

# Detector Considerations for $\nu$ Physics at a $\mu$ Collider Facility

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*Good  $\nu$ 's :  $\nu$  physics at a Muon Collider Workshop*

*Oct. 27 - 30, 2025*

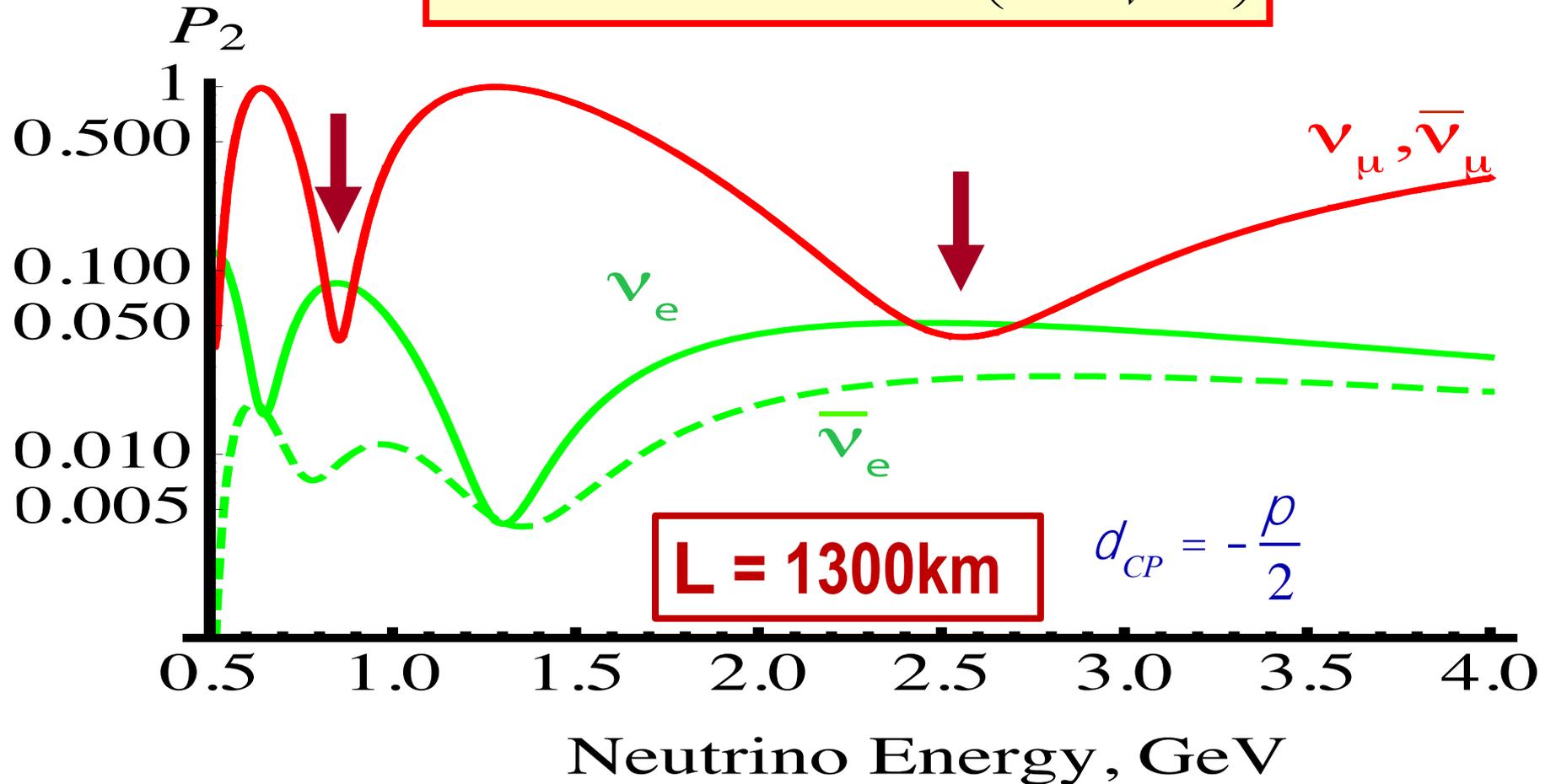


# How do we design a HEP experiment?

1. Identify physics goals to accomplish and the backgrounds to mitigate
2. Determine the capabilities and parameters for an experiment to meet the goals
3. Decide on the beam and the best detector technologies to meet the parameters
4. Perform R&D for beam and detectors
5. Design and build prototype detectors and perform testing
6. Design and build the full-scale experiment

