# Importance of detector effects in the $\delta_{CP}$ measurement


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**based on**

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# Outline

1. Why is an accurate reconstruction of the neutrino energy important?

2. Our treatment of the detector effects

3. Effect of the missing energy on a CP violation measurement

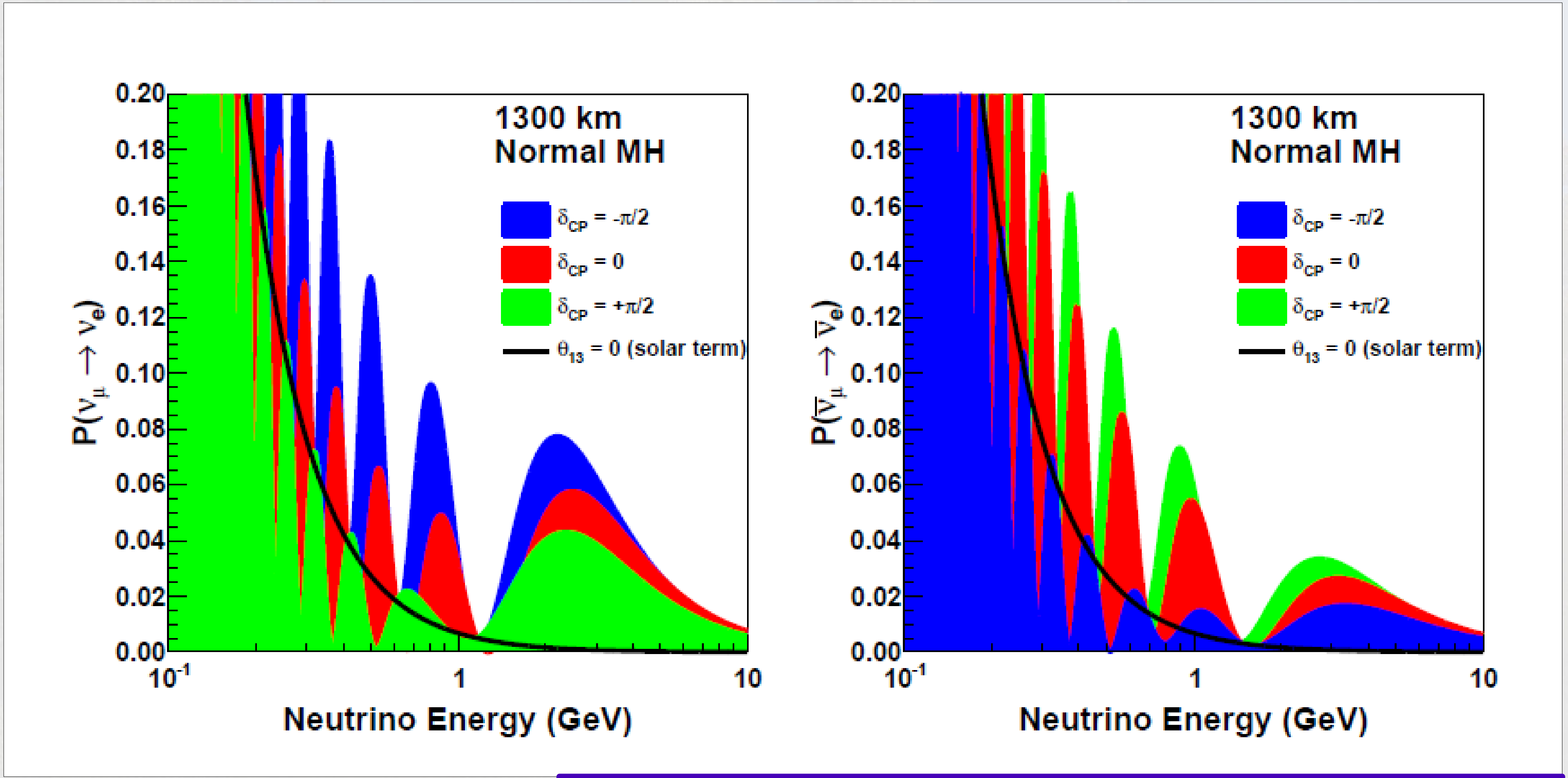
4. Summary

# $\nu_e$ and $\bar{\nu}_e$ appearance in DUNE

"The difference in probability amplitude for different values of $\delta_{CP}$ is larger at higher oscillation nodes, which correspond to energies less than 1.5 GeV. Therefore, a broadband experiment, capable of measuring not only the rate of $\nu_e$ appearance but of **mapping out the spectrum of observed oscillations down to energies of at least 500 MeV, is desirable**."

