SND@LHC

A Detector for Neutrino Physics at the LHC

Technology & Instrumentation in Particle Physics Conference

4 - 8 September 2023

Cape Town, South Africa

Anna Mascellani, École Polytechnique Fédérale de Lausanne (EPFL)
On behalf of the SND@LHC Collaboration

EPFL

LHC
Scattering and Neutrino Detector
at the LHC

CERN

Presentation Outline

- Introduction
- The SND@LHC detector
- Performance studies of the target tracker

Presentation Outline

- Introduction
- The SND@LHC detector
- Performance studies of the target tracker

Neutrinos at the Large Hadron Collider

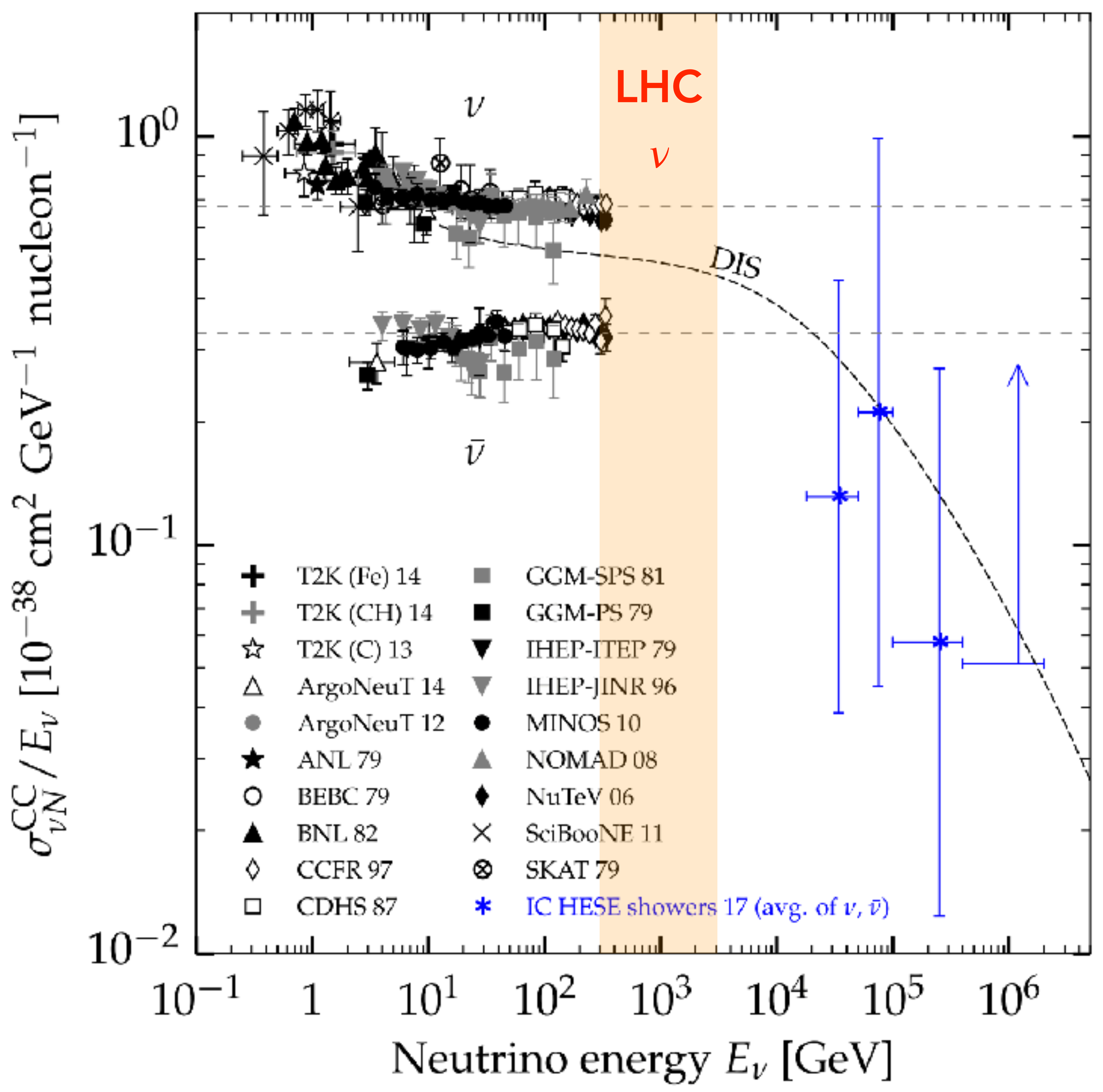
- Use of the Large Hadron Collider as a neutrino factory first proposed ~30 years ago (Nucl. Phys. B 405 (1993) 80)

- Why the LHC?
  - **Large neutrino fluxes** produced in the **forward region** by pp collisions
  - **High neutrino energy** $\Longrightarrow$ Large neutrino interaction cross-section

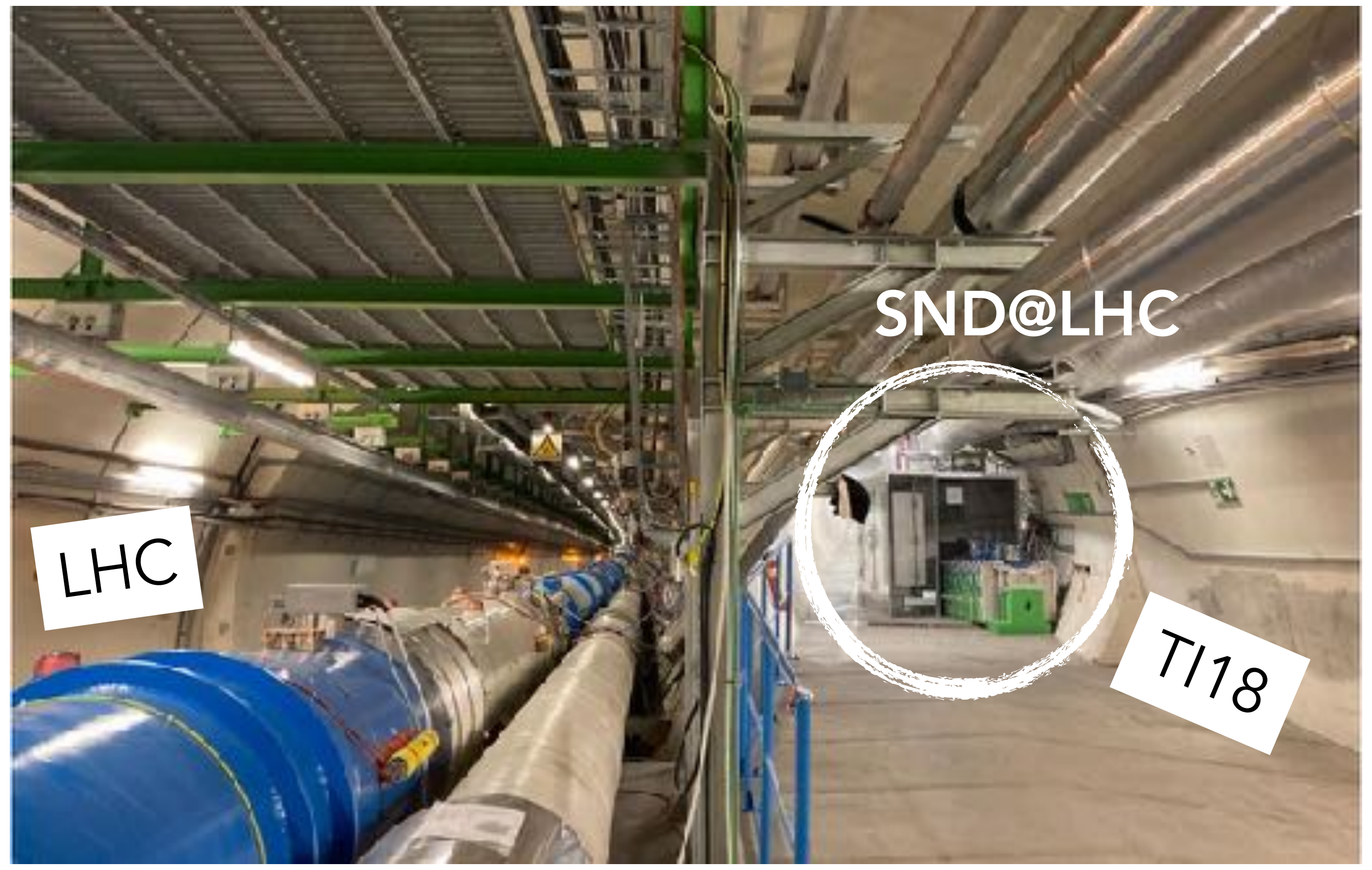
  ➡ All **three neutrino flavours** can be observed at the LHC with a **small-scale experiment**

  - **Unexplored energy region** $(E_\nu \in [10^2, 10^3]\ \mathrm{GeV})$

- Two neutrino experiments currently at LHC: **SND@LHC** and FASERν

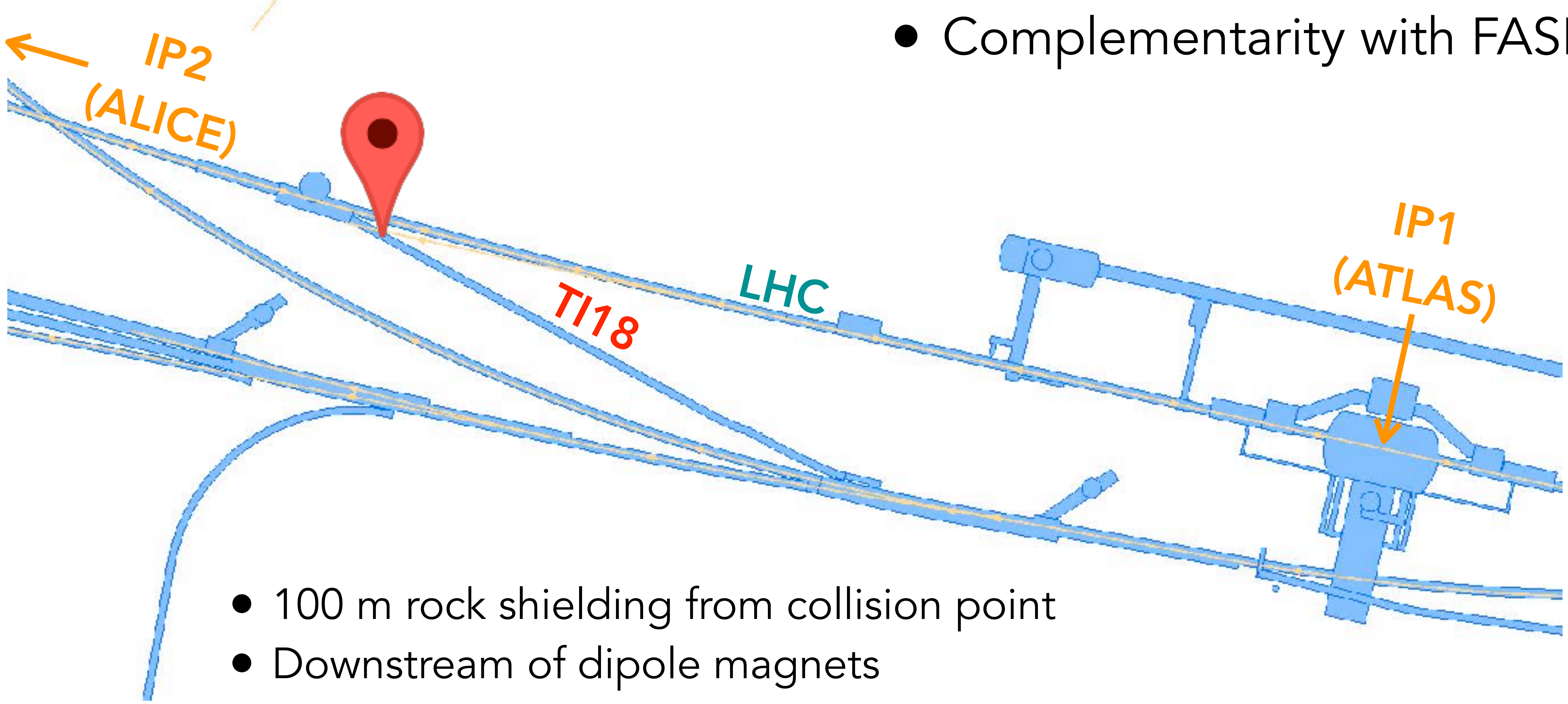


The SND@LHC Experiment



<u>**S**cattering and **N**eutrino **D**etector at the LHC</u>

- Measurement of high energy (~TeV) neutrino interactions from pp collisions
- Located in TI18 tunnel, **~480 m** away from the **ATLAS interaction point**
- **Off-axis** position: covered pseudorapidity of $7.2 < \eta < 8.4$
  - Enhanced neutrino production from **charm decays**
  - Complementarity with FASERν



- 100 m rock shielding from collision point
- Downstream of dipole magnets

Timeline

Letter of intent

August 2020

March 2021

CERN approval

Completion of detector installation

December 2021

April 2022

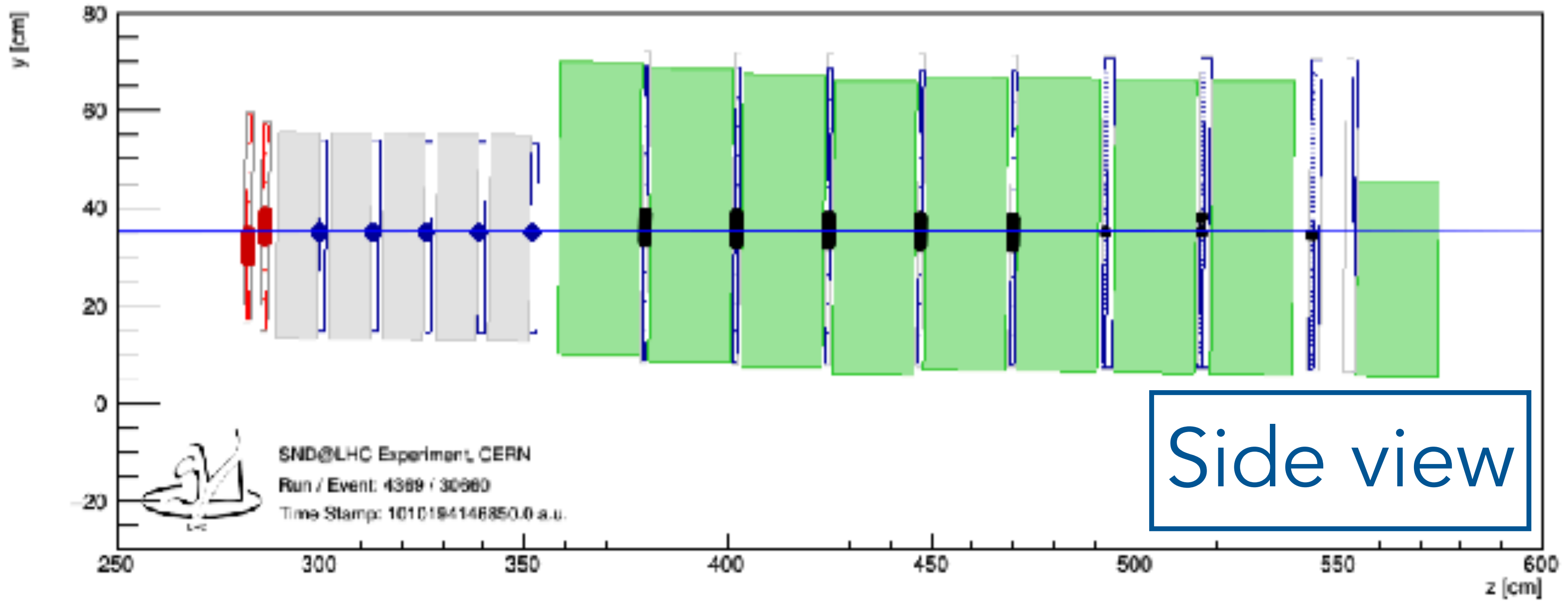
First data (beam splashes)

September 2021

December 2021

March 2022

Muon from 13.6 TeV collisions

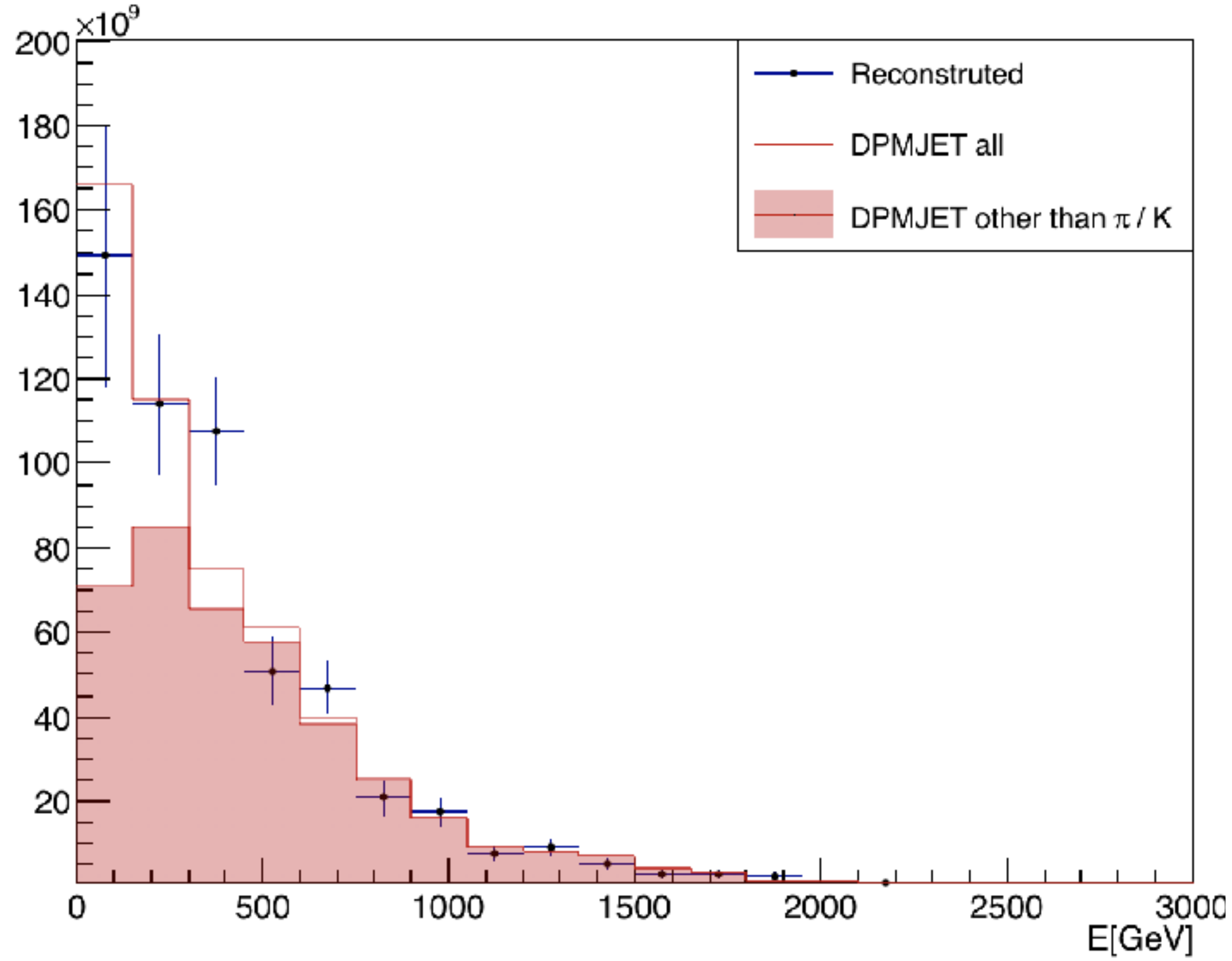


July 2022

Physics Program

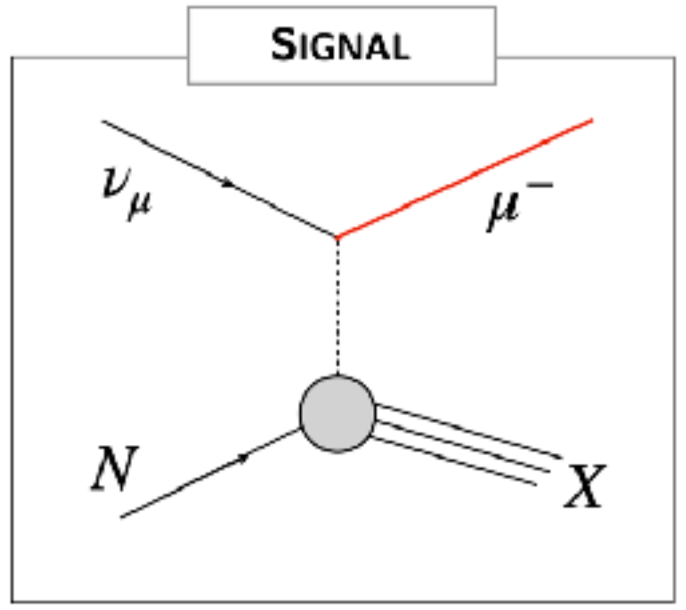
- **Charmed hadron production**
  - 90% of ν_e and $\bar{\nu}_e$ in acceptance produced in the decay of charmed hadrons
  - Electron neutrinos used to probe charm production in relevant pseudorapidity region and constrain gluon PDFs at very low x (10^{-6})
  - Impact on future higher energy hadron colliders and neutrino astrophysics
- Test **lepton flavour universality** in neutrino sector
  - Measurement of ν_e/ν_τ and ν_e/ν_μ
- Direct search of **feebly-interacting particles**
  - Including Time of Flight (ToF) measurements

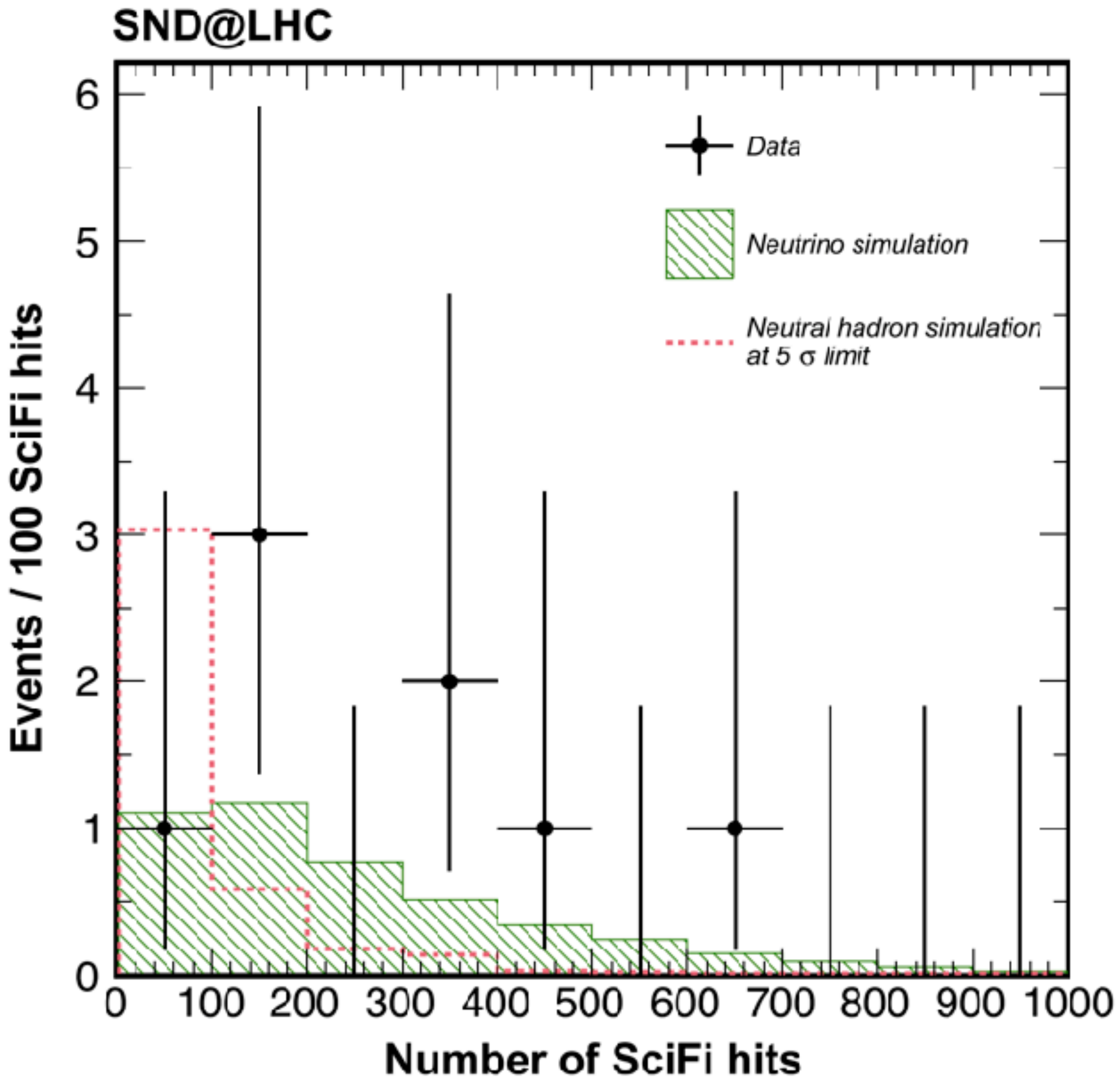
Reconstructed $\nu_e + \bar{\nu}_e$ spectrum at SND@LHC



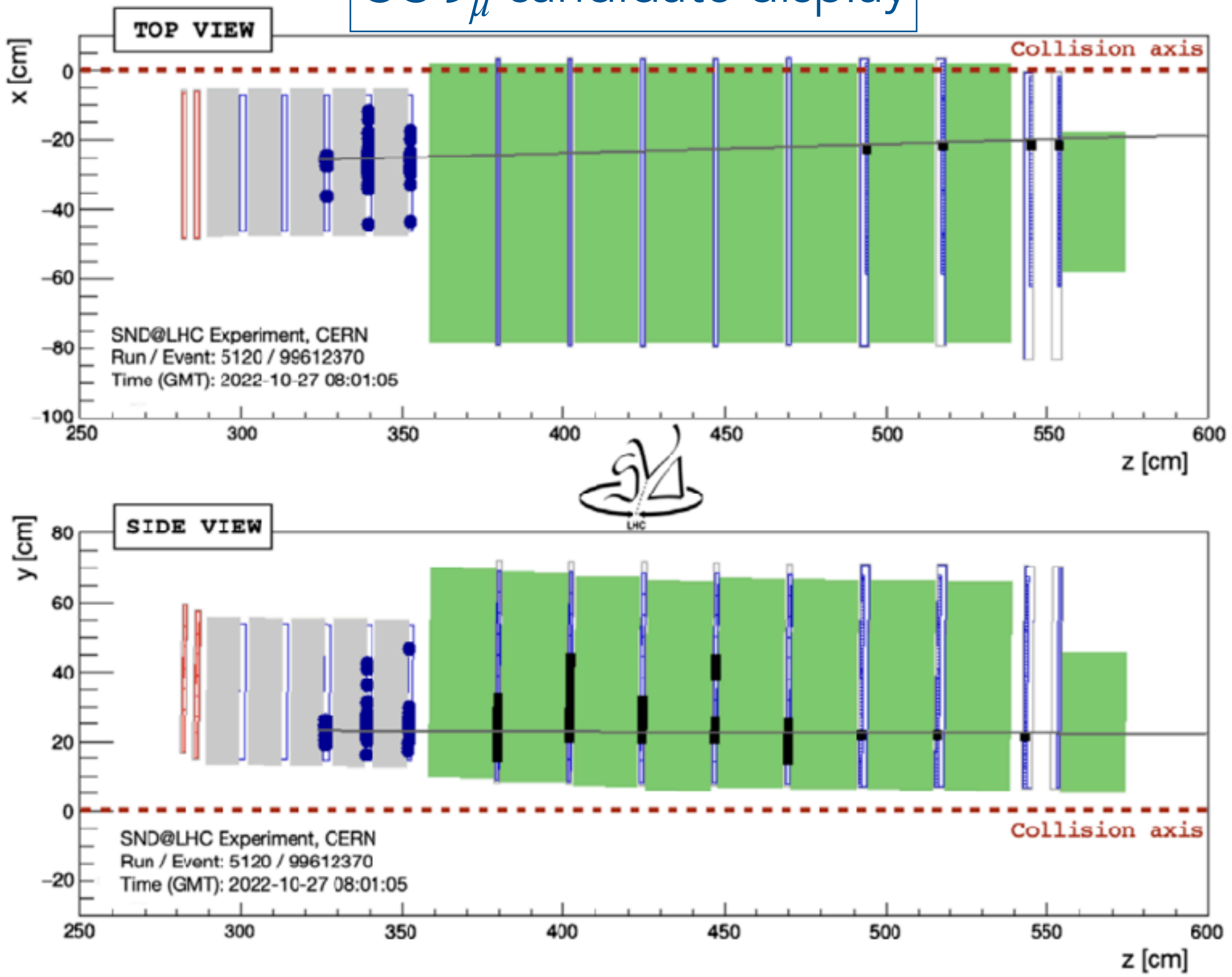
First Physics Result!

