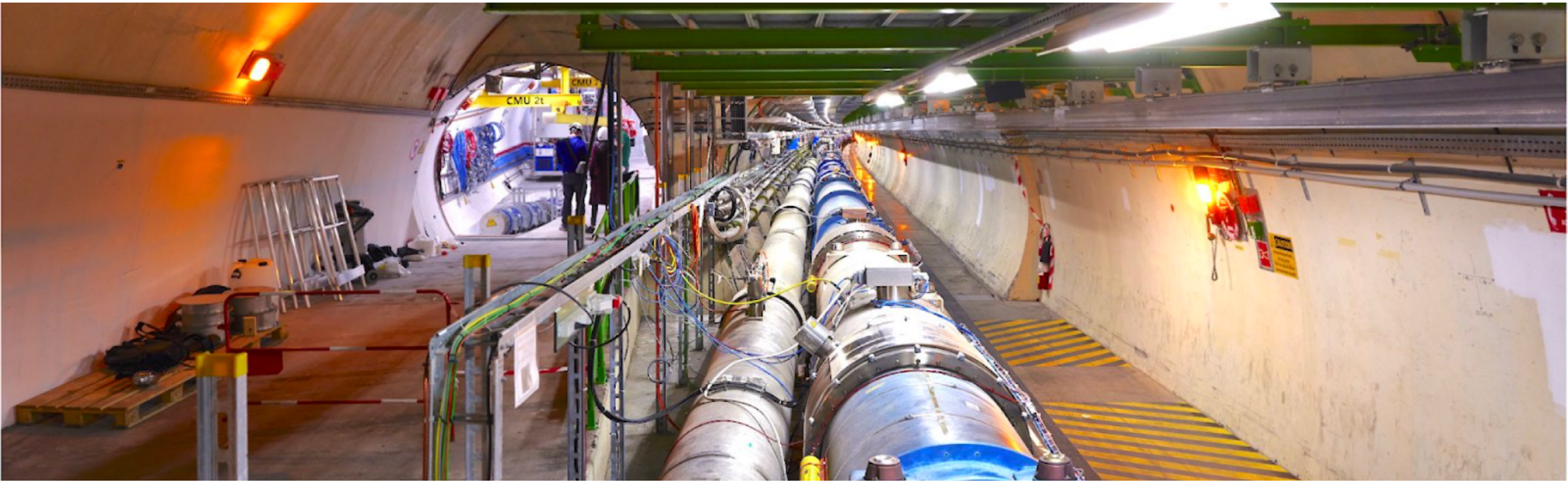
Academic Training Lecture Programme:

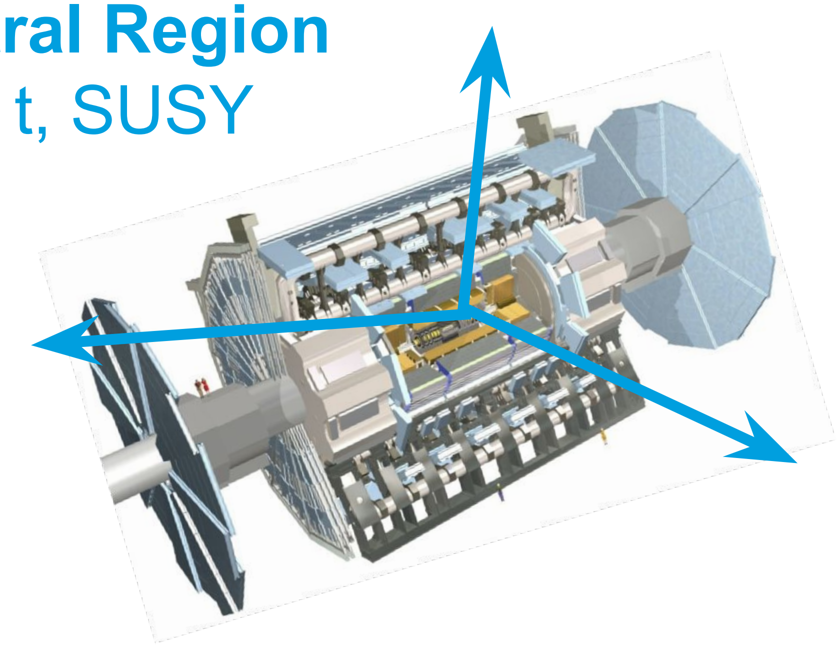
Forward detectors at the LHC for searches and high energy neutrinos measurements



Lecture 1: Experiments and Detectors

October 19th 2022
Felix Kling

Idea and Motivation

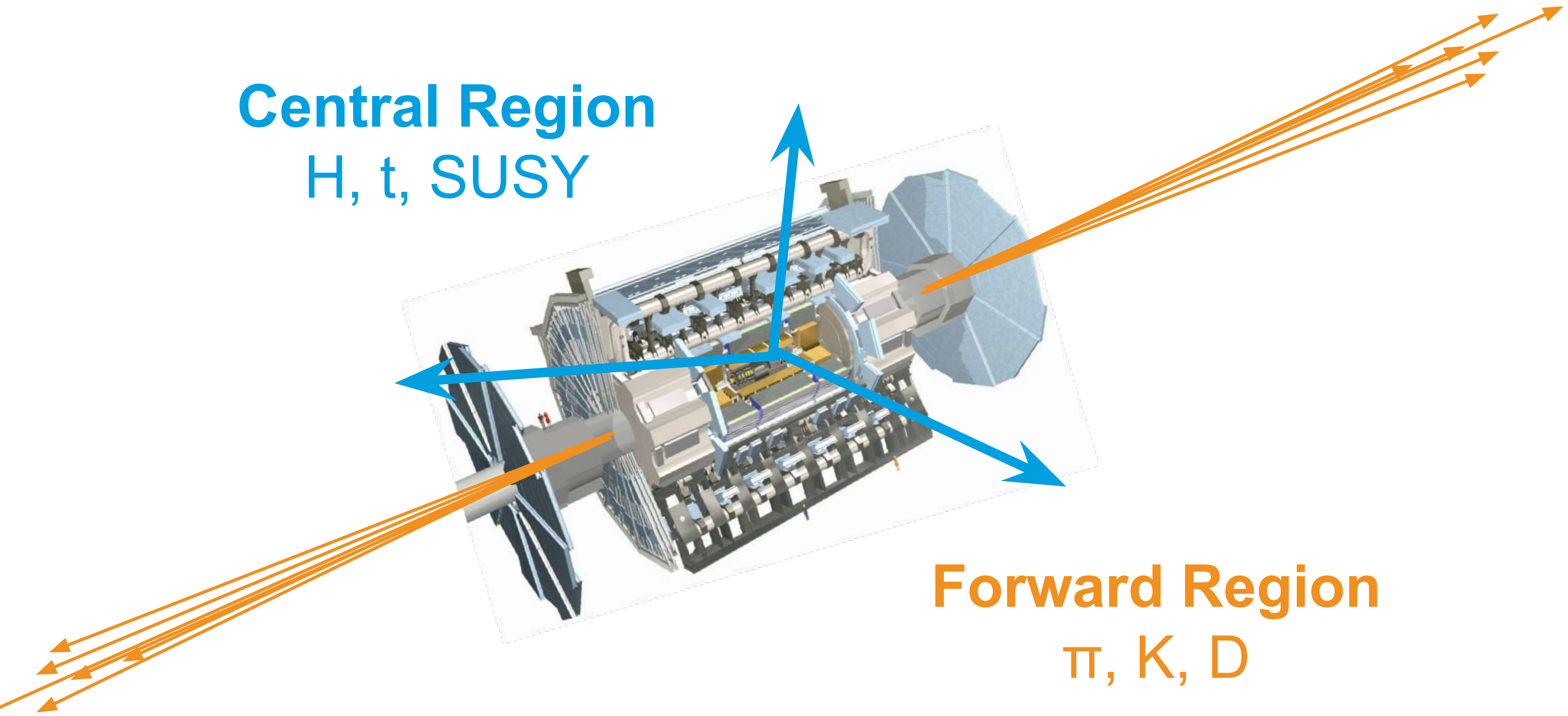


Idea and Motivation

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

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

Can we do something with that?



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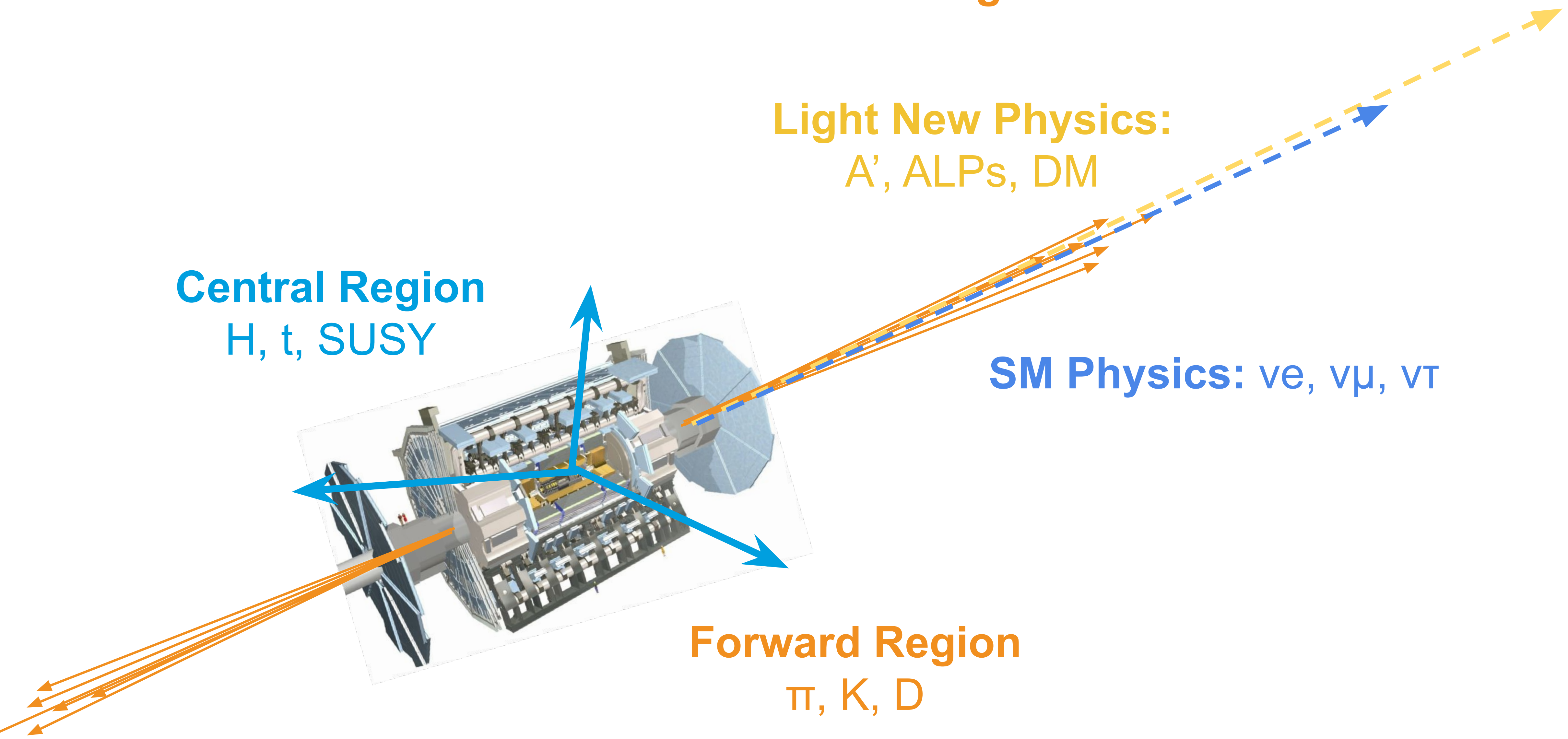

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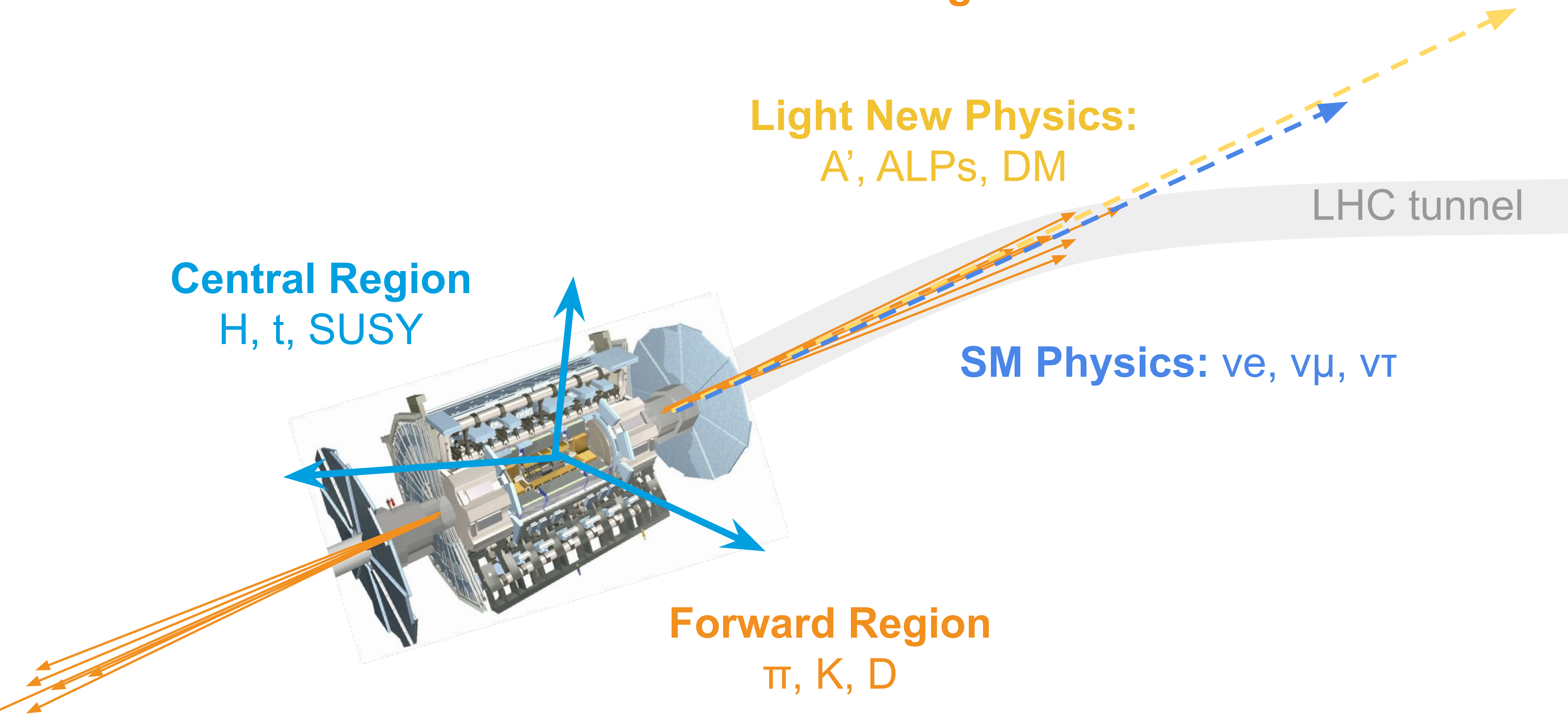

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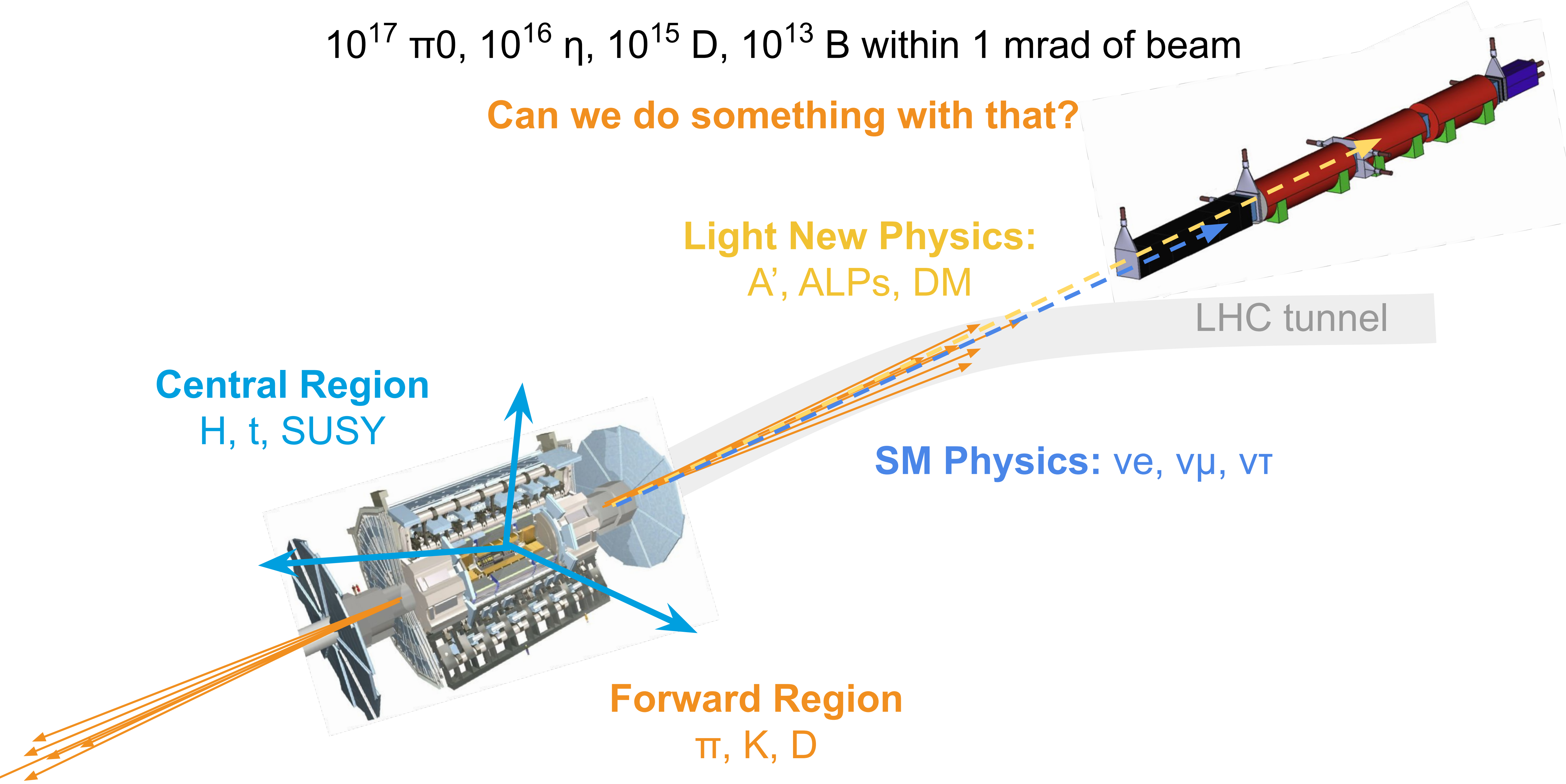
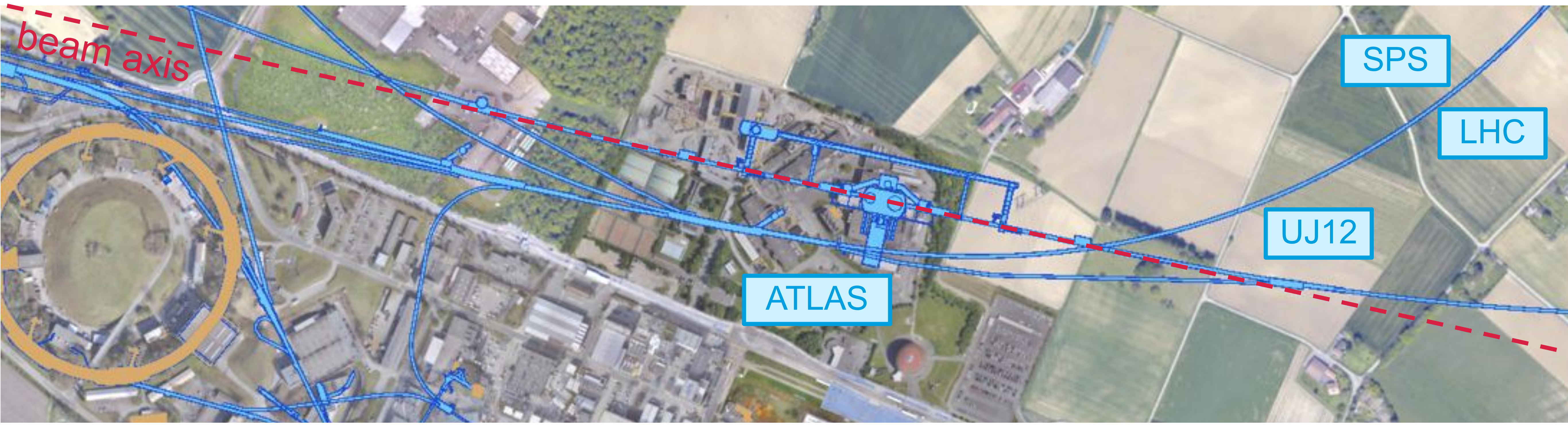


Location

There is potential for forward physics experiments along beam axis.



