Scattering and Neutrino Detector at the LHC

PERFORMANCE OVERVIEW OF SND@LHC AND FASER

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ON BEHALF OF THE SND@LHC AND FASER COLLABORATIONS

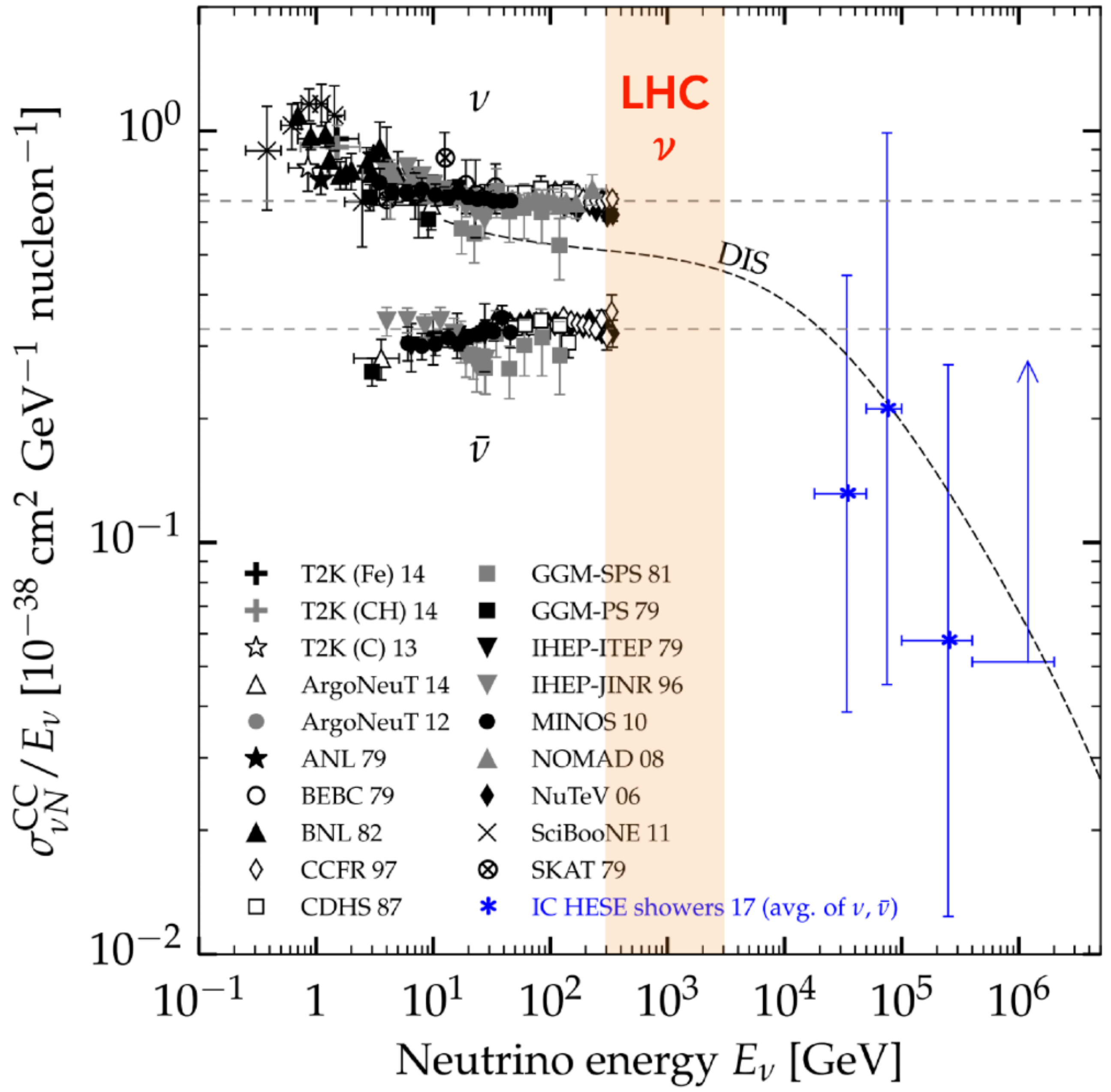
NEUTRINOS AND DARK SECTOR AT THE LHC

MOTIVATION

NEUTRINOS

- Collisions at the LHC produce high fluxes of ν in previously unexplored energies $E_\nu \in [10^2, 10^3]$ GeV
- In the forward region, neutrinos are produced mainly in decays of hadrons
  - ➡ Probe heavy flavour production at the LHC

[PRL 122 (2019) 041101]



DARK SECTOR

- Light dark sector particles could be produced in decays of SM hadrons
- At the LHC, these particles would be predominantly produced close to the beam direction

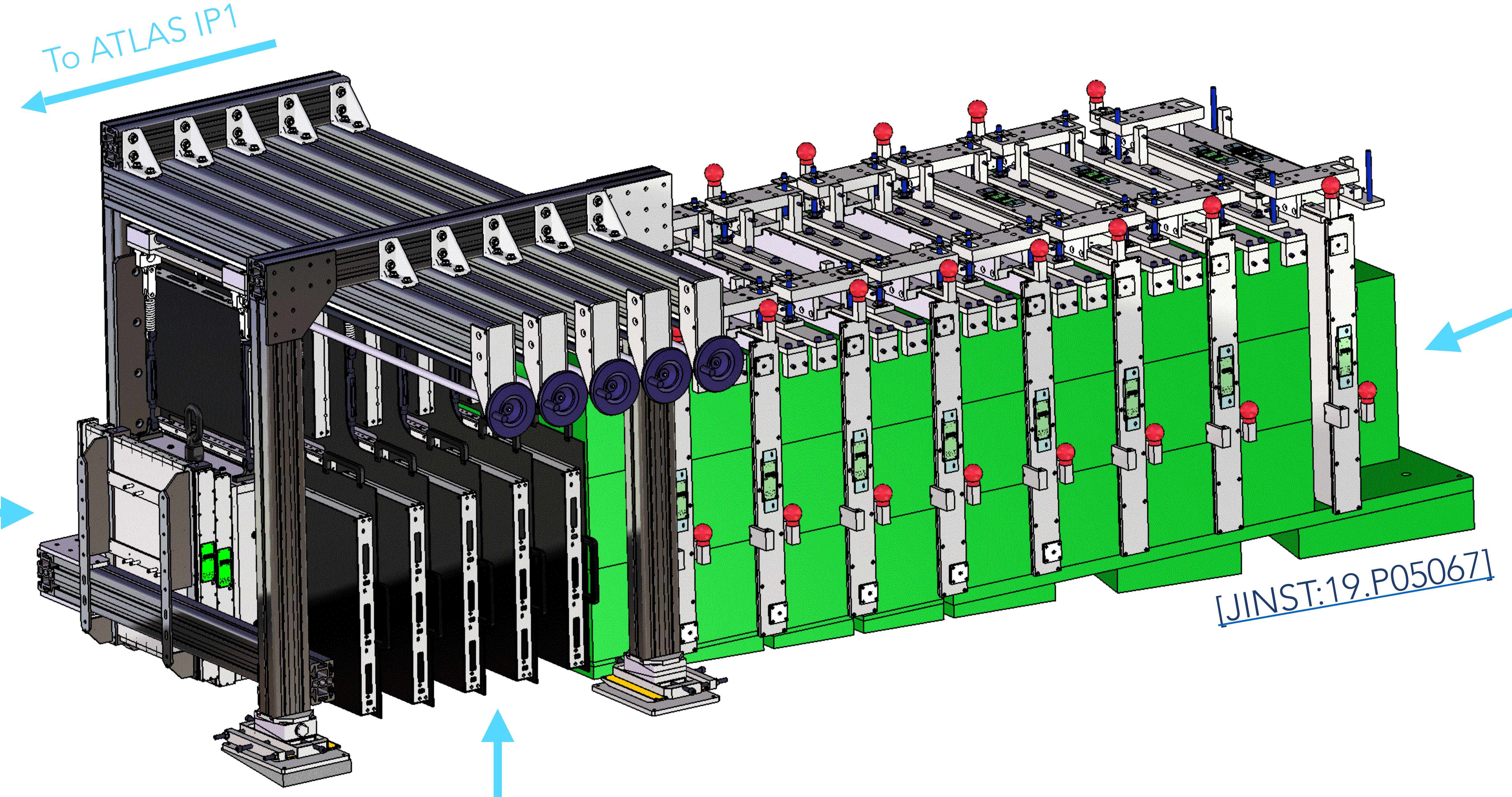
Even a small detector near an LHC interaction point, placed close to the beam axis, can study neutrinos of all flavours, and have sensitivity to long-lived dark sector particles

SND@LHC AND FASER

TWO COMPLEMENTARY EXPERIMENTS

	Acceptance	Target	Physics	Detector
SND@LHC	Off-Axis: $7.2 < \eta < 8.4$ ● Beam collision axis	800 kg of tungsten	• Detect & identify all neutrino flavours • Probe QCD with neutrinos from charm • Search for dark sector particle scattering	• Emulsion vertex detector • ECAL & HCAL
FASER	On-Axis: $\eta > 8.8$	1100 kg of tungsten	• Detect & identify all neutrino flavours • High energy & statistics for neutrinos • Probe QCD with neutrinos from charm • Search for dark sector particle decay	• Emulsion vertex detector • Spectrometer & ECAL

SND@LHC DETECTOR



VETO

- Three planes of scintillating bars
- Tags charged particles as they enter the detector

TARGET AND VERTEX DETECTOR

- Emulsion cloud chambers (ECC) with tungsten for ν identification via precise vertexing
- Scintillating fibre (SciFi) planes provide timing and calorimetric information

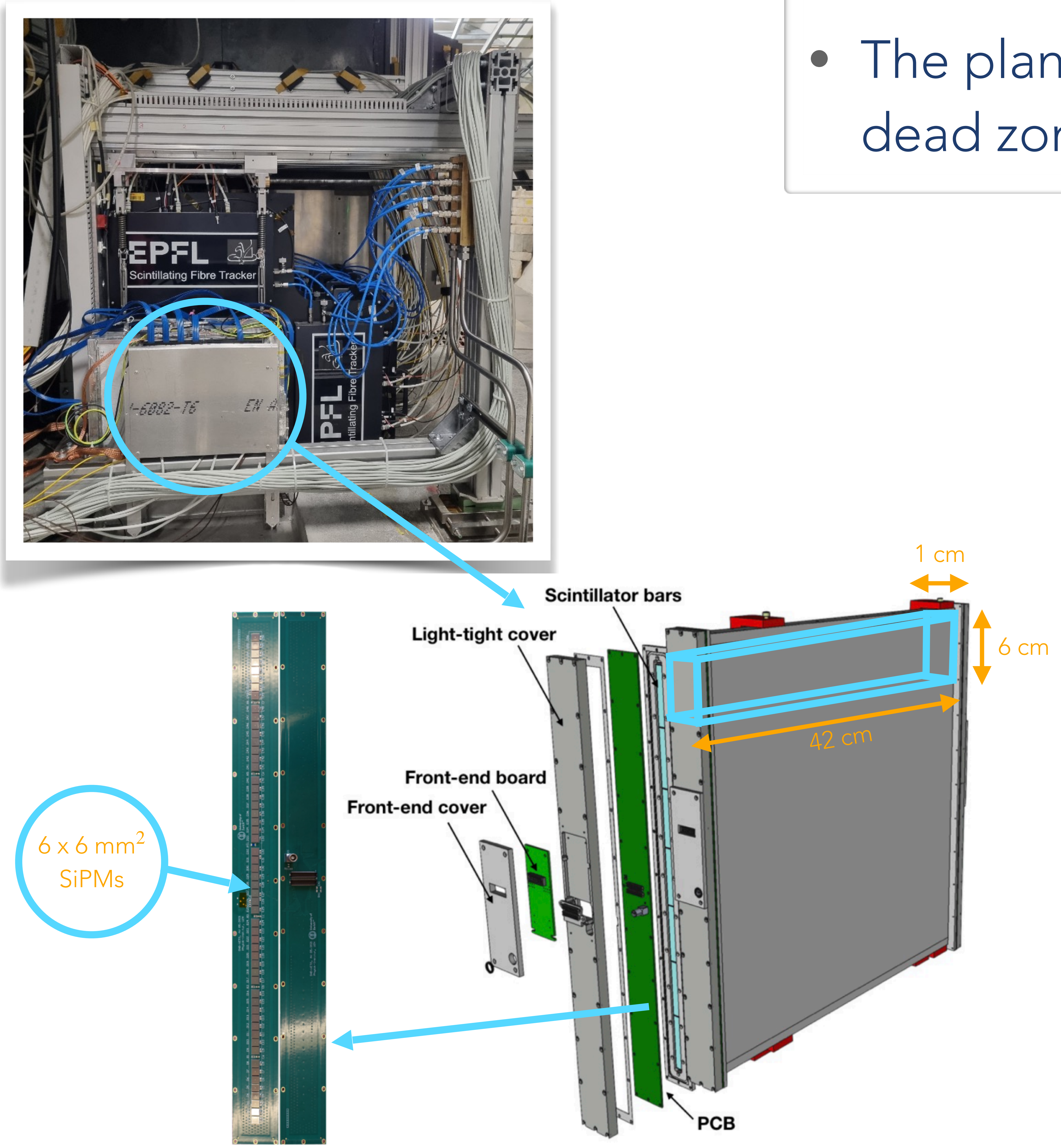
MUON SYSTEM AND HCAL

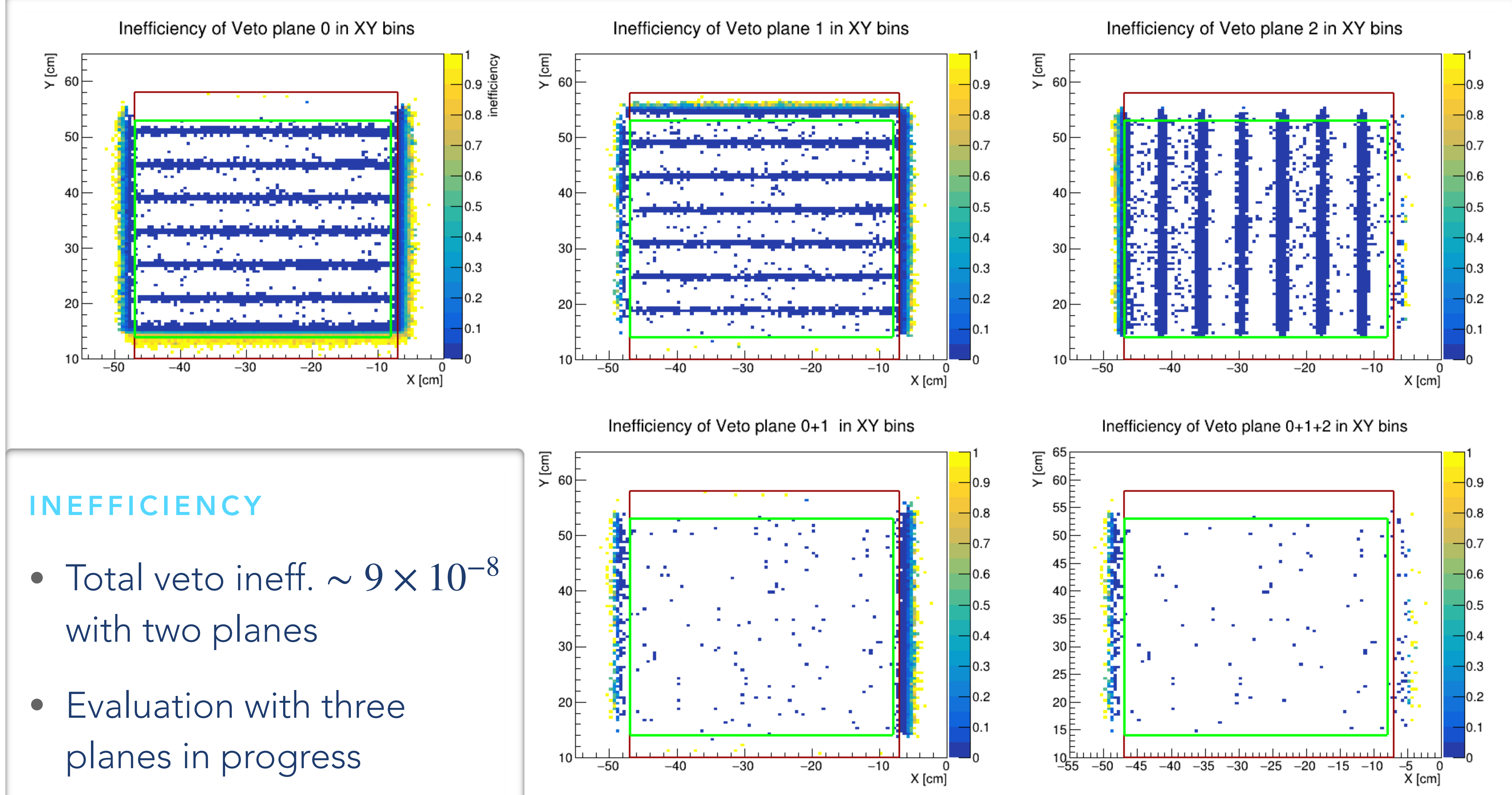
- Scintillating bars interleaved with iron walls, sampling every λ
- Timing, muon ID and energy measurement
- Higher granularity in downstream stations for muon tracking

VETO SYSTEM

SND@LHC

- Tags charged particles entering the detector
- Three (Two until 2024) planes with 7 scintillating bars in each, read out by SiPMs
- The planes cover the target surface area, and are staggered to mitigate dead zones between bars





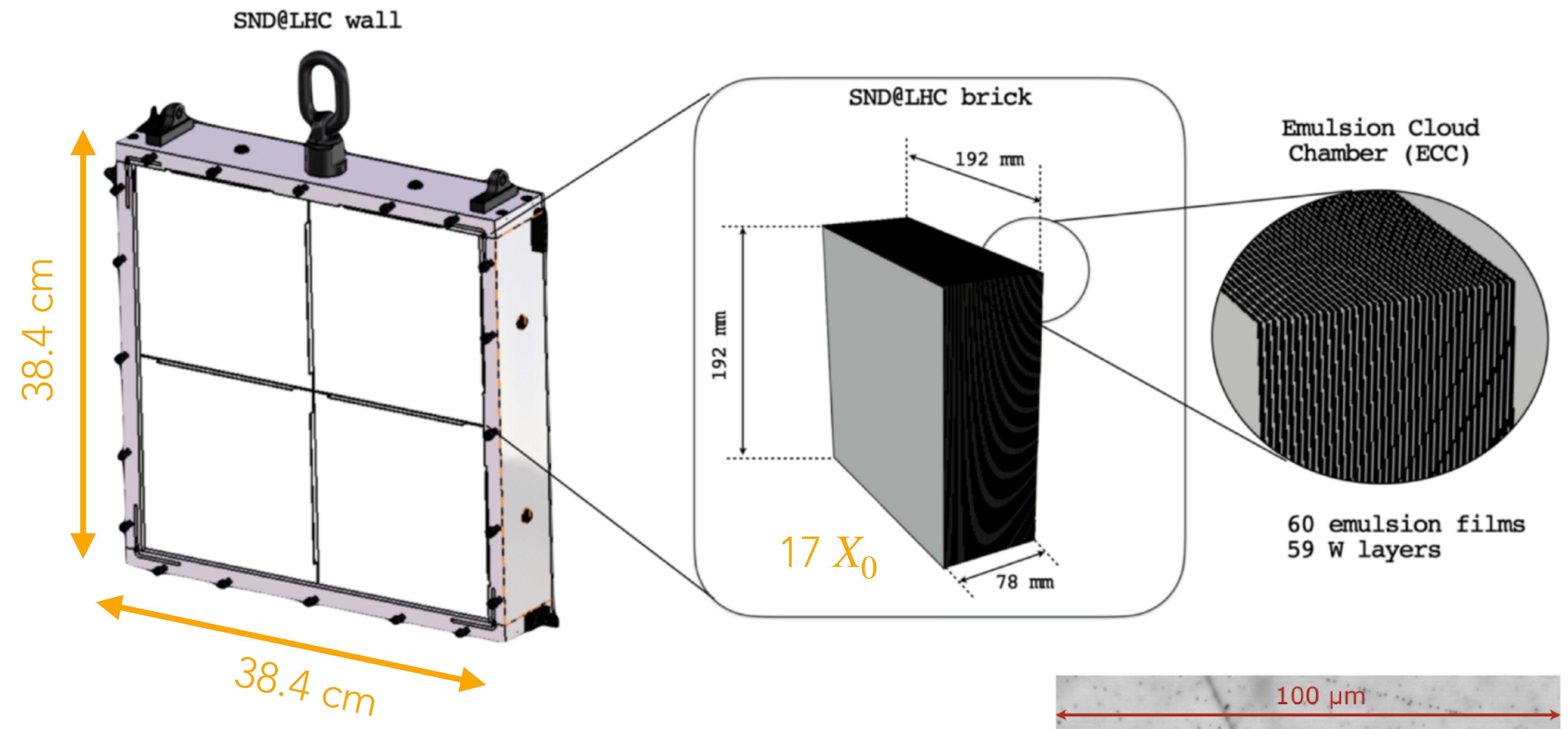
INEFFICIENCY

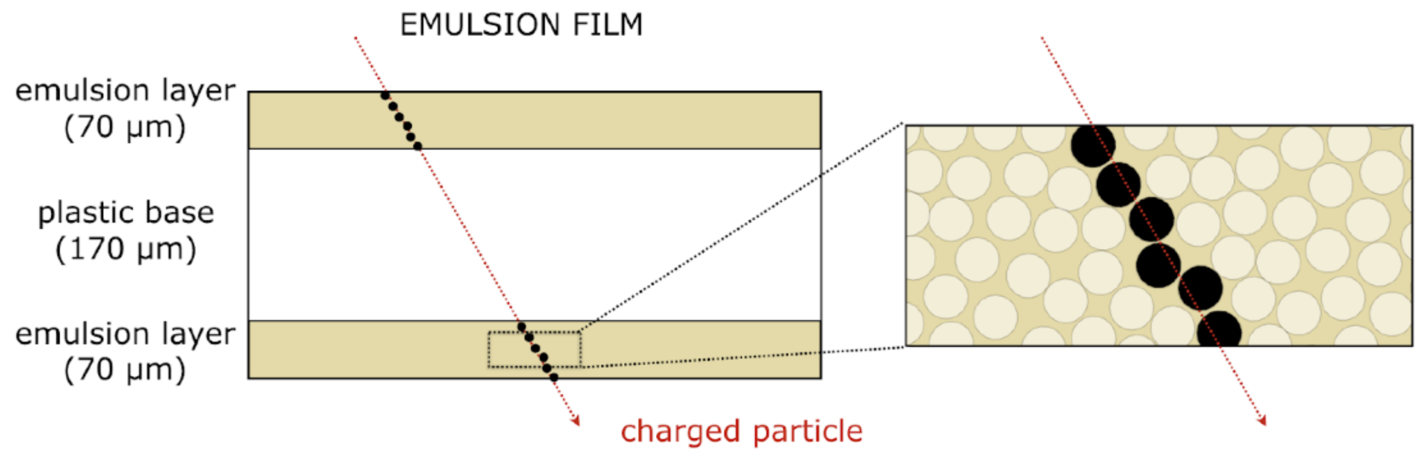
- Total veto ineff. $\sim 9 \times 10^{-8}$ with two planes
- Evaluation with three planes in progress