Search for Charged Current (CC) Deep Inelastic Scattering of $\nu_\mu + \bar{\nu}_\mu$ interactions in the SND@LHC electronic detectors





CC ν_μ candidate display



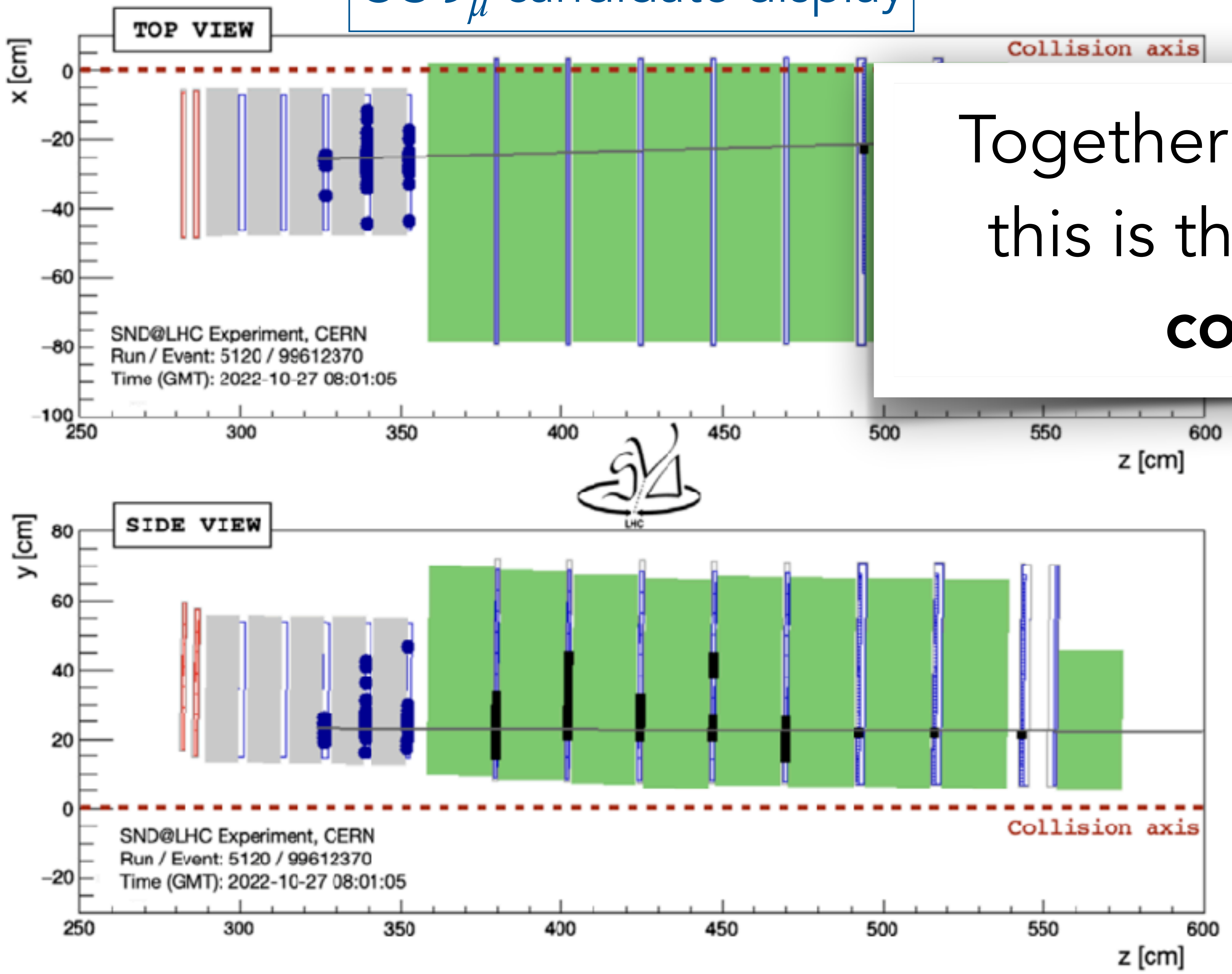
[PhysRevLett.131.031802]()

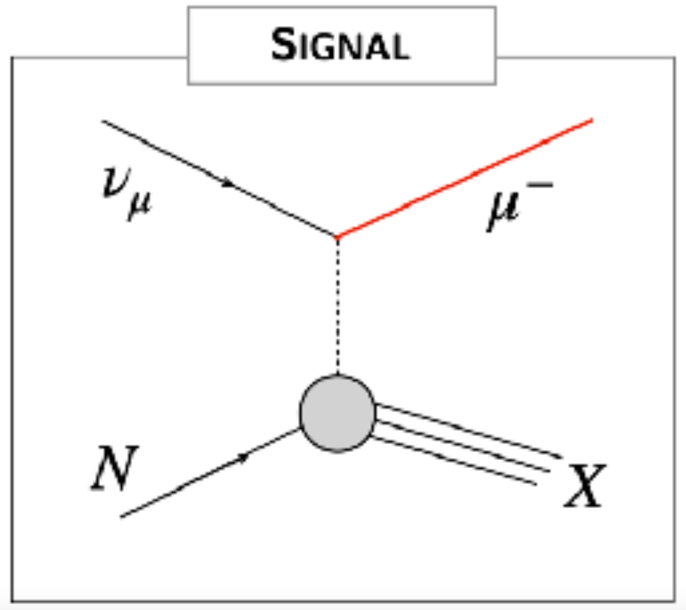
Observation of **8 ν_μ CC candidates** with a statistical **significance of 6.8σ**

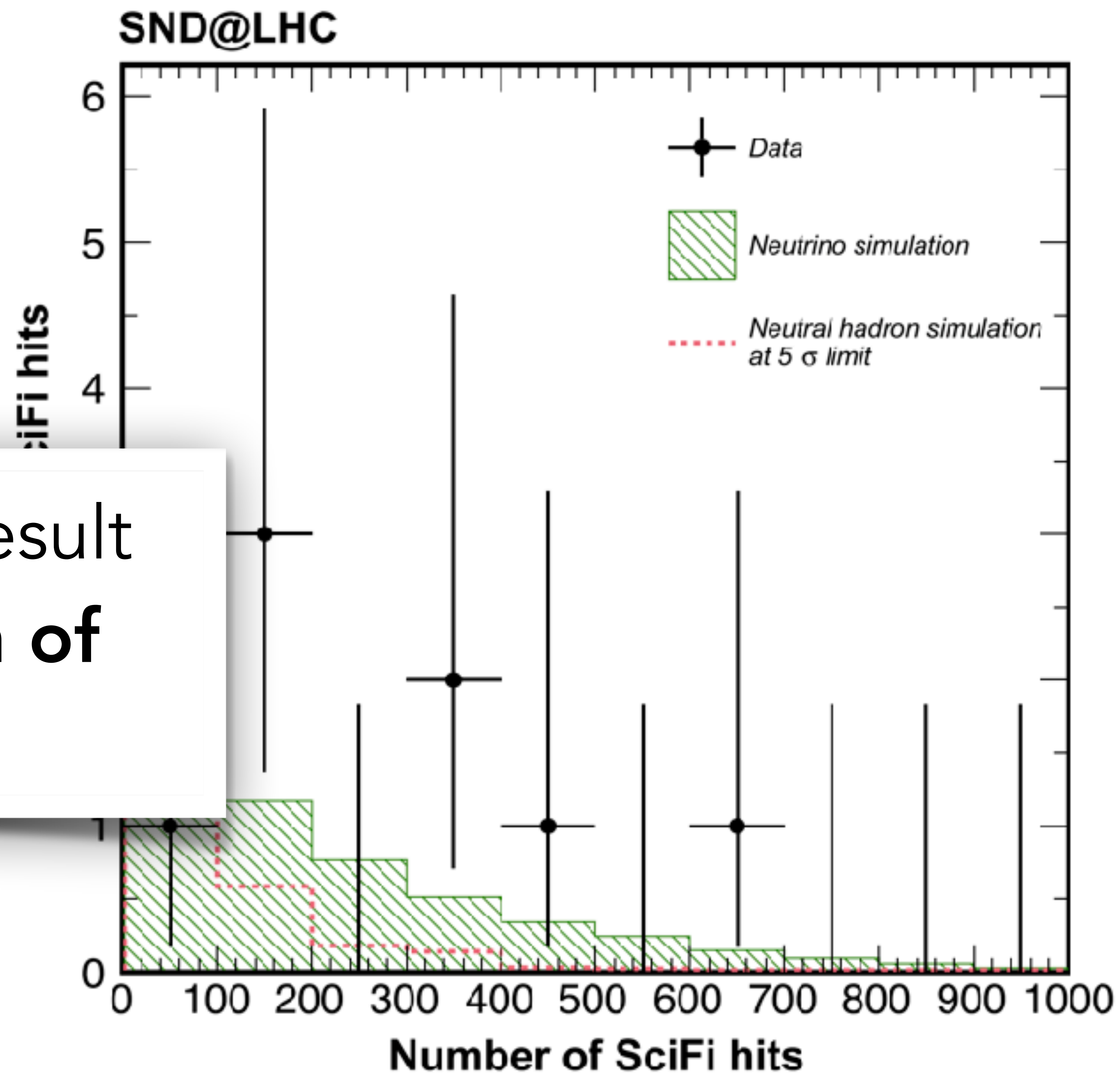
First Physics Result!

Search for Charged Current (CC) Deep Inelastic Scattering of $\nu_\mu + \bar{\nu}_\mu$ interactions in the SND@LHC electronic detectors

CC ν_μ candidate display







Together with the FASERν result this is the **first observation of collider neutrinos**

PhysRevLett.131.031802

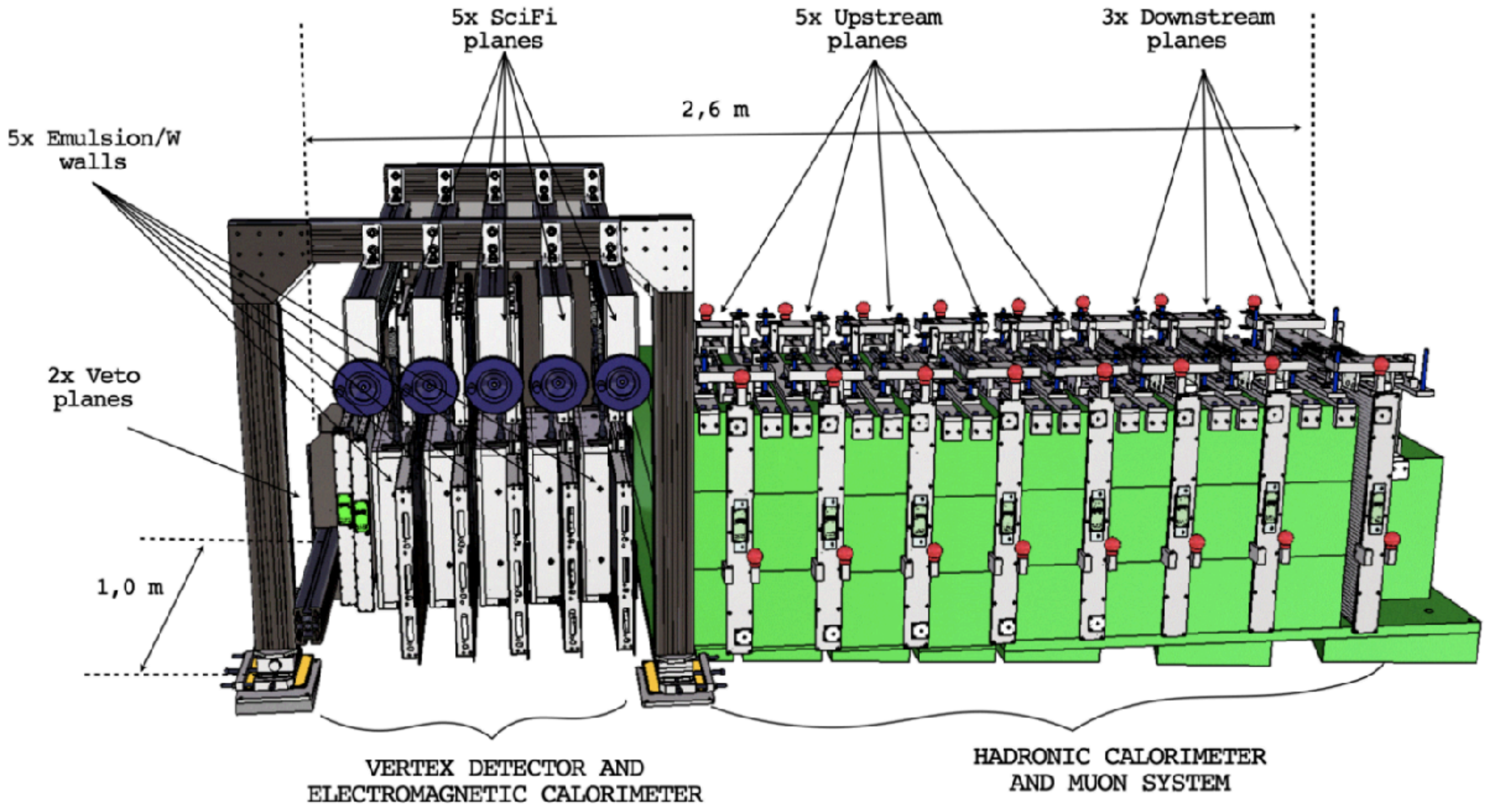
Observation of **8 ν_μ CC candidates** with a statistical **significance of 6.8σ**

Presentation Outline

- Introduction
- The SND@LHC detector
- Performance studies of the target tracker

Detector Outline

Hybrid detector optimised for the **identification of three neutrino flavours** and for the detection of **feebly interacting particles**

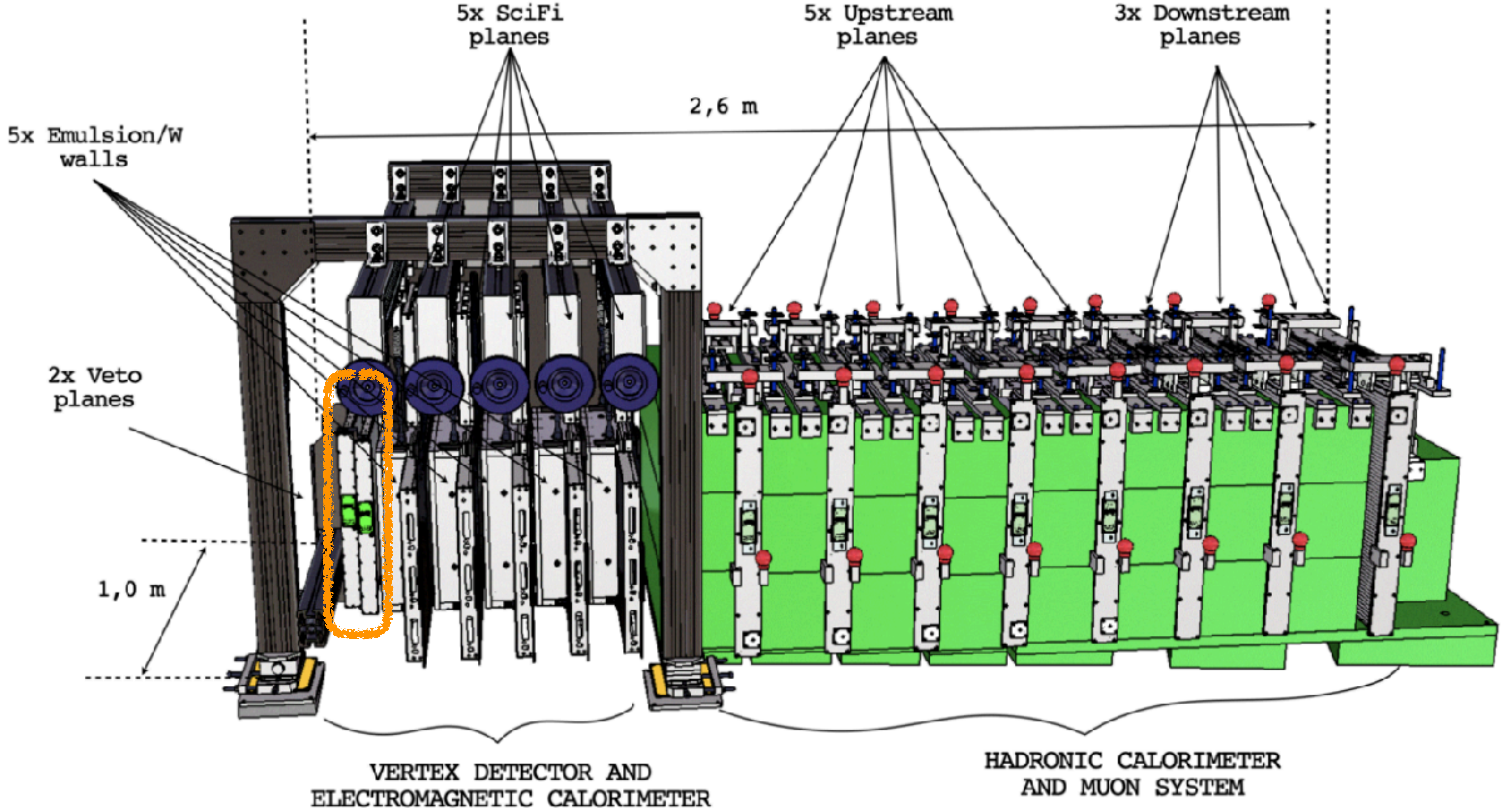


Detector Outline

Hybrid detector optimised for the **identification of three neutrino flavours** and for the detection of **feebly interacting particles**

Veto system

2 veto planes to tag charged particles



Detector Outline

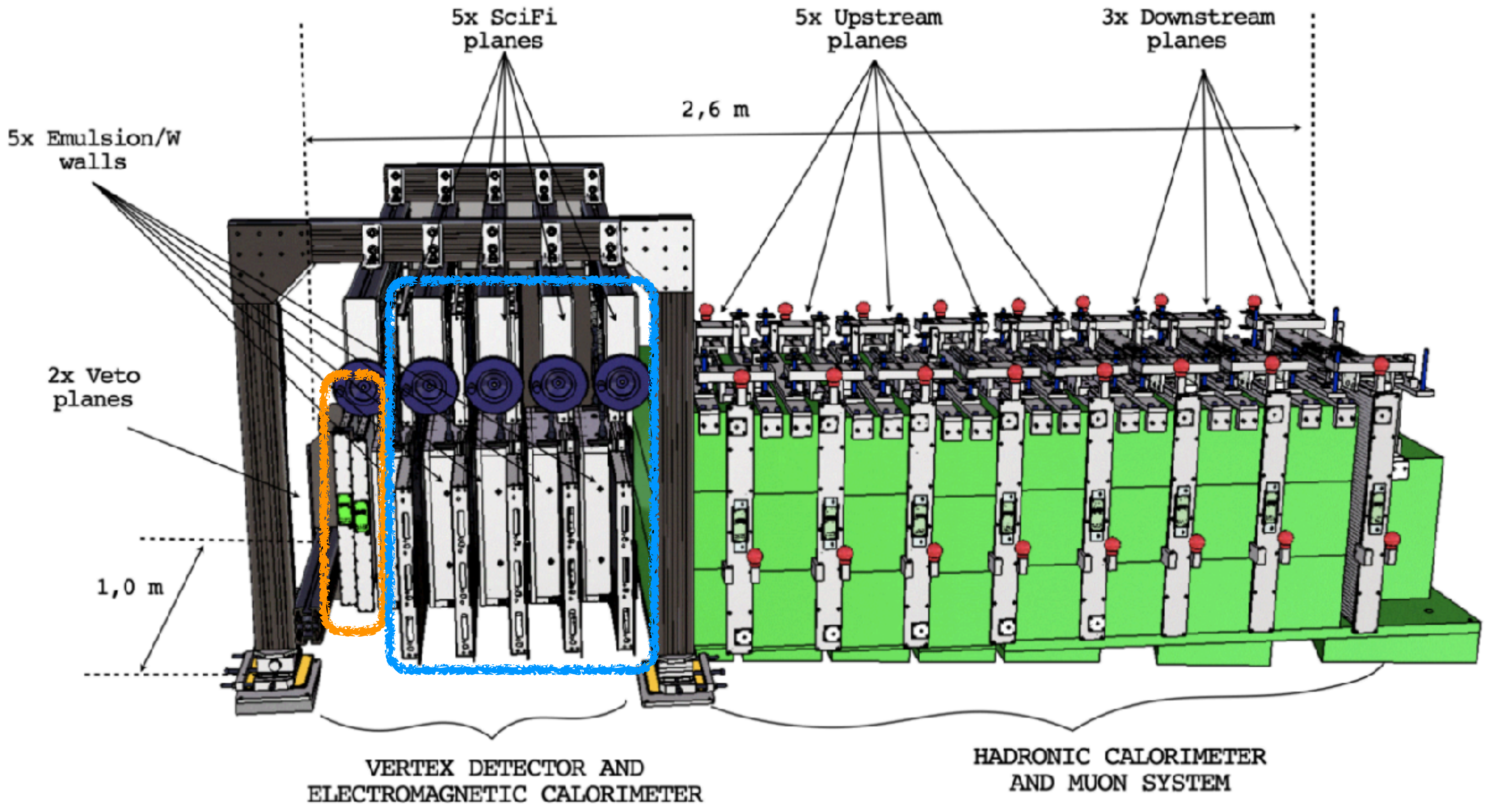
Hybrid detector optimised for the **identification of three neutrino flavours** and for the detection of **feebly interacting particles**

Veto system

2 veto planes to tag charged particles

Target region and ECAL

- 5 target walls instrumented with **emulsions**
- Each wall followed by a plane of scintillating fibers (**SciFi**)



Detector Outline

Hybrid detector optimised for the **identification of three neutrino flavours** and for the detection of **feebly interacting particles**

Veto system

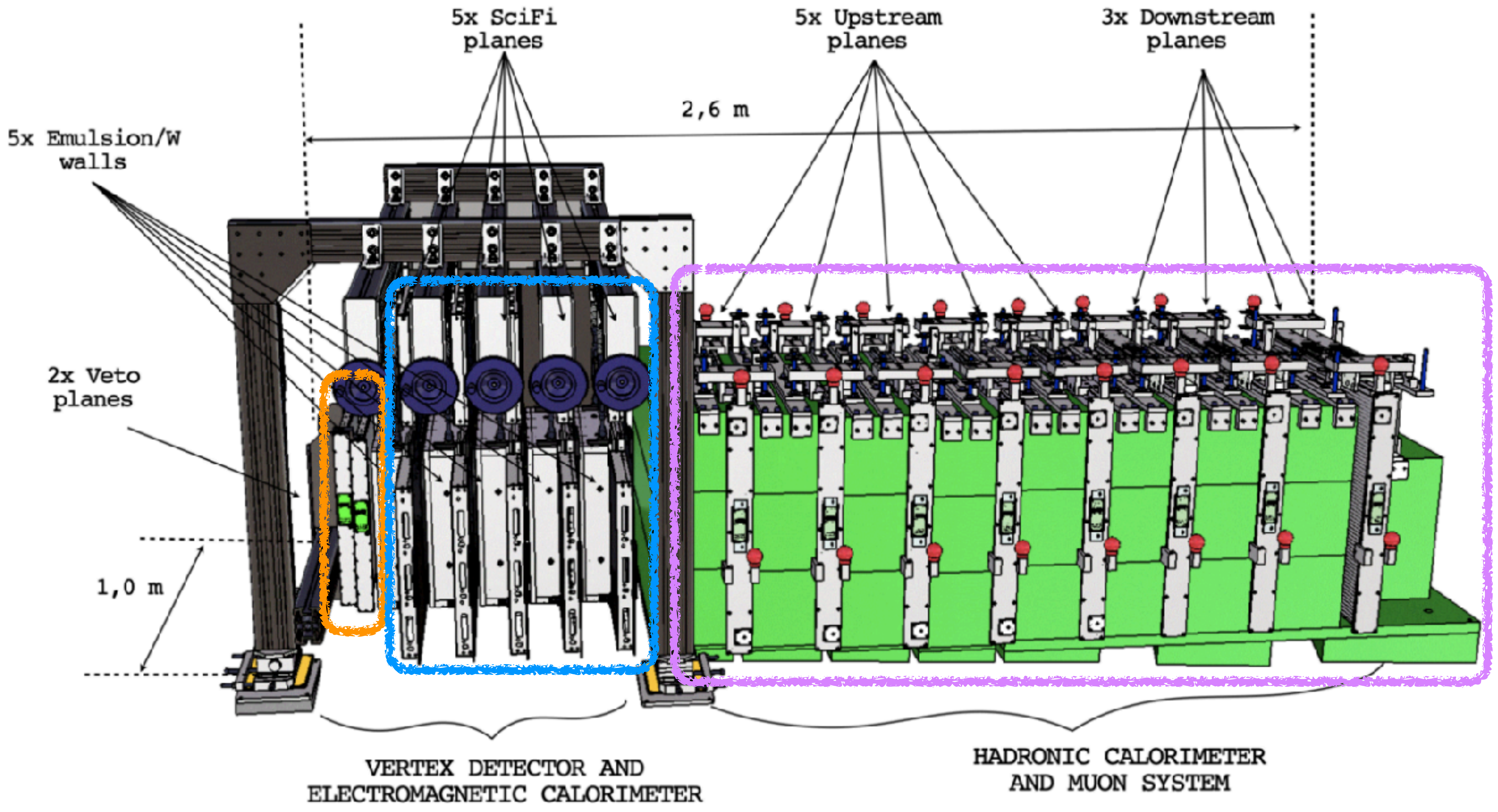
2 veto planes to tag charged particles

Target region and ECAL

- 5 target walls instrumented with **emulsions**
- Each wall followed by a plane of scintillating fibers (**SciFi**)

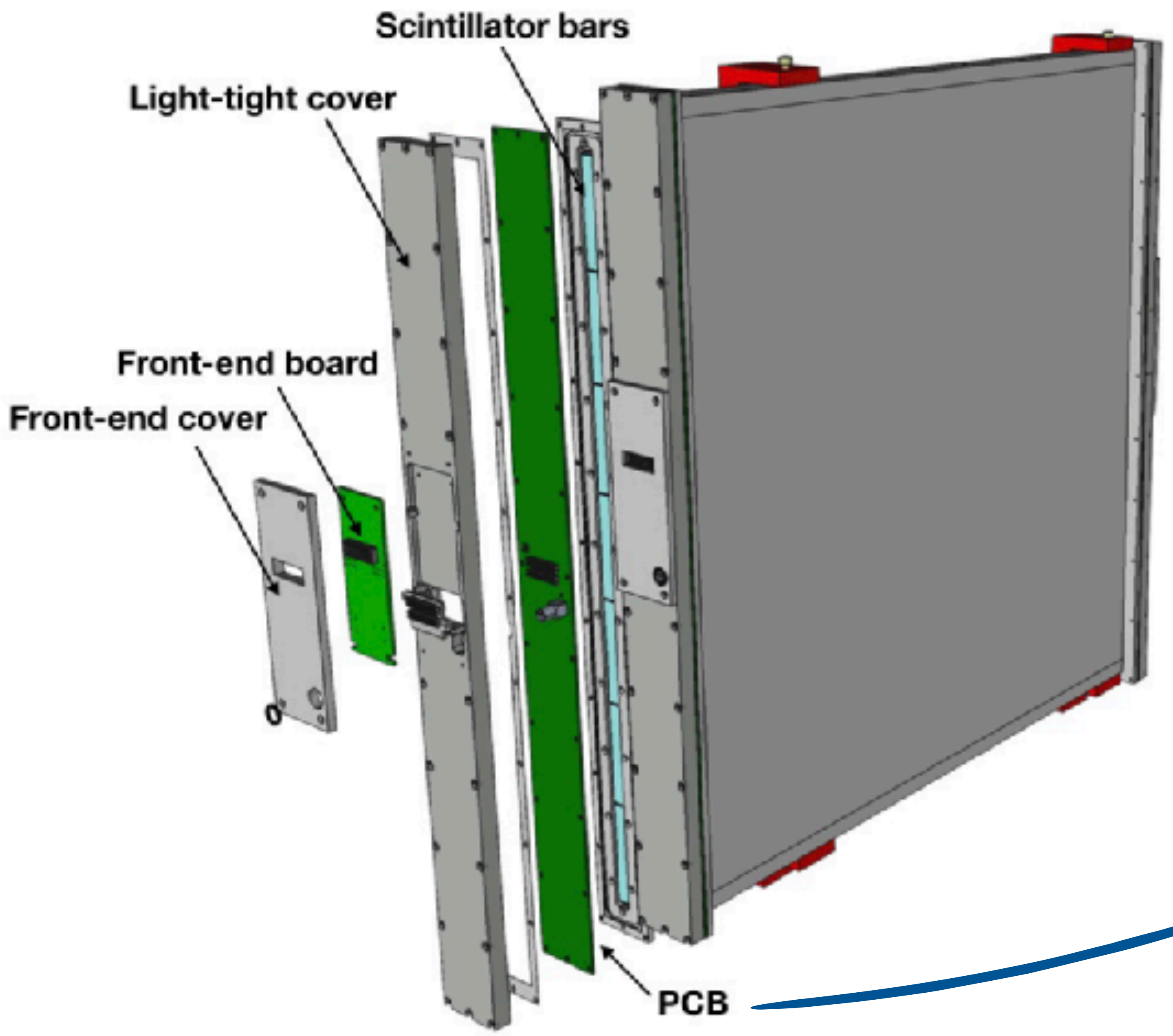
HCAL - Muon system

8 iron walls interleaved with plastic scintillator planes

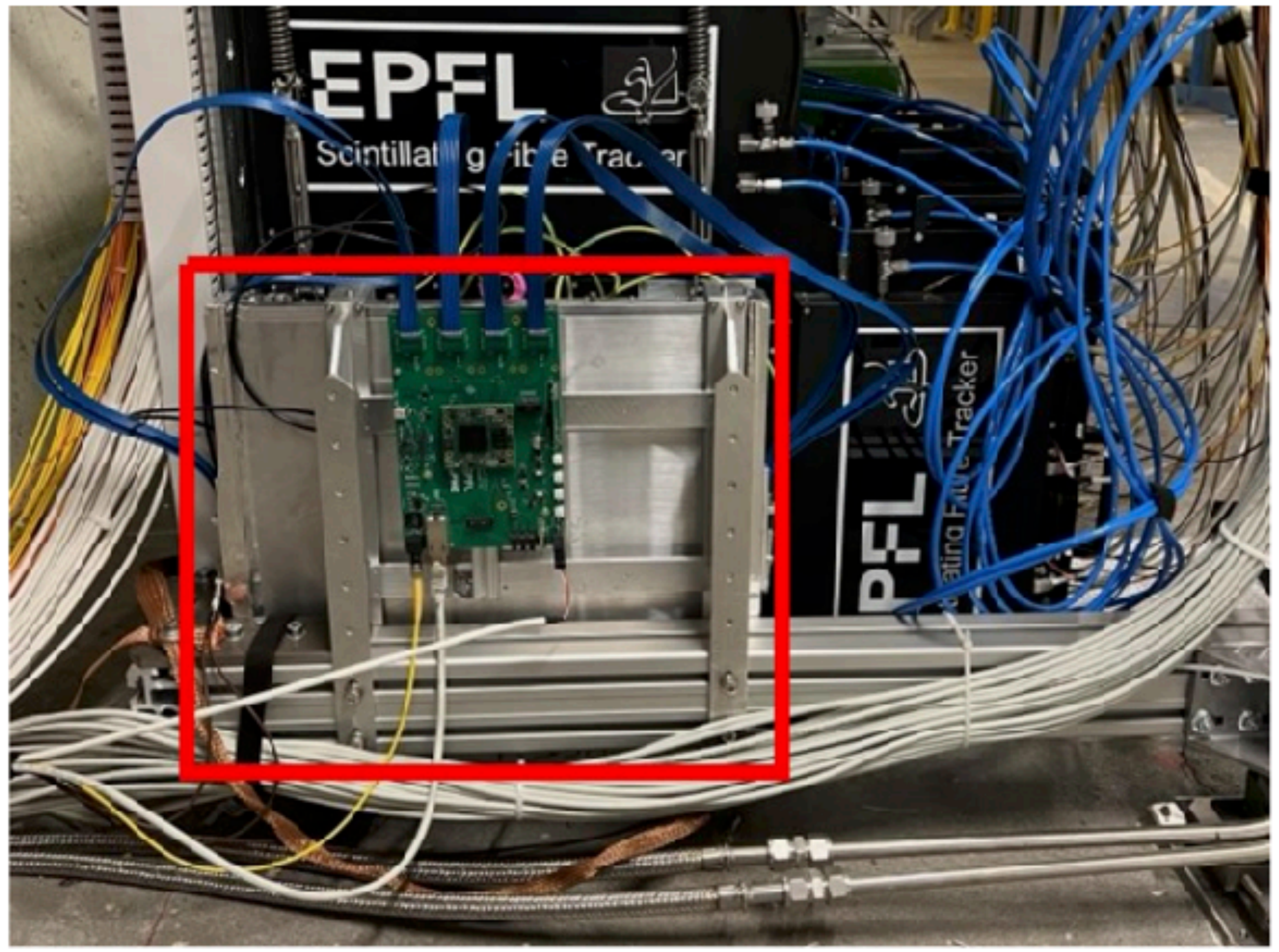


Veto System

- **2 veto planes** to **tag** entering **charged particles**
- Each plane populated with 7 horizontal **scintillator bars**
  - Bar dimension: 1 x 6 x 42 cm^3
  - Bars ready out on both ends by 8 **SiPMs** (dimension: 6 x 6 mm^2)
- Planes cover the target surface area and are vertically staggered to mitigate dead zones between bars