# Neutrino Oscillation Probability

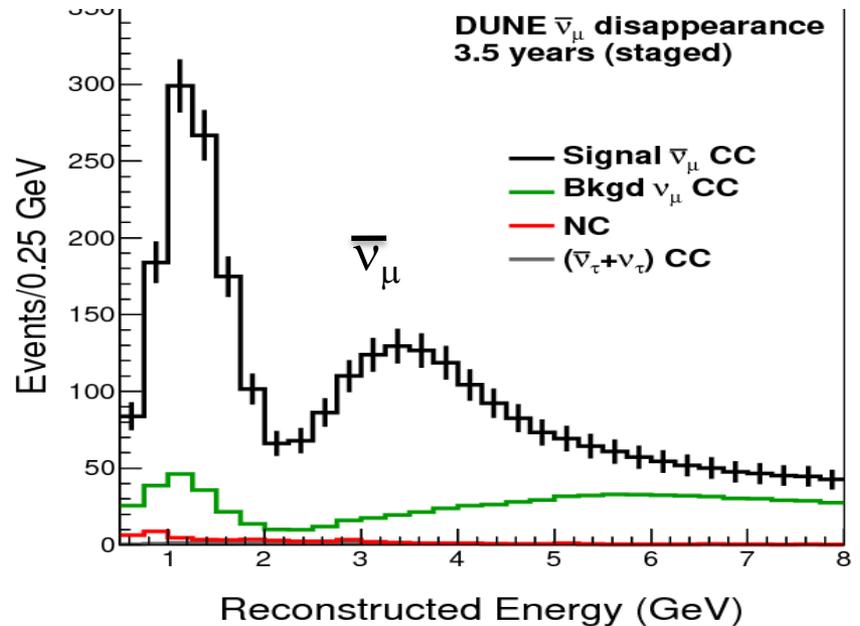
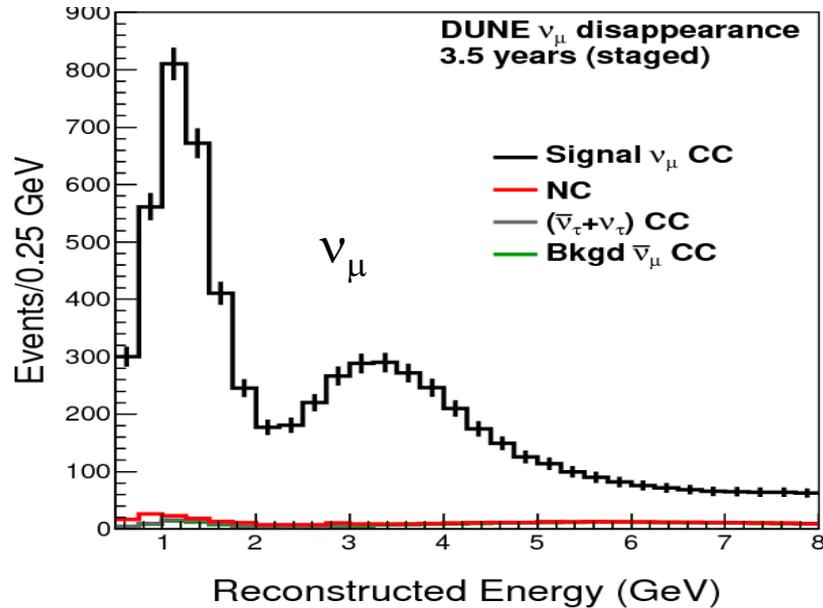
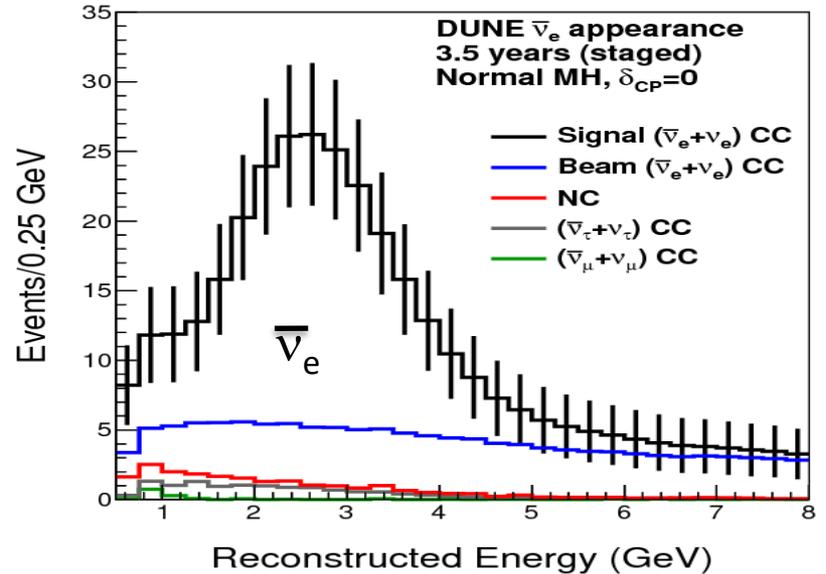
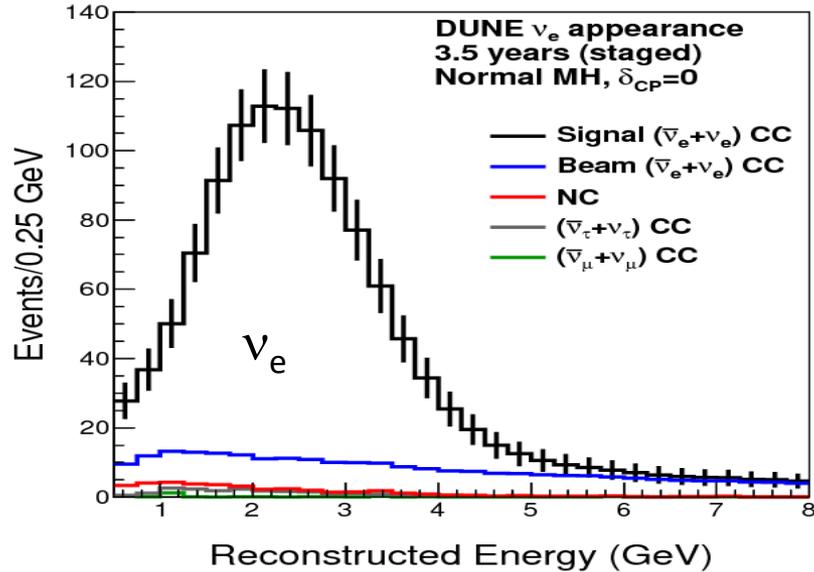
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right)$$



# What do we need for $\nu$ osc.?

- Need to measure the flux of each  $\nu$  flavor **before & after** the oscillations and compare them
  - Need to have high flux neutrino beams + Excellent ND
  - Need to be able to see e or  $\mu$  resulting from  $\nu_e$  and  $\nu_\mu$  charged current interactions
    - Need to be able to identify particles w/ high confidence
    - Need to have a precision 3D tracking
    - Need precision energy and momentum measurement with as low E threshold as possible
    - Still provide enough scattering centers for stats.

# Neutrino Flux



# DUNE Physics Requirements

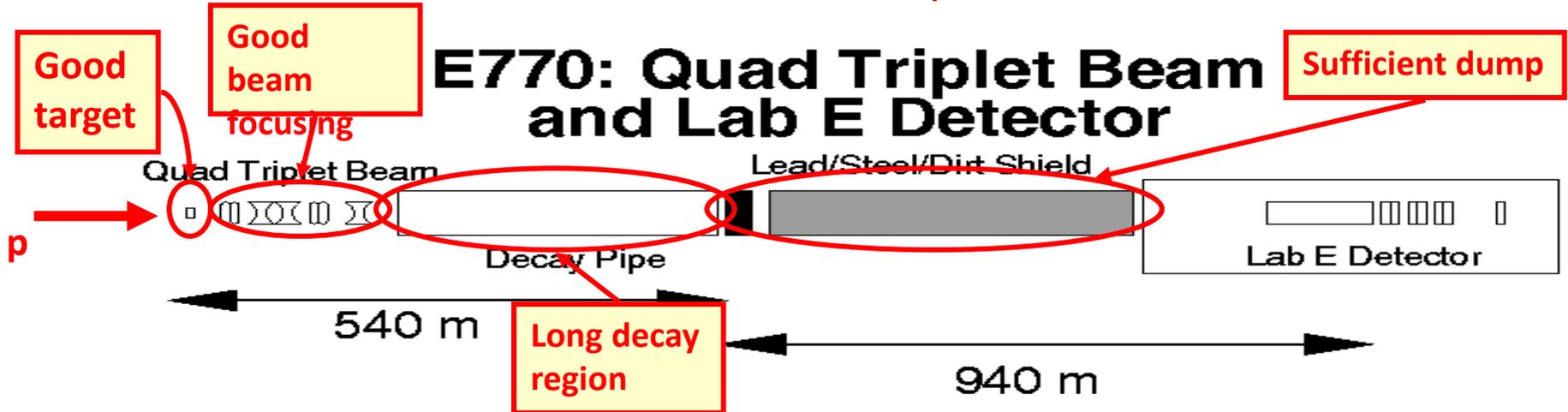
Table 4.1: Preliminary physics requirements that motivate APA design parameters.

Requirement	Value
MIP Identification	100% efficiency
High efficiency for charge reconstruction	>90% for >100 MeV
Vertex Resolution (x,y,z)	(1.5 cm, 1.5 cm, 1.5 cm)
<b>Particle Identification</b>	
Muon Momentum Resolution	<18% for non-contained <5% for contained
Muon Angular Resolution	<1°
Stopping Hadrons Energy Resolution	1-5%
Hadron Angular Resolution	<10°
<b>Shower identification</b>	
Electron efficiency	>90%
Photon mis-identification	<1%
Electron Angular Resolution	<1°
Electron Energy Scale Uncertainty	<5%

# Considerations for a $\nu$ Experiment

- Neutrino cross sections are small  $\sim 10^{-38} E_\nu$
- What should we do to increase statistics?
  - Increase the number of incident neutrinos
  - Increase the neutrino energy
  - Increase thickness of materials to interact with neutrinos  $\rightarrow$  Detectors with dense material
- Beam can be made to enrich a specific flavor of  $\nu$ 's in the optimal energy range
  - Focus and sign select charged mesons

# How to make a $\nu$ Beam?



- Use large number of protons on target to produce and focus as many secondary hadrons ( $\pi$ ,  $K$ ,  $D$ , etc) as possible
- Let charged  $\pi$  and  $K$ 's decay in-flight for  $\nu_\mu$  beam
  - $\pi \rightarrow \mu + \nu_\mu$  (99.99%),  $K \rightarrow \mu + \nu_\mu$  (63.5%)
- Other flavors of neutrinos are harder to make
- Let the beam go through shield and dirt to filter out  $\mu$  and remaining hadrons, except for  $\nu$ 
  - Dominated by  $\nu_\mu$