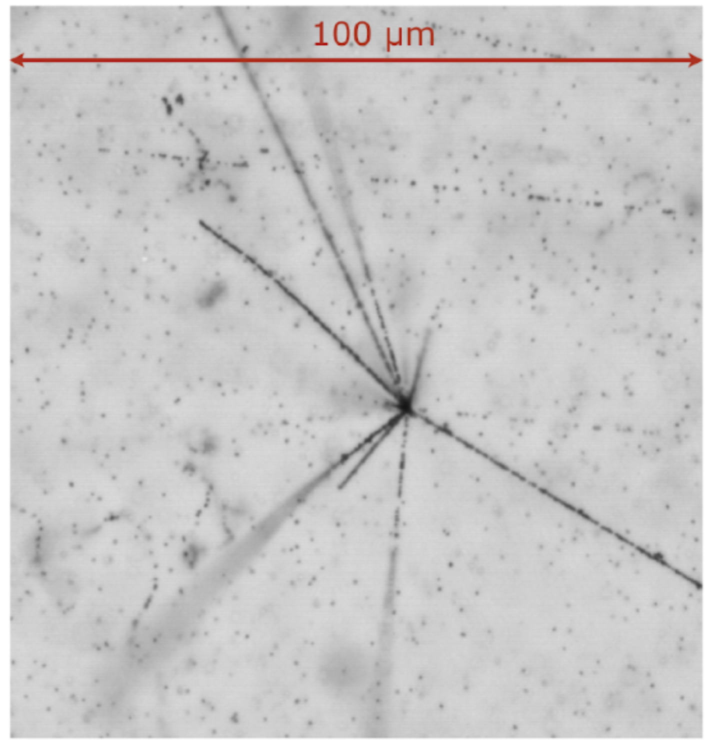
EMULSION TARGET

SND@LHC

- Five ECC walls used as a vertex detector
- 0.31 mm emulsion films interleaved with 1 mm tungsten plates
- Total target mass: 830 kg
- Emulsions changed every $< 20\ \text{fb}^{-1}$

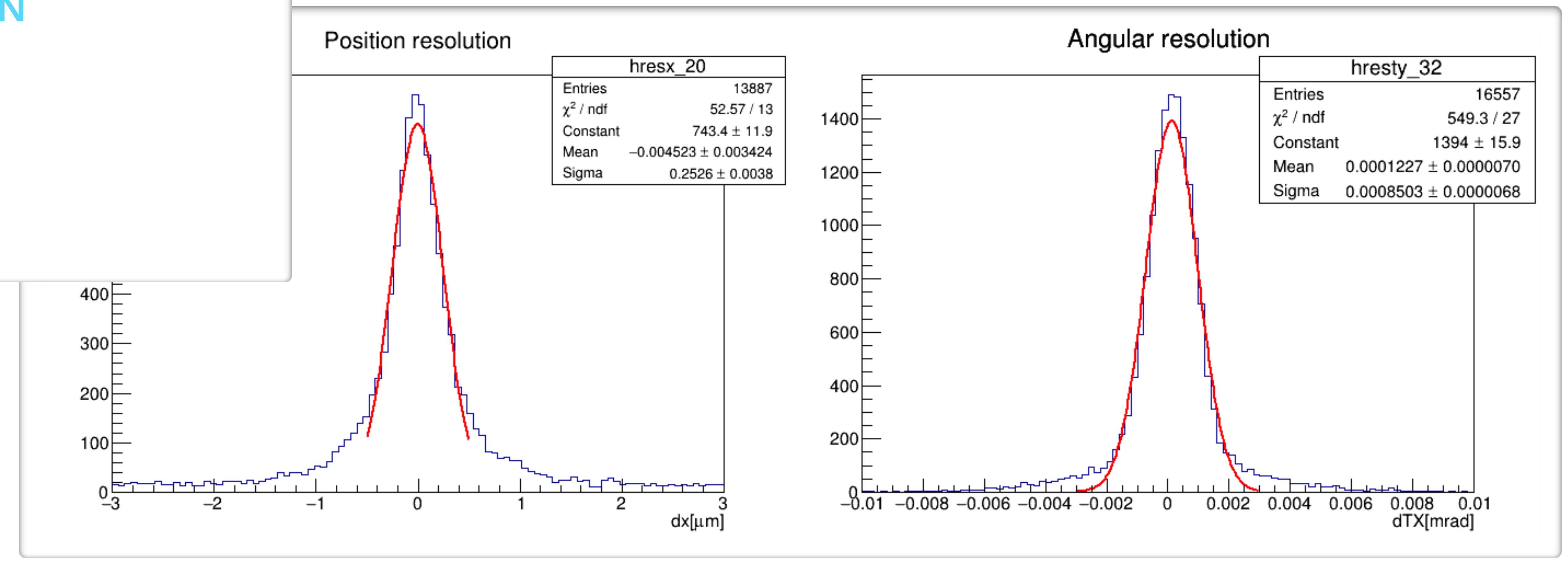






TRACKING RESOLUTION

- $\sigma_{x,y} \sim 0.7\ \mu m$
- $\sigma_{\tan(x,y)} \sim 10^{-6}$

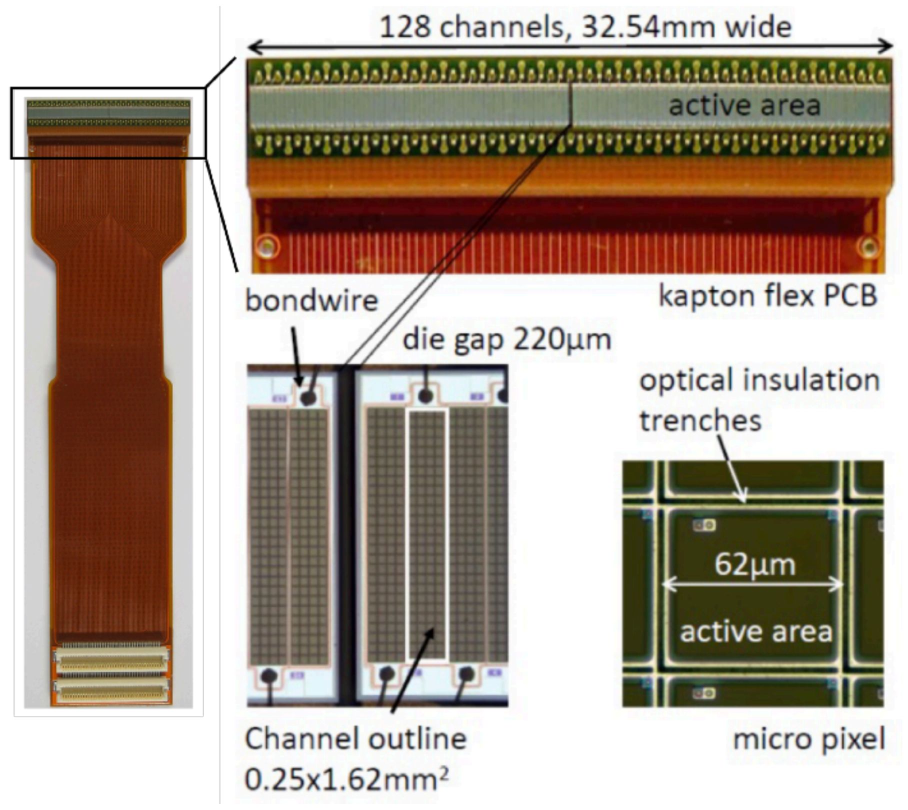


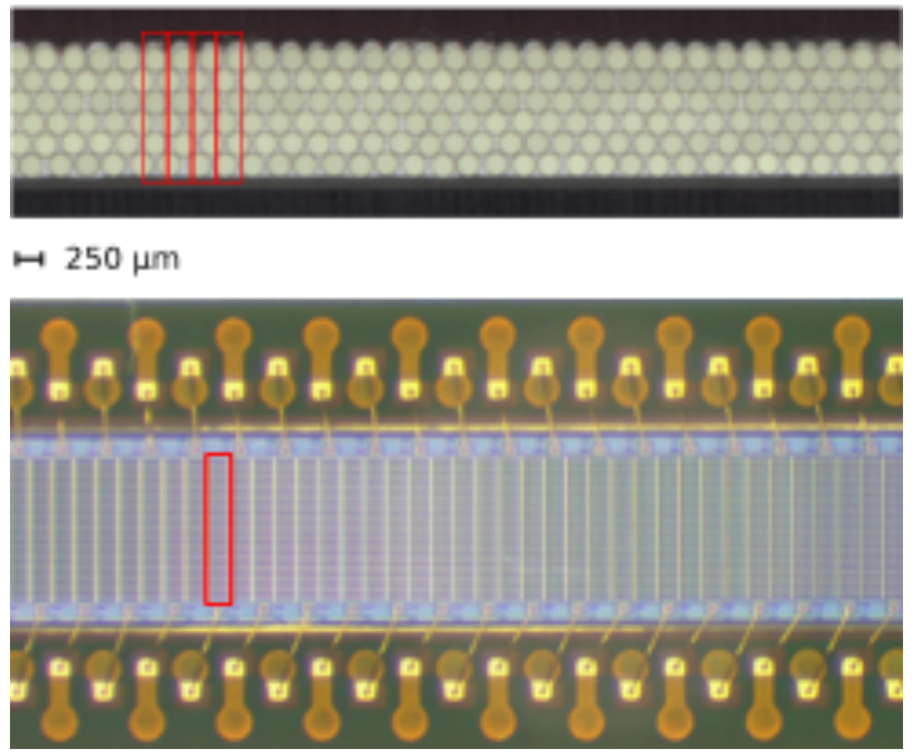
ECC target data is extracted by developing and scanning the emulsion films with microscopes

SCINTILLATING FIBRE TRACKER

SND@LHC

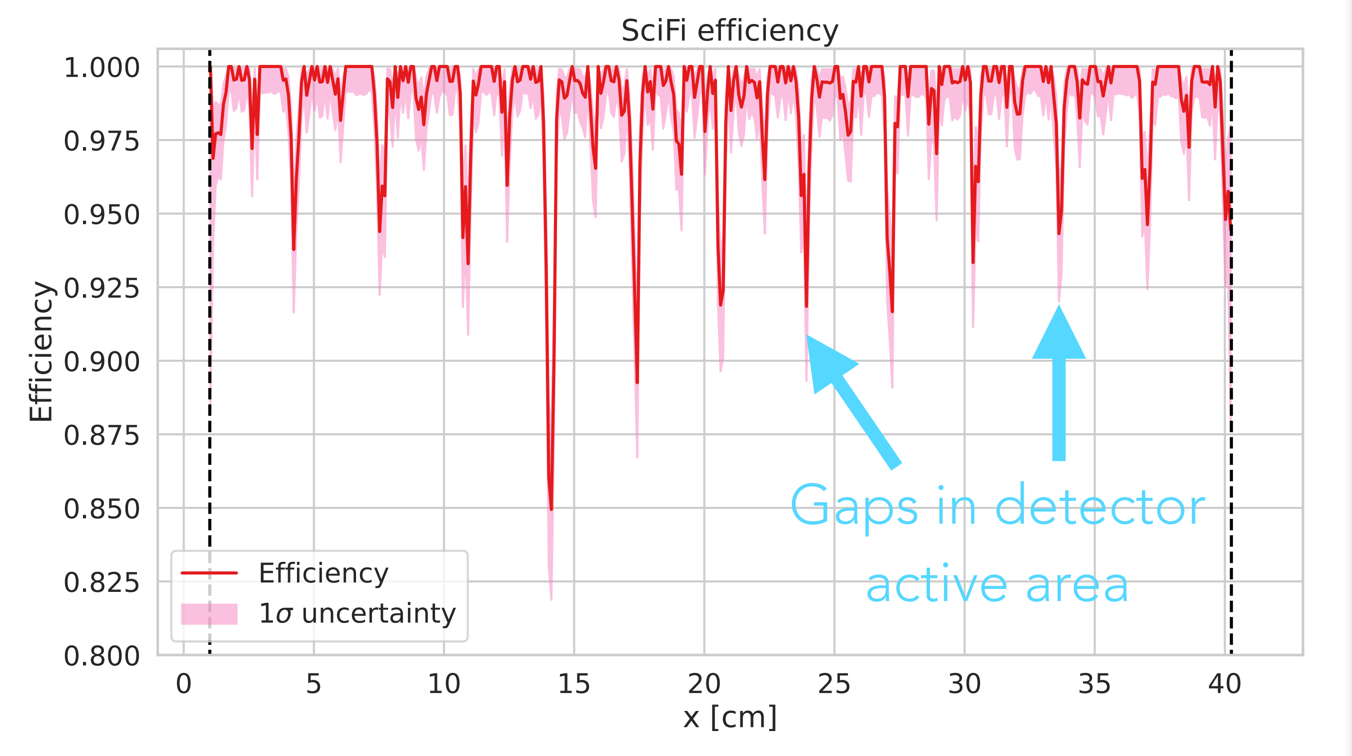
- Five SciFi stations interleaved with ECC walls, each with two perpendicular planes
- Provides timing and electromagnetic calorimetry together with the emulsions

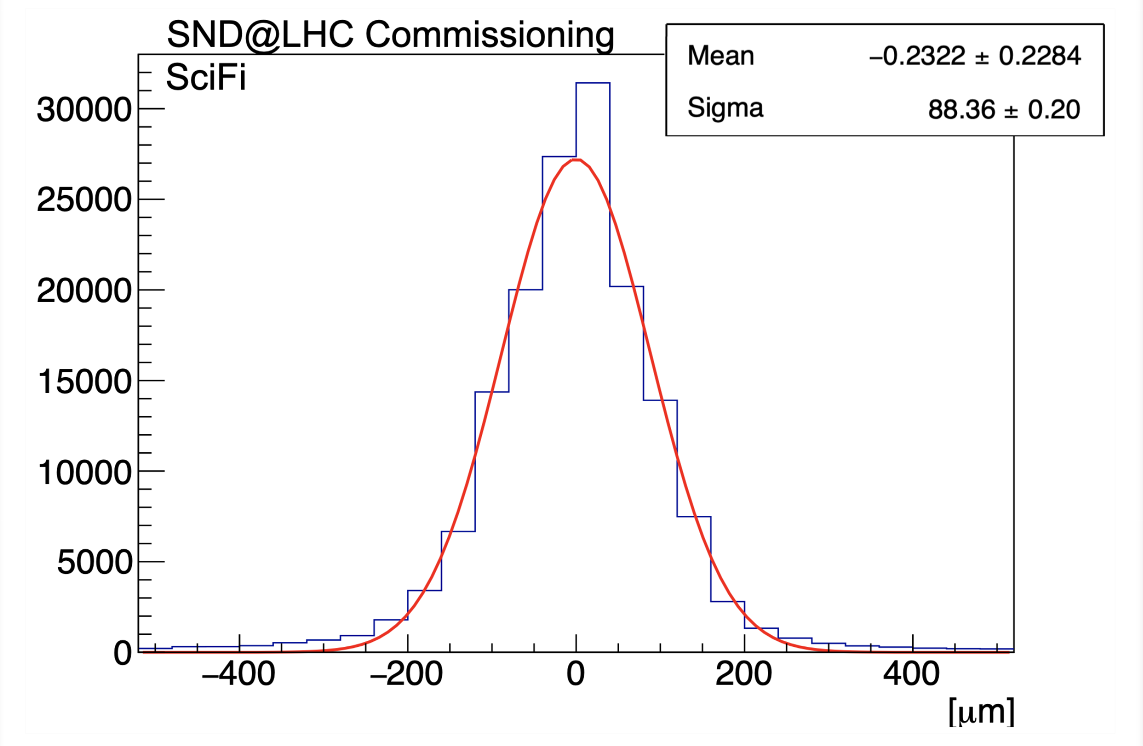




EFFICIENCY

- Evaluated in TI18 data
- ~98% in each plane
- ~99% in the active area / plane



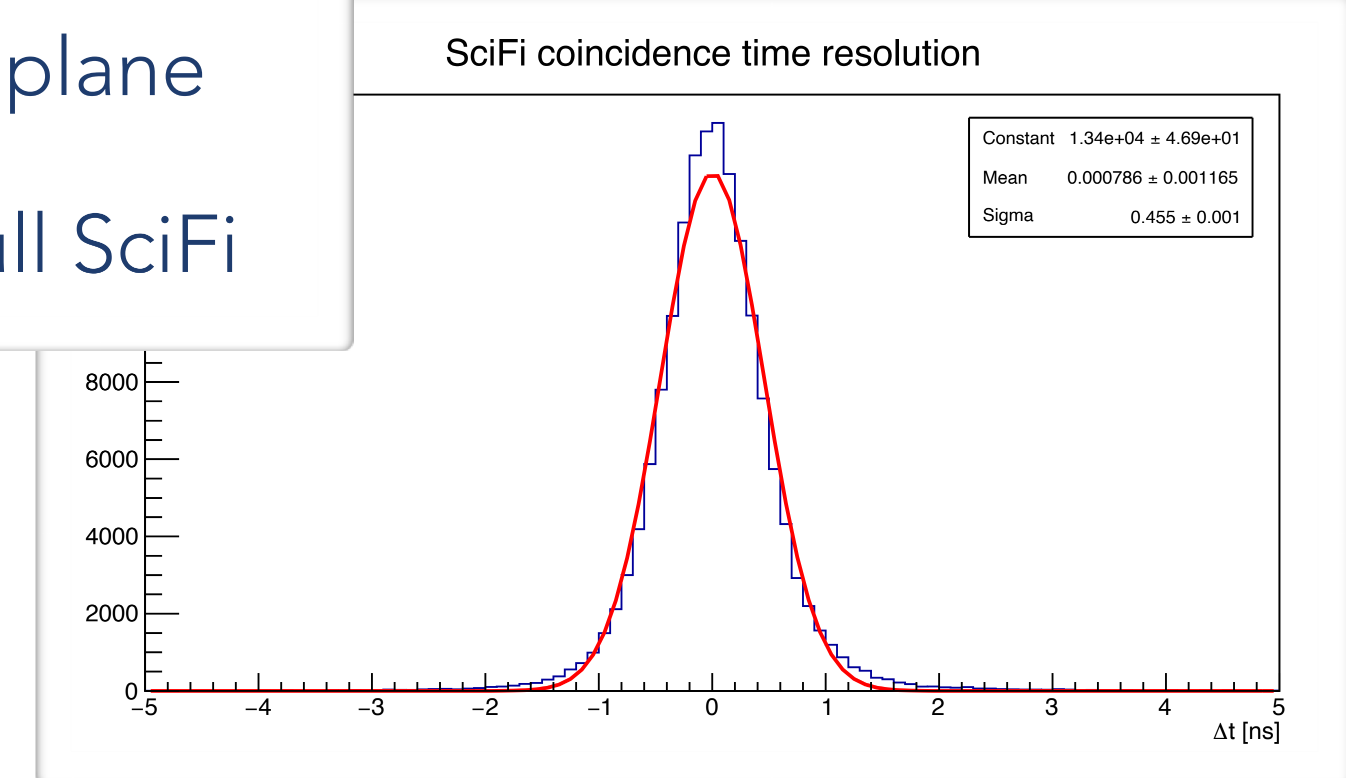


SPATIAL RESOLUTION

- Evaluated in muon testbeam data
- $\sigma_{X,Y} \sim 100\ \mu m$

TIME RESOLUTION

- Evaluated in TI18 data
- $\sim$ 320 ps in a layer
- $\sim$ 230 ps in a plane
- $\sim$ 100 ps in full SciFi

