DEEP UNDERGROUND NEUTRINO EXPERIMENT

# DUNE Astrophysical and Atmospheric Neutrinos

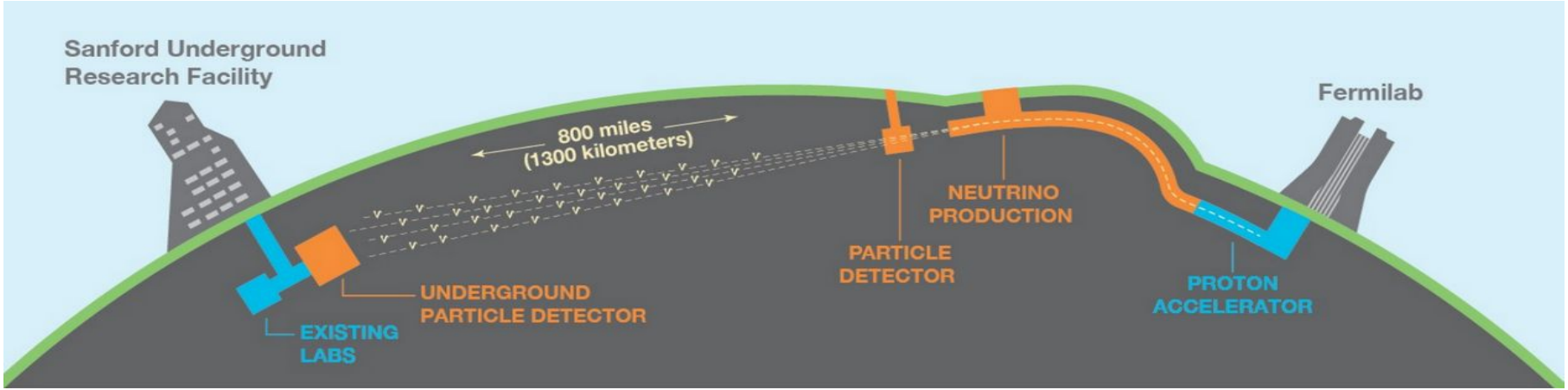

**Camille Sironneau**

*On behalf of the DUNE Collaboration*


**EPS-HEP conference**

**09/07/25**

# Presentation of the DUNE experiment




**Goals**

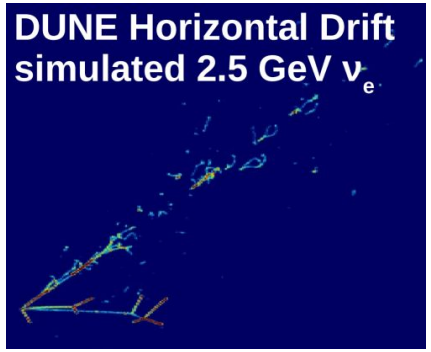
- Charge parity violation phase
- Neutrino mixing angles
- Neutrino mass hierarchy
- BSM searches

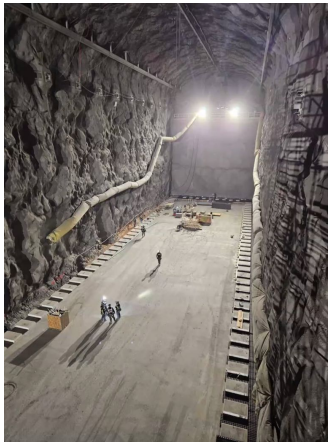
- **Neutrino beam** energy: 0.5 to 8 GeV with >2MW intensity
- Moveable **Near Detector** and separate on-axis detector 575m from the source
- **Far Detector (FD)** 1.5 km underground
- 4 modules of **17.5 kt each**

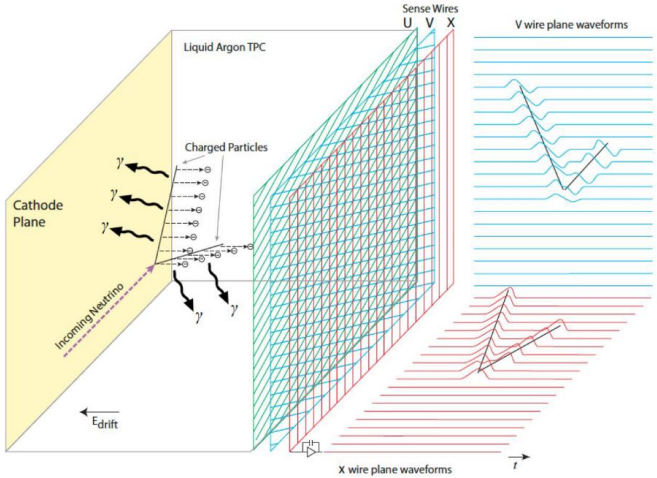
→ “DUNE Status and Science” talk given by Laura Pérez Molina yesterday

