Development of FORTVNE: Forward TeV Neutrino Detector

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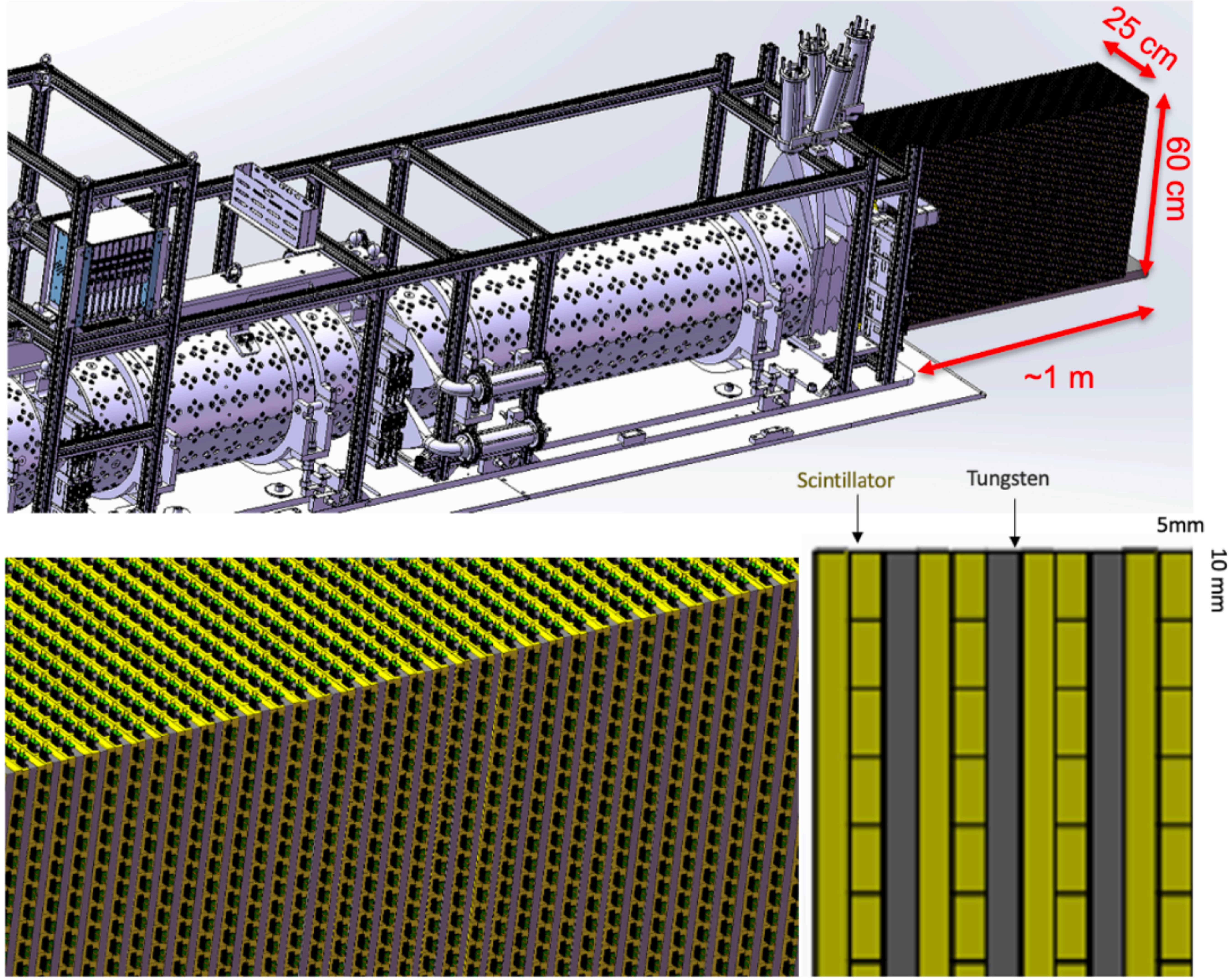
Background: FASER Run 4 Upgrade

- FASER and FASERν have proved the ability to discover and measure TeV neutrinos from the LHC
- FASER has been approved for Run 4
  - an upgraded detector will collect 680 fb^{-1}, and quite possibly up to 3 ab^{-1} if run through the end of HL-LHC
- Emulsion is expensive, cannot envision having emulsion in place for all 680 fb^{-1} of Run 4
- If we replace FASERν for all or most of Run 4, we should replace it with something that continues/enhances the neutrino program
- We have 1 or 2 boxes of tungsten that can be reused. Each box is ~1 tonne, consisting of 730 1 mm x 25 cm x 30 cm plates
- UCI group is pursuing a US NSF Major Research Infrastructure program
  - ~$20 set aside to fund construction projects up to $4M over 5 years (2025-30)
  - Each major University may submit 1 proposal, and we have been selected as UCI's proposal this year

Leading PIs at UCI:
Jonathan Feng
Jianming Bian
David Casper
Michael Smy

FORTVNE

- Tungsten/Scintillator bars
- 99 cm x 25 cm x 60 cm
  - 2 FASERν stacked up, with emulsion replaced by scintillator bars
- 66 repeating modules, each is
  - 5 mm tungsten (1.5 X_0)
  - 5 mm horizontal scint. bars (YZ view)
  - 5 mm vertical scint. bars (XZ view)
  - For each scint. bar: 0.5 cm x 1 cm
- Total mass: 0.954 tonnes
- Extended coverage upwards: η > 7.6 (FASERν: η > 8.5, FASER: η > 9.2)
- No CE required, no disruption to FASER spectrometer, re-uses 660 tungsten plates



Neutrino Physics

- Segmentation is too coarse for ν_τ physics. Would have preferred SciFi, 0.2 mm-diameter fibers. However, it would exceed \$4M budget. It would be good to re-visit this if other funding comes through
- Still there is significant physics case from both ν_e and ν_μ neutrinos at TeV energies, and possibly some BSM searches (thanks to Felix, Max, Roshan, Toni)

