

Reconstruction of atmospheric neutrinos in DUNE's horizontal-drift FD module

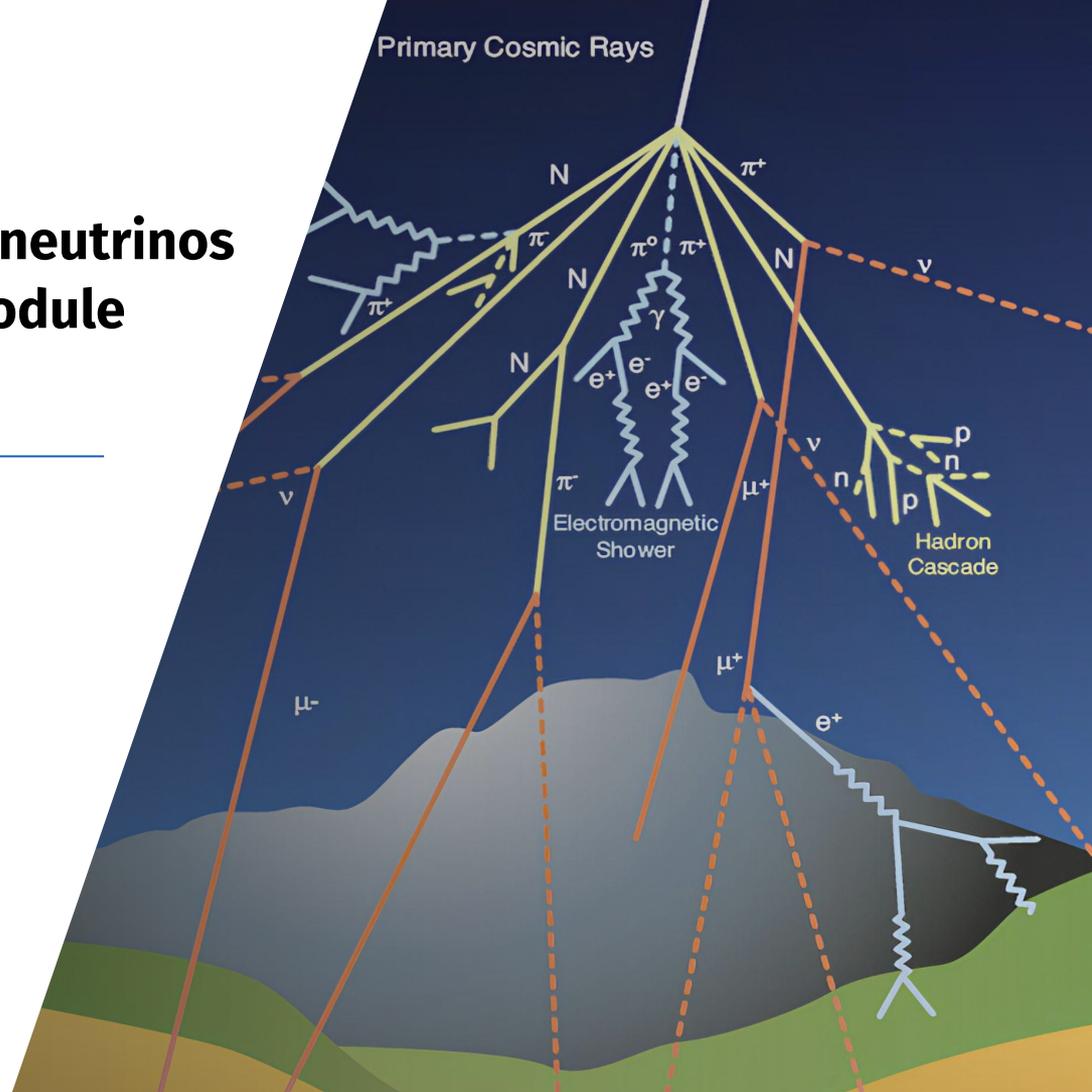
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NPC Journal club



Outline

- **Physics context**
- **Reconstruction results**
 - From [arXiv:2601.05697](https://arxiv.org/abs/2601.05697)
 - Outlining the main results
- **Hinting at future plans**

Physics case for atmospheric

An extra ν source **complementary to beam**:

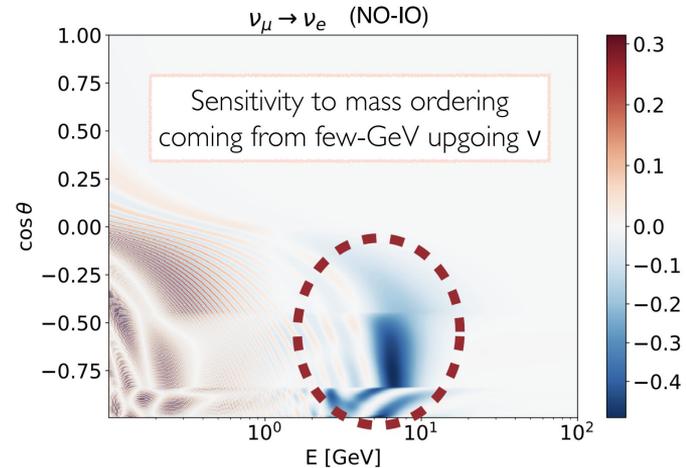
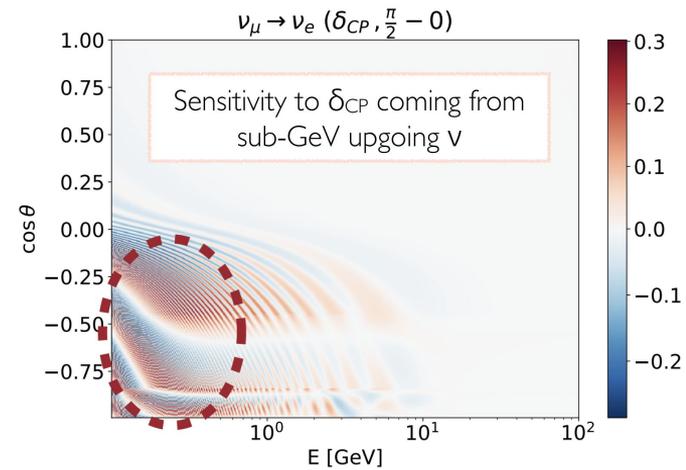
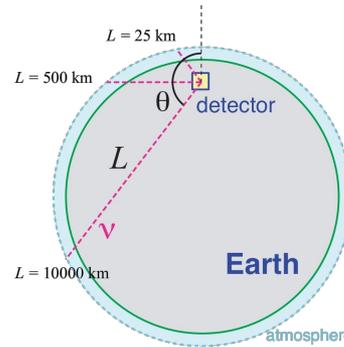
- Wide energy range: 0.1 GeV to > 100 GeV
- Wide baseline range: few km to $\sim 12\,800$ km
- Multiple flavours: $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

Allow to probe:

- **3 flavour oscillations**
- **matter effects**
- **same L/E with different L**

Challenges:

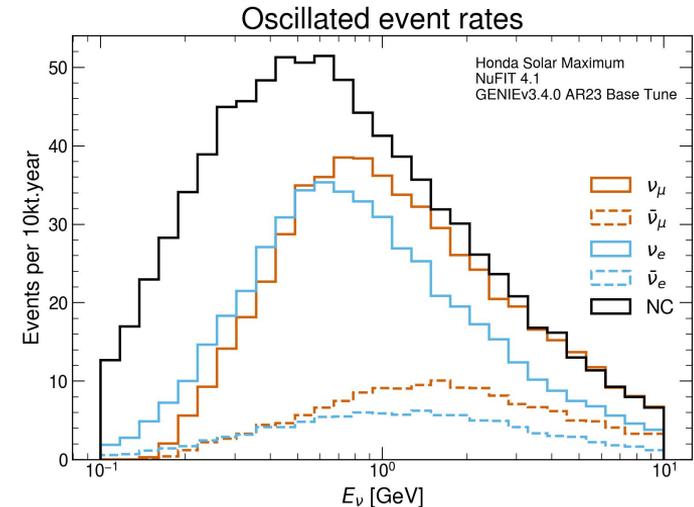
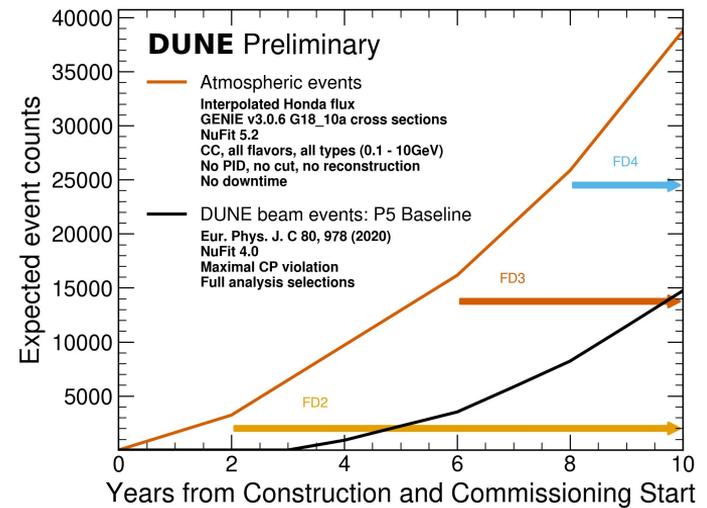
- **Wide range of energies** \rightarrow multiple processes, reconstruction methods
- Harder to **constrain systematics** (e.g. flux)
- Requires ν **direction reconstruction**



