

Status of detector systematics for atmospheric OA



Claire Dalmazzone, DUNE France meeting, Wednesday April 1st 2026

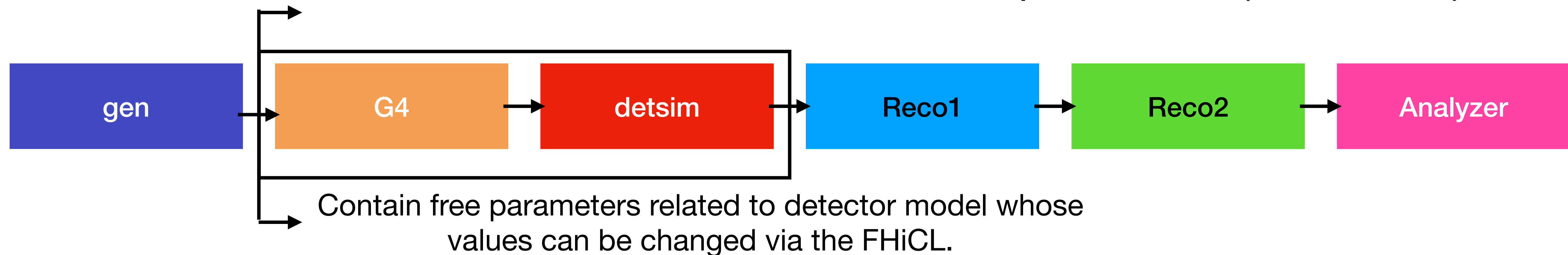
Introduction

Context



- Need **estimation of systematics related to detector model** for OA
- Machinery (see [wiki](#) and [Oct 2025 DUNE France meeting](#)) developed to

- ▶ **Re-run simulation with varied values** of free parameters (Alessandra)



- ▶ study **impact on analysis observables** and build **covariance matrix** readable by OA frameworks with the [CAF comparison tool](#) (Dan)



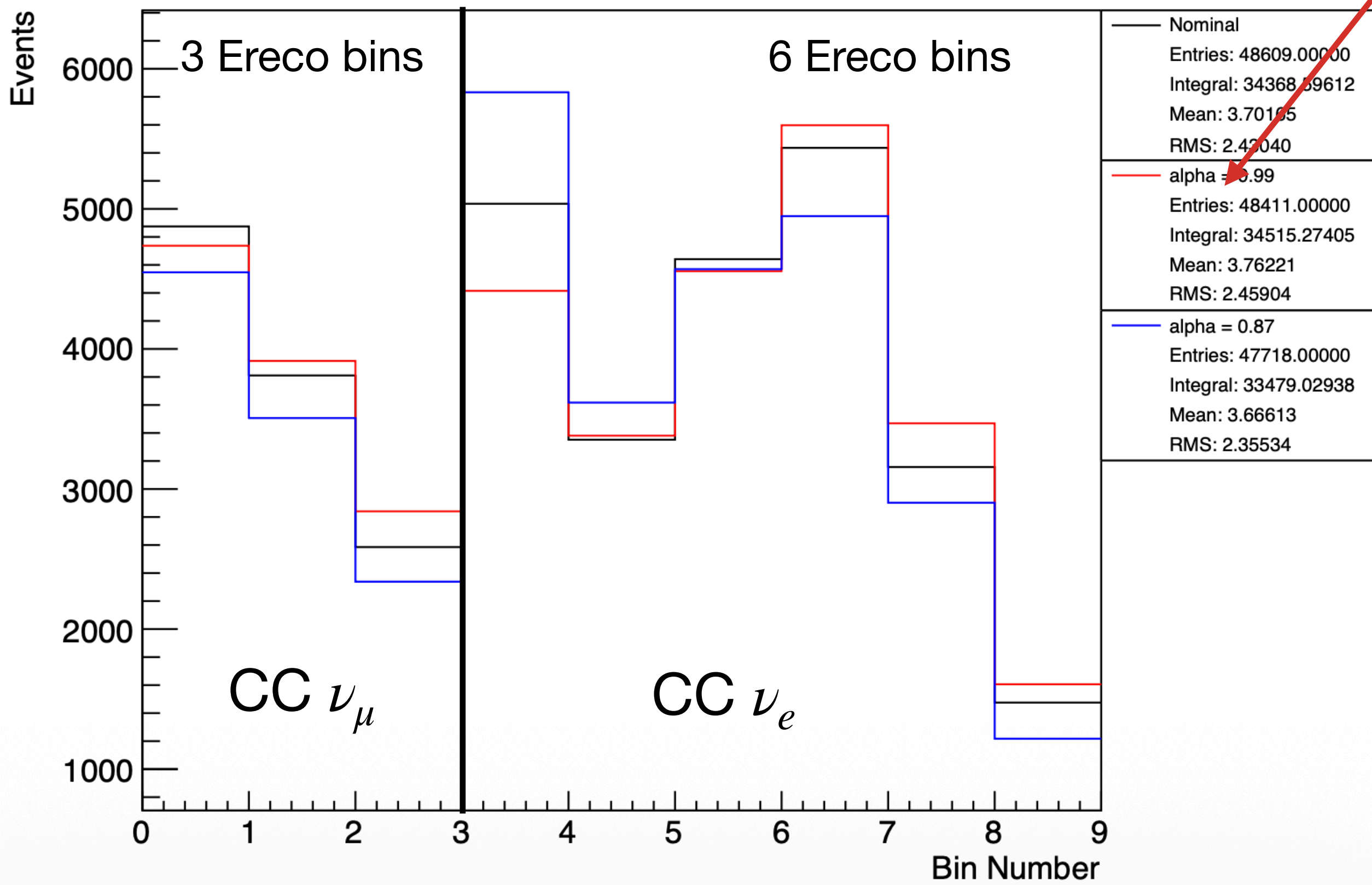
Introduction

Context

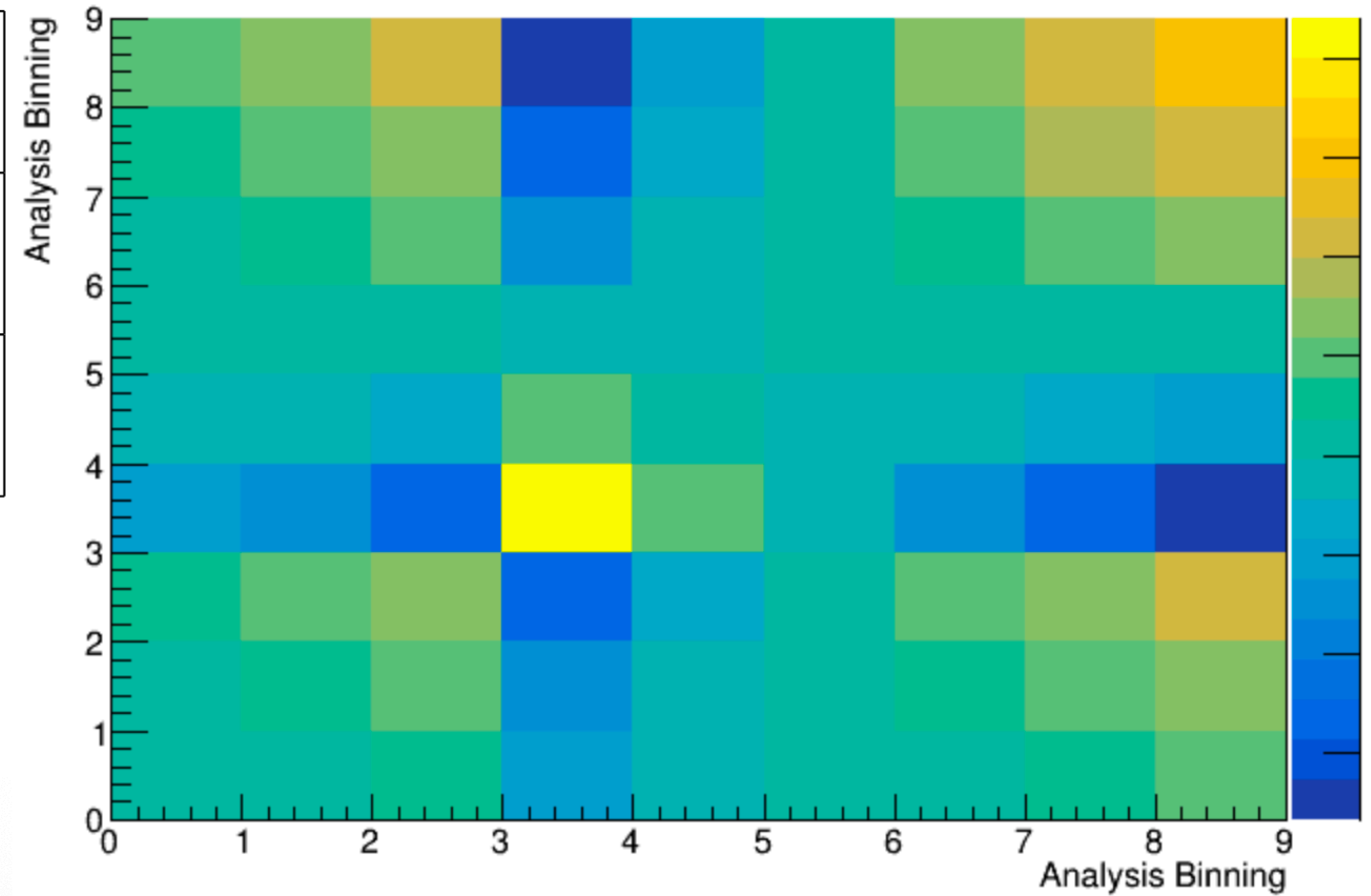


$$\frac{dQ}{dx} = \frac{\ln\left(\frac{\beta}{\rho(T)\mathcal{E}} \frac{dE}{dx} + \alpha\right)}{\frac{\beta W}{\rho(T)\mathcal{E}}}$$

Analysis Binning



Covariance Matrix



Covariance matrix encoding the systematic uncertainty caused by the parameter of interest

Impact of varying the modified box alpha parameter on analysis bins population

CM presentation



| Type of uncertainty | Parameter | Physics phenomenon | Location in MC chain | Fcl config |
|---------------------|------------------------|--------------------------------|----------------------------------|---|
| Energy scale | Modified box alpha | Recombination | IonAndScint | LArG4Parameters.ModBoxA |
| | Modified box beta | Recombination | IonAndScint | LArG4Parameters.ModBoxB |
| | Electronics gain | Charge readout | Detsim + wirecell | ? |
| | Electron lifetime | Attenuation | Detsim + wirecell | DetectorsPropertiesService.ElectronLifetime |
| | Drift field | Recombination, attenuation, FR | IonAndScint Detsim + wirecell | DetectorsPropertiesService.Efield + driftSpeed (wirecell) |
| | Wire collection | Charge readout | wirecell | X |
| PID | Transverse diffusion | Diffusion | Detsim | DetectorsPropertiesService.TransverseDiffusion |
| | Longitudinal diffusion | Diffusion | Detsim | DetectorsPropertiesService.LongitudinalDiffusion |
| Geometry | | Dead zones, misalignments | Reco1 | X |

- **Last CM discussion:**

- ▶ List of main effects
- ▶ MC statistics
- ▶ Person-power
- ▶ Alternative simulation method

WireModifier module or Wiremod

- Since then defined several tasks:

- ▶ Test **implementation in OA**: Will Barrett
- ▶ Study impact of **diffusion**: Noah Anderson

- ▶ Investigate **wiremod**: Me (+ Dominic Brailsford)
- ▶ **Finalise first production request**: Me

Main focus of today's presentation

List of parameters



List of parameters



Would also consider **conservative variations**: less MC statistics needed and effect on analysis observables can be shrunk under linearity assumption.

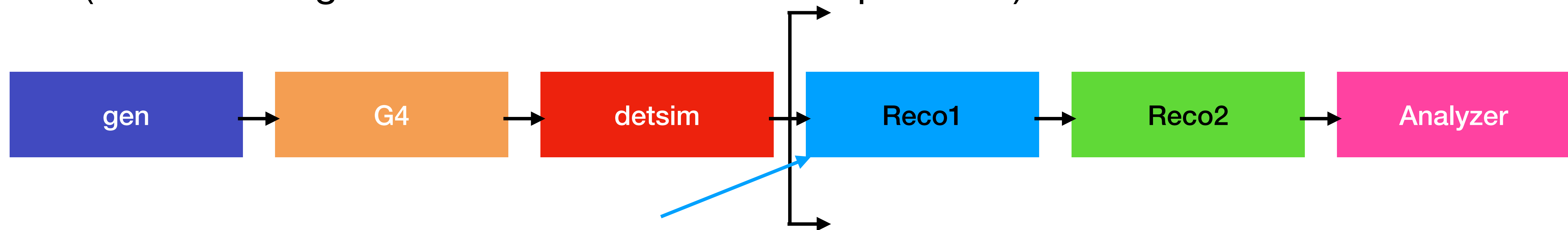
| Physics phenomenon | Location in MC chain | Fcl config -1sigma | Fcl config +1sigma |
|----------------------|---------------------------------|---|--|
| Recombination | IonAndScint | LArG4Parameters.ModBoxA: 8.7e-1 LArG4Parameters.ModBoxB: 2.18e-1 | LArG4Parameters.ModBoxA: 9.9e-1 LArG4Parameters.ModBoxA: 2.06e-1 |
| Attenuation | Detsim + wirecell | DetectorsPropertiesService.ElectronLifetime: 9360 | DetectorsPropertiesService.ElectronLifetime: 11440 |
| Drift field | IonAndScint + Detsim + wirecell | DetectorsPropertiesService.Efield: [4.9e-1, 6.66e-1, 8e-1] Physics.producers.tpcrawdecoder.wcls_main.structs.driftSpeed: 1.58957 | DetectorsPropertiesService.Efield: [5.1e-1, 6.66e-1, 8e-1] Physics.producers.tpcrawdecoder.wcls_main.structs.driftSpeed: 1.5976 |
| Transverse Diffusion | Detsim + wirecell | DetectorsPropertiesService.Transverse Diffusion: 7.04e-9 | DetectorsPropertiesService.Transverse Diffusion: 1.056e-8 |

Wiremod



Wiremod Presentation

- Most parameters just **modify the charge collected**: could rescale the charge at the **reco1 level**
- **Wiremod** module used in microBoone and ICARUS for similar purposes (rescale charge based on data vs MC comparisons)



Include wiremod to rescale the charge of signal ROIs based on matched simulated Edeps true info.

More details in the March FD sim/reco presentation

Detsim takes 100-200s per events VS ~1s for wiremod



Wiremod

Scale factor calculation

Each subROI is associated to **two scaling factors** for the total **charge amplitude** (r_Q) and **width** (r_σ).
 For now implemented **3 different rescaling options**:

- **Gain Scale**: uniform scaling factor $r_Q = G$ independent on truth info and $r_\sigma = 1$ (just for initial tests)

- **Electron lifetime**: $r_Q = e^{-\frac{|x|}{v_D} \left(\frac{1}{\tau_{var}} - \frac{1}{\tau_{nom}} \right)}$ and $r_\sigma = 1$

- **Modified box recombination** variation: $r_Q = \frac{\beta_{var} \log \left(\alpha_{var} + \frac{\beta_{var}}{\rho \mathcal{E} \frac{dE}{dx}} \right)}{\beta_{nom} \log \left(\alpha_{nom} + \frac{\beta_{nom}}{\rho \mathcal{E} \frac{dE}{dx}} \right)}$ and $r_\sigma = 1$

Truth properties used: $x, \frac{dE}{dx}$

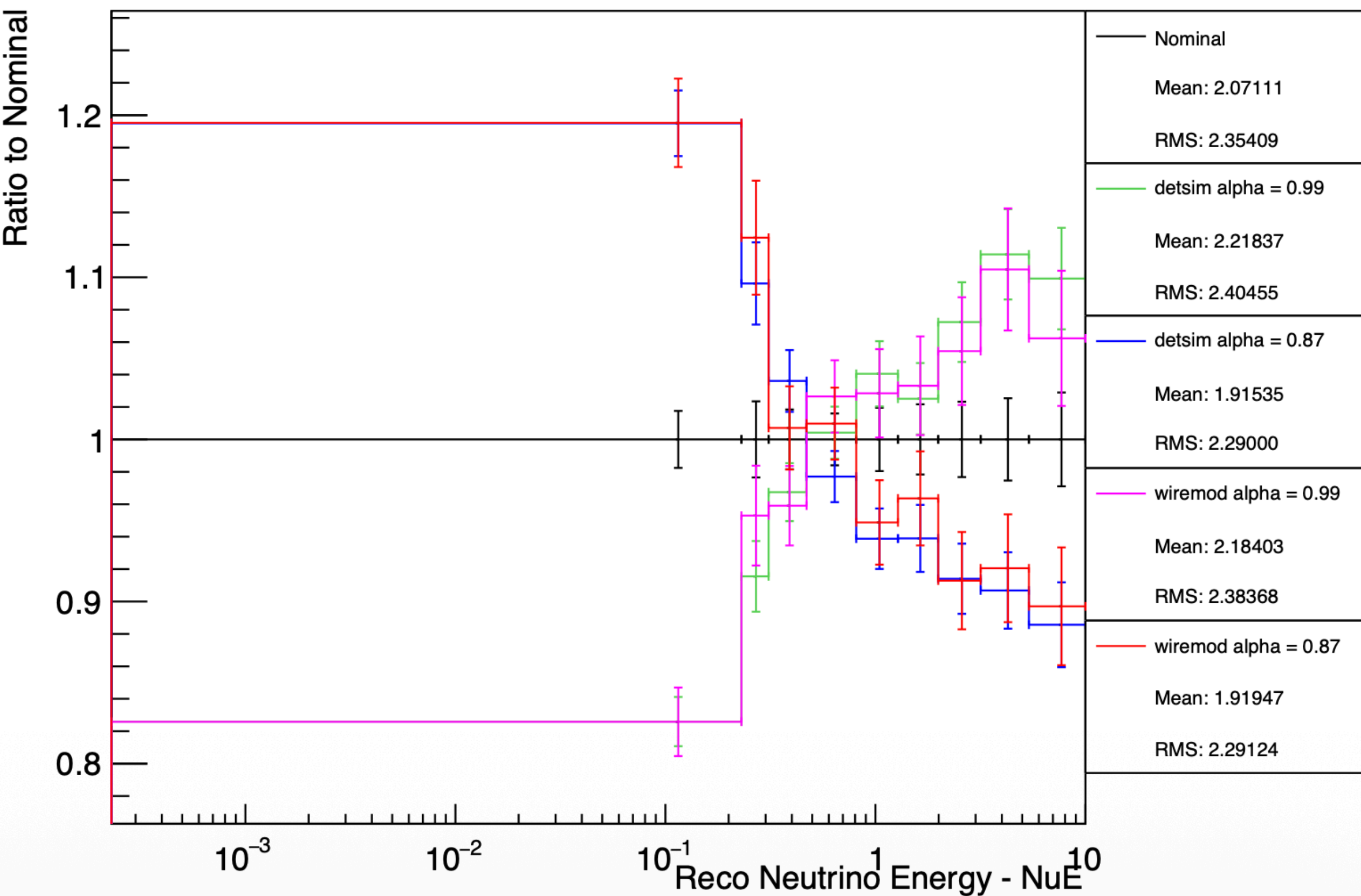


Preliminary results

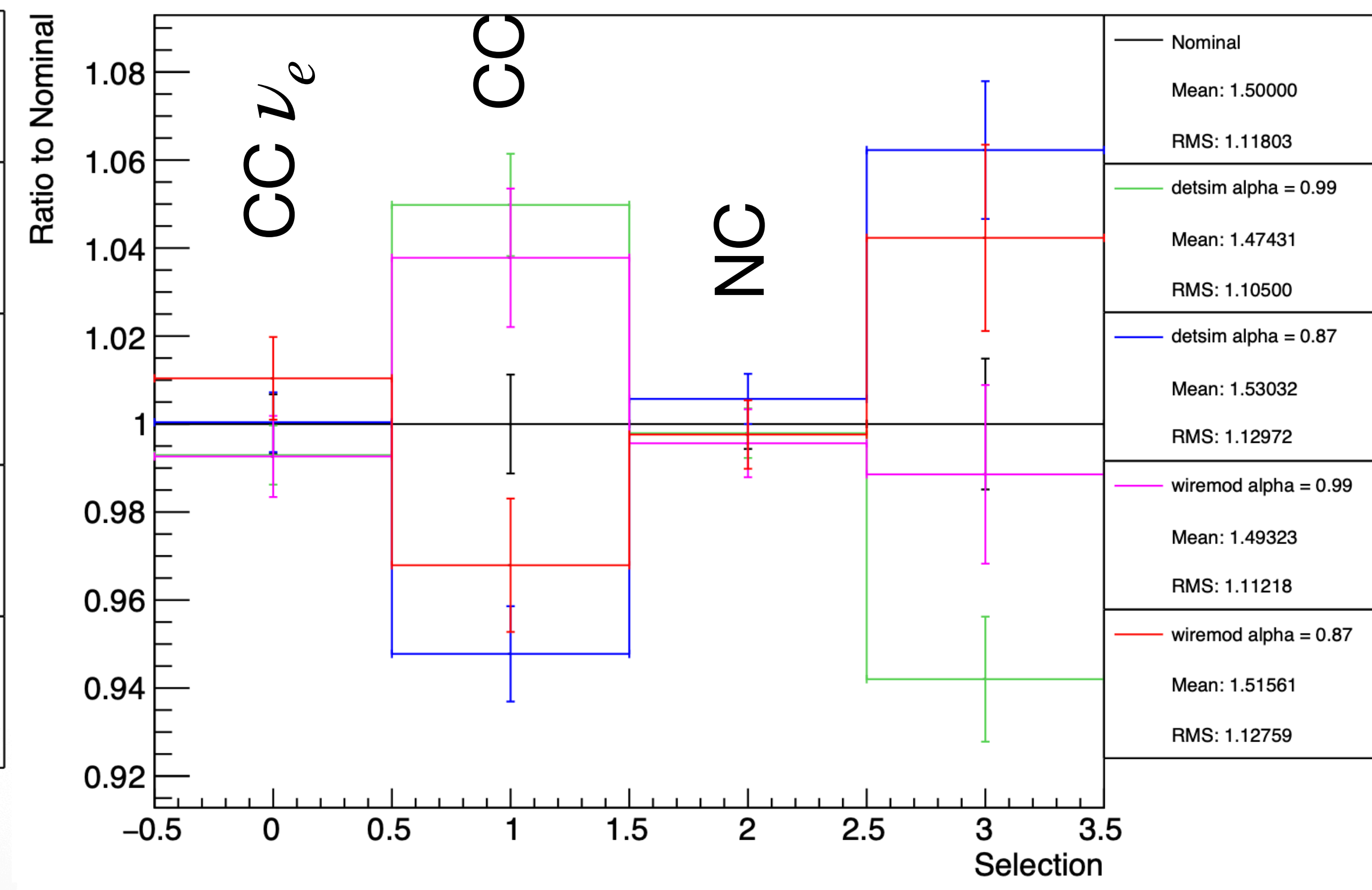
Analysis observables comparisons



Reco Neutrino Energy - NuE (-0.50 < kSelection < 0.50)