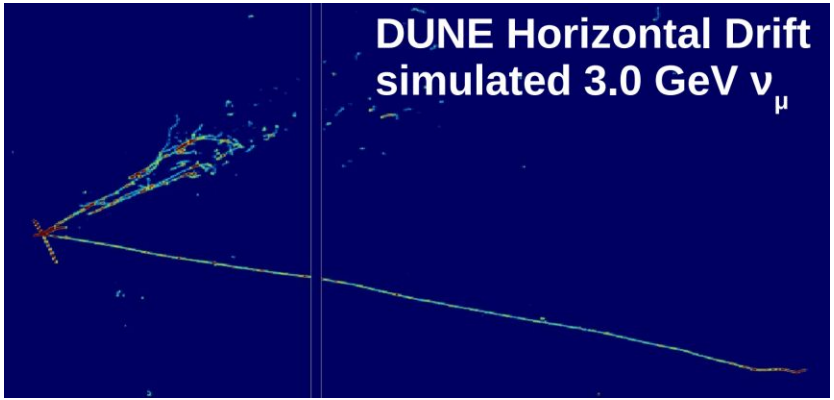
# DUNE FD

- LArTPC **high resolution event imaging** → kinematic reconstruction of nu interactions
- Excellent **event type classification** ($\nu_\mu$ CC, $\nu_e$ CC, NC and potential for $\nu_\tau$)
- Excellent **particle identification** (electron, mu, proton)
- **Photon Detection System**: timestamp for off beam events, 3D reconstruction
- **Low hadronic kinetic thresholds** → Proton ~*O*(25 MeV)
- Detector cavern has been excavated



