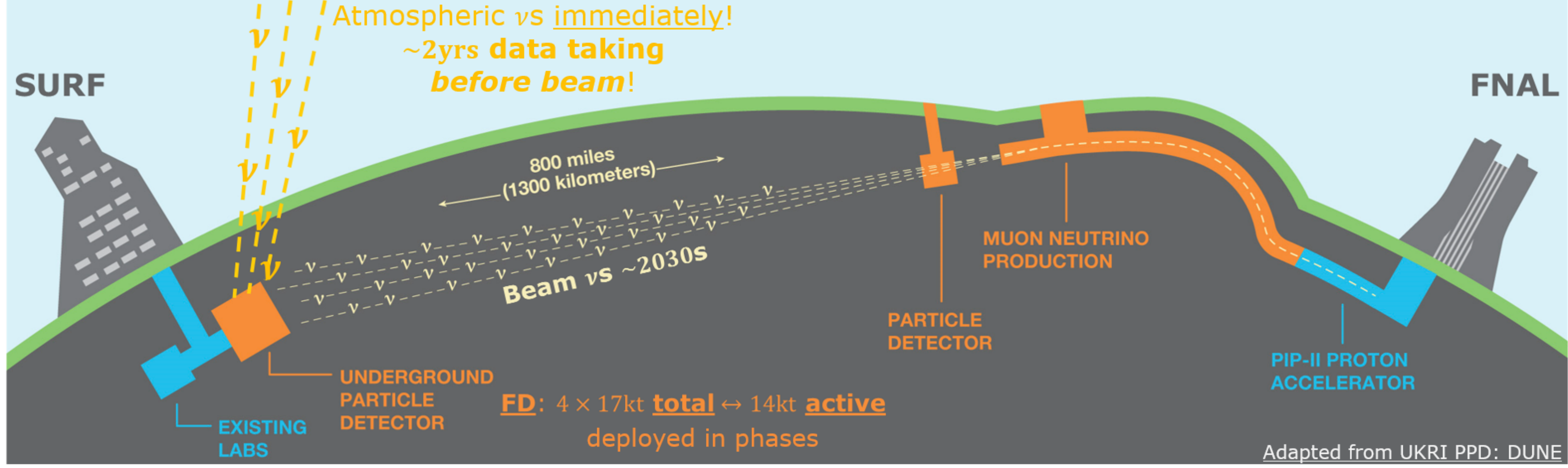
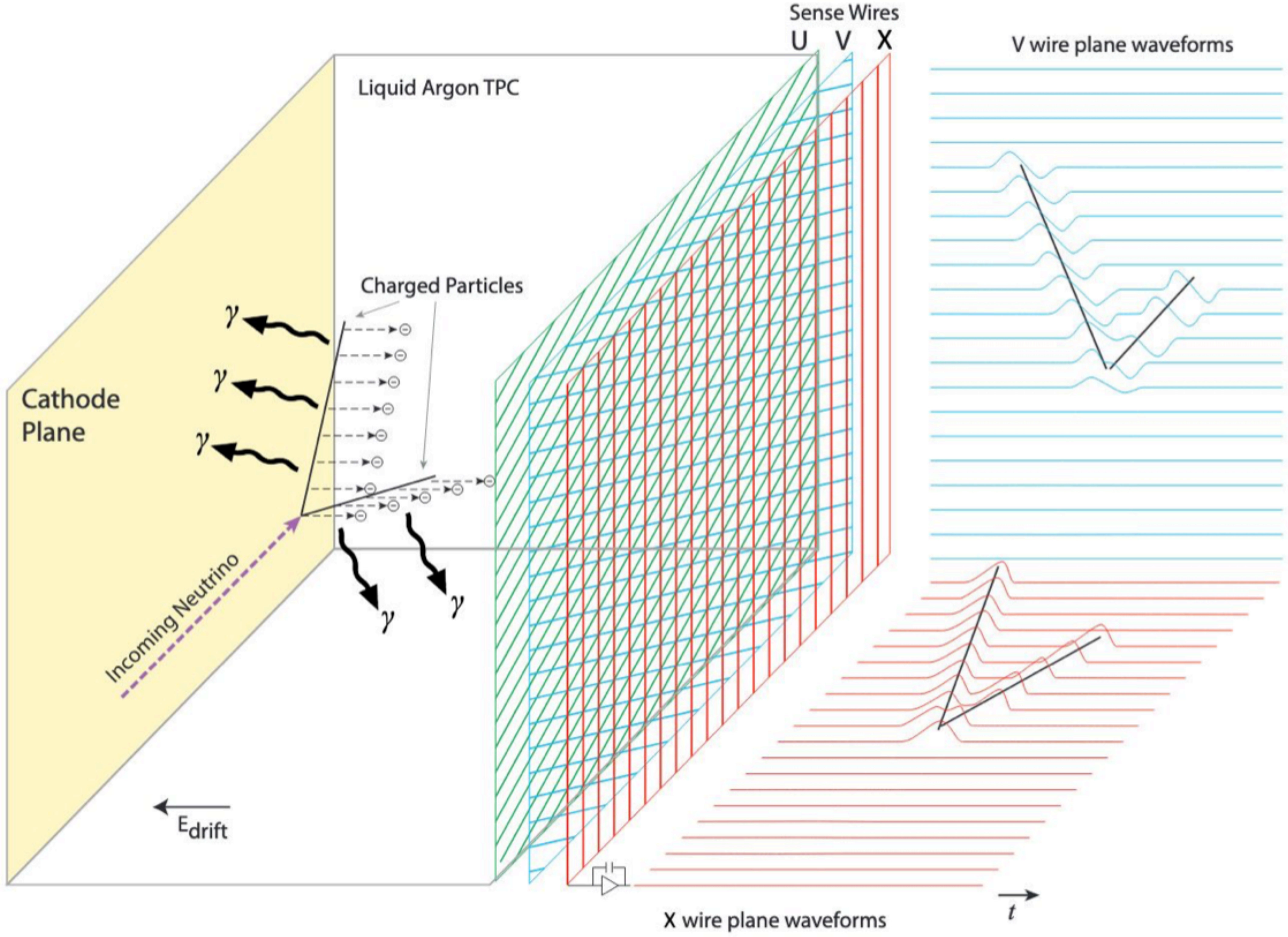
Detector related systematic uncertainties in the DUNE experiment

Claire Dalmazzone, APC, CNRS/IN2P3
dalmazzone@apc.in2p3.fr
IRN Neutrino 1st-2nd June 2026, IJCLab, Orsay, France

Introduction

- Thanks Sabrina for the nice overview!
- DUNE: long-baseline experiment that will perform **neutrino oscillation analysis** with two main sources:
  - Wideband, on-axis, 1.2 MW **accelerator neutrino beam** (Fermilab, 1300 km)
  - **Atmospheric neutrinos**
- With main physics goals to measure **CP violation and Mass Ordering**
- **Far detectors**: four 17kt underground modules of **LArTPC**

