DEEP UNDERGROUND NEUTRINO EXPERIMENT

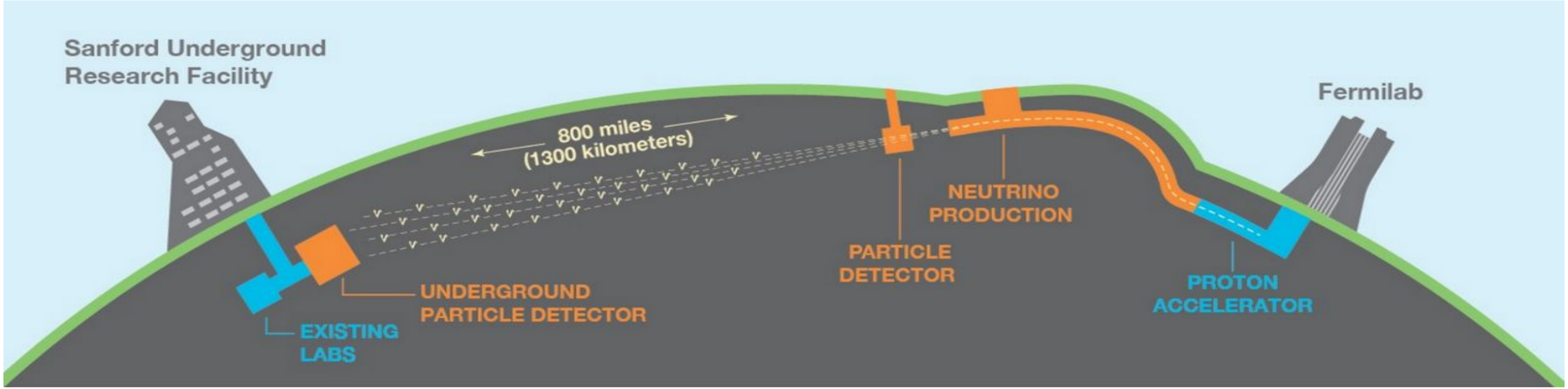
Atmospheric neutrinos in DUNE

Camille Sironneau
On behalf of the DUNE Collaboration

IRN Neutrino Paris
10/10/24

Université Paris Cité

Presentation of DUNE



Goals

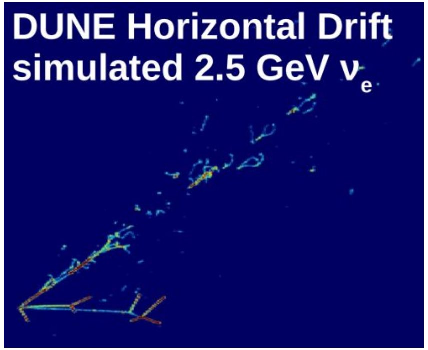
- Charge parity violation phase
- Neutrino mixing angles
- Neutrino mass hierarchy
- Search for proton decay
- Study of supernovae neutrinos

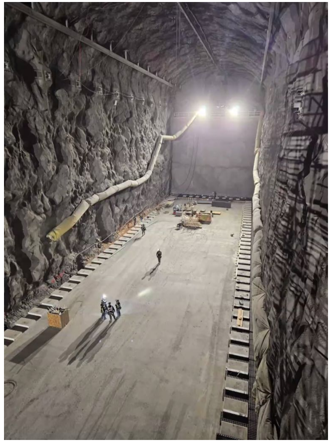
- **Neutrino beam** energy: 0.5 to 8 GeV
- **Near Detector** at 575m from the source
- **Far Detector (FD)** 1.5 km underground
- 4 LArTPCs modules of **17.5 kt each**