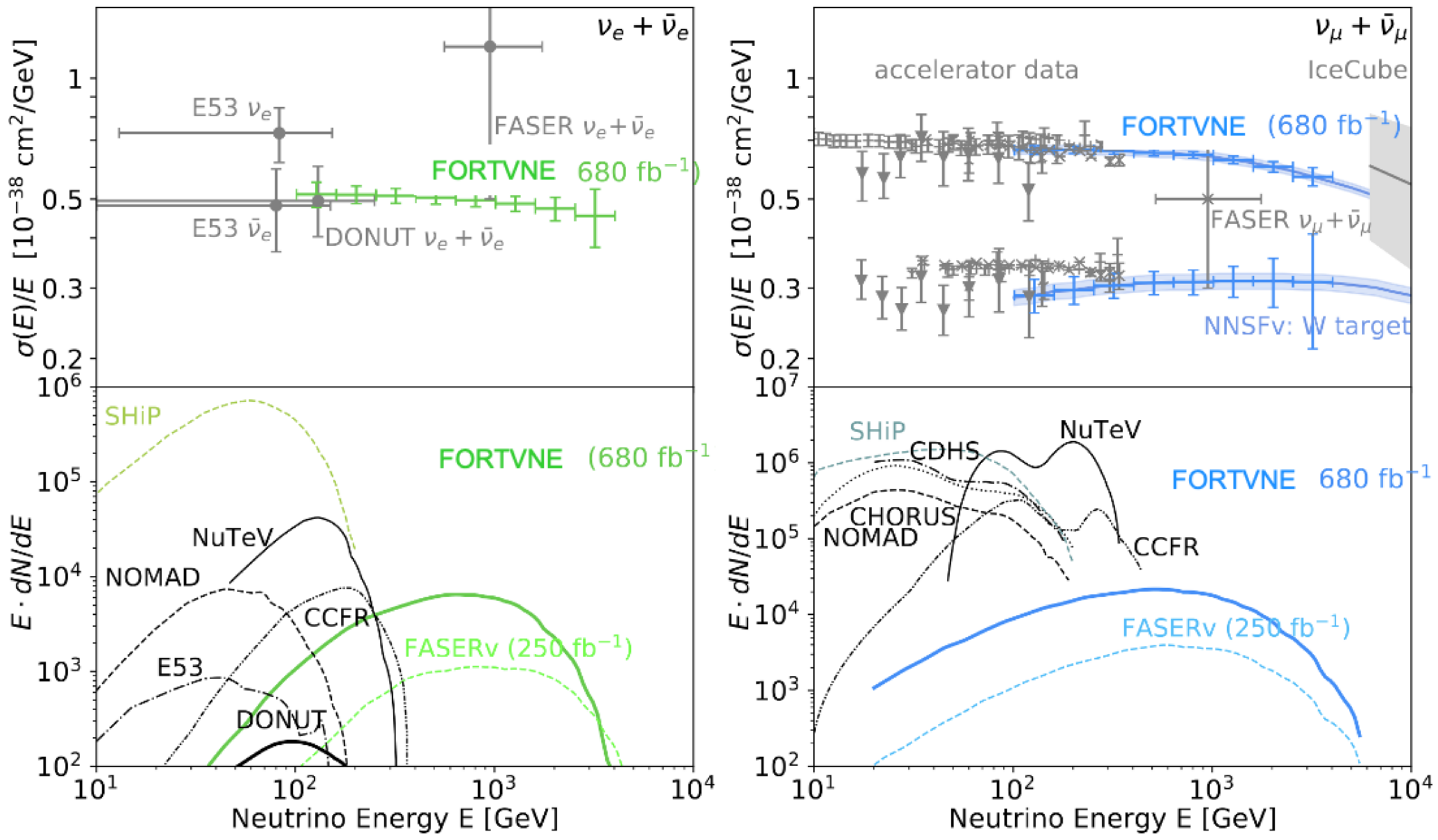
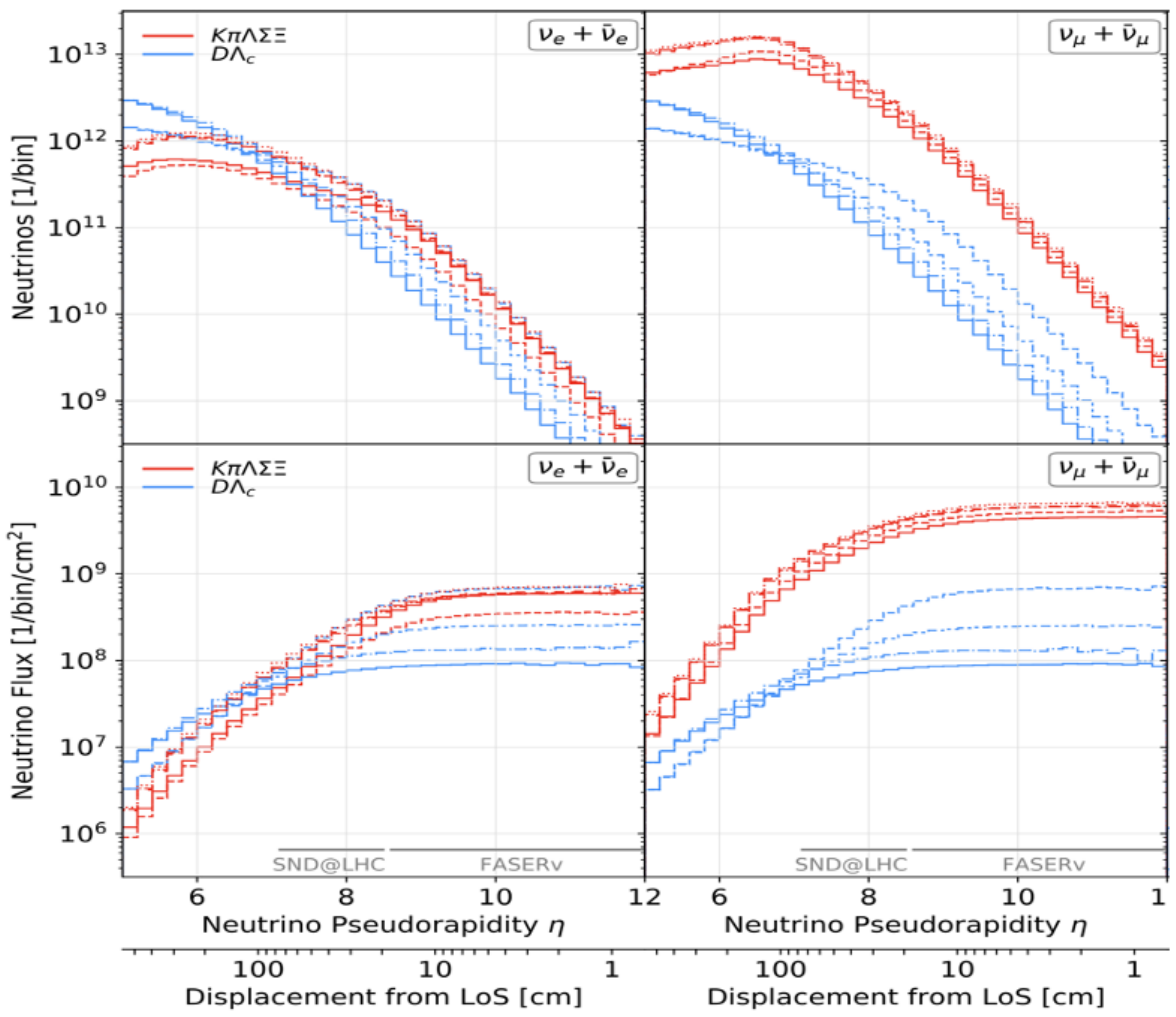
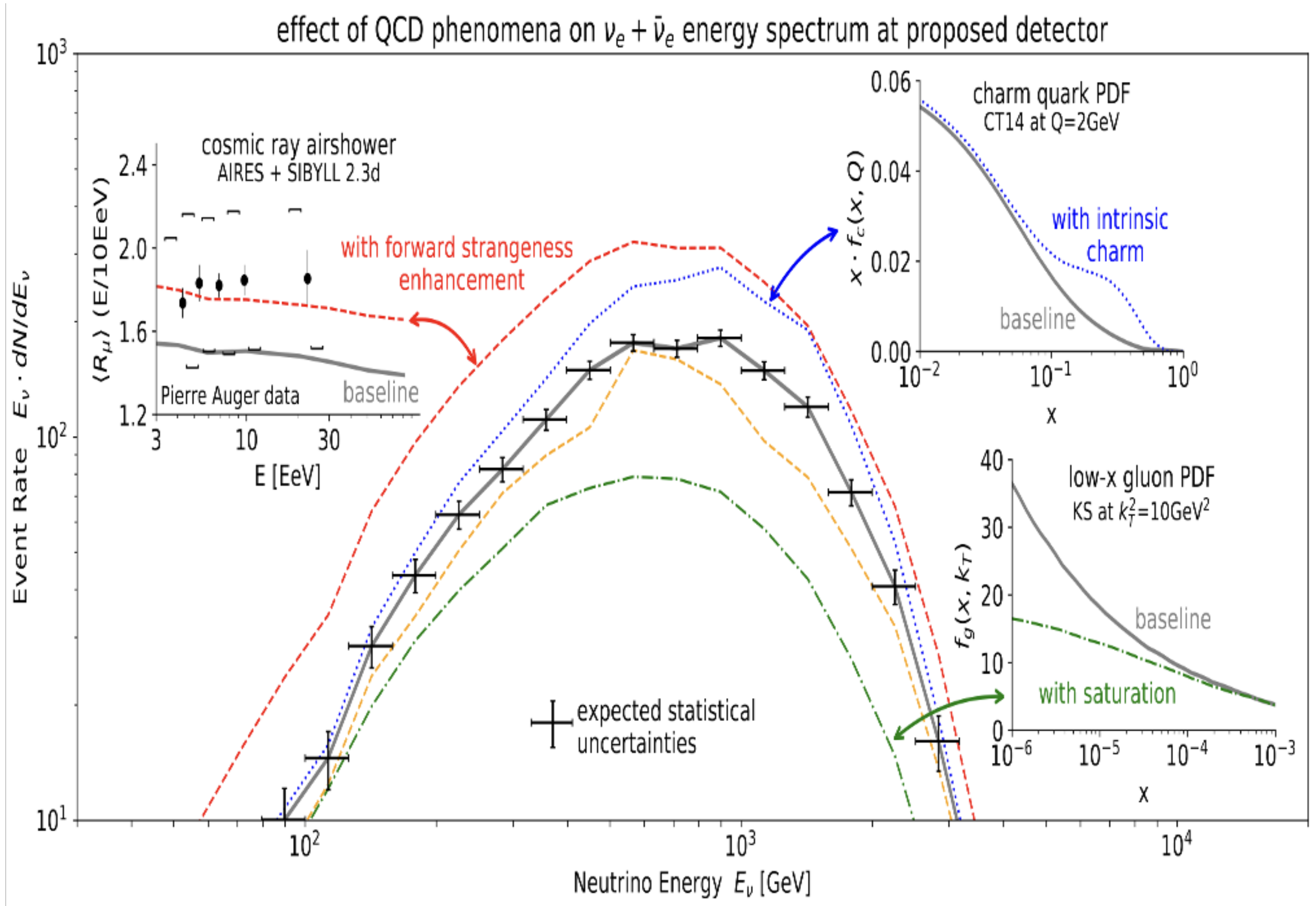


FIG. 1. **Neutrino yields and cross sections at the proposed detector.** The expected precision of measurements of neutrino interaction cross sections (top, statistical errors only) and the number of neutrinos interacting in the detector consisting of 0.25 m × 0.6 m × 0.3 m of tungsten (bottom) as a function of energy for electron (left) and muon (right) neutrinos. Existing data from accelerator experiments [1], IceCube [2], and the recent FASERν result [3] are also shown, together with the prospects for SHiP.

Proton Structure and Astroparticle Physics

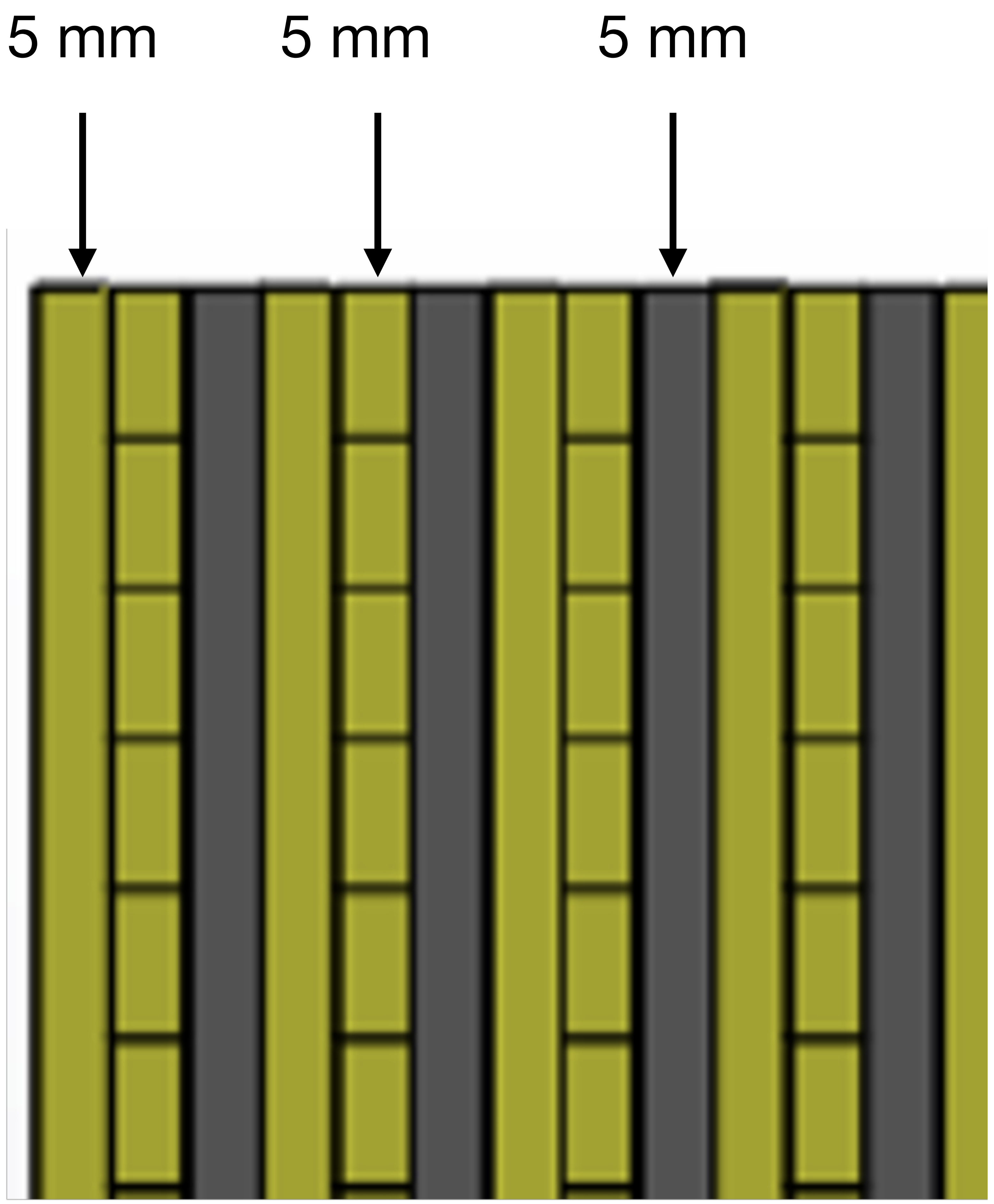
- FORTVNE extends to η > 7.6, overlaps SND's "off-axis" coverage
- Electron neutrino energy spectrum normalization and shape shed light on proton structure (intrinsic charm, low-x gluon pdf), astroparticle physics (cosmic muon puzzle), oscillations to sterile neutrinos or other states