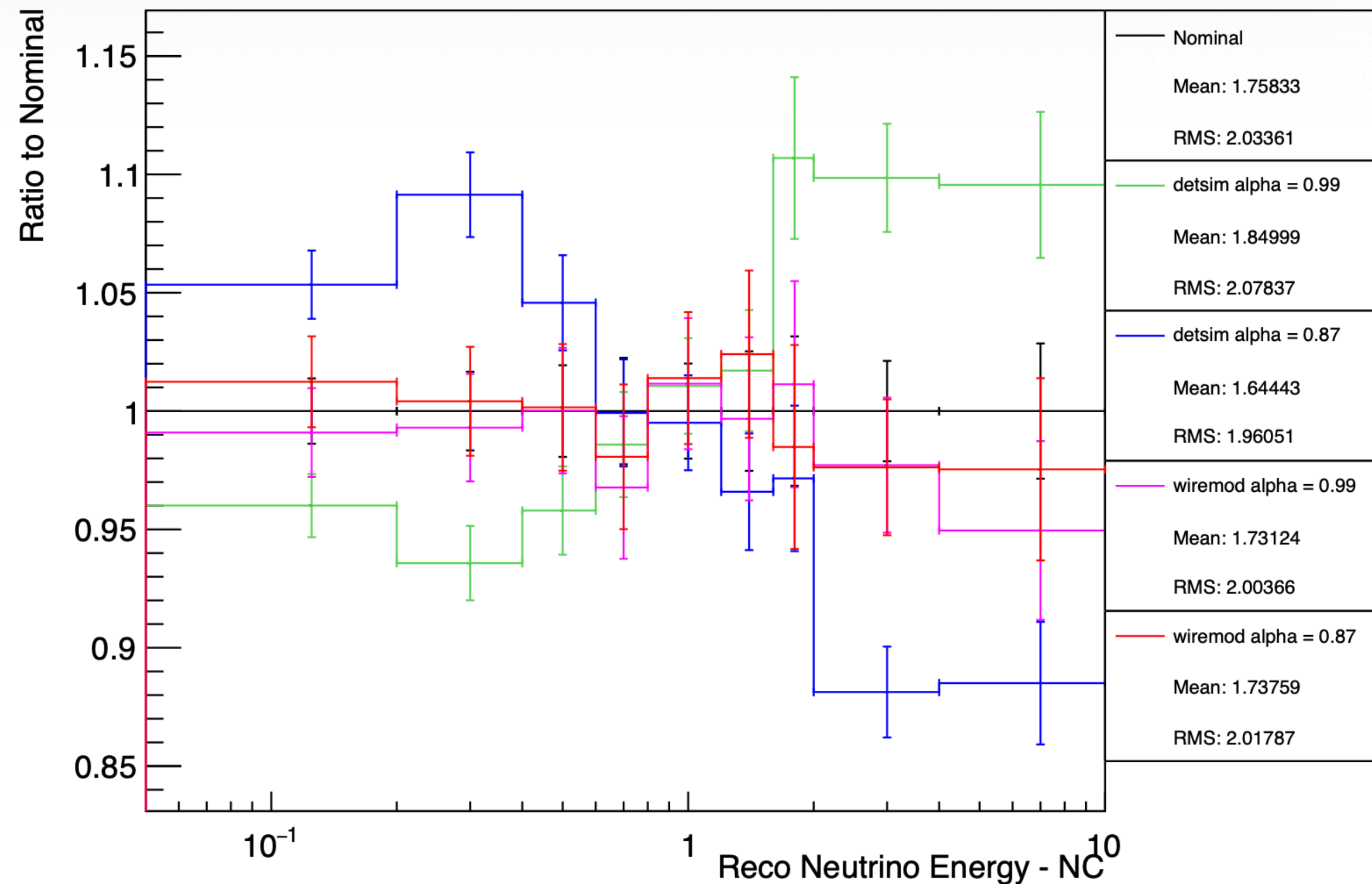
$CC \nu_{\mu}$ Selection



Preliminary results

Analysis observables comparisons

Reco Neutrino Energy - NC ($1.50 < k_{\text{Selection}} < 2.50$)



- Also reprocessed 100k atm nu events with wiremod variation of Mod Box α only to compare to already produced detsim variation (200k events)
- Impact on CC ν_e Erec spectra is a perfect match
- Impact on CC ν_μ selection might be slightly underestimated
- Impact on NC Erec spectra clearly underestimated...

Estimation of MC stat needed

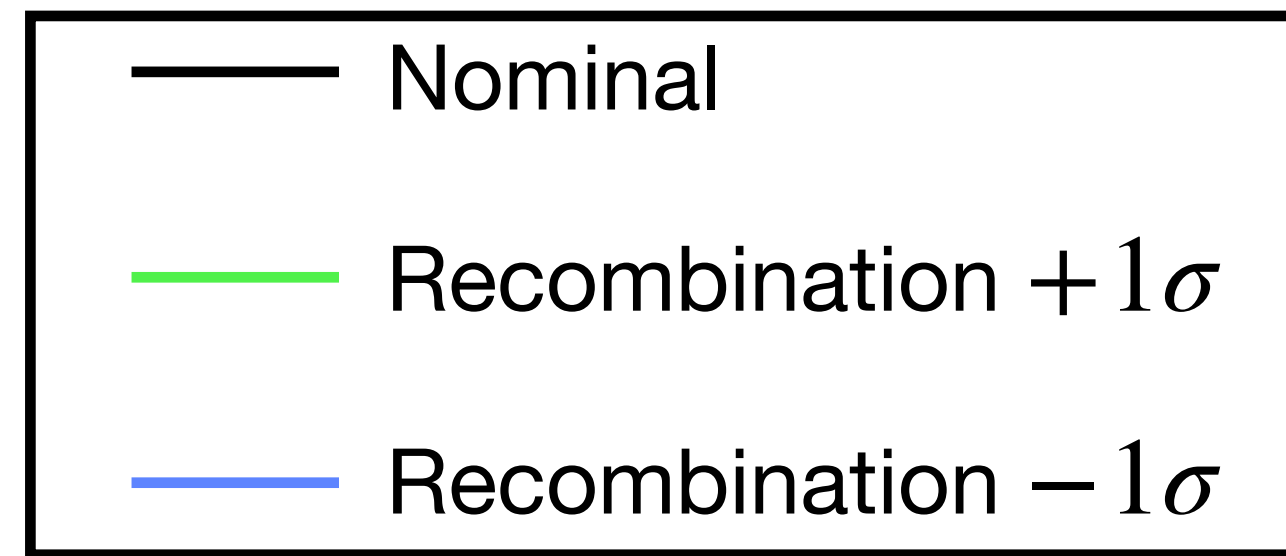


MC statistics

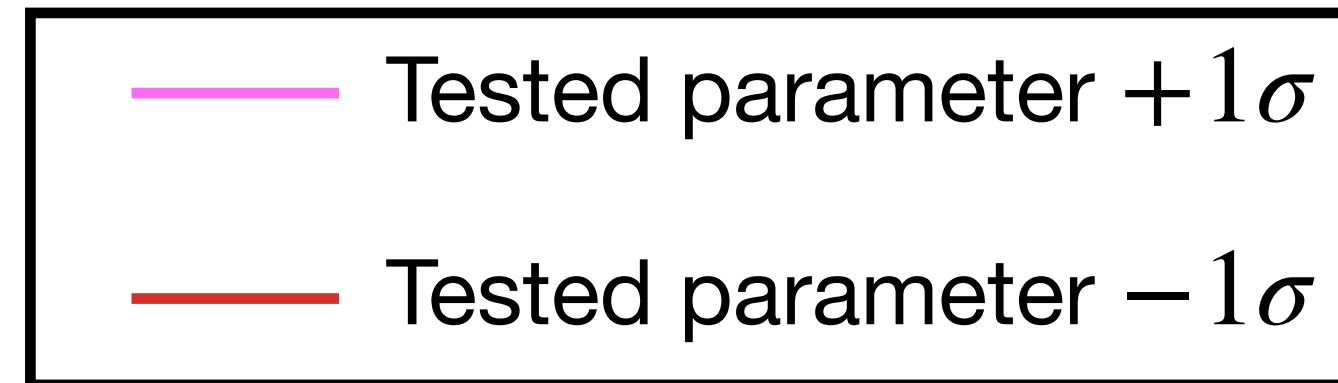
Effects comparison



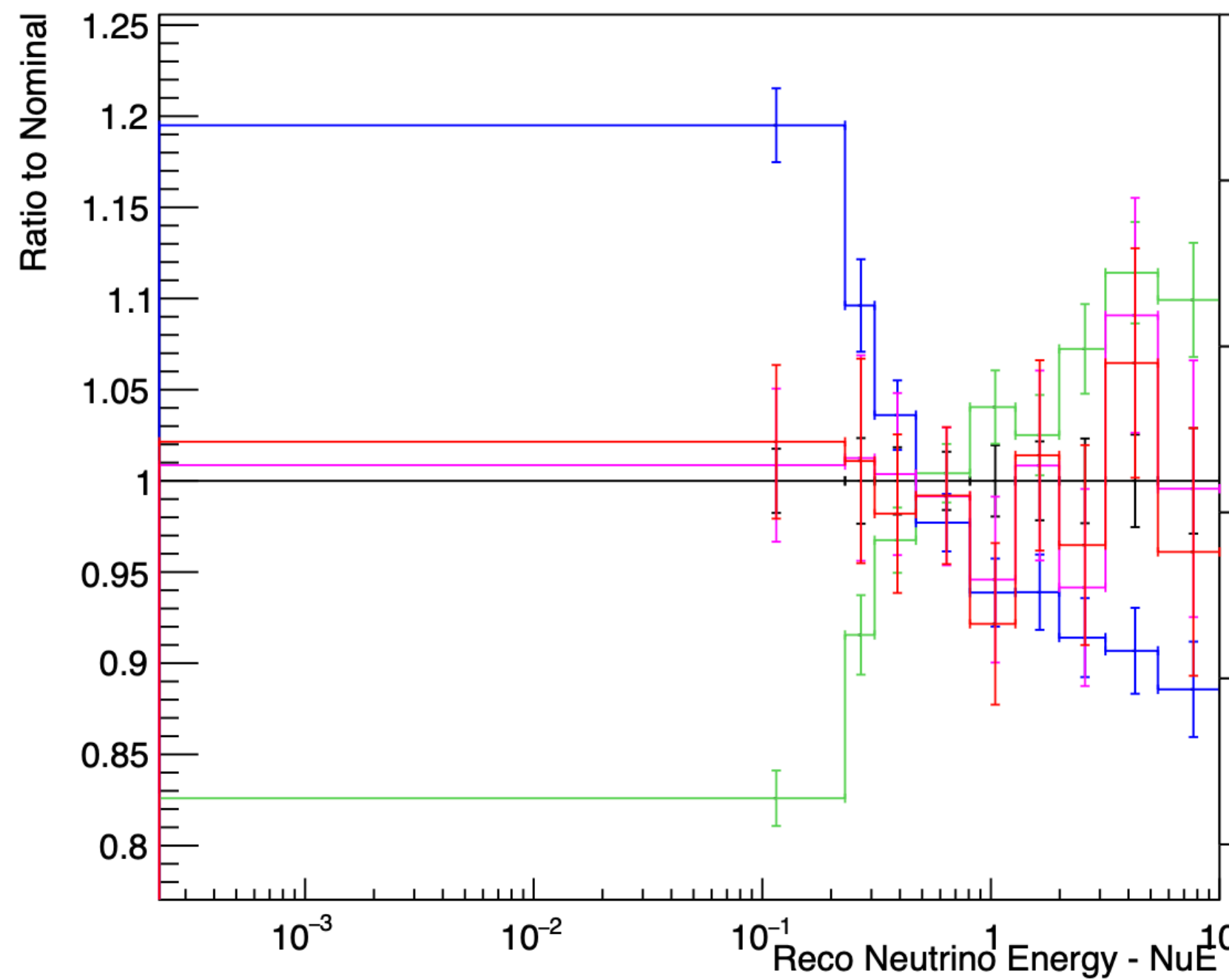
200k events



20k events

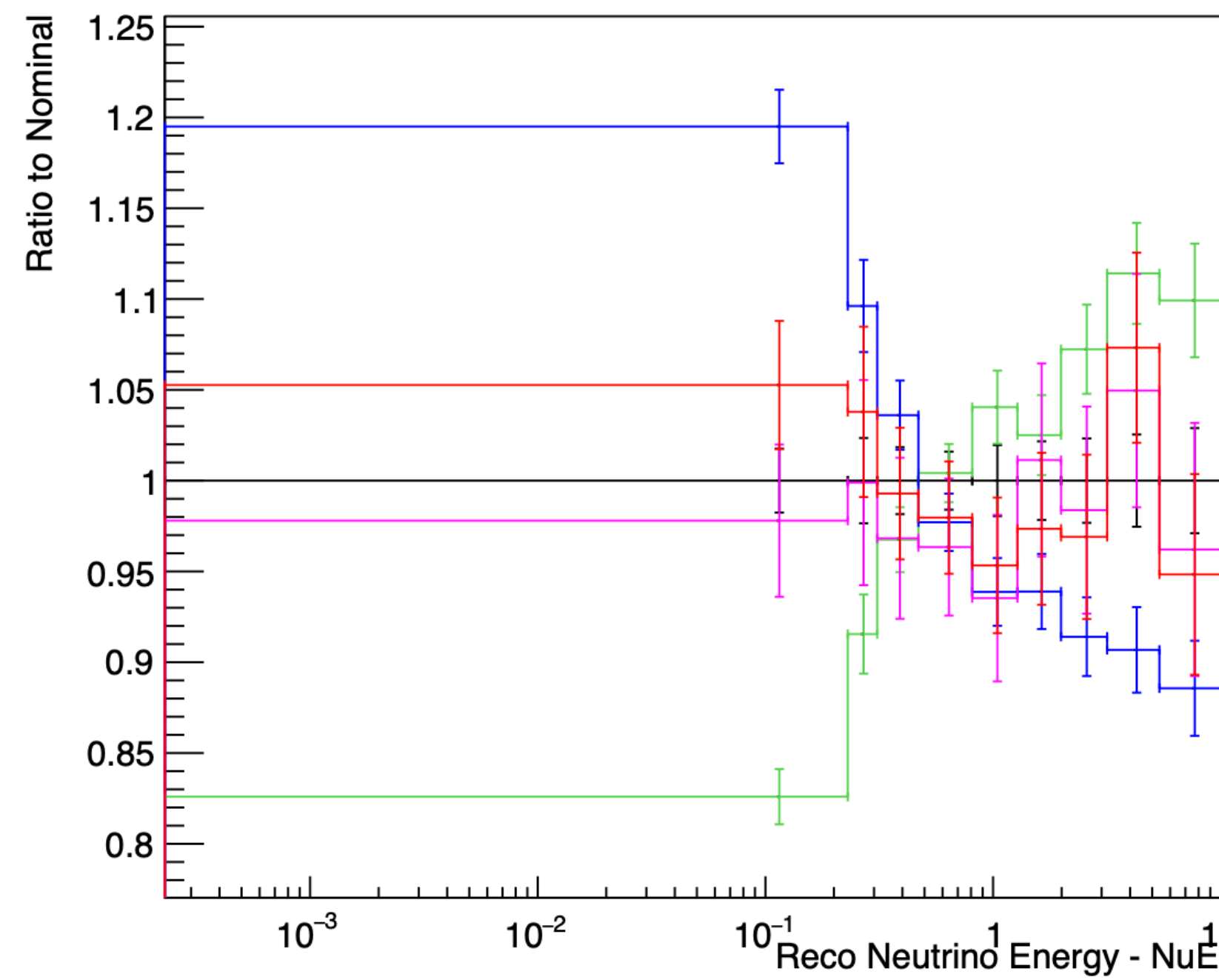


Reco Neutrino Energy - NuE (-0.50 < kSelection < 0.50)