# Primary Sources of $\nu$ Beams

- Traditional source of neutrino beams are from meson decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (BR=99.98\%)$$

$$K^+ \rightarrow \mu^+ + \nu_\mu, K^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (BR=63.56\%)$$

$$K^+ \rightarrow \mu^+ + \nu_\mu + \pi^0, K^- \rightarrow \mu^- + \bar{\nu}_\mu + \pi^0 \quad (BR=3.35\%)$$

$$K^+ \rightarrow e^+ + \nu_e + \pi^0, K^- \rightarrow e^- + \bar{\nu}_e + \pi^0 \quad (BR=5.07\%)$$

- Source of tau neutrinos ( $D_s$  decay to  $\tau$ ,  $BR = 5.79\%$ )

$$D_s^+ \rightarrow \tau^+ + \nu_\tau \rightarrow X + \nu_\tau + \nu_\tau$$

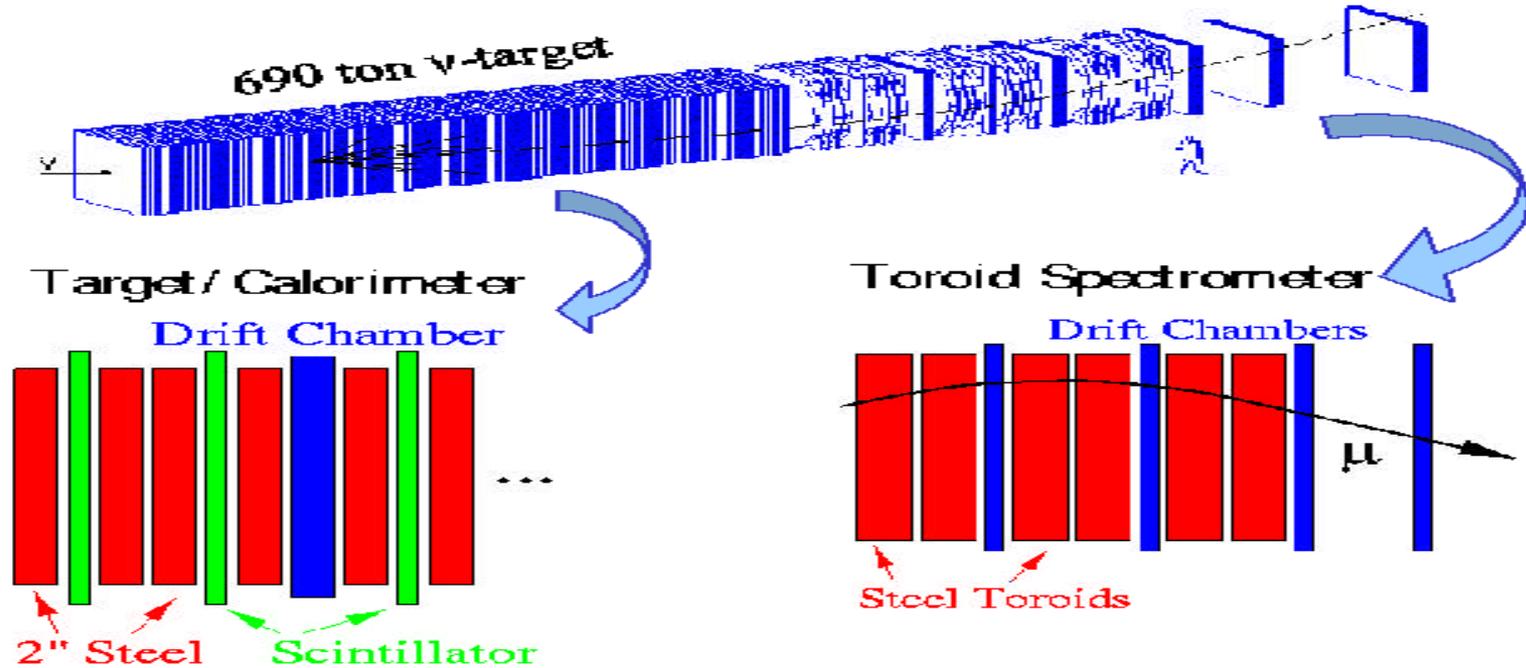
$$D_s^- \rightarrow \tau^- + \nu_\tau \rightarrow X + \nu_\tau + \bar{\nu}_\tau$$

- Detection through  $\tau$  decays in the detector (precision tracking!)

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-, \tau^+ \rightarrow \nu_\mu + \bar{\nu}_\tau + \mu^+$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^-, \tau^+ \rightarrow \nu_e + \bar{\nu}_\tau + e^+$$

# A Typical Past Neutrino Detector



- Purposed to probe the internal structure of the nucleons (DIS)
- Large amount of material in the path of neutrinos
- Insufficient capabilities for precision  $\nu$  oscillation measurements, can't tell  $\nu_e \rightarrow$  Some other technology needed
- $\nu_\tau$  requires identification of  $\tau$  leptonic decays ( $\nu_\tau \nu_\mu \mu / \nu_\tau \nu_e e$ )

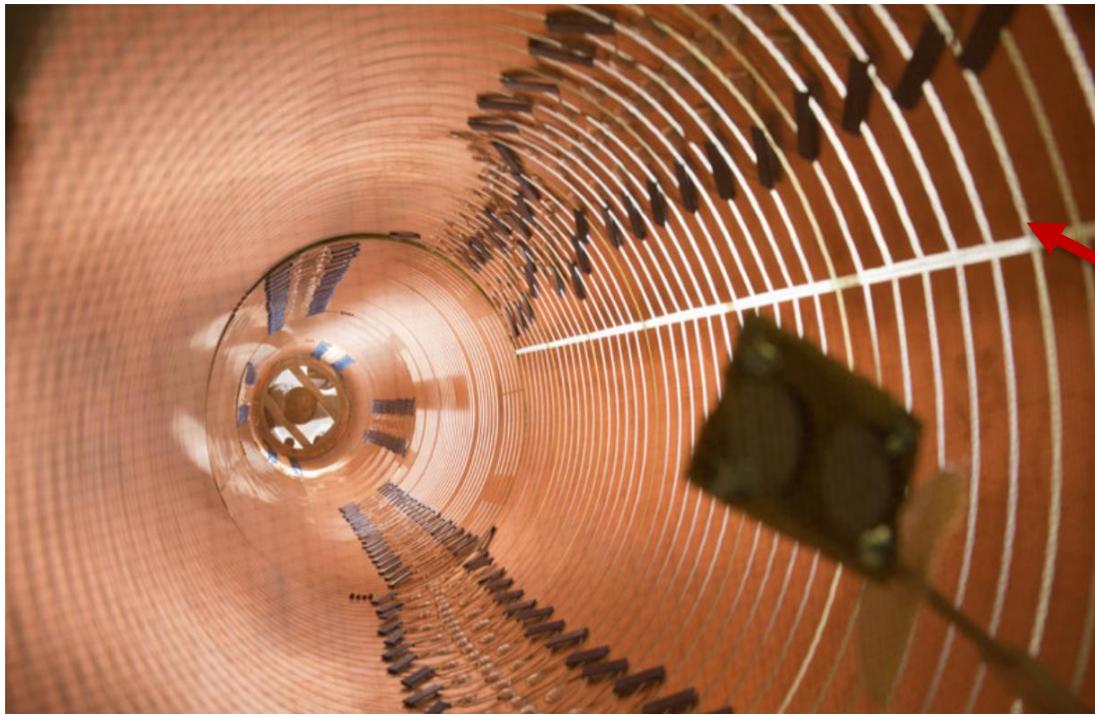
# The NuTeV Detector



*A picture from 1998. The detector has been dismantled to make room for other experiments, such as  $D\bar{D}$*