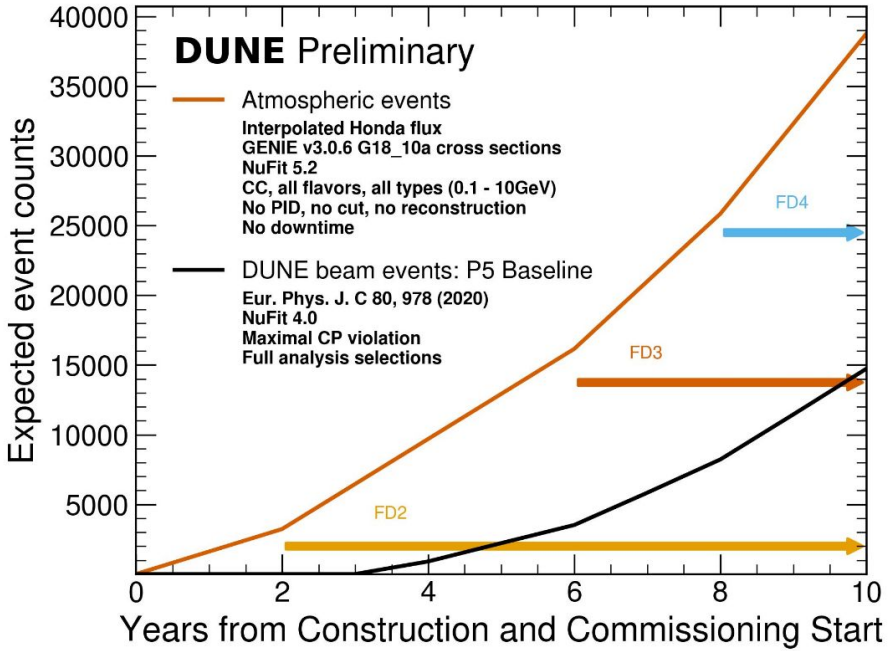


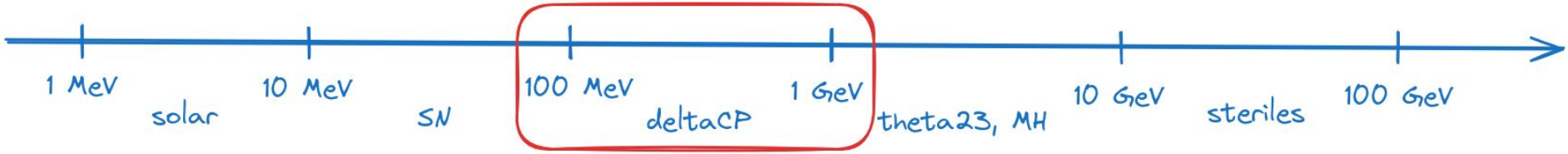
# Atmospheric neutrinos in DUNE

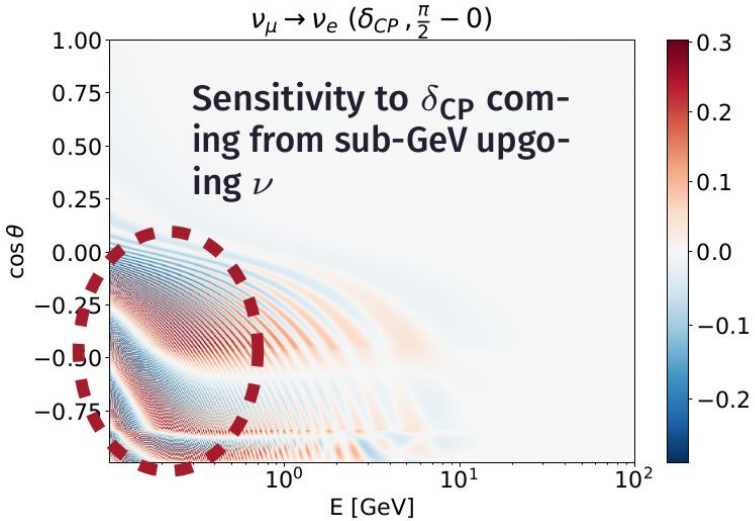
- Relevant → 2 DUNE FD modules will operate for **~2 years without any beam**
- Main source of neutrinos in early DUNE will be from atmospherics
- Expect **~2500 atmospheric neutrino events per 10kt per year** (including ~10 nutau events)

  → O($10^5$) atmospheric neutrinos expected in 20 years of DUNE operation

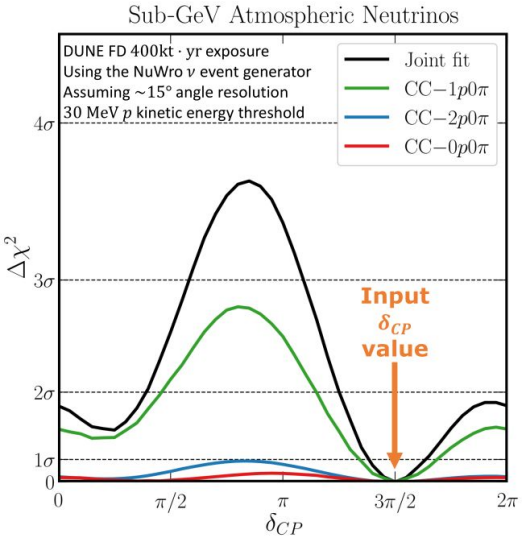


# Physics with atmospherics : $\delta_{CP}$



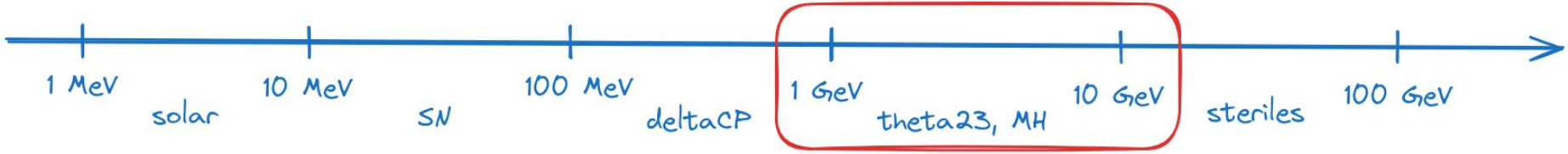




- Fast oscillations at E < 1 GeV
- Expect DUNE to be **able to reconstruct sub-GeV events**
- Sensitivity to $\delta_{CP}$ **complementary to beam**
- Subject to nuclear effects and cross-section systematics (different from beam due to energy range)

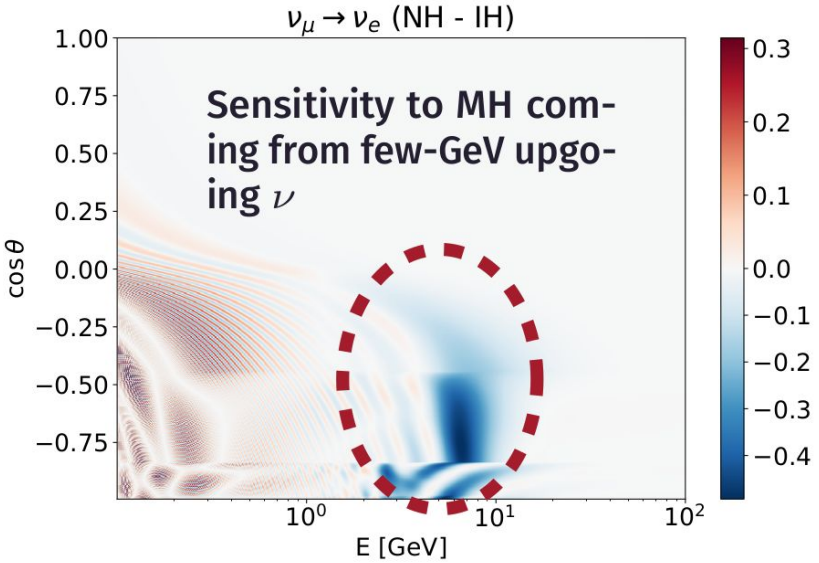



**April 2019 paper: "Sub-GeV Atmospheric Neutrinos and CP-Violation in DUNE"**

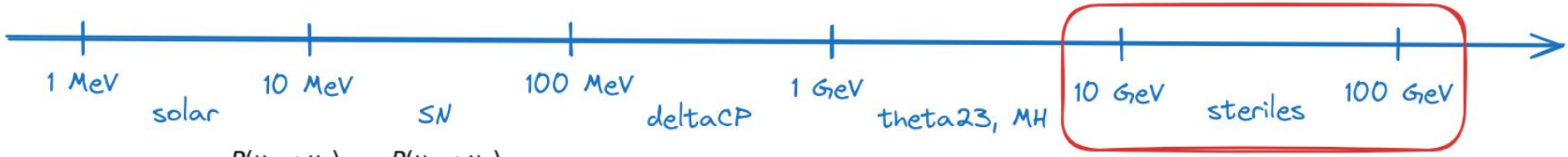
# Physics with atmospherics : MH and $\theta_{23}$