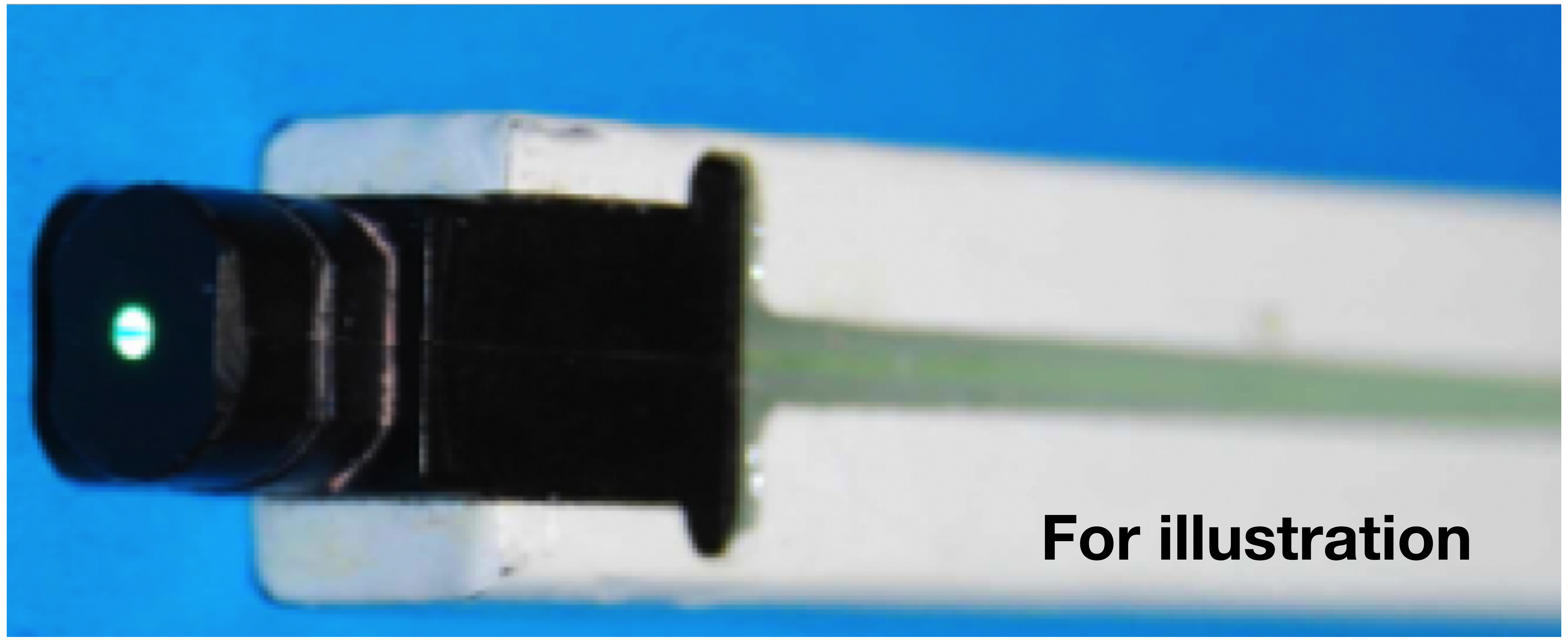
Detector Design Consideration

- Primary goal is ν_e CC measurement: reasonable longitudinal granularity of the scintillating bars is necessary to capture electron shower development. Tungsten thickness should be 1-2X_0 at most. Tungsten $X_0 = 3.5$ mm
- Sufficient tungsten to ensure statistics: 1 tonnes
- Minimize modifications due to the budget cap
  - limit the detector length to 1 meter, reuse existing 25 cm x 30 cm tungsten plates, stack up to increase total mass
- 5 mm thickness of tungsten (~1.5 X_0) for electron identification
  - Further thinning would require more scintillator channels, which is not feasible with budget constraint
- Use SiPM readout without cooling



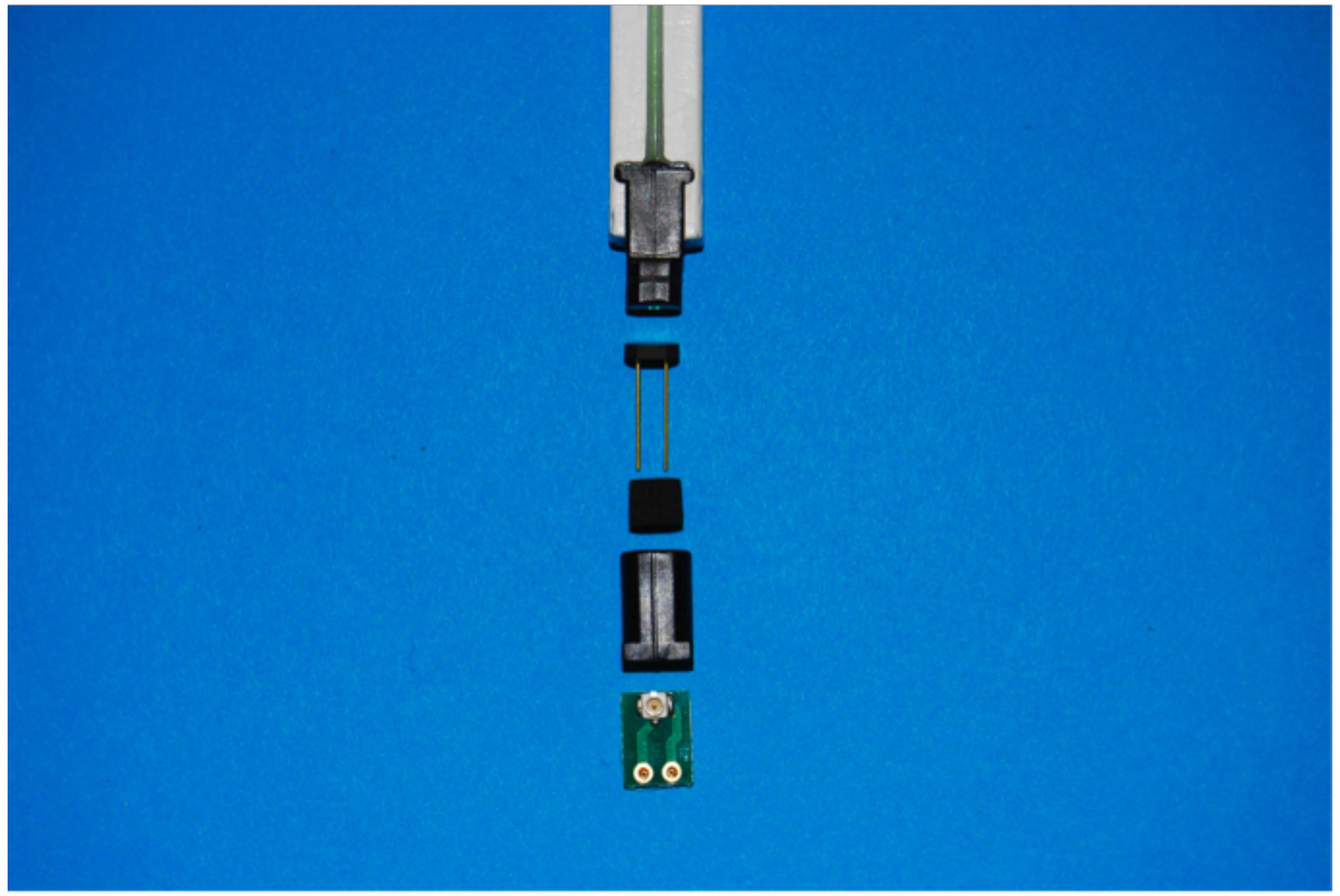
Scintillator bars

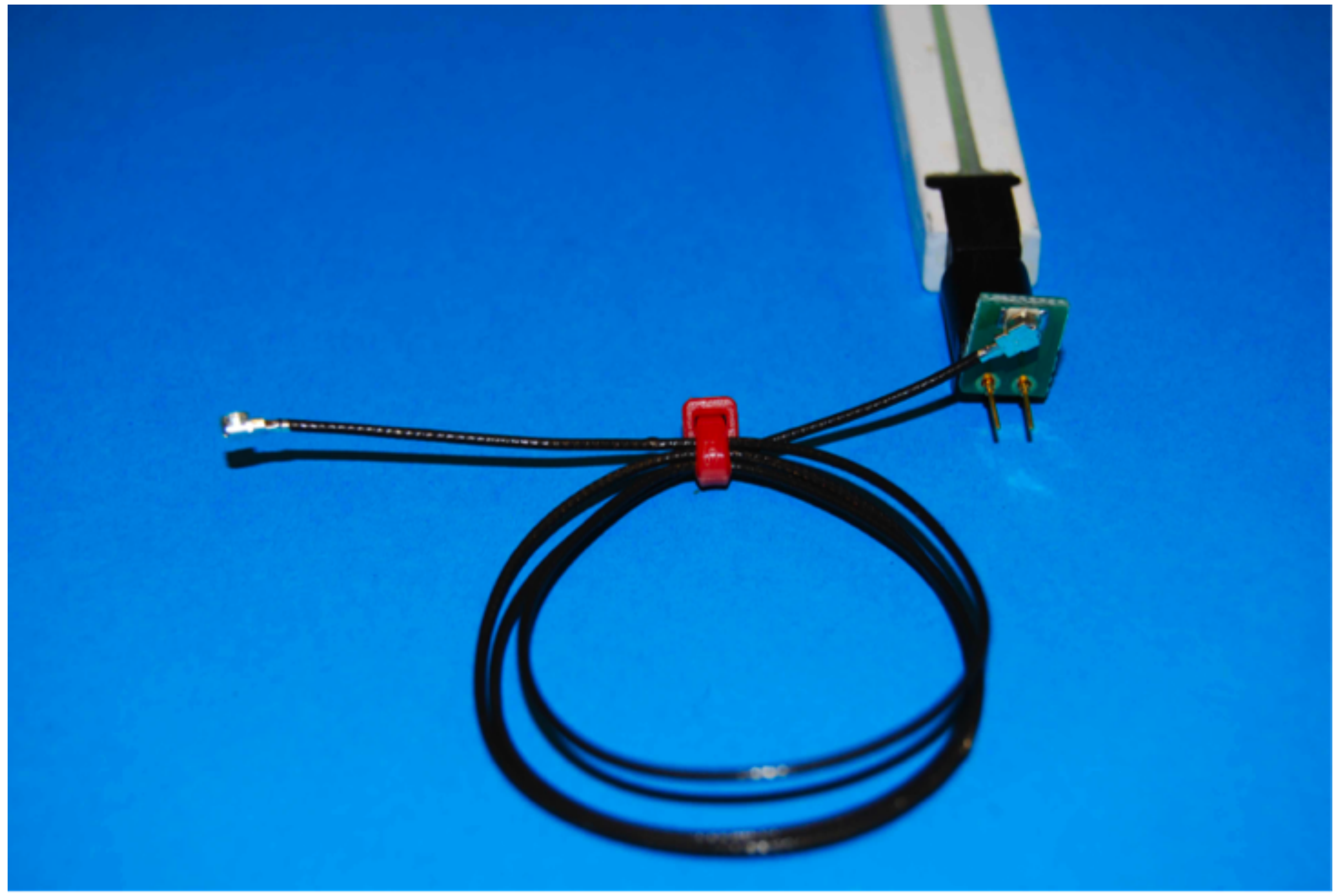
Baby-MIND style scintillator bar and SiPM system, proposed for FLArE HadCal



- BC408: a general-purpose plastic scintillator widely used high-energy physics experiments
- Geometry: 0.5 cm x 1 cm x 25 cm (60 cm) for horizontal (vertical)
- Each scintillator bar has two SIPMs coupled to it, one at each end, to enable photon detection in both low-energy and high-energy ranges
- Wrapped with a 100-200 μm Tyvek reflector to improve light collection. The reflector will also limit optical crosstalk between scintillator bars
- Two options for coupling with the SiPM: embedding a WLS fiber in a groove and directing the fiber end with the SiPM, or directly attach the SiPM to the end of the scintillator bars