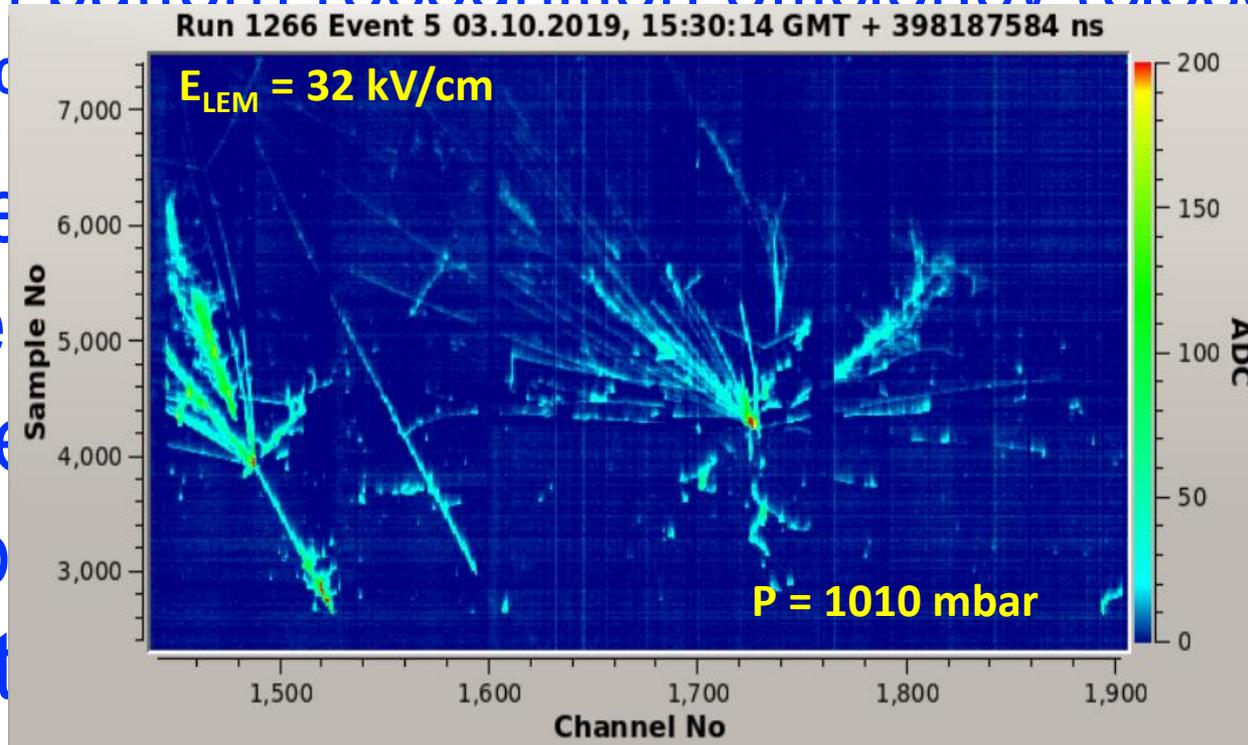
# What is a Time Projection Chamber?

- A precise particle tracking detector with 3D imaging capability and an energy measurement capability
- Initially developed in mid-1970's at SLAC for a tracking detector in  $e^+e^-$  collider experiments with a gas mixture

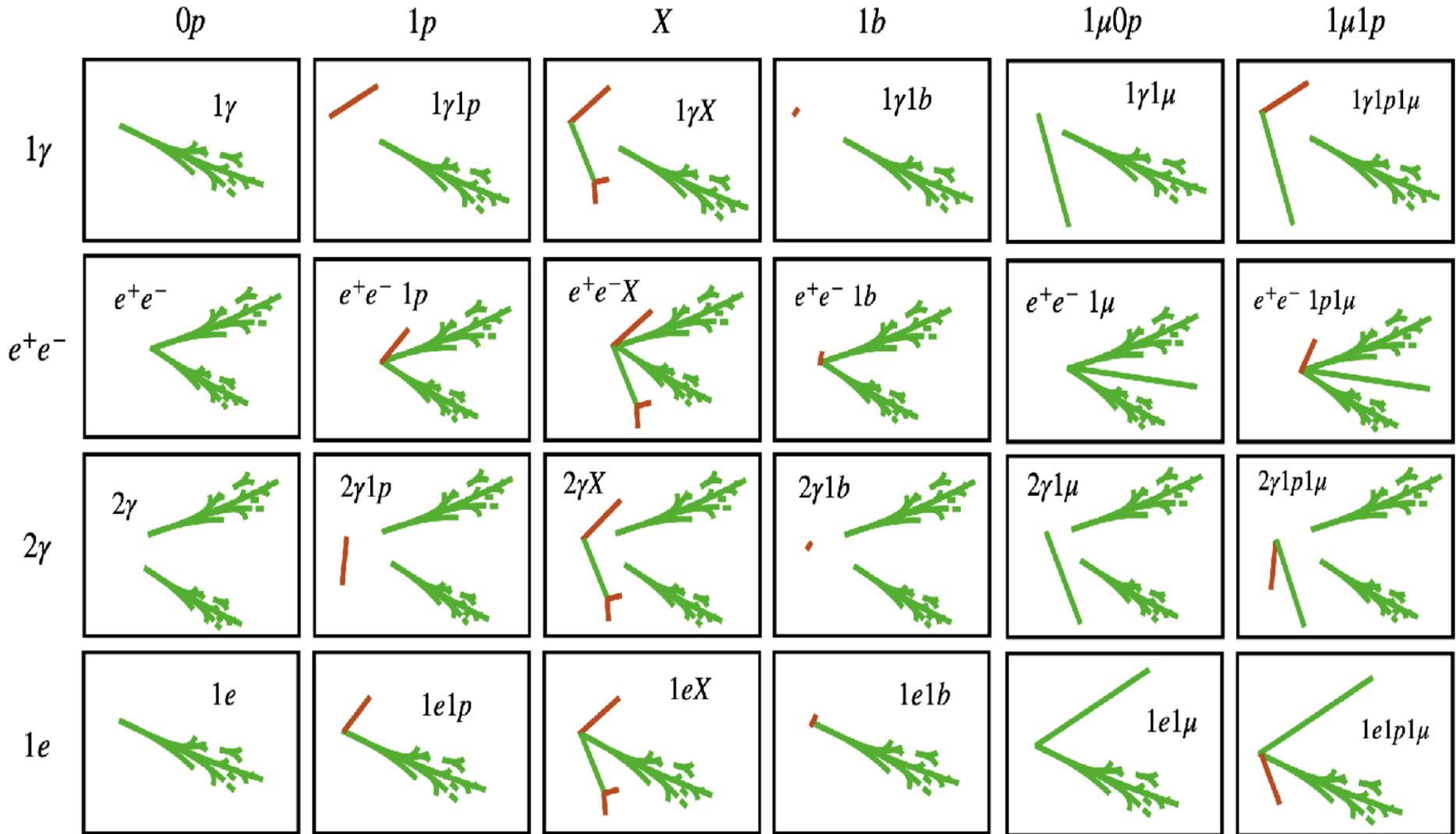


# Why TPC?

1. High 3D spatial resolution 50 ~ 200 $\mu\text{m}$
  2. High pattern recognition efficiency (close to 100%)  
excellent pattern recognition →
  3. Over 10 years of operation
  4. Excellent energy resolution
  5. Good timing resolution
  6. Fast readout
  7. Compatible with high magnetic field
  8. Reliable in operation
- Thresholds



