Supernova Pointing Resolution of DUNE

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for the DUNE
Collaboration

ICHEP
07.29.20

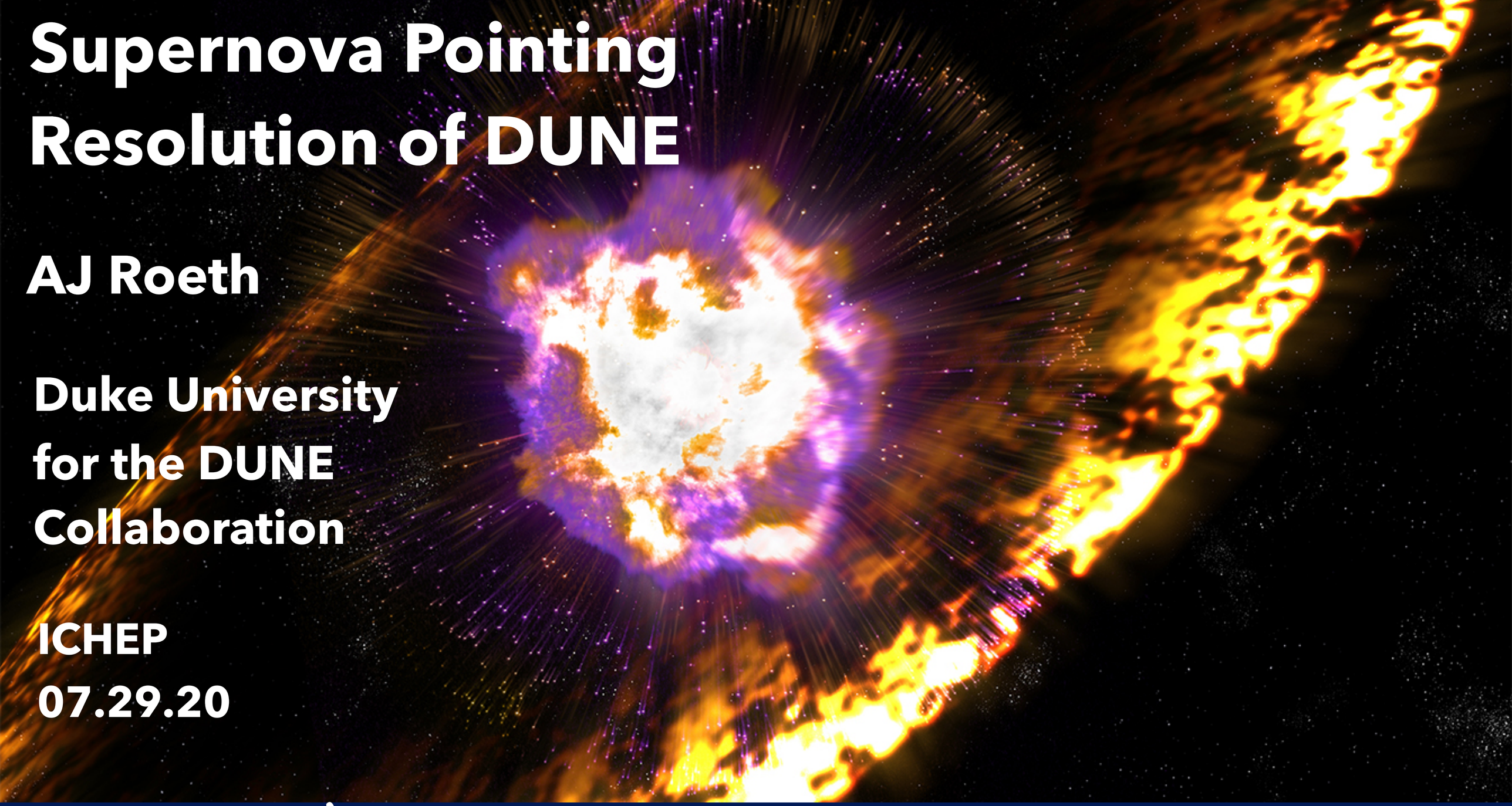


image: extremetech.com

Overview

- 40 kton fiducial volume liquid argon detector
- Capable of detecting supernova neutrinos
- For more information, see:
  - Clara Cuesta's talk "Core-Collapse Supernovae Burst Neutrinos in DUNE"
  - DUNE Supernova Burst paper (forthcoming): arXiv:1910.11068
- My goal: Determine and improve detector's pointing resolution for supernovae
  - Warning astronomers through Supernova Early Warning System (SNEWS)
  - Finding progenitor for no-supernova case

DEEP UNDERGROUND NEUTRINO EXPERIMENT

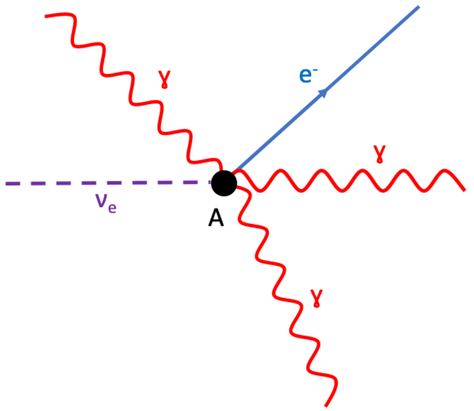
image: symmetrymagazine.org

Overview

- Interactions
  - ν_e charged current - majority of events
  - elastic scattering of neutrinos on electrons - most anisotropic, correlated with supernova direction
- Steps: Use simulations to find pointing resolution for…
  - single electrons
  - neutrino-electron elastic scattering events
  - supernova samples of those two interactions

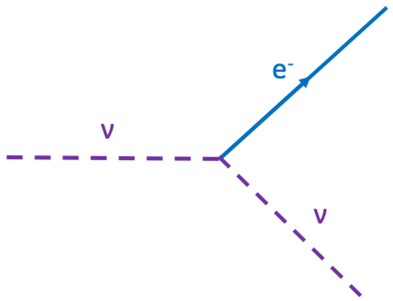
Charged Current

$$\nu_e \; {}^{40}Ar \rightarrow e^- \; {}^{40}K^*$$



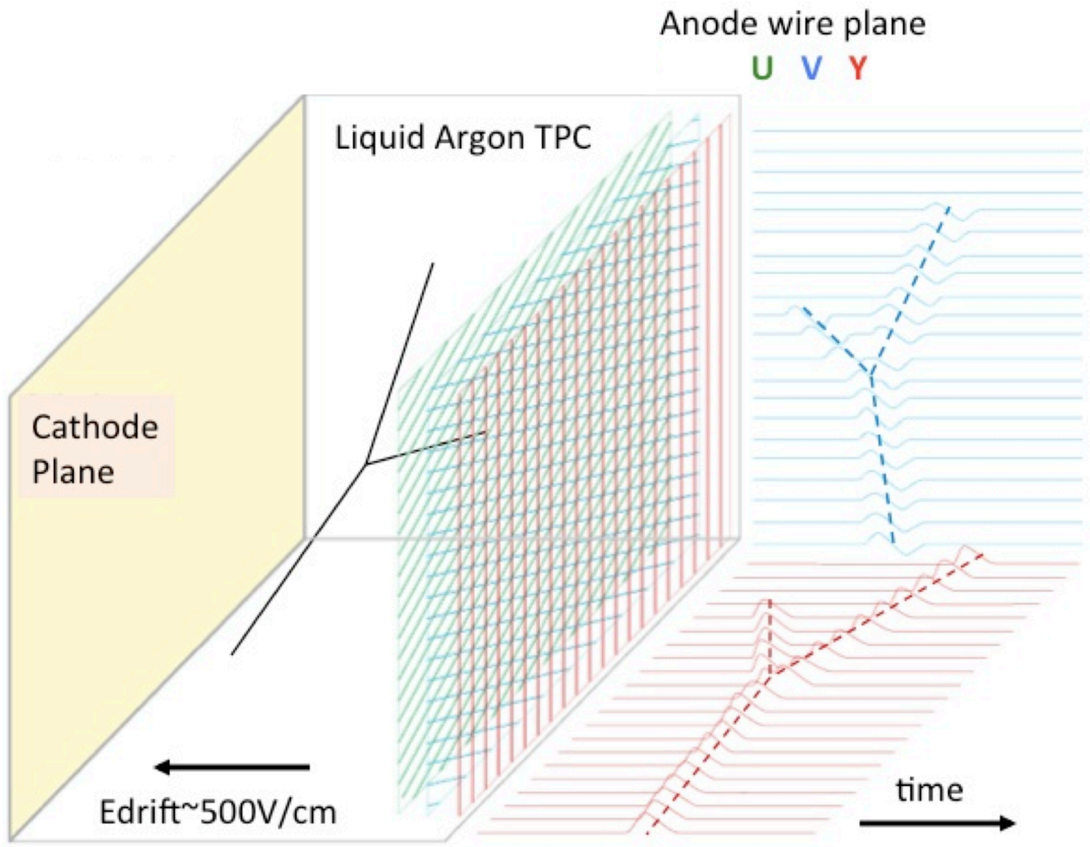
Elastic Scattering

$$\overset{(-)}{\nu} \; e^- \rightarrow \overset{(-)}{\nu} \; e^-$$



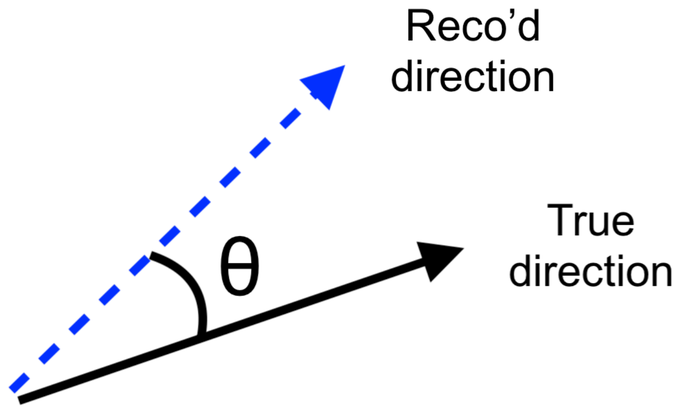
Reconstruction of supernova direction

- Supernova neutrinos interact in liquid argon
- Detected by products of interactions - electrons, gammas
- Ionize liquid argon, ionized electrons are collected using electric field and wire planes
- Software used to reconstruct particle tracks
  - LArSoft
  - Projection Matching Algorithm
- Direction of particle tracks gives info about supernova direction



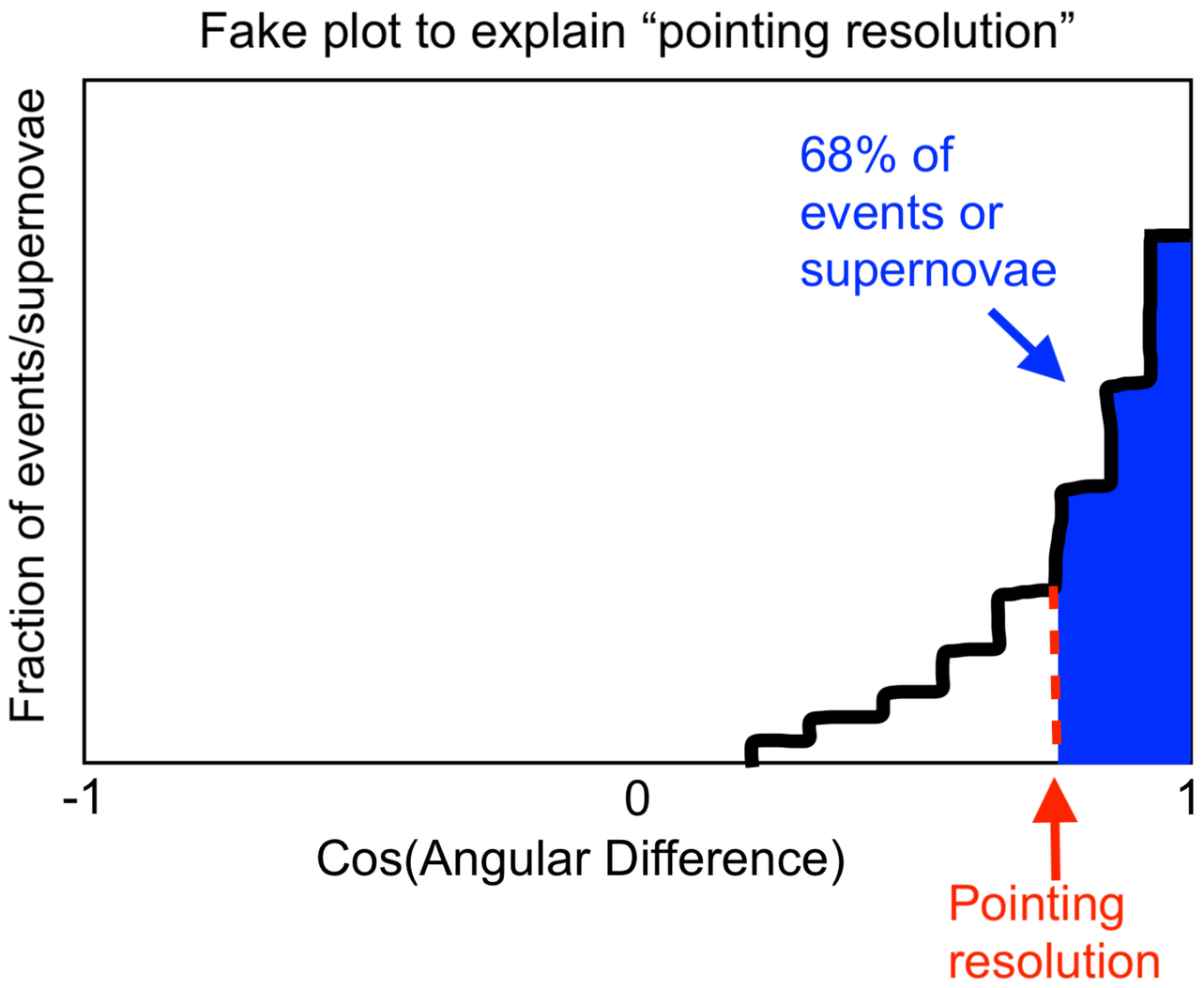
Pointing resolution

- Measure of how well we can determine the direction of something
  - A particle, a supernova
- There is error between true and reconstructed directions of particles
  - Reconstructed direction = direction vector of the first point of the track (as defined by track reconstruction software)
- There is also error in reconstruction of supernova directions
  - Error in individual particle direction error
  - Uncertainty in inferring supernova direction from collection of events