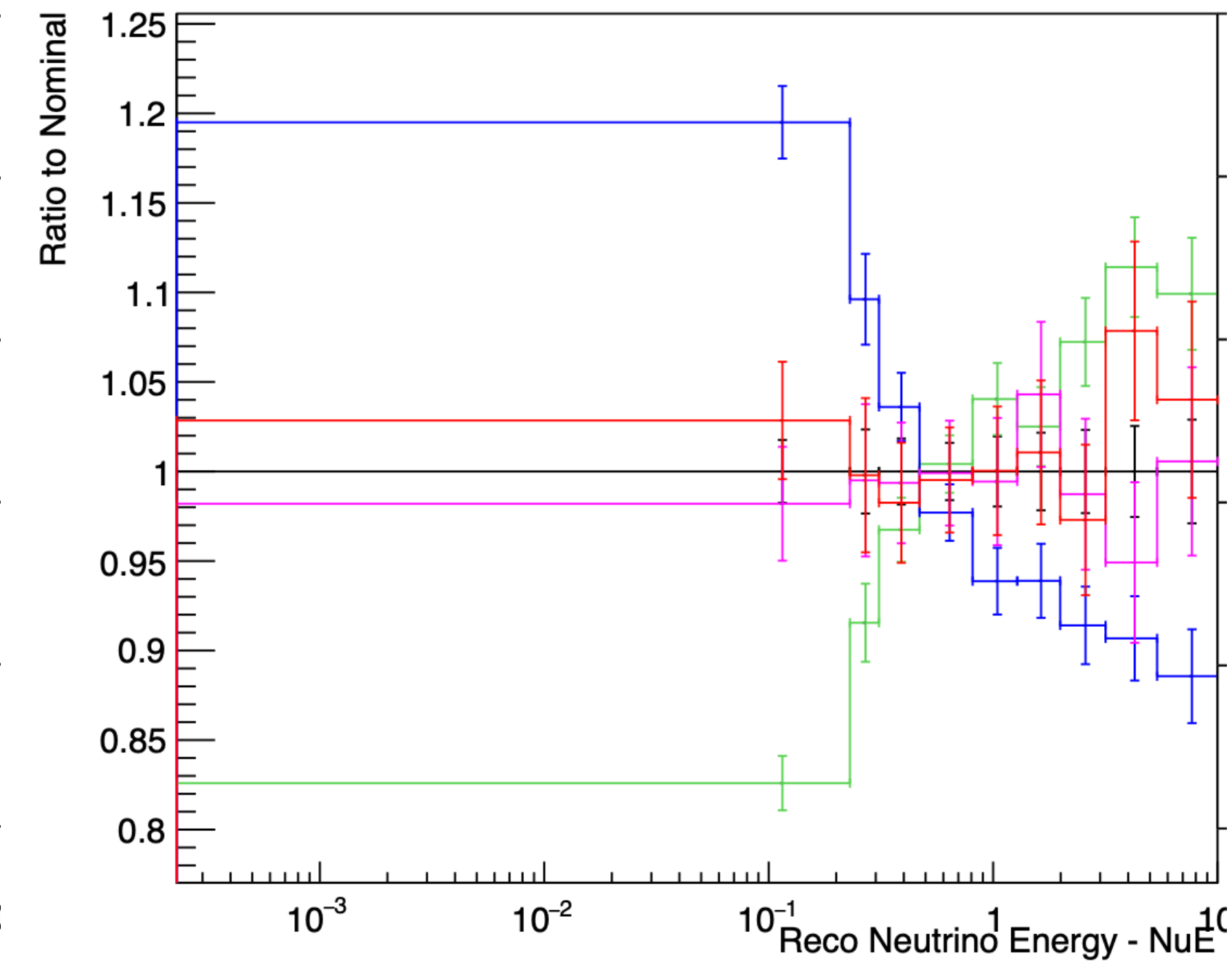
Drift field

Reco Neutrino Energy - NuE (-0.50 < kSelection < 0.50)



Attenuation

Reco Neutrino Energy - NuE (-0.50 < kSelection < 0.50)



Transverse diffusion



MC statistics

Conclusions



Based on this study using only ~20k events per variation:

- **Recombination** effect is the most important: based on previous studies, will need **at least 200k events** (from covariance matrix stability studies)
- **Attenuation** effect is ~1/3-1/4 of recombination effect: would need $\times 9-16$ statistics (**at least 1800k events**)
- **Transverse diffusion** effect is almost **comparable to attenuation?**
- **Drift field 2% variation is negligible BUT we did not include the impact on Field response!**



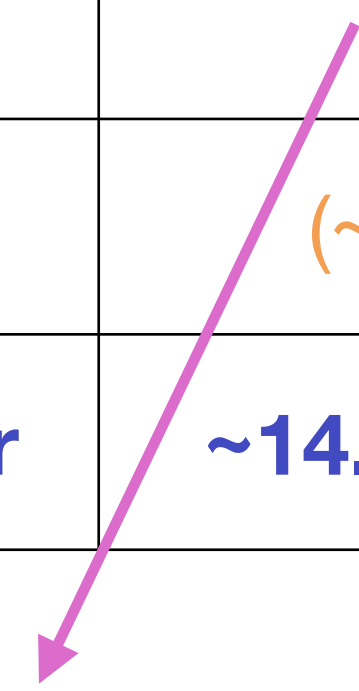
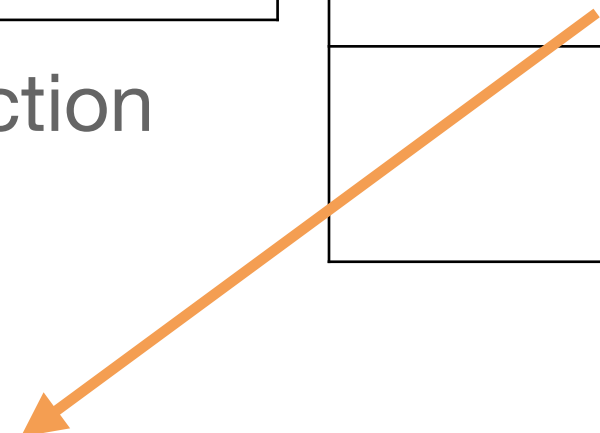
MC statistics

Status of computing resources request



| Stage | CPU | RAM | File size | | CPU Time (variation) | CPU Time (wiremod) |
|---------------------------|------|-------|-----------|---|----------------------|--------------------|
| G4 | 5s | 1.0GB | 8MB | Mod. Box: 2*200k events | ~23.4 khr | ~0.7 khr |
| Detsim | 200s | 2.9GB | 10MB | Attenuation: 2*1800k events | ~205.4 khr | ~6.5 khr |
| Reco1 | 0.4s | 1.1GB | 10MB | Transverse diffusion: 2*2000k events | ~233.8 khr | ~7.2 khr |
| reco1 +wiremod | 1.5s | 1.1GB | 10MB | Drift field: 2*2000k events | (~233.8 khr) | (~233.8 khr) |
| Reco2 | 5s | 1.4GB | 10MB | Total | ~462.6 (696.4) khr | ~14.4 (248.2) khr |

Based on footprint of October 2023 atm production



Not sure yet if needed

Will request if effect similar to attenuation and transverse diffusion

Not available yet in wiremod, not so easy...



Conclusions



Conclusions

Tentative timeline

- The **main effects** to take into account for systematics related to detector model have been **identified: recombination, attenuation, diffusion** (+drift field?)
- For now the strategy would be to **consider conservative variations** (can extrapolate the less conservative systematics)
- A more CPU-time effective method is being investigated for **recombination and attenuation** at least: **wiremod**
- **MC stat request is progressing**, in case we use wiremod, we might be more generous with stat
- Foreseen planning:
 - May CM: final production plan
 - September CM: Technical Note

Approach applicable to LBL OA as well but need person-power for dedicated studies!

Thanks!

List of parameters

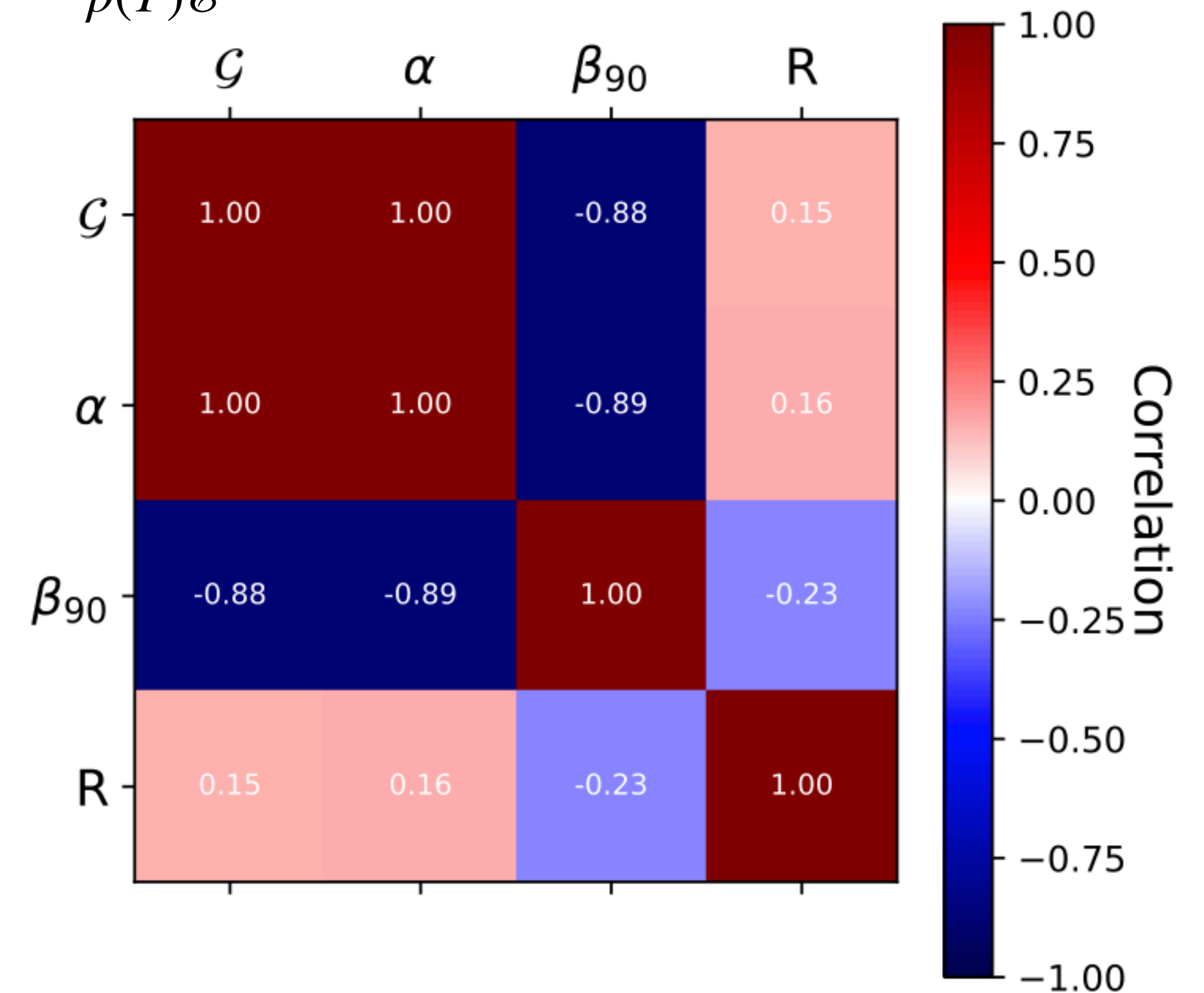
$$\frac{dQ}{dx} = \frac{\ln \left(\frac{\beta}{\rho(T)\mathcal{E}} \frac{dE}{dx} + \alpha \right)}{\frac{\beta W}{\rho(T)\mathcal{E}}}$$



Special case of recombination:

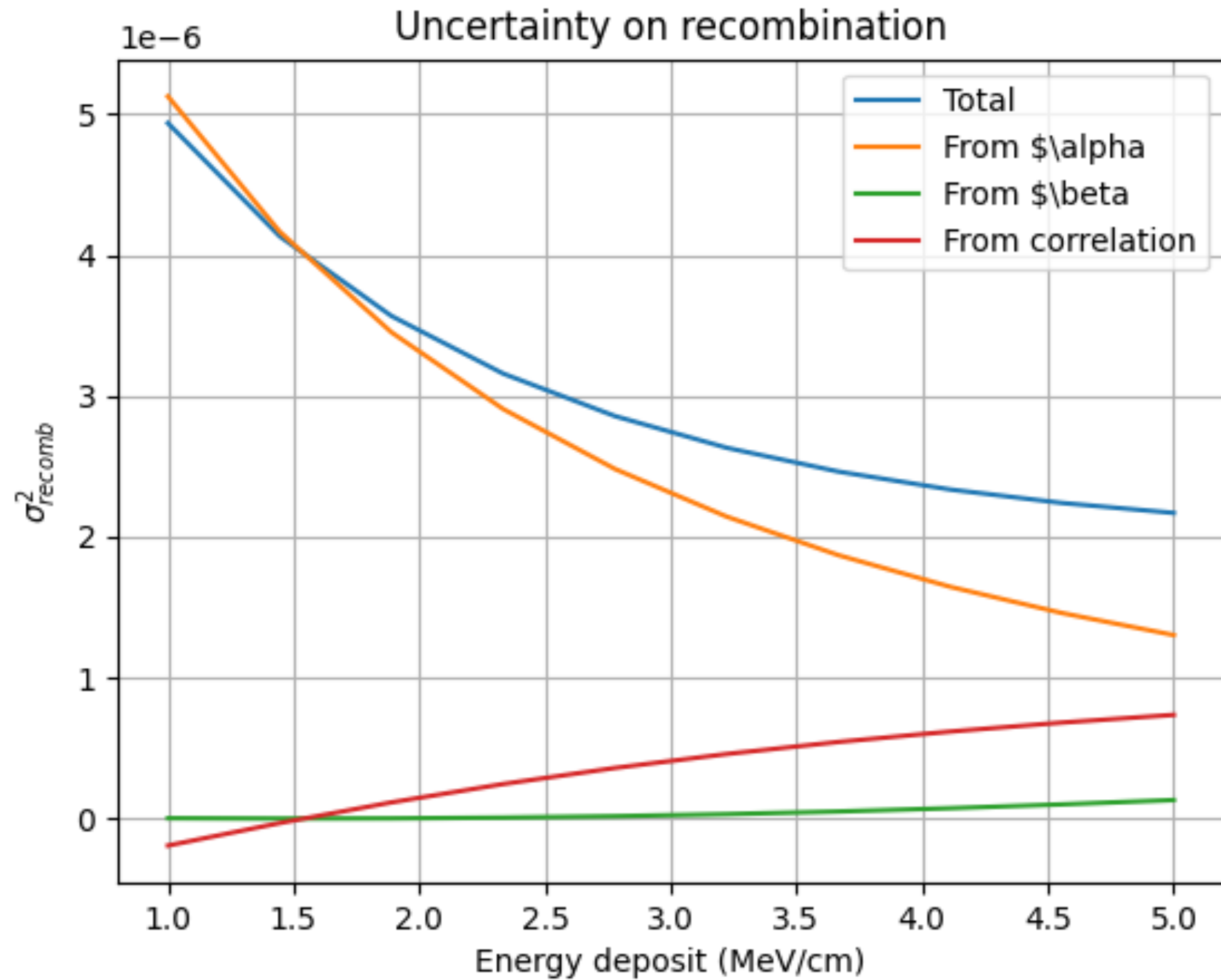
- We use modified box model with parameters values from ArgoNeuT
- Parameters should be strongly anti-correlated
- Only ICARUS provides a correlation matrix for recombination measurements but they use an angle dependent model...

$$\beta(\phi) = \frac{\beta_{90}}{\sqrt{\sin^2 \phi + (\cos^2 \phi)/R^2}}$$

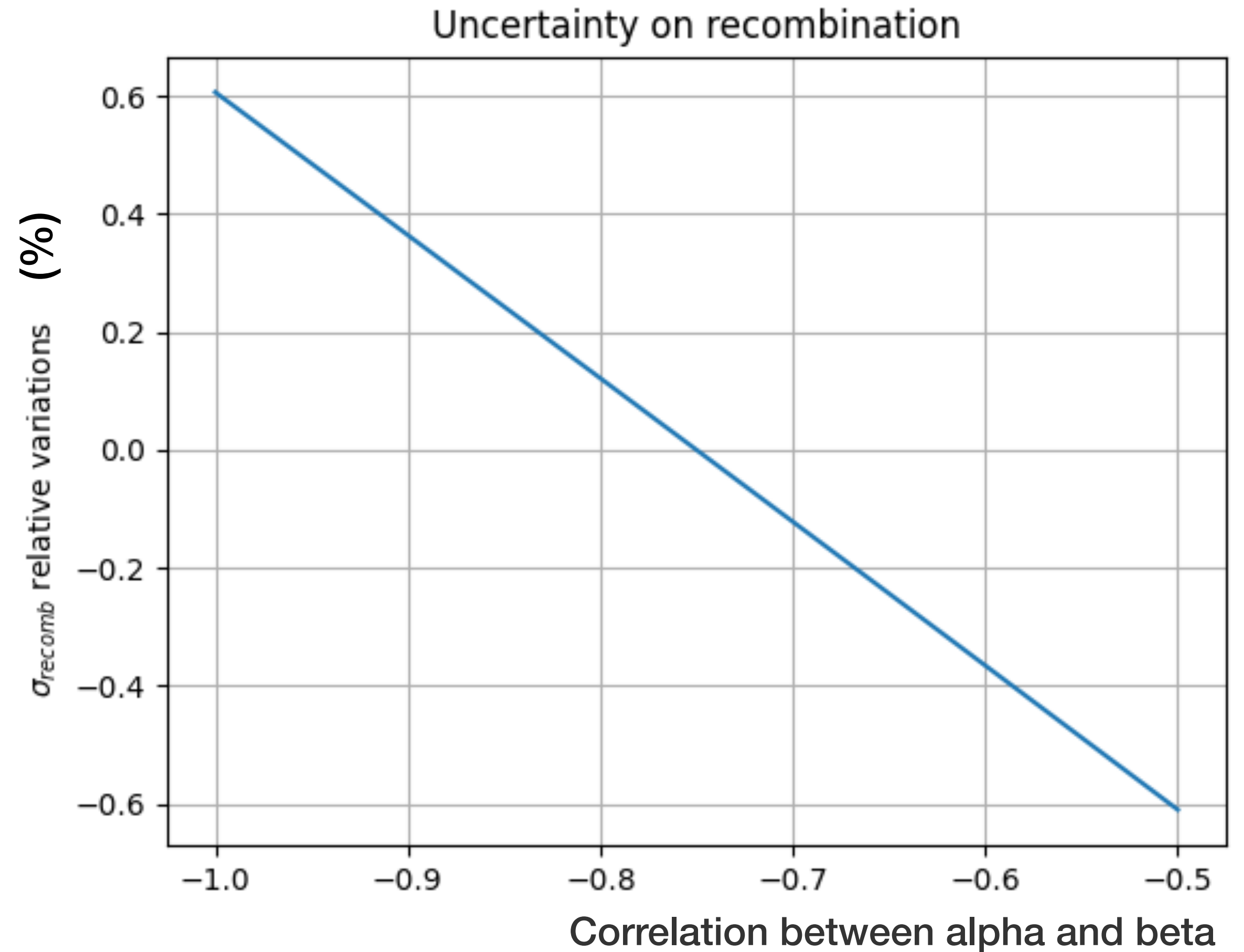


Correlation matrix reported by ICARUS for the measurement of the ellipsoidal modified box model parameters: \mathcal{G} is the electronics gain.