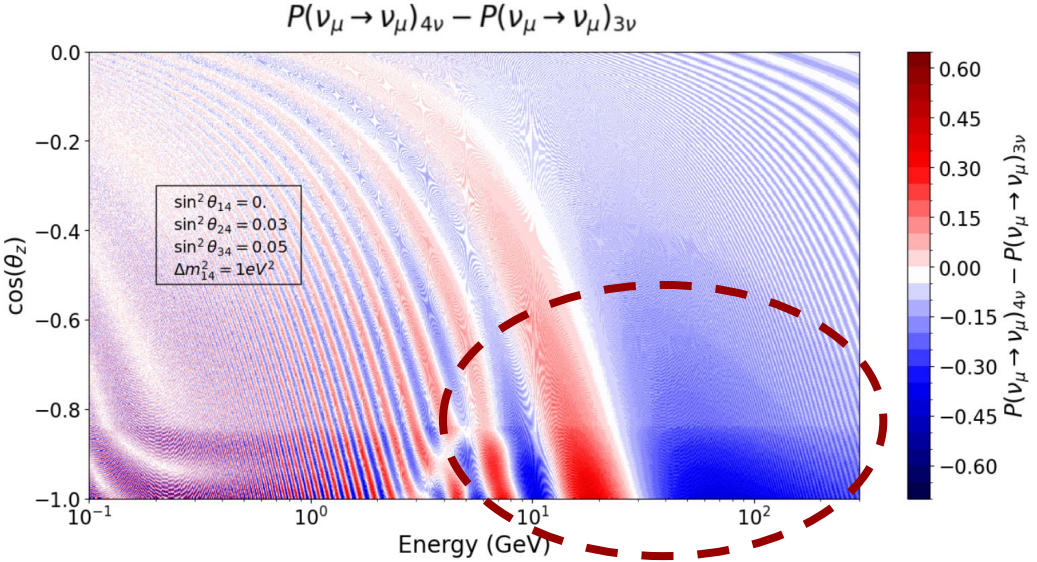



- **Most visible effect ~2-10 GeV** → well within the range of DUNE's capabilities
- Enhanced by capability to **separate nu/anti-nu events** → work on-going
- **Complementarity to beam** for BSM as well
- Ability to see **3 flavor oscillation modes** with nutau appearance



# Physics with atmospherics : sterile neutrinos

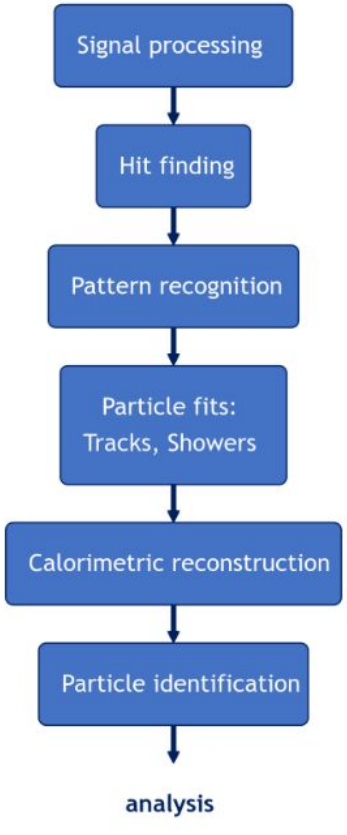



$sin^2\theta_{14} = 0$, $sin^2\theta_{24} = 0.03$, $sin^2\theta_{34} = 0.05$, $\Delta m^2_{14} = 1\ eV^2$

