FASER (and FASERν)

Imperial Seminar

19/5/2021

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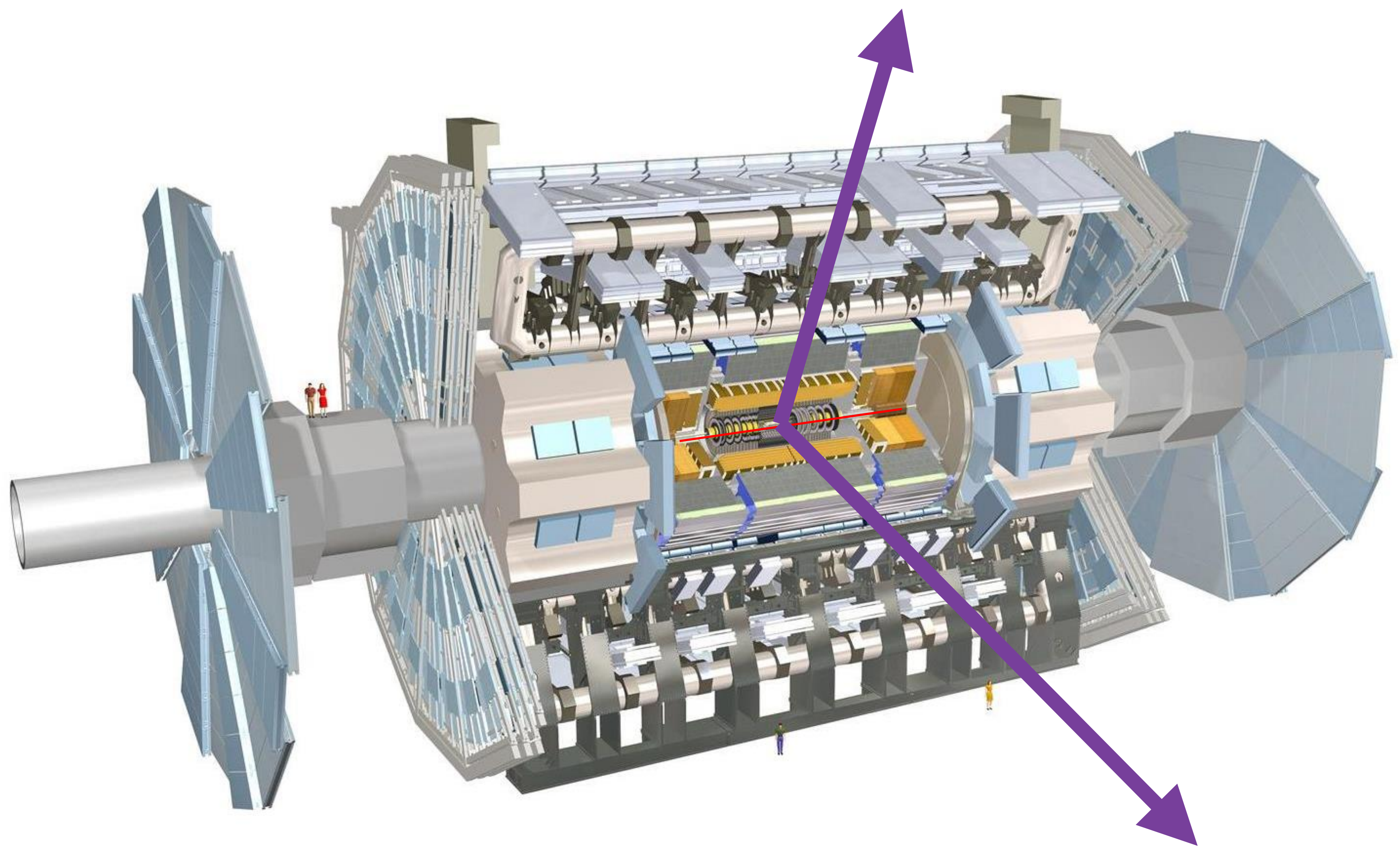
faser.web.cern.ch

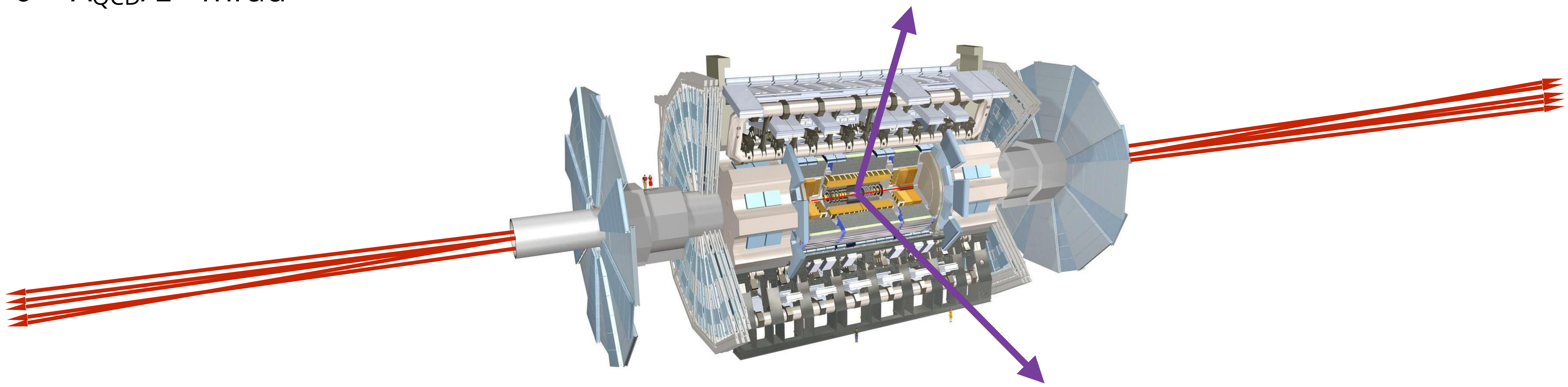
Landscape

- LHC searches/experiments focus on **heavy, strongly interacting particles**
  - Produced ~isotropically and at relatively low rates, especially in high p_T regions
    - σ ~ fb to pb → In Run-3 N ~ $10^2 - 10^5$



Landscape

- Could be misguided - Need to target light and weakly interacting particles
  - Lack of results in "traditional" searches.
  - Scenarios that e.g. satisfy Dark Matter relic density.
  - Exploit the huge inelastic cross section at the LHC
    - σ_{inel} ~75 nb → 10^{16} collisions in Run 3 → 10^{17} π, 10^{13} B
  - **Light meson**: low $p_T \sim \Lambda_{QCD}$ → particles are collimated:
    - $\theta \sim \Lambda_{QCD}/E$ ~mrad



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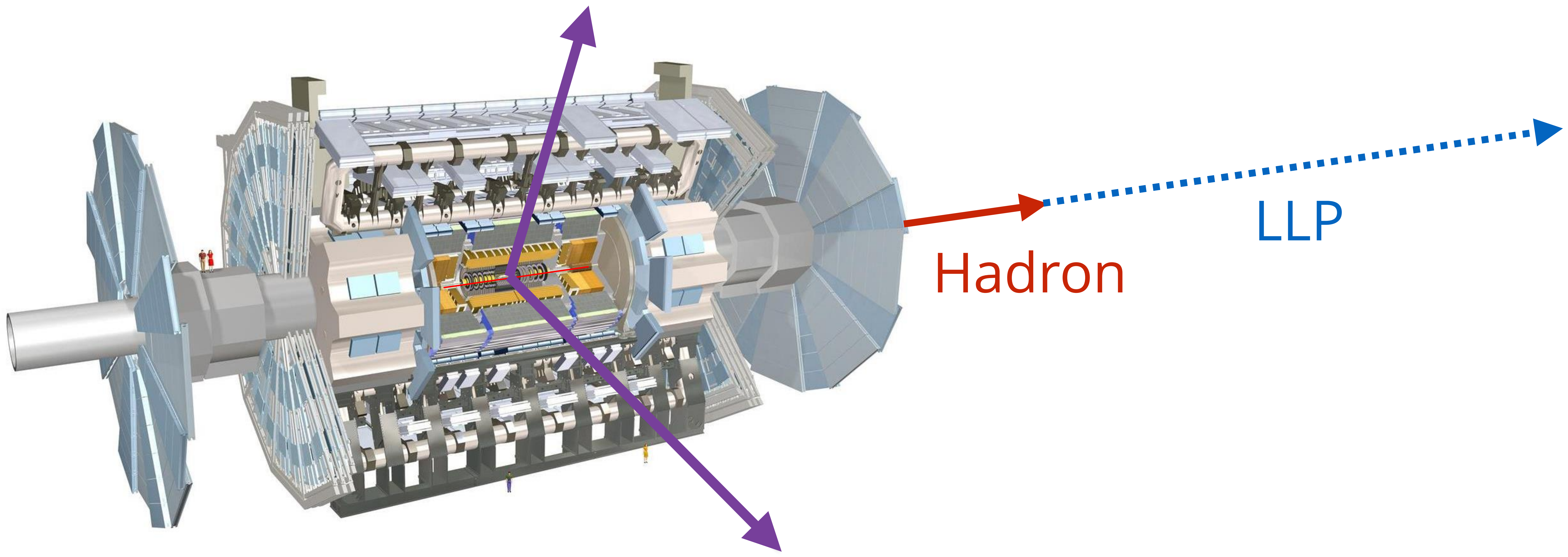
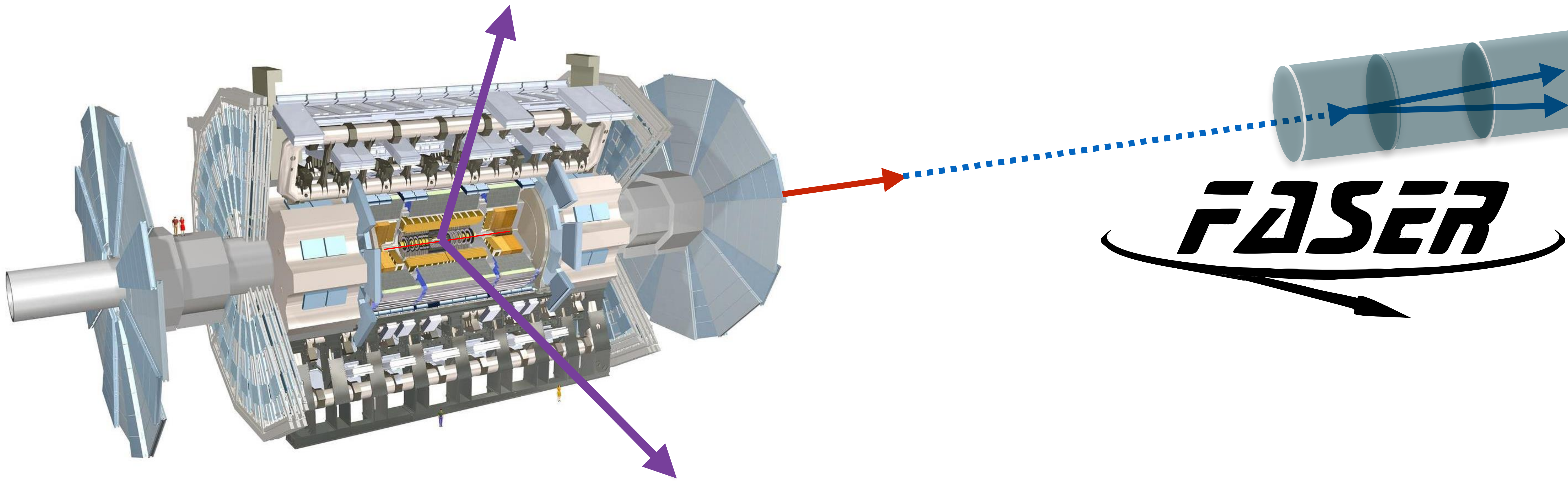
  - **Light meson**: low $p_T \sim \Lambda_{QCD}$ → particles are collimated:
    - $\theta \sim \Lambda_{QCD}/E$ ~mrad
  - Gain sensitivity to **long-lived particles with very weak couplings**.



FASER Philosophy

- **FASER** is a new experiment, to start running after LS2, designed to cover this scenario at the LHC.
  - First concept in 2017 (Feng, Galon, Kling, Trojanowski)
  - Approved by CERN in March 2019 (limited budget ~ $2M)
- Detector to be placed 480m from ATLAS IP1
  - Directly on the beam collision axis line of sight (LOS)
  - Transverse radius of only 10cm covering the mrad regime (η>9.1)



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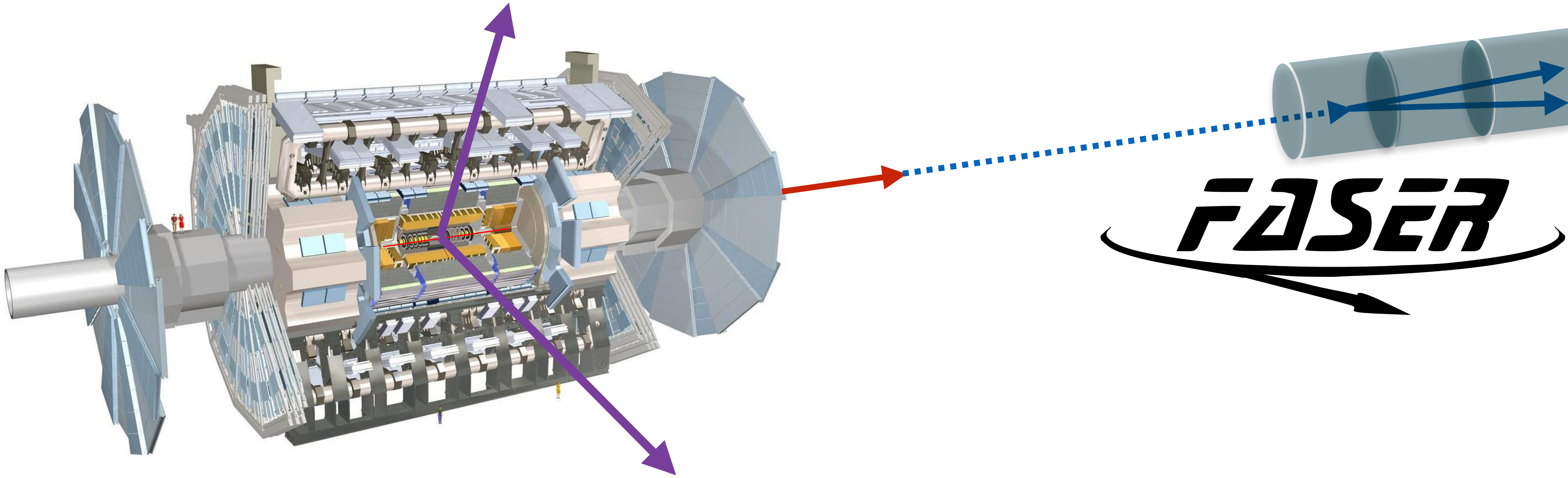
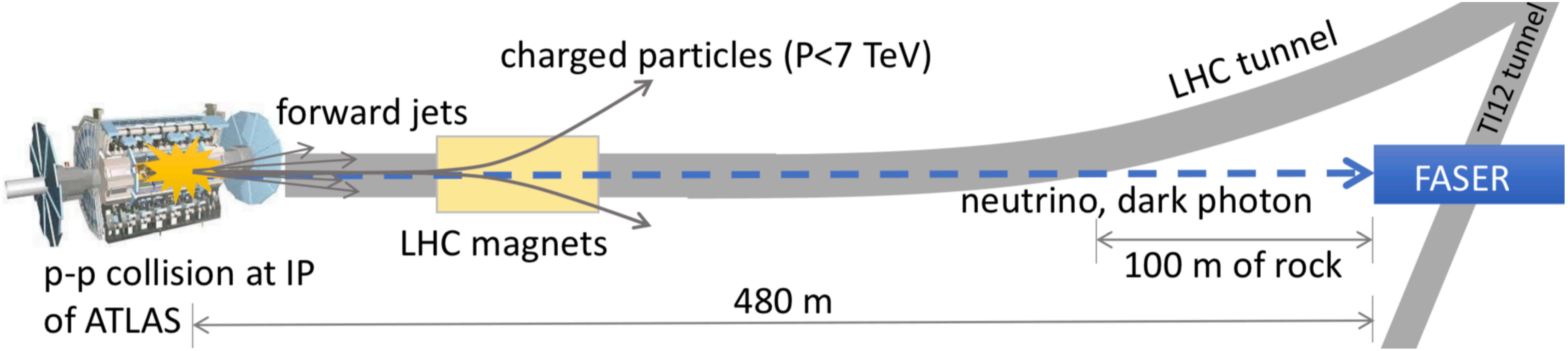
- From only 10^{-8} of solid angle 1% of π_0s are in acceptance.



FASER Location

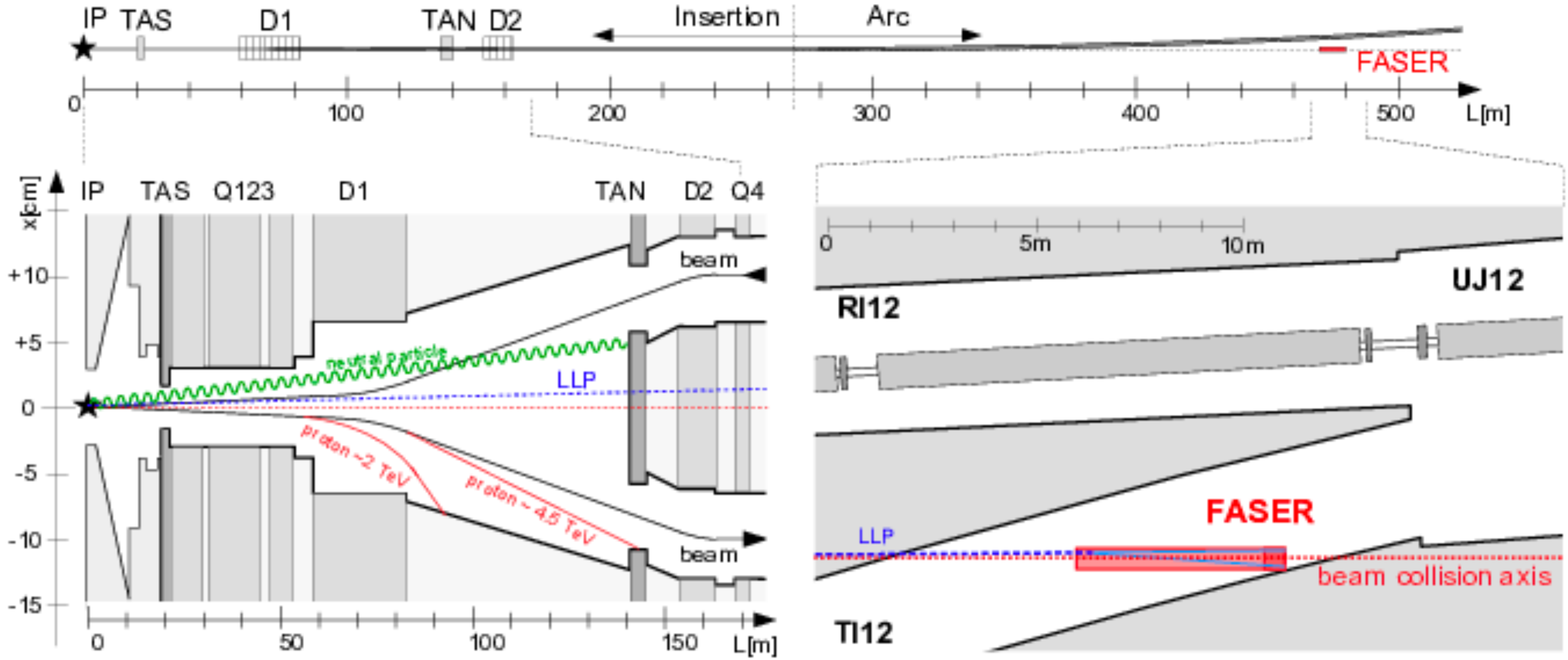
- The TI12 service tunnel just happens to be in just the right place for FASER:



- Old SPS → LEP tunnel
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds
    - Charged particles bent by LHC magnets

FASER Location

- A closer look at the LHC infrastructure on the line-of-sight:

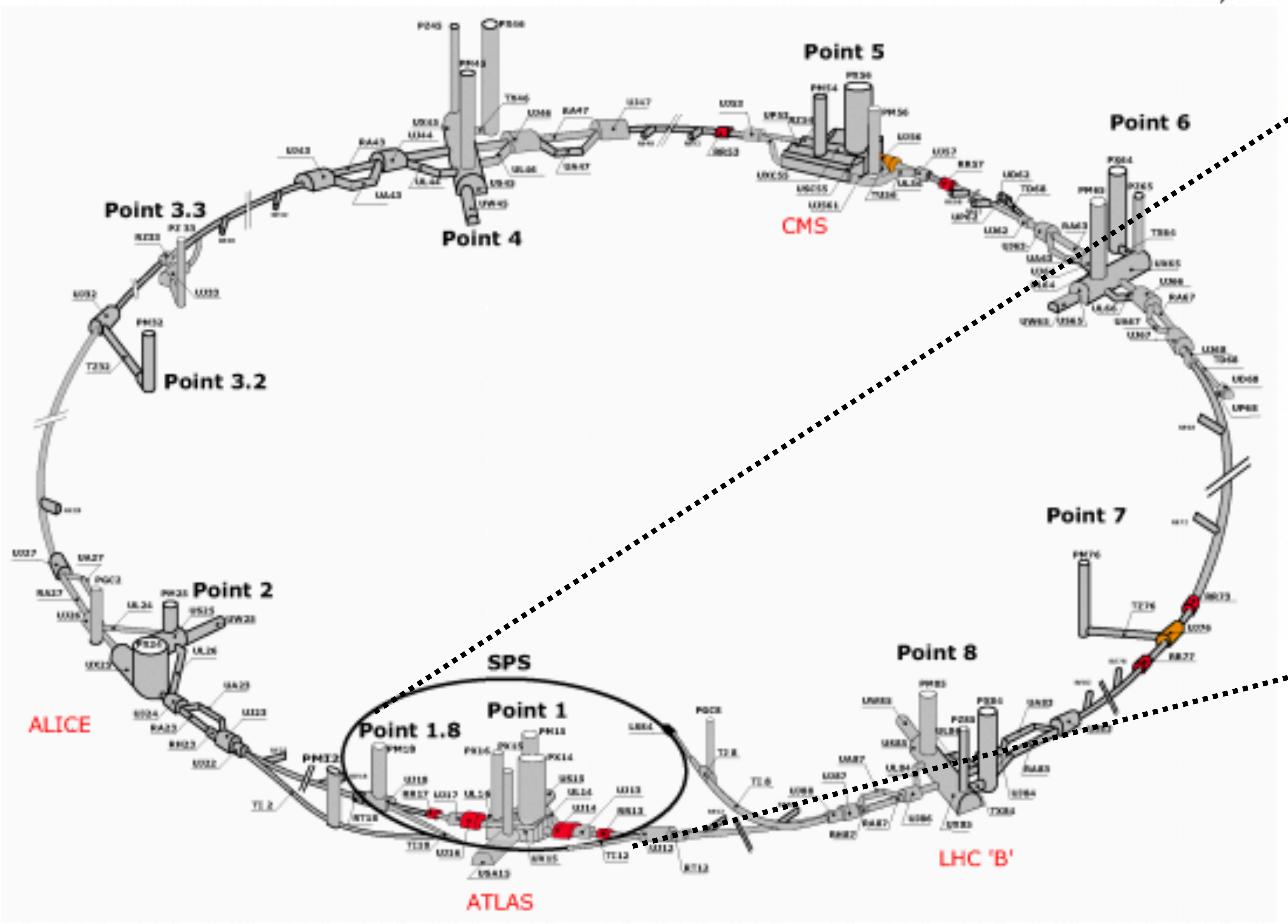


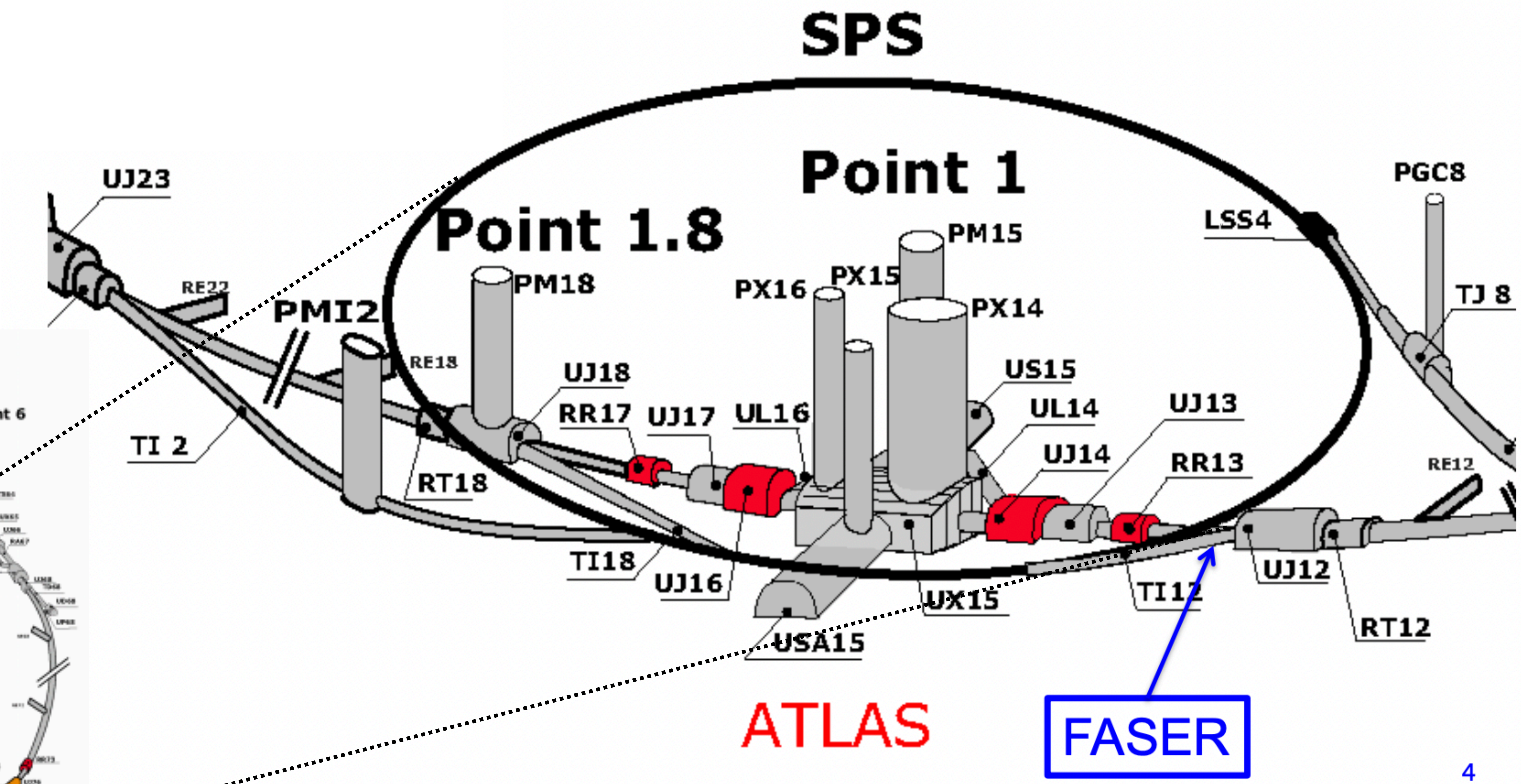
FASER Location

- In relation to ATLAS at Point 1

FASER Location

- Wider setting at the LHC





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In real life | From first scouting photos...

new physics
(hidden in the dark)

main LHC tunnel

In real life | To this!

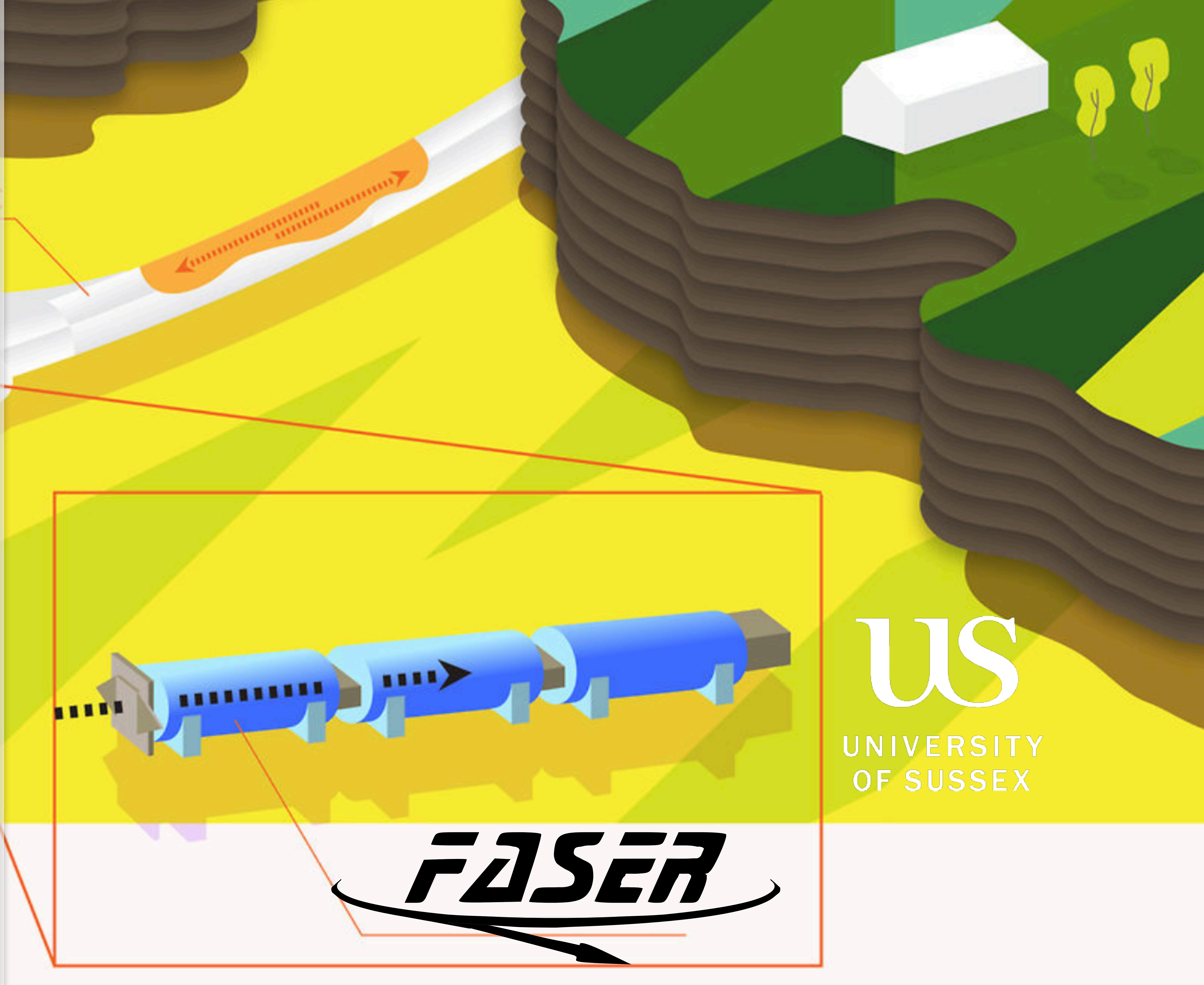
UNIVERSITY OF SUSSEX

In real life

In real life

Outline

- Overview of physics motivation
- Overview of FASER detector
- Preparations underground
- FASERν
- Looking to HL-LHC

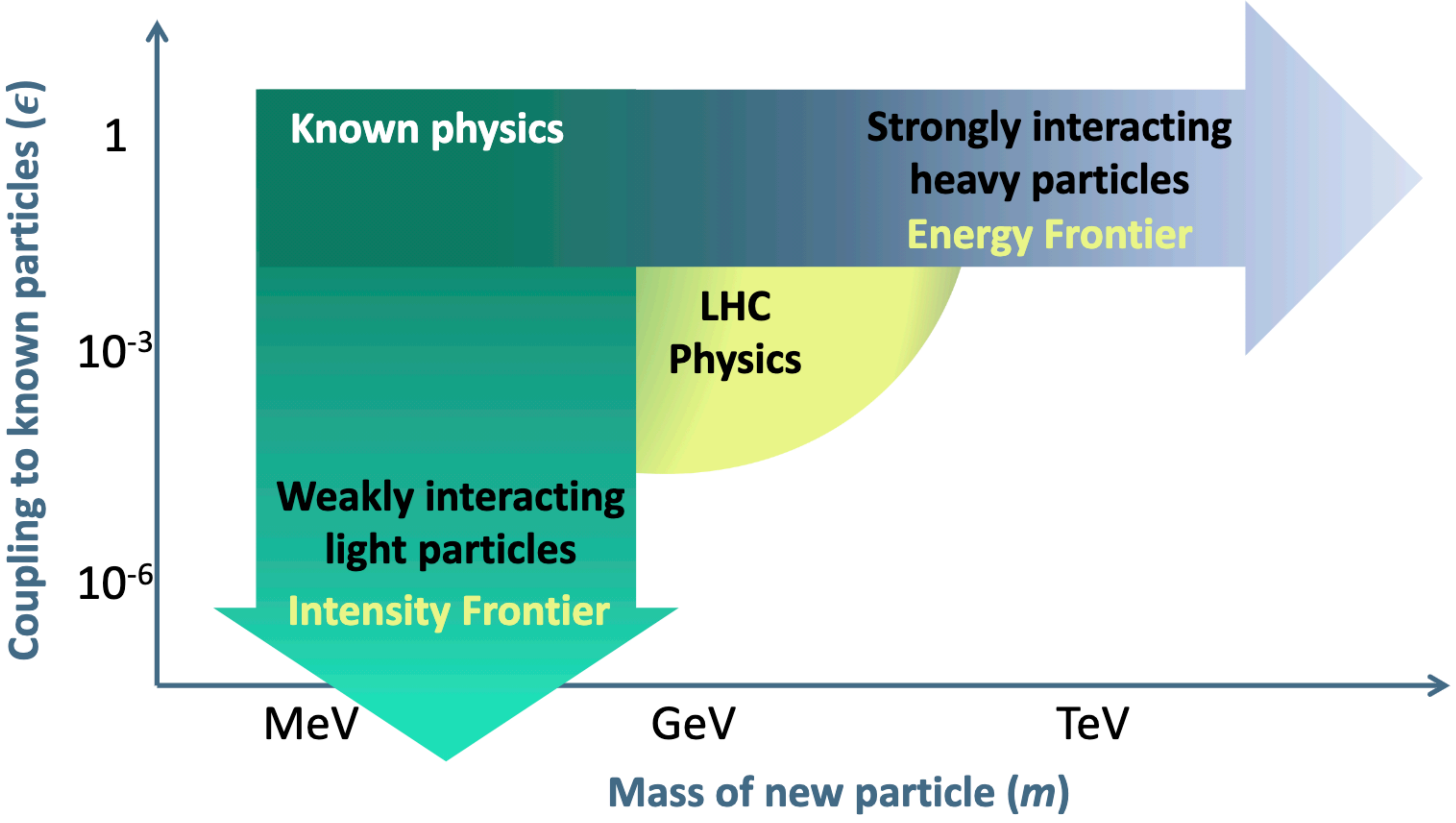


Physics Motivation

Physics Motivation

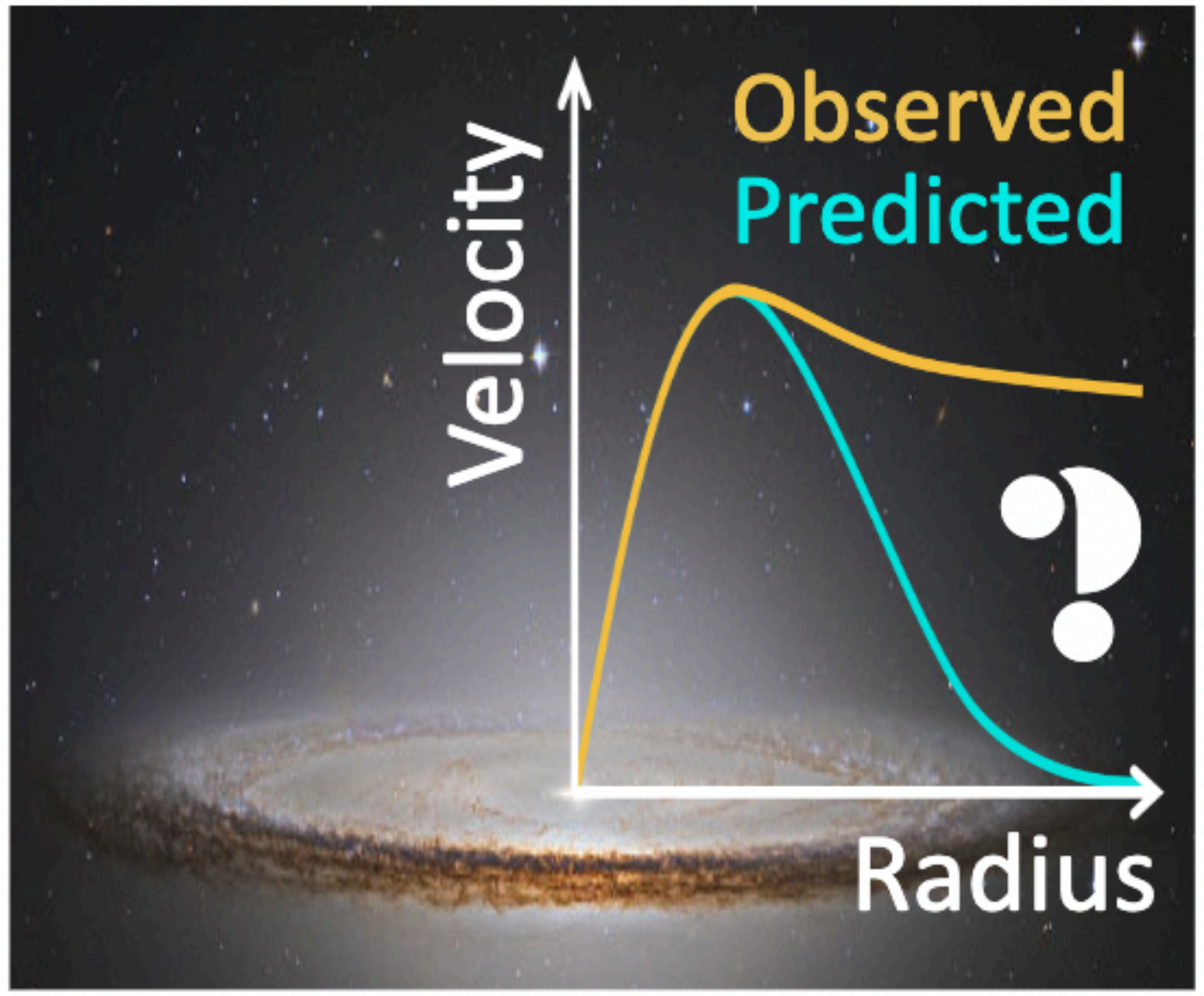
- The **LHC experiments** are producing incredible results, searching in previously unexplored phase spaces and performing increasingly precise measurements.