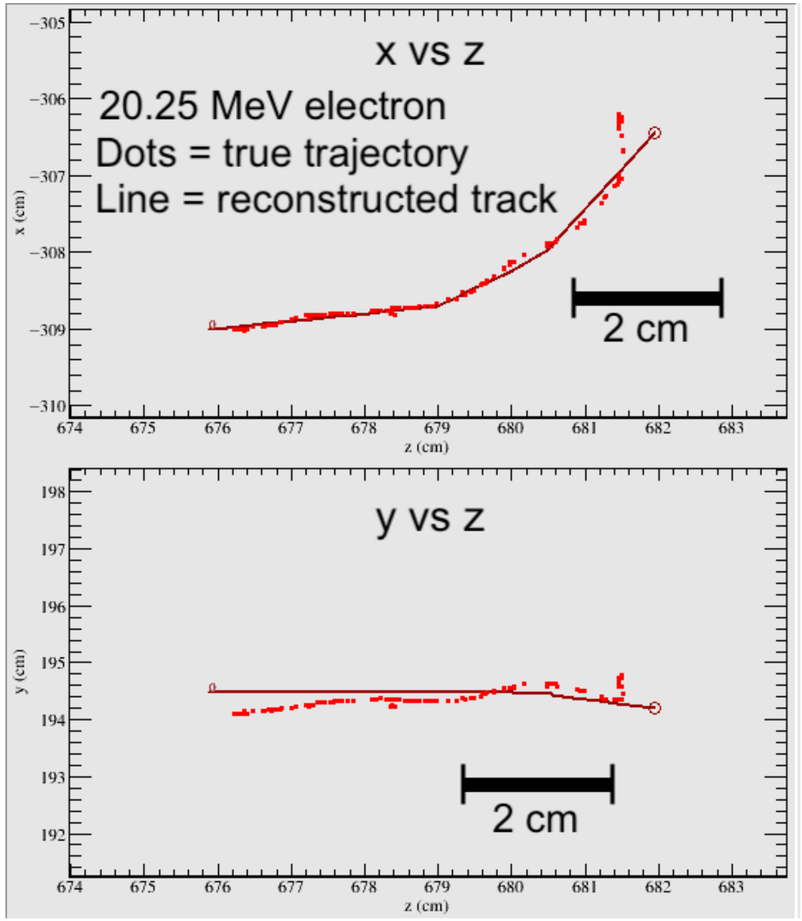
Pointing resolution

- Obtained using Monte Carlo
- Steps:
  - Generate sample
  - Find distribution of angles between true directions and reconstructed directions
  - Pointing resolution is angle where 68% are closer to truth



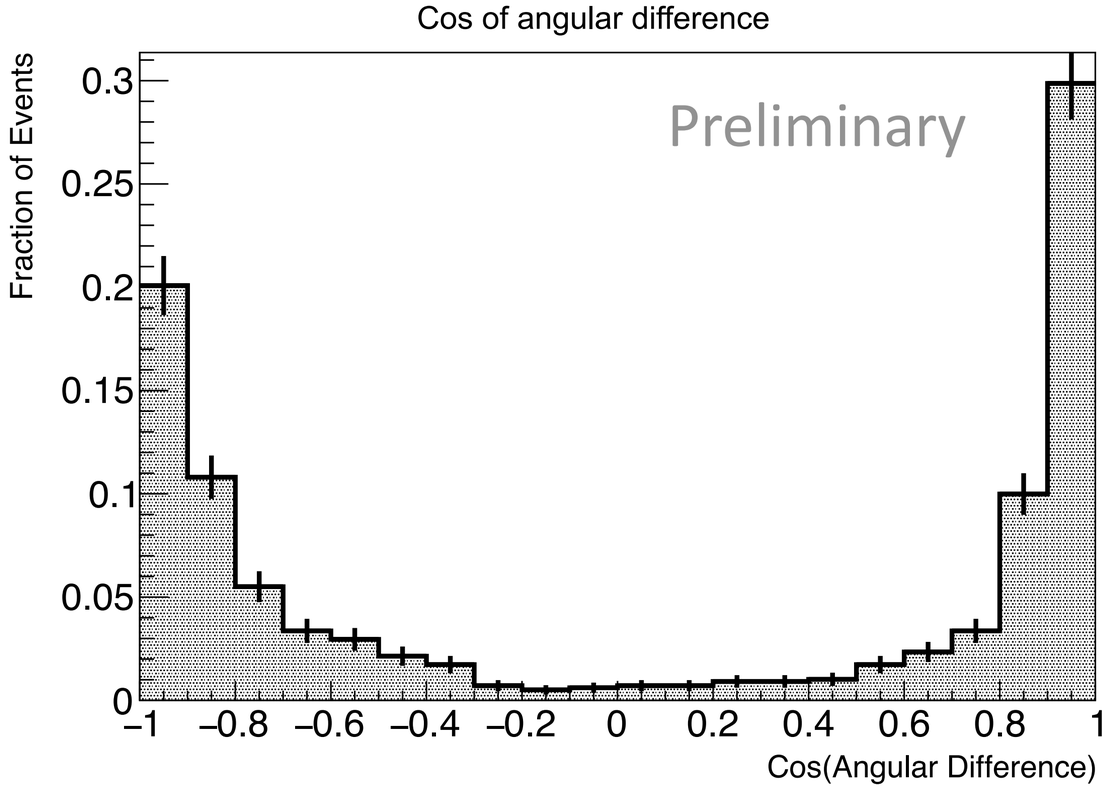
Single electrons

- Simulated and reconstructed isotropic single electrons
- Several tracks per event due to daughter particles
  - From bremsstrahlung gammas Compton scattering
  - Assume longest track is primary electron
    - Accuracy rate of 95% (clean) or 93% (with backgrounds and noise)
- Calculated angles between true start electron direction and reconstructed direction (θ)



Directional ambiguity

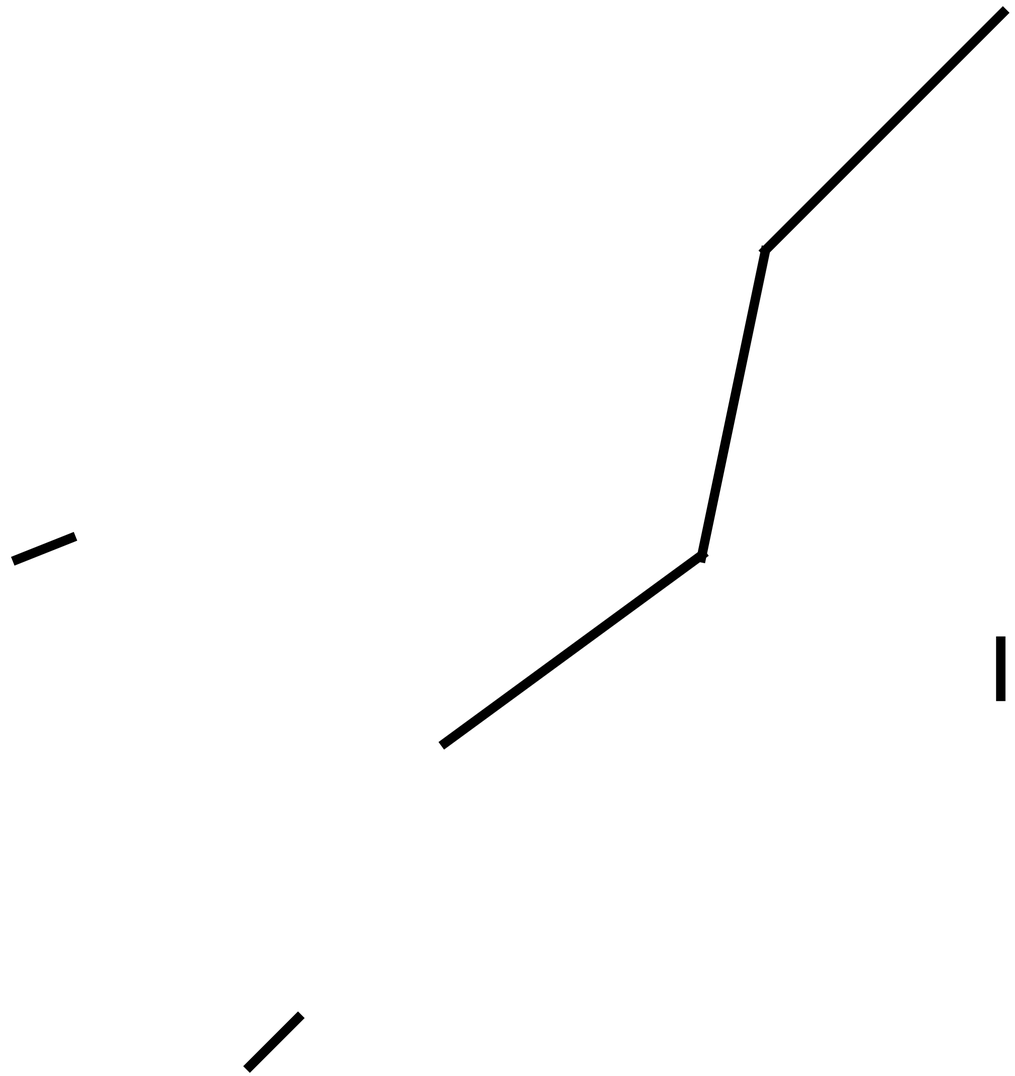
- Plotted cos of angles between true start electron direction and reconstructed direction (θ)
  - Can see directional ambiguity - two peaks
- Resolving this important for determining supernova direction
- One method: daughter tracks correlate with electron direction



20.25 MeV electrons

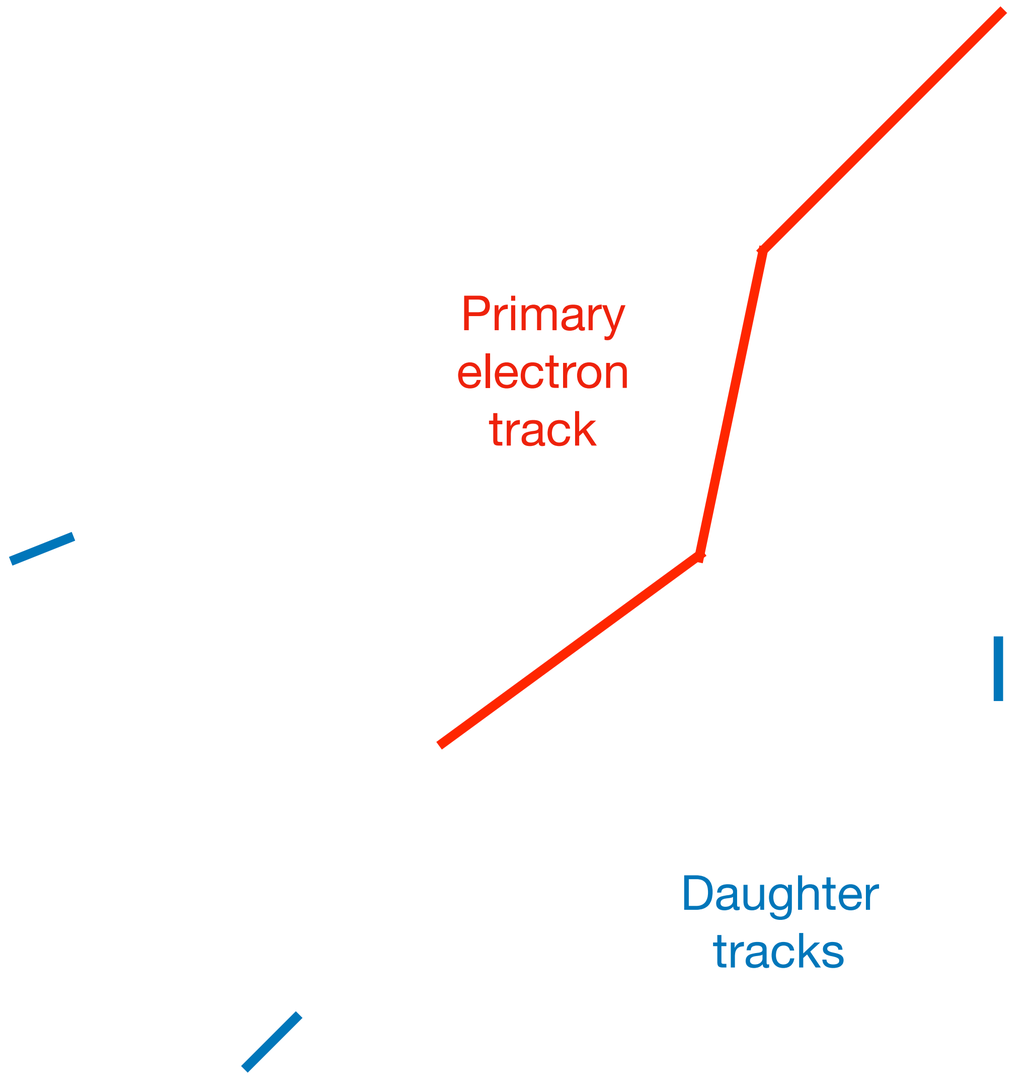
Daughter flipping

- Simplified example event topology to demonstrate daughter flipping:



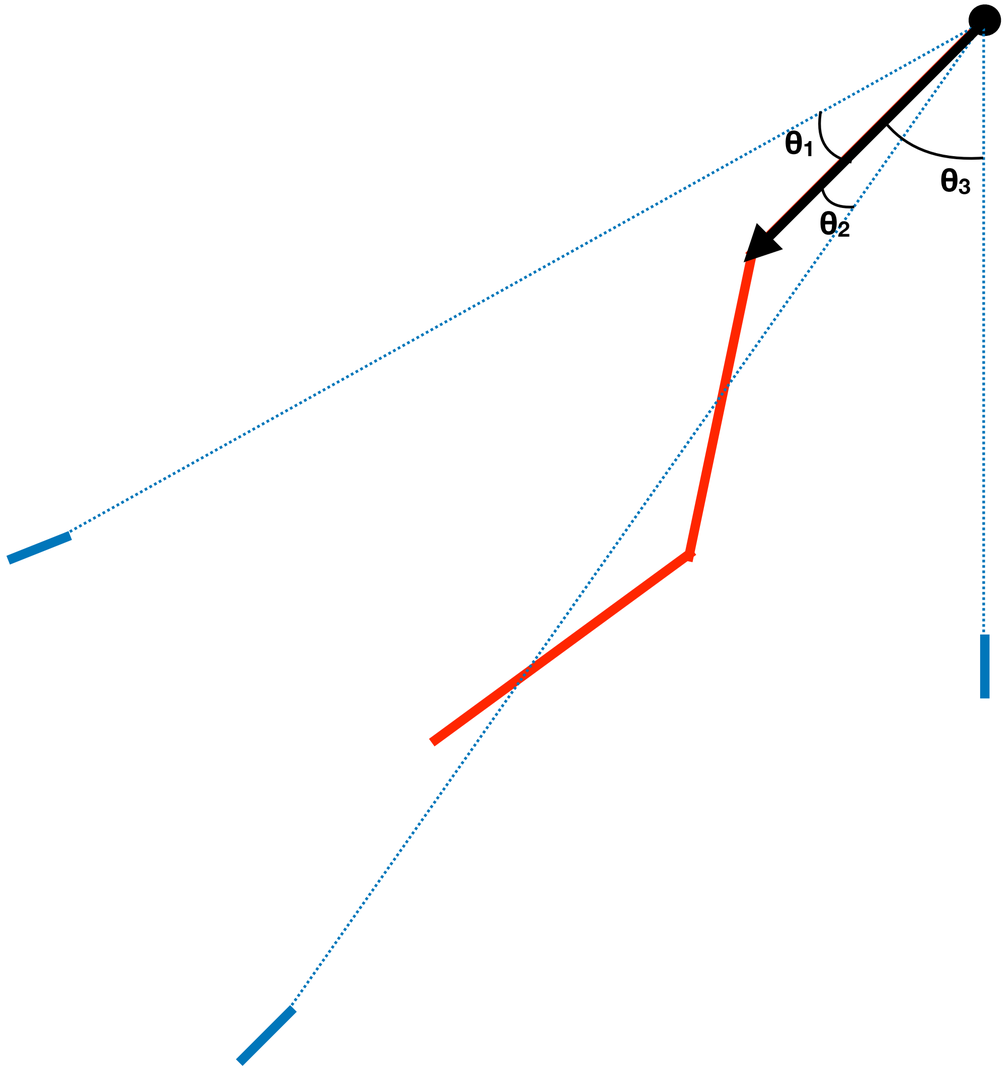
Daughter flipping

- Select longest track as primary electron



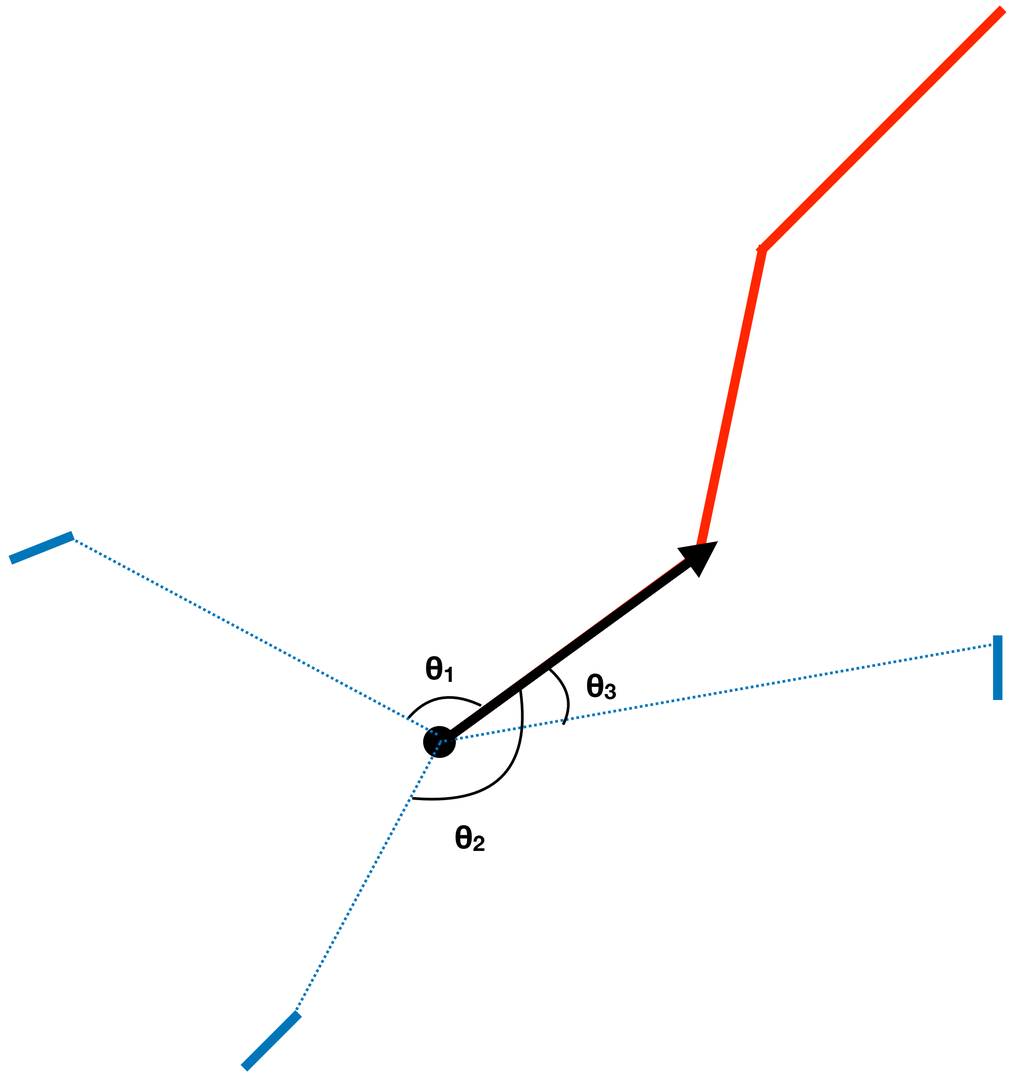
Daughter flipping

- Calculate angles between reconstructed direction of one end of track and daughter tracks
- Calculate average of cosines of those angles



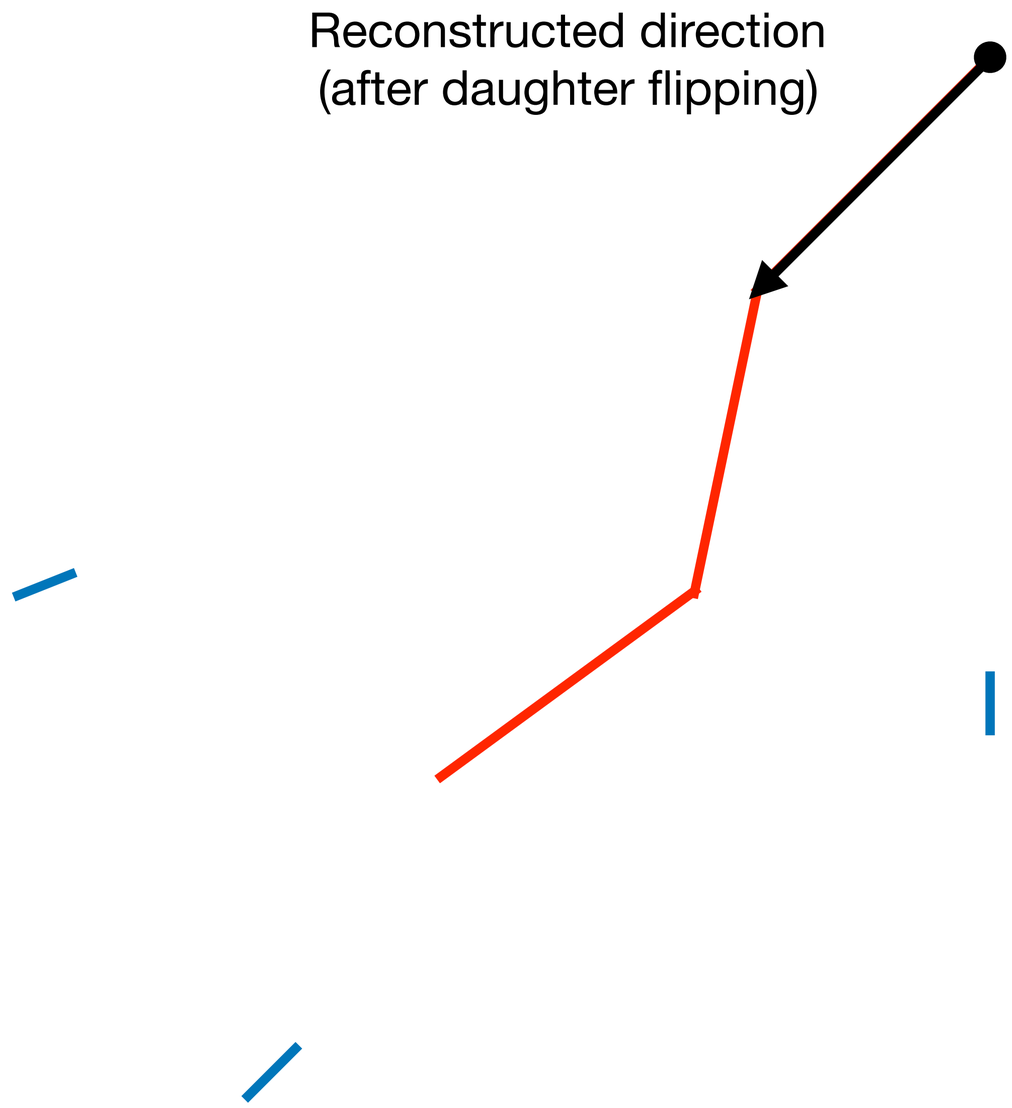
Daughter flipping

- Calculate angles between reconstructed direction of the other end of track and daughter tracks
- Calculate average of cosines of those angles