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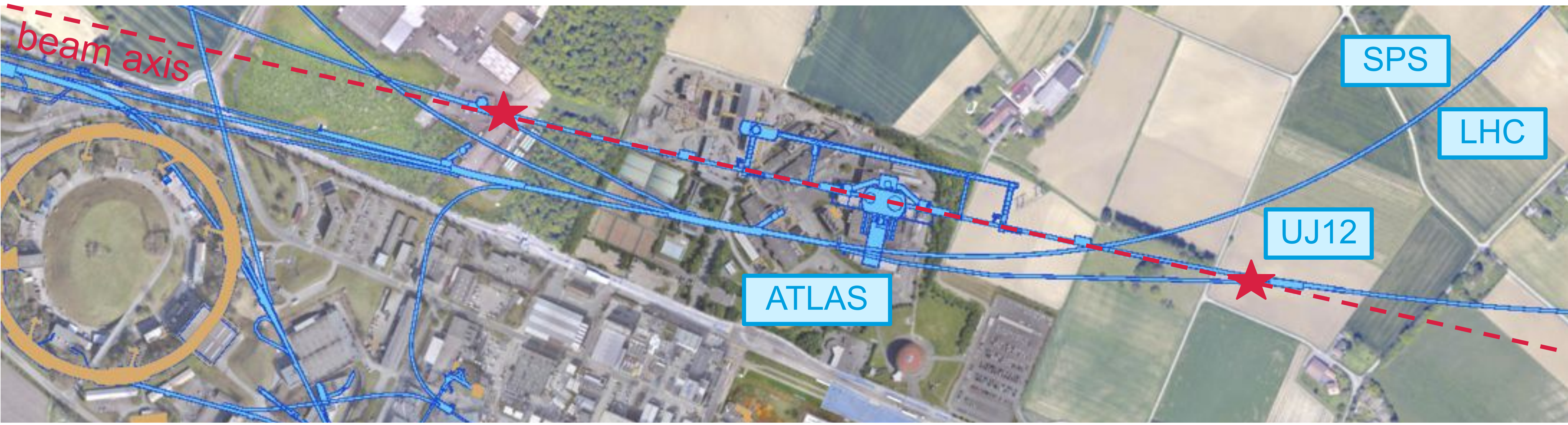
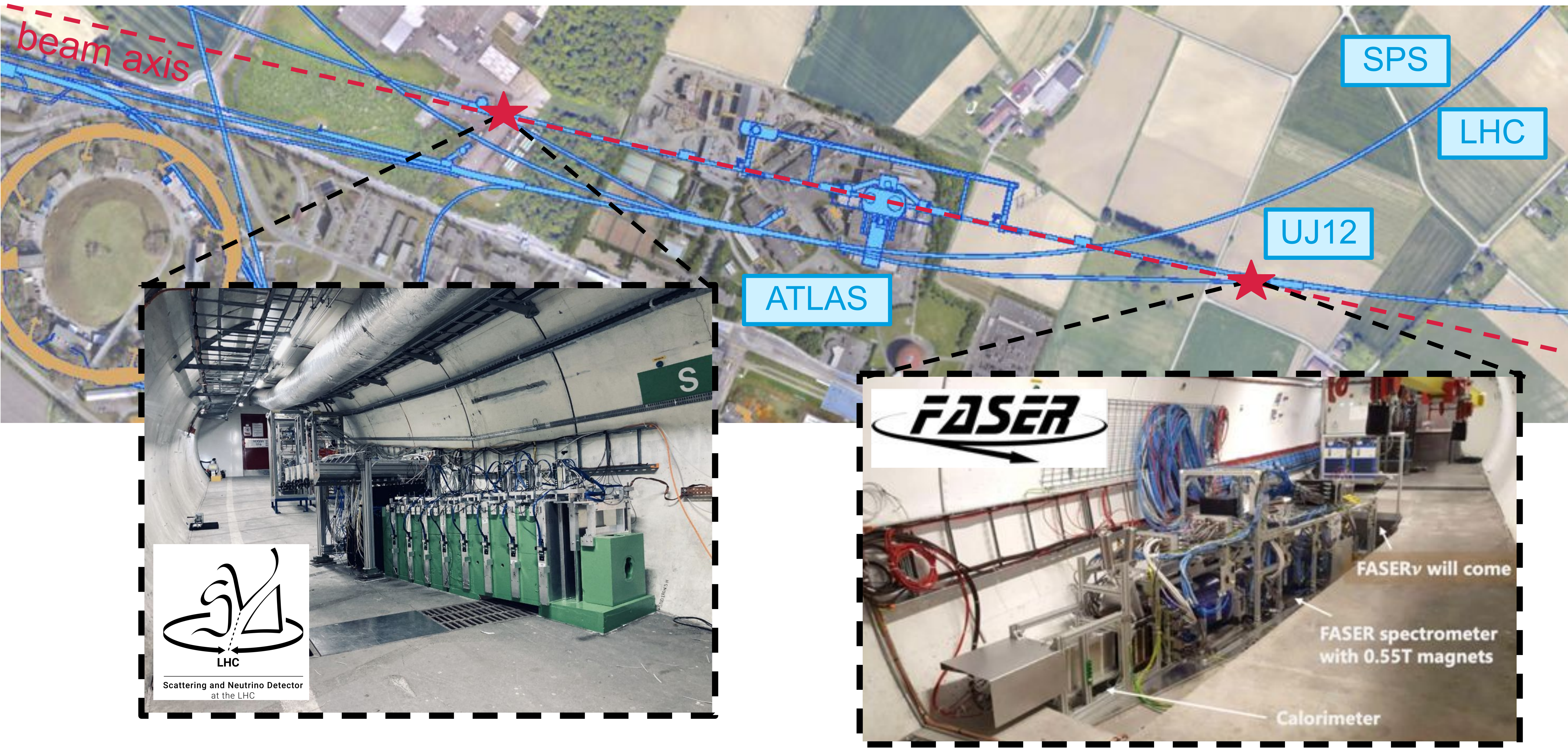


Location

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, FASERν — 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

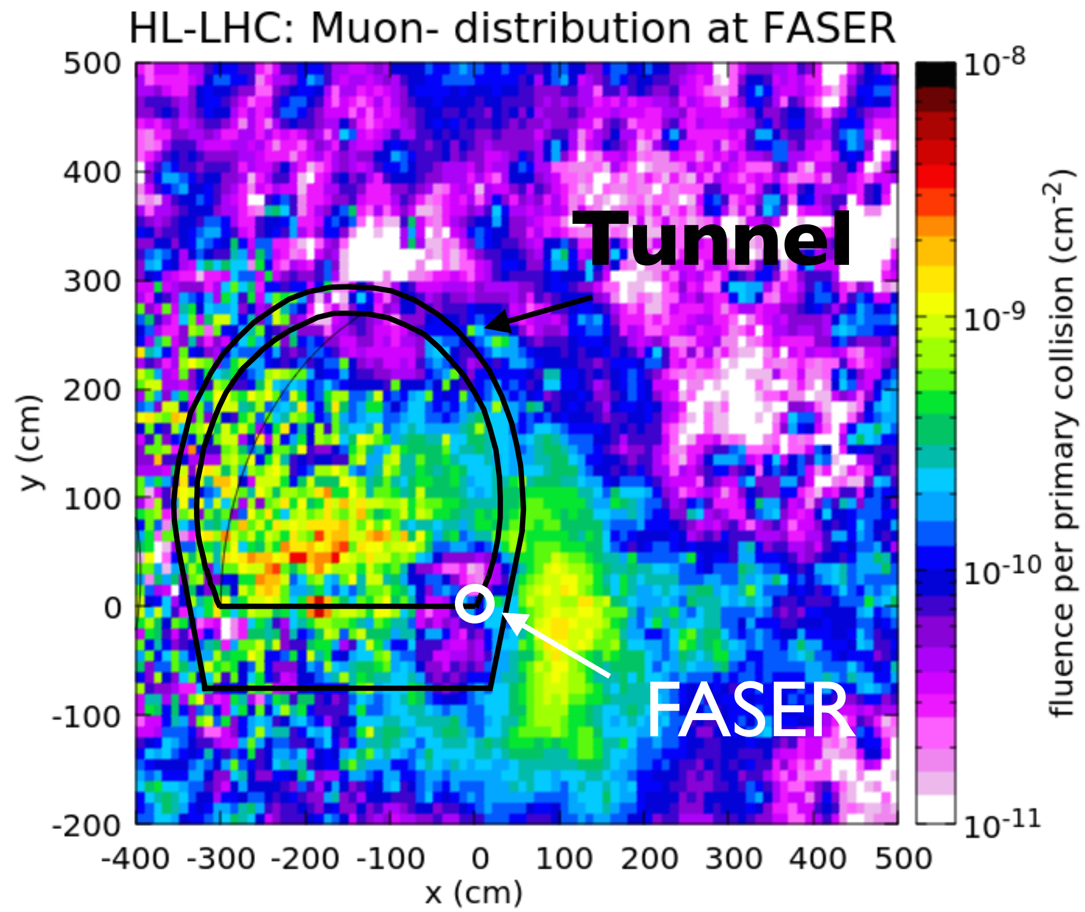
Environment

One Slide of Physics Motivation

General Considerations

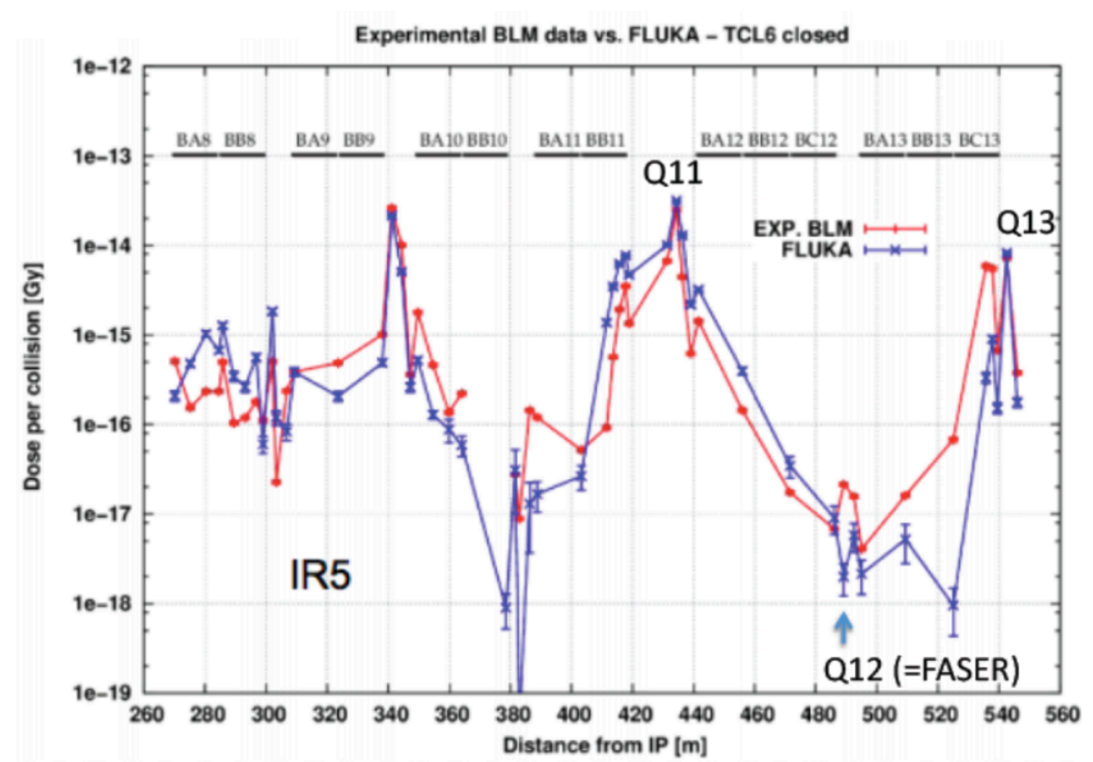
- LLP/neutrino signals have TeV energies, come from ATLAS IP
- shielding: natural (rock) and LHC infrastructure (magnets, absorbers)
- only muons/neutrino can transport TeV energies through ~100m rock

→ TI12/TI18 location is pretty quiet



FLUKA simulation (by CERN STI group)

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



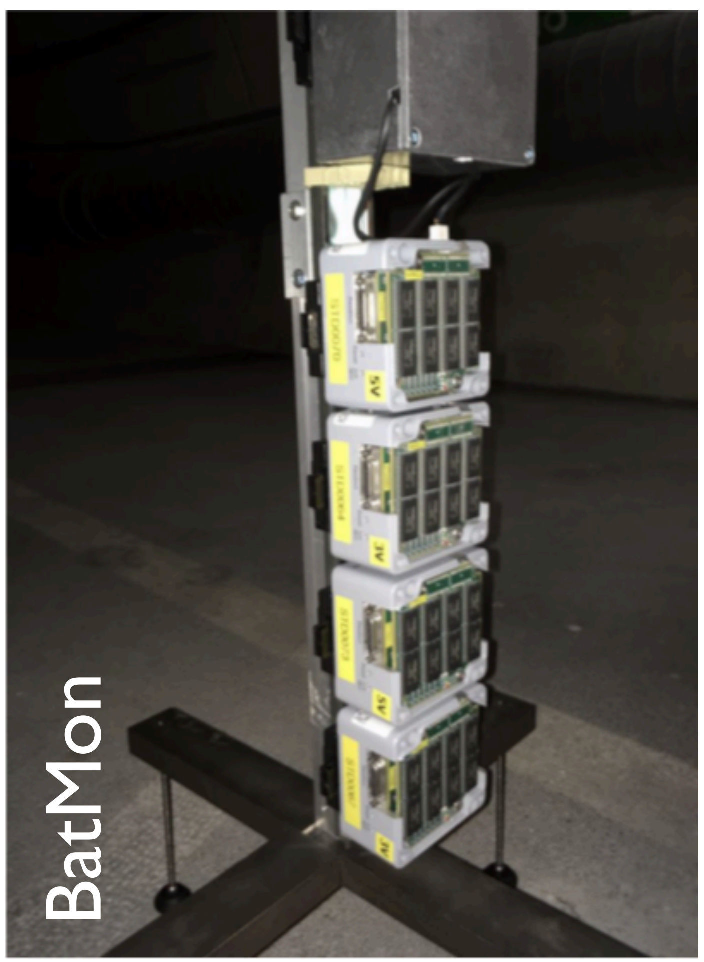
Sabate-Gilarte, Cerutti, Tsinganis (2018)

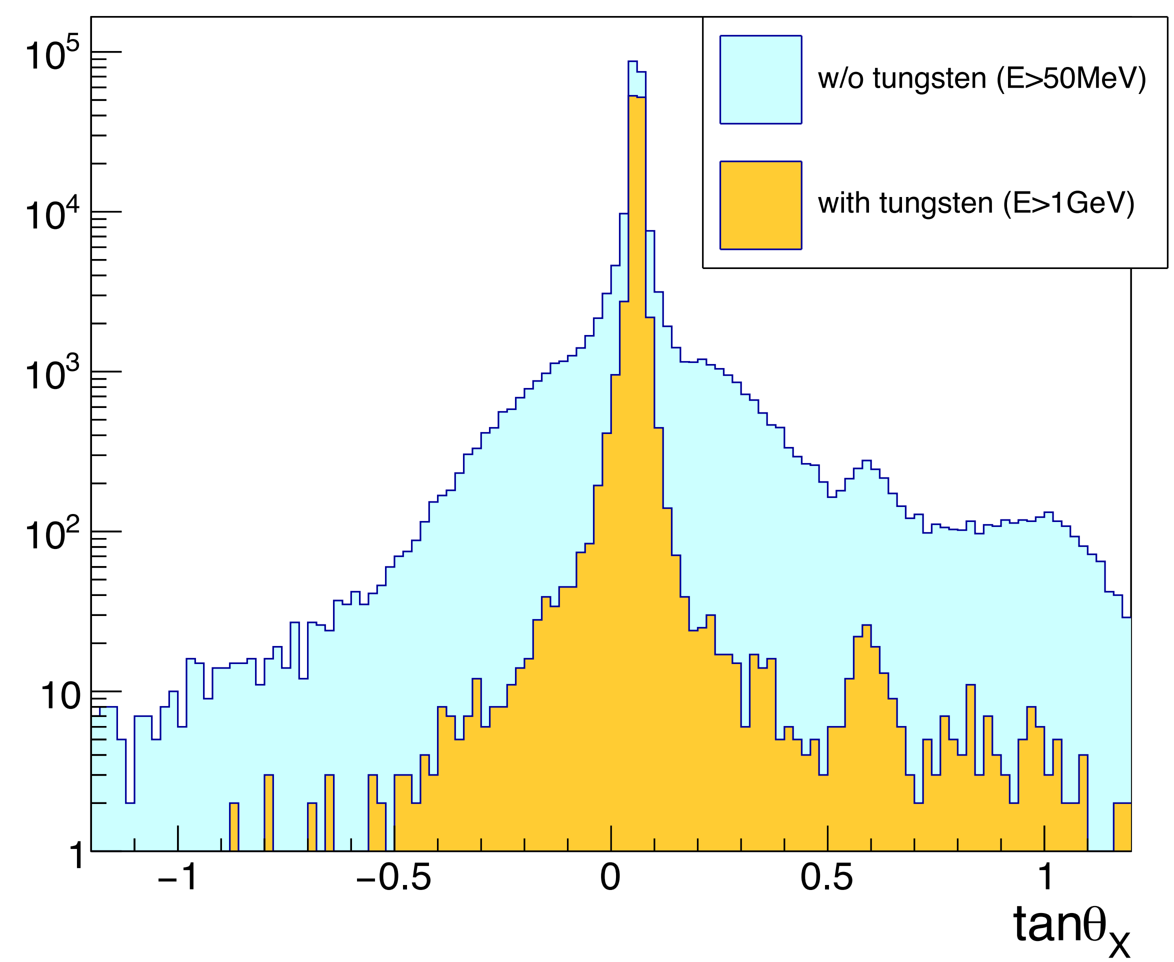
One Slide of Physics Motivation

In-Situ Measurements

- BatMon radiation monitor:
  * low-energy radiation levels are promisingly low
- emulsion detector installed in 2018 in both TI18 and TI12
  * consistent with FLUKA simulations
  * more data analysis on-going

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





FASER

One Slide of Physics Motivation

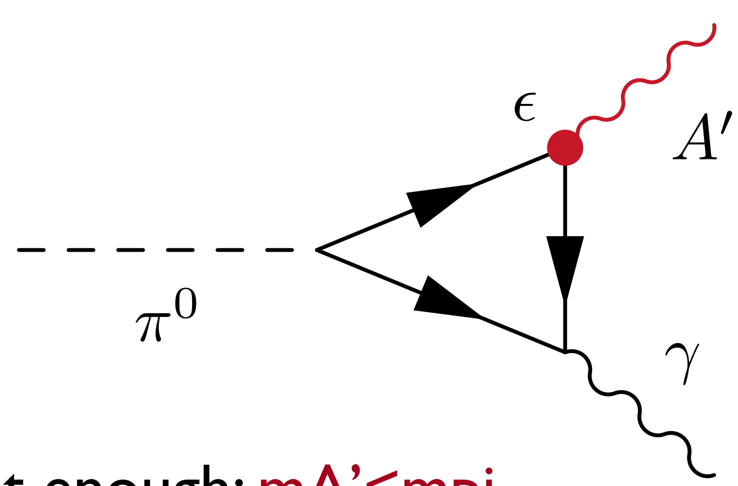
There are light long-lived particles in the SM: muon, pion, kaon, neutron …

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

Example: dark photon

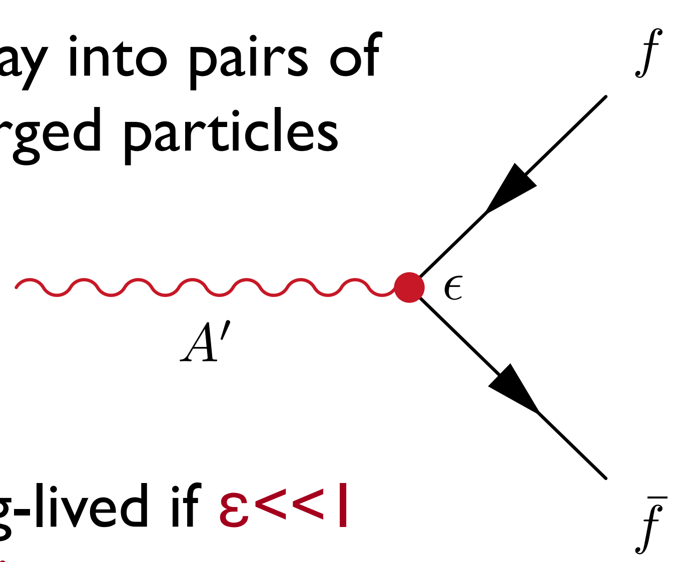
similar to the SM photon but with mass mA’ and couplings to SM particles suppressed by ε

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



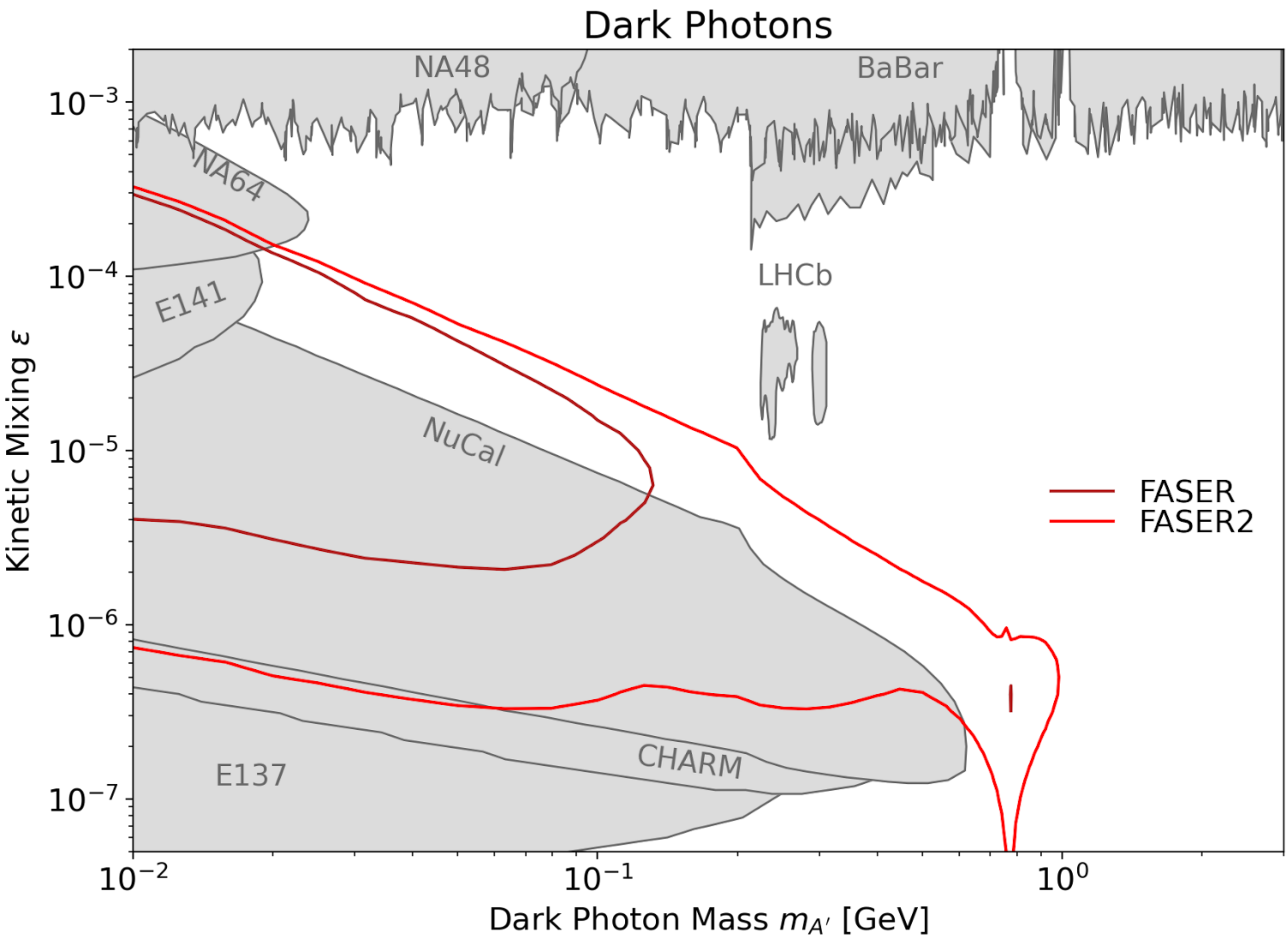
if light enough: mA’<mpi
produced via meson decays

- decay into pairs of charged particles



- long-lived if ε<<1 lifetime

One Slide of Physics Motivation

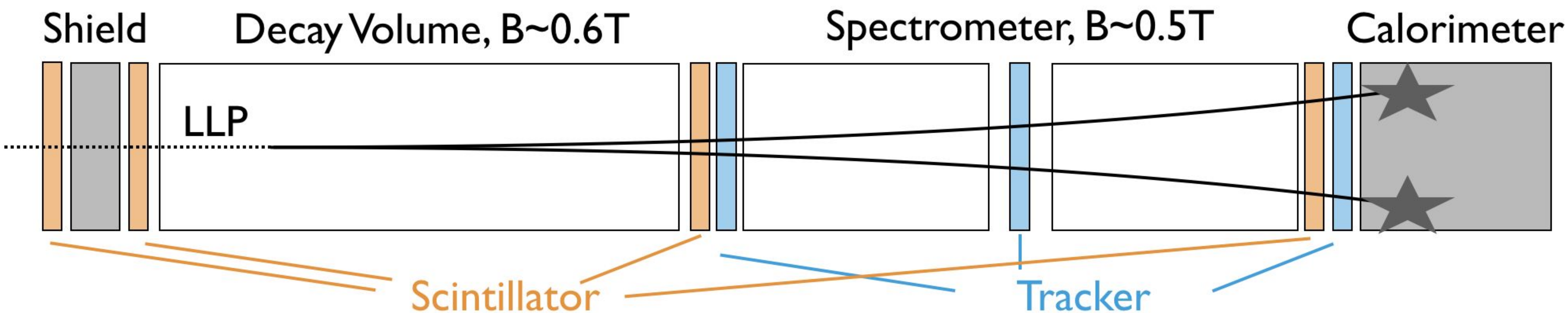


Detector Design

FASER: search for light long-lived particles

pp → LLP + X, LLP travels ~ 480m, LLP → charged tracks + X

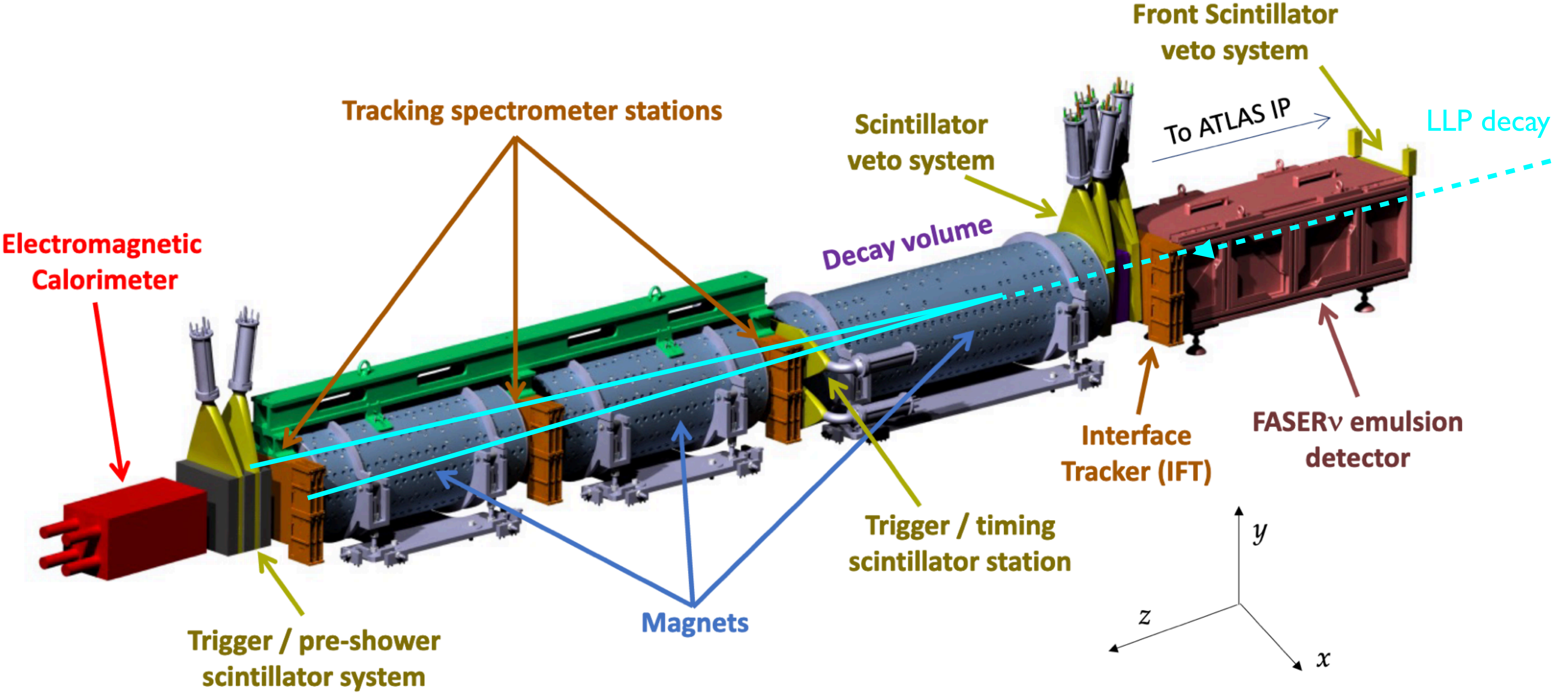
Signal is striking:
* highly energetic particles (E ~ TeV)
* common vertex in an empty decay volume
* point back to the IP through 90 m of rock

