

# Academic Training Lecture Programme: Forward detectors at the LHC for searches and high energy neutrinos measurements



## Lecture I: Experiments and Detectors

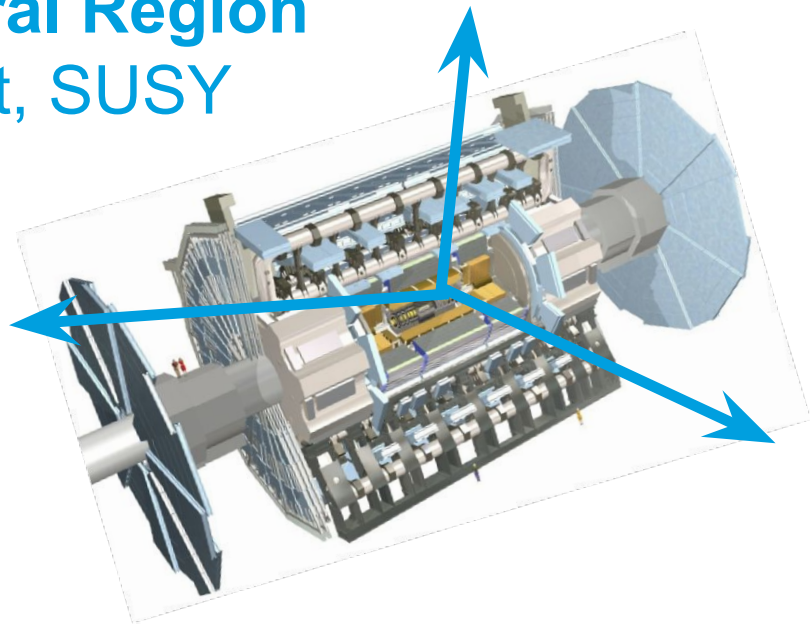
October 19th 2022  
Felix Kling



# Idea and Motivation

---

Central Region  
H, t, SUSY





# Idea and Motivation

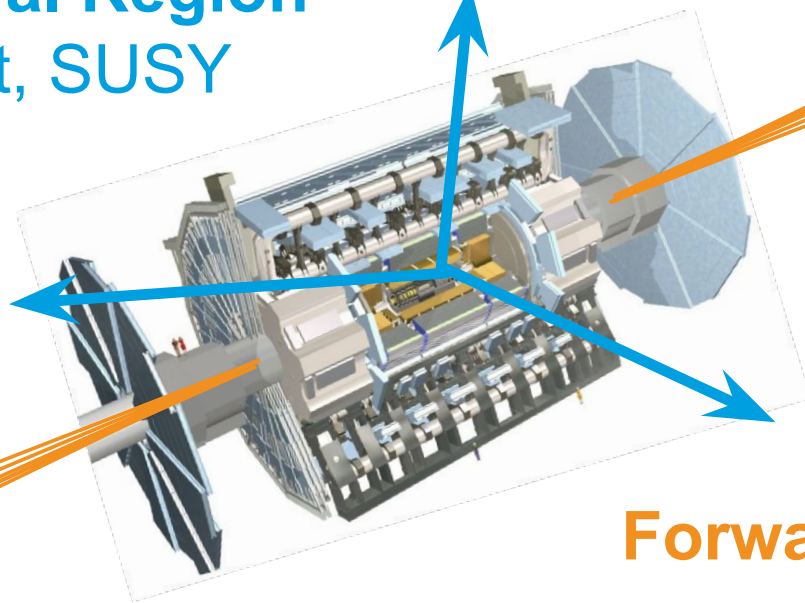
---

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

$10^{17}$   $\pi^0$ ,  $10^{16}$   $\eta$ ,  $10^{15}$  D,  $10^{13}$  B within 1 mrad of beam

**Can we do something with that?**

**Central Region**  
H, t, SUSY



**Forward Region**  
 $\pi$ , K, D

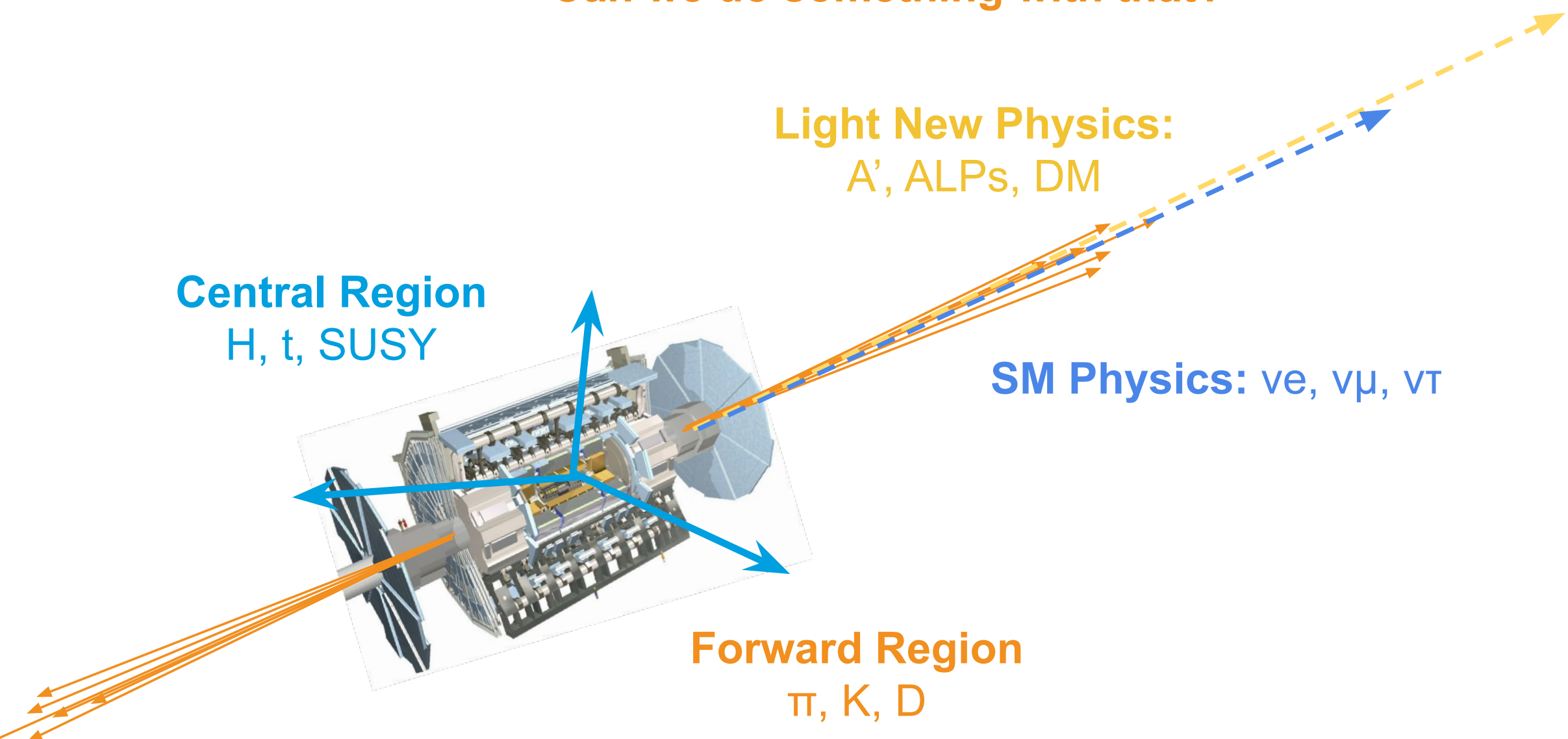
# Idea and Motivation

---

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

$10^{17}$   $\pi^0$ ,  $10^{16}$   $\eta$ ,  $10^{15}$   $D$ ,  $10^{13}$   $B$  within 1 mrad of beam

**Can we do something with that?**



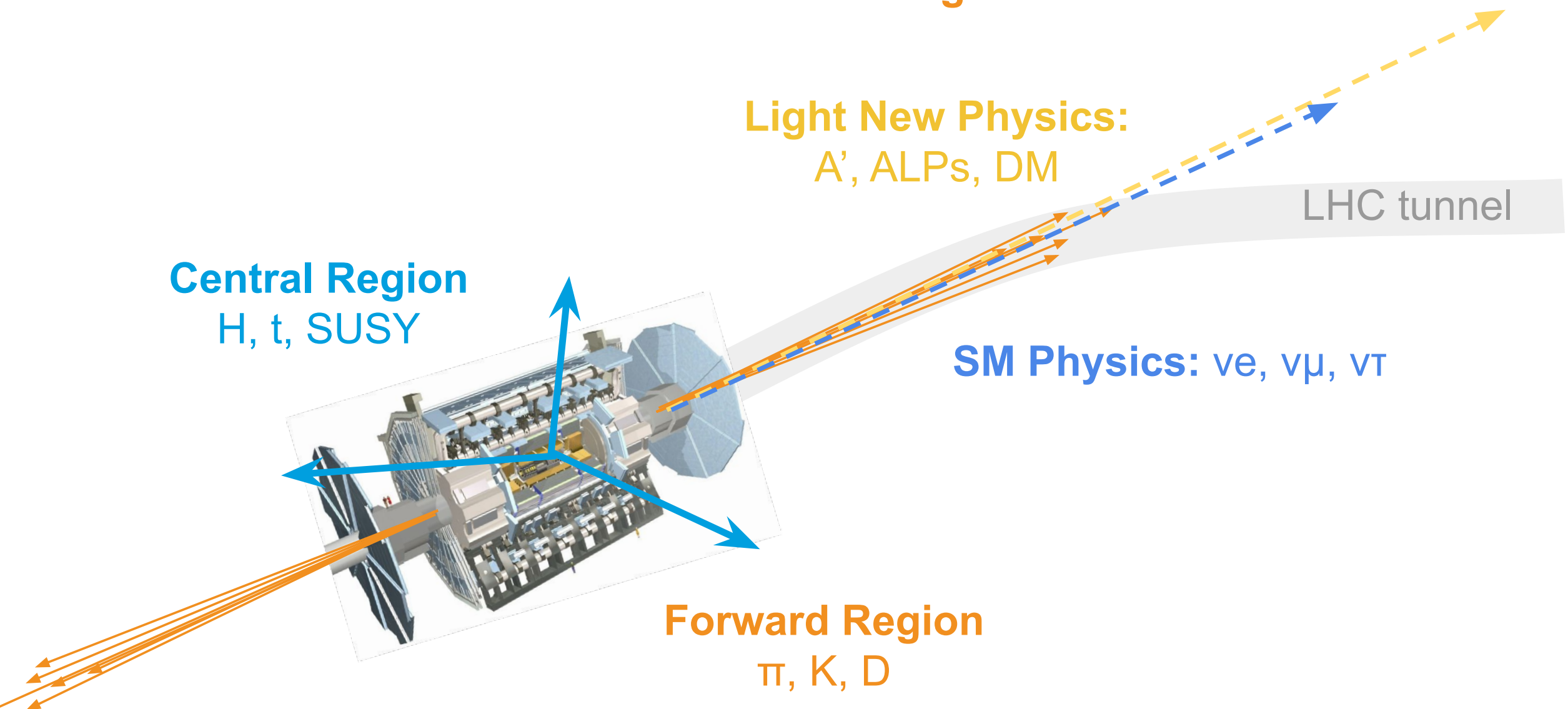


# Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

$10^{17}$   $\pi^0$ ,  $10^{16}$   $\eta$ ,  $10^{15}$   $D$ ,  $10^{13}$   $B$  within 1 mrad of beam

**Can we do something with that?**



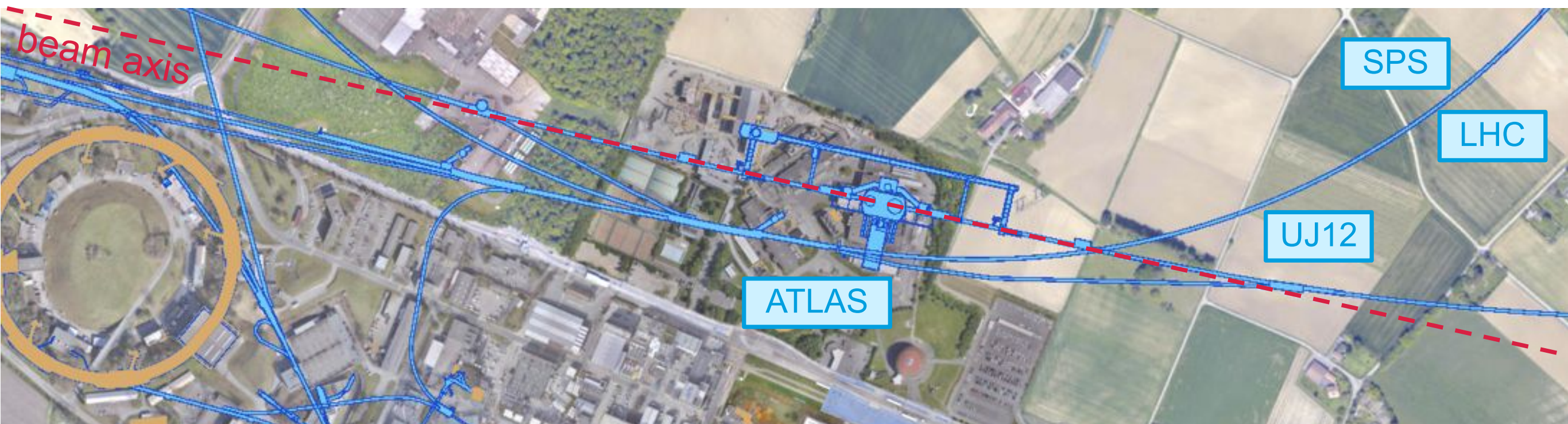




# Location

---

There is potential for forward physics experiments along beam axis.

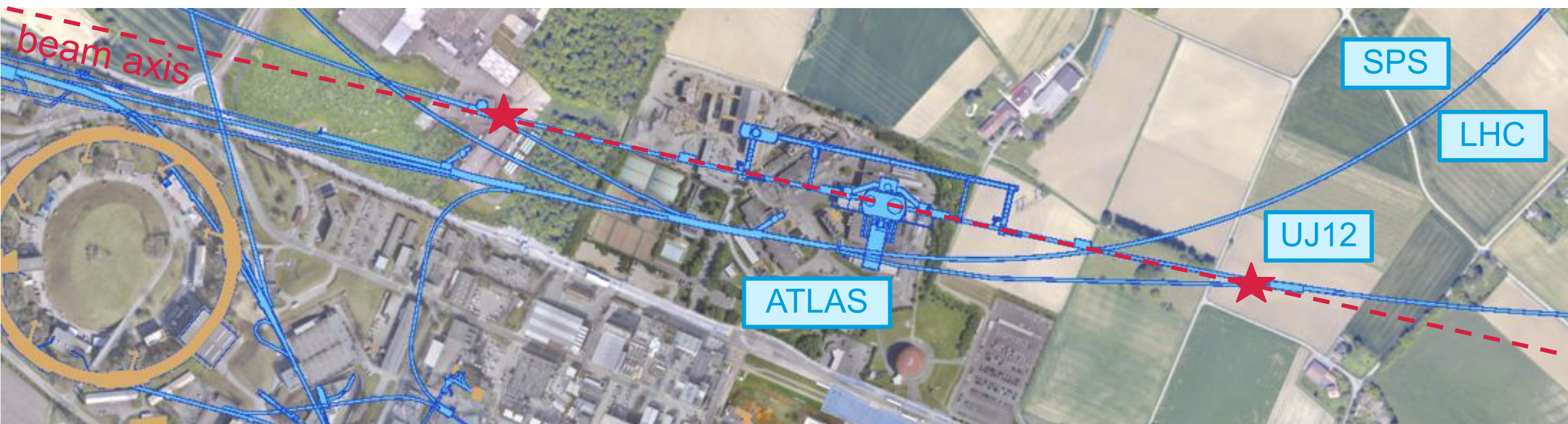




# Location

---

There is potential for forward physics experiments along beam axis.

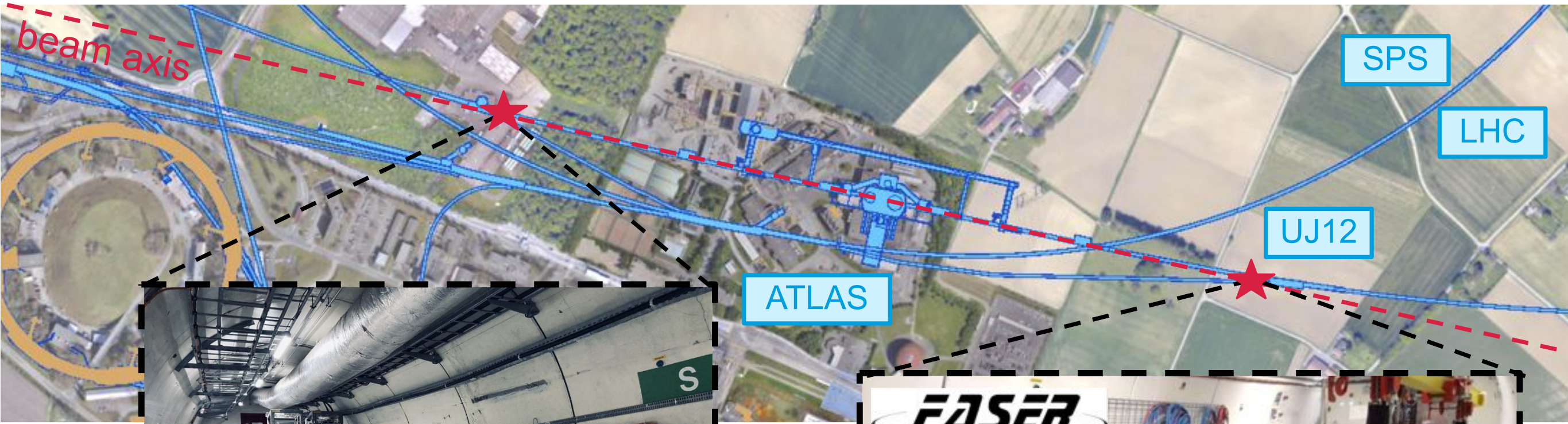




# Location

There is potential for forward physics experiments along beam axis.

Two new experiments will exploit this potential during run 3 of the LHC:  
SND@LHC and FASER.



# Outline



# Outline

---

## Lecture 1: Experiments and Detectors

FASER, FASER<sub>v</sub> — SND@LHC — Forward Physics Facility

## Lecture 2: BSM Searches

Motivation Dark Sectors — Long-Lived Particles — Other Signatures

## Lecture 3: Neutrino Measurements

Motivation — Fluxes — Interactions — Physics Potential

**Environment**

# One Slide of Physics Motivation

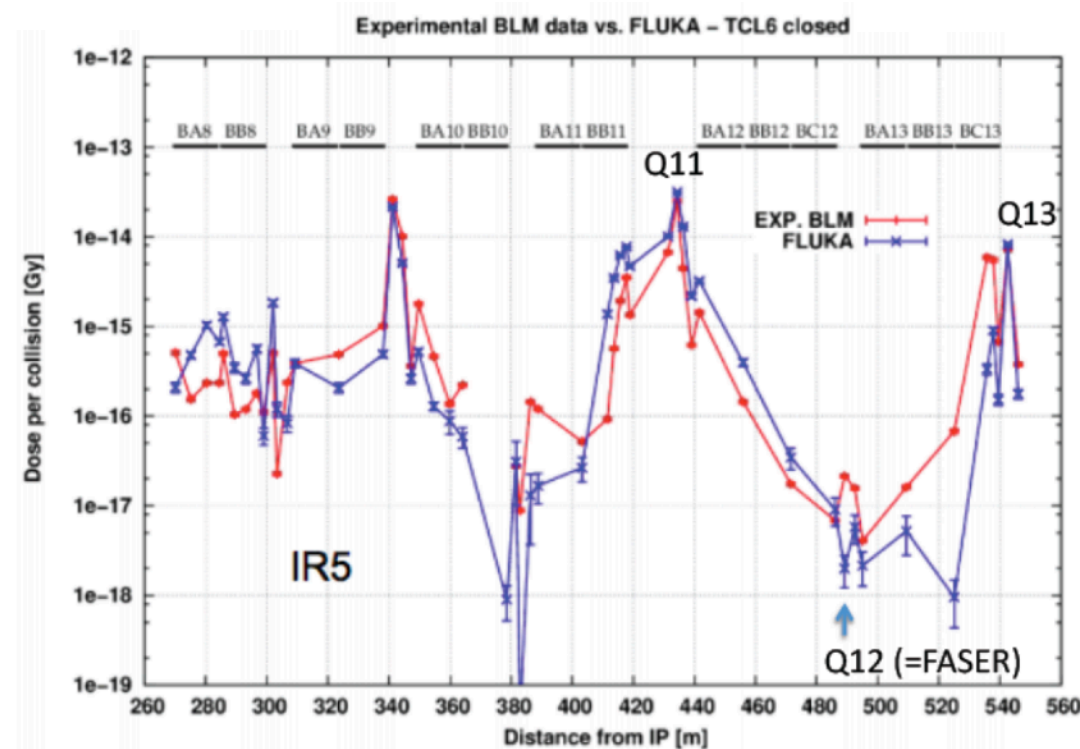
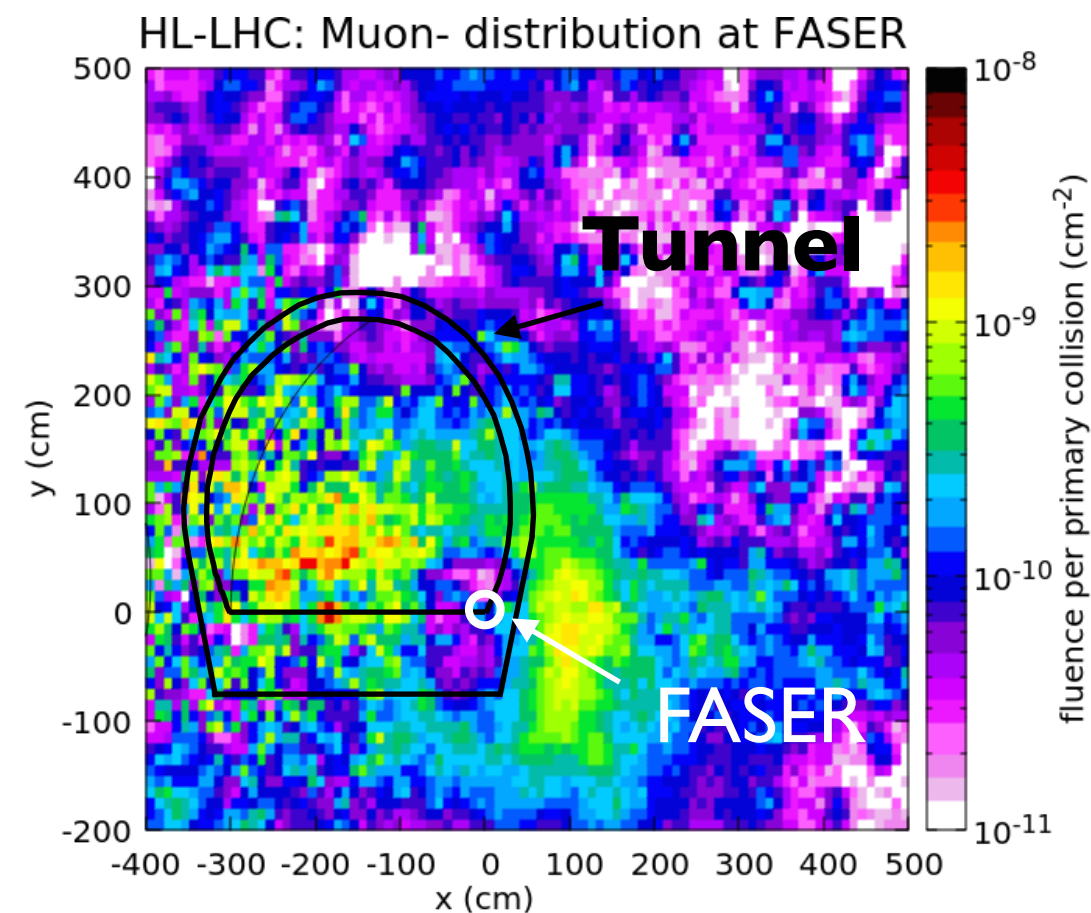
## General Considerations

- LLP/neutrino signals have TeV energies, come from ATLAS IP
- shielding: natural (rock) and LHC infrastructure (magnets, absorbers)
- only muons/neutrino can transport TeV energies through  $\sim 100\text{m}$  rock