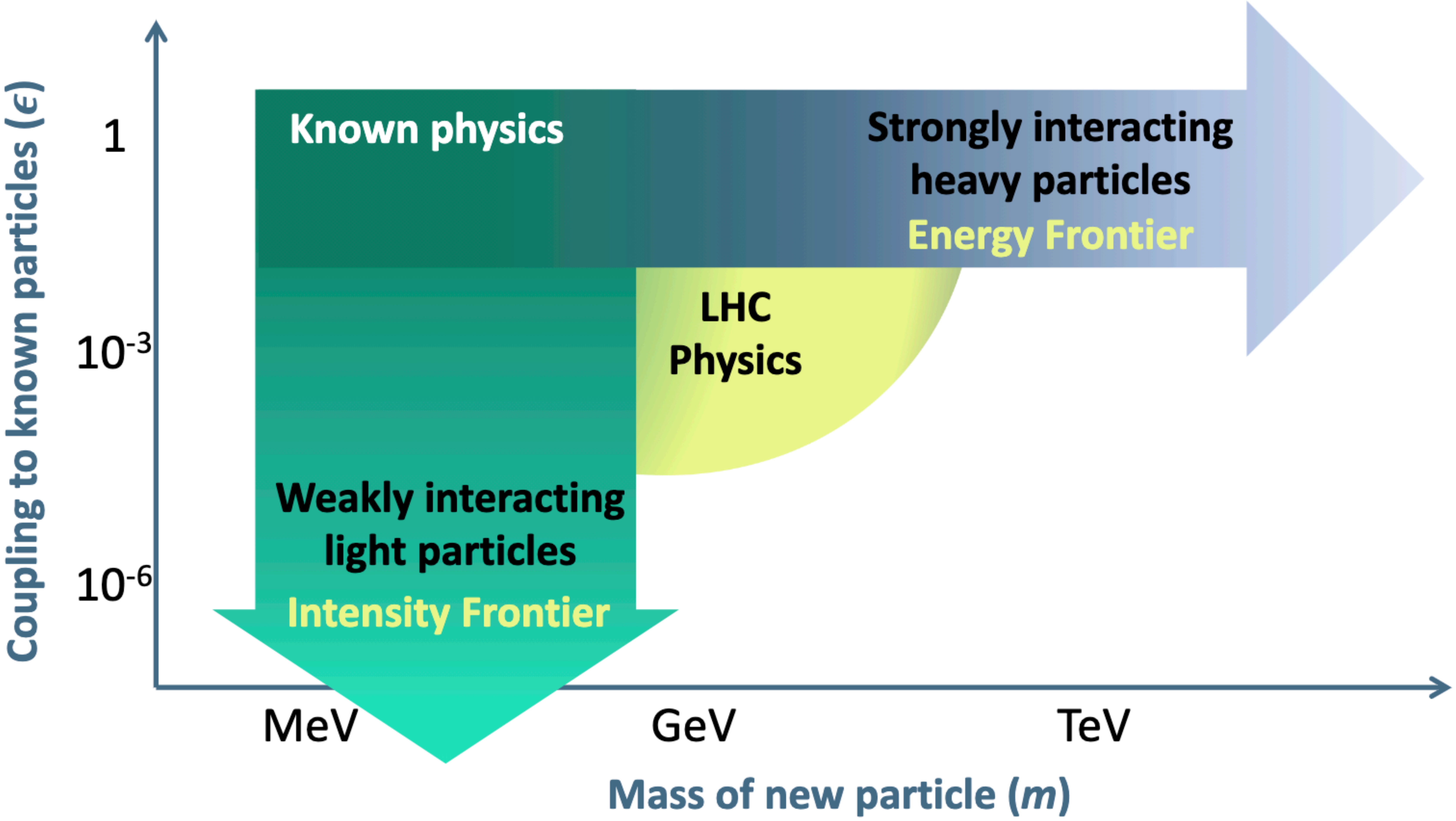
- But the lack of any observation of BSM physics motivates **looking elsewhere** too.



Physics Motivation

- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

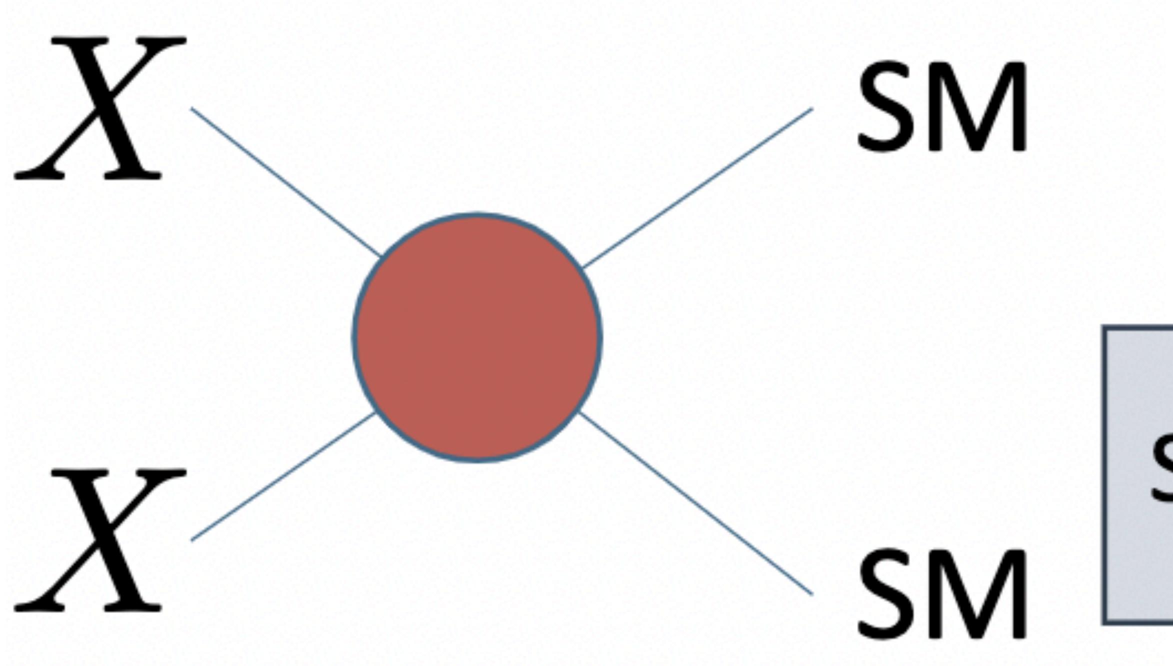


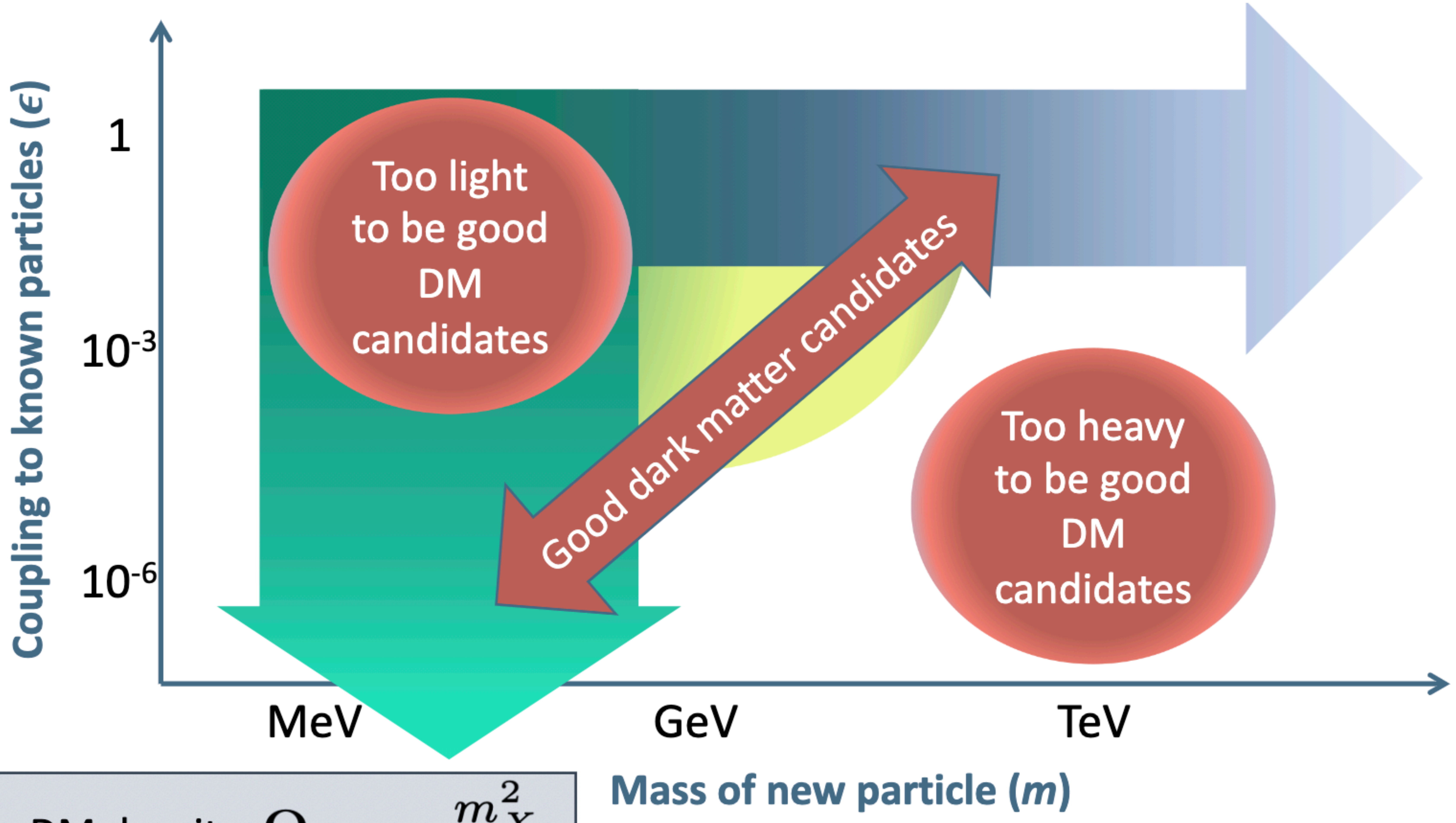


Physics Motivation

- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

- Main region of interest is for new particles that satisfy DM relic density requirements.

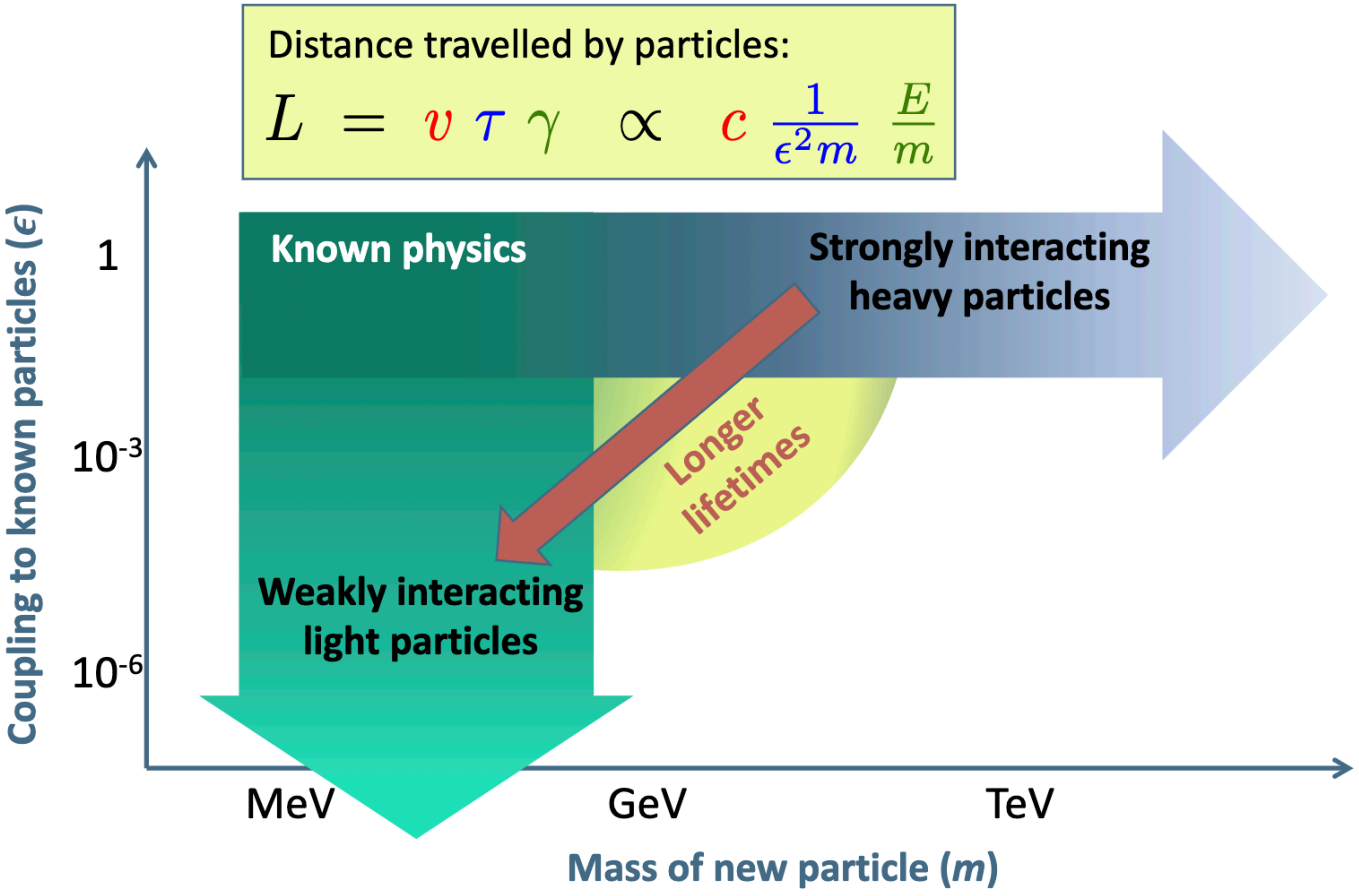




Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

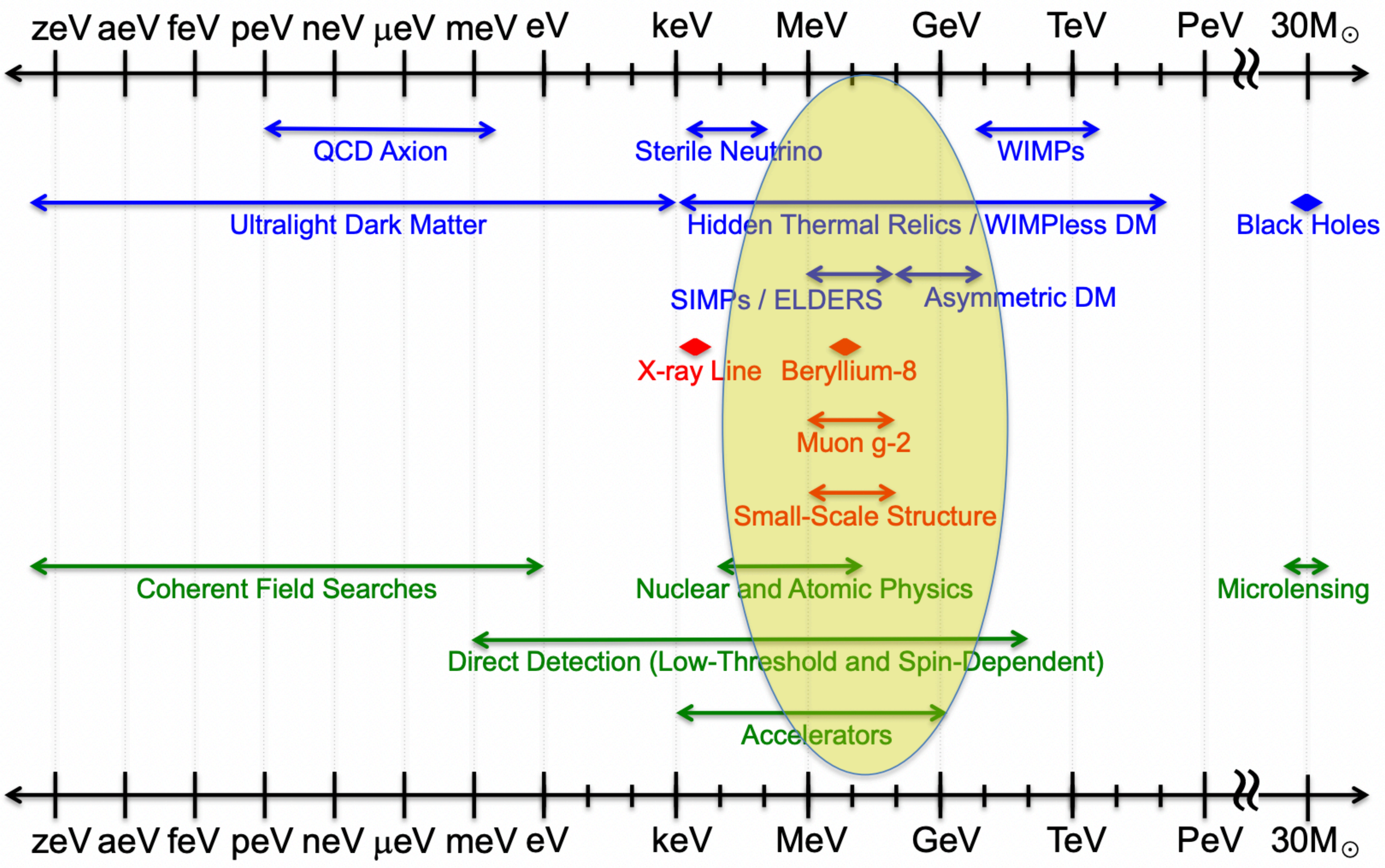
Physics Motivation

- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- Distinct signatures
- Opportunity for exploration!



Physics Motivation | Intrigue…

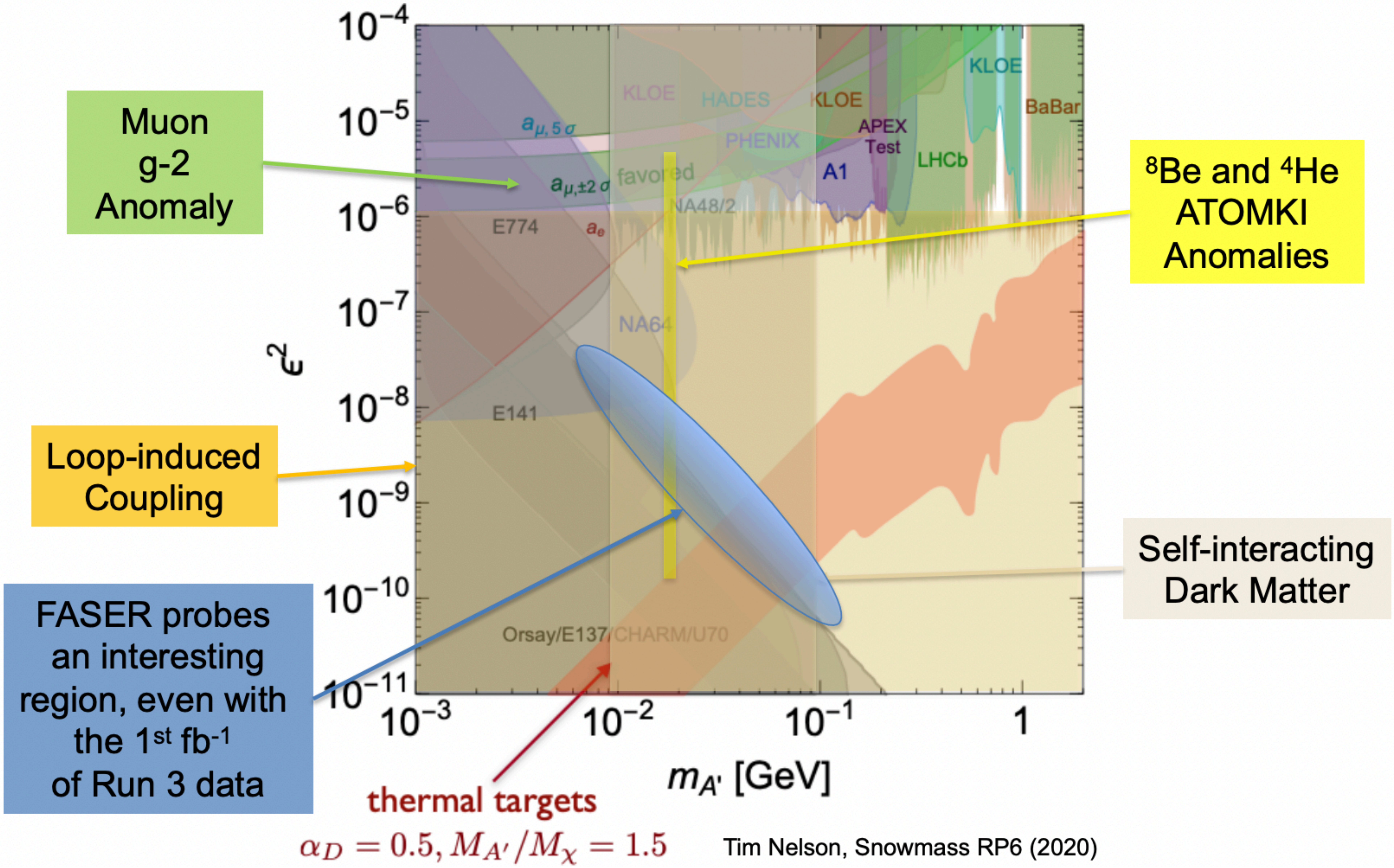
- Focusing on the mass scale
  - Dark Sector Candidates
  - Anomalies
  - Search Techniques
- We see some interesting things in the ~MeV range



Cosmic Visions Report (2017)

Physics Motivation | Dark photon plane

- FASER is probing a very interesting region of phase space
- New sensitivity in this region will come even with only a small fraction of Run 3 data.



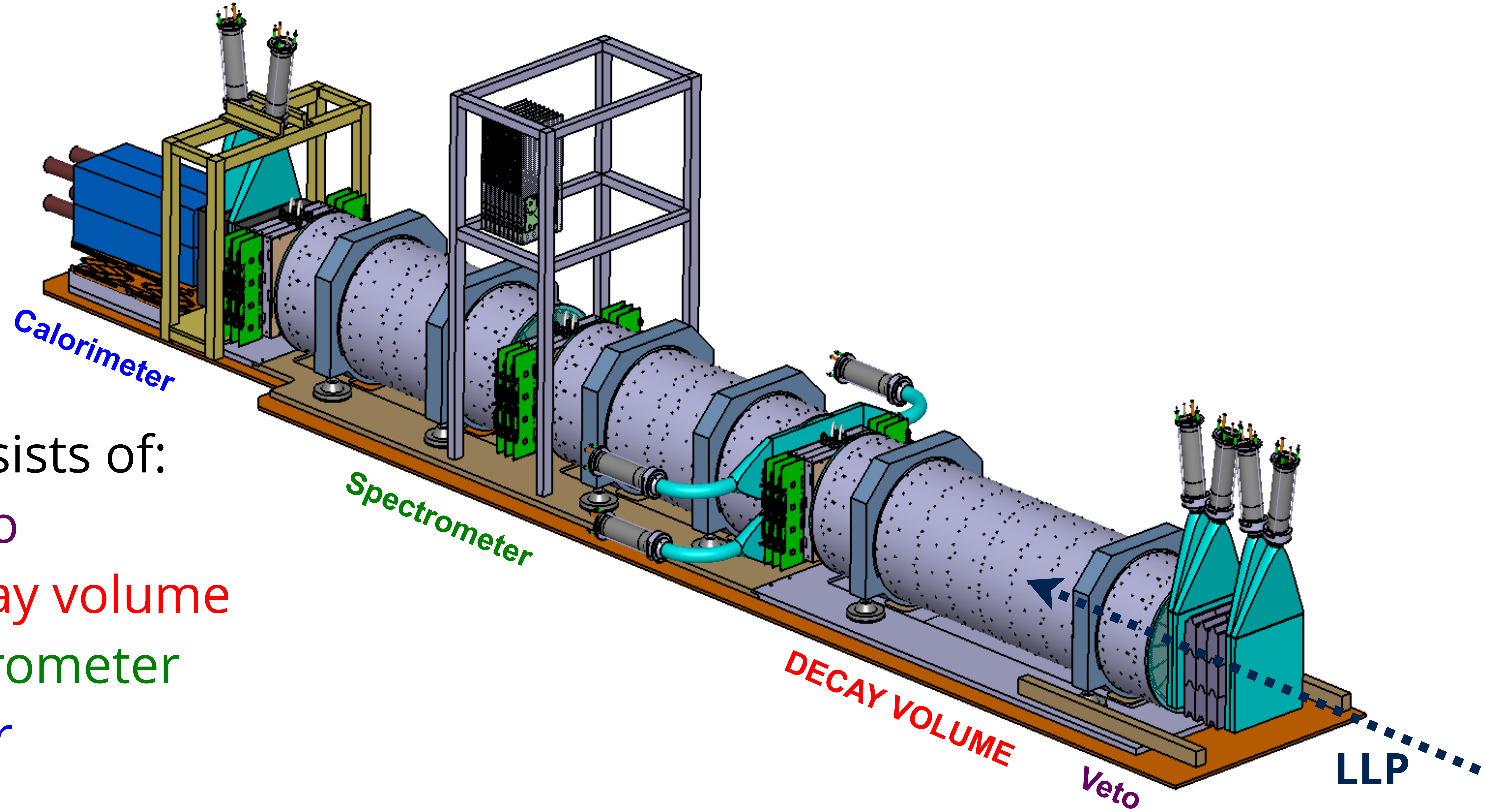
Tim Nelson, Snowmass RP6 (2020)

FASER Detector

FASER Collaboration

- 70 collaborators, 19 institutions, 8 countries:

Detector | Brief overview



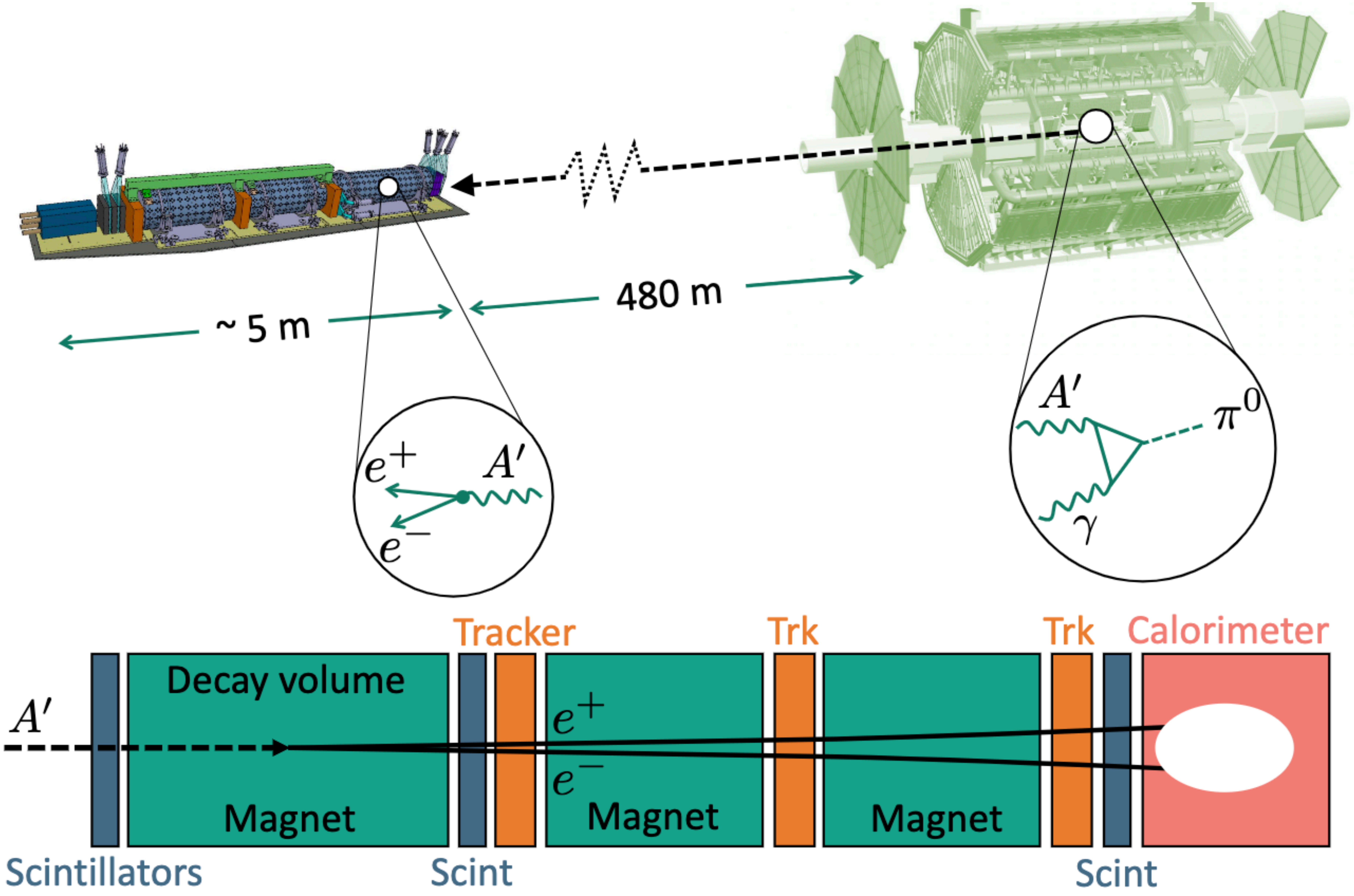
The detector consists of:
- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

Detector | Philosophy

- Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:
  - Detector that can be constructed and installed **quickly & cheaply**
  - Have tried to **re-use existing detector components** where possible
  - Aimed for a **simple, robust detector** (access difficult)
  - Tried to **minimize the services** to simplify the installation and operations

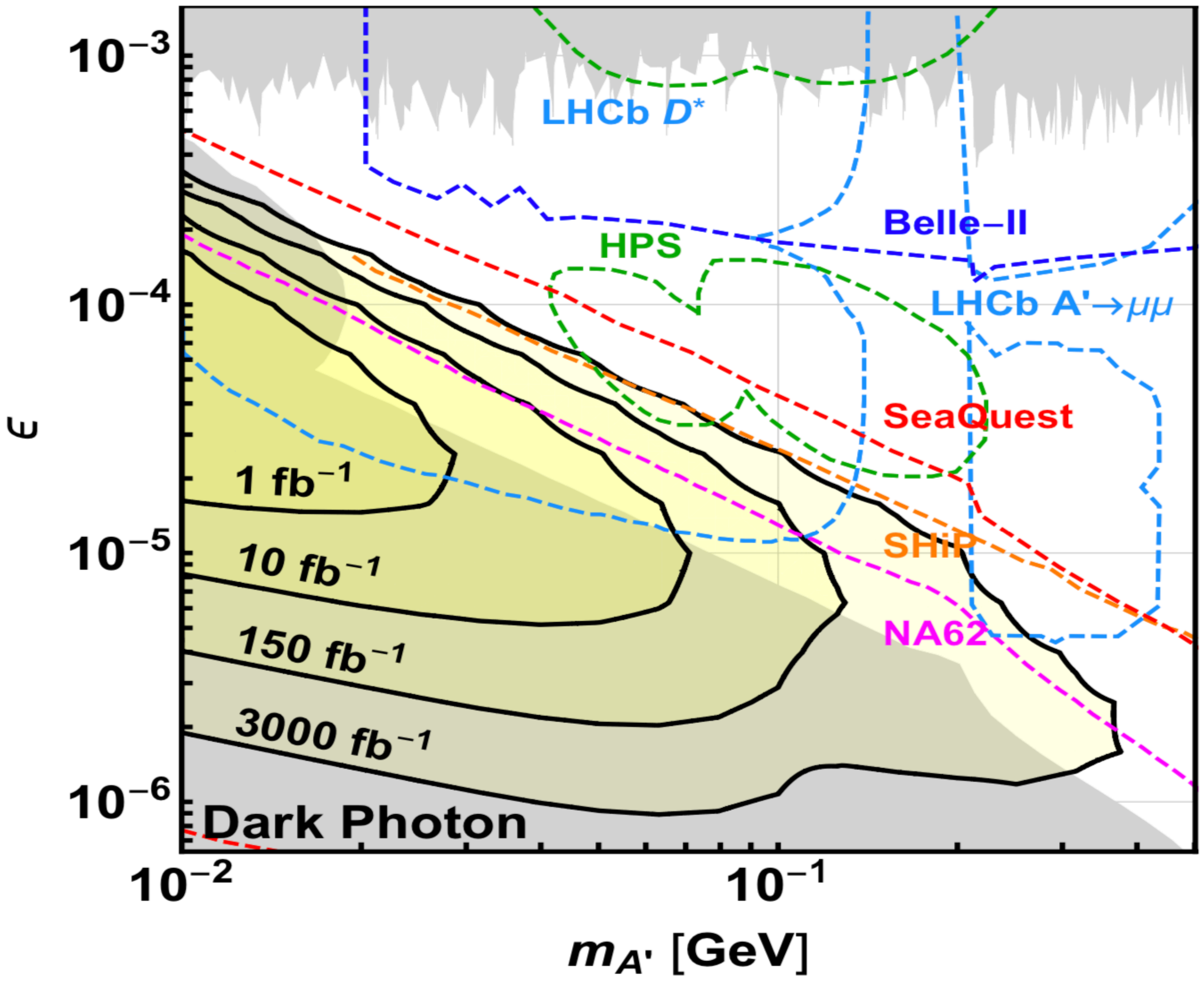
- Many challenges of the large LHC experiments not there for FASER:
  - trigger rate ~500Hz (mostly single muon events)
  - low radiation
  - low occupancy / event size

Target scenarios | Dark photon



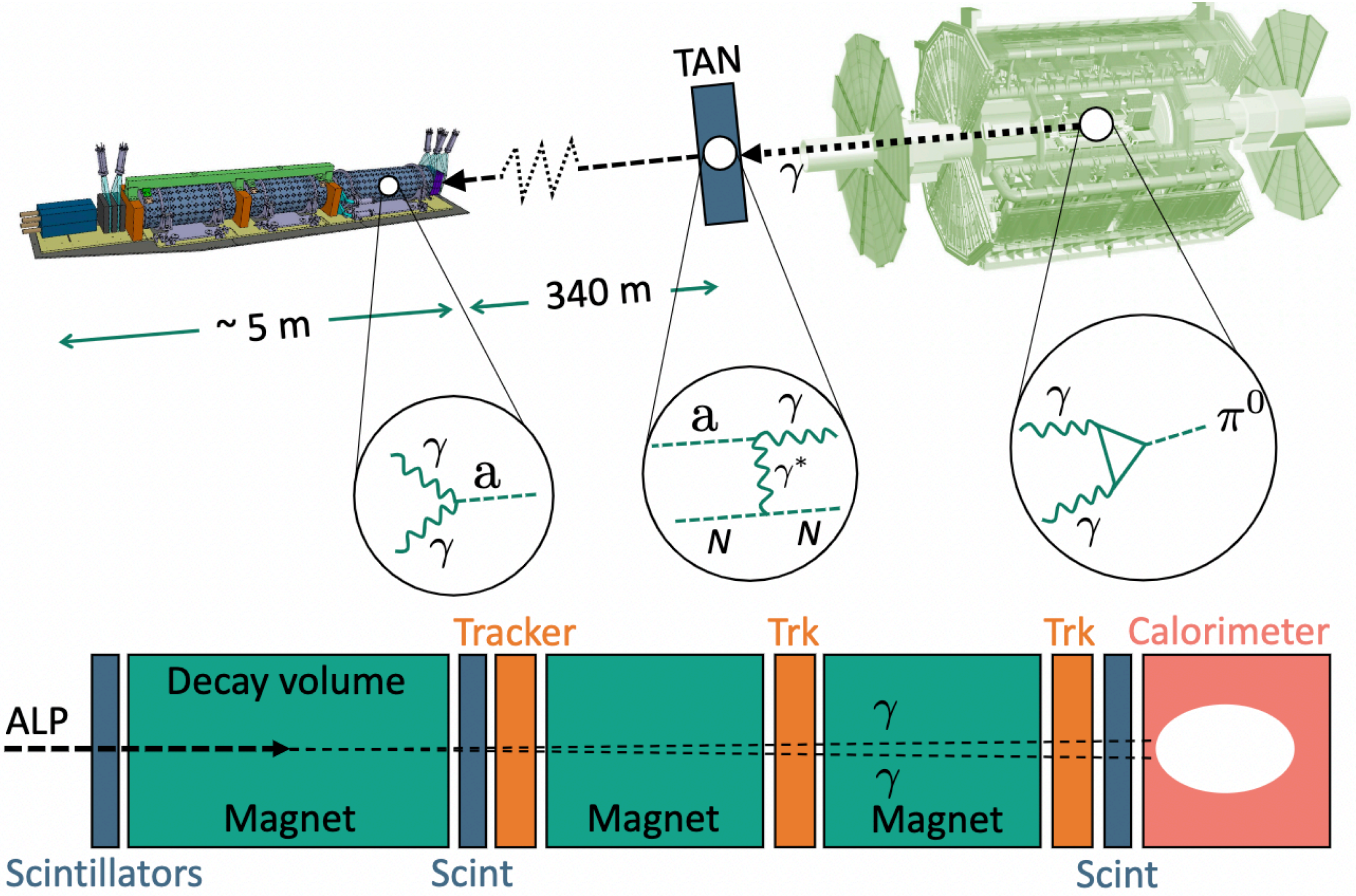
Target scenarios | Dark photon

- Expected sensitivity of FASER for **dark photons**
- Detector signature:
  - A′ → e+e-
  - Charged tracks appearing in decay volume
  - Opposite charges separate through detecto
  - Significant energy deposit in calorimeter
- Sensitivity
  - Considers all production channels
    - Assumes no background, requires N=3 events
  - Reach limited by decay length (high ε) and production rate (low ε)