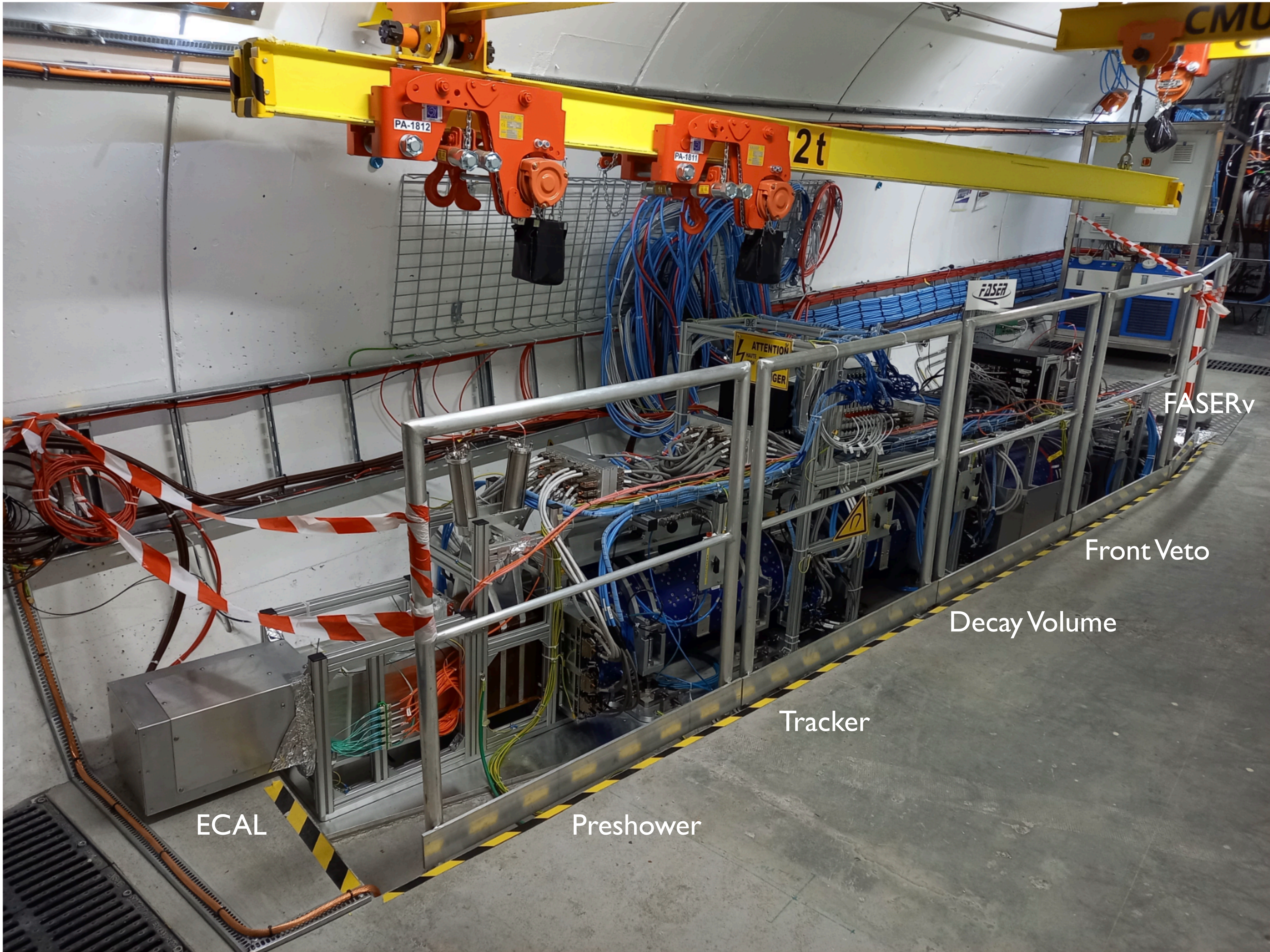


Background considerations:
* large flux of muons from the LHC cause muon-associated radiative events
* use scintillators veto to reduce BG to negligible levels

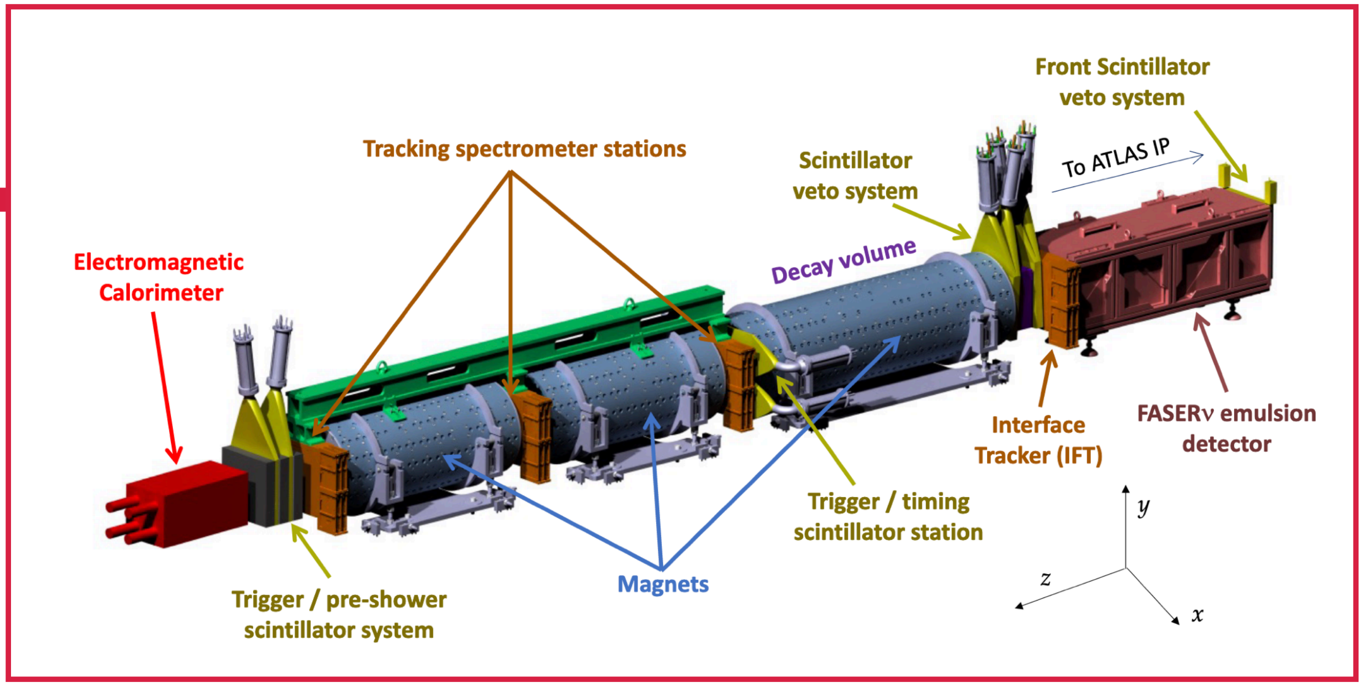
FASER Detector

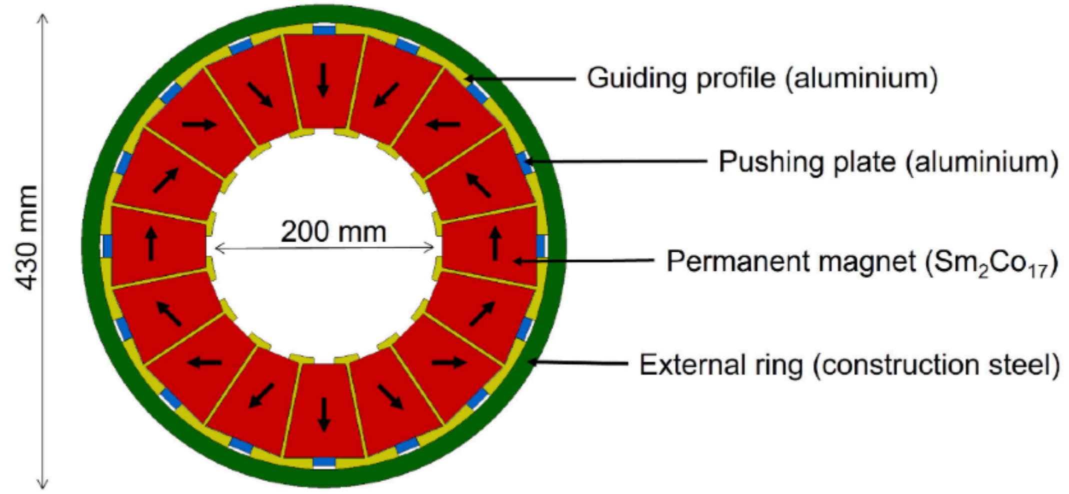
Documentation:
LOI: 1811.10243
TP: 1812.09139
Detector Paper: 2207.11427

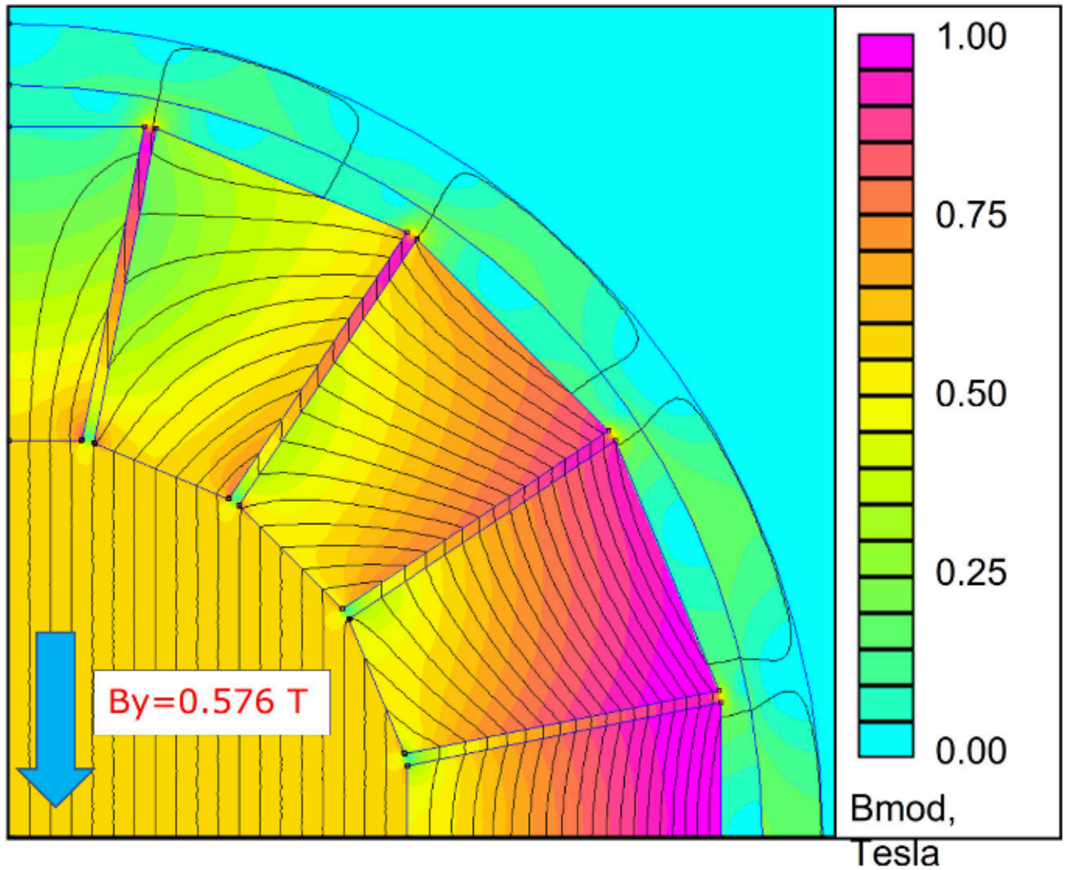



FASERν
Front Veto
Decay Volume
Tracker
Preshower
ECAL

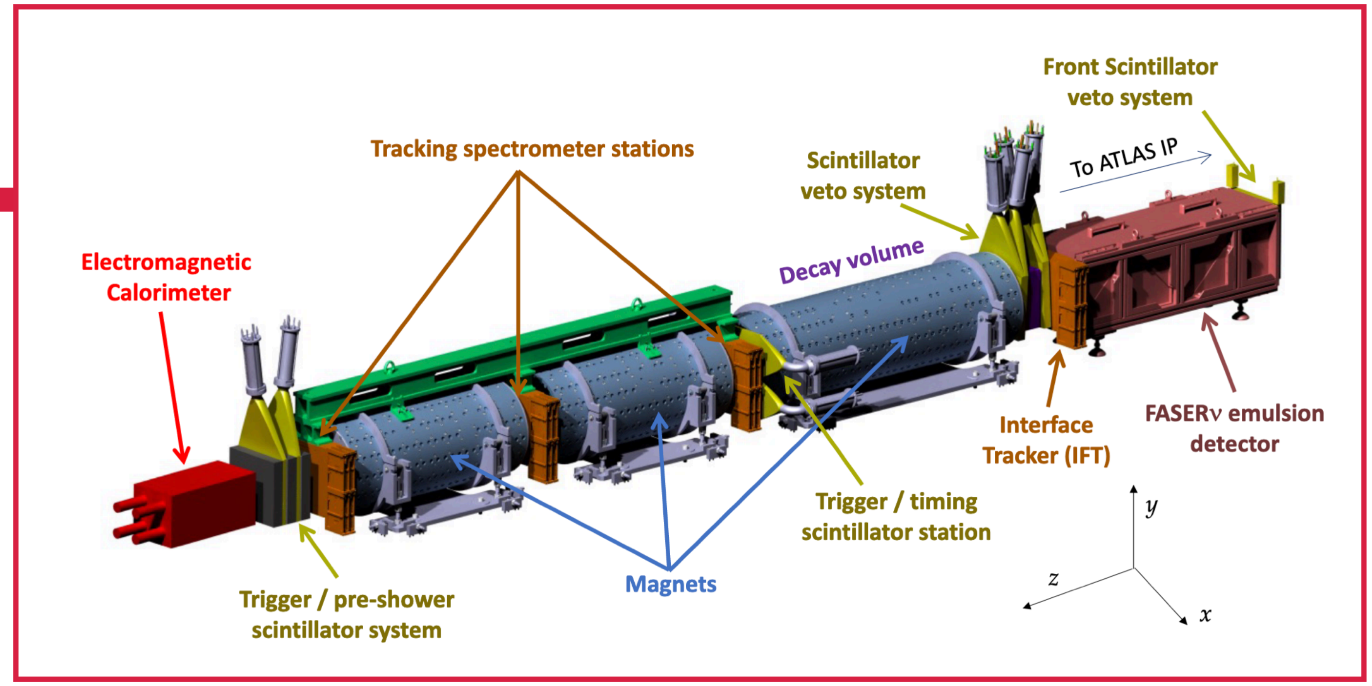
FASER Magnets

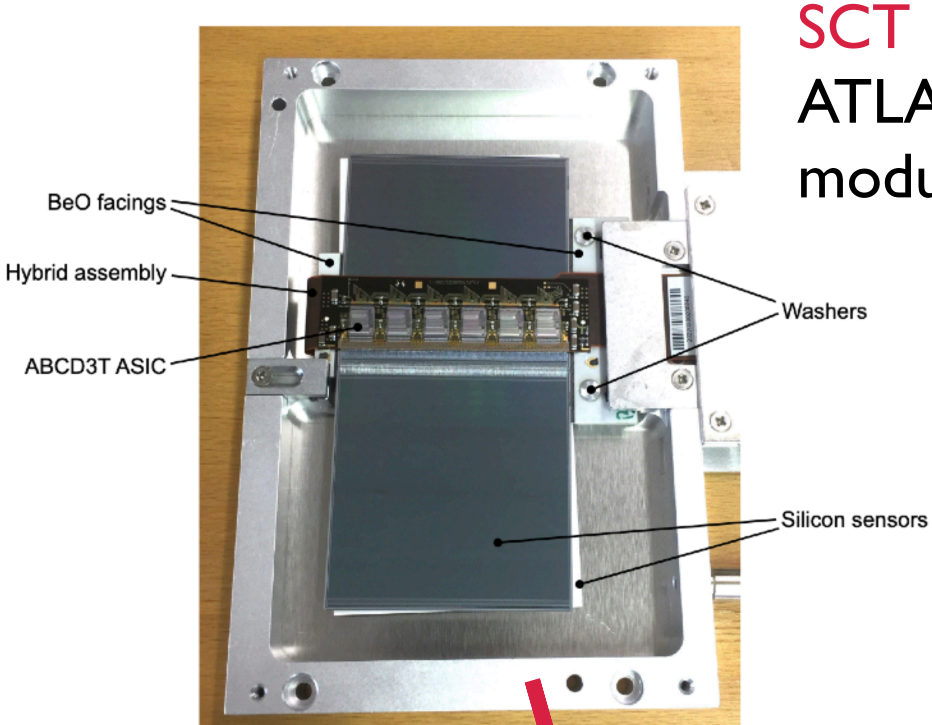




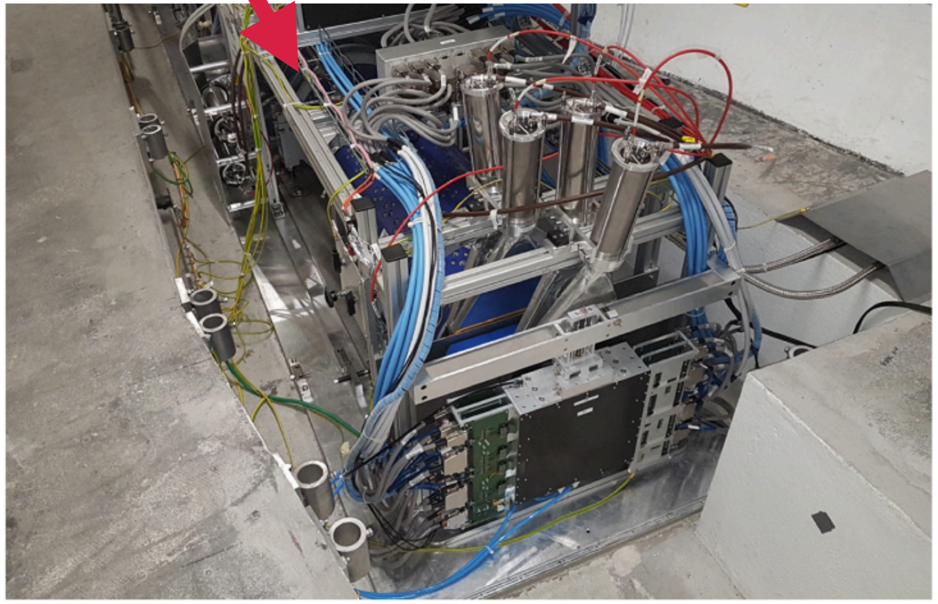


FASER Tracker

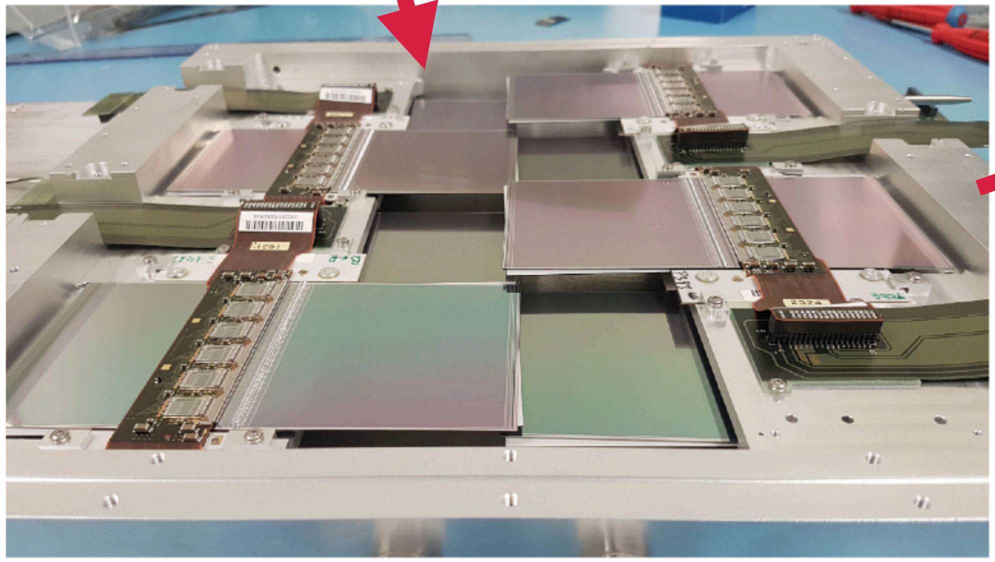




SCT module
ATLAS spare modules



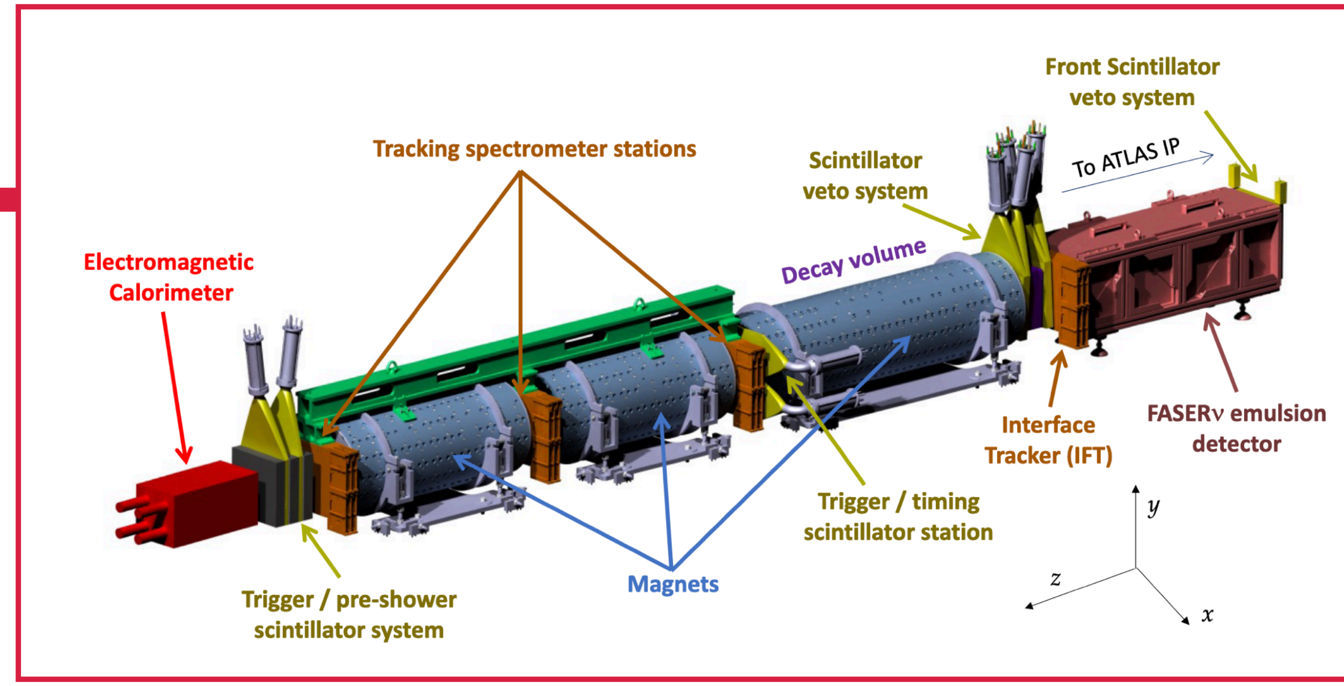
Tracker Station



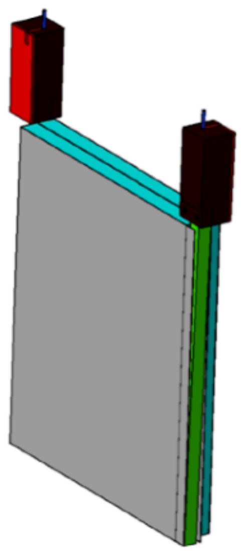
Tracker Plane

Resolution in the bending direction: ~20 μm.
Resolution in the non-bending direction: ~550 μm.
FASER Tracker paper: 2112.01116

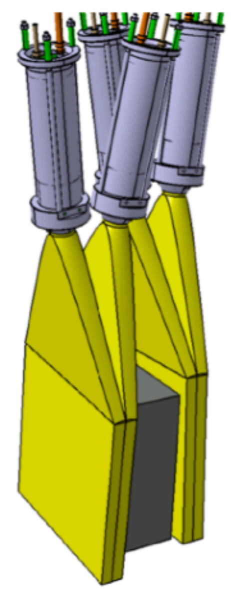
FASER Scintillators



Front Veto

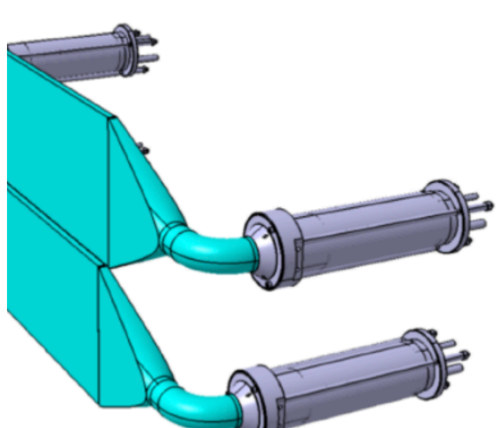


(a) First veto station.