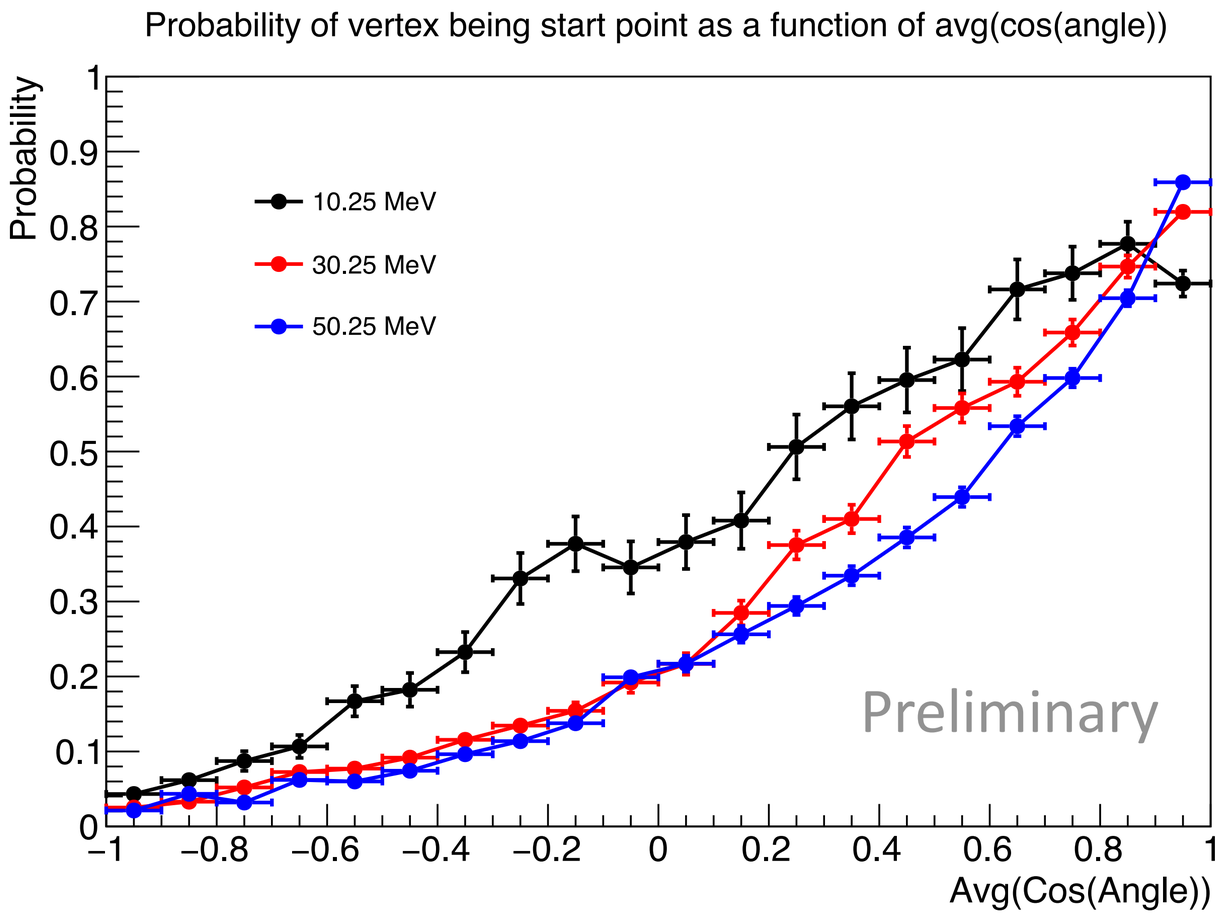


Daughter flipping

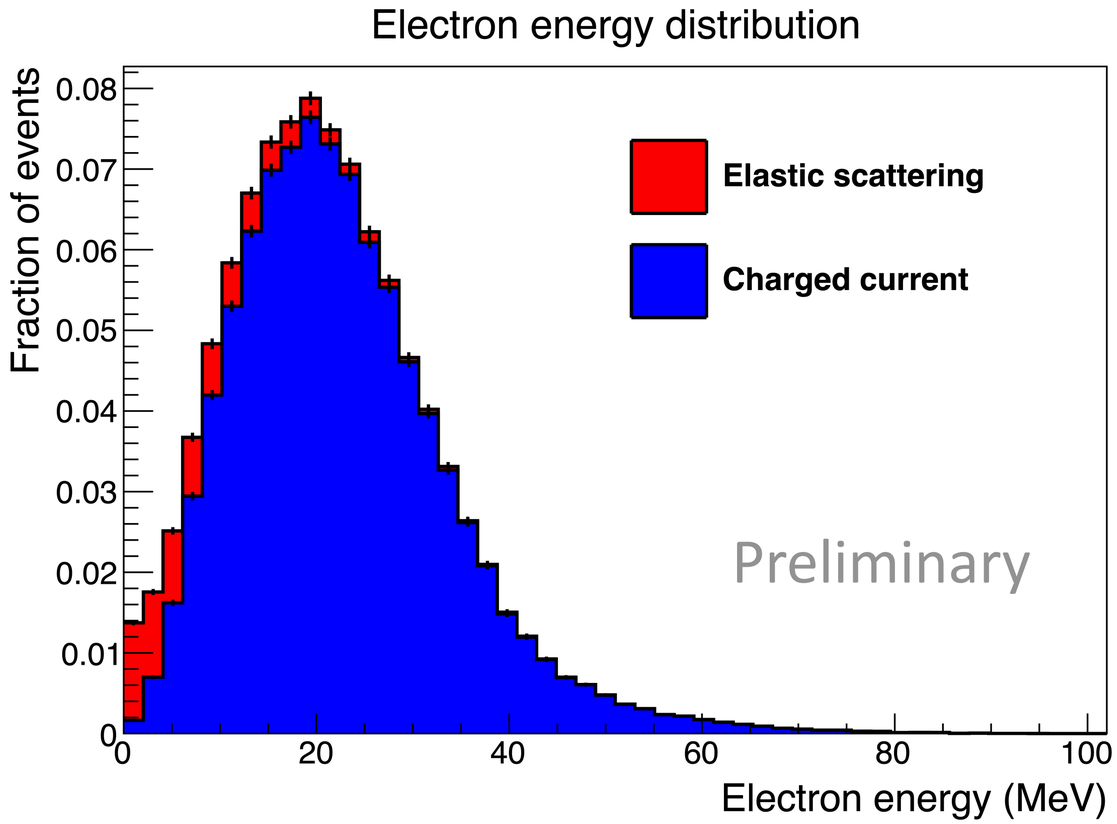
- Reconstructed direction becomes the one with higher average cosines



Daughter flipping

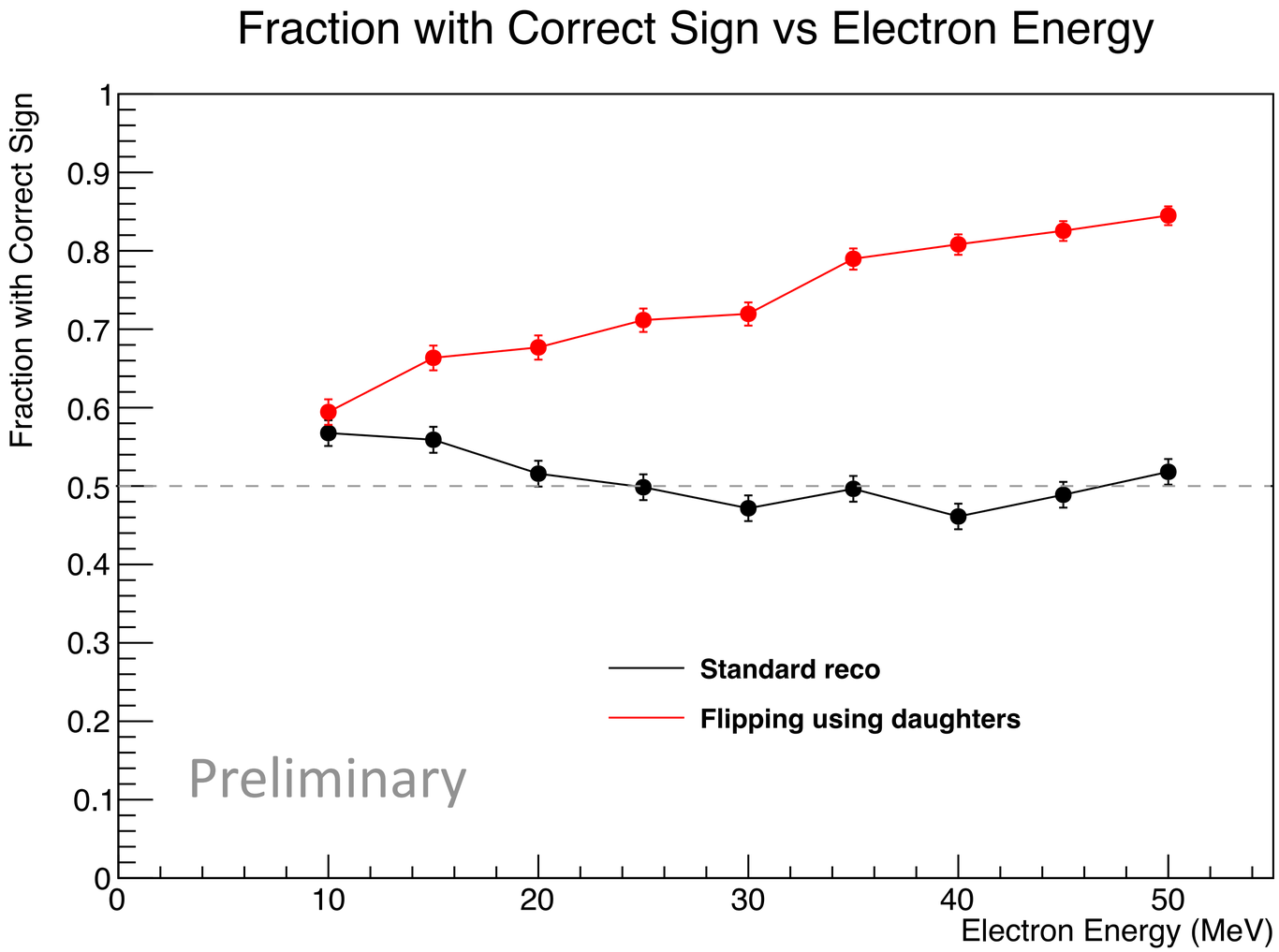


- Left: Truth info shows that the higher the average cosine, the more likely to be the correct starting end of the track (from single electron events)
- Below: Distribution of electron energy (GVKM model)



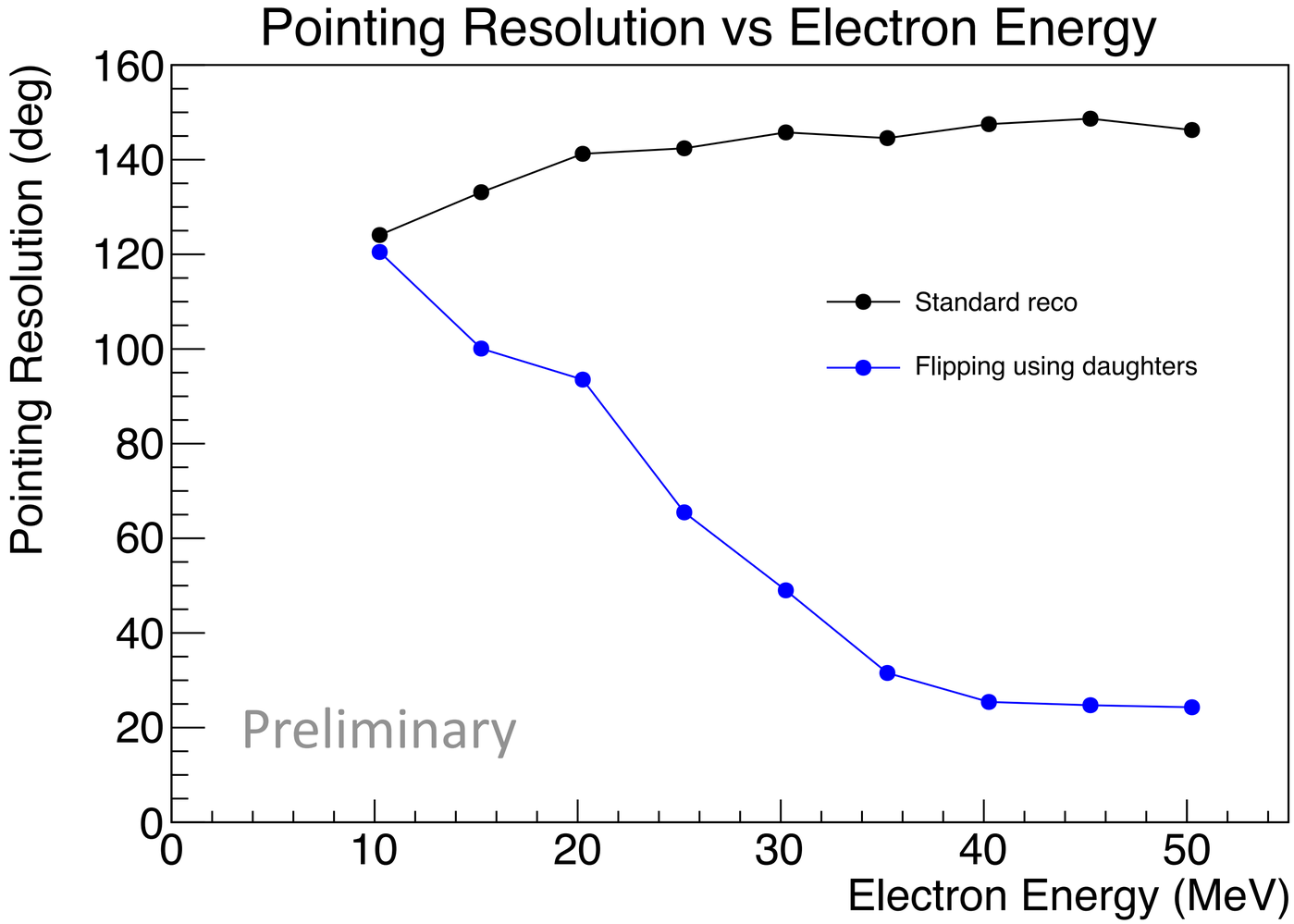
Directional ambiguity

- Fraction of tracks with correct sign ($\cos(\theta) > 0$) vs electron energy
- With daughter flipping, higher and above 50% correct