R. Acciarri et al. (DUNE Collab.), arXiv:1512.06148

# $\nu_e$ and $\bar{\nu}_e$ appearance in DUNE

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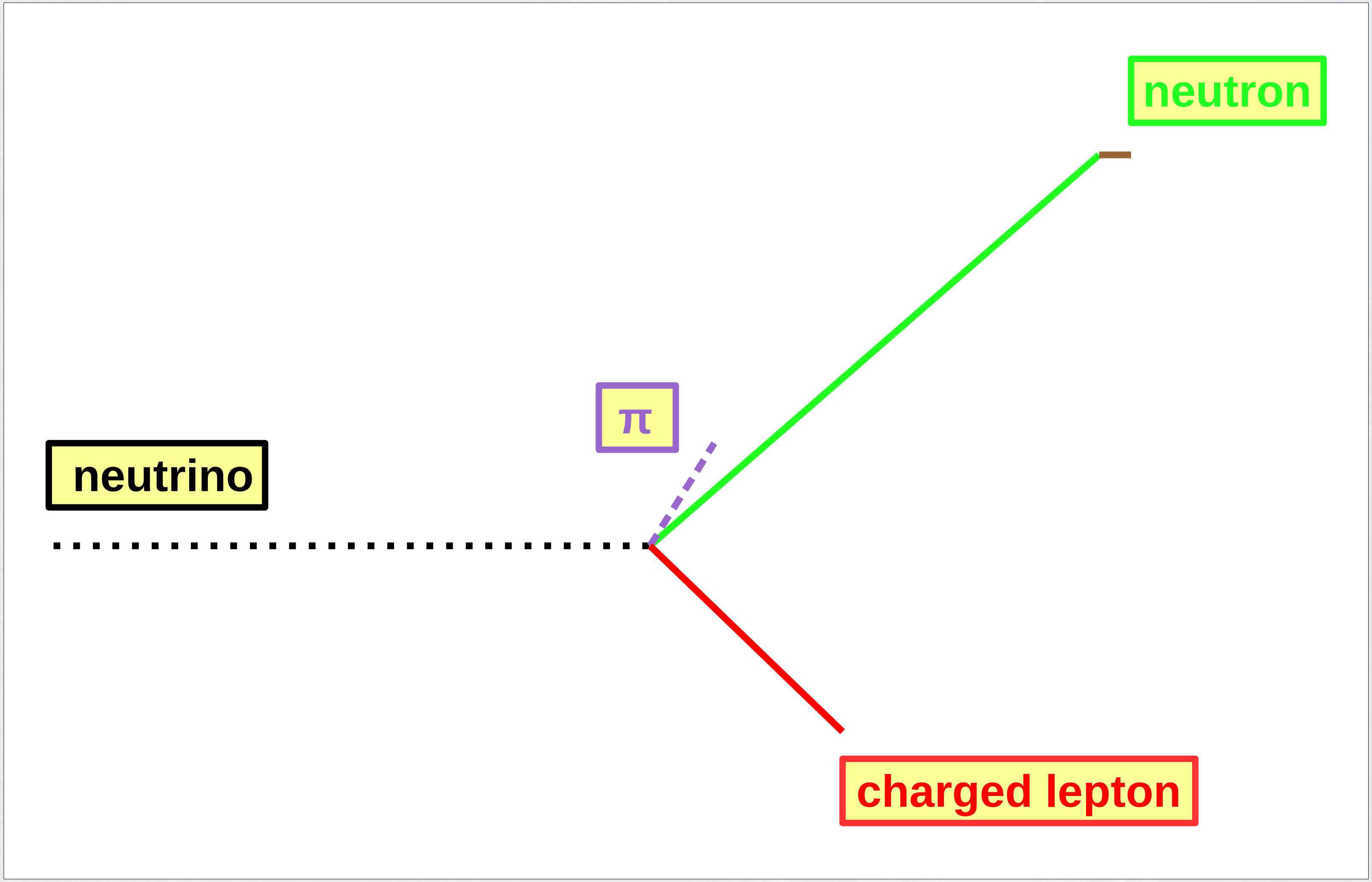
# Calorimetric $E_\nu$ reconstruction