- **New parameter space probed with just 1 fb^{-1} in 2022**

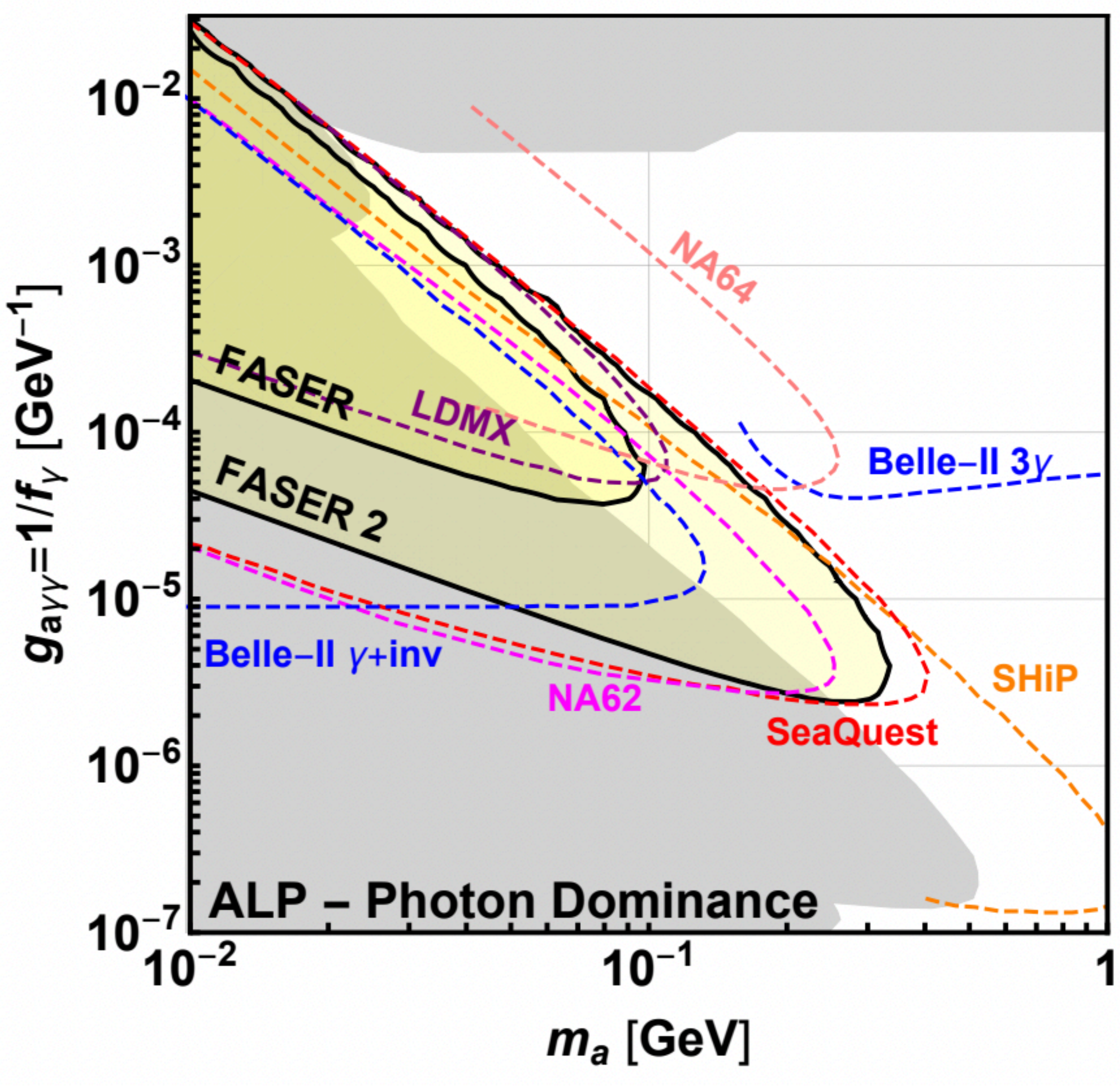
Target scenarios | Axion-like particles



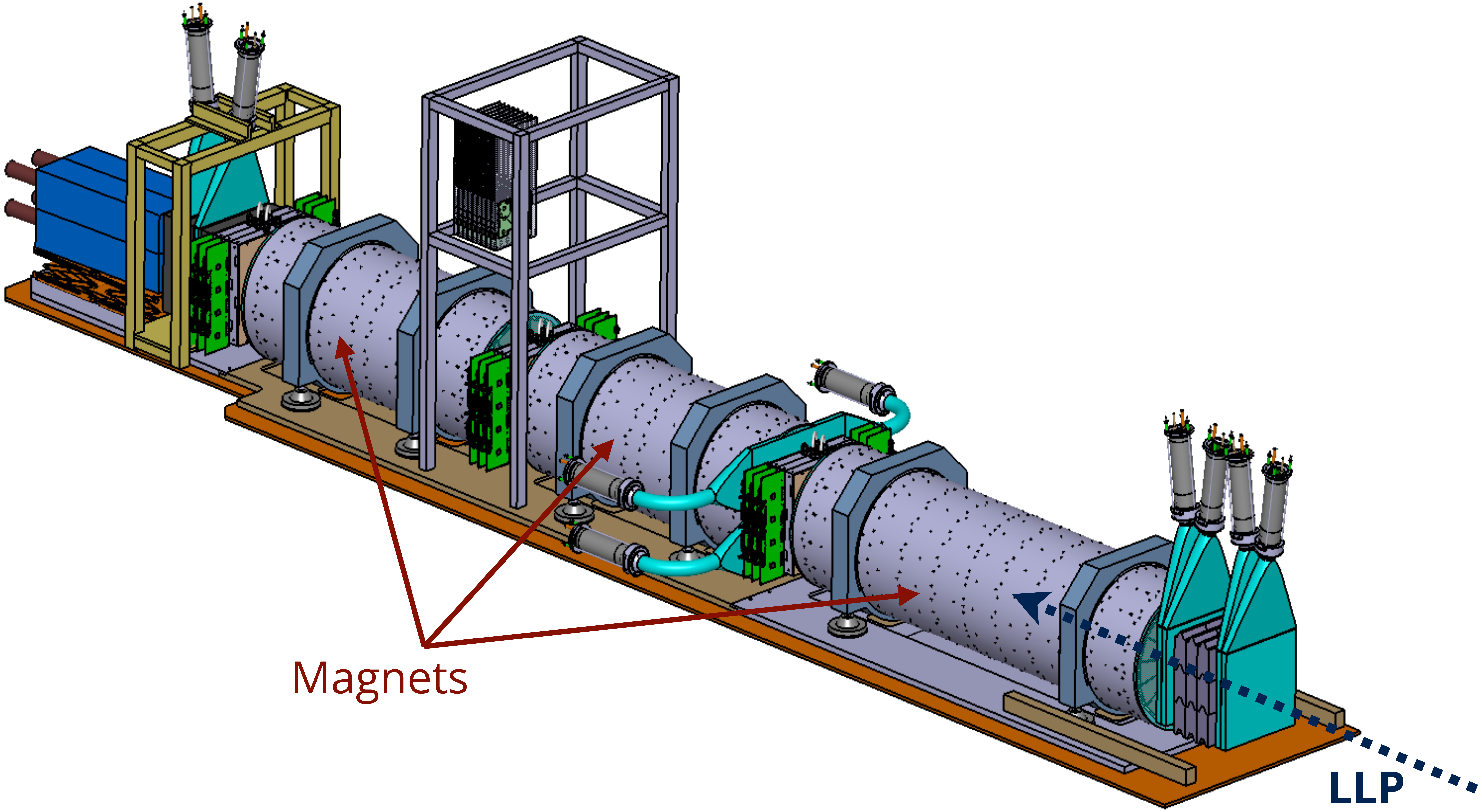
Target scenarios | Axion-like particles

- Expected sensitivity of FASER for **ALPs**
- Detector signature:
  - ALP → ɣ ɣ
  - Photons appearing in decay volume
  - Significant energy deposit in calorimeter
- Sensitivity
  - Considers all production channels
    - Assumes no background, requires N=3 events
  - Reach limited by decay length (high g) and production rate (low g & high mass)

- **Can probe currently unconstrained parameter space.**

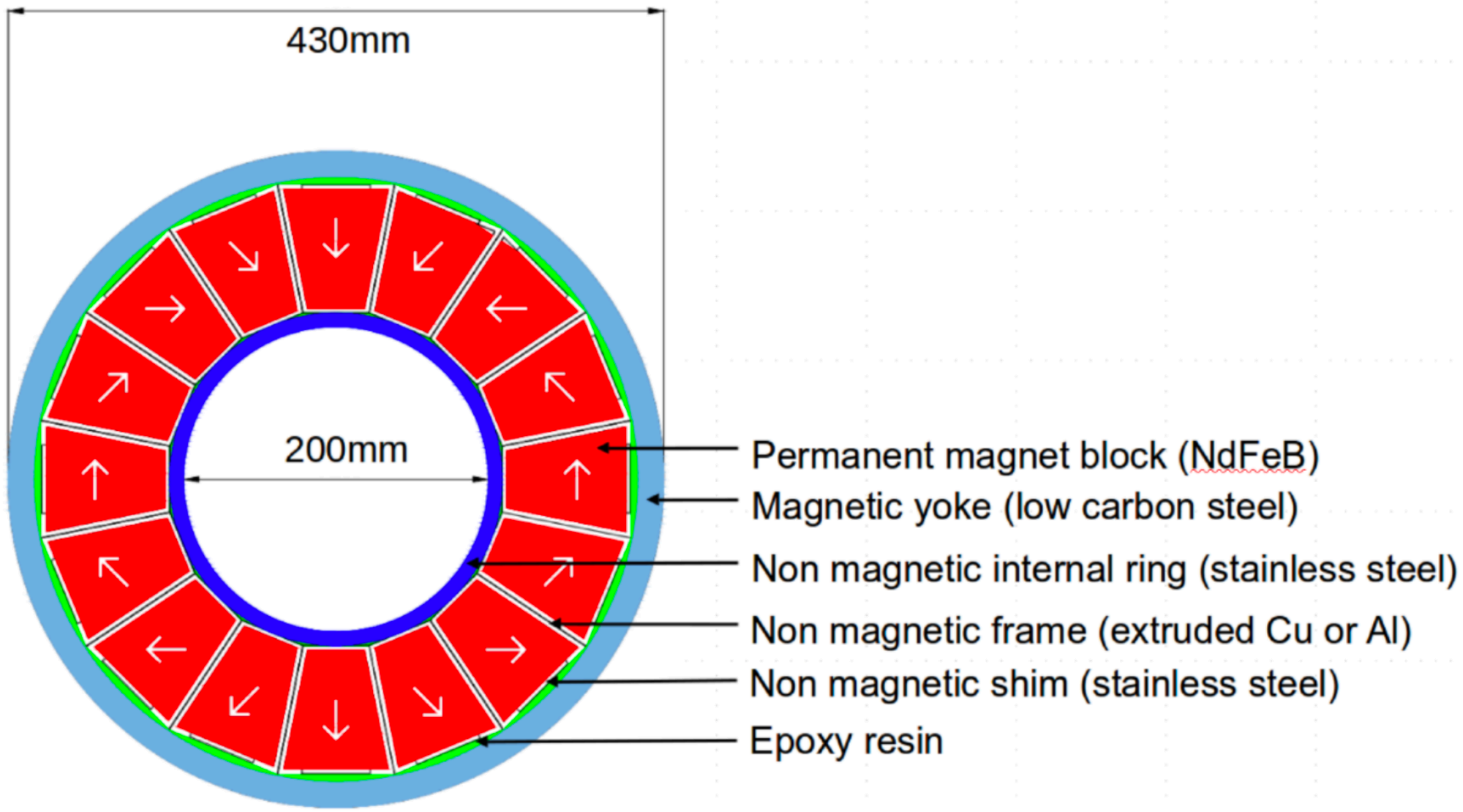


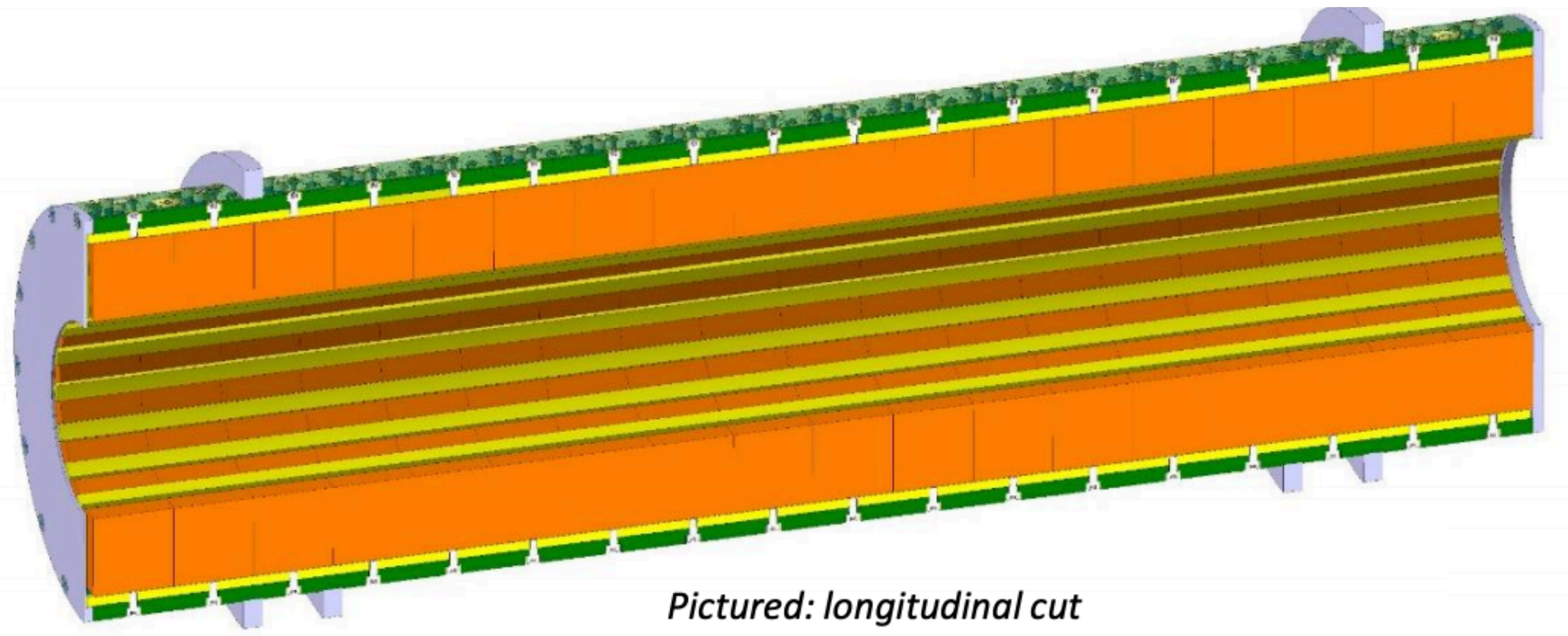
Magnets



Magnets | Overview

- The FASER magnets are 0.55 T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet centre with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed and constructed by magnet group at CERN.

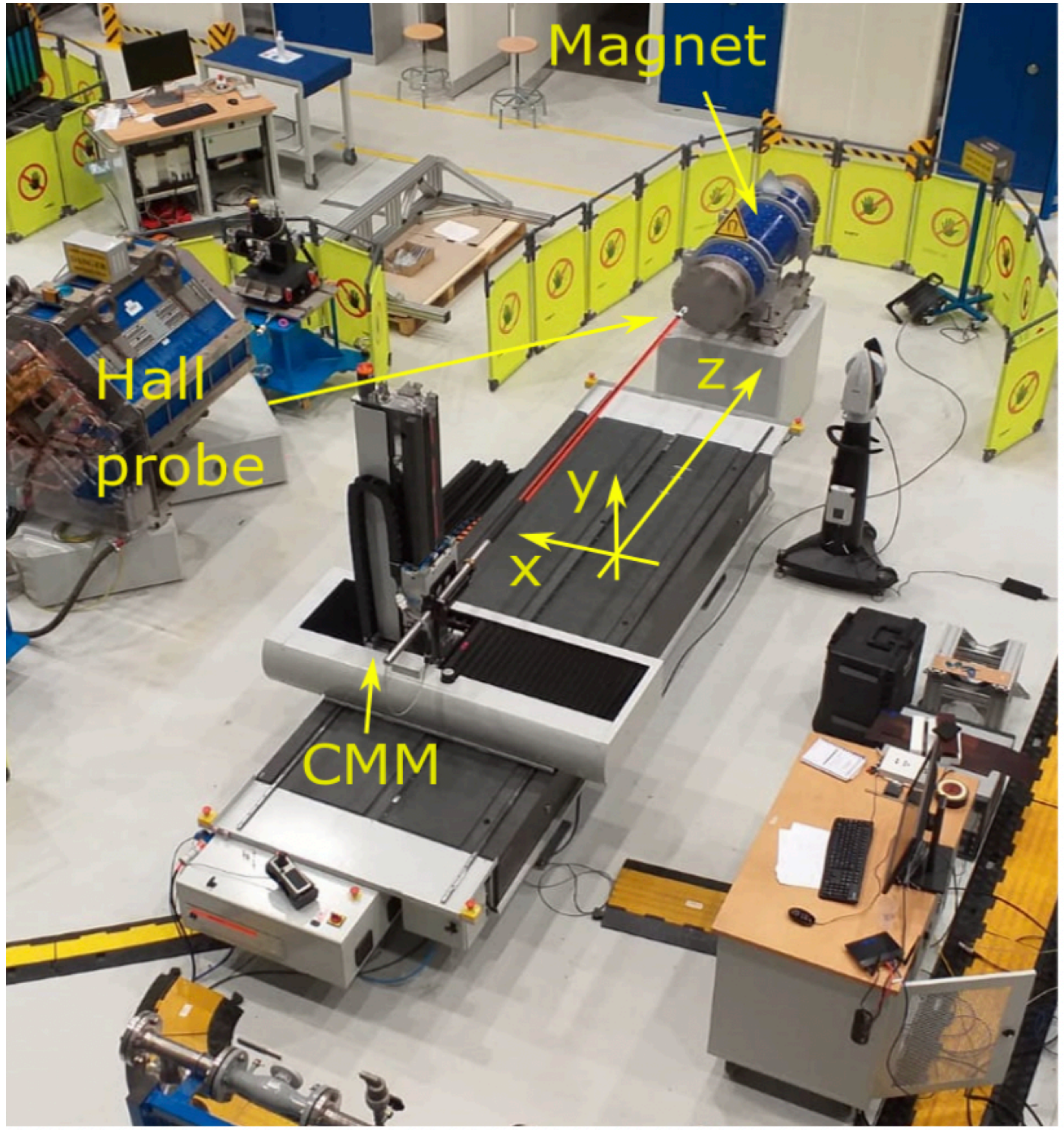




Pictured: longitudinal cut

Magnets | Construction and testing

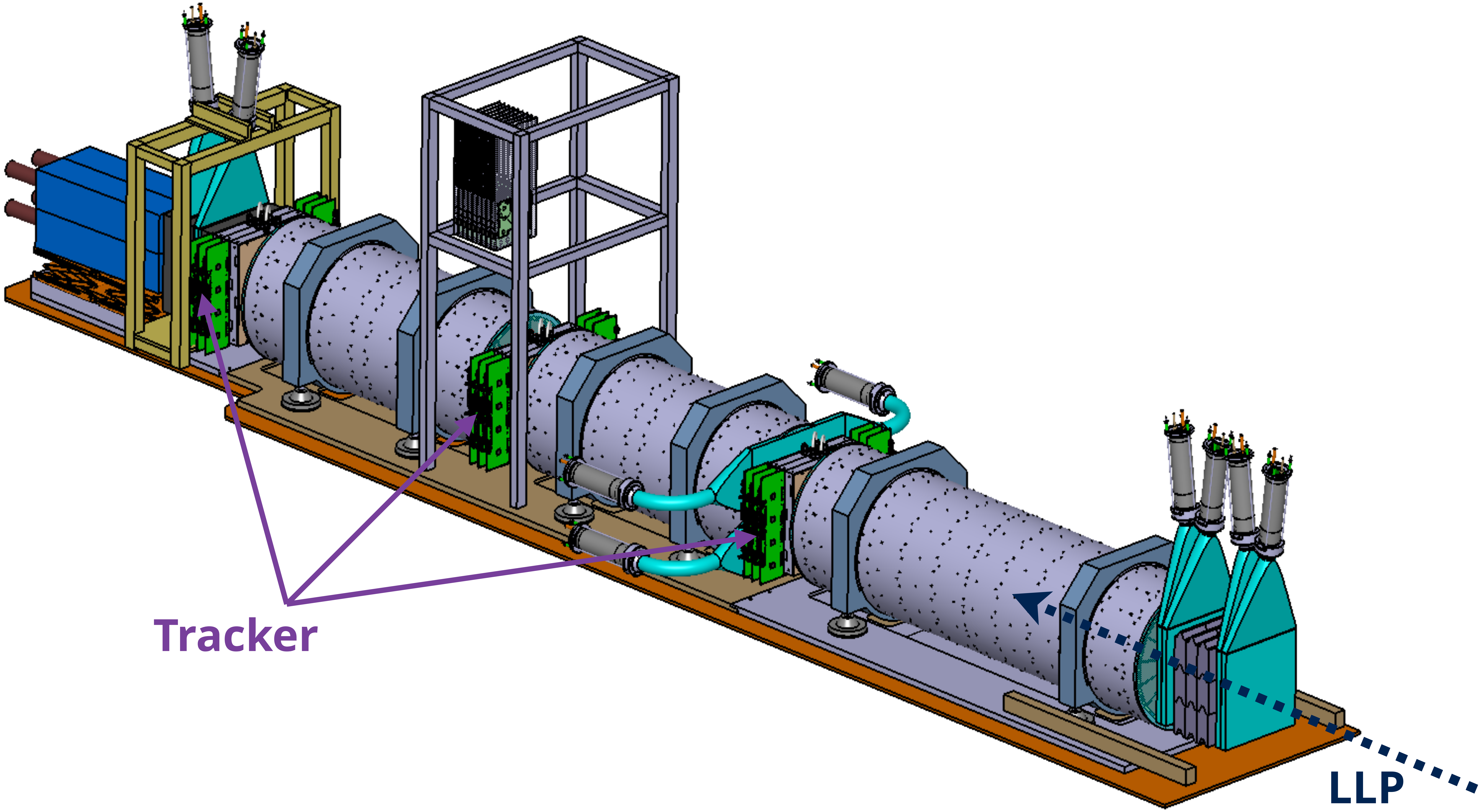
- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN
- Measured field quality well within specifications.



Magnets | Installation

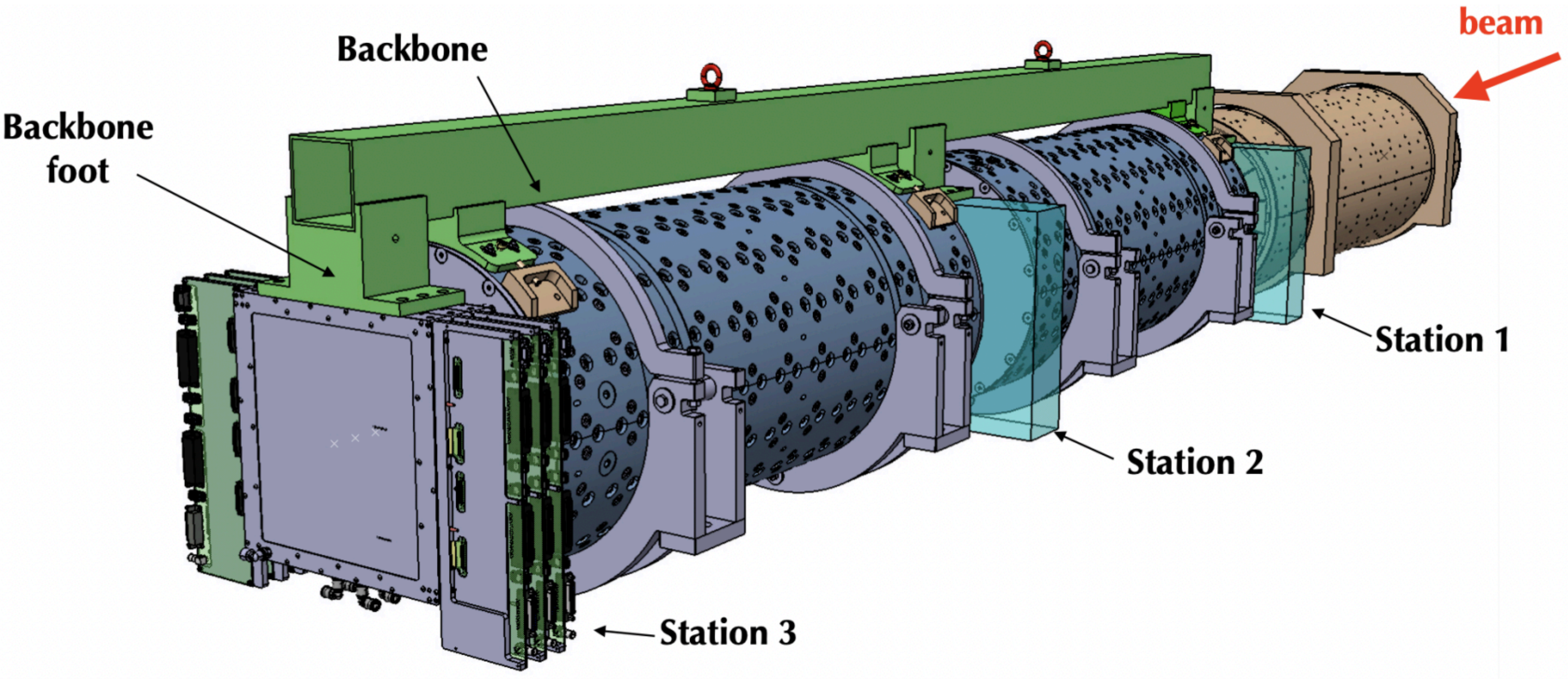
- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN
- Measured field quality well within specifications.
- All magnets now installed underground!

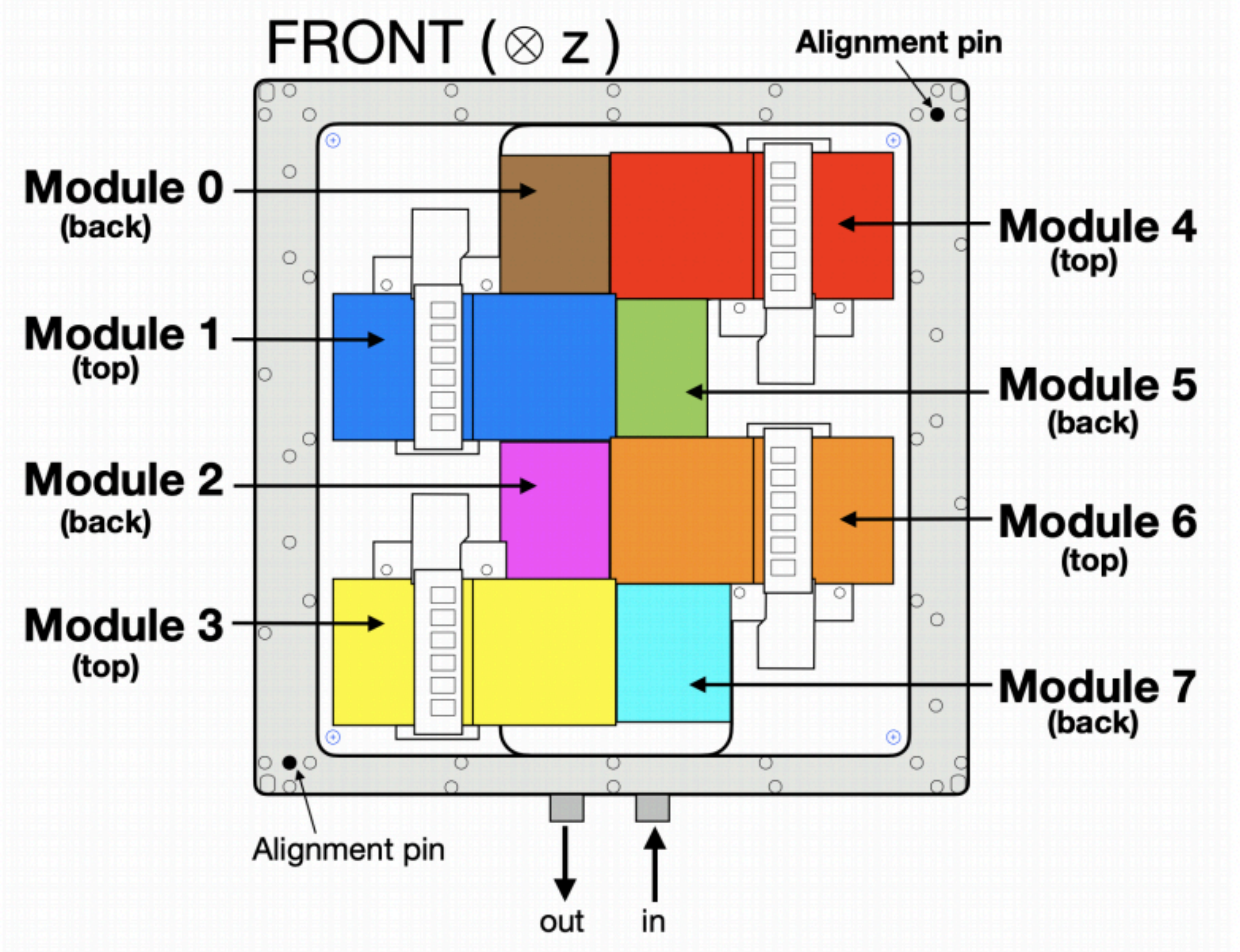
Tracker



Tracker | Overview

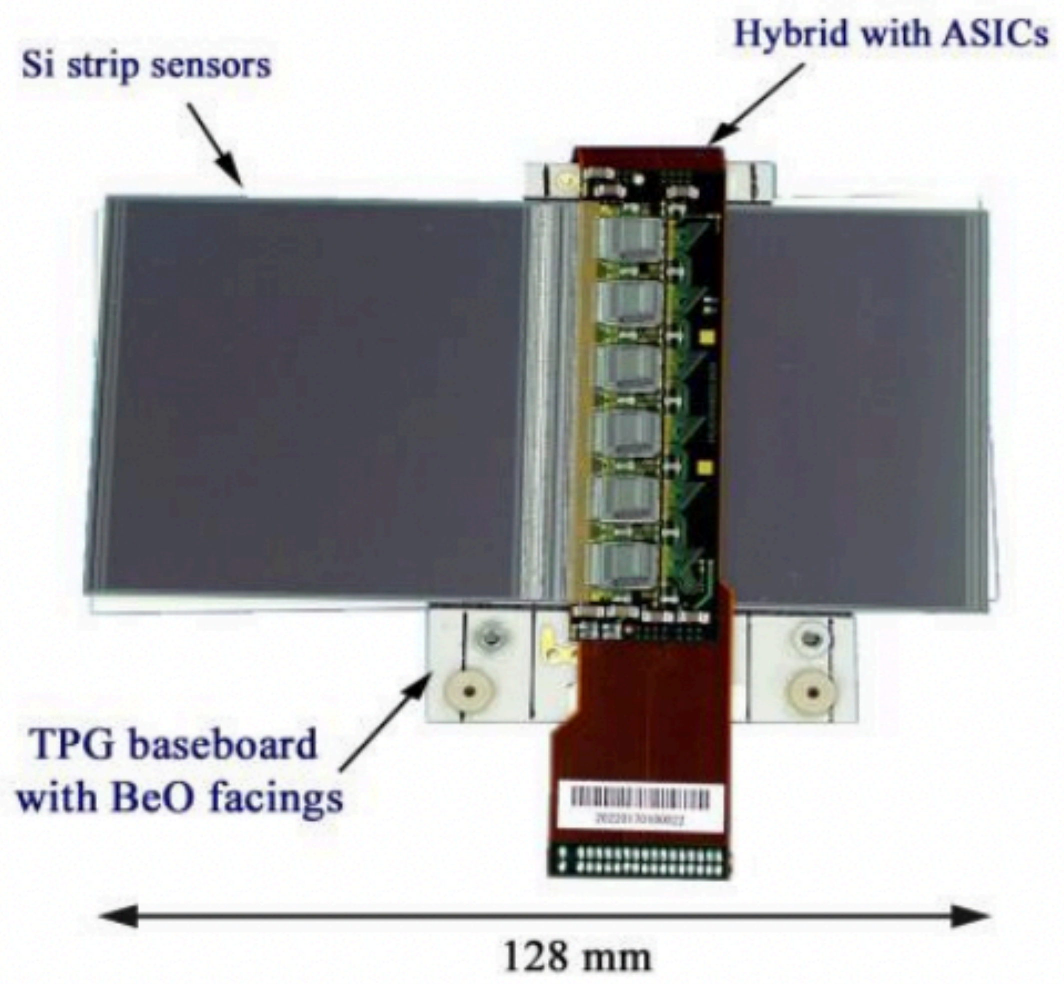
- Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 3 tracking stations.
- Each stations has 3 layers of 8 modules.



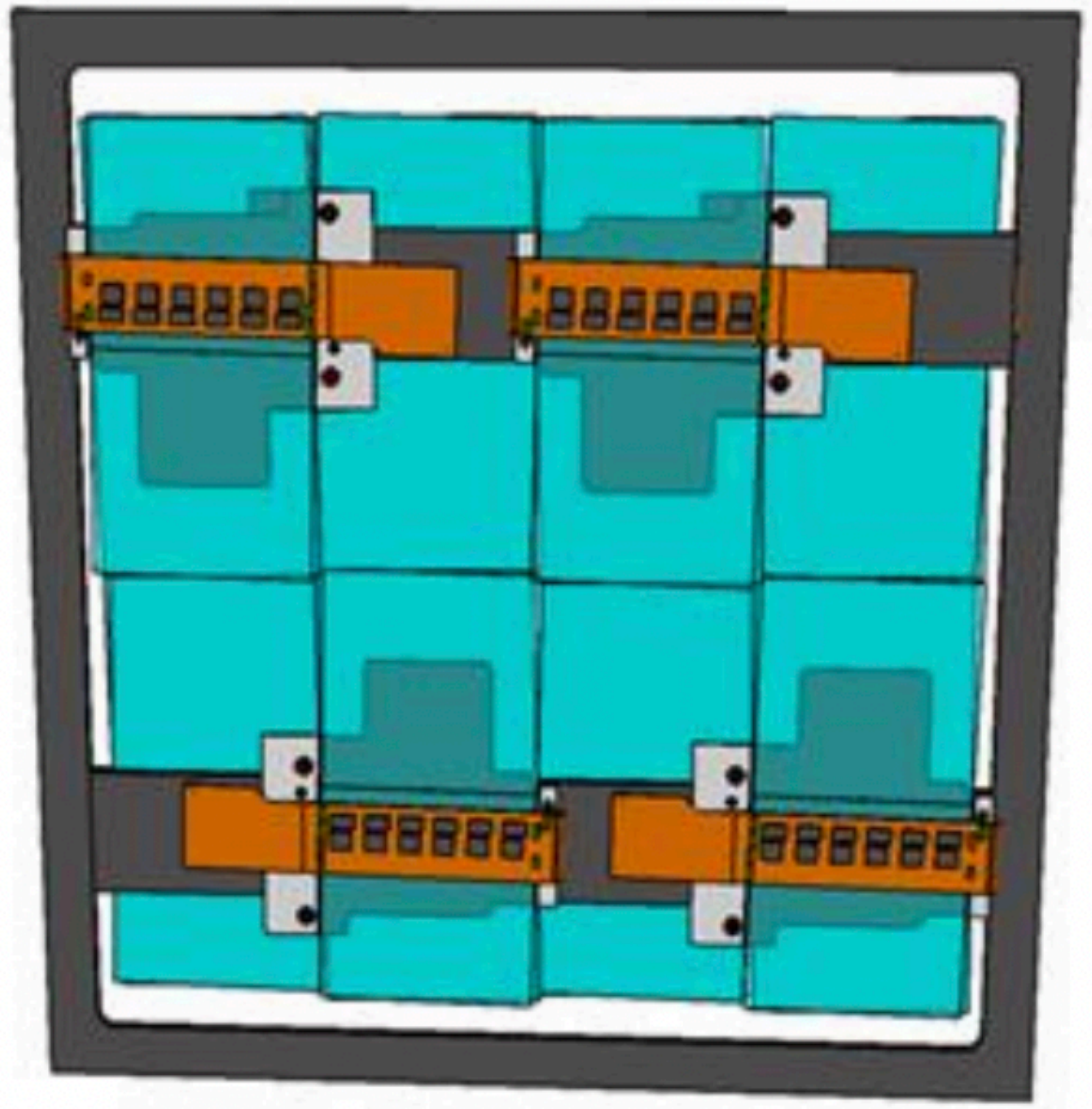


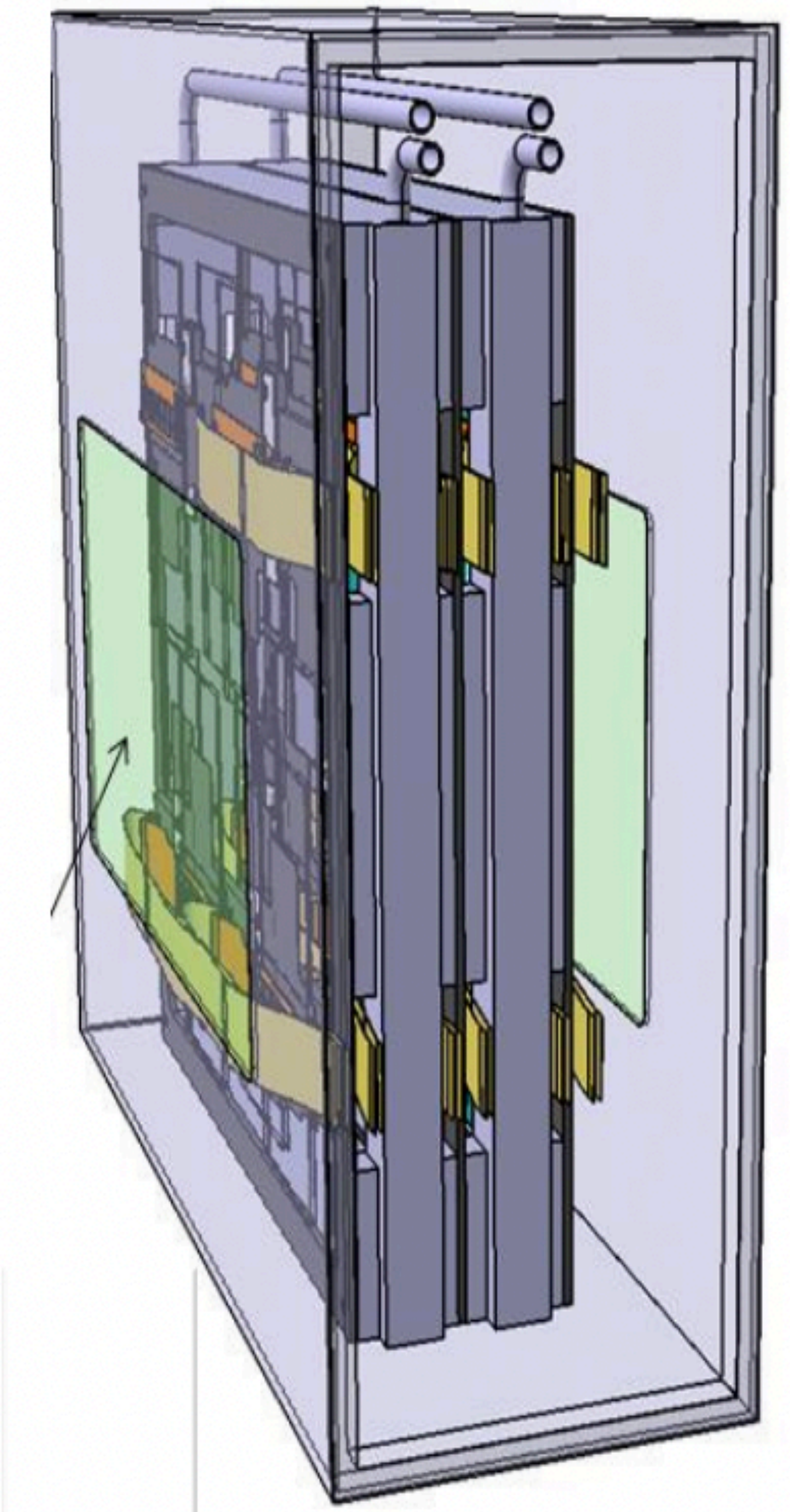
Tracker

- From design...