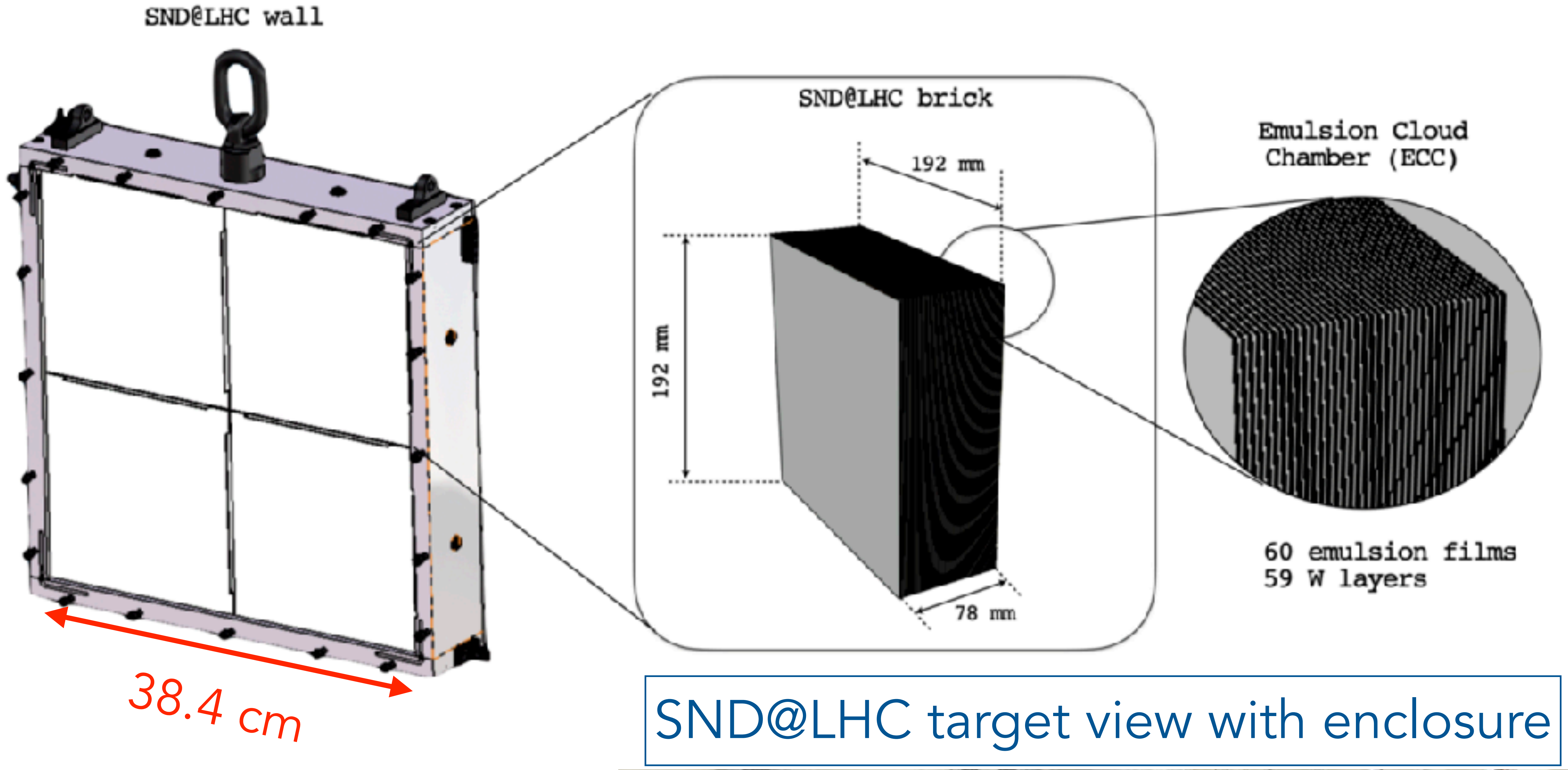


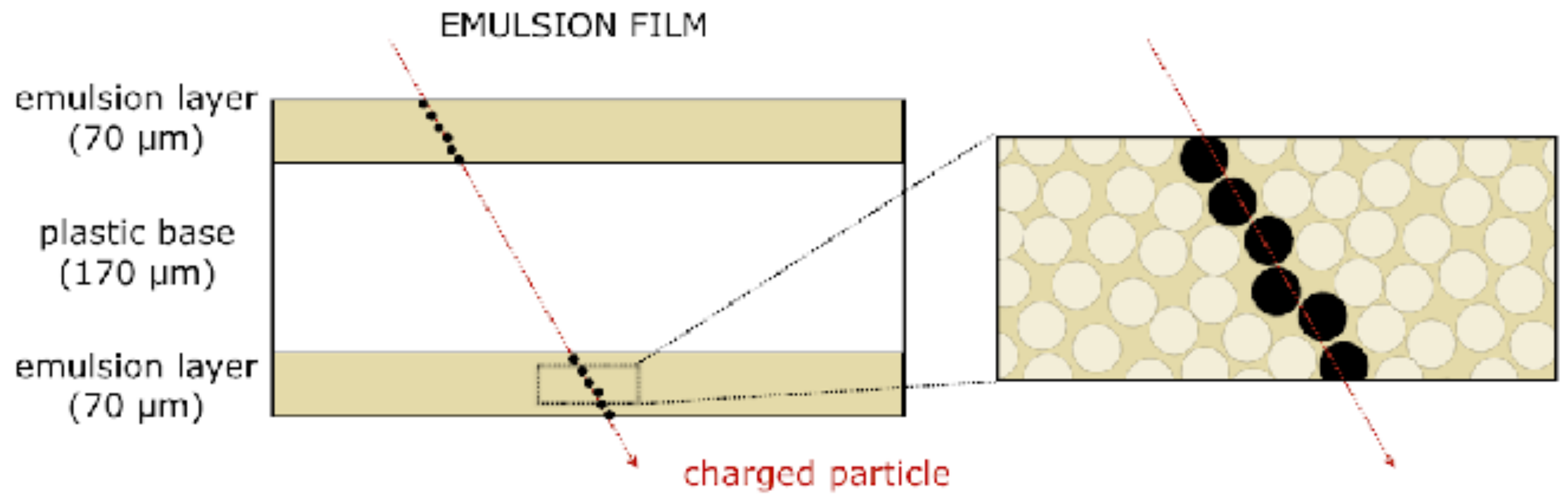
Two sides of the PCB with the SiPMs for the veto system

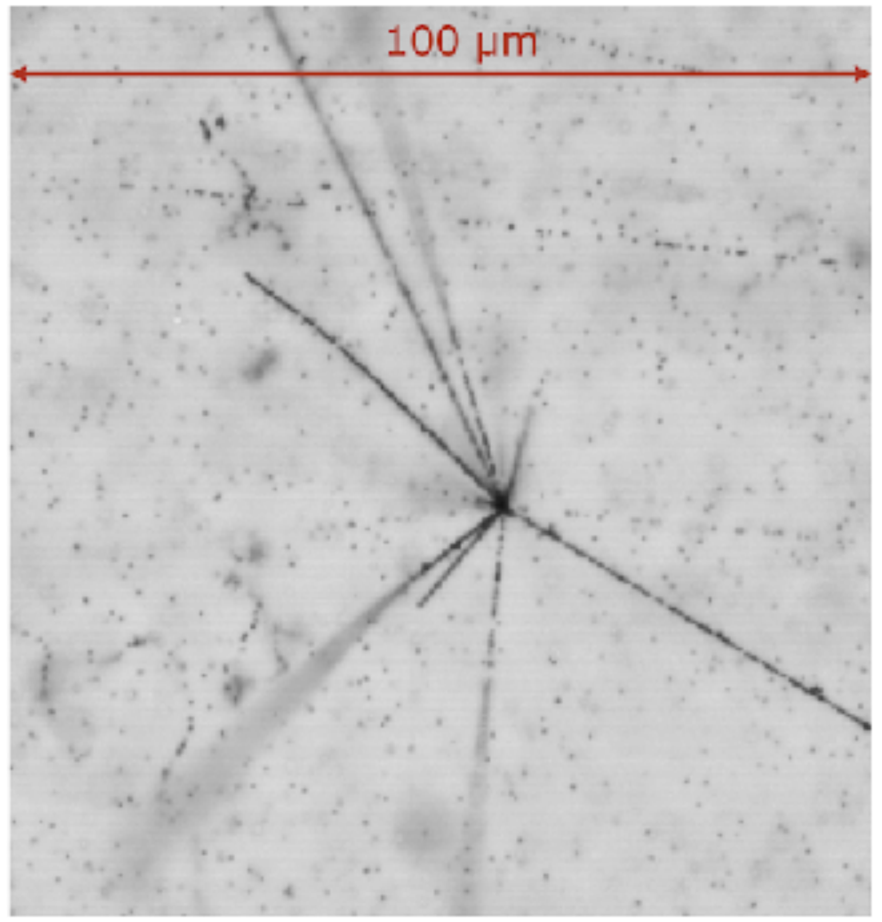


Emulsion Target

- 5 target walls acting as **vertex detector**
- **Emulsion Cloud Chamber** (ECC) technology: emulsion films interleaved with tungsten plates
- Each **target wall** is populated with **4 ECC bricks**, 78 mm thick (**~17 X_0**)
- Total **target mass: 830 kg**
- Surrounded by acrylic and borated polyethylene enclosure to shield neutrons and control T (15 °C) & RH (45%)



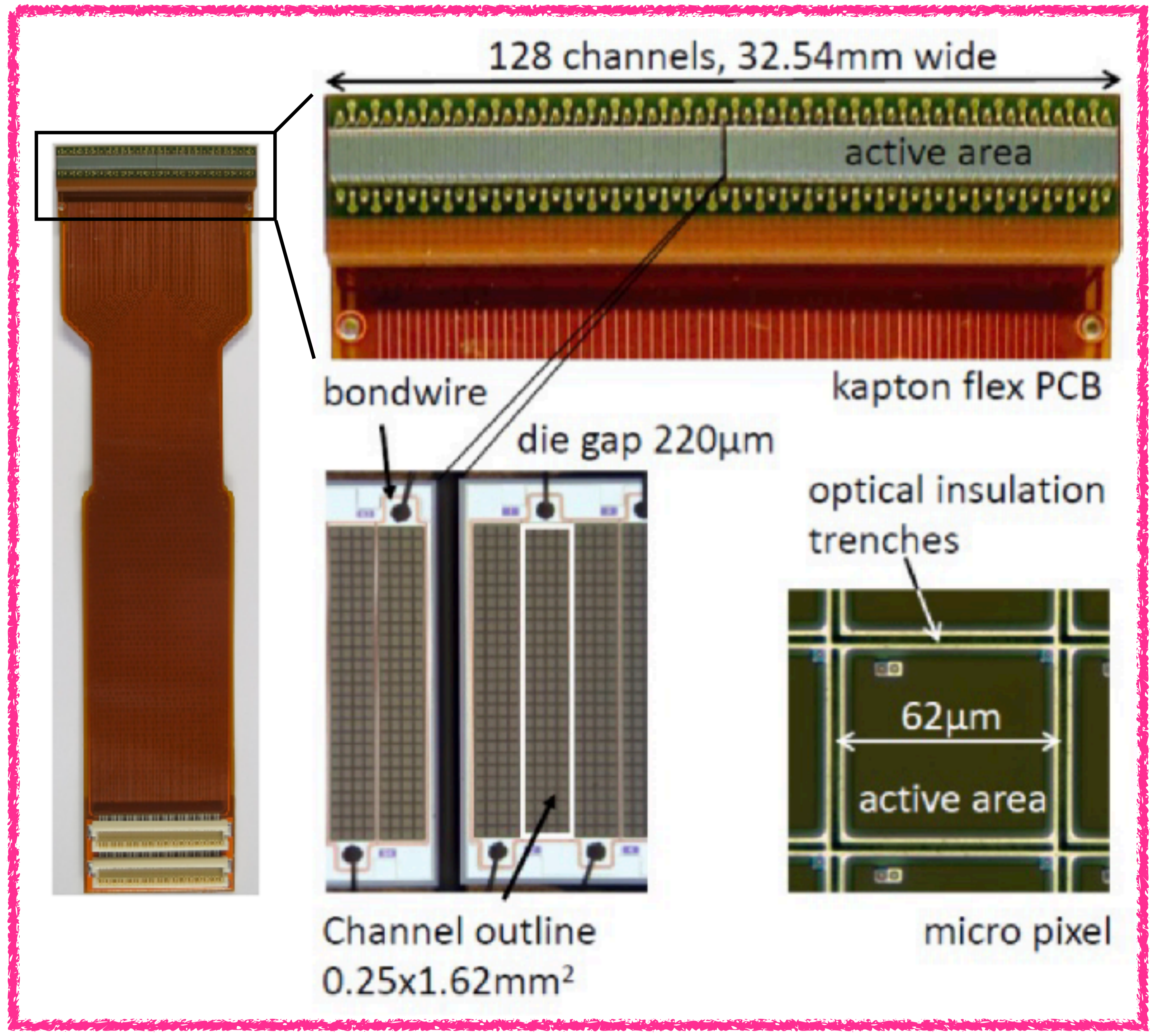




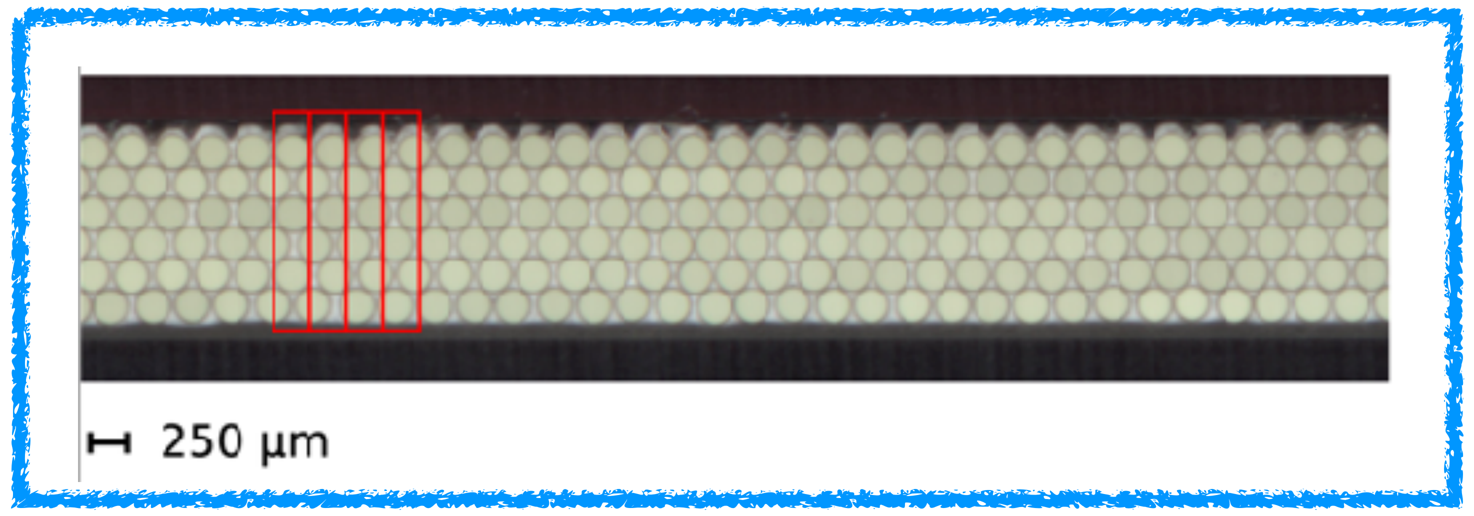
SND@LHC target view with enclosure

Scintillating Fibre Target Tracker

- Role of SciFi detector
  - **Interface** emulsion detector with electronic detectors and provide **time information**
  - Electromagnetic **calorimetry** (together with the emulsions)
- **5 SciFi stations** interleaved with the emulsion walls
- Each station consists of two planes: one **vertical**, one **horizontal**



Single SciFi station

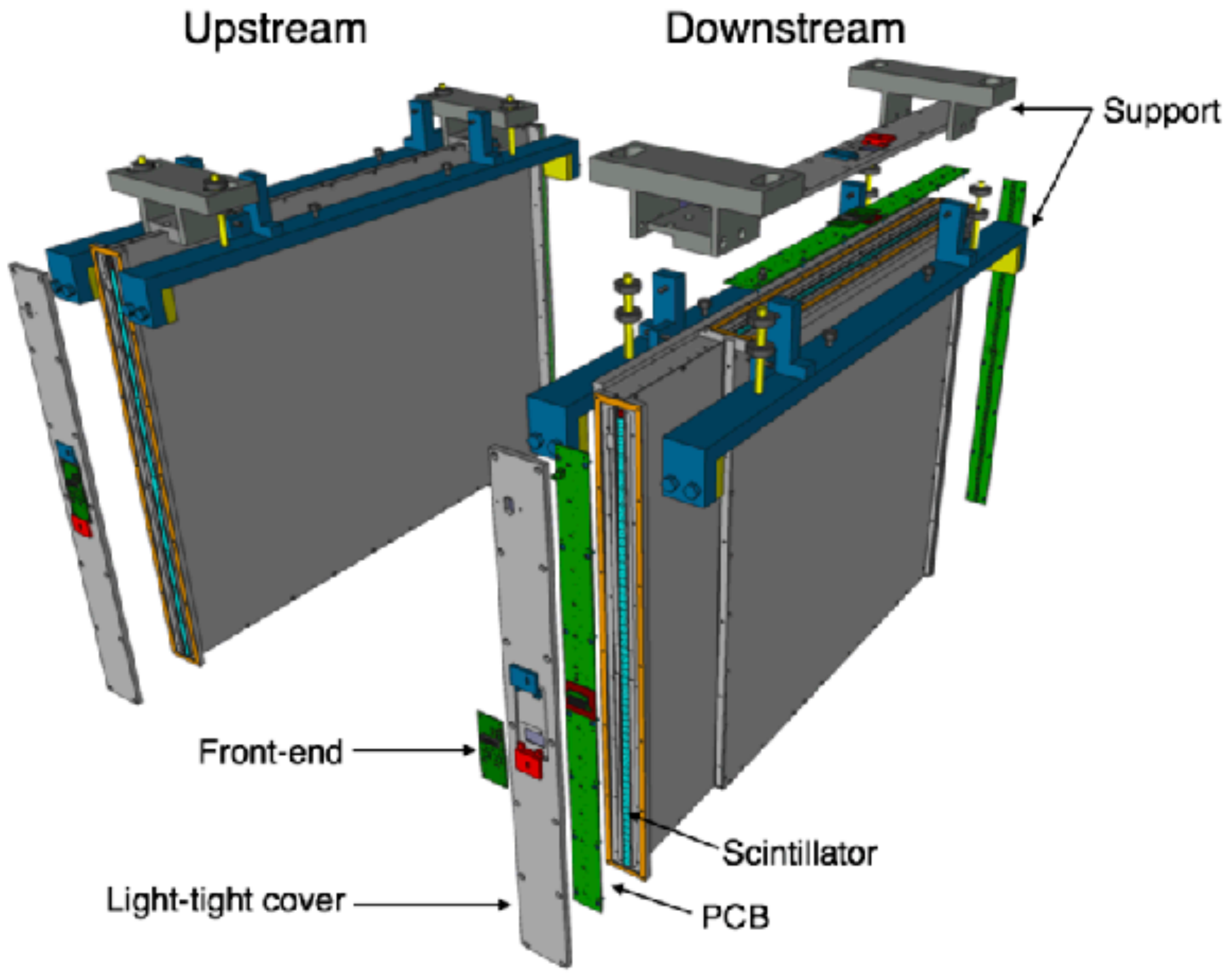


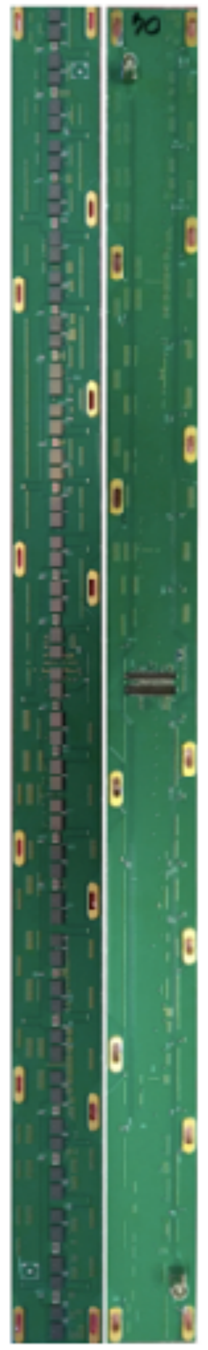
- Each plane is composed of
  - **Staggered layers of fibres** with 250 µm diameter
  - Readout by **SiPM arrays** with channel pitch of 250 µm

HCAL - Muon system

8 layers of **scintillating bars** interleaved with 20 cm-thick **iron slabs** (**9.5 λ_{int}**)

- First 5 stations form the **upstream** system → hadron calorimetry
- Last 3 stations form the **downstream** system → muon identification

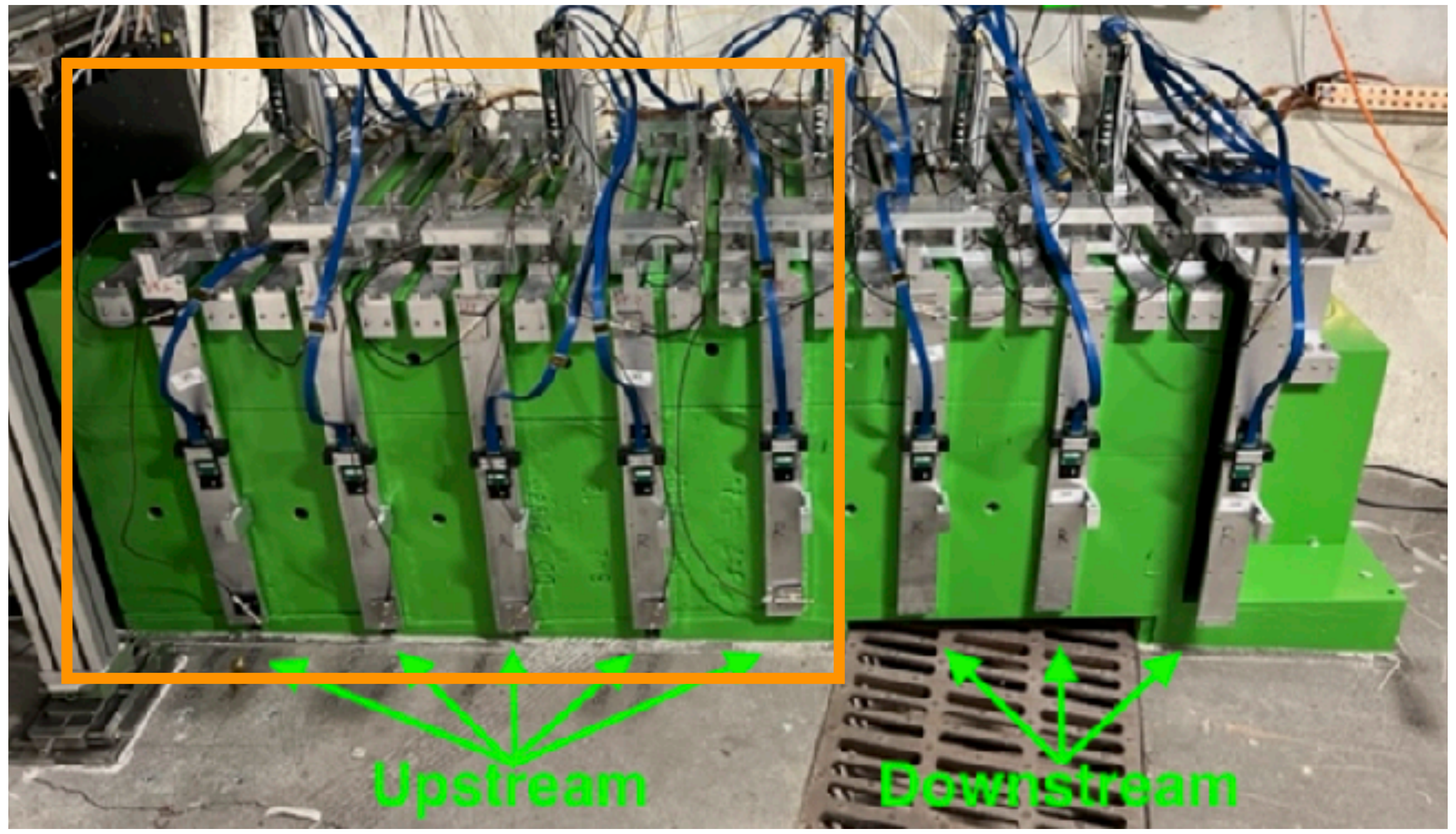


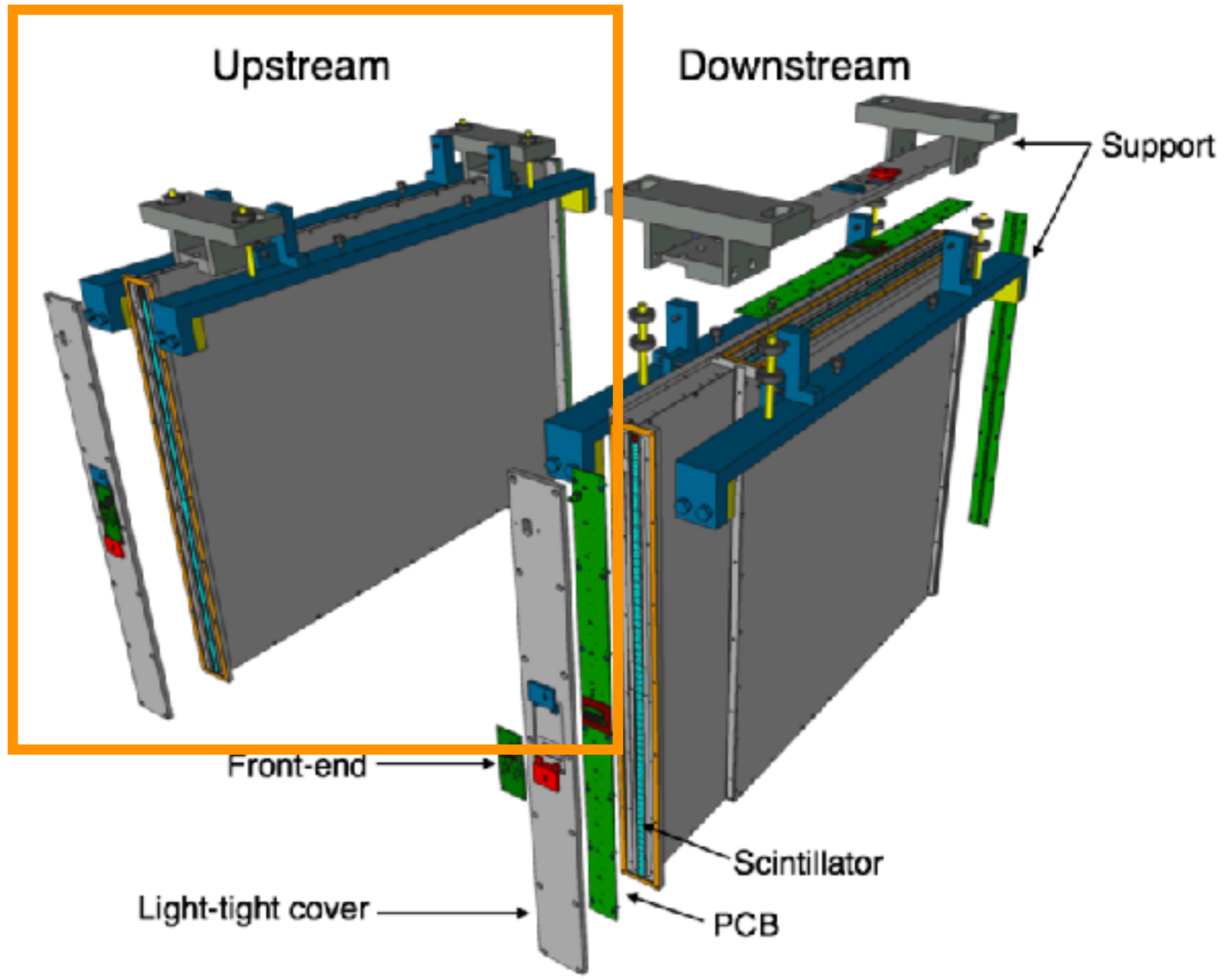


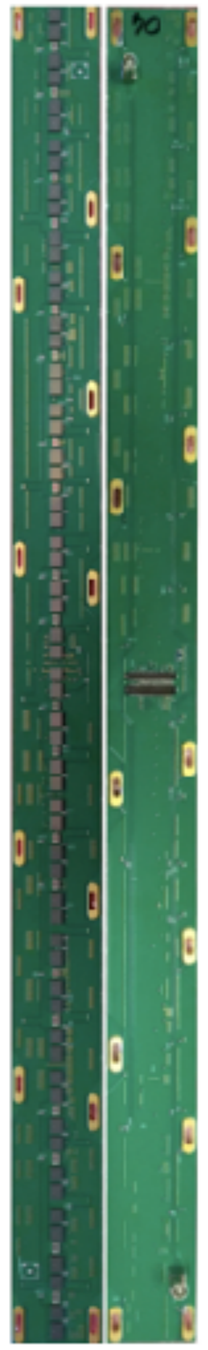
HCAL - Muon system

8 layers of **scintillating bars** interleaved with 20 cm-thick **iron slabs** (**9.5 λ_{int}**)