Add the deposited energy

$$E_\nu^{\mathrm{cal}} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j,$$

- Applicable to any final state
- Accurate hadron reconstruction required
- Used by MINOS(*), NOvA, planned in DUNE

# Missing energy



# Calorimetric $E_\nu$ reconstruction

- protons

  **kinetic** energy + separation energy

  below the threshold: $E_{miss}$ up to **~70 MeV**

- pions

  **total** energy

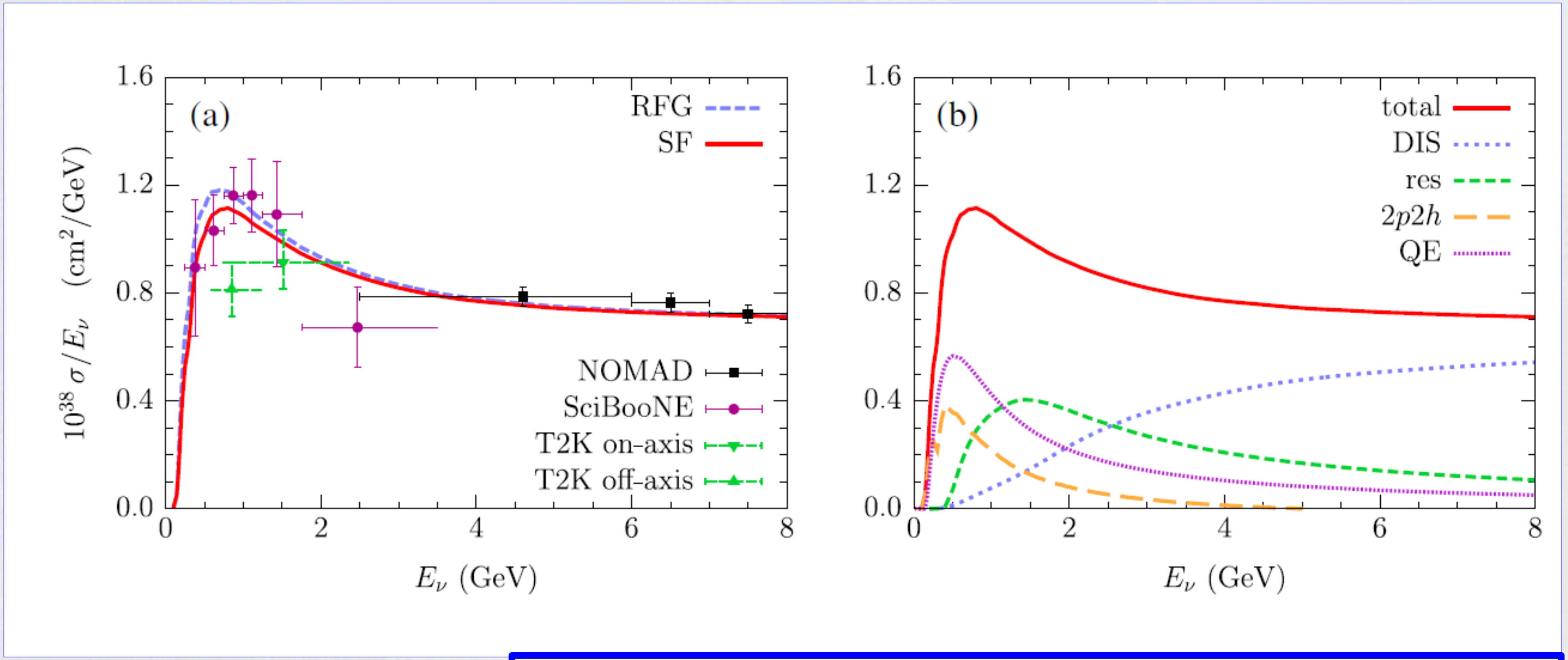
  below the threshold: $E_{miss}$ up to **~160 MeV**(*)

# Idea of our analysis

We want to quantify **how accurately the missing energy needs to be estimated** to avoid a sizable bias in the extracted $\delta_{CP}$ value.

Owing to the importance for DUNE (background removal), we consider a calorimetric detector capable of fine-grained tracking.

