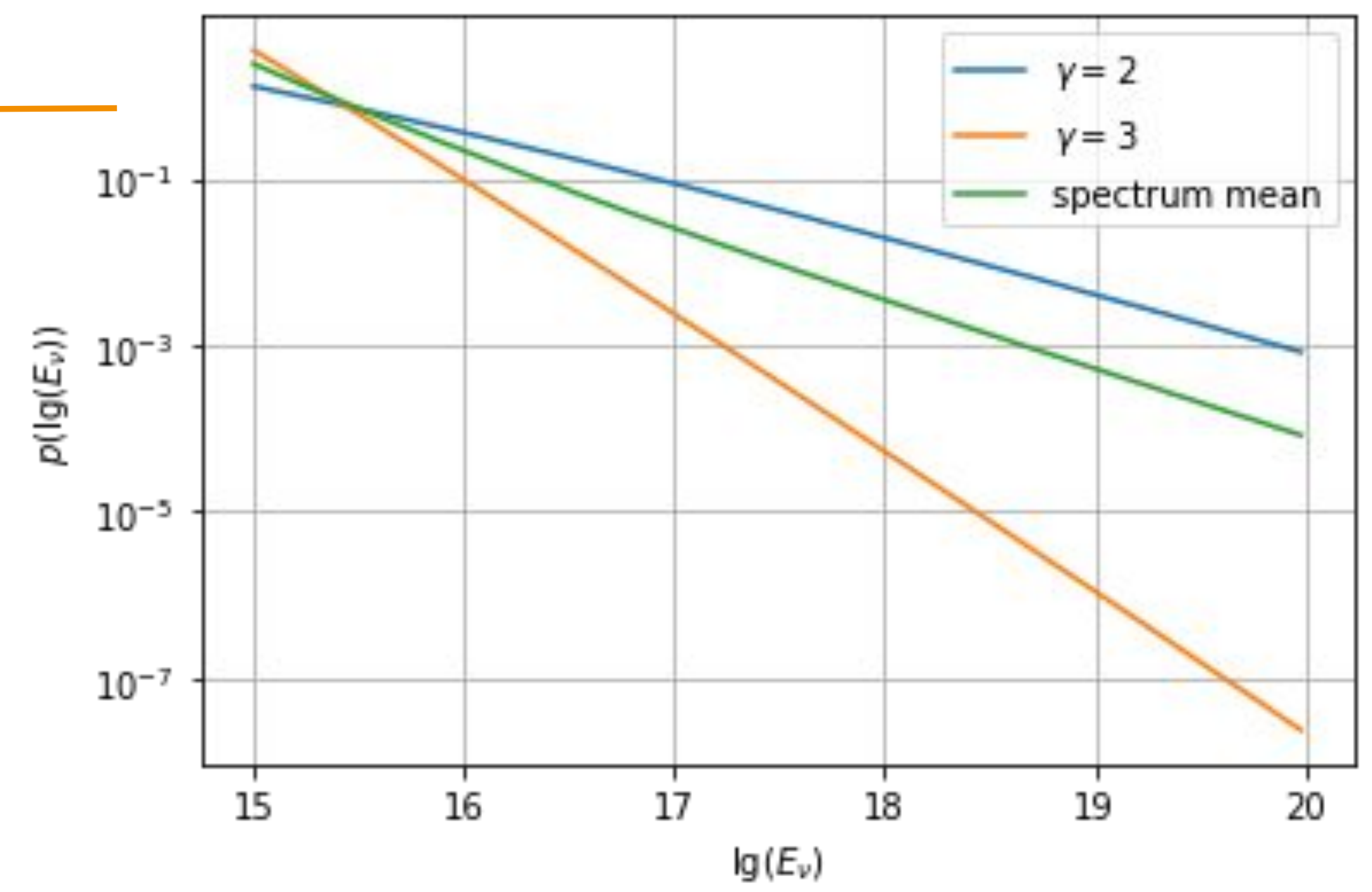


Fig 1: Prior neutrino energy distribution for a set of spectral models (green) and for the minimum and maximum spectral indices.