List of parameters



Obtained using ArgoNeut values with a -0.89 correlation



Conservative approach would be to set correlation to -1 (dEdx=2 MeV/cm)

Wiremod

DUNE FD implementation



- Started to implement **wiremod for DUNE FD**: in branch feature wiremod of dunereco (Larsoft v10_04, e26:prof). Using the **SBN implementation** but with **different method for the scaling factors**.
- Basic working principle (see backup for more details):
 1. **Match the sim energy deposits** (edepts)
 2. **Match hits** to signal ROIs and **define subROIs**
 3. **Match edeps to subROIs** and compute **truth properties**
 4. **Calculate scaling factors** (dependent on truth properties) of each subROI
 5. **Modify the ROI**



Wiremod

Edep matching



Edep matching to ROIs:

1. Get the **edeps channel and ticks from true position** (using planeXToTick)
2. Match channel to wire
3. Check the **wire has signal ROI**
4. Fill the map **if the tick of the edep falls inside** a signal ROI



Wiremod

subROI calculation

- **Hit matching** to ROIs work on same principle as edep matching.
- **One subROI** is defined **for each hit** in a signal ROI
- The **subROI properties** are identified to the **hit properties**:
 - `subROI.total_q = hit->Integral()`
 - `subROI.center = hit->PeakTime()`
 - `subROI.sigma = hit->RMS()`
- If there is no matched hit, `subROI=ROI`



Wiremod

Truth properties calculation

- **Matching edeps to subROI** requires edep **tick in subROI center \pm sigma**
- **Truth properties** of a subROI are calculated **from all the matched edeps**
 1. Group edeps by trackID
 2. **Select dominant track** (most energy deposited)
 3. Compute **energy weighted averages** of position (x,y,z), spatial spread, track direction and dE/dx*

* Added a non energy weighted average of dE/dx for recombination rescaling, see why later in the presentation



Wiremod

ROI modification

For full ROI modification, **loop over ticks**:

1. **Original waveform** approximated as **sum (over subROIs) of Gaussians**

$$\hat{s}_{raw}(t) = \sum_{\text{subROIs}} \mathcal{G} \left(t_{peak}, \sigma, q_{tot} \right)$$

2. **Modified waveform** approximated as sum of Gaussians

$$\hat{s}_{mod}(t) = \sum_{\text{subROIs}} \mathcal{G} \left(t_{peak}, \sigma \cdot r_{\sigma}, q_{tot} \cdot r_Q \right)$$

3. **multiply the real ROI by the ratio:**

$$s_{mod}(t) = s_{raw}(t) \cdot \frac{\hat{s}_{mod}(t)}{\hat{s}_{raw}(t)}$$



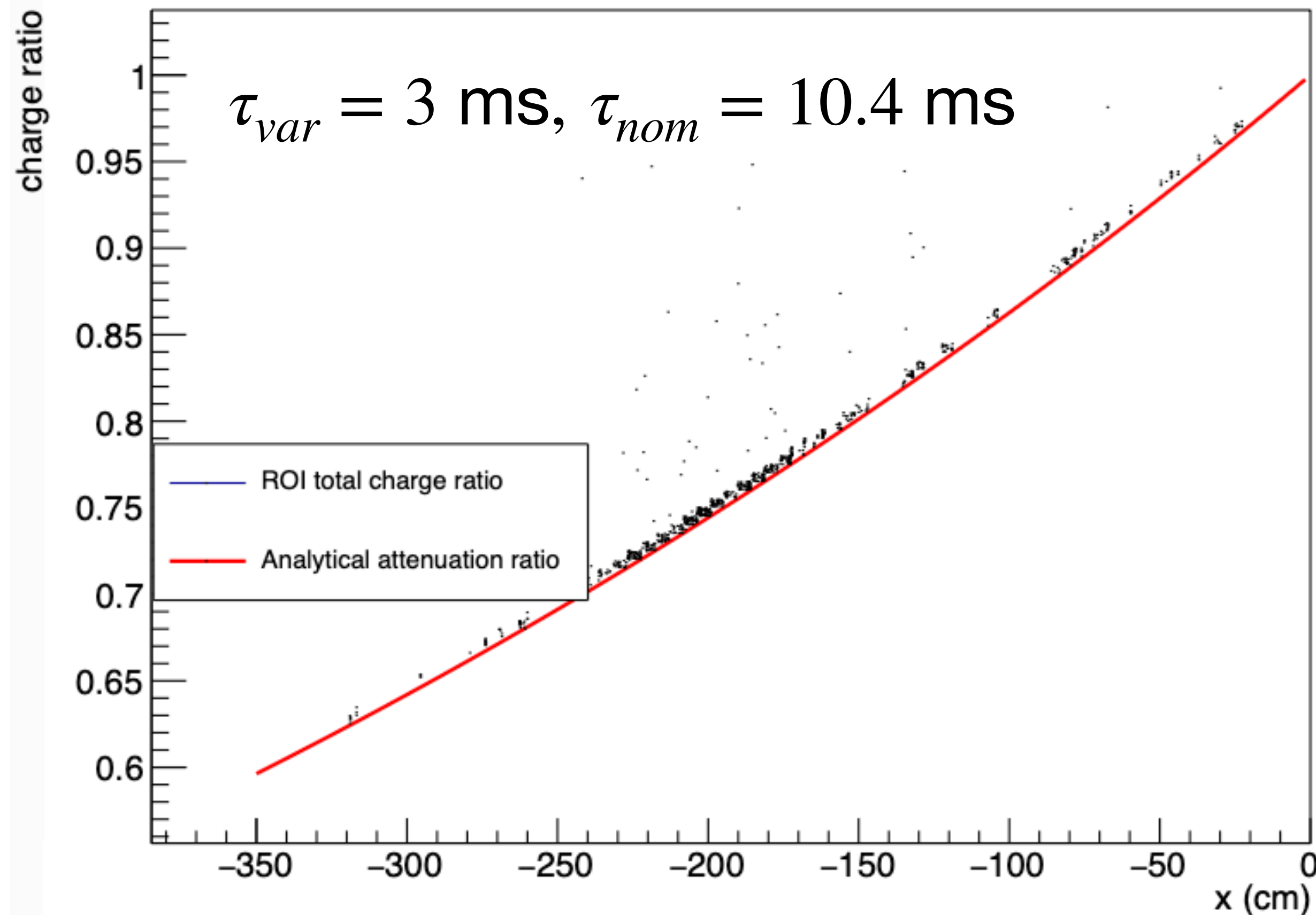
Preliminary results

Cross-checks: charge scaling consistency

With same 20k atm nu events

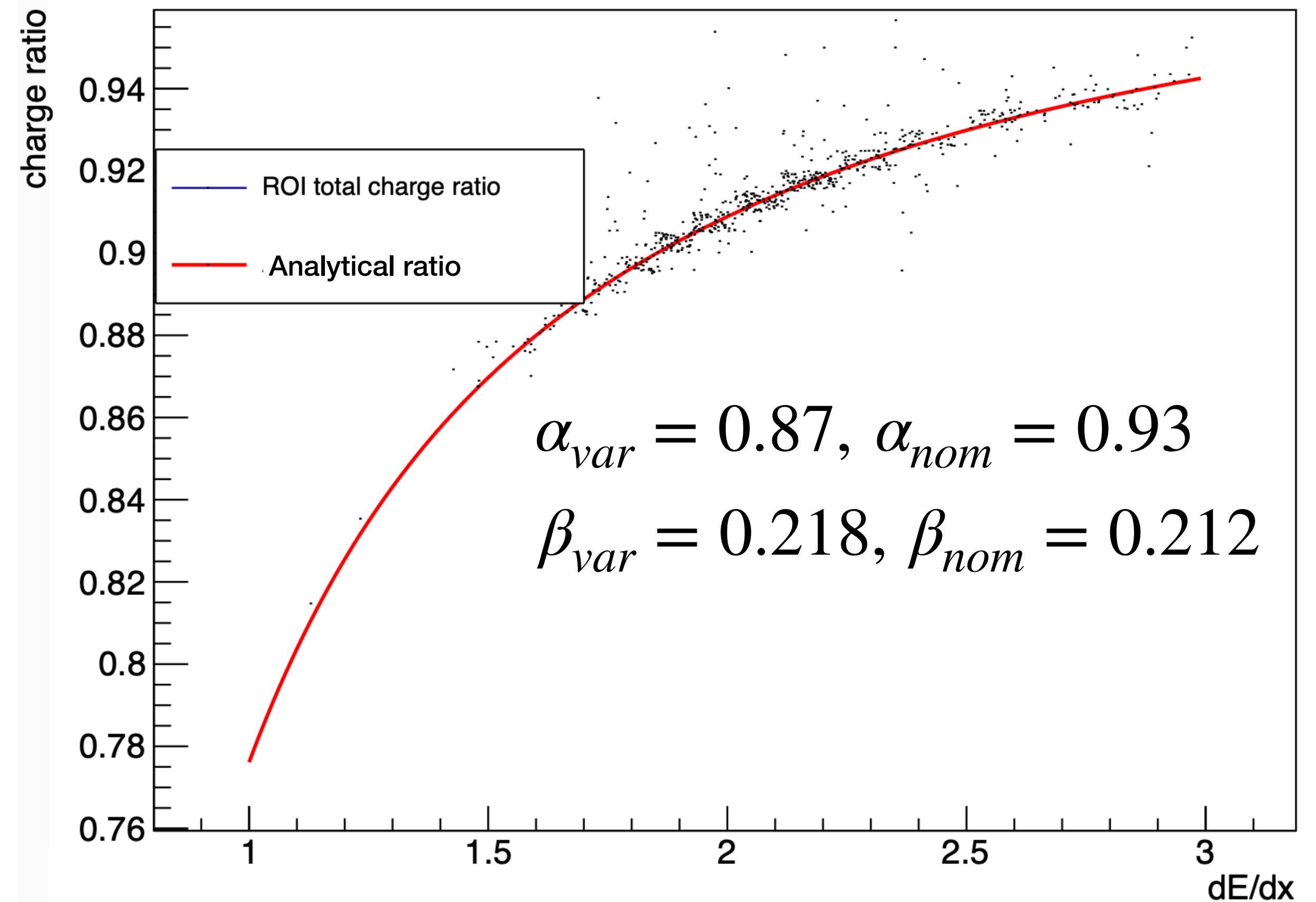


Total charge after/before scaling vs x



Result for one atm nu event for **lifetime variation**

Total charge after/before scaling vs dE/dx



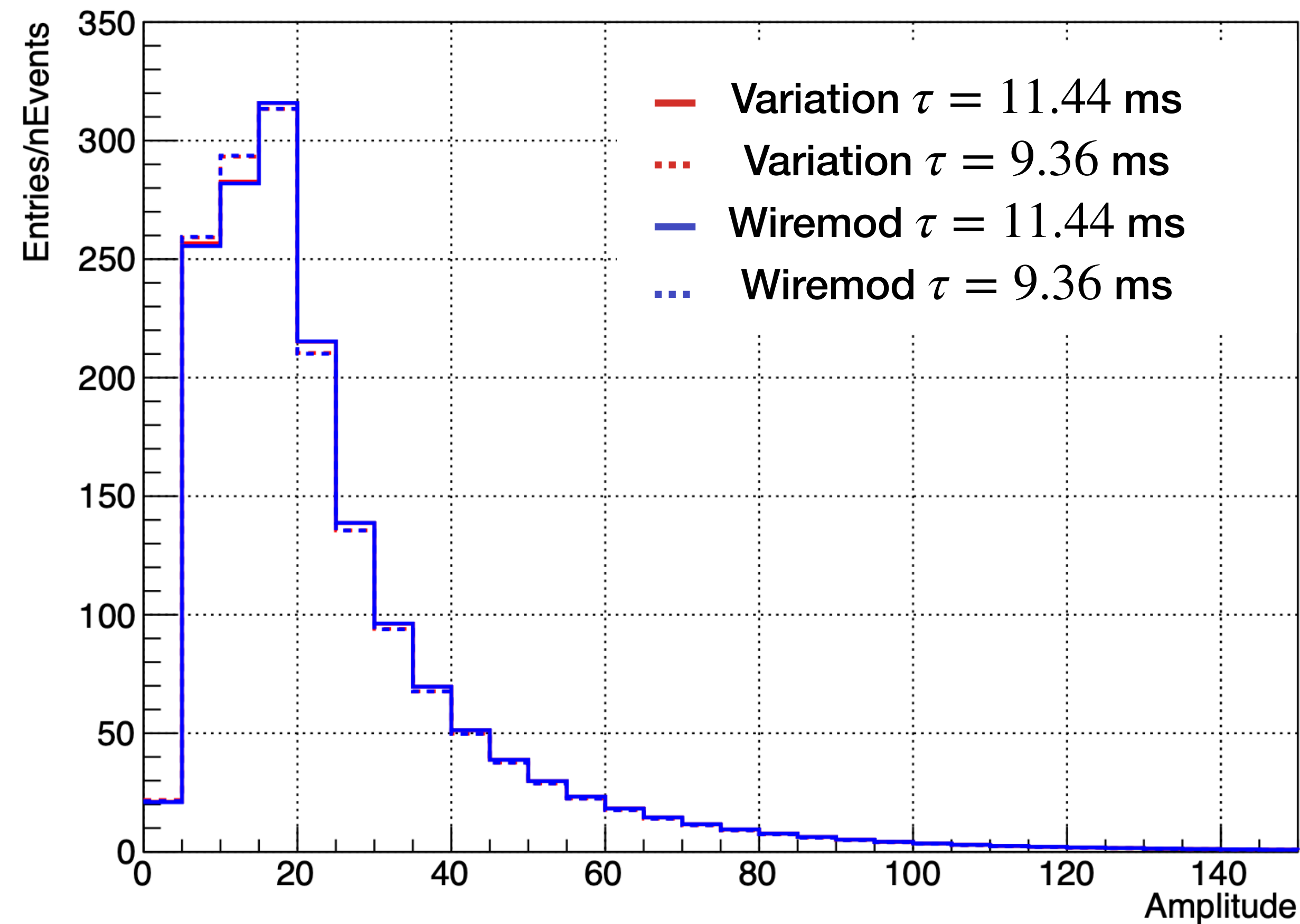
Result for one atm nu event for **recombination variation**

Preliminary results

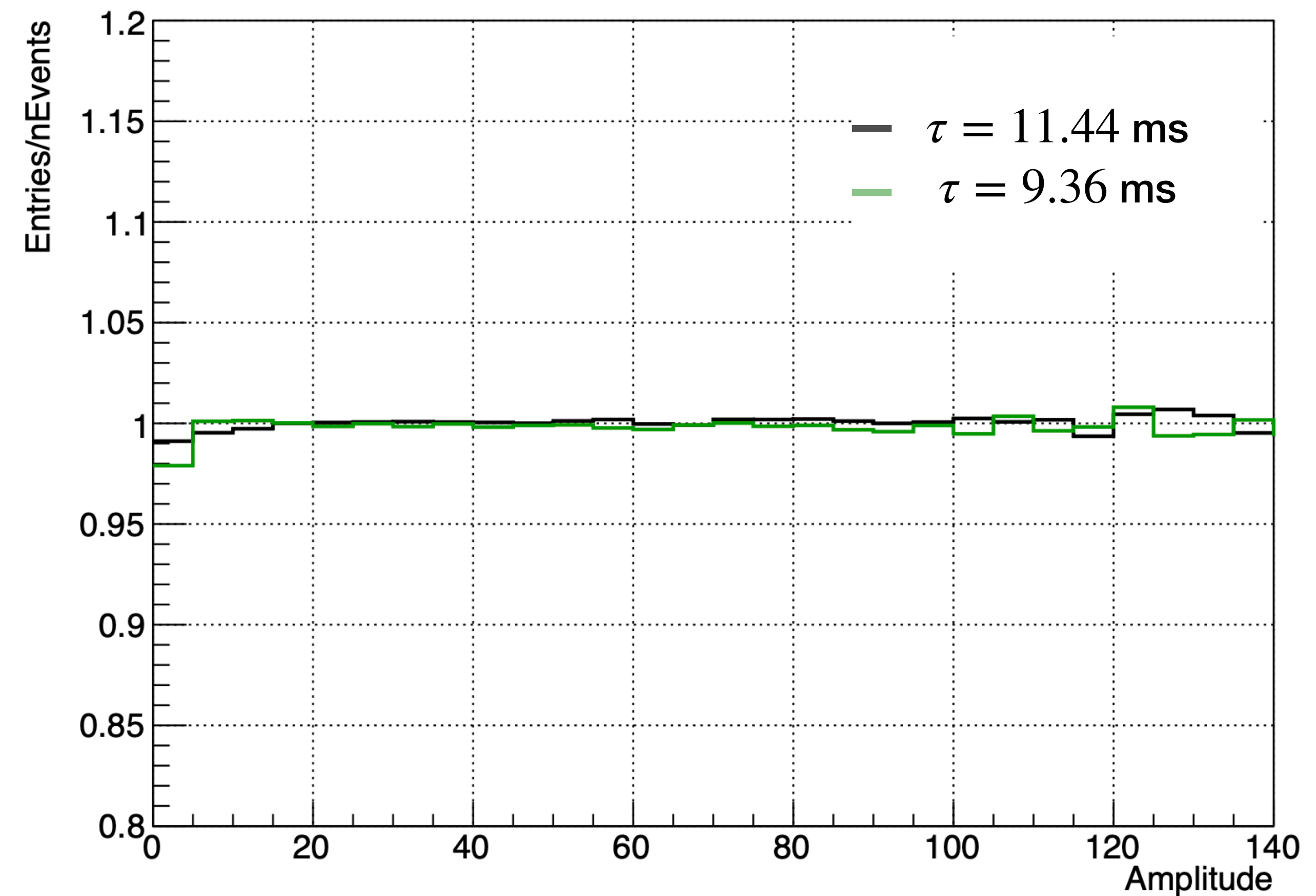
Hit peak amplitude comparisons

The same events are being reprocessed either with a different lifetime value (variation) or with wiremod rescaling