# LArTPC Performance from $\mu$ BooNE

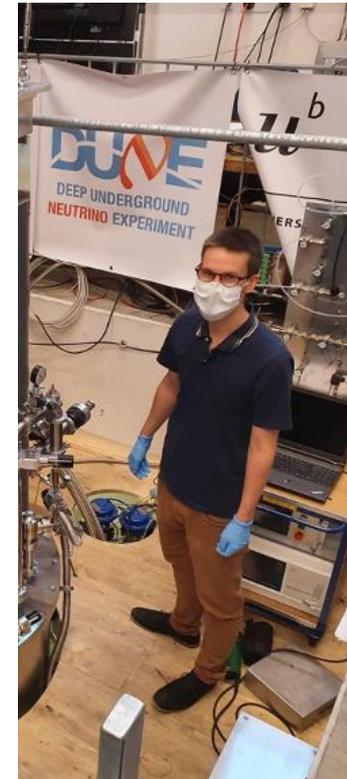
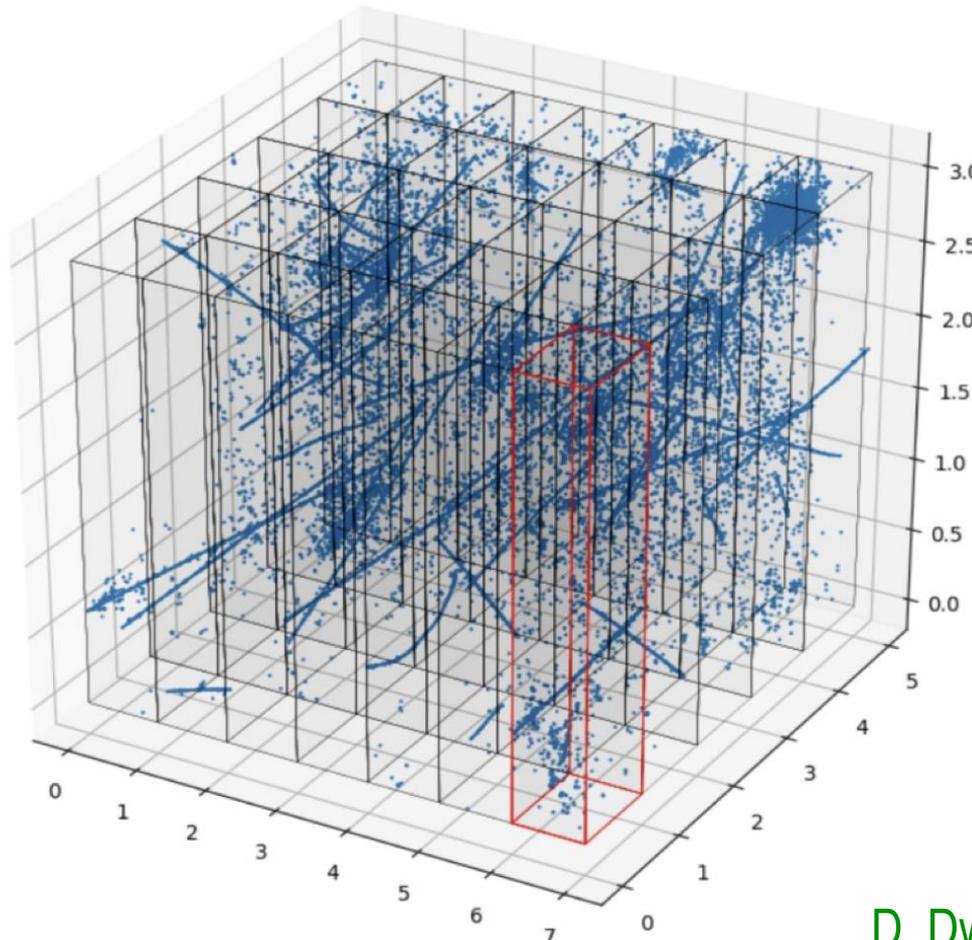
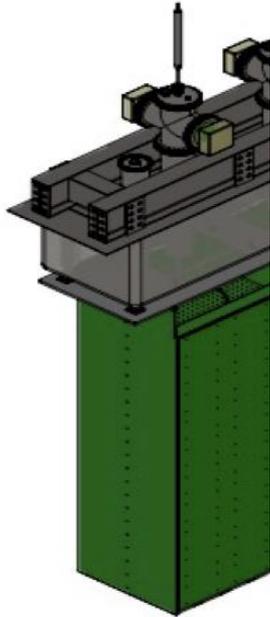


D. Caratelli & B. Littlejohn

# DUNE ND Ar Cube

- DUNE ND – 3m (H) x7m(W)x5m(L) – consists of 35 Ar cube modules in 7 banks of 5 modules with pixelate ( $10^7$  pixels, 4mm pitch) readout design → each module is 3m (H)x1m(W)x1m(L)

LOW POWER SUPPLY: LOW HIGH VOLTAGE F  
LOW POWER DISSIPATION



# Traditional $\nu$ Exp. Beams & Trigger

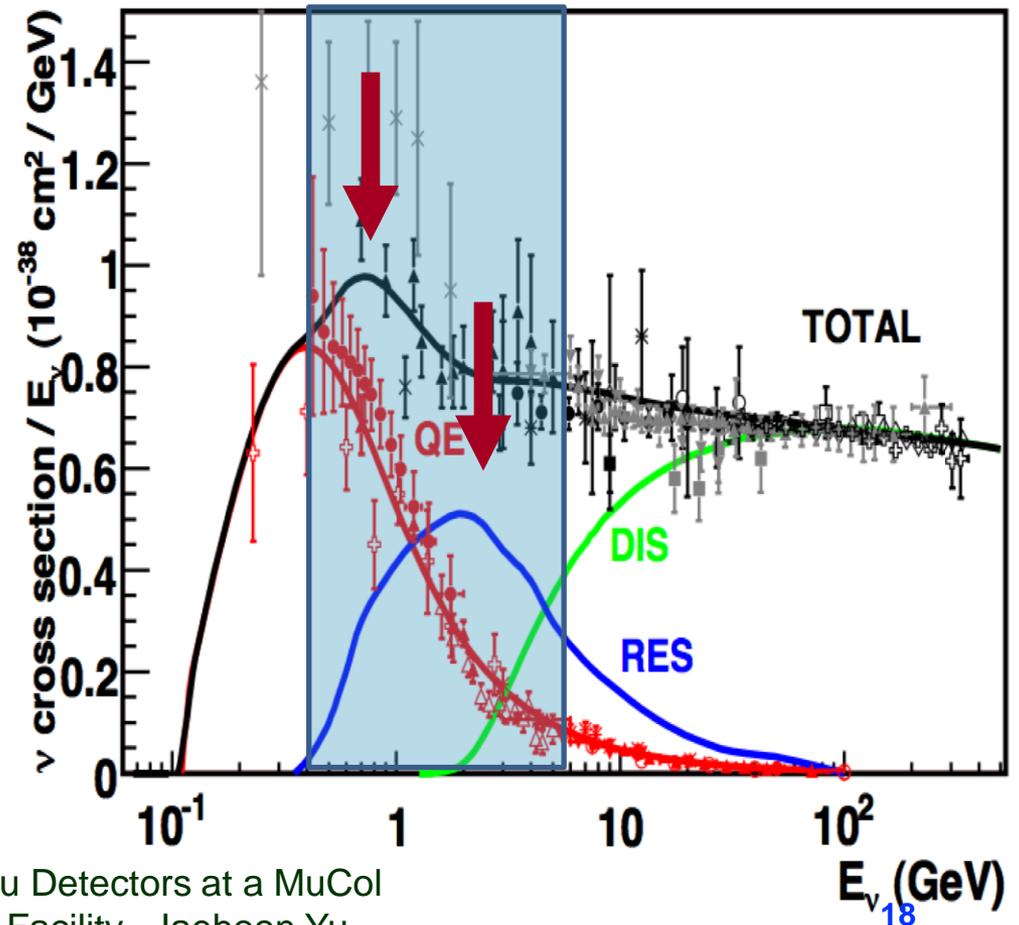
- To minimize the impact of cosmic rays, the proton beams are injected in successive short pulses, called the pings
- Detectors receive the accelerator timing information to open the "gates" for them to trigger and record the interesting events
- Use scintillation lights from the  $\nu$ -N interaction as the initial trigger