Expected event rates

- Expecting some time with **FD 1&2 installed without beam:**
 - Atmospheric neutrinos will be the **first neutrino source of DUNE**
 - Might allow to test/calibrate reconstruction before beam arrives

- Around **2200 events/year/10kt** (varying with xsec models, flux models, osc. params values):
 - Enough to provide **relevant sensitivities** to the oscillation parameters
 - Also expecting **$\sim 10 \nu_\tau$ events/year/10kt** \rightarrow very relevant for **unitarity tests**



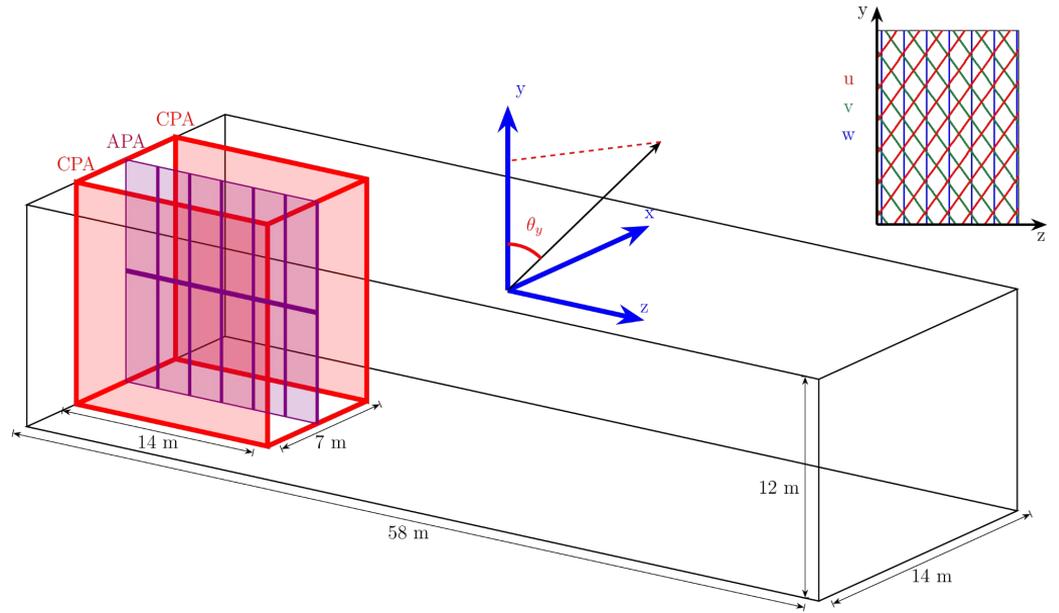
How does DUNE compare to others?

	IceCube, KM3Net	Hyper-Kamiokande	DUNE
Fiducial mass	$\mathcal{O}(1 \text{ Mt})$	260 kt	40 kt
Event rates	$\mathcal{O}(10^5 \text{ events/year})$	$\mathcal{O}(10^4 \text{ events/year})$	$\mathcal{O}(10^3 \text{ events/year})$
Energy reconstruction	Calorimetric	Kinematic	Kinematic & calorimetric
< 1 GeV	Below detection	Lepton and pions reconstruction p below threshold	Full event reconstruction Low proton detection thresholds
1 GeV to 10 GeV	Event classification into showers and tracks	ν FS particles reconstruction	Full event reconstruction
High-energy	Very good containment	Limited containment	Limited containment

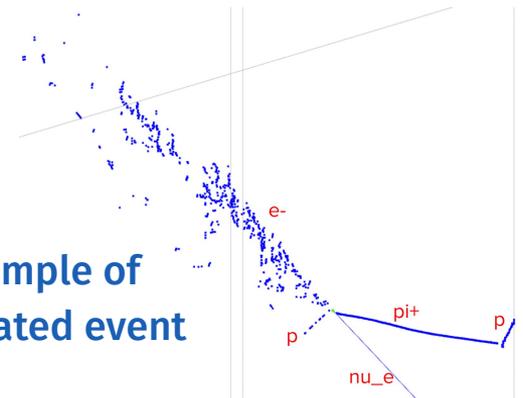
- DUNE will observe **less events** than other experiments and will provide **lower containment**
 - **However** it might be compensated by its capabilities at **reconstructing the event topology** allowing for:
 - **Excellent energy resolution**
 - **Excellent direction reconstruction**
 - **Better understanding of nuclear effects**
- } **Challenging to exploit in practice**

Sim&Reco workflow

- **HD Atmospheric sample** produced in the end of 2023
- Workflow **largely similar to LBNF** neutrinos.
- **Reweightable flux simulation** using a custom GENIE driver
- **Mostly reusing LBL reco** with focus on:
 - **Retuning algorithms** e.g. vertex reco
 - Adapt to handle **isotropy**
 - Neutrino **direction reconstruction**

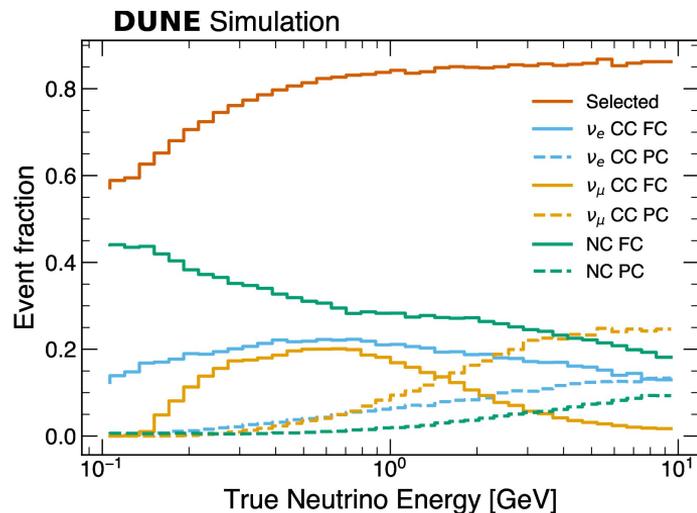
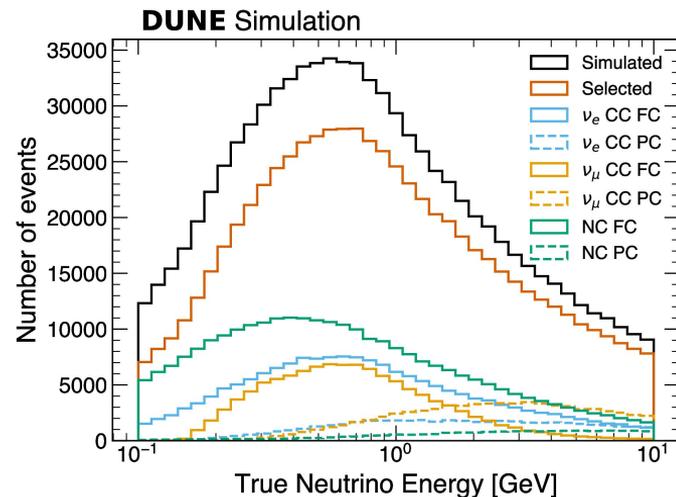


Example of simulated event



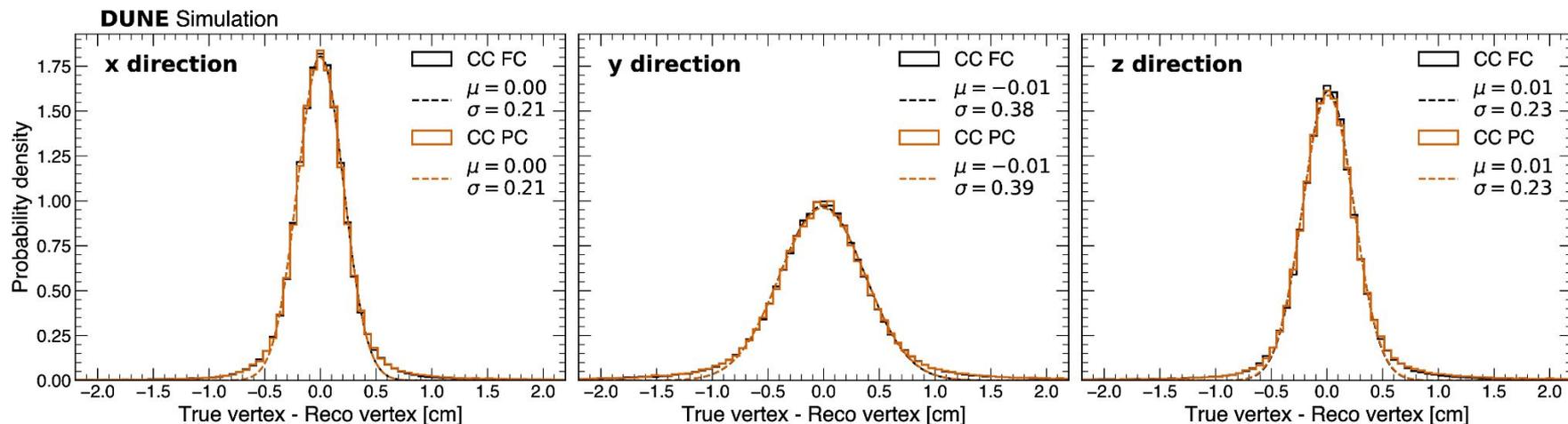
Fiducialization and containment

- Fiducial Volume (FV) cut of **20cm around the Active Volume**
- Only selecting events with:
 - **At least one reconstructed Pandora object**
 - **Vertex within the FV**
- Containment definition:
 - **Fully Contained (FC):** no reconstructed Pandora spacepoint belonging to a PFP outside the FV
 - **Partially Contained (PC):** not FC