→ T112/T118 location is pretty quiet

## FLUKA simulation (by CERN STI group)

- experiments in remarkable quiet spot
- estimated muon flux from IP:  $2 \cdot 10^4 \text{ fb/cm}^2$
- HE particles from beam-gas collisions and proton losses are small
- other HE particles produced in muon radiative processes

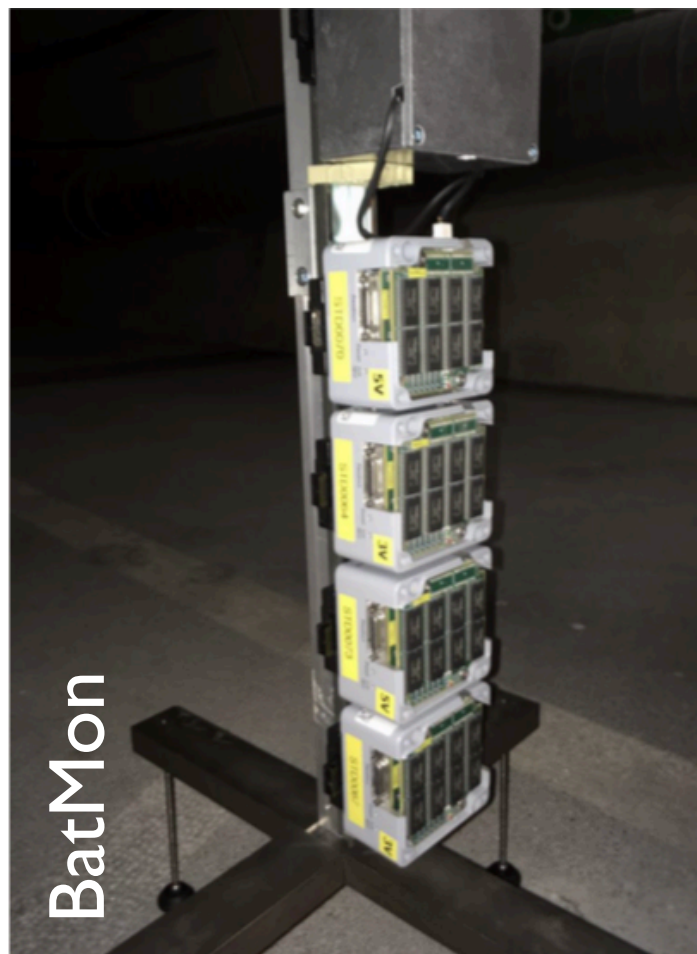




# One Slide of Physics Motivation

## In-Situ Measurements

- BatMon radiation monitor:
  - \* low-energy radiation levels are promisingly low
- emulsion detector installed in 2018 in both T118 and T112
  - \* consistent with FLUKA simulations
  - \* more data analysis on-going

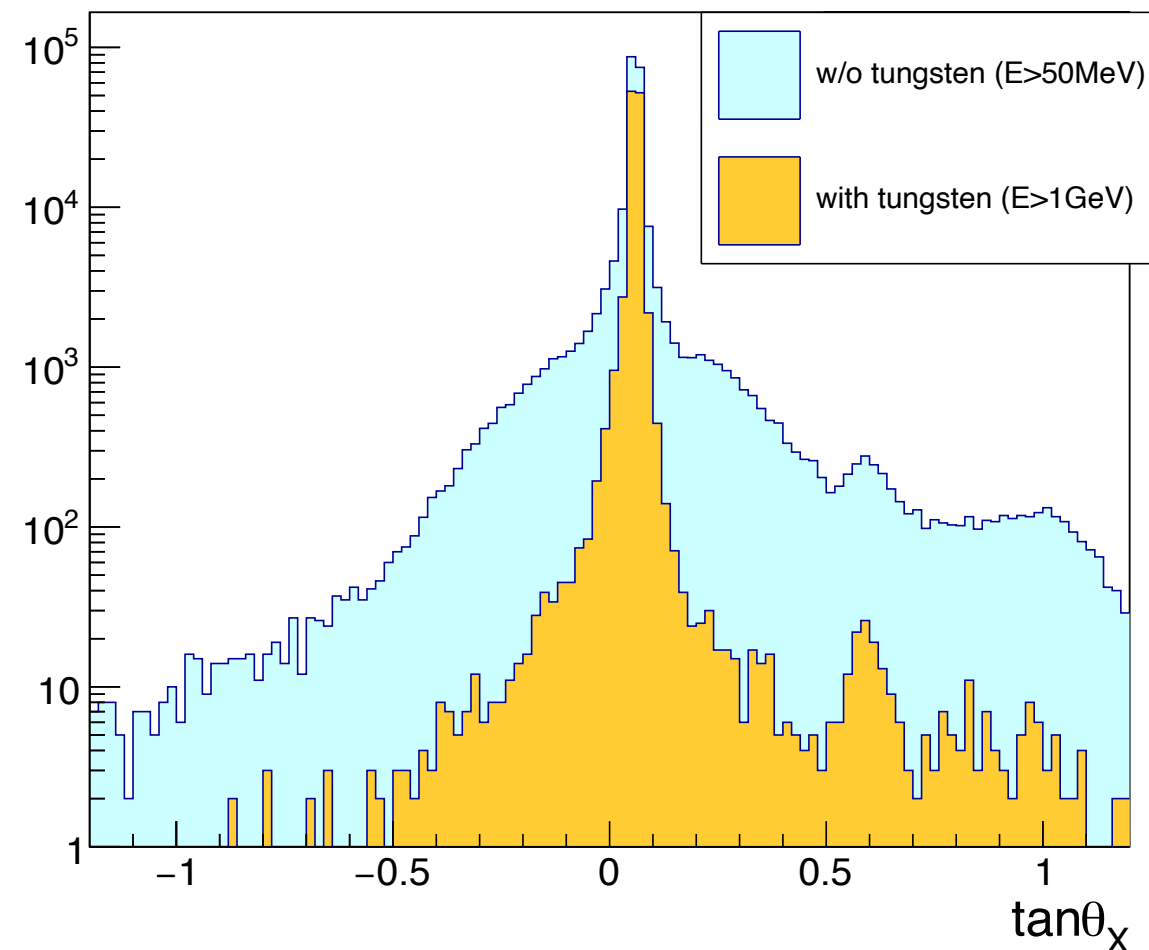


BatMon



Emulsion

FLUKA:  $2 \cdot 10^4 \text{ fb/cm}^2$   
Emulsion Detector:  $(1.2-1.9) \cdot 10^4 \text{ fb/cm}^2$



**FASER**

# One Slide of Physics Motivation

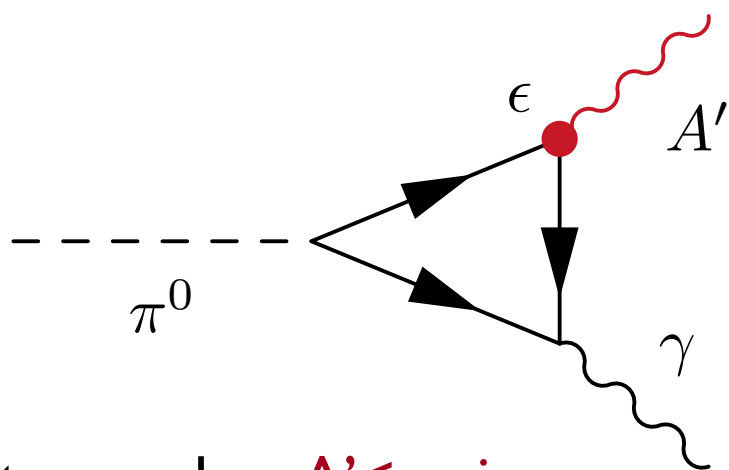
There are light long-lived particles in the SM: muon, pion, kaon, neutron ...

many BSM scenarios also include (light) long-lived particles

## Example: dark photon

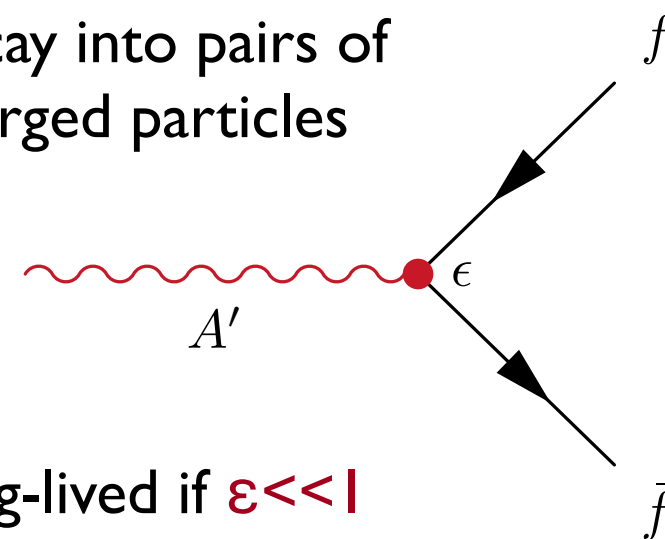
similar to the SM photon but with mass  $m_{A'}$  and couplings to SM particles suppressed by  $\epsilon$

$$\mathcal{L} = \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \sum \bar{f} (i \not{\partial} - \epsilon e q_f A') f$$



if light enough:  $m_{A'} < m_{\pi}$   
produced via meson decays

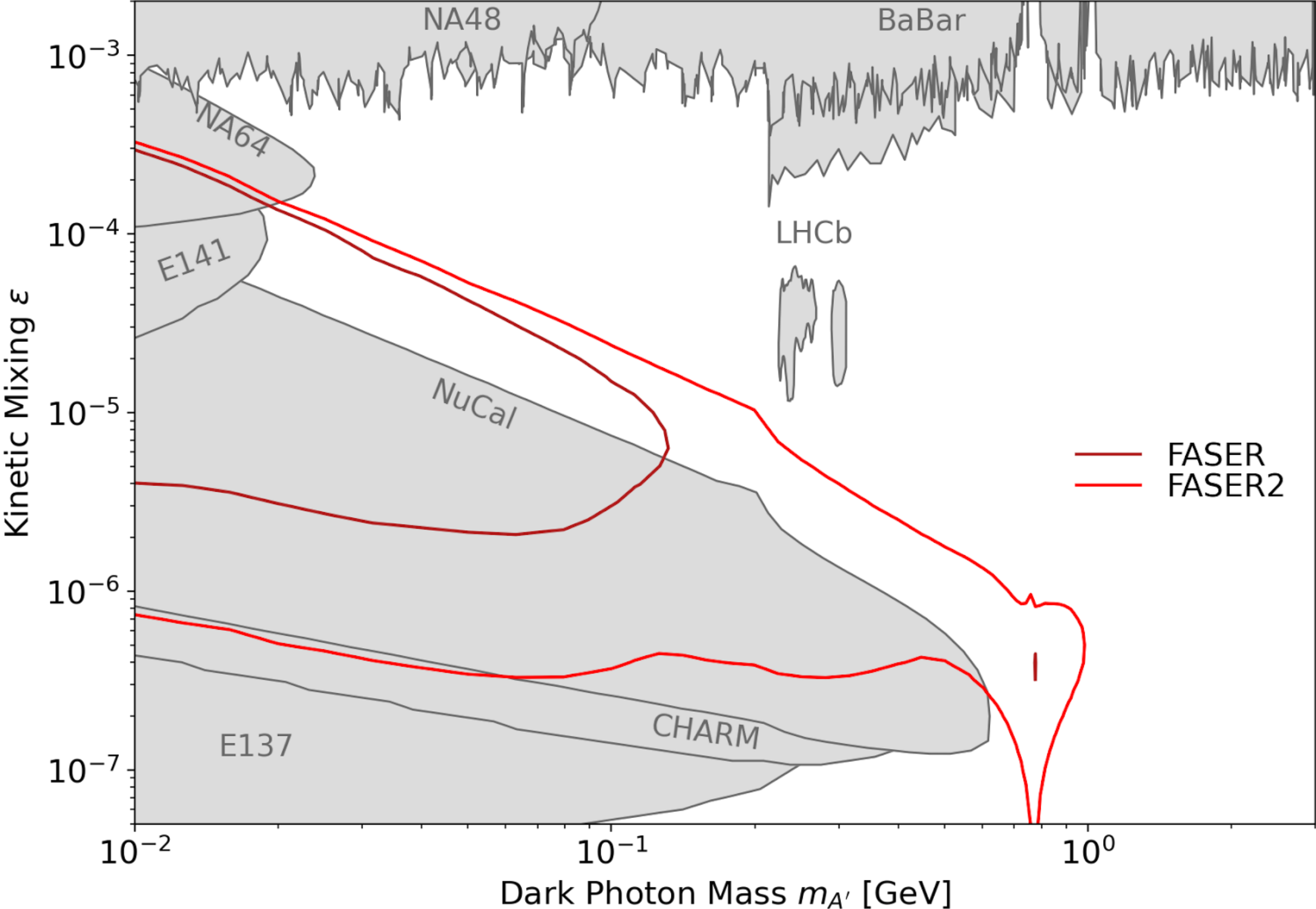
- decay into pairs of  
charged particles



- long-lived if  $\epsilon \ll 1$   
lifetime

# One Slide of Physics Motivation

## Dark Photons





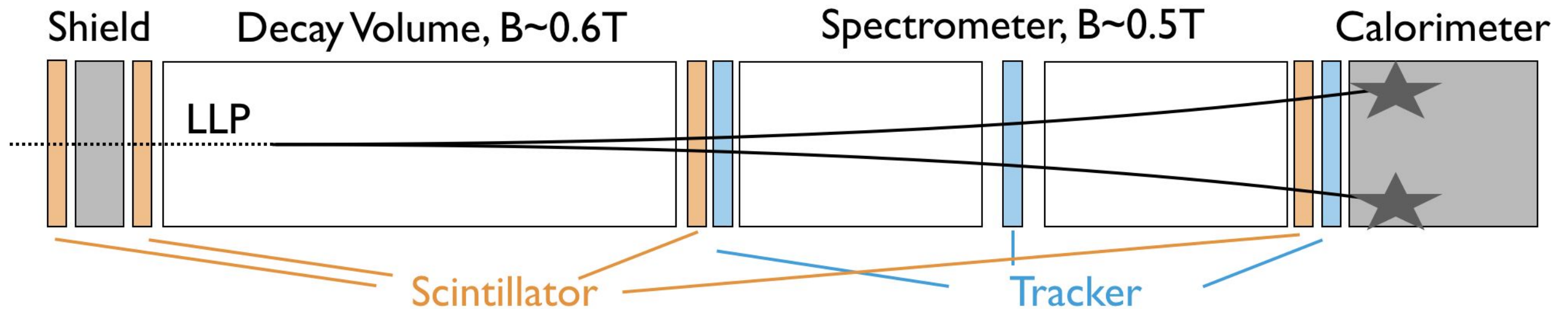
# Detector Design

## FASER: search for light long-lived particles

$pp \rightarrow \text{LLP} + X$ , LLP travels  $\sim 480\text{m}$ ,  $\text{LLP} \rightarrow \text{charged tracks} + X$

### Signal is striking:

- \* highly energetic particles ( $E \sim \text{TeV}$ )
- \* common vertex in an empty decay volume
- \* point back to the IP through 90 m of rock



### Background considerations:

- \* large flux of muons from the LHC cause muon-associated radiative events
- \* use scintillators veto to reduce BG to negligible levels

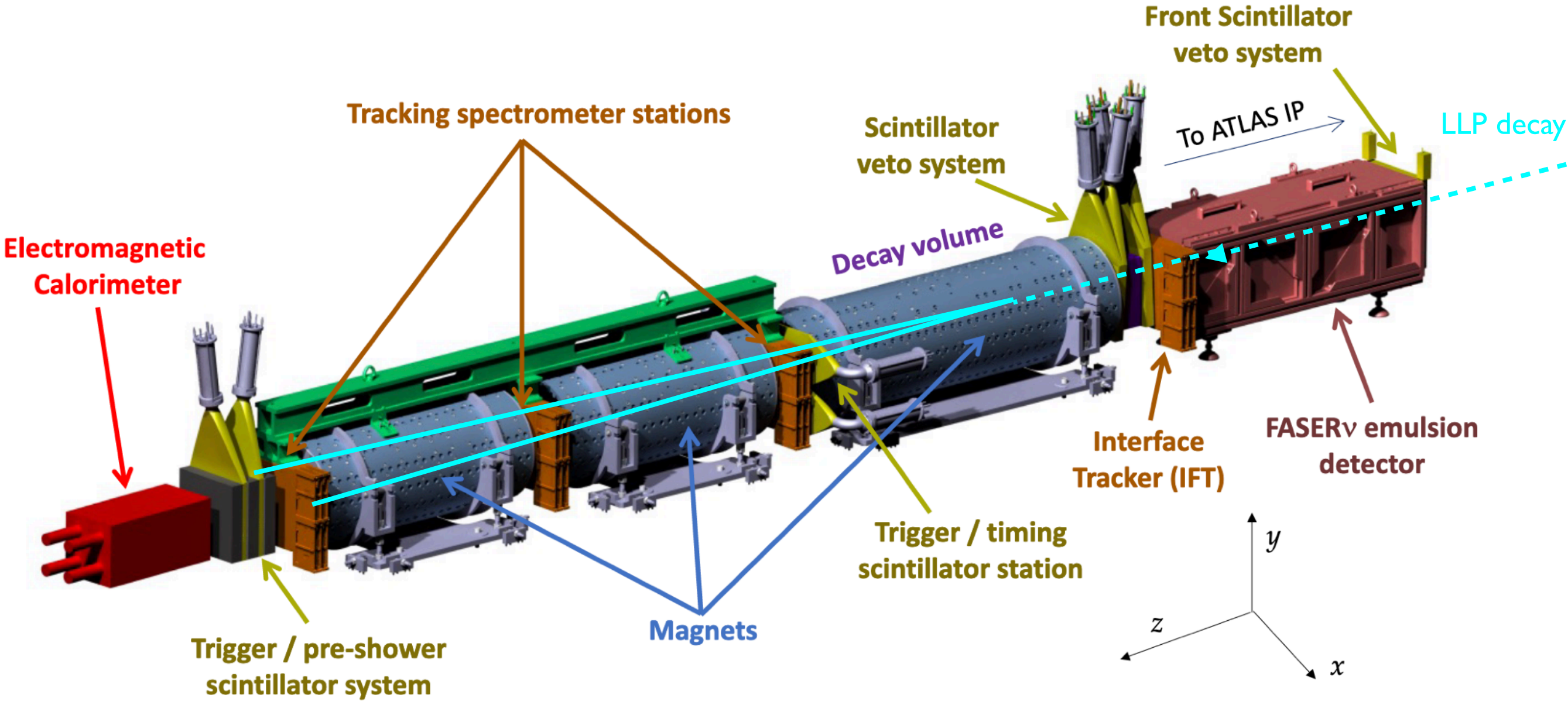
# FASER Detector

Documentation:

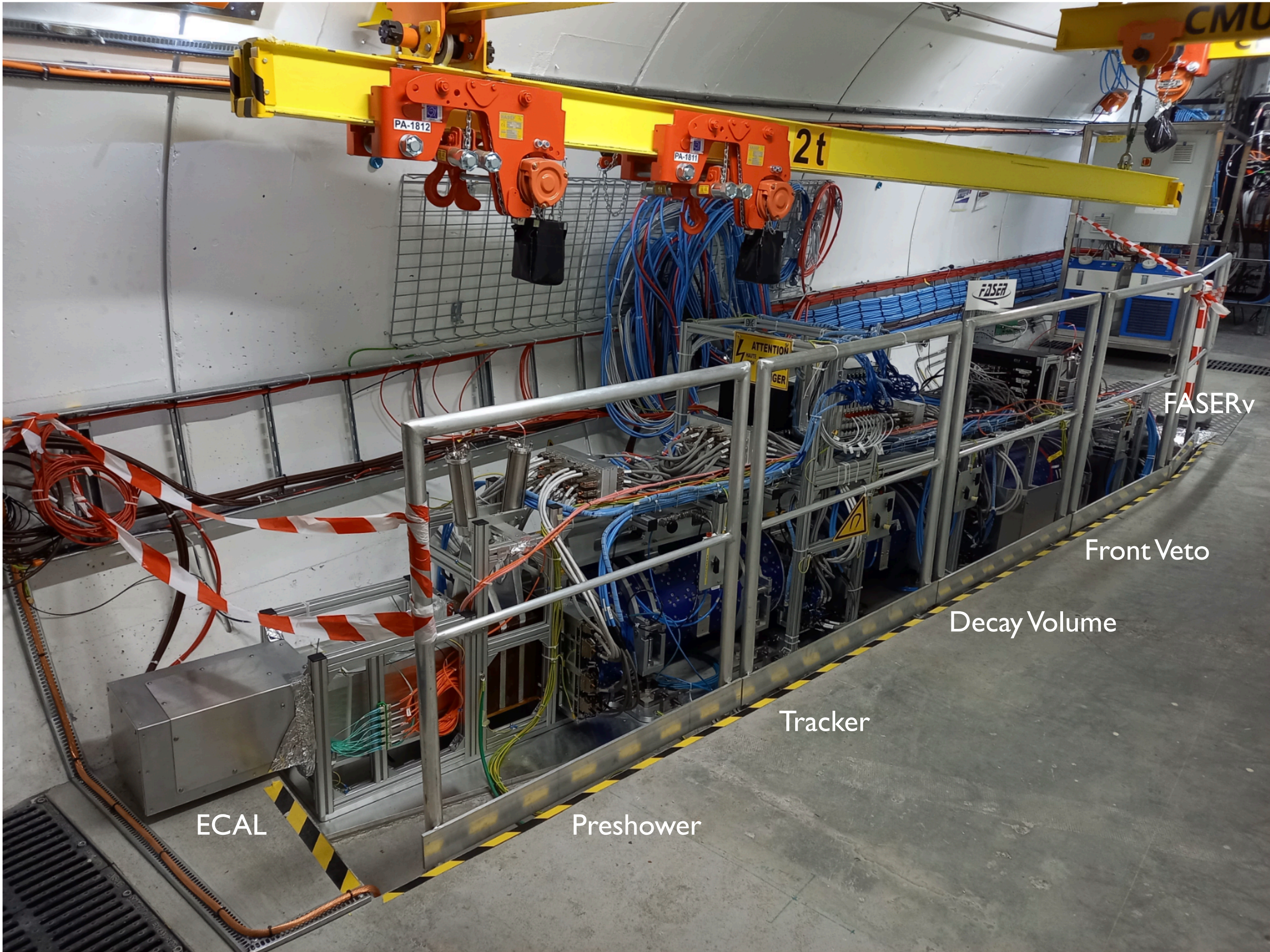
LOI: [1811.10243](#)

TP: [1812.09139](#)

Detector Paper: [2207.11427](#)