- First 5 stations form the **upstream** system → hadron calorimetry
- Last 3 stations form the **downstream** system → muon identification







Upstream

5 stations, each instrumented with **10 horizontal scintillator bars**

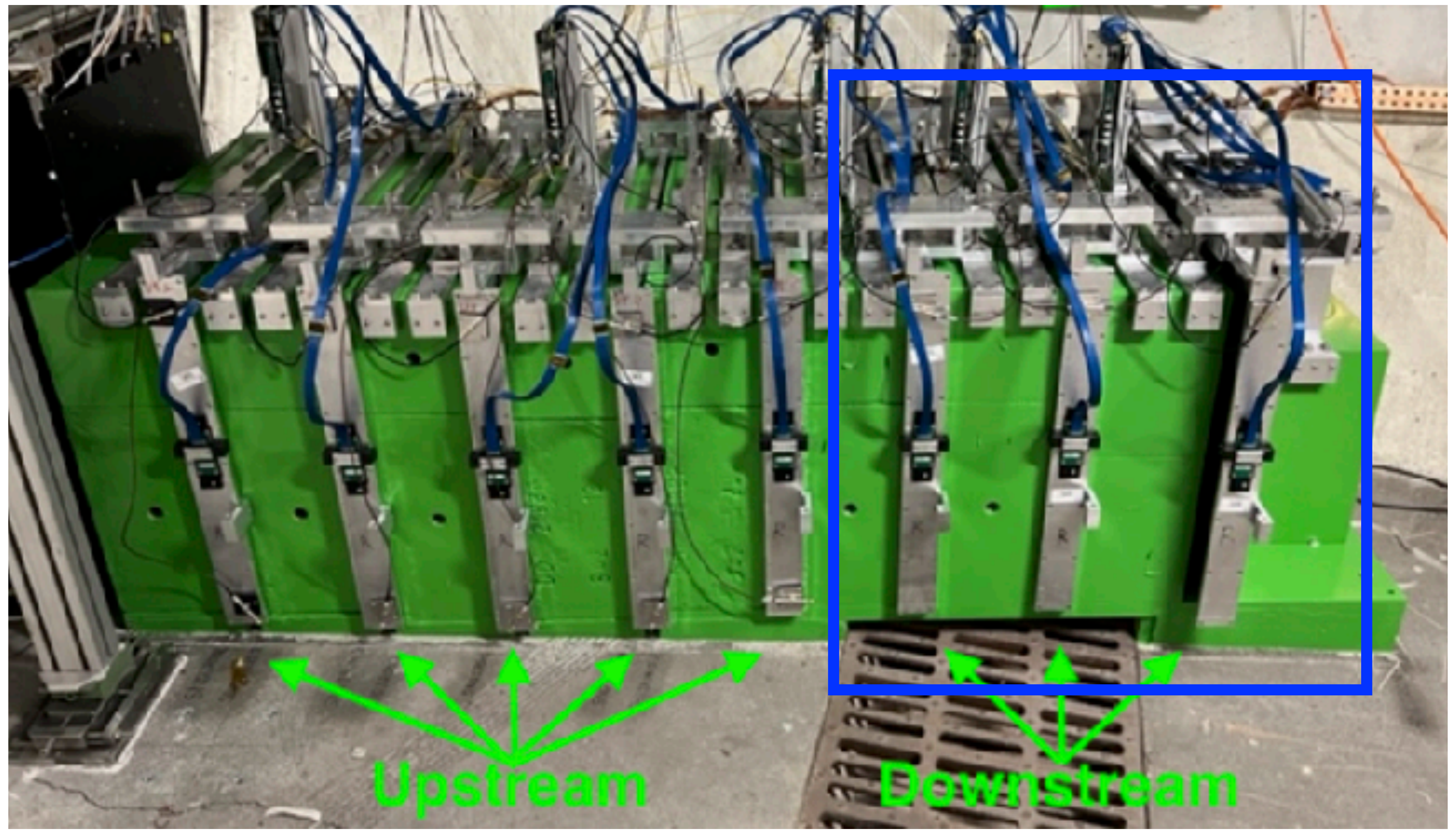
- Bar dimension: 1 x 6 x 81 cm^3
- Read out on both sides by 6 **large** (6 x 6 mm^2) and 2 **small** (3 x 3 mm^2) **SiPMs**

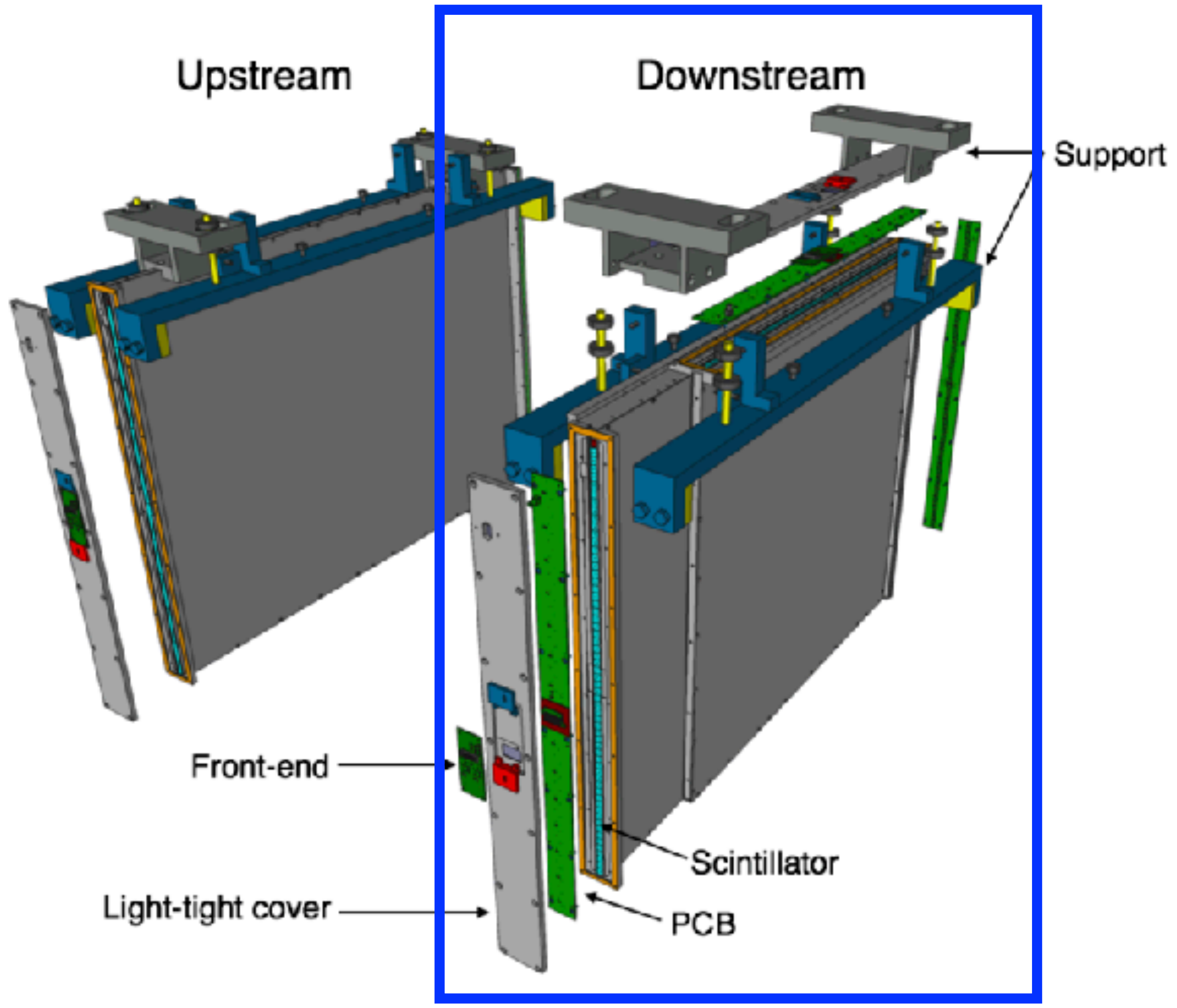
  Small SiPMs have more pixels and extend the dynamic range beyond the saturation of the large SiPMs

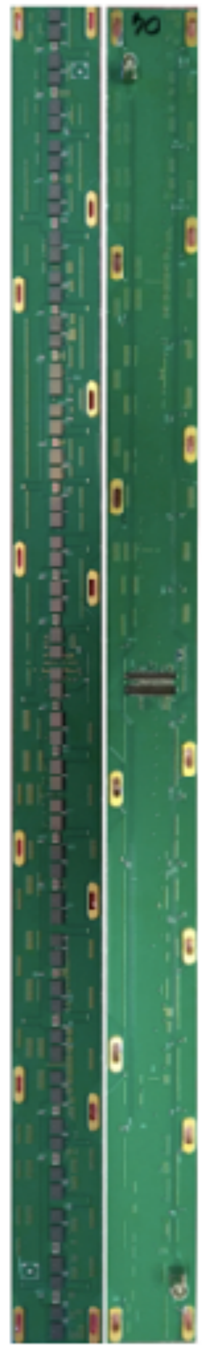
HCAL - Muon system

8 layers of **scintillating planes** interleaved with 20 cm-thick **iron slabs** (**9.5 λ_{int}**)

- First 5 stations form the **upstream** system → hadron calorimetry
- Last 3 stations form the **downstream** system → muon identification







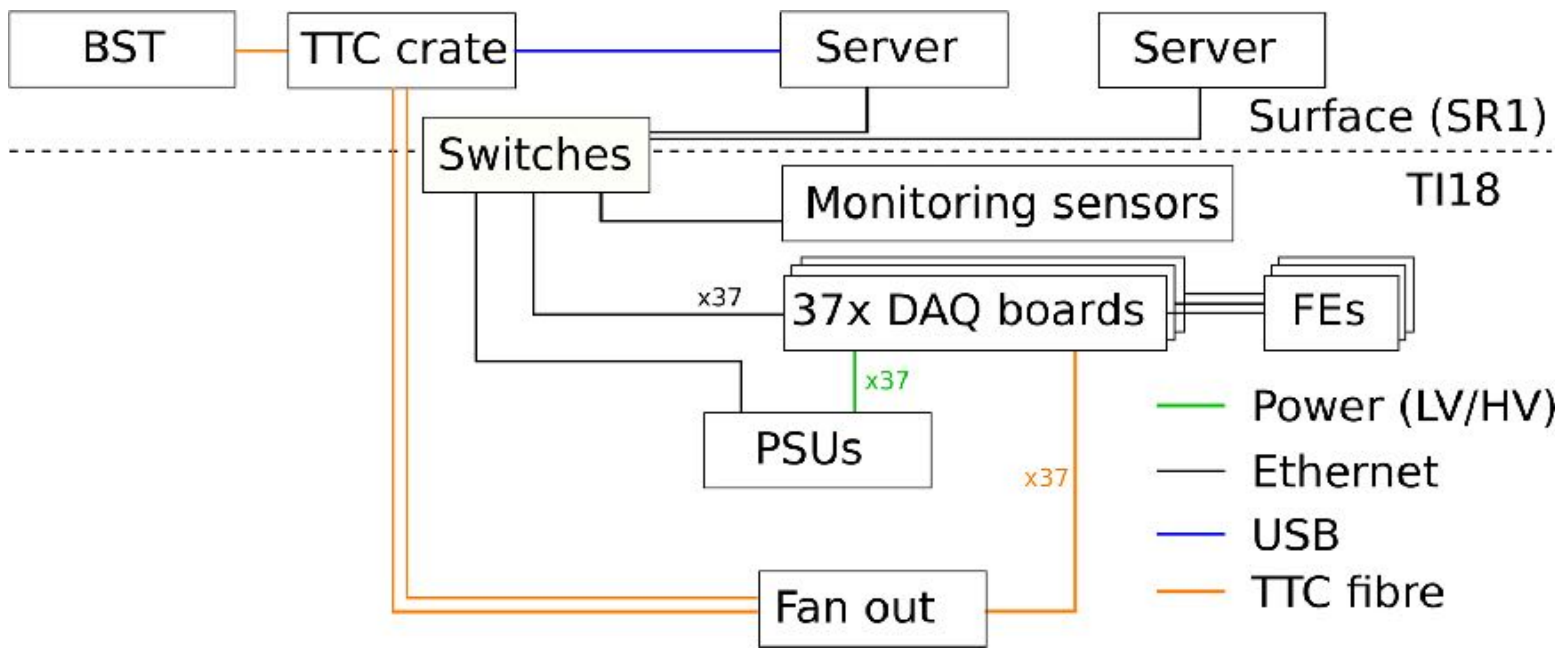
Downstream

3 stations, each instrumented with one plane of **60 horizontal bars** and one plane of **60 vertical bars** (+ additional vertical plane in the last station)

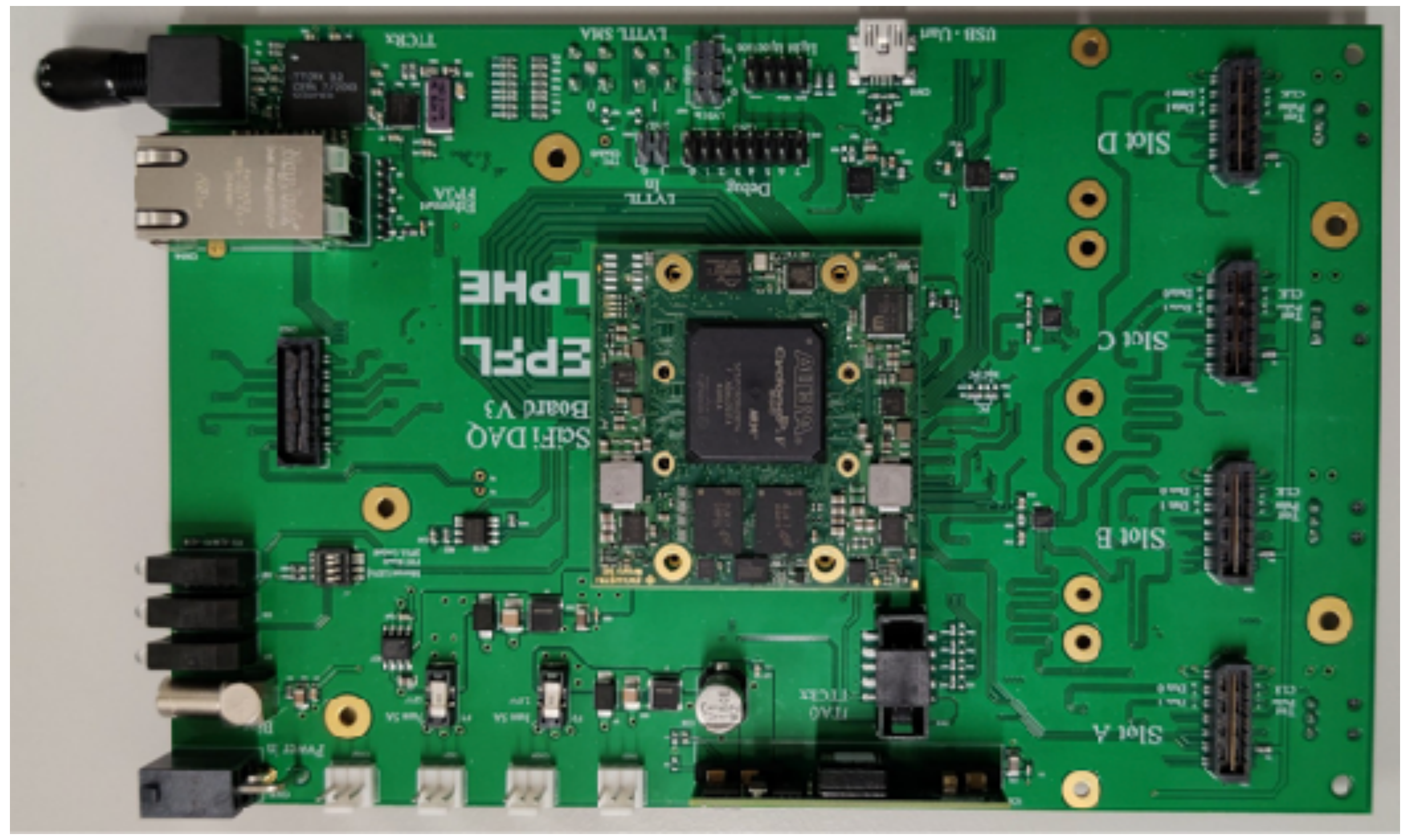
- Bar cross-section: 1 x 1 cm^2
- Length: 81 cm (horizontal) or 60 cm (vertical)
- Readout by large SiPMs: 1 SiPM on each side of horizontal bars, only 1 SiPM on top of vertical bars

DAQ and Front-End Electronics

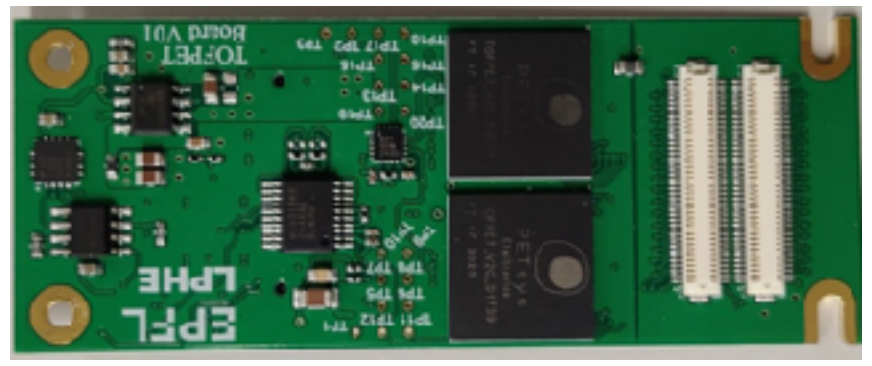
- All electronic detectors read out by **TOFPET-based FE**
  - Low signal threshold: 0.5 p.e.
  - Good timing: 40 ps TDC binning
  - 128 channels
- **DAQ boards** based on Cyclone V FPGA
  - Run at 160 MHz, aligned with the LHC clock
  - Collect data from 4 front-end boards (128 x 4 = 512 channels)
  - Send hits above threshold to DAQ server over ethernet
- **DAQ server**
  - Receives hits from all DAQ boards
  - Runs timestamp-based event-building code
  - Saves data to disk in ROOT format



DAQ board

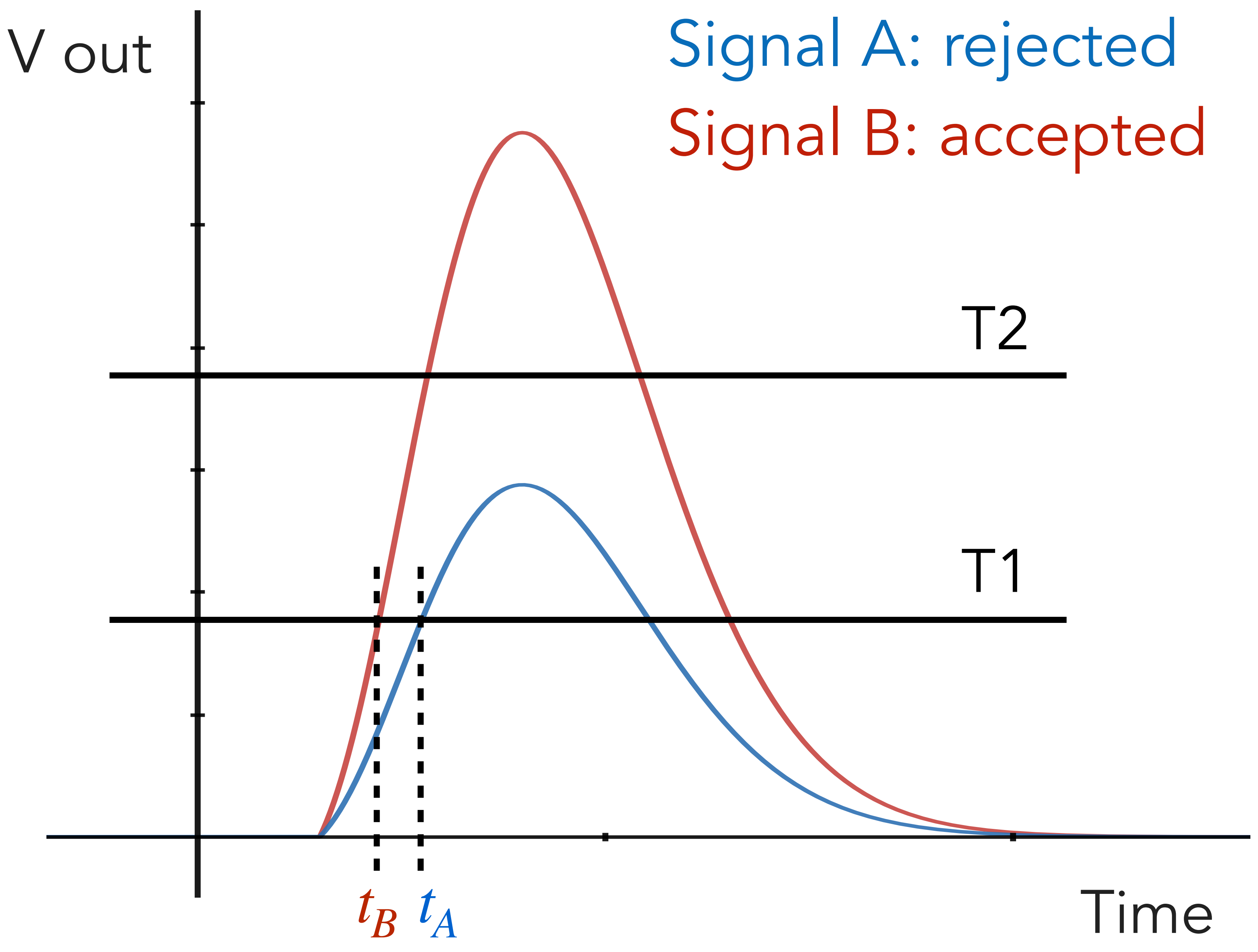


TOFPET2 ASIC by PETsys used as FE for all detectors



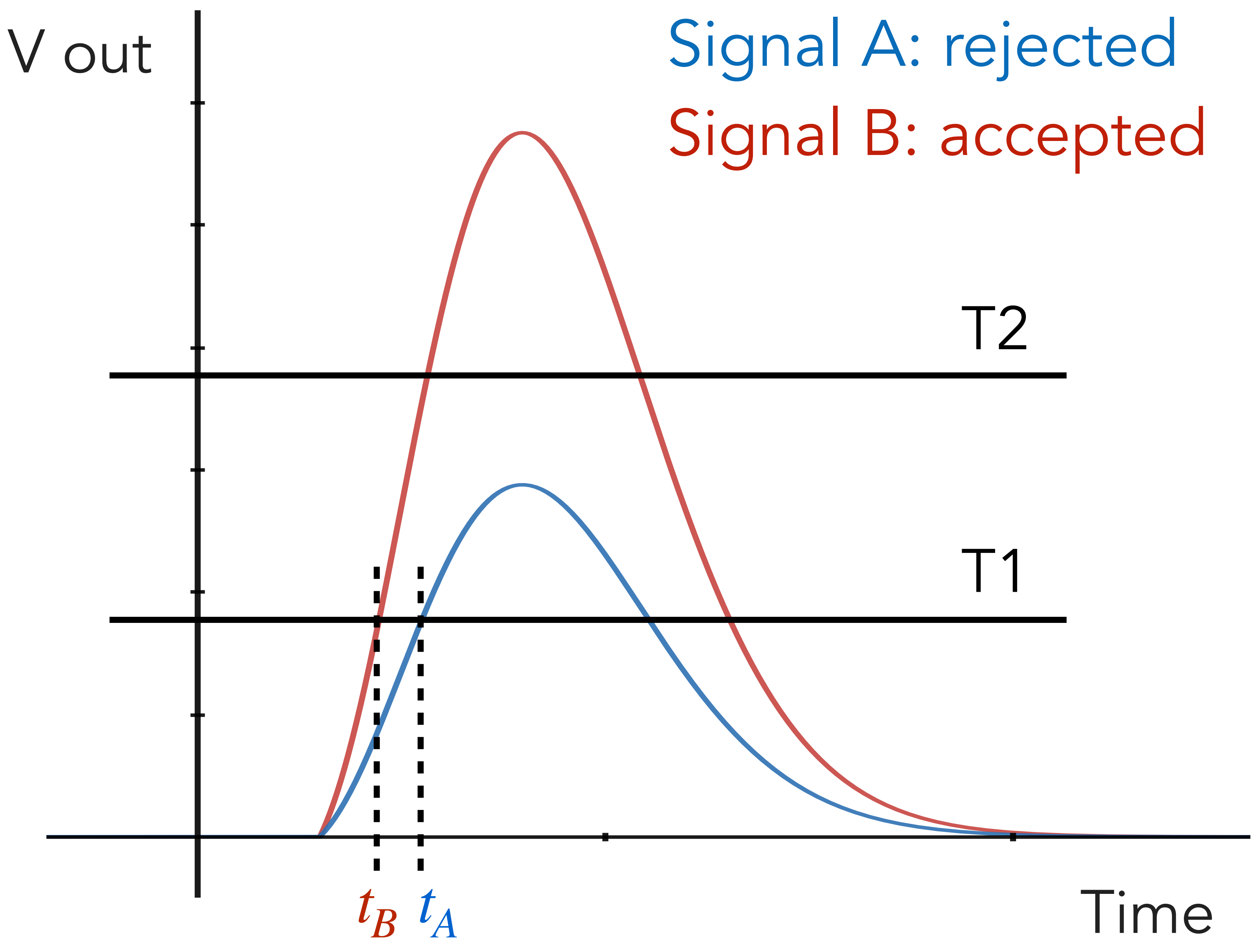
TOFPET Trigger Settings

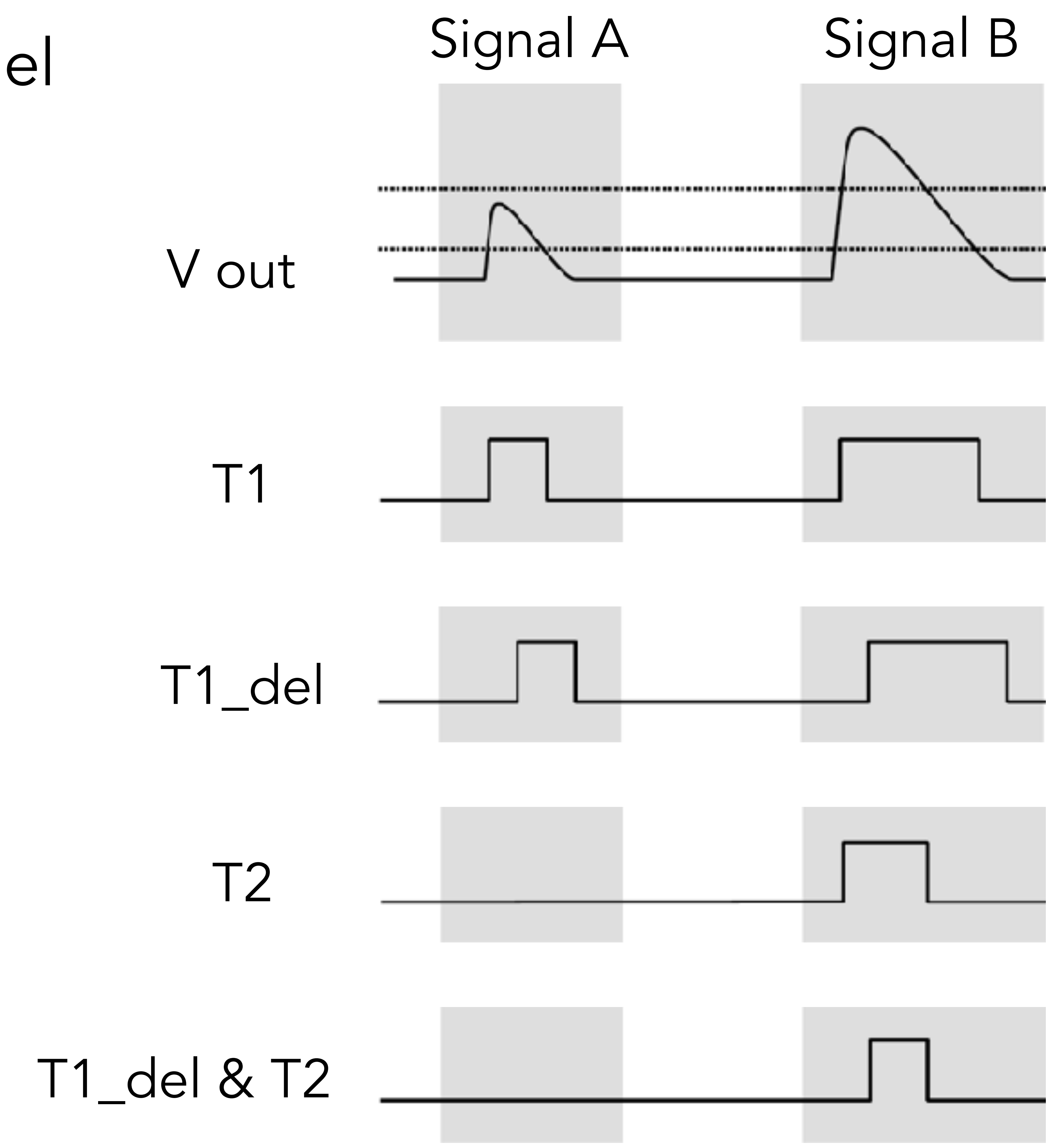
- **Two thresholds** used to trigger each channel
  (1) Time threshold (T1)
  (2) Amplitude confirmation threshold (T2)
- Why? **Suppress dark noise** (T2) while preserving **time resolution** (T1)