Single electron pointing resolution

- Pointing resolution = Angle at which 68% of events are closer to truth
- Daughter flipping helps more at higher energies - more daughter tracks with more energy



Neutrino-electron elastic scattering pointing resolution

$$\overset{(-)}{\nu} \; e^- \rightarrow \overset{(-)}{\nu} \; e^-$$

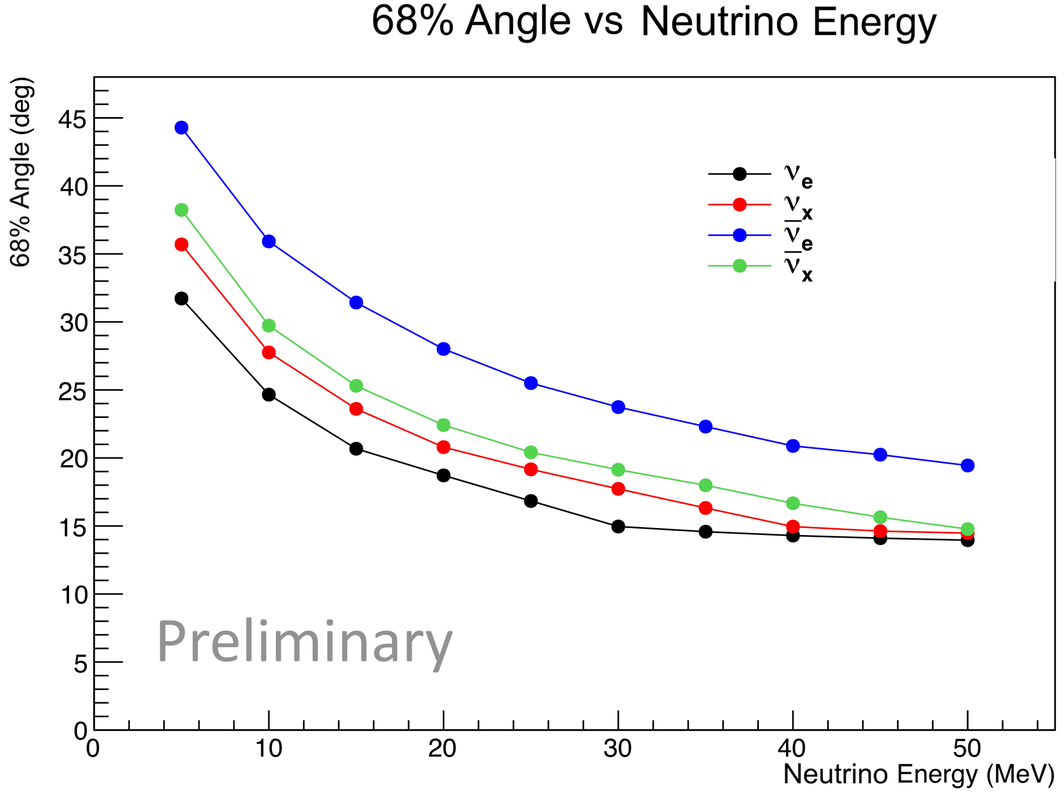
$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_A + g_V)^2 + (g_V - g_A)^2(1 - \frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{(E_\nu)^2}]$$

species	g_A	g_V
ν_e	$\frac{1}{2}$	$2\sin^2\theta_W + \frac{1}{2}$
$\bar{\nu}_e$	$-\frac{1}{2}$	$2\sin^2\theta_W + \frac{1}{2}$
$\nu_{\mu,\tau}$	$-\frac{1}{2}$	$2\sin^2\theta_W - \frac{1}{2}$
$\bar{\nu}_{\mu,\tau}$	$\frac{1}{2}$	$2\sin^2\theta_W - \frac{1}{2}$

$$\cos\theta = \frac{E_\nu + m_e}{E_\nu}\sqrt{\frac{T}{T + 2m_e}}$$

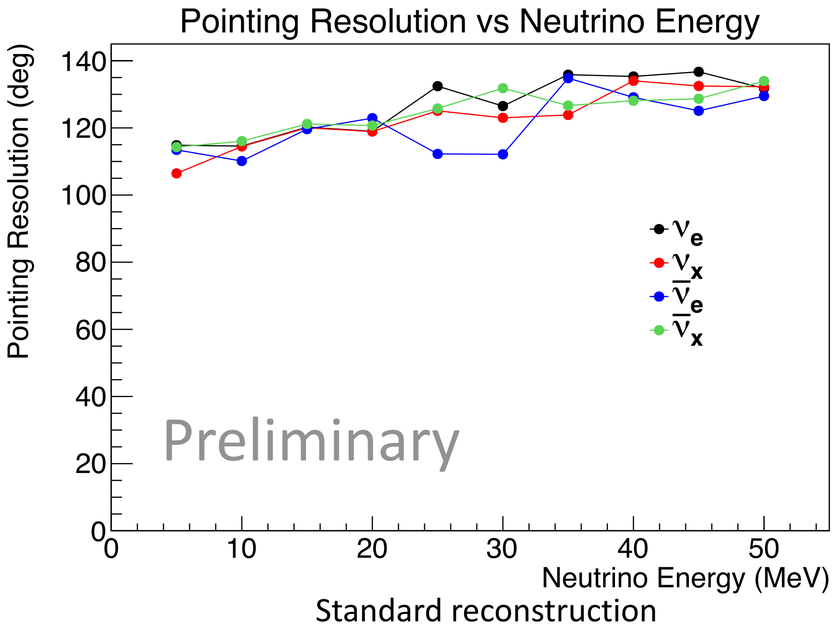
Alex Nikrant, Ranjan Laha & Shunsaku Horiuchi, Phys. Rev. D **97**, 023019 (2018)

- Simulated and reconstructed neutrino-electron elastic scattering events for different energies and flavors
- Total pointing resolution comes from combination of:
  - neutrino-electron angle spread
  - electron reconstruction error
- Computed angle at which 68% of true electron directions are closer to true neutrino direction

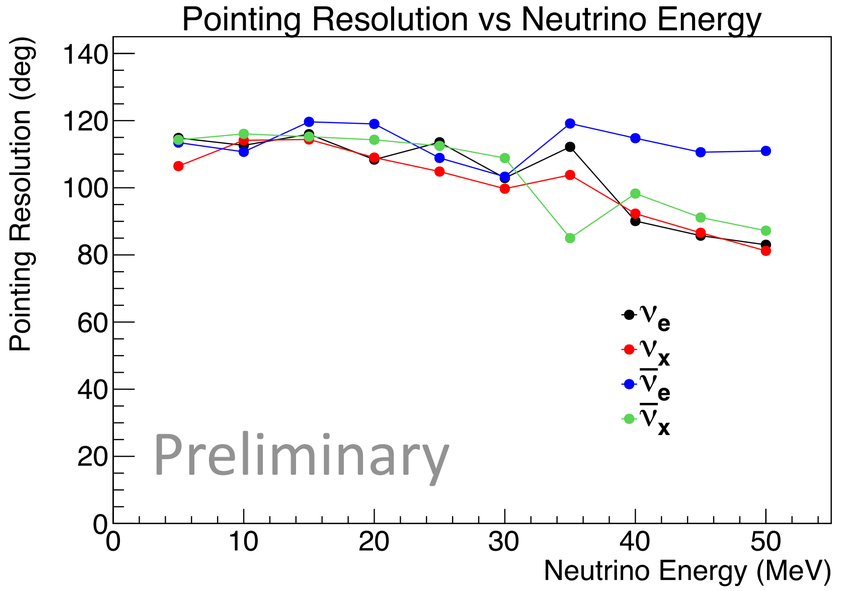


ν-e elastic scattering pointing resolution

- Computed pointing resolution of reconstructed electron direction with respect to neutrino direction
  - Standard reconstruction vs daughter flipping
  - Daughter flipping helps resolve ambiguity
  - ν_x = muon and tau neutrinos



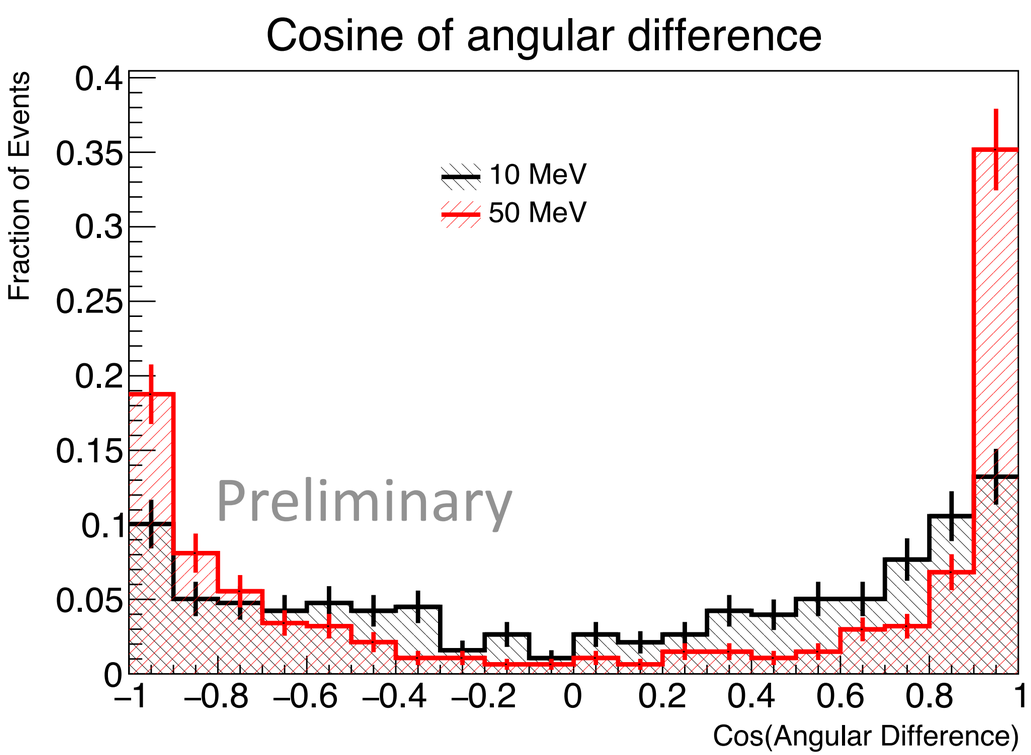
Standard reconstruction



After daughter flipping

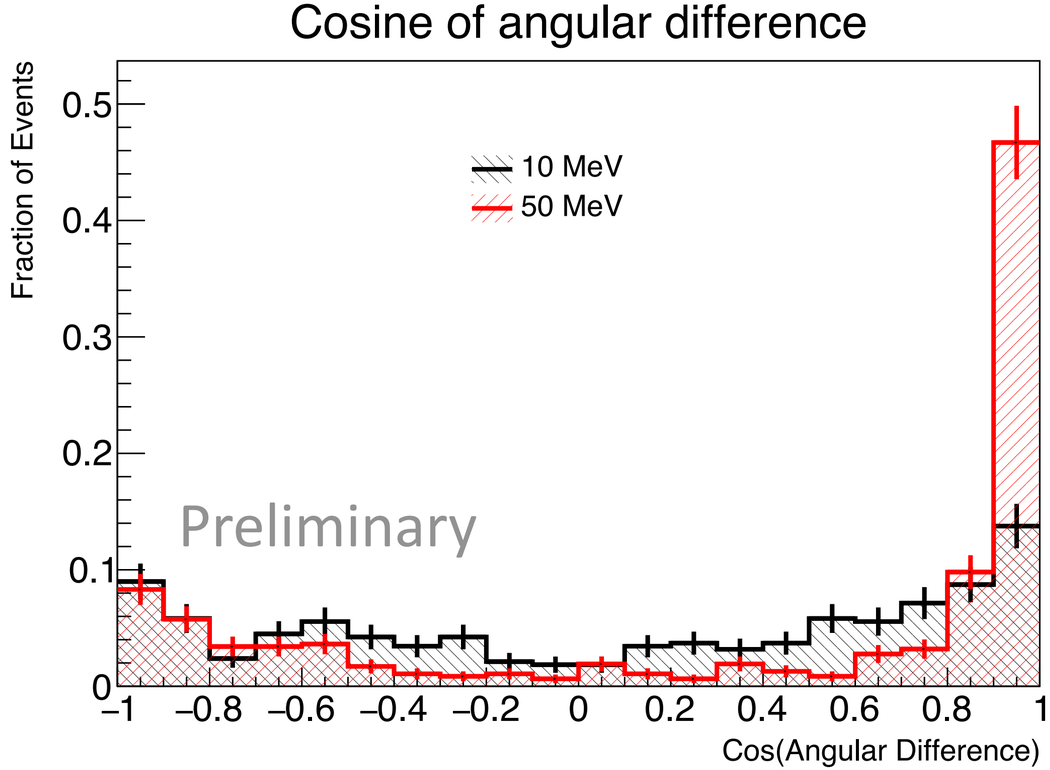
Elastic scattering cos(θ) comparisons (ν_e)