# What are possible $\nu$ physics?

- Further precision measurements of neutrino properties, including the oscillation (matter effect?) and CPV properties → Would be good if we could use an existing experimental facility, such as DUNE
- Can we measure the neutrino mass, since we can see both neutrinos and anti-neutrinos of e and  $\mu$  species?
- High precision  $\nu$ -N cross section measurement at various energies?
- But definitely BSM topics involving  $\nu$
- Would be even better if we had discovered (a) new particle(s)

# Low $E_\nu$ Interactions

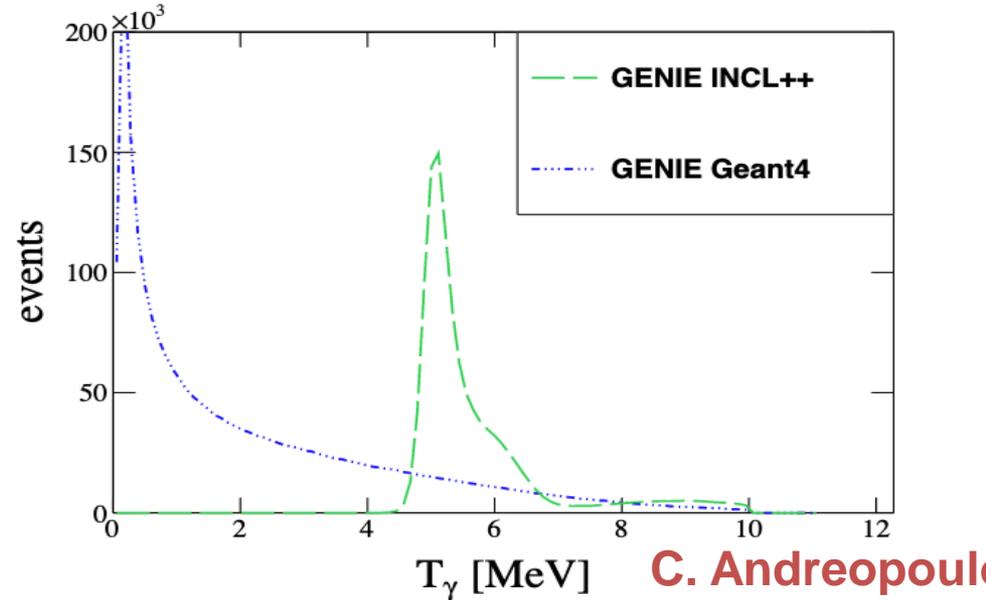
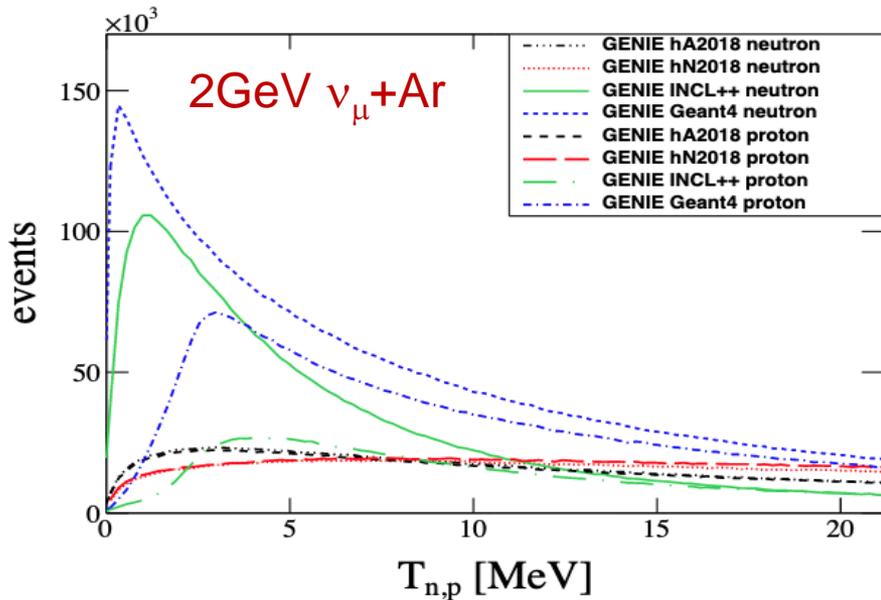
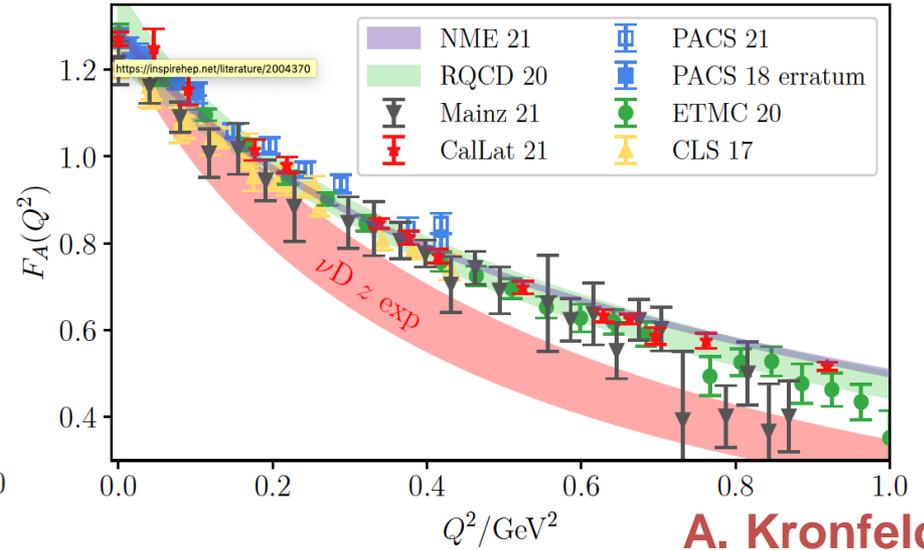
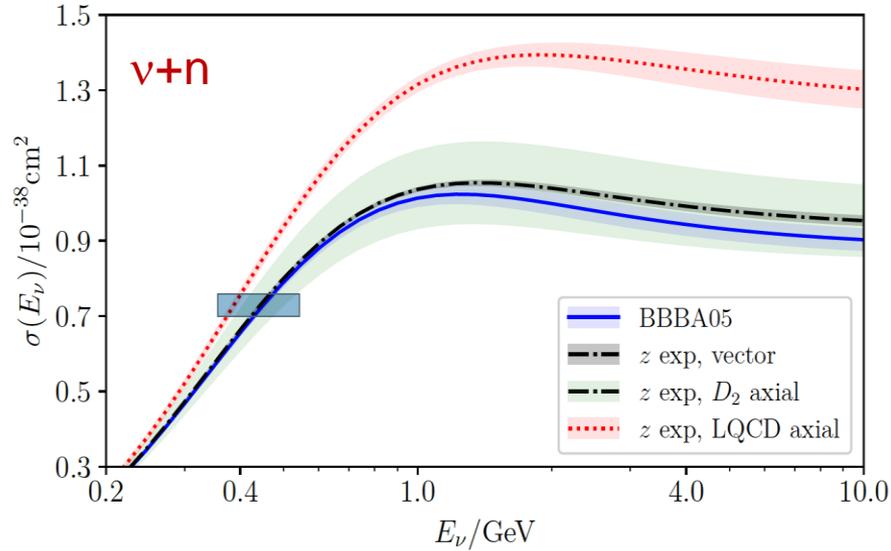
- QE & RES dominates  $\nu$ -N interactions in  $E_\nu$  range where the two oscillation maxima reside, for the case of DUNE  $\rightarrow$  Critical for more precision detection & BSM
- Large uncertainties for  $\nu$ -N x-sec calc.
- Intense  $\nu$  beam at  $\mu$ -col could provide precision x-sec measurements
- Higher  $E_\nu$  dominated by DIS and somewhat better understood