TOFPET Trigger Settings

- **Two thresholds** used to trigger each channel
  (1) Time threshold (T1)
  (2) Amplitude confirmation threshold (T2)
- Why? **Suppress dark noise** (T2) while preserving **time resolution** (T1)



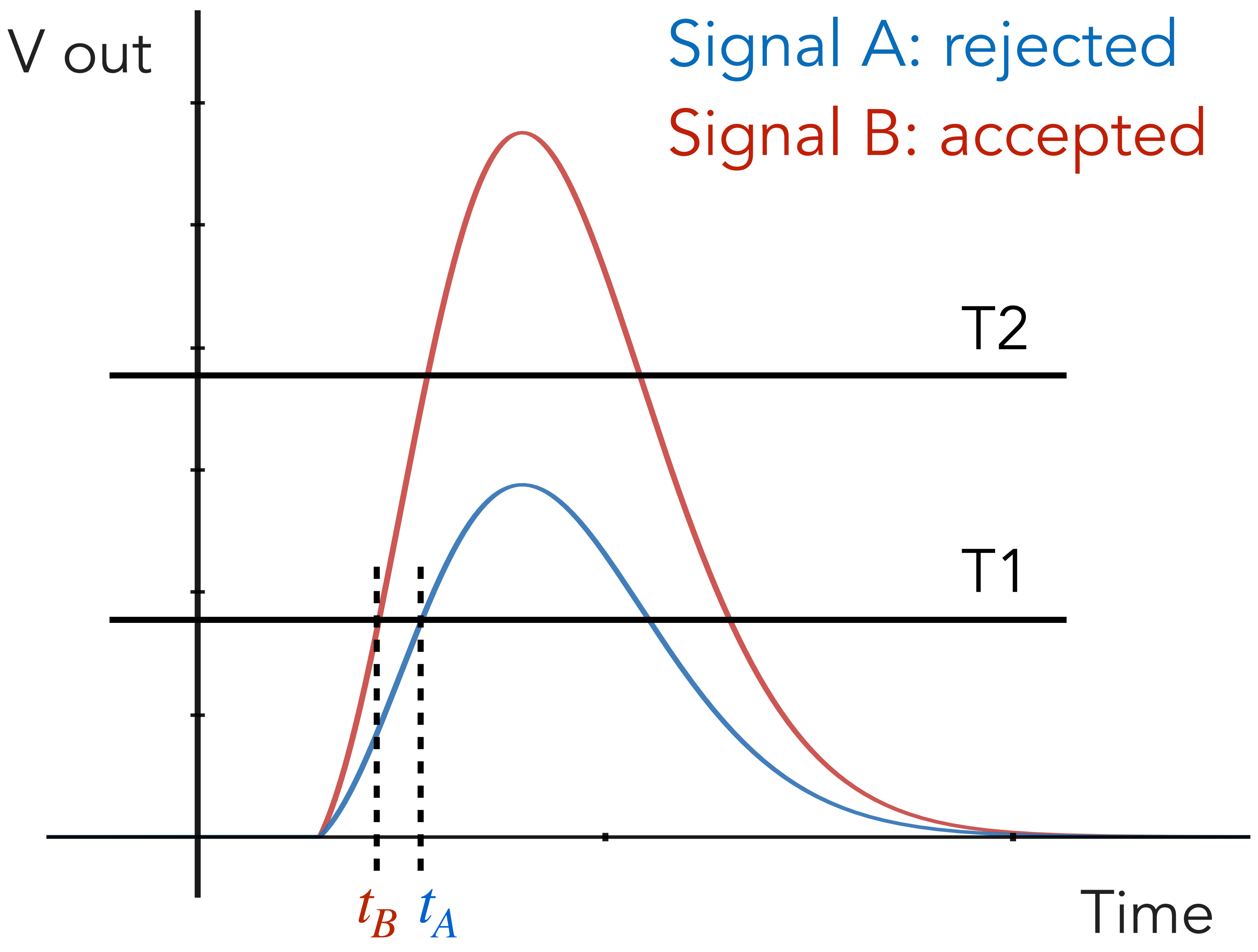


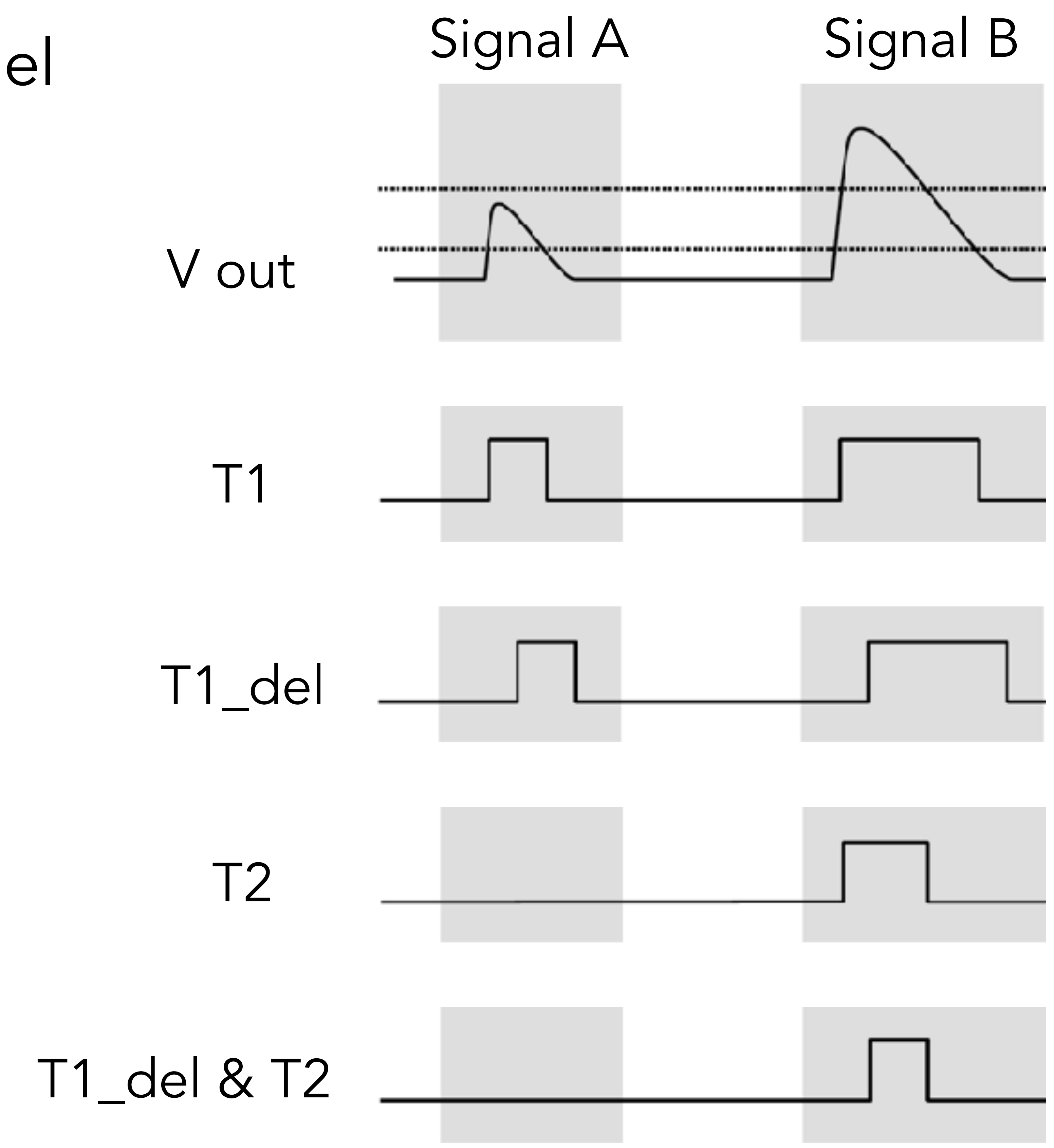
Different possible **trigger modes**:

- **Dual Threshold Trigger** (DTT) Mode
  - T1 triggers digitisation (dead time due to dark counts)
- DTT with **Fast Dark Count Rejection** (FDCR) Mode
  - T2 triggers digitisation
  - Timestamp recovered by introducing a delay in T1

TOFPET Trigger Settings

- **Two thresholds** used to trigger each channel
  (1) Time threshold (T1)
  (2) Amplitude confirmation threshold (T2)
- Why? **Suppress dark noise** (T2) while preserving **time resolution** (T1)





Different possible **trigger modes**:

- **Dual Threshold Trigger** (DTT) Mode
  - T1 triggers digitisation (dead time due to dark counts)
- DTT with **Fast Dark Count Rejection** (FDCR) Mode
  - T2 triggers digitisation
  - Timestamp recovered by introducing a delay in T1

T1, T2 and the trigger mode have potential effects on time resolution, amplitude measurement and efficiency

Presentation Outline

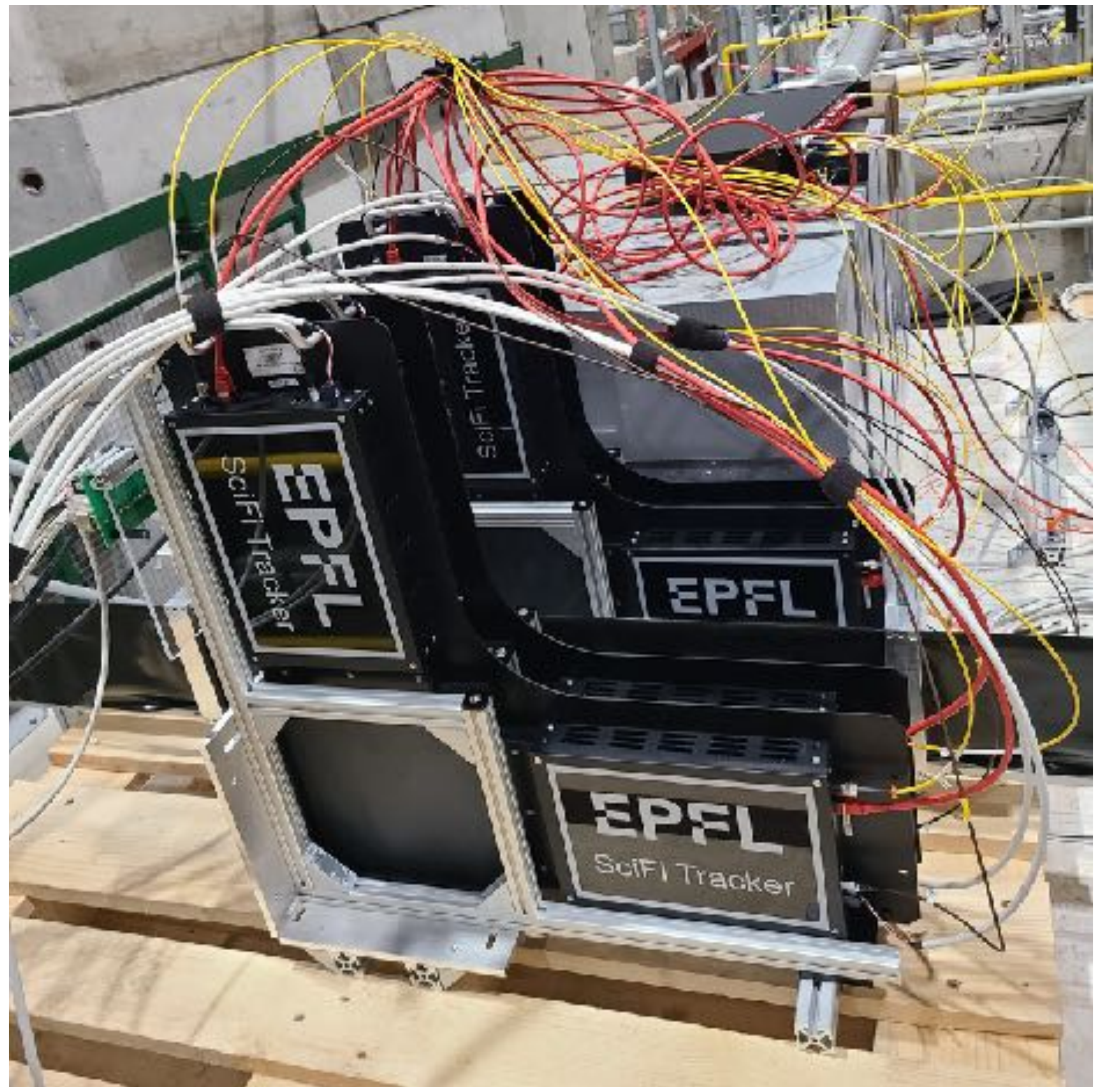
- Introduction
- The SND@LHC detector
- Performance studies of the target tracker

Test Beam & Time Resolution Studies

SND@LHC test beam campaign performed **in 2023** to study extensively detector performance

- CERN beam line in North Area - hadron beam at 180 GeV
- 4 SciFi planes with active area of 13 x 13 cm^2
- Varied operation parameters:
  - Time threshold (**T1**)
  - Amplitude confirmation threshold (**T2**)
  - SiPMs' Over-Voltage (**OV**)
  - **Trigger modes**: DTT + FDCR (**off**, **3 ns**, **6 ns** delay on T1)

SciFi tracker setup for the test beam



Single test-beam SciFi module: same as in SND@LHC, but smaller

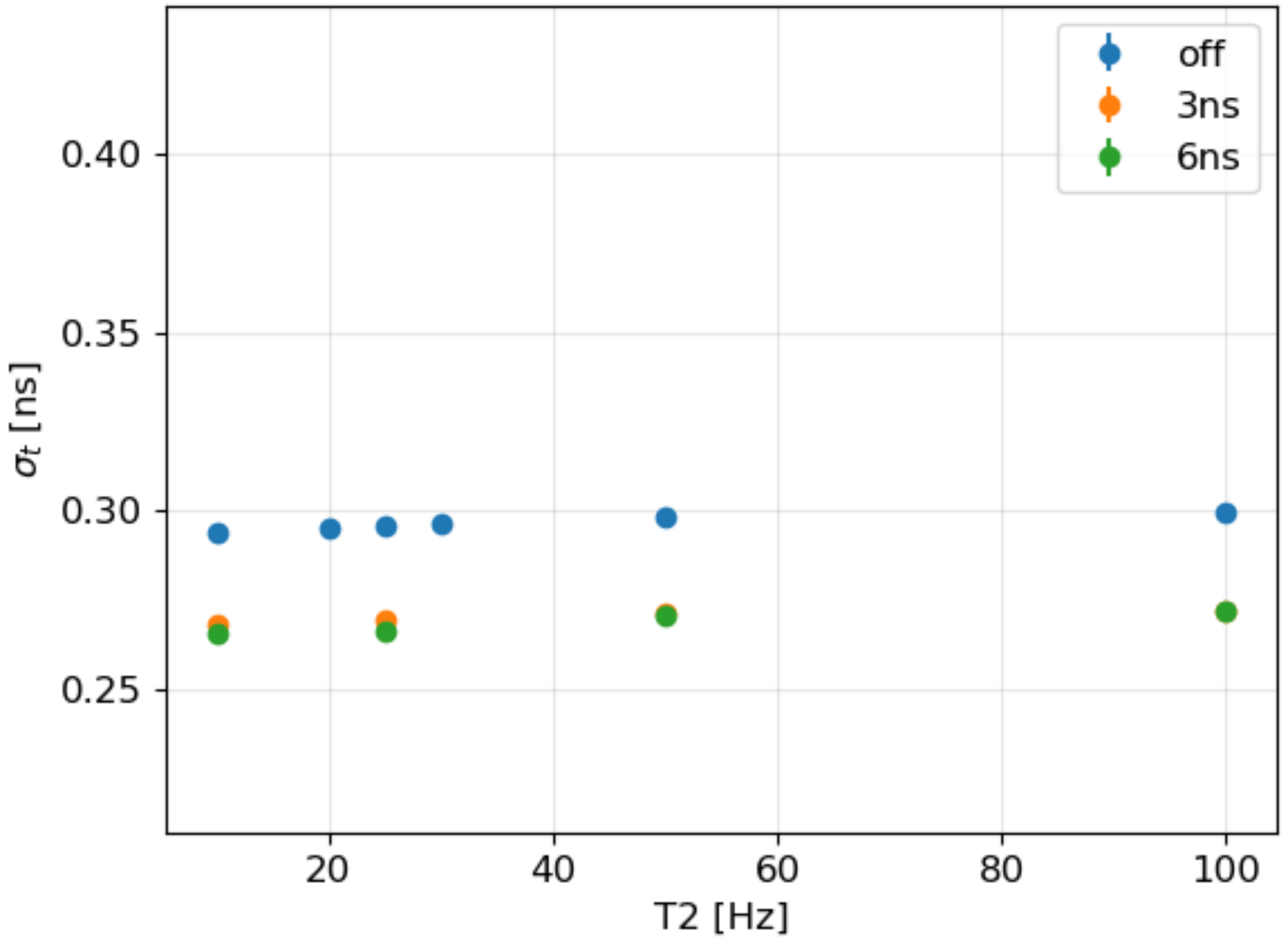
Time resolution measurement

- σ_t obtained from **coincidence time resolution** (CTR) between X and Y planes: $\sigma_t = CTR/\sqrt{2}$
  - Gaussian fit to the $\Delta t = t_x - t_y$ distribution
- Goal: asses the **SciFi timing performance** and determine the **best conditions for operation** in SND@LHC

Time Resolution Results

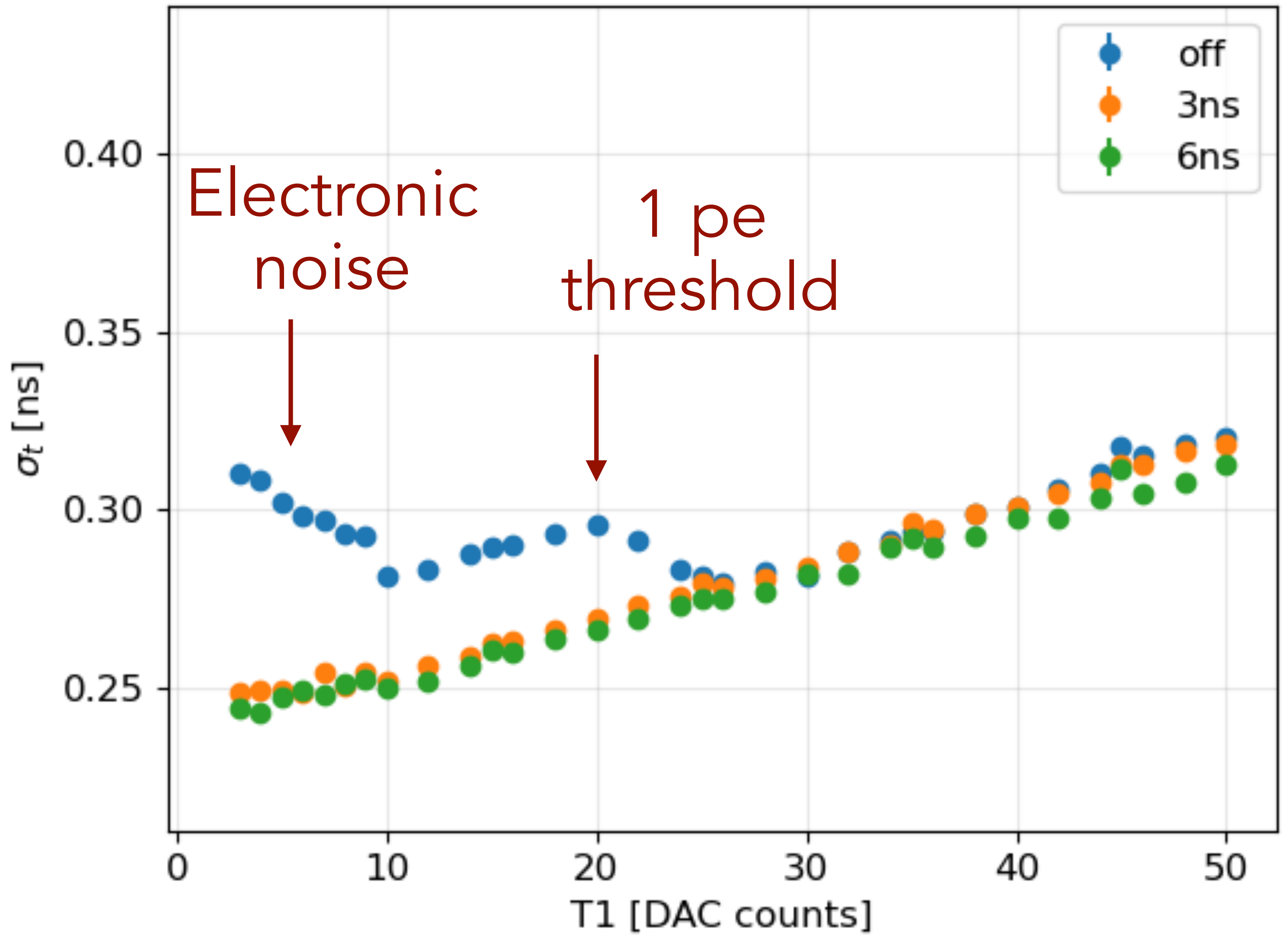
LHC Scattering and Neutrino Detector at the LHC

σ_t VS **T2**



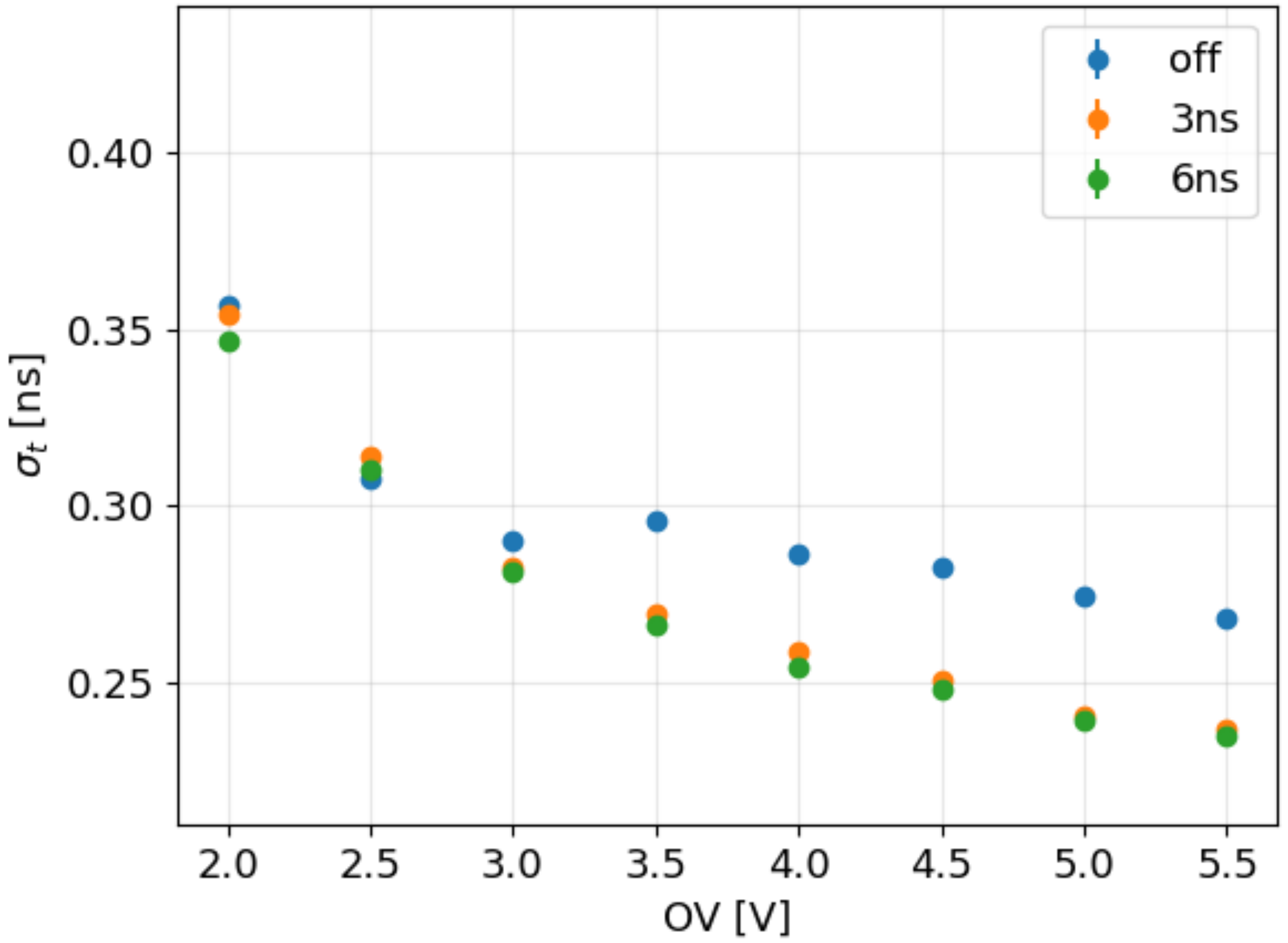
σt stable with T2 (within 10 ps in the studied range)

σ_t VS **T1**



- σ_t improves at lower T1
- Dark count rate (DCR) degrades σ_t in DTT mode

σ_t VS **OV**



- σ_t improves at higher OV
- σ_t degradation due to DCR also visible

Current SND@LHC operation	
T1 [DAC counts]	20
T2 [Hz]	25
OV [V]	3.5

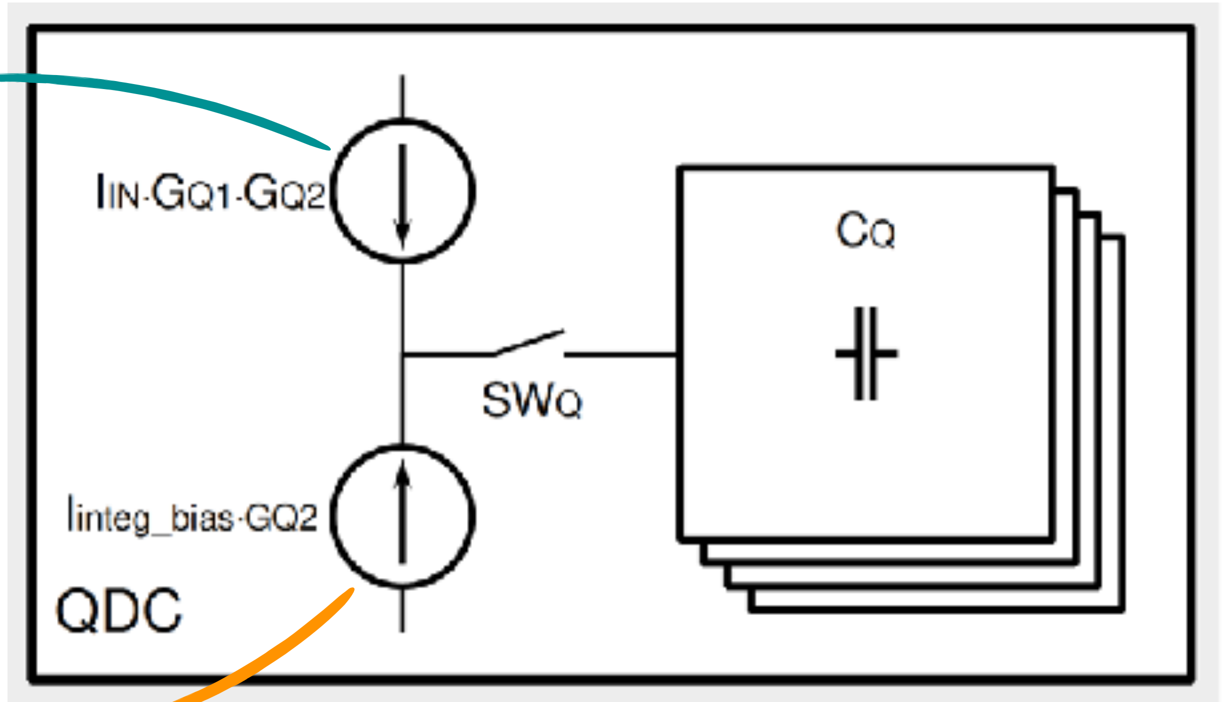
- FDCR mode is preferable, no significant correlation with the delay
- Better time resolution at high OV → Need to study effect of higher OV on total rate