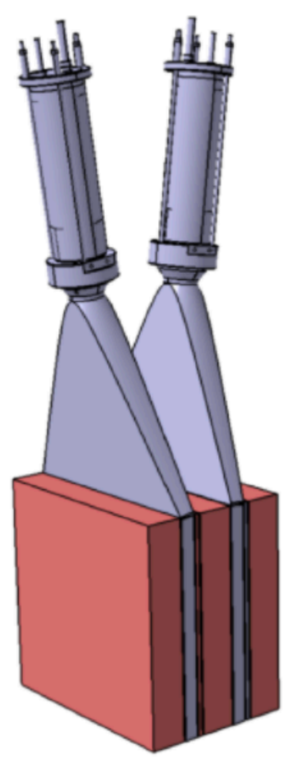


(b) Second veto station.

Timing and Trigger

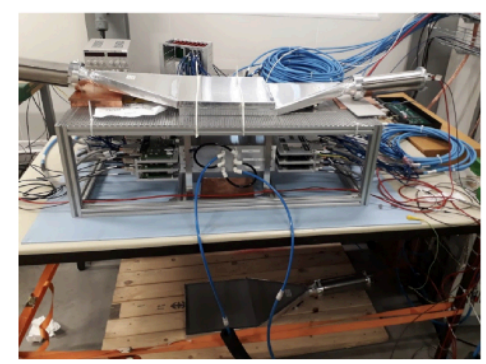


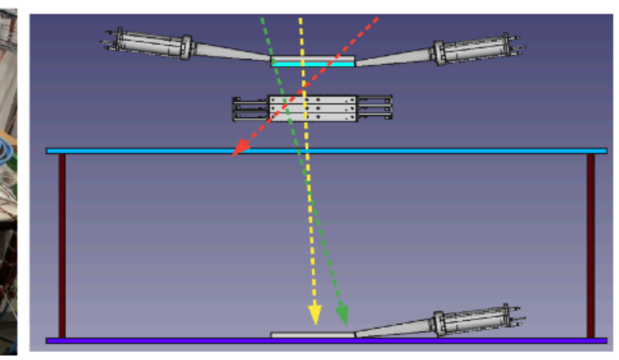
(c) Timing station.



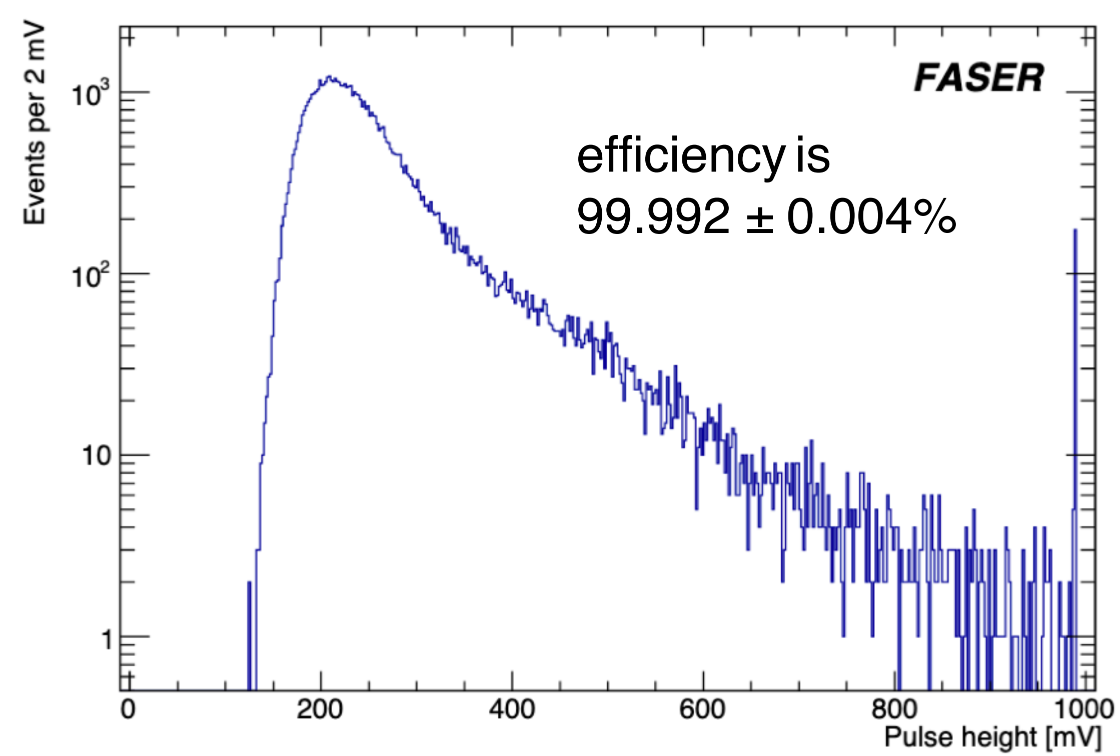
(d) Preshower station.

Cosmic Muon Measurements

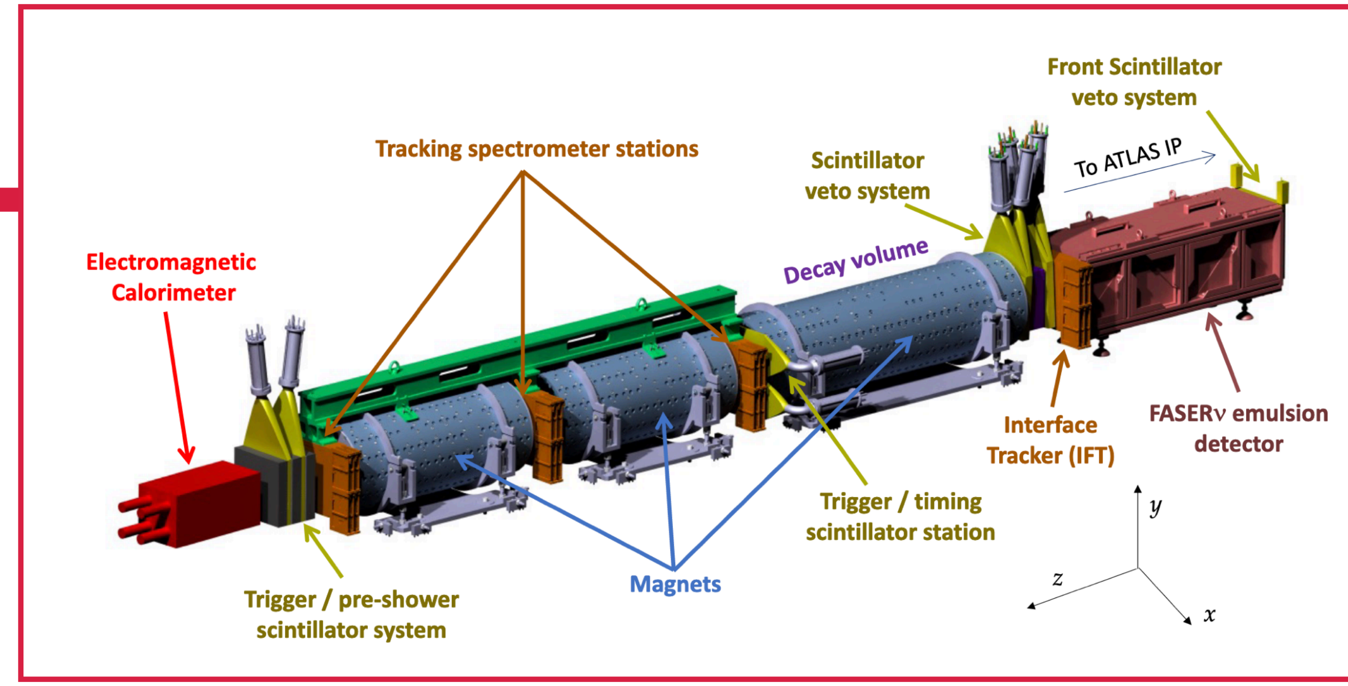




Veto station 2, module 2

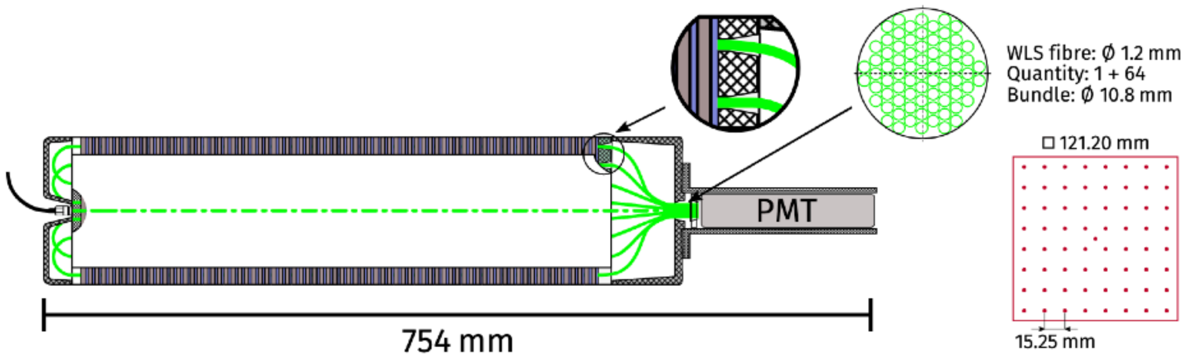


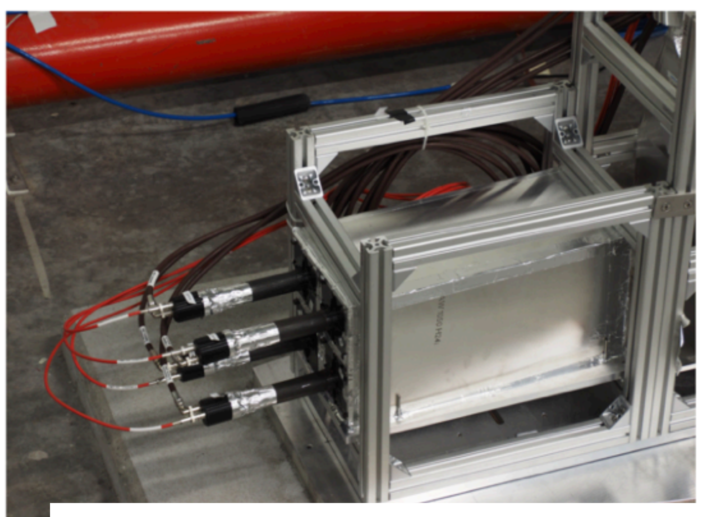
FASER Calorimeter



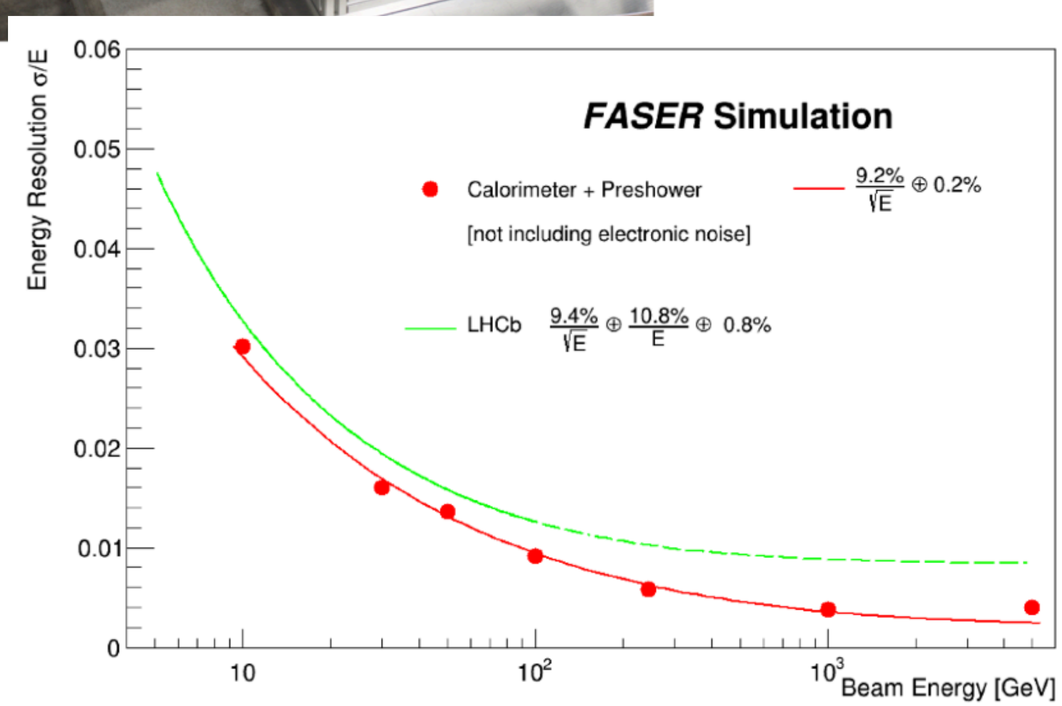
Calorimeter

made of spare LHCb modules



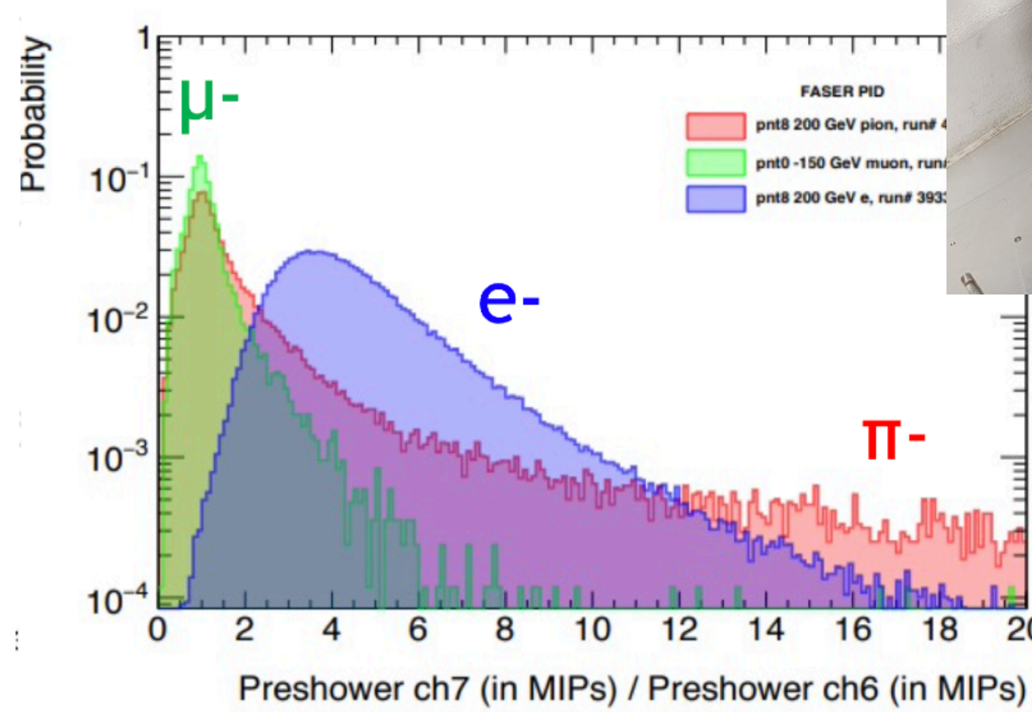


optimised to measure multi-TeV deposits



Preshower

Trigger and particle identification.



FASER First Data

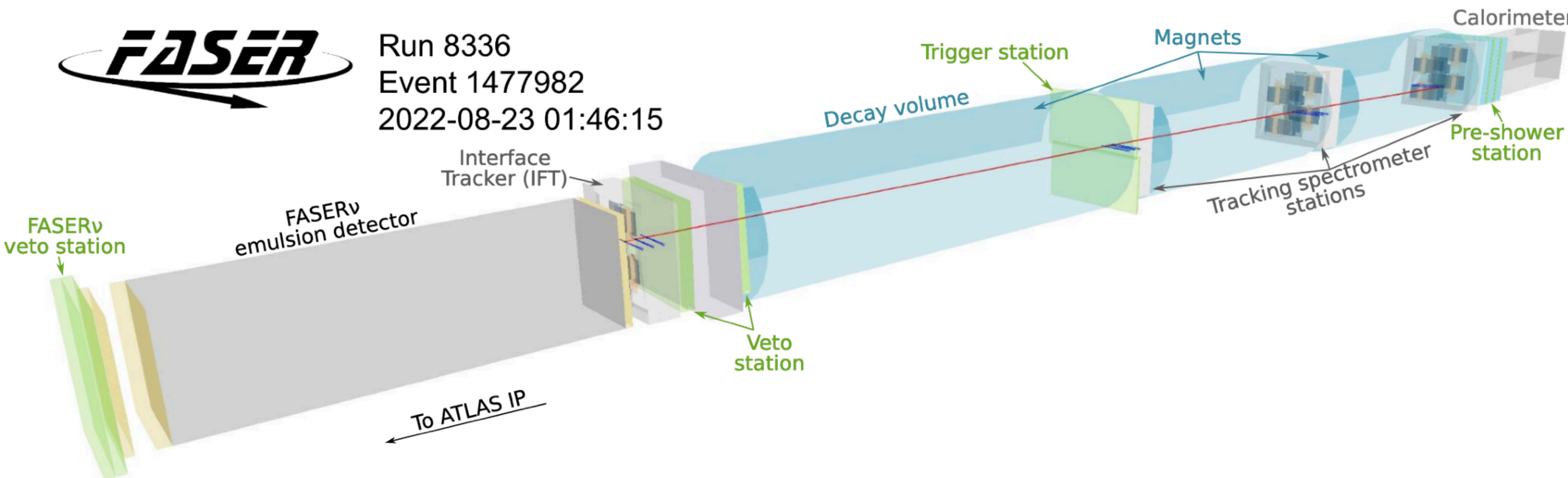


Figure 4: Collision event with a muon traversing FASER. Measured momentum of 21.9 GeV. The ATLAS interaction point is on the picture in the left direction. The detected hits in the semiconductor tracker modules are shown with blue lines and the reconstructed track is shown with a red line.