- Need prior $p(\lg(E_\nu))$ on the neutrino energy
- Spectrum at these energies is unknown
- Assume set of power law spectra: $\Phi_\nu \propto E^{-\gamma}$
- Assume all spectral indices equally likely
- Also consider neutrino interaction length $\lambda_\nu(E_\nu)$
- Then we can calculate the neutrino energy prior:

$$p(\lg(E_\nu)) = \int d\gamma \quad p(\gamma)\cdot\lambda_\nu(E_\nu)\cdot E^{-\gamma+1}$$

(ignoring normalization)

Interaction Dynamics

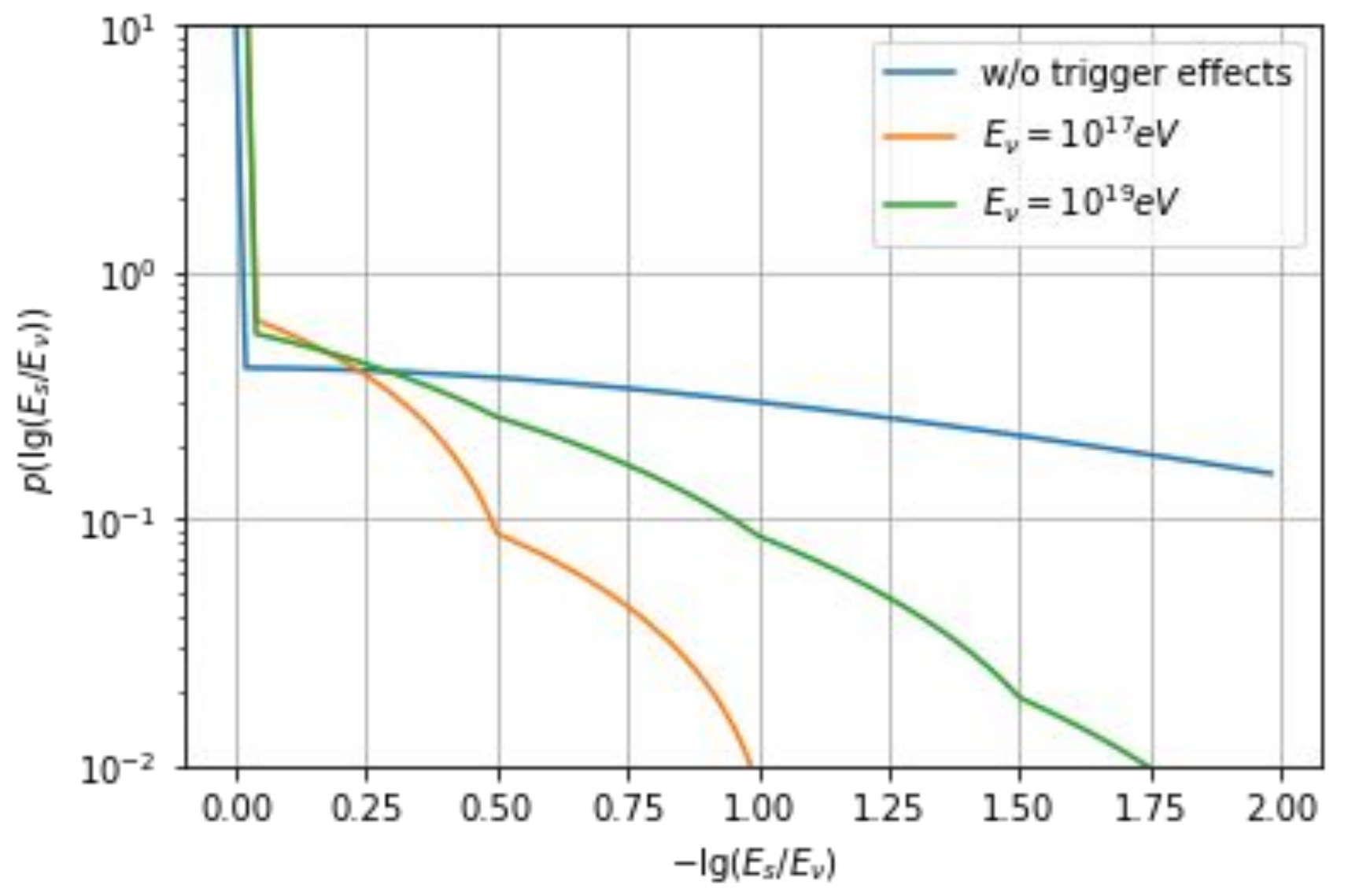


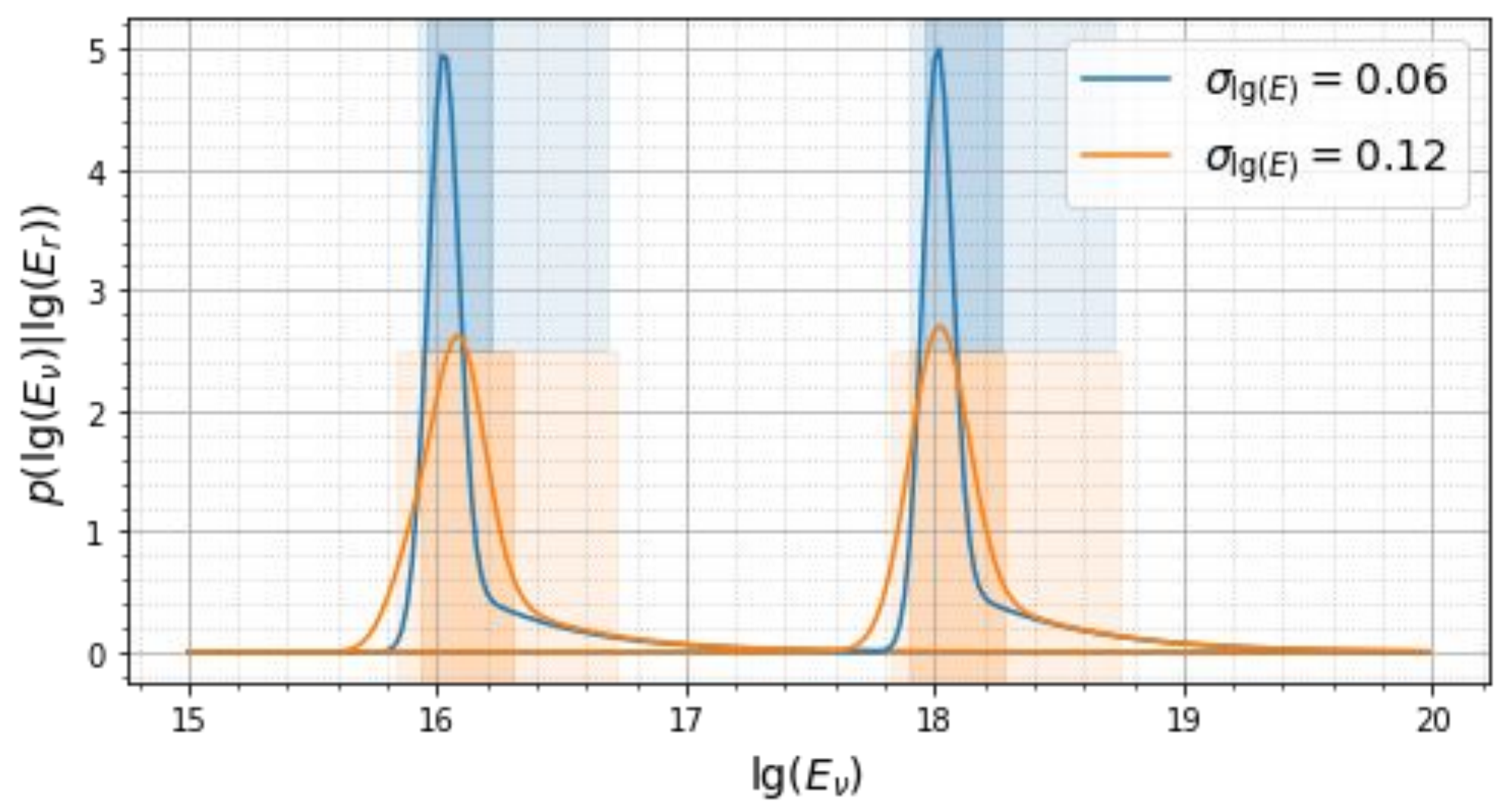
Fig2: Distribution of the fraction of the neutrino energy that is transferred into the shower, without (blue) and with (orange, green) considering trigger effects.

- Looking for probability of shower energy, given the neutrino energy
- Only fraction κ of the neutrino energy goes into the shower
- For hadronic showers: given by interaction inelasticity y
- For ν_e +CC events: κ=1
- Also need to consider trigger probability $p_T(\lg(E_s))$

$$p(\lg(E_s)|\lg(E_\nu) = p_T(\lg(E_s))\cdot p(\lg(\kappa) = \lg(E_s/E_\nu))$$

Improving Shower Energy Reconstruction

Fig 6: Posterior distributions of neutrino energies for uncertainties on $\lg(E_s)$ of 12% and 6%. Shaded regions show the 68% and 90% quantiles.