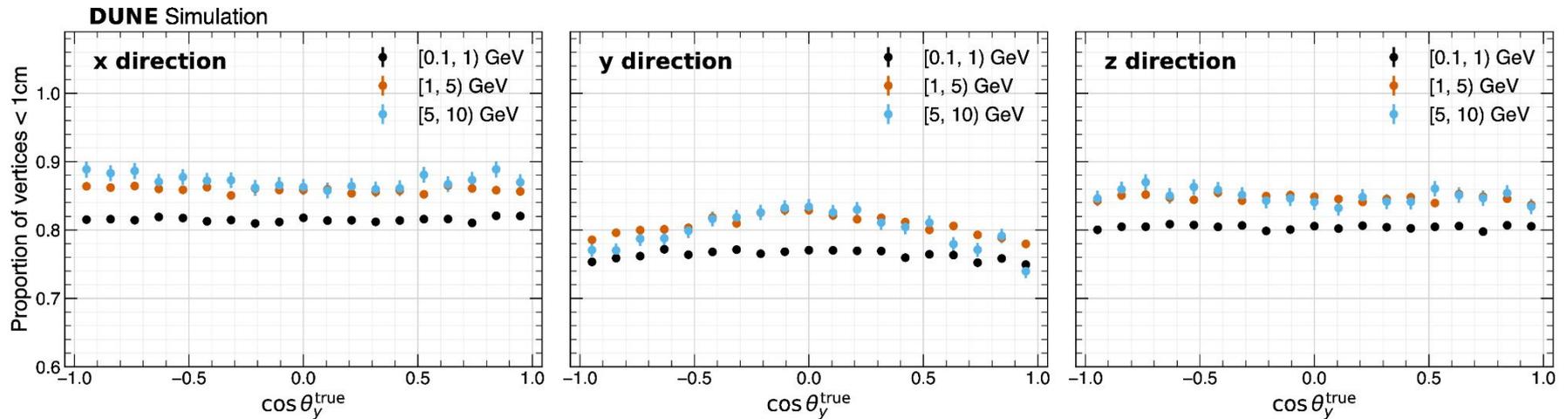
Vertex reconstruction

- **Retraining** of the LBL Pandora **DeepLearning Vertexing** ([Eur. Phys. J. C 82, 903](#)) to account for:
 - **Direction isotropy**
 - **Different energy spectrum**
- Some **direction dependencies** (wires oriented along y)
- Average resolution **below 5mm**
- Final performance similar to LBL sample: **> 80% of the events** have their vertex reconstructed **< 1cm from the interaction point**



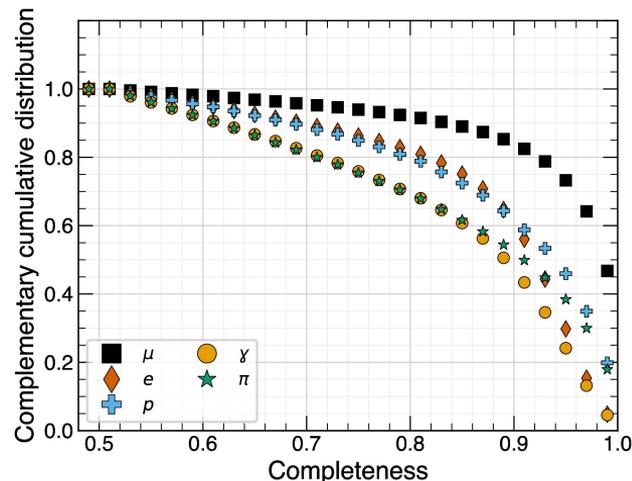
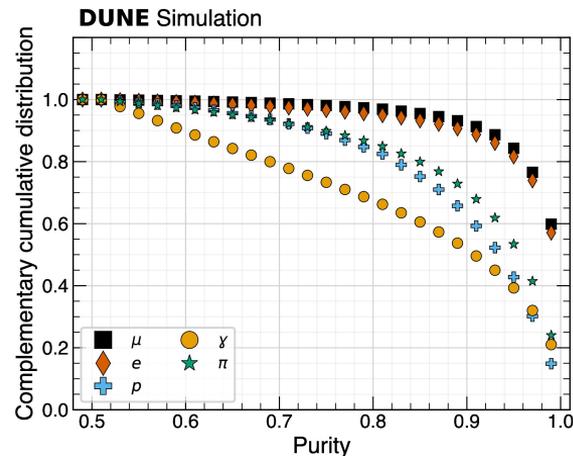
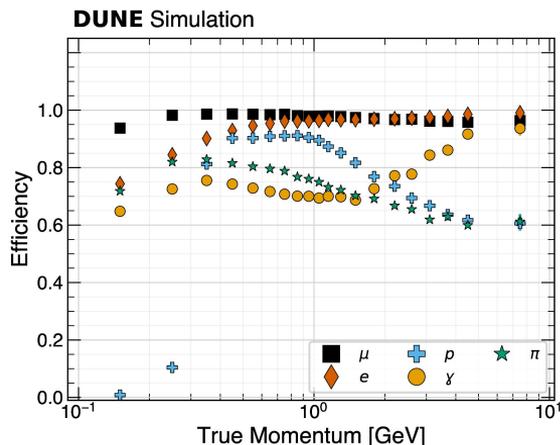
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Particle reconstruction efficiency

- **Pandora workflow similar to LBL** (+ retraining of Track/Shower BDT)
- **Efficiency** defined as the fraction of true particles that have an associated reconstructed Pandora object (PFO) with:
 - **Purity > 50%** → > 50% of the PFO hits belong to the MC particle
 - **Efficiency > 50%** → > 50% of the MC particle hits belong to the PFO
- Some **drop of performance wrt LBL**, understood by **directionality effects** → **identical after flux reweighting**



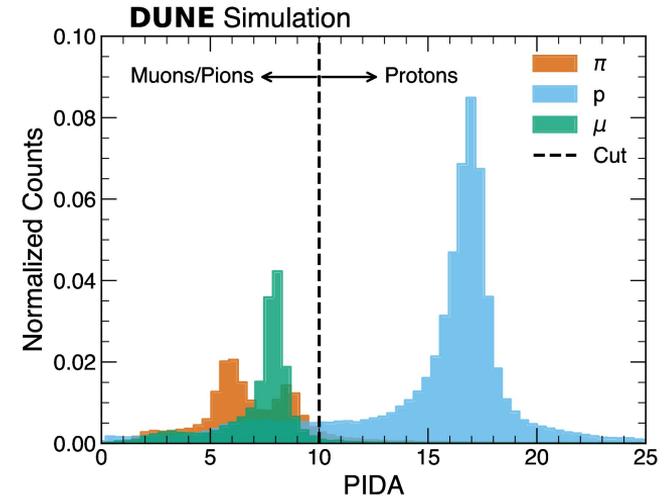
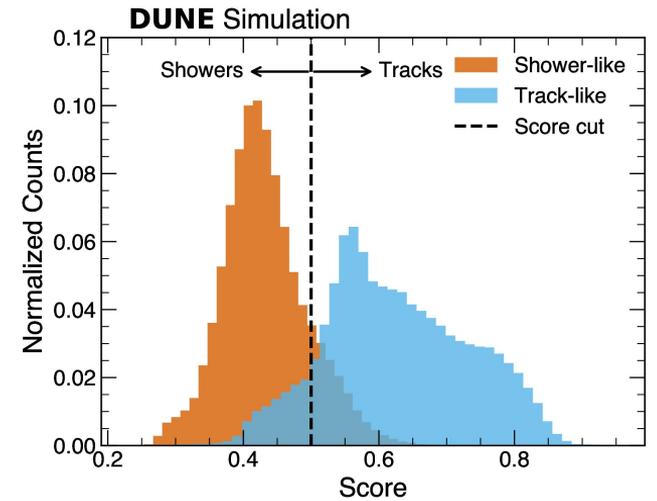
Particle Identification