# Event generating




**GENIE + *ν*T: Jen *et al.*, PRD 90, 093004 (2014)**

# Considered setup

- 40 kton far detector located 1300 km from the neutrino source

- the 80-MeV primary proton beam of 1.08 MW, 3 + 3 years of running

- systematic uncertainties: shape (2%), normalization (2%), background norm. (5%), no explicit use of the near detector

# Detector effects

We take into account

- energy smearing,
- efficiencies,
- thresholds,

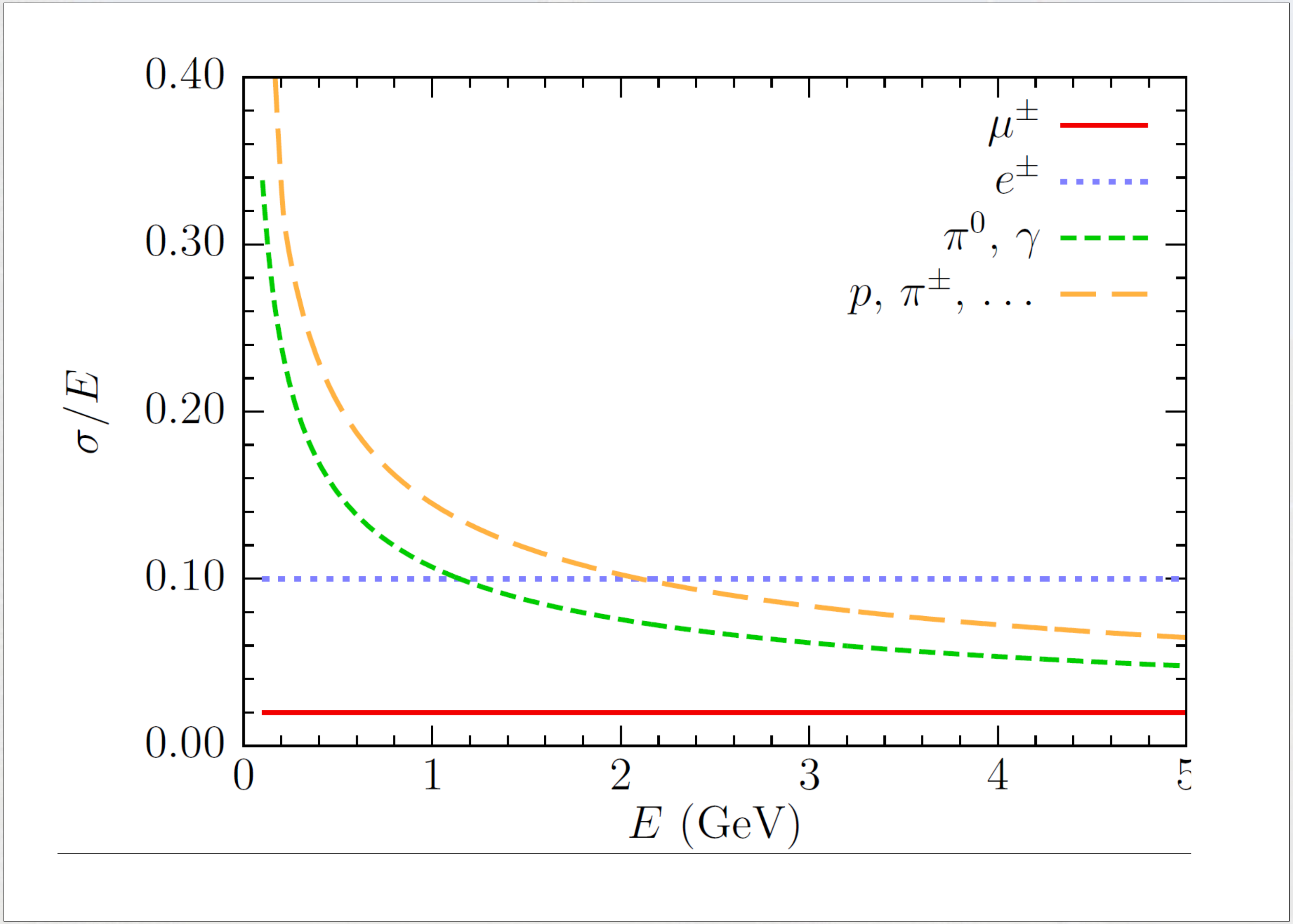
treating separately $\mu$, $e$, $p$, $n$, $\pi^0$, and other mesons