ECAL

Preshower

Tracker

Decay Volume

Front Veto

FASERv

2t

PA-1812

PA-1811

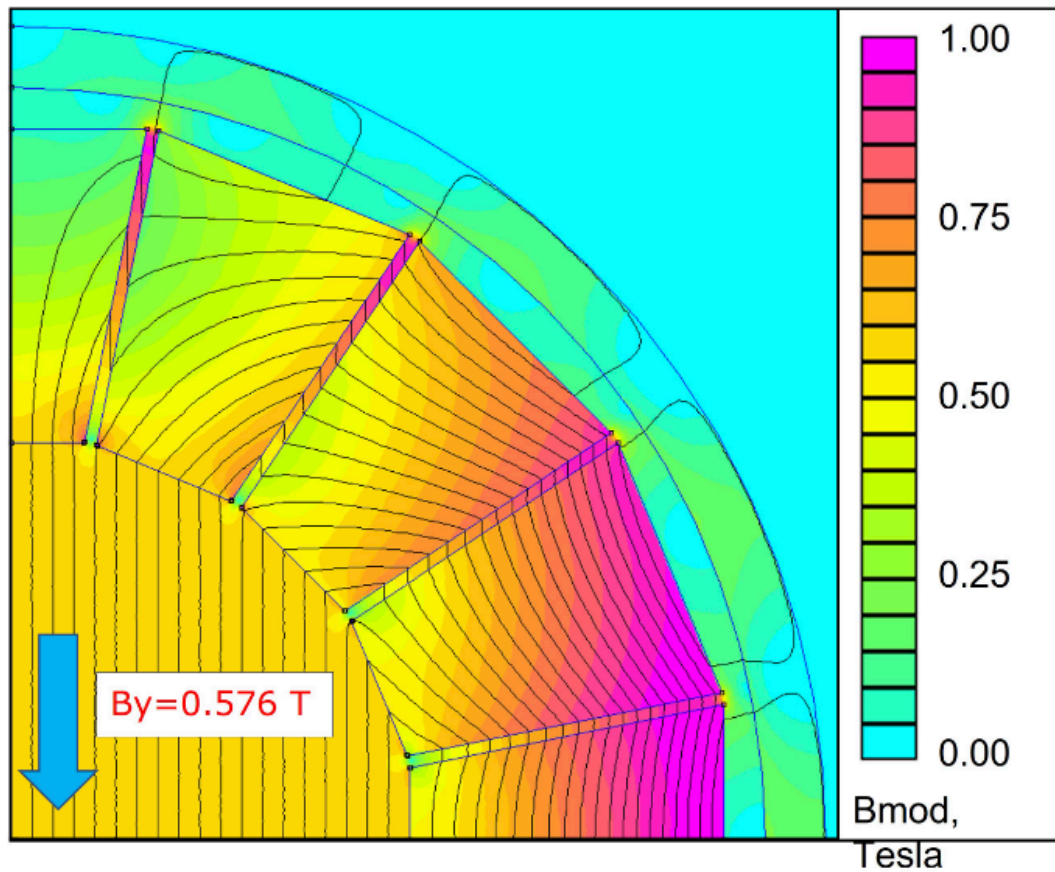
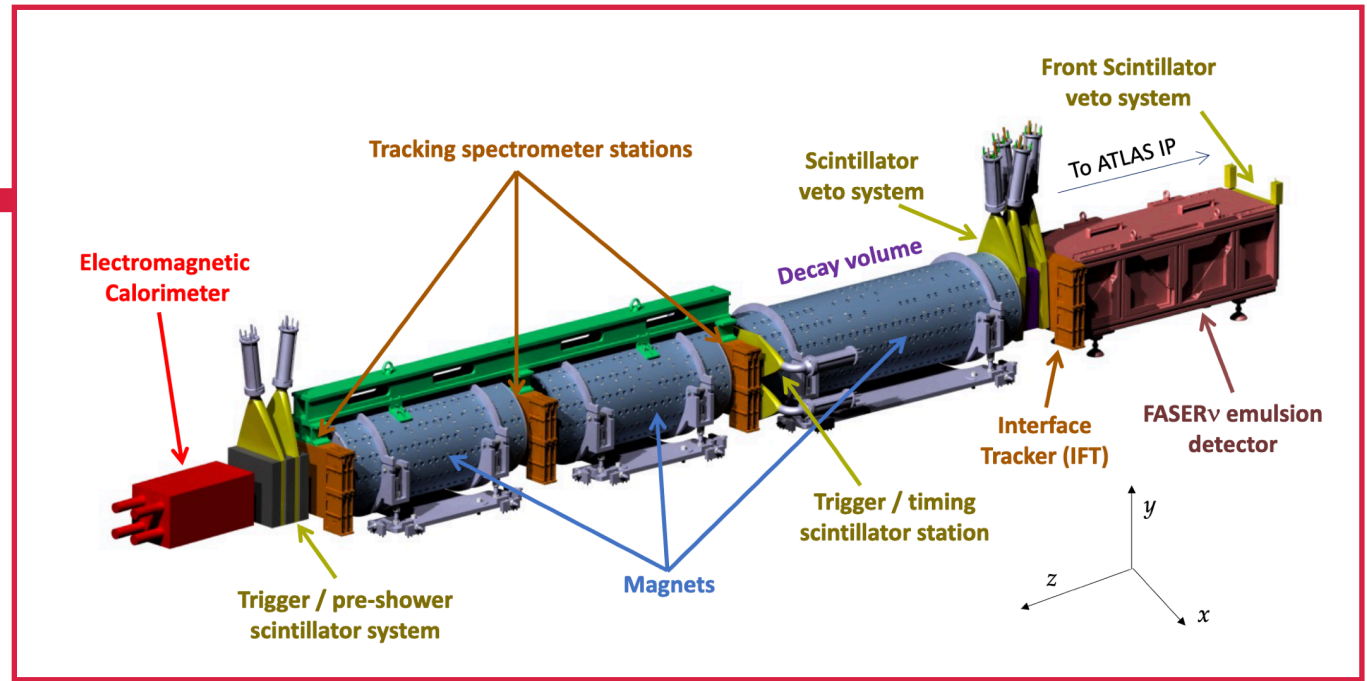
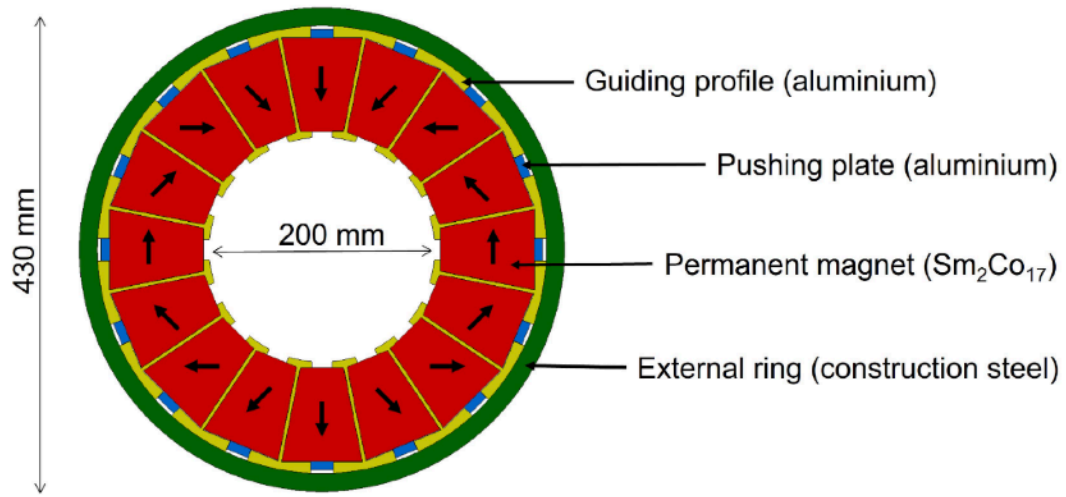
ATTENTION  
HAUTE  
TENSION

FASERv

CMU



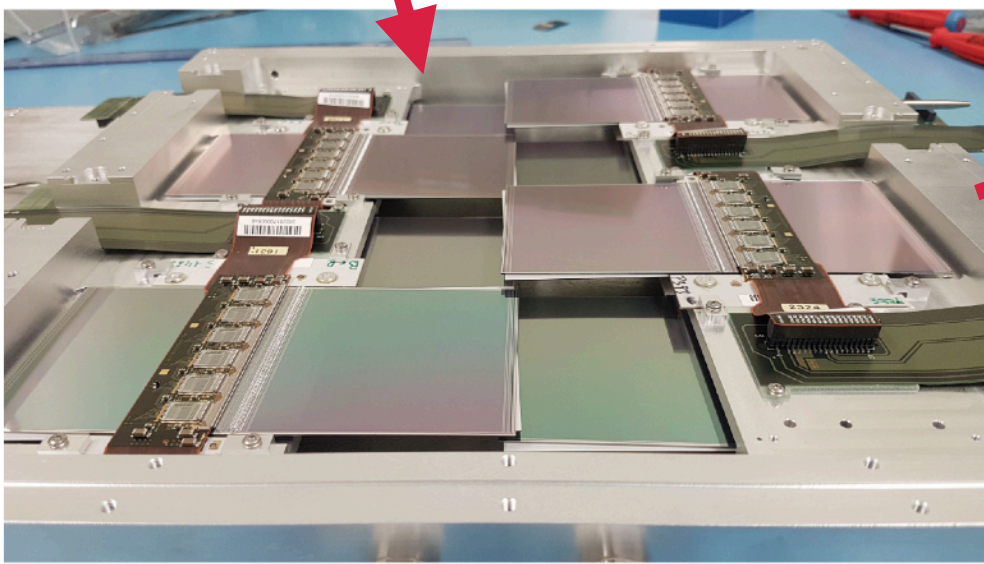
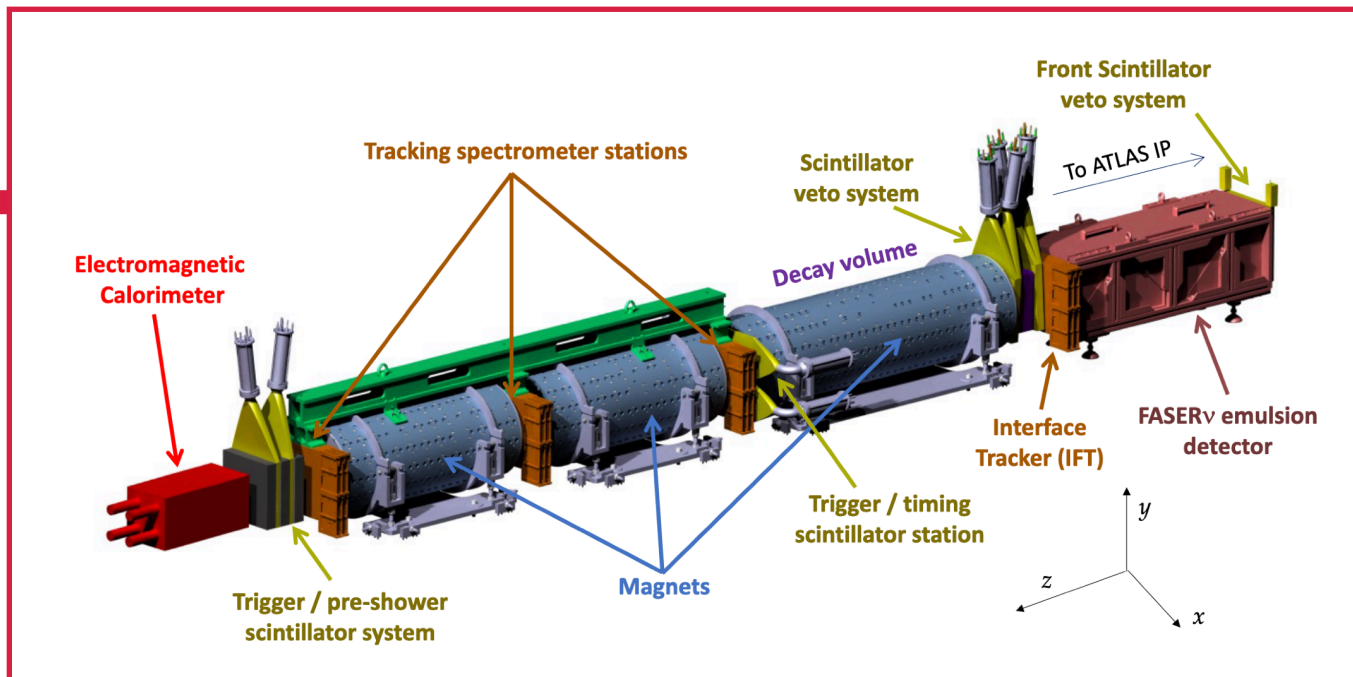
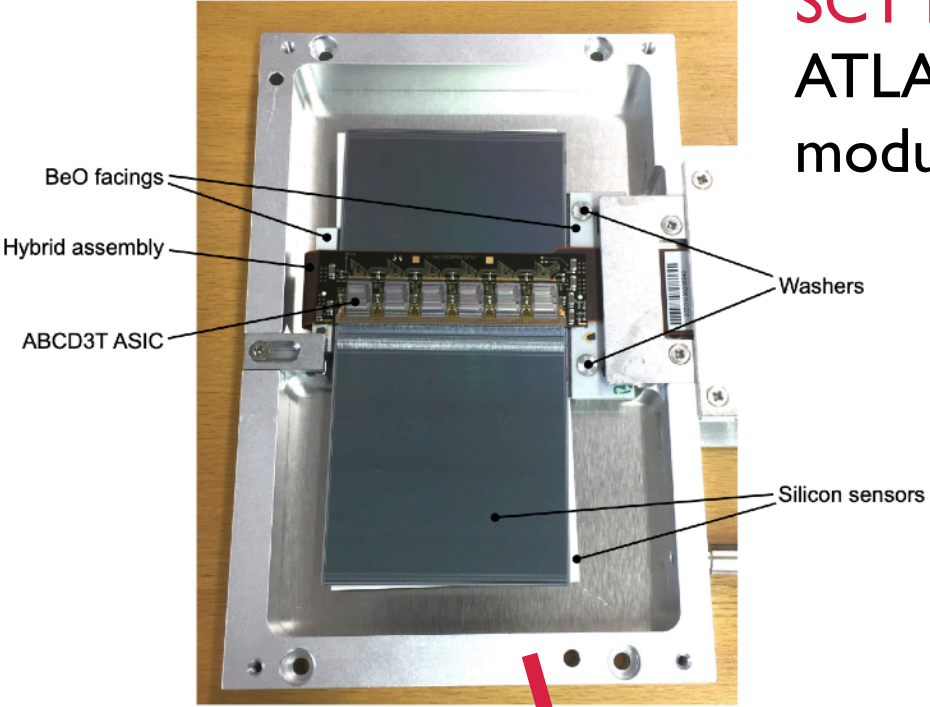
# FASER Magnets





# FASER Tracker

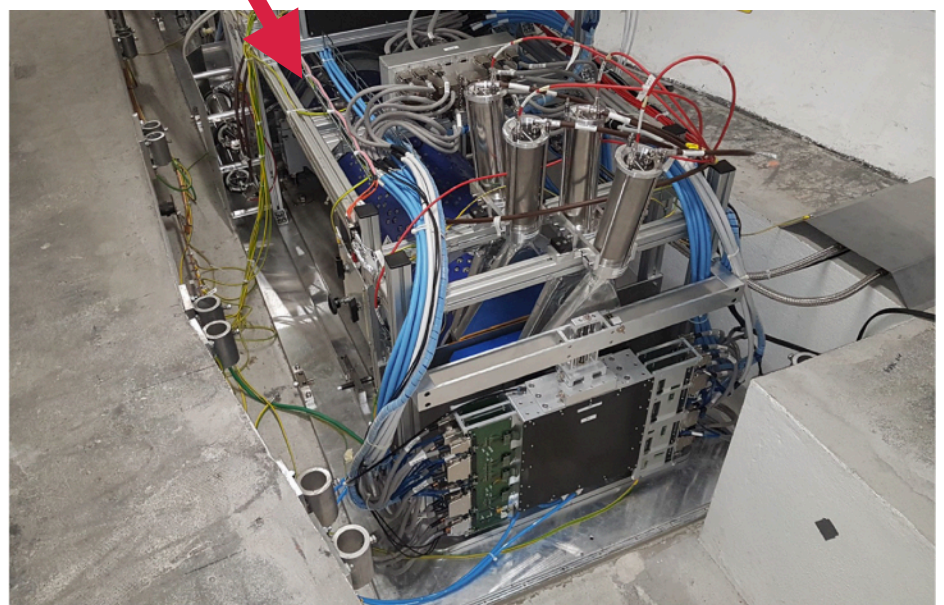
SCT module  
ATLAS spare  
modules



Tracker Plane



Tracker Station

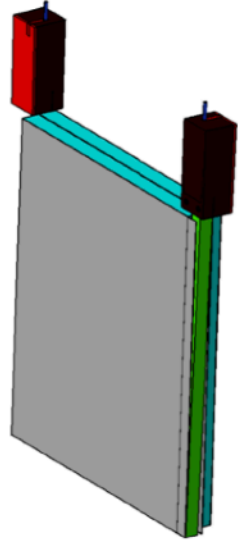


Resolution in the bending direction:  $\sim 20 \mu\text{m}$ .  
 Resolution in the non-bending direction:  $\sim 550 \mu\text{m}$ .  
 FASER Tracker paper: [2112.01116](#)

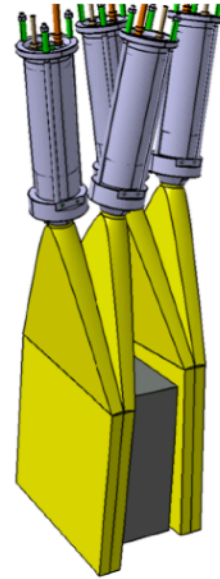


# FASER Scintillators

## Front Veto

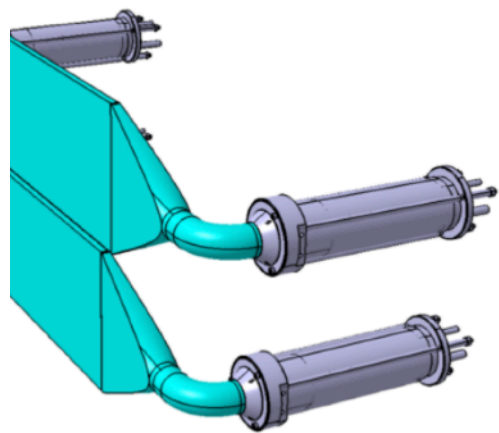


(a) First veto station.

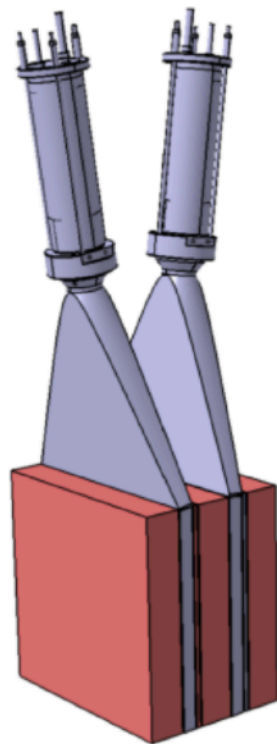


(b) Second veto station.

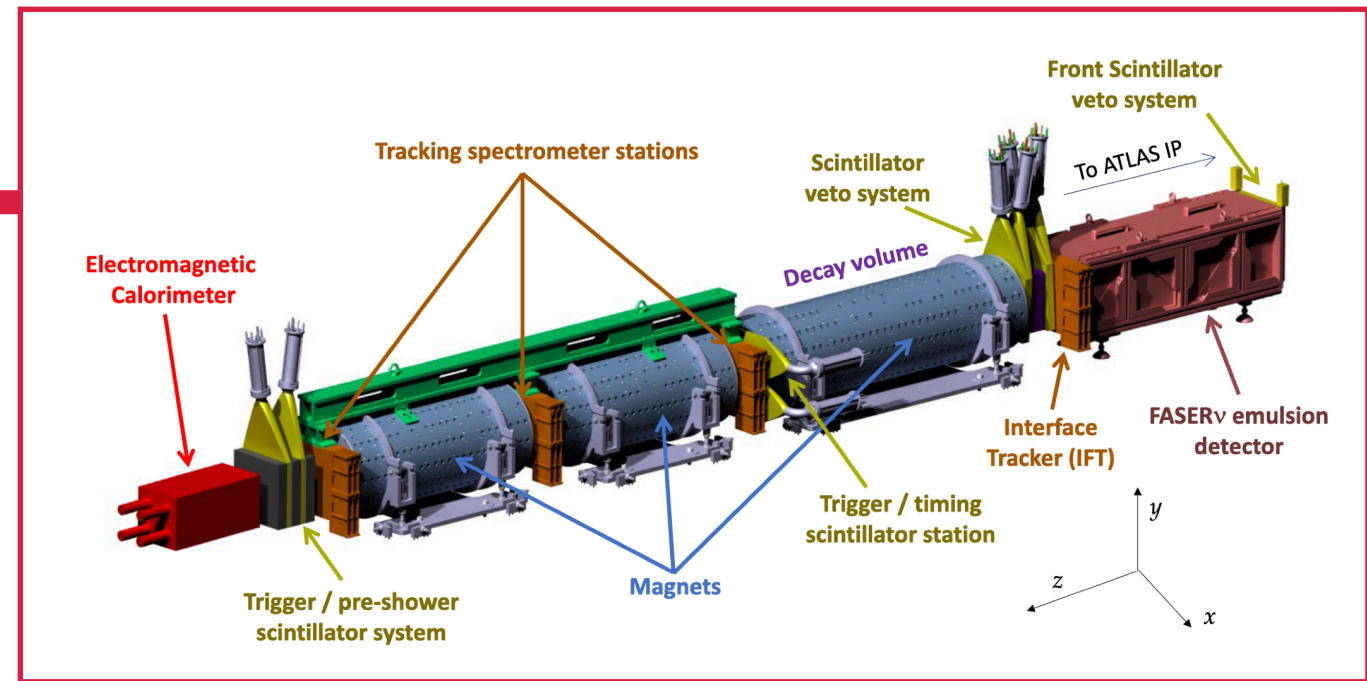
## Timing and Trigger



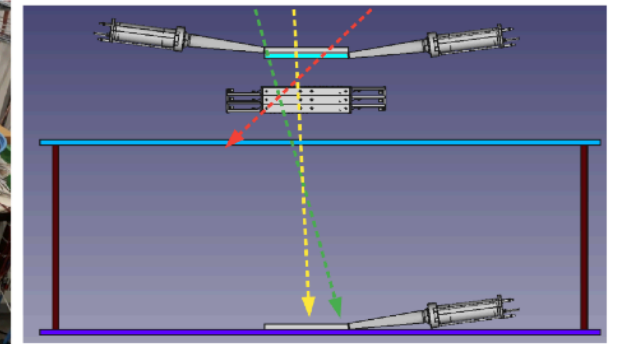
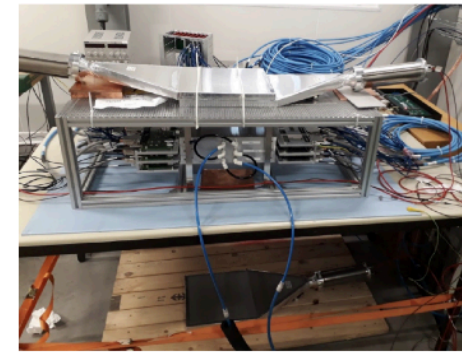
(c) Timing station.



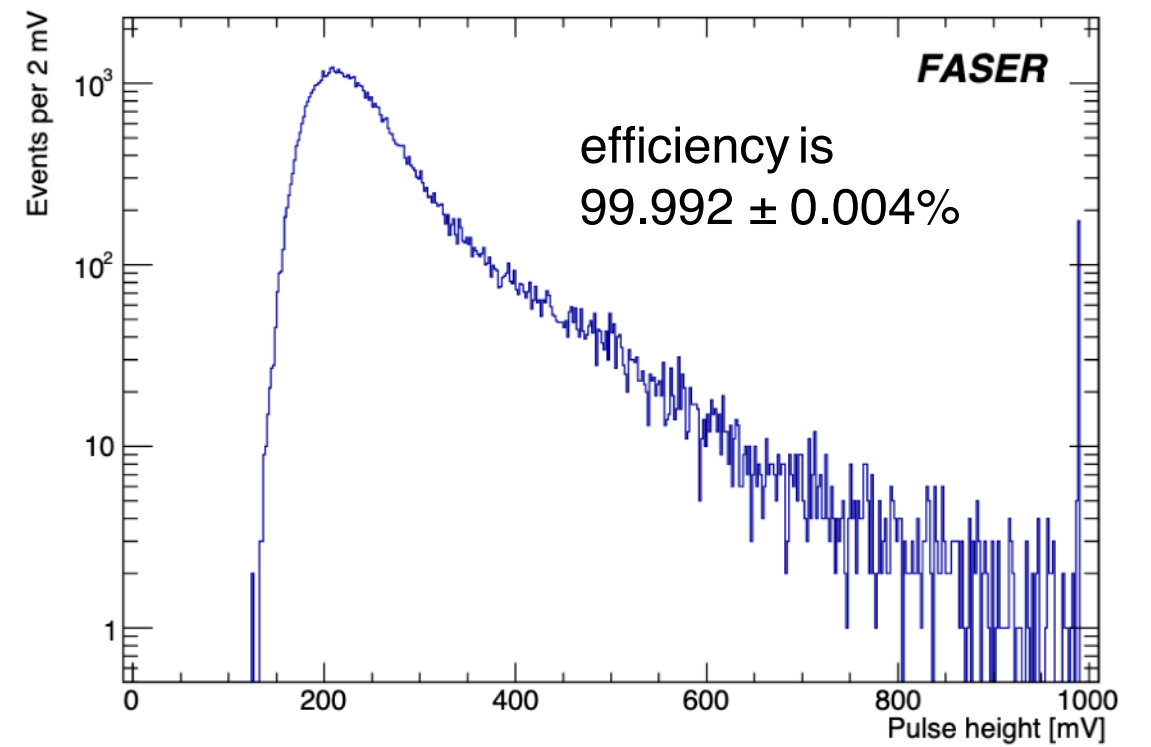
(d) Preshower station.