Photosensors - SiPM

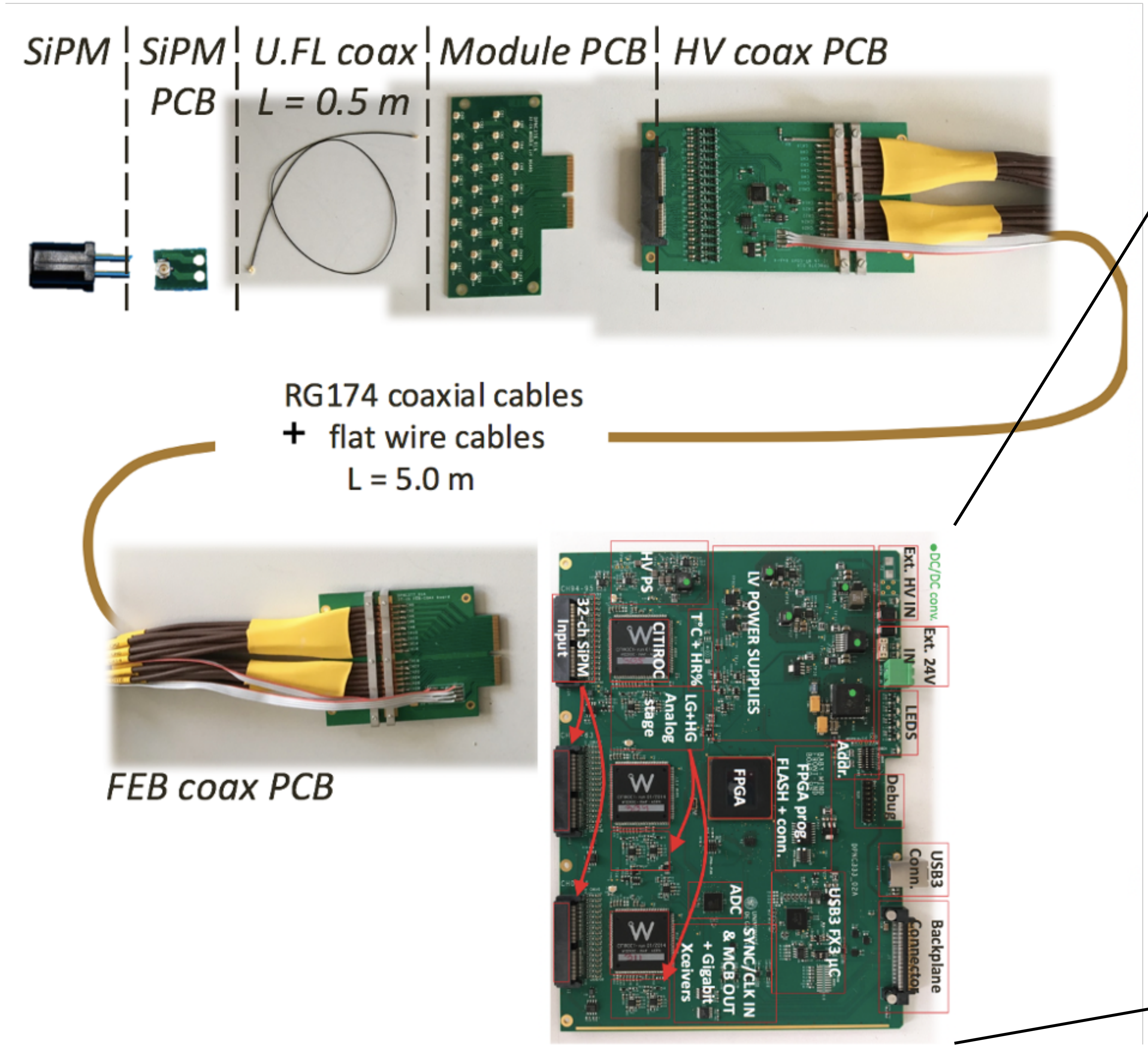


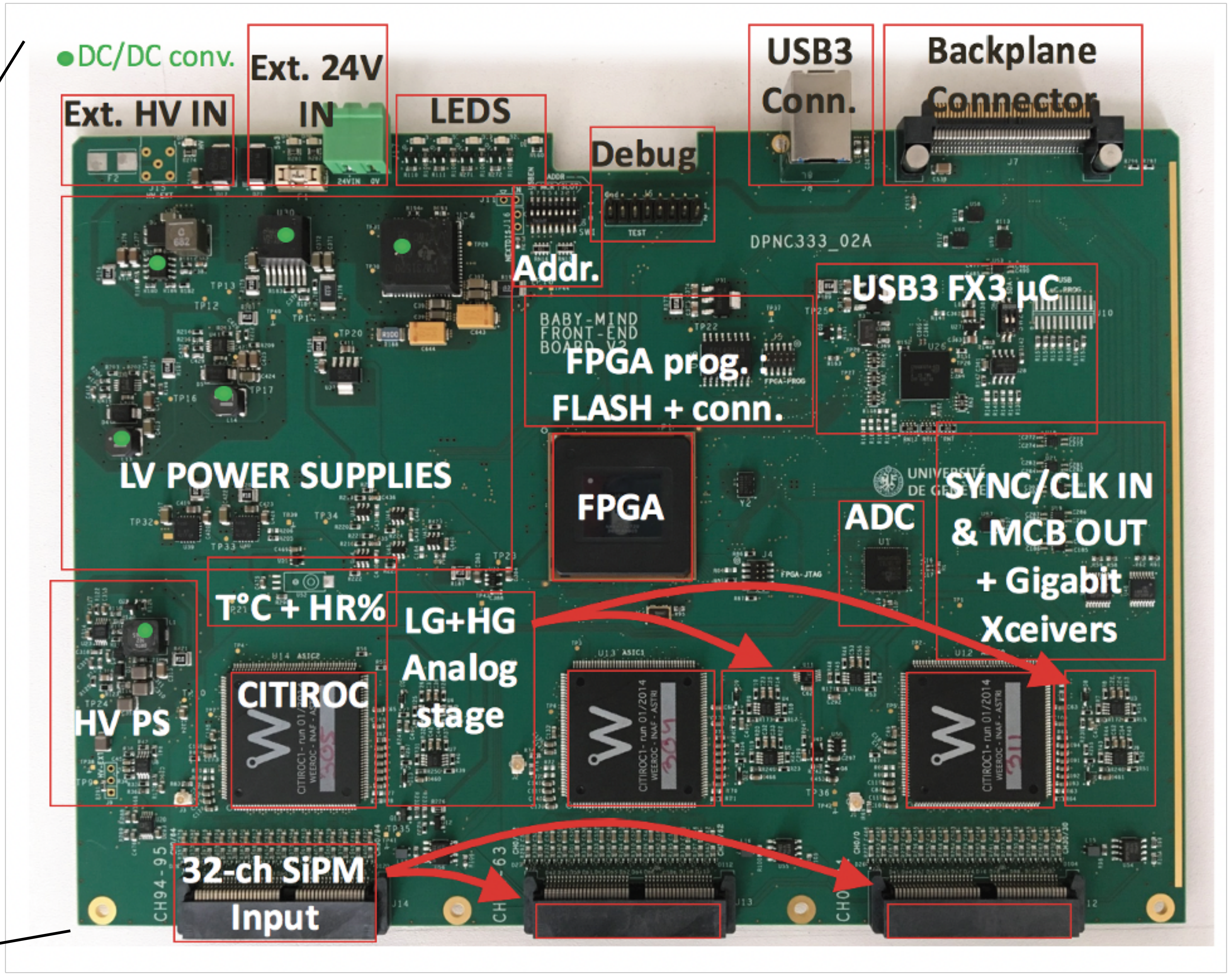


BabyMIND
Scintillator bar + SiPM

- Hamamatsu MPPC 13360-3025CS/PE SiPMs
  - 14,400 pixels within a 3 mm x 3 mm active area, PDE 40% at 450 nm
- Fiber connectors are glued to the ends of the bars to align the fiber ends with the SiPMs
- Each SiPM will be mounted on a mini PCB board to facilitate connections to the electronics via coaxial cables
- Two SiPMs for each scintillator bar, one with a neutral density optical filter to reduce light yield for high-energy measurements, and the other without a filter for low-energy measurements
  - High dynamic range: from MIP tracks to high-energy-density EM showers

Readout Electronics

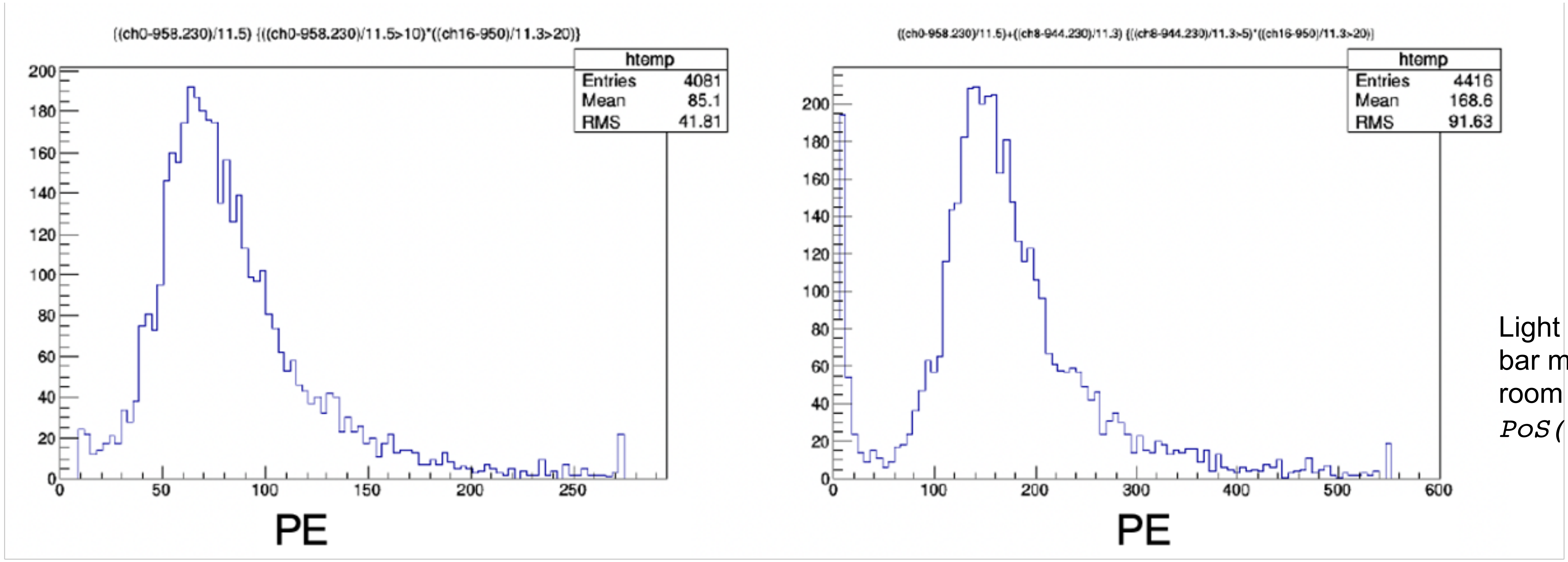




Baby MIND electronics readout, developed by UniGe
https://doi.org/10.7566/JPSCP.27.011011