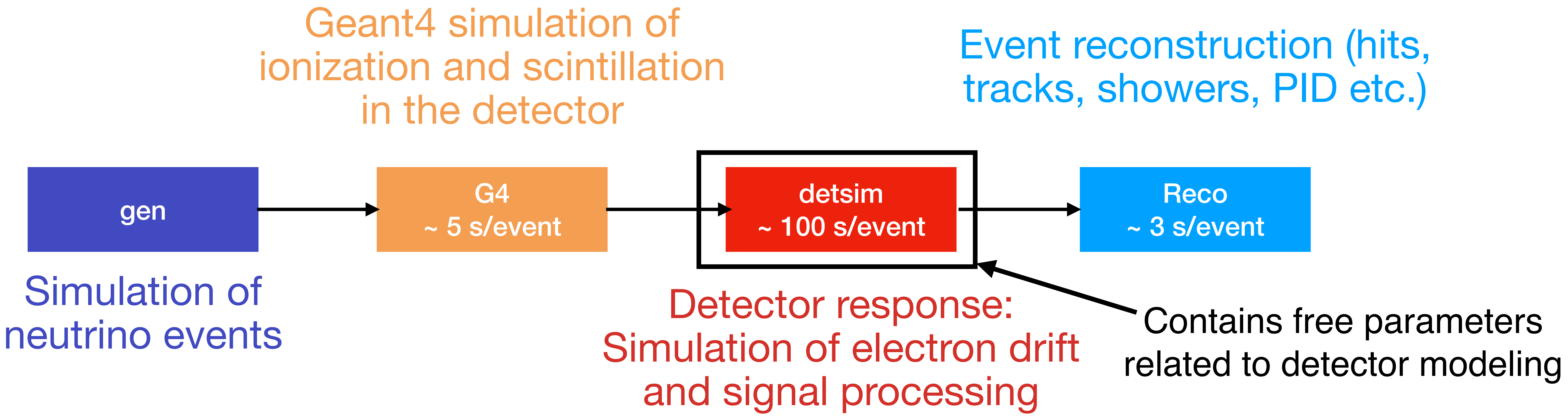




Schematic representation of the Horizontal Drift Far Detector

Introduction

- Today focus on **detector related systematic uncertainties** for atmospheric oscillation analysis
- These can be estimated by looking at the impact of **varying detector model related parameters in the simulation** on the analysis observables



What detector effects?

- First step is to identify the **main sources of uncertainty** in the detector model:
    - **Recombination** of electrons with their parent ions
    - **Electron attenuation** due to attachment to electronegative impurities during drift: potential strong time/space fluctuations, requires careful monitoring (purity monitors)

$$Q_{\text{att}} = Q_0 e^{-t_D/\tau}$$

t_D: drift time
τ: electron lifetime

ProtoDUNE purity monitors* demonstrated a monitoring of the value of τ at the <5% level

*JINST (2025) 20 P09008

What detector effects?

- First step is to identify the **main sources of uncertainty** in the detector model:
  - **Recombination** of electrons with their parent ions
  - **Electron attenuation** Today's focus
  - **Diffusion**: modify charge spreading across wires (transverse), waveform width (longitudinal): can impact PID*
  - Space Charge Effects
  - Electronics gain

  Should be well under-control in DUNE
  - Etc.

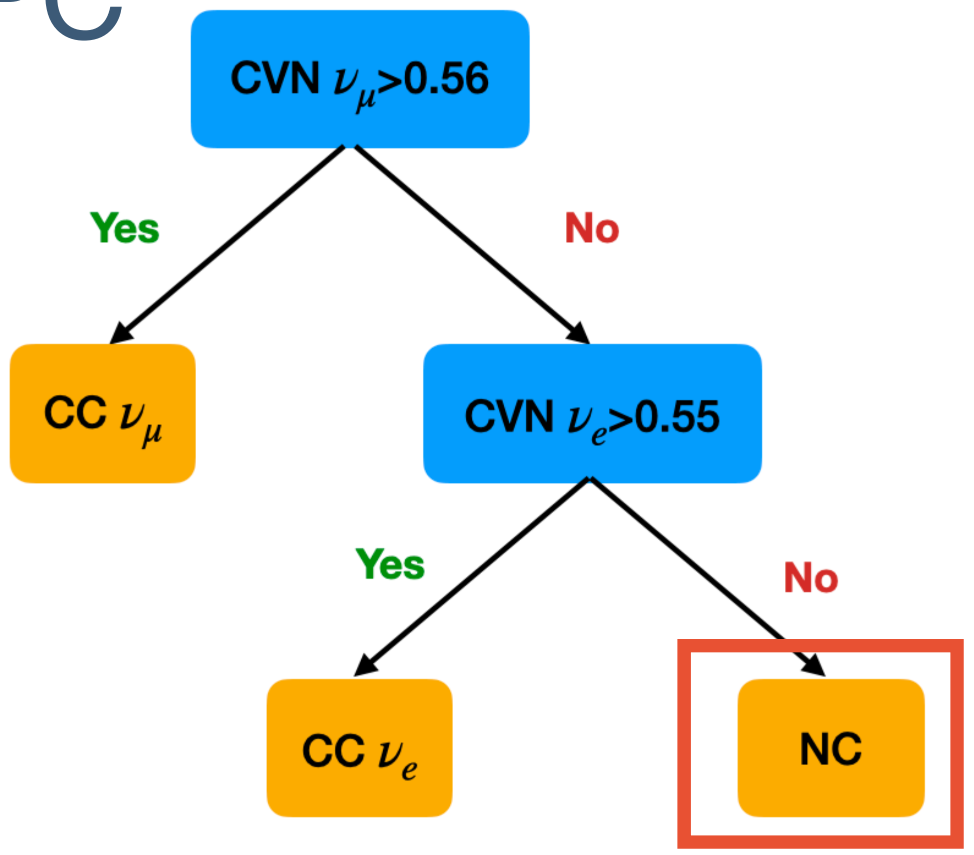
A. Lister and M. Stancari 2022 JINST **17 P07016*

Impact on analysis

Varying the value of a detector parameter can impact: **event classification** (CC ν_μ, CC ν_e or NC) via the CVN scores and **reconstructed neutrino energy**.

The CVNs

- Stands for Convolutional Visual Network (ResNet CNN)
- Applies neutrino flavour identification score to entire LArTPC image



Atmospheric classification based on scores from CVN ν_μ and CVN ν_e

Not used in DUNE atm OA

Energy reconstruction

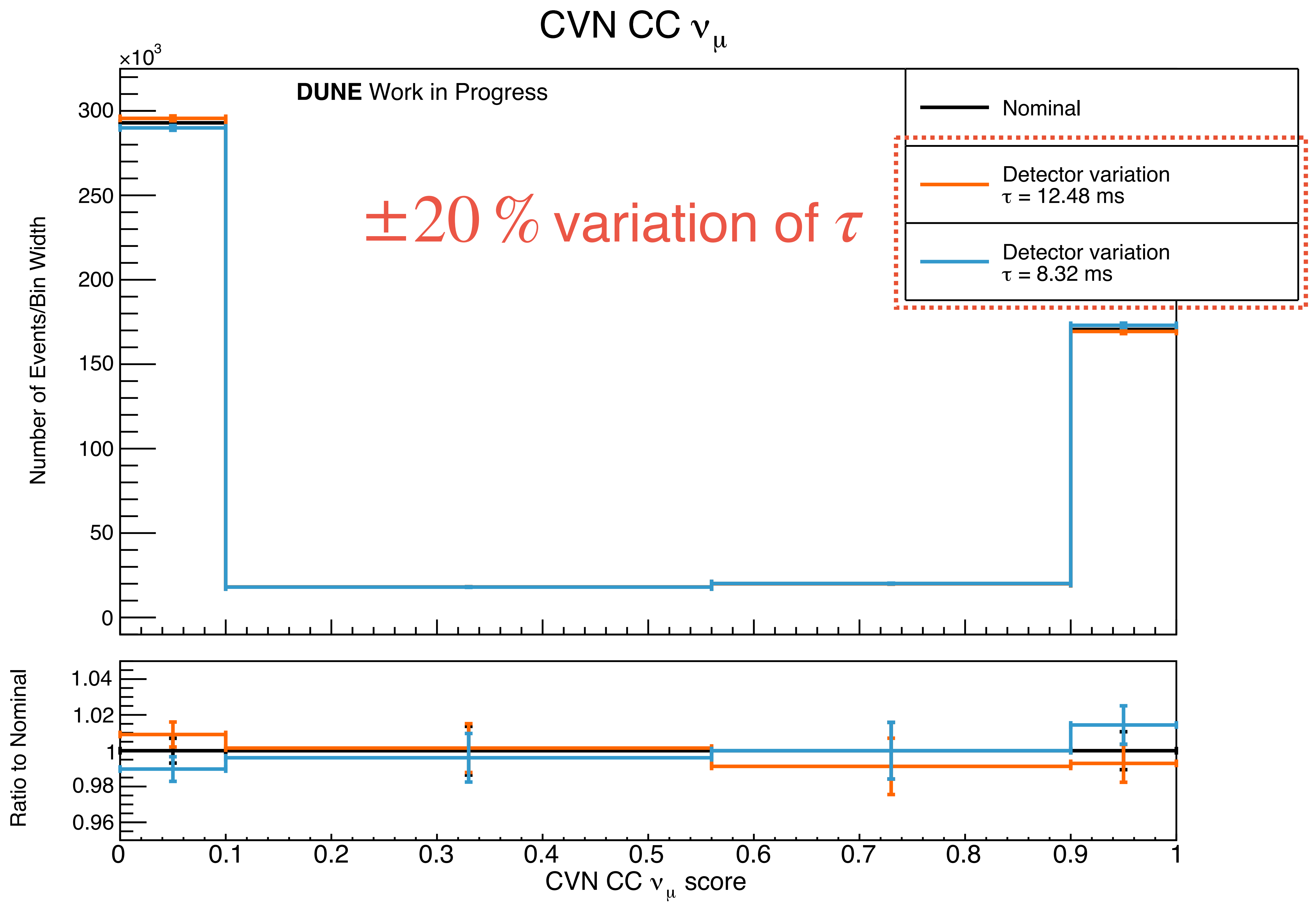
Depends on interaction type:

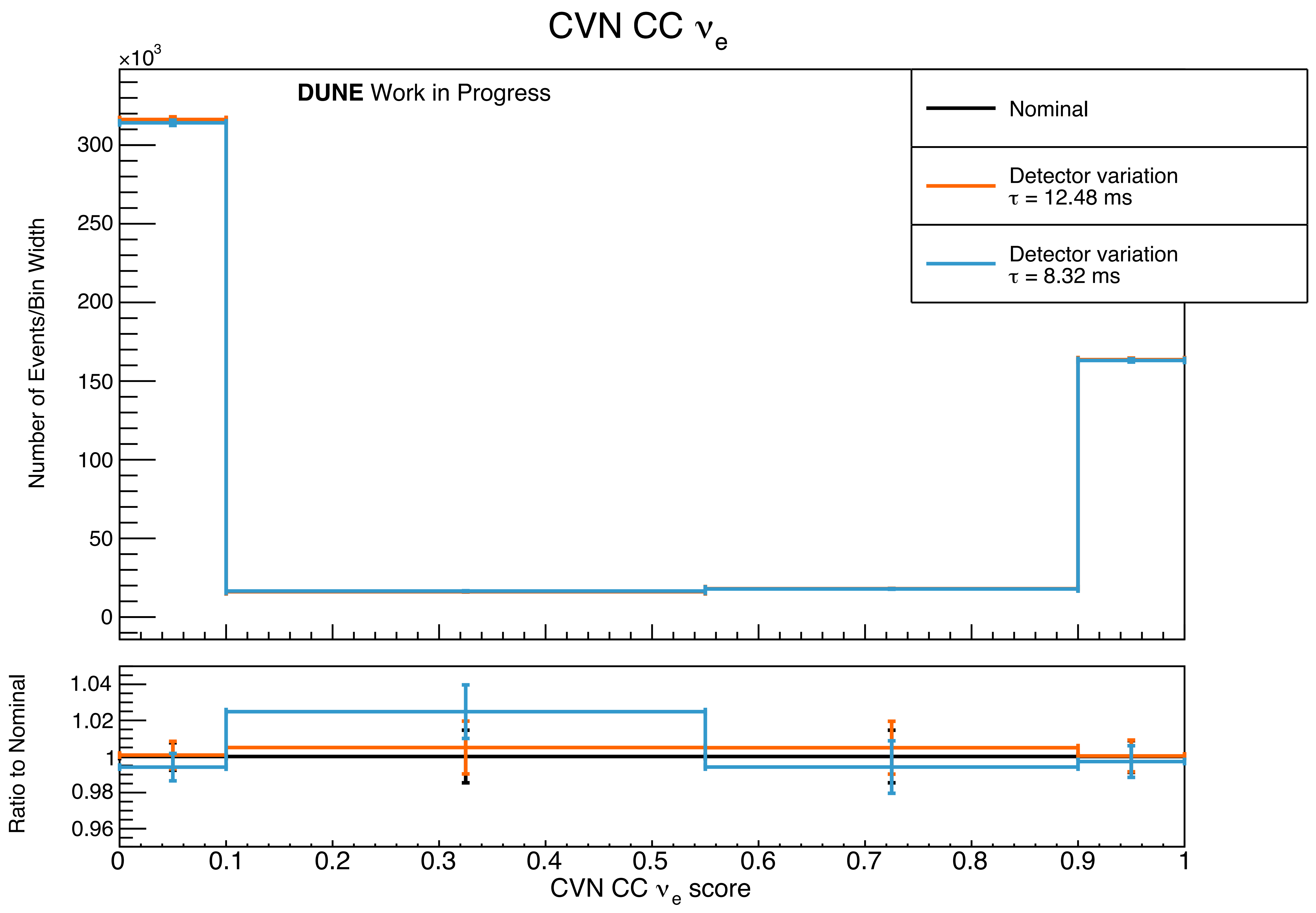
- NC: all hits calorimetry
- CC: main shower electromagnetic calorimetry (ν_e) or main track properties (ν_μ) + remaining hits calorimetry

Impact on analysis

**Horizontal Drift Far Detector*

- ~150 000 event sample of atmospheric neutrino events in HD-FD* reduced geometry
- Expect impact on the number of selected event per interaction type: especially for CC ν_μ