## Cosmic Muon Measurements

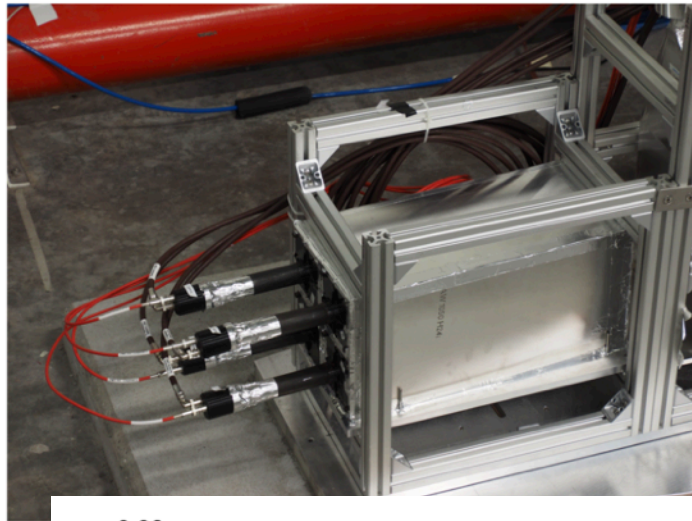
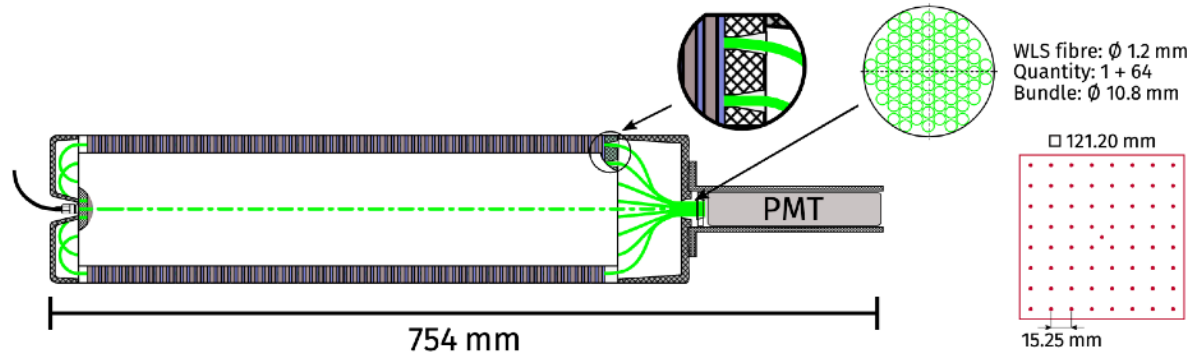


Veto station 2, module 2

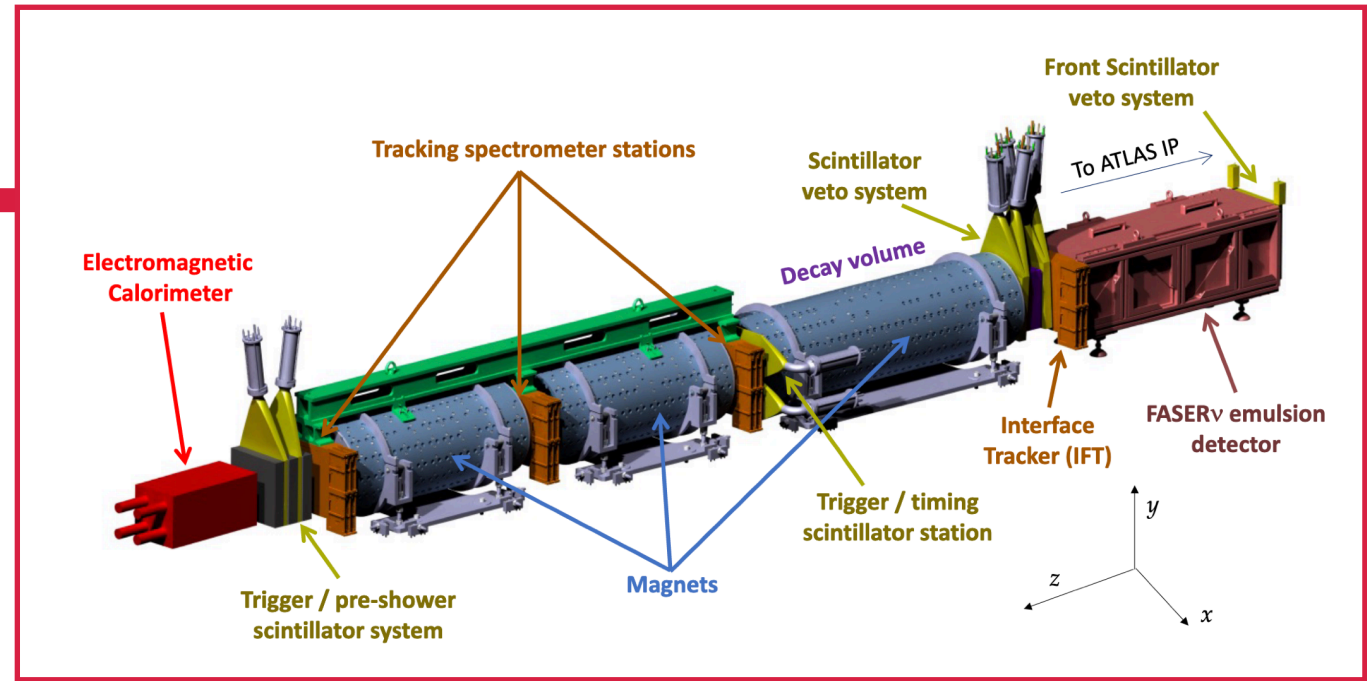
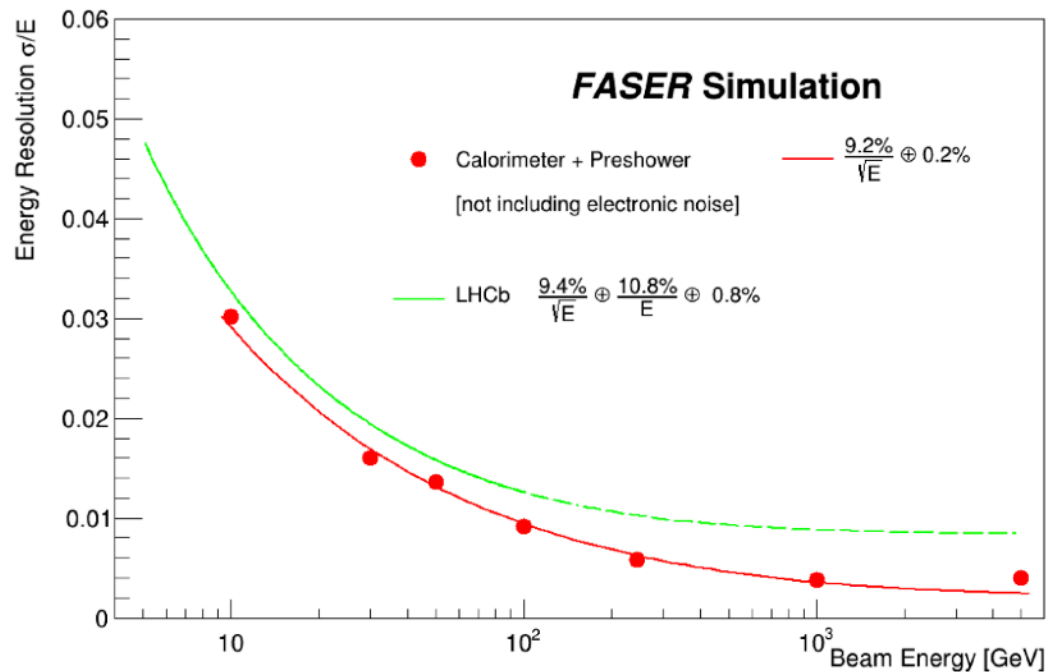


# FASER Calorimeter

Calorimeter  
made of spare LHCb modules

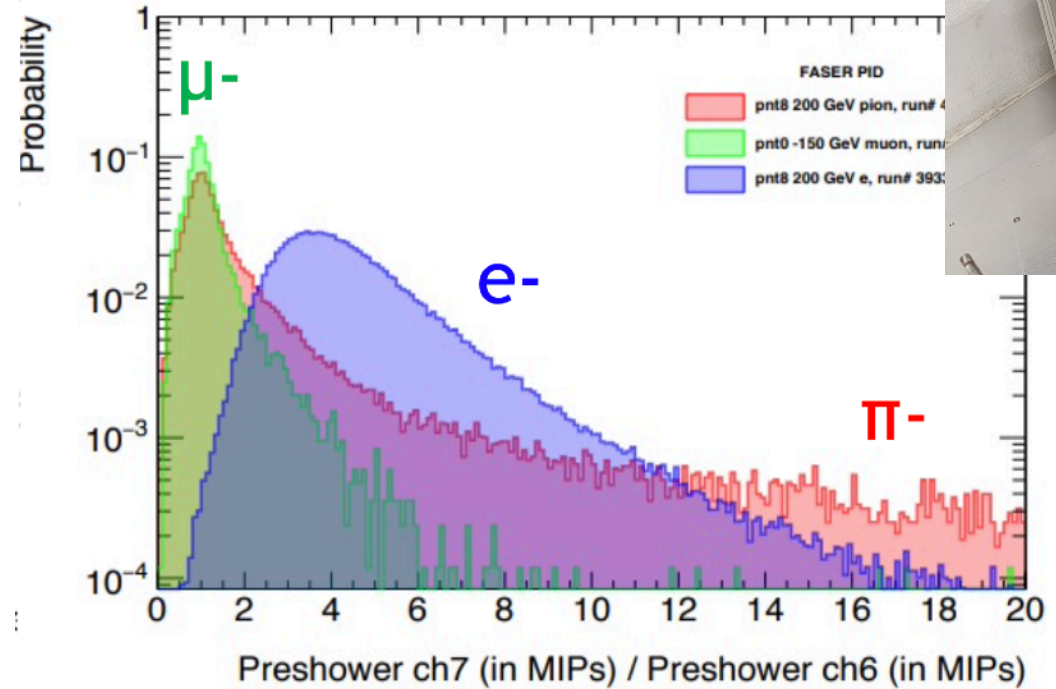


optimised to measure  
multi-TeV deposits



## Preshower

Trigger and particle  
identification.





# FASER First Data

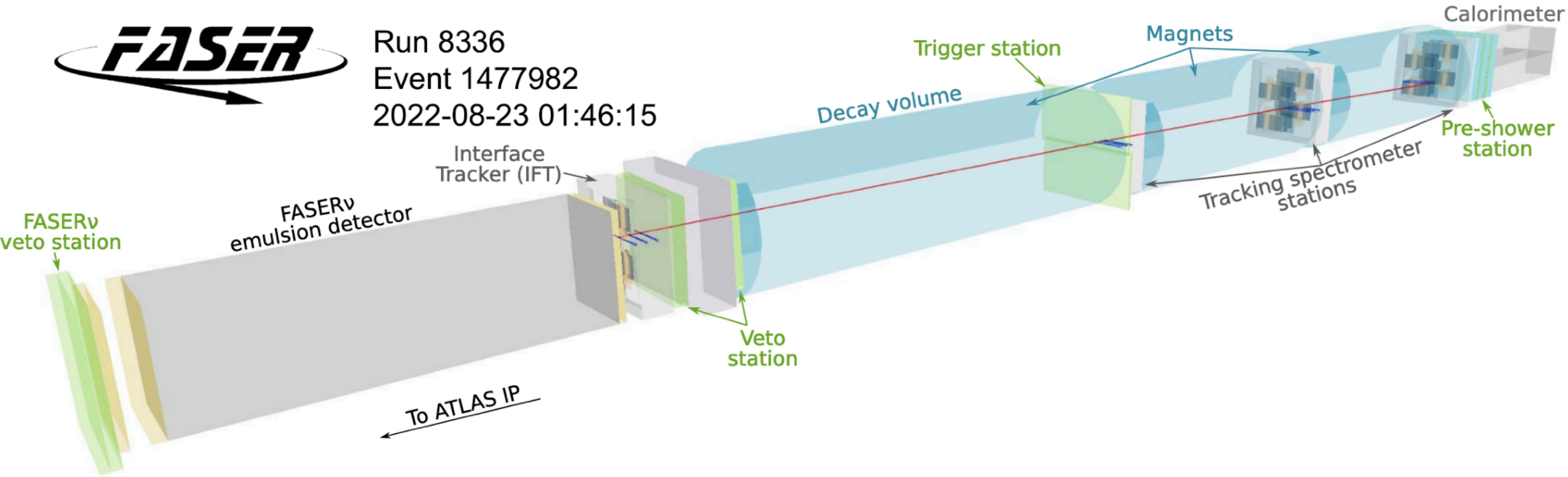


Figure 4: Collision event with a muon traversing FASER. Measured momentum of 21.9 GeV. The ATLAS interaction point is on the picture in the left direction. The detected hits in the semiconductor tracker modules are shown with blue lines and the reconstructed track is shown with a red line.



# FASER First Data



Run 8336  
Event 1477982  
2022-08-23 01:46:15

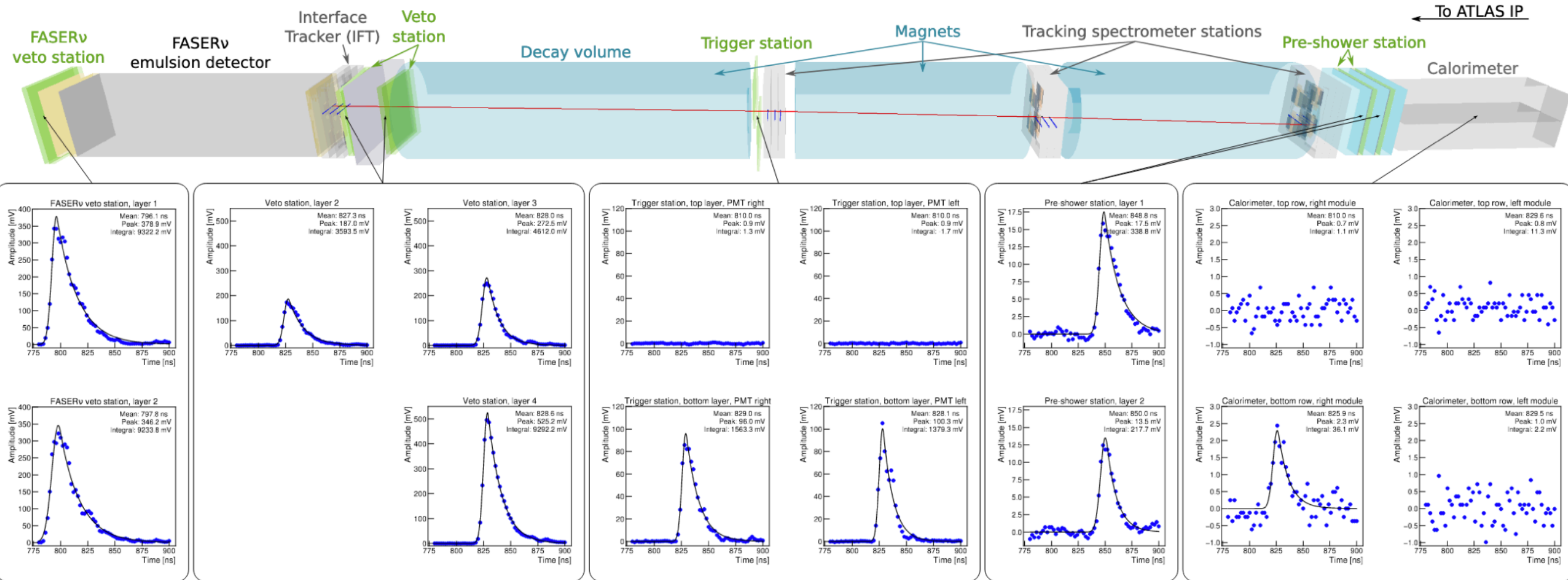
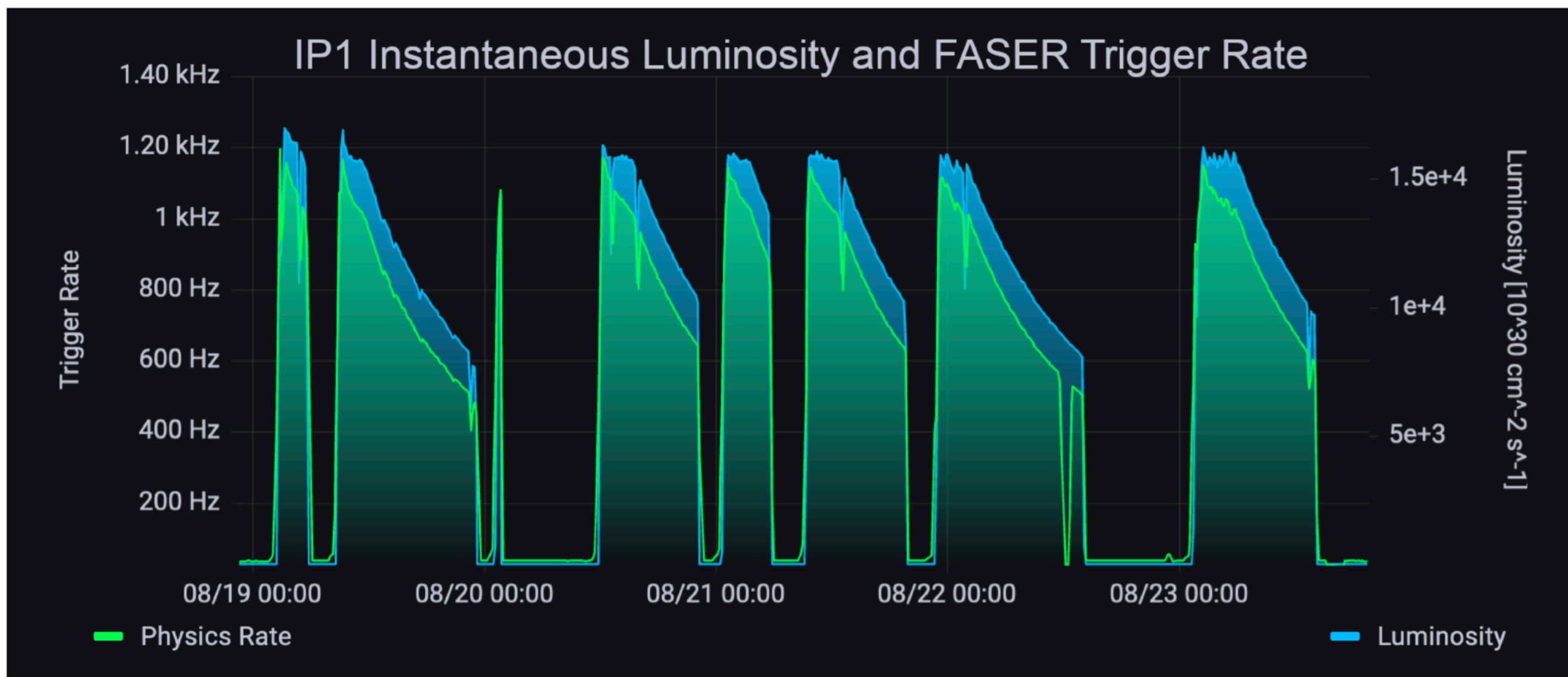


Figure 1: Collision event with a muon traversing FASER. Measured momentum of 21.9 GeV. Waveforms shown for signals in scintillators and calorimeter modules. All PMT waveforms are consistent with a muon passing through the scintillators and one of the calorimeter modules. The event has been triggered by modules in the FASER $\nu$  veto station, veto station and trigger station with pulses above 25 mV, and by modules in the pre-shower station with pulses above 3 mV. The ATLAS interaction point is on the picture in the left direction. The detected hits in the semiconductor tracker modules are shown with blue lines and the reconstructed track is shown with a red line. The positions of the PMTs in the trigger station and calorimeter modules are defined facing the downstream direction.

# FASER First Data



Since July 2022 FASER has been collecting  $\sqrt{s} = 13.6$  TeV collision data

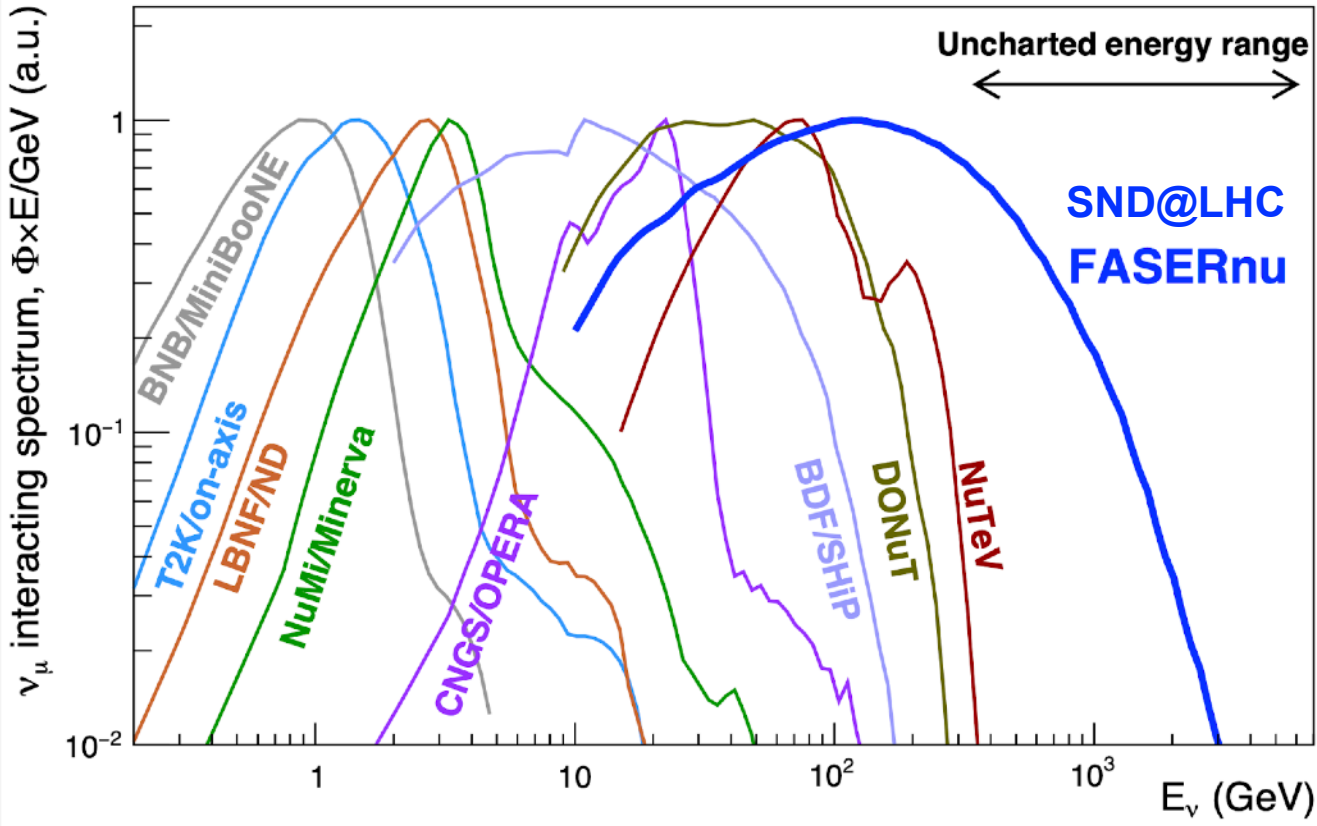
- no problems observed.
- maximum trigger rate is  $\sim 1.2$  kHz (nearly 2x the expectation), but this is not a problem for physics.
- more than  $L_{\text{INT}} = 11 \text{ fb}^{-1}$  data have been recorded.
- many performance studies are ongoing.