Hit Peak Amplitude



Ratio wiremod/variation

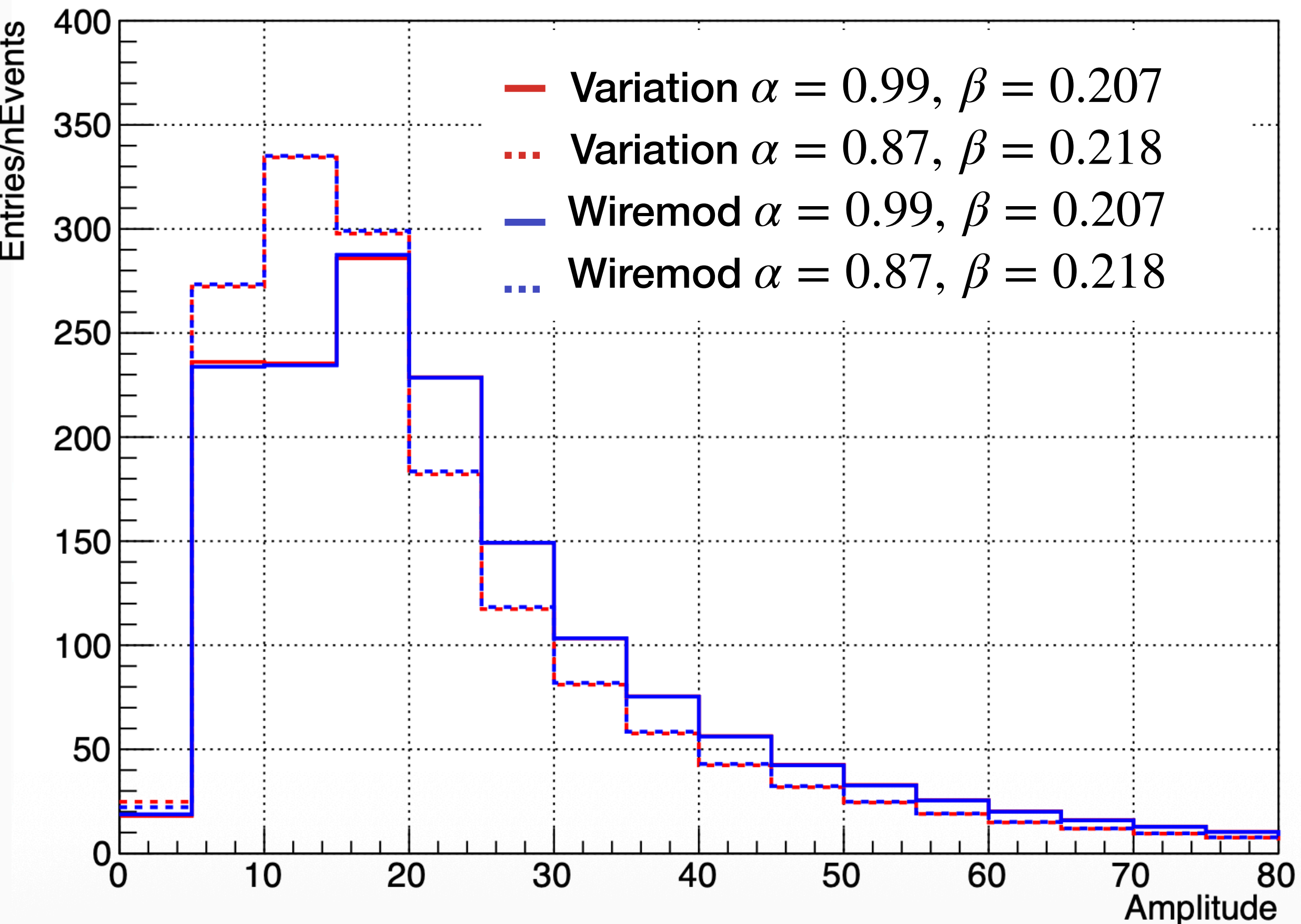


Preliminary results

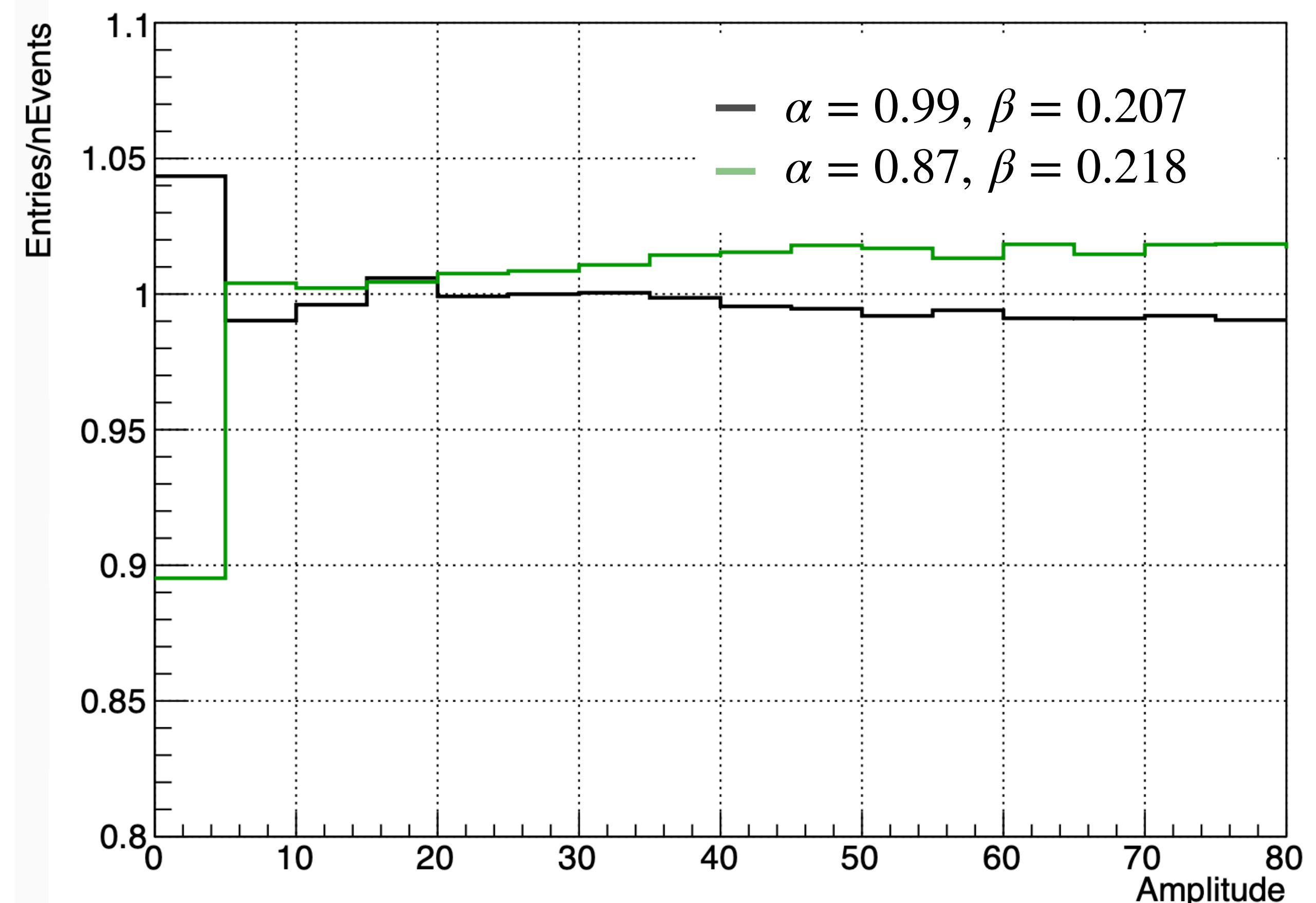
Hit peak amplitude comparisons

The same events are being reprocessed either with a different lifetime value (variation) or with wiremod rescaling

Hit Peak Amplitude

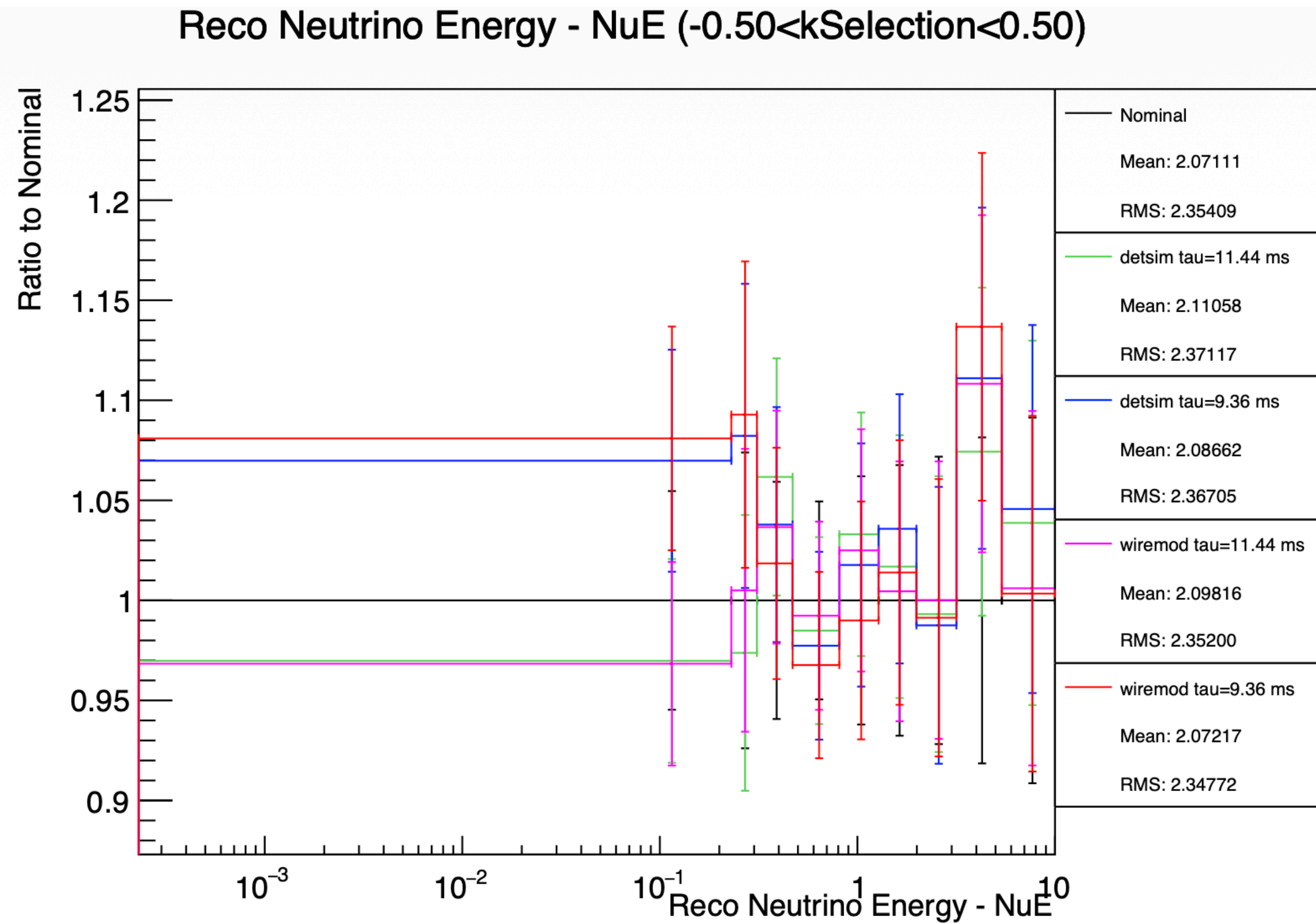


Ratio wiremod/variation



Preliminary results

Analysis observables comparisons



- Reprocessed the same 20k atm nu events and compared real detsim variations to wiremod variations
- Within the (big) error bars, impact on analysis observables relevant for atm OA is similar
- See example with a $\pm 10\%$ lifetime variation impact on CC ν_e Erec spectra

Preliminary results

ROI matching efficiency



- Atm nu events have a majority of low charge signal ROIs (total_q < 80)
- Matching efficiency for low charge ROIs is very low (whatever the sample): ~5%
- As a consequence, ROI matching efficiency for atm nu events is much lower than for through going muons

| | signal ROIs charge < 80 / total | Signal ROIs charge < 80 matched / total charge < 80 | signal ROIs matched / total |
|----------------------------|---------------------------------|---|-----------------------------|
| Atm nu events | 78 % | 6 % | 19 % |
| Through going muons | 38 % | 4 % | 64 % |

Summary of ROI matching efficiency for atm nu events and through going muon events.



Preliminary results

ROI matching efficiency

In both samples (CC and NC), 99% of the matched ROIs lead to an hit.



| | Charge < 80 | Charge > 80 | Charge < 80 with hits | Charge > 80 with hits | With hits | Total |
|-------------------------|-------------|-------------|-----------------------|-----------------------|-----------|-------|
| CC atm nu events | 6 % | 92 % | 9 % | 96 % | 37 % | 25 % |
| NC atm nu events | 5 % | 90 % | 8 % | 92 % | 24 % | 16 % |

Summary of ROI matching efficiency for atm nu events CC vs NC

Preliminary results

ROI matching efficiency



Conclusions on ROI matching efficiency

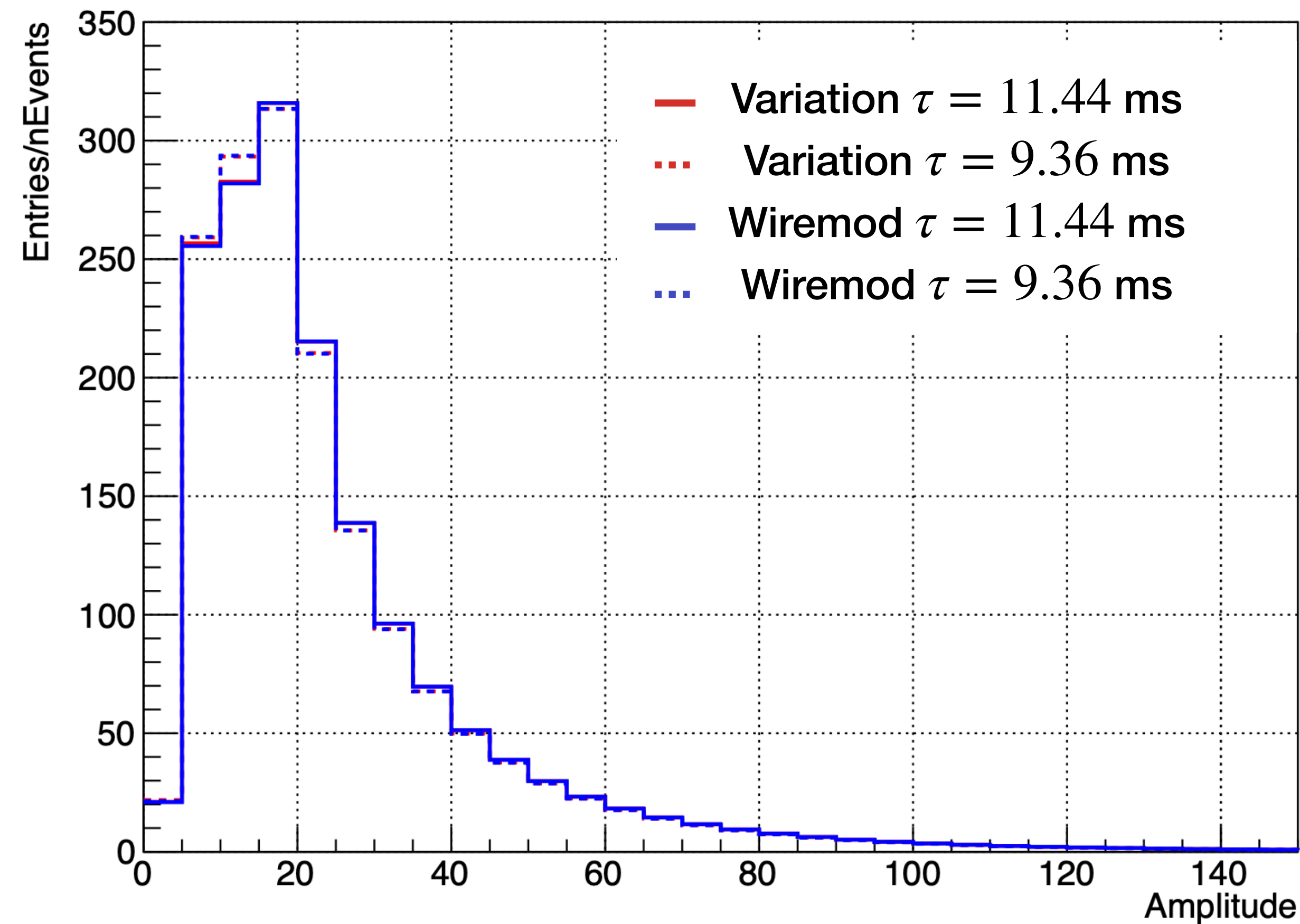
- The low efficiency of the matching ROIs to an edep seems dominated by the low efficiency in the low charge region:
 - Matching efficiency in the high charge region is $> 90\%$
 - Leading to an hit is only a necessary condition to have a matching
- Do we want to improve matching efficiency in the low charge region?

Preliminary results

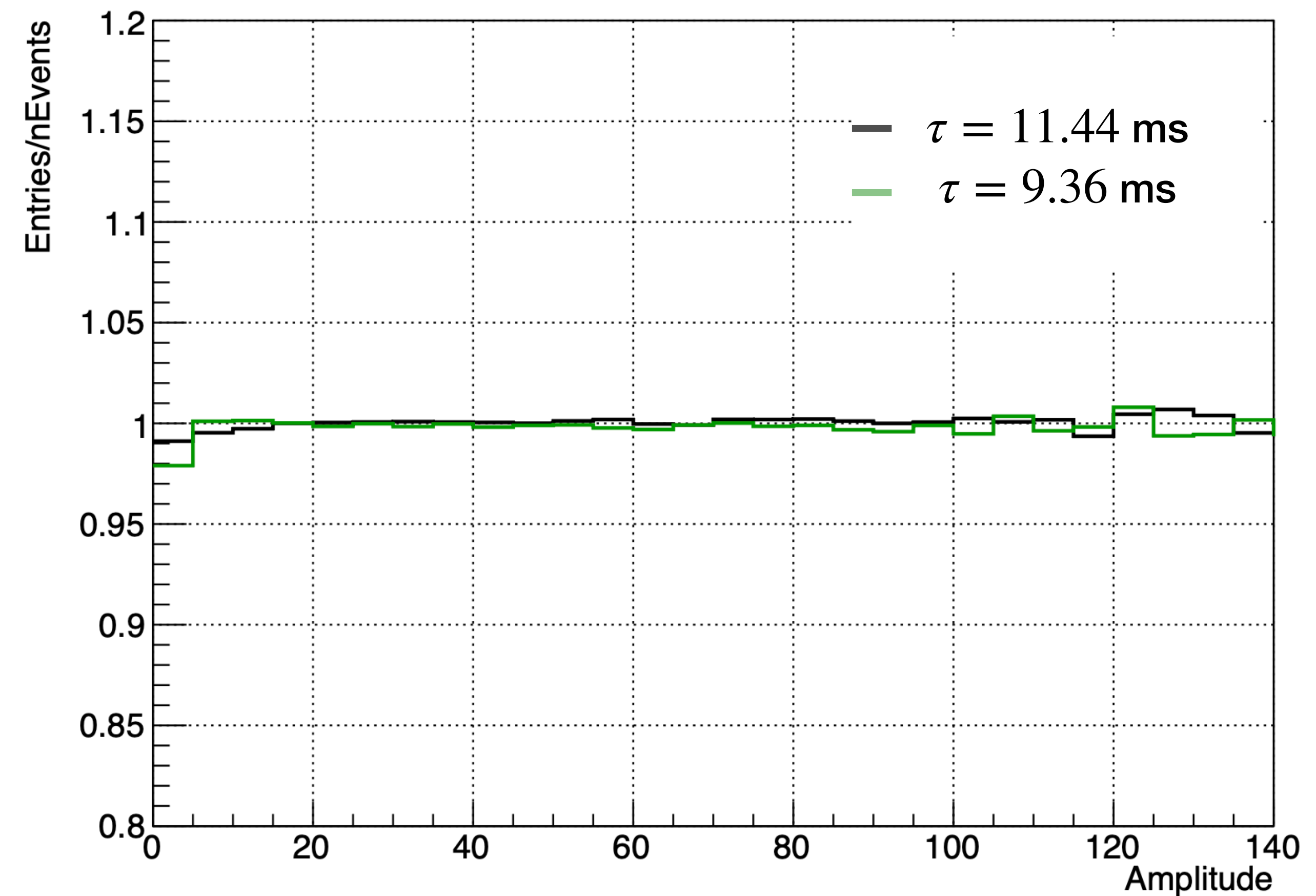
Hit peak amplitude comparisons

The same events are being reprocessed either with a different lifetime value (variation) or with wiremod rescaling