Standard reconstruction



Pointing Resolution **gets worse** with energy because of directional ambiguity and inclusion of narrower peak at cos(θ) = -1

With daughter flipping



Pointing Resolution **improves** with energy because of better directional disambiguation

Supernova samples of elastic scattering events

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_A + g_V)^2 + (g_V - g_A)^2(1 - \frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{(E_\nu)^2}]$$

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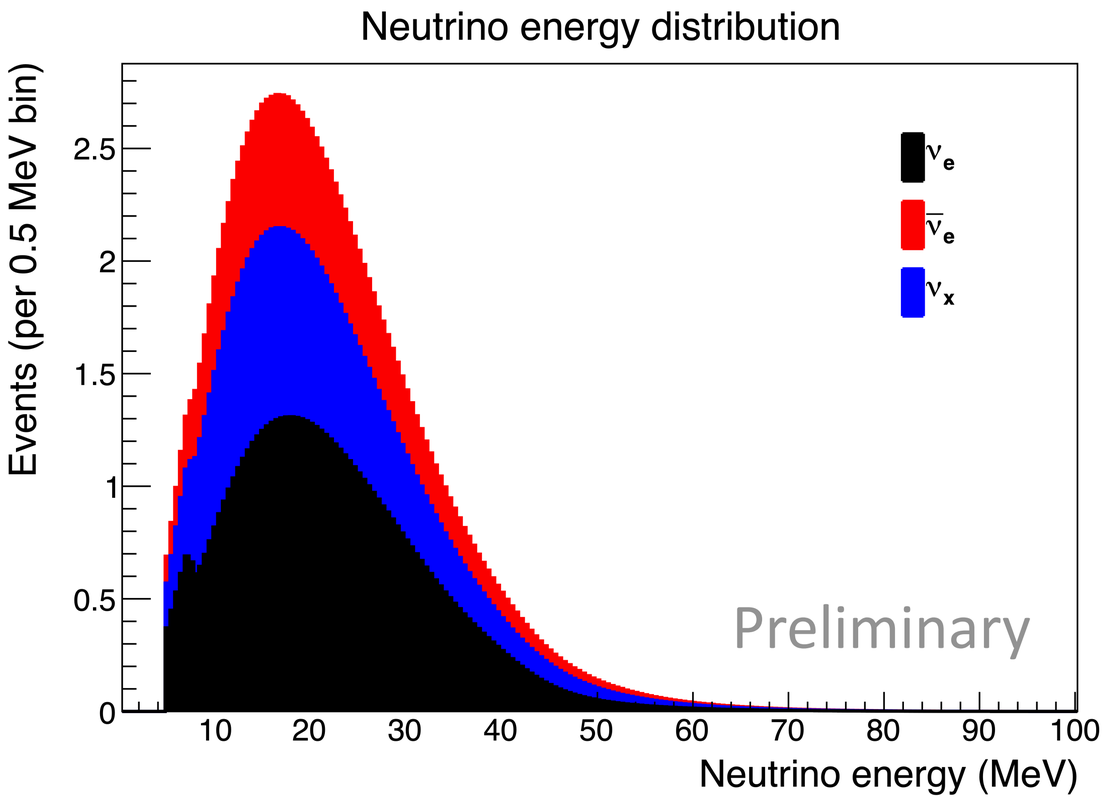
$$\cos\theta = \frac{E_\nu + m_e}{E_\nu}\sqrt{\frac{T}{T + 2m_e}}$$

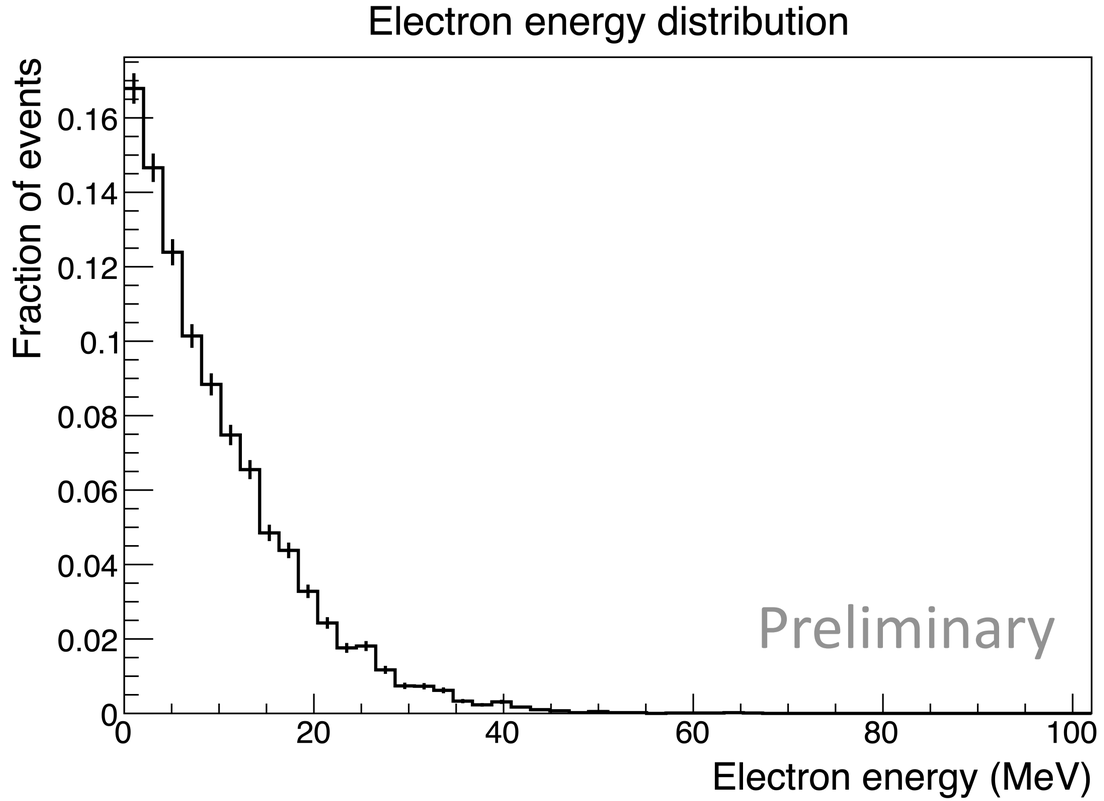
Alex Nikrant, Ranjan Laha & Shunsaku Horiuchi, Phys. Rev. D **97**, 023019 (2018)

- Chooses neutrino interacted energy and flavor
- GVKM model distribution from SNOwGLoBES (https://webhome.phy.duke.edu/~schol/snowglobes/, arXiv:0902.0317)
- Simulated 500 isotropic supernovae
- 260 elastic scattering events each in same direction (GVKM model 10kpc SN)
- Elastic scattering events = ~7% of total, charged current ~93%
- Without noise or radiologicals

Supernova samples of elastic scattering events

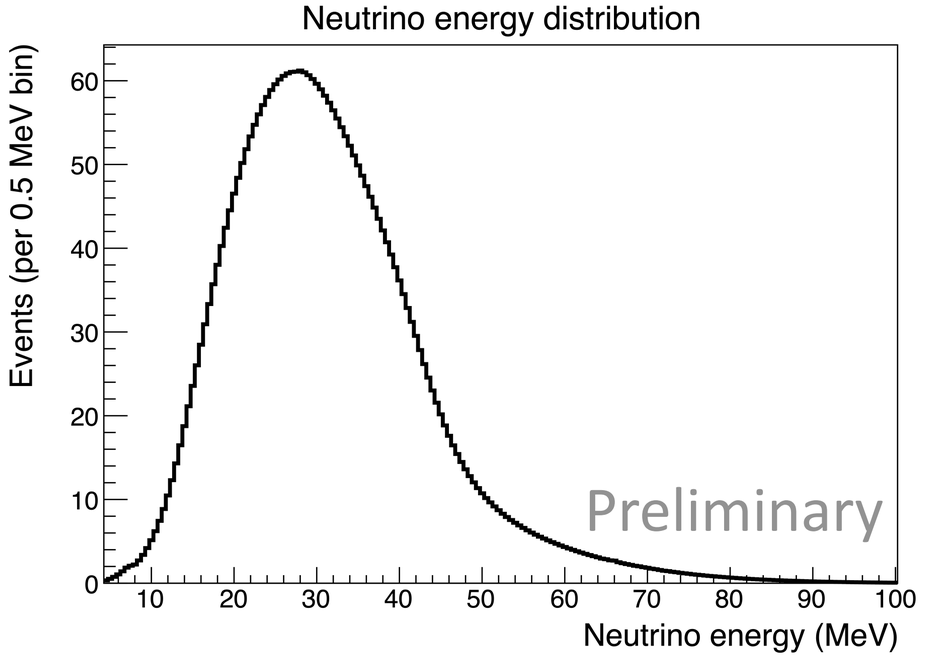
- Left: neutrino energy distribution (event rate in plot is for a 10 kpc SN)
- Right: electron energy distribution
- GVKM model

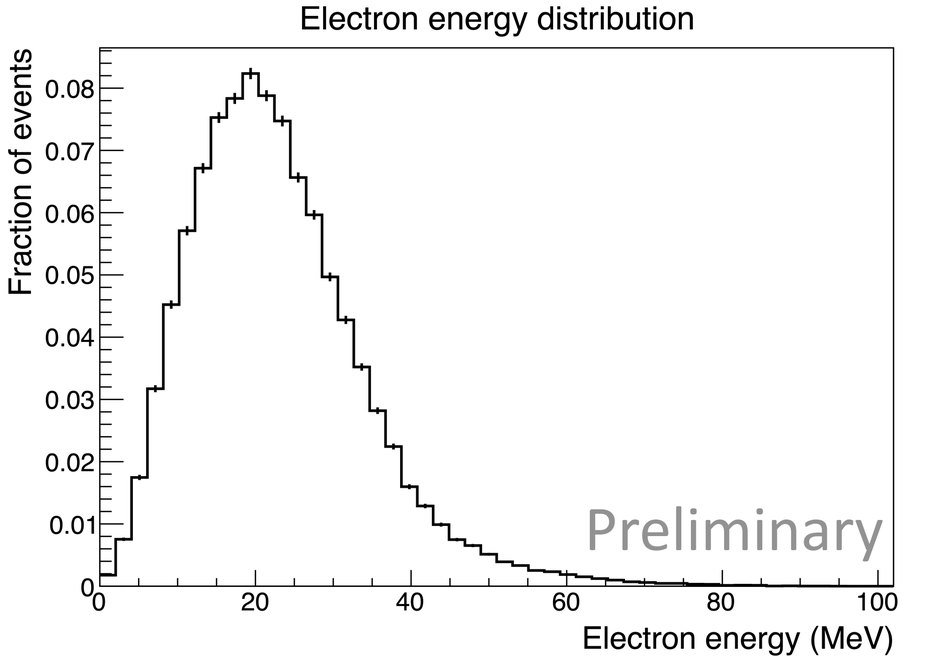




Supernova samples of elastic scattering + charged current events

- Used a pre-existing sample of clean charged current events
- Sampled according to GVKM model SN energy distribution from SNOwGLoBES (event rate in plot is for a 10 kpc SN)
- Rotated to match elastic scattering neutrino directions
  - Ignores detector anisotropy
- Added to elastic scattering sample to get 500 full SN samples
  - Each SN has 260 elastic scattering and 3350 charged current events (GVKM model 10 kpc SN)