# Smearing

To simulate the energy smearing in the detector, we use Gaussian distributions:

$$f(x_{\text{meas}}) = \frac{1}{\sqrt{2\pi}\sigma(x_{\text{true}})} \exp\left[-\frac{1}{2}\left(\frac{x_{\text{meas}} - x_{\text{true}}}{\sigma(x_{\text{true}})}\right)^2\right].$$

# Energy resolutions in our analysis



# Treatment of efficiencies

We treat them as energy independent, taking

- 80% for electrons,
- 80% for charged pions, all kaons, and gammas,
- 60% for neutral pions,
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**set to optimistic values compared to existing detectors**

# Thresholds in our analysis

- 0 MeV for muons and electrons,
- 20 MeV for pions and kaons,
- 40 MeV for protons.

# Neutrons

- travel some distance before scattering in the detector, hard to associate with the event
- deposit only a fraction of energy

**Assumed to escape detection**

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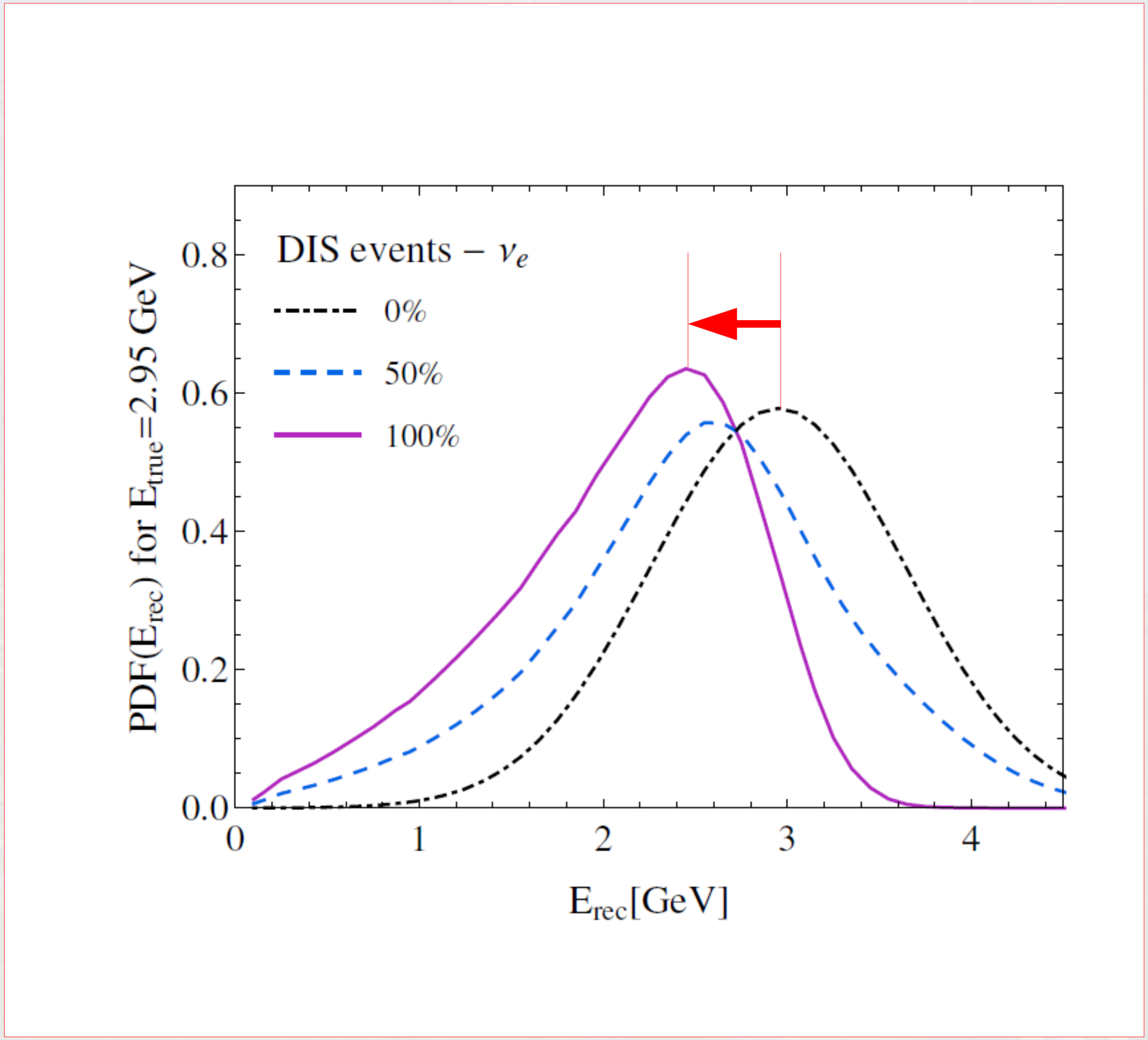
**For comparison, DUNE prelim. studies assume the neutron efficiency of 90% for $|p| < 1$ GeV/*c*.**