Hit Peak Amplitude



Ratio wiremod/variation

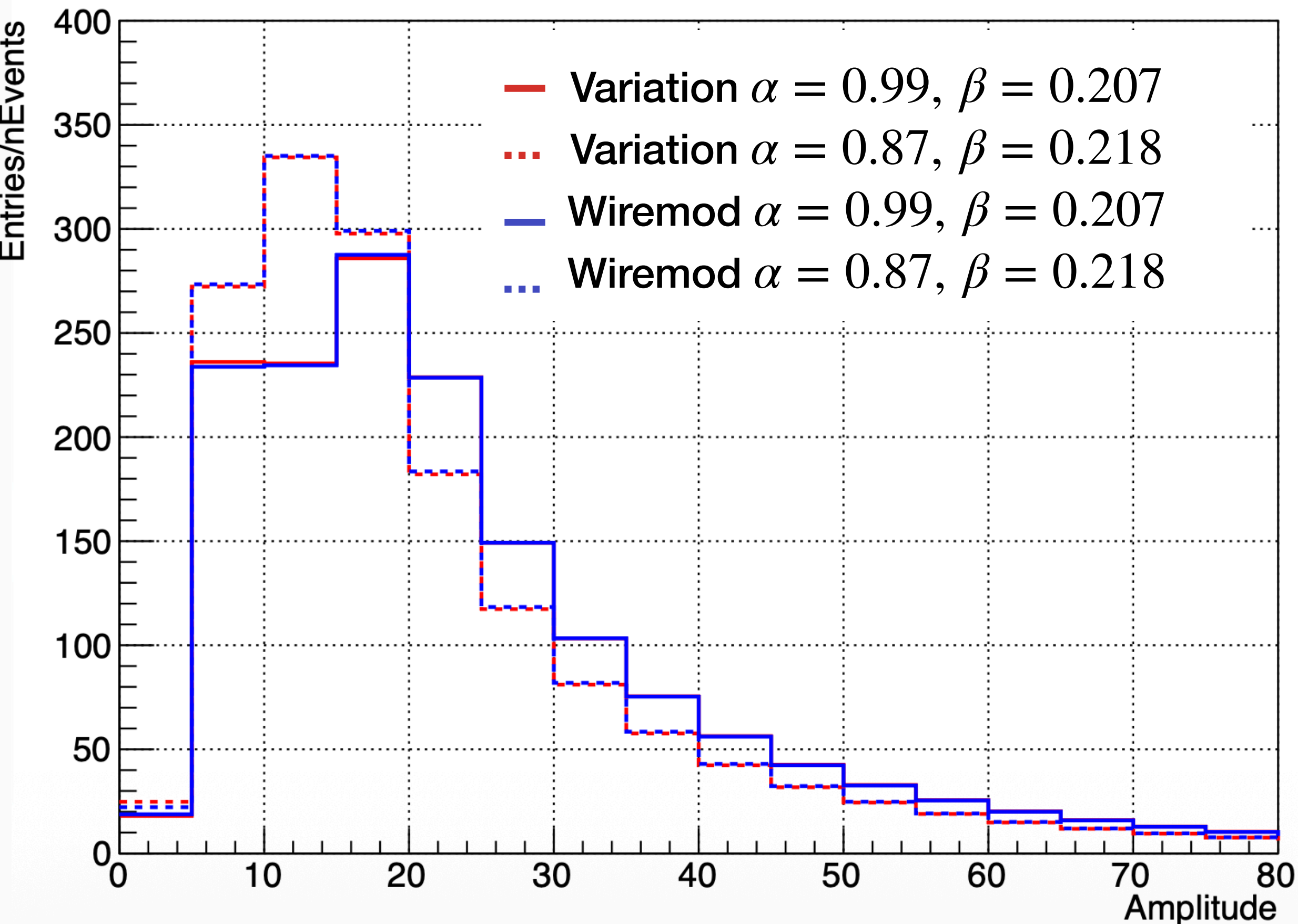


Preliminary results

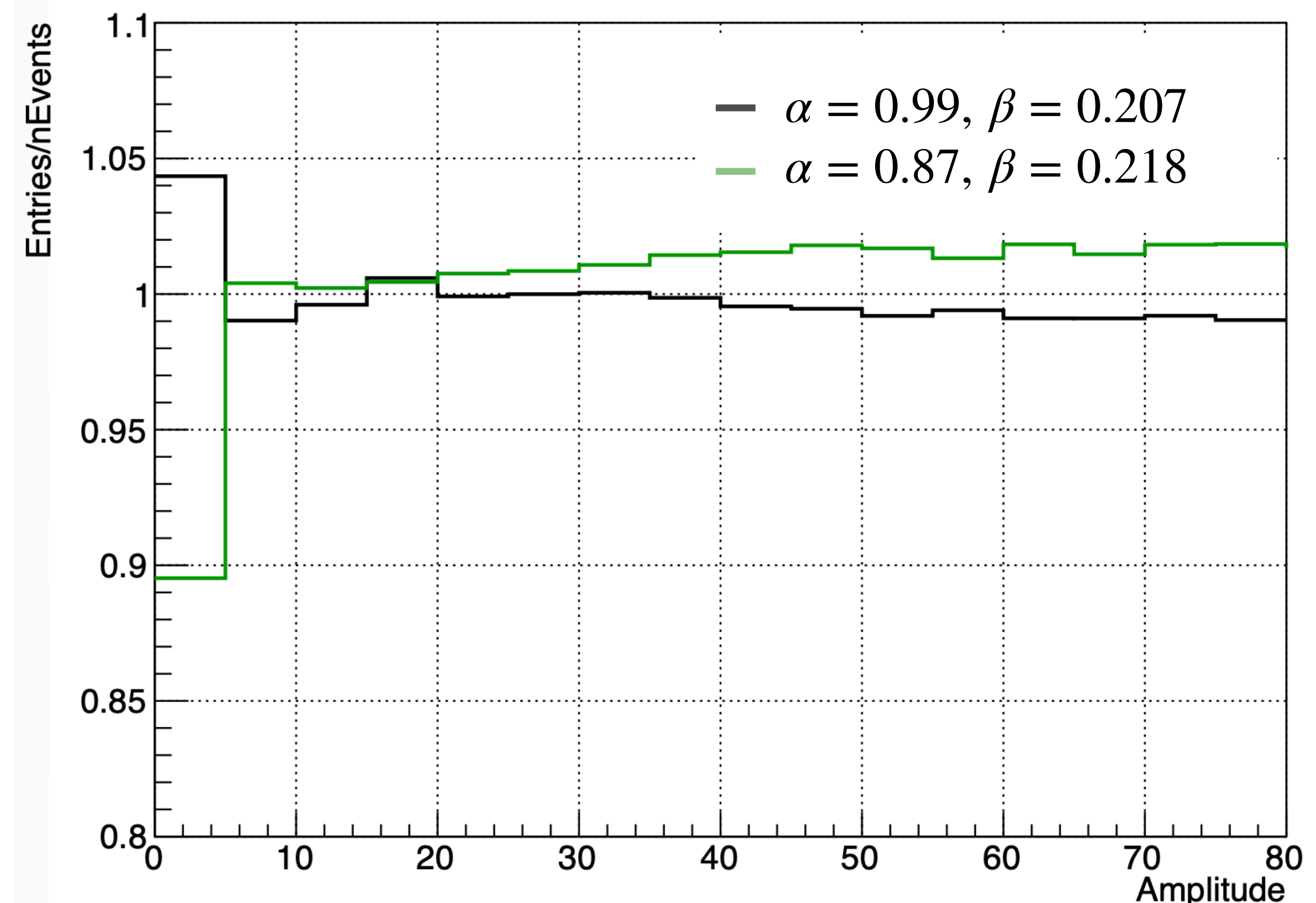
Hit peak amplitude comparisons

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Hit Peak Amplitude

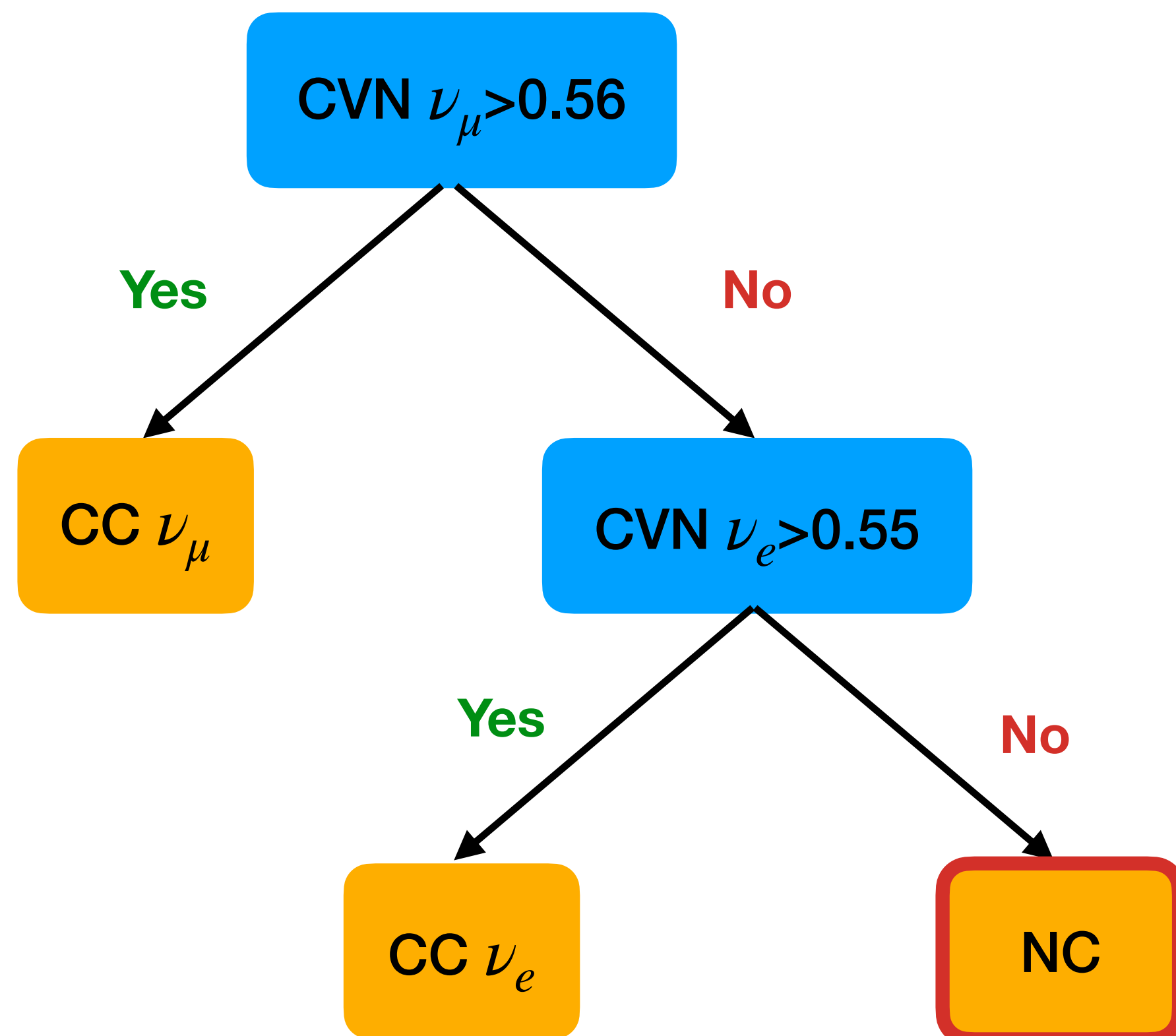


Ratio wiremod/variation



Event selection

- Event classification



- FV cuts

```
// private correspondance from Pierre Granger
template <typename T, typename C = Proxyable_t<caf::SRInteraction, T>>
inline bool InFV(T const &fd_int) {
    if (std::fabs(fd_int.vtx.x) > 343) {
        return false;
    }
    if (std::fabs(fd_int.vtx.y) > 588) {
        return false;
    }
    float const &z = fd_int.vtx.z;
    if ((z < 20) || (z > 1374)) {
        return false;
    }

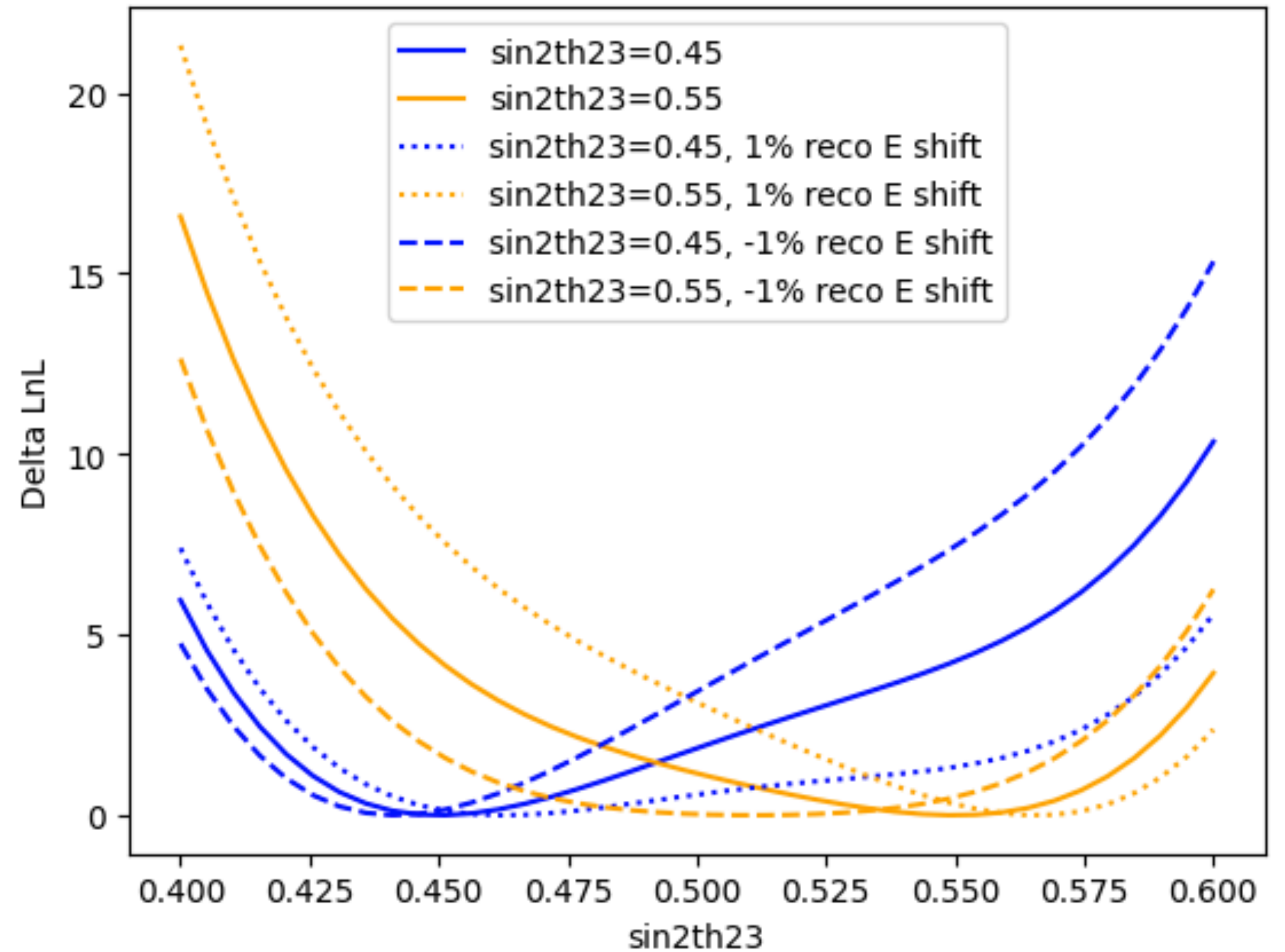
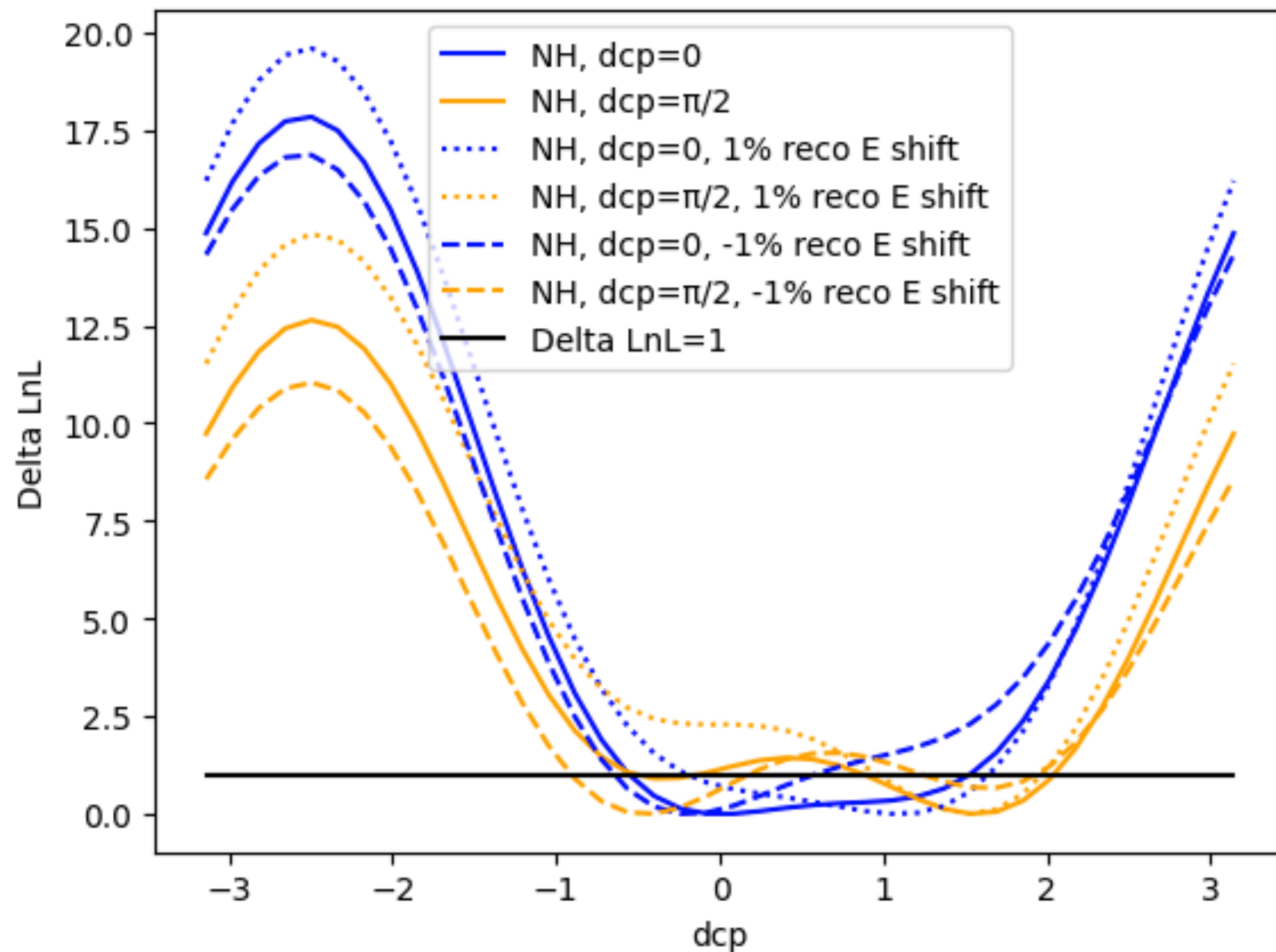
    return true;
}
```

Not considered yet in atm OA.

Energy scale

Impact on sensitivity

Obtained using fast-osc-feedback by applying a systematic shift in energy to the observed data compared to expected.



Modified Box α example

Example of the Modified box parameter α

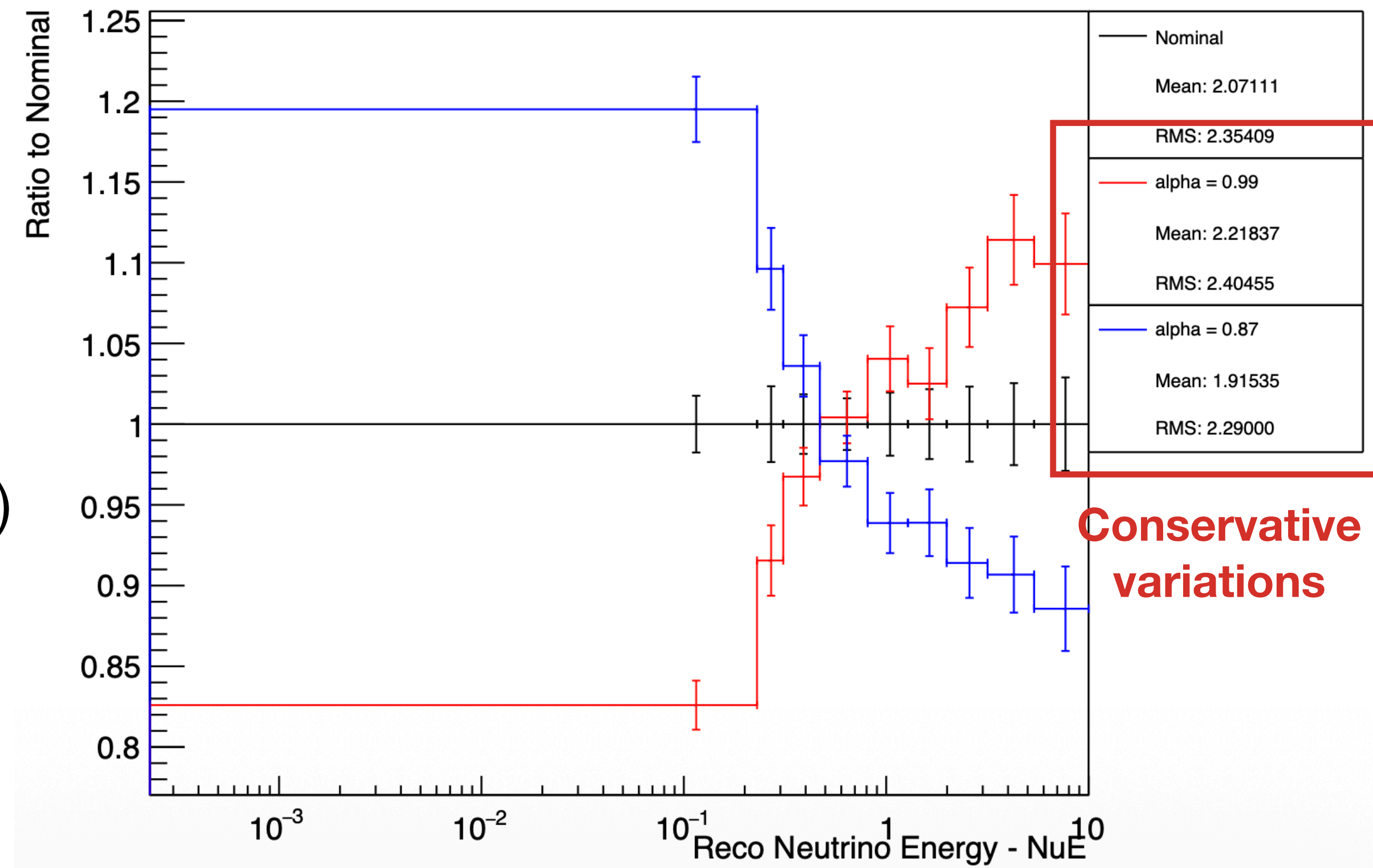
$$\frac{dQ}{dx} = \frac{\ln\left(\frac{\beta}{\rho(T)\mathcal{E}} \frac{dE}{dx} + \alpha\right)}{\frac{\beta W}{\rho(T)\mathcal{E}}}$$

From R Acciarri et al 2013 JINST 8 P08005 (ArgoNeut)

- Central value: 0.93
- Ideal uncertainty: ± 0.02
- Conservative uncertainty: ± 0.06

Other energy scale parameters variations in backup

Reco Neutrino Energy - NuE (-0.50 < kSelection < 0.50)