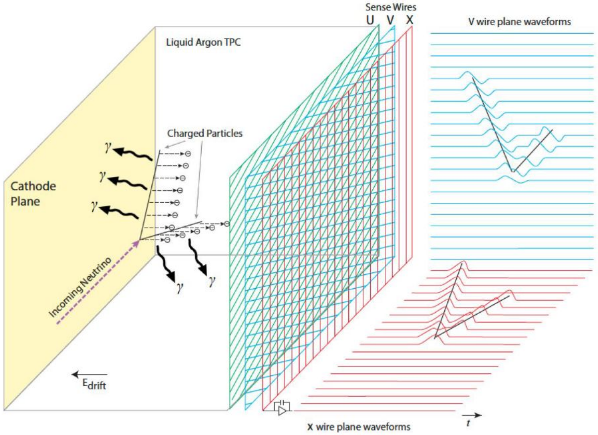
See Alessandra's talk

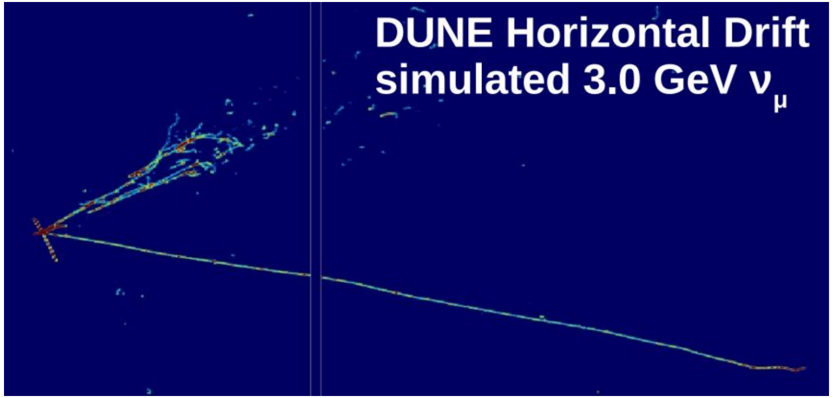
DUNE FD

- LArTPC **high resolution event imaging** → kinematic reconstruction of nu events
- Excellent **event type classification** (numu CC, nue CC, NC and potential for nutau)
- Excellent **particle id** (e, mu, proton)
- **Photon Detection System**: trigger, 3D reconstruction