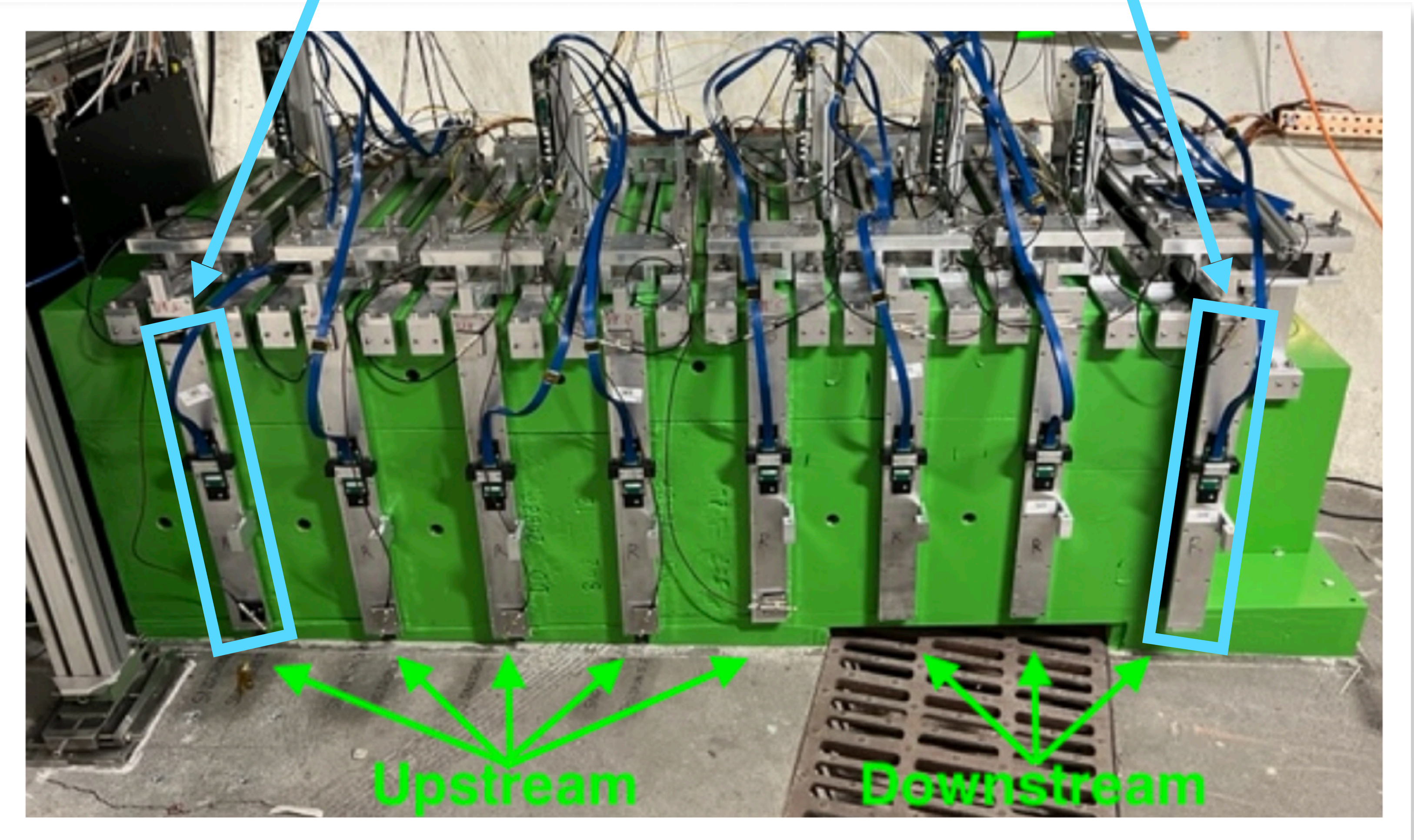


MUON SYSTEM AND HCAL

SND@LHC

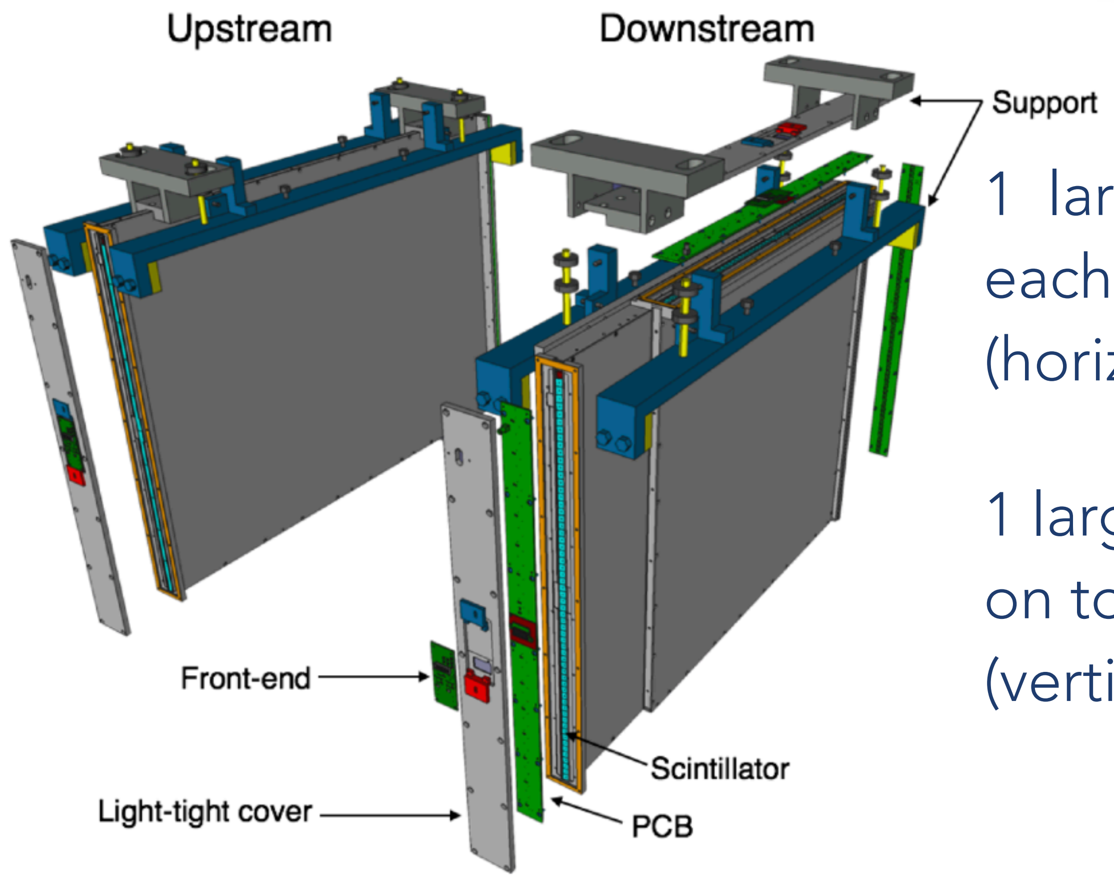
10 bars, (1 x 6 x 81 cm^3)

60 horizontal bars (1 x 1 x 81 cm^3)
60 vertical bars (1 x 1 x 60 cm^3)



6 large (6 x 6 mm^2) SiPMs each side +

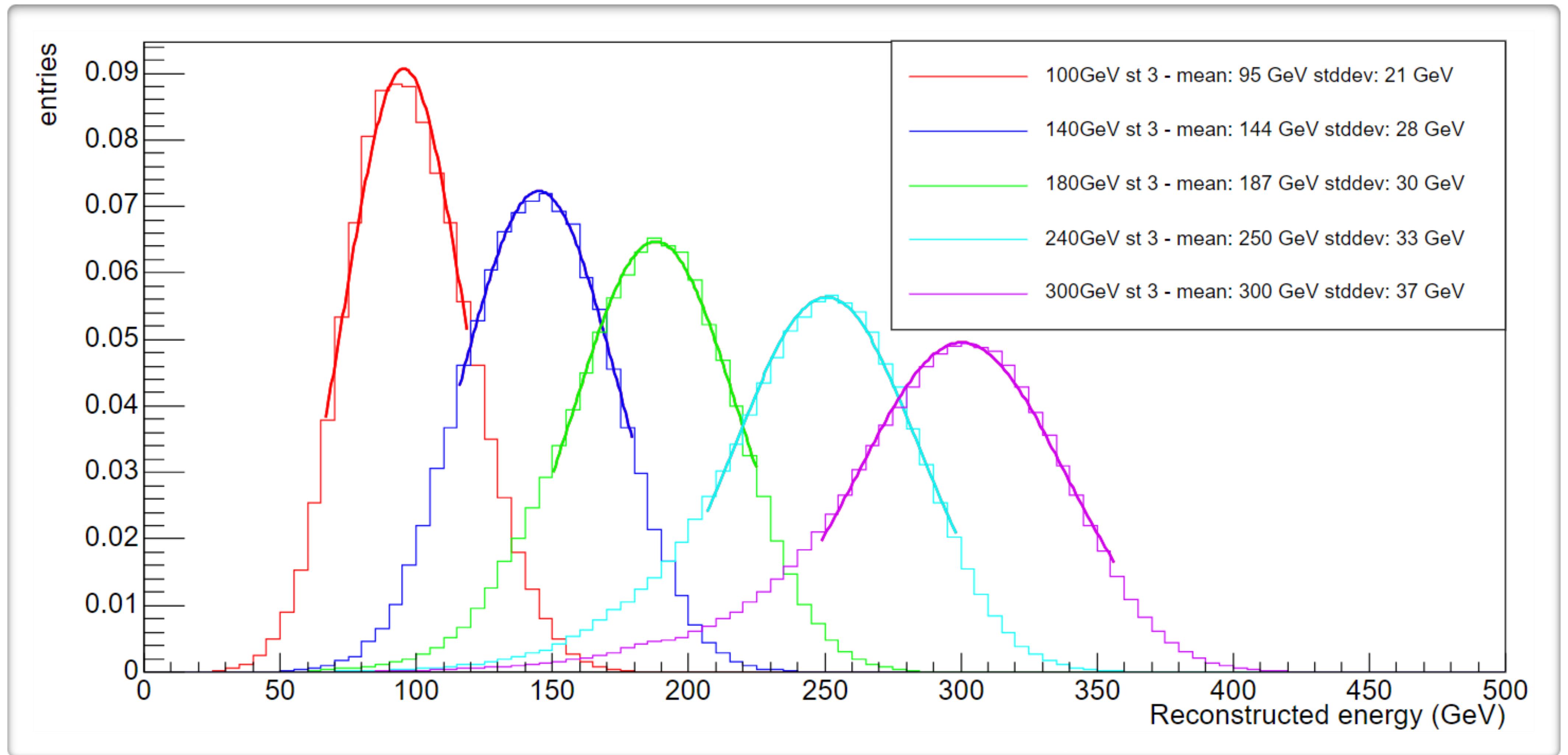
2 small (3 x 3 mm^2) SiPMs each side



1 large SiPM each side (horizontal)

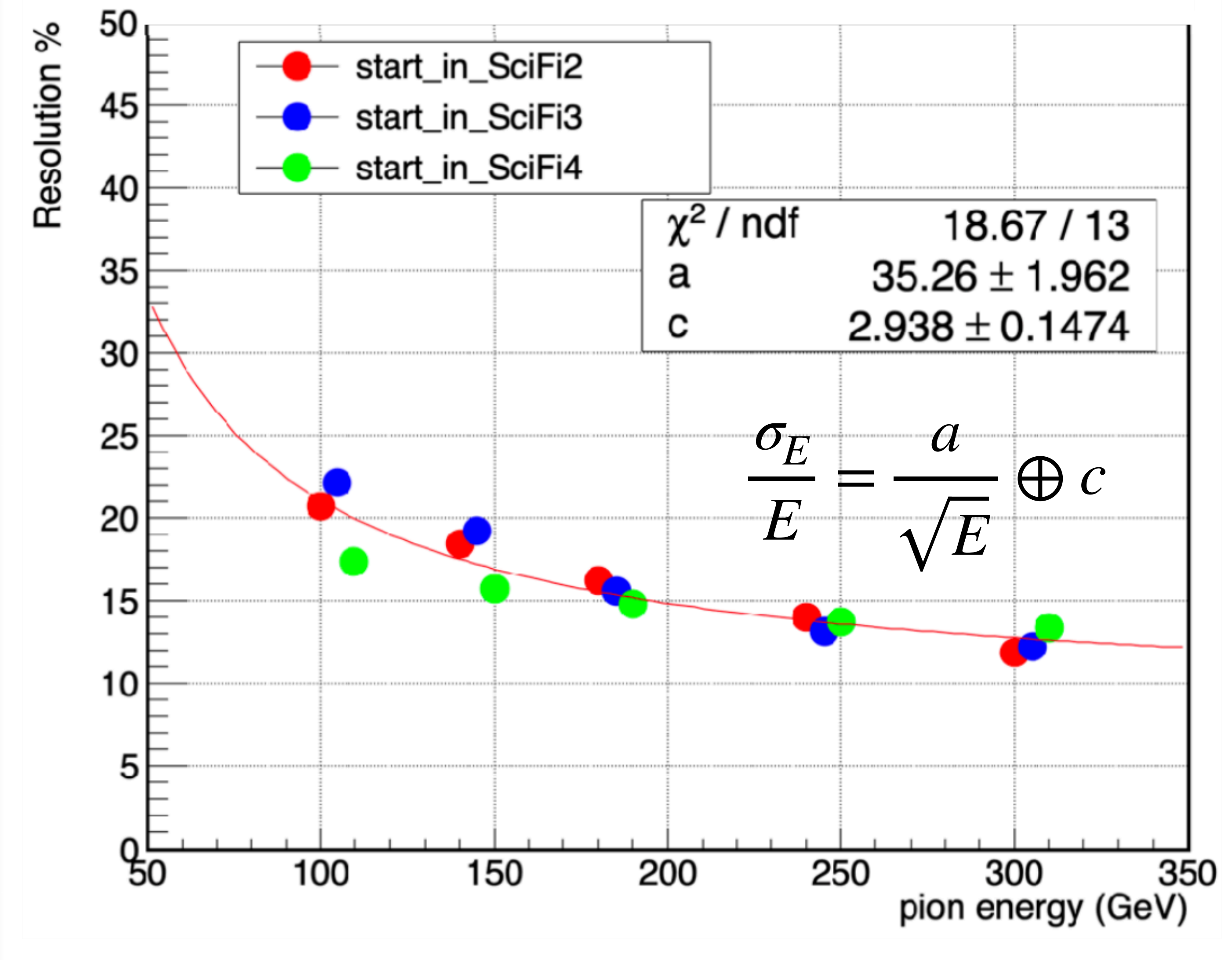
1 large SiPM on top (vertical)

- 8 stations of scintillating bars, interleaved with 20 cm iron slabs (1 slab $\sim \lambda_{int}$)
  - Five upstream stations - hadronic calorimetry
  - Three downstream stations - muon identification



Energy calibration with 100-300 GeV pion testbeam

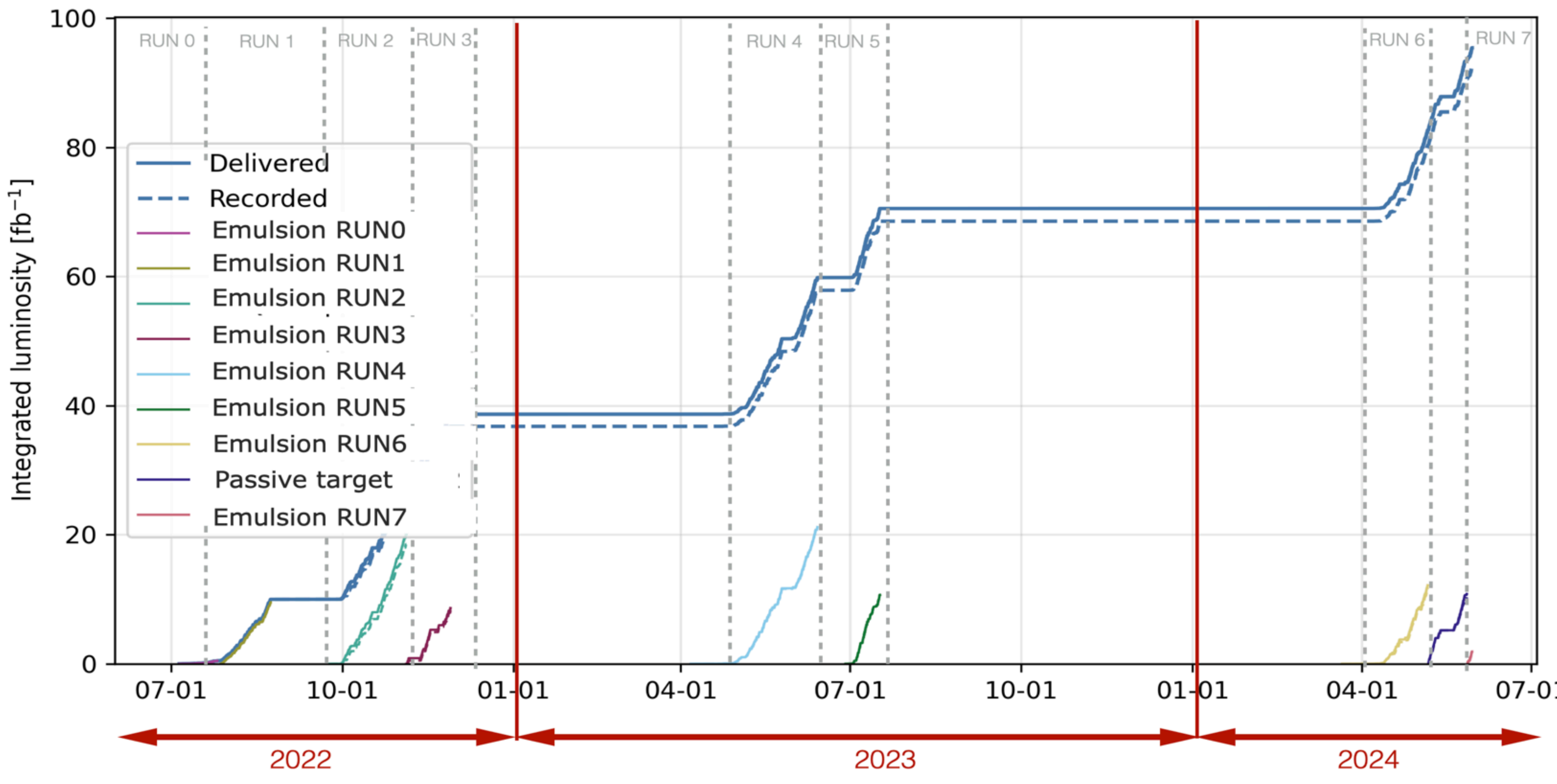
→ Energy resolution of 14% for 300 GeV pions



OPERATION

SND@LHC

- The electronic data acquisition is done triggerlessly - all hits passing a threshold are sent to the server for event building
- The detector has been operated with high efficiency, collecting
  - 95% of the delivered luminosity in 2022
  - 99.7% of the delivered luminosity in 2023



2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN0													39 kg	0.46 fb^{-1}
EMULSION RUN1													807 kg	9.5 fb^{-1}
EMULSION RUN2													784 kg	20.0 fb^{-1}
EMULSION RUN3													792 kg	8.6 fb^{-1}

2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN4													797 kg	21.2 fb^{-1}
EMULSION RUN5													784 kg	10.7 fb^{-1}

2024	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN6													797 kg	12.1 fb^{-1}
EMULSION RUN7													398 kg	*in progress*

FASER DETECTOR

DECAY VOLUME & TRACKING SPECTROMETER

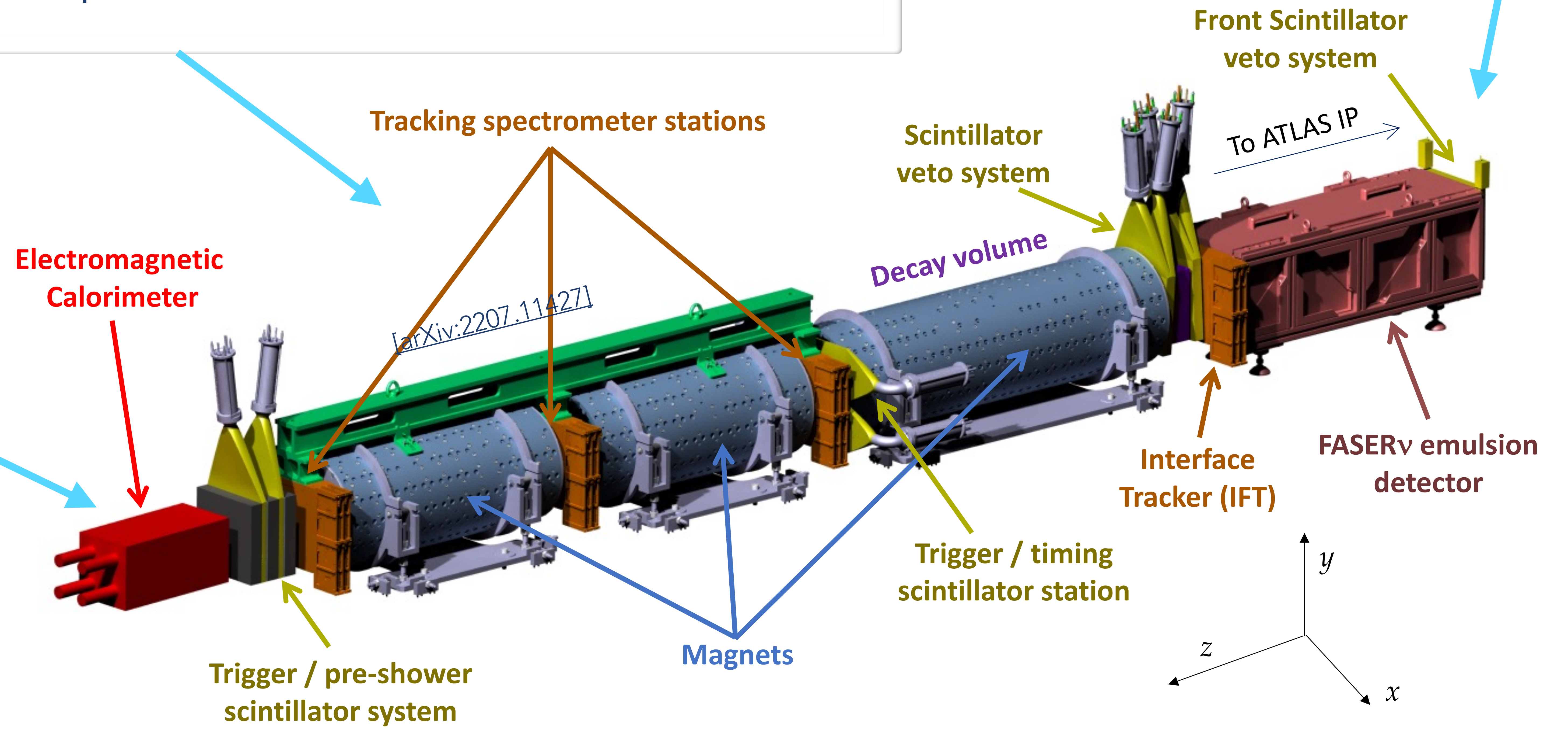
- Dipole magnets separate collimated opposite charged particles and measure the charge of μ from ν interactions
- Silicon strip trackers to measure position, charge & momentum of charged particles