# Role of the missing energy

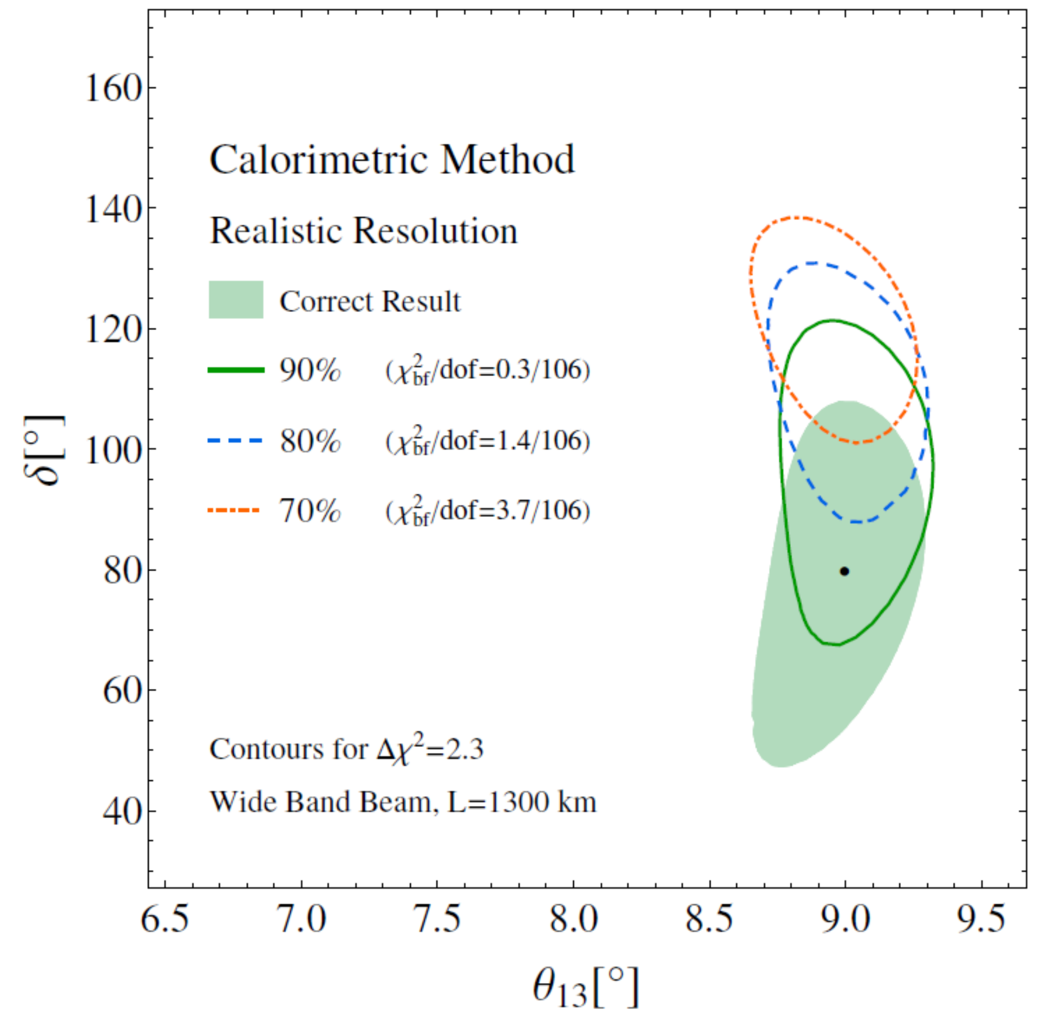
We manually tune the amount of the missing energy accounted for in the migration matrices, keeping constant the width of the reconstructed energy distributions

$$N_i^{fit} = \sum_X \sum_j \{ \alpha M_{ij}^{X,real} + (1-\alpha) M_{ij}^{X,Gauss} \} N_i^X$$