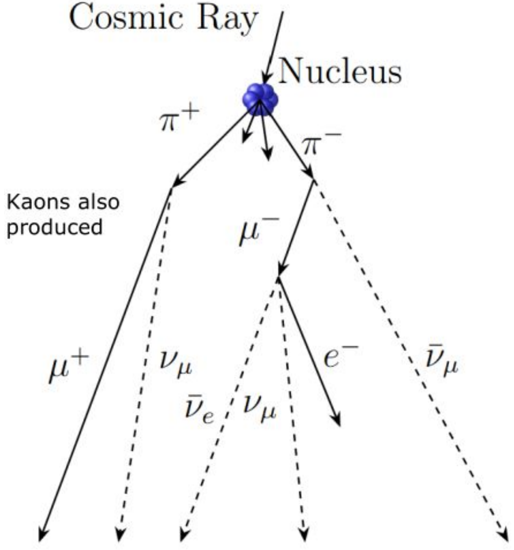




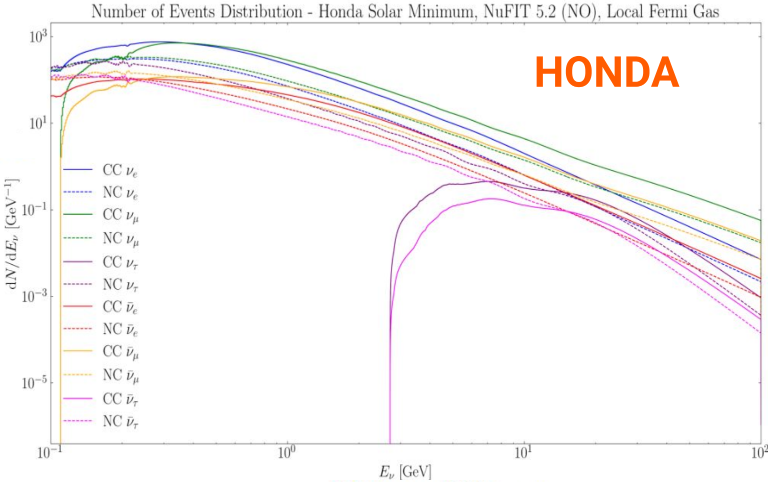




Atmospheric neutrinos



$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2,$$



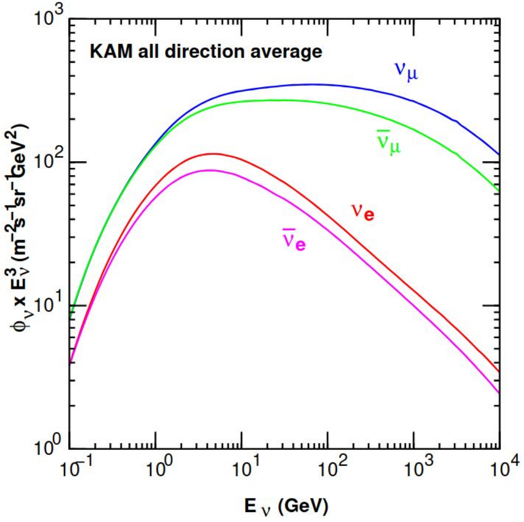
Totals per 10 kt · yr

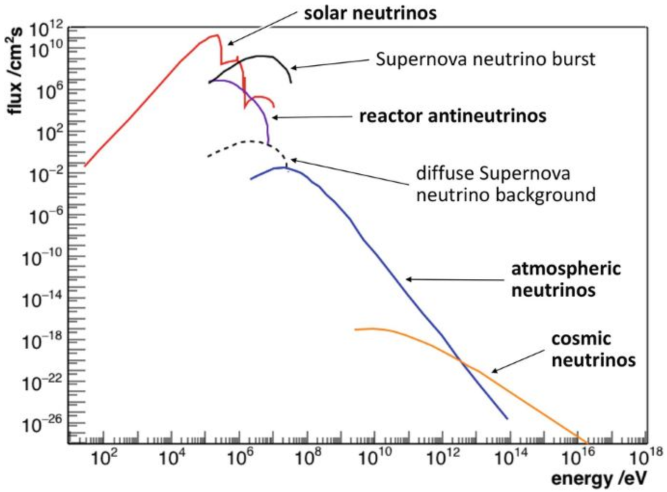
	Solar Maximum, NuFIT 5.2 (NO), Local Fermi Gas			
	Sub-GeV [0.1 – 1.0] GeV	Multi-GeV [1.0 – 10.0] GeV	High-GeV [10.0 – 100.0] GeV	Total [0.1 – 100.0] GeV
CCν_e	391.8	216.6	13.5	622.0
CCν_μ	389.9	319.1	41.4	750.4
CCν_τ	0.0	2.5	4.3	6.7
CC$\bar{\nu}_e$	61.3	57.2	4.5	122.9
CC$\bar{\nu}_\mu$	74.2	102.4	14.9	191.5
CC$\bar{\nu}_\tau$	0.0	0.9	1.6	2.4
NC	565.9	293.8	29.4	889.2
Total	1483.1	992.5	109.5	2585.1

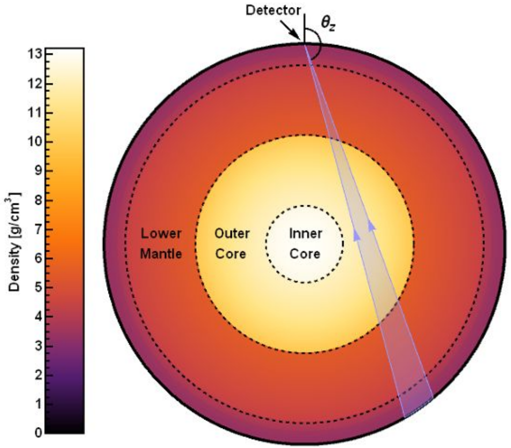
- Extra source of neutrinos **in addition to beam**
- Relevant → will operate DUNE FD(s) for **~2 years without beam**
- Expect **~2000 atmospheric neutrino events per 10kt per year** (including ~10 nutau events)
  → available data

Marcelo Oliveira-Ismerio

Atmospheric neutrinos characteristics







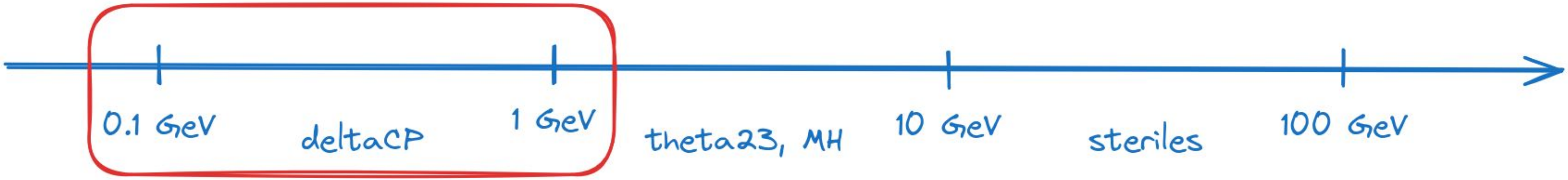
Constant flux of multiple flavors of neutrinos

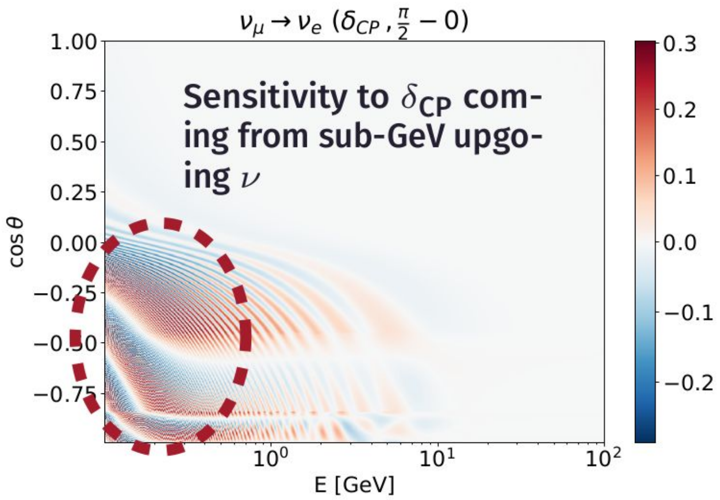
Wide energy range
→ from ~MeV to ~PeV

Come from every direction and go through different matter densities
→ different baselines/matter effects