Impact of modified box α variations on the reconstructed energy spectrum for selected CC ν_e

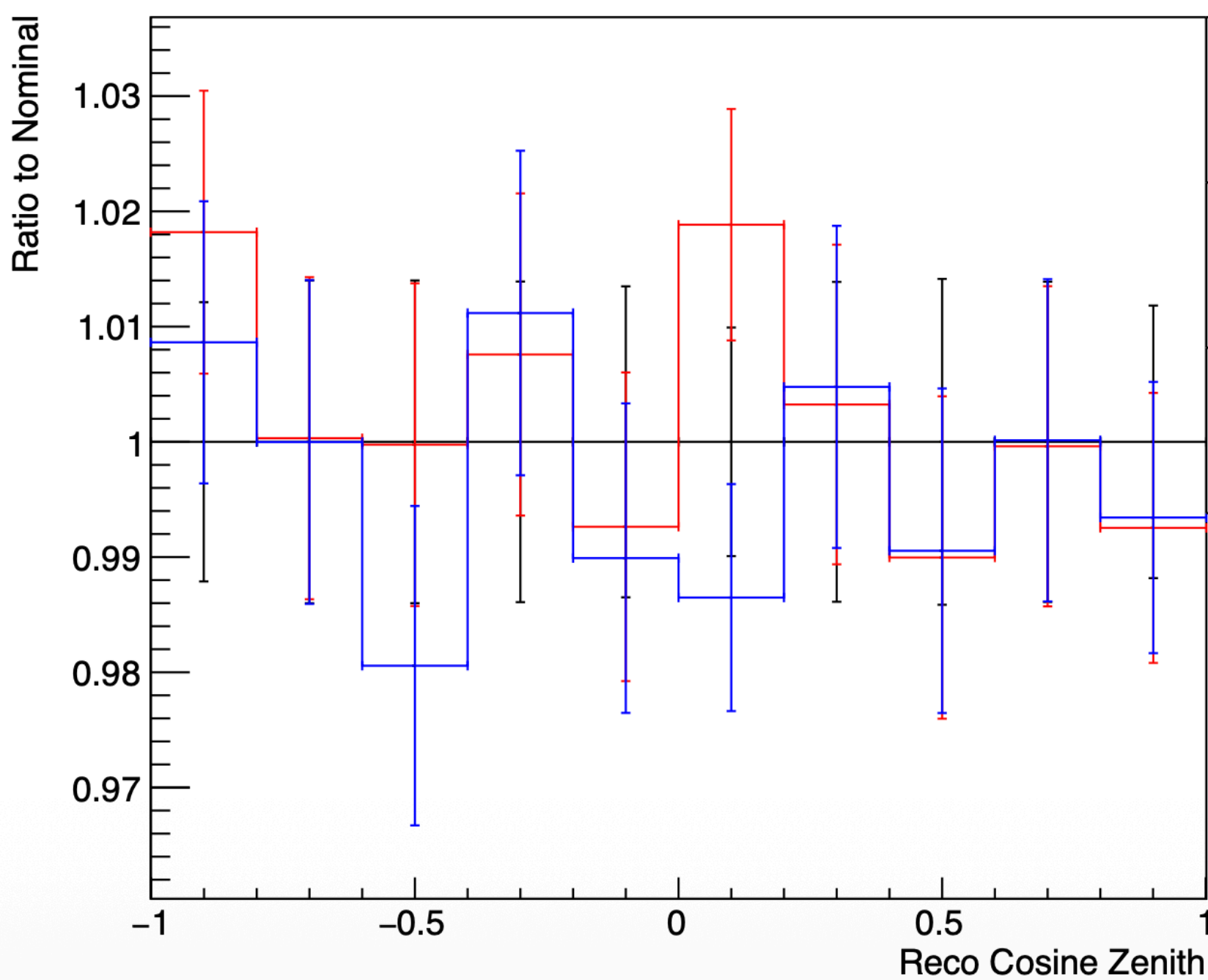


Modified Box α example

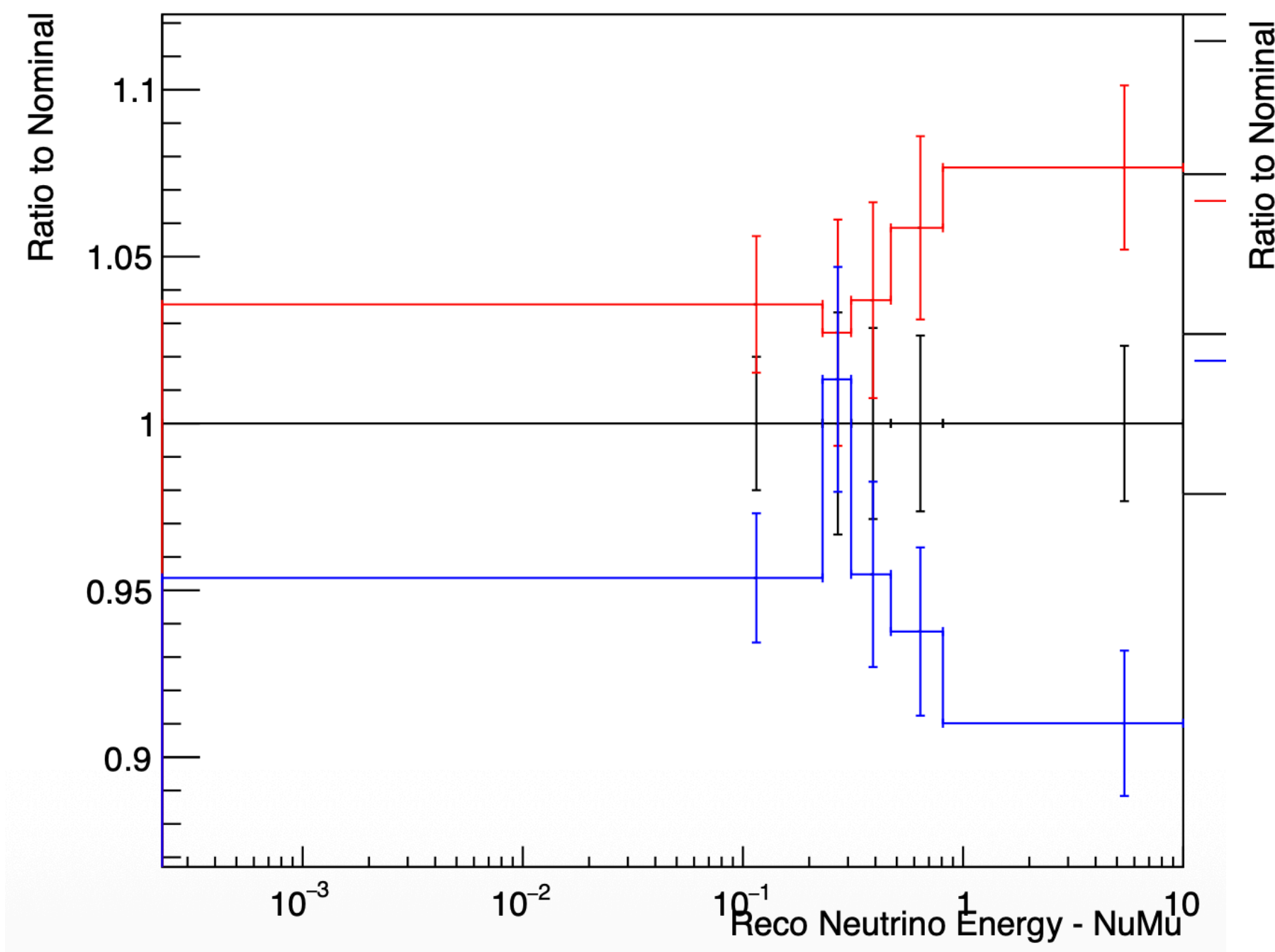


| | |
|---|----------------|
| — | Nominal |
| | Mean: -0.00000 |
| | RMS: 0.57461 |
| — | alpha = 0.99 |
| | Mean: -0.00271 |
| | RMS: 0.57458 |
| — | alpha = 0.87 |
| | Mean: -0.00109 |
| | RMS: 0.57523 |

Reco Cosine Zenith



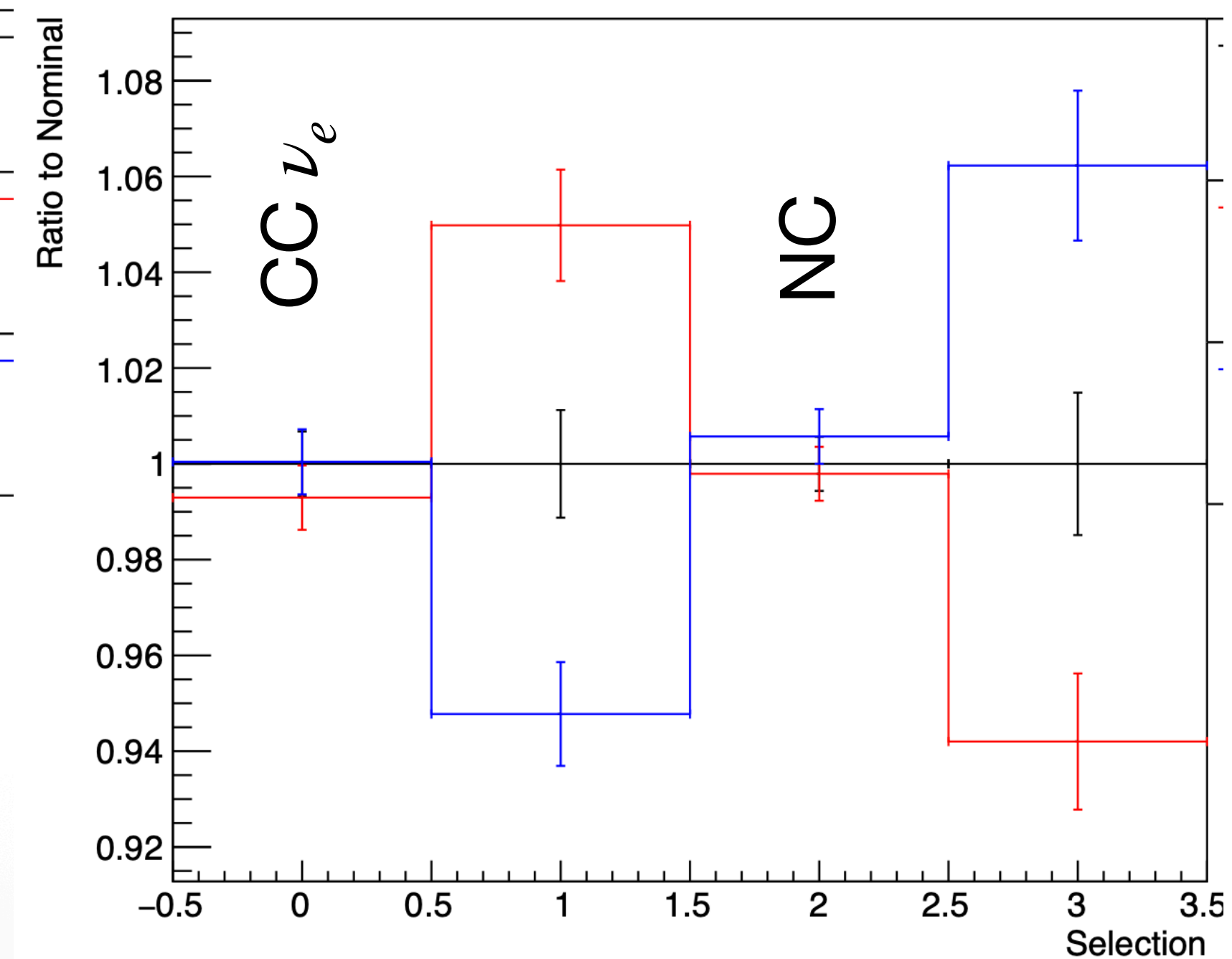
Reco Neutrino Energy - NuMu (0.50 < kSelection < 1.50)



$CC \nu_\mu$

Selection

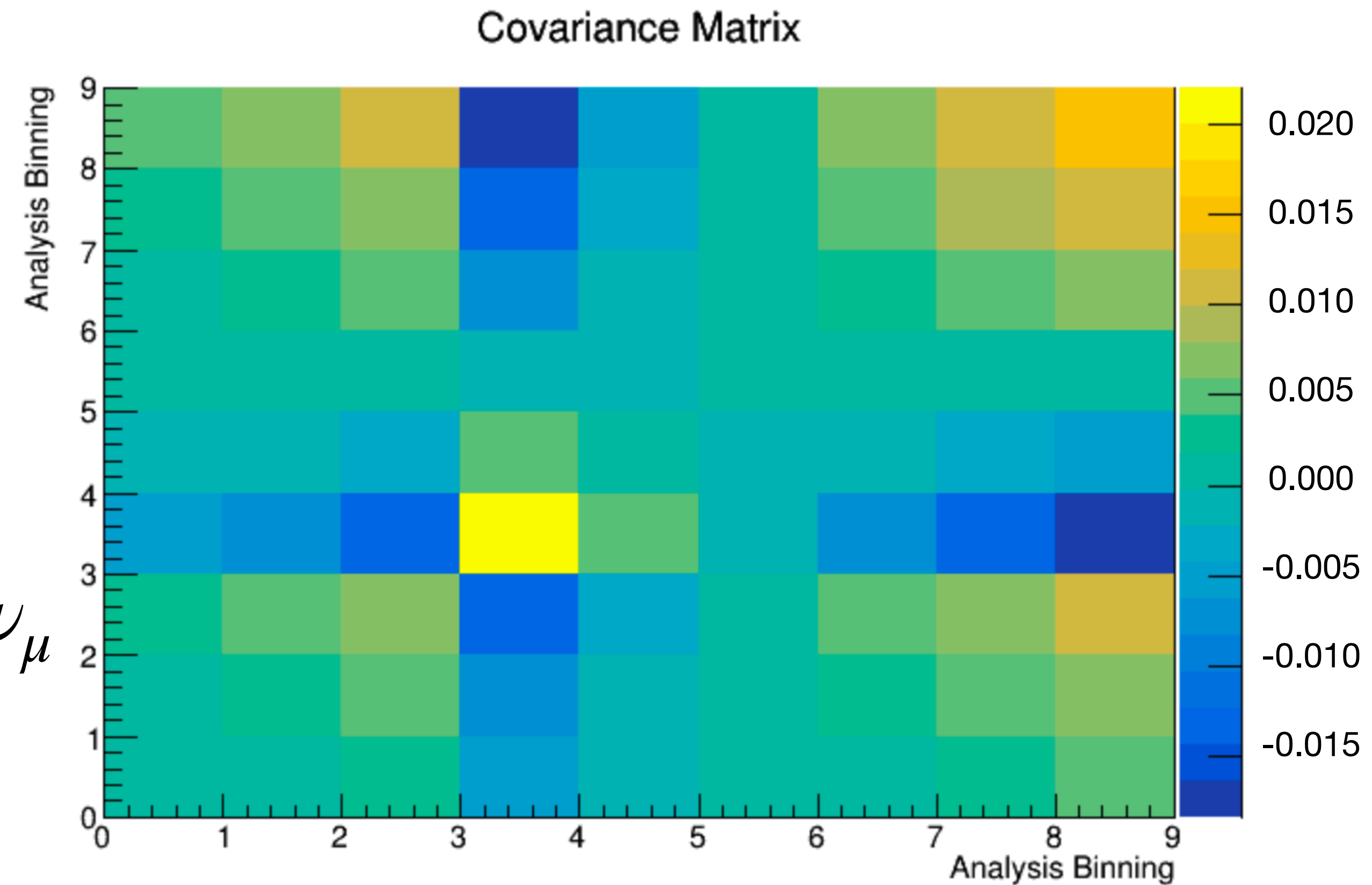
unselected



Modified Box α example

Example of the **covariance matrix** obtained for

- Conservative variations of α
- **200k events** per variation
- Binning only in **Ereco**: 3 bins for CC ν_μ (0-2) and 6 bins for CC ν_e (3-8)



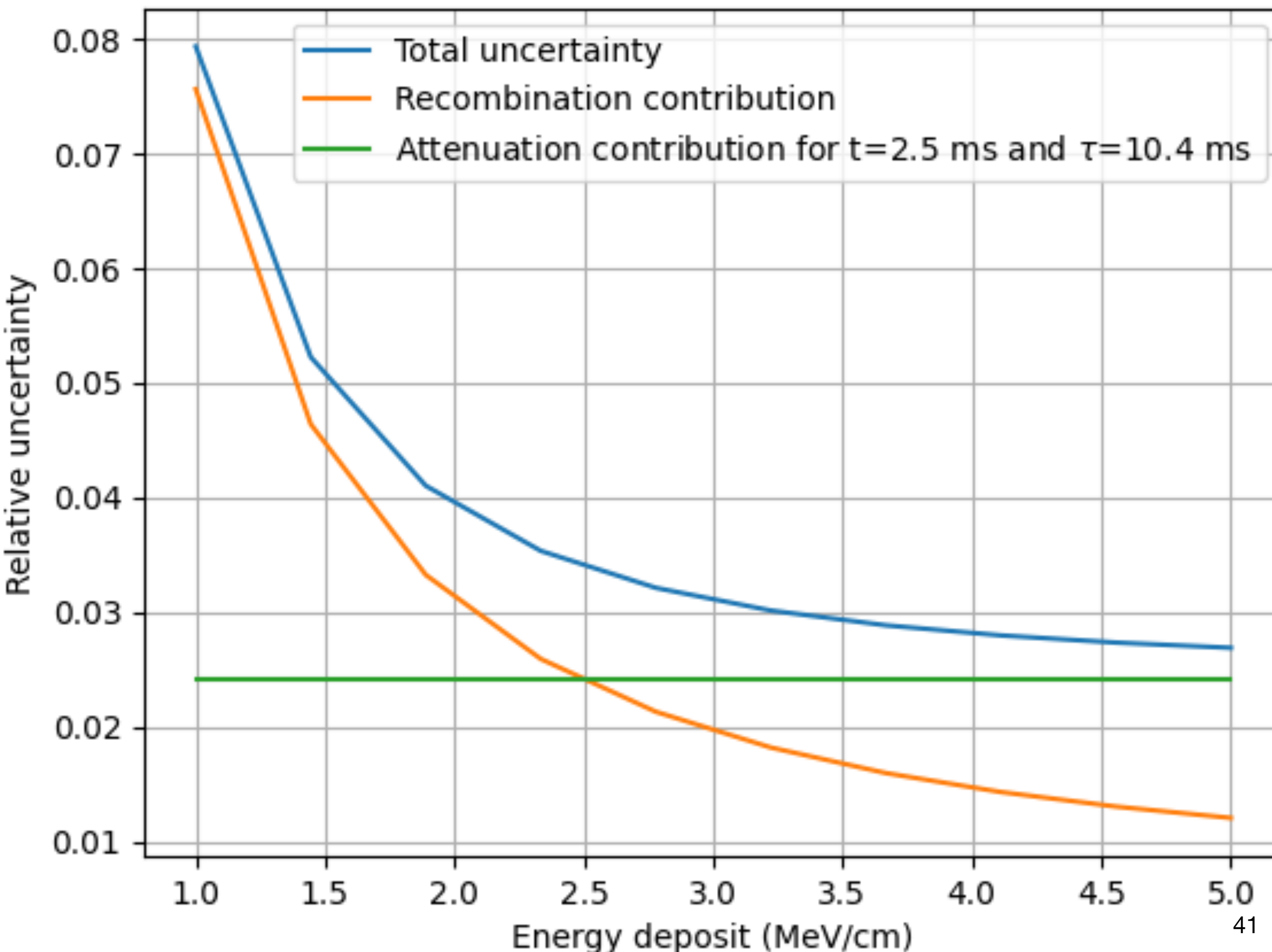
Effects comparison using analytical formulae



Analytical studies

At the hit level, it is easy to estimate the relative importance of the different sources of uncertainty using the analytical formula.