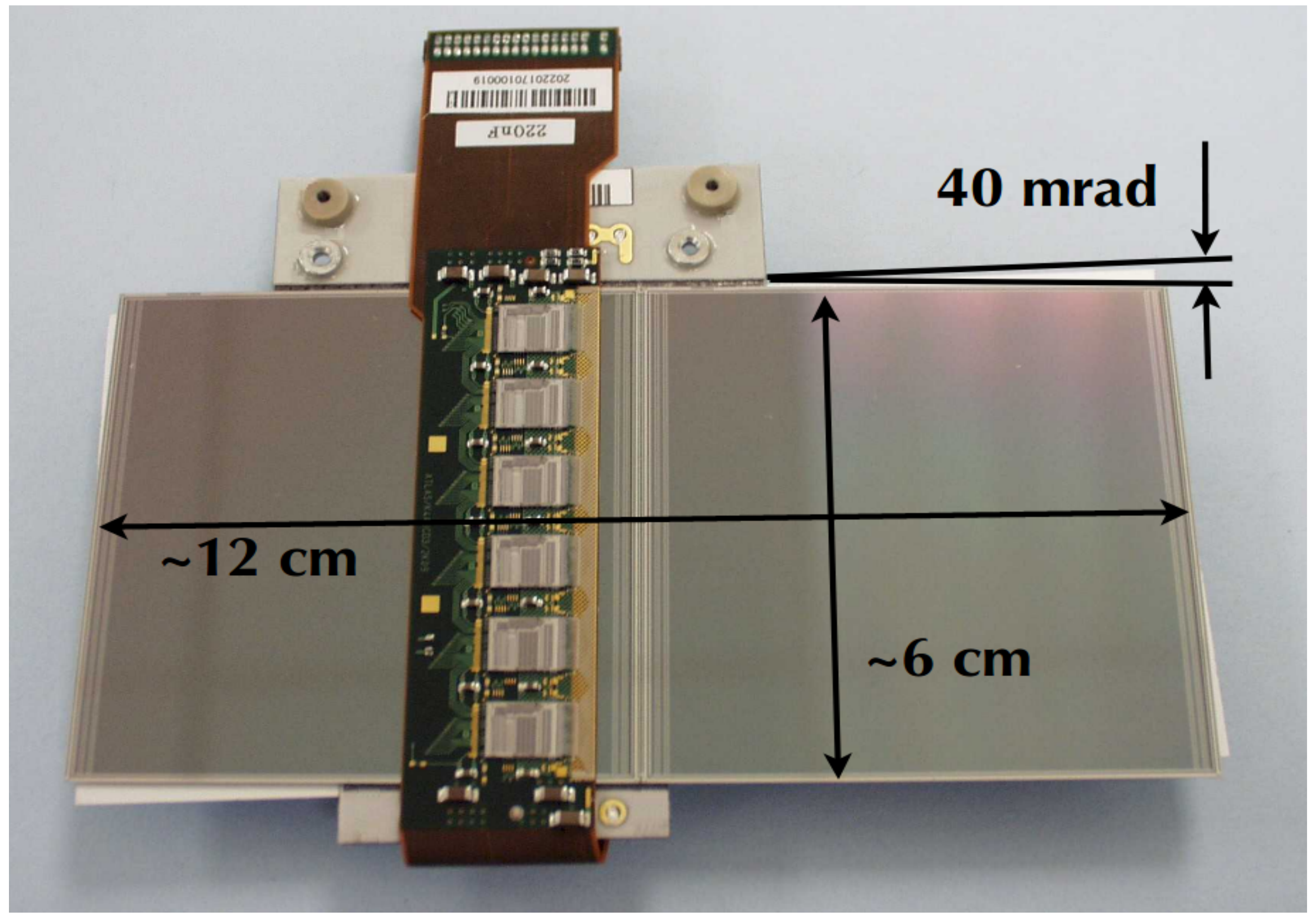
SCT module

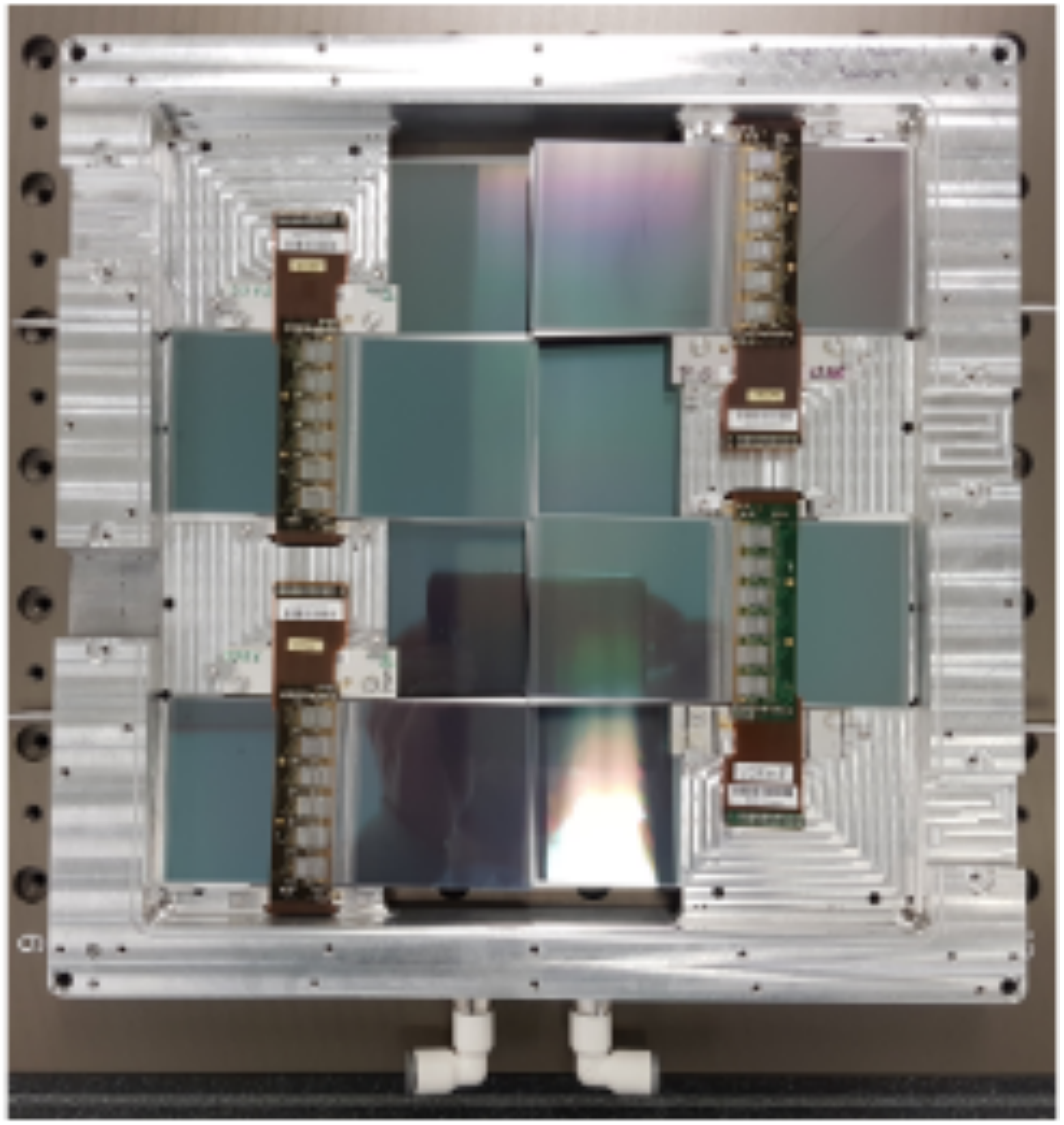

Tracking layer


Tracking station

Tracker

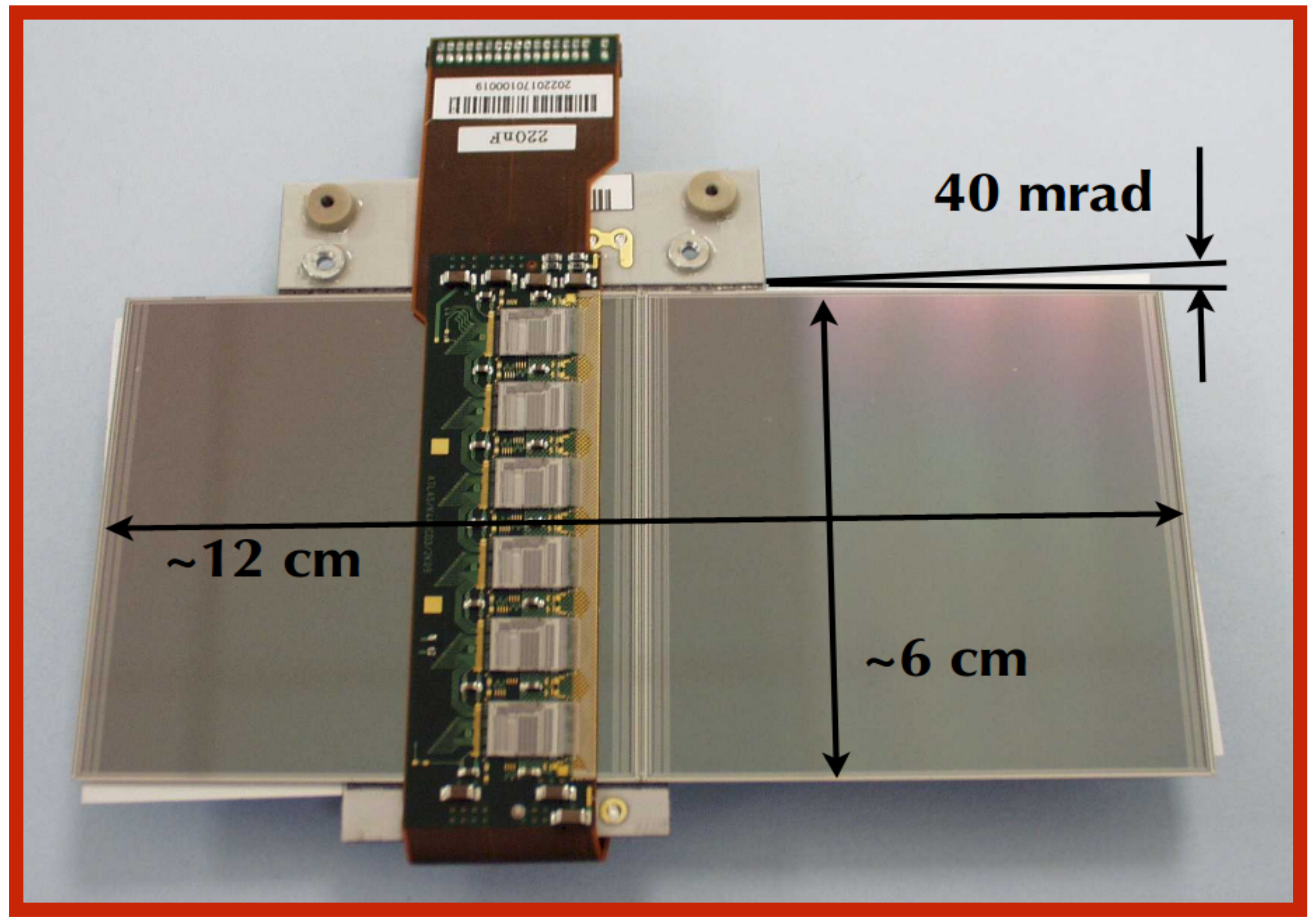
- … to today

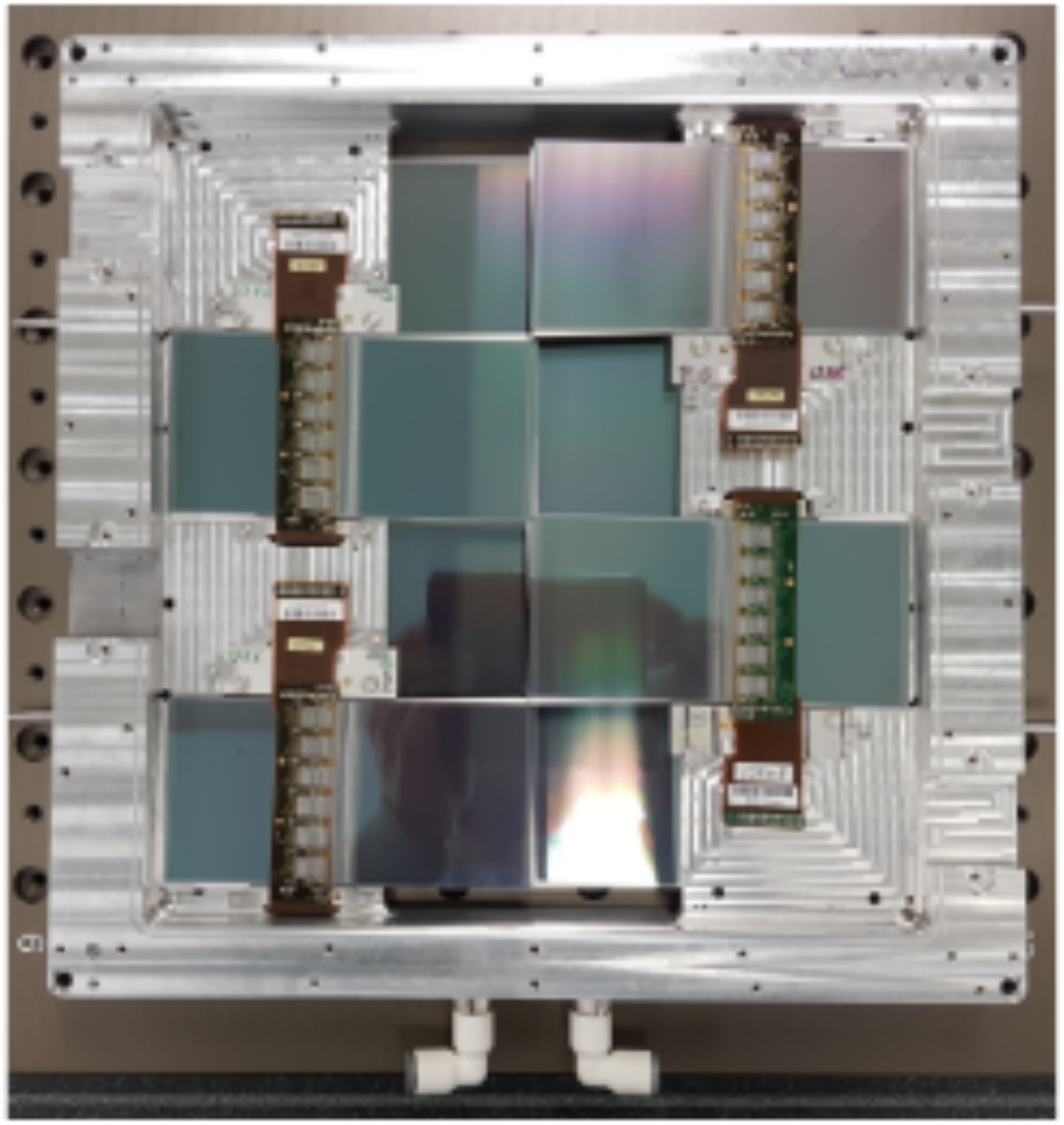




Tracker | Modules

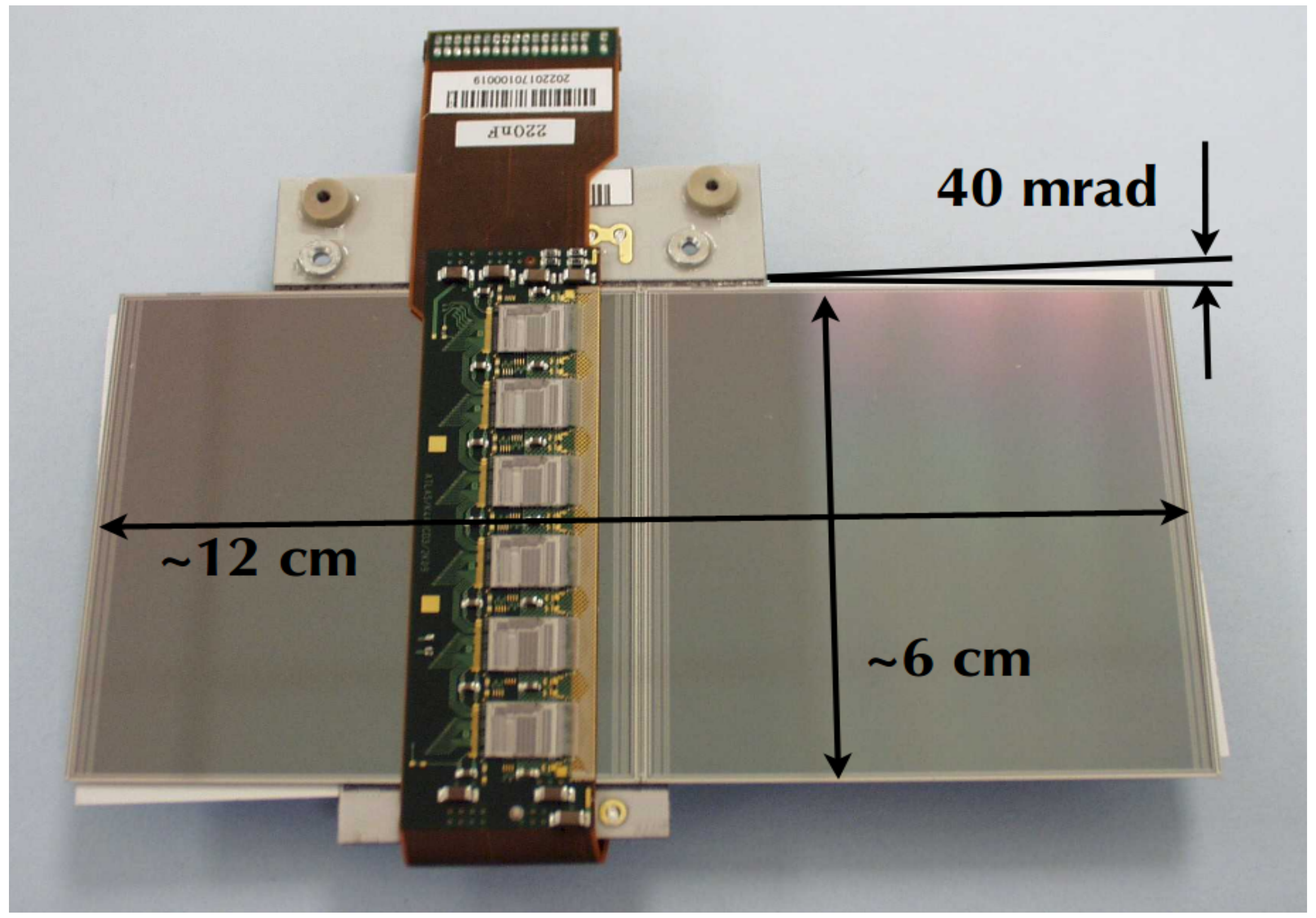
- Spare ATLAS SCT modules are used
  - 80μm strip pitch, 40 mrad stereo angle (17μm / 580μm resolution)
    - precision measurement in bending (vertical) plane
  - Many thanks to the ATLAS SCT collaboration!

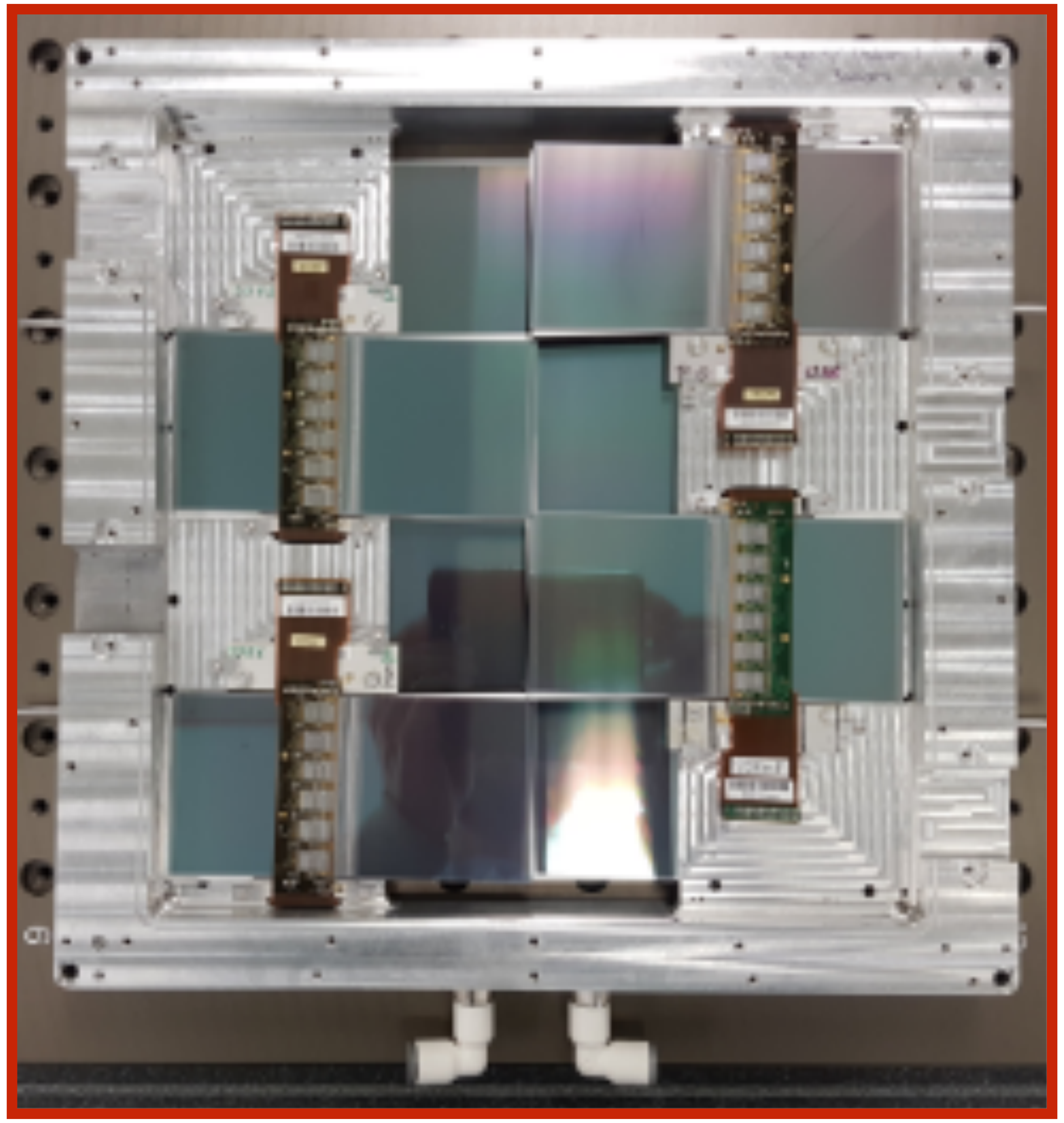




Tracker | Layers

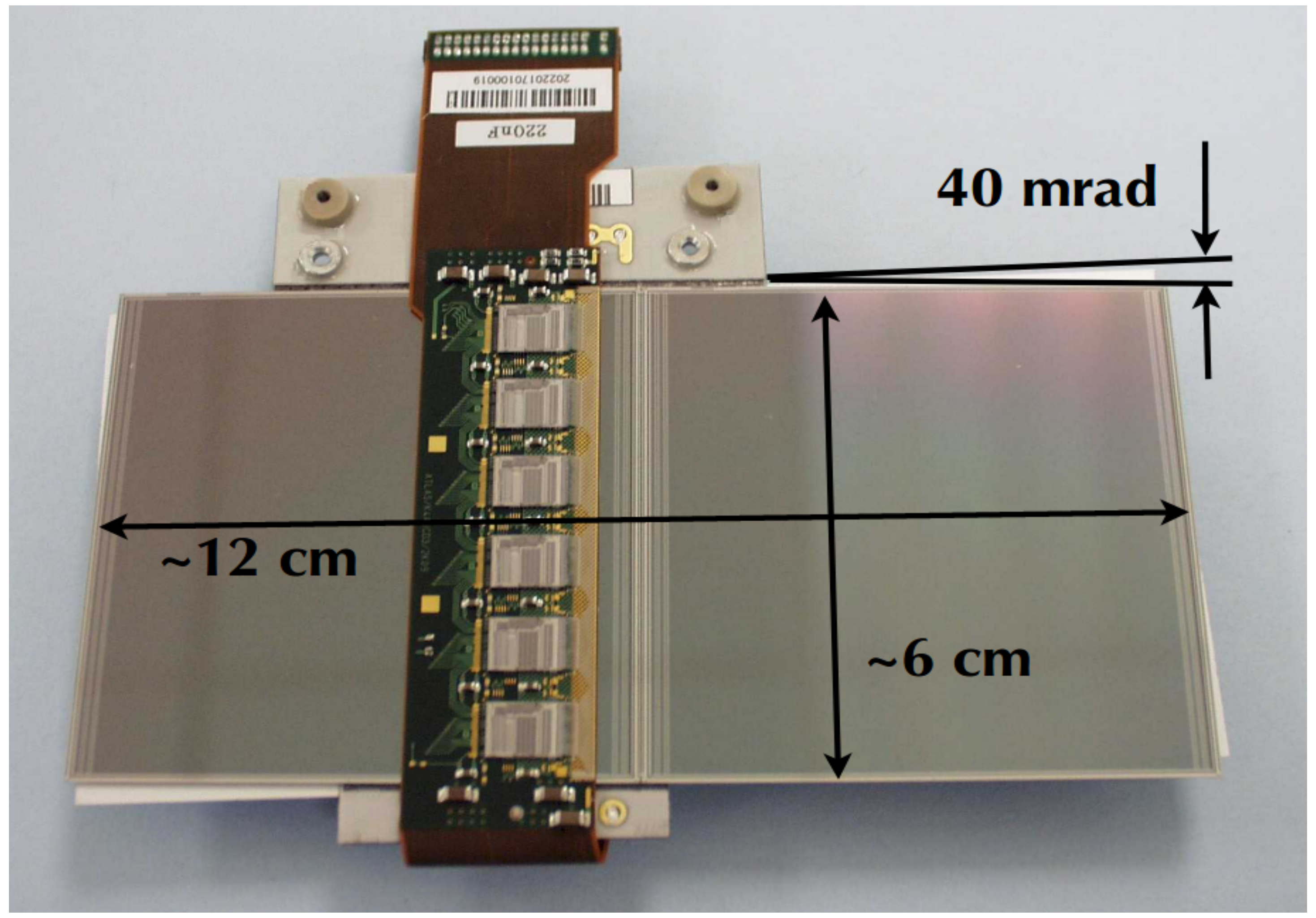
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) → 72 SCT modules needed for the full tracker

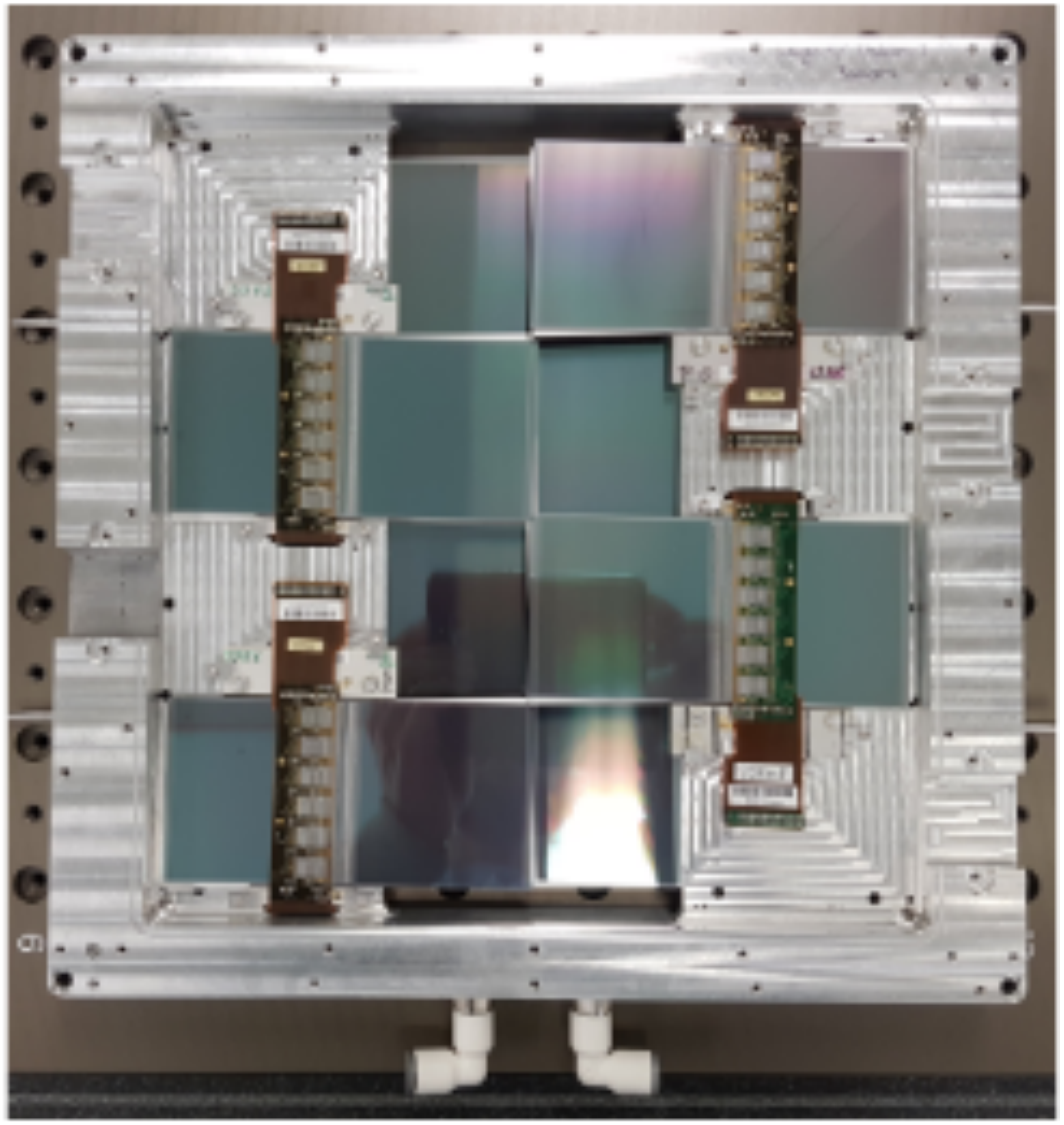




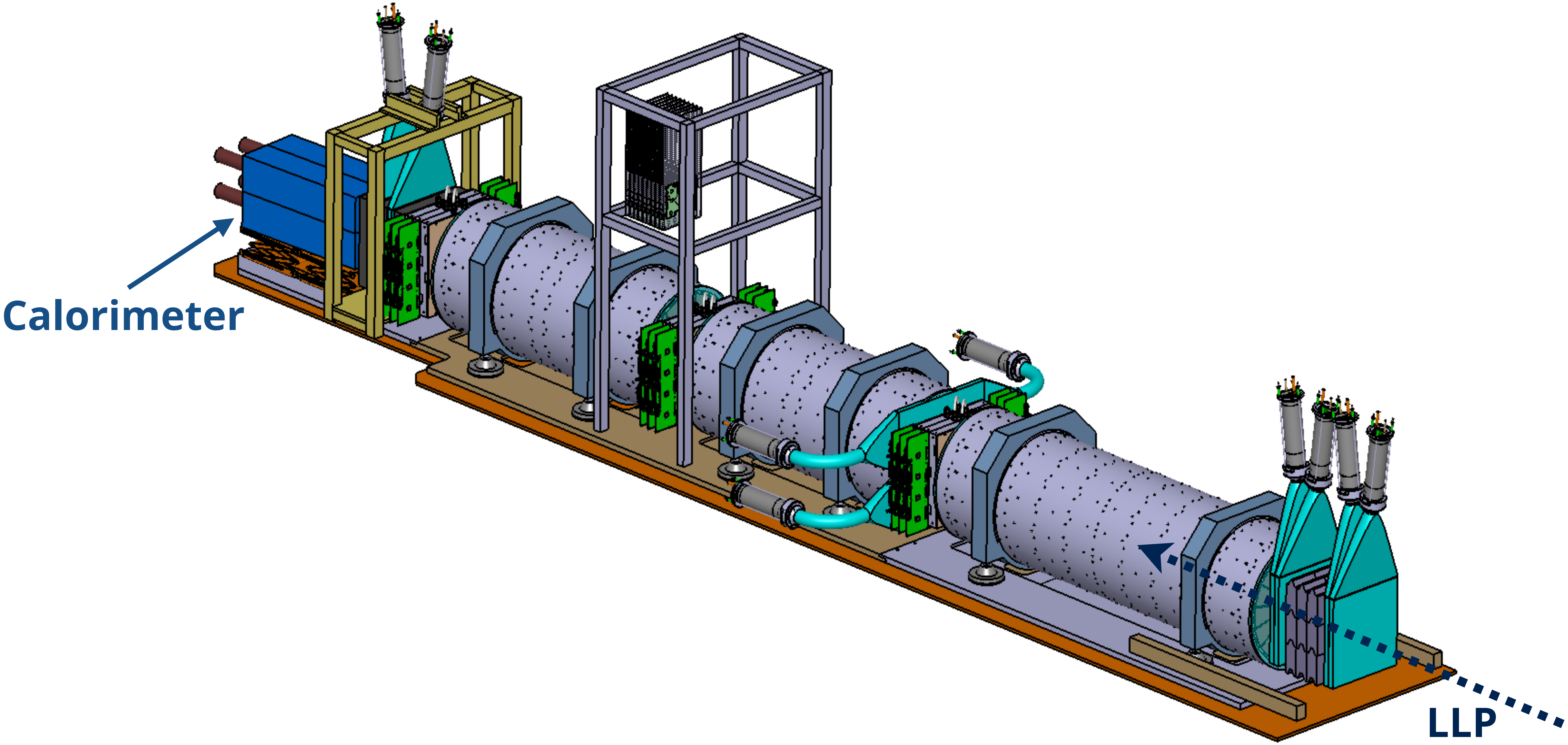
Tracker | Stations

- Low radiation levels in TI12 allows silicon to be operated at room temp.
  - But the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)