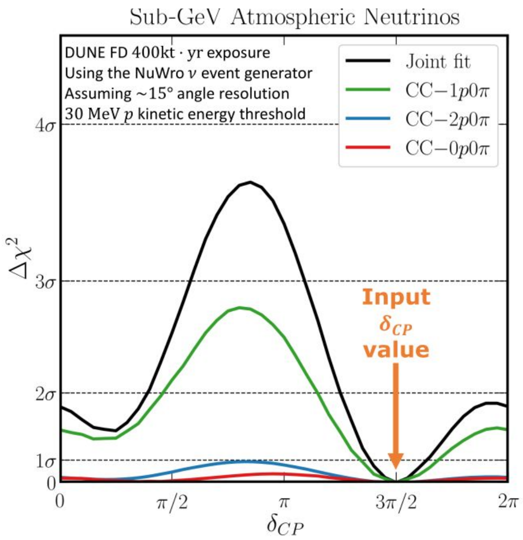
→ Complementarity with beam data

Physics with atmospherics : deltaCP



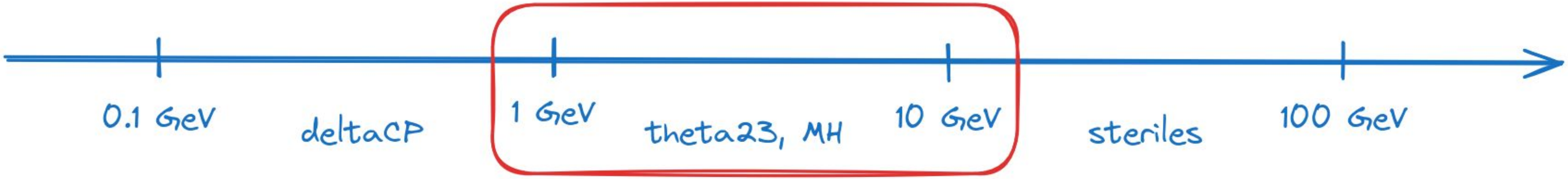


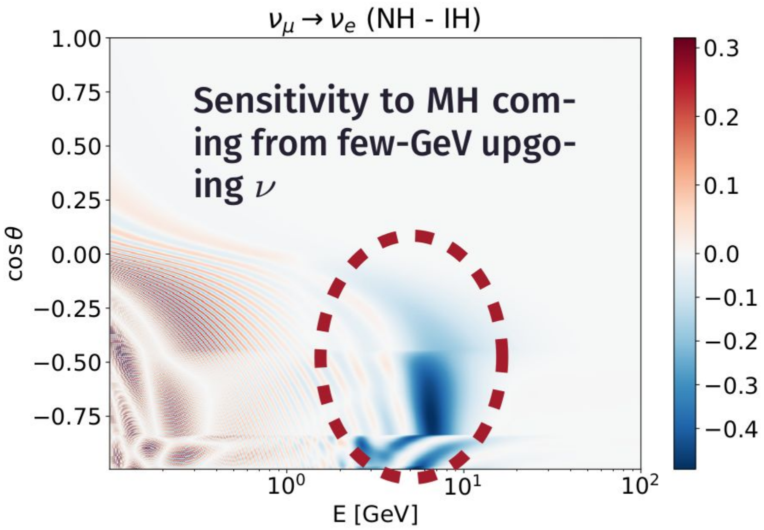
- Fast oscillations at low-E
- Expect DUNE to be able to reconstruct sub-GeV events
- Biggest challenge is handling Fermi motion as well as constraining the flux and cross-section systematics



https://arxiv.org/abs/1904.02751

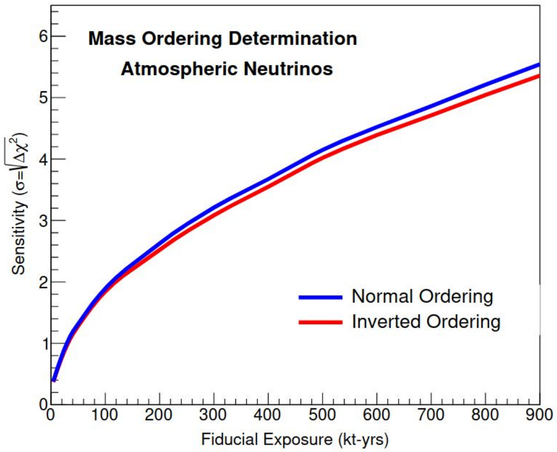
Physics with atmospherics : MH and θ_{23}