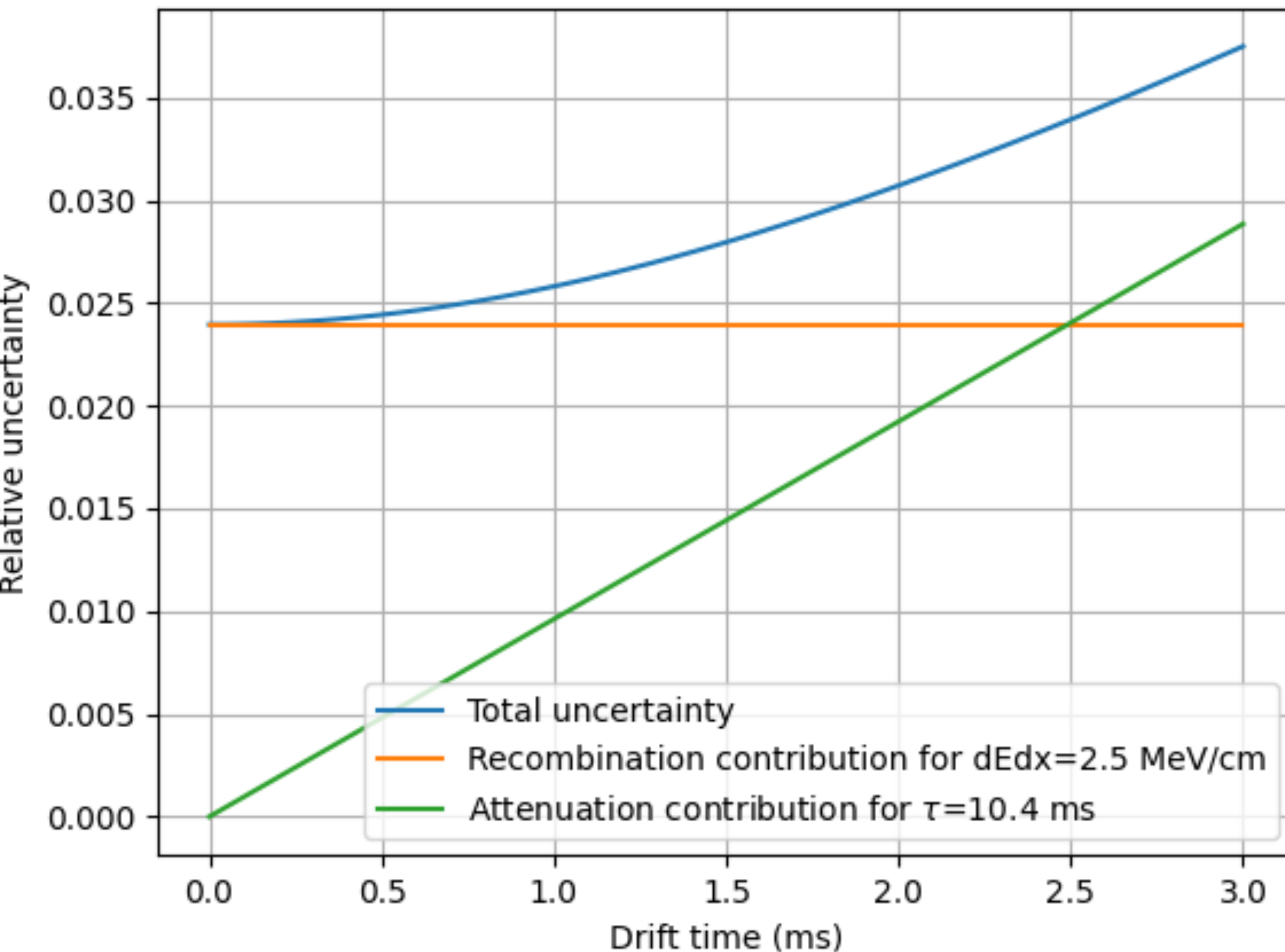
$$Q = \frac{\ln \left(\alpha + \frac{\beta}{\rho \mathcal{E}} \frac{dE}{dx} \right)}{\frac{\beta W}{\rho \mathcal{E}}} \cdot e^{-t/\tau}$$



- α and β completely anti-correlated
- Drift time: 2.5 ms
- Conservative uncertainties
- Ignoring drift field uncertainty

Recombination uncertainty dominates for low energy deposits (<2.5 MeV/cm)

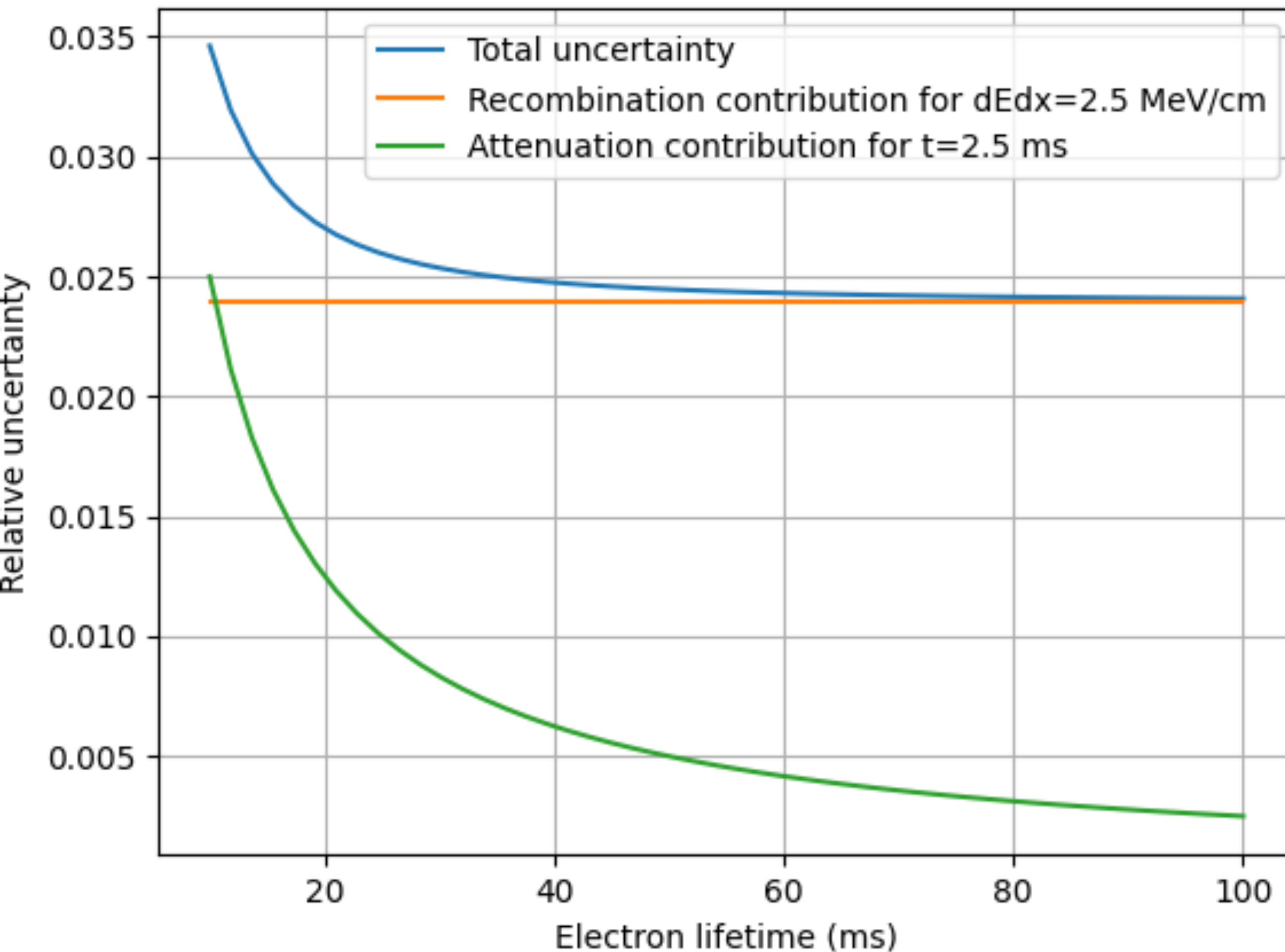
Analytical studies



- α and β completely anti-correlated
- Energy deposit: 2.5 MeV/cm
- Conservative uncertainties
- Ignoring drift field uncertainty

Recombination uncertainty dominates excepts for maximum drift time (small fraction of hits?)

Analytical studies



- α and β completely anti-correlated
- Energy deposit: 2.5 MeV/cm
- Drift time: 2.5 ms
- Conservative uncertainties
- Ignoring drift field uncertainty

For larger lifetimes (>50 ms),
attenuation uncertainty could be totally
ignored.

Impact of drift field



Energy scale

Drift velocity in wirecell



Drift velocity in wirecell needs to be changed in two places:

1. drift stage:

- Calculate new drift velocity using $v(\mathcal{E}) = \mu(\mathcal{E}) * \mathcal{E}$
- use “`physics.producers.tpcrawdecoder.wcls_main.structs.driftSpeed: NEWVALUE`” in fcl file (successfully tested)
- Expect linearity between drift velocity and energy scale: can be merged with other linear effects?

2. detector response simulation:

- Can be done by changing sampling rate: assuming $v(\mathcal{E}) \propto \sqrt{\mathcal{E}}$, 2% variation of drift field = 1% variation of velocity = can be simulated by a 1% variation of sampling rate

Drift velocity

Approximations

$$v = \mu(\mathcal{E}) \cdot \mathcal{E} = \frac{a_0 + a_1 \mathcal{E} + a_2 \mathcal{E}^{3/2} + a_4 \mathcal{E}^{5/2}}{1 + a_1/a_0 \mathcal{E} + a_4 \mathcal{E}^2 + a_5 \mathcal{E}^3} \cdot \mathcal{E}$$

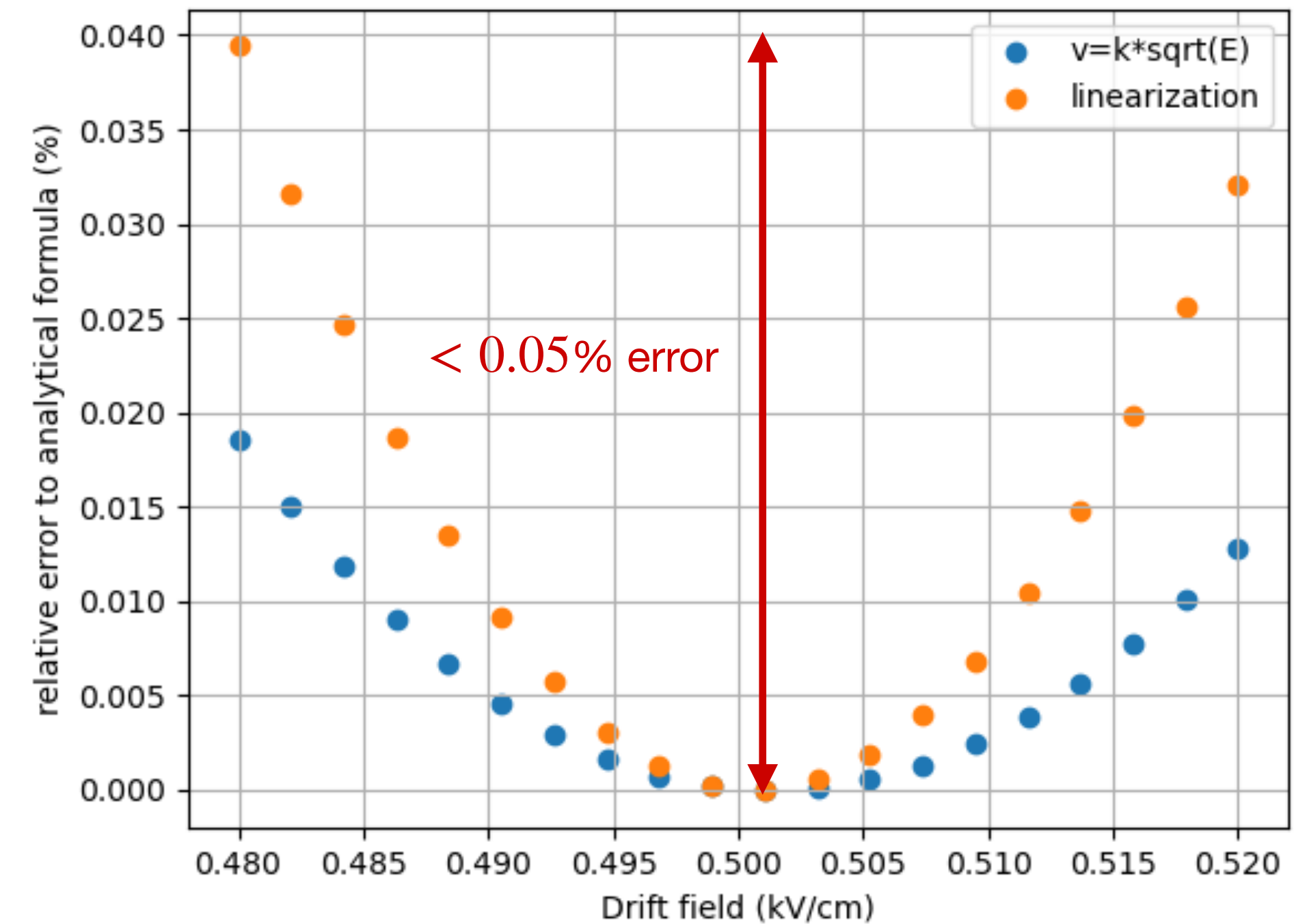
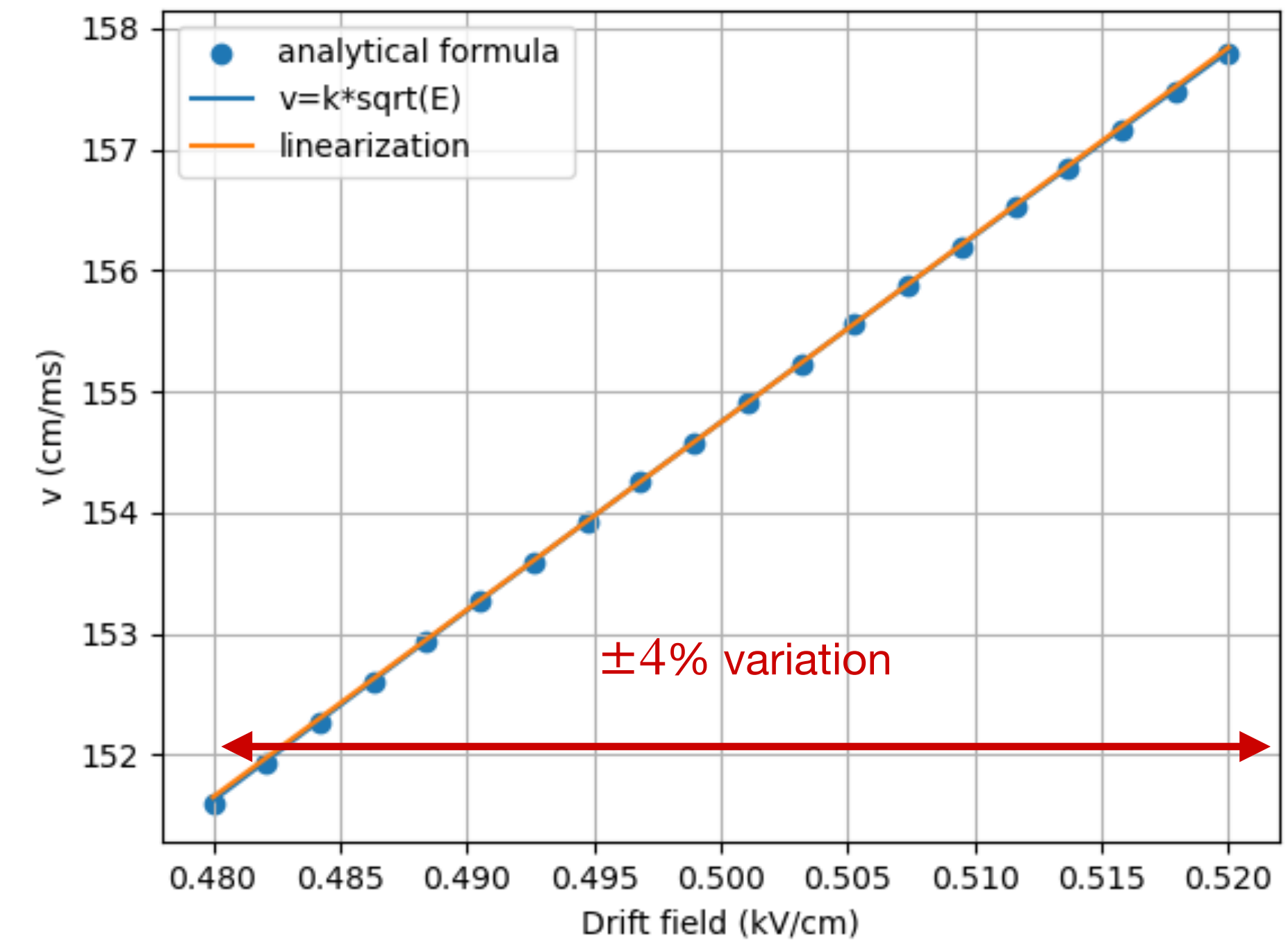
Analytical formula taken from: <https://lar.bnl.gov/properties/trans.html>

$$v \approx k \cdot \sqrt{\mathcal{E}} = \frac{a_0 \sqrt{\mathcal{E}_0} + a_1 \mathcal{E}_0^{3/2} + a_2 \mathcal{E}_0^2 + a_4 \mathcal{E}_0^3}{1 + a_1/a_0 \mathcal{E}_0 + a_4 \mathcal{E}_0^2 + a_5 \mathcal{E}_0^3} \cdot \sqrt{\mathcal{E}}$$

SQRT approximation with $\mathcal{E}_0 = 0.5$ kV/cm

$$v \approx k \cdot \sqrt{\mathcal{E}_0} + \frac{k}{2\sqrt{\mathcal{E}_0}} (\mathcal{E} - \mathcal{E}_0)$$

Linear approximation with $\mathcal{E}_0 = 0.5$ kV/cm



Impact of drift field

Recombination

$$\frac{dQ_r}{dx} = \frac{\ln \left(\frac{B}{\rho(T)} \frac{dE}{dx} + \alpha \right)}{\frac{BW}{\rho(T)}} \quad \text{with } B = \frac{\beta}{\mathcal{E}}$$

$$\frac{\sigma_B}{B} = \sqrt{\left(\frac{\sigma_\beta}{\beta} \right)^2 + \left(\frac{\sigma_{\mathcal{E}}}{\mathcal{E}} \right)^2 - 2 \frac{\rho(\mathcal{E}, \beta) \sigma_\beta \sigma_{\mathcal{E}}}{\beta \mathcal{E}}}$$

Impact of \mathcal{E} on attenuation can be absorbed by inflating variations of β : could ignore correlation at least for the conservative scenario.



Impact of drift field Recombination

| Systematic uncertainty | Ideal scenario | Conservative scenraio |
|--|-----------------------|------------------------------|
| Uncertainty on beta ((kV/cm)(g/mL)) | 0.002 | 0.015 |
| Relative uncertainty on beta | 0.9 % | 7.1% |
| Relative uncertainty on field | 1 % | 2 % |
| Relative uncertainty on beta/E | 1.4% | 7.4% |
| Possible variations of beta ((kV/cm)(g/mL)) | +/-0.003 | +/-0.016 |



Impact of drift field Attenuation

$$\epsilon_{att} = e^{-\frac{d}{p\sqrt{\mathcal{E}}\tau}}$$

Varying the electron lifetime

with $v(\mathcal{E}) = p\sqrt{\mathcal{E}}$

See for instance ICARUS results
Journal of Physics Conference Series
888(1):012060

Given the uncertainties foreseen (3%-10% for lifetime, 1%-2% for drift field), impact of drift field on attenuation could be ignored?

$$\frac{\sigma_{\epsilon}}{\epsilon} = \frac{d}{p\sqrt{\mathcal{E}}\tau} \sqrt{\left(\frac{\sigma_{\tau}}{\tau}\right)^2 + \left(\frac{\sigma_{\mathcal{E}}}{2\mathcal{E}}\right)^2 + \frac{\rho(\tau, \mathcal{E})\sigma_{\mathcal{E}}\sigma_{\tau}}{\tau\mathcal{E}}}$$

9e-4 (ideal) - 1e-2 (conservative)
 2.5e-5 (ideal) - 1e-4 (conservative)
 3e-5 (ideal) - 2e-4 (conservative) for 10% correlation

Impact of \mathcal{E} on attenuation can be absorbed by inflating variations of lifetime or dQ/dx