Signal Amplitude Studies

Measurement of signal amplitude in the FE through a Charge to Digital Converter (QDC)

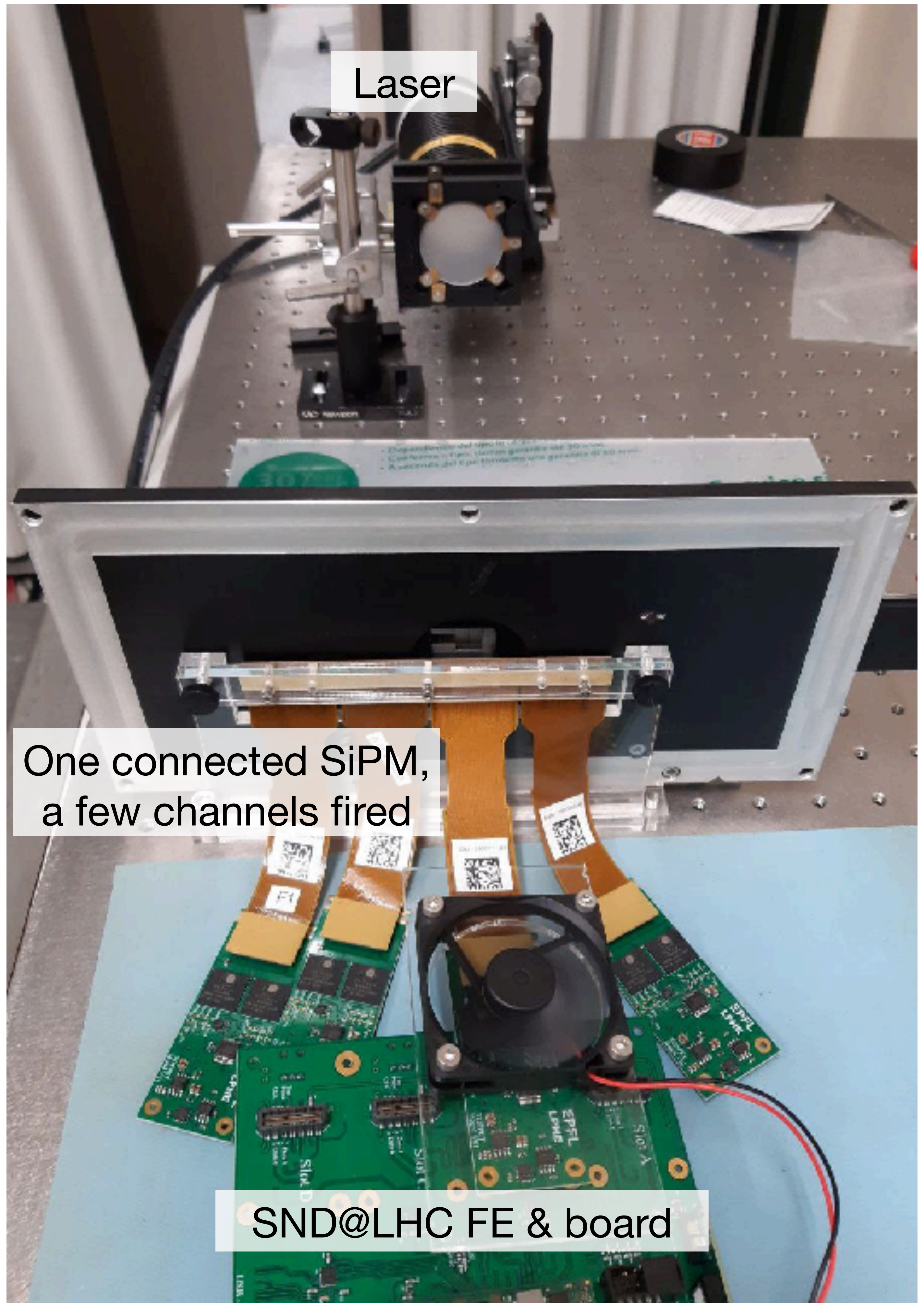
- Signal amplitude = integrated current in a given time window
- Integration time depends on the FE trigger mode, with possible effects on the QDC value

Signal



Constant (calibrated before data-taking)

Laboratory setup



Signal amplitude studies

- Goal: **study QDC response** (linearity, dynamic range, channel-by-channel variability) at different **FE trigger modes**

- Measurement setup:
  - Direct **laser injection into the SiPMs** with variable intensity
  - Previous laser calibration allows to know signal amplitude (number of detected photons) at given intensity

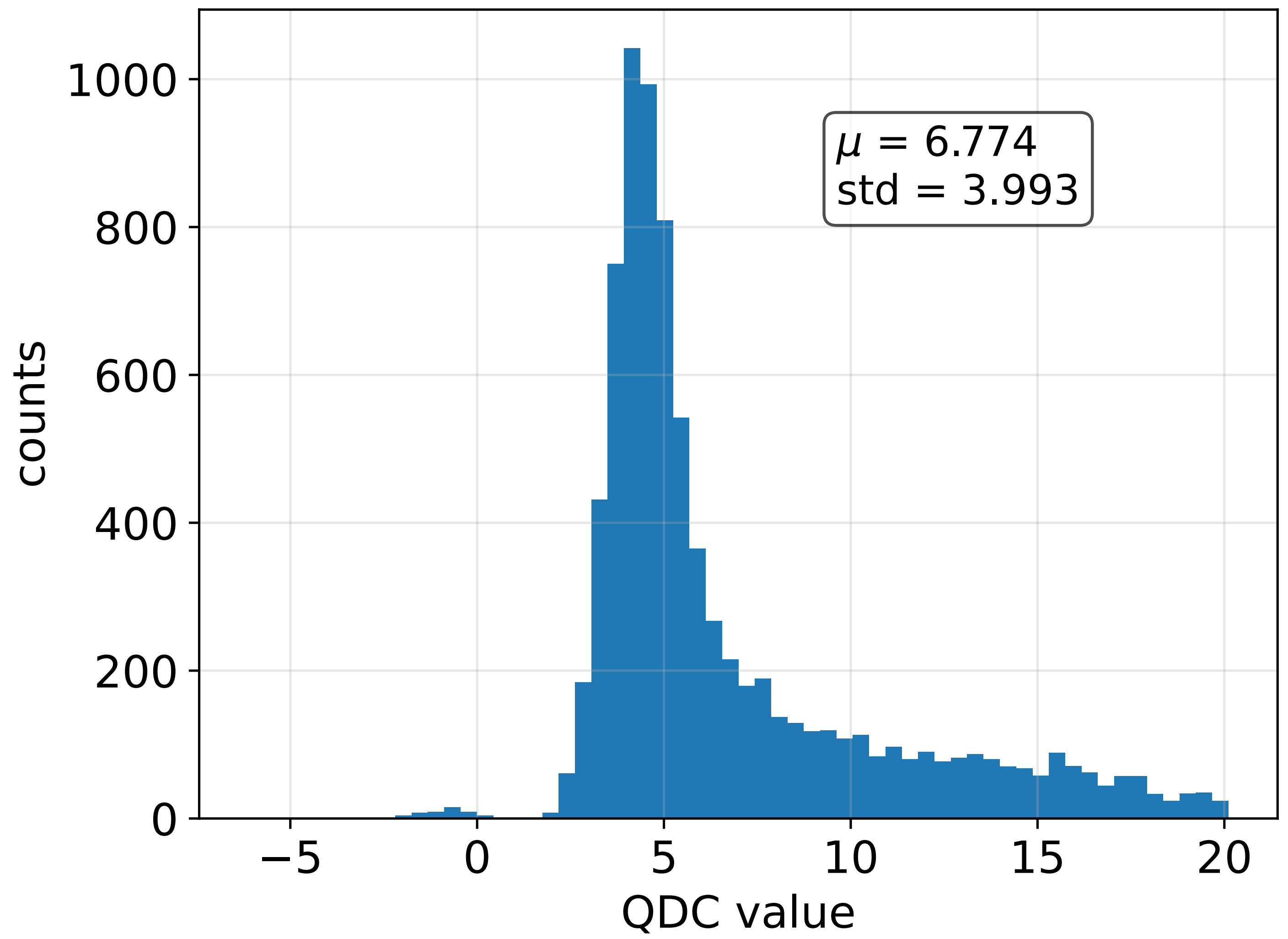
Signal Amplitude Results

Issues at low signal amplitude
(Detected photons $\lesssim$ 10) in **FDCR mode**

- Loss in **hit efficiency**
  → Effective threshold higher than validation threshold
- Long **tails** at high QDC values
- Issues enhanced at **high delay (6ns)**

Single channel (SiPM) QDC distribution

Laser Int. = 5%. Detected photons ~ 4



- High delay in FDCR mode should be avoided due to issues at low signal amplitudes

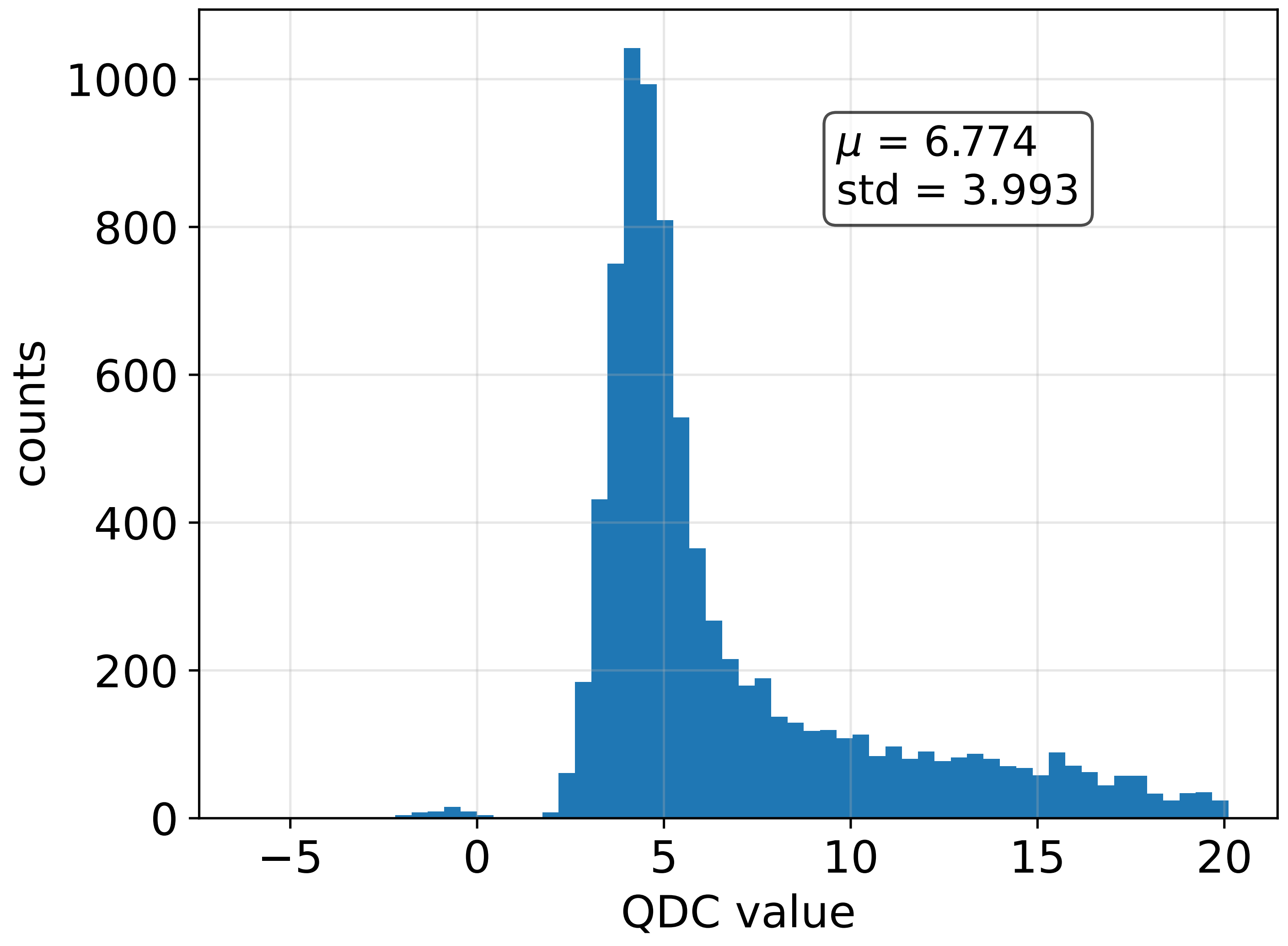
Signal Amplitude Results

Issues at low signal amplitude (Detected photons $\lesssim$ 10) in **FDCR mode**

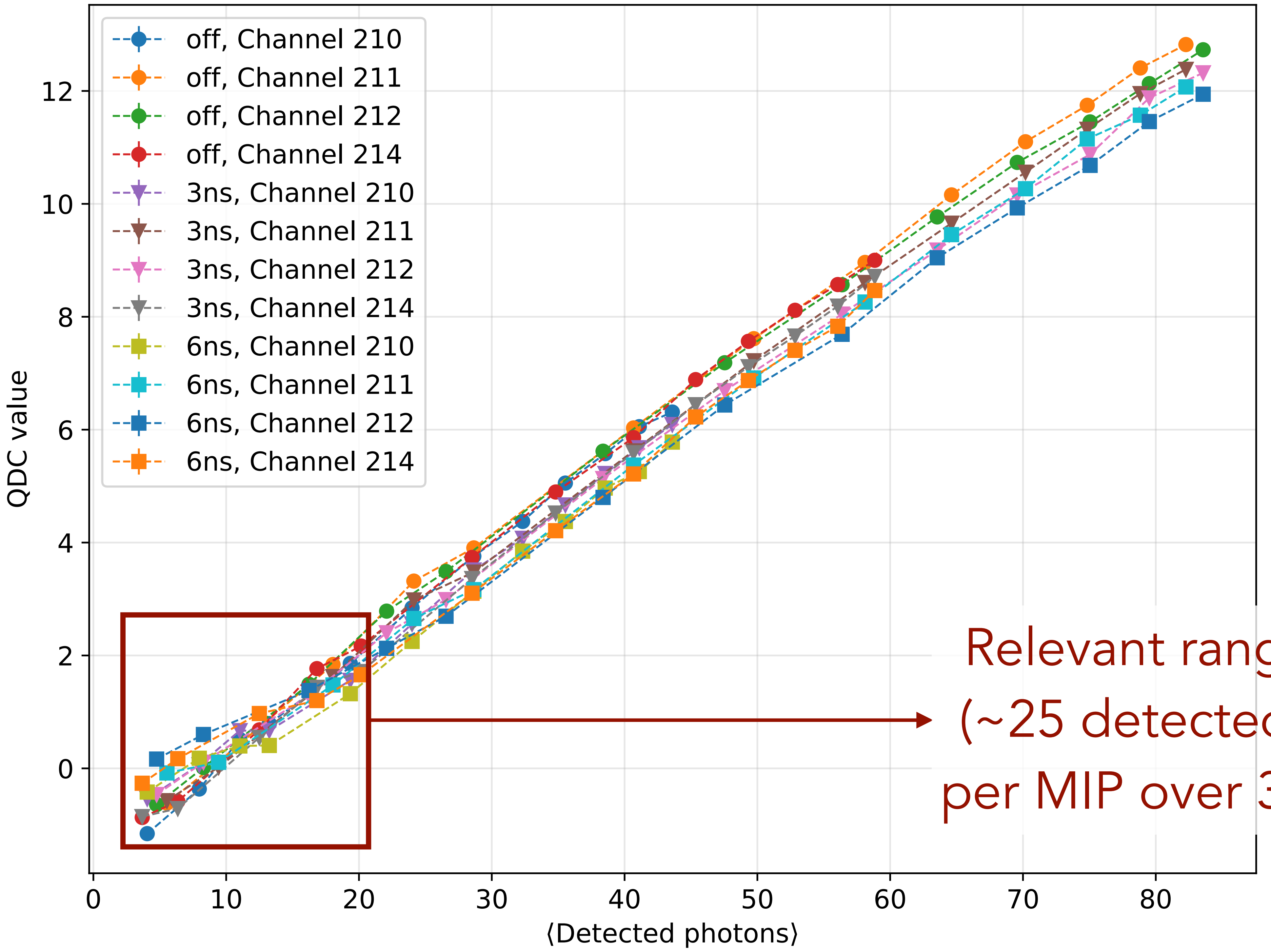
- Loss in **hit efficiency**
  → Effective threshold higher than validation threshold
- Long **tails** at high QDC values
- Issues enhanced at **high delay (6ns)**

Single channel (SiPM) QDC distribution

Laser Int. = 5%. Detected photons ~ 4



Average QDC value VS number of deleted photons



Relevant range in SciFi (~25 detected photons per MIP over 3 channels)

- High delay in FDCR mode should be avoided due to issues at low signal amplitudes

- Observed limited QDC dynamic range at relevant signal amplitudes for SciFi

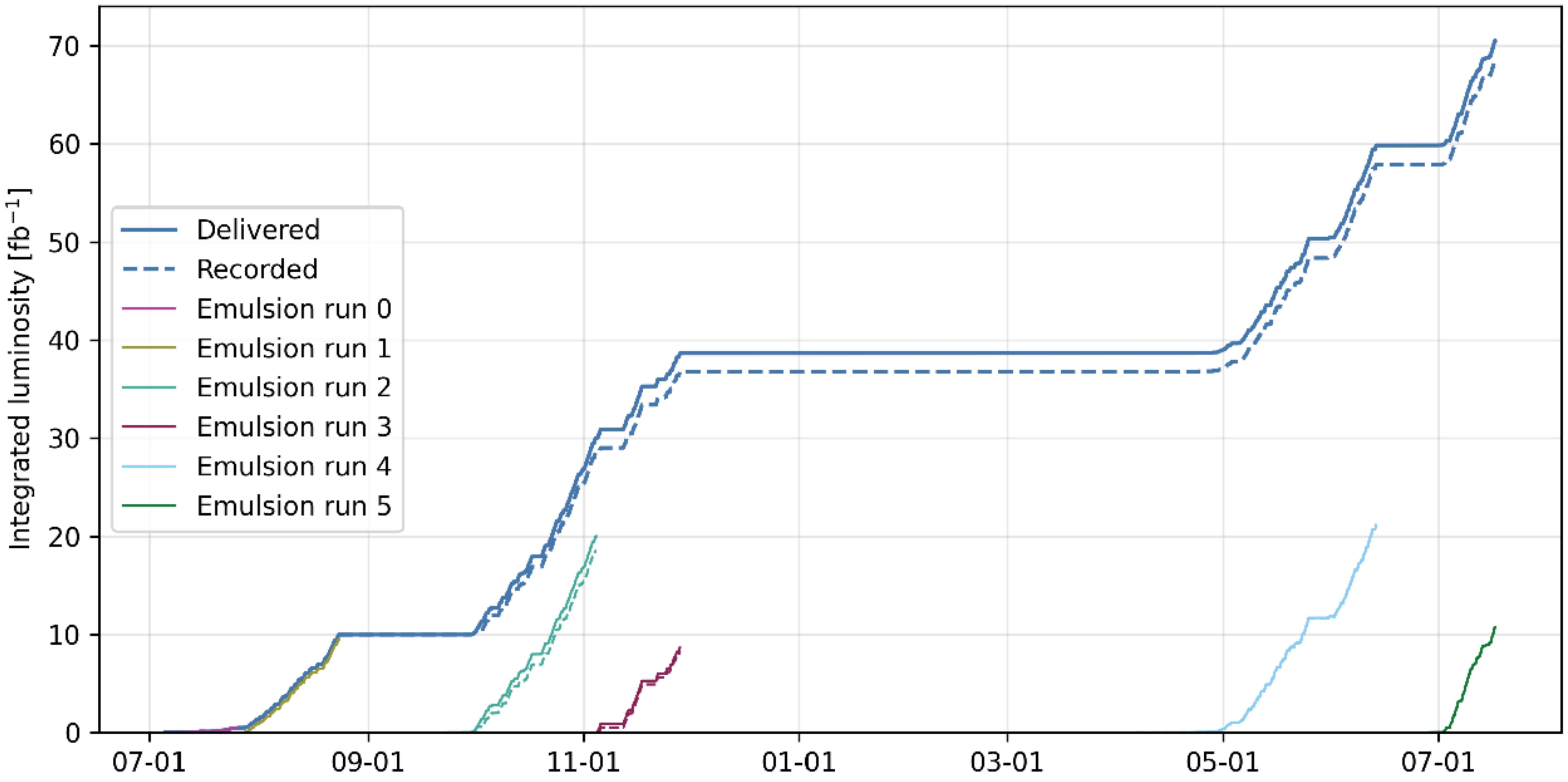
Summary and Conclusions

- SND@LHC has been successfully taking data since the start of LHC Run 3
  - Less than two years between the letter of intent and first physics data!
  - **First physics result** in July 2023: **observation of muon neutrinos CC interactions** with high statistical significance
- Combination of **emulsion technology** and **electronic detectors**
  - High spatial resolution (vertex location)
  - Good time resolution (ToF studies)
  - Measurement of neutrino energy spectrum

- **Test beams** and **laboratory measurements** performed in parallel with Run 3 data-taking to asses the performance of sub-detectors and improve operation conditions
- **SciFi tracker case**: studies of time resolution and signal amplitude measurement
  - Identified directions of improvement: higher SiPMs' OV and lower time thresholds (to be validated with data)
  - Successful development of techniques to analyse the detector response at variable signal amplitudes → useful for simulation improvement

Backup

Data Taken in Run 3



Run 3

Delivered:

70.51 fb^{-1}

Recorded
(by electronic detectors):

68.55 fb^{-1} (97%)

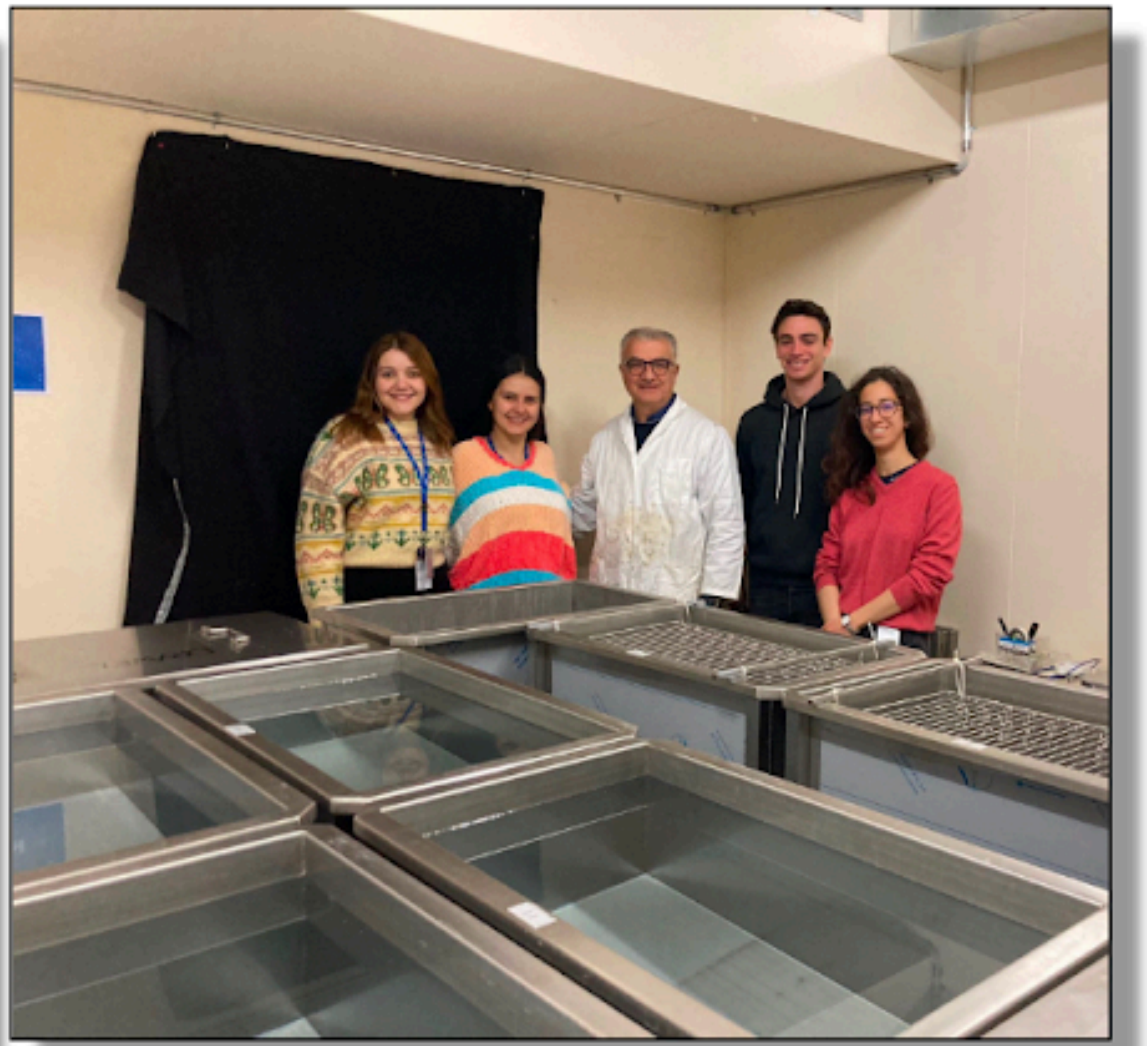
Emulsion Replacement

- Emulsions need to be replaced every ~ 20 fb^{-1} to keep occupancy at acceptable level for analysis
- Wall replacements take place during technical stops or even during a short access if necessary
  - Procedure takes only 4 to 5 hours to complete