FASERν EMULSION DETECTOR

- Emulsion cloud chambers with tungsten for ν identification via precise vertexing
- IFT tracking station for matching of emulsion tracks with electronic detector information

ECAL

- Plastic scintillator interleaved with lead
- Measures the total electromagnetic energy



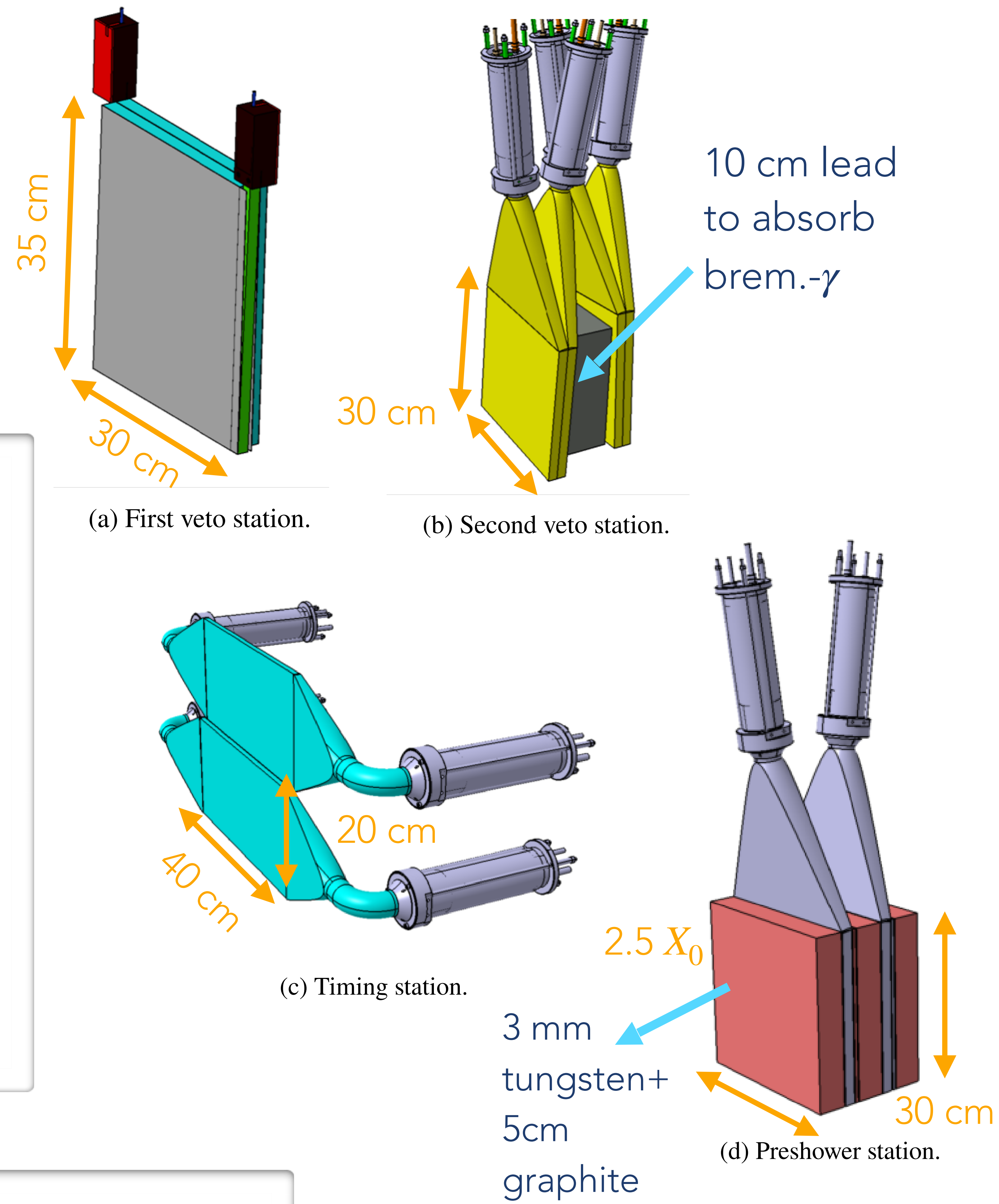
SCINTILLATORS

- Scintillator counters for veto, trigger, and timing

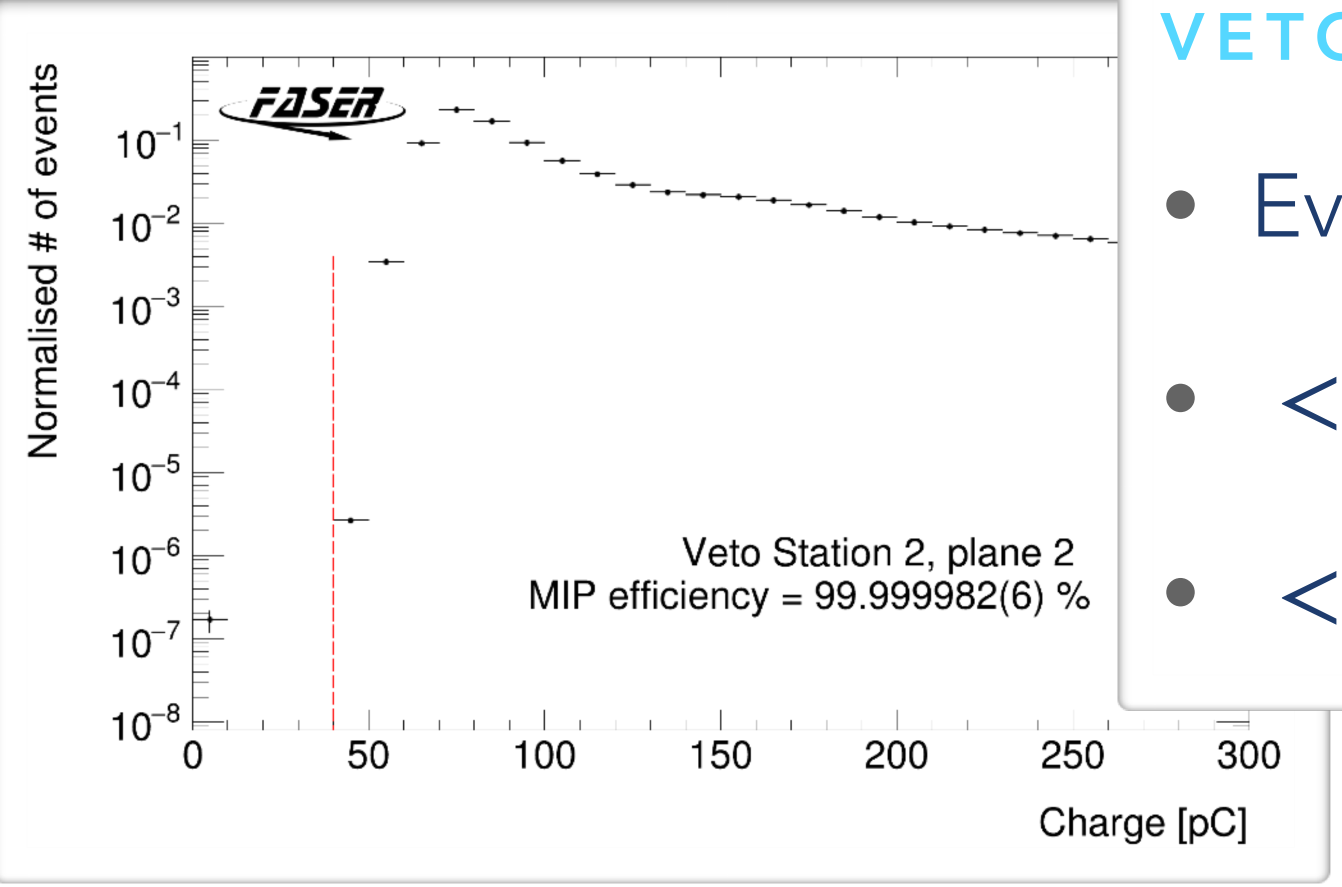
SCINTILLATOR SYSTEM

FASER

- Four scintillator stations made of multiple layers of plastic scintillator
  - Veto stations before and after FASERν to tag charged particles entering the detector
  - A trigger and timing station before first tracker
  - A pre-shower station before the ECAL for additional trigger and distinguishing neutrino DIS in the ECAL
- Read-out by photomultiplier tubes (PMTs)



(a) First veto station.
(b) Second veto station.
(c) Timing station.
(d) Preshower station.

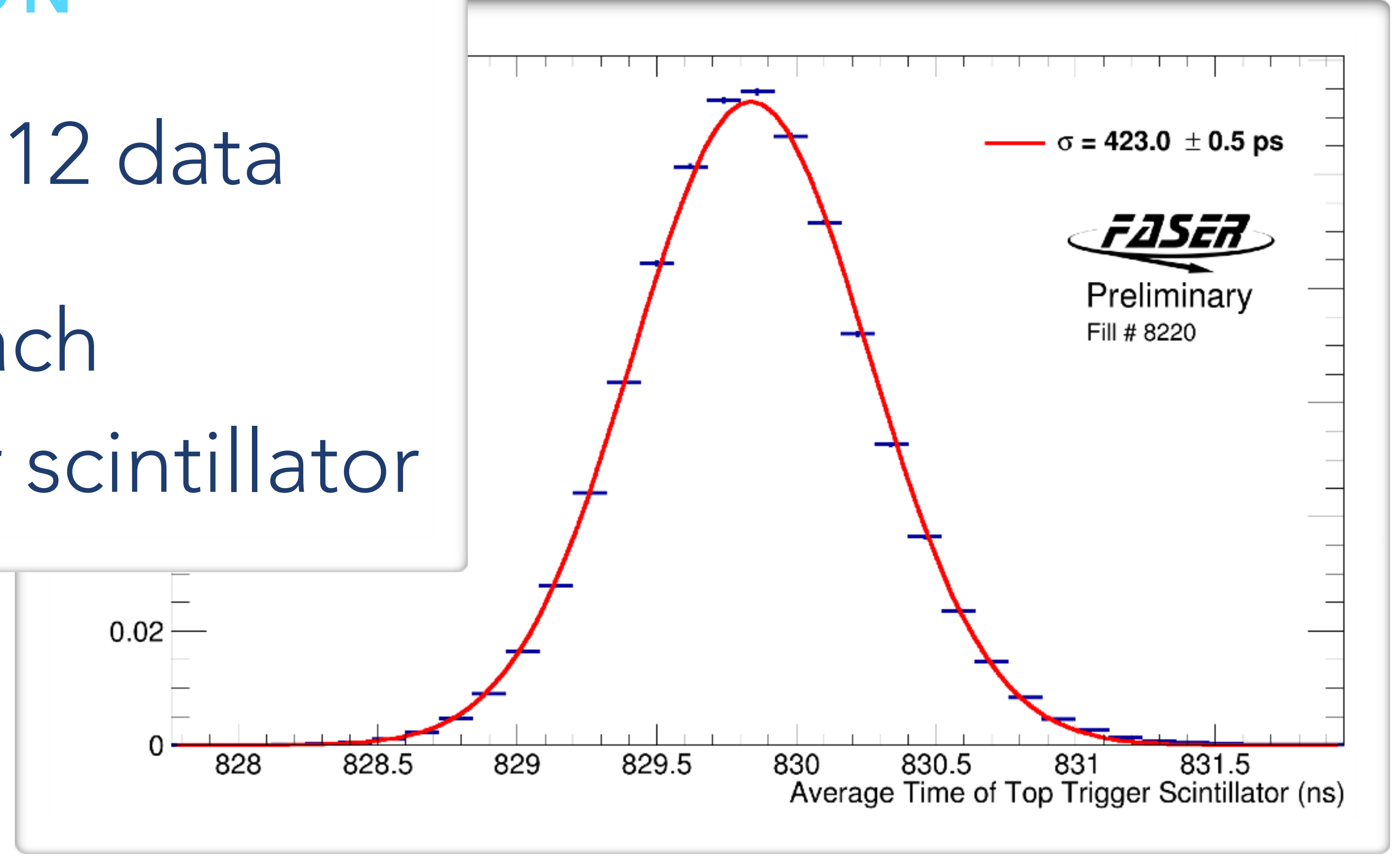


VETO INEFFICIENCY

- Evaluated in TI12 data
- $< 10^{-6}$ in each veto scintillator
- $< 10^{-20}$ total veto inefficiency

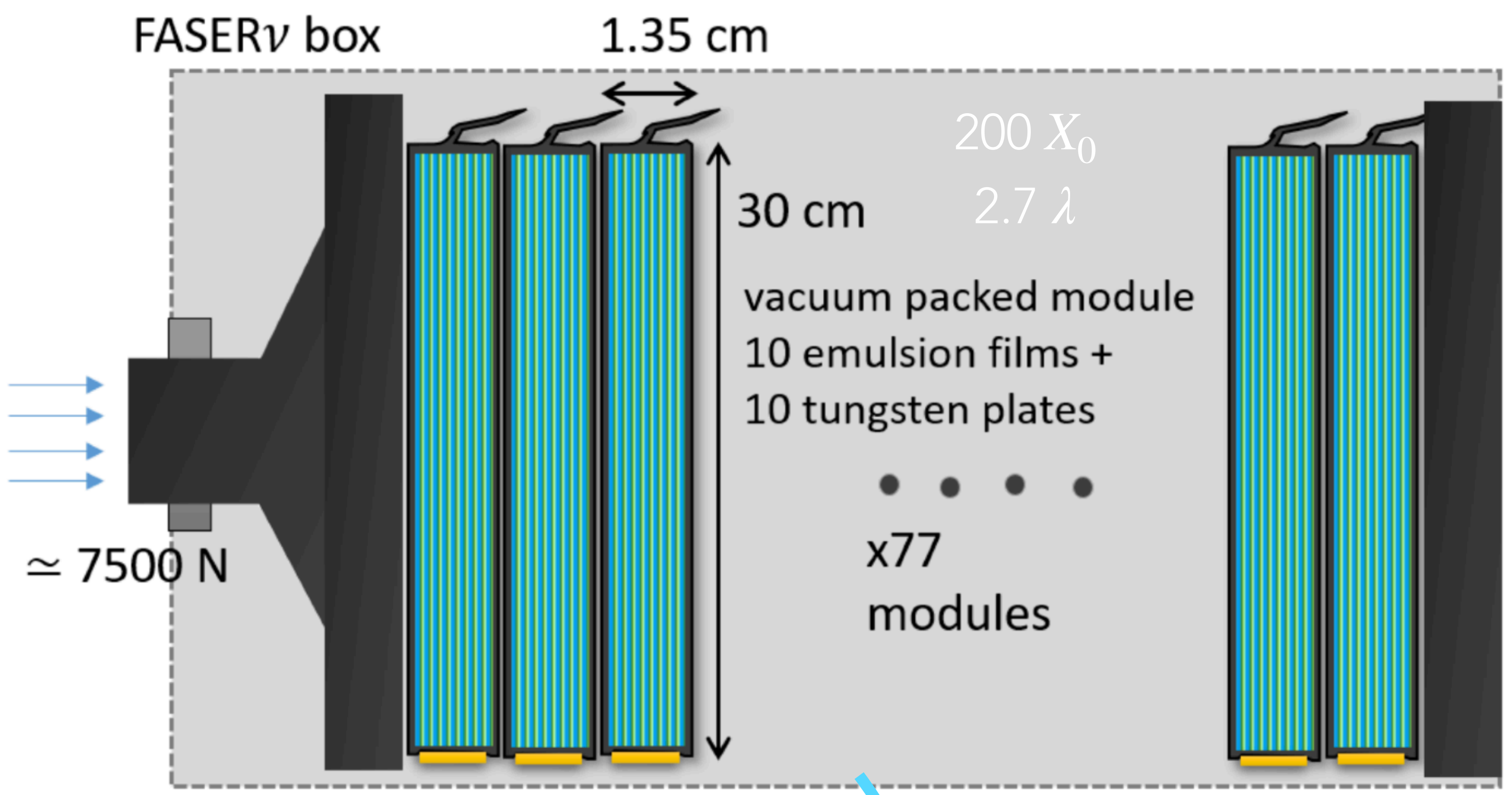
TIME RESOLUTION

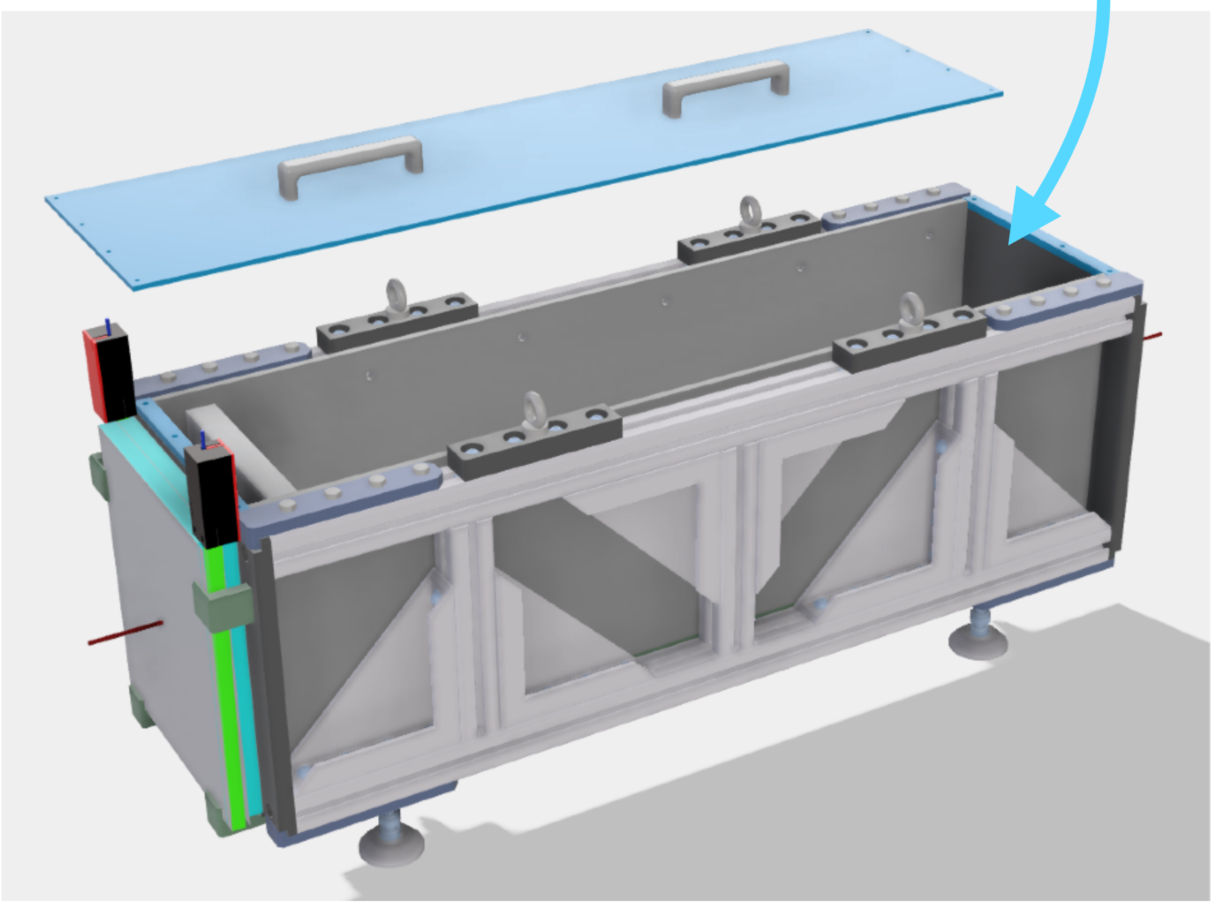
- Evaluated in TI12 data
- ~ 420 ps in each timing&trigger scintillator