FASER First Data

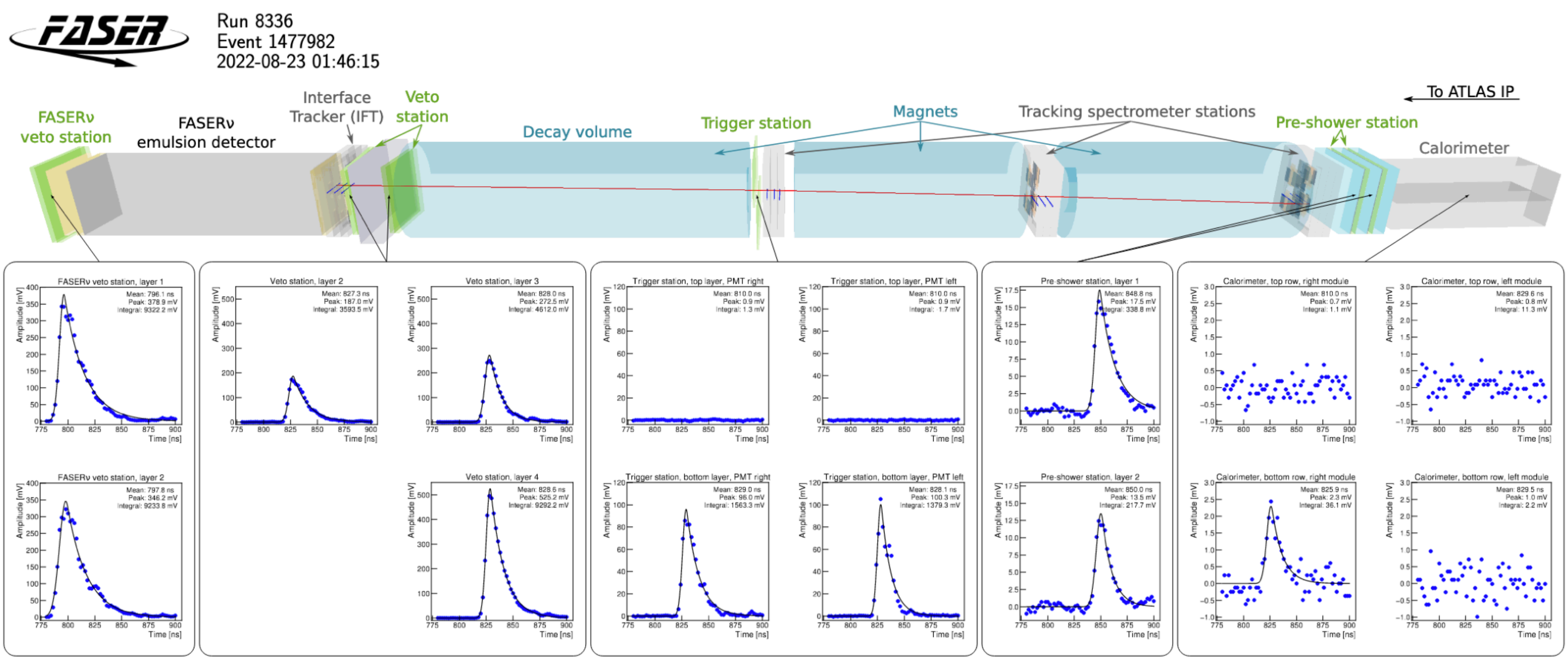
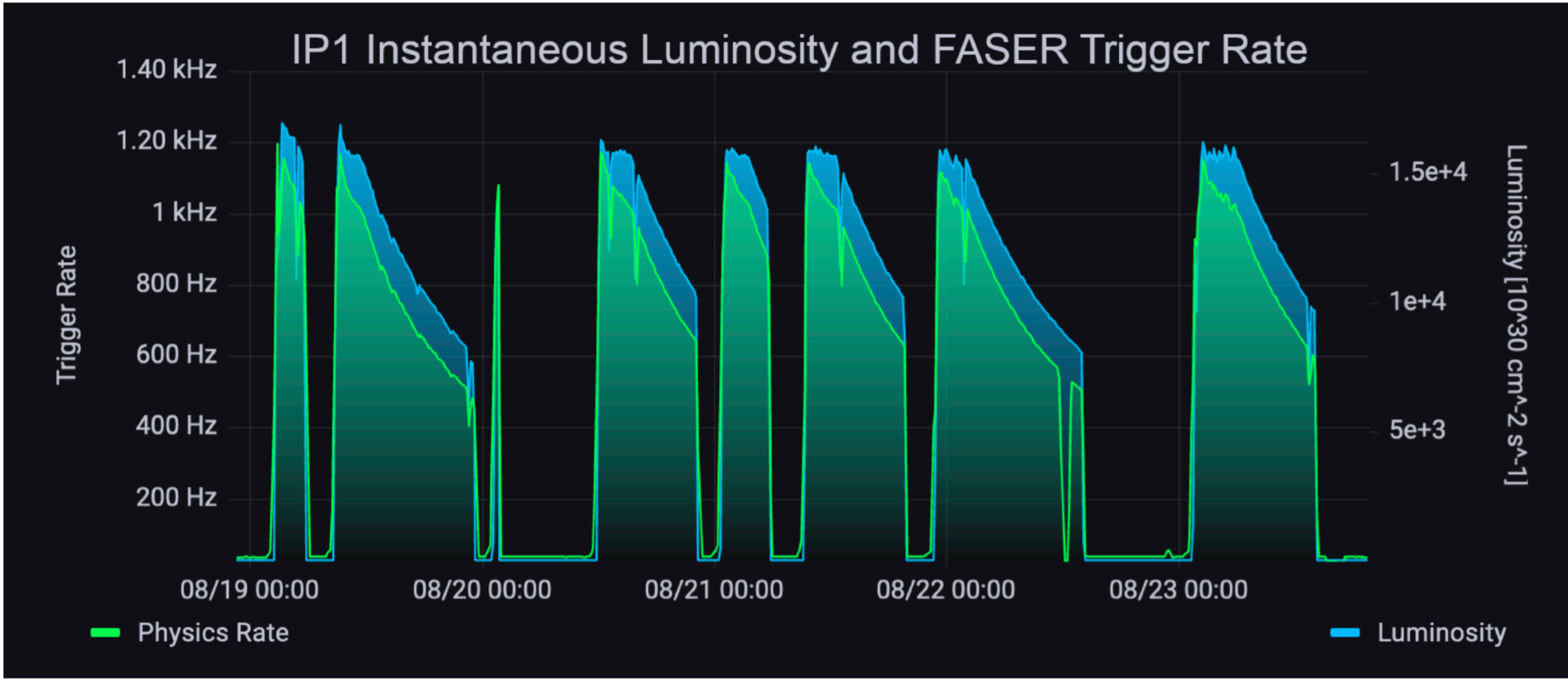


Figure 1: Collision event with a muon traversing FASER. Measured momentum of 21.9 GeV. Waveforms shown for signals in scintillators and calorimeter modules. All PMT waveforms are consistent with a muon passing through the scintillators and one of the calorimeter modules. The event has been triggered by modules in the FASERν veto station, veto station and trigger station with pulses above 25 mV, and by modules in the pre-shower station with pulses above 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

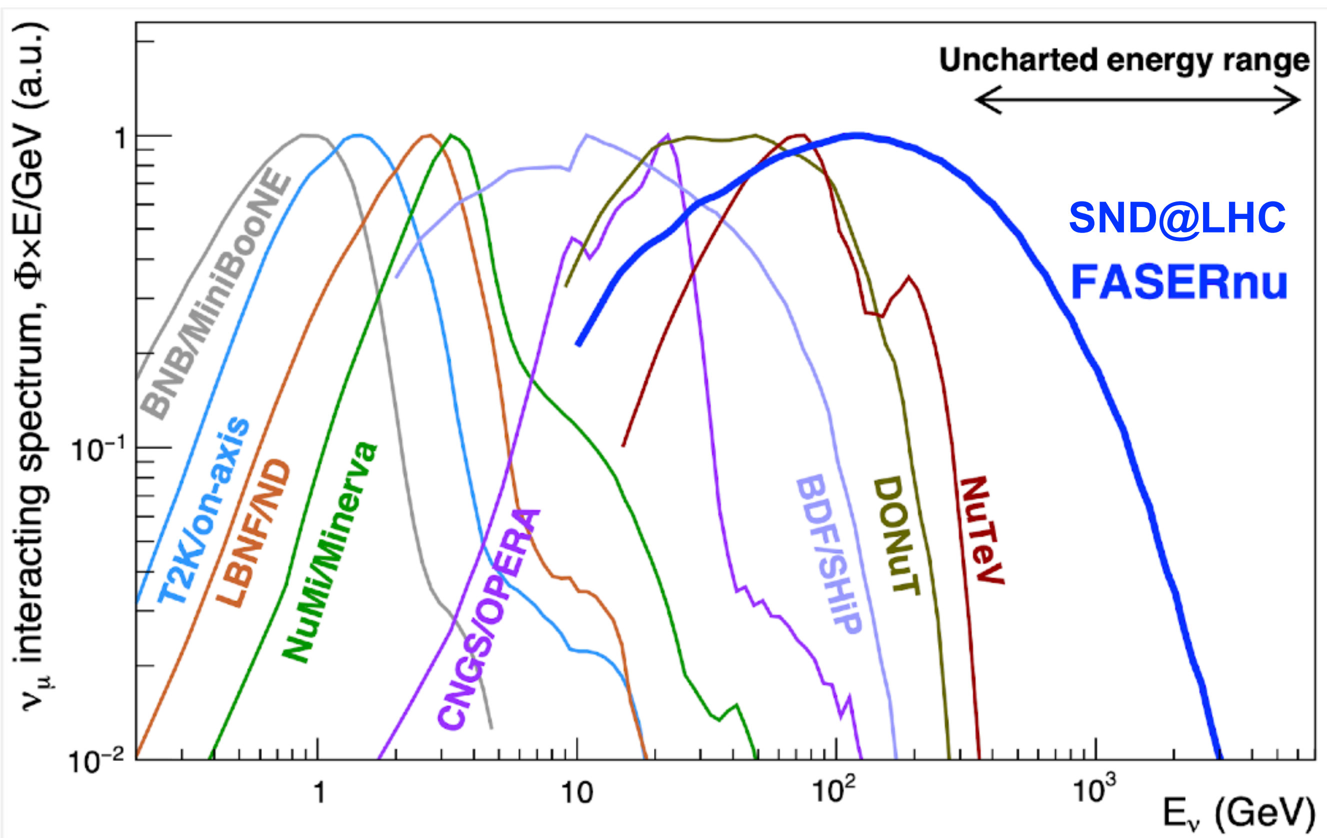
- no problems observed.

- maximum trigger rate is ~1.2kHz (nearly 2x the expectation), but this is not a problem for physics.
- more than L_{INT} = 11 fb^{-1} data have been recorded.
- many performance studies are ongoing.

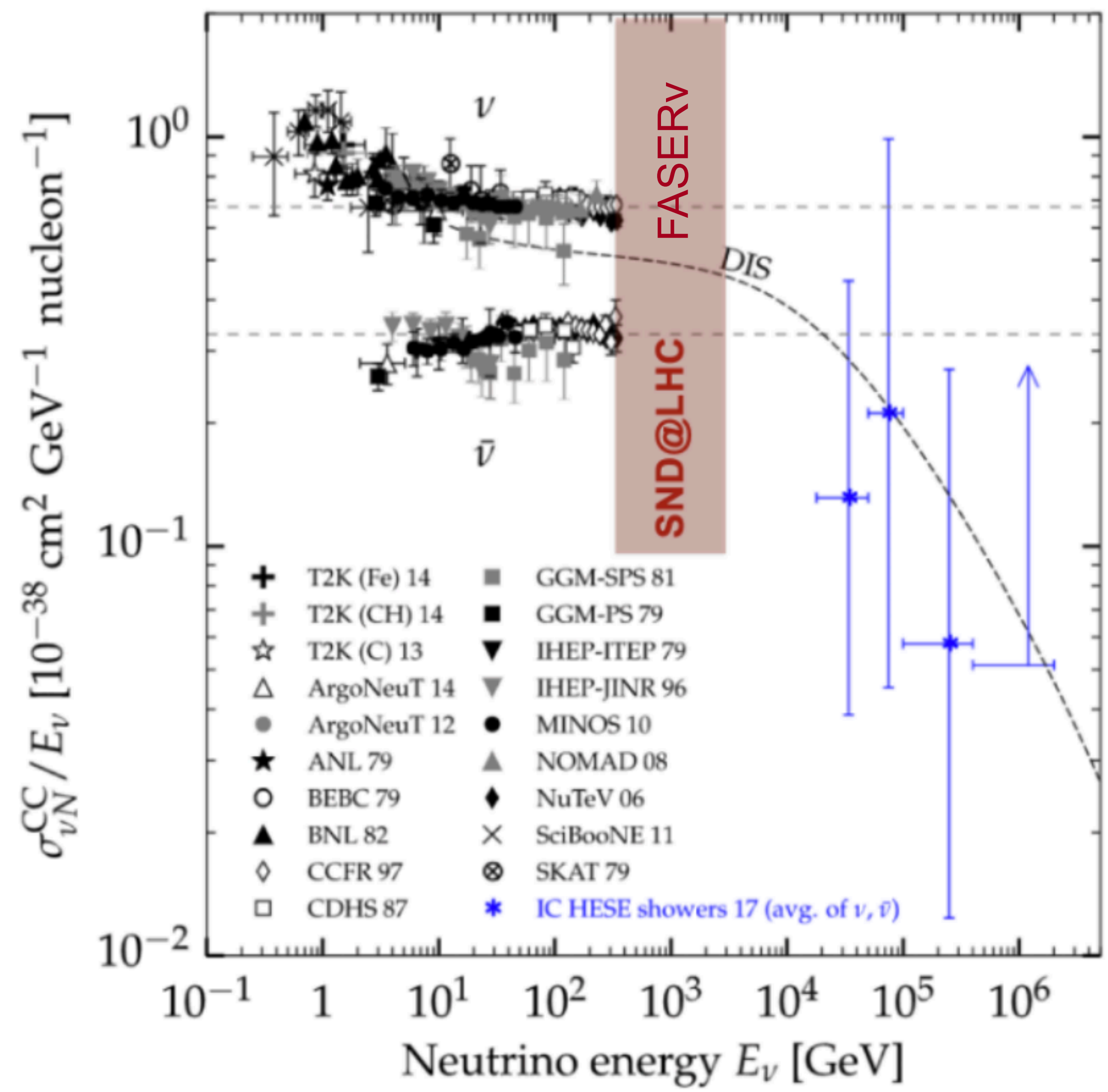
FASERν

One Slide of Physics Motivation

(for both FASERν and SND@LHC)

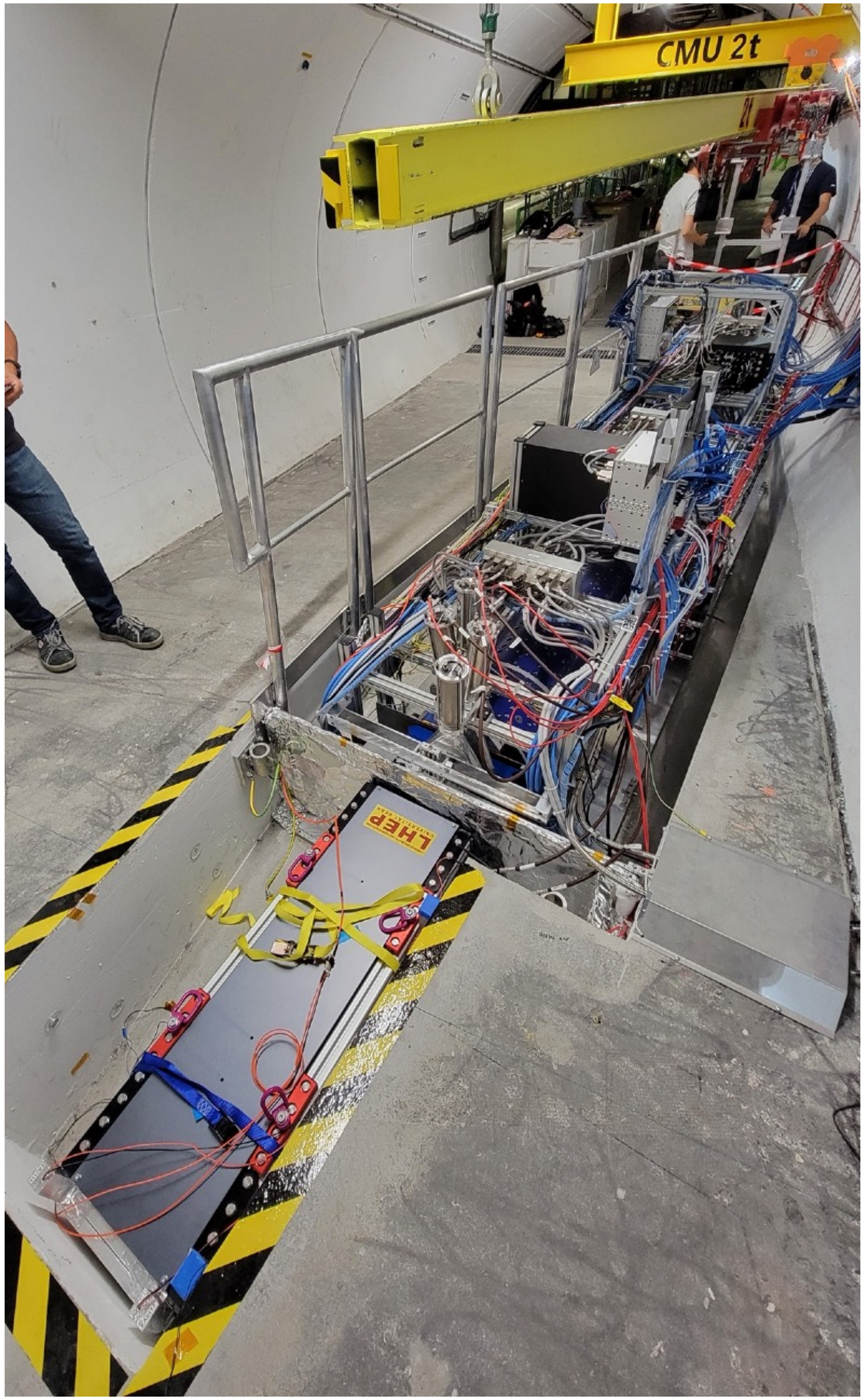


PRL 122 (2019) 041101



FASERν Detector

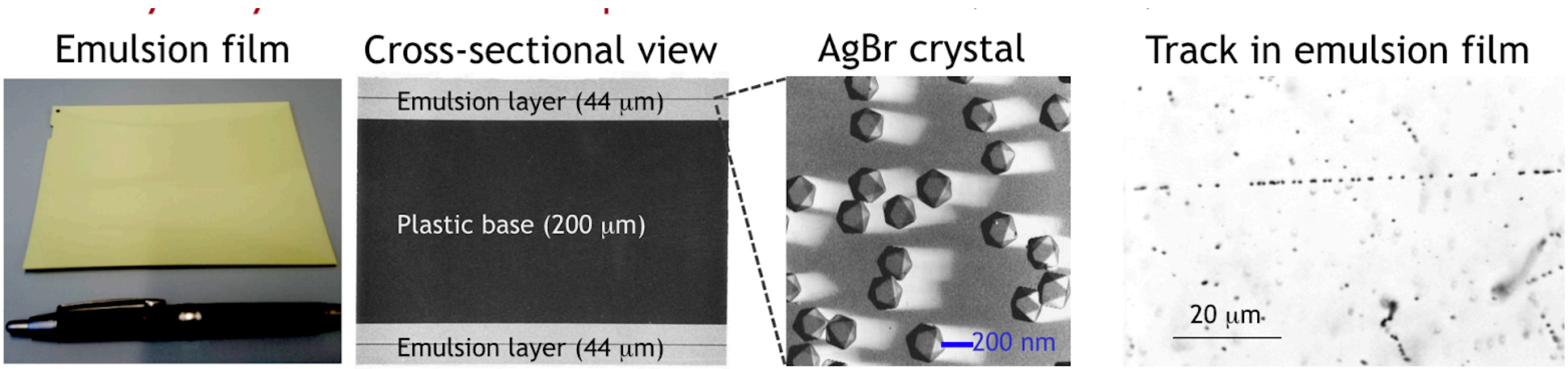
FASERν neutrino detector in front of FASER
* 25cm x 25cm x 1.3m emulsion detector
* tungsten target with 1.2 ton mass
* placed on-axis: η > 9 angular coverage
* ~1000 νe, ~10000 νμ, ~10 ντ
during LHC Run 3

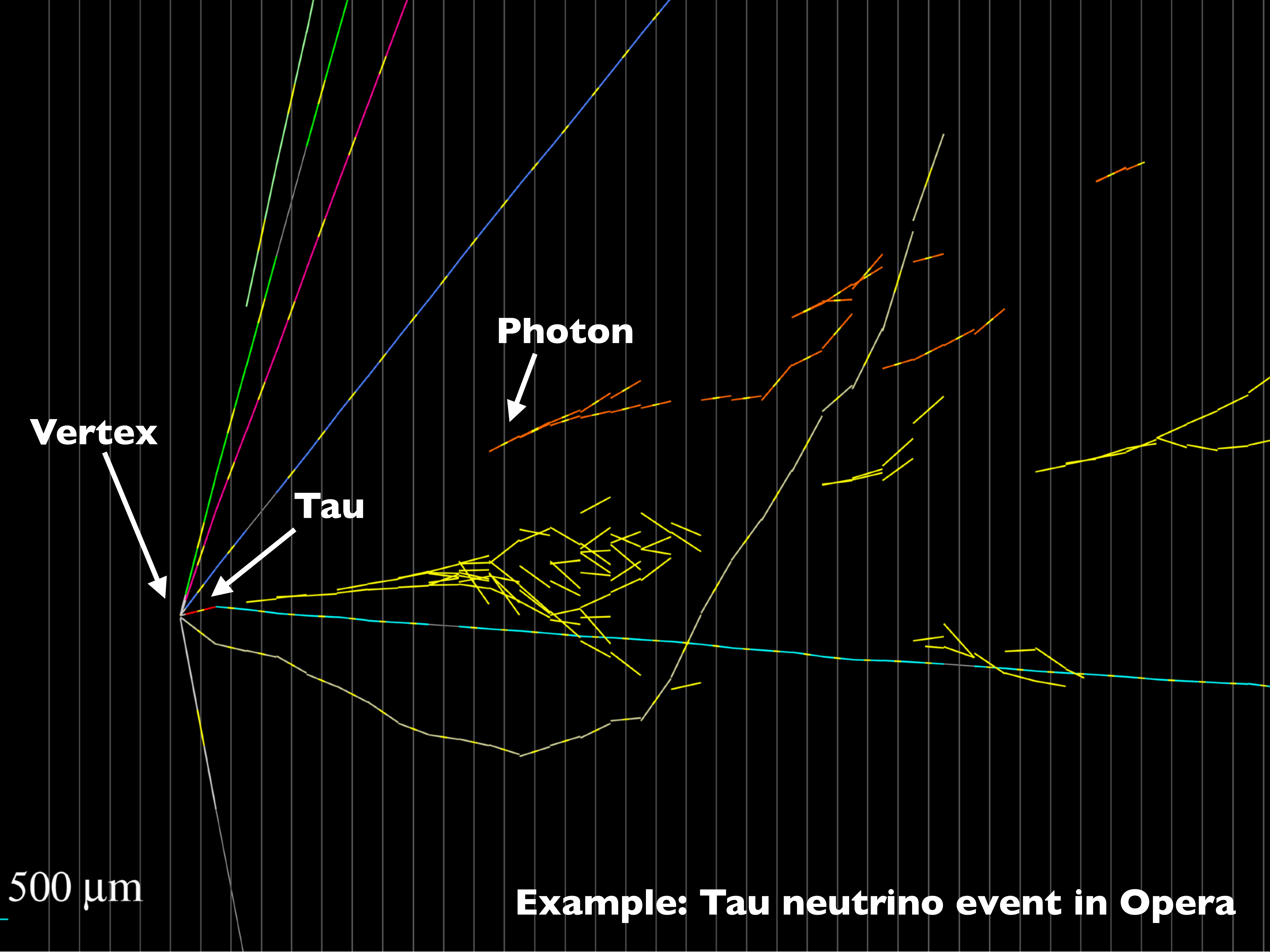


FASERν Detector

Emulsion detectors technology

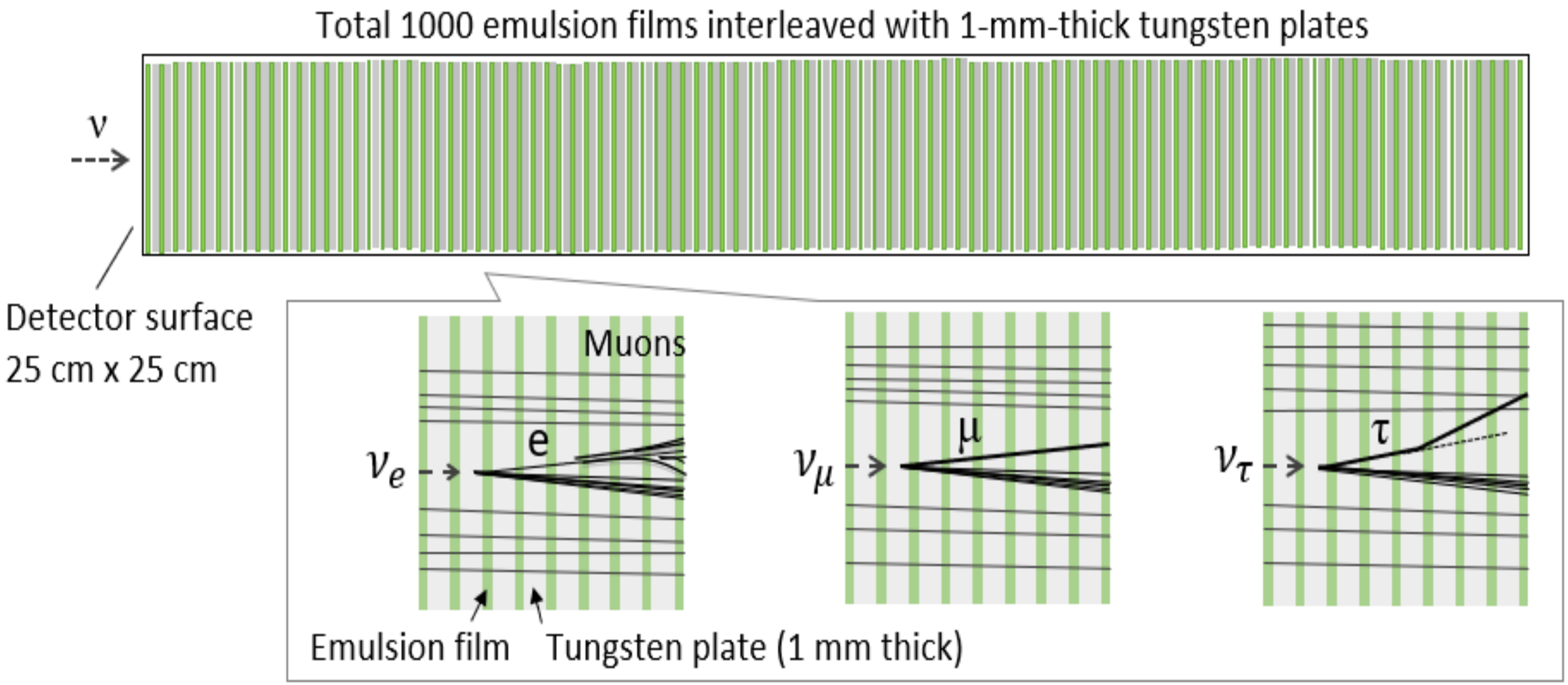
* used by many other neutrino experiments: CHORUS, DONUT, OPERA
* 1000 emulsion films interleaved with 1mm tungsten plates
* 3D tracking devices with 50 nm spatial precision
* global reconstruction with the FASER detector possible