# The missing energy



# CP violation for a DUNE-like setup



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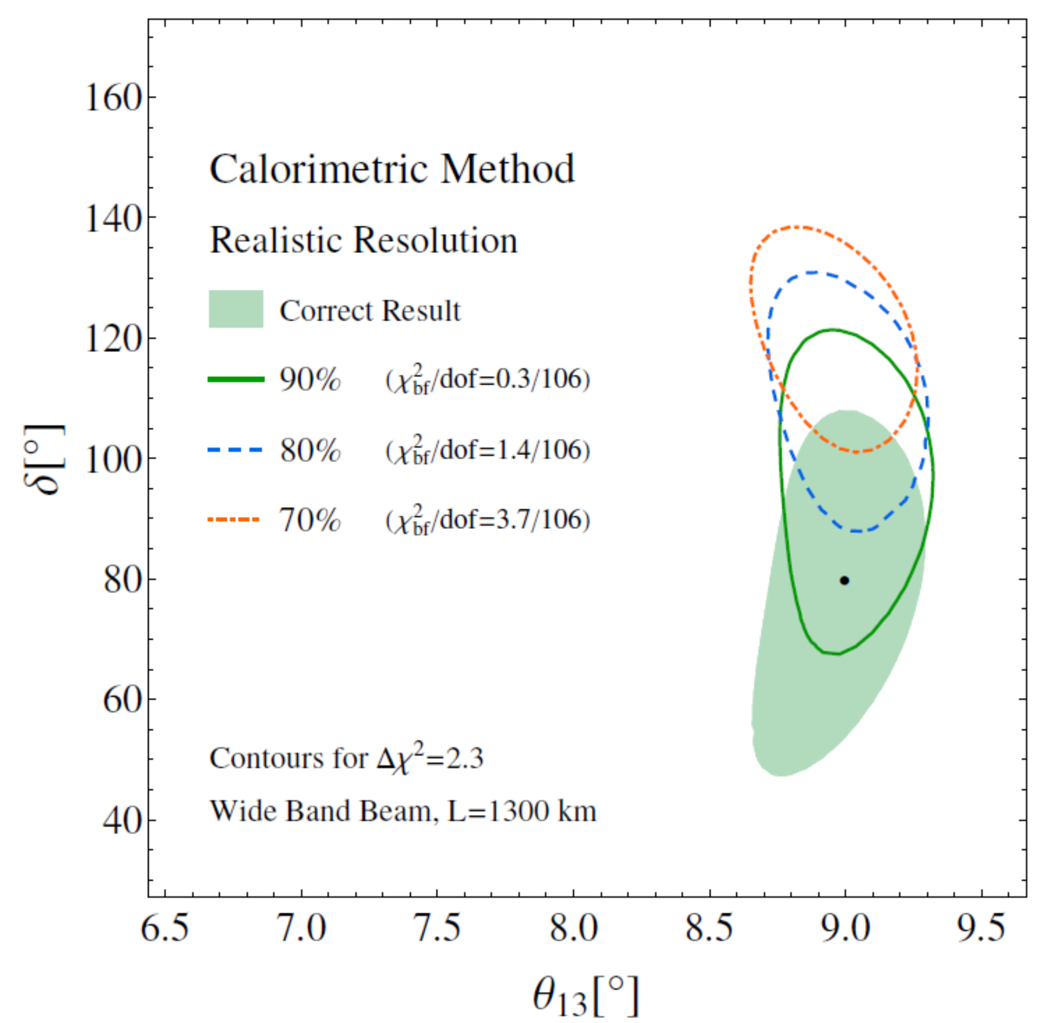
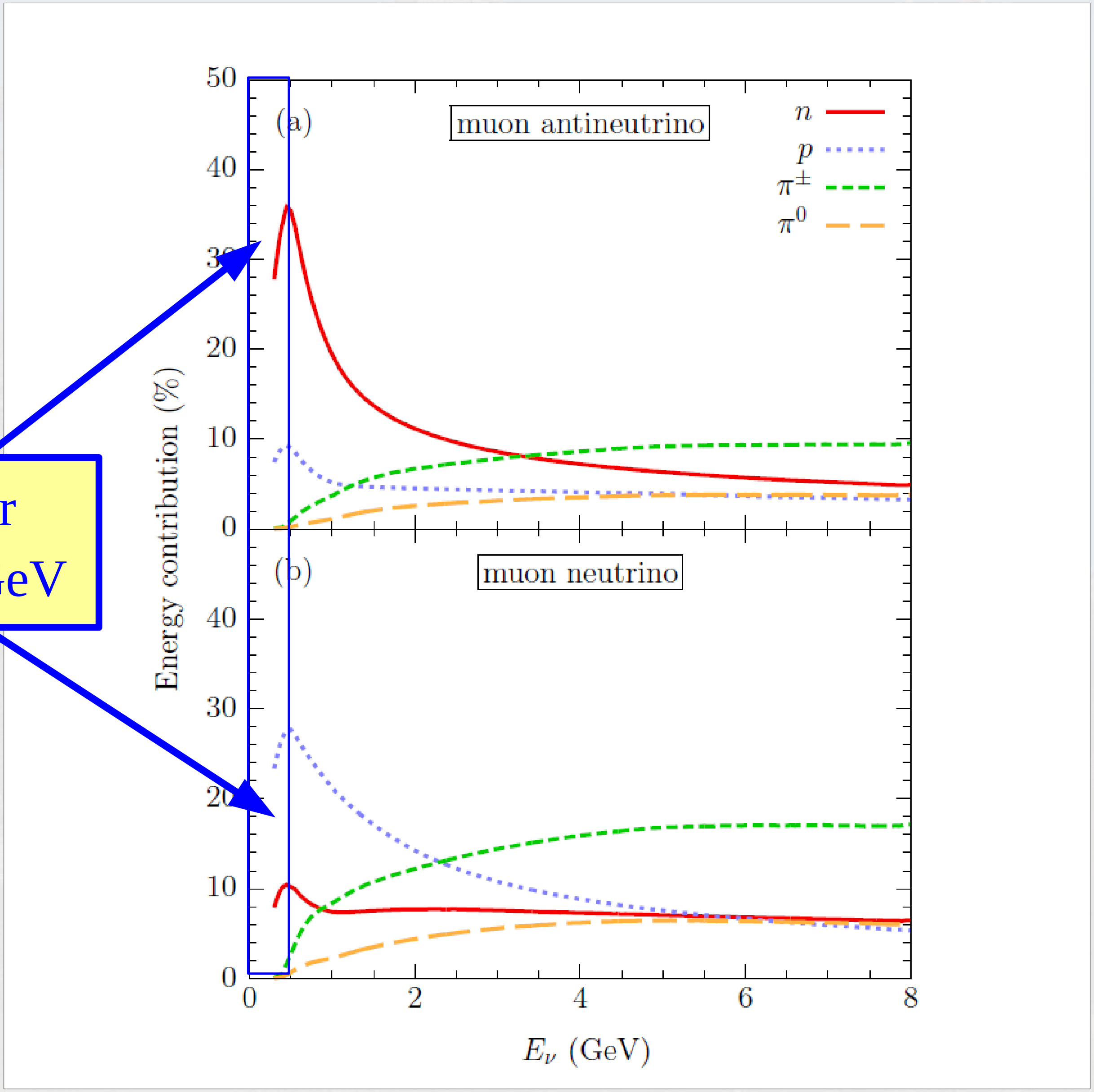



**The missing energy needs to be estimated with a ~20% accuracy or better**

# Final-state energy contributions




$\nu_e$ and $\nu_\mu$ differ only at $E < 0.5$ GeV

# Summary

❶ An accurate energy reconstruction down to 500 MeV requires sensitivity to low energy nucleons and pions (muons).

❷ Below the detection threshold, protons (pions) may carry out up to 70 MeV (160 MeV). Sensitivity to low energy muons may be helpful.

❸ An accurate determination of CP violation in a DUNE-like experiment requires the missing energy to be known in the analysis with an accuracy exceeding 20%.

# Backup slides