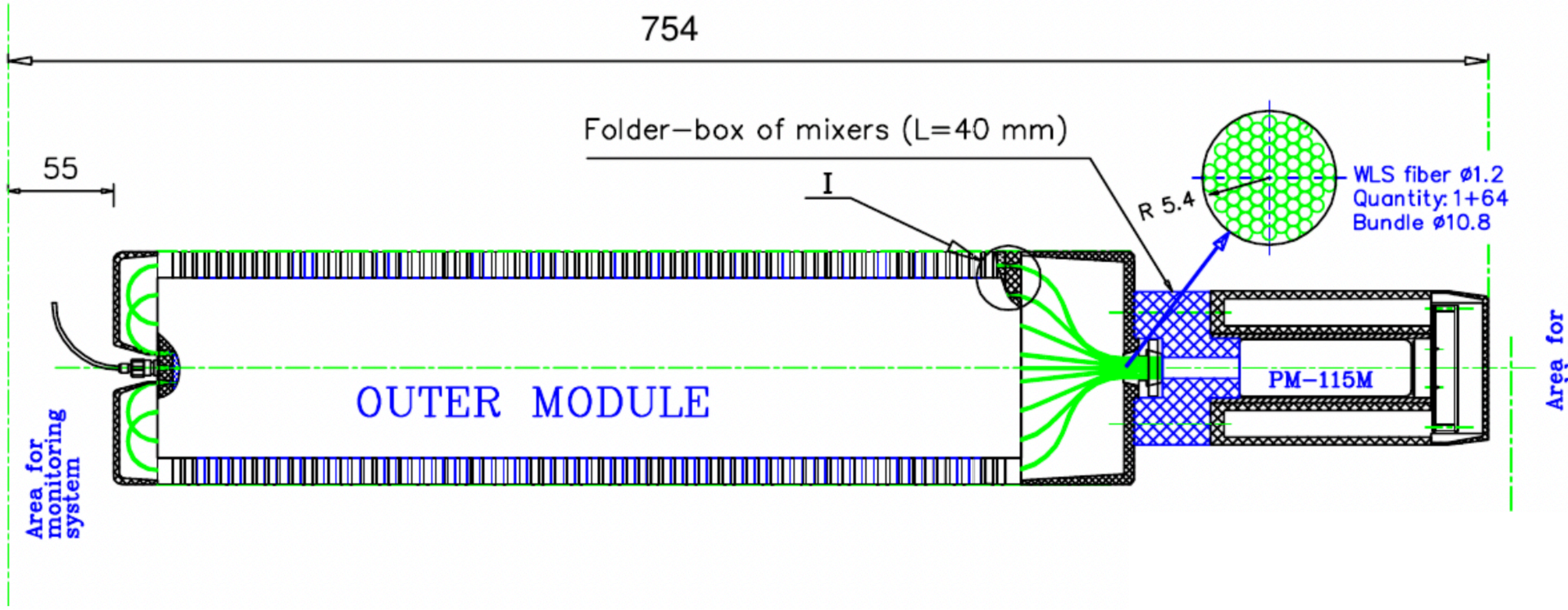


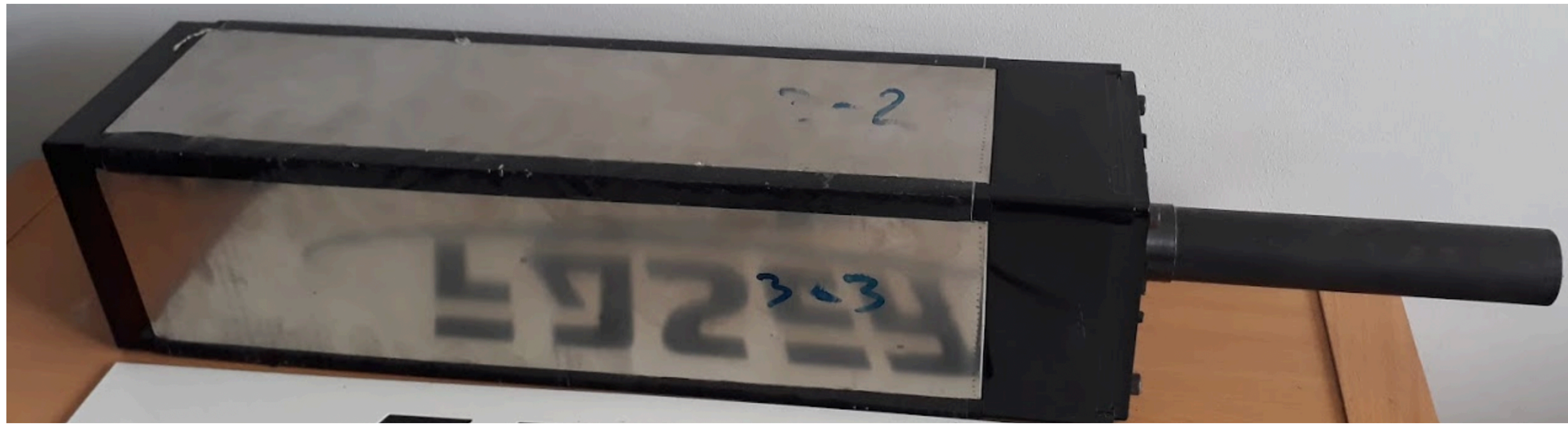
Calorimeter



Calorimeter

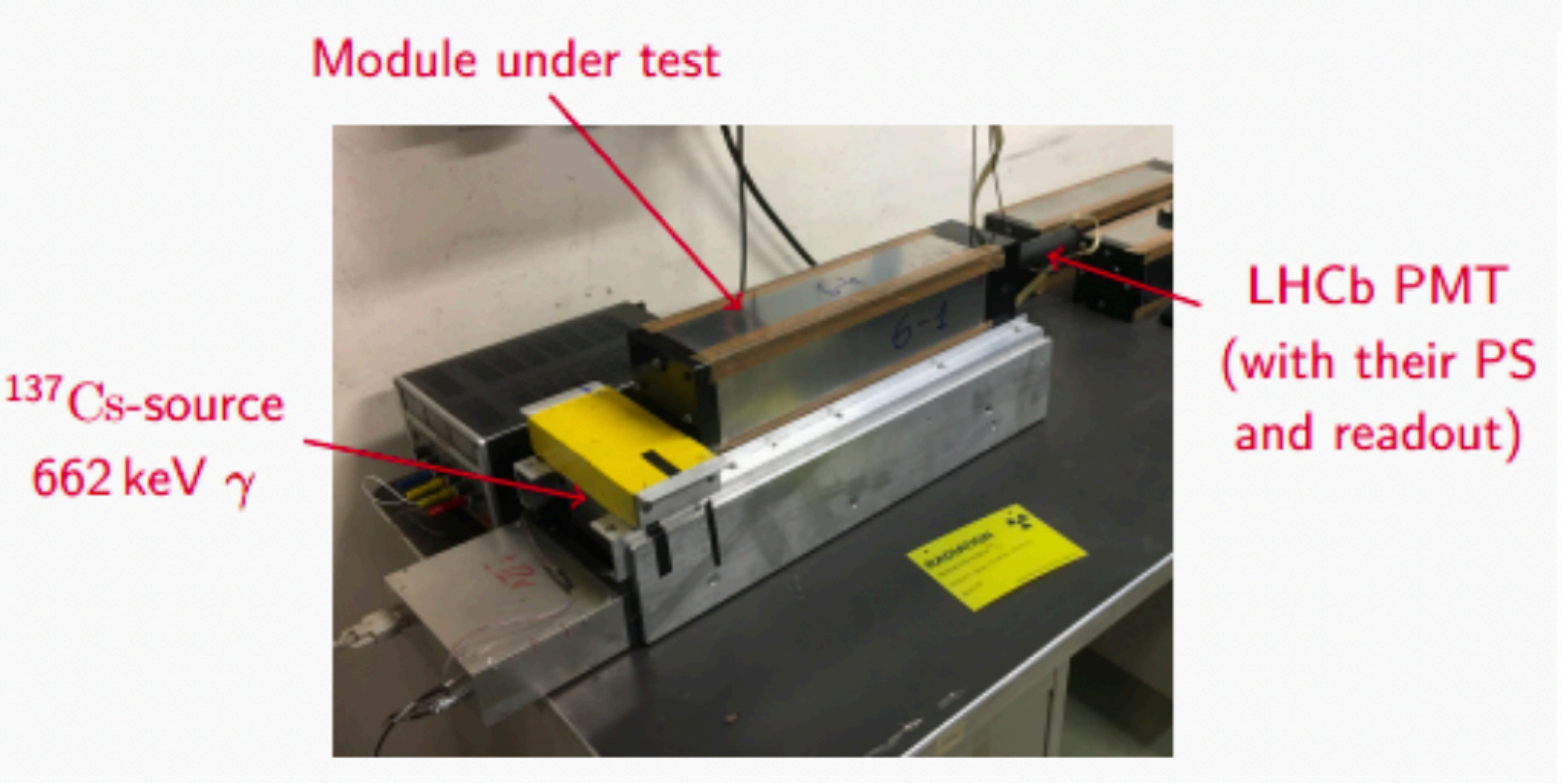
- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Uses 4 spare LHCb outer ECAL modules
  - Many thanks to LHCb for the use of these!
    - PMTs also from LHCb, but new voltage dividers
  - Readout by PMT (no longitudinal shower information)
    - Only 4 channels in full calorimeter
  - Provides ~1% energy resolution for 1 TeV electrons

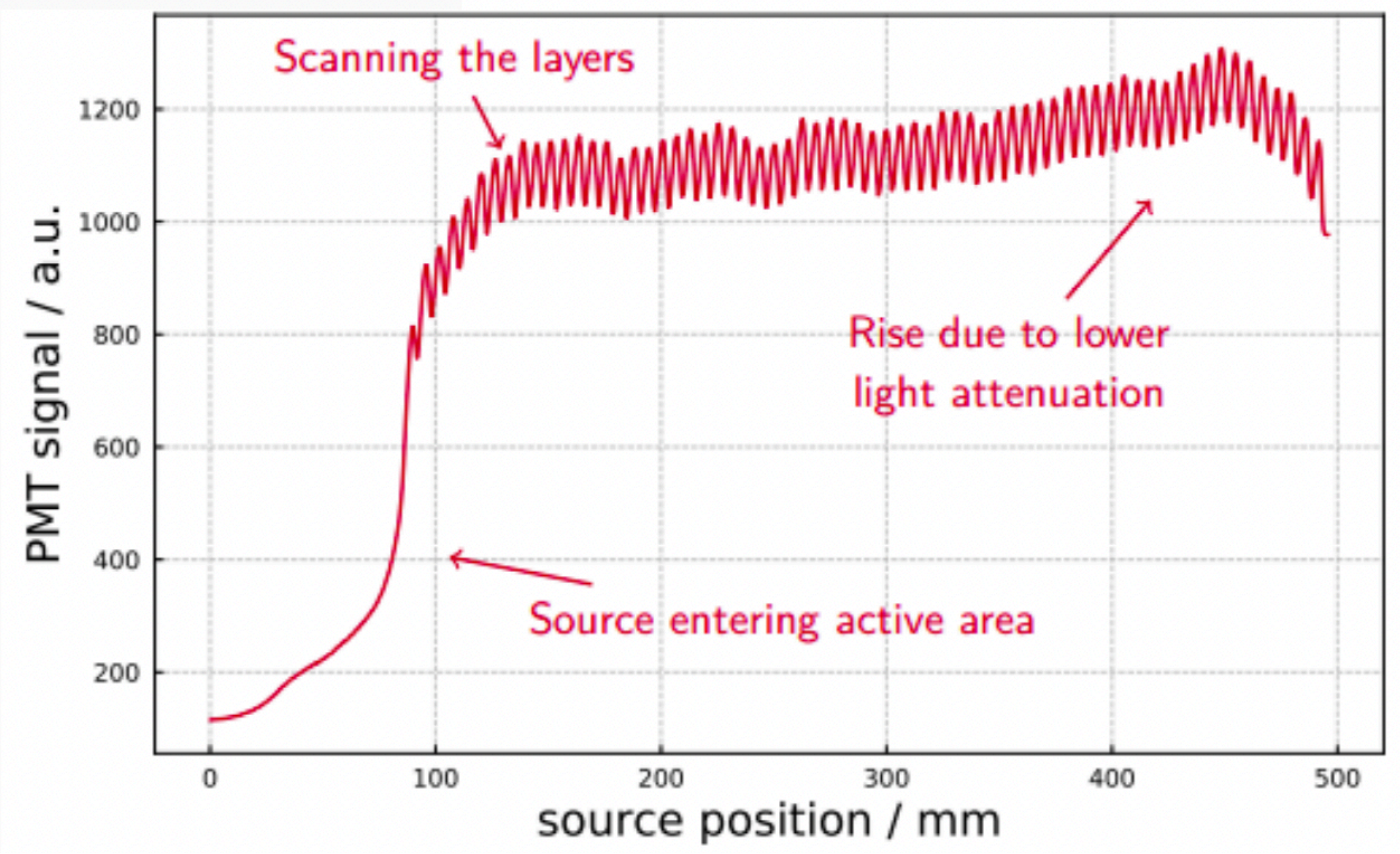




Calorimeter | Testing

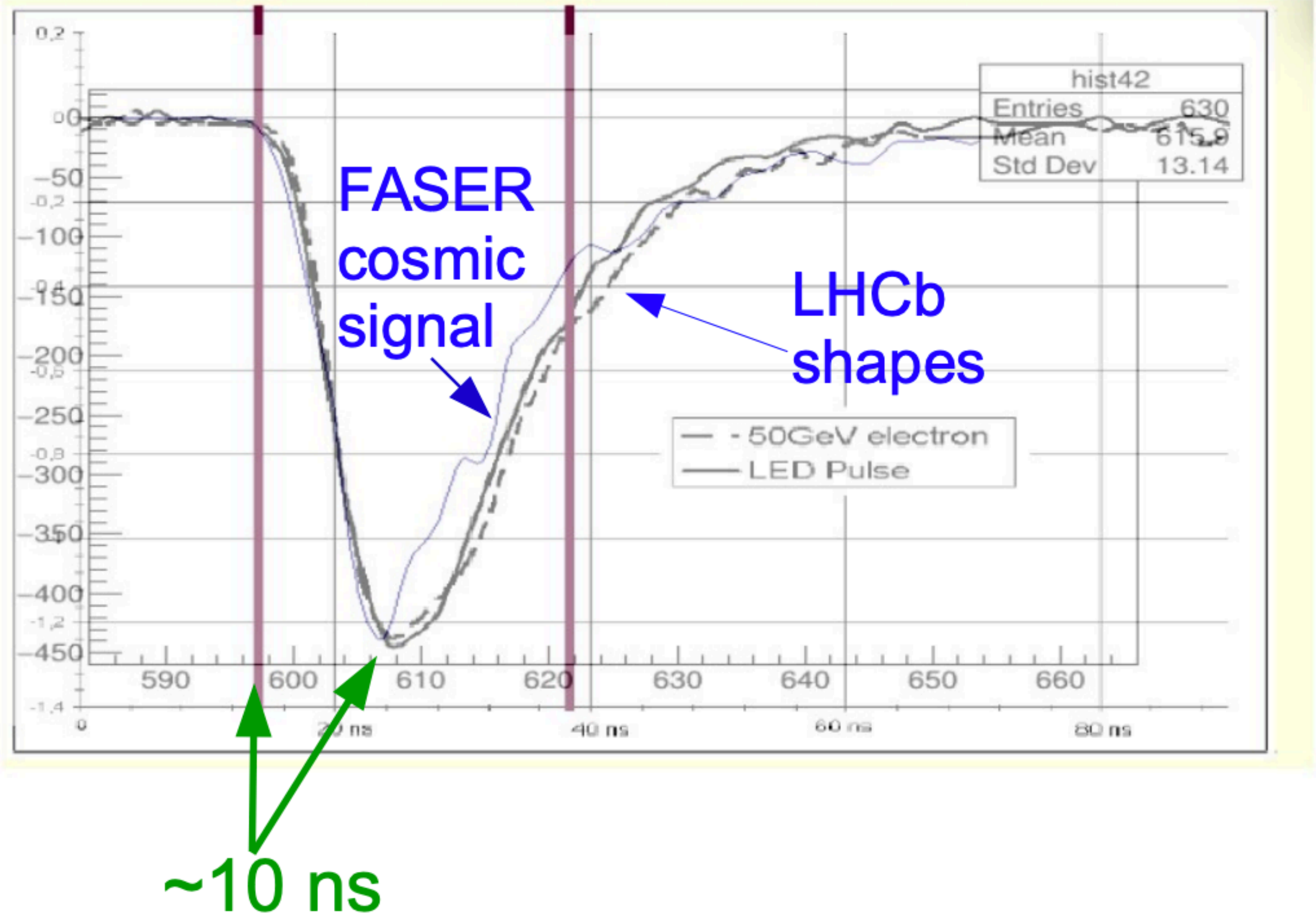
- Early testing performed at CERN
- Caesium source used to check response in all available modules.
- Modules performed as expected.

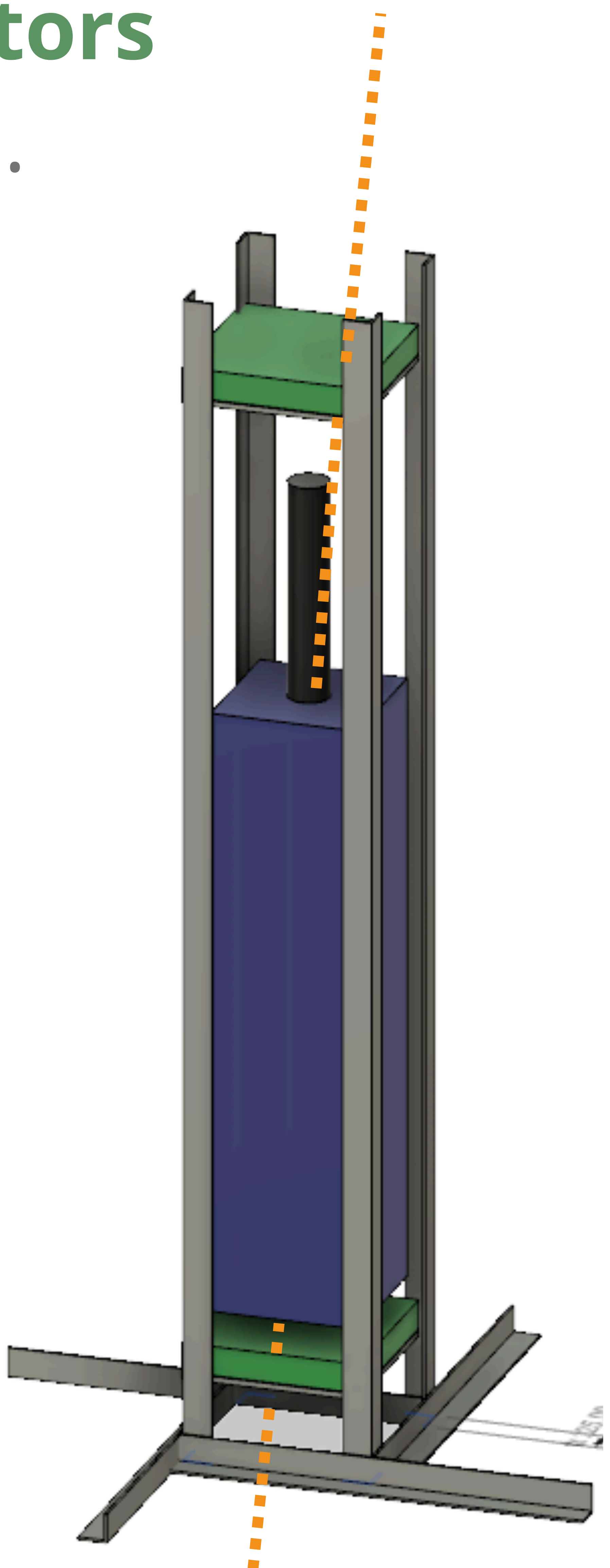


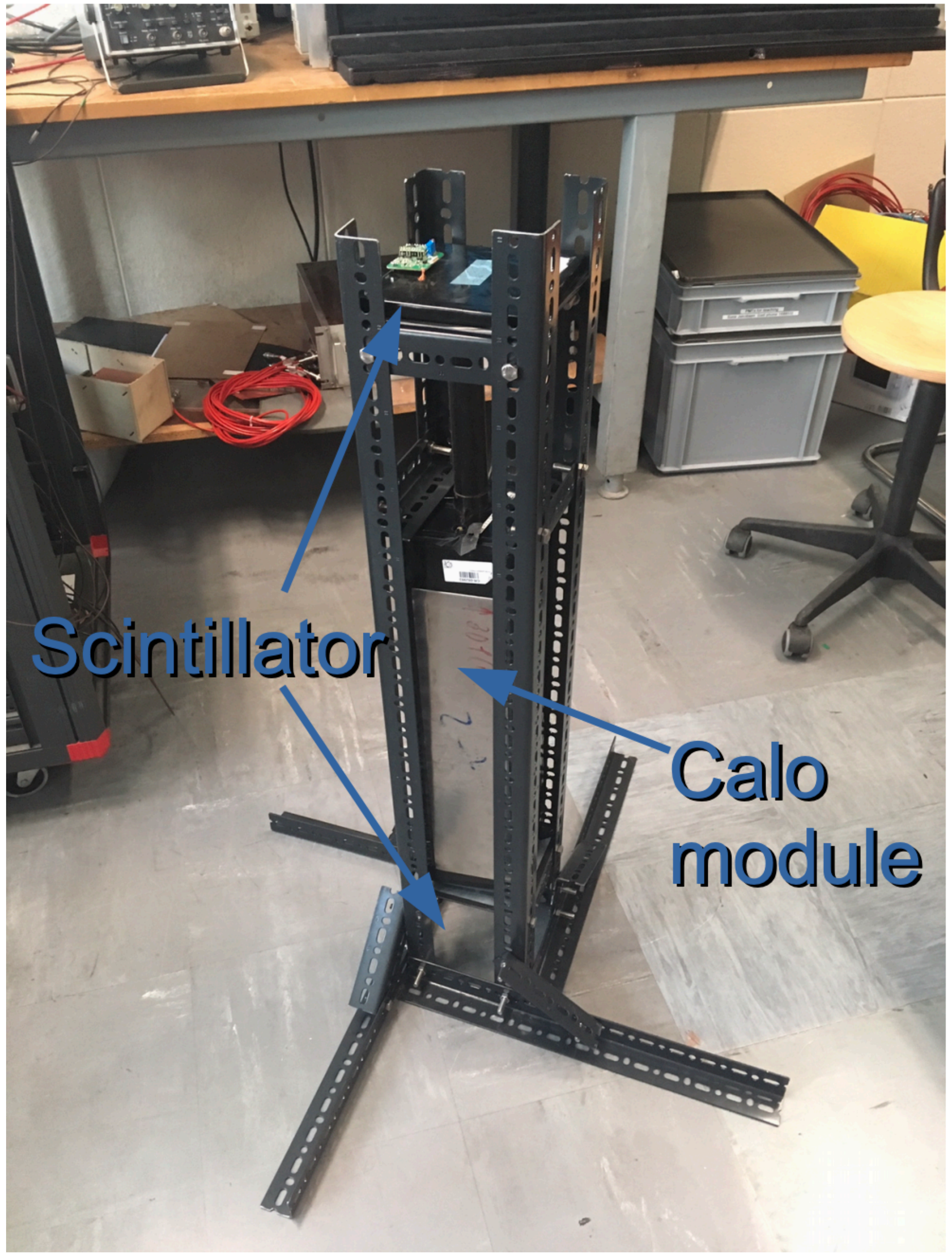


Calorimeter | Cosmic ray test stand

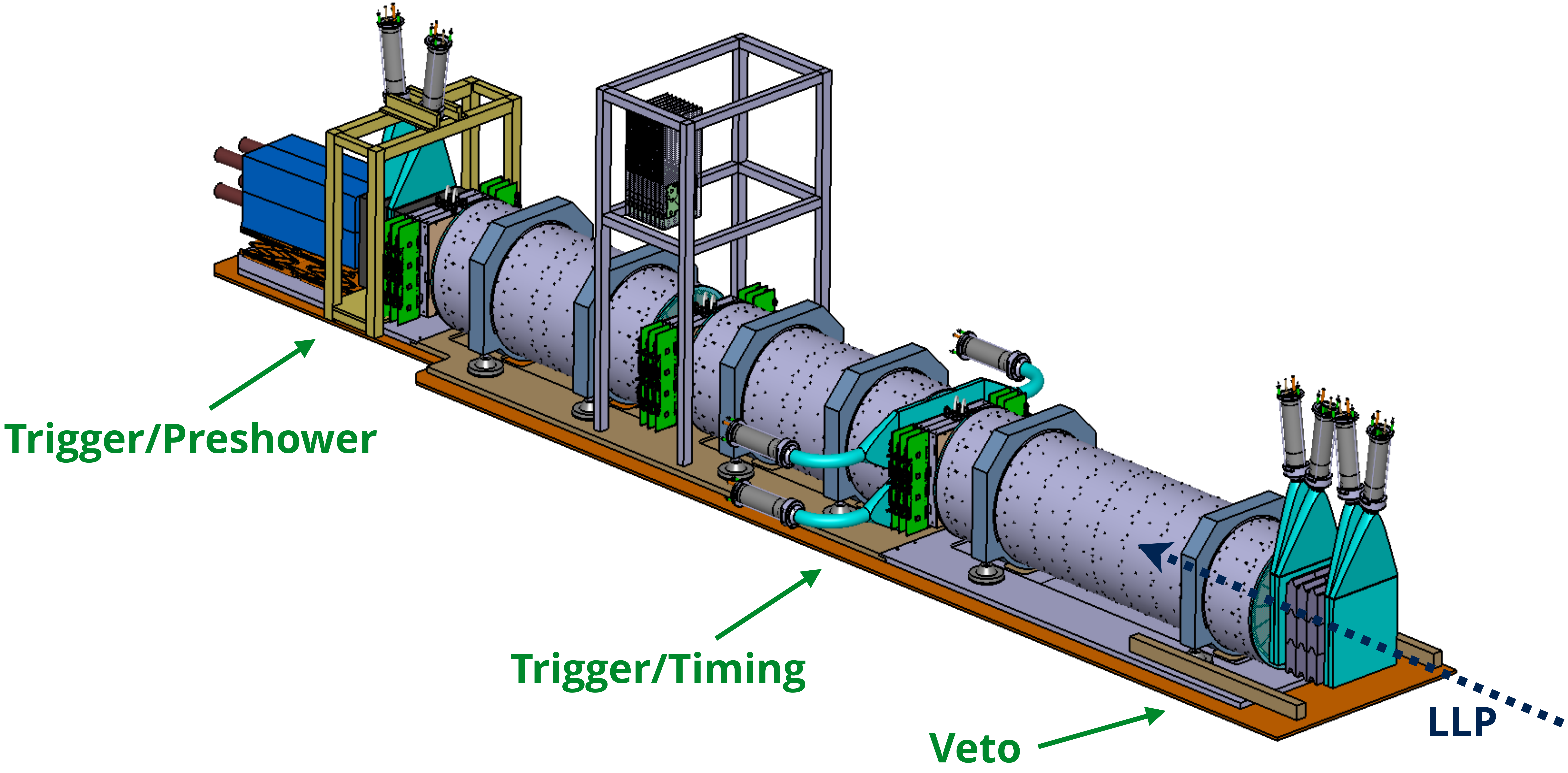
- Cosmic ray test stand used to test calorimeter response and calibrate PMTs.
  - **Calorimeter** signal is read when **scintillators** see coincident signals from **cosmic muon**.
  - Read-out very close to final design
- Good agreement with LHCb pulses observed:





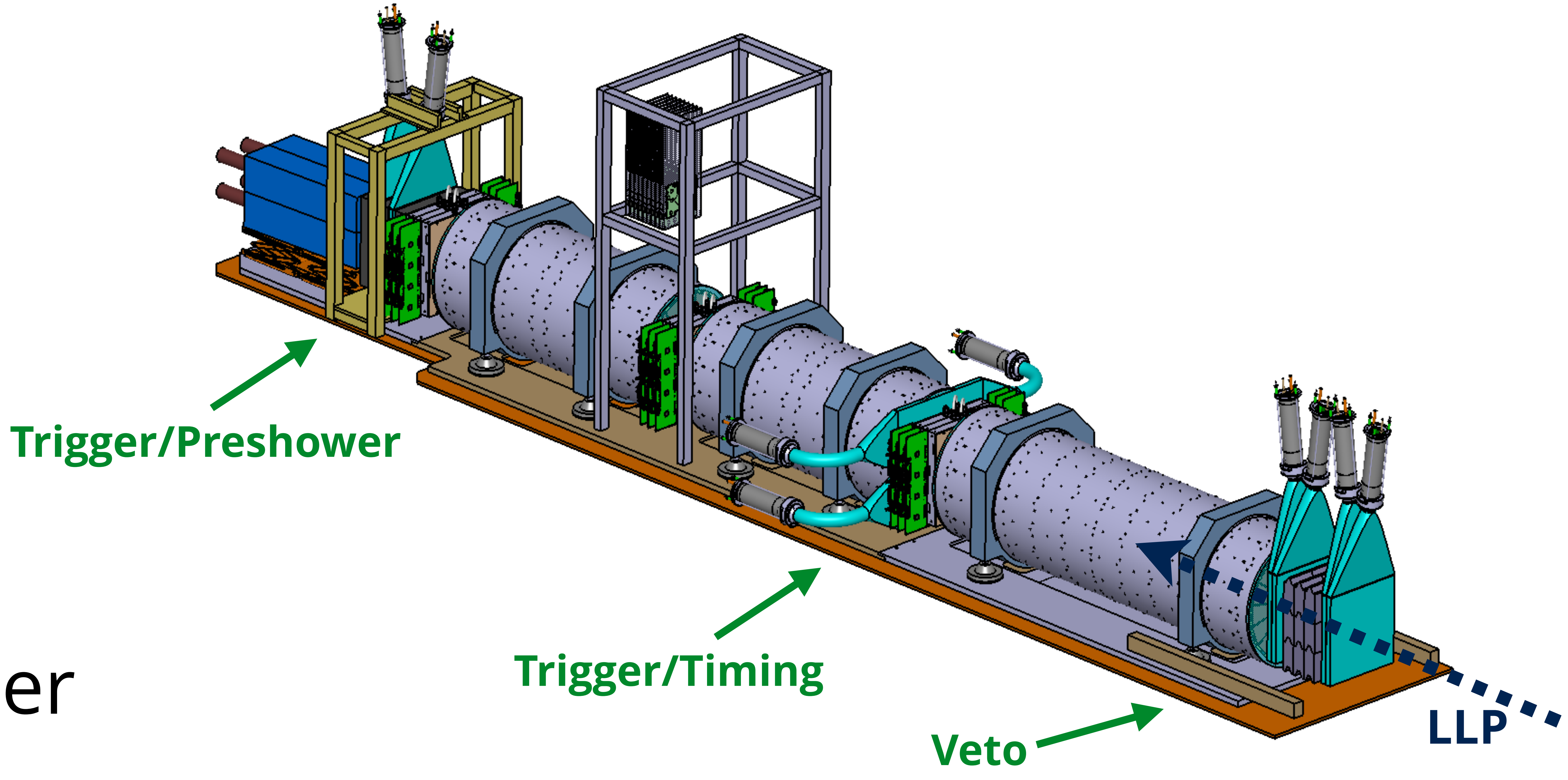


Scintillators



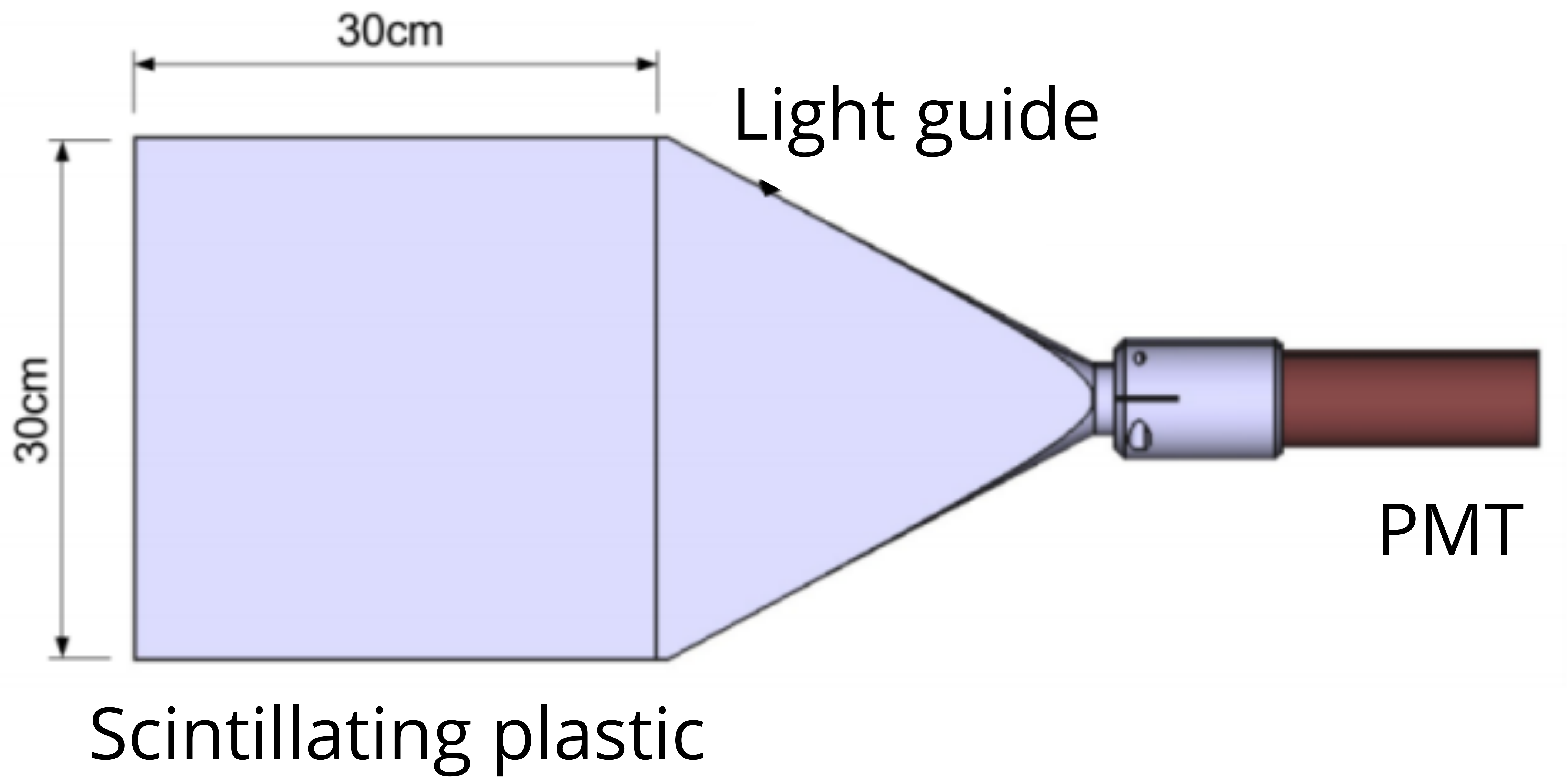
Scintillators

- Vetoing incoming charged particles
  - Very high efficiency needed - O(10^8) incoming muons in 150/fb
- Triggering
- Timing measurement
  - ~1ns resolution
  - Important for timing with LHC clock
- Simple pre-shower for Calorimeter



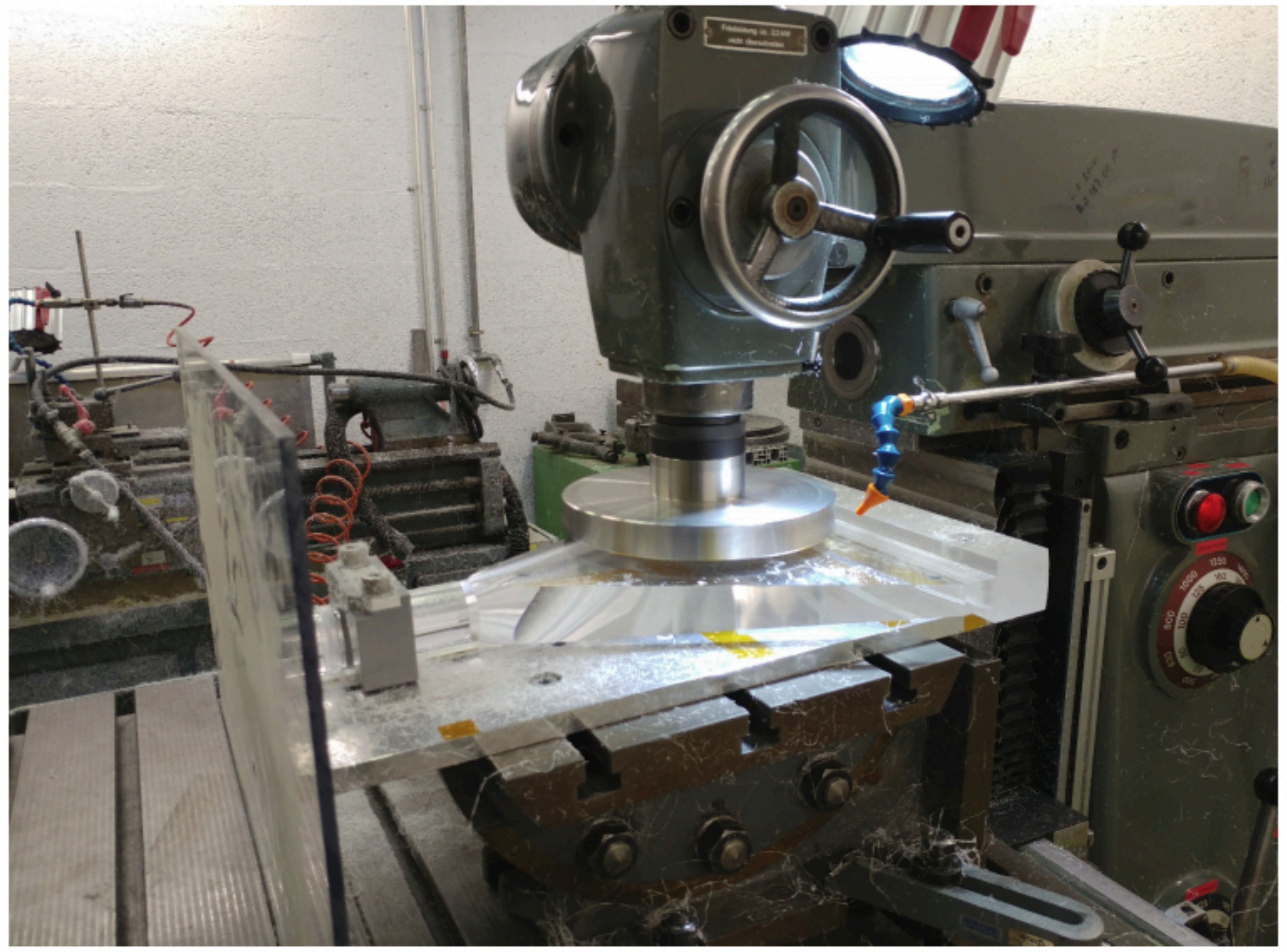
Scintillators

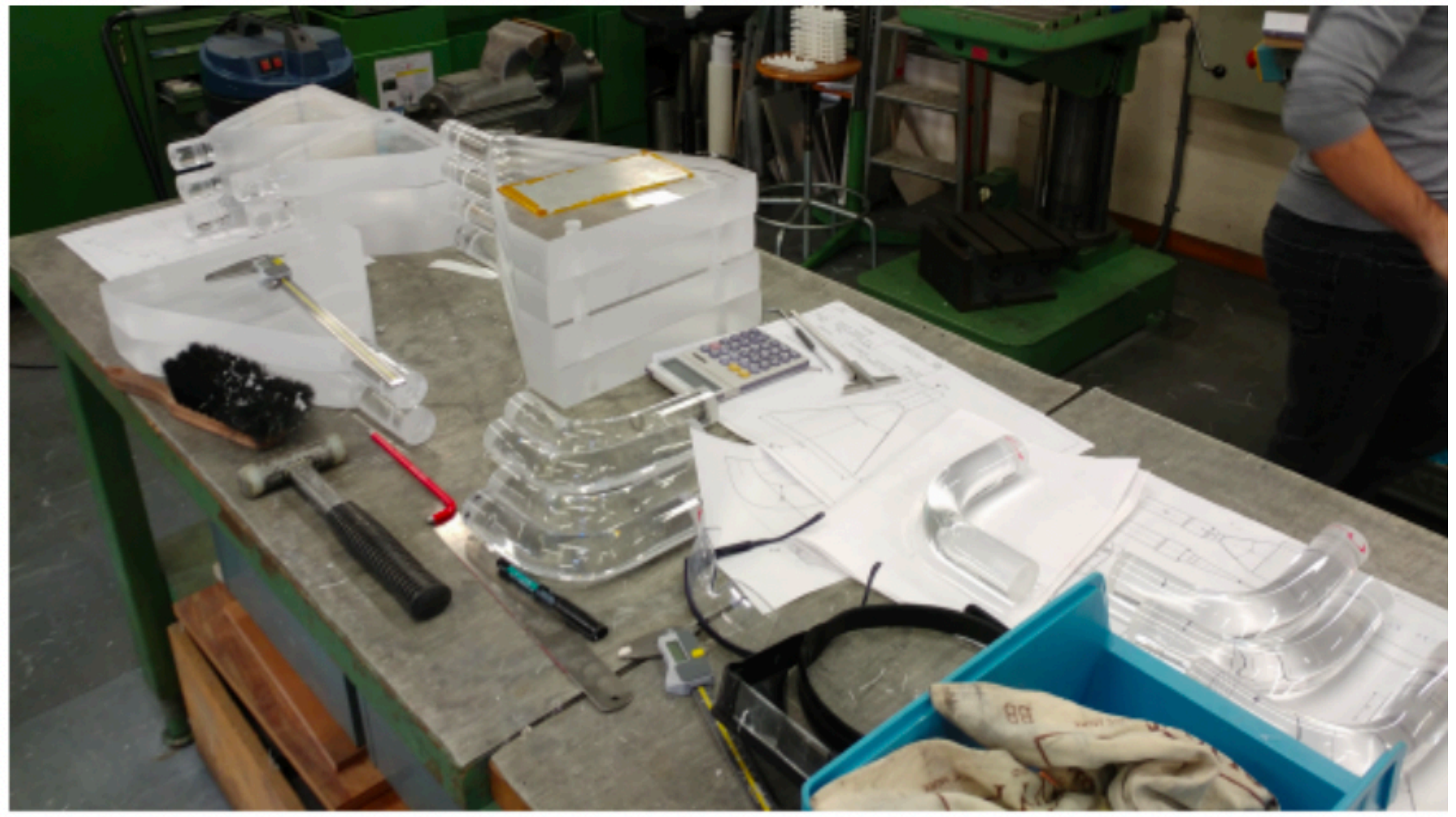
- From Technical Proposal…

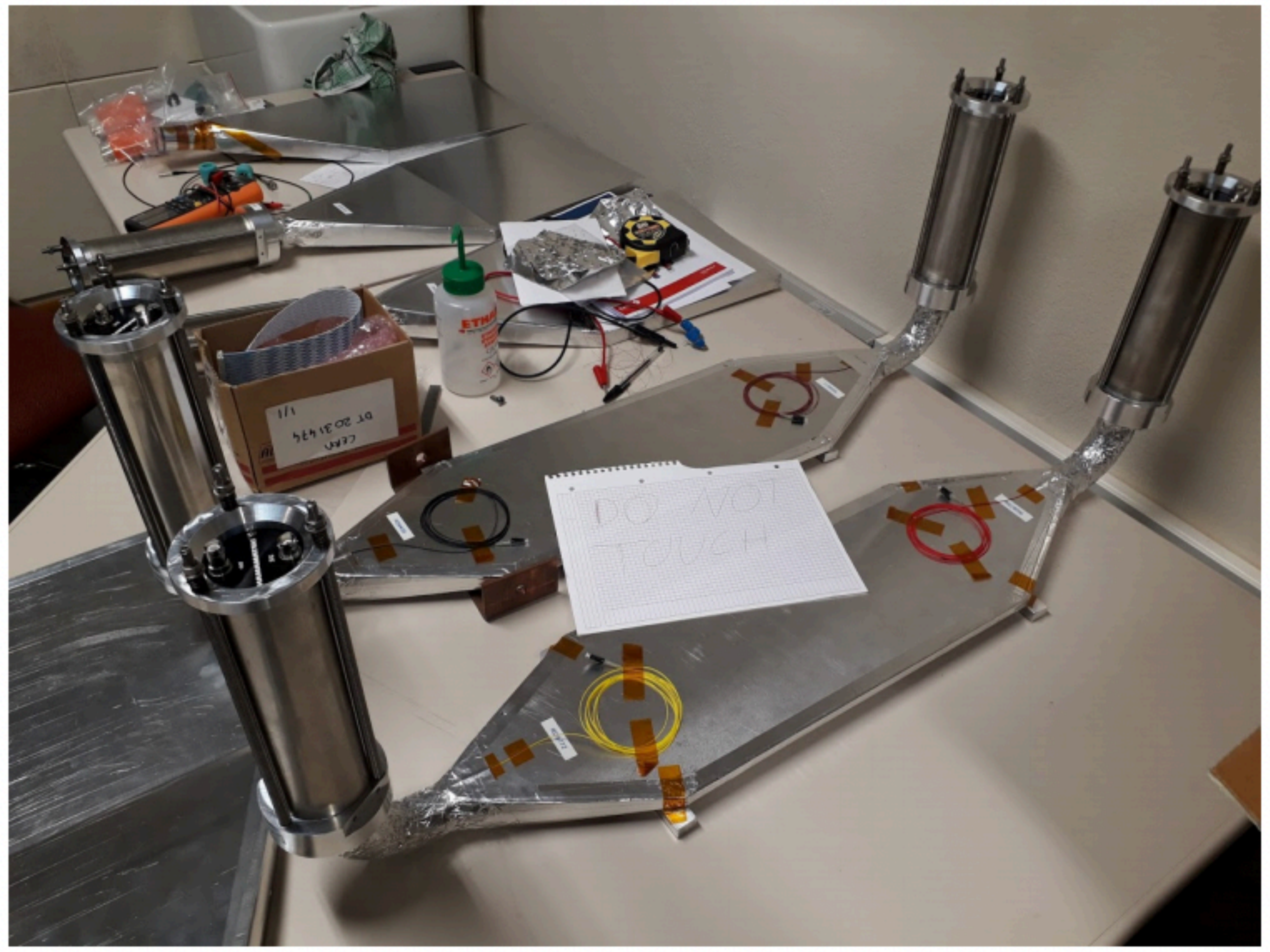


Scintillators | Construction

- Many thanks to the CERN scintillator lab for producing the scintillators and light guides.