- **Track/Shower discrimination** performed by Pandora BDT
- Track selection with **89% efficiency, rejecting 91% of the showers**
- Track PID performed with **PIDA score on track's last 30cm**

$$\frac{dE}{dx} \simeq AR^b$$

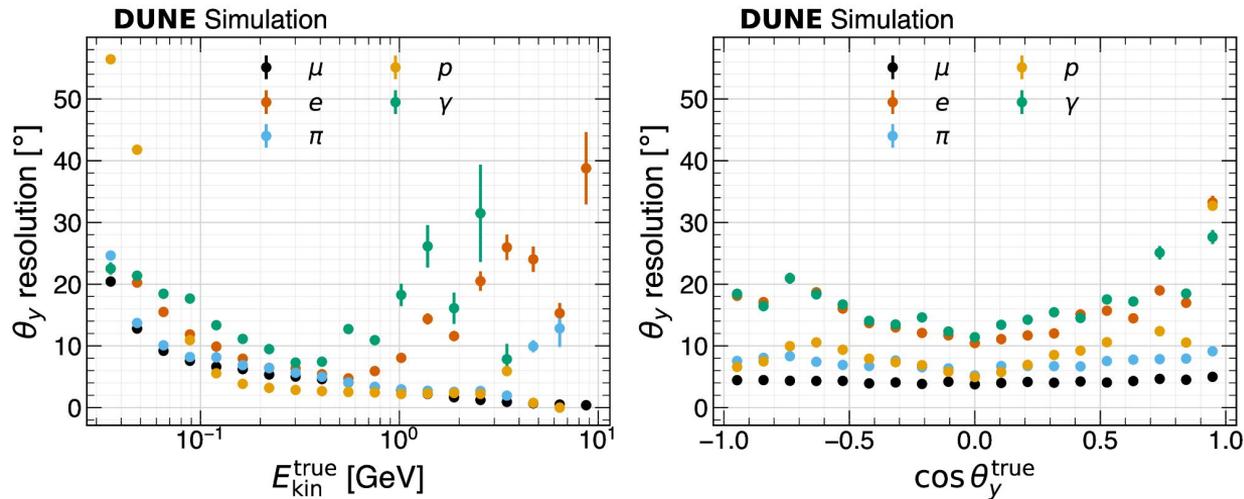
$$\text{PIDA} = \frac{1}{N_{\text{points}}} \sum_i^{N_{\text{points}}} \left(\frac{dE}{dx} \right)_{\text{reco},i} R_i^{0.42}$$

- **PIDA > 10 cut** → **87% proton efficiency with 91% purity**
- Currently no identification between pions and protons (similar energy deposition profiles)



Particle direction resolution

- Particle direction reconstruction is very important for **v direction reconstruction**
- Best performance obtained for **track-like particles ($\sim 5^\circ$), improving with KE**
- **Loss of performance for HE showers** (overclustering)
- **Directionality effects** (wire orientations)
- Reconstructed **length effect** \rightarrow expected **improvement at HE in full detector geometry** (but not so much along **y** for which we already simulate the full extent)



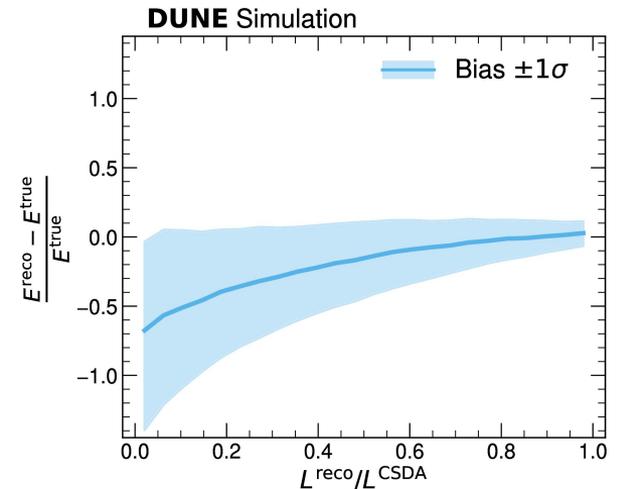
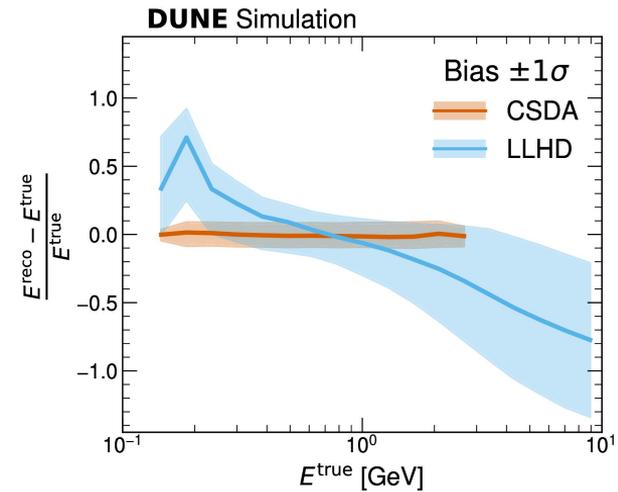
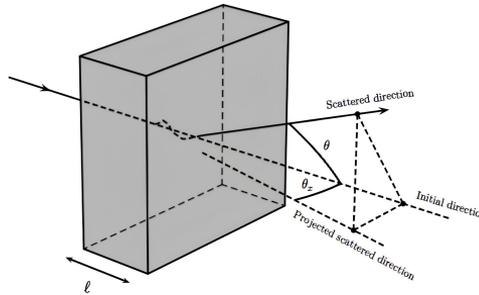
Muon energy reconstruction

Different methods to **reconstruct the muons energy**:

- **Stopping muons:**
 - Constant Slow Down Approximation (CSDA) → **P(range)**
 - **Percent level** energy resolution
- **Uncontained muons:**
 - Multiple Coulomb Scattering (LLHD) → **likelihood fit of muon scattering**
 - Degraded performance → **~ 20% at 1GeV**
 - **Depends on contained length** → should improve in full geometry

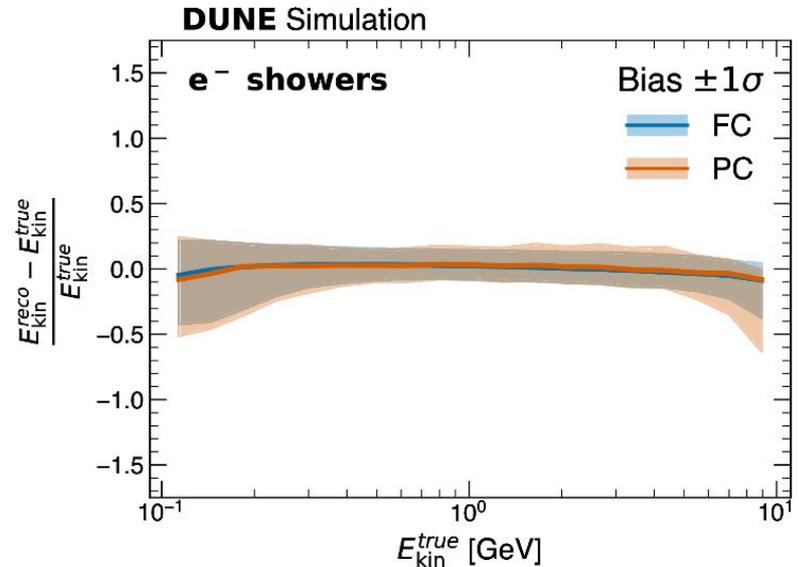
$$f(\Delta\theta) = \frac{1}{\sqrt{2\pi\theta_0^2}} \exp\left[-\frac{1}{2}\left(\frac{\Delta\theta}{\theta_0}\right)^2\right]$$

$$\theta_0 = \frac{\kappa(p)}{\beta cp} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{xz^2}{X_0\beta^2}\right)\right]$$



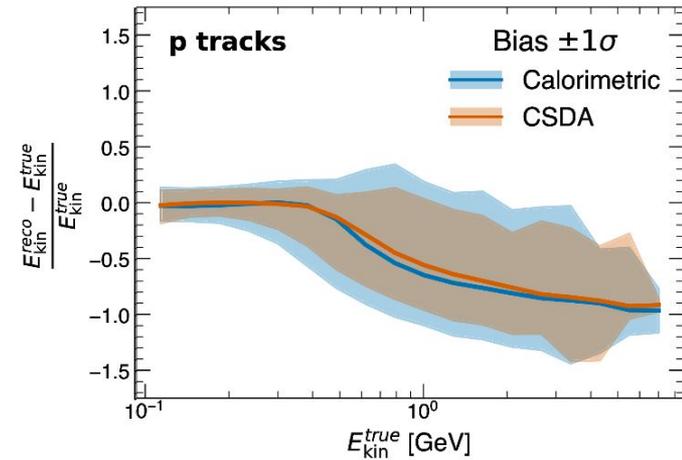
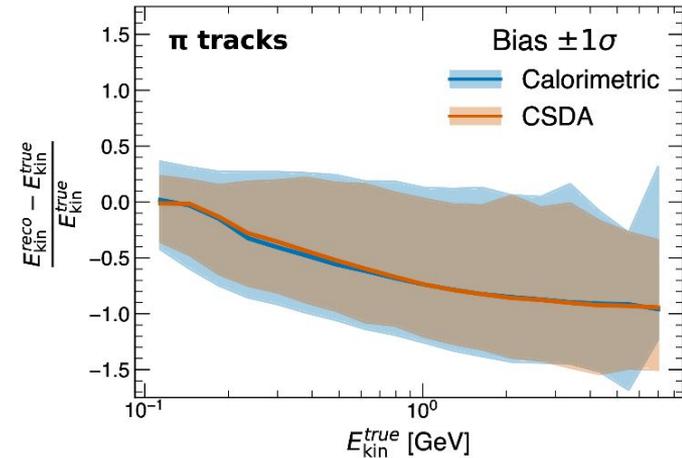
Electron energy reconstruction

- **Calorimetric reconstruction:**
 - Converting **all the shower hits on the collection plane** to deposited charge
 - **Correcting for attenuation** effects
 - **Summing all the charges** and converting to energy
 - Multiplying by a **linear scaling factor to account for invisible energy** (e.g. soft shower electrons)
- **Performance:**
 - **~ 15% resolution at 1 GeV**
 - **Degraded performance at low-E**
→ invisible energy, under-clustering
 - **Degraded performance at high-E**
→ over-clustering
 - **Direction-dependent** (relying on collection plane)