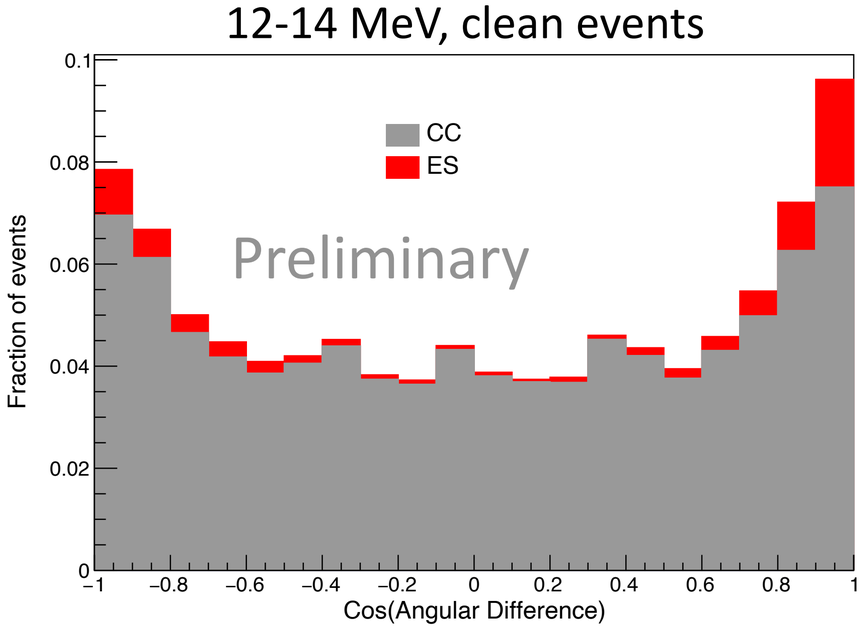


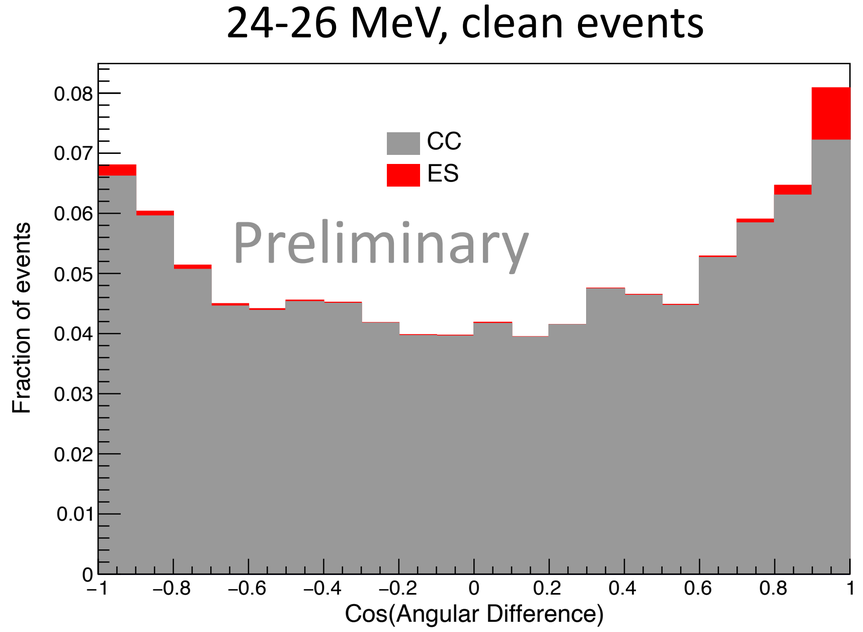
Charged current directionality

$$\nu_e \; {}^{40}Ar \longrightarrow e^- \; {}^{40}K^*$$

$$\text{Fermi: } 1 + \frac{v}{c}\cos\theta$$
$$\text{Gamow-Teller: } 1 - \frac{1}{3}\frac{v}{c}\cos\theta$$

- Plots: Distributions of angular difference between reconstructed charged current events and true directions
- Charged current events less directional, but still have directional information





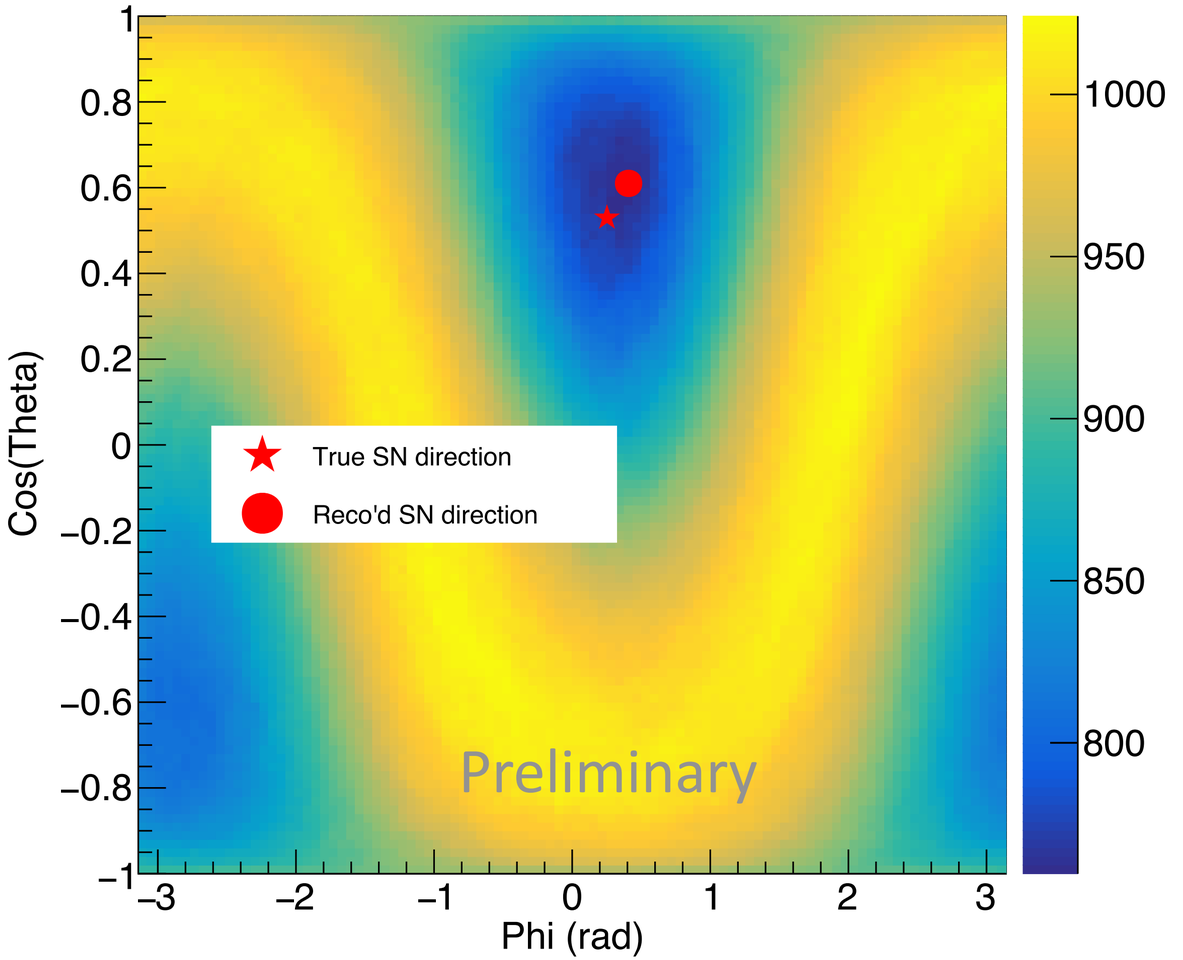
Reconstructed supernova direction

- Wrote likelihood function to find supernova direction from all electron directions and energies

$$L = \prod_i P(E_i, \hat{d}_i, \hat{d}_{SN})$$

E_i = reconstructed electron energy
$\hat{d}_i$ = reconstructed electron direction
$\hat{d}_{SN}$ = reconstructed SN direction

- Plot: likelihood function values for one example supernova
- Minimum of negative sum of log likelihood function is reconstructed supernova direction
- Used 250 supernovae to make probability distribution functions for likelihood function, then found pointing resolution of remaining 250



Example of likelihood function values for 1 supernova sample of elastic scattering events, with radiological backgrounds and noise

Supernova pointing resolution

- 10kpc SNe, ~10s (GVKM model)
- Daughter flipping, likelihood function help
- CC events help
- Studies with radiological backgrounds and noise underway, but preliminary results show degradation is minor

	ES only, clean No extra flipping, maximum bin is SN direction	ES only, clean Daughter flipping, maximum bin is SN direction	ES only, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function, >10 MeV electrons	CC only, clean Daughter flipping + likelihood function
Pointing resolution	147.2°	30.6°	9.7°	4.7°	4.2°	4.1°

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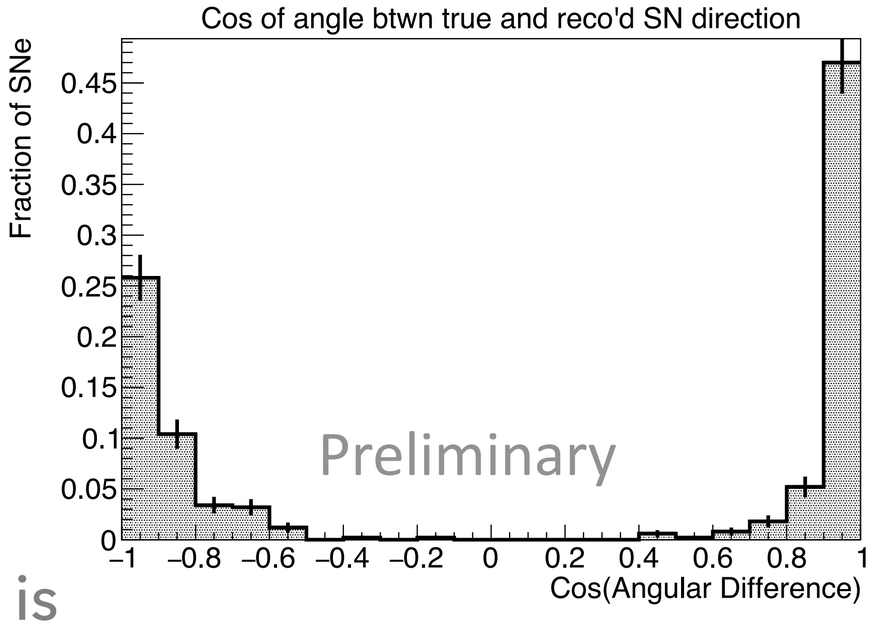

Plot: ES only, clean, no extra flipping, maximum bin is SN direction

	ES only, clean **No extra flipping, maximum bin is SN direction**	ES only, clean Daughter flipping, maximum bin is SN direction	ES only, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function, >10 MeV electrons	CC only, clean Daughter flipping + likelihood function
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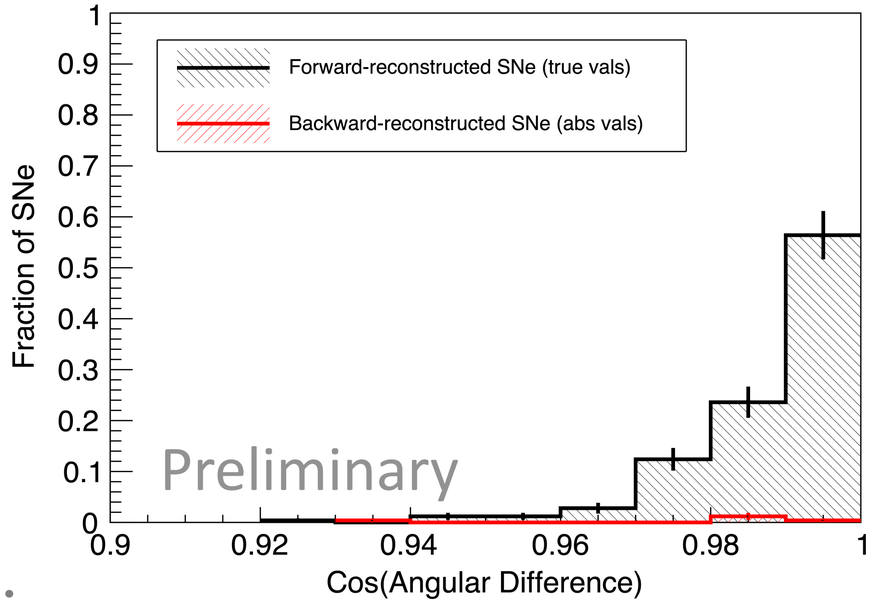

Plot: ES only, clean, daughter flipping and likelihood function

	ES only, clean No extra flipping, maximum bin is SN direction	ES only, clean Daughter flipping, maximum bin is SN direction	**ES only, clean** **Daughter flipping + likelihood function**	ES + CC, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function, >10 MeV electrons	CC only, clean Daughter flipping + likelihood function
Pointing resolution	147.2°	30.6°	**9.7°**	4.7°	4.2°	4.1°