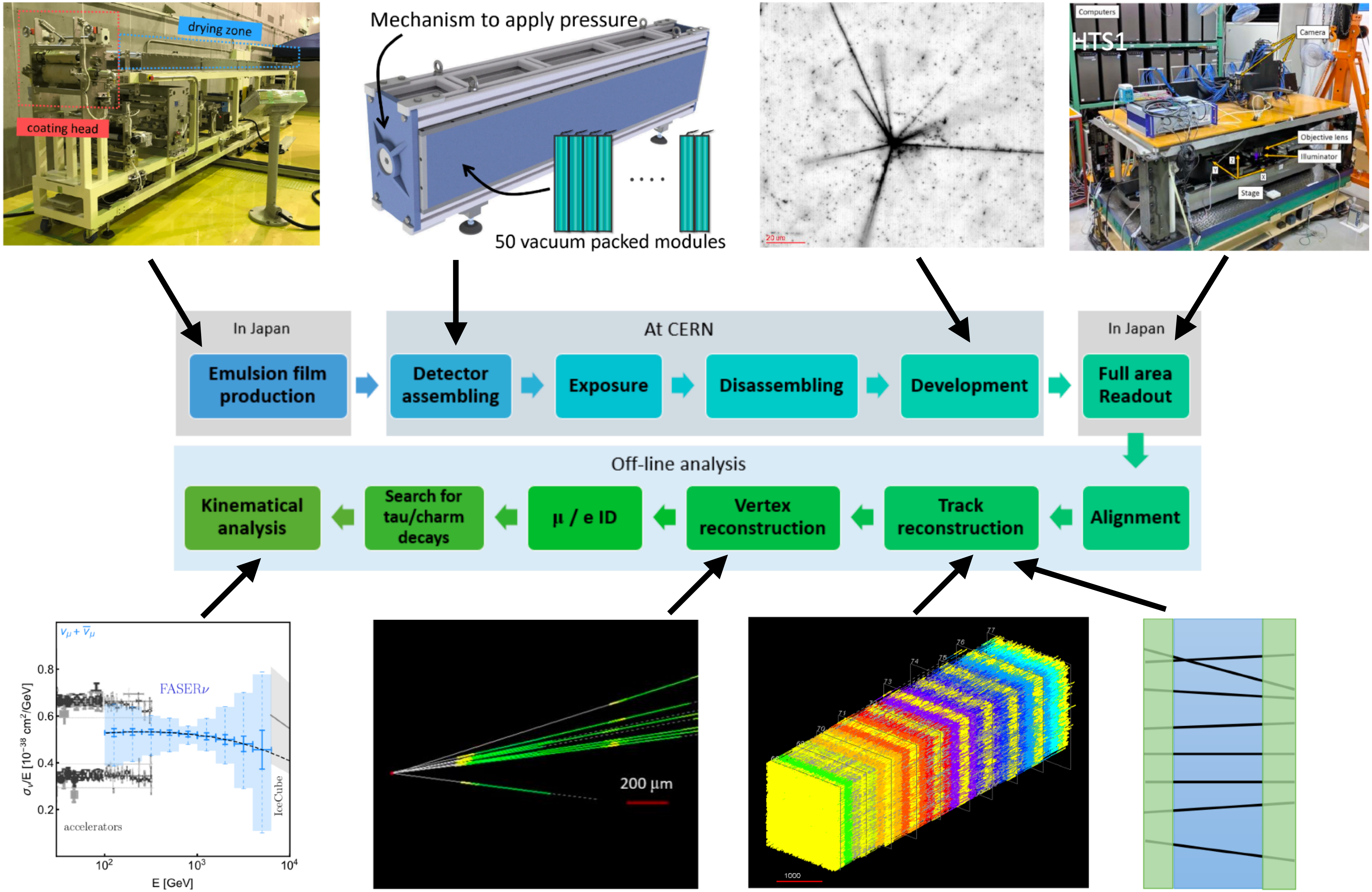


Example: Tau neutrino event in Opera

FASERν Detector



FASERν Detector

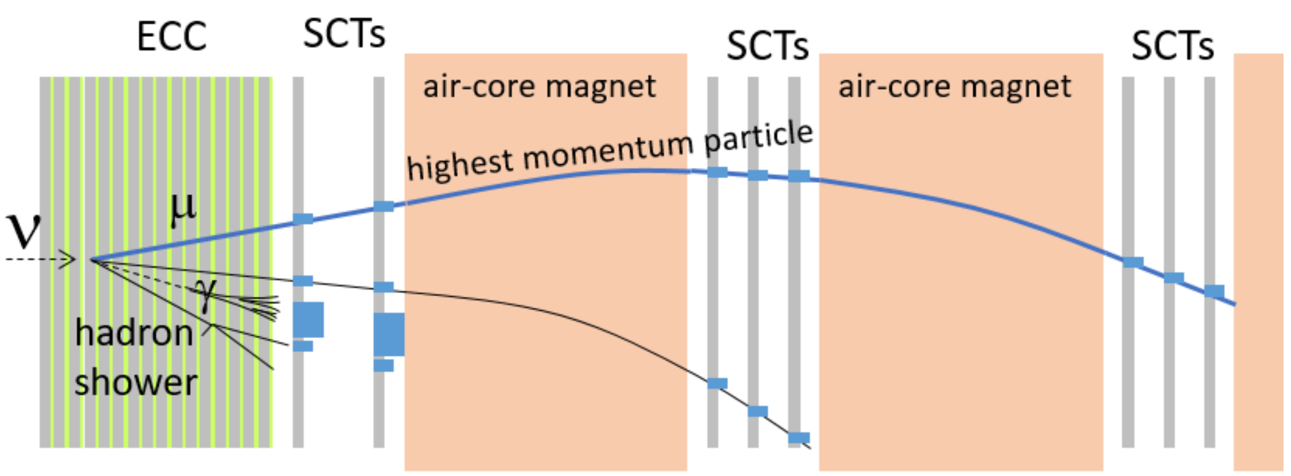


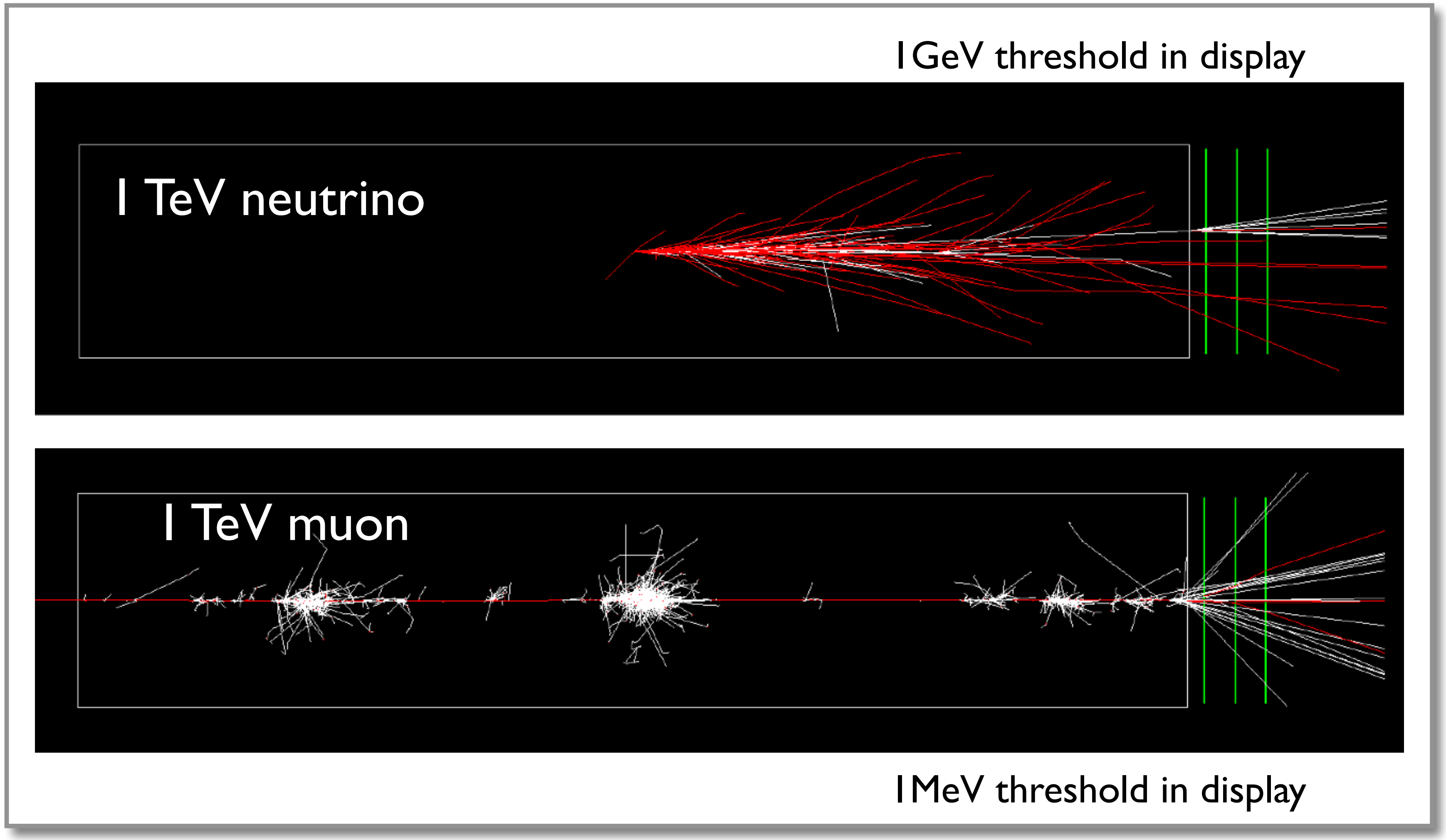
FASERν Detector

Interface Detector

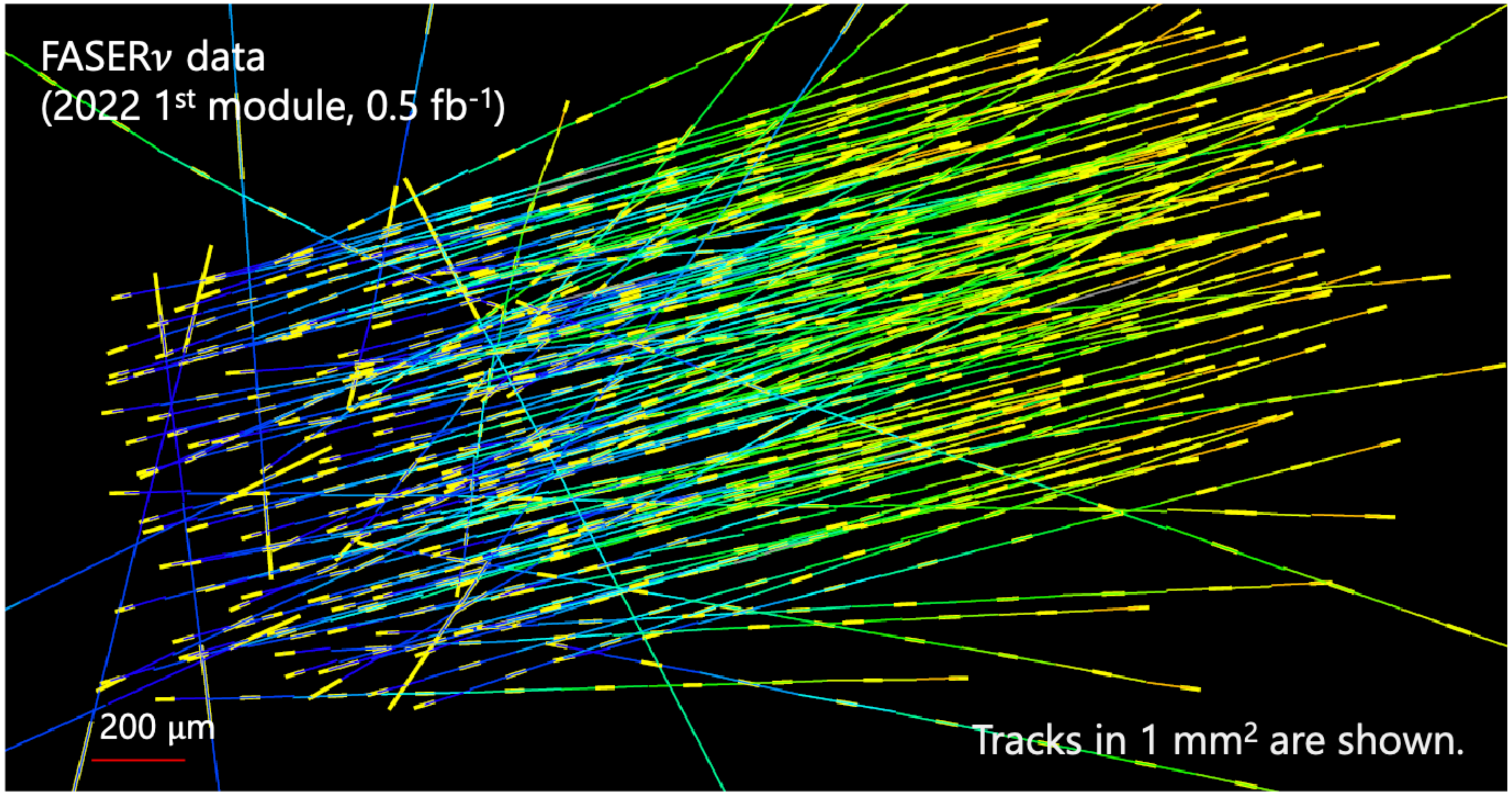
- possibility for future: global reconstruction with the FASER detector
  * interface FASERν to the FASER spectrometer
  * additional tracking layer to allow matching

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





FASERν: First Data



SND@LHC

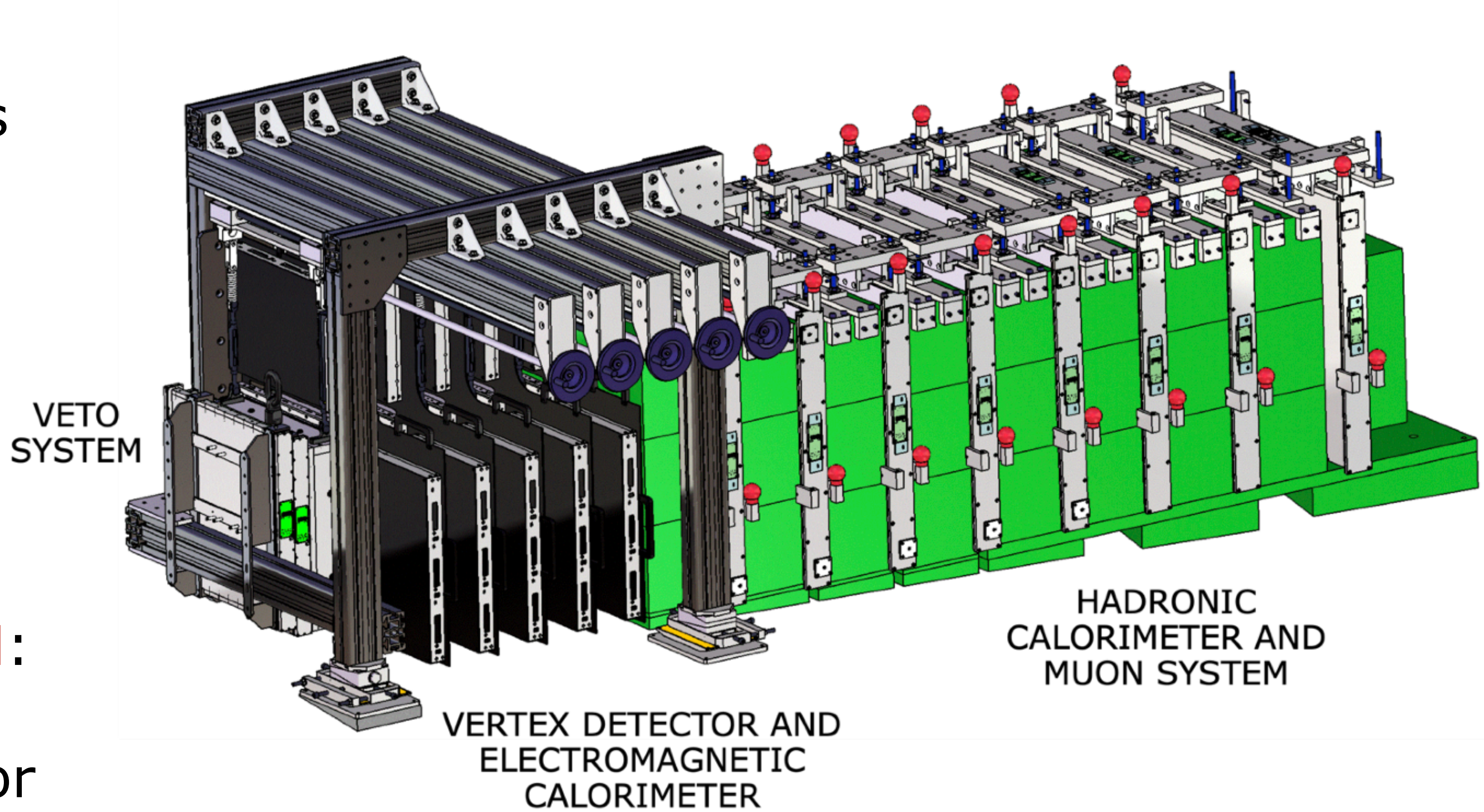
SND@LHC Concept

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



Electromagnetic calorimeter ~40 X_0

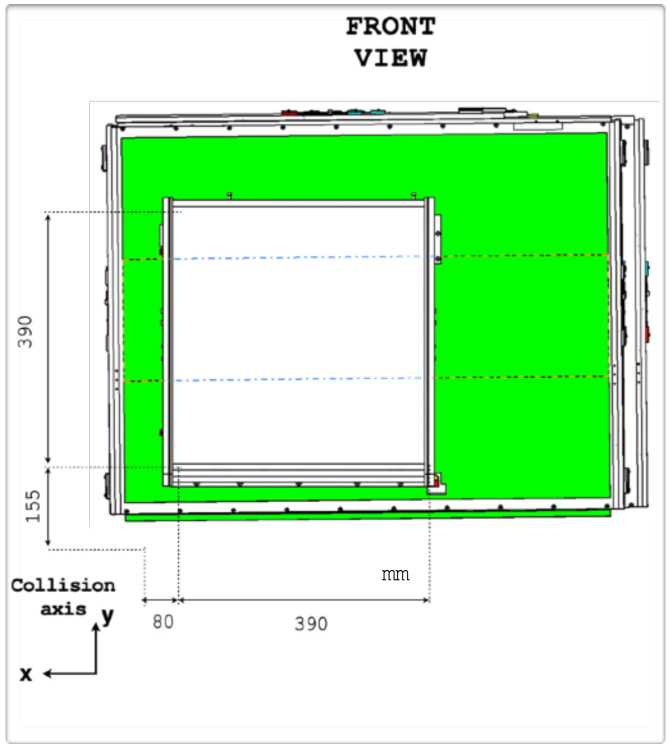
Hadronic calorimeter ~10 λ

Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC Layout

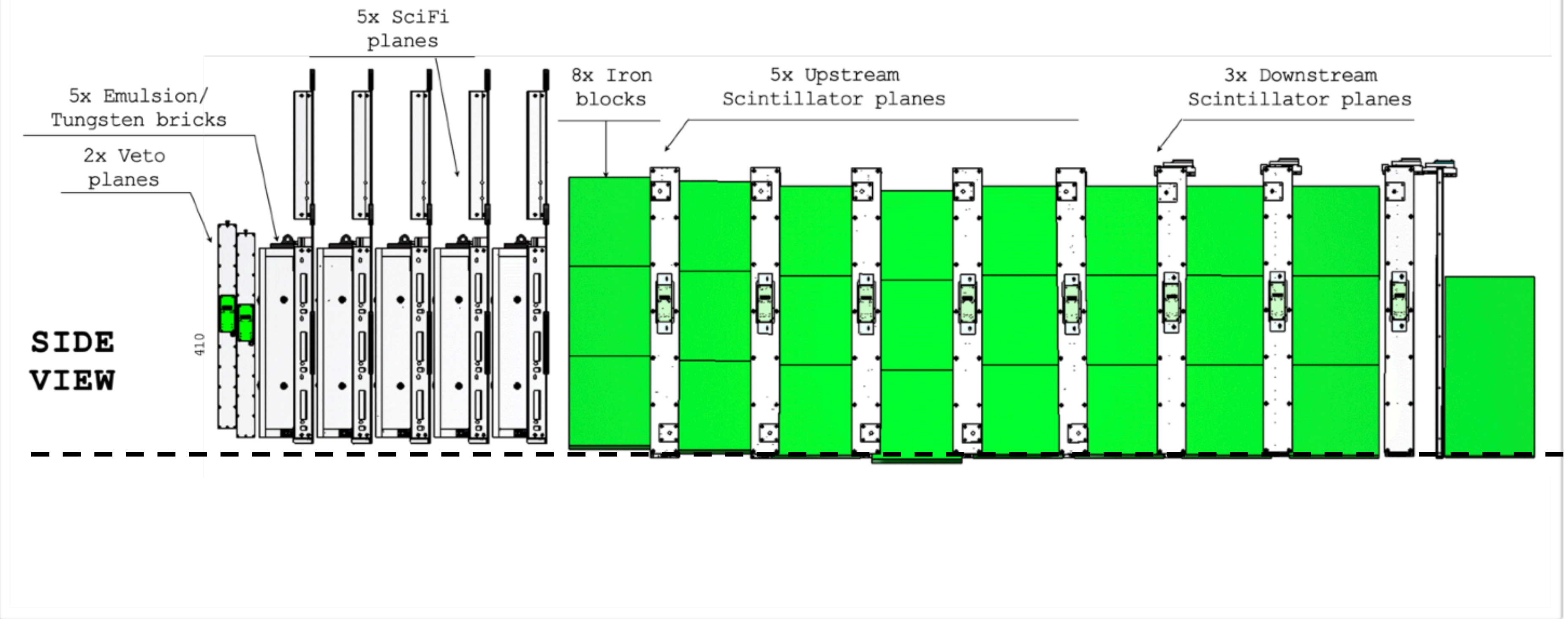
- Angular acceptance: $7.2 < \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location



Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ



Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC: Installation

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

September 2021

December 2021

March 2022

Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC: Installation

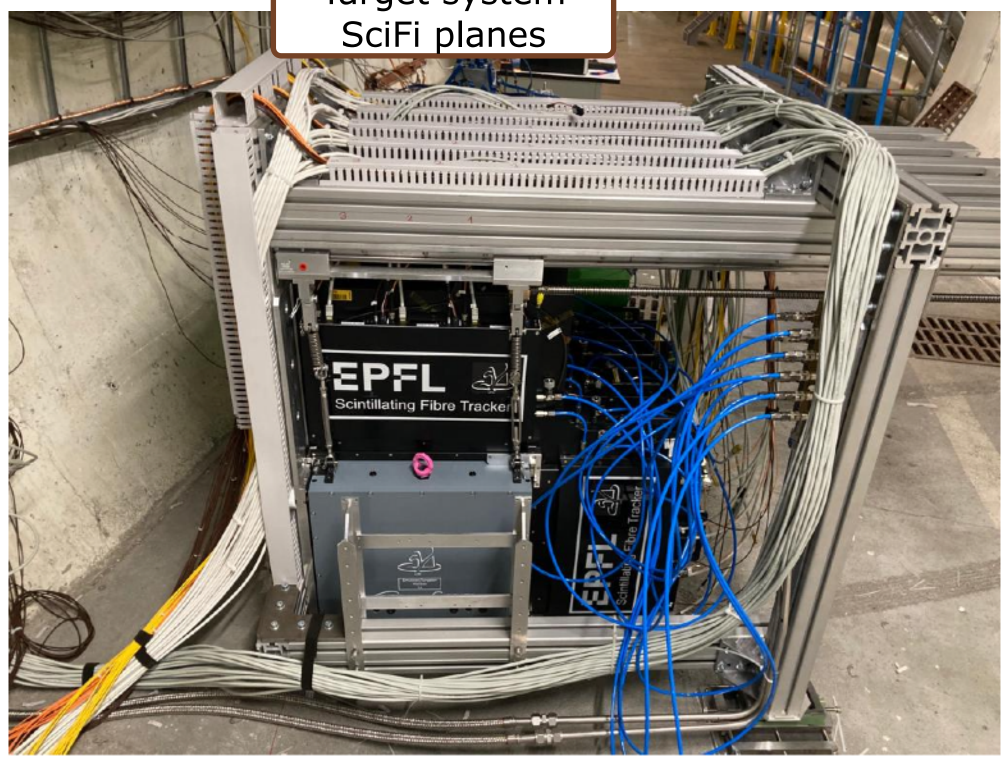
- View of the machine to the IP (left) and of the detector in TI18 (right)