Hadrons energy reconstruction

- **CSDA/Range** reconstruction → similar to what is done for muons
 - Less performant than for muons because of **hadronic interactions**
 - ~ **50% / 25%** KE resolution for **500 MeV pions / protons**
 - **Requires performant PID** (pion range \neq proton range for identical KE)
- **Calorimetric reconstruction** → similar to what is done for the electrons
 - **Slightly less performant but doesn't require PID**
- Can hopefully be improved in the future
 - **Track-length extension** fitting algorithm
 - Accounting for **inelastic hadronic interactions** children particles' energy and invisible energy (e.g. neutrons)



Muon neutrino energy reconstruction

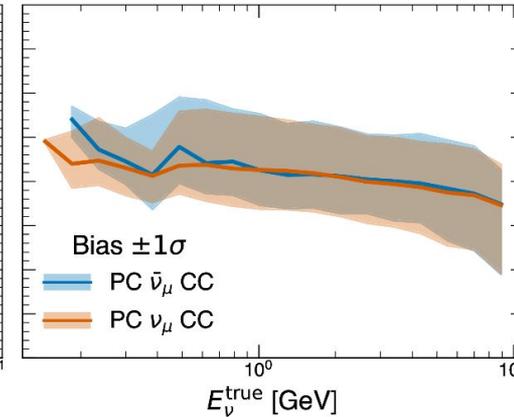
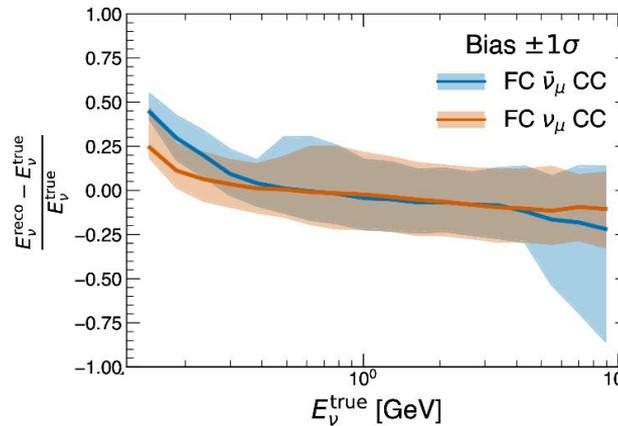
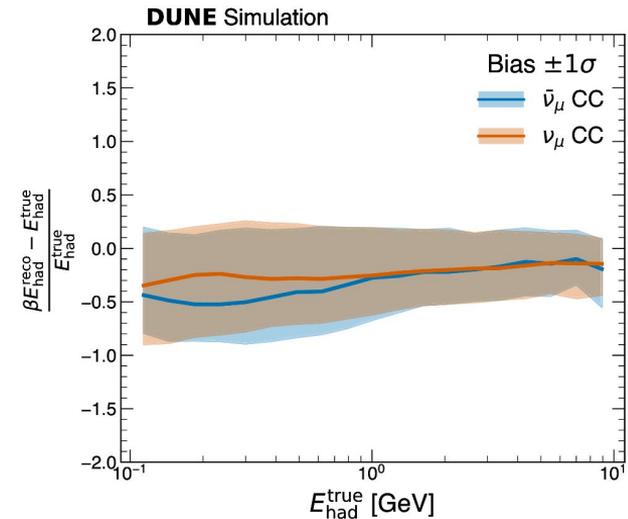
Methodology:

- Using the **calorimetric energy estimate** for the hadronic system / electromagnetic showers
- Using the **CSDA/MCS method for muons**
- Applying some **linear scaling to both the hadronic and leptonic energies** to reconstruct the neutrino energy

Results:

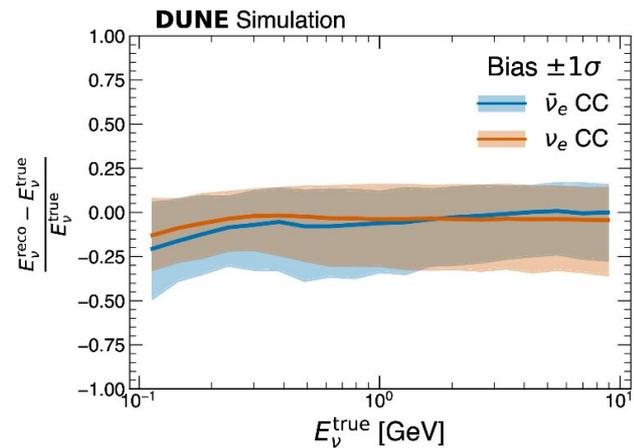
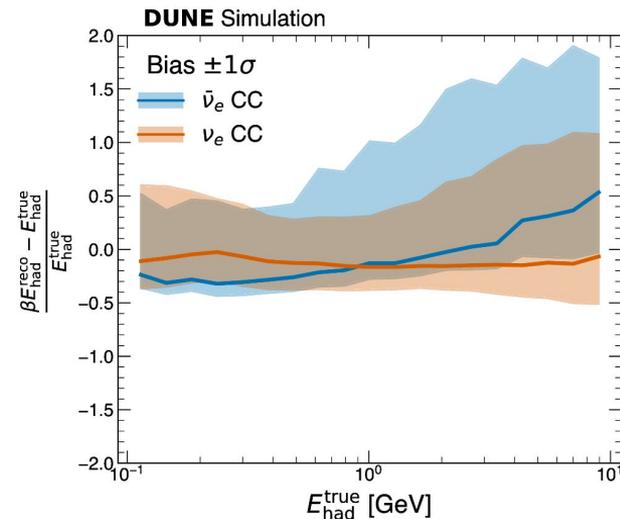
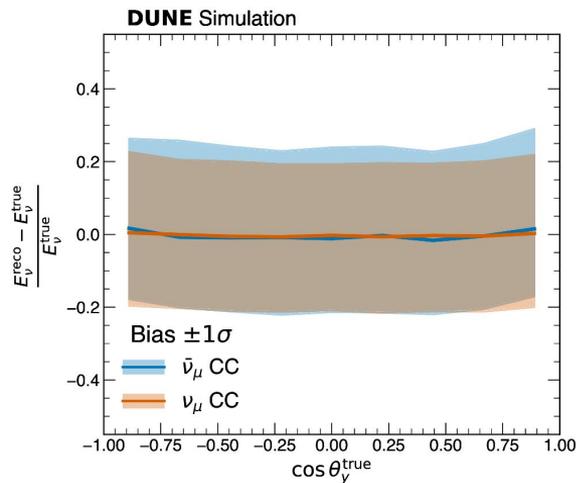
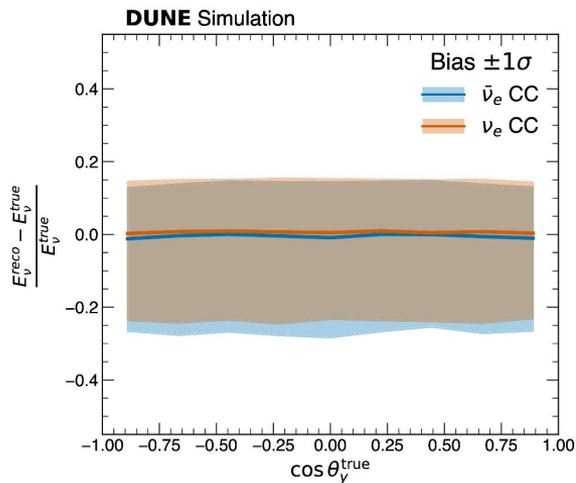
$$E_{\nu}^{\text{reco}} = \alpha E_{\text{lep}}^{\text{reco}} + \beta E_{\text{had}}^{\text{reco}}$$

- **Similar performance** for $\nu_{\mu} / \bar{\nu}_{\mu}$
- **FC events:**
 - Eres < 10% at low-E
 - Eres ~ 15% at higher energies
- **PC events:**
 - ~ 20% res for few-GeV events



Electron neutrino energy reconstruction

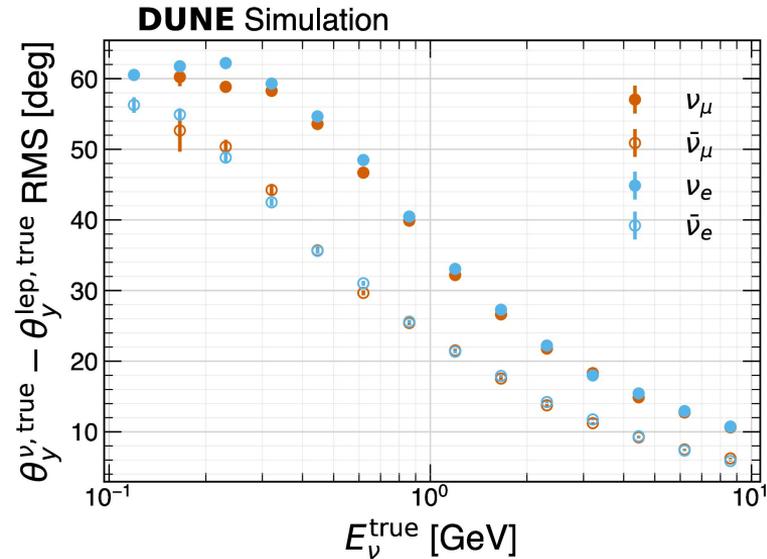
- **Similar performance** for ν_e and $\bar{\nu}_e$
- Energy resolution **< 15% at low-E**
- Energy resolution **~ 20% at higher energies**
- Minimal overall impact from the **neutrino direction**