CITIROC (Cherenkov Imaging Telescope Integrated Readout Chip) used in the Baby-MIND detector of the WAGASCI experiment and the SuperFGD detector of the T2K experiment, 32 channels, 3 chips per FEB

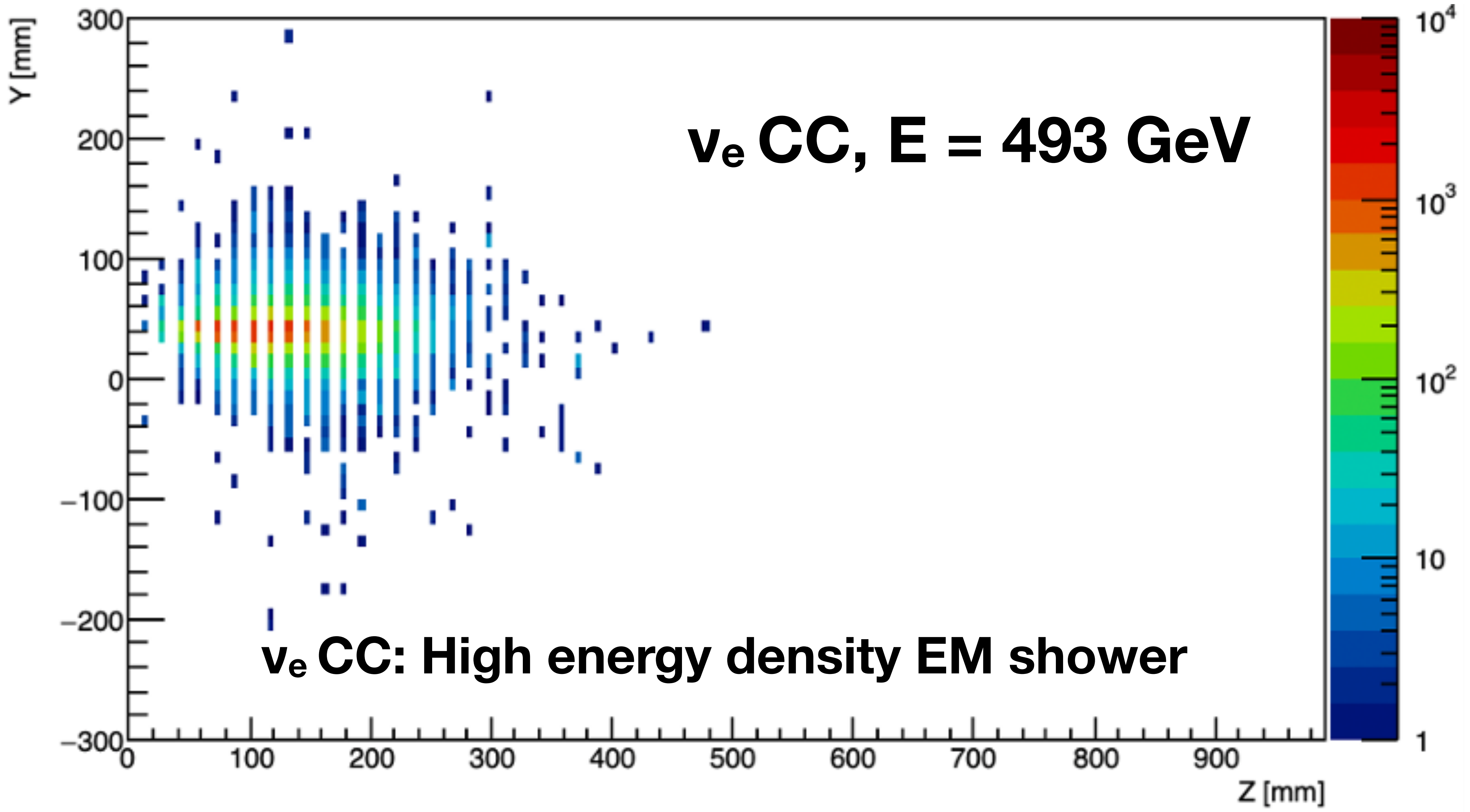
Light Yield



Light yield (PE) of 1 scintillator bar measured with cosmic rays in room temperature – BabyMIND `PoS(PhotoDet2015)031`

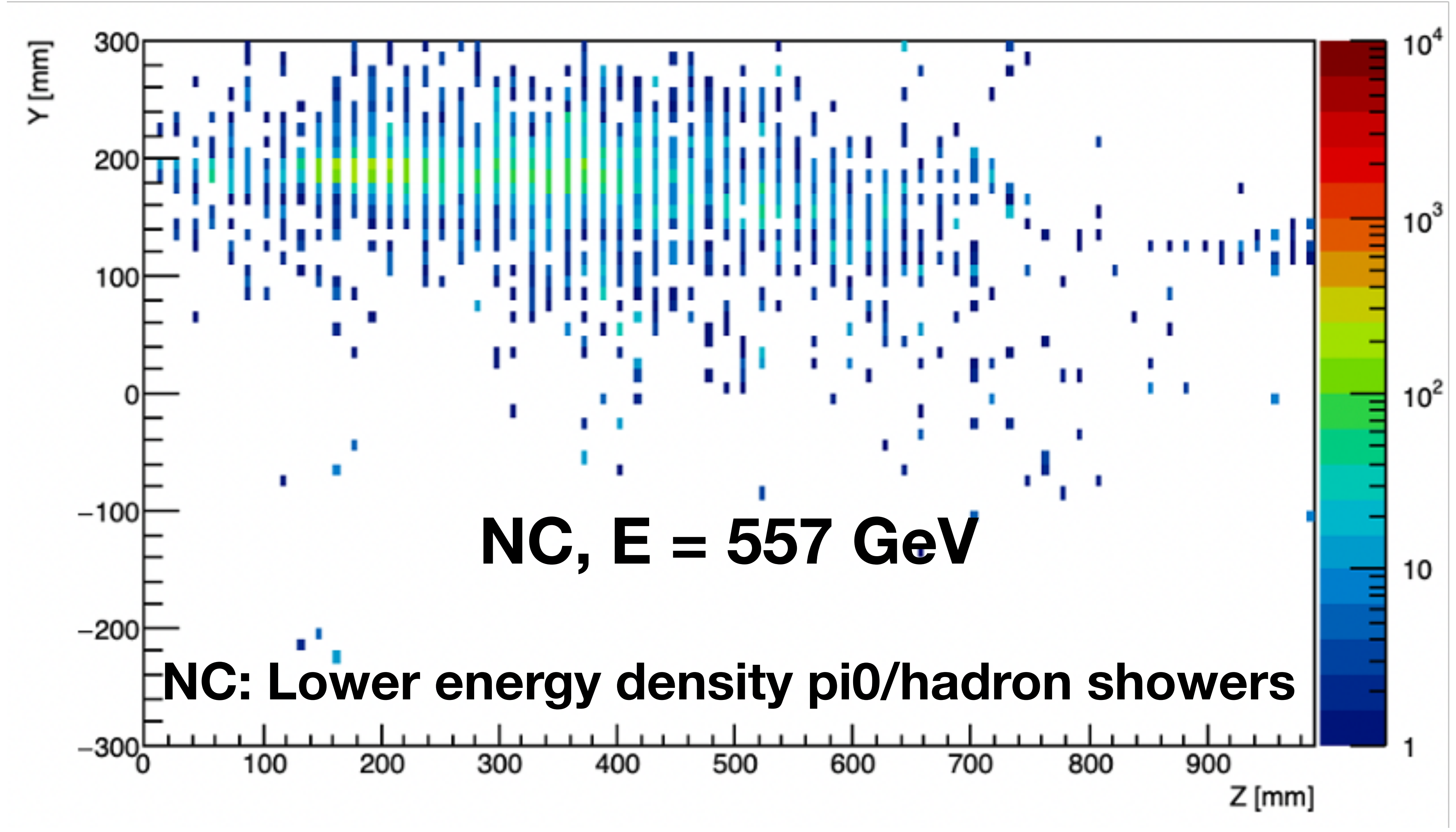
- The detector simulation involves first simulating energy deposits in the scintillators and then the digitized response in the SiPMs to these deposits
- In the simulation, the light yield of a single scintillator bar is set to 30 p.e./MIP, and the dark noise is set to 2 p.e. per channel, based on BabyMIND results.
- Other effects considered include detector cell non-uniformity, light attenuation, SiPM saturation, readout electronics non-linearity, and background noise.