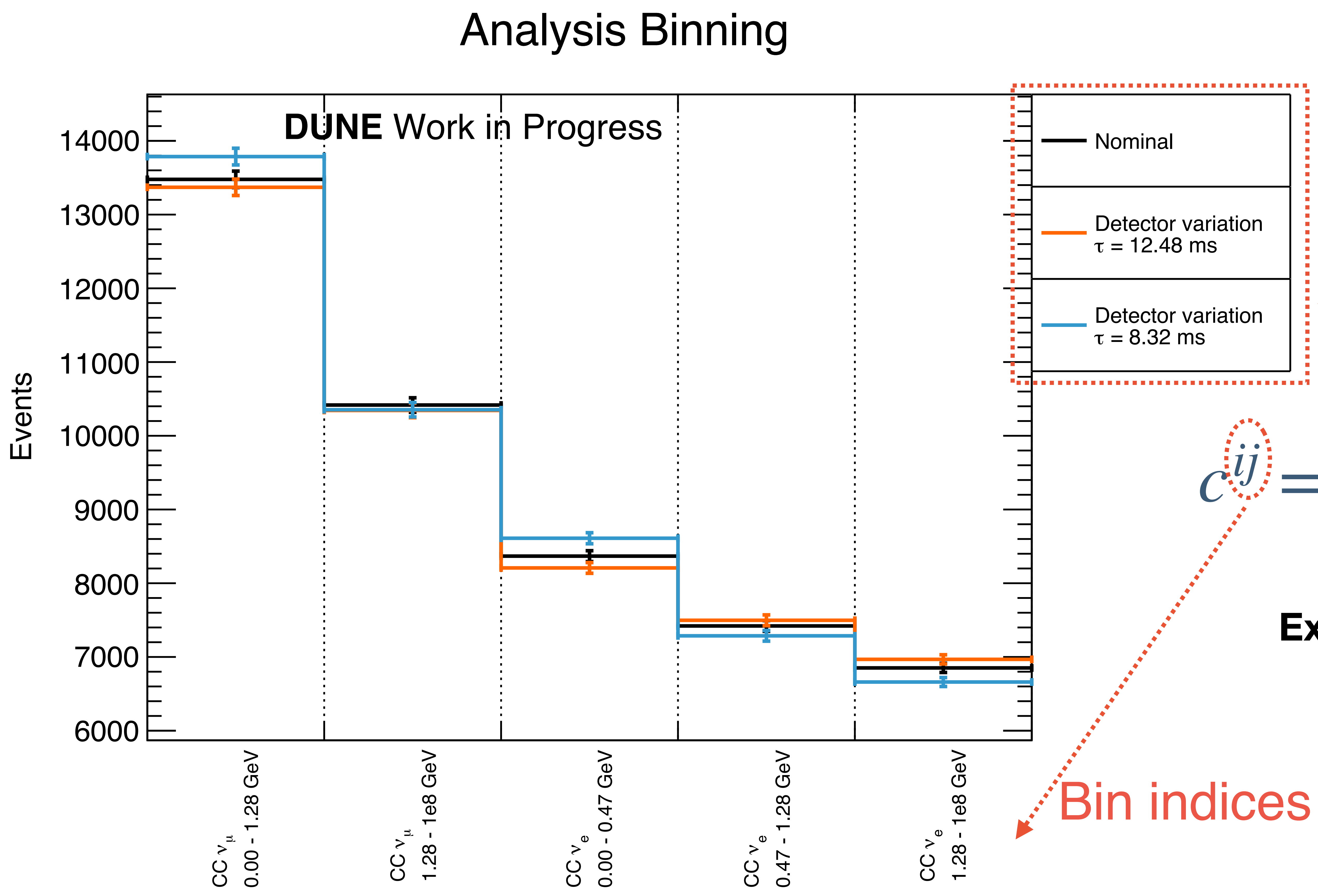
Impact on analysis

Strong shape effect on the reconstructed neutrino energy, especially for CC ν_e events

Covariance matrix

Build **covariance matrix** of number of events per bin as input for the OA fitters

NB: Arbitrary binning for illustration purposes, final binning will be based on sensitivity studies.



NB: $\sqrt{c^{ii}}$ is the related systematic uncertainty on number of events in bin i

$$c^{ij} = \frac{1}{N_{samples}} \Sigma_{s \in samples} (N_s^i - N_{nom}^i) \times (N_s^j - N_{nom}^j)$$