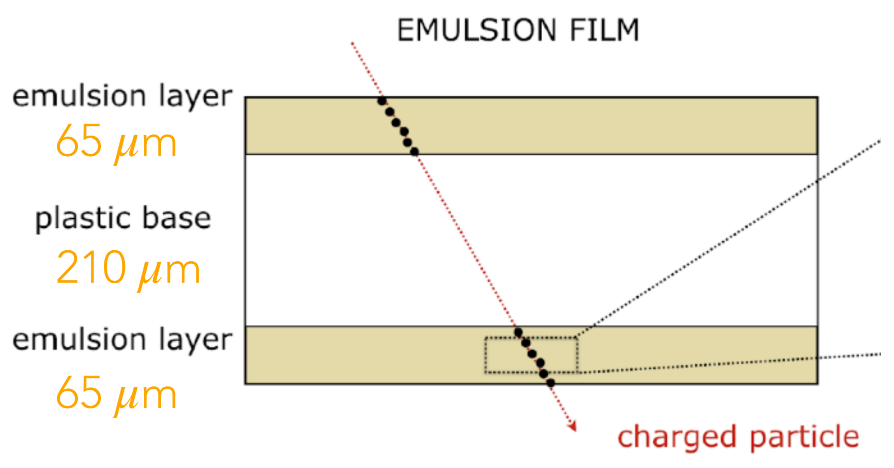
FASERν

FASER



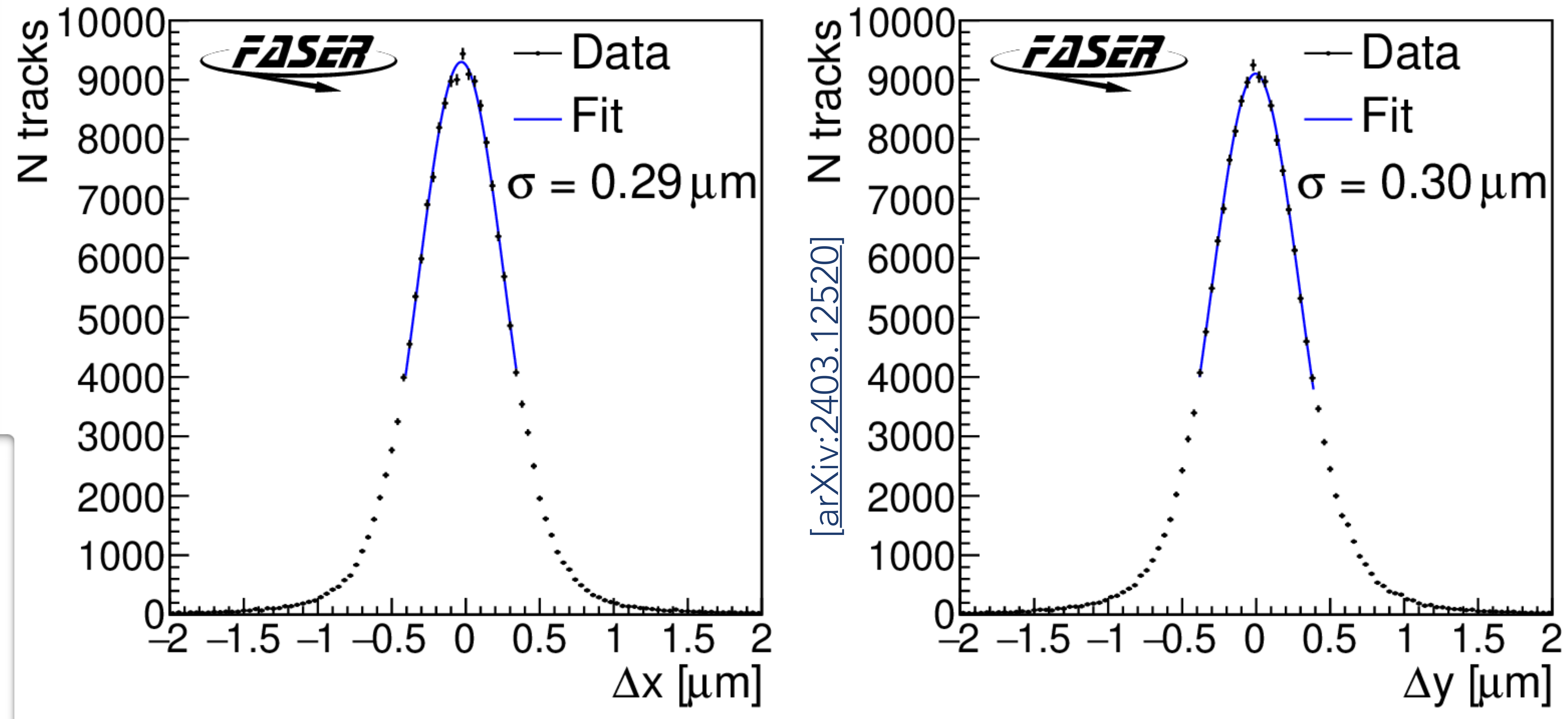


- Emulsion cloud chamber with tungsten for neutrino detection and identification via precise vertexing
- 0.34 mm thick 20 x 30 cm emulsion films interleaved with 1.1 mm tungsten plates (730 plates total)
- Mechanical support with a presser ensures sub-micrometric alignment of the emulsion modules
- Total target mass: 1100 kg
- Emulsions changed every 10-30 fb^{-1}



TRACKING RESOLUTION

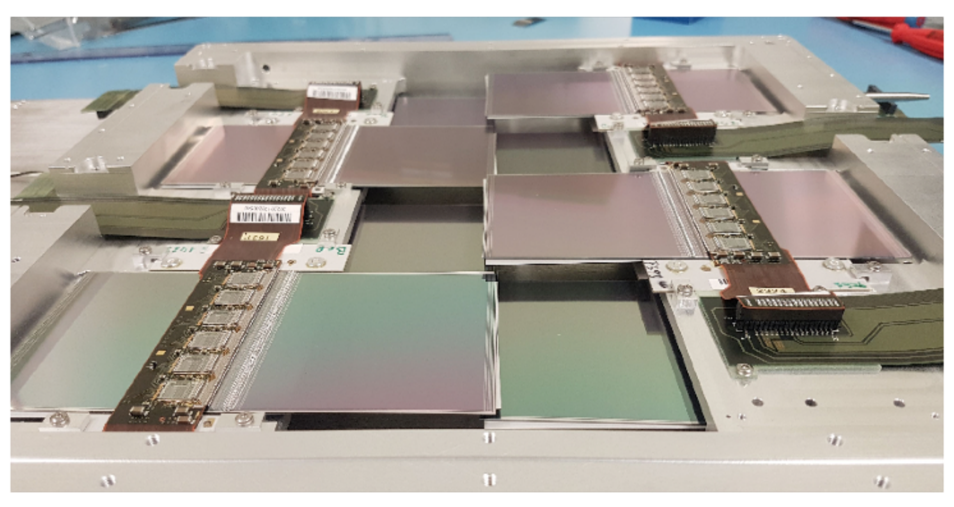
- $\sigma_{x,y} \sim 0.3\ \mu m$



TRACKING SPECTROMETER

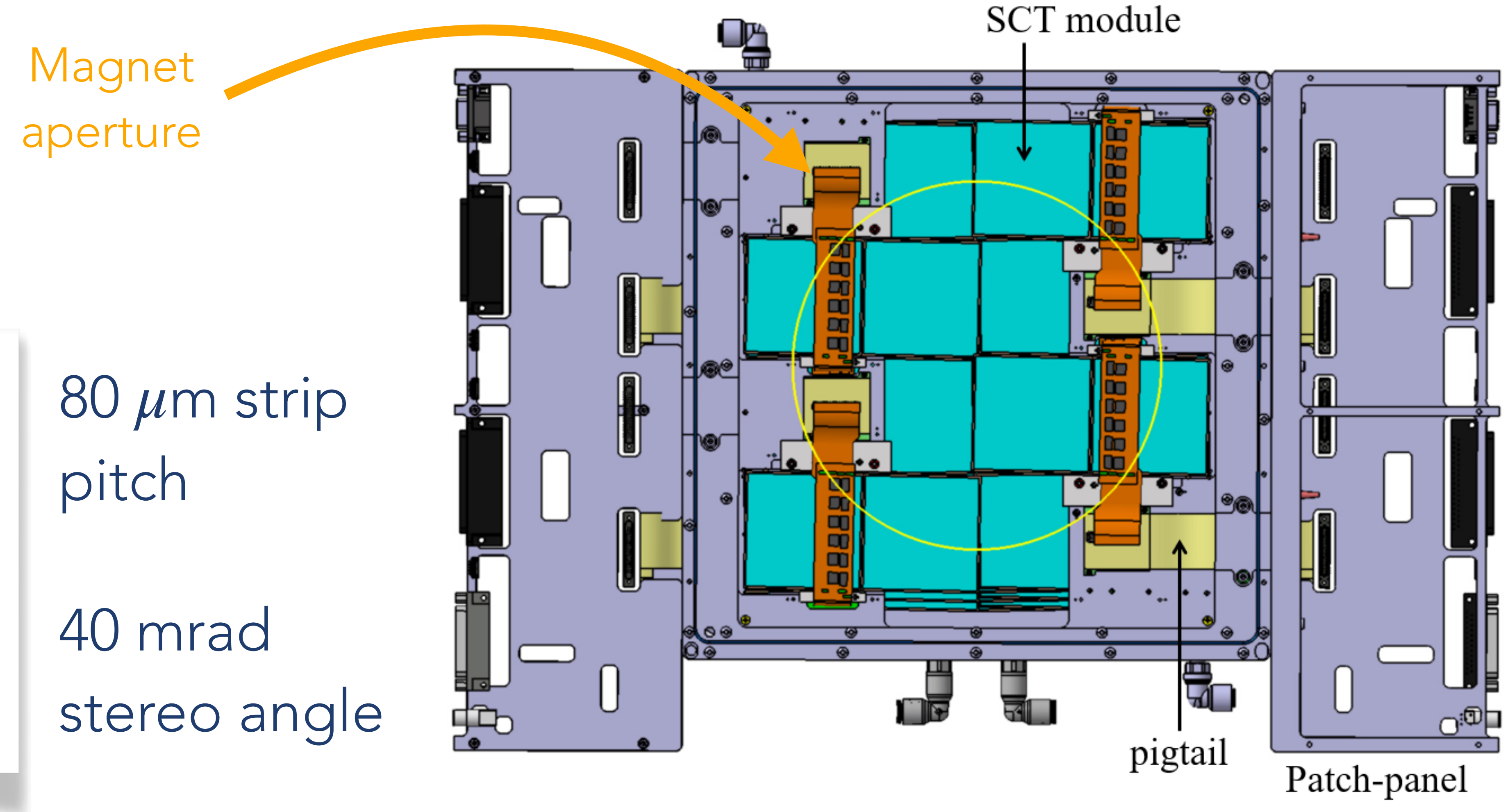
FASER [NIMA:2022.166825]

- Separates opposite charged particles produced in the decay of a long-lived particle
- Measures the position and momentum of charged particles
- Three stations separated by two permanent 0.57 T dipole magnets
  - Each station consists of silicon double strip modules that were spares of the ATLAS SCT barrel detector
- Separate interface tracker (IFT) station allows for matching of neutrino interaction tracks to spectrometer tracks