Oct. 28, 2025

Nu Detectors at a MuCol  
Facility, Jaehoon Yu

# $\nu$ -N interaction Modeling Uncertainty



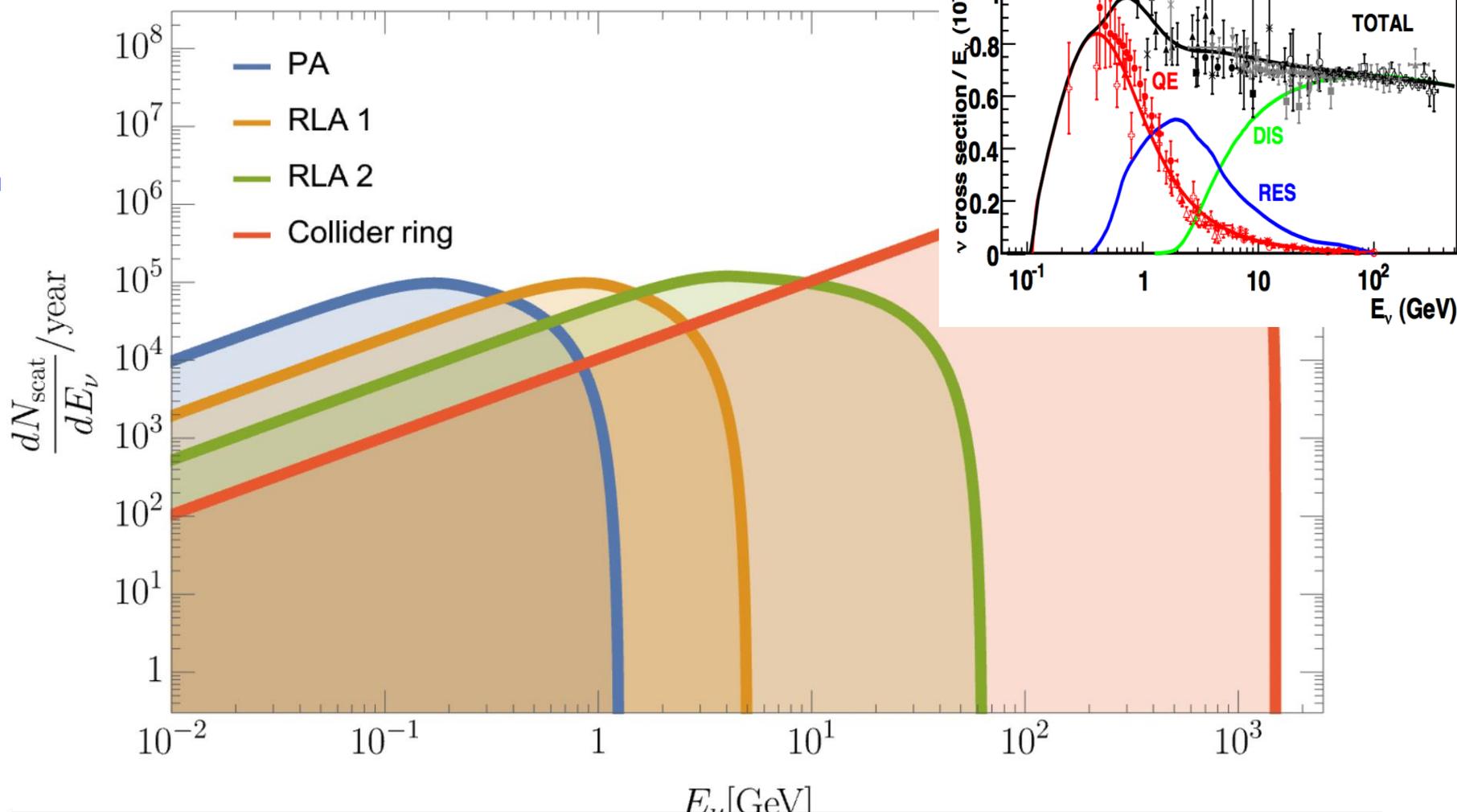
# $\nu$ Event Rates

- Previous experiments : very low rates in both ND and FD (few hundreds of events in FD in a year)
- Event rates for DUNE LArND :  $10^8 \nu_{\mu}$  CC/yr
- Event rates for Mu Col :  $1.7 \sim 5.4 \times 10^9$  CC/yr in E+HCAL
  - Accounting the  $\rho$  and  $V$  difference, rate is similar to DUNE ND
- Given the rates and higher neutrino energies, a paradigm change of detection method necessary  $\rightarrow$  DUNE ND style, cubed modular detectors with pixelated readout with a self triggering capability
  - Self-triggering pixel readout chip (Q-Pix) R&D on going