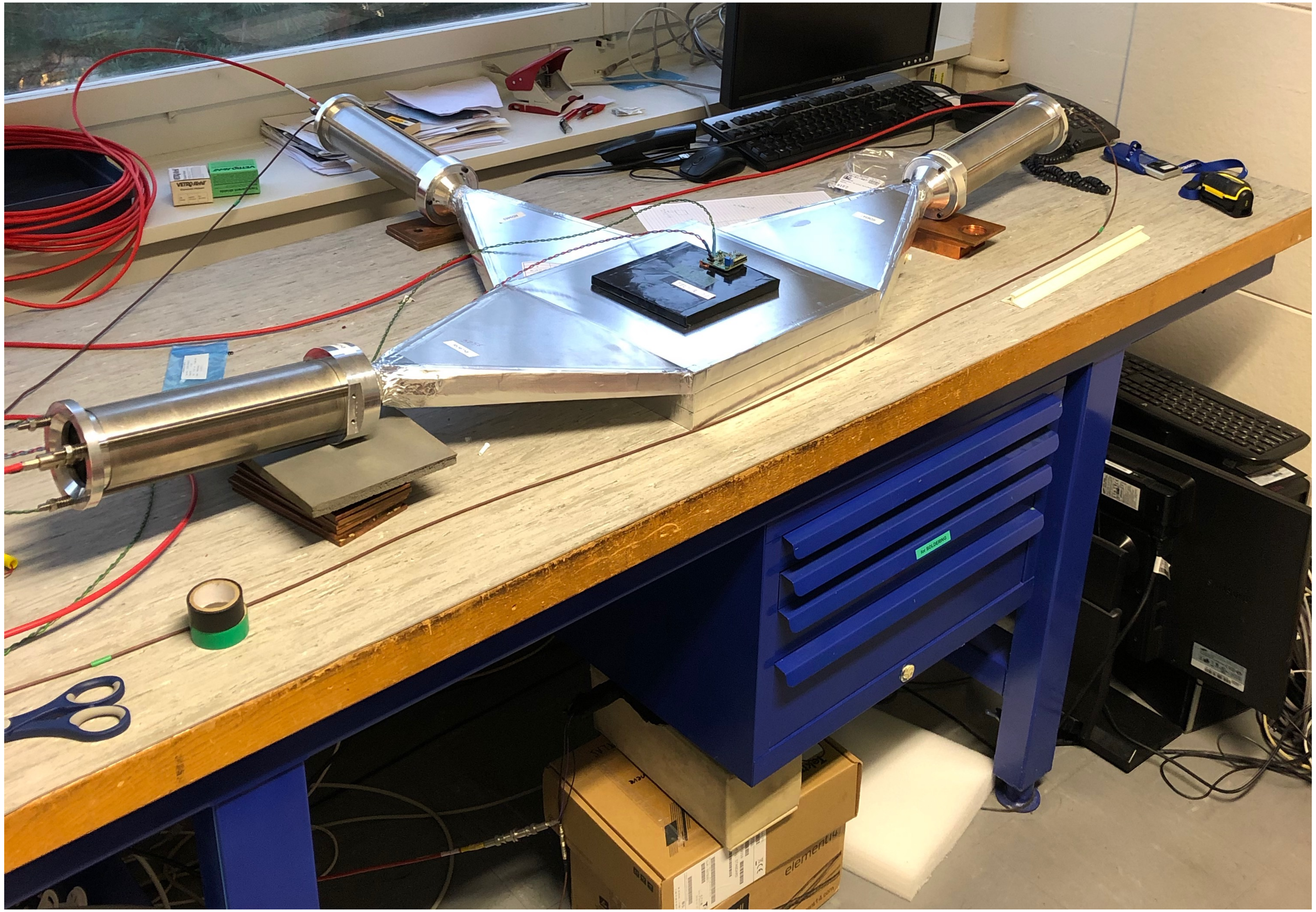






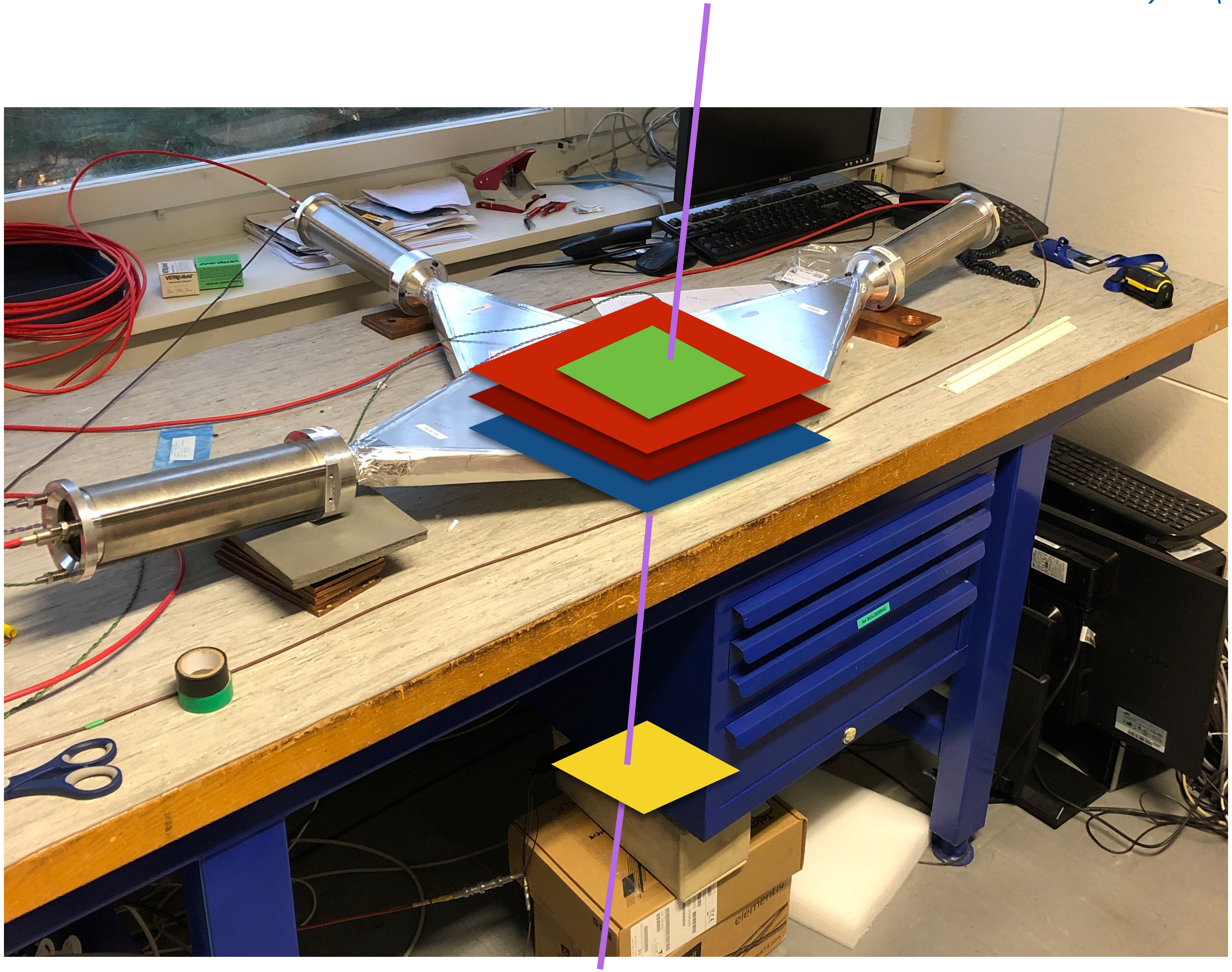
Scintillators | Characterisation

- Use cosmic muons to measure the scintillator response & inefficiency



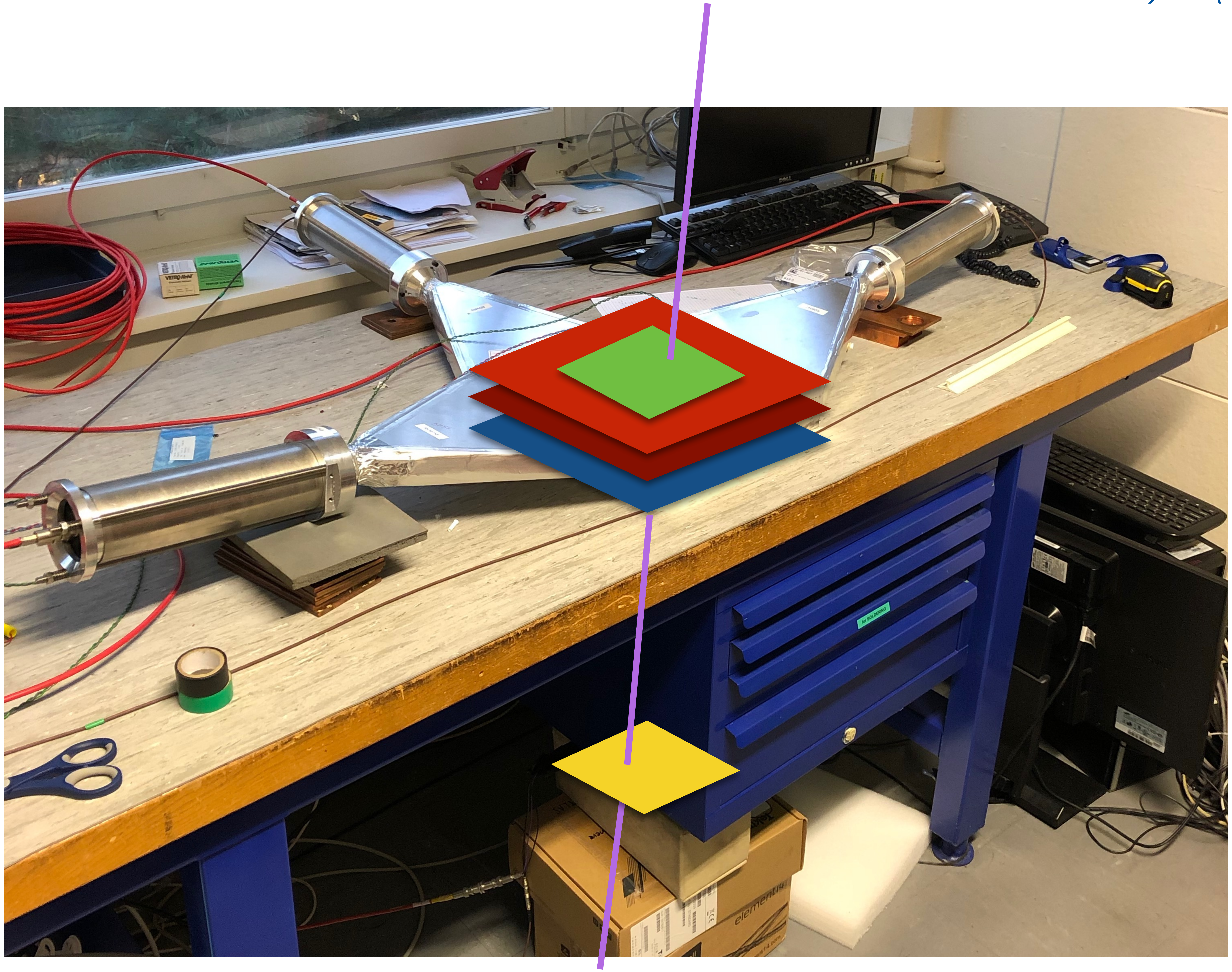
Scintillators | Characterisation

- Use cosmic muons to measure the scintillator response & inefficiency
- Trigger on ~vertical muons using small top and bottom scintillators

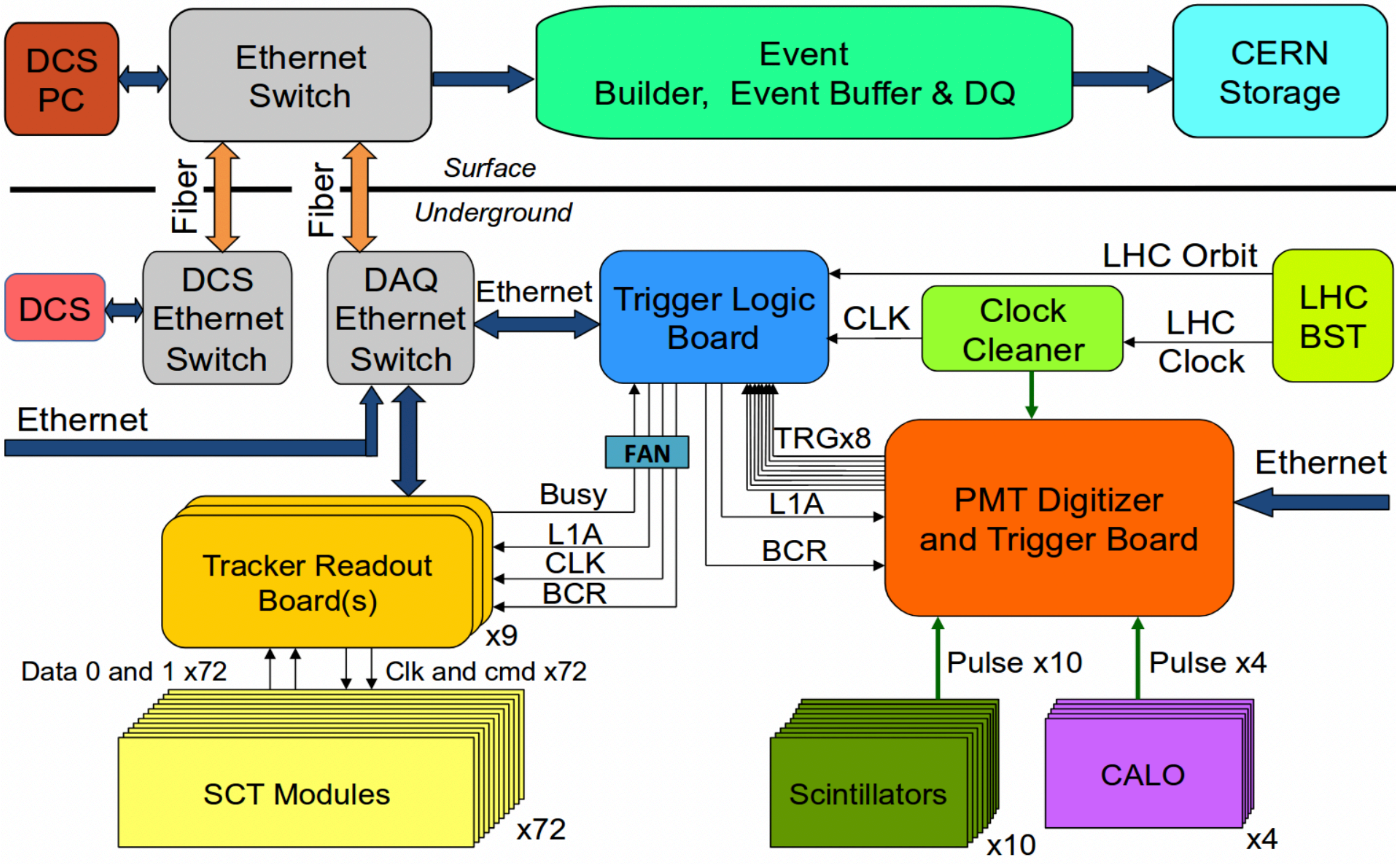


Scintillators | Characterisation

- Use cosmic muons to measure the scintillator response & inefficiency
- Trigger on ~vertical muons using small top and bottom scintillators
- Efficiency >99.9% measured
  - Within specification



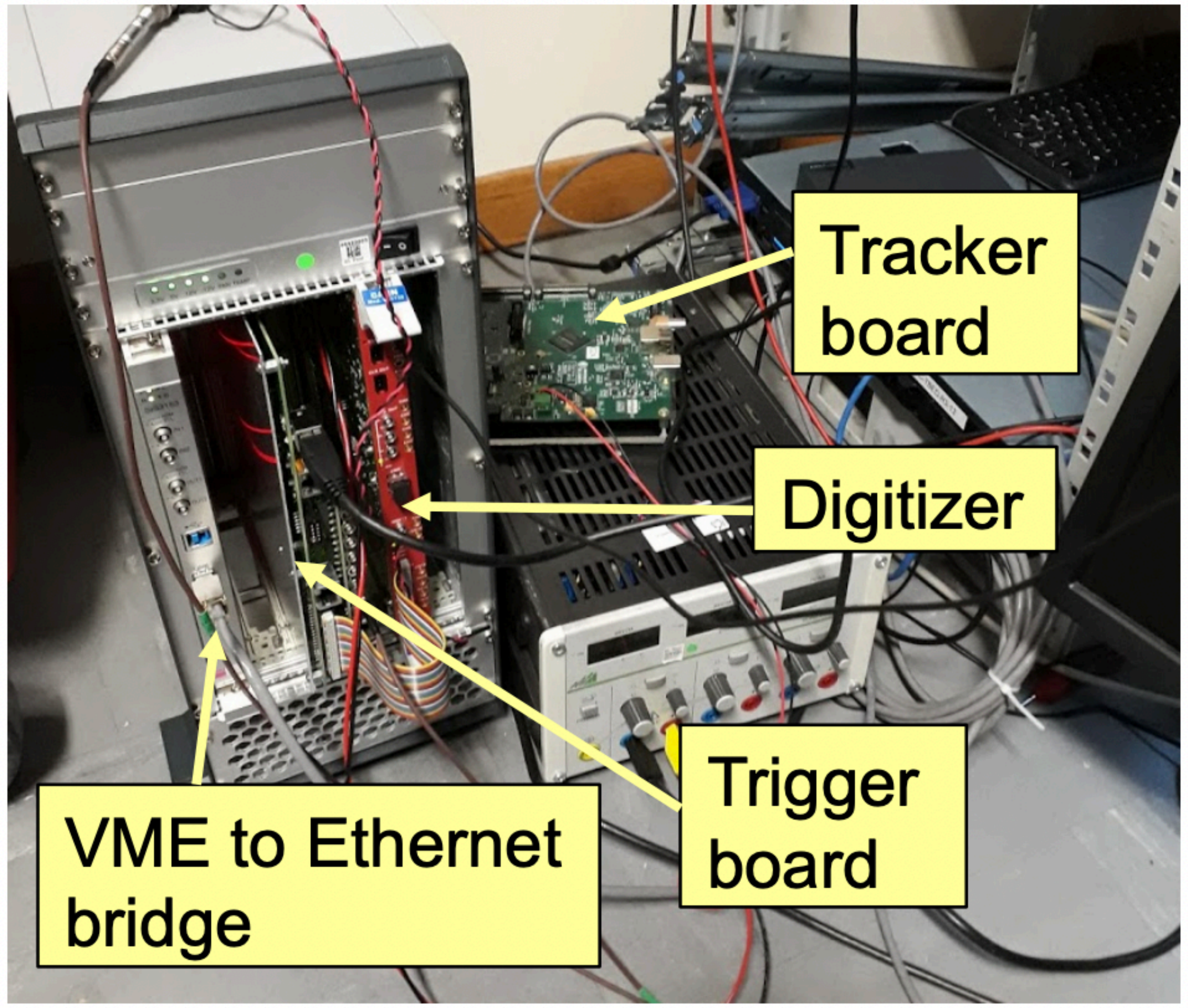
TDAQ | Schematic



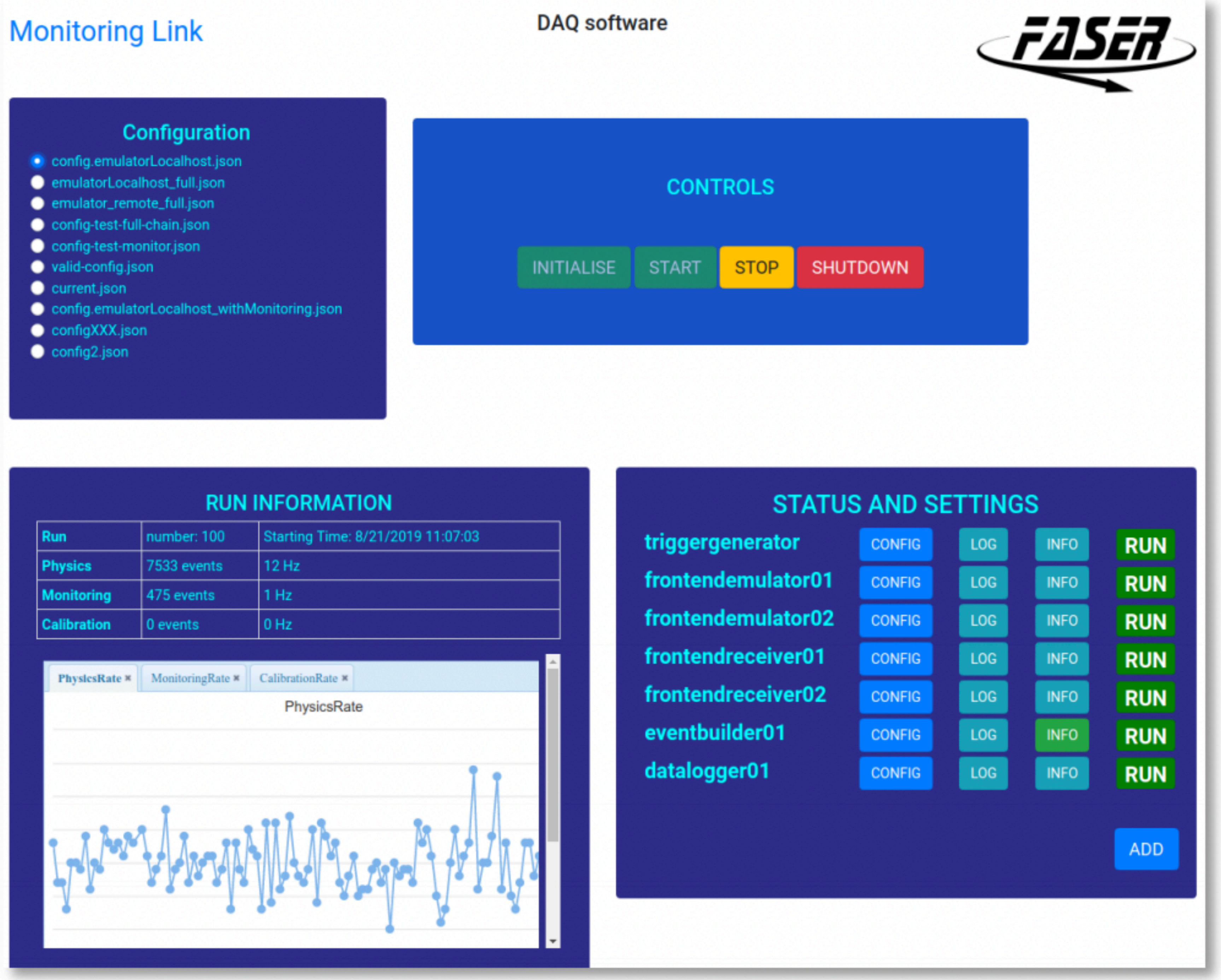
TDAQ | Commissioning

- All hardware for Tracker Readout and Trigger Logic produced and tested by Spring 2020.
- All firmware implemented and tested by Summer 2020.
- DAQ s/w for all readout boards implemented and tested by summer 2020
- TDAQ setup exercised in cosmic runs and full system test over the summer
  - Gained valuable operational experience

TDAQ test setup



Web-based run-control



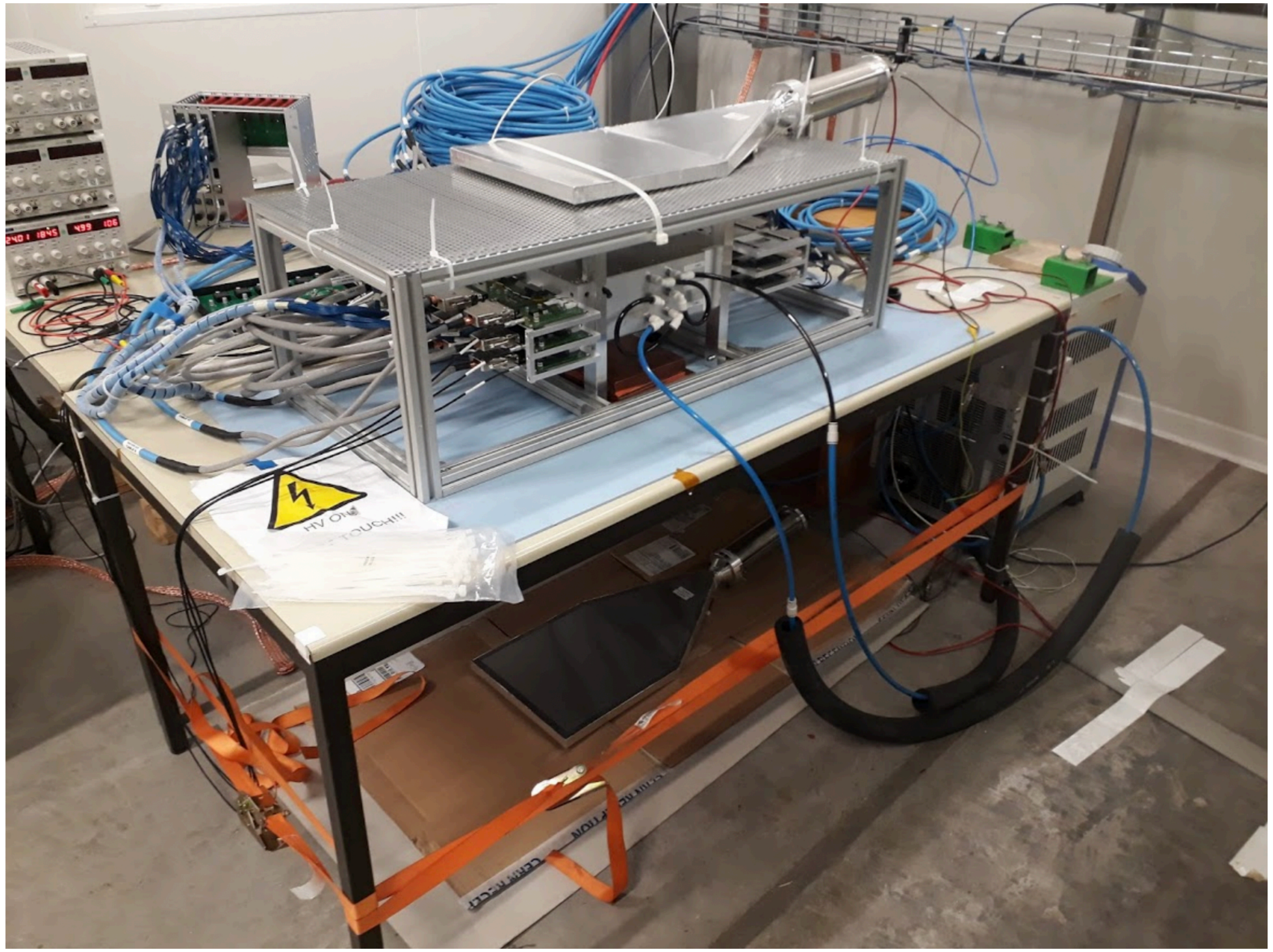
Overground testing

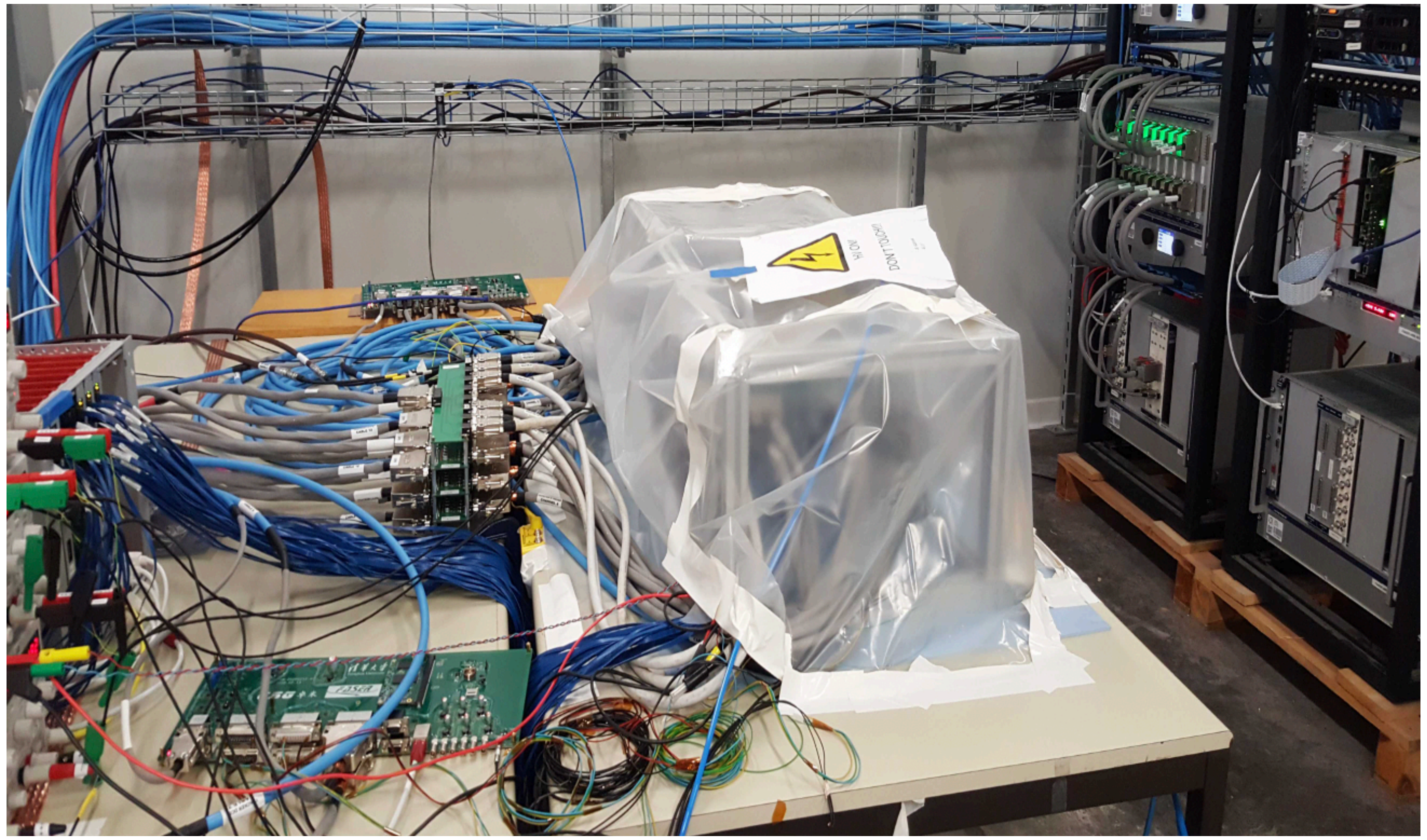
- Have space at CERN Prevessin site (same building as Neutrino Platform)
- Used for dry run above ground
  - Assembly took place in Feb-April 2020
    - Test mechanical assembly
  - Commissioning from March 2020
    - Detector installation
    - Alignment procedures
    - Cabling
    - Cooling
    - TDAQ
    - Cosmics runs

	Nov	Dec	Jan	Feb	Mar	April	May
Prepare ENH1	■	■	■				
Install Det. Support				■			
Install Calo/Scin & TDAQ				■			
(Partial) System Commissioning					■ (light)	■	

Overground testing | Tracker

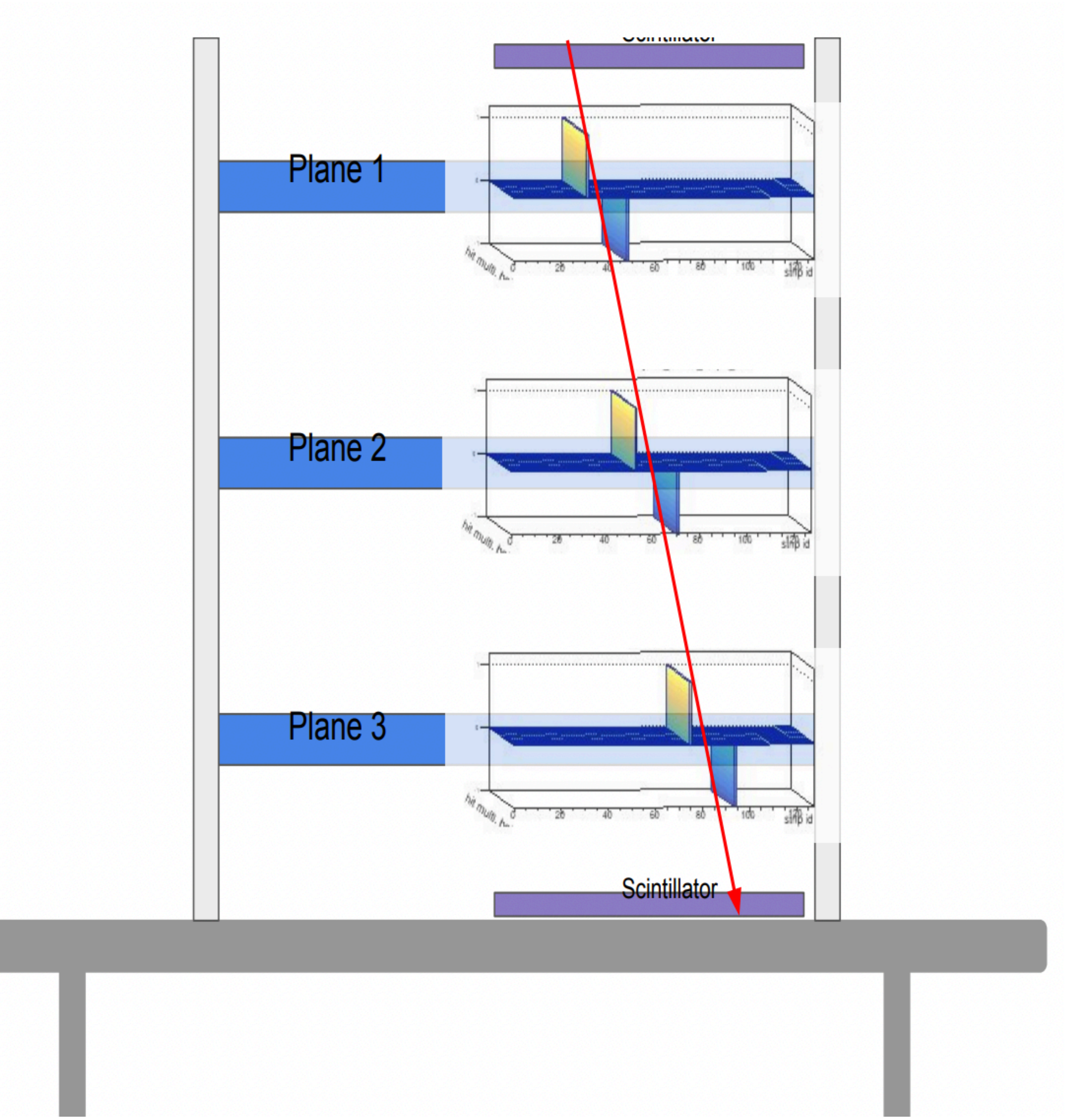
- Cosmic data taking with station on its side, and a scintillator on top/btm.
- Use full FASER TDAQ system to take data.
  - Operational experience
  - Tracker efficiency, resolution and alignment studies
  - Offline s/w debugging