Transport

Target replacement

SciFi installation



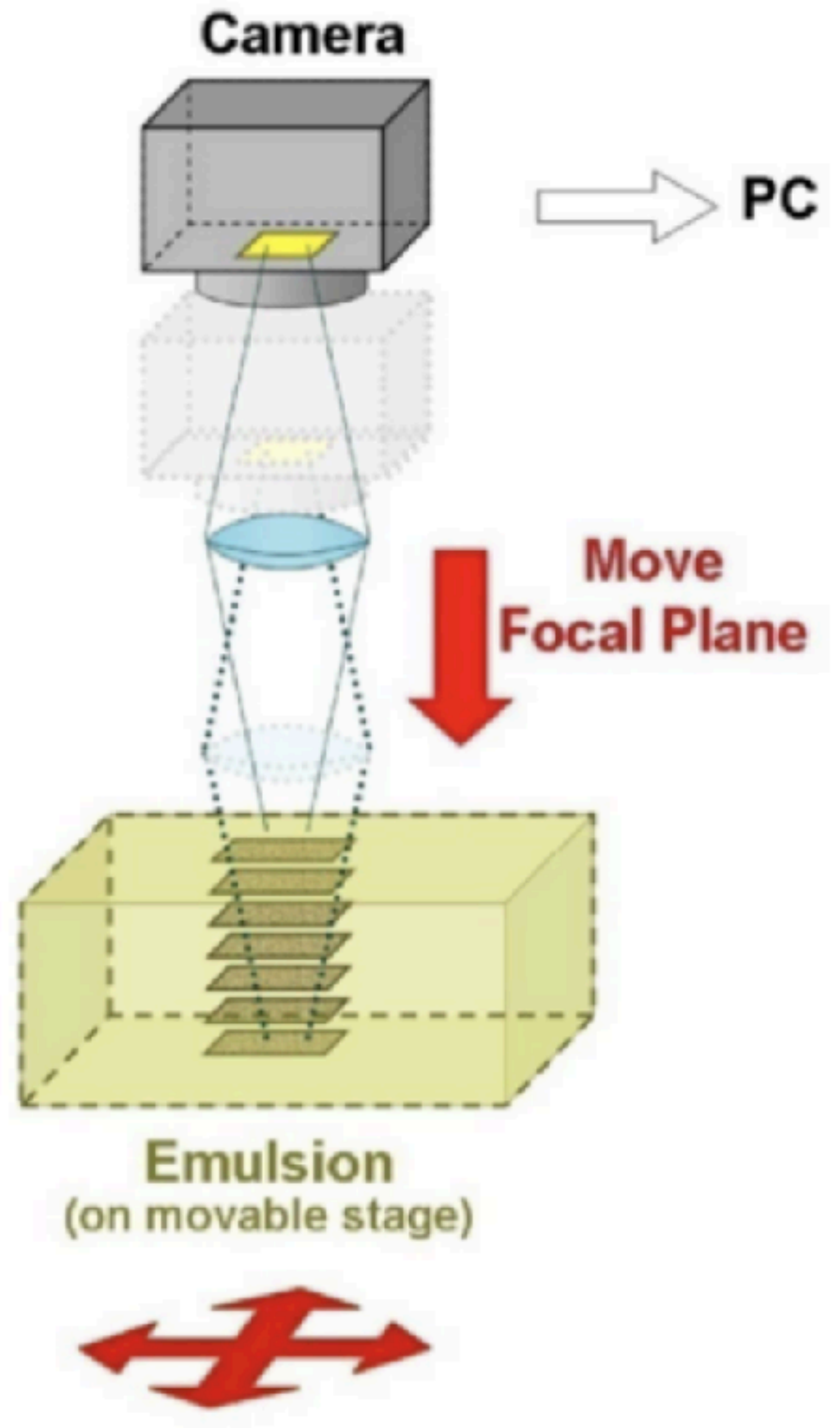
Development

Emulsion Scanning

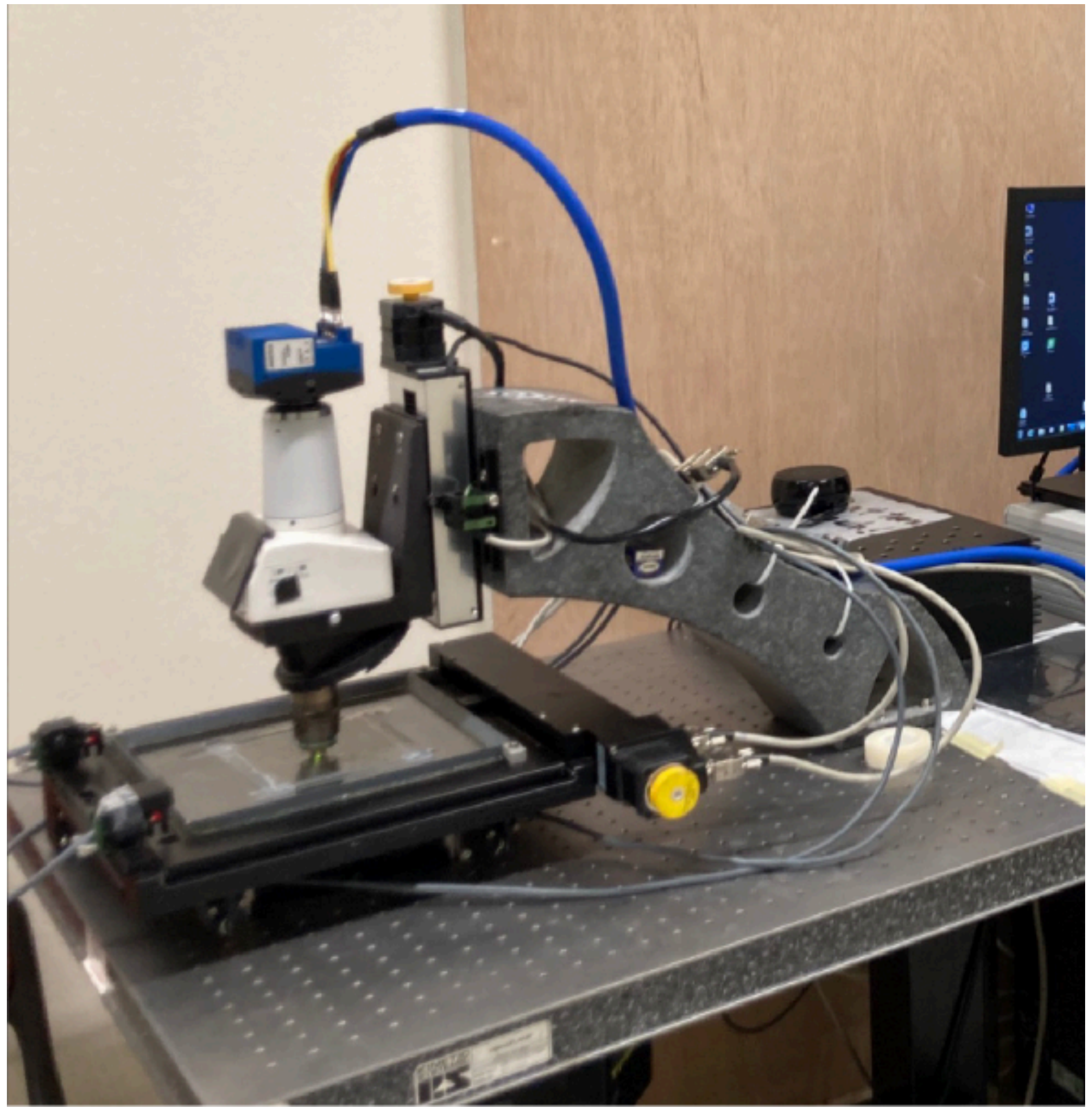
- **Five** emulsion **scanning stations**

  @ CERN, Bologna, Lebedev, Napoli, Zurich

- Each microscope currently scans one emulsion film per day
- Prohibitive to store raw microscope images in disk
  - Scanning **bottleneck: image processing**
- Speed up foreseen
  - More microscopes coming online
  - Distributed data processing

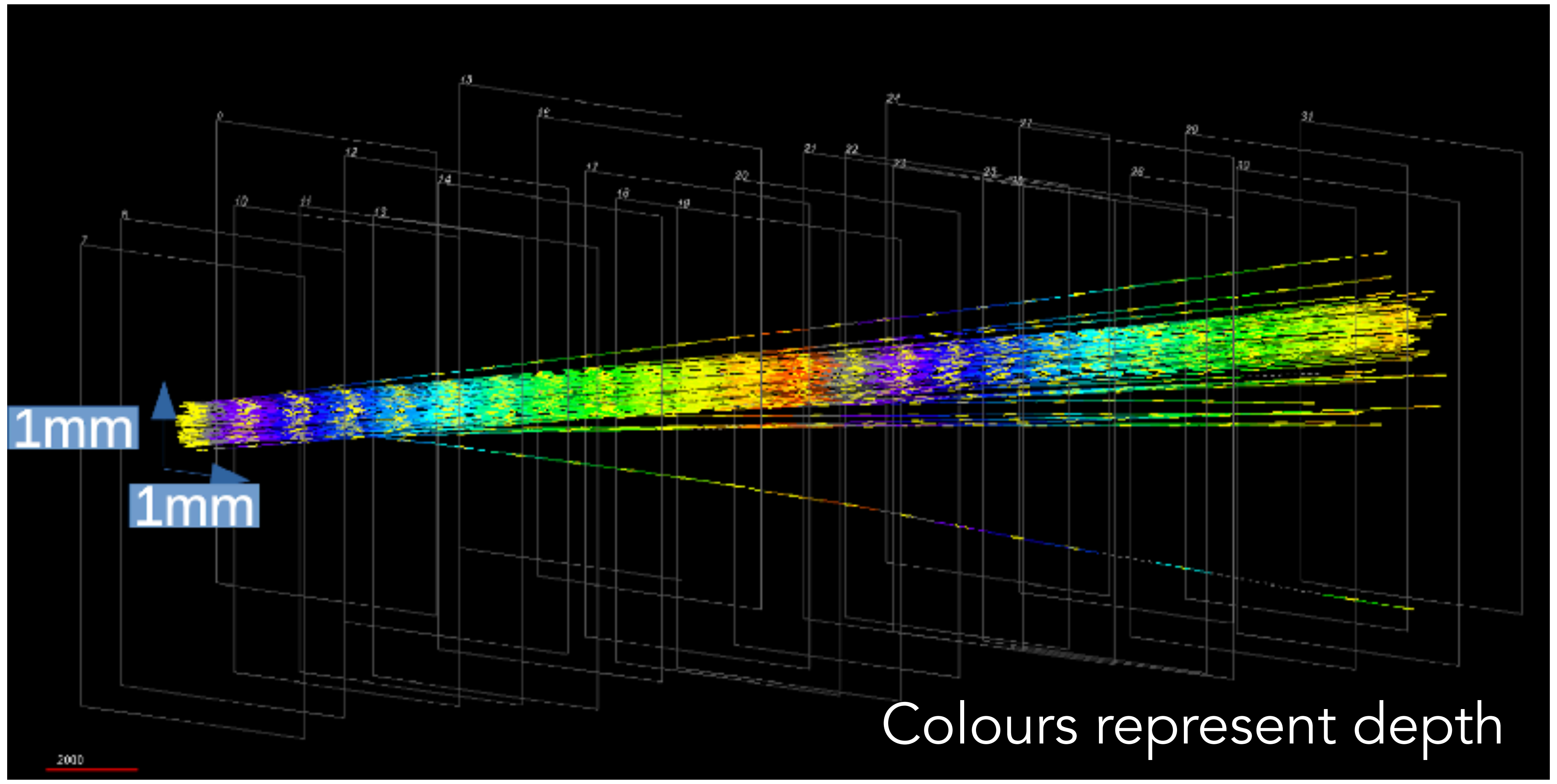


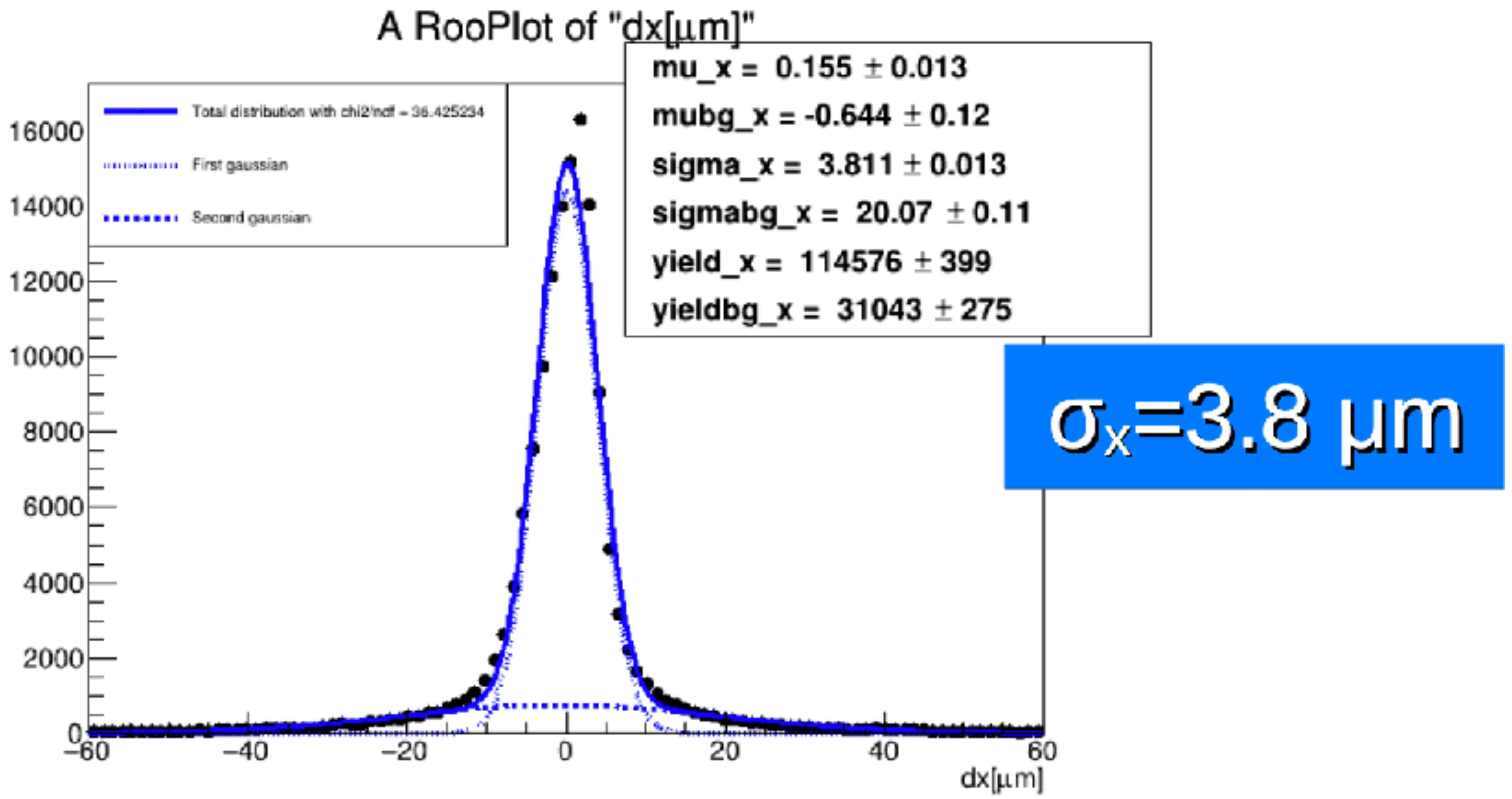
Scanning microscope at CERN

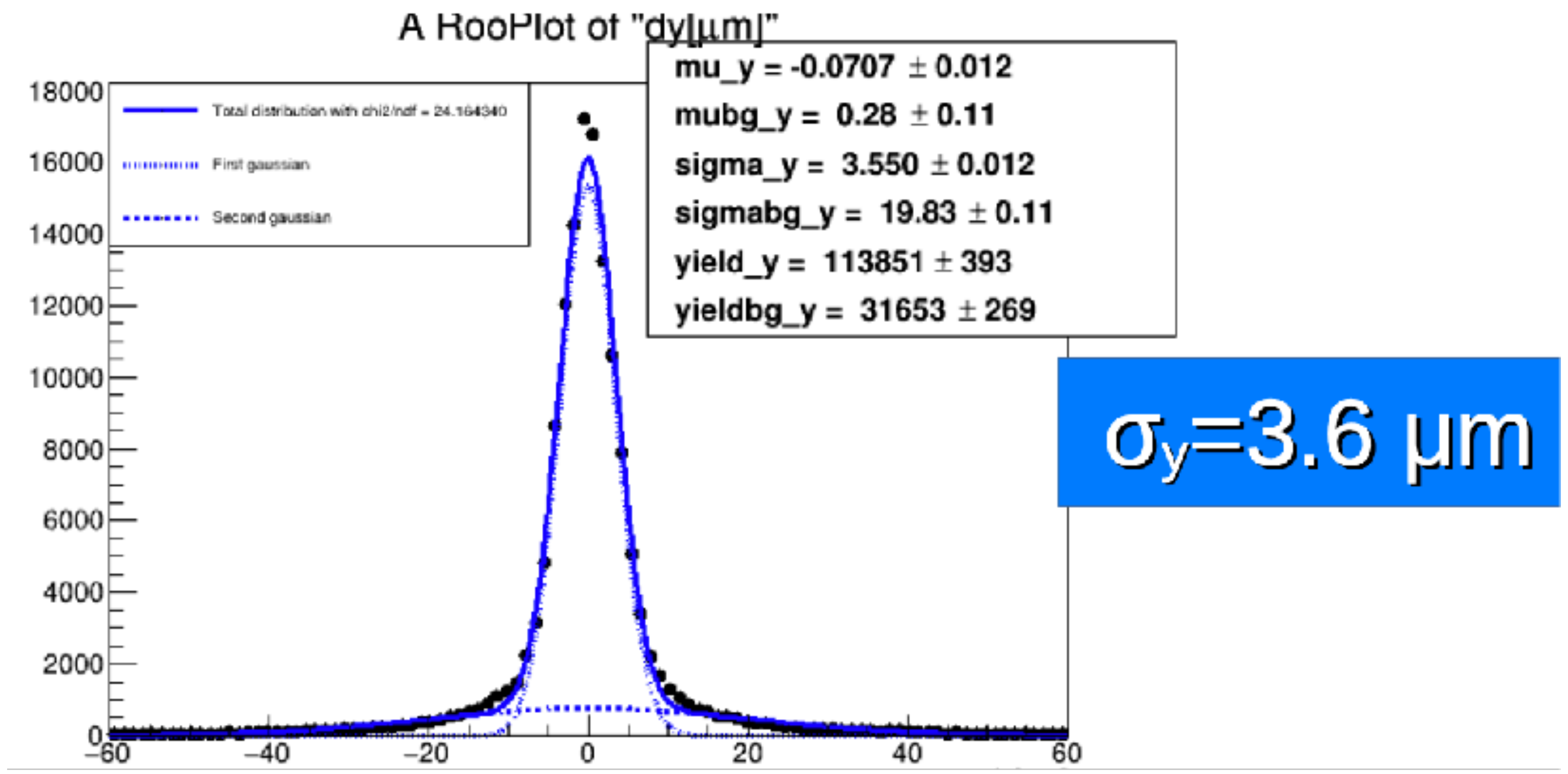


Emulsion Detector Performance

- A small portion of the target was instrumented at the start of the LHC Run 3
- Exposed for 0.52 fb^{-1}
  - Data consists mostly of muon tracks originating from IP1
- Analysed to measure the muon flux with relatively low occupancy



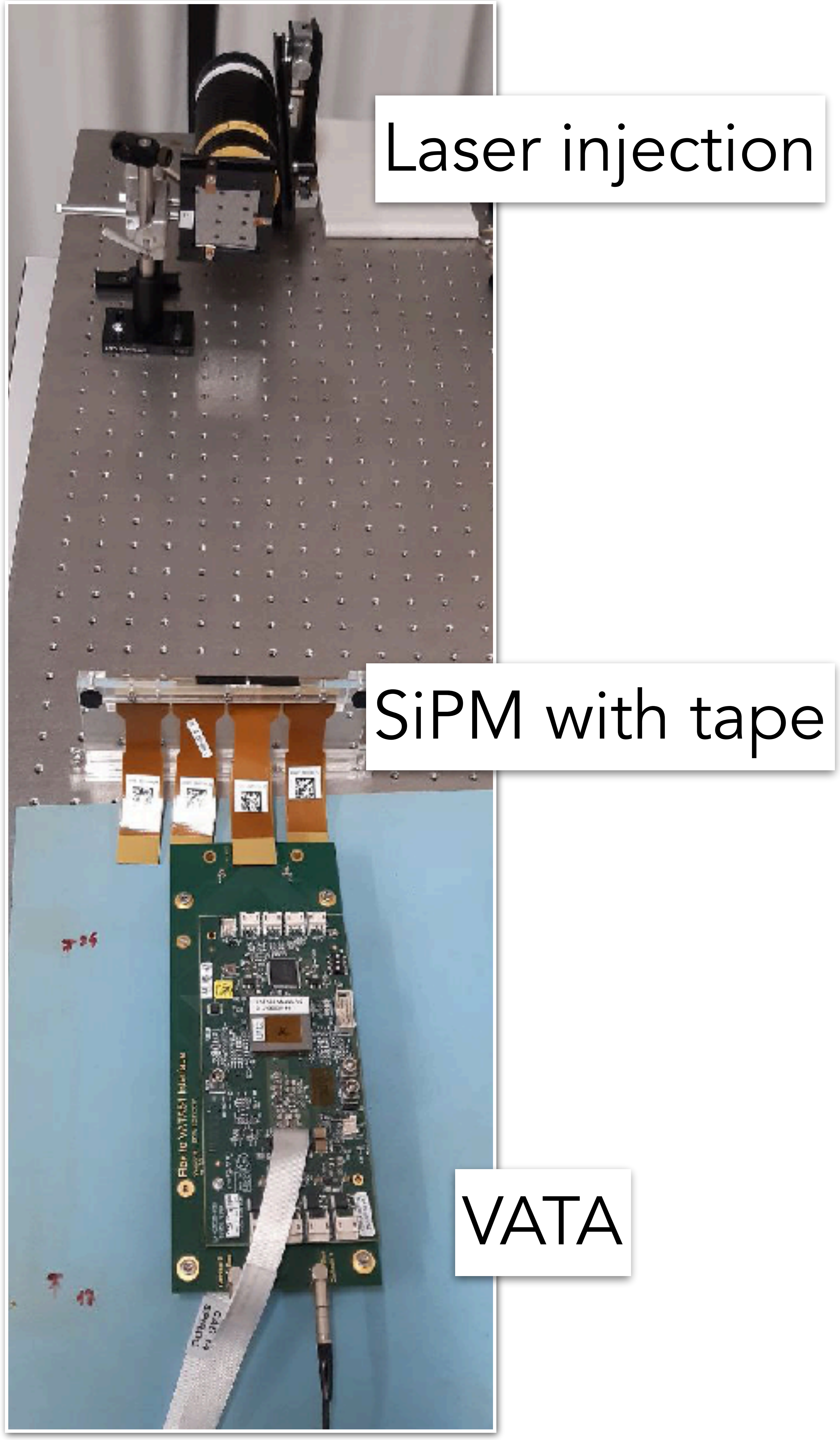




Laser Calibration

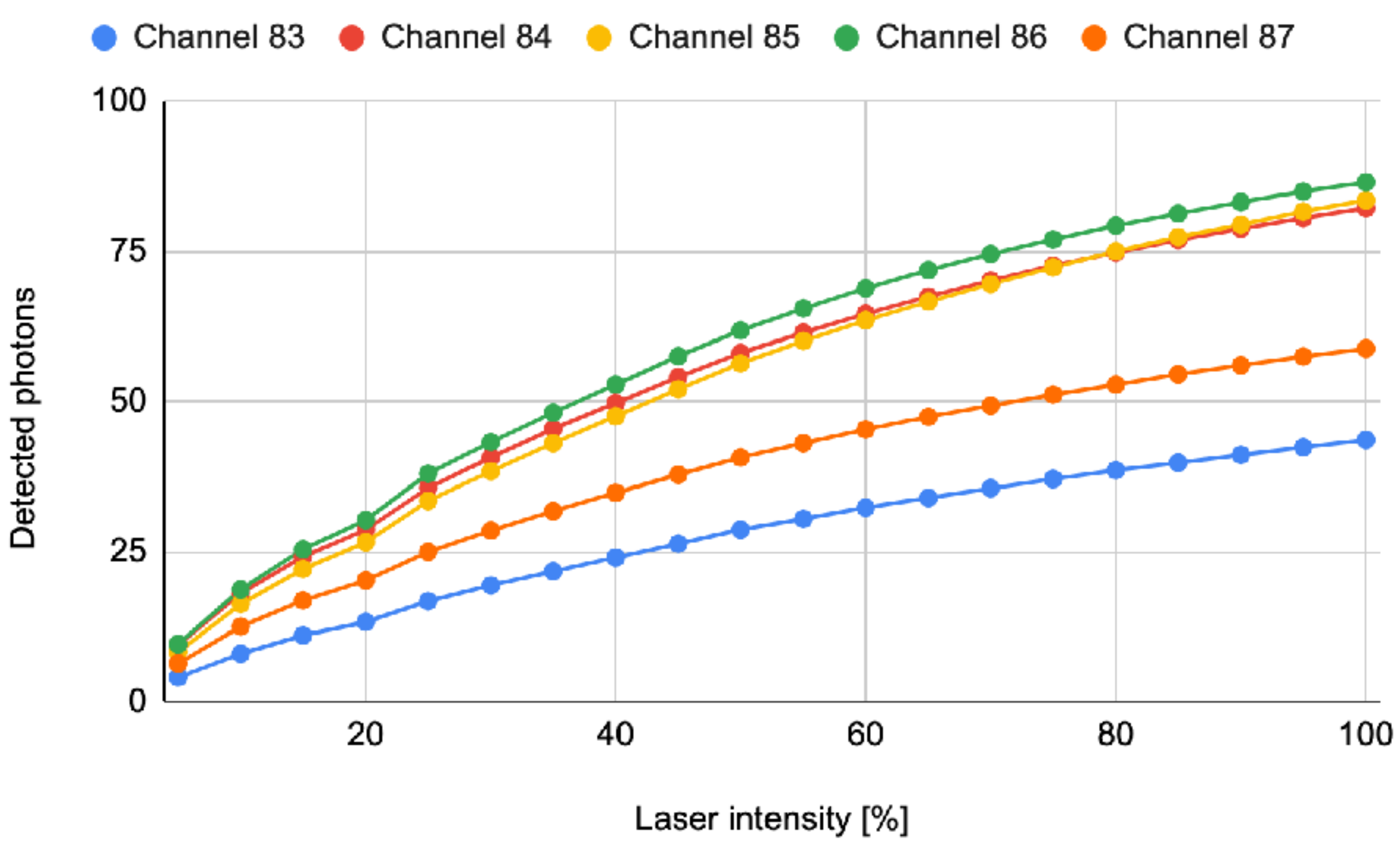
Goal: measure the laser intensity as a function of detected (or incident) photons into the SiPM

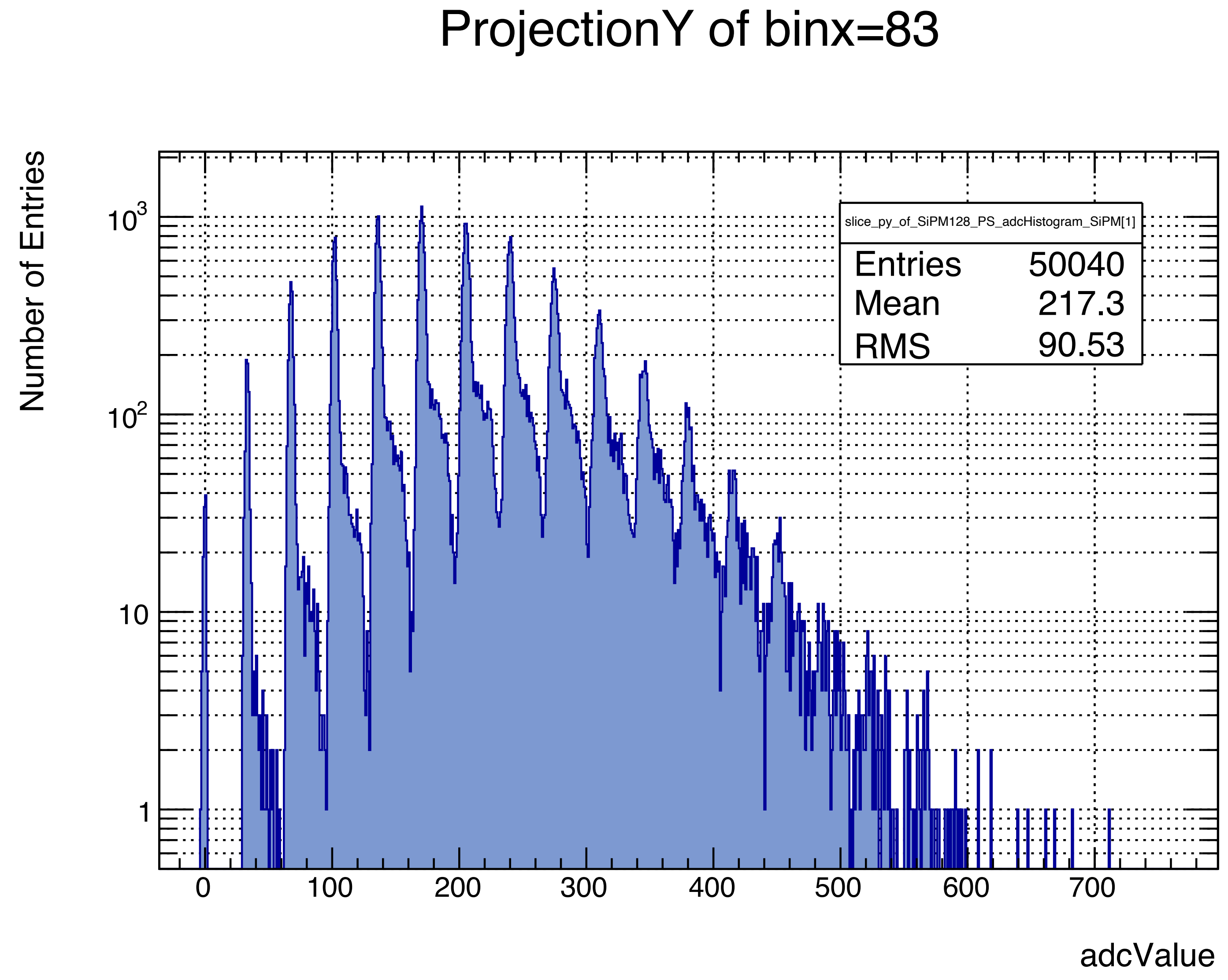
- SiPM connected to VATA system → High energy resolution which allows to distinguish single-photon peaks
- Pulsed regular laser injection with variable intensity
- Only a few (5) SiPM channels fired
- Data taken at different laser intensities, corresponding to different numbers of PhotoElectrons (PE) on each channel