Simulation: Event Displays, Y-Z view



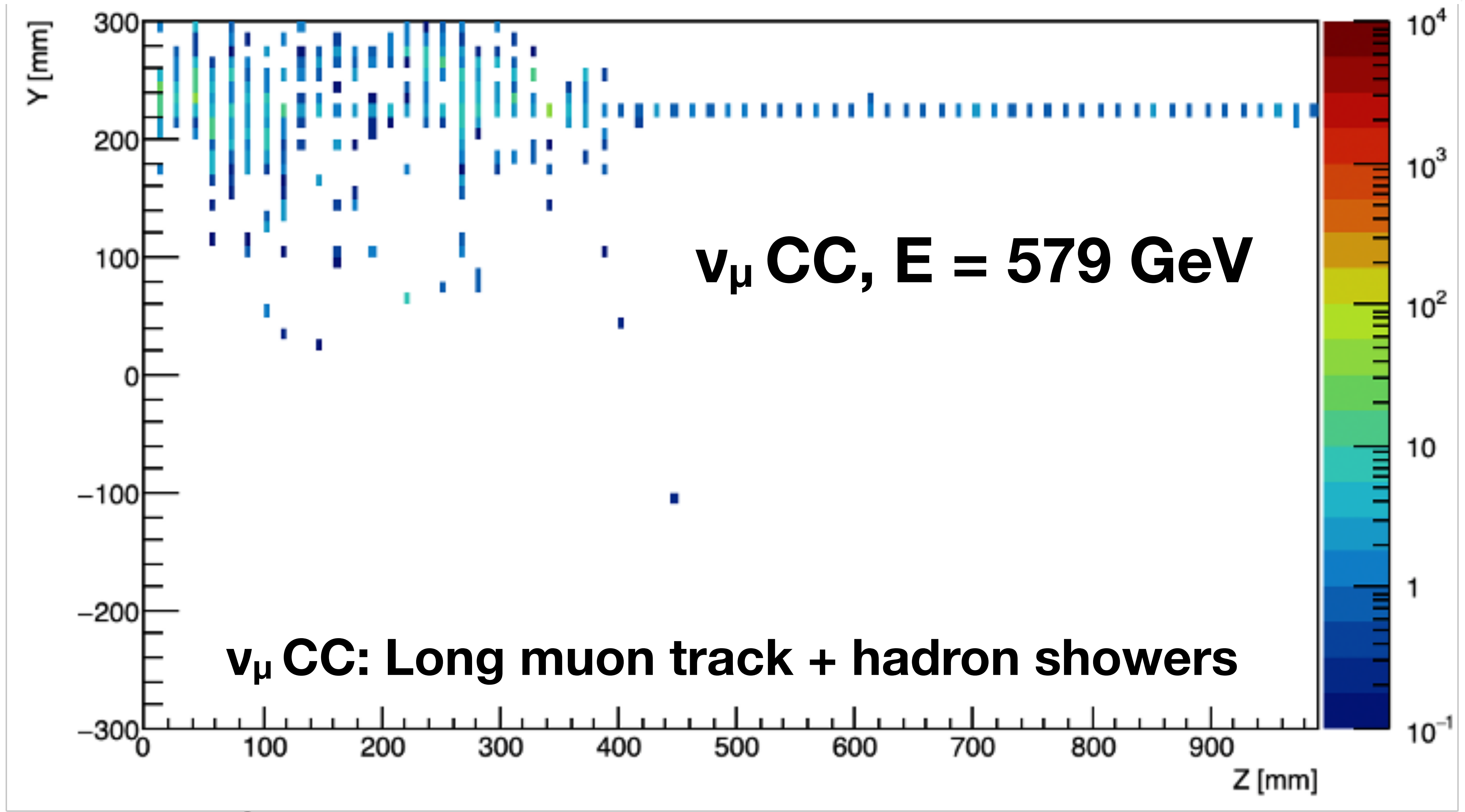
ν_e CC, E = 493 GeV

ν_e CC: High energy density EM shower



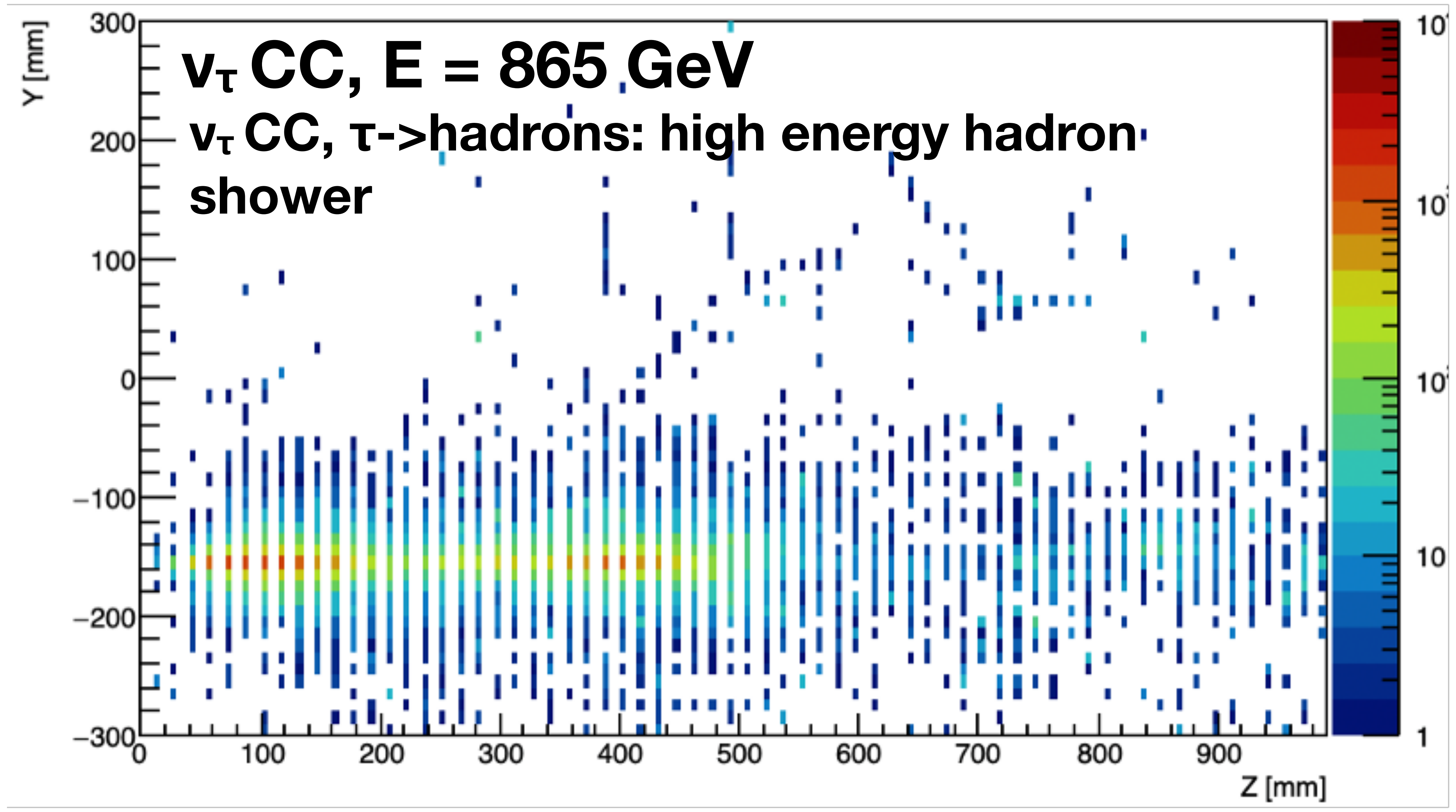
NC, E = 557 GeV

NC: Lower energy density pi0/hadron showers



ν_μ CC, E = 579 GeV

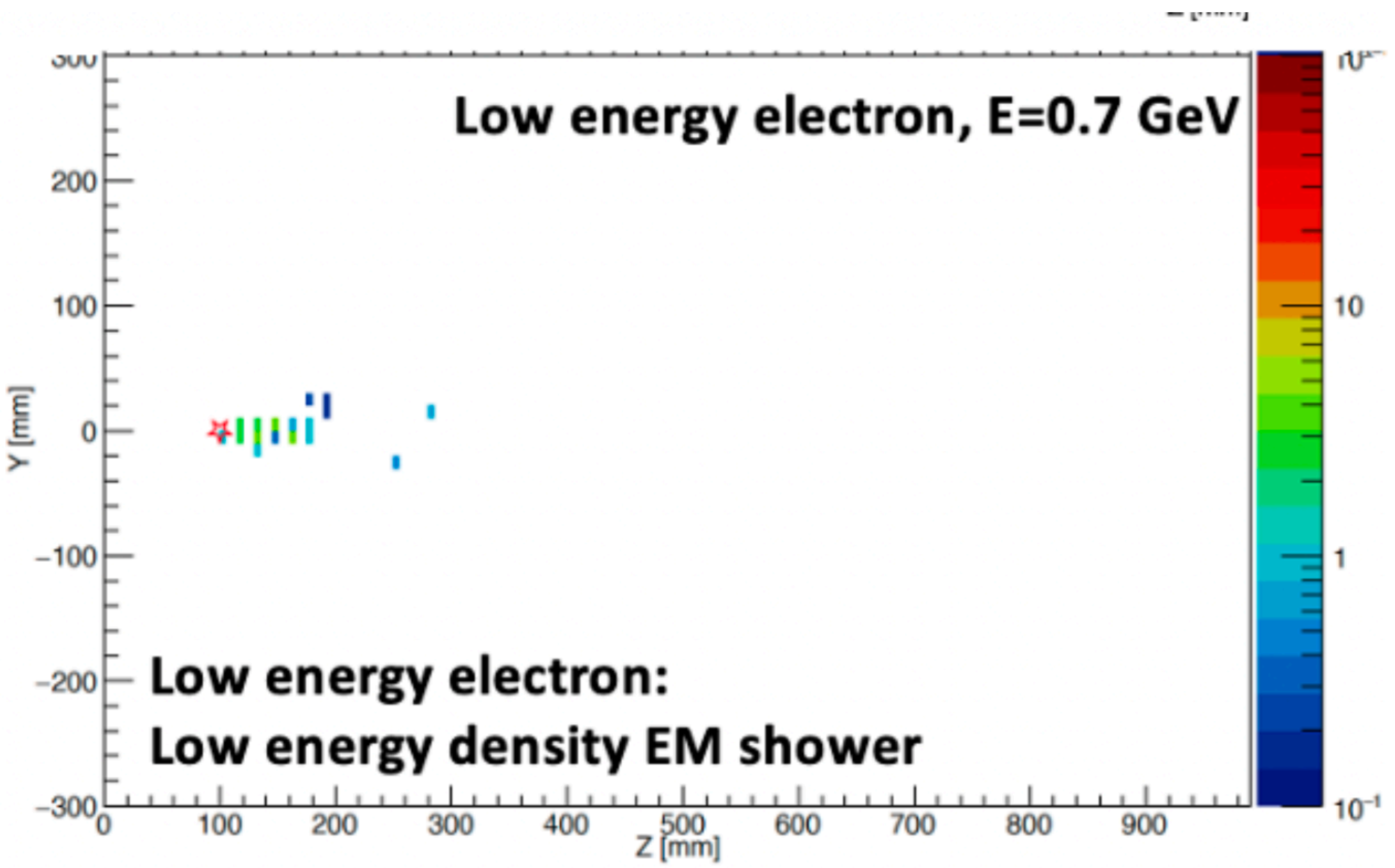
ν_μ CC: Long muon track + hadron showers