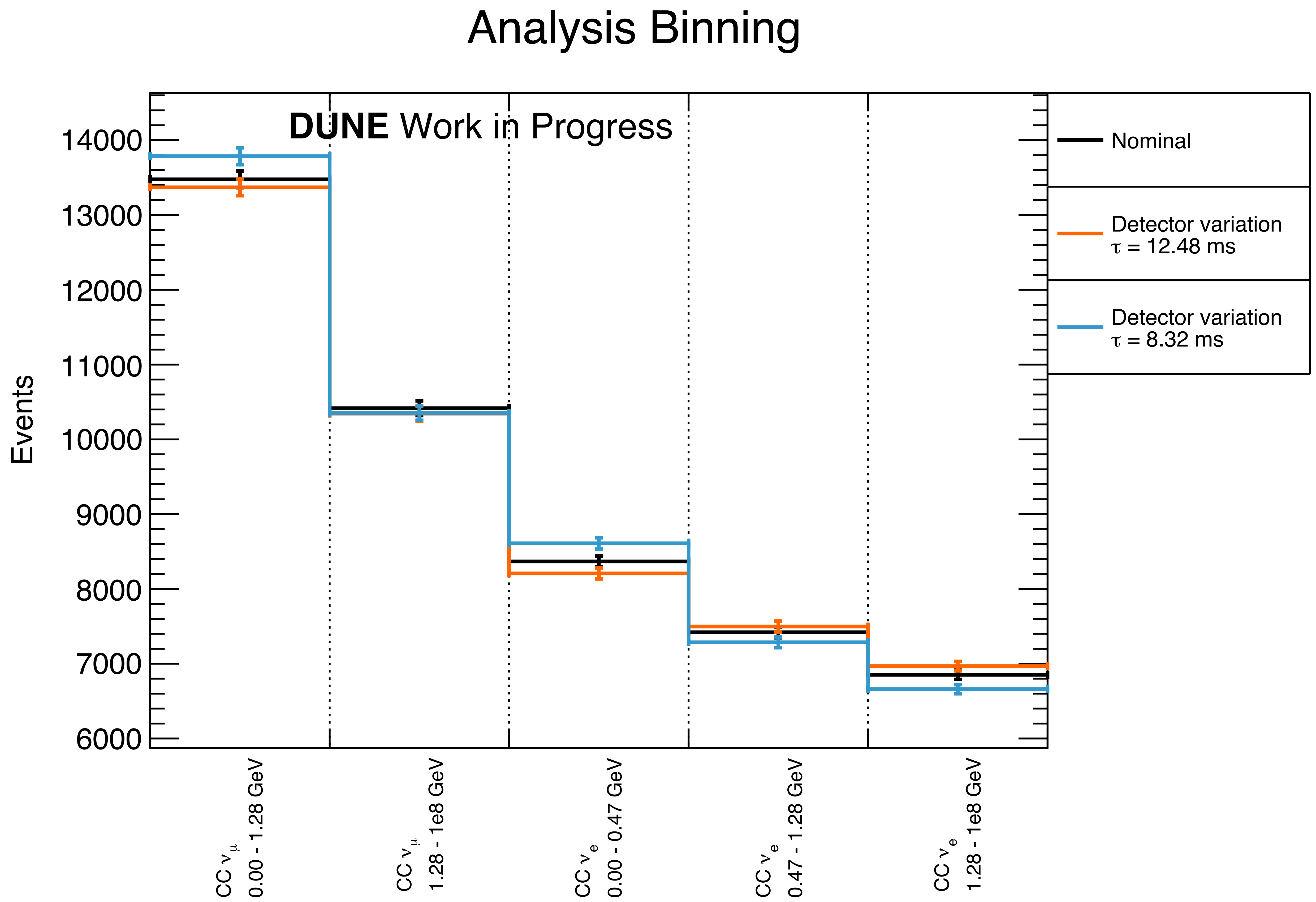
Bin indices

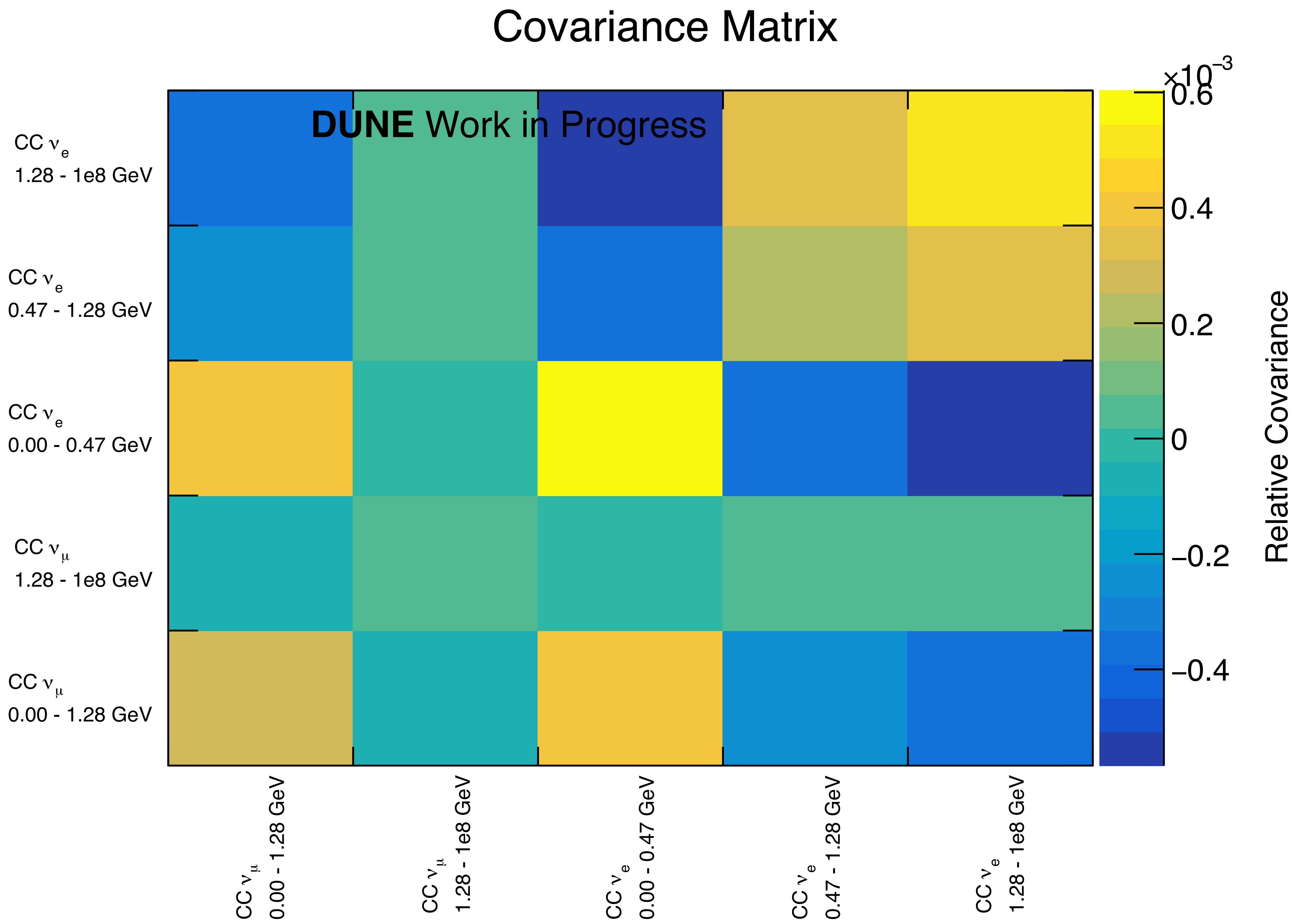
Expression of the covariance for the bin ij (uses variation of bin content from bins i and j)

Covariance matrix

Build **covariance matrix** of number of events per bin as input for the OA fitters

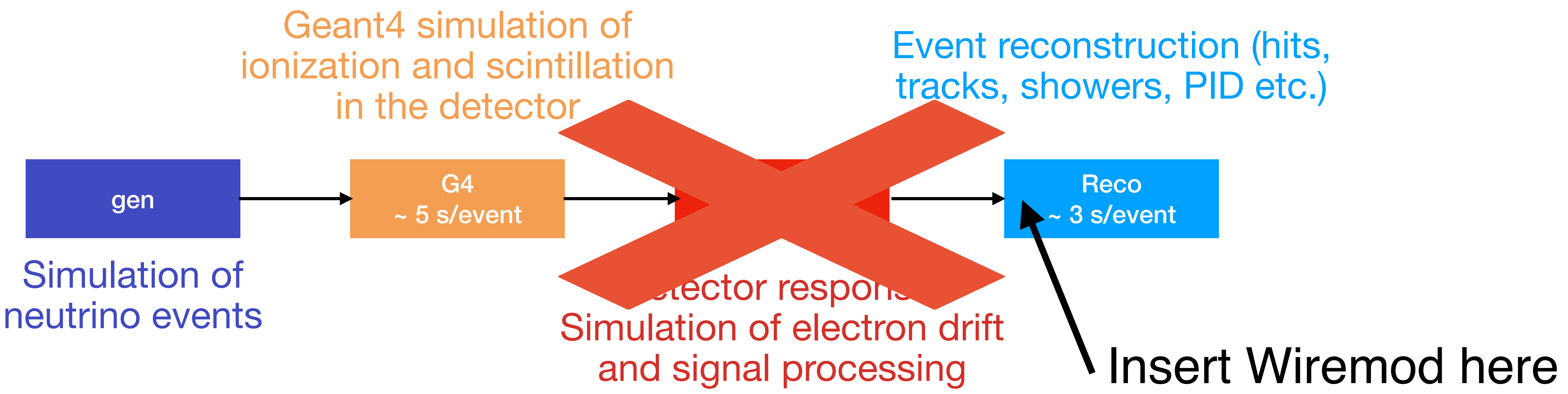
NB: Arbitrary binning for illustration purposes, final binning will be based on sensitivity studies.





Wiremod: a less CPU-consuming method

- Detector variation simple but **CPU-consuming**: detsim takes ~**100 s/event**
- Most effects modify the charge according to an analytical model
- Idea: Use **Wiremod***, a tool developed by MicroBooNE to **rescale the waveforms** for estimation of detector systematics based on data vs MC comparisons
- Implementation for DUNE with an **analytical rescaling of simulated waveforms**

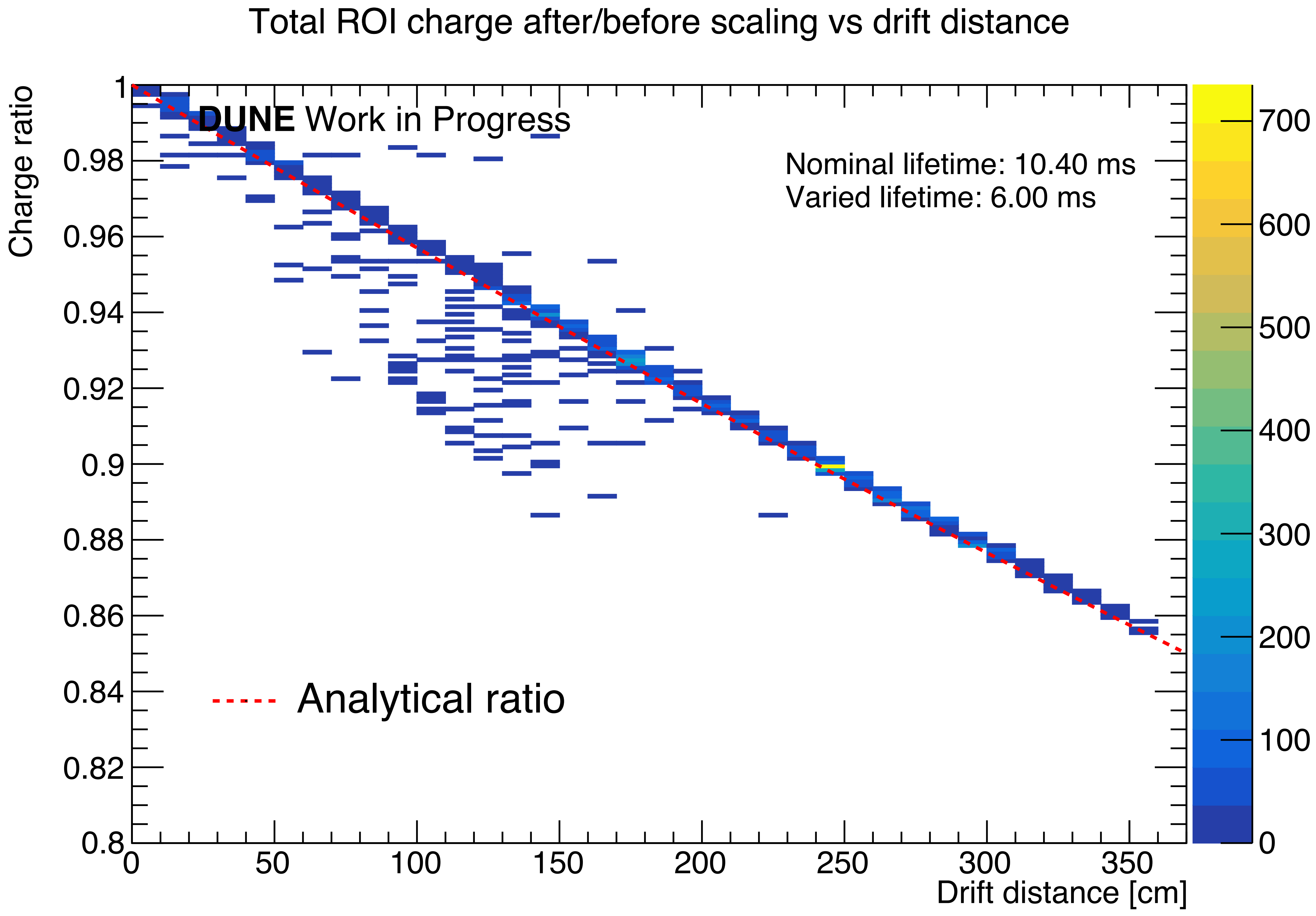


* *Eur. Phys. J. C 82, 454 (2022)*

Wiremod

*ROI: Region of Interest = regions of activity on wires

- The **simulated energy deposits are matched to the ROI*** on each wire
- The properties of these energy deposits (energy, position etc.) are used to **estimate « truth properties »** associated to an ROI
- The **waveform** of an ROI is **rescaled (amplitude, width) analytically** based on its « truth properties »
  - **Drift distance** for attenuation rescaling