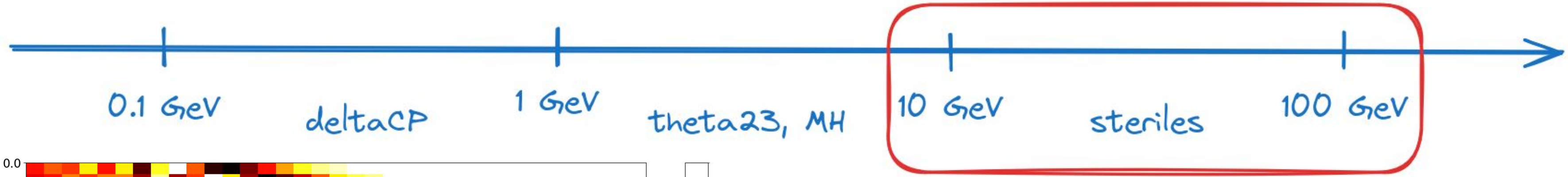


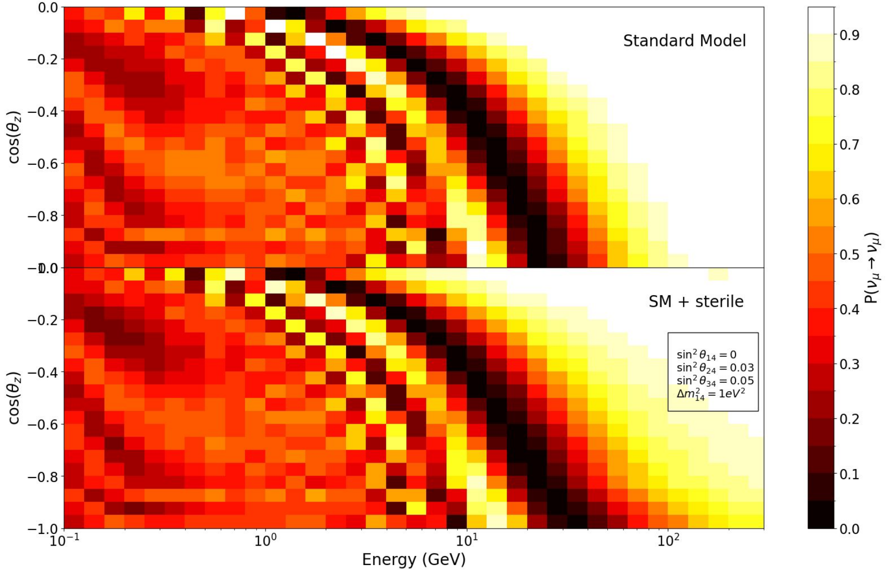
- Most visible effect ~5-10 GeV → well within the range of DUNE's capabilities (for both beam and atm)
- Ability to see 3 flavor oscillation modes with nutau events

DUNE TDR
https://arxiv.org/pdf/2002.03005



Physics with atmospherics : sterile neutrinos





$sin^2\theta_{14} = 0, sin^2\theta_{24} = 0.03, sin^2\theta_{34} = 0.05, \Delta m^2{}_{14} = 1\ eV^2$

- Big part of sterile neutrino effects are at high energy → atmospherics are good sources to see that
- Seen as differences in expected number of events due to additional oscillation state
- Important to properly reconstruct events (both energy and angle) and tag neutrino flavors to estimate this
- DUNE could be competitive with other experiments for sterile mass < 1 eV^2
- Containment effects will be challenging, plan is to improve reco with MCS and ML

Camille Sironneau

DUNE FD as an atmospheric neutrino detector

IceCube, KM3NeT	Hyper-Kamiokande	DUNE
Very high energy astro-particle physics and atmospheric neutrinos	Accelerator LBL and atmospheric neutrino oscillation	Accelerator LBL and atmospheric neutrino oscillation
O(1) Mt O(10^5 events/year)	260 kt O(10^4 events/year)	40 kt O(10^3 events/year)
Event classification into showers and tracks	ν flavor identification	Low hadronic thresholds, low energy protons visible
E > O(1 GeV)	E > O(1 MeV)	E > O(1 MeV)