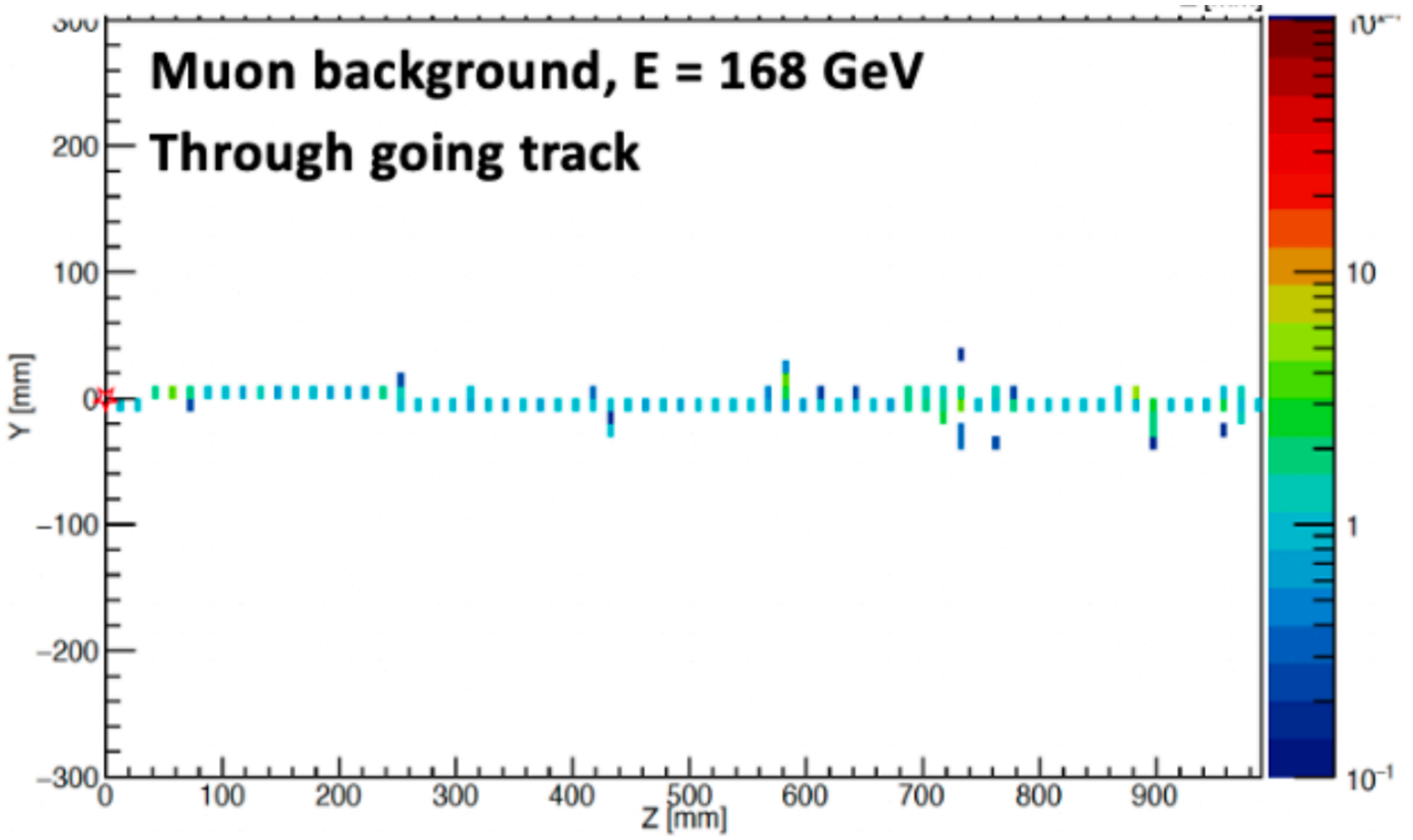


ν_τ CC, E = 865 GeV

ν_τ CC, τ->hadrons: high energy hadron shower

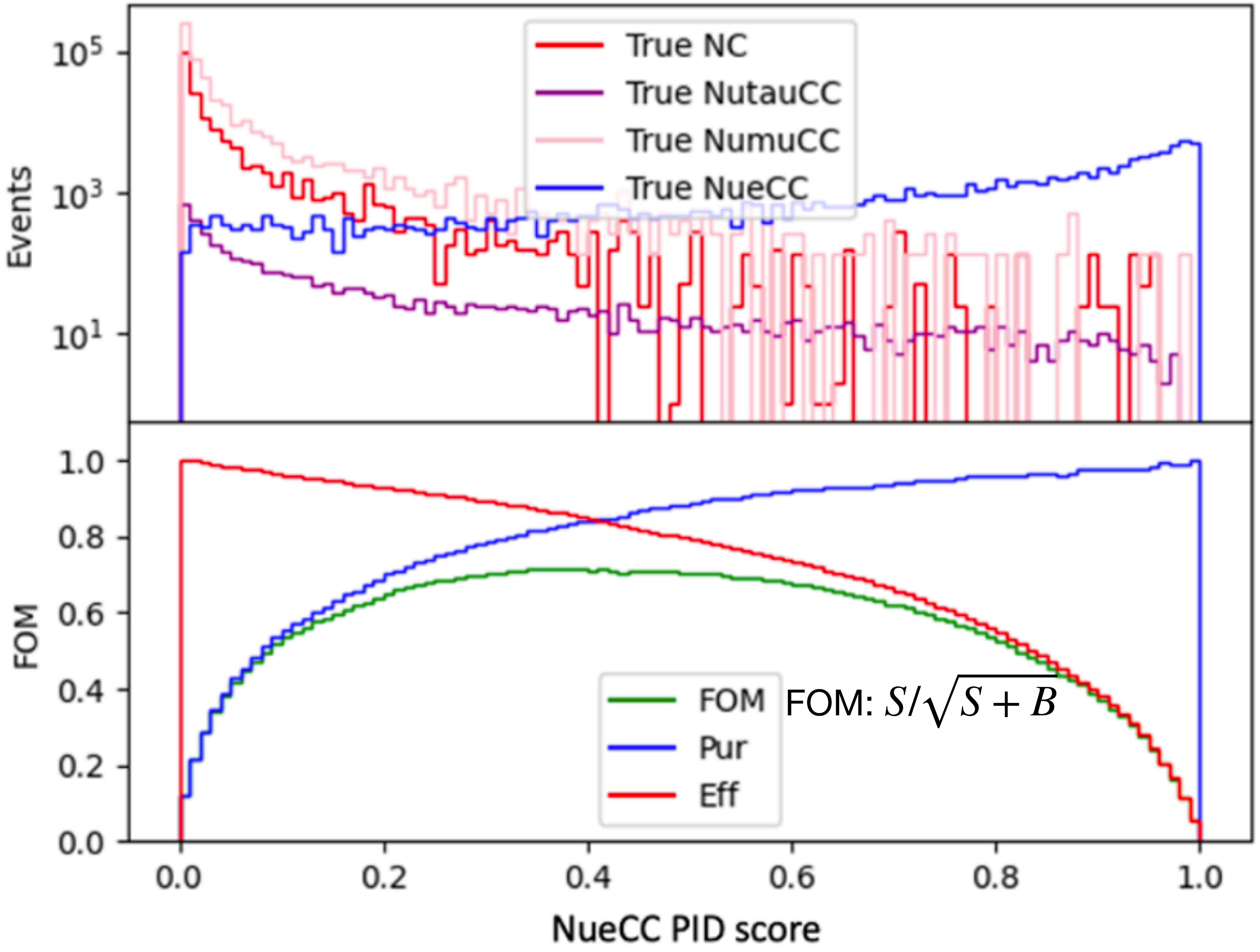
Simulation: Event Displays, Y-Z view





Each type of event exhibits clear topological signatures that can be distinguished from the others

ν_e Identification with CNN



- Train a CNN PID for ν_e CC Identification
- With the event composition of $\nu_\mu : \nu_e : \nu_\tau$ = 131:24:1
  - ν_e CC Eff: 86%, Pur: 83%
  - ν_μ CC Eff: 99%, Pur: 72%
  - ν_τ CC Eff: 8%, Pur: 48%

ν_e CC can be identified with good efficiency and purity

- The relatively high impurity in ν_μ CC and low efficiency in ν_τ CC could be improved by combining FASER's spectrometer and calorimeter

ν_e CC Calorimetric Energy Resolution

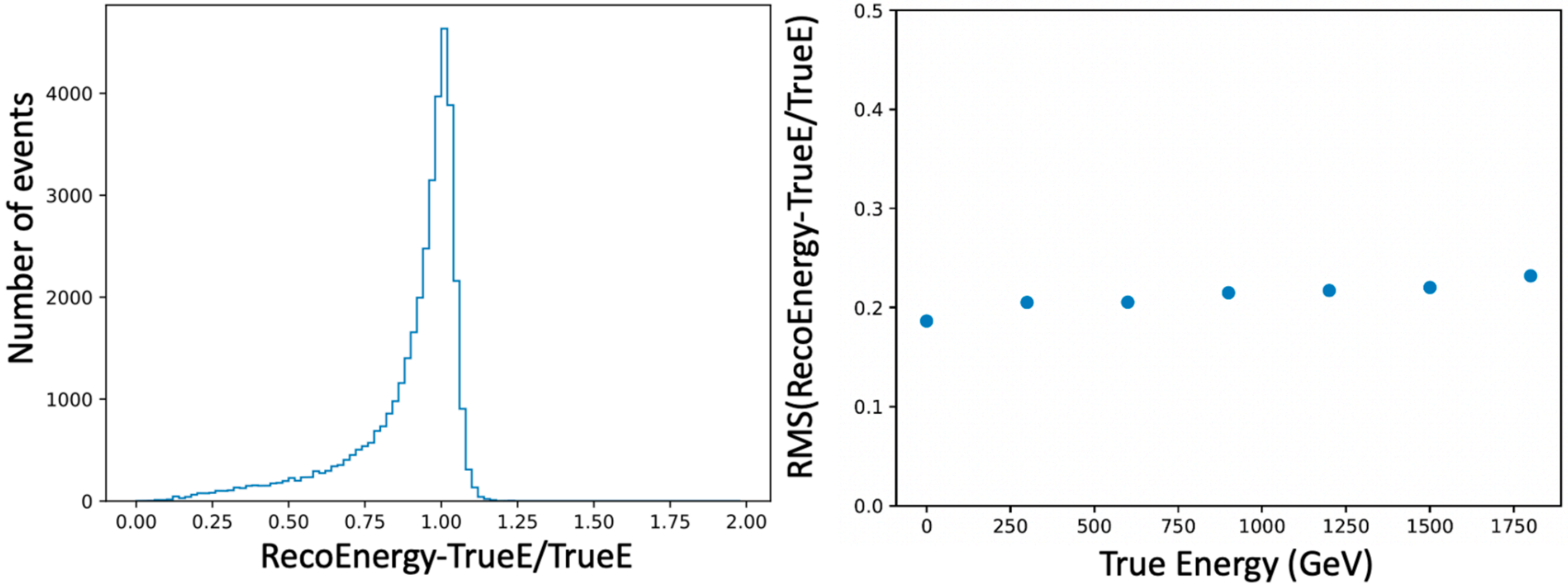


FIG. 10: **Simulated ν_e CC energy resolution in FORTVNE. Left:** The overall energy resolution. **Right:** Energy resolution as a function of the true neutrino energy.

- Reconstructing Calorimetric Energy by adding up deposit energies in scintillator bars, no shower/track clustering
- Shift the peak of (RecoE−TrueE)/TrueE to 1. The RMS of the (RecoE−TrueE)/TrueE distribution is defined as the energy resolution, ~20%
- The long tail in the (RecoE−TrueE)/TrueE distribution is caused by the detector containment and the invisible energy of hadronic interactions in ν_e CC events.