Direction reconstruction: methods

3 different reconstruction methods:

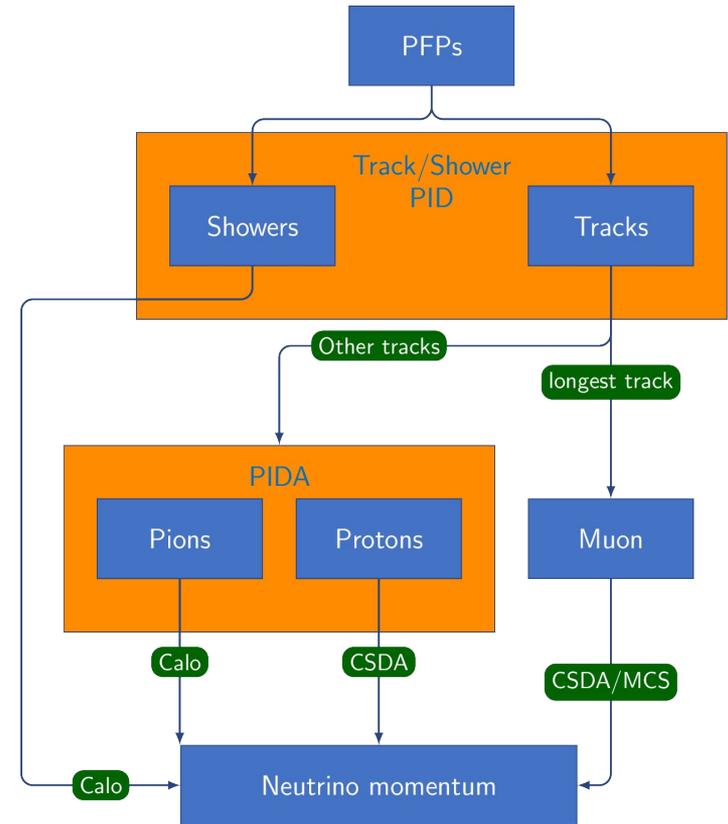
- Using **only the primary lepton** → low precision but easy to implement and rather insensitive to most nuclear effects



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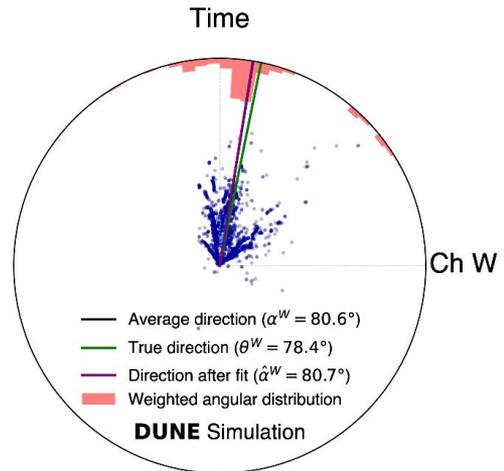
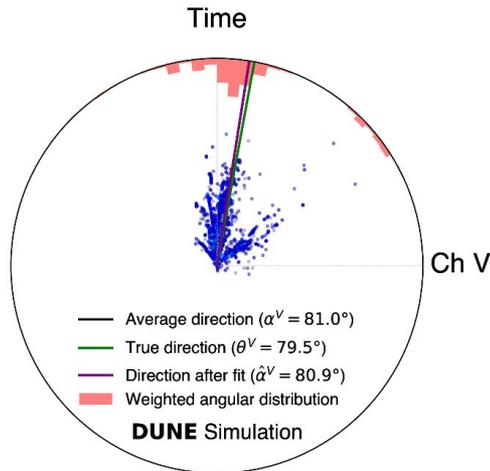
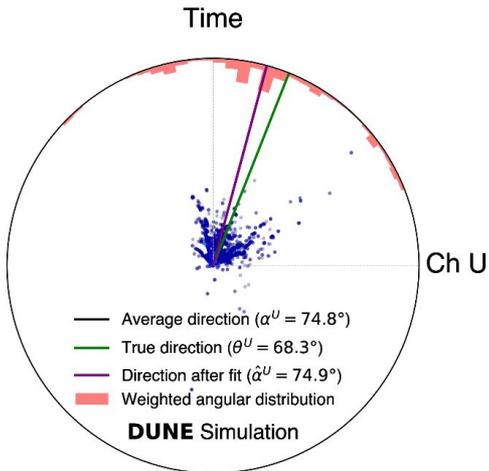
- Using **only the primary lepton** → low precision but easy to implement and rather insensitive to most nuclear effects
- Using **all the reconstructed FS particles** → uses the rich FS information from LArTPC. Requires some good PID and understanding of the nuclear models impact



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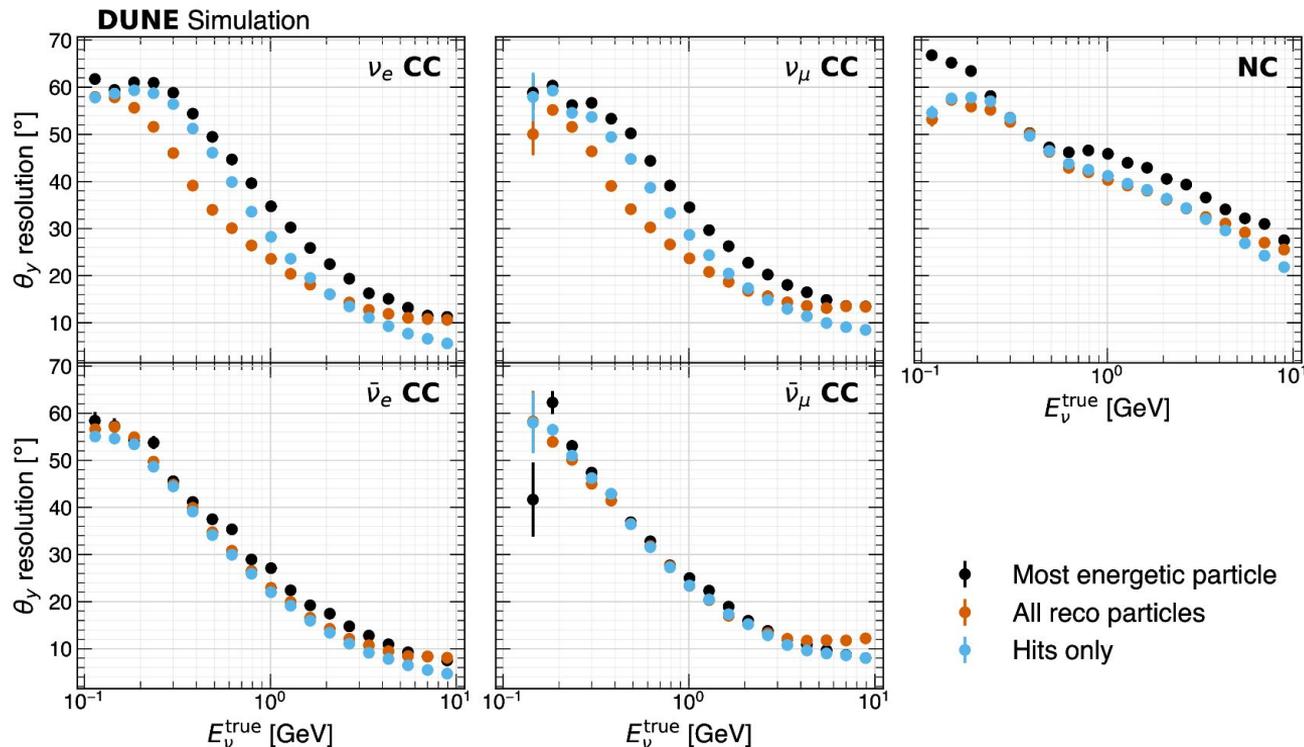
- Using **only the primary lepton** → low precision but easy to implement and rather insensitive to most nuclear effects
- Using **all the reconstructed FS particles** → uses the rich FS information from LArTPC. Requires some good PID and understanding of the nuclear models impact
- Using **all the reconstructed detector hits** for a calorimetric direction reconstruction → assumes KE direction \approx momentum direction