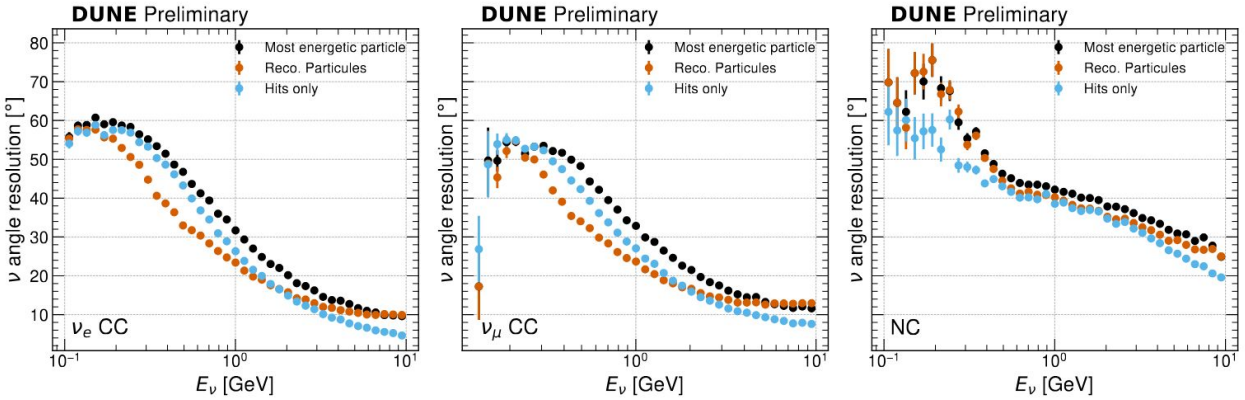
- Big part of **sterile neutrino effects are at high energy**
- Difference in event rate due to additional mixing states
- Important to properly reconstruct interactions to estimate this → **energy, direction, pid, …**
- **DUNE could be competitive with other experiments** for $\Delta m^2_{41} < 1\ eV^2$
- Challenges due to **containment effects**

# Reconstruction of atmospheric neutrinos




**MC simulation of 15M atmospheric events** used for studies with full event reconstruction optimized for atmospheric neutrinos:

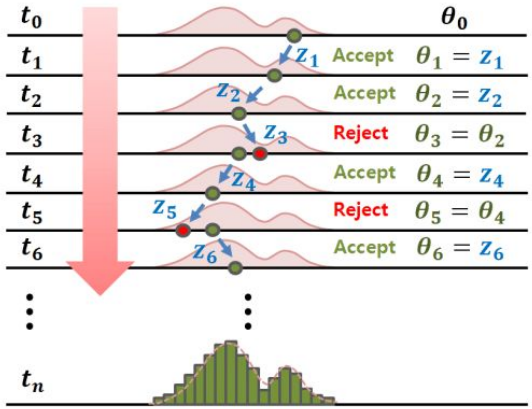
- **Neutrino direction** → needed to estimate the baseline. 3 methods for this:
  - Using **only the primary lepton** → like most detectors
  - Using **all reco final state particles** → need to measure kinematics of each particle
  - Using **all reco detector hits** for a calorimetric direction reconstruction
- Energy reconstruction of **partially contained muons**




**Paper on atm $\nu$ reco in DUNE coming soon**

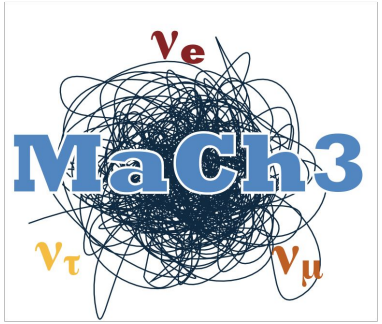
# Towards atm sensitivity studies

**MaCh3 software used as oscillation fitter** → relies on the sampling of posterior likelihood using Markov Chains. Already used in T2K
**Implementation of DUNE atmospherics in MaCh3 ready to go**

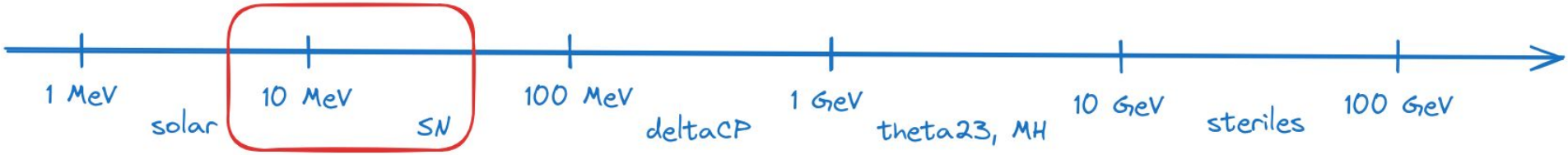



**Next steps:**

- First **statistics-only fits** with the reconstructed atmospheric sample for standard oscillation parameters and **multiple BSM scenarios**
  → NuOscillator package provides interface between MaCh3 and multiple oscillation probability computation frameworks
- Implementation of realistic **flux** (expecting updated Bartol and FLUKA models), **cross-section** (newly implemented GENIE tune) and **detector systematics**