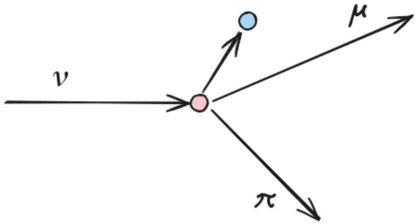
- Underground → **shielding from cosmogenic events**
- Expect **good control and knowledge on detector systematic uncertainties**
- DUNE → **smaller so less statistics but can solve event topologies** and see protons
- Expect **good energy and direction reconstruction** in DUNE for both multi-GeV and sub-GeV ν

→ challenge : software was built to reconstruct beam events, need some tuning

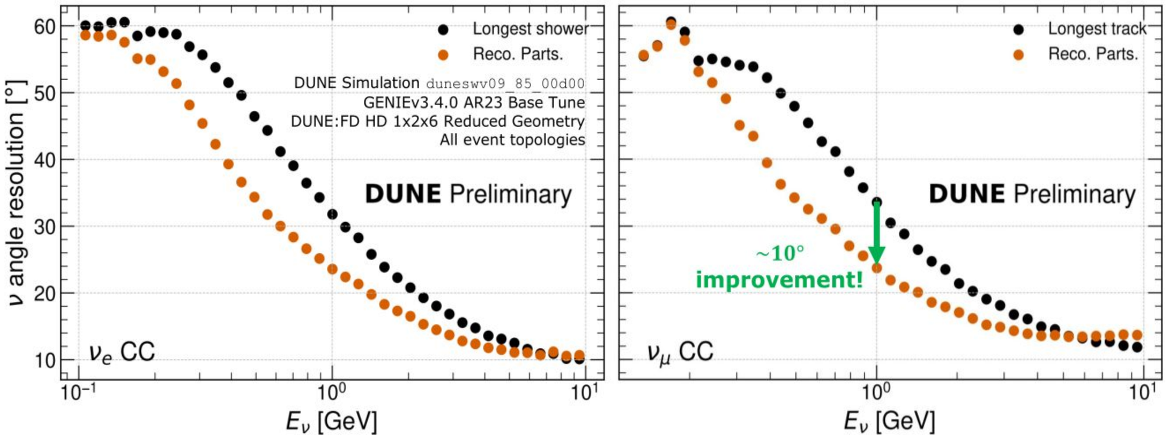
Angular resolution

- **Neutrino angle reconstruction is not a current central focus of beam analyses**
- To do this for atmospherics, we **need access to particle's 3-momentum**, which requires :
  - particle direction
  - particle kinetic energy
  - particle identification

  } **LArTPCs should be good at this**
- **But some info is not available :** momentum carried by neutrons, nuclear effects → Fermi motion, nuclear interactions, etc...

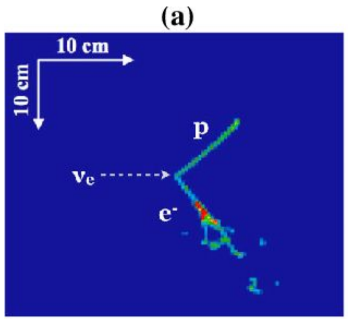


$$\vec{p}_\nu + \vec{p}_{\text{Fermi}} = \sum \vec{p}_{FS}$$



Atm simulation of ~15M events in 1/8th of full detector size

Better estimation for neutrino angle when using all particles in the event

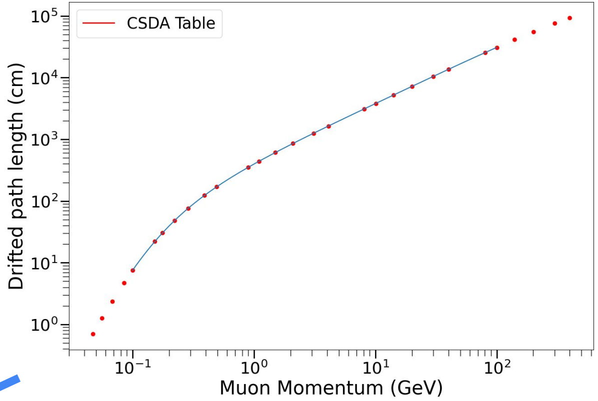


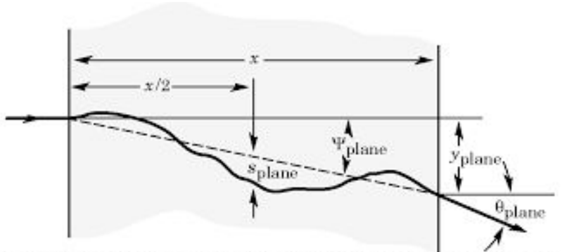
Henrique Souza, Pierre Granger

Energy resolution

- **Reco neutrino energy = lepton energy + hadronic energy** (sum of energy depositions)
- For numu (CC) events, longest track is selected as muon candidate
- For **contained events**:
  - **Momentum is computed with the particle's range** using the Constant Slow Down Approximation **(CSDA)**
- For **uncontained** events:
  - **Momentum is computed with Multiple Coulomb Scattering (MCS)**

Henrique Souza, Pierre Granger





ure 27.9: Quantities used to describe multiple Coulomb scattering.