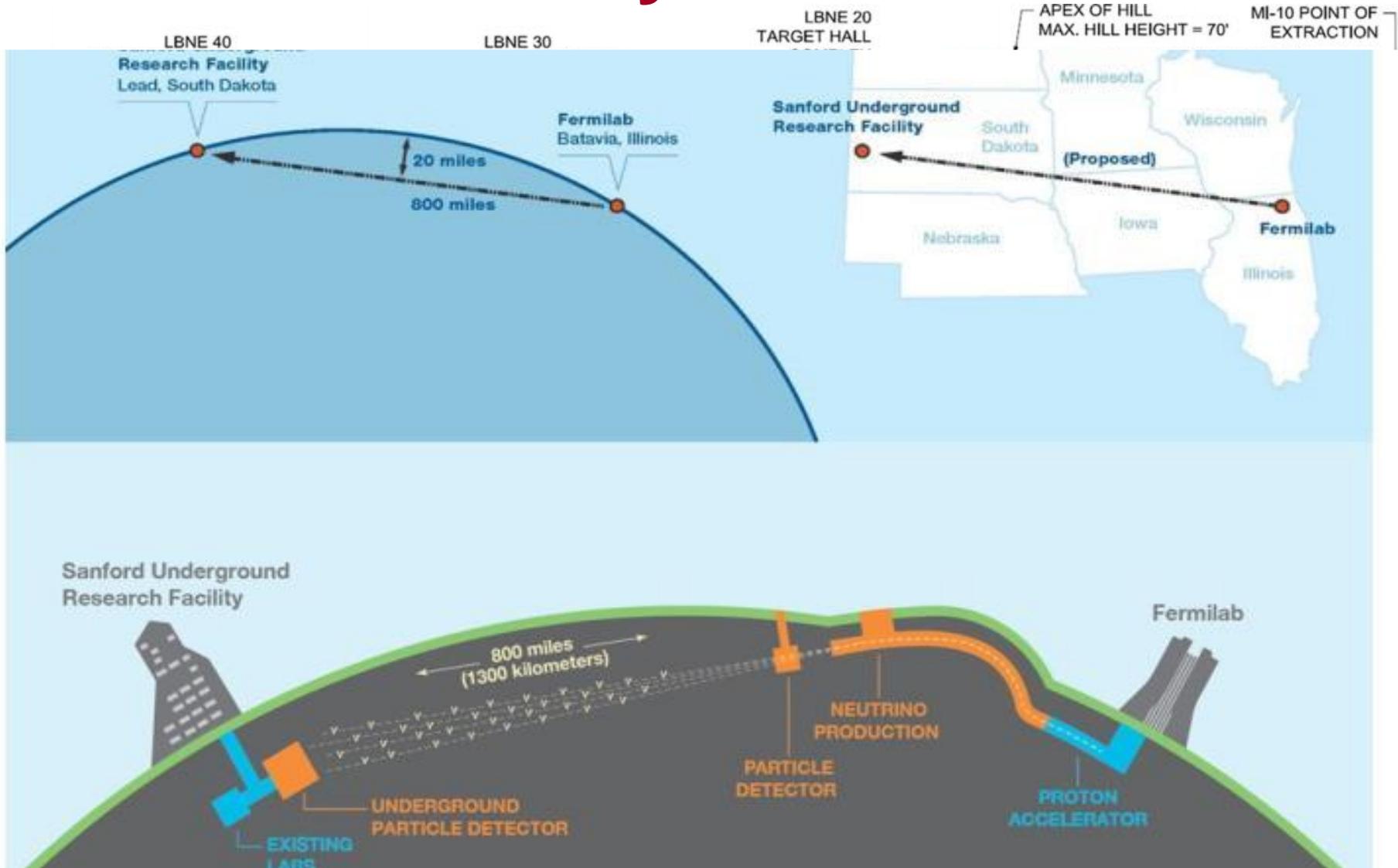
# Taking Advantage of Existing Exp.

- We

$\nu$  emitted w/ 1 meter of LAr (not



# Anatomy of DUNE



Cosmic  $\mu < 1/100M/s/cm^2$

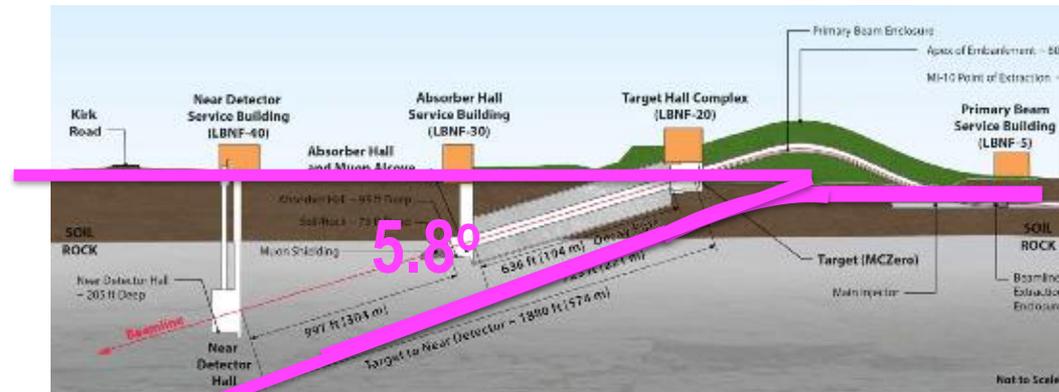
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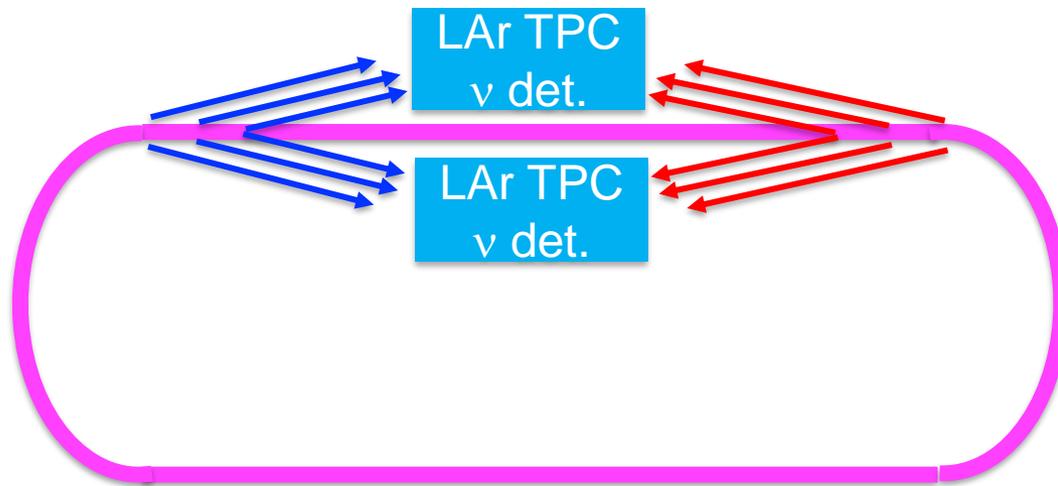
# Consideration for Race-Track Style

- We will still need to do precision measurements of  $\nu$  properties
- Taking advantage of better understood beams of both  $\nu$  species and the existing DUNE ND and FD, along with the deep underground nature ( $N_{\mu} < 10^{-8}/s/cm^2$ ) of DUNE essential
- The storage ring, however, needs to be built with the correct angle to aim DUNE or HK (even stiffer!)



# Detectors along a straight section?

- A dedicated  $\nu$ -slice detector can be placed sufficiently away from the collider ring to ensure neutron absorption  $\rightarrow$  FASER experience would be helpful in estimating the backgrounds
- Could also contemplate such dedicated detector near the straight section of a race-tracked storage ring, RLA or the collider ring with a straight section for high intensity  $\nu$  beams



# $\nu$ Detector Requirements @ $\mu$ -col

- Fast timing and excellent timing resolution  $\rightarrow$  needed to overcome the pile-up events from particles unassociated with the collisions
- Excellent position and vertex resolution
- Capability to provide the directional information  $\rightarrow$  is the event caused by the  $\nu$  circling clockwise or counter-clockwise?
- Excellent energy and mass resolutions
- Ability to measure momentum and the sign of the charge
- Self-triggering capability to capture  $\nu$  interactions unrelated to the collision
- Ideal if located underground
- Should be able to take advantage of AI  $\rightarrow$  pixels may be better than the wire-based geometry

# How is $\nu$ Experiment Different @ $\mu$ -col?

- Systematics from the  $\nu$  flux not an issue
- $\nu$  event statistics similar to DUNE ND
- Detector related systematics still remain
- Understanding the  $\nu$ -N interactions essential for expected physics topics at a  $\mu$ -col facility  $\nu$ -experiments
  - $\nu$ 's become serious backgrounds, especially for high  $E_\mu$  collider facility

# Summary

- Precision detector experiences at DUNE and other next gen  $\nu$  exp. would be essential for  $\mu$ -col facility  $\nu$ -exp
- Essential to have good ideas on physics goals
  - Which facility?
  - Final states?
  - Background?
- Need to determine the detector requirements for the goal
  - Need to establish detector R&D plan to meet the requirements in a timely fashion
- Need to have a much better understanding of the  $\nu$ -N interaction modeling