Total charge of the ROIs after wiremod rescaling divided by original charge for a variation corresponding to $\tau' = 6$ ms (nominal value is 10.4 ms)

NB: Outliers due to inefficiencies in matching to simulated energy deposits, under investigation

Wiremod

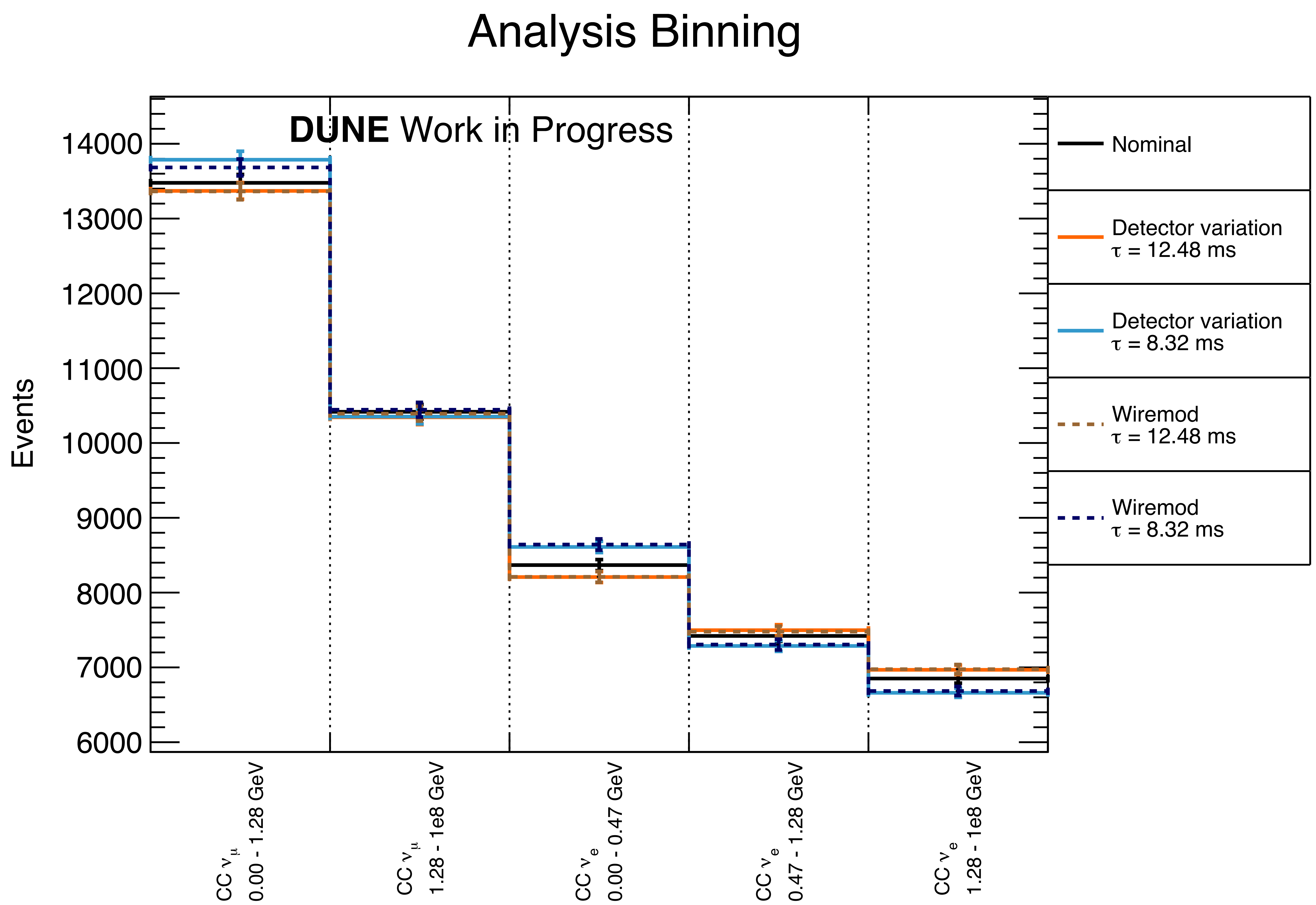
- **Wiremod** takes from **0.001 to ~35 s** of CPU-Time per event
- No need to run detsim simulation stage which takes on average ~100 s of CPU-Time per event
- **In total the new method is > 10 times faster!**
- But is it equivalent to a real detector variation?

DUNE Work In Progress Stage	Detector variation	Wiremod
Detsim	101.4 s	X
Reco1	0.1 s	4.8 s
Reco2	3.0 s	3.2 s
Sum	104.5 s	8 s

Average CPU-Time of each simulation stage in case of a detector variation or wiremod variation. For wiremod, the reco1 stage is slightly longer but this is largely compensated by the drop of the detsim stage.

Wiremod

- Same ~150,000 events sample as before with additional **wiremod variations** of electron lifetime
- Small discrepancies in CC ν_μ under investigation
- **Stay tuned** for final results and other variations (recombination, diffusion etc.)!



Conclusions

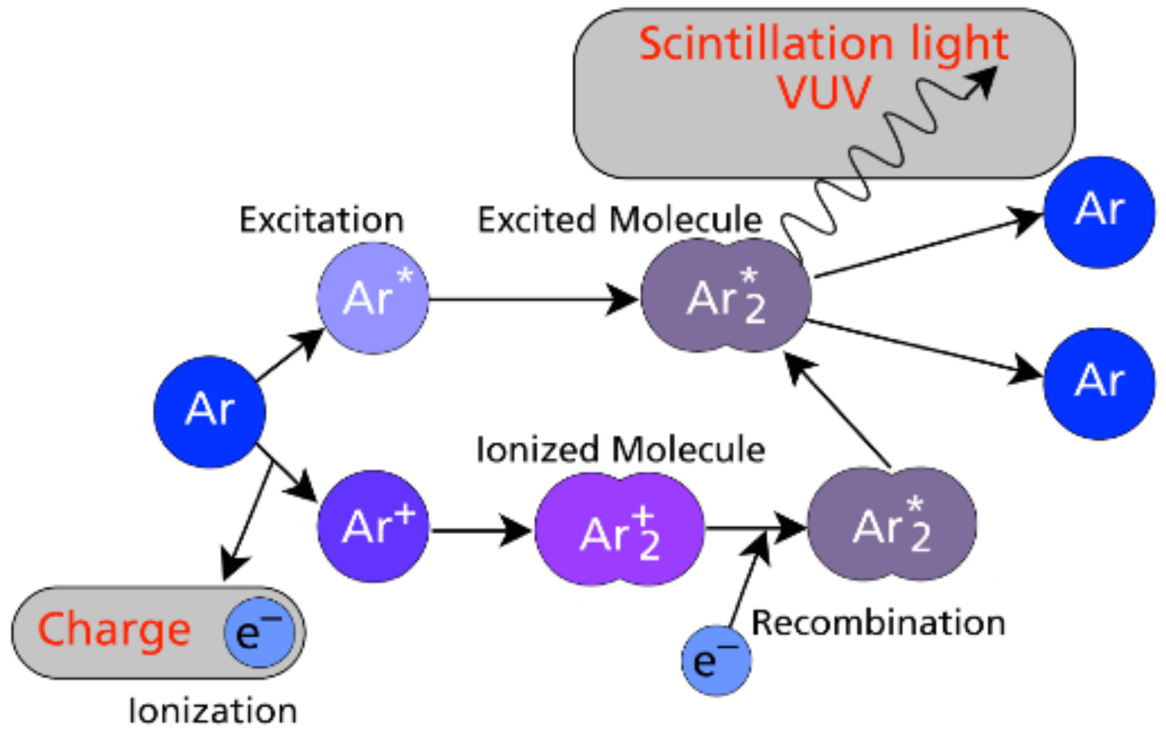
- DUNE has **strong physics potential** (CP violation, Mass Ordering), making **reliable detector systematic uncertainty modeling** essential for **large-scale LArTPCs**
- Presented **two methods** to estimate uncertainties in atmospherics OA:
  - Classic **detector variation**: partial re-processing of simulation with varied value of a detector model related parameter
  - **Wiremod**: a **less CPU-Time consuming** method consisting in analytically rescaling the simulated waveforms. Only reconstruction needs to be re-run
- First results with electron lifetime variation are encouraging, **stay tuned!**
- Next steps: **larger statistics** production with **realistic variations** + apply methods to other analyses (e.g., accelerator neutrinos)