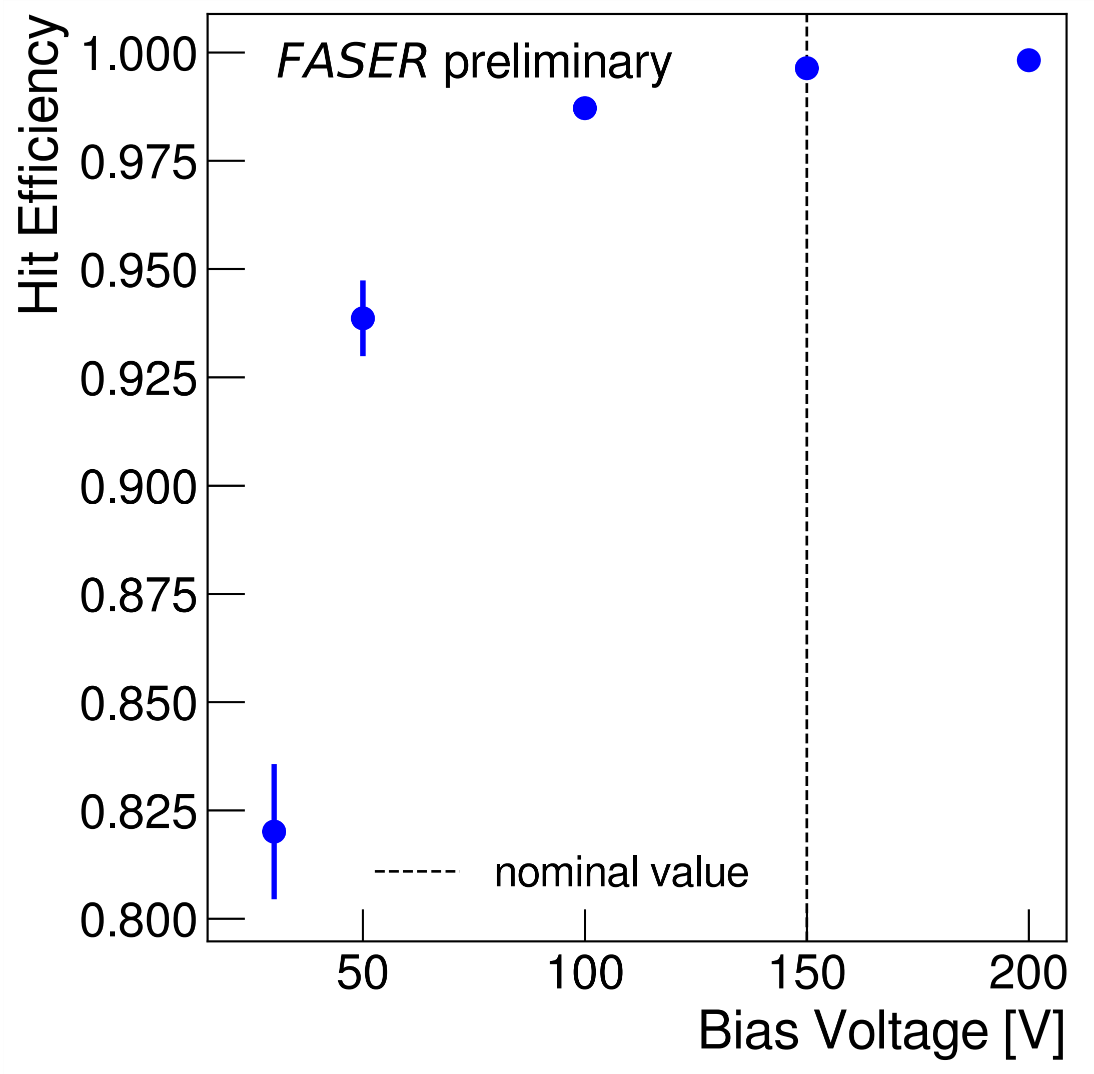
80 μm strip pitch

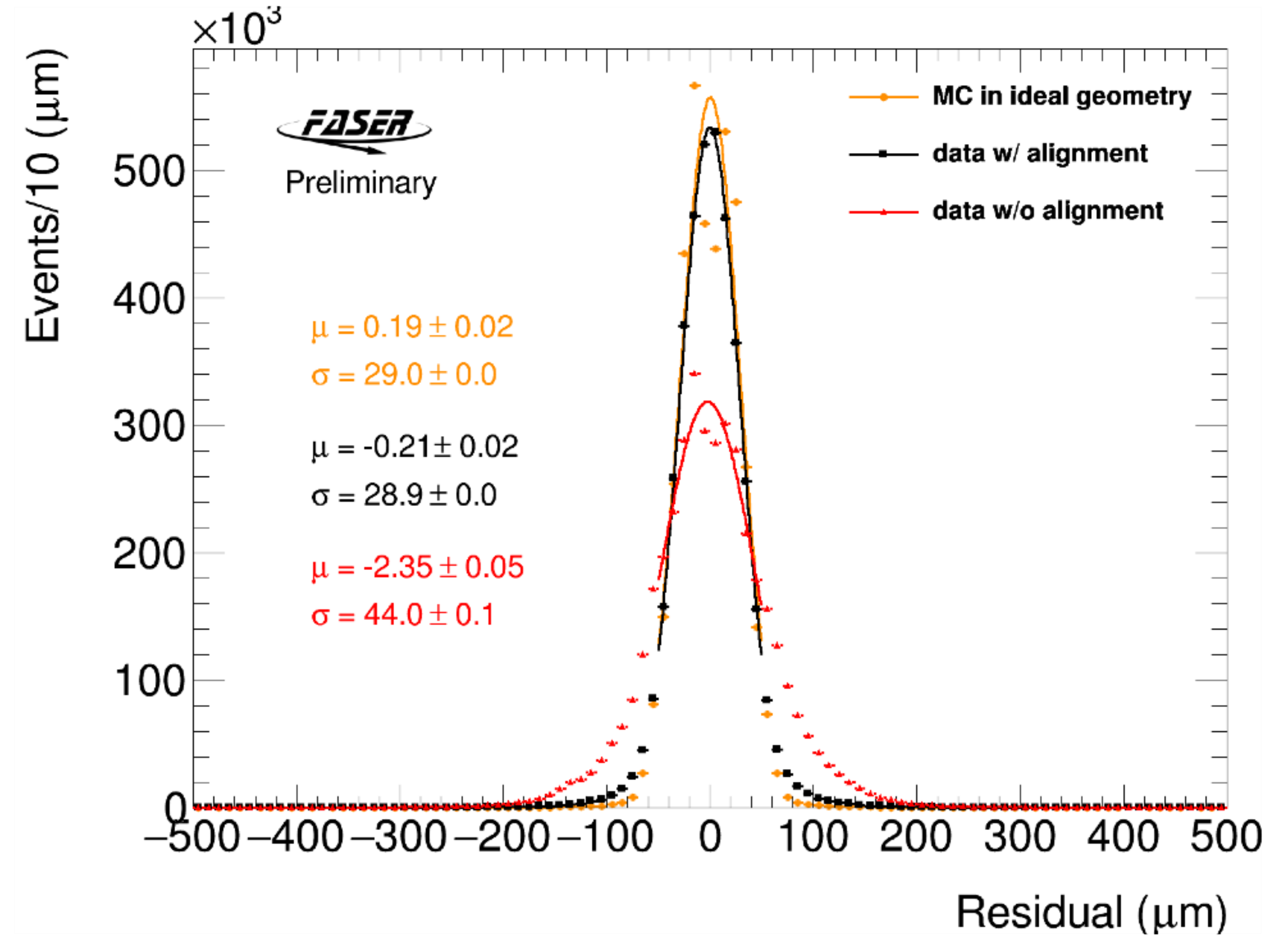
40 mrad stereo angle



EFFICIENCY

- Evaluated in dedicated TI12 runs
- ~ 99.6 % hit efficiency



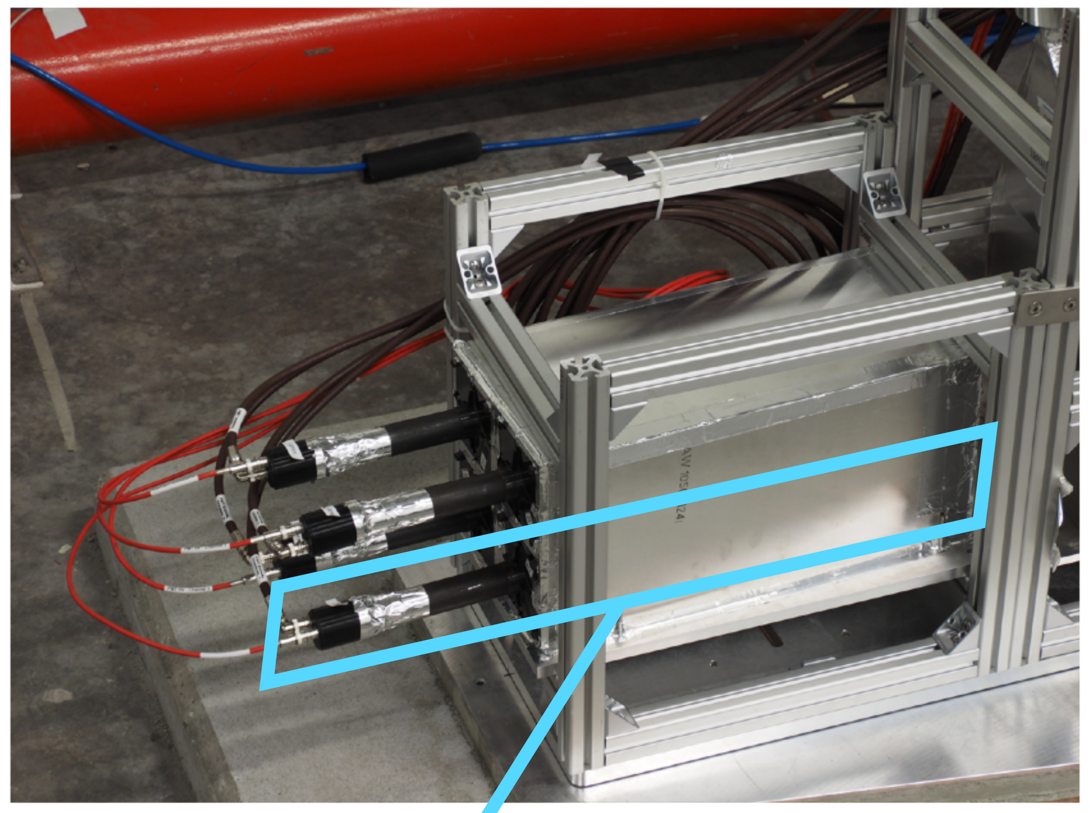


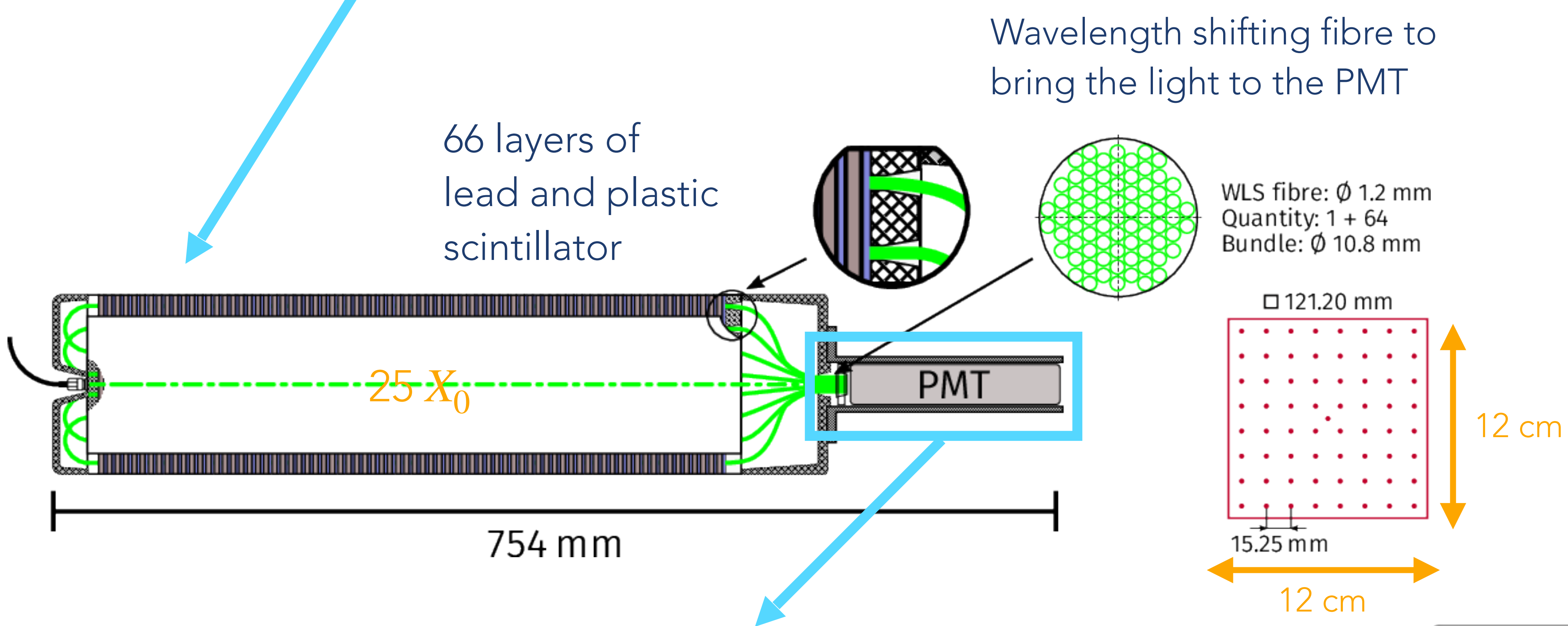
SPATIAL RESOLUTION

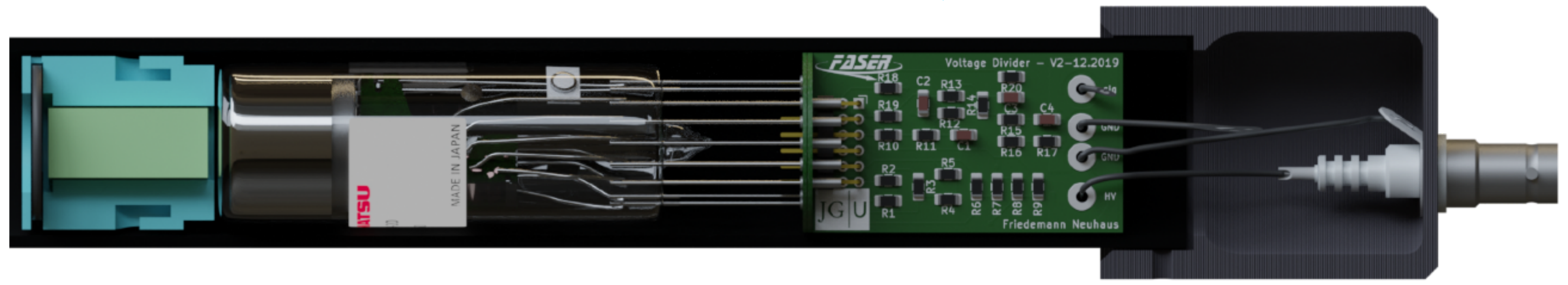
- $\sim 30\ \mu$m
- Good alignment demonstrated in TI12 data

ECAL

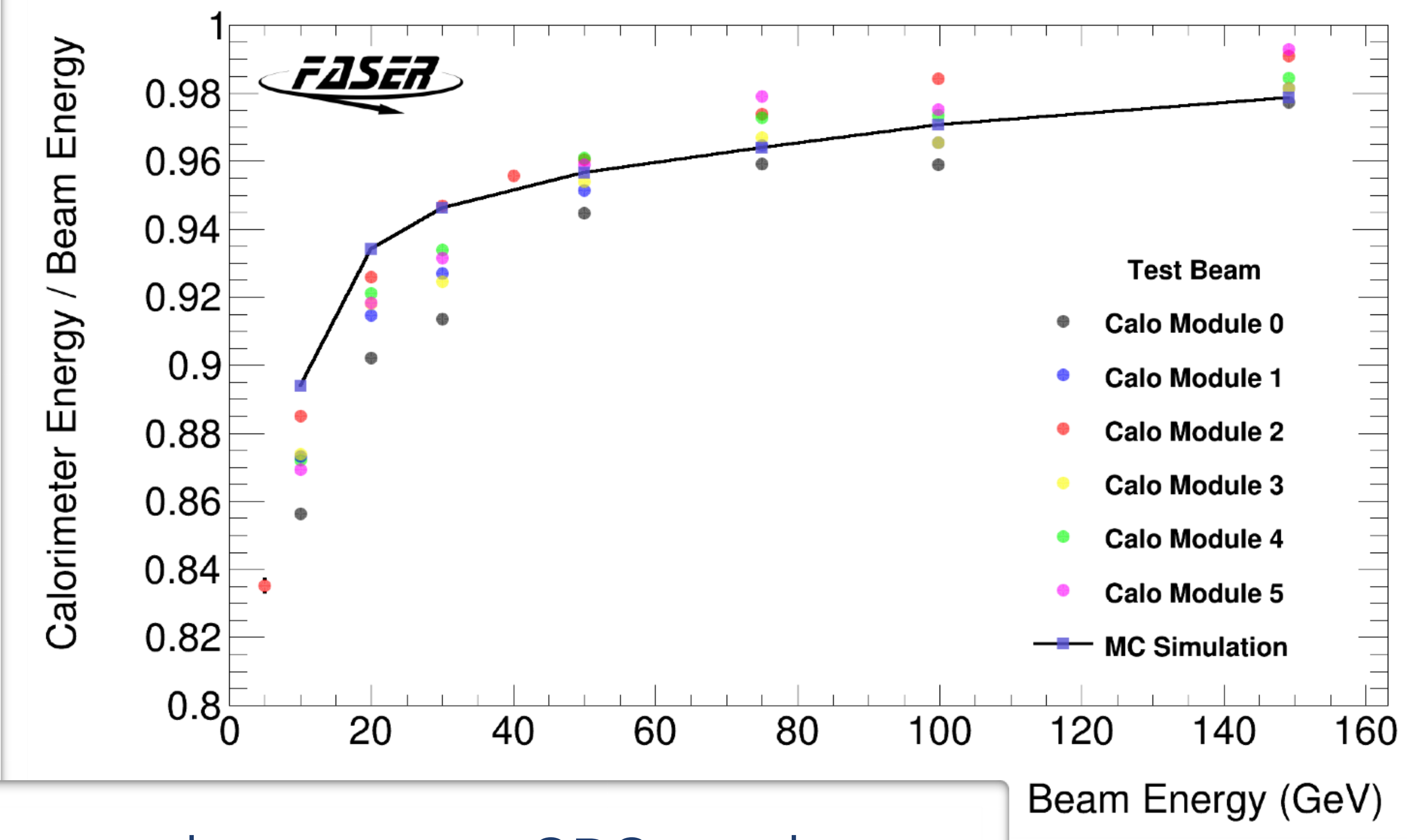
FASER







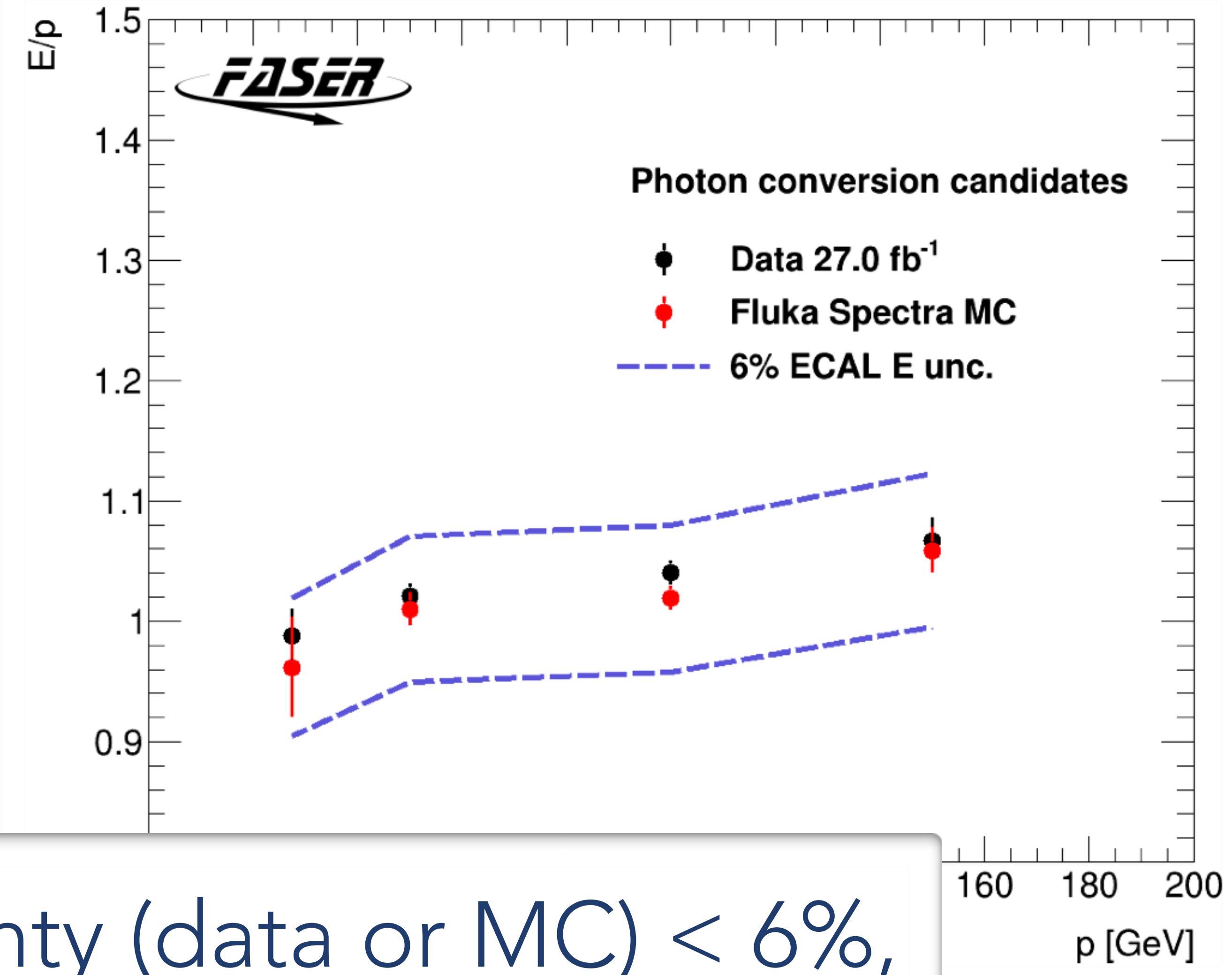
- Measures the total electromagnetic energy of events
- Four LHCb outer ECAL modules in a 2x2 configuration



Energy calibration with electrons and muons at SPS testbeam

ENERGY RESOLUTION

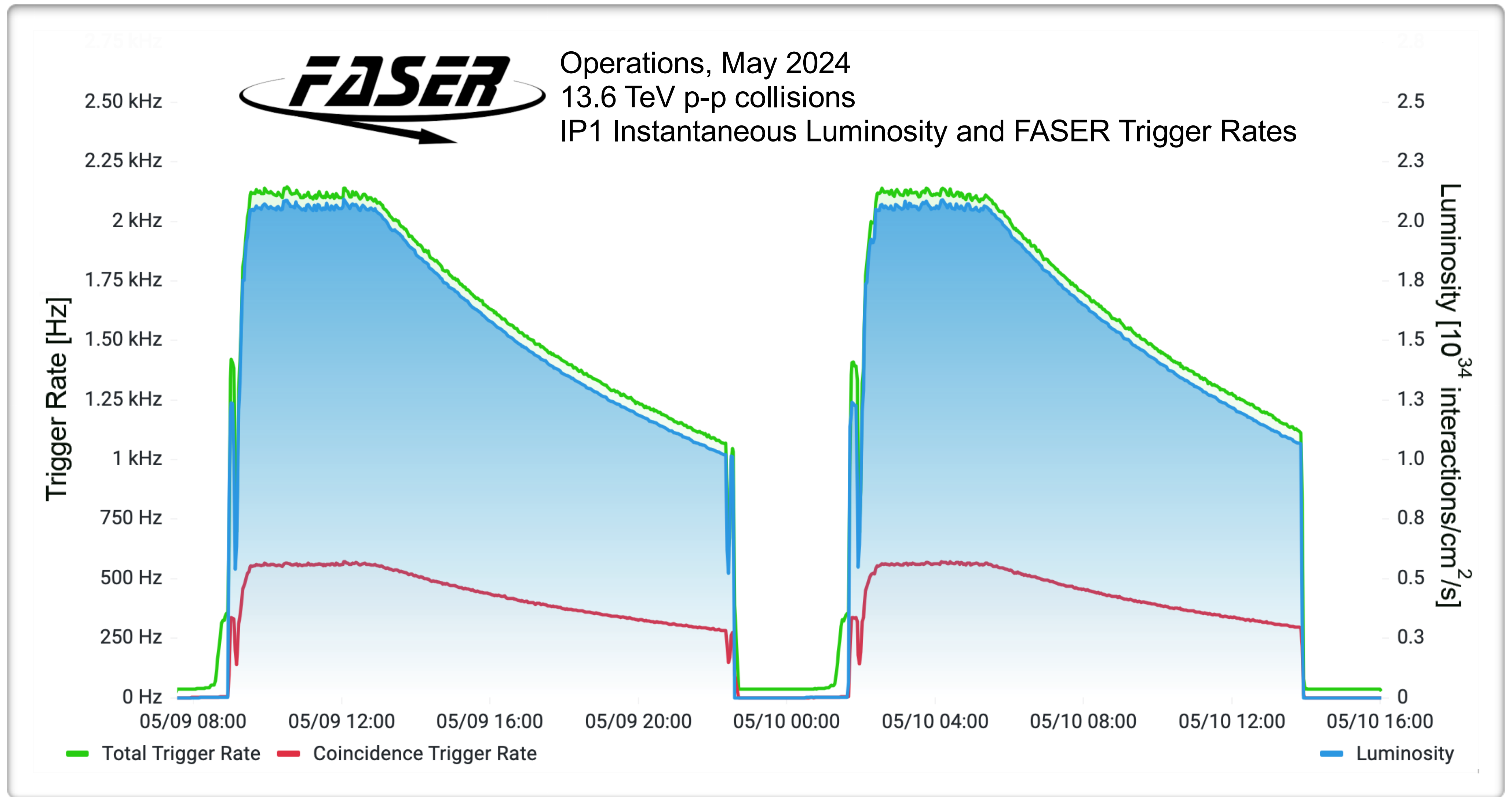
- Evaluated with high energy electrons at SPS testbeam (up to 300 GeV)
- $\Delta E/E \sim 1\,\%$



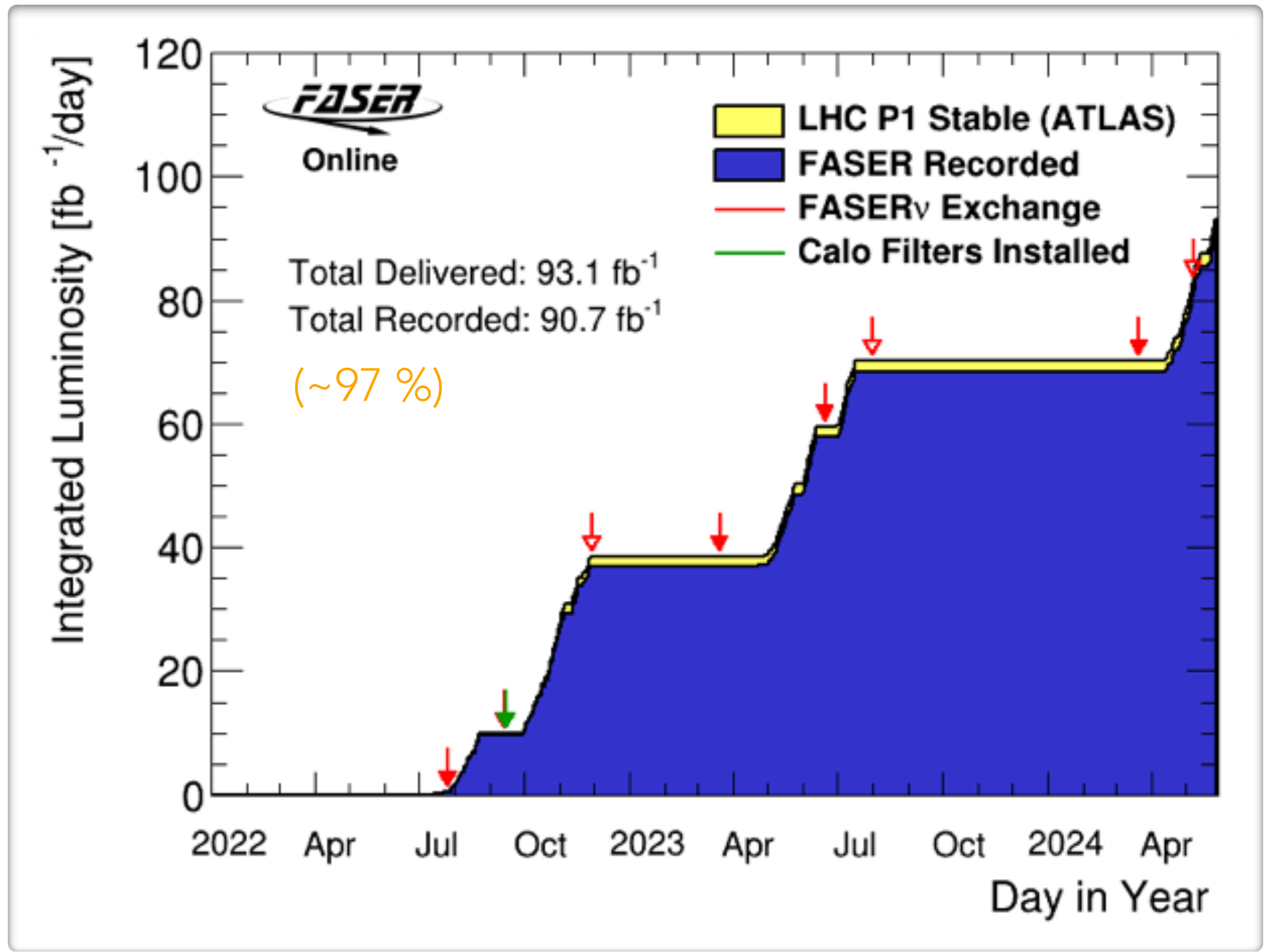
Calorimeter energy scale uncertainty (data or MC) < 6%, validated with photon conversion events in situ

TRIGGER & OPERATION

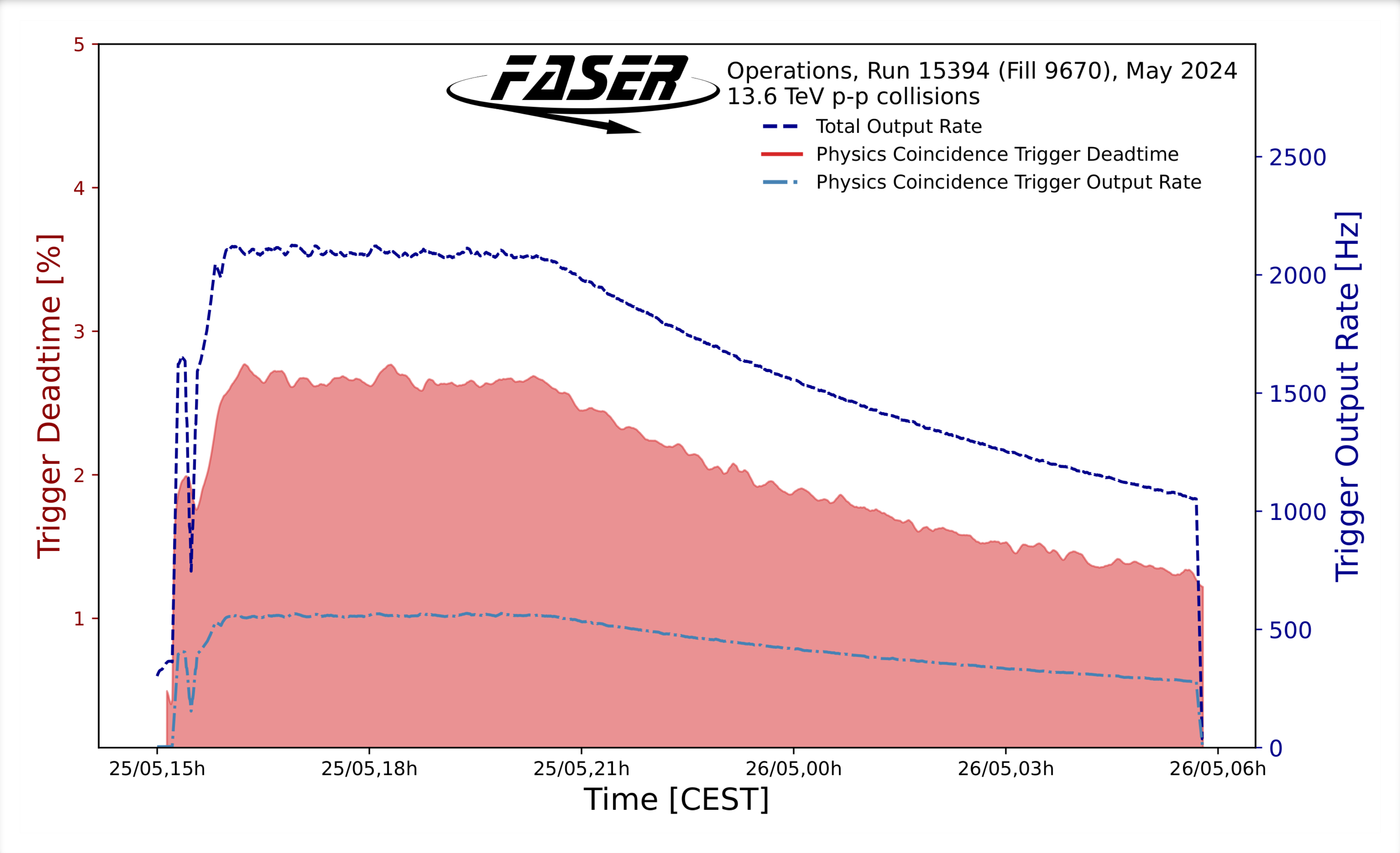
FASER [JINST:16.P12028]