**FASERv**

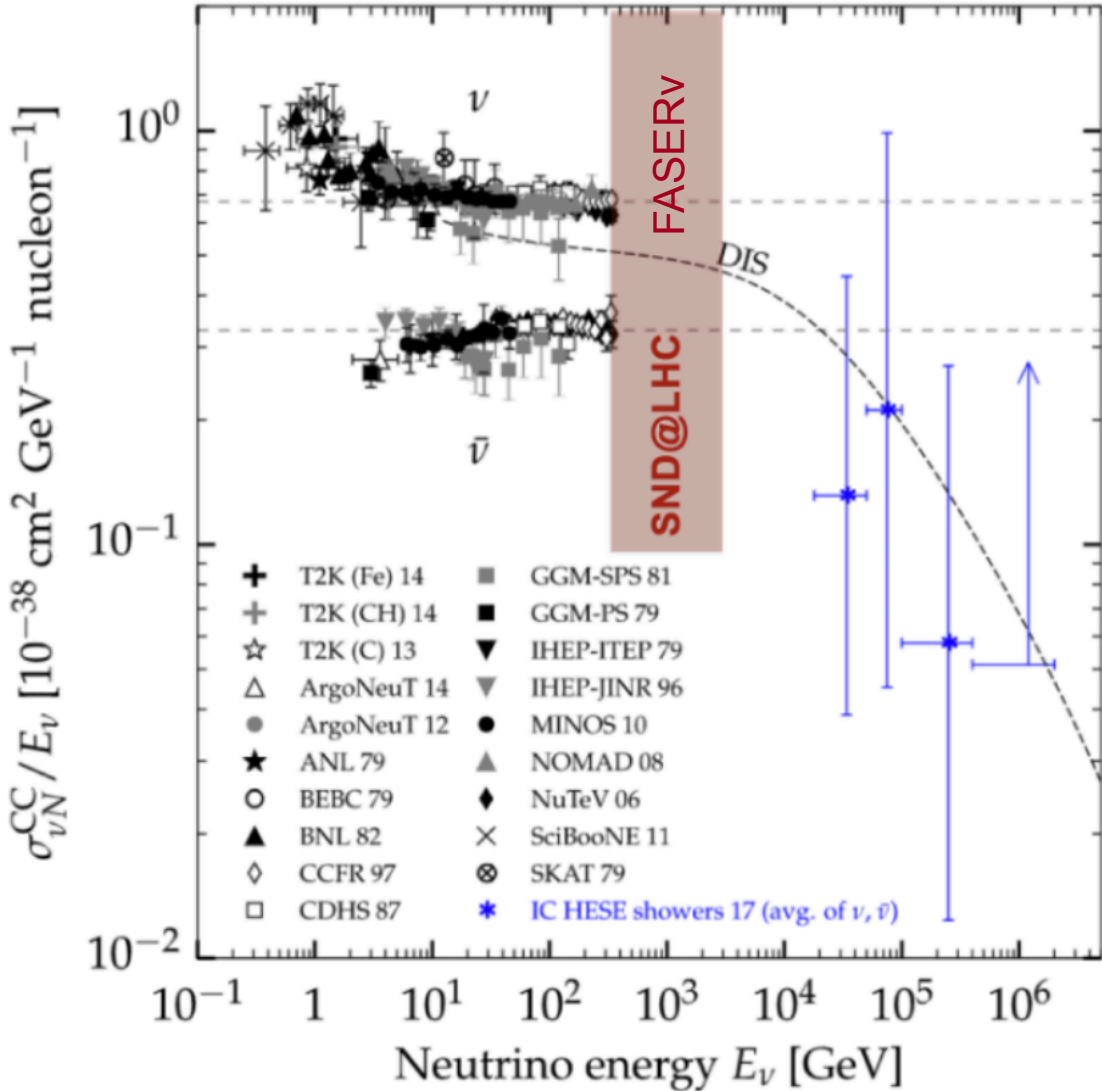


# One Slide of Physics Motivation

(for both FASERν and SND@LHC)



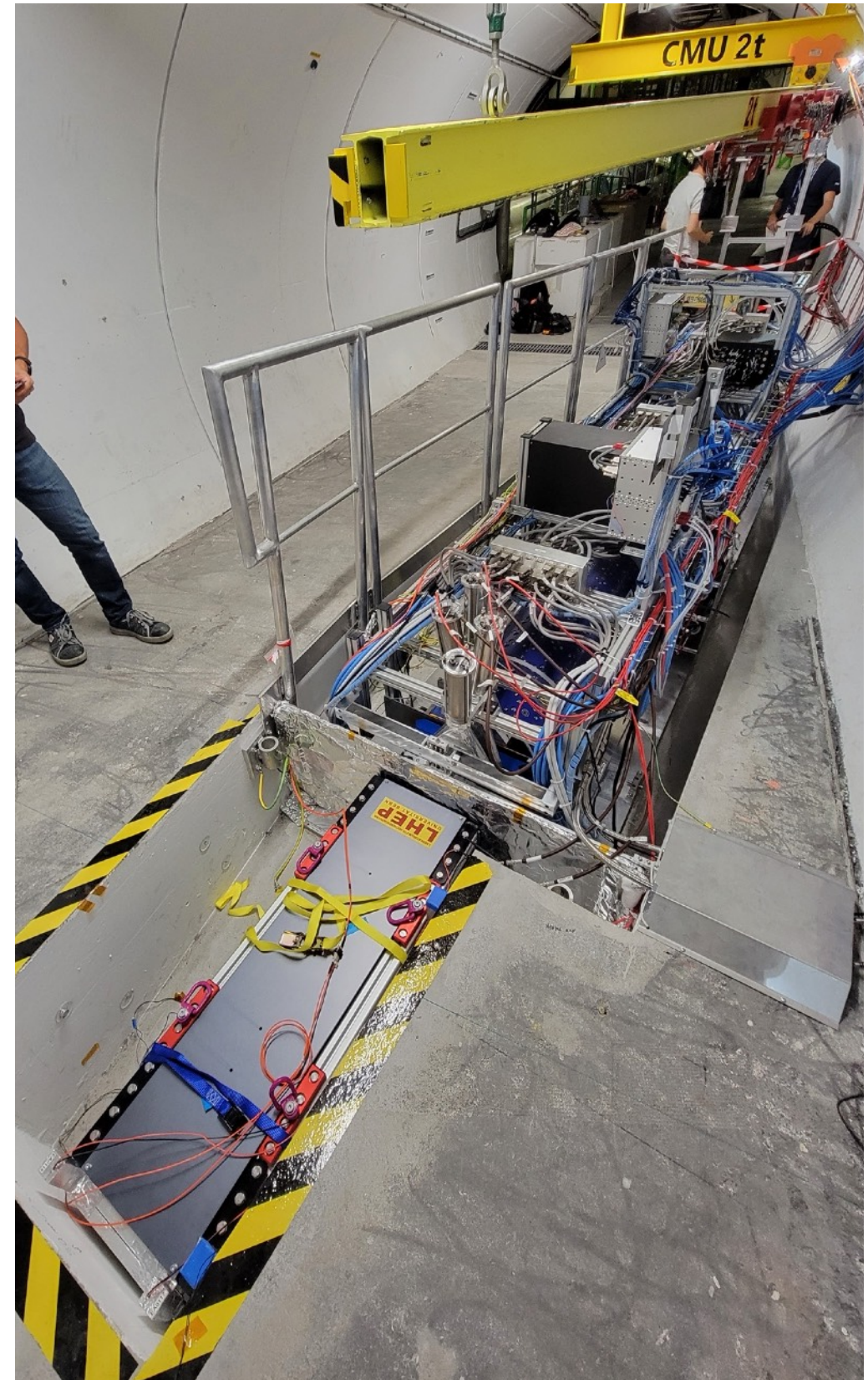
PRL 122 (2019) 041101



# FASERν Detector

**FASERν neutrino detector** in front of FASER

- \* 25cm x 25cm x 1.3m emulsion detector
- \* tungsten target with 1.2 ton mass
- \* placed on-axis:  $\eta > 9$  angular coverage
- \*  $\sim 1000 \nu_e$ ,  $\sim 10000 \nu_\mu$ ,  $\sim 10 \nu_\tau$   
during LHC Run 3

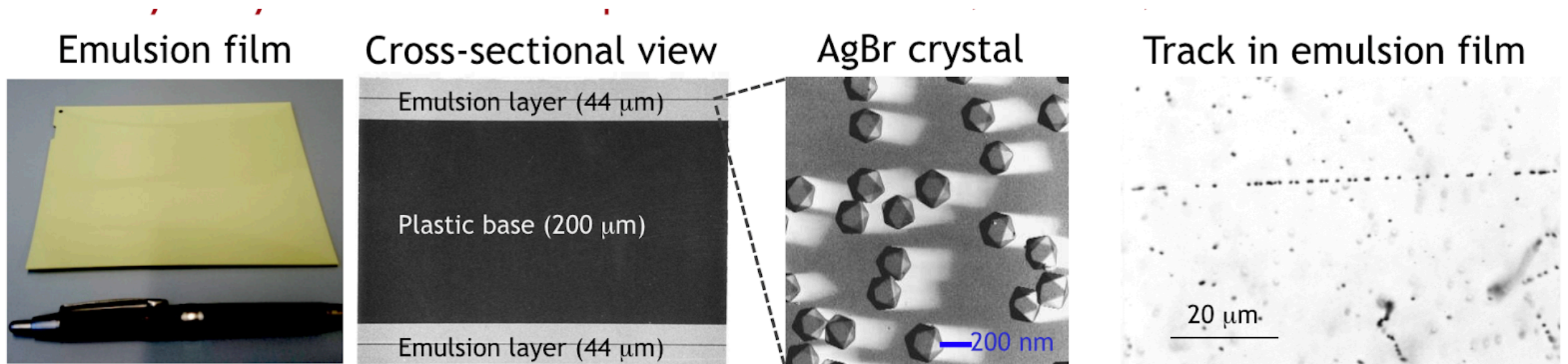




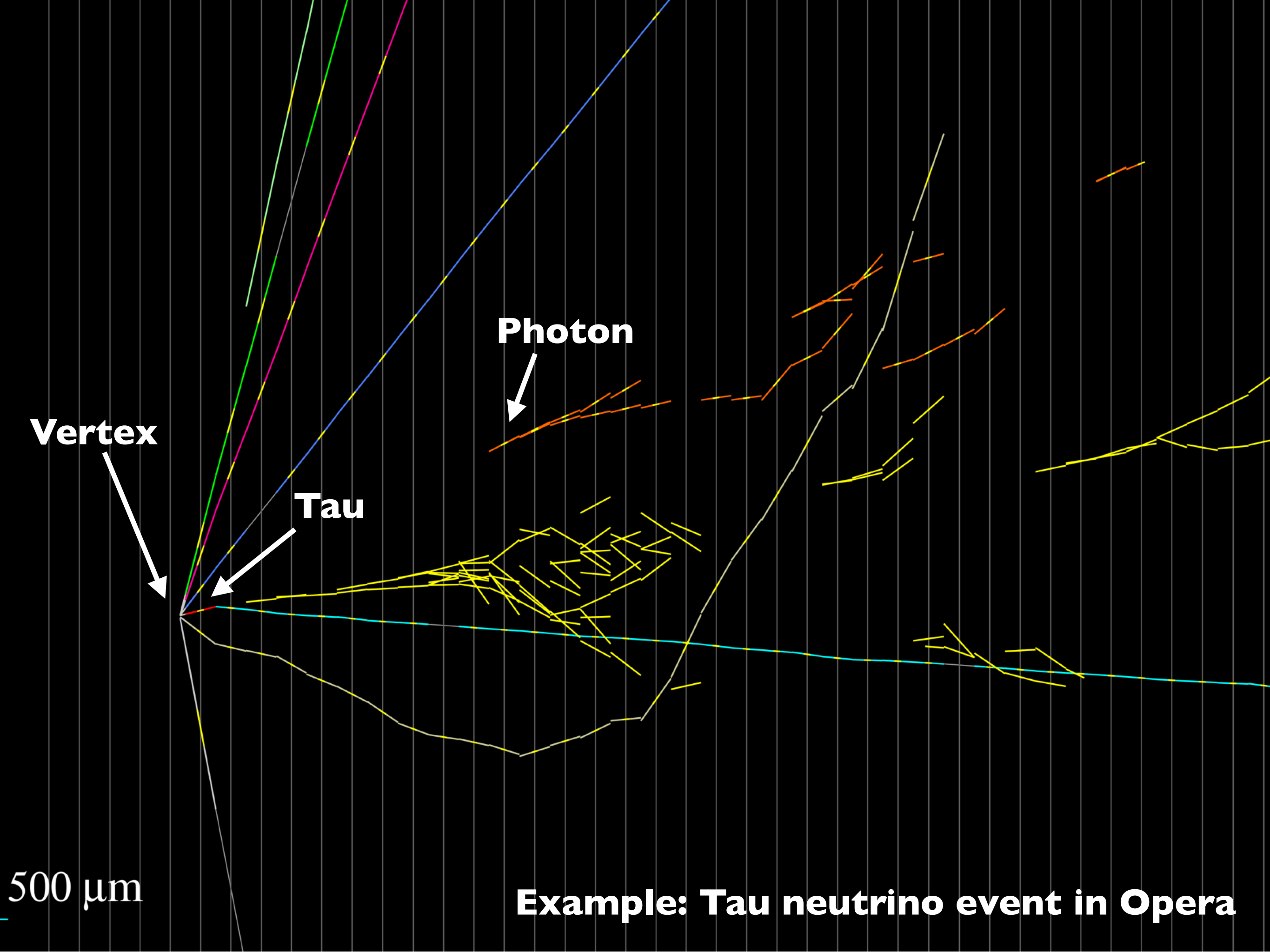
# FASER $\nu$ Detector

## Emulsion detectors technology

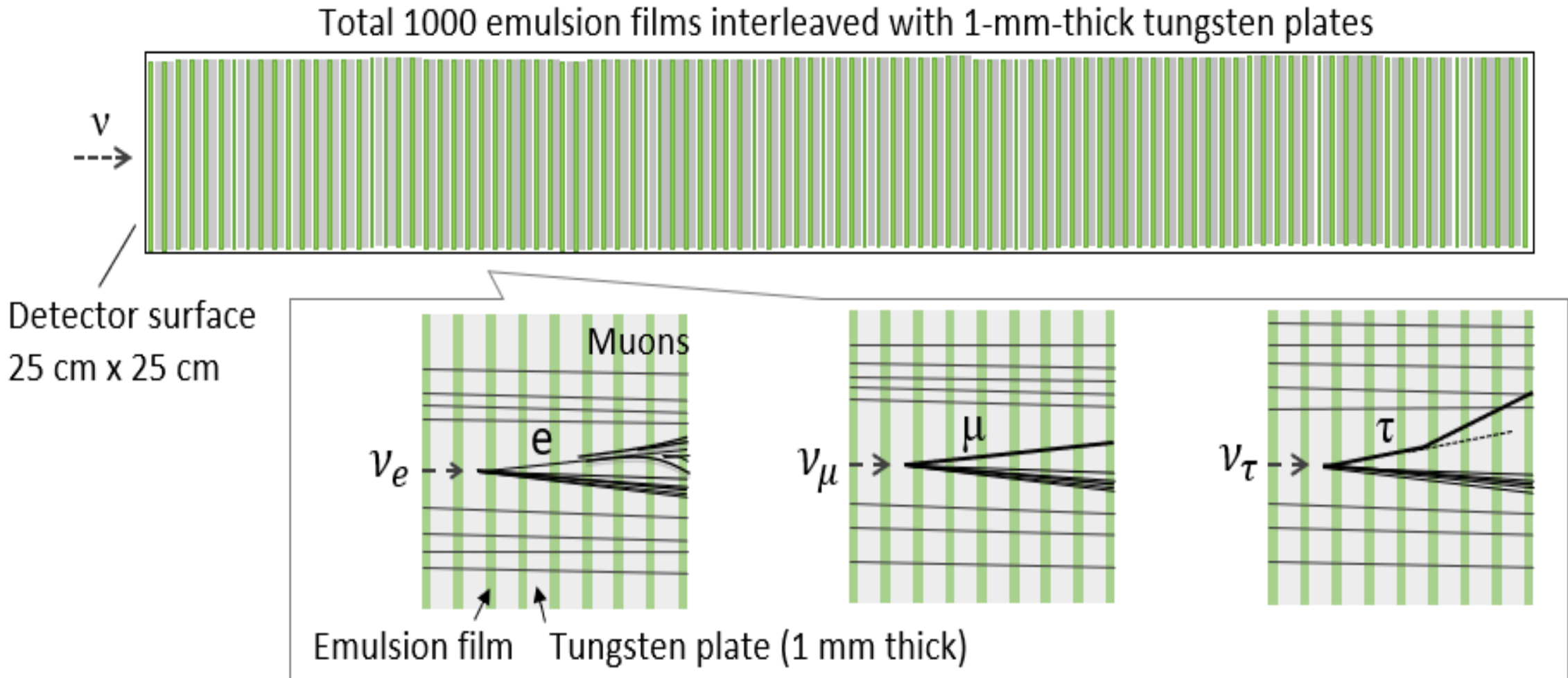
- \* used by many other neutrino experiments: CHORUS, DONUT, OPERA
- \* 1000 emulsion films interleaved with 1mm tungsten plates
- \* 3D tracking devices with 50 nm spatial precision
- \* global reconstruction with the FASER detector possible





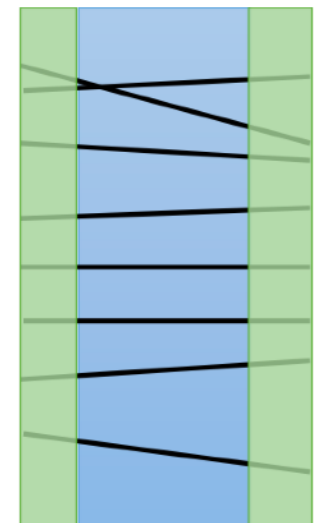
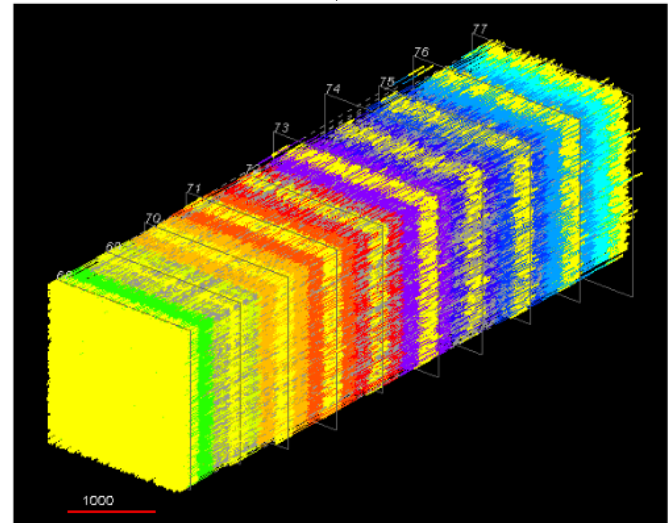
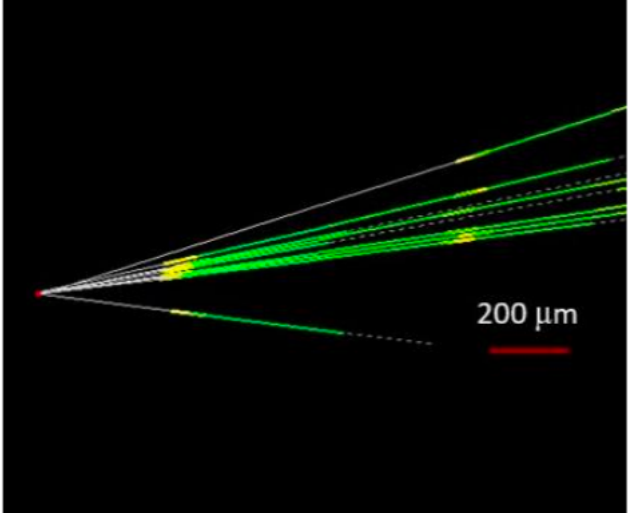
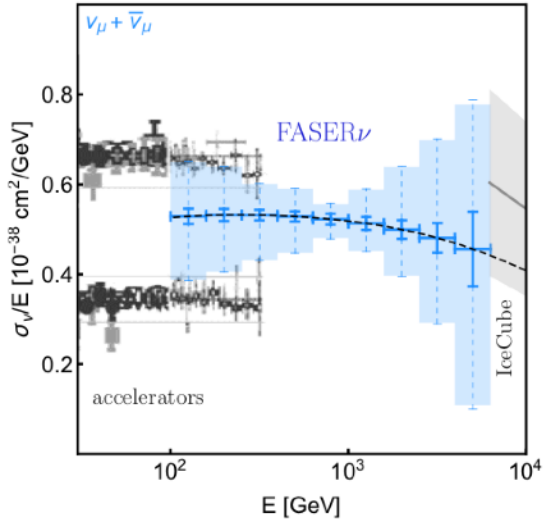
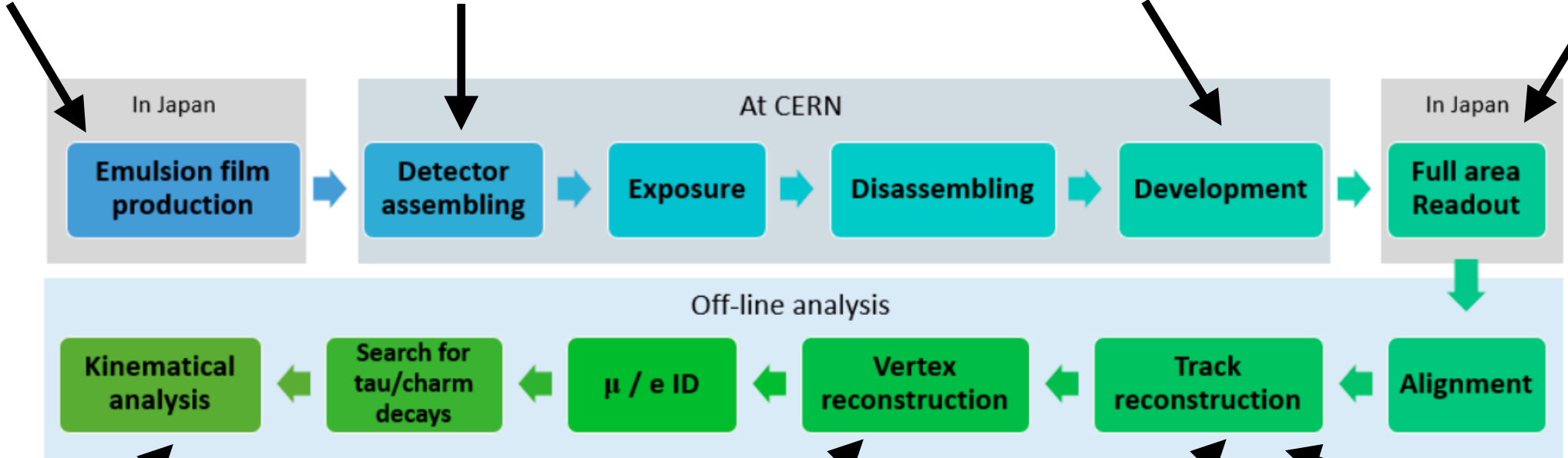
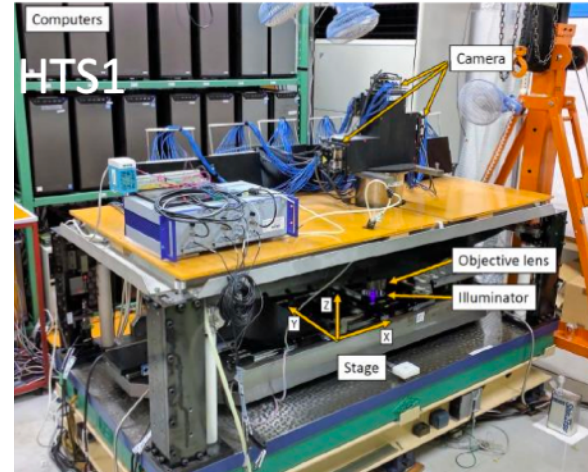
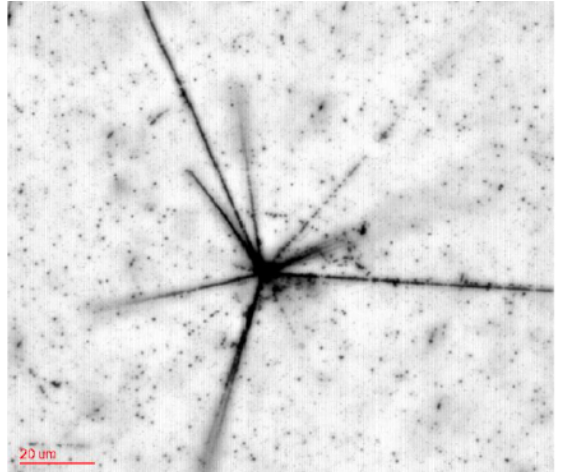
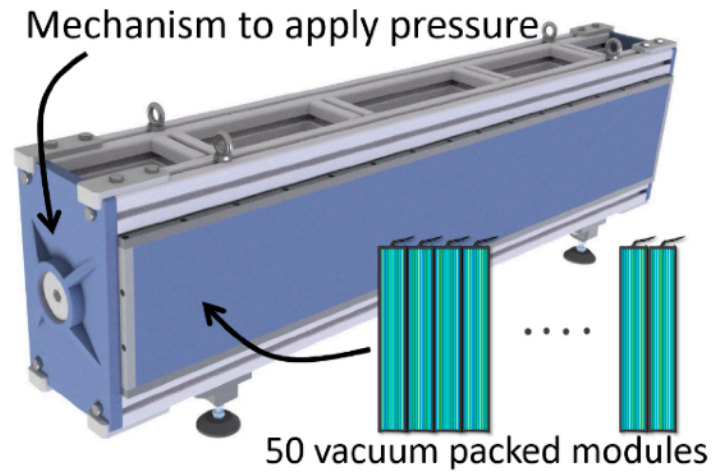
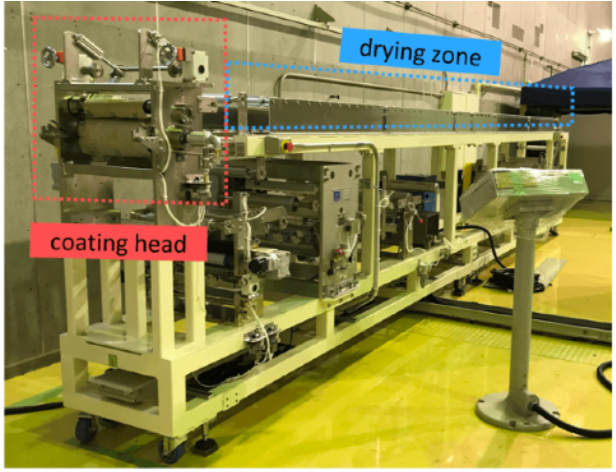