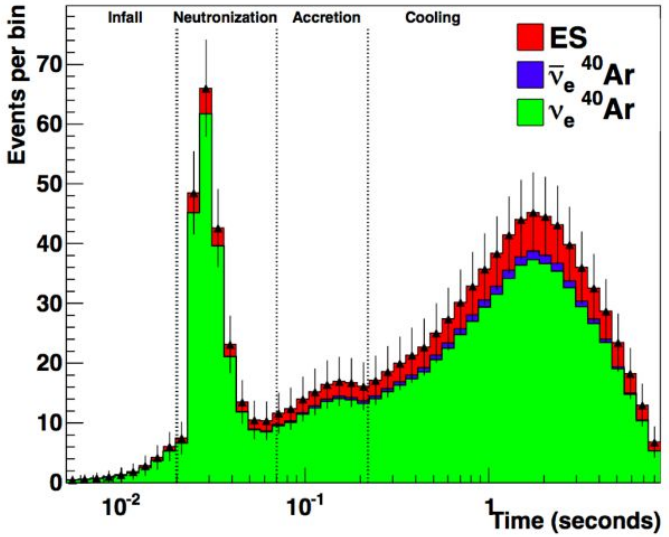


# Supernovae neutrinos in DUNE




- DUNE expects to see a **~3770 neutrino interactions** from the next galactic core collapse SN at 10kpc
- Expect DUNE to be **most sensitive to $\nu_e$ flux** produced from neutronization due to large CC cross-section
- DUNE **increases expected global $\nu_e$ rate from a 10kpc SN by a factor 150***
- **Charge and light systems of each module will trigger independently** on a SN burst to minimize downtime

*data from https://snews2.org/about/




**Expected number of SN neutrino interactions in DUNE with a 40 kt fiducial volume**

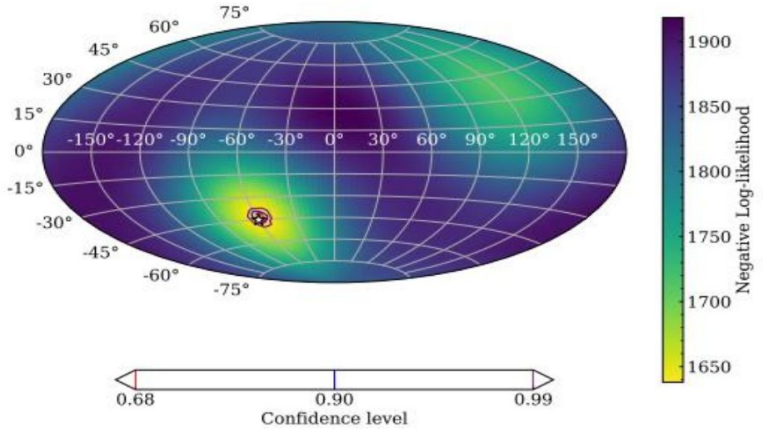
# SN physics and pointing

- Most models predict **flux described by pinched thermal distribution**
- DUNE will measure model parameters to describe conditions within the collapsed star

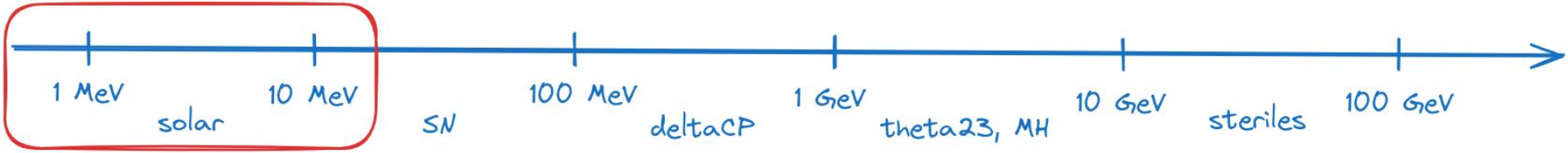
  → **measurement at 10kpc can distinguish between current models**
- Possibility to **probe neutronization burst** → mass ordering, collapse model, …
- **SN pointing:** neutrino experiments need to predict the source location in the sky
- In DUNE → **ES interactions carrying directional info are isolated using channel tagging algo**
- **Pointing resolution is 4.3°** (40kt mass, SN at 10kpc)

**May 2021 paper: "Supernova neutrino burst detection with DUNE"**

**May 2025 paper: "Supernova pointing capabilities of DUNE"**

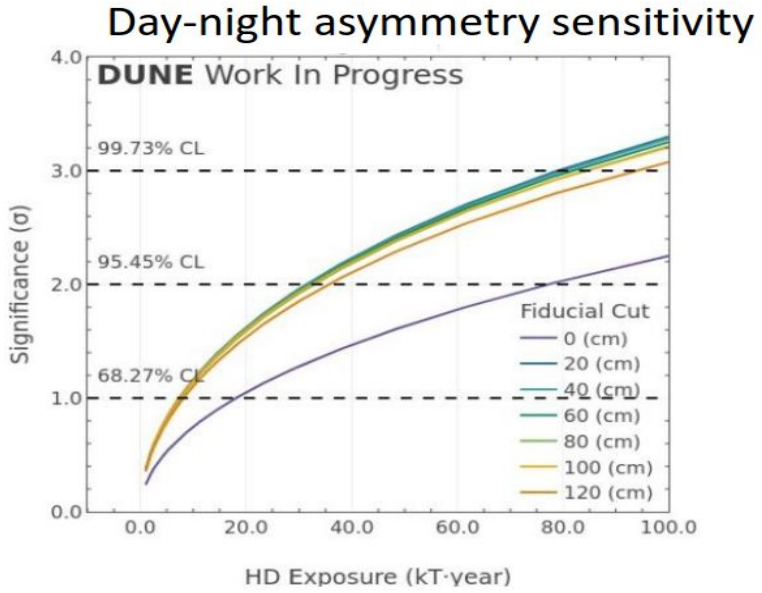


# Solar neutrinos in DUNE




- DUNE will record **several solar neutrino events/day/kt**
- DUNE has **no outer veto** → need to evaluate and characterize sources of background
- **External backgrounds** limit DUNE sensitivity → **new measurements in first years of operation** will improve current models
- Strong **sensitivity to $\Delta m^2_{21}$ due to day-night asymmetry** → **visible at $2\sigma$ within few years of operation**