Many thanks to Antonia Di Crescenzo for providing the slides

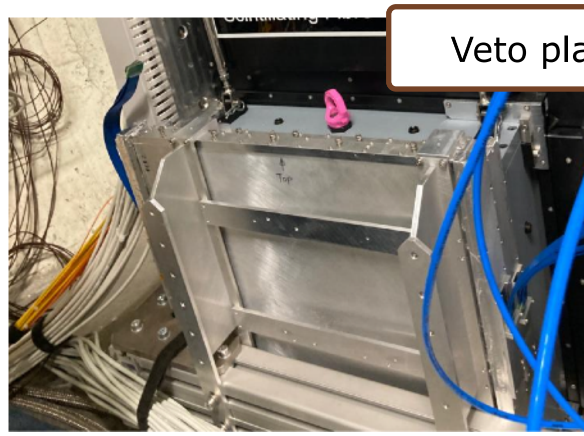
SND@LHC: Installation

Target wall

Target system SciFi planes



Veto plane

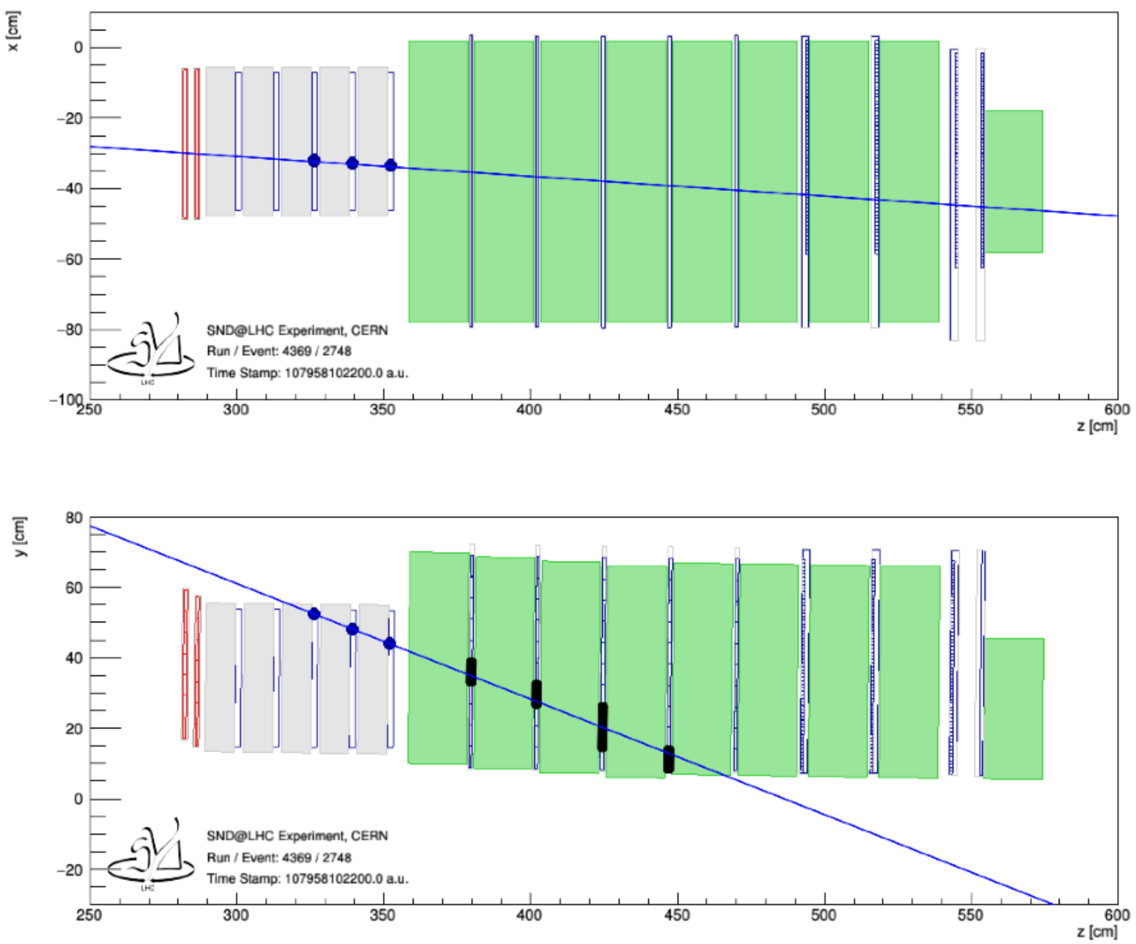


Muon system

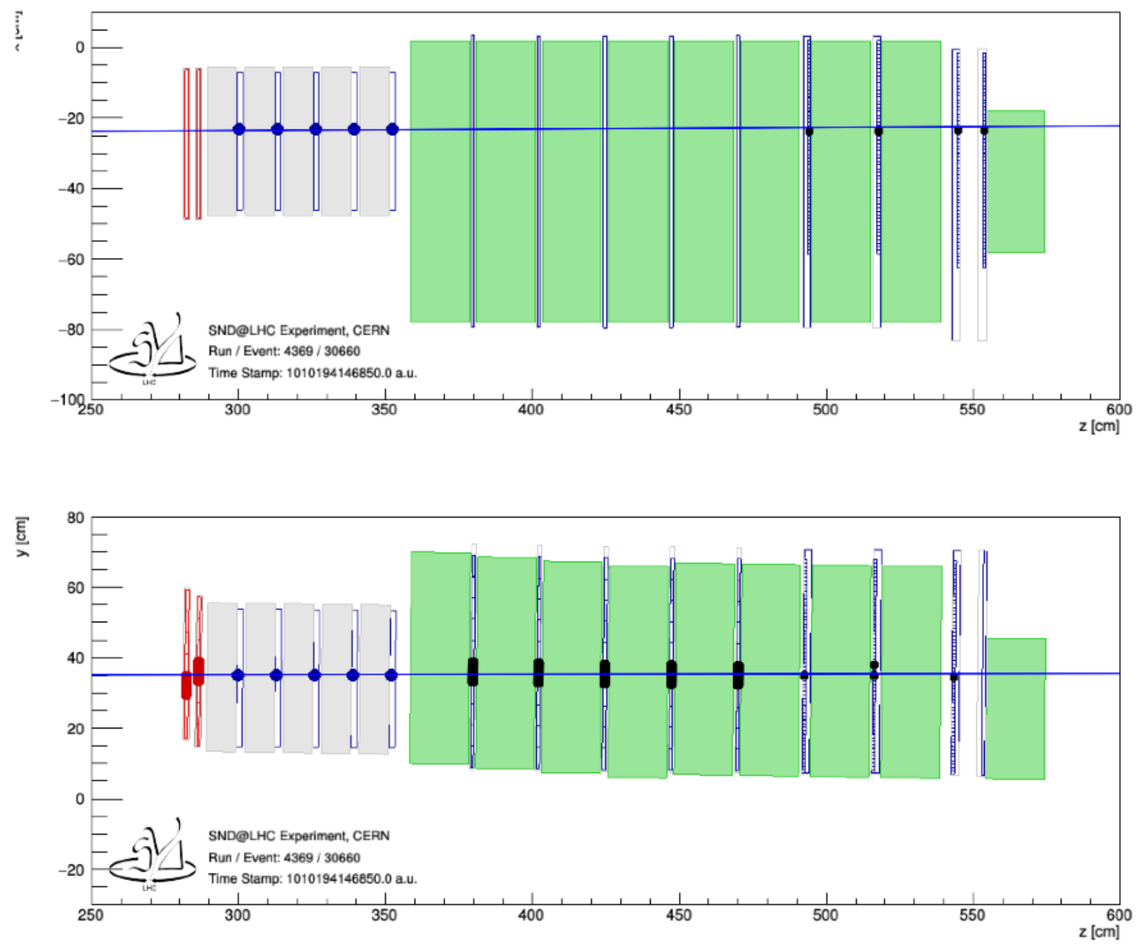
Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC: Data Taking in TI18

Cosmic ray
(March 5th 2022)



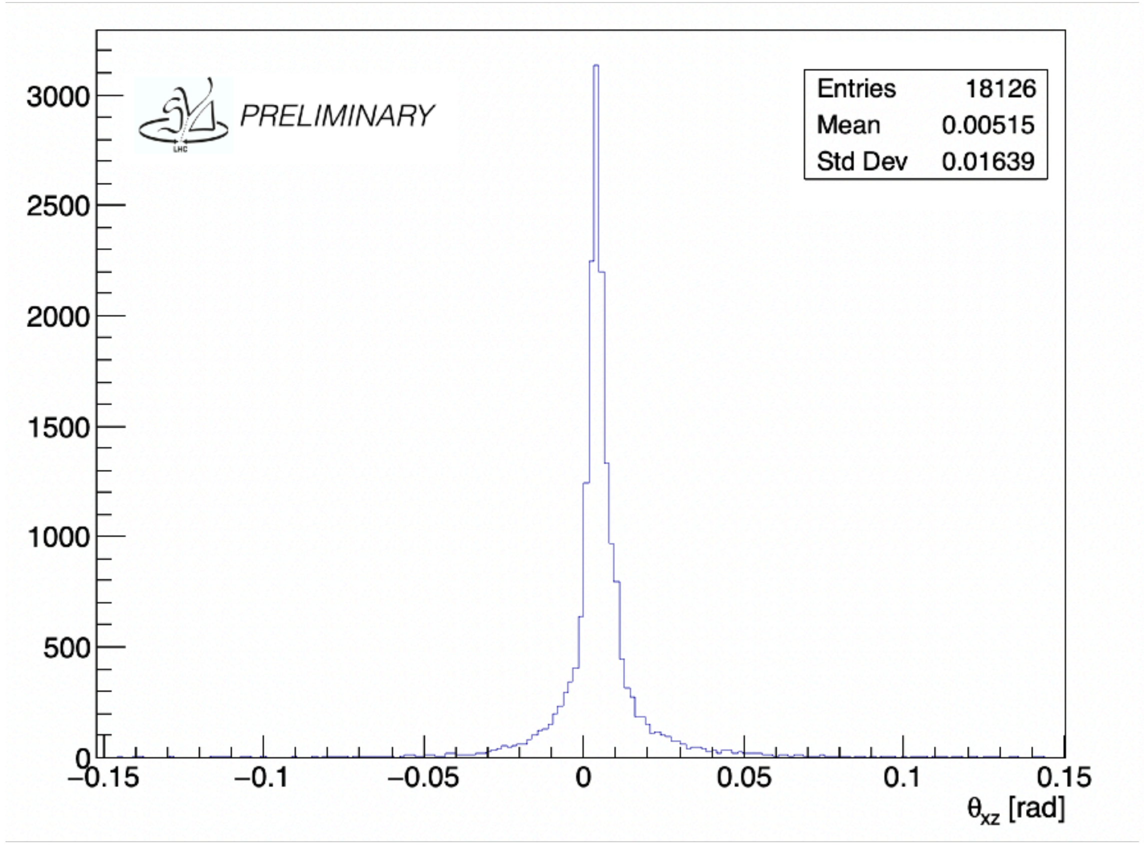
Muon from pp collisions @13.6 TeV
(July 6th 2022)

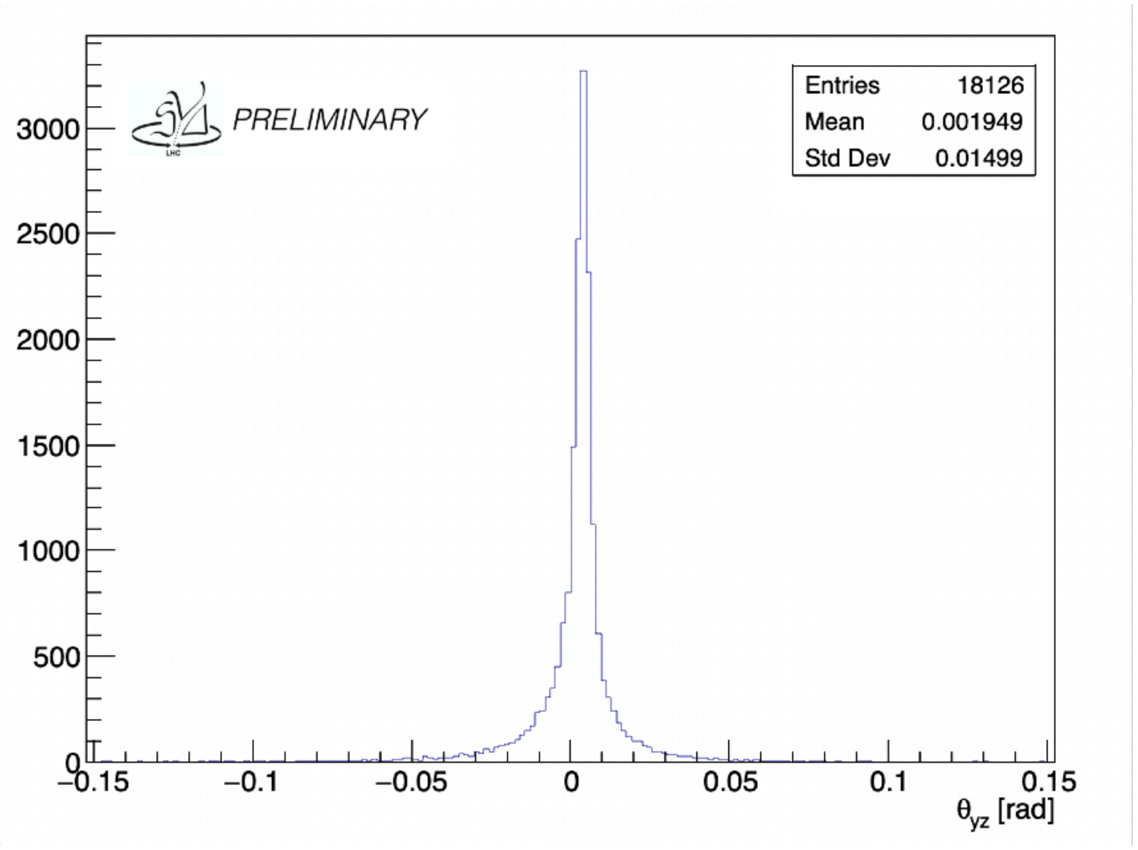


Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC: First Beam Data

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

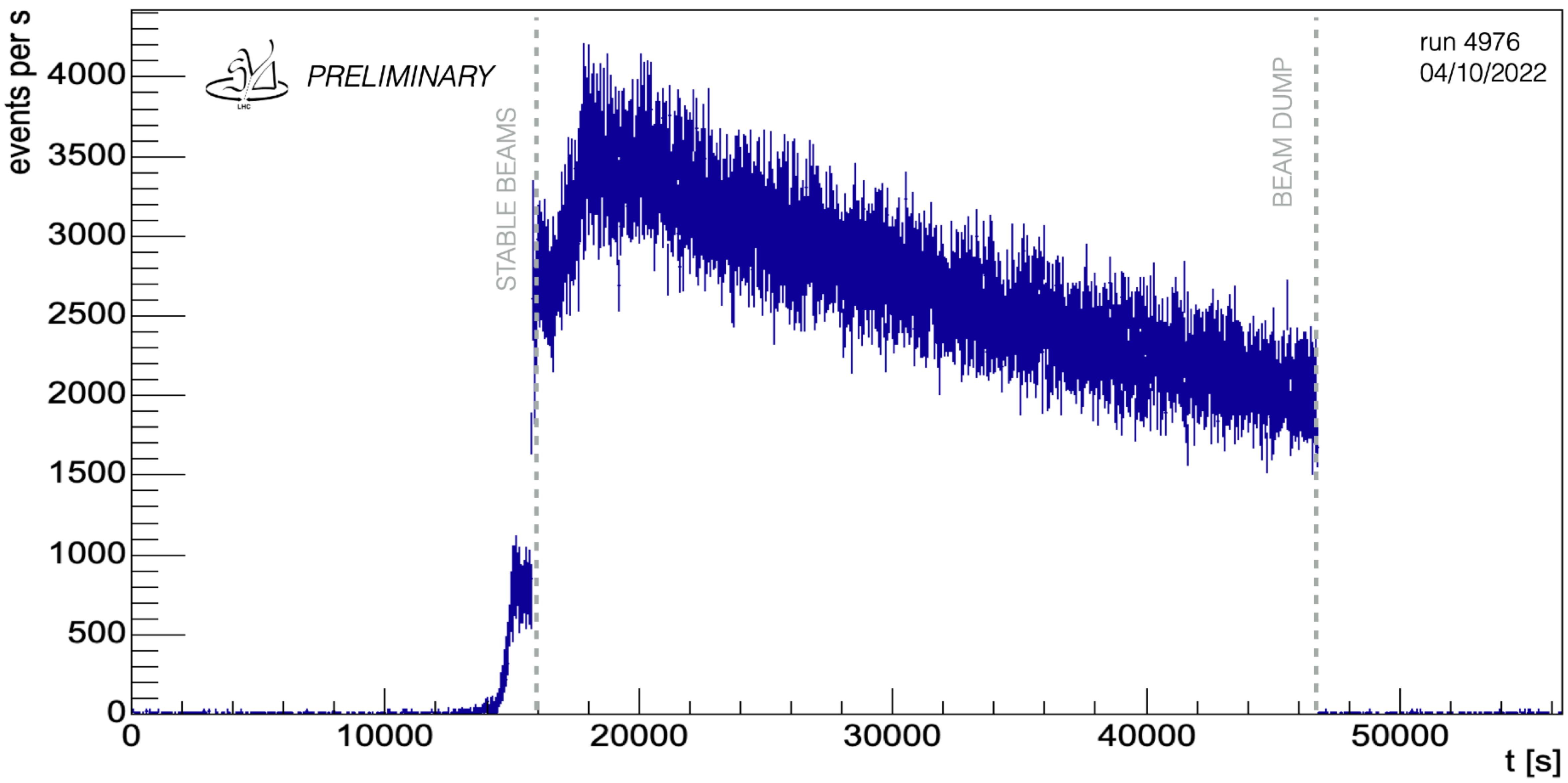




Many thanks to Antonia Di Crescenzo for providing the slides

SND@LHC: Data Taking in TI18

Event rate for one run
Start: October 4th 2022, 18:12:22
End: October 5th 2022, 09:52:21

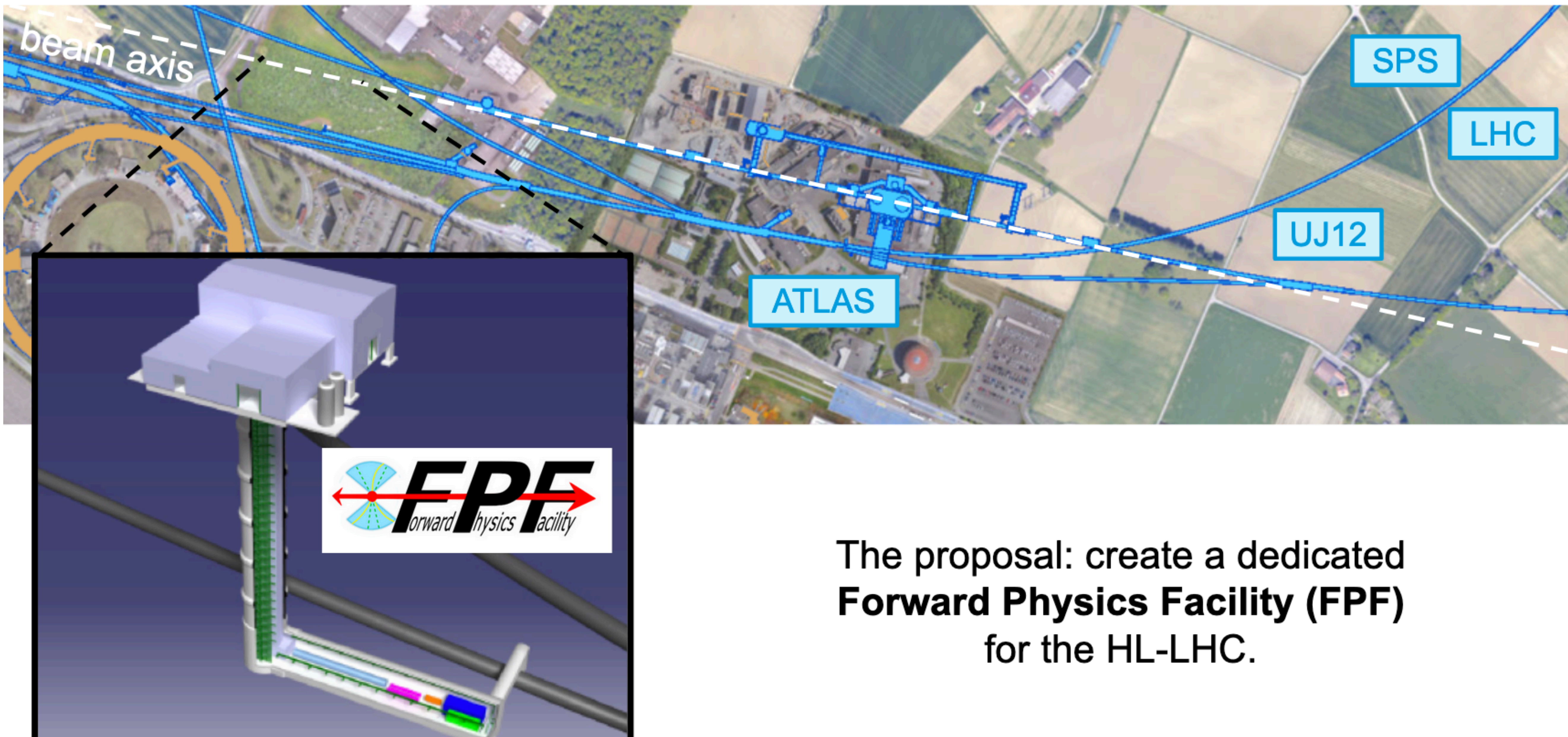


Many thanks to Antonia Di Crescenzo for providing the slides

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.

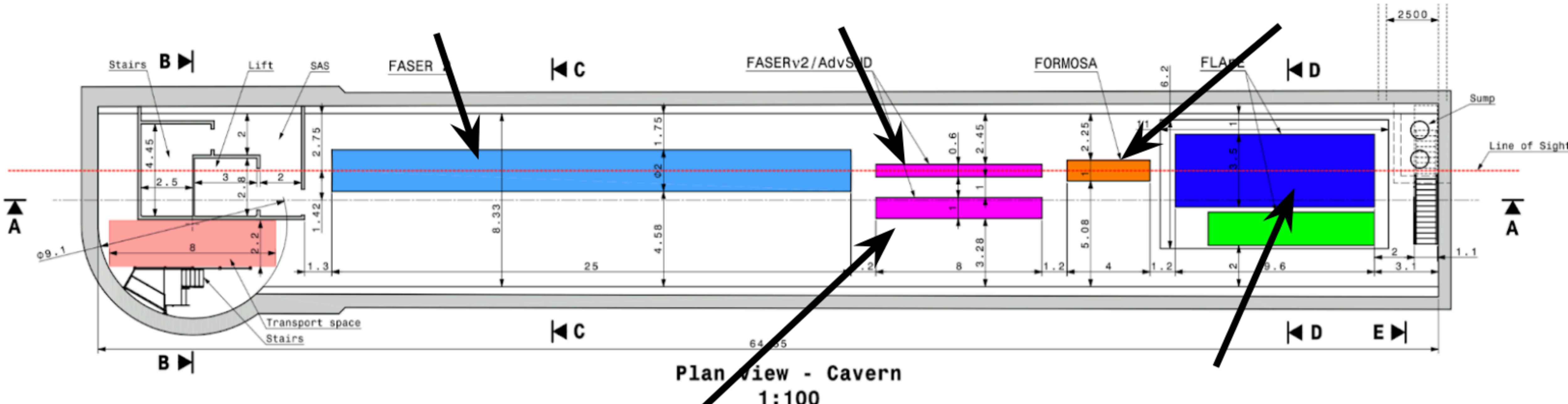
Forward Physics Facility

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.