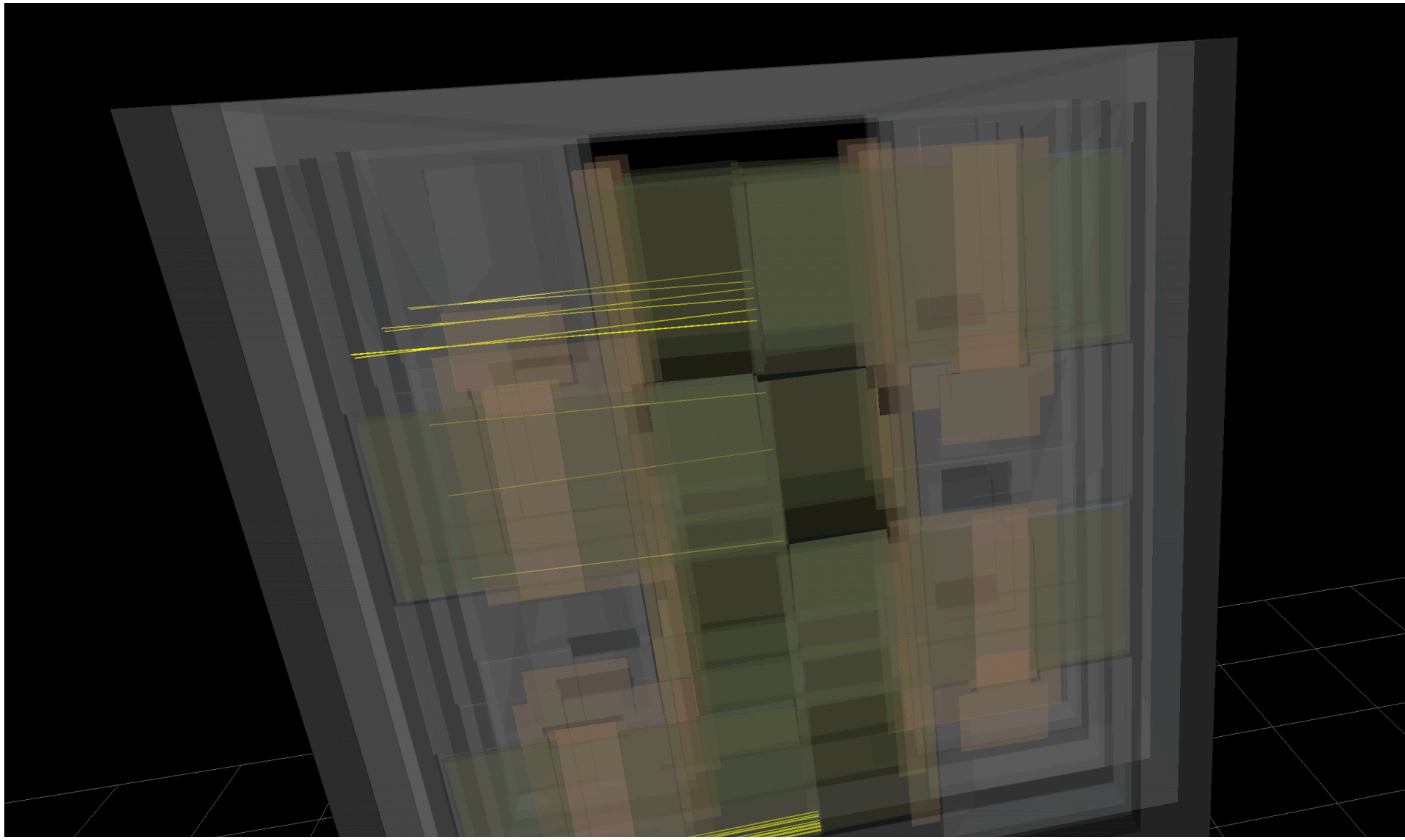




Overground testing | Tracker

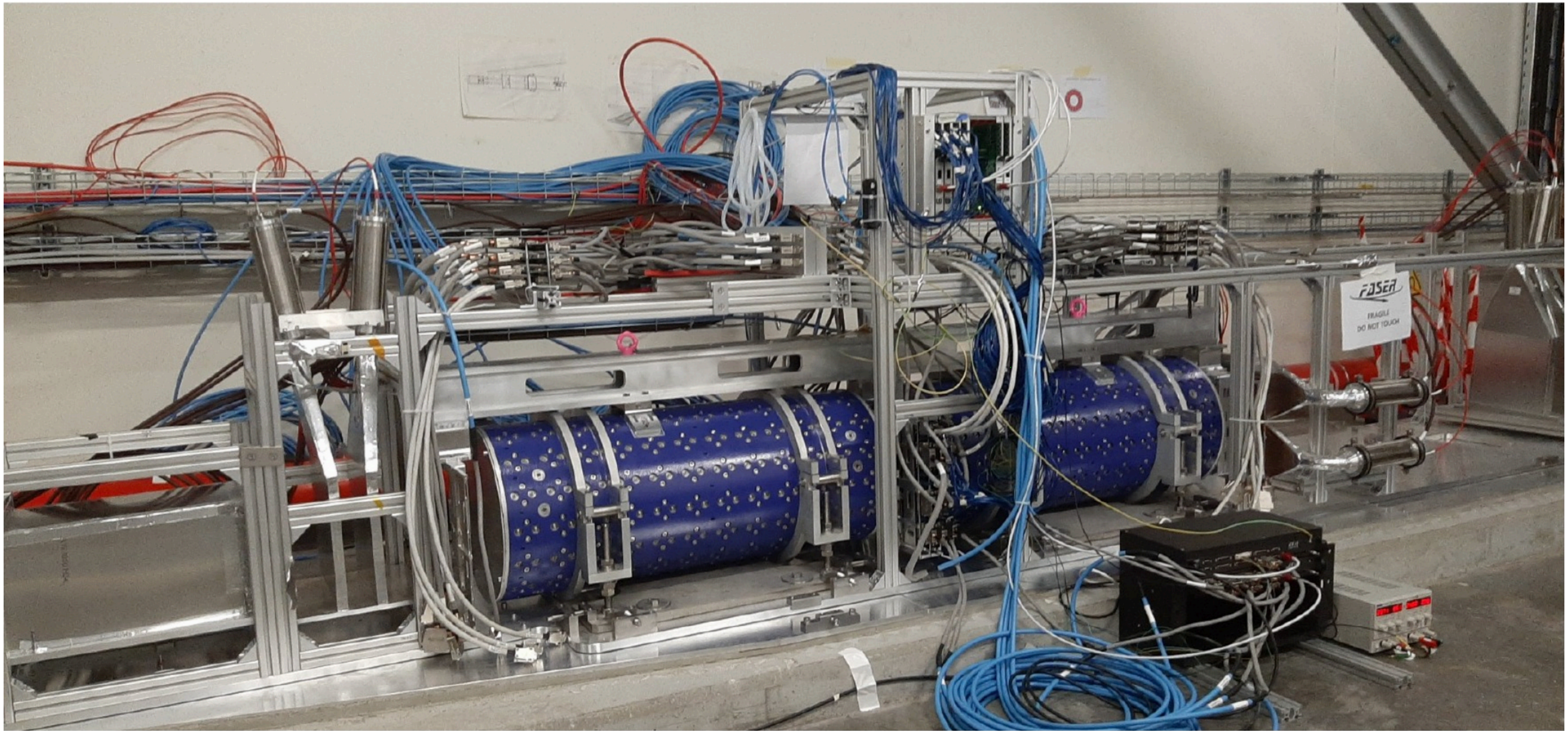
- Straight track candidate along with event display:





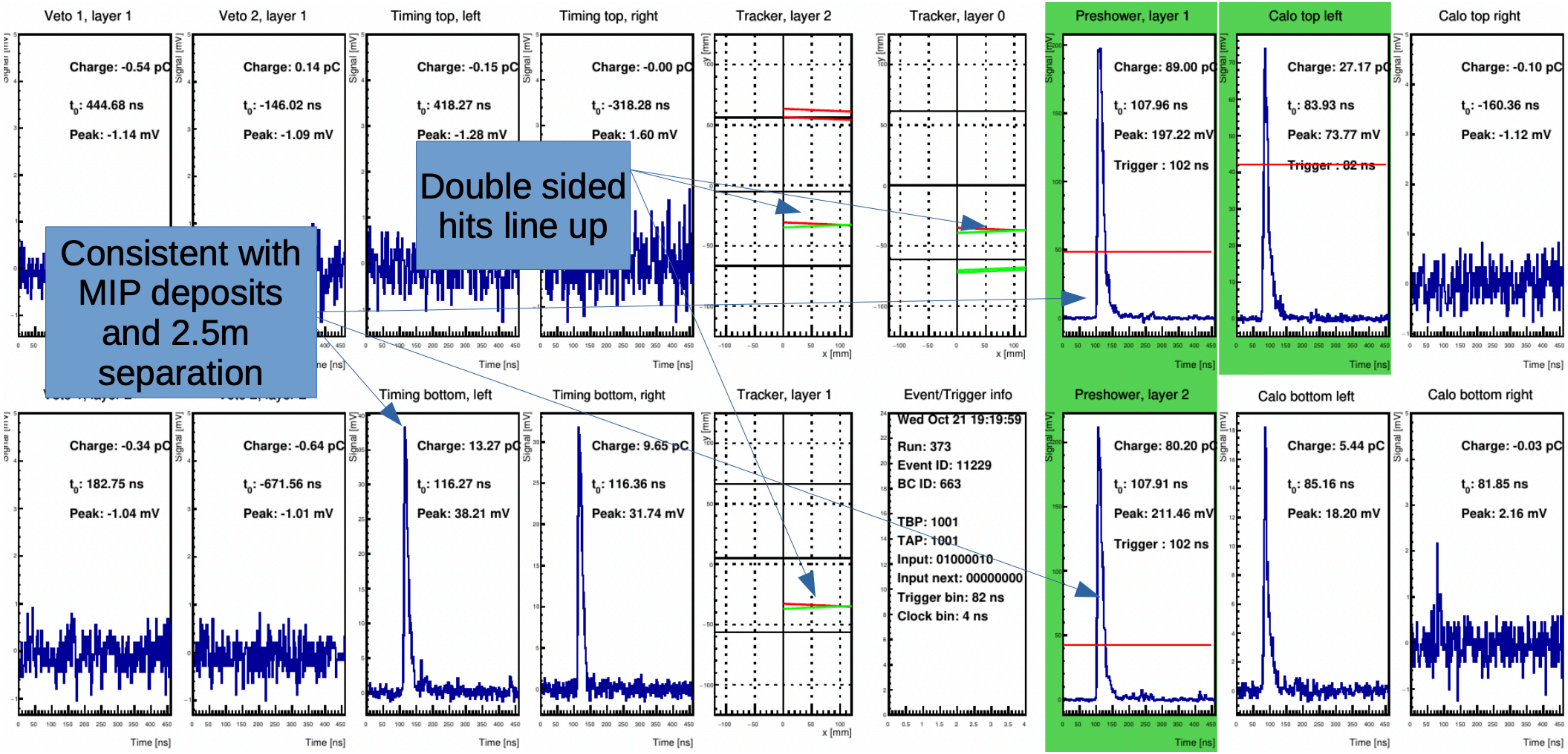
Commissioning | Overground

- Also have partial detector combined run
  - All scintillators and calorimeters with one tracker station



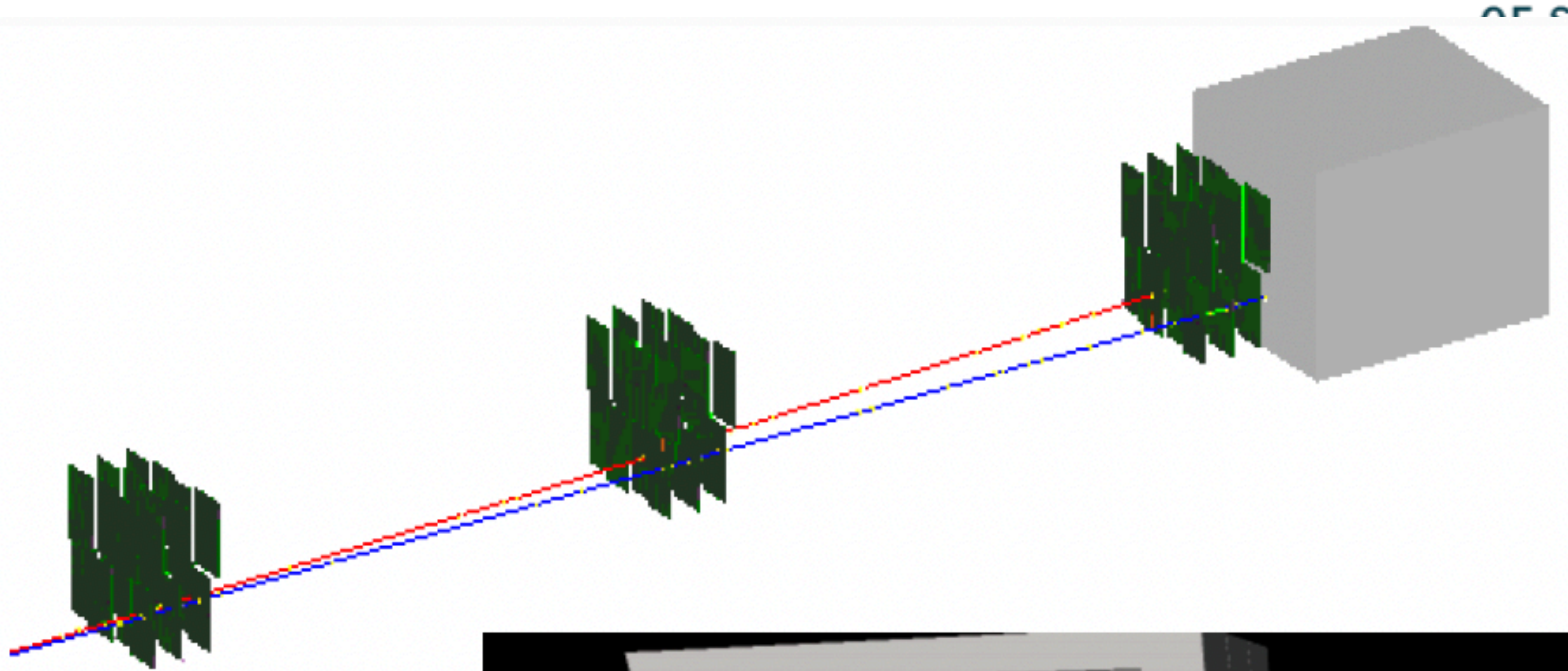
Commissioning | Overground

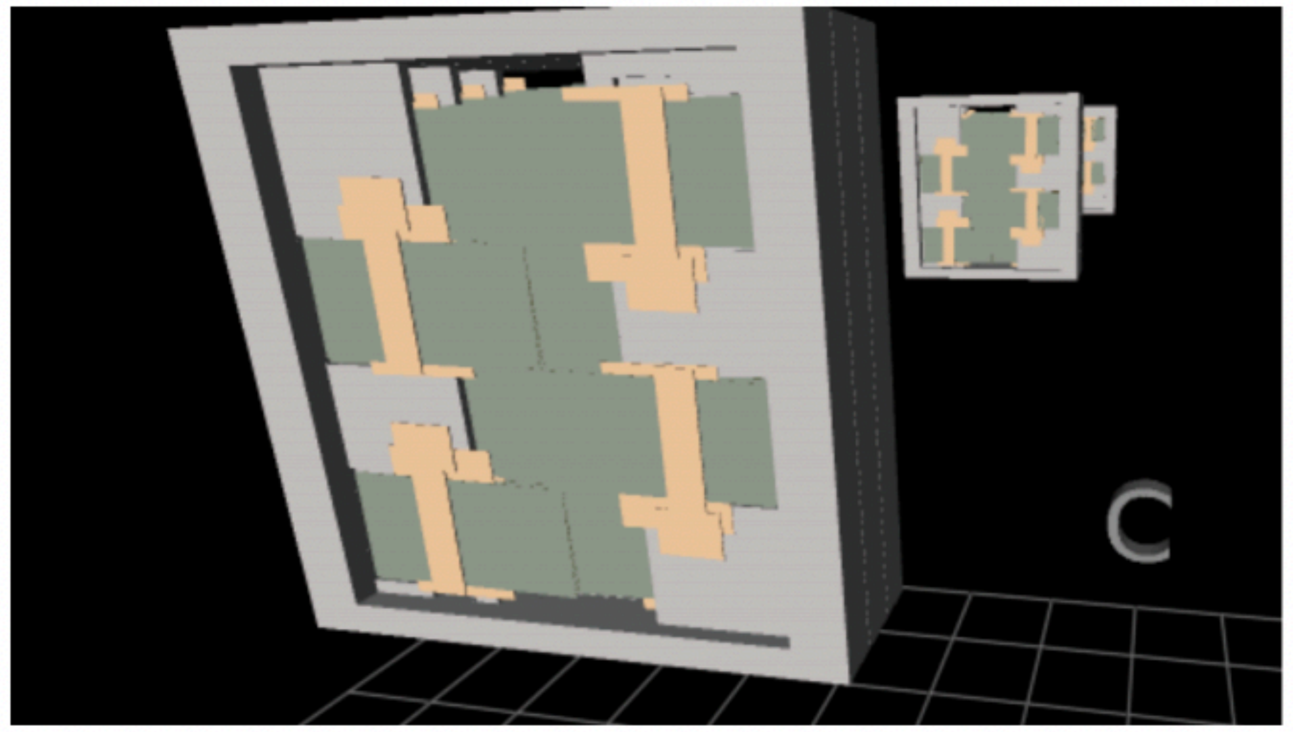
- Very rarely (few events per run) see events consistent with MIP passing through detector:

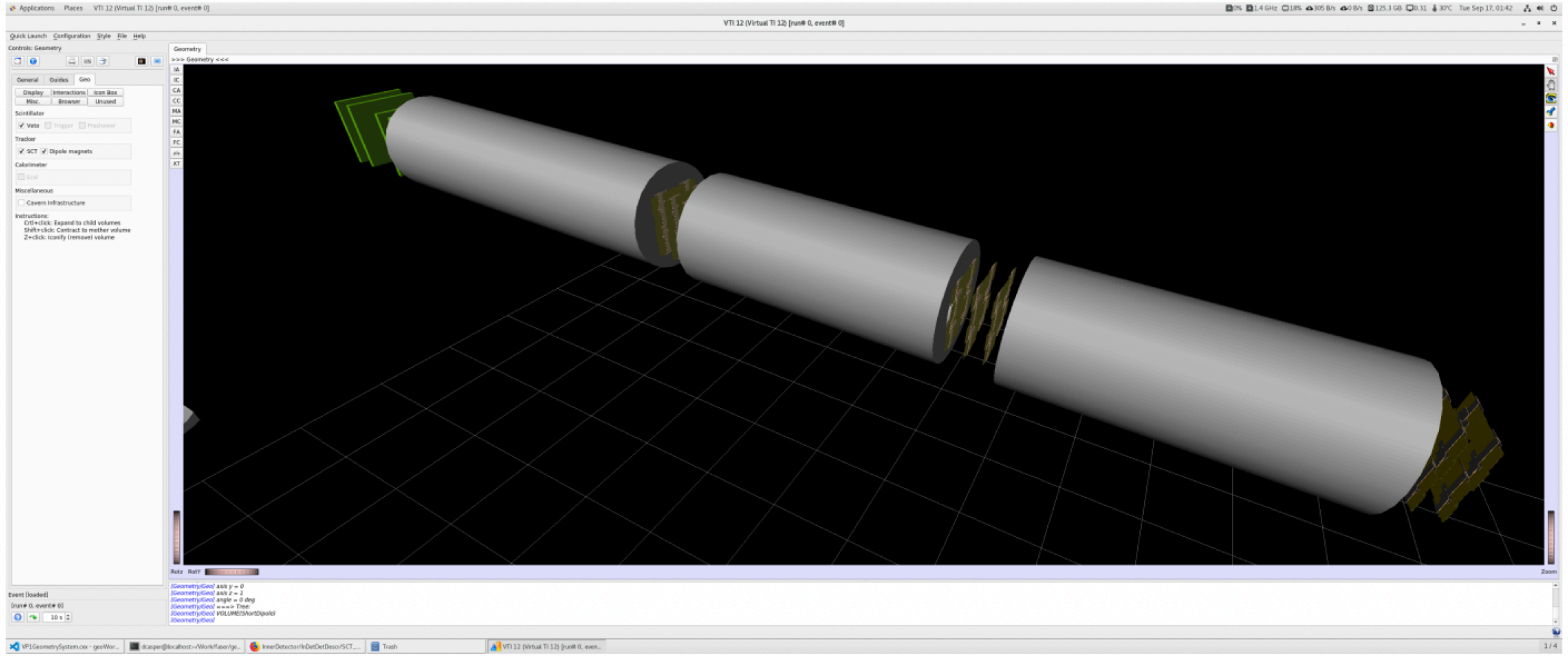


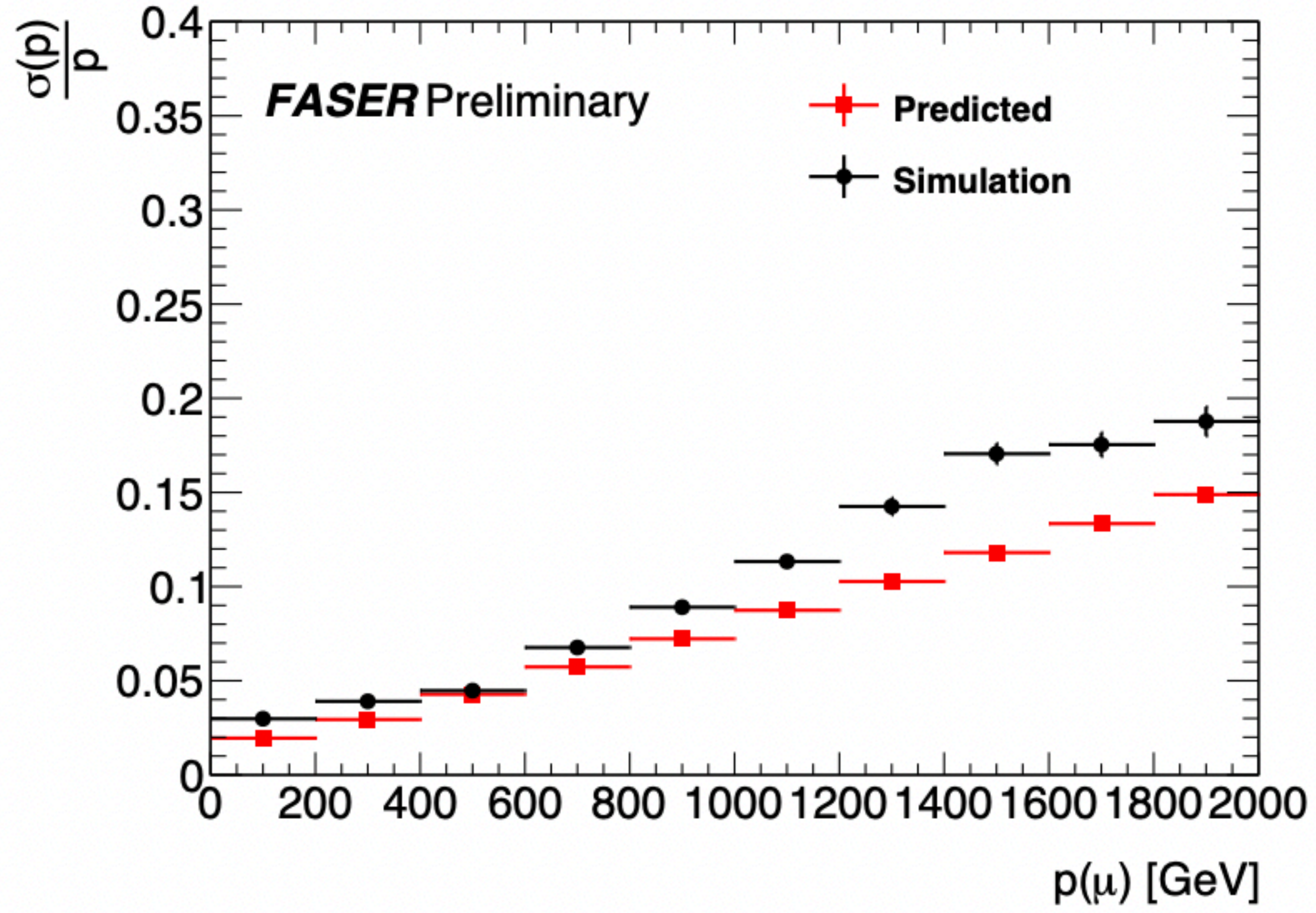
Offline software and Simulation

- Software based on open source ATLAS Athena "Calypso" framework
- First versions of detector description, GEANT4 simulations and event display working
- Track reconstruction with ACTS under development









Underground preparations

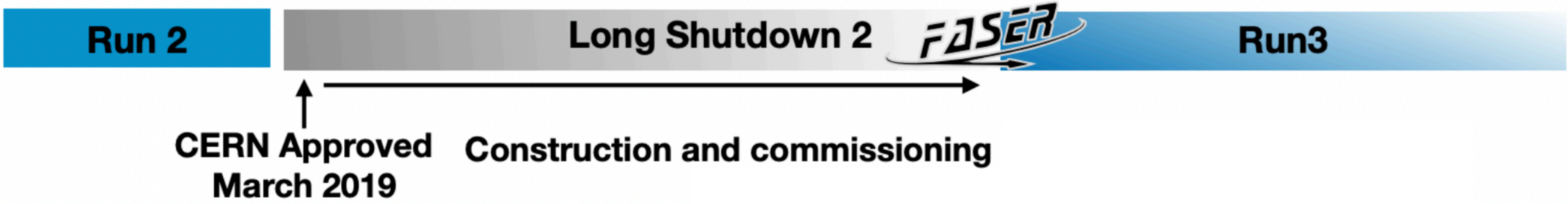
Commissioning to data taking

- Despite tight timescale, full FASER detector installation now finished!
  - Still lots of commissioning work to do.
- Run-3 during 2022-2024
  - Expecting 150/fb at 13(4) TeV

Milestone	Where	When
Individual component commissioning	CERN labs	July
Detector commissioning	EHN1	September
Installation of magnets	EHN1	September
Surface commissioning – part 1	EHN1	October
Detector installation – part 1	TI12	November
Surface commissioning – part 2	EHN1	February
Detector installation – part 2	TI12	March
In-situ dry commissioning	TI12	During 2021

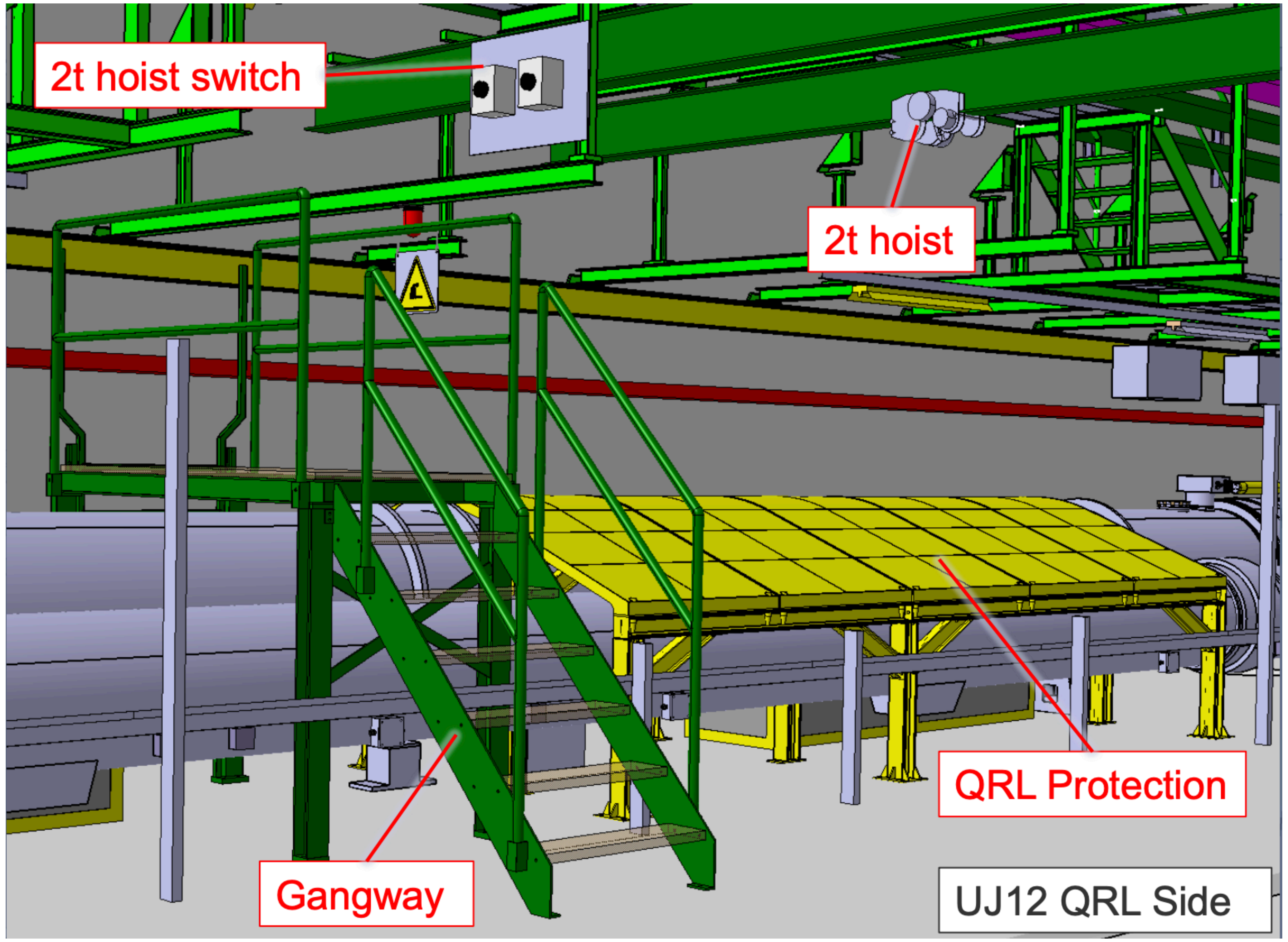
2020

2021



Preparation for FASER

- Preparation in LHC tunnel (UJ12)
  - Mostly related to getting things over the LHC!



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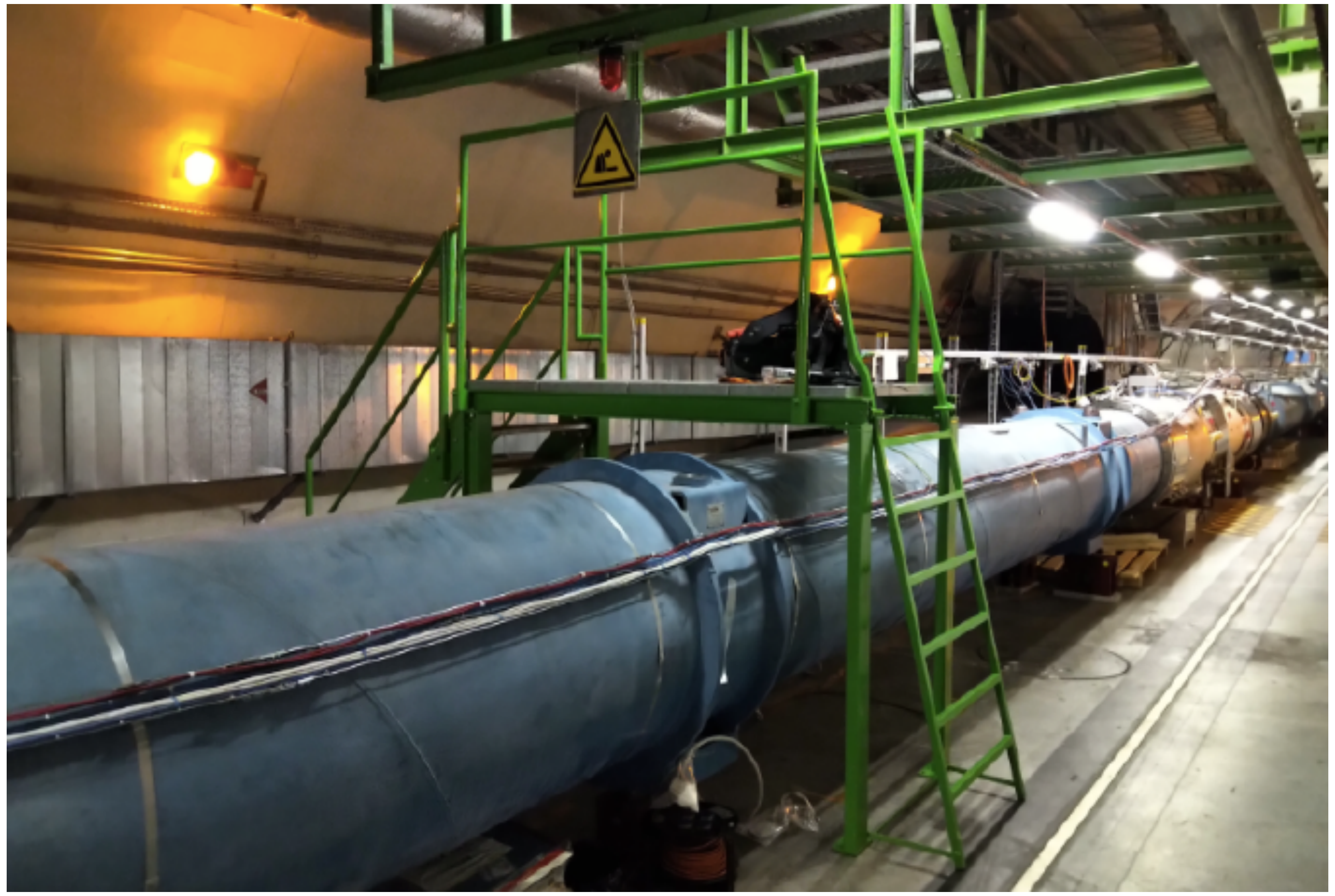
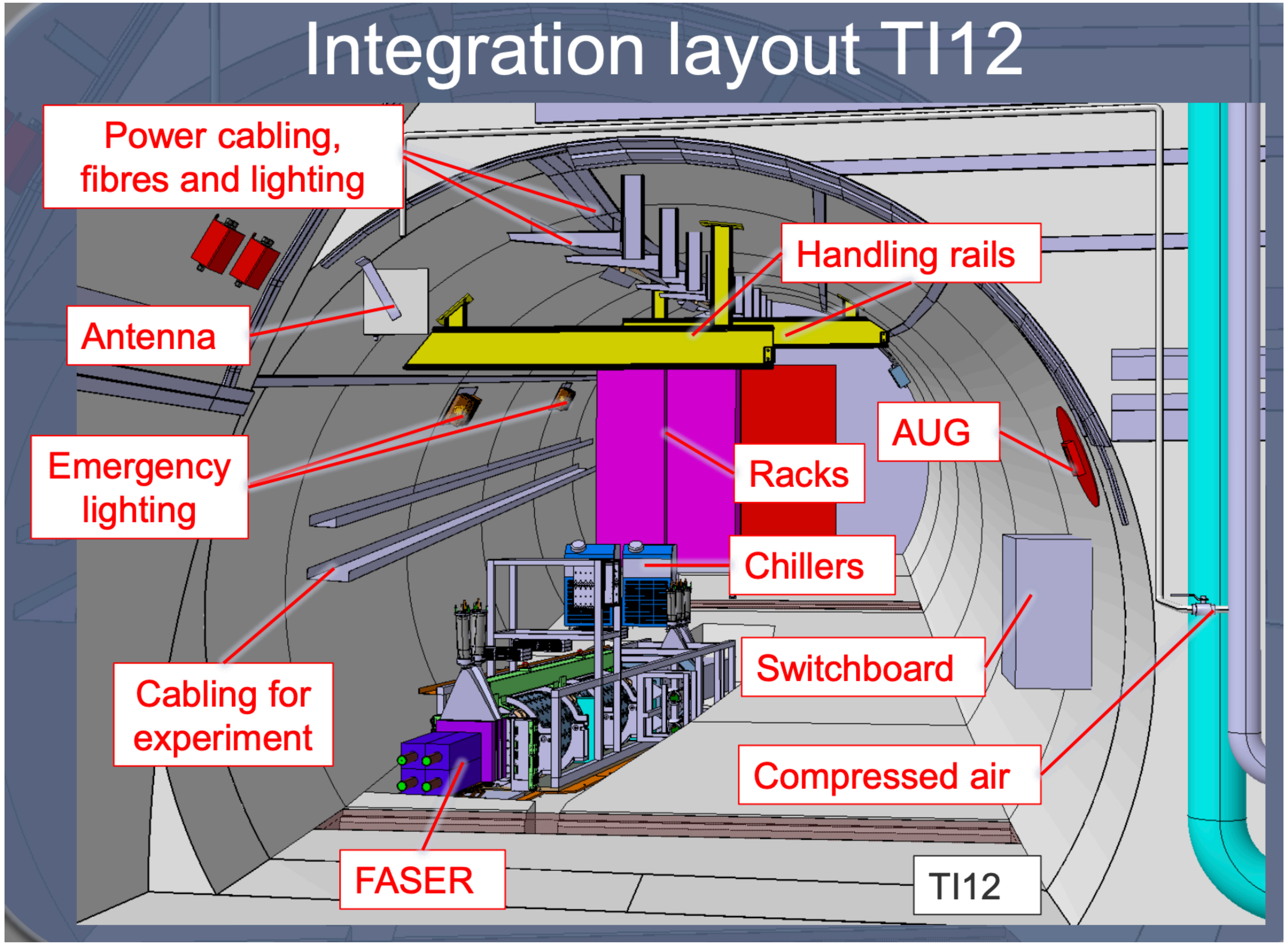


Preparation for FASER

- Preparation in LHC tunnel (UJ12)
  - Mostly related to getting things over the LHC!