**Sensitivity analysis maturing and heading towards publication**



# Reconstructing low energy neutrinos

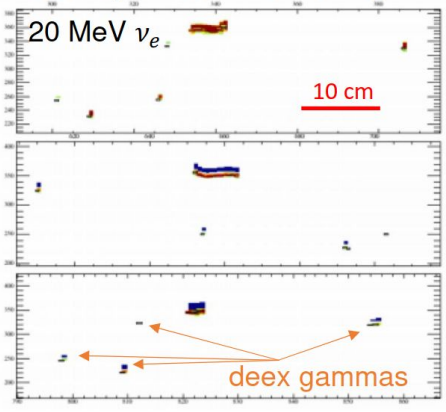
**Reconstruction:**

→ Largest labeled primary cluster → **$e^-$ candidate**

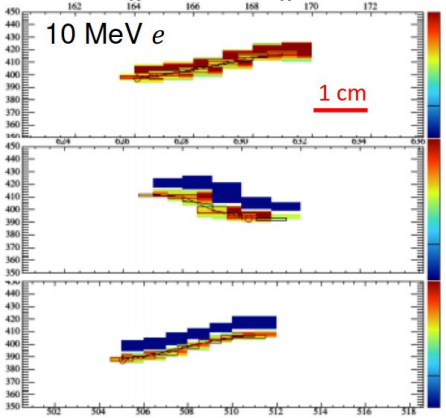
→ Adjacent clusters tagged as **de-ex $\gamma$ Compton**

→ Calorimetric reco of $e^-$ and $\gamma$ ionization energy

CC: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

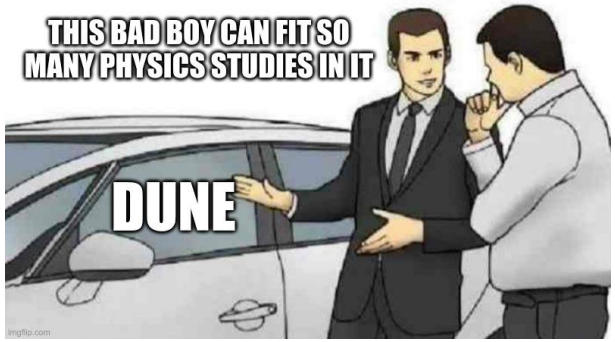



ES: $\nu_x + e^- \rightarrow \nu_x + e^-$




- **Sub-dominant channels:** NC interactions on Ar and neutrinos scattering off electrons (ES)
  → can be isolated with DUNE's precision tracking technology
- **Sub-cm resolution** shows distinctive signal topologies
- Information to **discriminate various low-energy signals + background**
- Work on-going → **deep learning for channel selection**

# Summary and conclusions

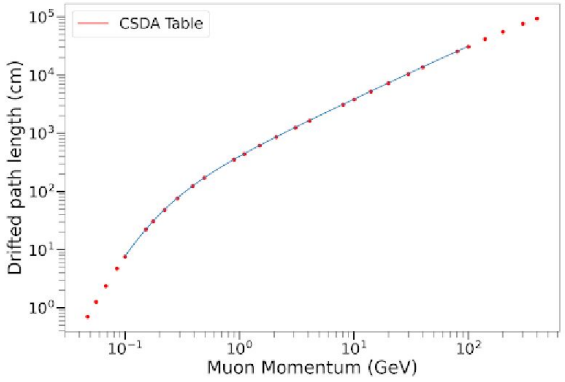


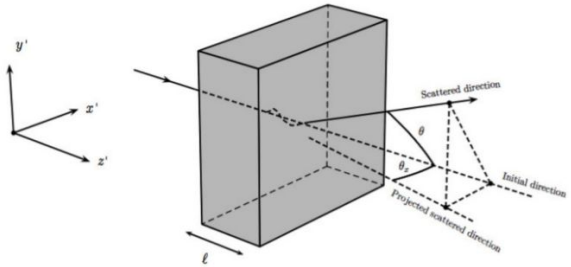

- **Wide range of physics studies** available for DUNE in addition to the beam program
- **Atmospheric oscillation analysis program progressing quickly** → targeted developments improving energy and direction resolution
- Sensitivity to $\delta_{CP}$, **mass hierarchy** and **BSM searches** like sterile neutrinos
- Next steps → **first statistics-only bayesian sensitivities** using MaCh3 + **implementation of various systematics** (flux, neutrino interaction, detector modelling, …)
- When operational, **DUNE will change the global SN neutrino landscape** → first $\nu_e$-sensitive detector at the multi-kt scale with 4.3° pointing resolution at 10kpc
- **Feasibility of solar neutrino measurements in a detector with no veto** is a testament to the LArTPC tracking technology → precision measurement of neutrino mixing and fluxes