# FASER $\nu$ Detector





# FASERν Detector

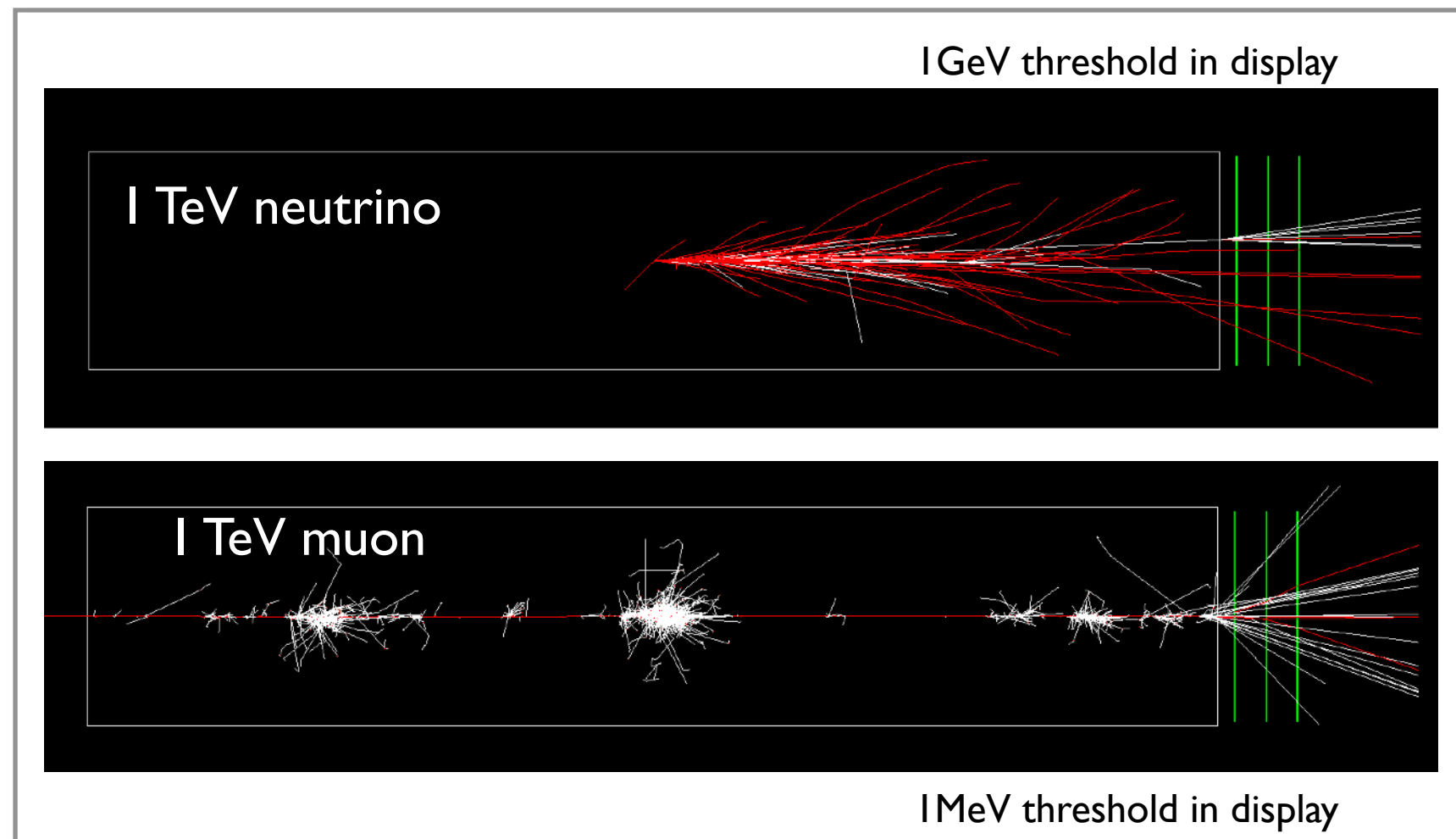
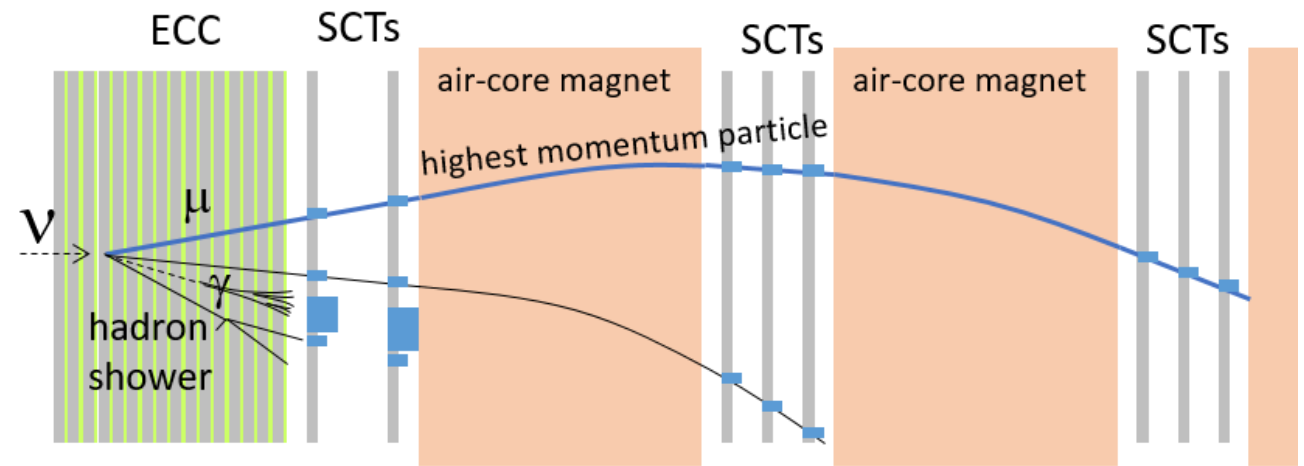


# FASER $\nu$ Detector

## Interface Detector

- possibility for future: global reconstruction with the FASER detector
  - \* interface FASER $\nu$  to the FASER spectrometer
  - \* additional tracking layer to allow matching

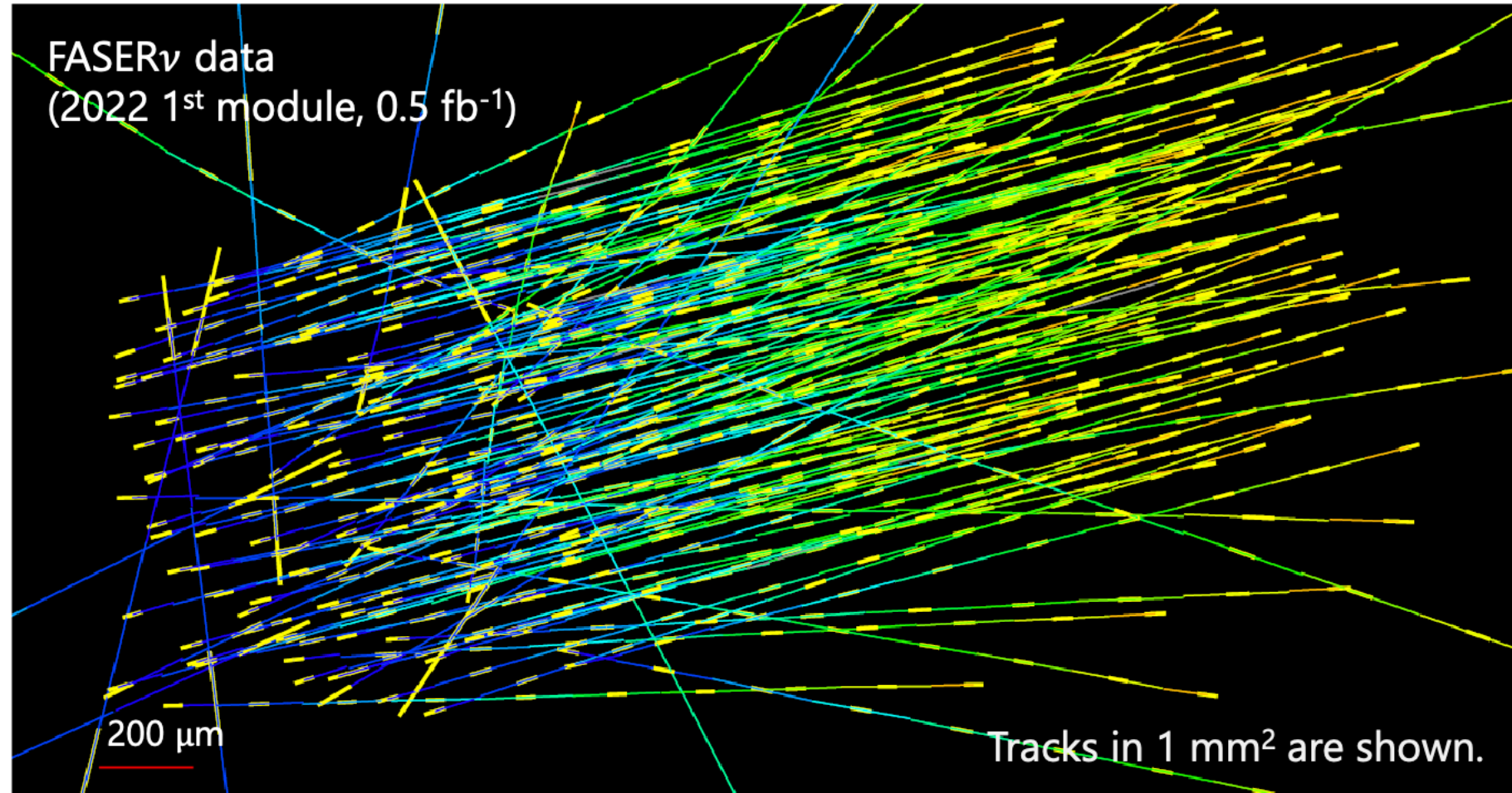
- muon charge identification
  - distinguish neutrino / anti-neutrino
- momentum of charged tracks
  - improve neutrino energy reconstruction
- timestamp events and identify additional activity (muon)
  - background rejection





# FASER $\nu$ : First Data

---



**SND@LHC**

# SND@LHC Concept

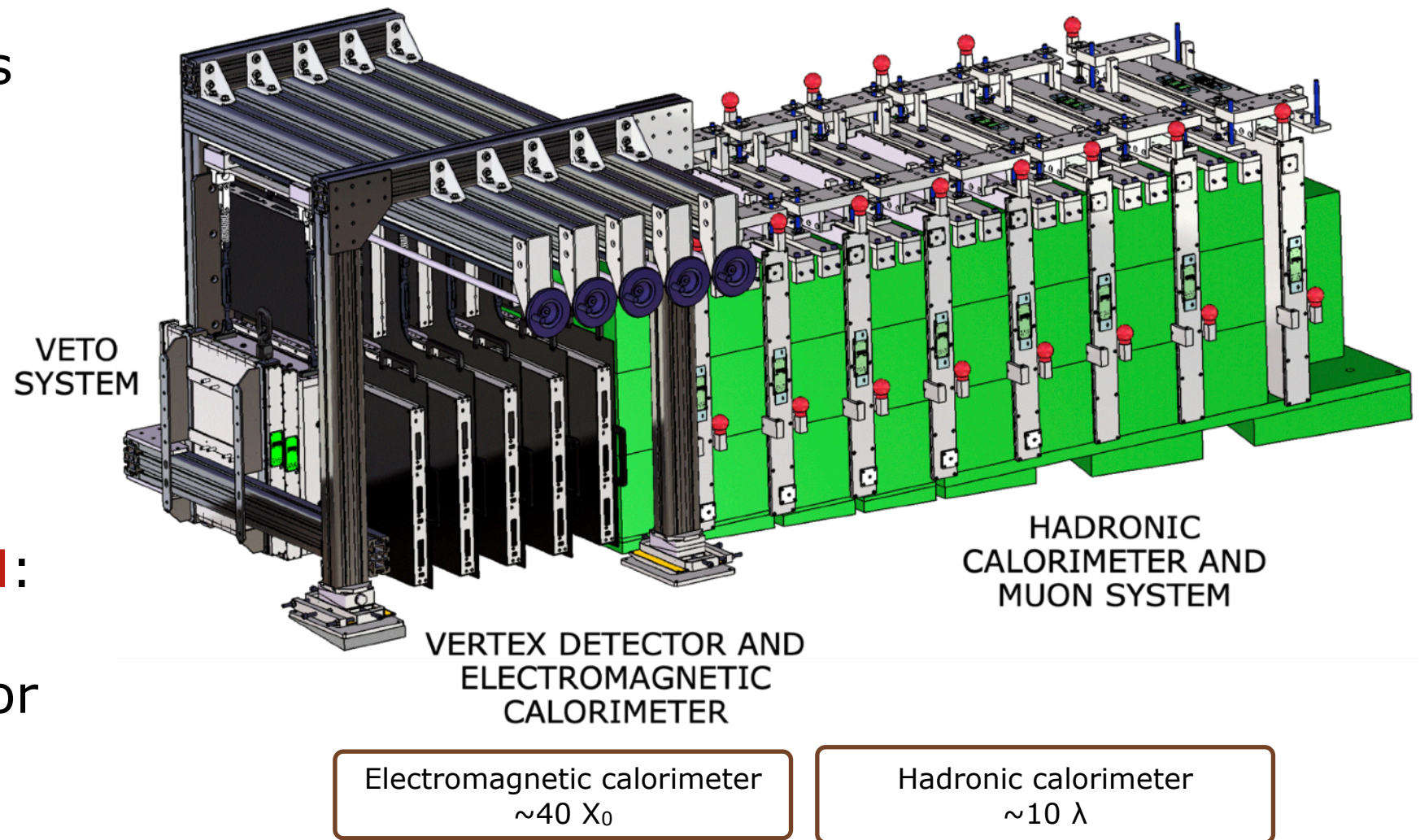
**VETO SYSTEM:**  
tag penetrating muons

**VERTEX DETECTOR + EM CAL:**

- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

**HAD CAL + MUON SYSTEM:**  
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement

- Documentation:
- LOI: [2002.08722](#)
- TP: [CDS: 2750060](#)
- Detector: [2210.02784](#)



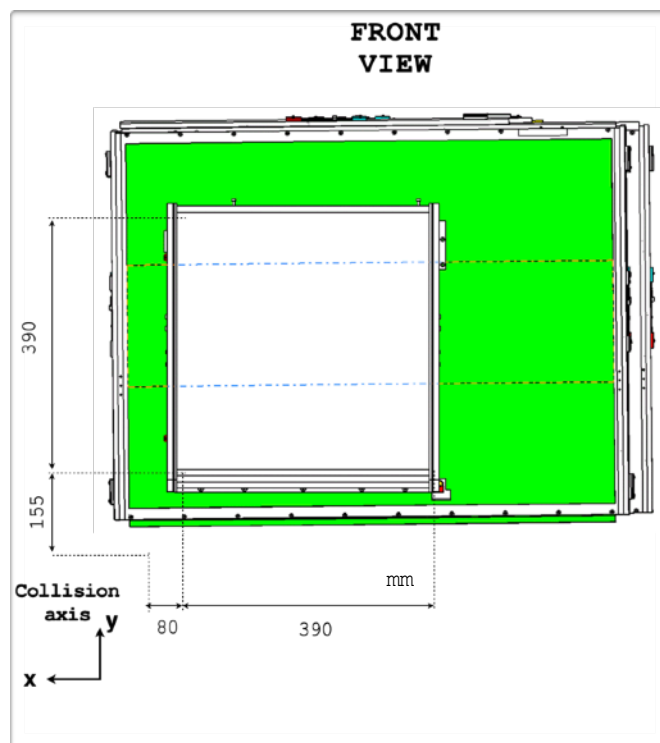
Many thanks to Antonia Di Crescenzo for providing the slides



# SND@LHC Layout

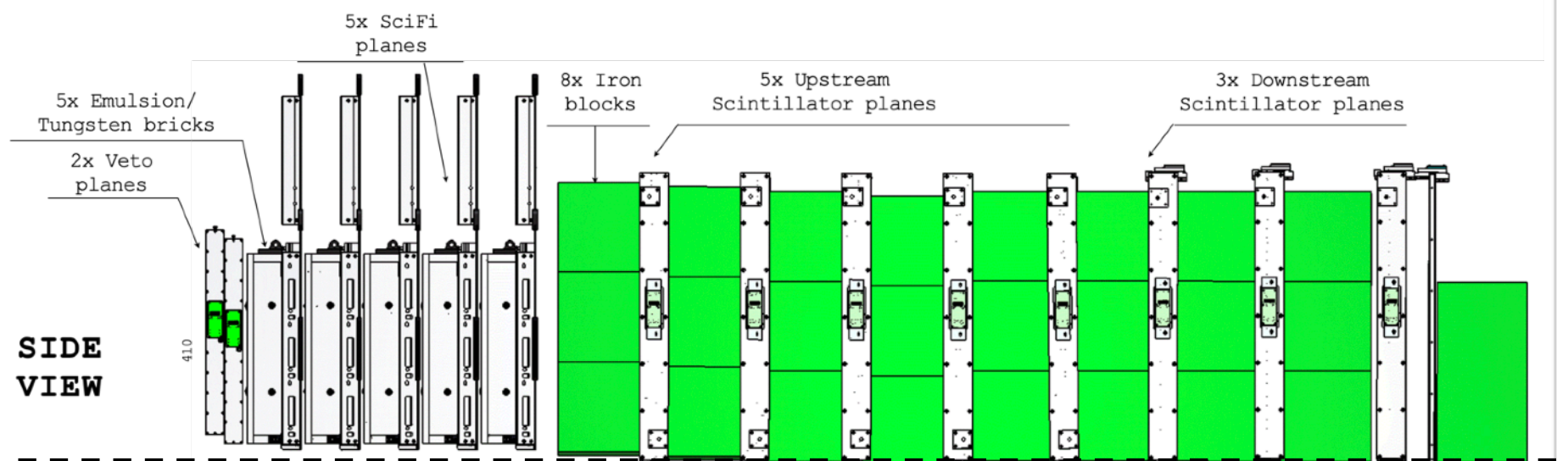
- Angular acceptance:  $7.2 < \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm<sup>2</sup>

Off axis location



Electromagnetic calorimeter  
 $\sim 40 X_0$

Hadronic calorimeter  
 $\sim 10 \lambda$



Many thanks to Antonia Di Crescenzo for providing the slides

# SND@LHC: Installation

- Installation in TI18 started on November 1<sup>st</sup> 2021
- Electronic detector installation completed on December 3<sup>rd</sup> 2021
- Installation of the neutron shield completed on March 15<sup>th</sup> 2022

September 2021



December 2021



March 2022



Many thanks to Antonia Di Crescenzo for providing the slides



# SND@LHC: Installation

---

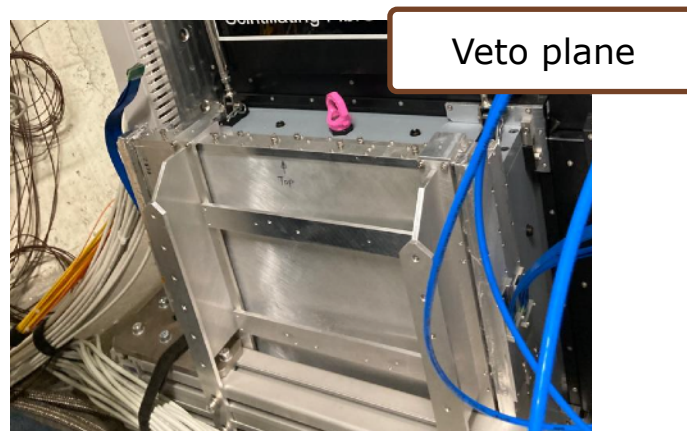
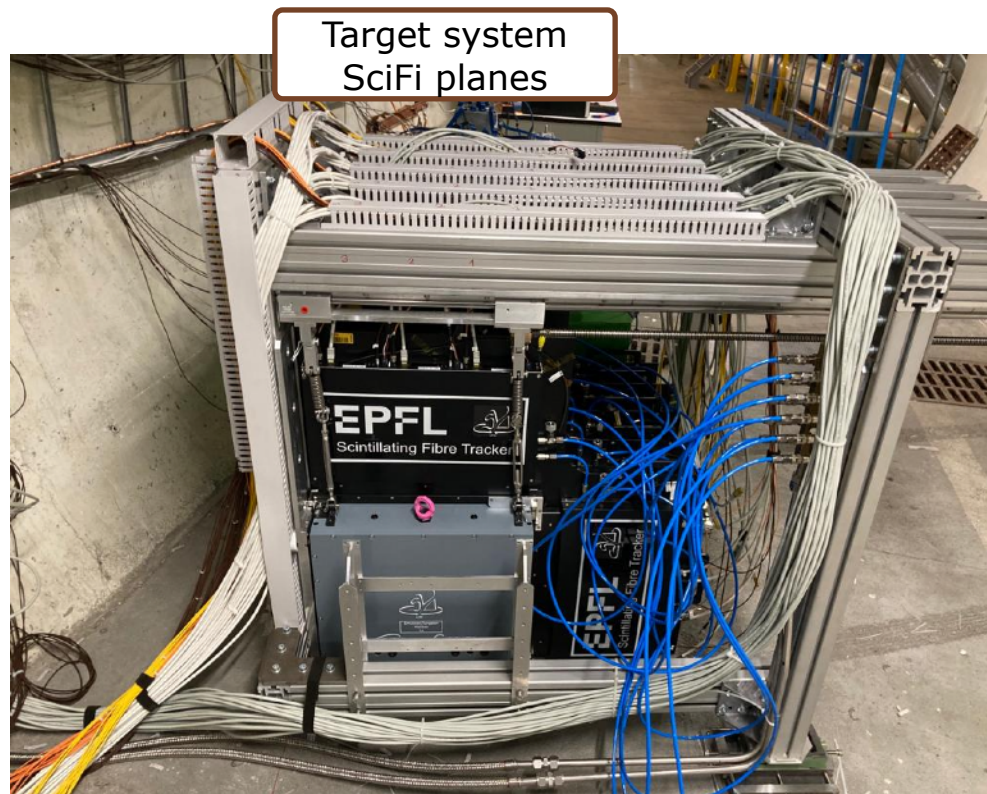
- View of the machine to the IP (left) and of the detector in TI18 (right)