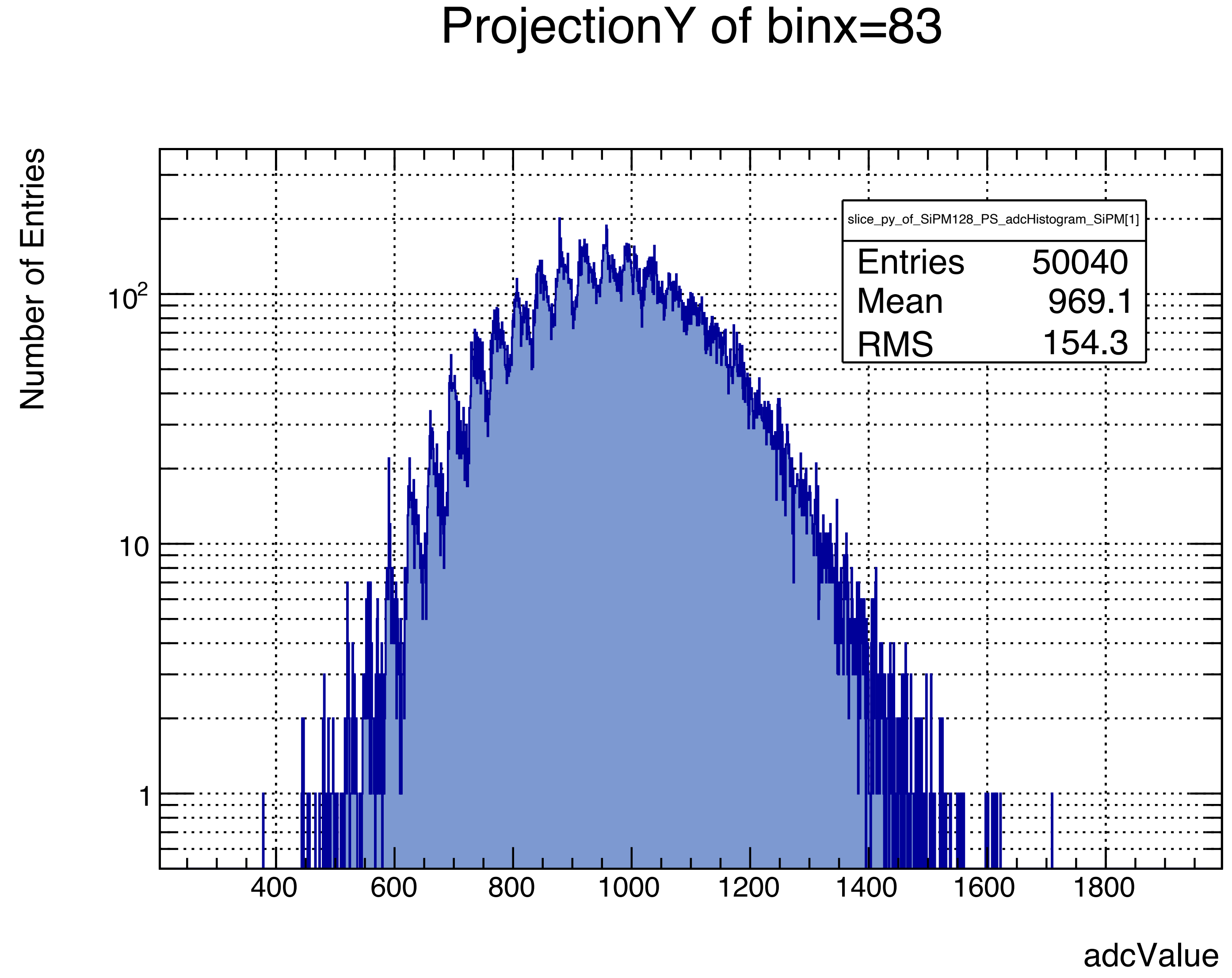
Detected Photons VS Laser Intensity

Number of **detected** photons as a function of laser intensity for 5 fired SiPM channels





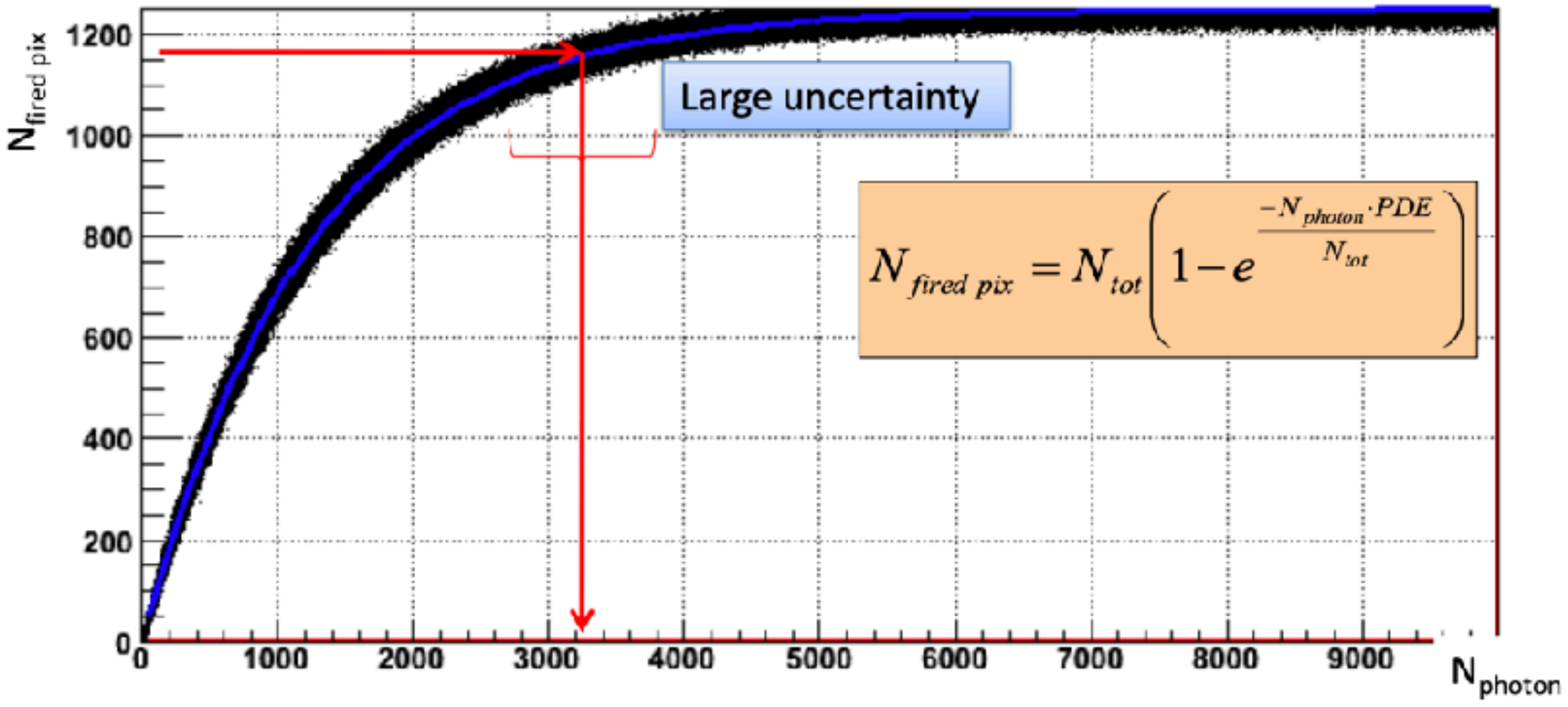
Laser Int. 15%



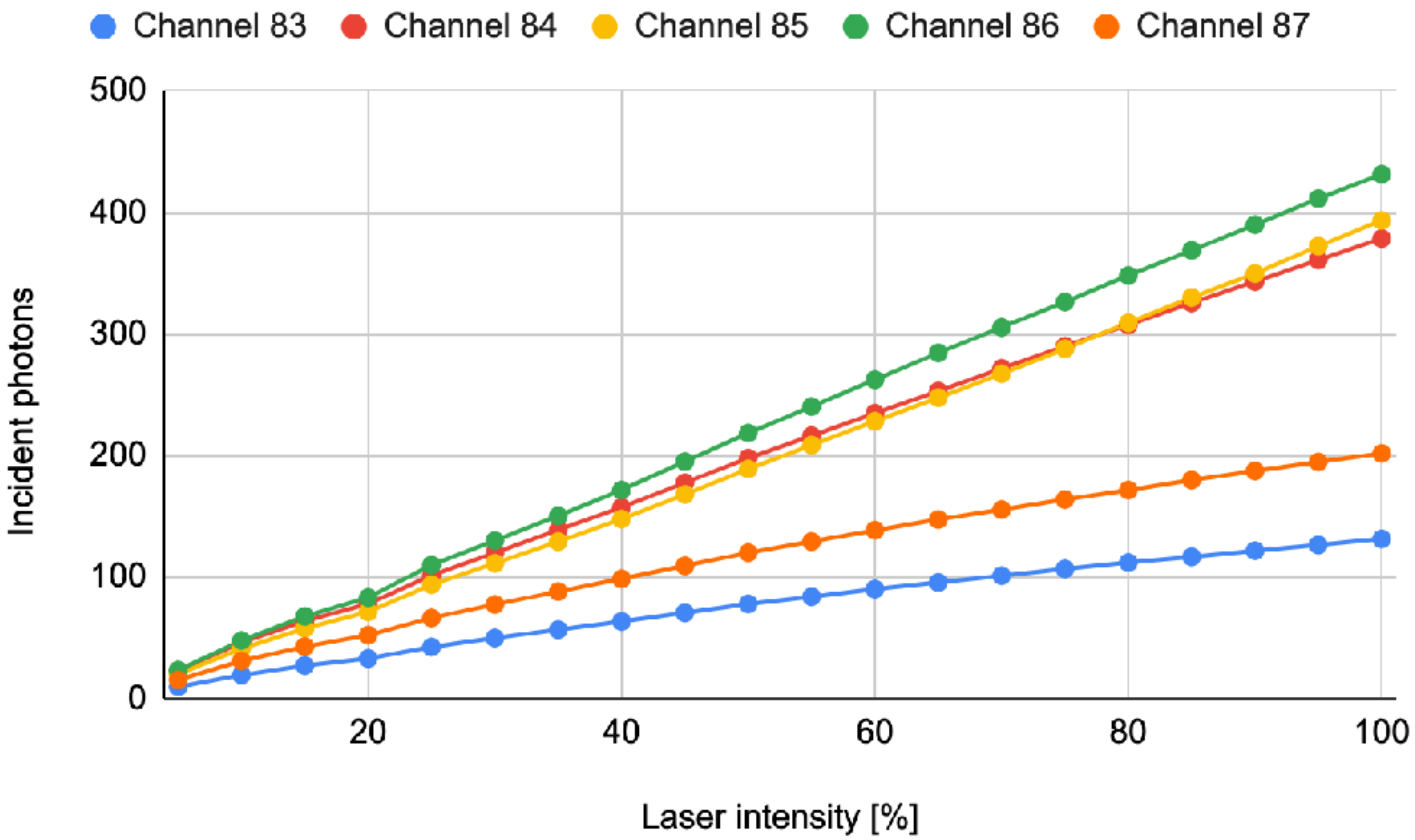
Laser Int. 85%

- VATA gain: 34.2 ADC counts per photon peak
- Number of detected photons obtained from mean VATA value as: $N_{DP} = Mean_{vata}/Gain$

Incident Photons VS Laser Intensity



Number of **incident** photons as a function of the laser intensity for the 5 fired SiPM channels



- Known relation between Number of detected photons (fired pixels) and number of incident photons
- Inverting the above relation:

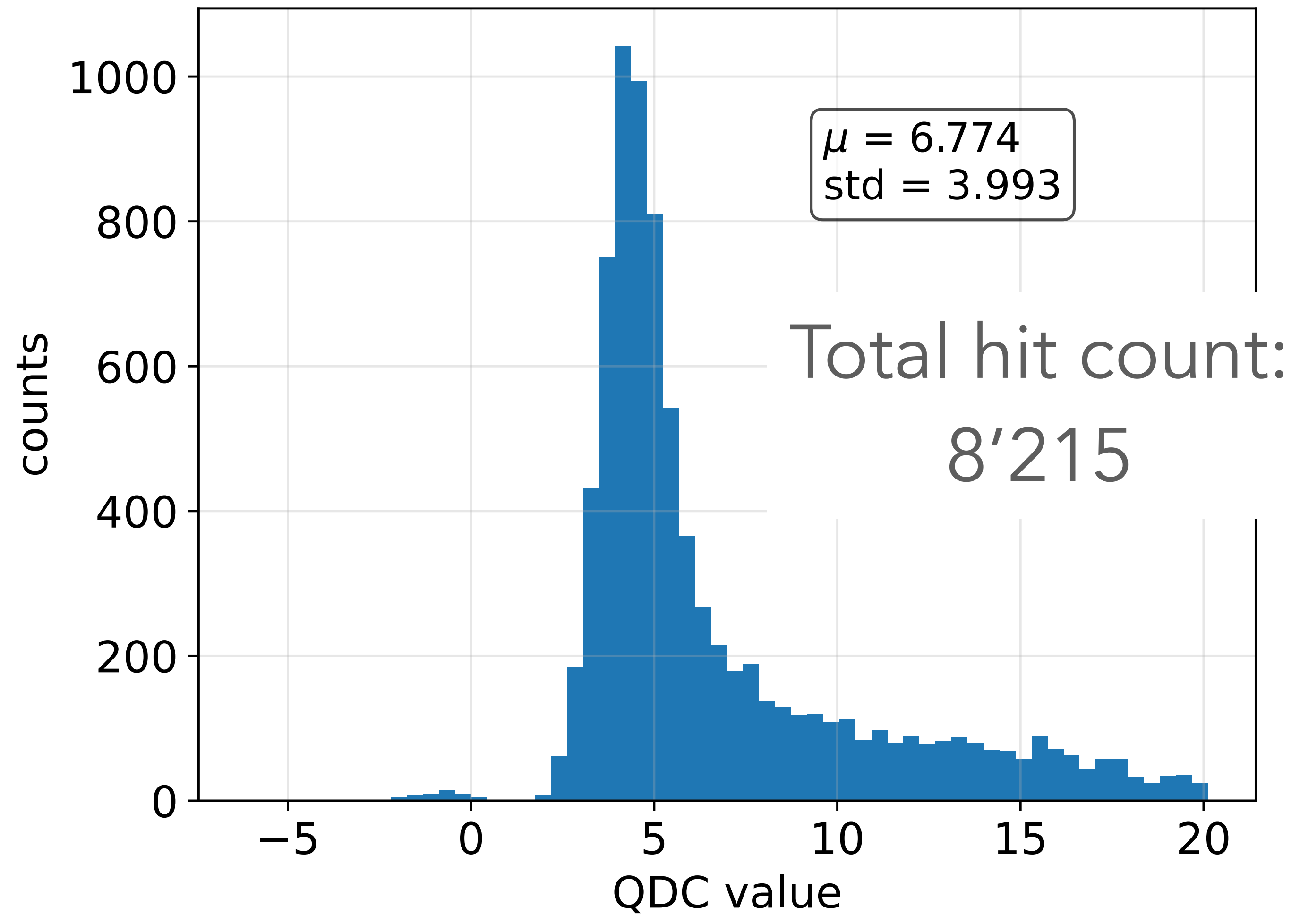
$$N_{\text{photons}} = -\frac{N_{\text{tot}}}{\text{PDE}} \ln\left(1 - \frac{N_{\text{fired pixels}}}{N_{\text{tot}}}\right)$$

$N_{\text{tot}} = 104$ number of pixels in a SiPM channel

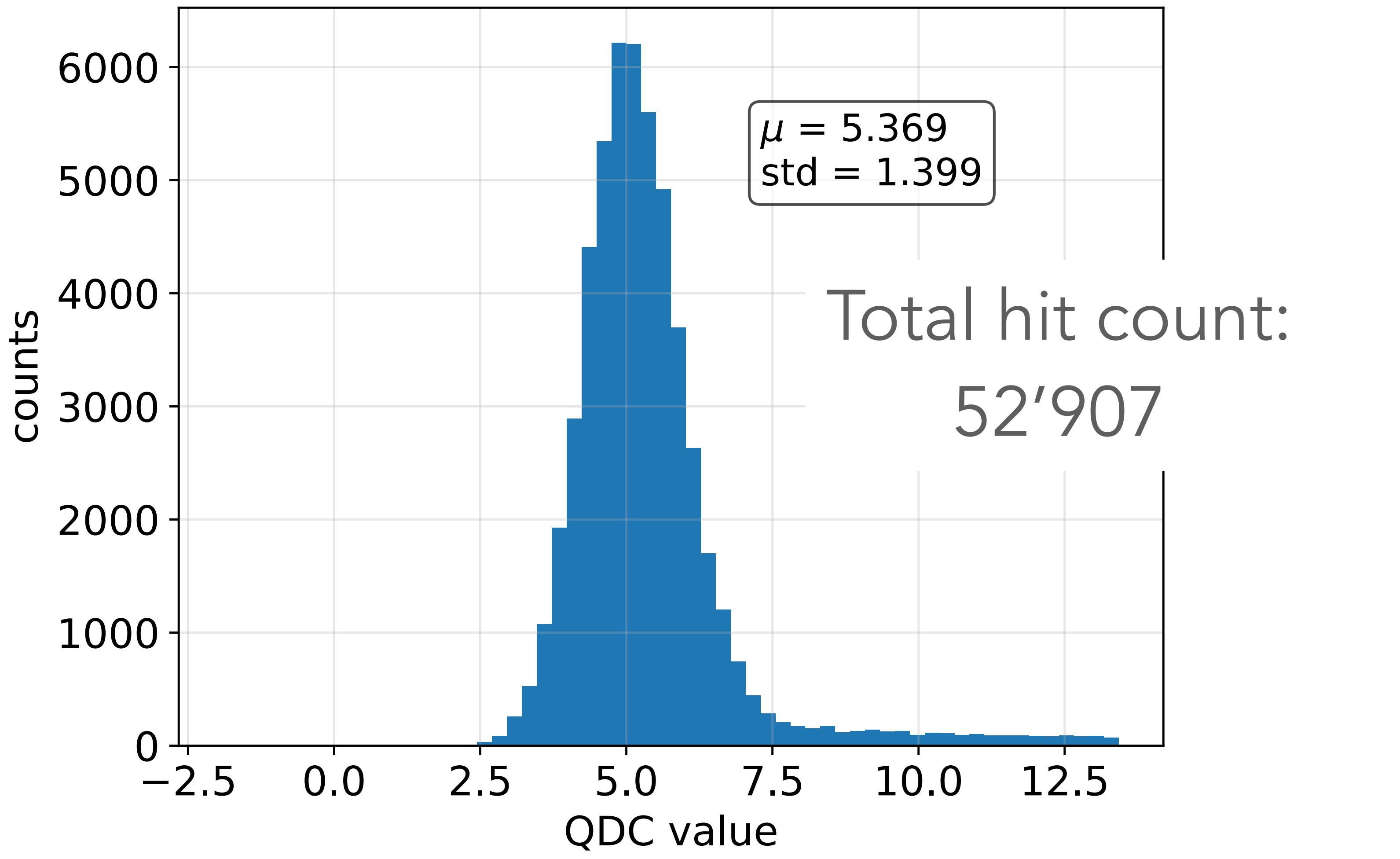
$\text{PDE} = 43\ \%$

Issues at Low Intensity in FDCR Mode (I)

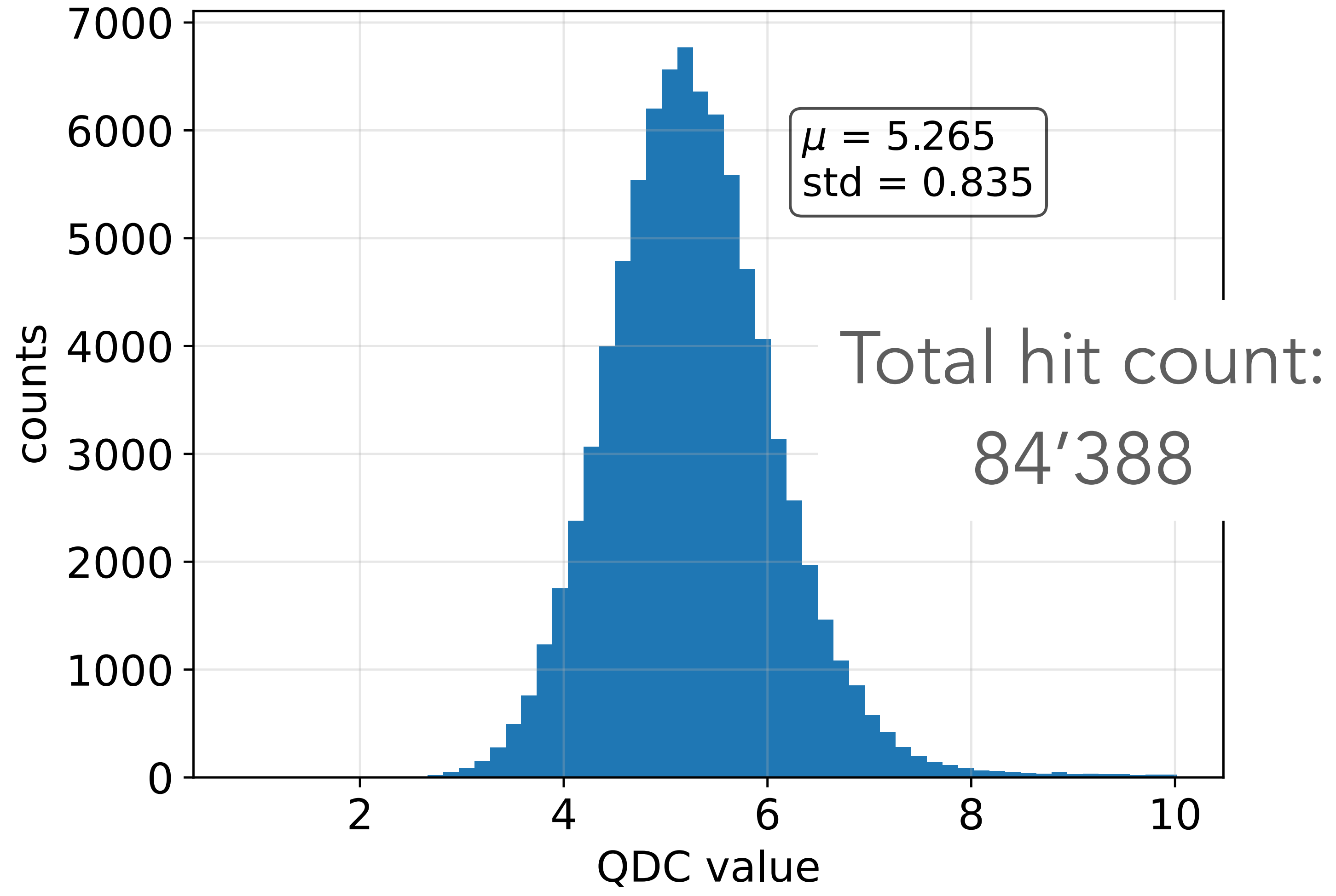
Laser Int. = 5%. Detected photons ~ 4



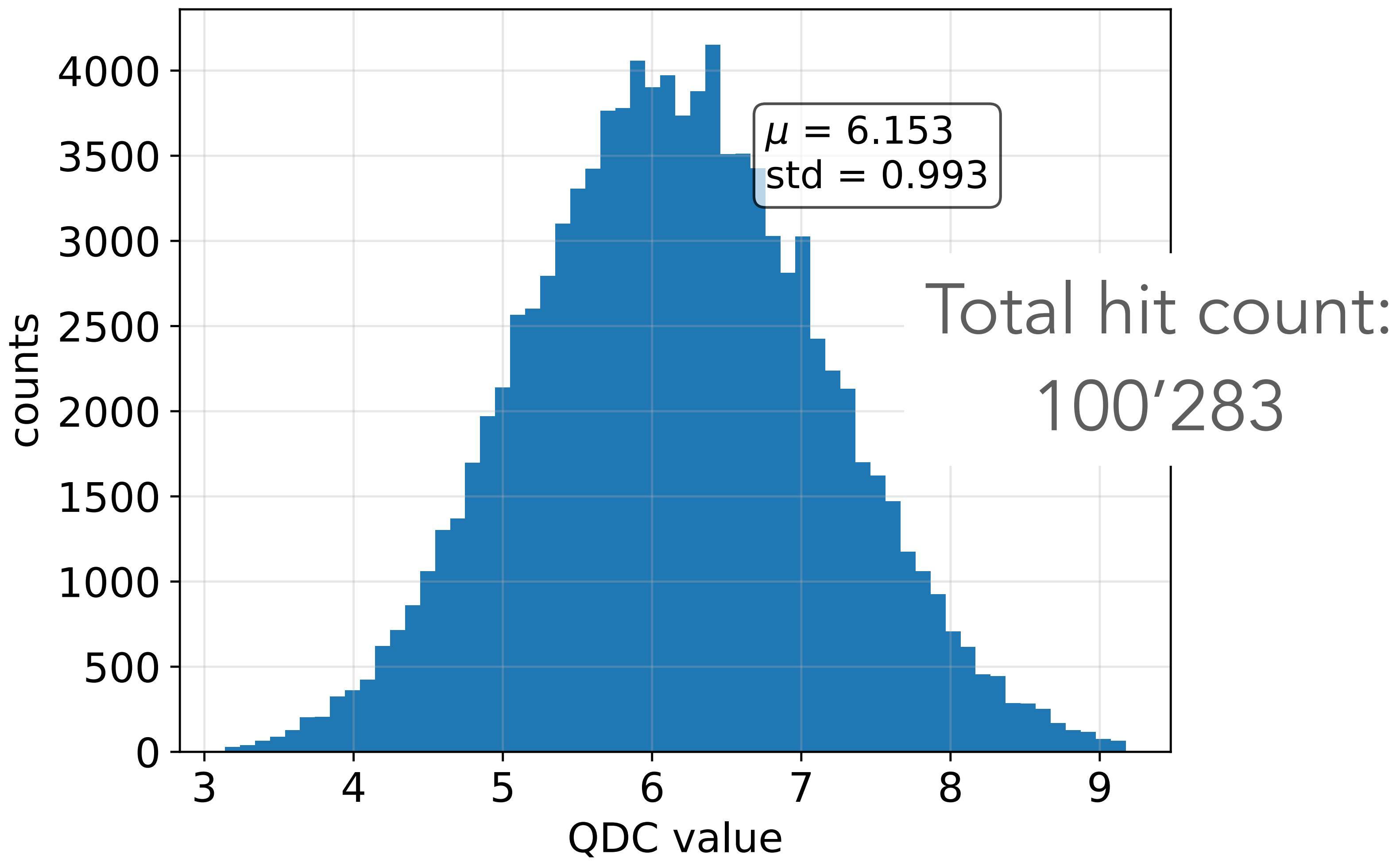
Laser Int. = 10%. Detected photons ~ 8



Laser Int. = 15%. Detected photons ~ 11



Laser Int. = 30%. Detected photons ~ 19



QDC distributions at different laser intensity in the same SiPM channel.

Noise rejection: $N_{hits} > 1$ per event

Total expected counts

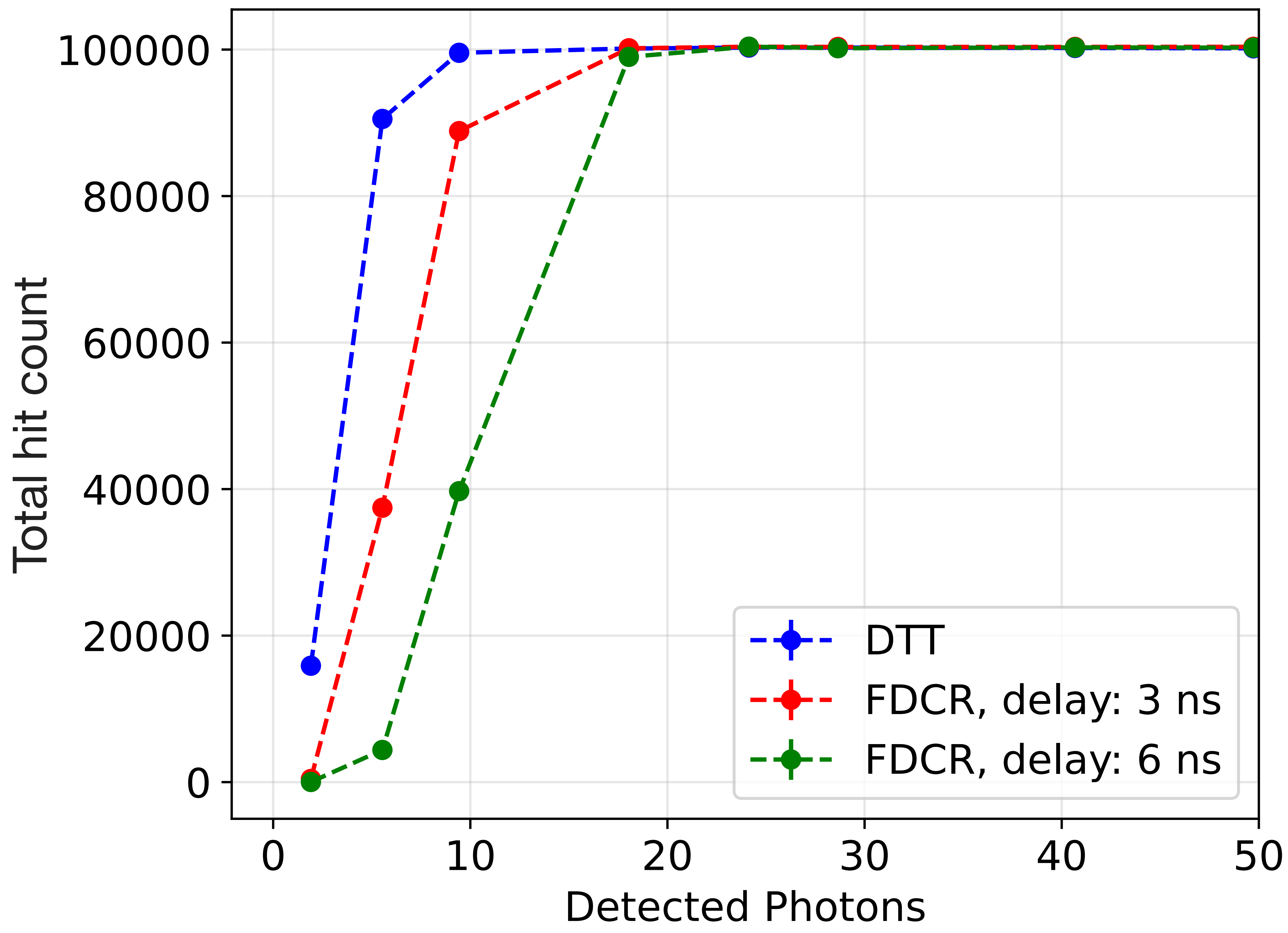
- 100 seconds of acquisition
- laser frequency at 1 kHz

→ Expected ~100k hits at low T2 threshold (corresponding to ~3 photon signal)

- Too few hits recorded with possible effect on efficiency
- Long tails at high QDC values

Issues at Low Intensity in FDCR Mode (II)

- Loss in hit efficiency observed in FDCR mode and worsen by higher delay
    - Effective threshold higher than validation threshold in FDCR mode
- Long tails in QDC distribution also observed in FDCR mode only



Total hit count in single channel VS Signal amplitude (in number of detected photons) in the three different settings