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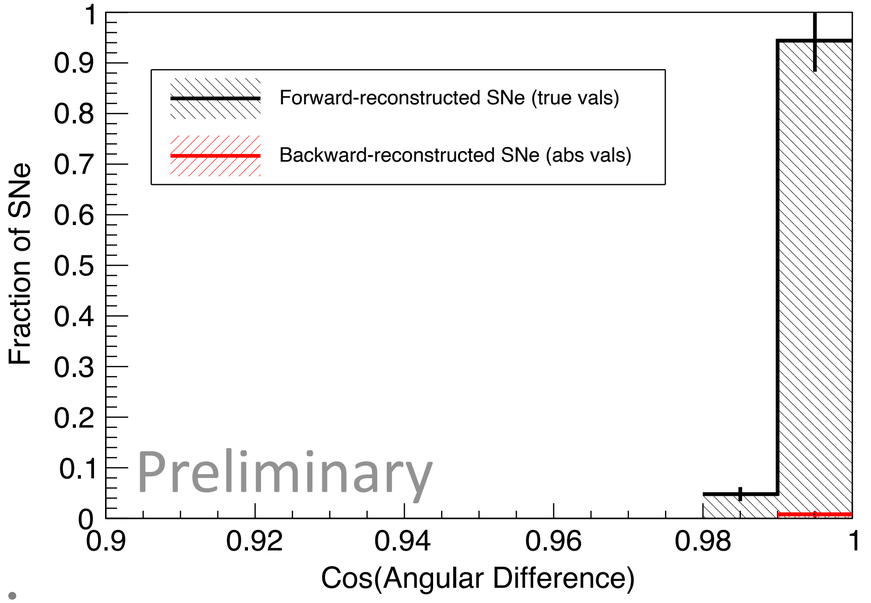

Plot: ES and CC, clean, daughter flipping and likelihood function

	ES only, clean No extra flipping, maximum bin is SN direction	ES only, clean Daughter flipping, maximum bin is SN direction	ES only, clean Daughter flipping + likelihood function	**ES + CC, clean** **Daughter flipping + likelihood function**	ES + CC, clean Daughter flipping + likelihood function, >10 MeV electrons	CC only, clean Daughter flipping + likelihood function
Pointing resolution	147.2°	30.6°	9.7°	**4.7°**	4.2°	4.1°

Supernova pointing resolution

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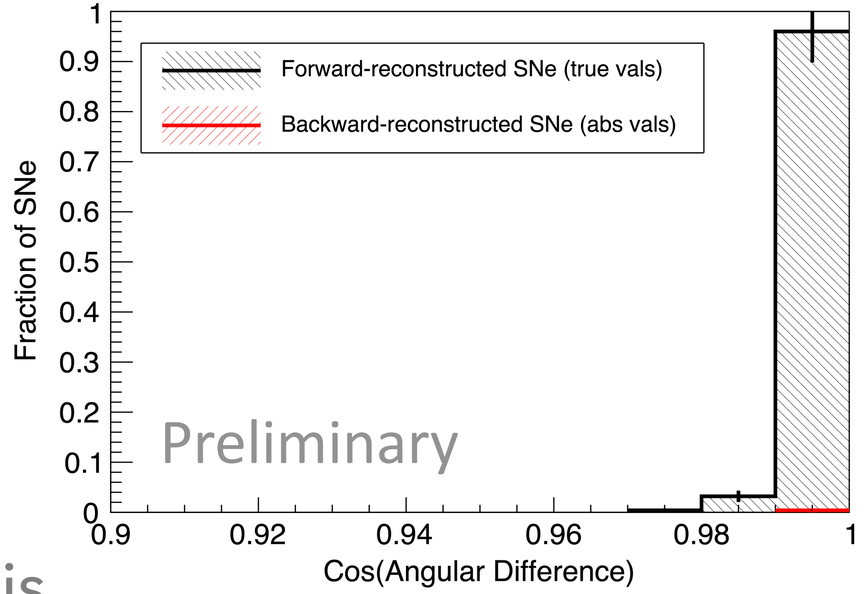
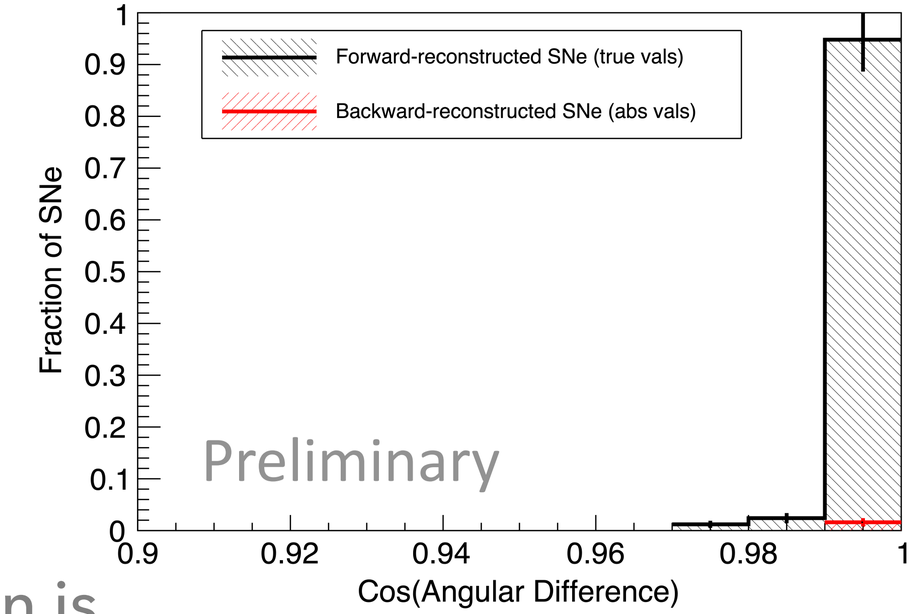


Plot: ES and CC, clean, daughter flipping and likelihood function, >10 MeV electrons

	ES only, clean No extra flipping, maximum bin is SN direction	ES only, clean Daughter flipping, maximum bin is SN direction	ES only, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function	**ES + CC, clean** **Daughter flipping + likelihood function, >10 MeV electrons**	CC only, clean Daughter flipping + likelihood function
Pointing resolution	147.2°	30.6°	9.7°	4.7°	**4.2°**	4.1°

Supernova pointing resolution

- 10kpc SNe, ~10s (GVKM model)
- Daughter flipping, likelihood function help
- CC events help
- Studies with radiological backgrounds and noise underway, but preliminary results show degradation is minor



Plot: CC only, clean, daughter flipping and likelihood function

	ES only, clean No extra flipping, maximum bin is SN direction	ES only, clean Daughter flipping, maximum bin is SN direction	ES only, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function	ES + CC, clean Daughter flipping + likelihood function, >10 MeV electrons	**CC only, clean** **Daughter flipping + likelihood function**
Pointing resolution	147.2°	30.6°	9.7°	4.7°	4.2°	**4.1°**

Future steps

- Samples with radiological backgrounds and noise
  - Radiological backgrounds: Ar-39 and Ar-42 majority, plus Kr-85, Cu-60, neutrons, K-40
- Find pointing resolution…
  - as function of SN distance
  - assuming different elastic scattering/charged current distinguishing capabilities
  - as function of SN direction

Summary

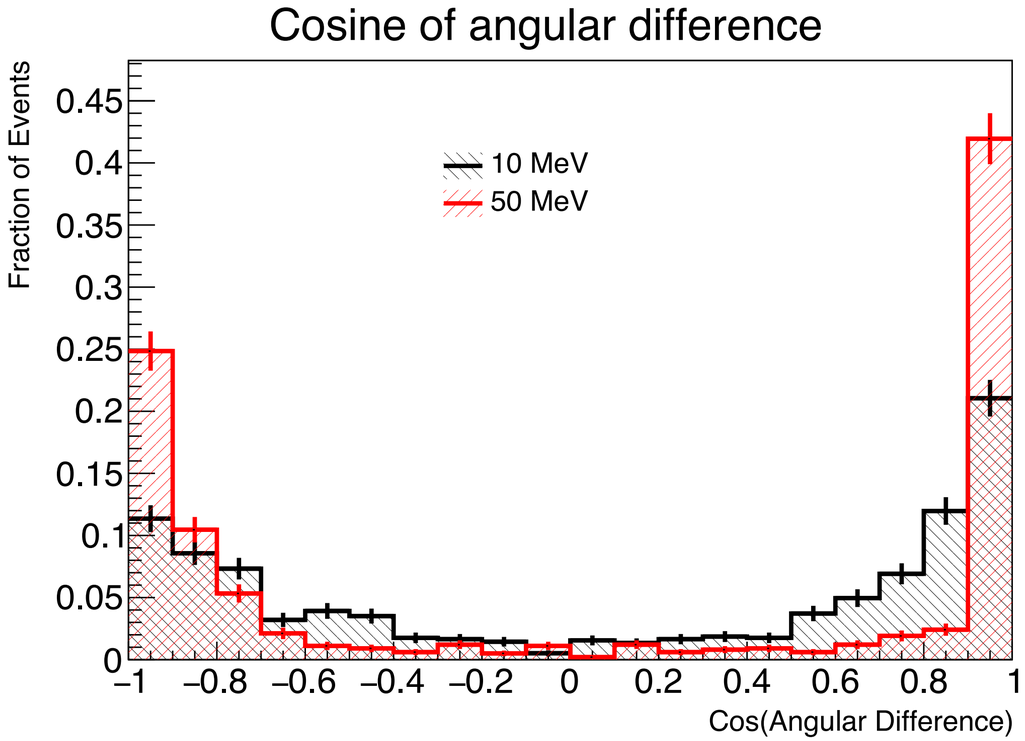
- Goal: Determine and improve DUNE's pointing resolution for supernovae
- Simulated and reconstructed
  - single electrons (clean)
  - neutrino-electron elastic scattering events (clean)
  - supernova samples of elastic scattering and charged current events (clean)
- Found current reconstruction has track direction ambiguity
  - Negatively affects pointing resolution
- Used daughter tracks to flip tracks
- Used a likelihood function

- Pointing resolution = 4.7 degrees (10kpc supernovae, elastic scattering and charged current, clean)
- Comparable to pointing resolution of water Cherenkov detectors (arXiv:1601.04778)
- Further work needed to get more realistic pointing resolution with noise and radiologicals and study as function of supernova distance
- Studies with radiological backgrounds and noise underway, but preliminary results show degradation is minor

Additional Info

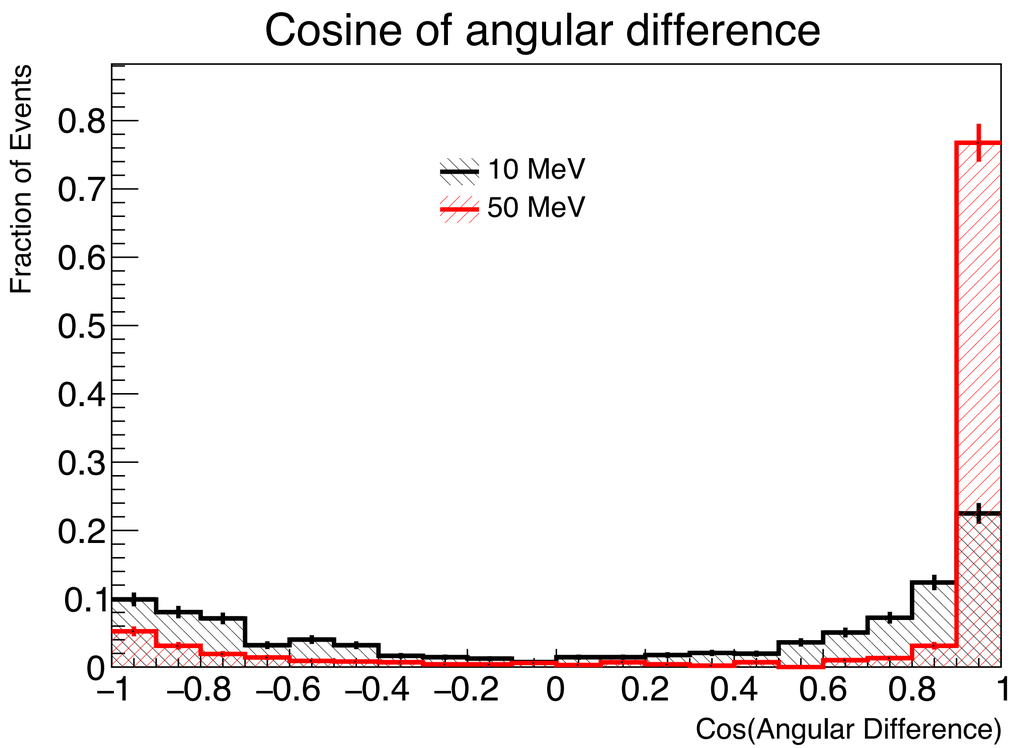
Single electron cos(θ) comparisons

Standard reconstruction



Pointing Resolution **gets worse** with energy because of directional ambiguity and inclusion of narrower peak at cos(θ) = -1

With daughter flipping



Pointing Resolution **improves** with energy because of better directional disambiguation

Channel tagging

- Work underway by Erin Conley
- Charged current and neutrino-electron elastic scattering produce different topologies
- Erin is attempting to use these to distinguish types of interactions in DUNE