Many thanks to Antonia Di Crescenzo for providing the slides



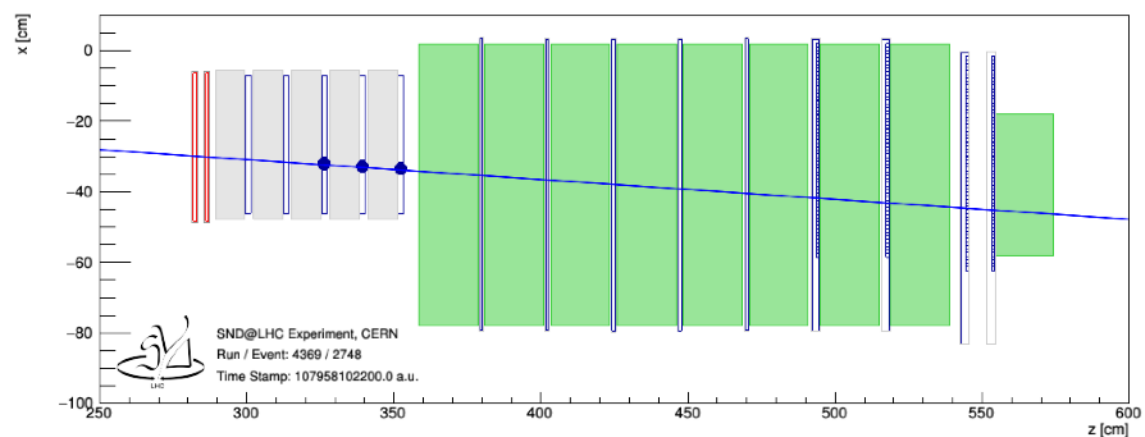
# SND@LHC: Installation



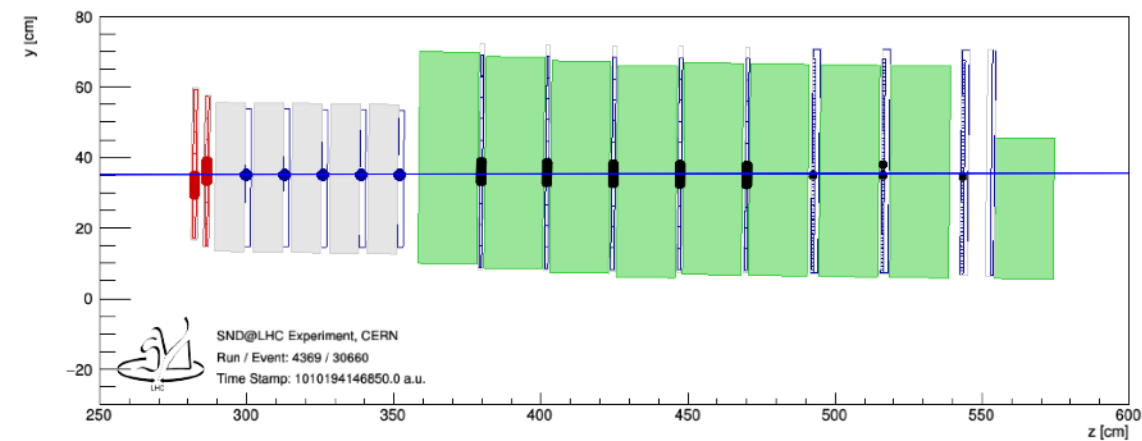
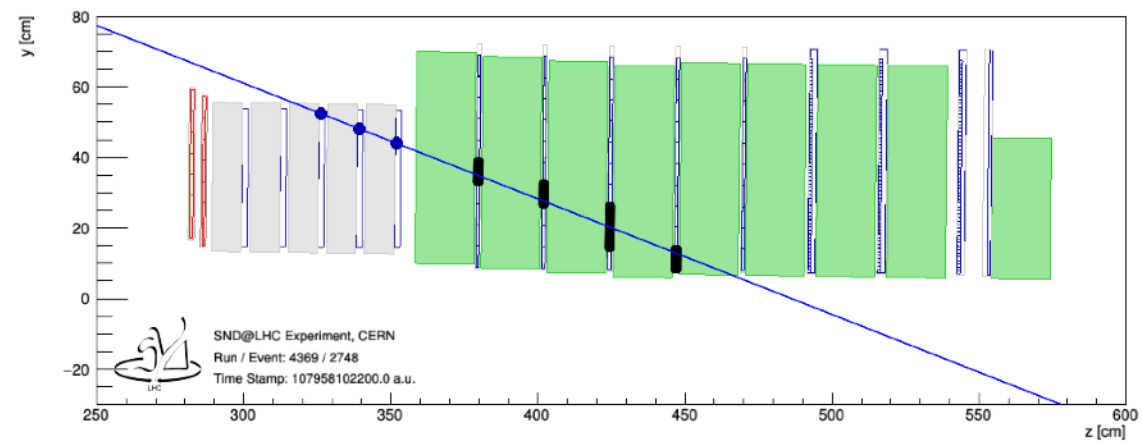
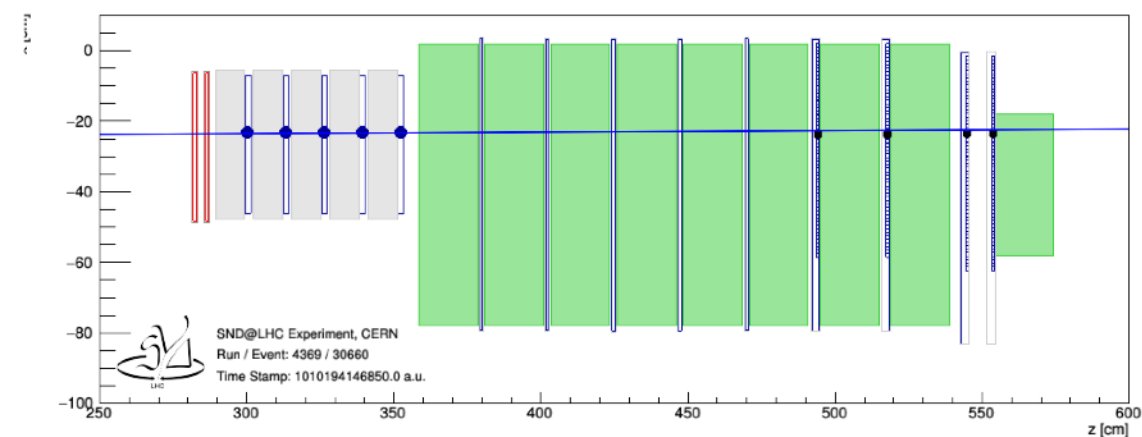
Many thanks to Antonia Di Crescenzo for providing the slides

# SND@LHC: Data Taking in T118

Cosmic ray  
(March 5<sup>th</sup> 2022)



Muon from pp collisions @13.6 TeV  
(July 6<sup>th</sup> 2022)

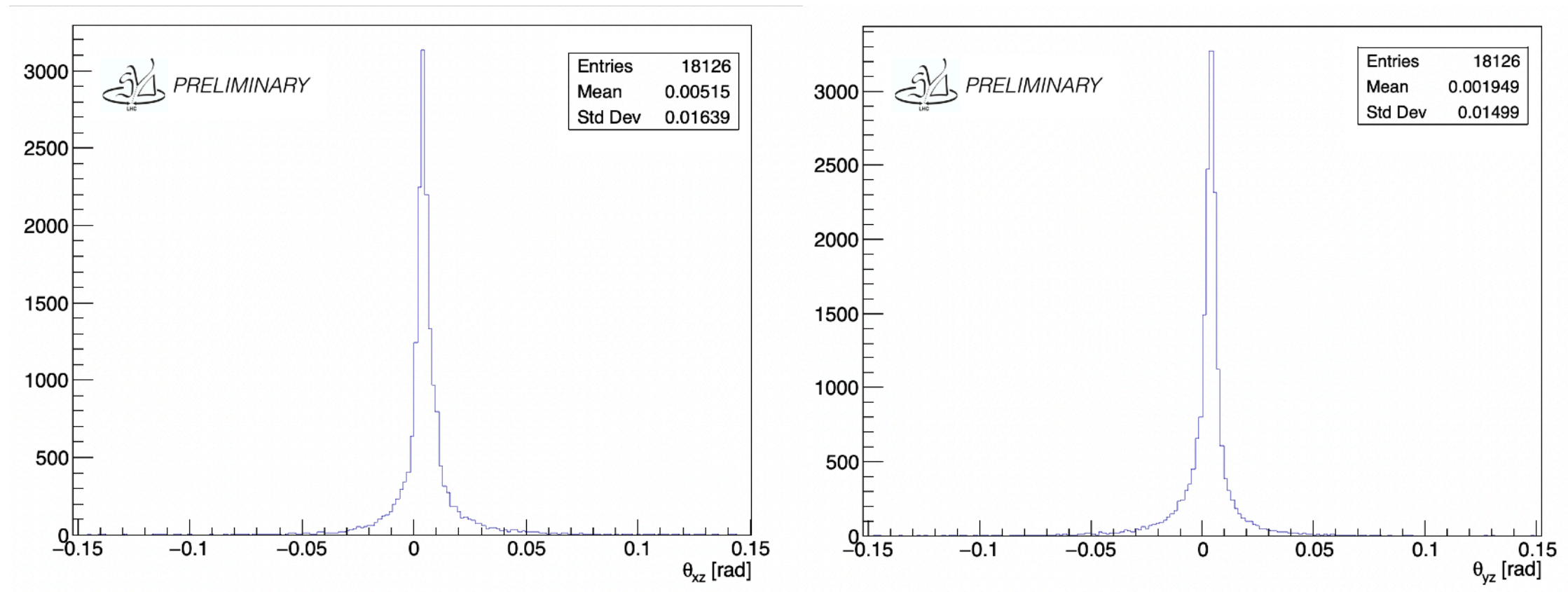


Many thanks to Antonia Di Crescenzo for providing the slides



# SND@LHC: First Beam Data

Reconstructed tracks in the first runs @13.6 TeV  
Direction compatible with coming from pp collisions at IP1



Many thanks to Antonia Di Crescenzo for providing the slides

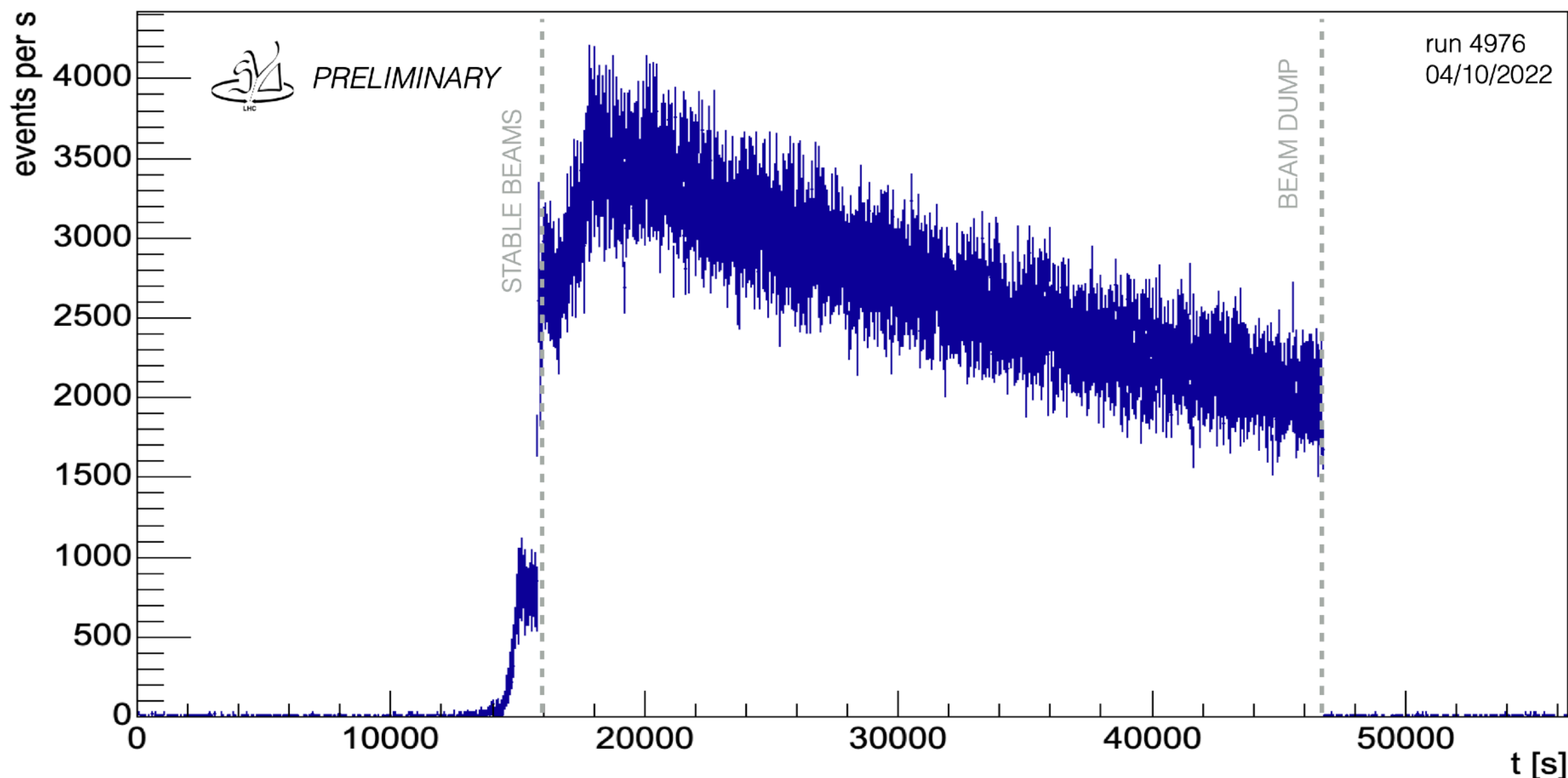


# SND@LHC: Data Taking in T118

Event rate for one run

Start: October 4<sup>th</sup> 2022, 18:12:22

End: October 5<sup>th</sup> 2022, 09:52:21



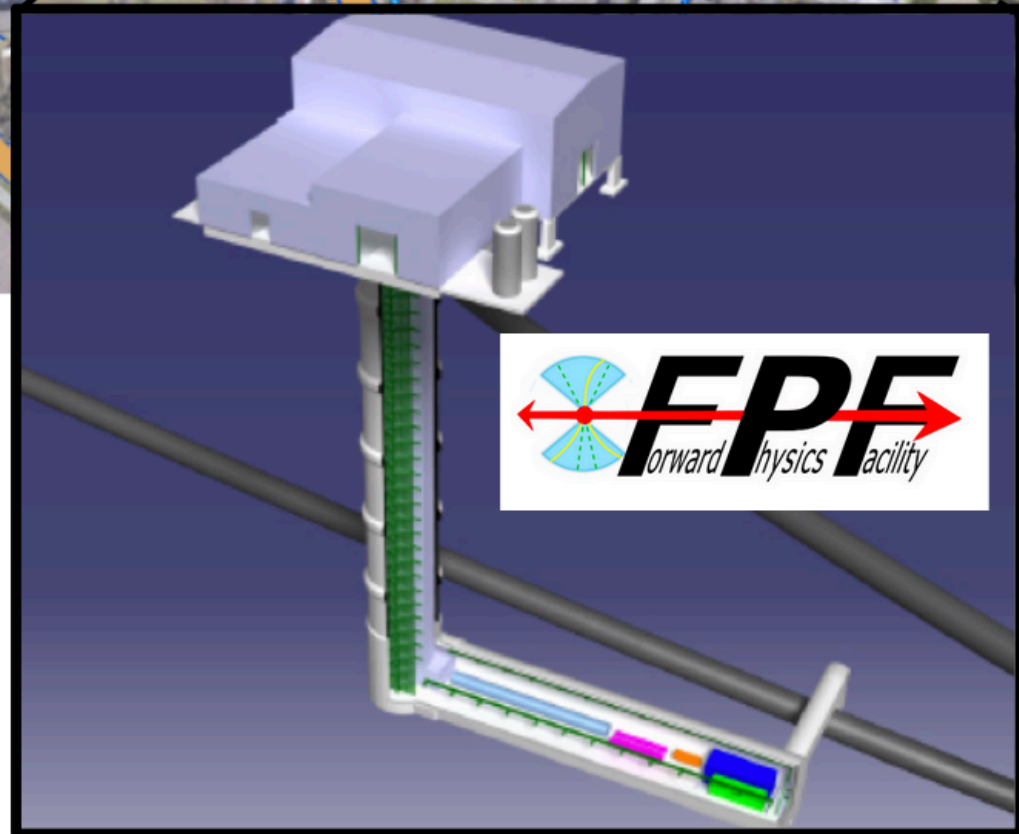
Many thanks to Antonia Di Crescenzo for providing the slides

# **Forward Physics Facility**

# Forward Physics Facility

---

FASER and SND@LHC are currently highly constrained by 1980's infrastructure that was never intended to support experiments

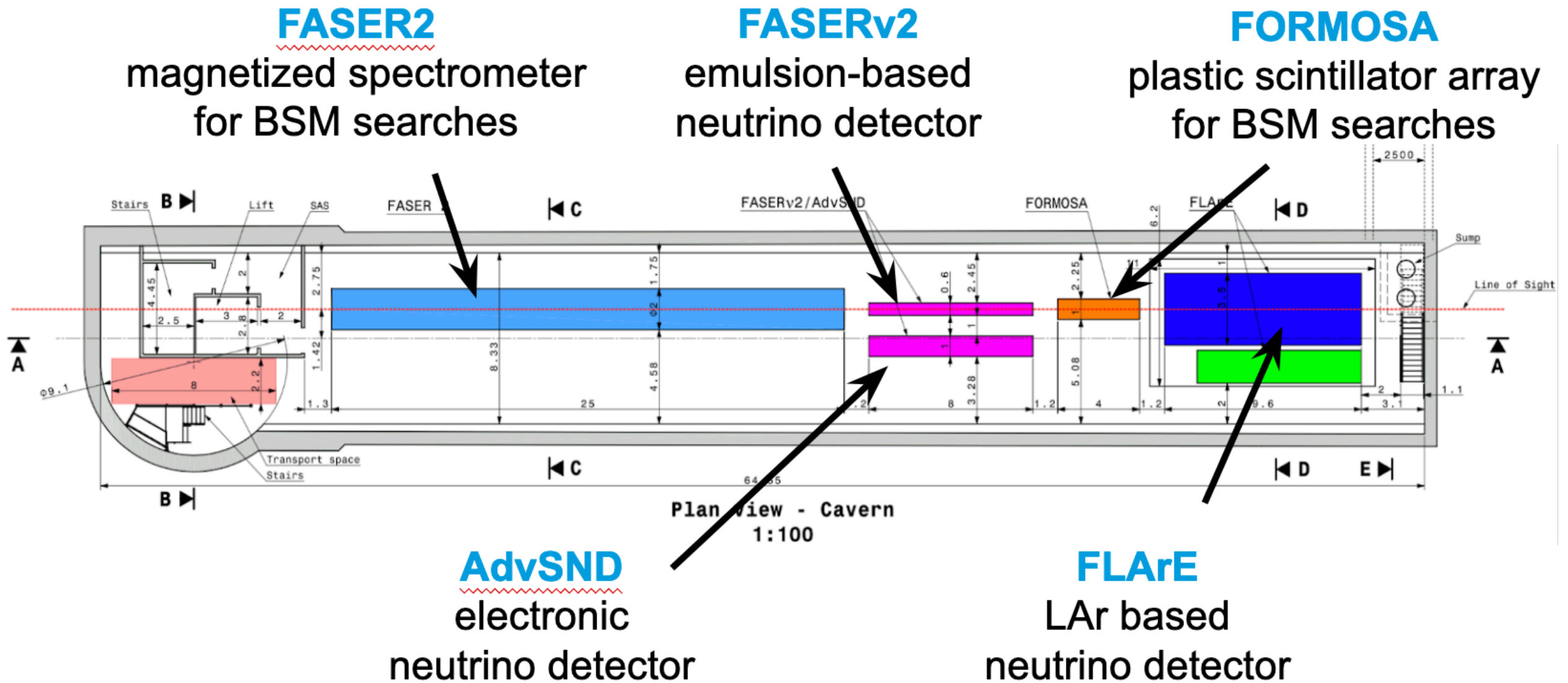


The proposal: create a dedicated **Forward Physics Facility (FPF)** for the HL-LHC.



# Forward Physics Facility

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches**, **neutrino physics** and **QCD**.



# FPF Documentation

**FPF workshop series:**  
[FPF1](#), [FPF2](#), [FPF3](#), [FPF4](#), [FPF5](#)

**FPF Paper:**  
[2109.10905](#)

~75 pages, ~80 authors

**Snowmass Whitepaper:**  
[2203.05090](#)

~450 pages, ~250 authors

4th Forward Physics Facility Meeting

31 January 2022 to 1 February 2022  
Europe/Zurich timezone

Enter your search term

Overview

Call for Abstracts

Timetable

Contribution List

My Conference

My Contributions

Book of Abstracts

Registration

Participant List

Starts 31 Jan 2022, 16:00  
Ends 1 Feb 2022, 21:00  
Europe/Zurich

There are no materials yet.

The Forward Physics Facility (FPF) project is moving forward!

At the 4th Forward Physics Facility Meeting we will discuss the facility, experiments, and physics goals of the proposed FPF at the HL-LHC. The meeting takes place just before the completion of the FPF Snowmass White Paper and will provide an opportunity to summarize the current status of the White Paper and the final steps in its preparation. The whole event will be held online.

The Zoom links are:  
Plenary sessions (both Monday and Tuesday): <https://uci.zoom.us/j/91591021575>  
[u-iive.zoom.us](https://u-iive.zoom.us/j/94645515841)  
[RQnRzTjlpdz09](https://u-iive.zoom.us/j/94645515841)  
[s://uiowa.zoom.us/j/94645515841](https://u-iive.zoom.us/j/94645515841)  
[oom.us/j/97280888150](https://u-iive.zoom.us/j/97280888150)

## The Forward Physics Facility: Sites, Experiments, and Physics Potential

Luis A. Anchordoqui,<sup>1,\*</sup> Akitaka Ariga,<sup>2,3</sup> Tomoko Ariga,<sup>4</sup> Weidong Bai,<sup>5</sup> Kincsó Balazs,<sup>6</sup> Brian Batell,<sup>7</sup> Jamie Boyd,<sup>6</sup> Joseph Bramante,<sup>8</sup> Adrian Carmona, Francesco G. Celiberto,<sup>11,12,13</sup> Grigorios Chachamis,<sup>14</sup> Matthew Citre, Albert de Roeck,<sup>6</sup> Hans Dembinski,<sup>18</sup> Peter B. Denton,<sup>19</sup> Antor Milind V. Diwan,<sup>20</sup> Liam Dougherty,<sup>21</sup> Herbi K. Dreiner,<sup>22</sup> Yong Yasaman Farzan,<sup>25</sup> Jonathan L. Feng,<sup>26,†</sup> Max Fieg,<sup>26</sup> Patric Foroughi-Abari,<sup>28</sup> Alexander Friedland,<sup>29,\*</sup> Michael Fucilla,<sup>30</sup> Maria Vittoria Garzelli,<sup>33,‡</sup> Francesco Giuliani,<sup>34</sup> Victor P. Gonca, Francis Halzen,<sup>37</sup> Juan Carlos Helo,<sup>38,39</sup> Christopher S. Hill,<sup>4</sup> Ameen Ismail,<sup>42</sup> Sudip Jana,<sup>43</sup> Yu Seon Jeong,<sup>44</sup> Krzysztof Jo Kumar,<sup>20</sup> Kevin J. Kelly,<sup>46</sup> Felix Kling,<sup>29,47,§</sup> Rafal Maciula, Abraham,<sup>41</sup> Julien Manshanden,<sup>33</sup> Josh McFayden,<sup>49</sup> Mohammed Pavel M. Nadolsky,<sup>50,\*</sup> Nobuchika Okada,<sup>51</sup> John Osborne,<sup>6</sup> Hic Pandey,<sup>52,46,\*</sup> Alessandro Papa,<sup>30,31</sup> Digesh Raut,<sup>53</sup> Mary Hall R Adam Ritz,<sup>28</sup> Juan Rojo,<sup>55</sup> Ina Sarcevic,<sup>56,\*</sup> Christiane Scherb Holger Schulz,<sup>59</sup> Dipan Sengupta,<sup>60</sup> Torbjörn Sjöstrand,<sup>61,\*</sup> Tyler B. Anna Stasto,<sup>62</sup> Antoni Szczurek,<sup>48</sup> Zahra Tabrizi,<sup>63</sup> Sebastia Yu-Dai Tsai,<sup>26,46</sup> Douglas Tuckler,<sup>66</sup> Martin W. Winkler,<sup>67</sup> Kepin

The Forward Physics Facility (FPF) is a proposal to create a infrastructure to support a suite of far-forward experiments at during the High Luminosity era. Located along the beam collis the interaction point by at least 100 m of concrete and rock, the F that will detect particles outside the acceptance of the existing L will observe rare and exotic processes in an extremely low-backgr work, we summarize the current status of plans for the FPF, in civil engineering in identifying promising sites for the FPF; the L envisioned to realize the FPF's physics potential; and the many physics topics that will be advanced by the FPF, including searc probes of dark matter and dark sectors, high-statistics studies of flavors, aspects of perturbative and non-perturbative QCD, and physics.