**Publications coming soon on these different topics**

# Thanks a lot for your attention !

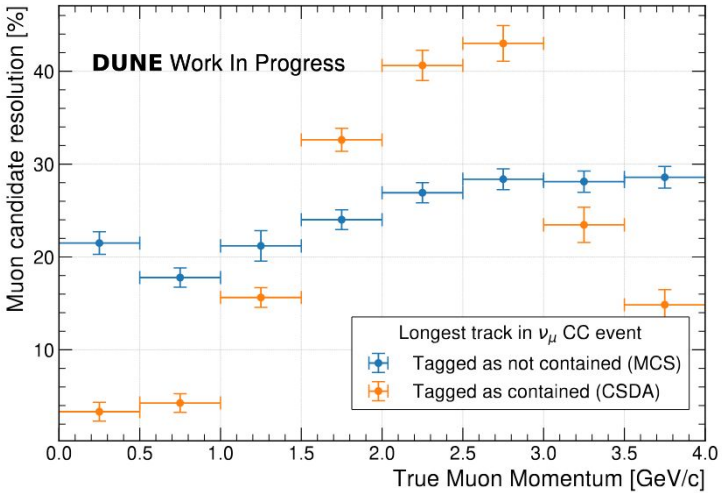
# Energy reconstruction of atm neutrinos



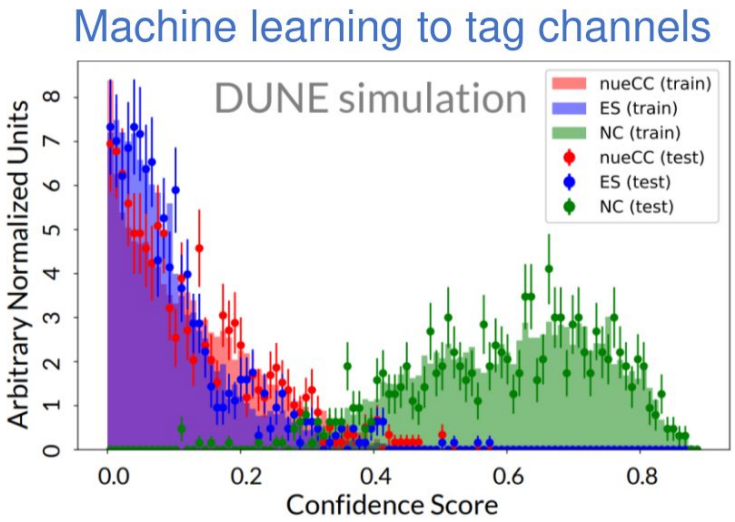

For contained tracks:
**Constant Slow Down Approximation (CSDA)**

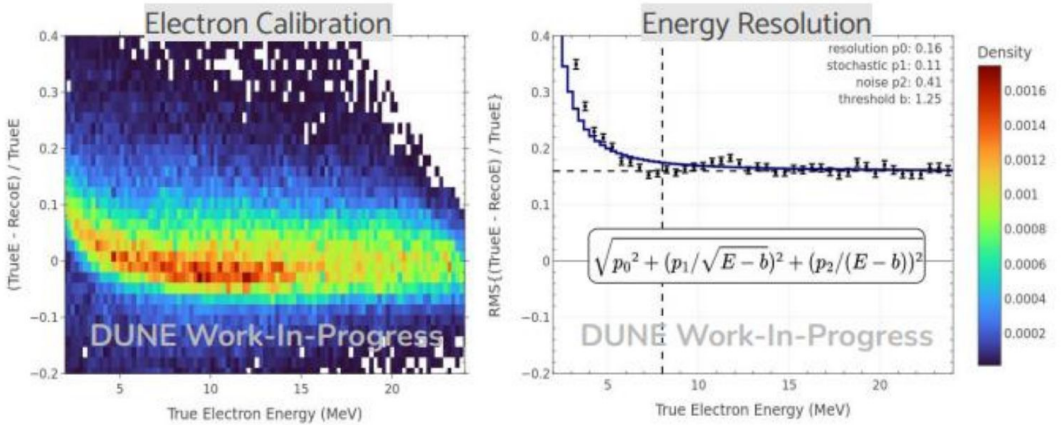
For uncontained tracks:
**Multiple Coulomb Scattering (MCS)**




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

# Reconstruction of low-energy neutrinos



# Solar neutrino backgrounds in DUNE

- **Internal argon:** from measurements of atmospheric argon activity by dark matter experiments
- **Components:** assay data of construction materials
- **Externals:** assays of rock and shotcrete with simulation of neutron and gamma backgrounds