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

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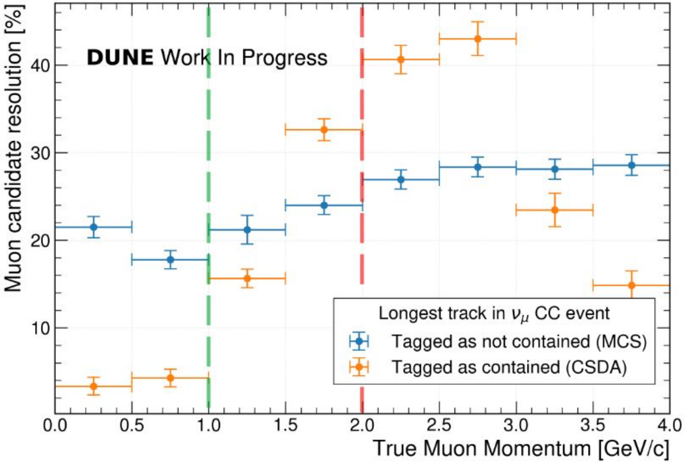


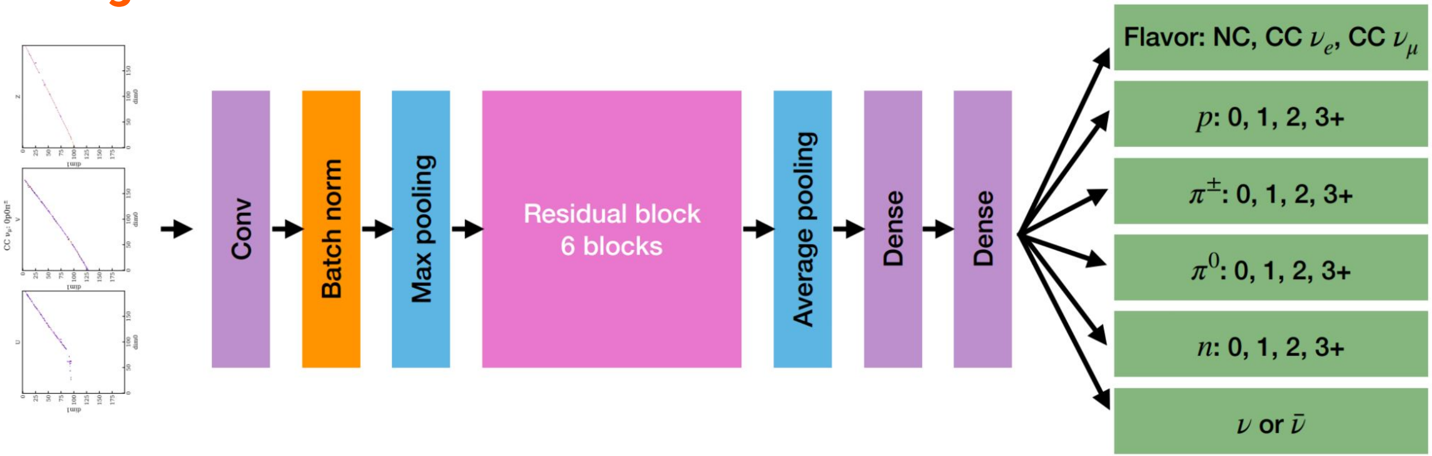
At low-E → contained, CSDA works well
Higher-E → uncontained, MCS is better but needs to be improved

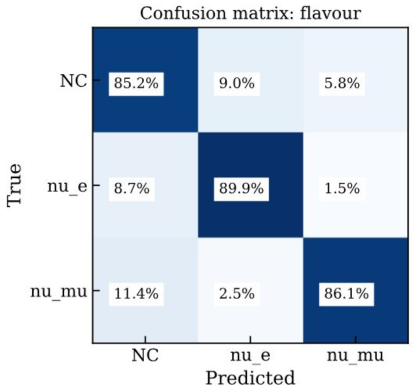
Henrique Souza, Pierre Granger

Flavor identification

Using a Convolutional Visual Network

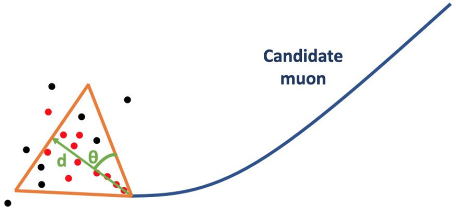
DUNE work in progress





Additional statistical separation can be obtained for numu/numubar with Michel e^- tagging:

- μ^+ always decays in e^+
- μ^- can decay to e^- (~ 28%) or be captured on Argon nuclei (~72%)

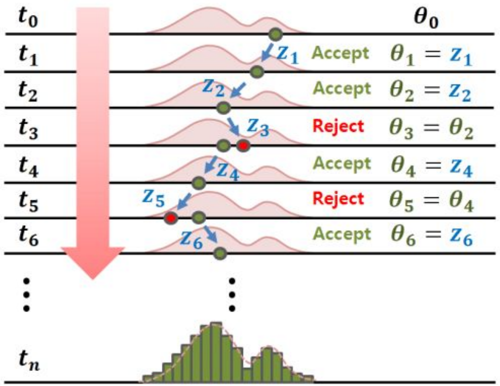


Sofia Farrell, Aaron Higuera, Matteo Galli

Sensitivity studies

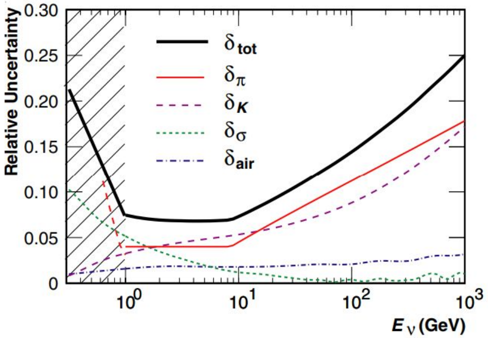
MaCh3 used as oscillation fitter → relies on the sampling of posterior likelihood using Markov Chains

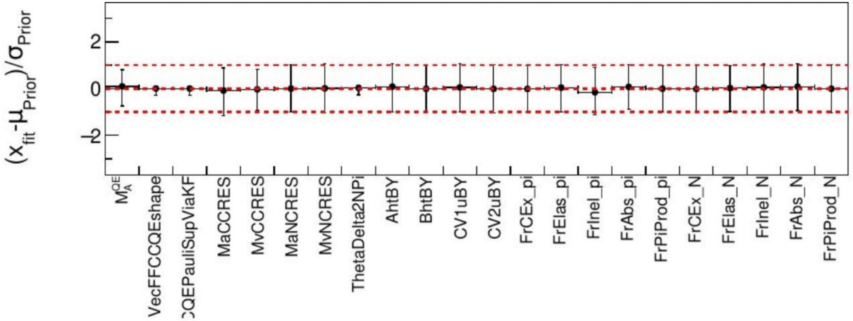
Implementation of DUNE atmospherics in MaCh3 ready to go



Next steps:

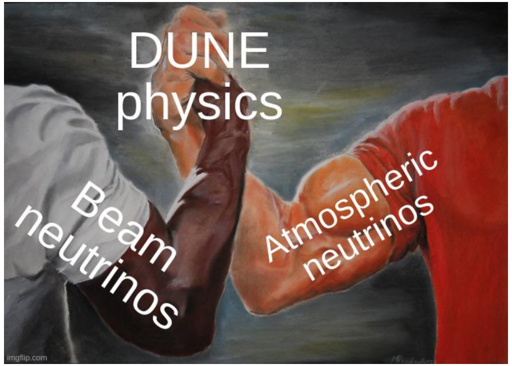
- First statistics-only fits with the reconstructed atm. sample
- Implementation of realistic flux, cross-section and detector systema





Daniel Barrow, Pierre Granger, Marcelo Oliveira-Ismerio

Summary and conclusions



- Presented strong **motivations for doing physics with atmospheric neutrinos in DUNE** :
  - detector capabilities + experiment timeline
  - complementarity with beam neutrinos
    → **potential to achieve higher sensitivities with joint analysis**
- Reconstruction is challenging, efforts are ongoing to adapt software to atmospherics specificities
- In addition to angular and energy reco, current work being done to improve **vertex reconstruction** (I Cheong Hong)
- Also investigating reconstruction of **tau neutrinos** (Barbara Yaeggy)
- **Analysis infrastructure with MaCh3 in development to produce updated oscillation sensitivity projections** → full implementation of different systematics in the works
- **First A&E paper on reconstruction for atmospheric neutrinos in progress**

Thanks a lot for your attention !