Direction reconstruction: performance

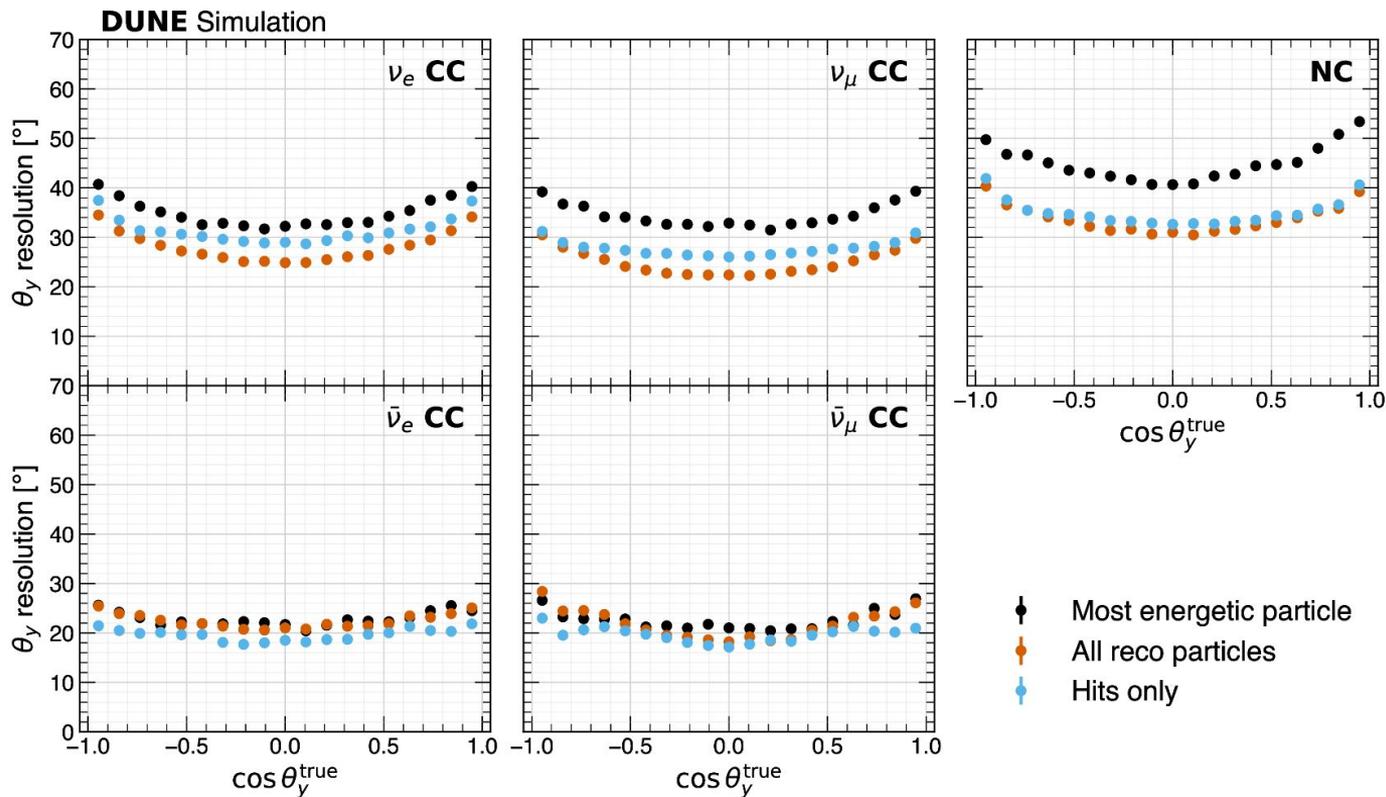
Both methods using more than the primary lepton **are overperforming**

- **low-E: using all particles**
→ importance of particles' masses
- **high-E: using directly the hits** → bypasses overclustering



Direction reconstruction: performance

Resolution depends a lot on the initial direction \rightarrow expected from wires orientation



Direction reconstruction: performance

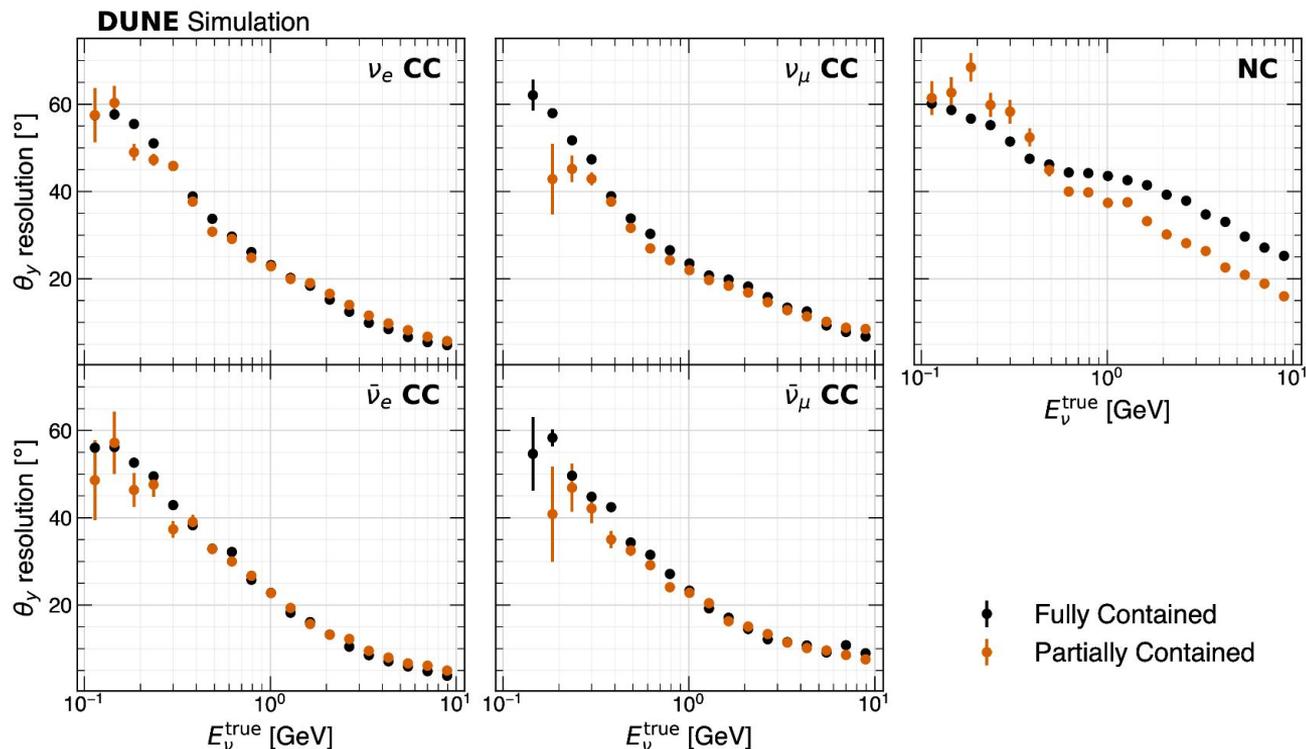
Methods can be combined based on reco information:

- nb reco particles > 1 and $E_{\text{reco}} < 1.3\text{GeV}$ → **all particles method**
- other cases → **calorimetric method**

CC interactions resolution:

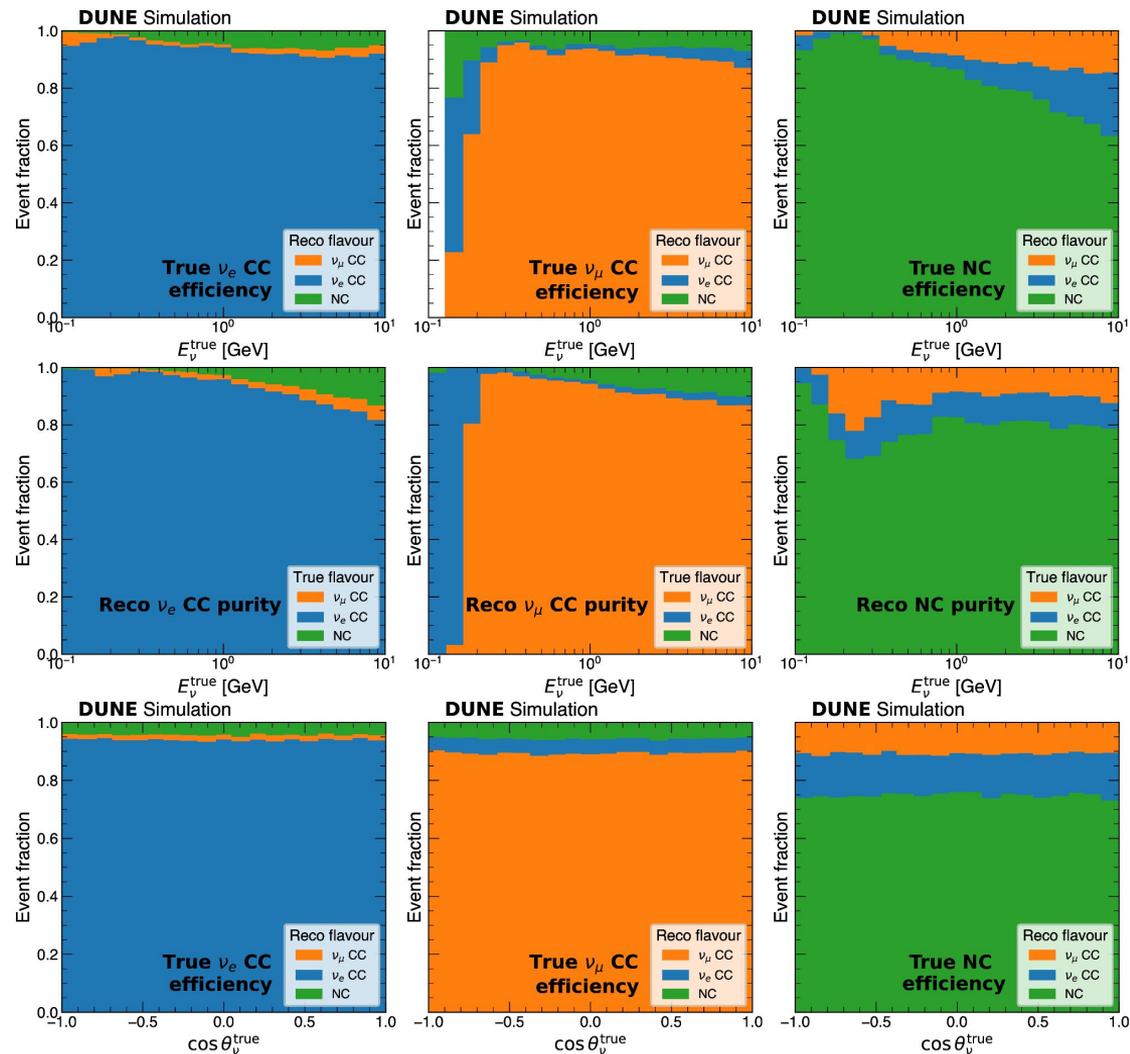
- $1\text{GeV} \rightarrow 25^\circ$
- $10\text{GeV} \rightarrow 7^\circ$ (9°) for ν_e (ν_μ)