Submitted to the US Community Study  
on the Future of Particle Physics (Snowmass 2021)



## The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from an LHC interaction point and shielded by concrete and rock, will host a suite of experiments to probe standard model processes and search for physics beyond the standard model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from standard model expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will trace back to fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector and simulation studies, and on future directions to realize the FPF's physics potential.

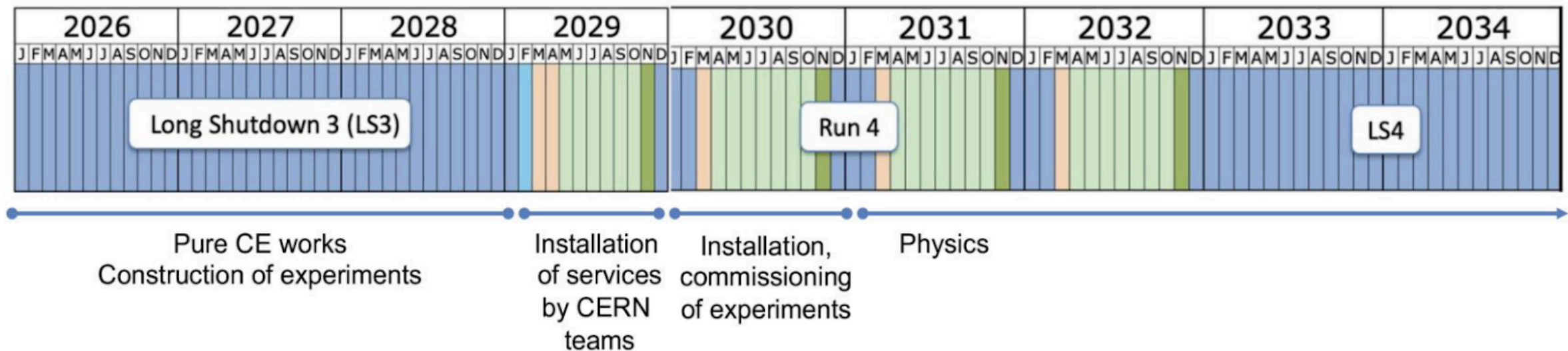
# FPF Timeline

---

radiation protection studies indicate that there is no danger from working in the FPF while the LHC is running

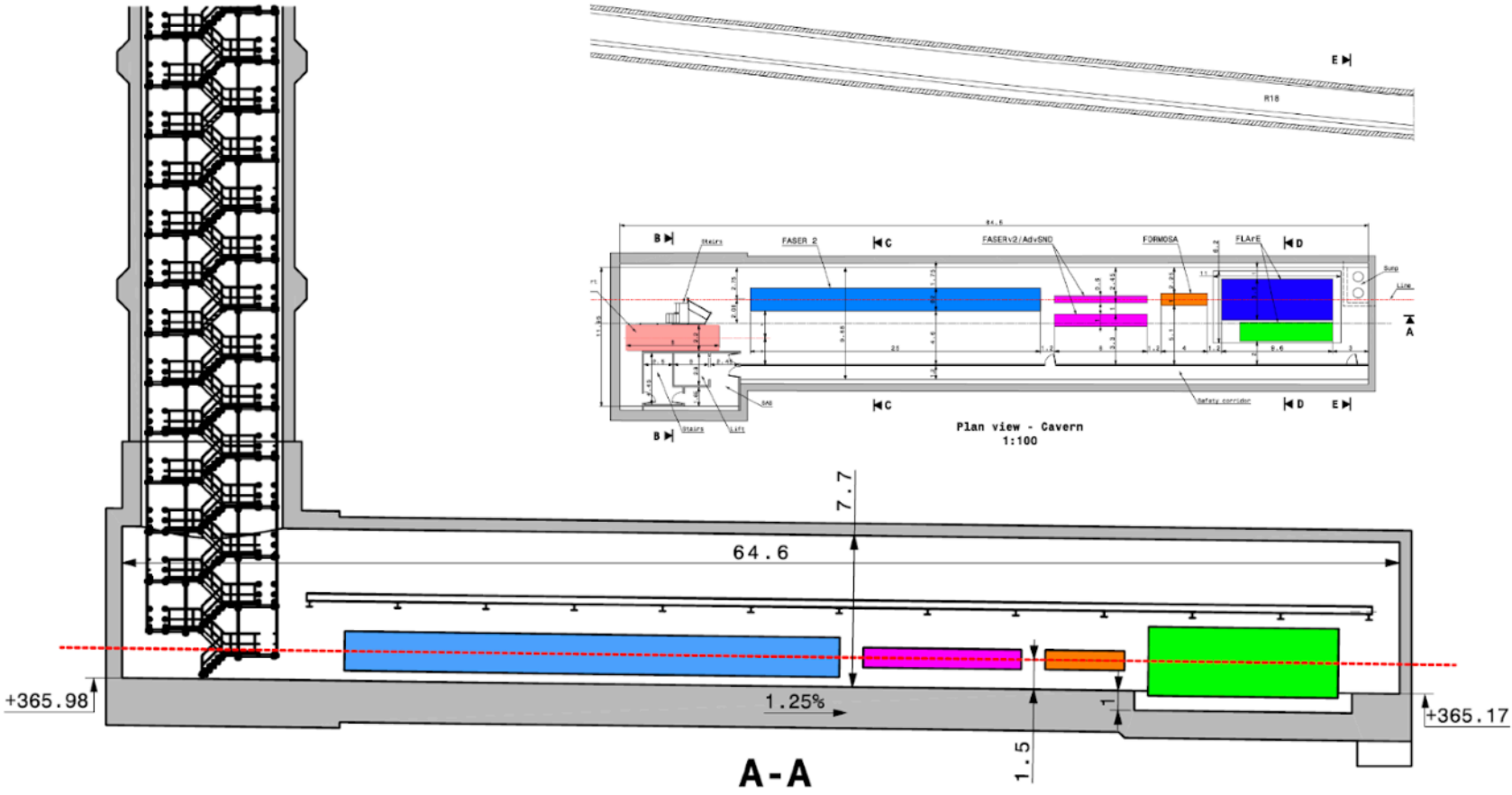
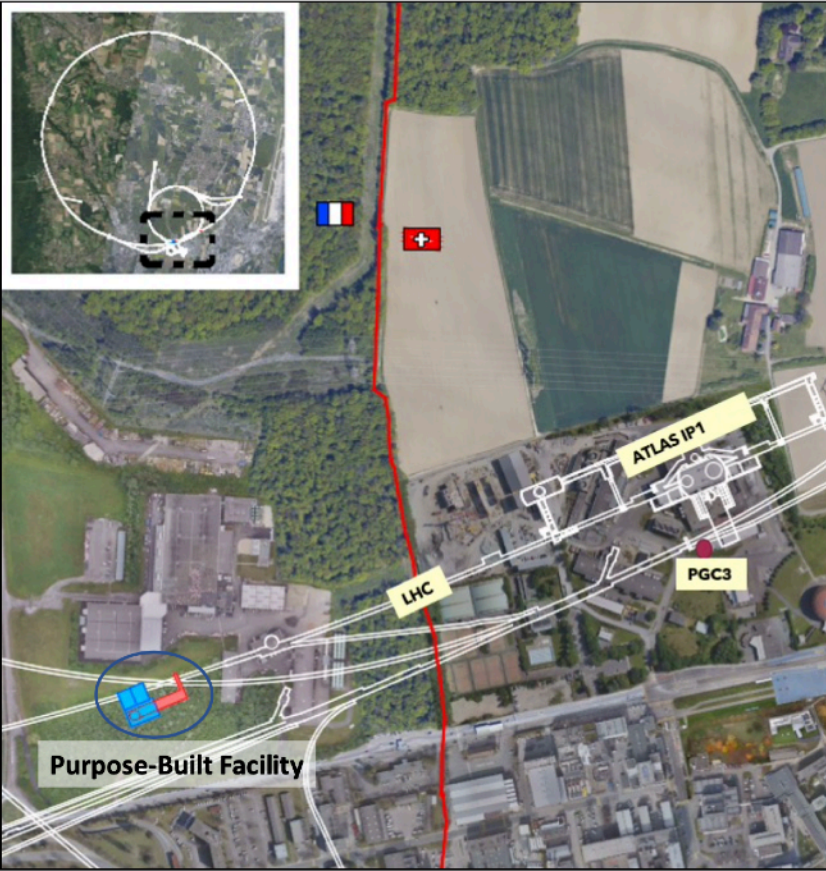
vibration studies indicate that construction of the FPF, installation of services, experiments, will not interfere with LHC operations

## Possible timeline

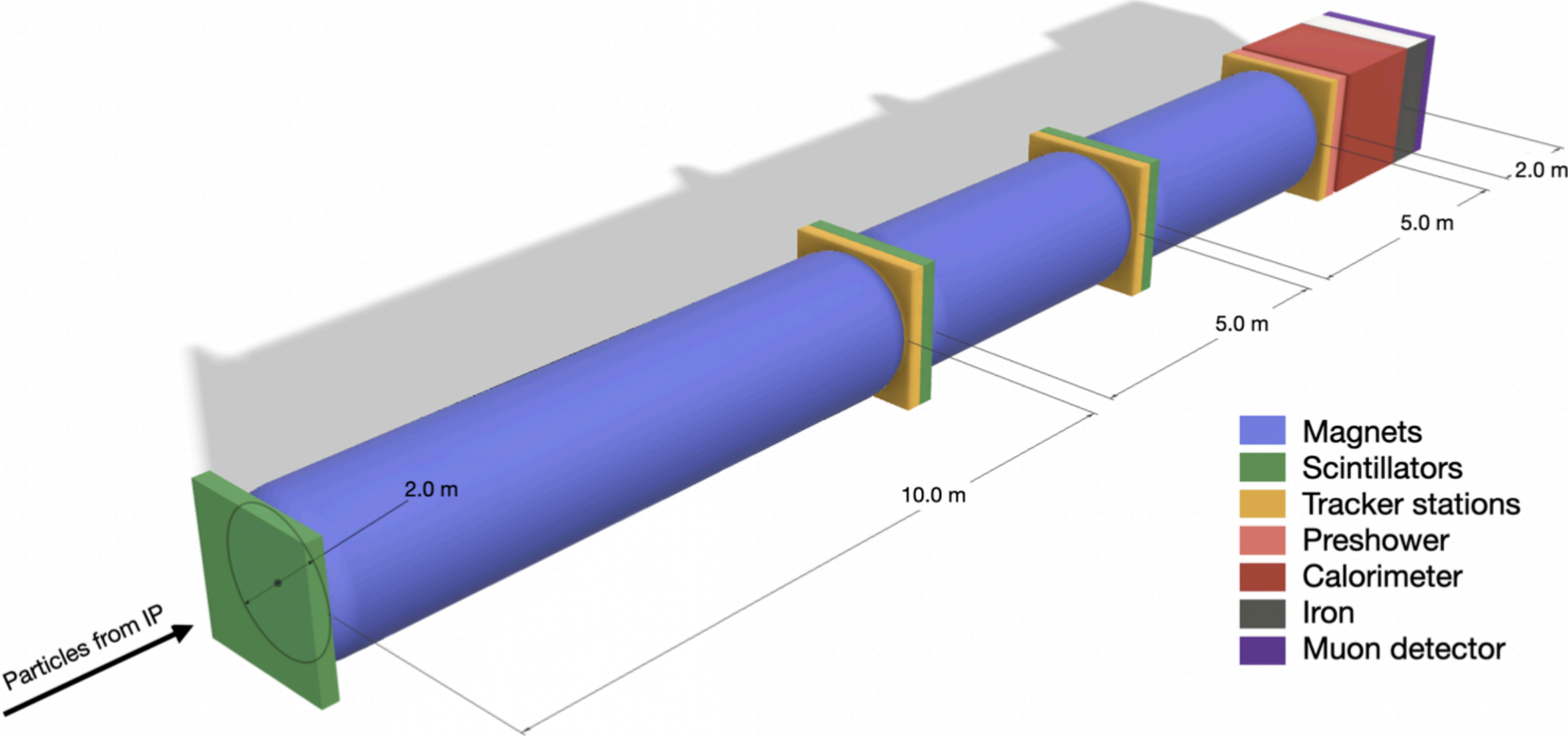




# FPF Facility

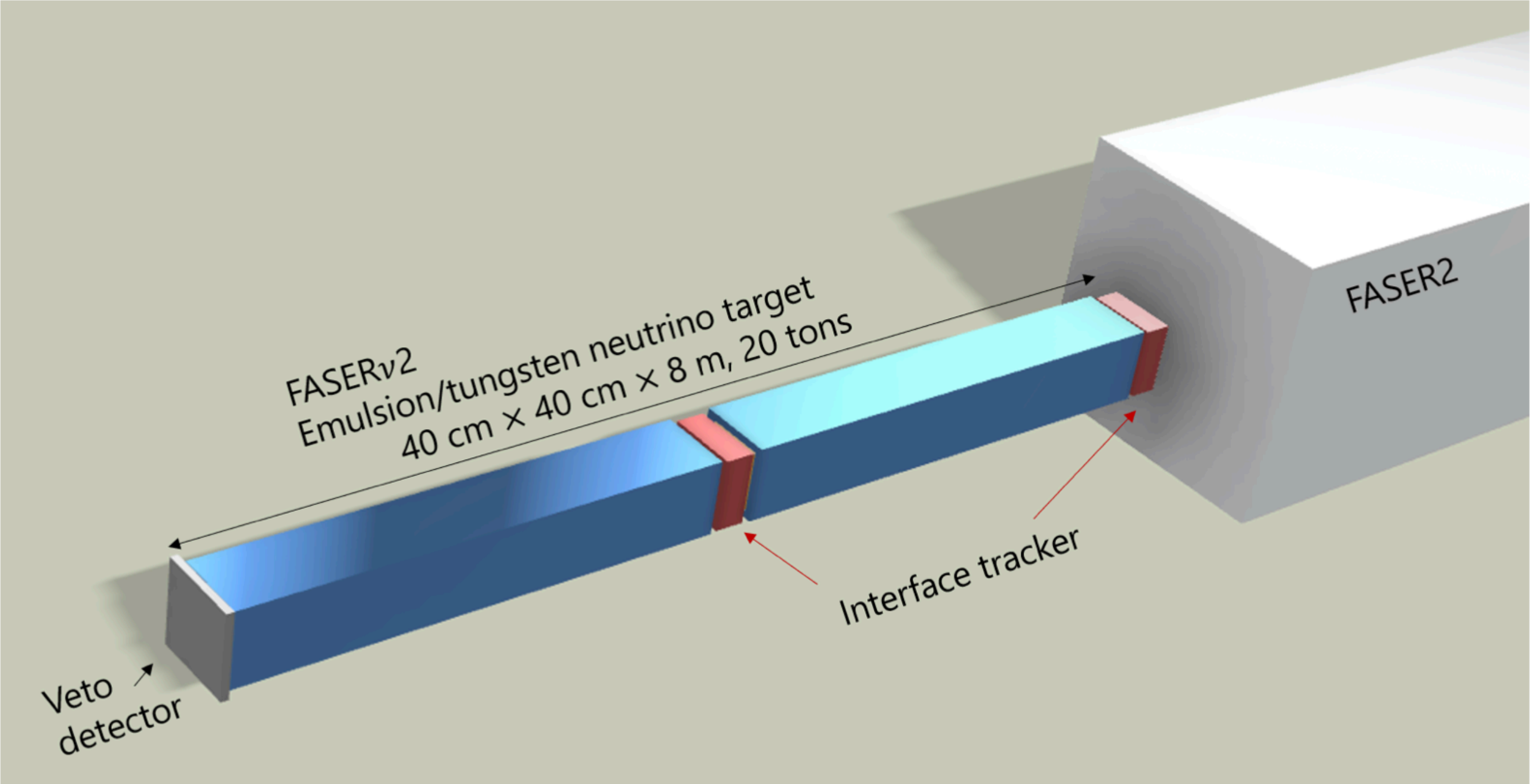


# FPF Experiments: FASER2



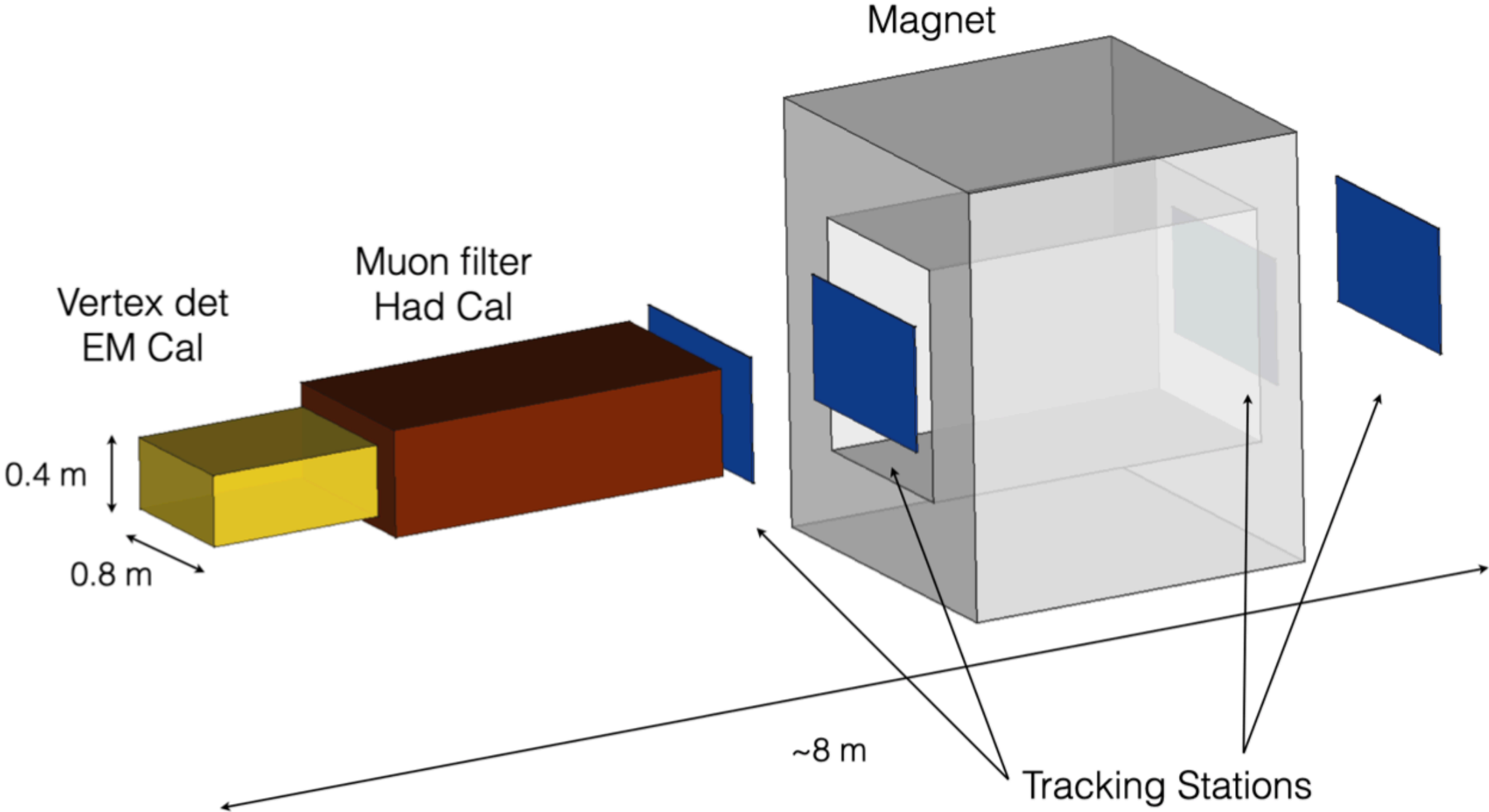
# FPF Experiments: FASERv2

---



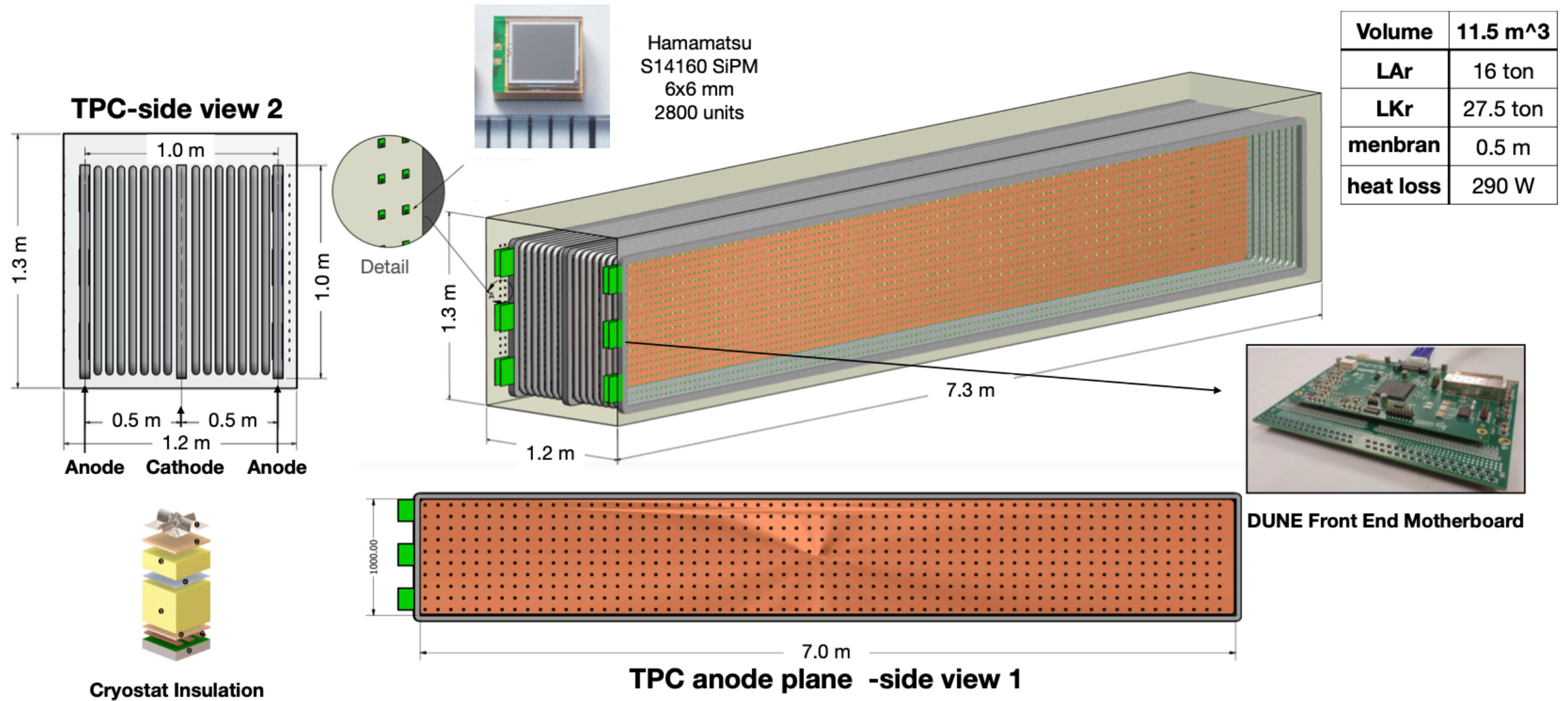


# FPF Experiments: Advanced SND



# FPF Experiments: FLArE

## FLArE Detector Preliminary Sketch



# FPF Experiments: FORMOSA

---