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

FPF Documentation

FPF workshop series:
FPF1, FPF2, FPF3, FPF4, FPF5

FPF Paper:
2109.10905
~75 pages, ~80 authors

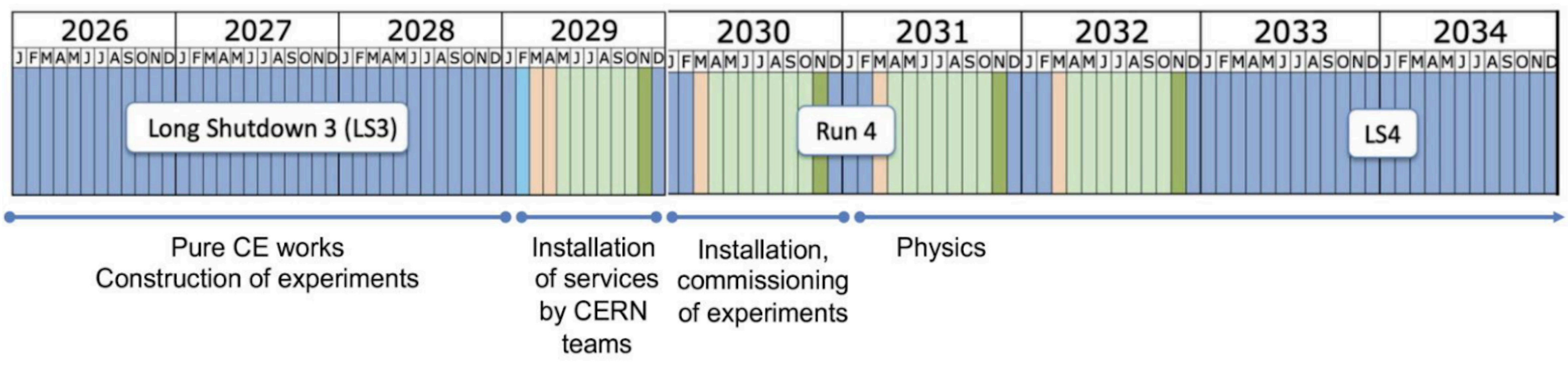
Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

FPF Timeline

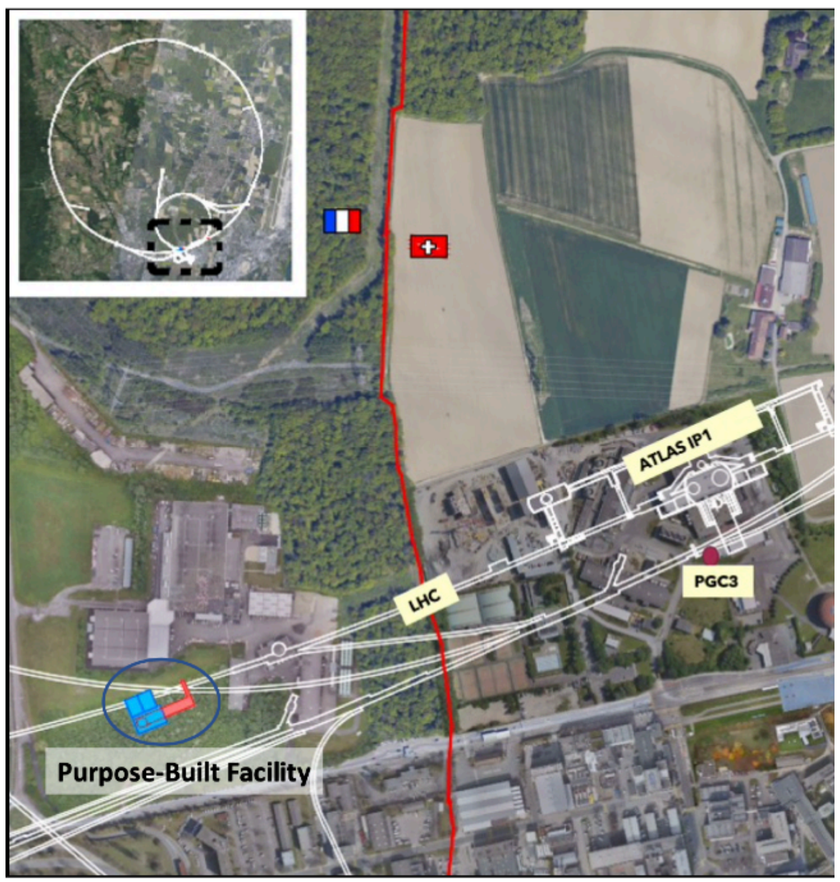
radiation protection studies indicate that there is no danger from working in the FPF while the LHC is running

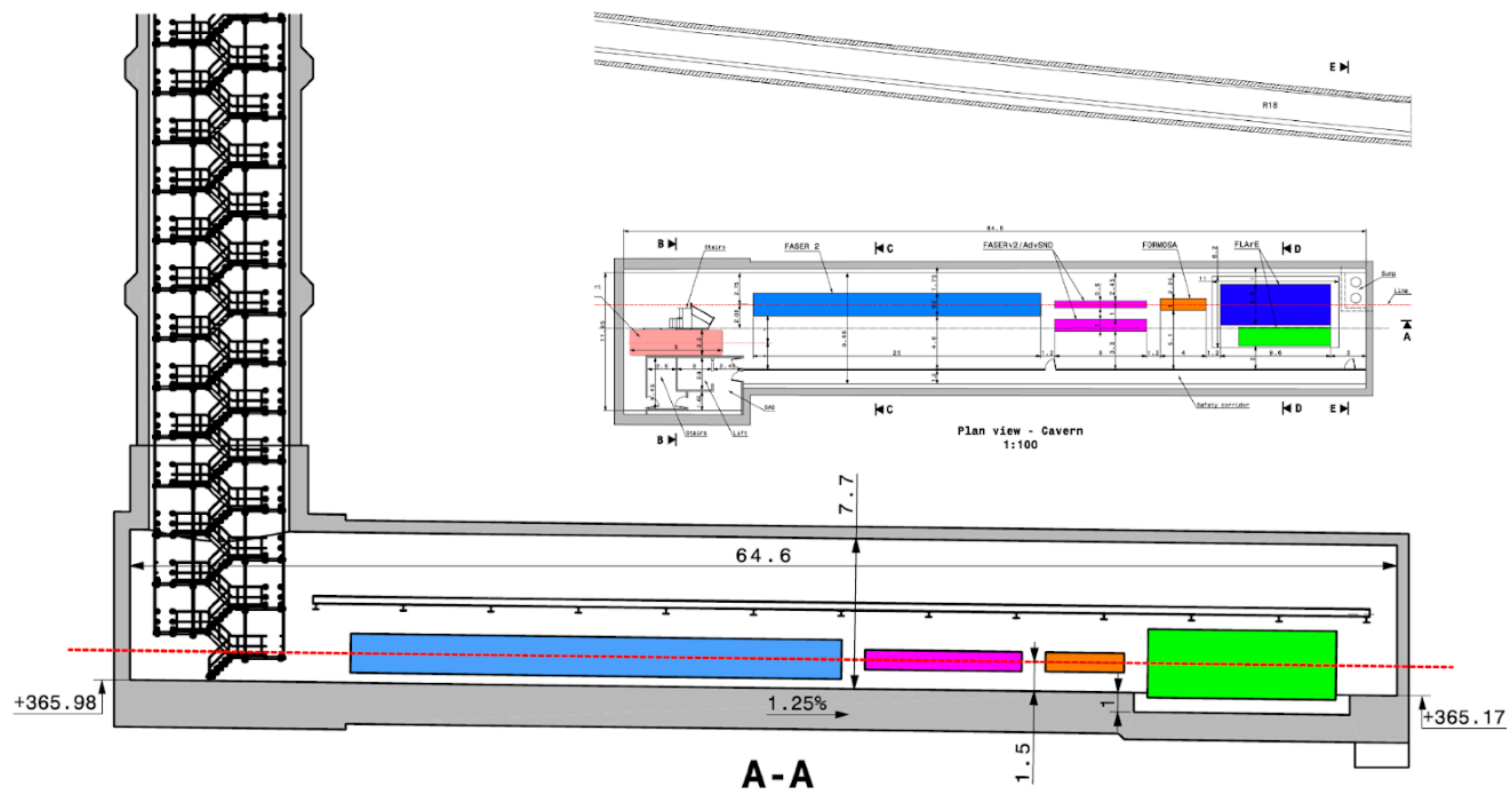
vibration studies indicate that construction of the FPF, installation of services, experiments, will not interfere with LHC operations

Possible timelinne

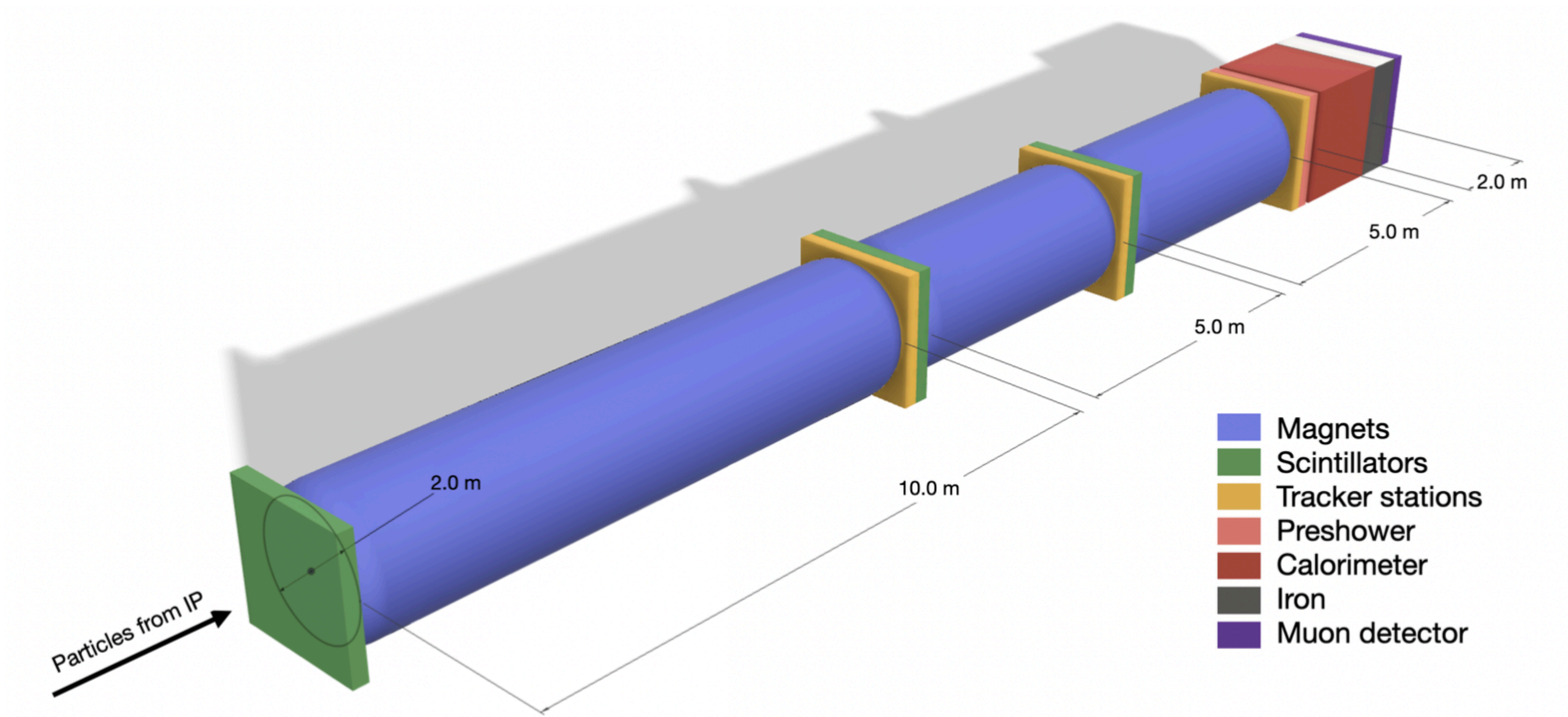


FPF Facility

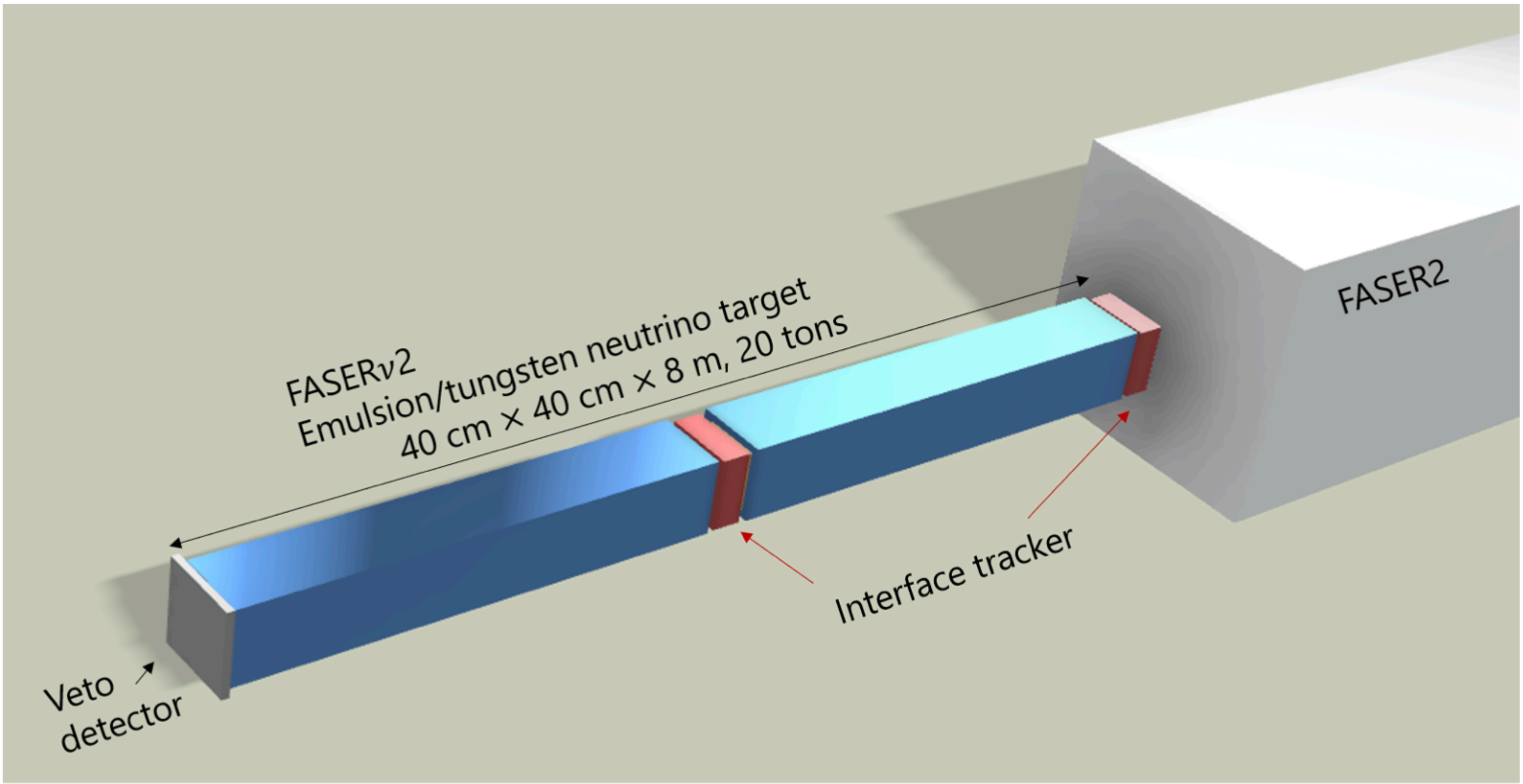




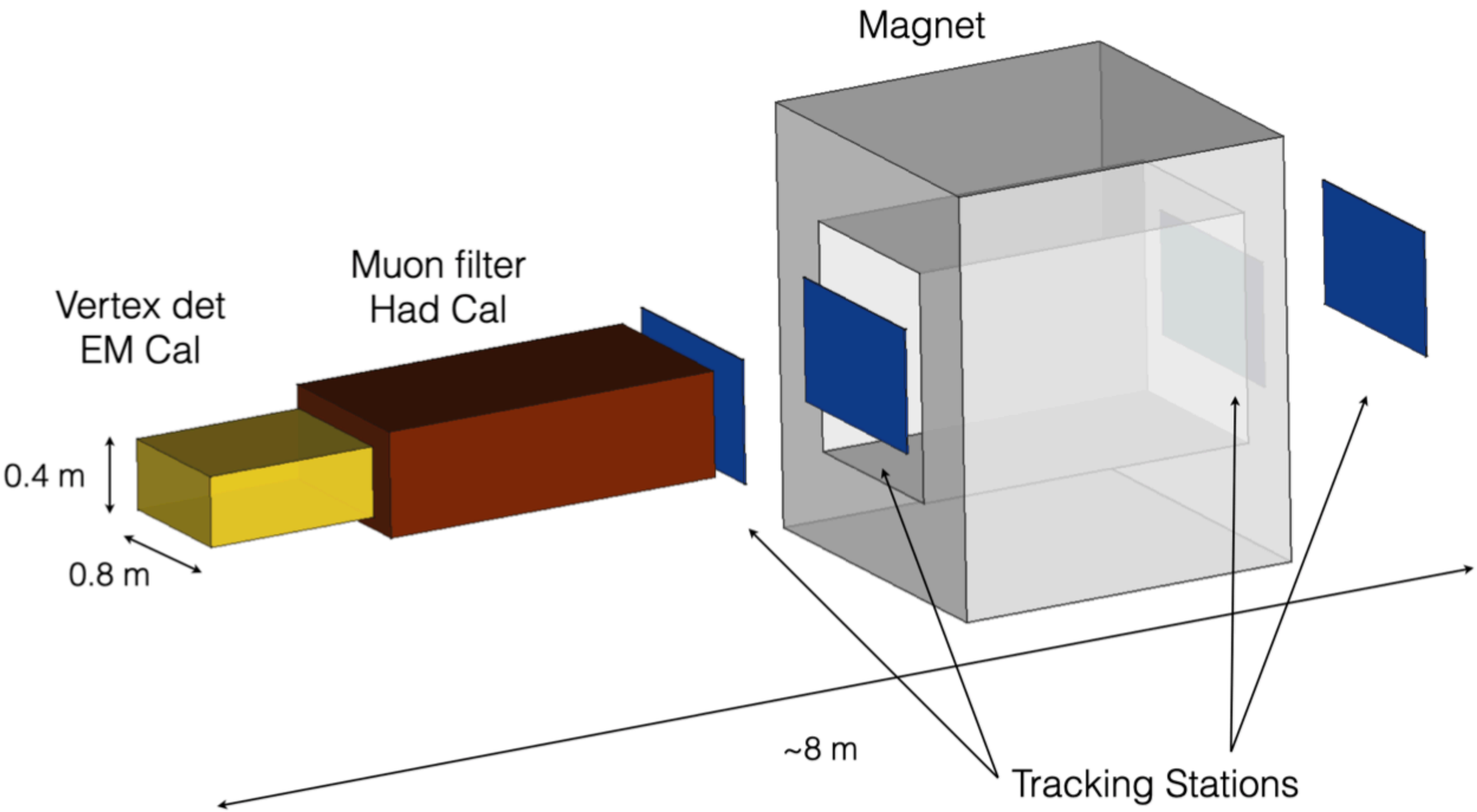
FPF Experiments: FASER2



FPF Experiments: FASERν2



FPF Experiments: Advanced SND

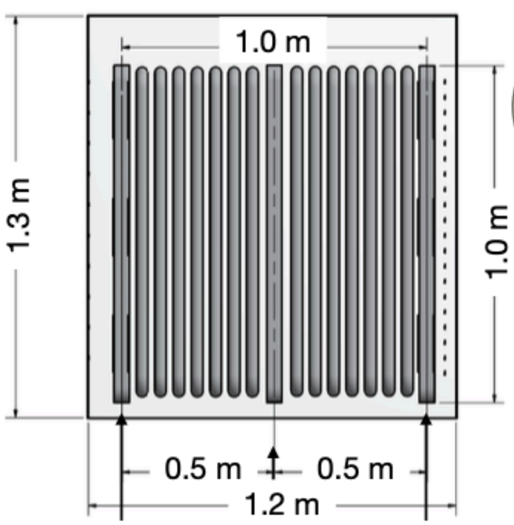


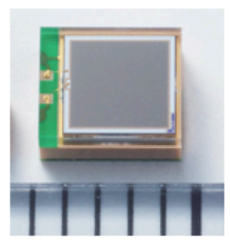
FPF Experiments: FLArE

Brookhaven National Laboratory

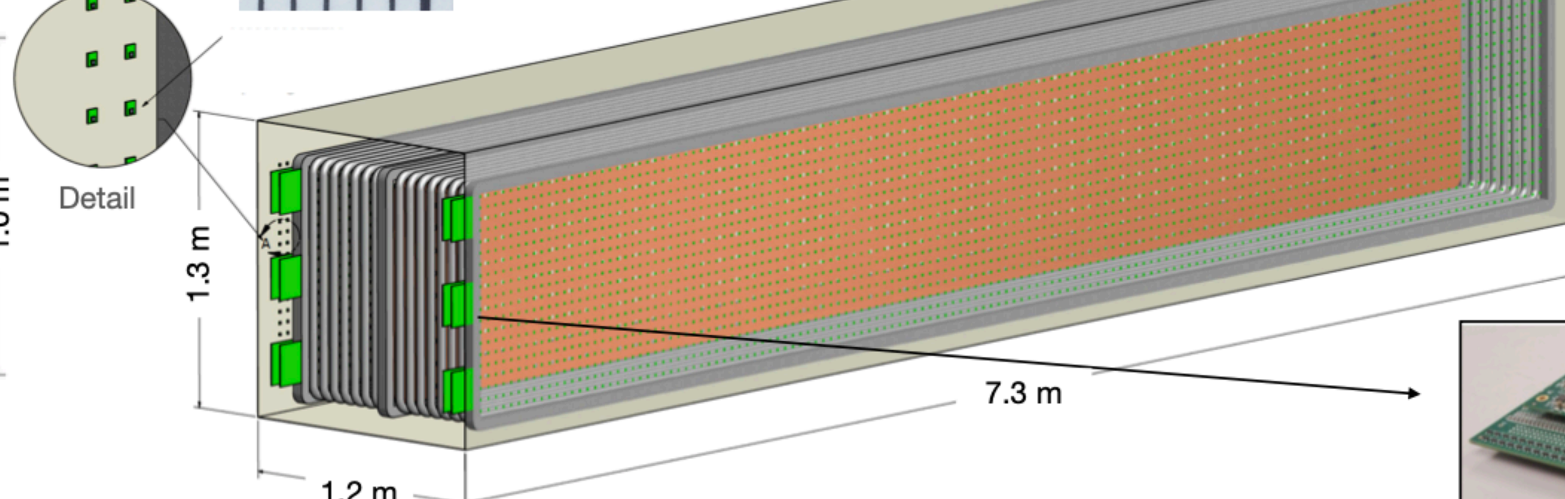
FLArE Detector Preliminary Sketch

TPC-side view 2

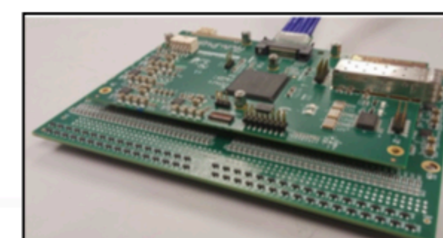




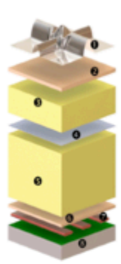
Hamamatsu
S14160 SiPM
6x6 mm
2800 units



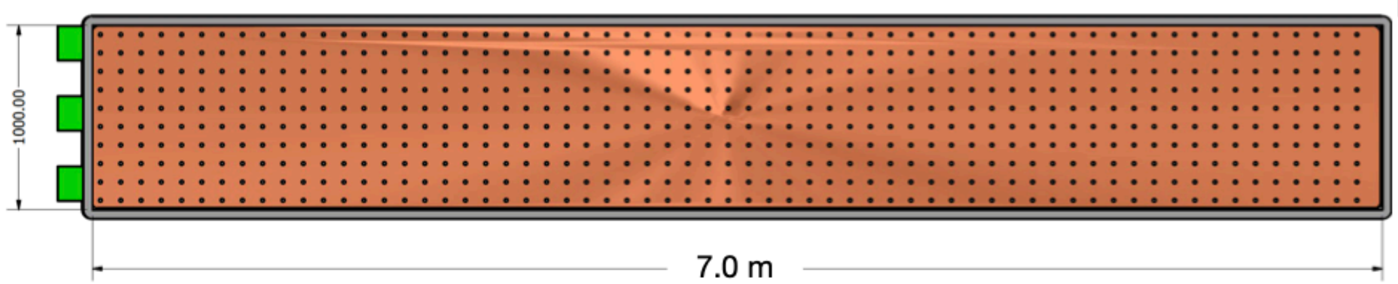
Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W



DUNE Front End Motherboard



Cryostat Insulation



TPC anode plane -side view 1

FPF Experiments: FORMOSA