Thank you!

What detector effects?

- First step is to identify the main sources of uncertainty in the detector model:
    - Recombination of electrons with their parent ions, simulated with the Modified Box model: energy scale highly sensitive to the value of A

$$\frac{dQ}{dx} = \frac{\ln\left(A + \frac{B}{\rho\mathscr{E}}\frac{dE}{dx}\right)}{\frac{BW}{\rho\mathscr{E}}\frac{dE}{dx}}$$



Use ArgoNEUT* measurements of $A = 0.93 \pm 0.02$ and $B = 0.212 \pm 0.002$ (g.kV)/(MeV.cm^2)

* *R Acciarri et al 2013 JINST* ***8*** *P08005*

Detector calibration plans

Plan calibration in 3 steps:

1. Position based (drift velocity, E-field etc.)
   - Using frequent laser data (ionization and photo-electric lasers)
   - Cross-check with cosmic
2. Charge based (detector response, lifetime, diffusion etc.)
   - Laser data
   - Cross checks with cosmic, ^{39}Ar radioactive source and purity monitors
3. Recombination
   - Stopping muons and protons
   - Cross check with laser data

Detector systematics in TDR*

In TDR sensitivity studies, energy scales modeled as

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

Table 5.9: Uncertainties applied to the energy response of various particles. p_0, p_1, and p_2 correspond to the constant, square root, and inverse square root terms in the energy response parameterization given in Equation 5.12. All are treated as uncorrelated between the ND and FD.

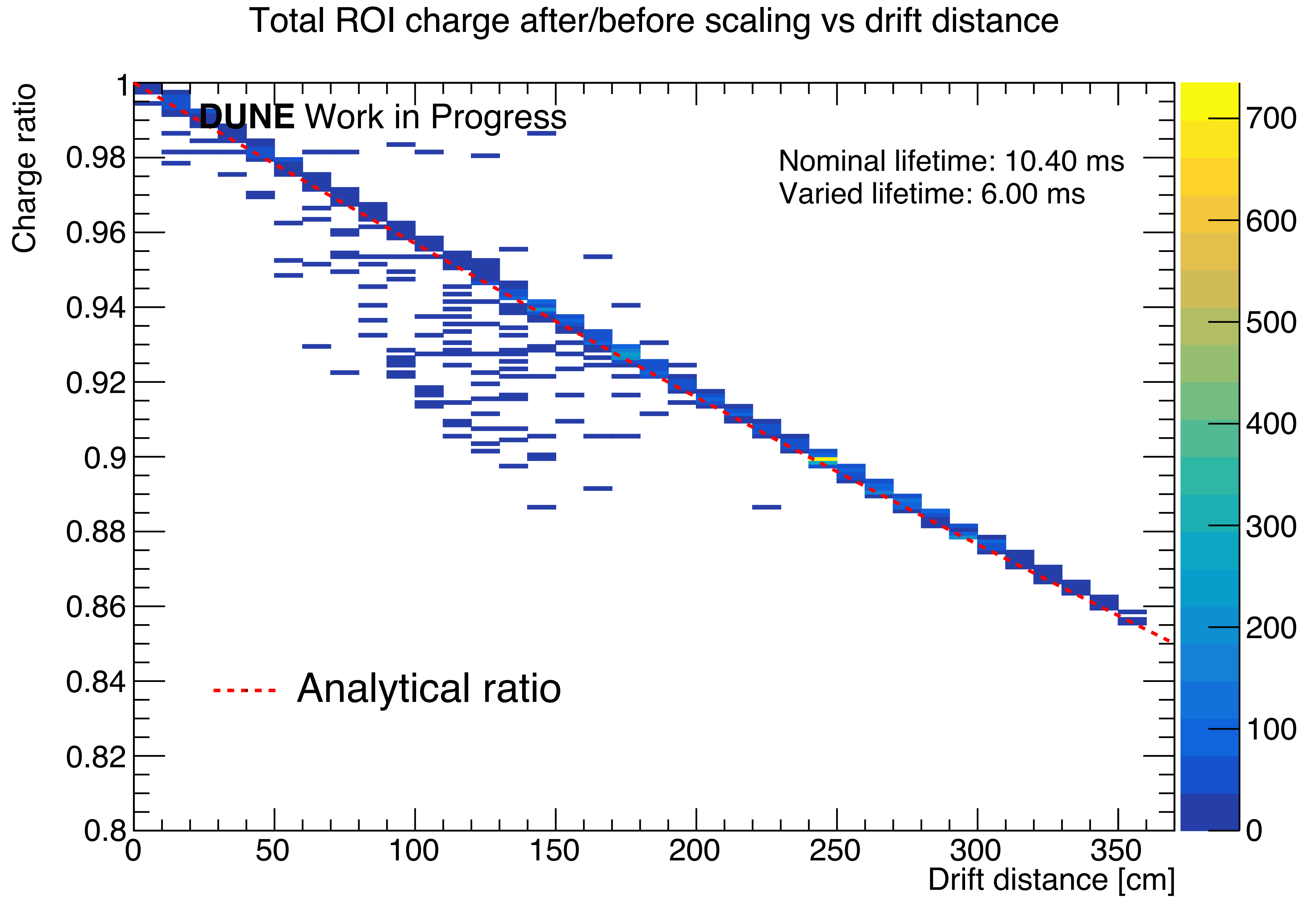
Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