- The physics coincidence trigger selects events with coincident signal in a front veto scintillator station and the preshower scintillator station
  - Coincidence trigger rate factor 4 smaller than individual trigger rate → dominant triggered background from particles triggering individual stations rather than energetic muons

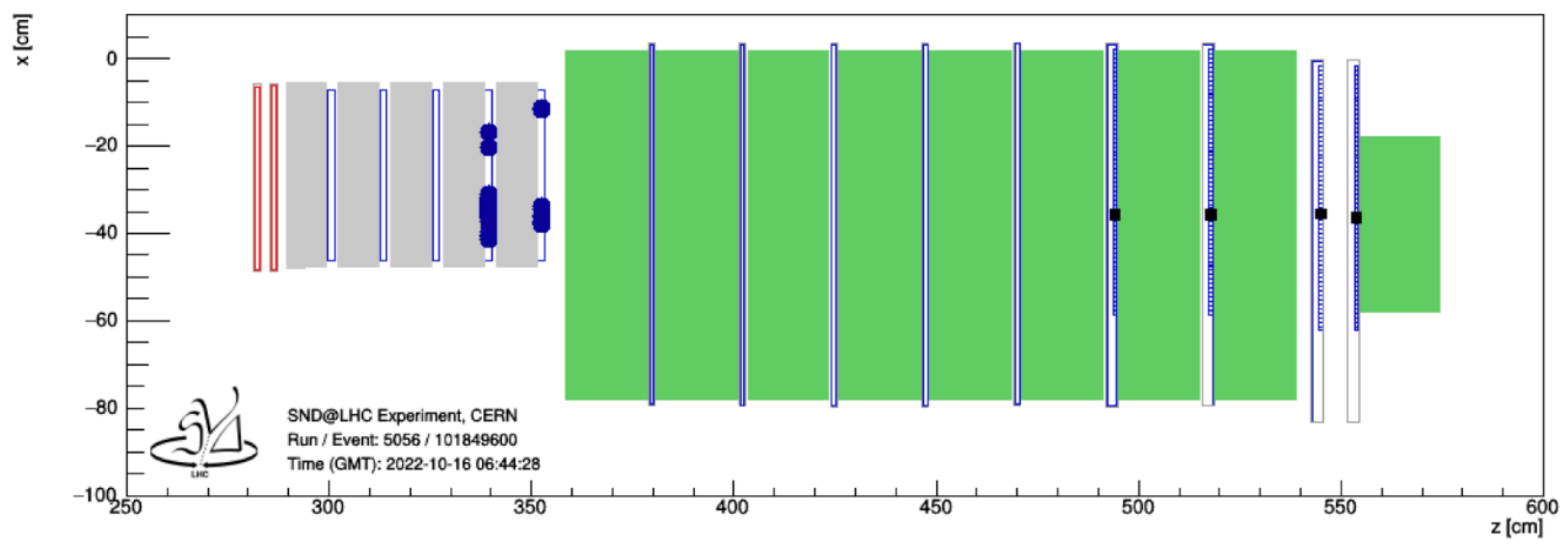


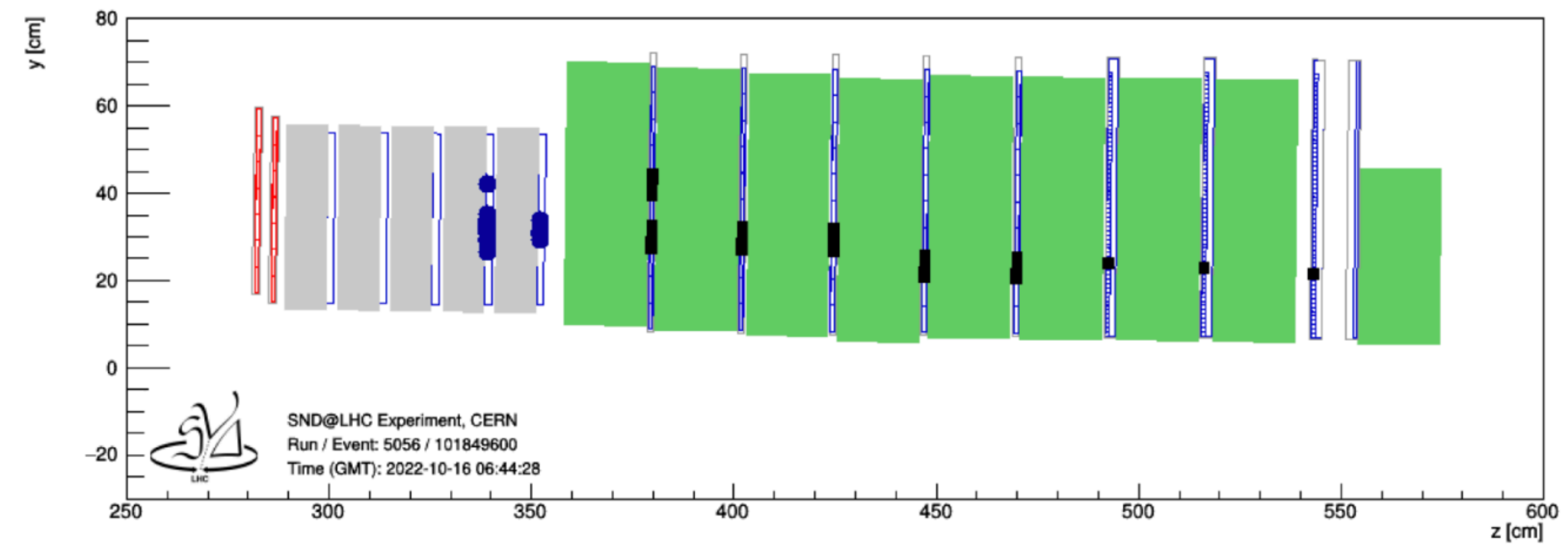
Coincidence trigger deadtime ~ 2 %

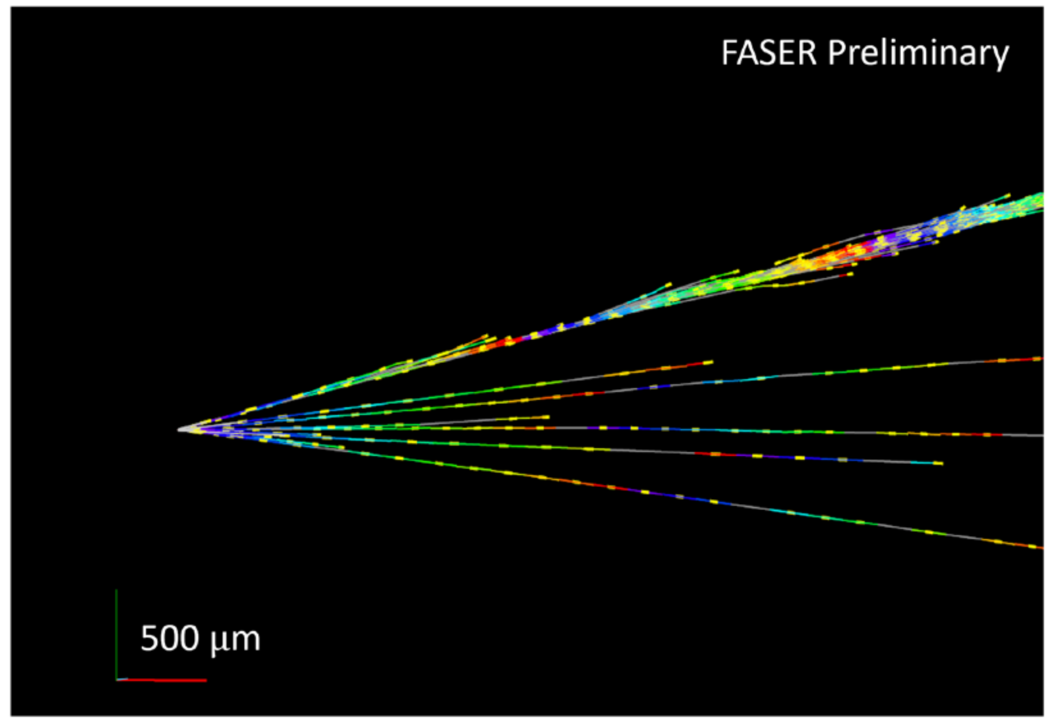


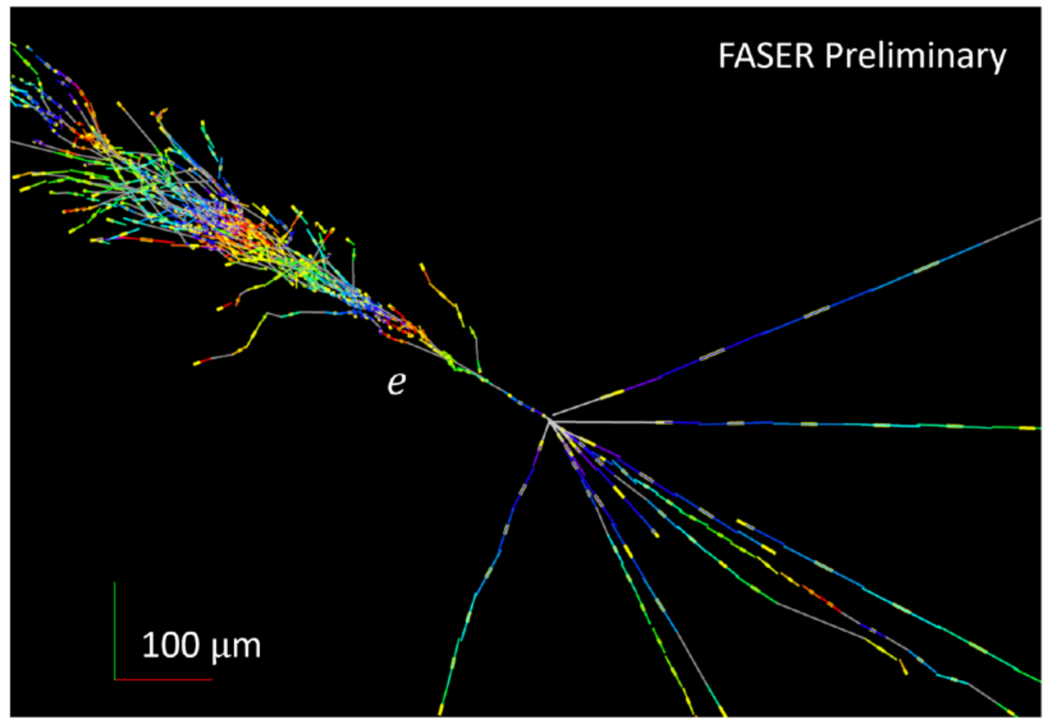
CONCLUSION

- The LHC provides a unique environment for neutrino physics and long-lived dark sector particle searches
- Two complementary experiments, **SND@LHC** and **FASER** are currently in operation, located symmetrically on both sides of the ATLAS IP1
- Detector performance of both experiments is well understood, with more studies currently ongoing







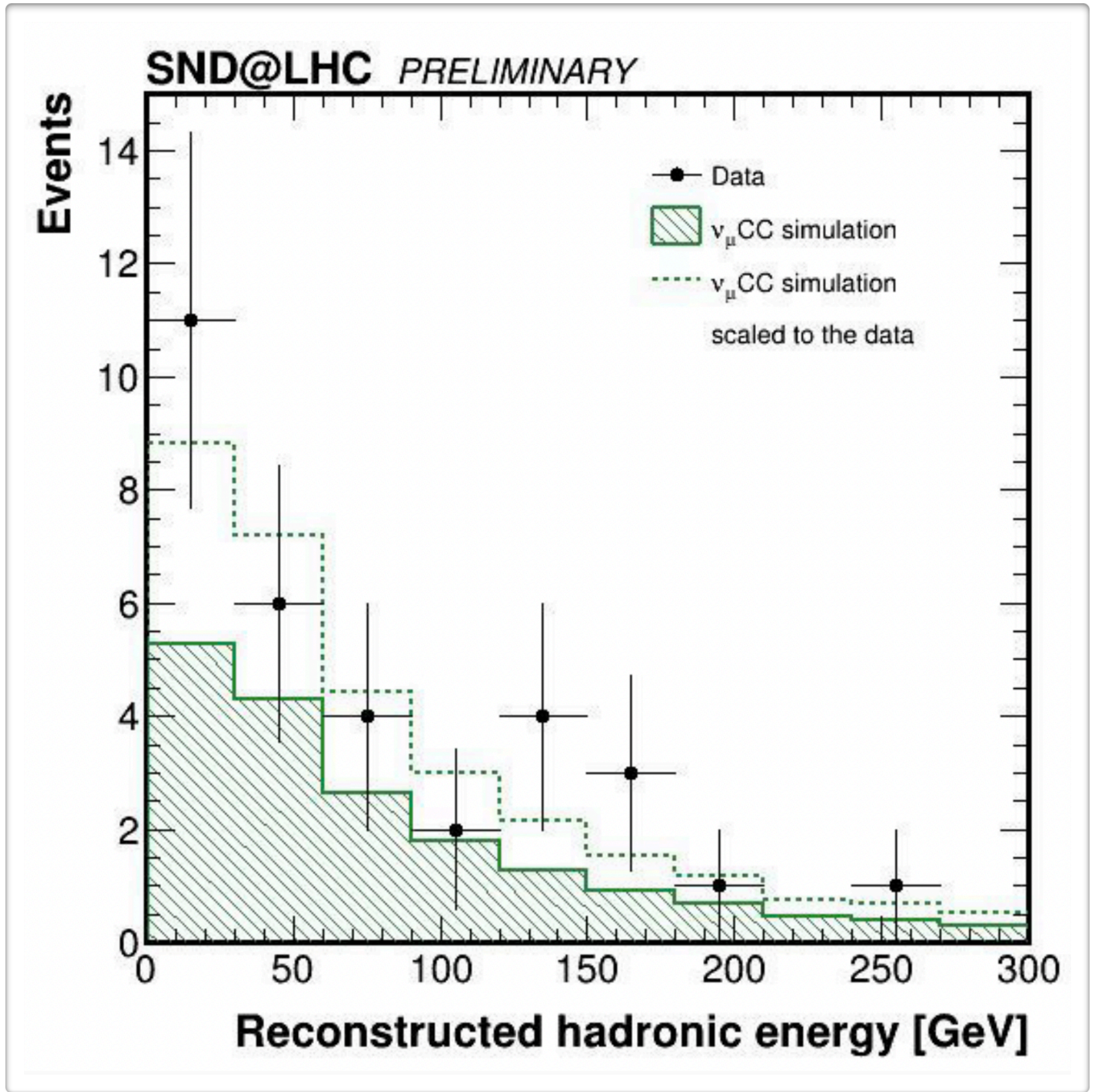


See also dedicated talks on SND@LHC and FASER physics results! [1,2,3]

BACKUP

ν_μ ENERGY RECONSTRUCTION

SND@LHC



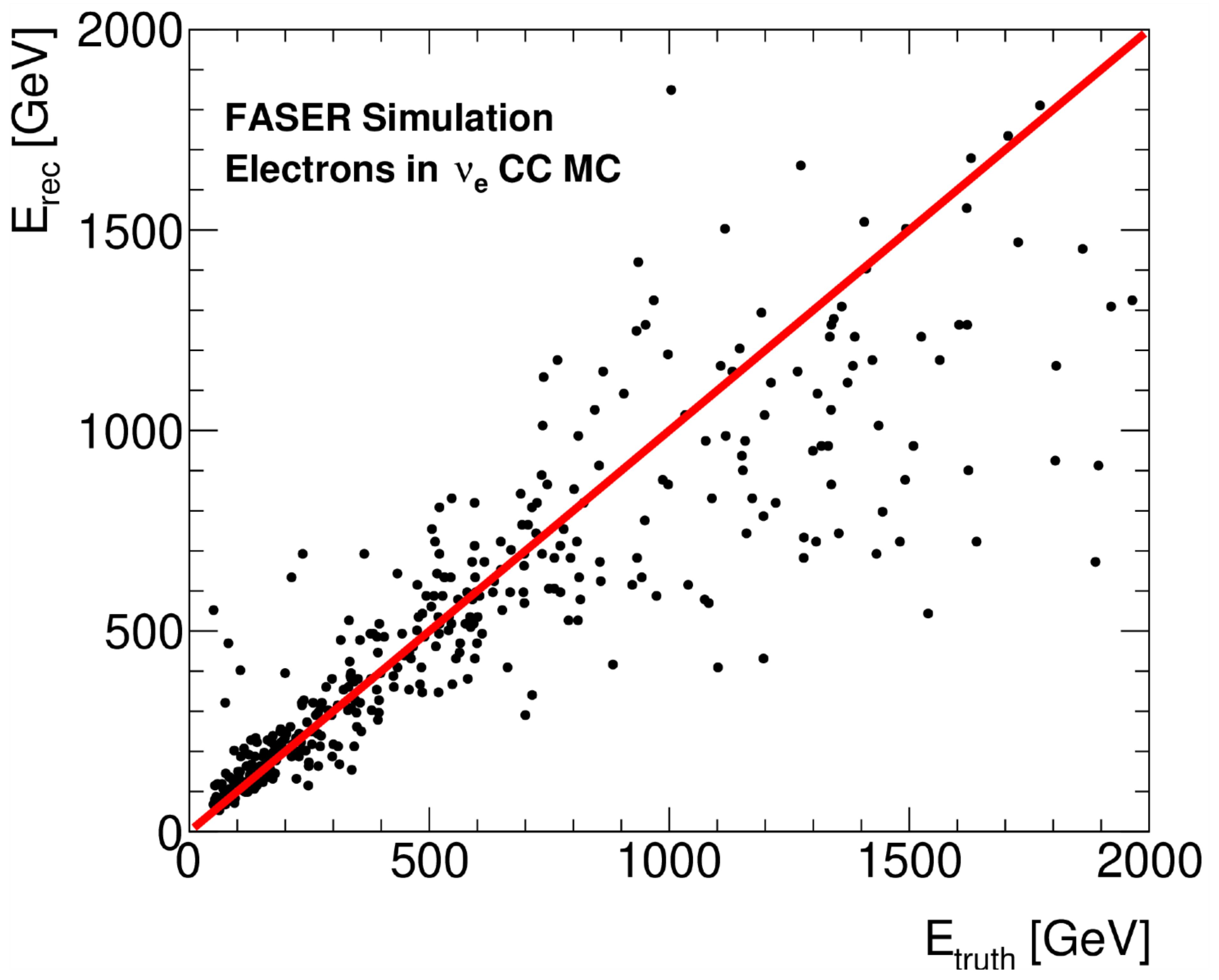
[Moriond2024.QDC]