Containment only has a minor impact



Flavor identification

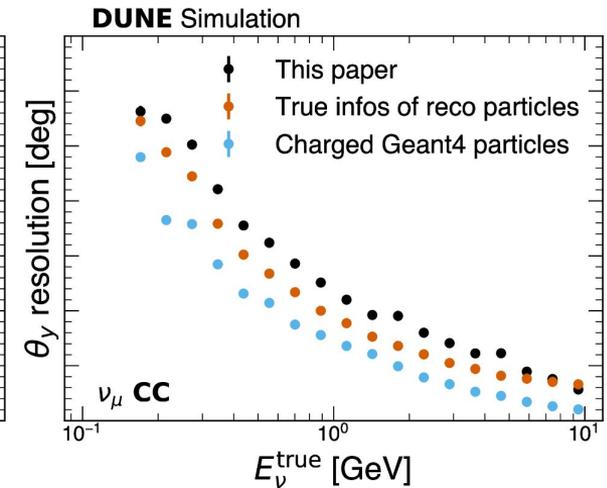
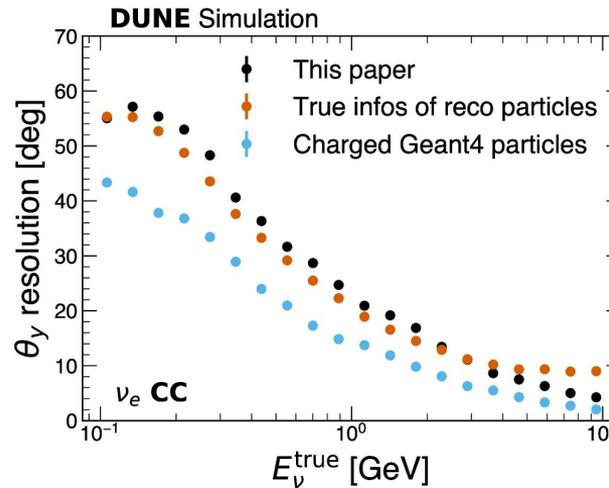
- Using a **Convolutional Neural Network** with a modified architecture with respect to LBL
- Classifying events into **CC ν_e , CC ν_μ and NC** categories
- Selection **efficiency ~ 90% for CC interactions** across the E range
- Performance drop with energy** → more difficult identification for high-E DIS events
- Performance **independent of the neutrino direction**



Future directions

This work is a baseline reconstruction performance that can be improved in many ways:

- Improving PID
- Using PID for energy reconstruction
- Using light information (PDS system)
- Using ML frameworks for improved performance (e.g. SPINE)
- Michel electron tagging
- ν_{τ} identification
- ...



Summary

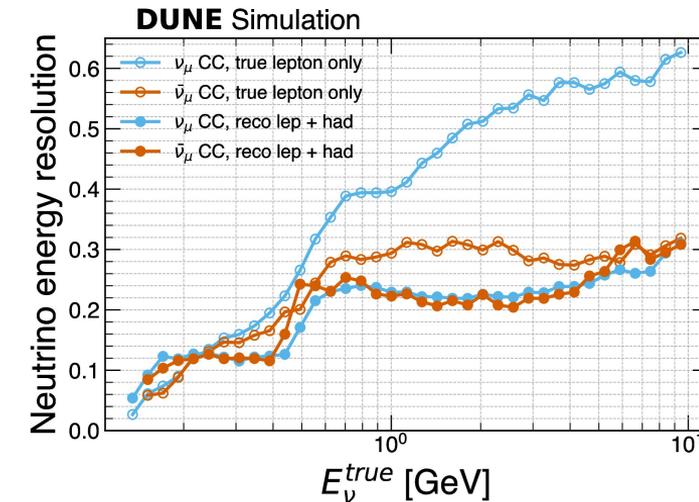
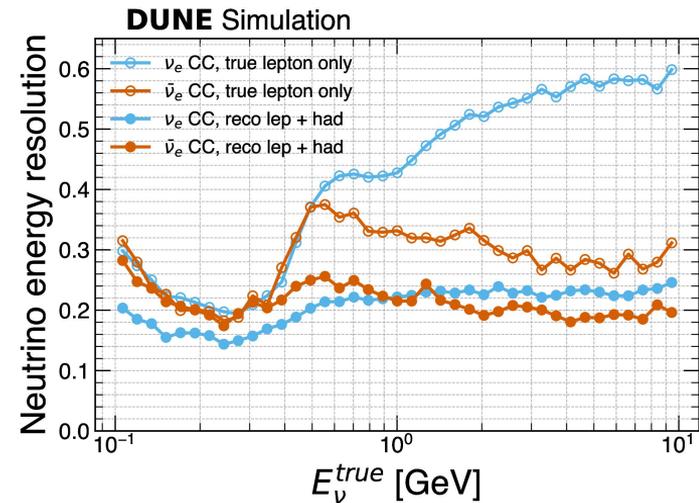
- DUNE's LArTPCs will provide **improved energy and direction resolution** on atmospheric neutrinos compared to many other experiments
- These improvements **might allow for increased sensitivity to oscillation parameters** with atmospheric neutrinos

Current major effort within the DUNE atmospheric group to deliver first oscillation sensitivity results. Ongoing work on:

- Detector, Flux, Cross-section systematic
- Sample definition
- Fitting frameworks

Hope to have results to share “soon”.

Stay tuned!



Backup

Resolution definition

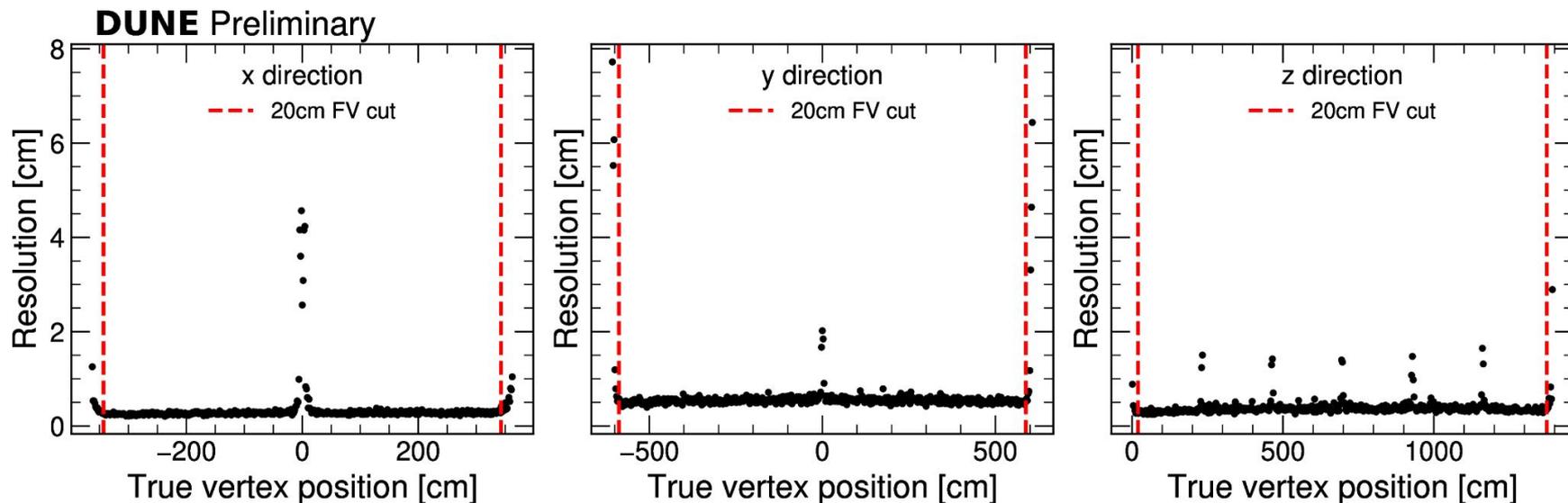
Relative bias is defined as the mean value of the $(\text{reco} - \text{true})/\text{true}$ ratio, for a given variable, for all events falling into a given bin.

Absolute resolution is defined in the following way in order to apply to non-gaussian distributions:

- The events are sorted into bins according to a given variable;
- For all events within each bin, the $(\text{reco} - \text{true})$ distribution is computed;
- For each bin, the 16% and 84% quantiles of the distribution are evaluated;
- This inter-quantile measurement is divided by 2, corresponding to the definition of 1 standard deviation in the case of a gaussian distribution.

Relative resolution is computed using the same procedure as for the absolute resolution except that the distribution evaluated in each bin is now $(\text{reco}/\overline{\text{reco}})$ where $\overline{\text{reco}}$ is the mean value of the reco variable within the bin.

Why 20cm FV cut?



CVN scores