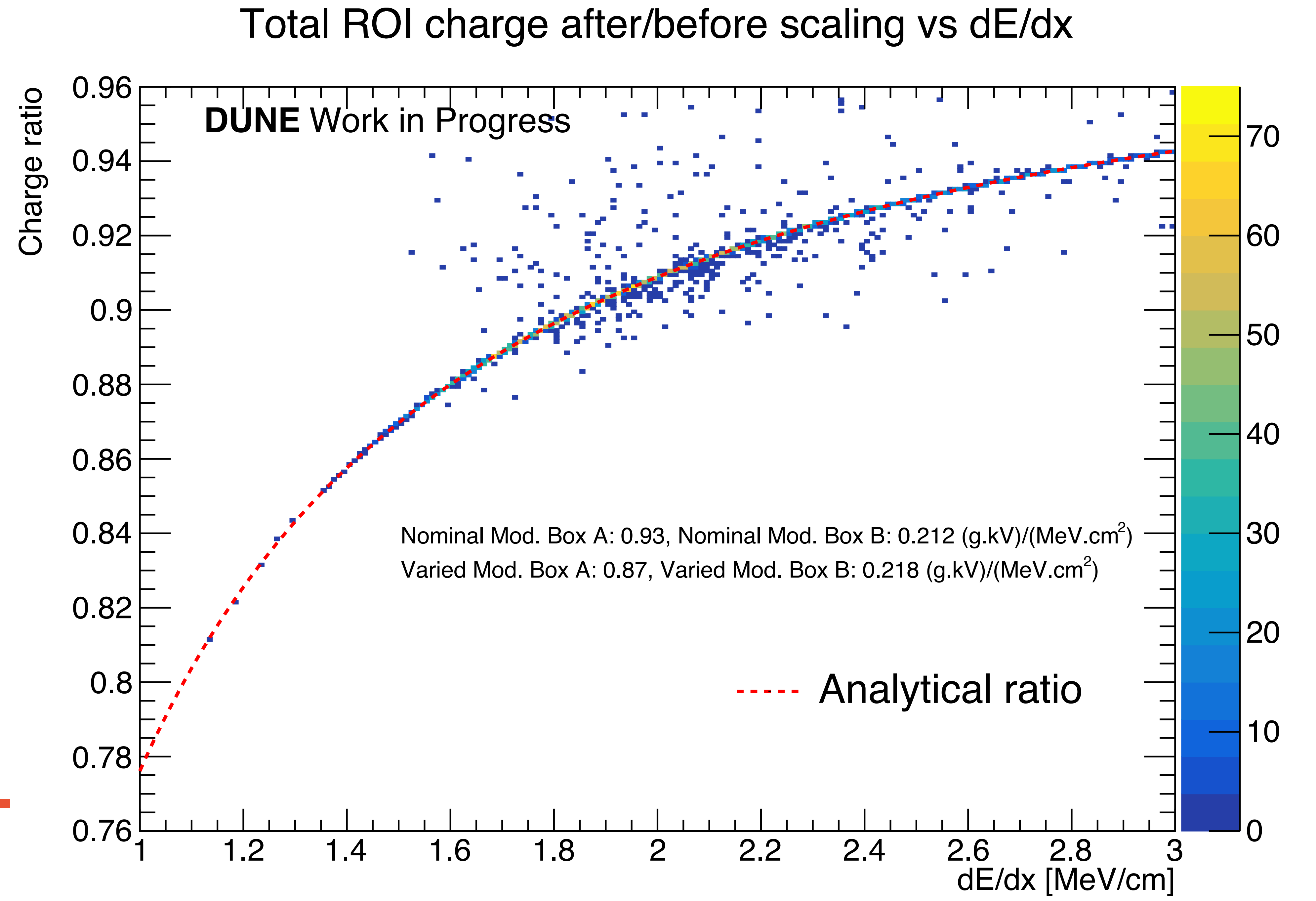
Uncertainties on the free parameters derived from recent experiments

* *https://doi.org/10.48550/arXiv.2002.03005*

Wiremod

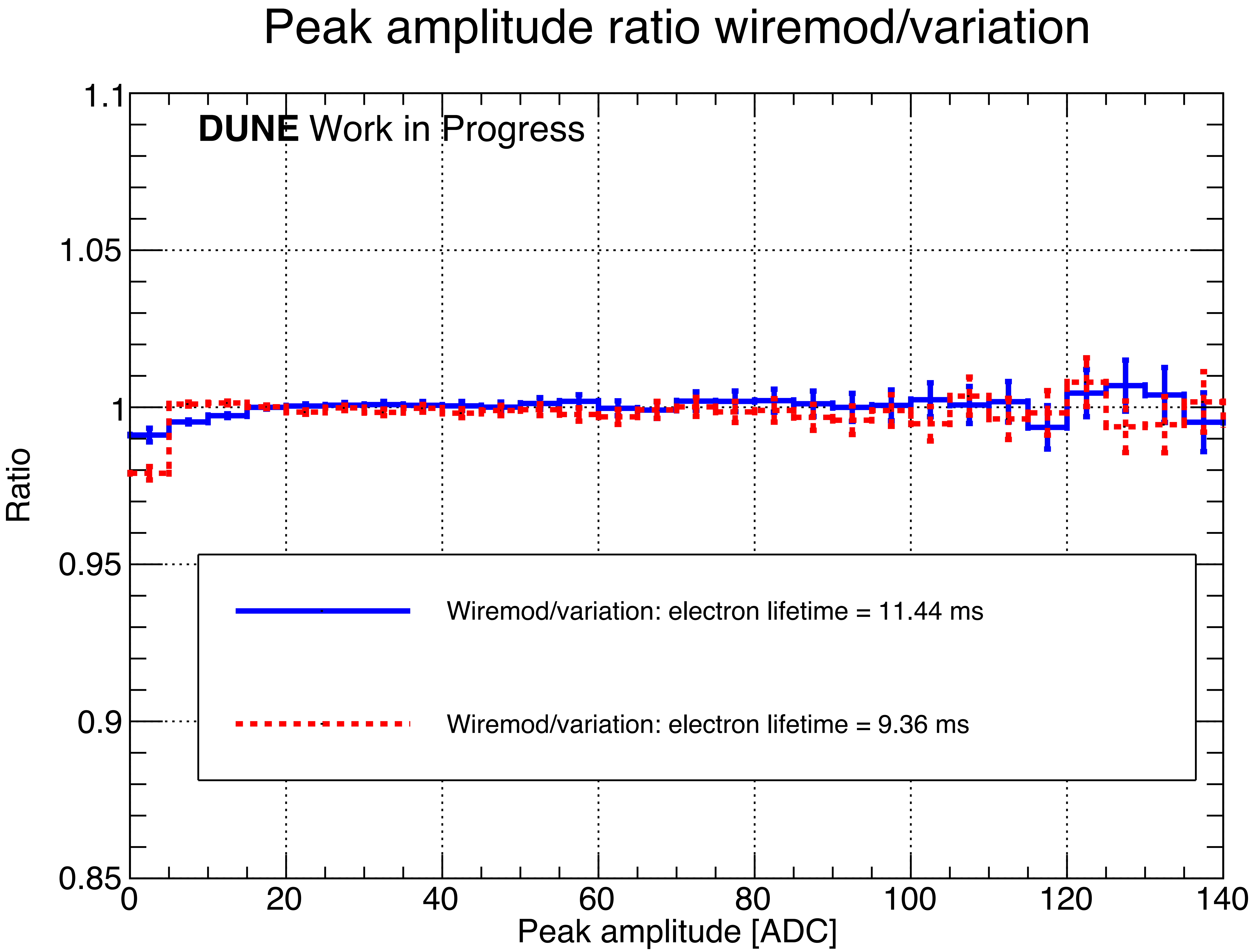
- The simulated energy deposits are matched to the ROI on each wire
- The properties of these energy deposits (energy, position etc.) are used to estimate « truth properties » associated to an ROI
- The waveform of an ROI is rescaled (amplitude, width) analytically based on its « truth properties »
  - Drift distance for attenuation rescaling
  - $\frac{dE}{dx}$ for recombination rescaling





Wiremod

- ~20,000 events samples of atmospheric neutrino events in HD-FD
- Electron lifetime $\pm 10\,\%$ variation
- Look at **Hits peak amplitude distributions**: ratio of distributions wiremod/detector variation
- Ratio consistent with 1, except at very low amplitude (<15 ADC)



NB: We believe discrepancy is also linked to inefficiencies in matching simulated energy deposits

Wiremod

- Outliers are caused by inefficiencies in matching to simulated energy deposits. This leads to
  - Bias in estimation of true properties (x-axis)
  - Non-rescaling of part of the waveform (y-axis bias)
- Efficiency drops with energy/charge, hence hits peak amplitude discrepancies at lower charge
- Investigating ways to improve matching efficiency