Summary

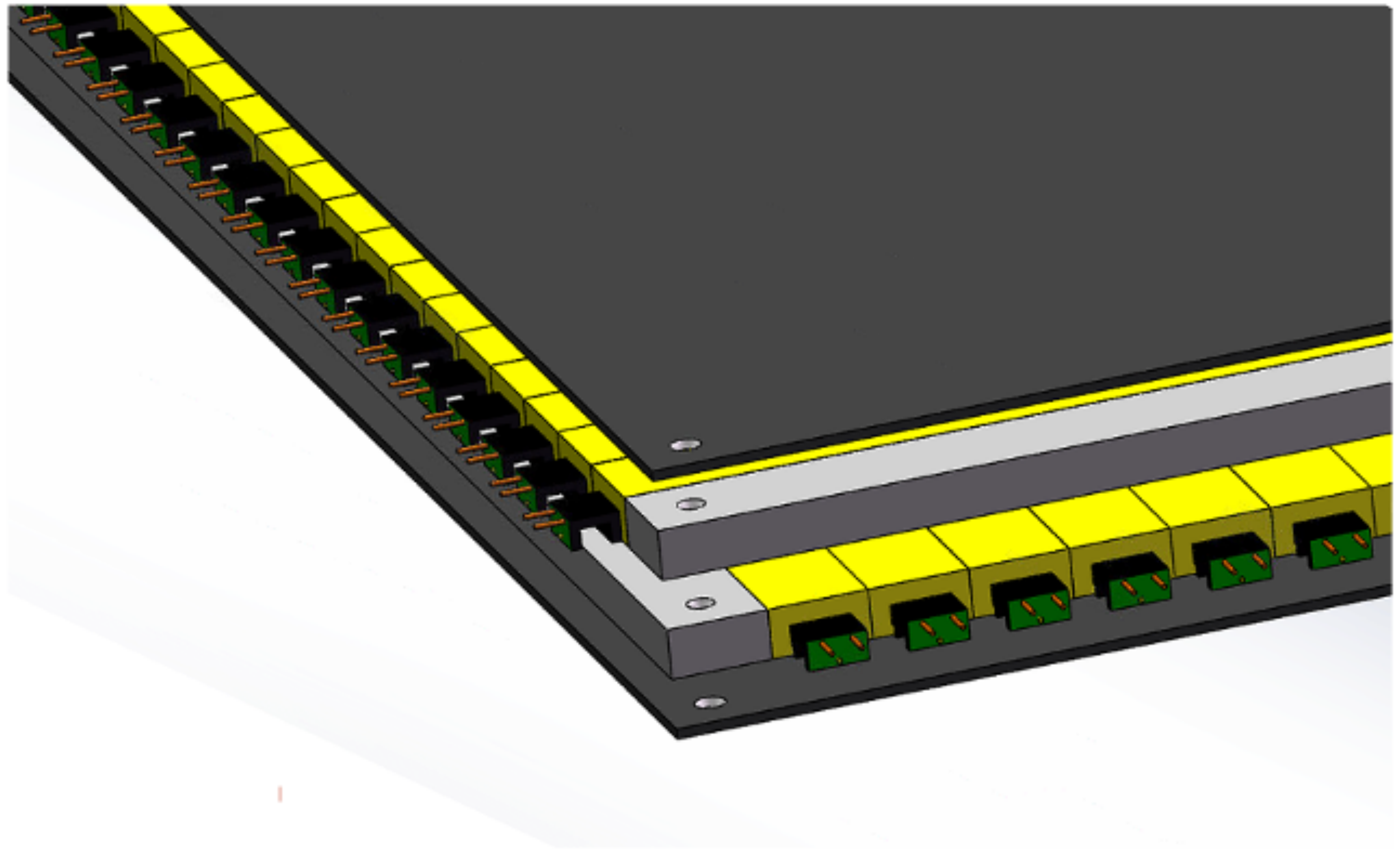
- Tungsten target/scintillator bars combination is a well-established technology, with it FORTVNE can:
  - Identify ν_e CC from NC and other backgrounds
  - Measure ν_e energy with a resolution of approximately ~20%
- Due to smaller absorber thickness, the containment of ν_μ and ν_τ events is reduced, requiring the track spectrometer for muon momentum reconstruction
- Single electron identification is understudy
- Due to reduced hadron/muon containment, ν_τ identification is challenging. Using CNN pattern recognition to identify ν_τ hadronic decay mode may have a chance
- Physics cases: neutrino properties at TeV energies, QCD, proton structure, astroparticle connections
- Potential upgrades in the future
  - Add SciFi between tungsten plates in FORTVNE to improve vertex resolution for ν_τ
  - Replace the current Magnetized decay pipe with hadronic calorimeter/Muon *Spectrometer after* FORTVNE to improve hadron containment and muon momentum measurement

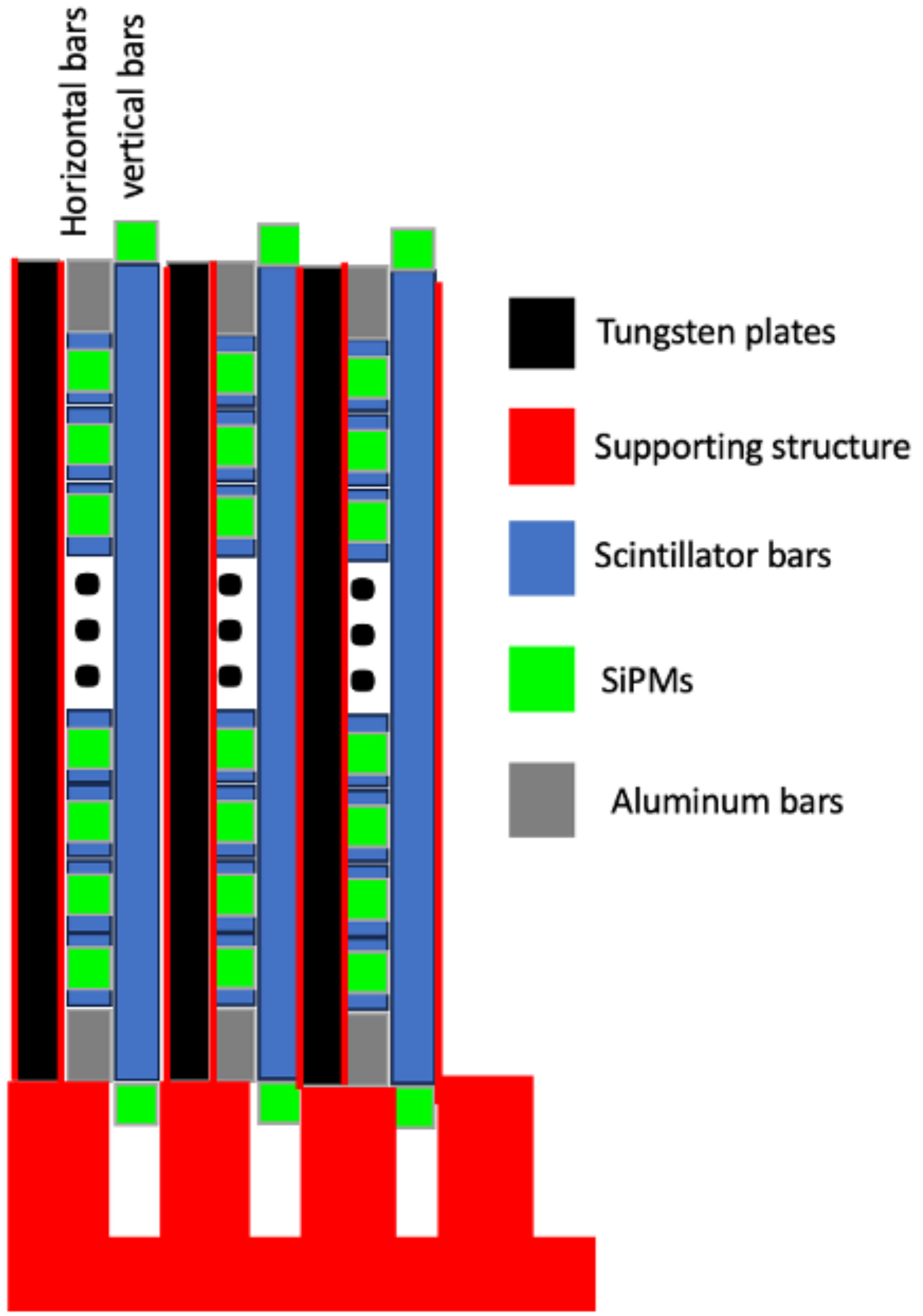
Thank you!

Backup Materials

FORTVNE

Supporting Structure





Search for New Particles

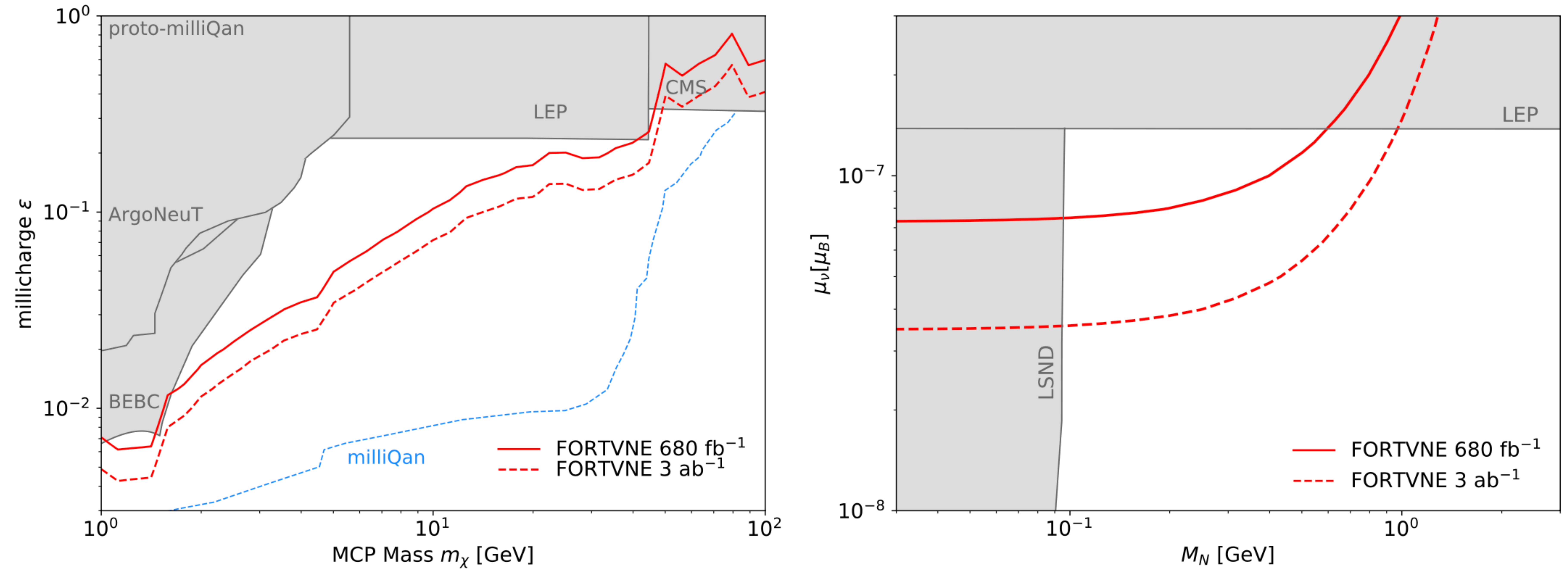


FIG. 4: **New Particle Searches at FORTVNE.** The discovery reach for milli-charged particles [48] (left) and heavy neutral leptons coupling to the SM through the magnetic dipole operator (see text) [49] (right) for LHC Run 4 (680 fb^{-1}) and the HL-LHC (3 ab^{-1}). The contours are $N = 3$ signal contours, and the signal is single electron recoils with energies from 300 MeV to 10 GeV.

Cost Estimate

Scintillator + sipm system			
Number of x+y modules		66	
Channels per module (x + y)		85	
		cost in $	
Scintillator material cost per channel		50	quote from luxium
Scintillator machining per channel		140	2 hours of machine shop @ 70/hour
Scintillator assembly per channel		45	3 hours of UG labor @ 15/hour
SiPM cost per channel		200	quote from Hamamatsu
Readout electronics cost per channel		100	BabyMIND readout
Scintillator + sipm system cost		3001350	
Tungsten absorber		cost in USD	
Tungsten		0	from current FASERnu
Tungsten supporting structure		35000	50 hours of machine shop @ $70/hour
Personnel (26% overhead)	cost/year	cost in USD	
Technician	100000	500000	100k/year for 5 years, engineer design, prototyping, overlook production
Postdoc	80000	240000	80k/year for 3 years, simulation, Qa/Qc, analysis, detector assembly and commissioning
PhD students	70000	210000	70k/year for 3 years, supervise UGs for scintllator production
Total cost		3986350	

Construction/Management Plan

- Simulation and Detector parameter optimization
- Engineering design
- Scintillator bar and SiPM procurement
- Scintillator bar machining, UCI Physical Sciences Machine Shop @ $70/hours
- Scintillator bar + SiPM assembly @ UCI High Bay
- Readout electronics construction/procurement
- QA/QC
- Prototyping
- Beam test
- Detector assembly and commissioning