- Compare neutrino energy resolution if shower energy uncertainty is cut in half
- Small effect on neutrino energy due to interaction inelasticity

Flavor Sensitivity

Fig 7: Posterior distributions of the neutrino energy if the event is identified as a $\nu_e + CC$ event with a probability of 80%.
Shaded regions show the 68% and 90% quantiles

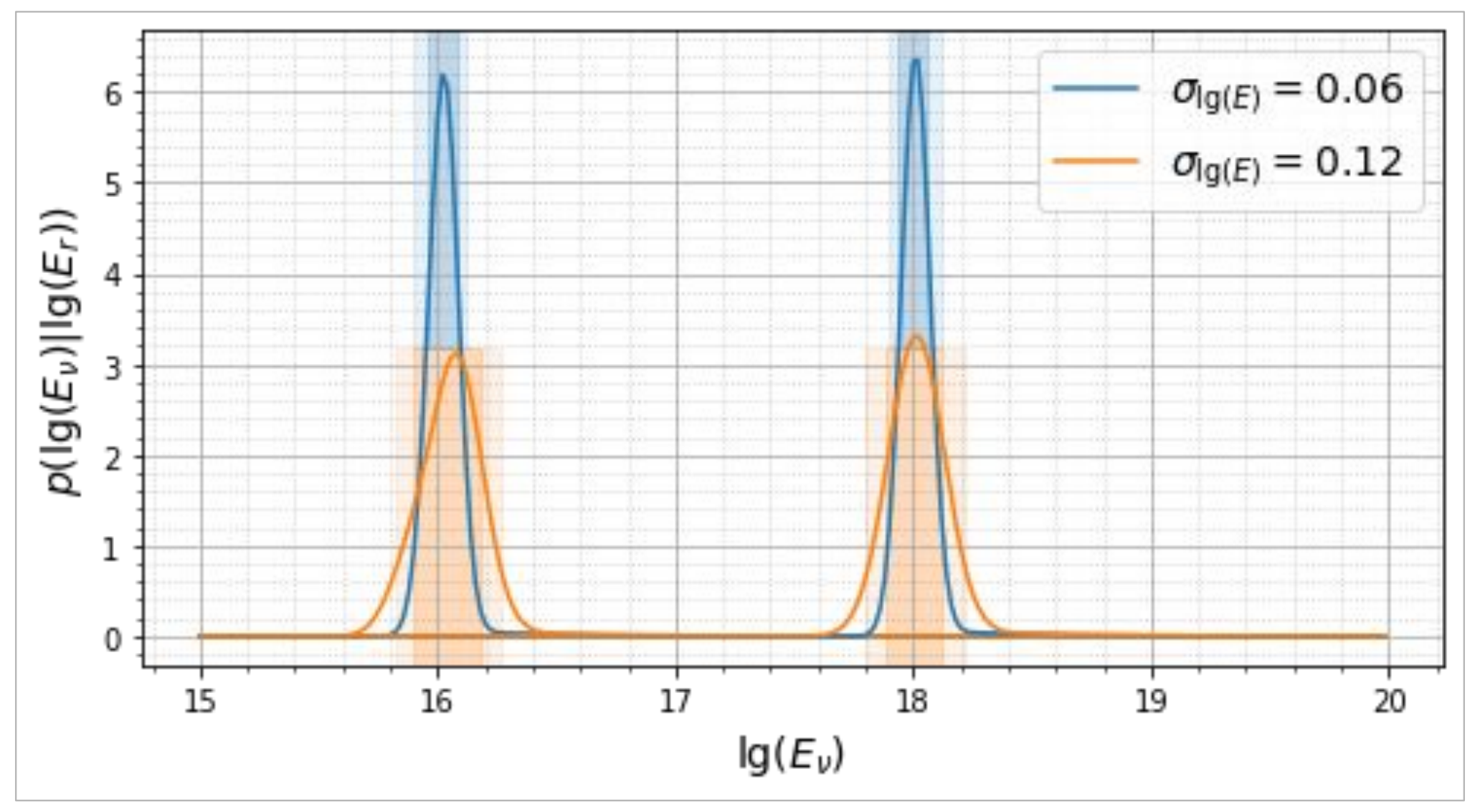


Figure 6: Correlation between channels for a given vertex position.

- If an electron neutrino undergoes CC interaction, all its energy goes into the shower
- No quantitative study on how to identify those done so far
- Being able to do so could lead to large improvement in neutrino energy resolution for those events

References

[1] Design and Sensitivity of the Radio Neutrino Observatory in Greenland (RNO-G), Aguilar et al., JINST 16, 2021, arxiv:2010.12279

[2] Reconstructing non-repeating radio pulses with Information Field Theory, Welling et al. JCAP 04, 2021, arxiv:2102.00258