Energy calibration applied to 32 ν_μ candidates from 2022-2023 data

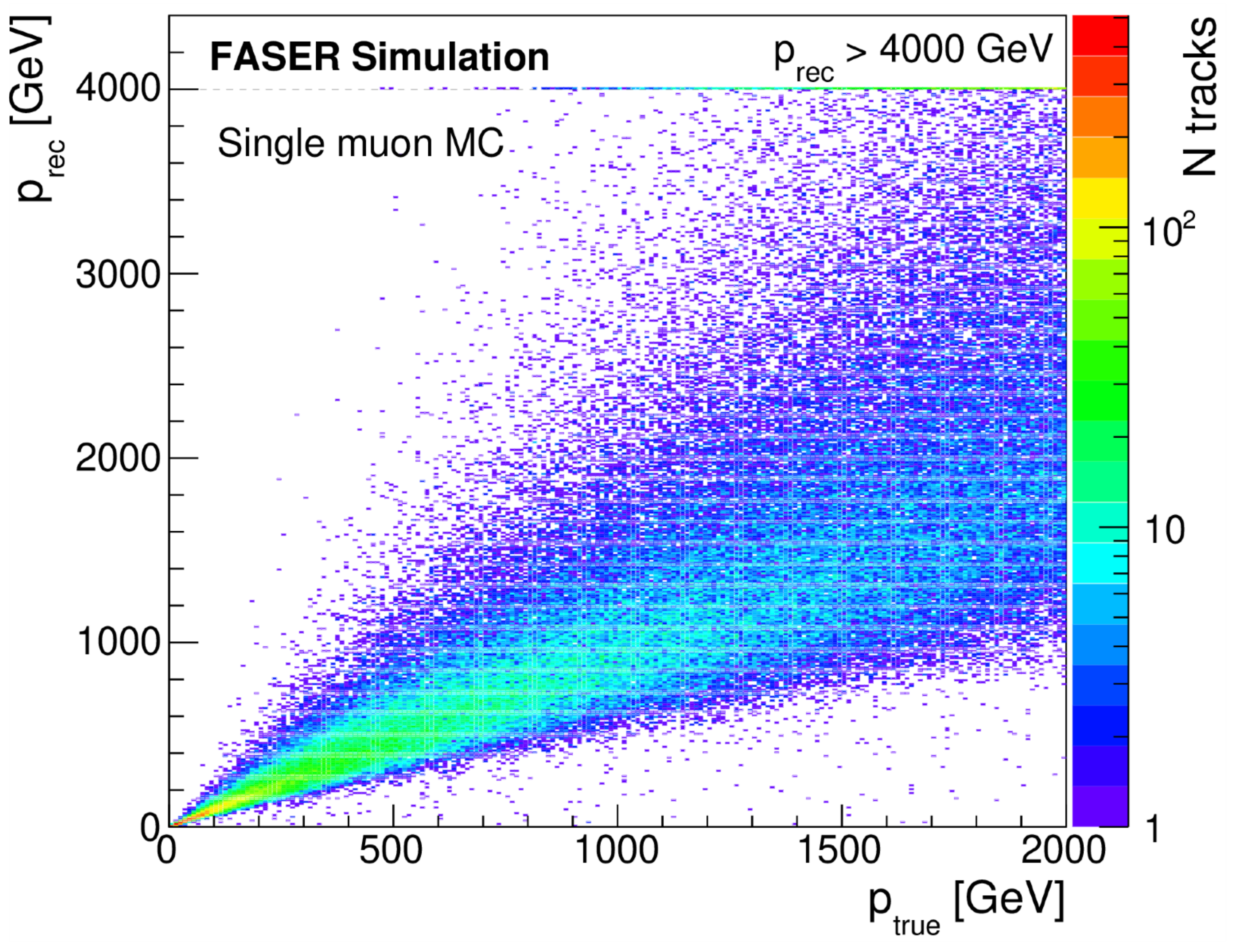
→ Good agreement with Monte Carlo predictions

ENERGY & MOMENTUM RECONSTRUCTION

FASER

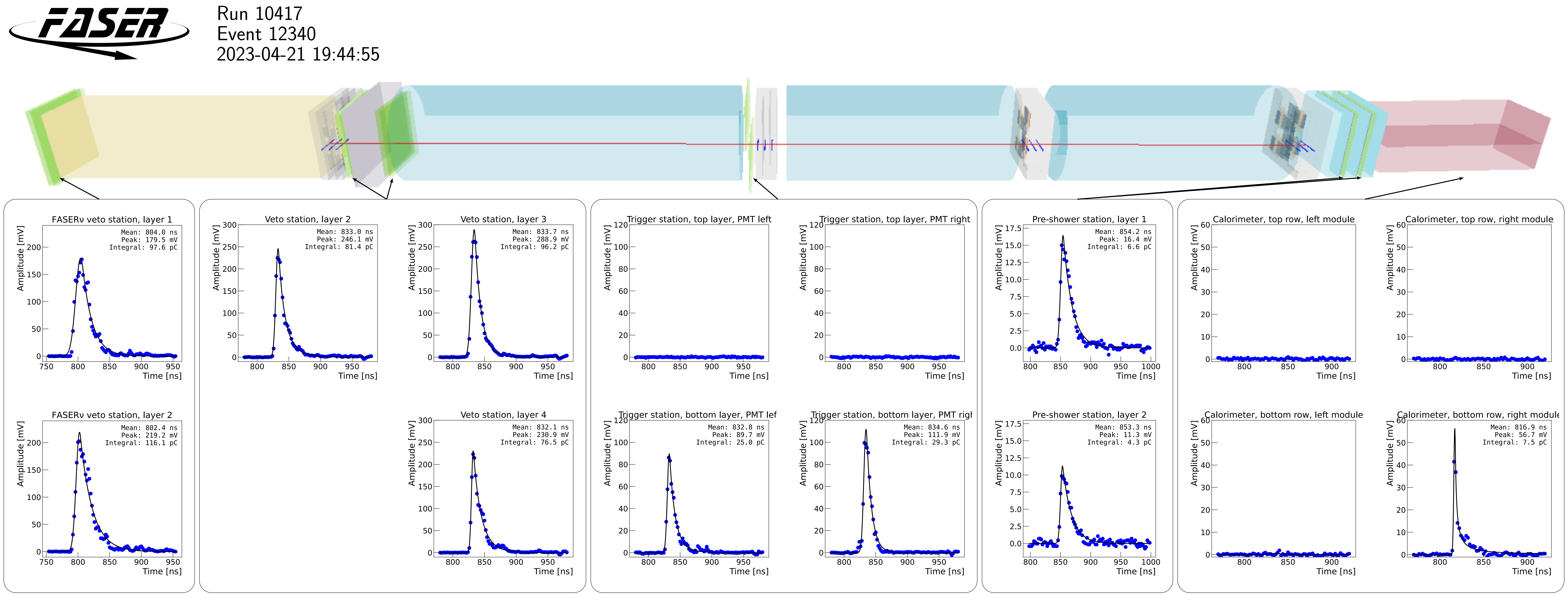


Reconstructed vs true electron energy in simulated ν_e charged current events



Reconstructed vs true muon momentum in simulated muon tracks with a flat momentum distribution of [1-2000] GeV

EVENT DISPLAY

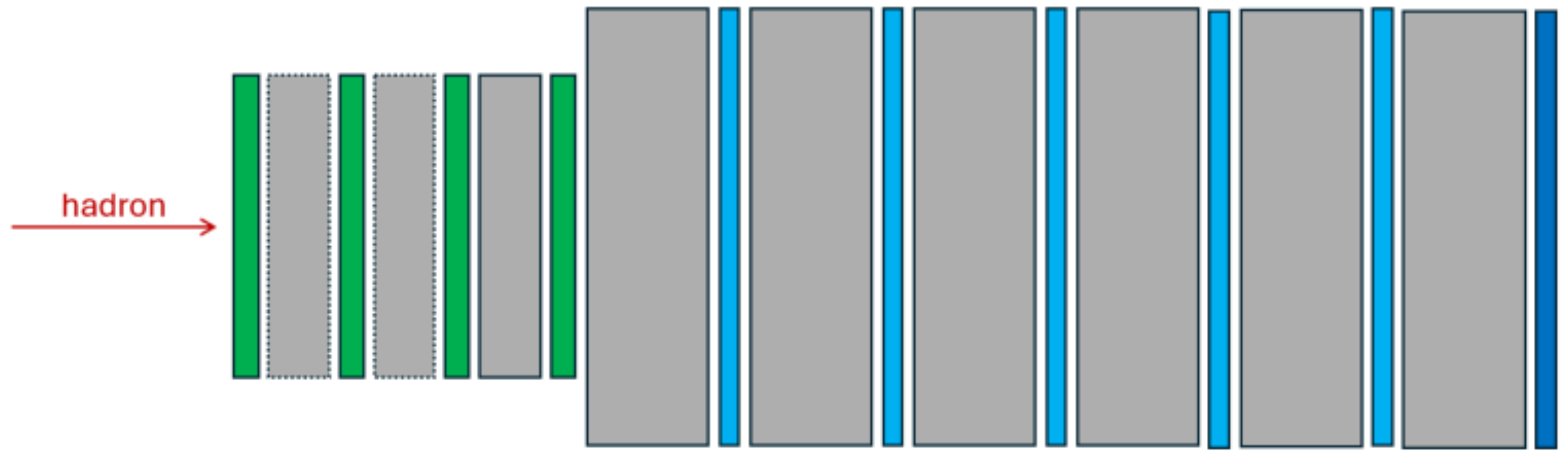


Event display of a muon traversing FASER recorded on 21 April 2023 with 6.8 TeV stable beams

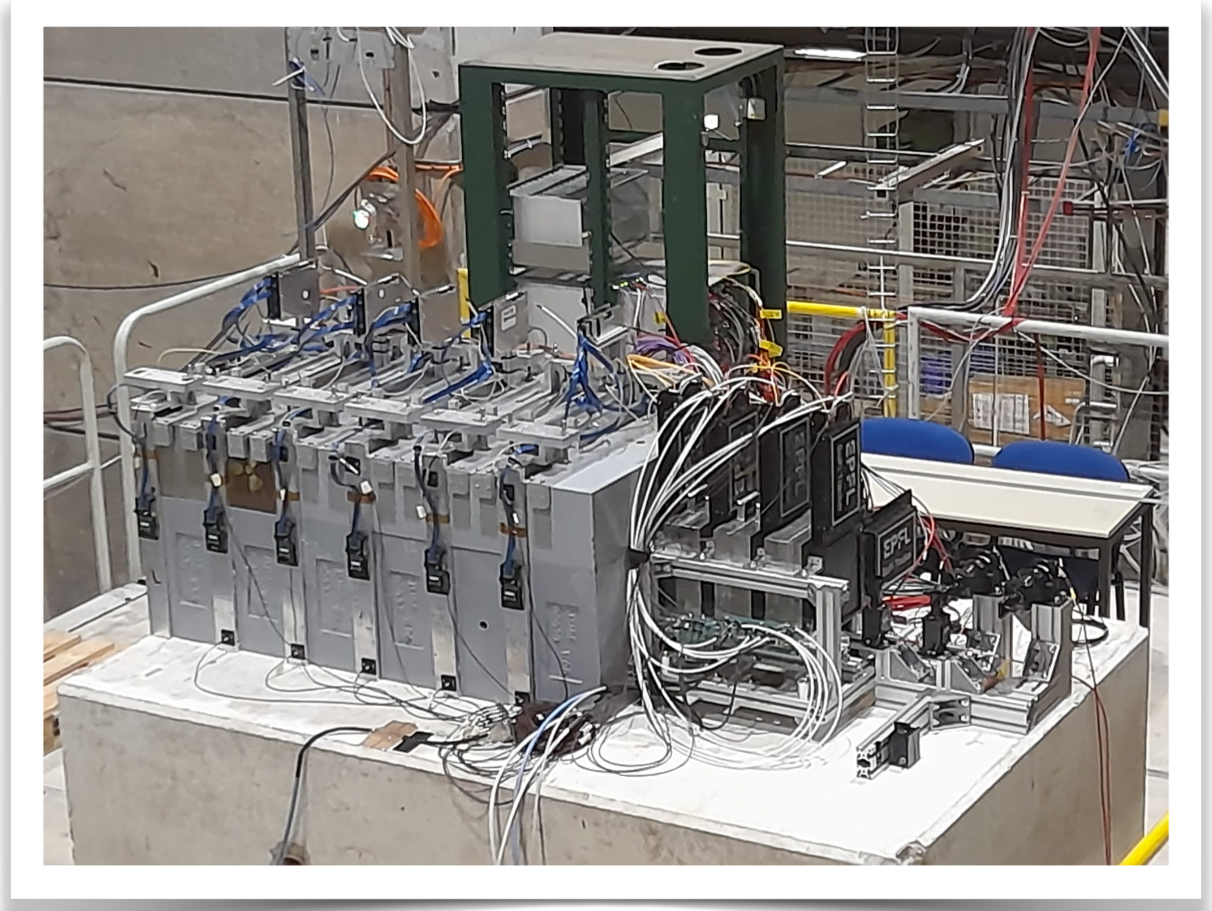
HCAL TESTBEAM

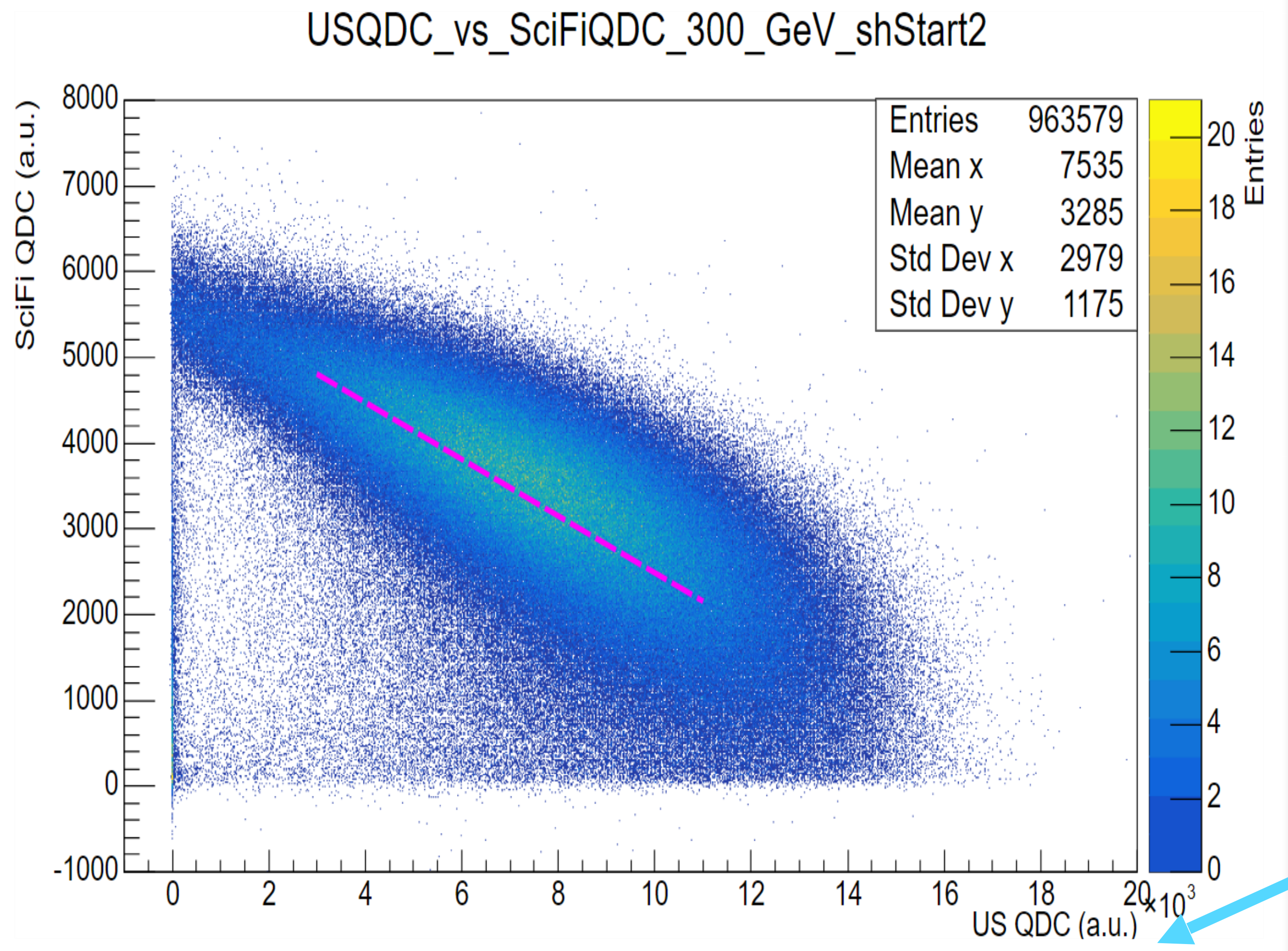
SND@LHC

For more details, see
Calor2024 talk by G.Vasquez



- Testbeam setup:
  - 4 SciFi modules interleaved with 0.5 λ_{int} iron blocks
  - 5 upstream (US) modules with horizontal bars & 1 downstream (DS) module with horizontal and vertical bars interleaved with 1 λ_{int} iron blocks
- [100, 140, 180, 240, 300] GeV pion beam
- Shower containment 95%





Energy calibration with non-homogeneous calorimeter model

$$E_{shower} = k \times QDC_{SciFi} + \alpha \times QDC_{HCAL}$$

QDC = digitised measure of charge deposit

Notes:

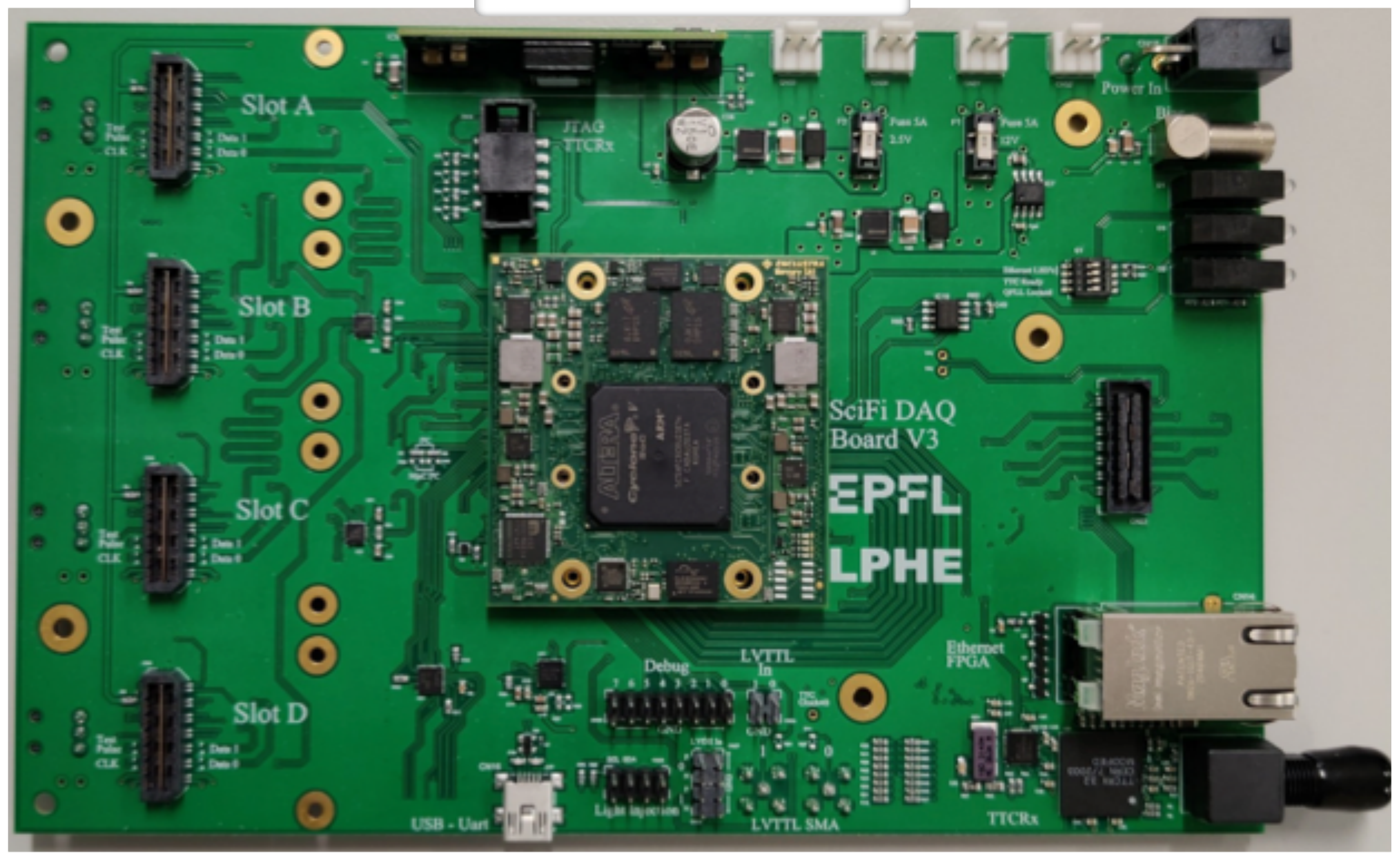
- MIP response agrees with SND@LHC data
- QDC distributions change depending on which SciFi wall the shower originates from
- Saturation in US observed - cause confirmed in the lab to be the electronics rather than SiPMs

DATA ACQUISITION

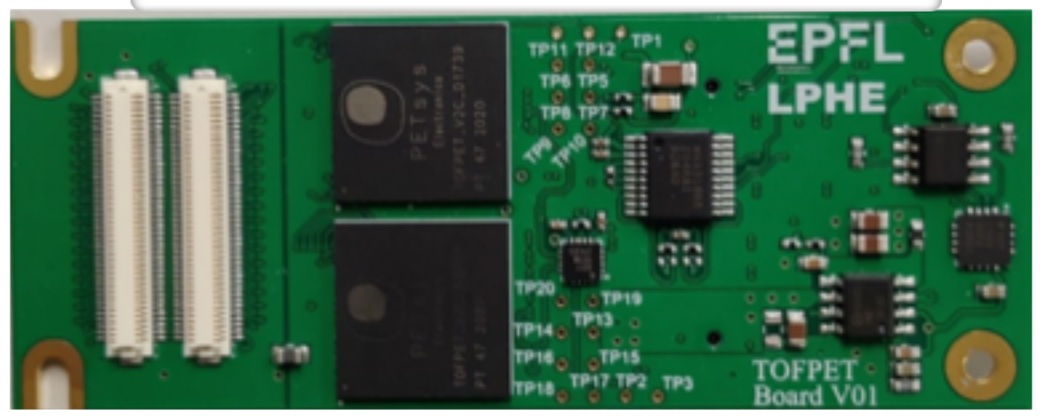
SND@LHC

- All electronic detectors are read out by TOFPET2-based front-end boards
  - Low signal threshold
  - Good timing: 40 ps binning
  - 128 channels

DAQ board



TOFPET2 frontend



- DAQ boards based on Cyclone V FPGA.
  - Runs at 160 MHz, aligned with the LHC clock
  - Collects data from four front-end boards (4x128=512 channels)
  - Gets clock from LHC via optical fibre
  - Triggerless DAQ: all hits above threshold sent to server over ethernet.
- DAQ server
  - Receives hits from DAQ boards, 17k channels in total
  - Runs timestamp-based event-building code
  - Applies online noise filter
  - Saves data to disk in ROOT format