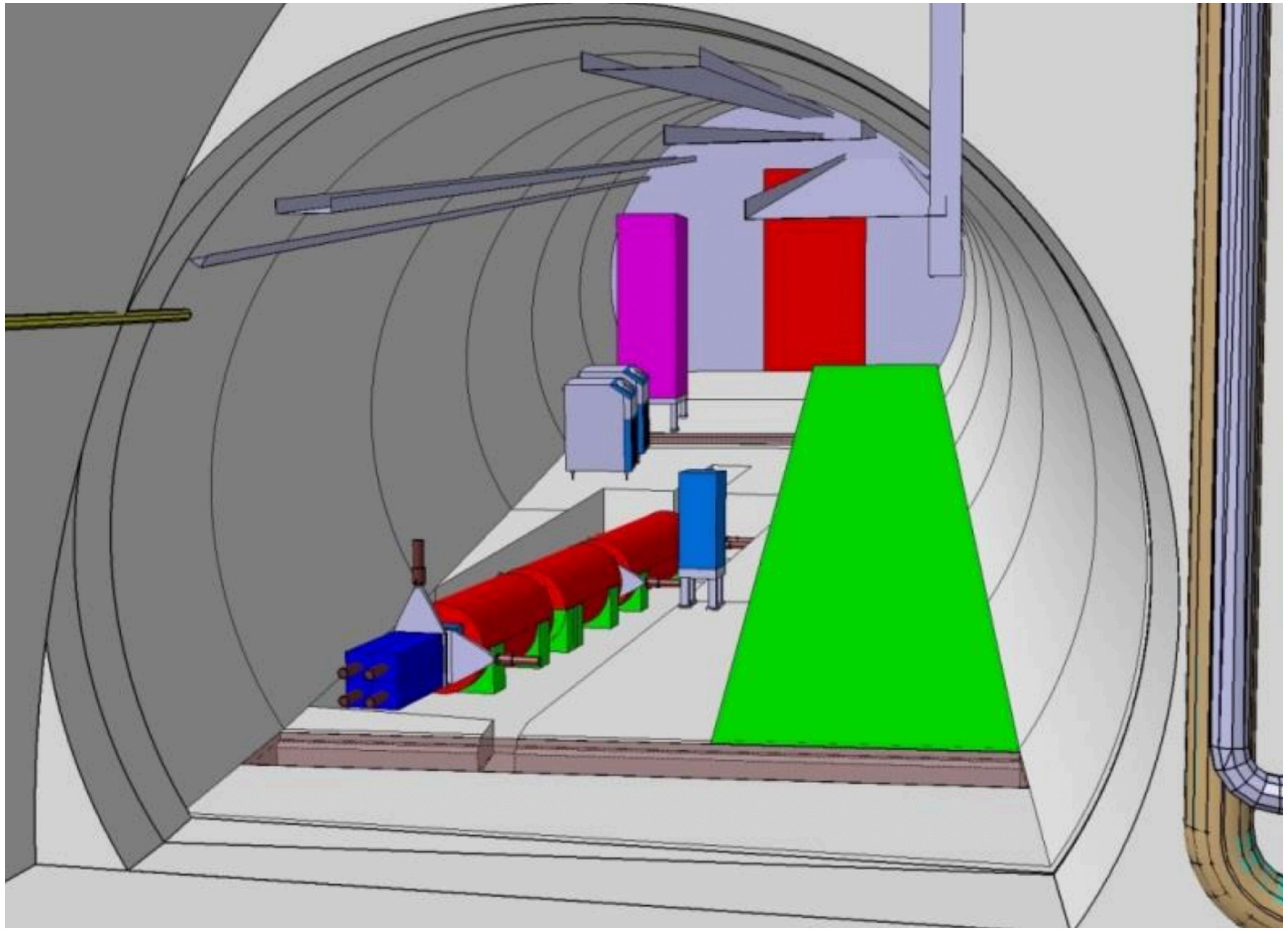
Preparation for FASER

- Preparation of TI12 tunnel
  - Civil engineering work mostly related to digging trench to ensure FASER is on line-of-sight.
  - Rest of the work mainly installing infrastructure.



Preparation of TI12

- From Technical Proposal…

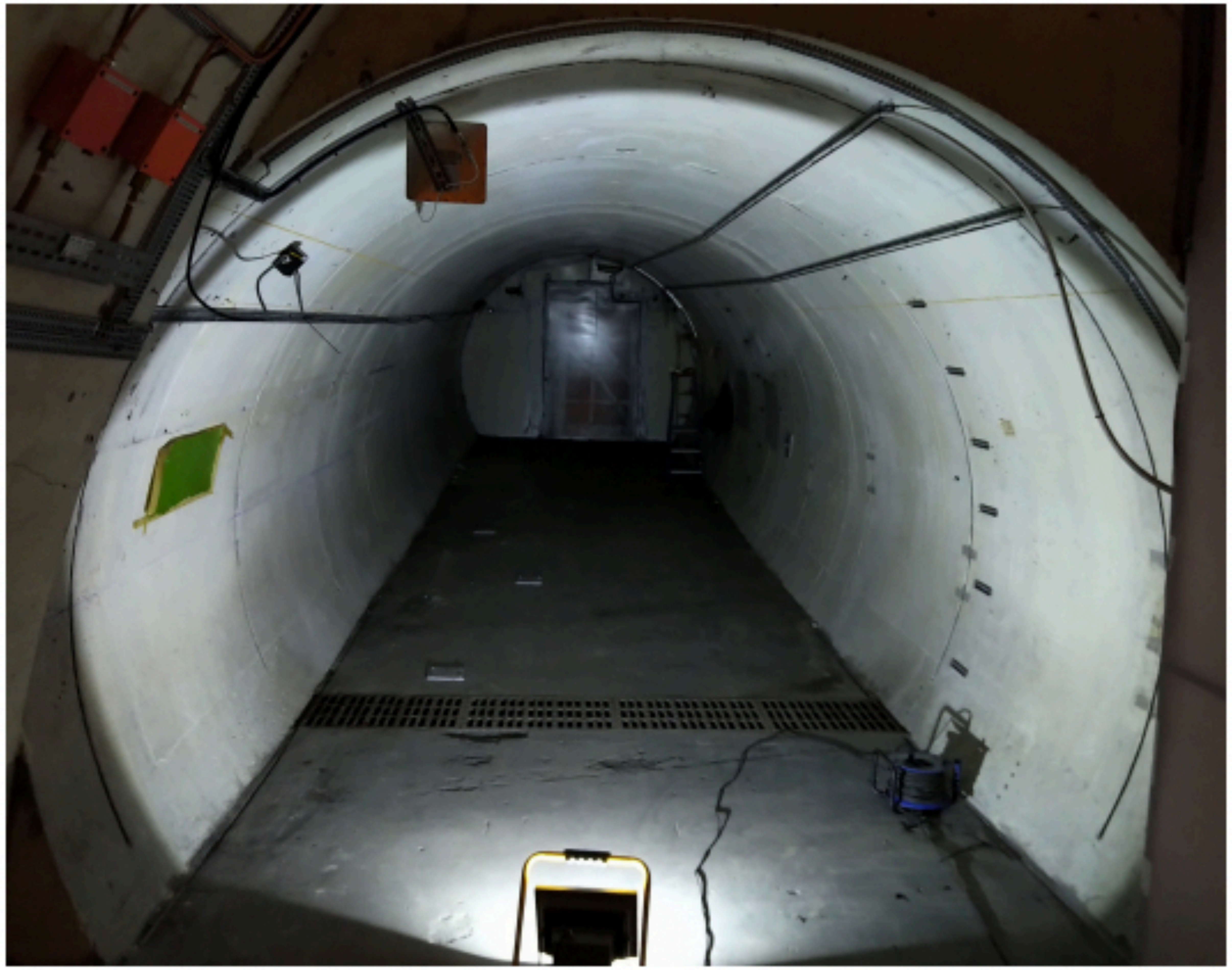


Preparation of TI12

- August 2018

Preparation of TI12

- August 2019



Preparation of TI12

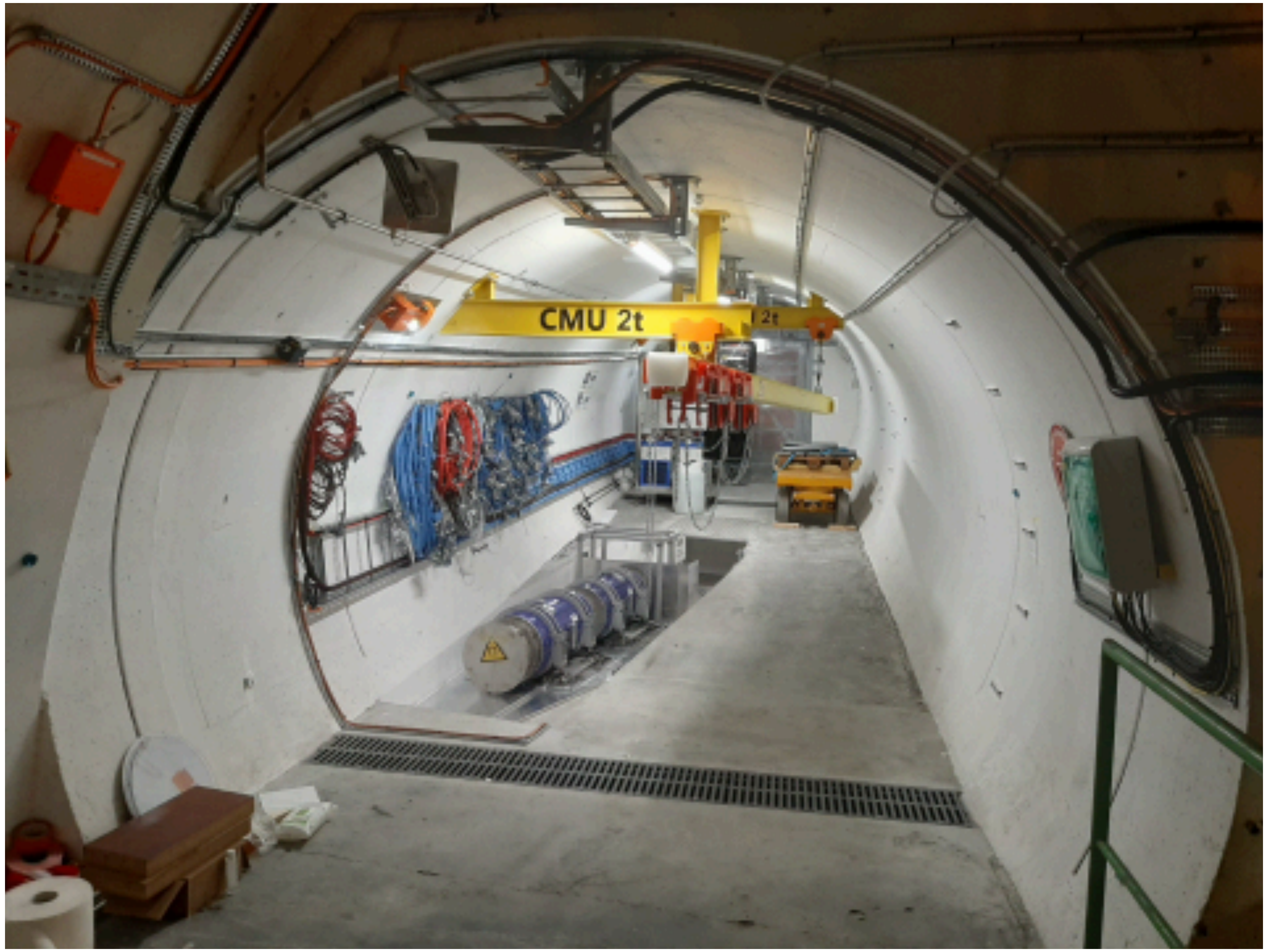
- December 2019

Preparation of TI12

- March 2020

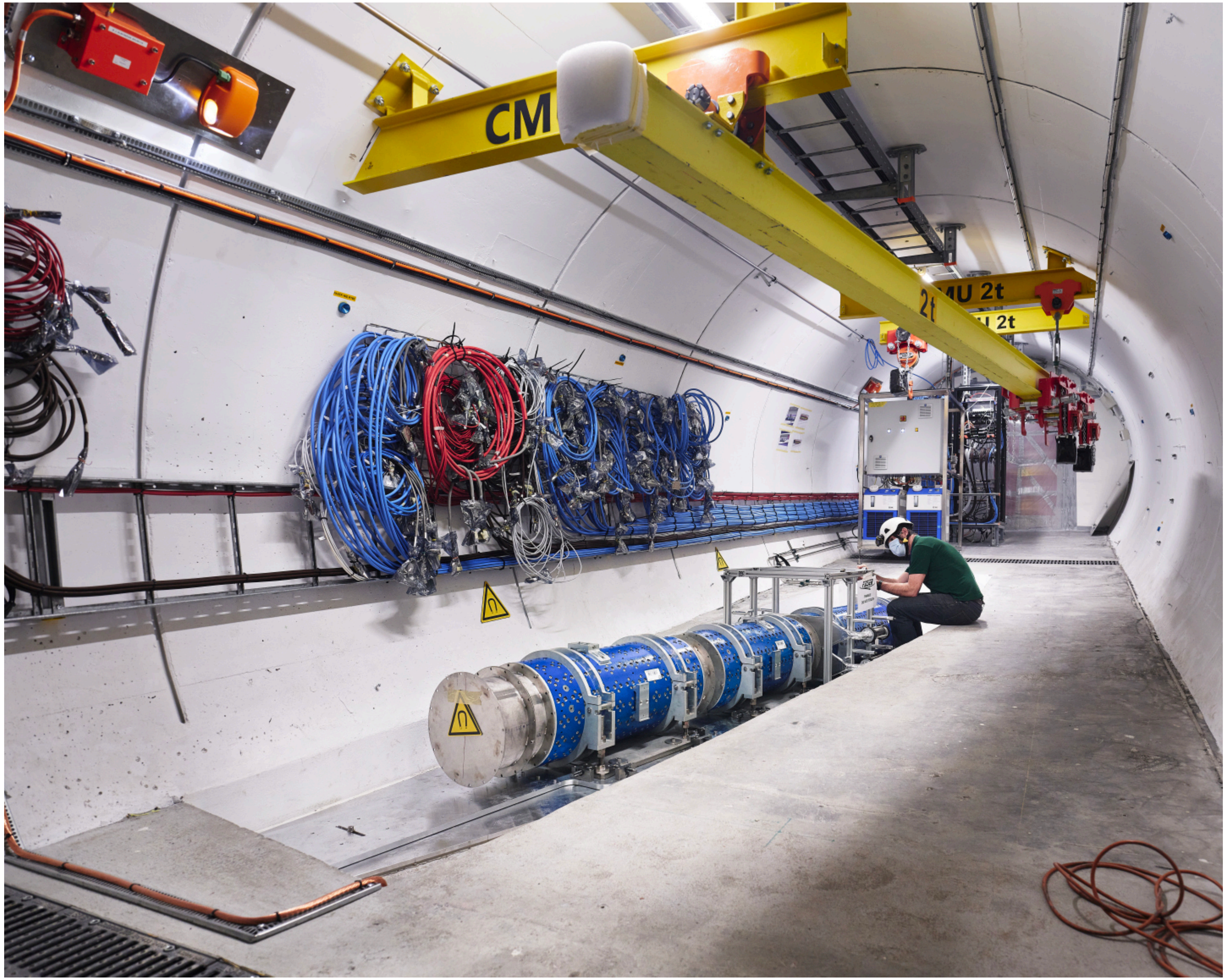
Preparation of TI12

- November 2020



Preparation of TI12

- November 2020



Preparation of TI12

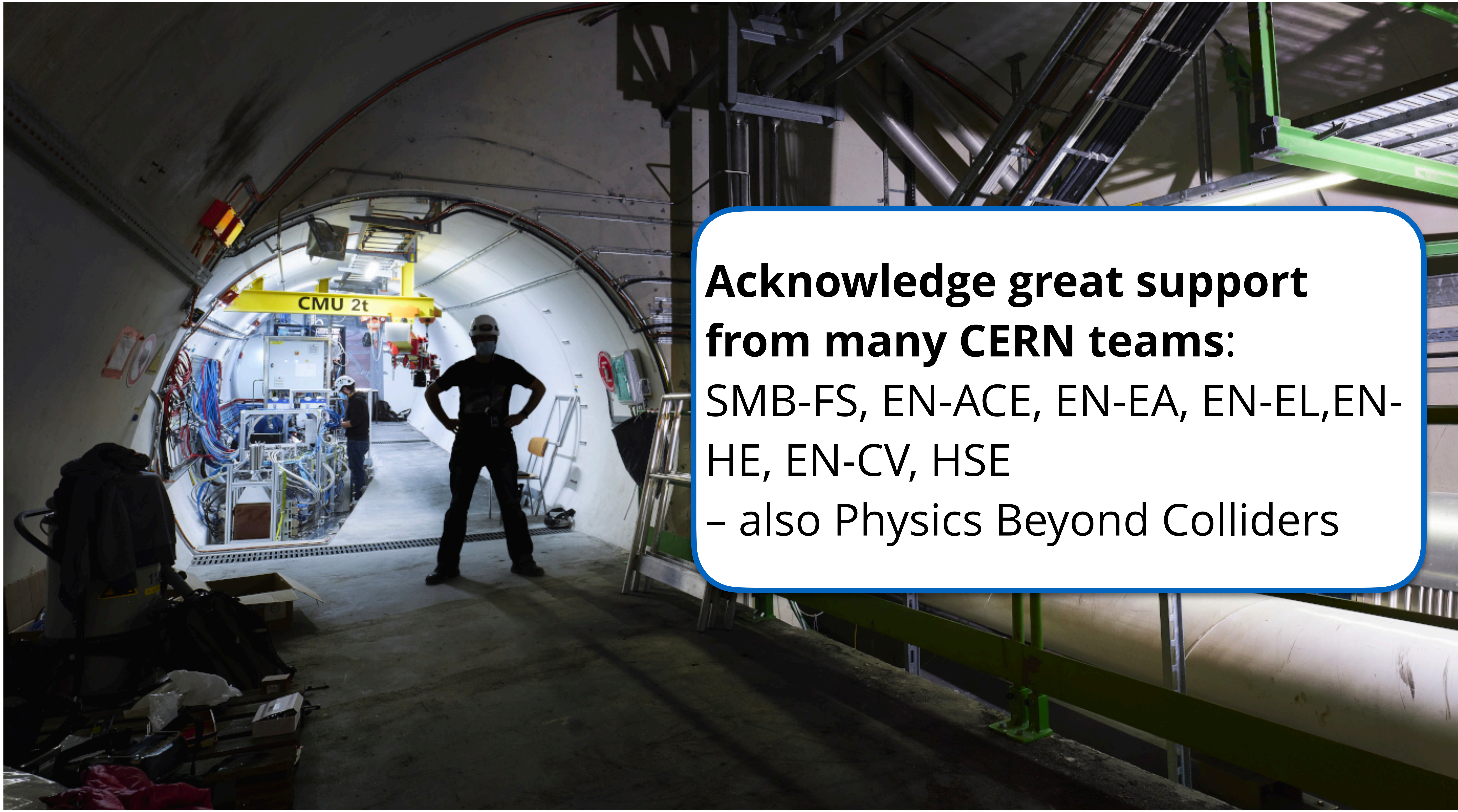
- April 2021

Preparation of TI12

- April 2021

Preparation of TI12

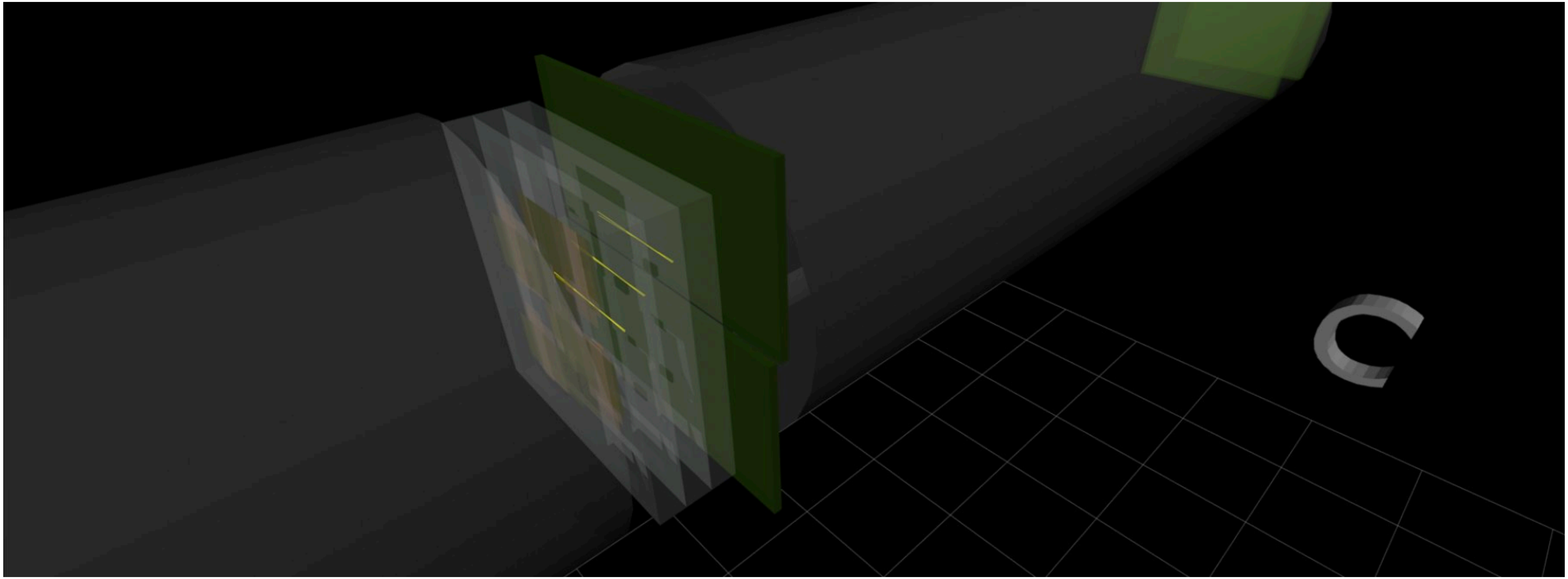
- April 2021



Acknowledge great support from many CERN teams:
SMB-FS, EN-ACE, EN-EA, EN-EL,EN-HE, EN-CV, HSE
– also Physics Beyond Colliders

Commissioning | Underground

- First comics candidates!



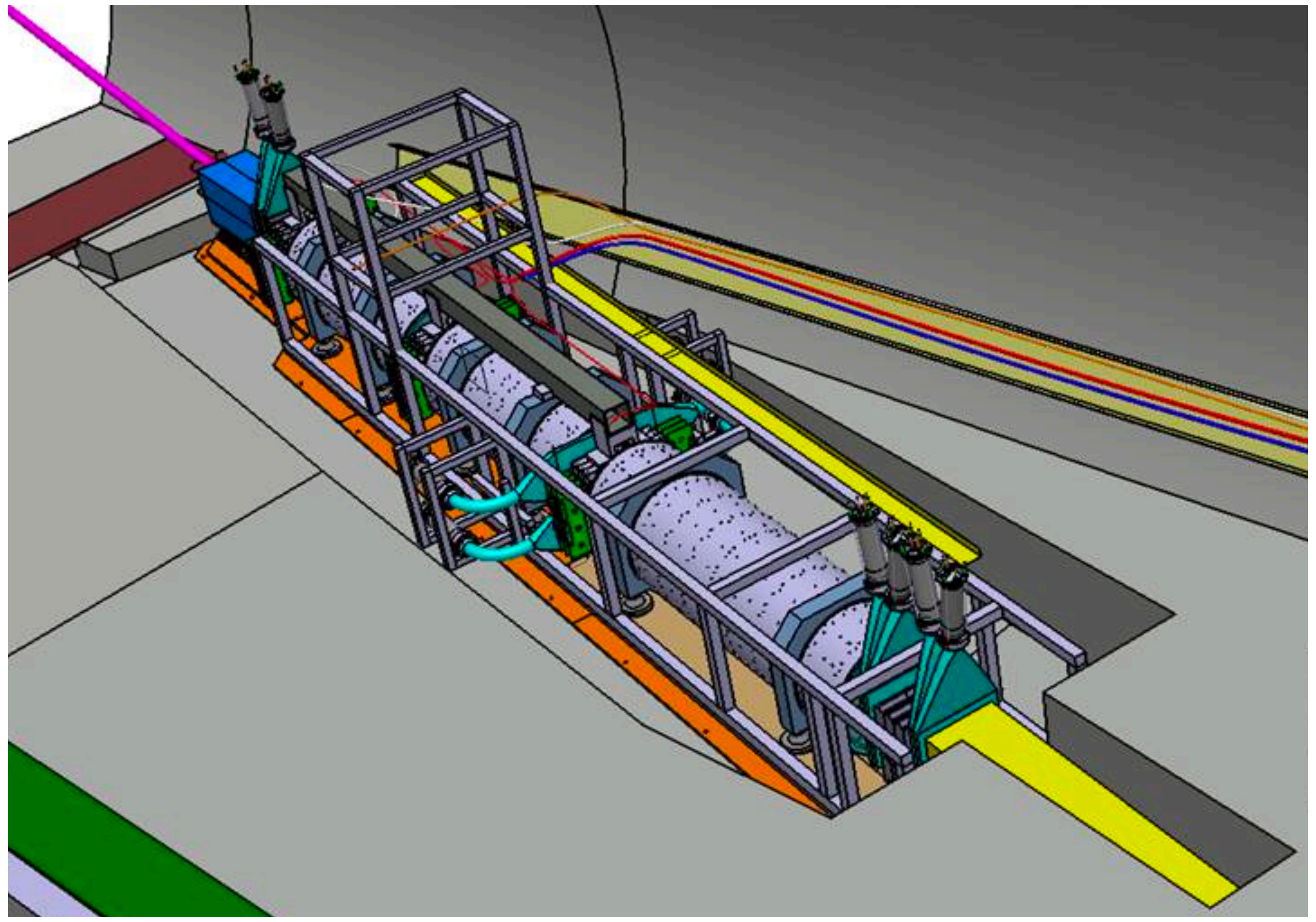
Commissioning | Underground

- First comics candidates!

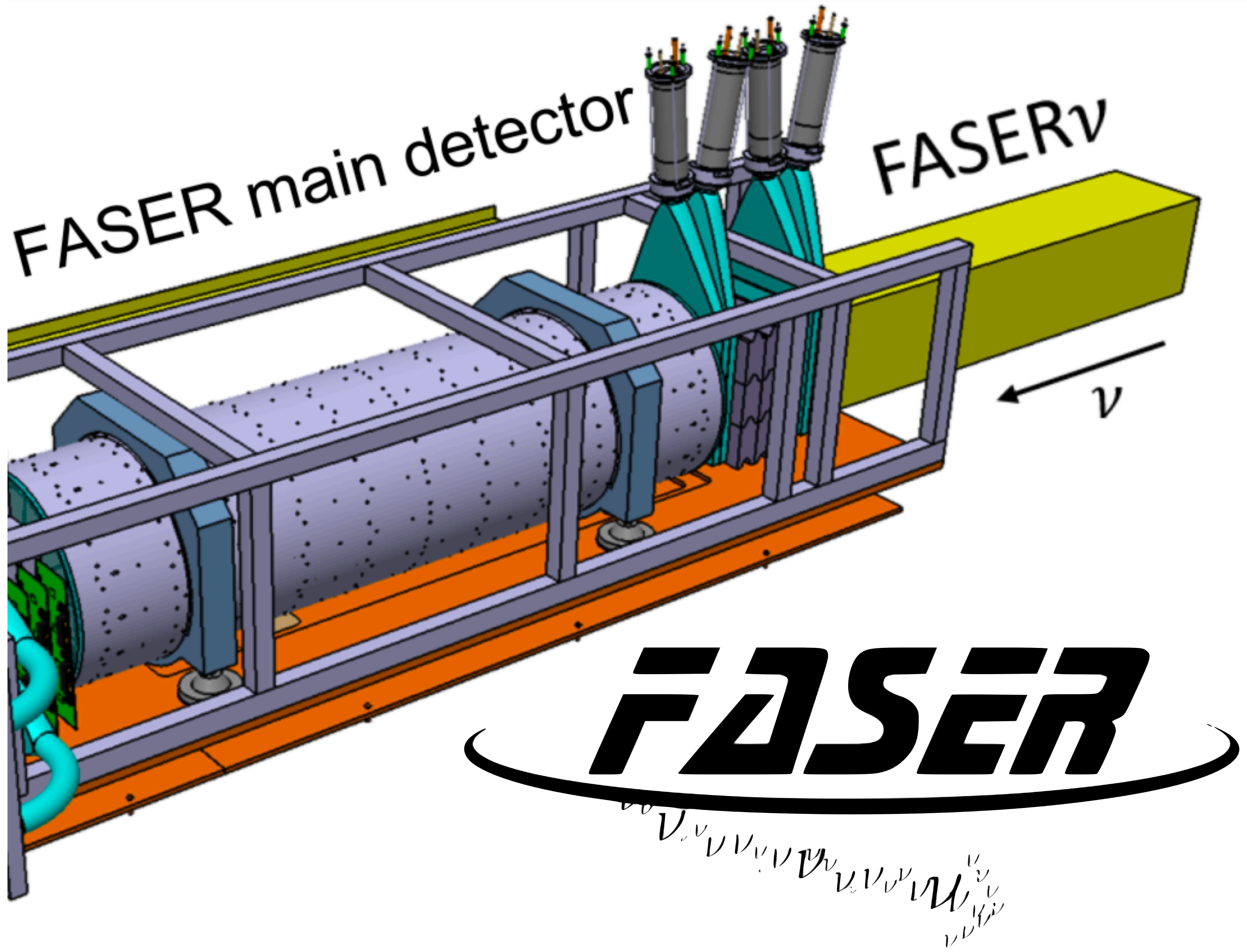
FASERν

FASERν | Overview

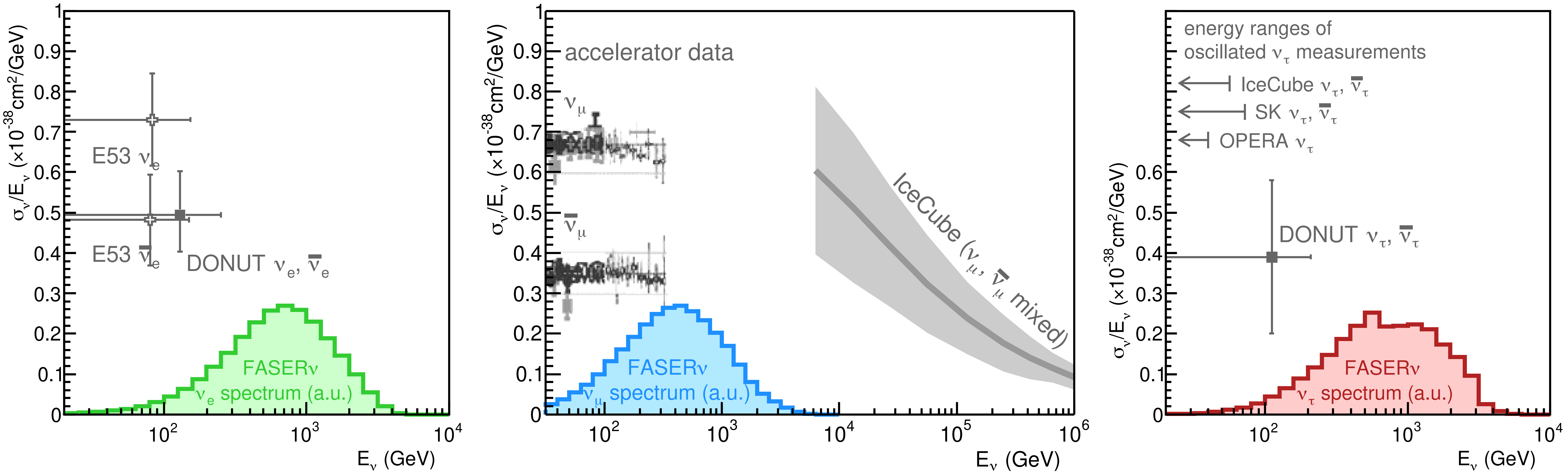
- A huge number of neutrinos produced in the LHC collisions (hadron decay) traverse the FASER location covering an unexplored neutrino energy regime.
- FASERν is a emulsion/tungsten detector to be placed in front of the main FASER detector to detect neutrinos of all flavours.



150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERν 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERν (1.2tn Tungsten)	~1300	~20000	~20

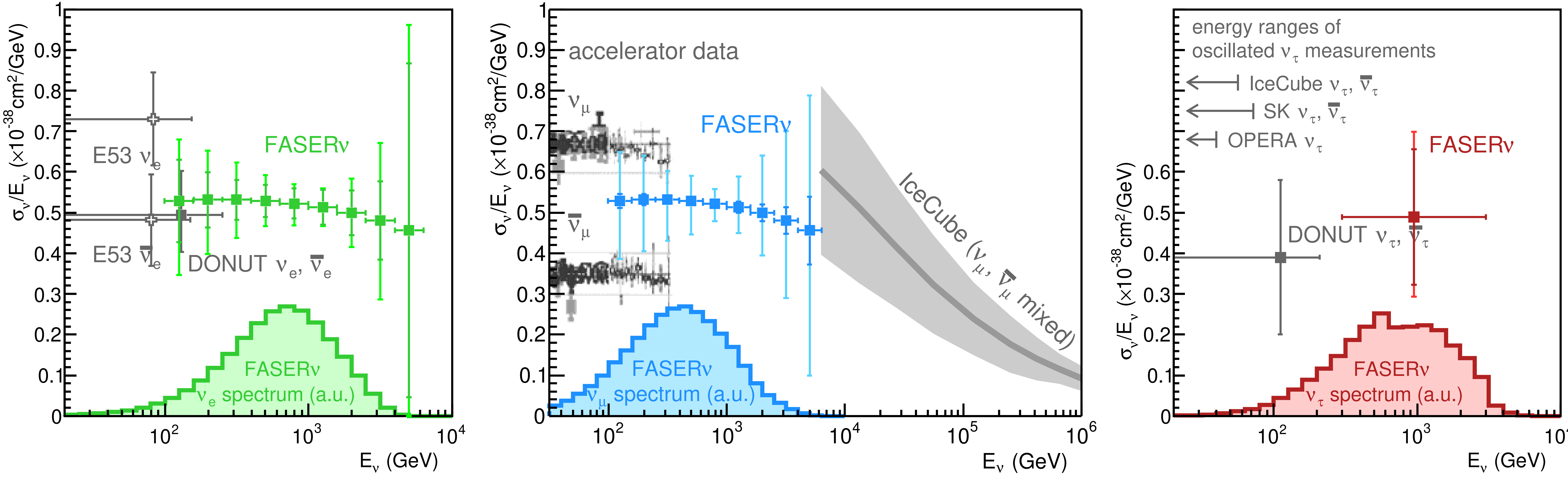


- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments:



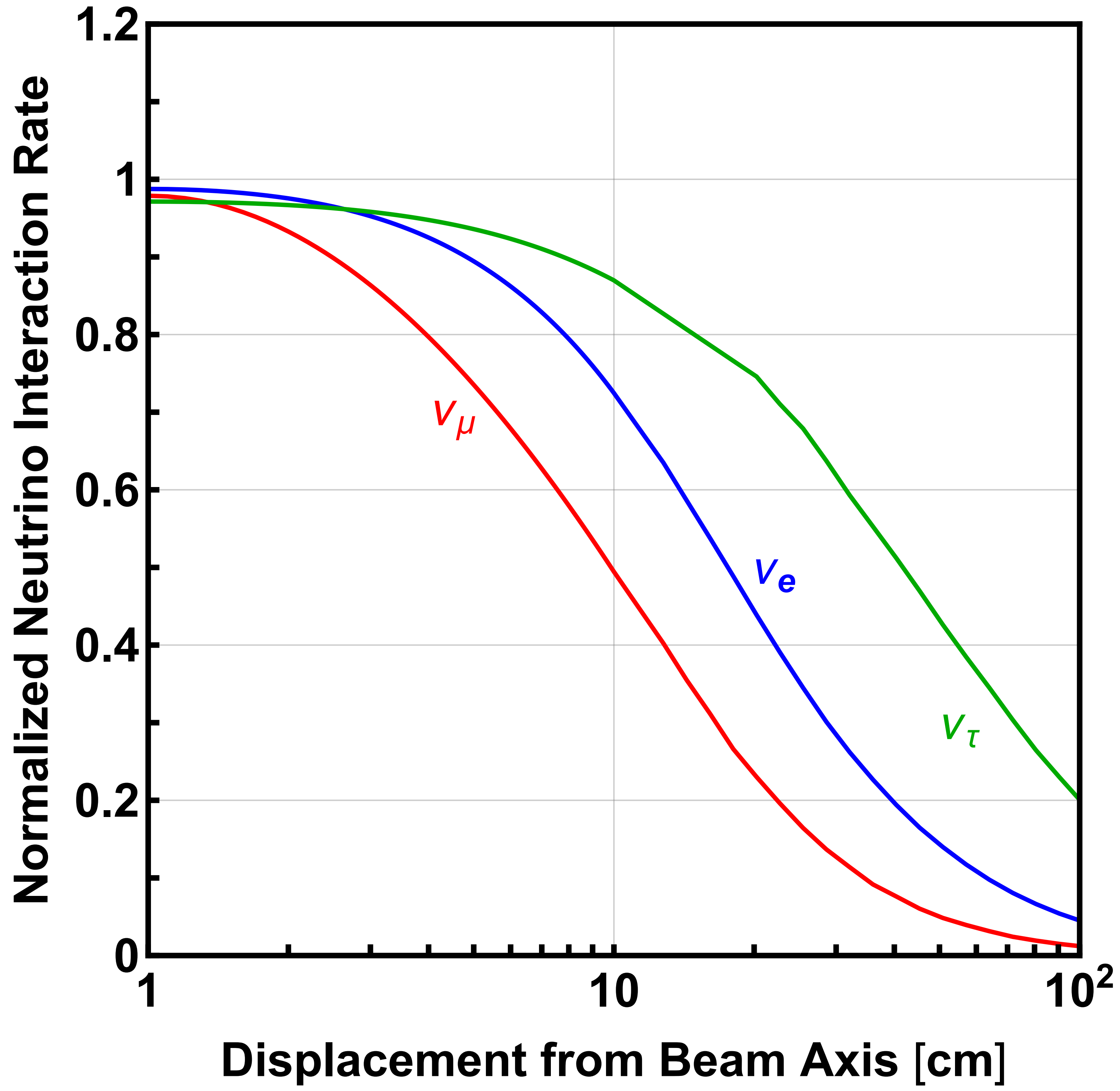
FASERν | Physics case

- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb^{-1}):
  - Uncertainty from neutrino production important. E_ν reco resolution ~30% (sim).



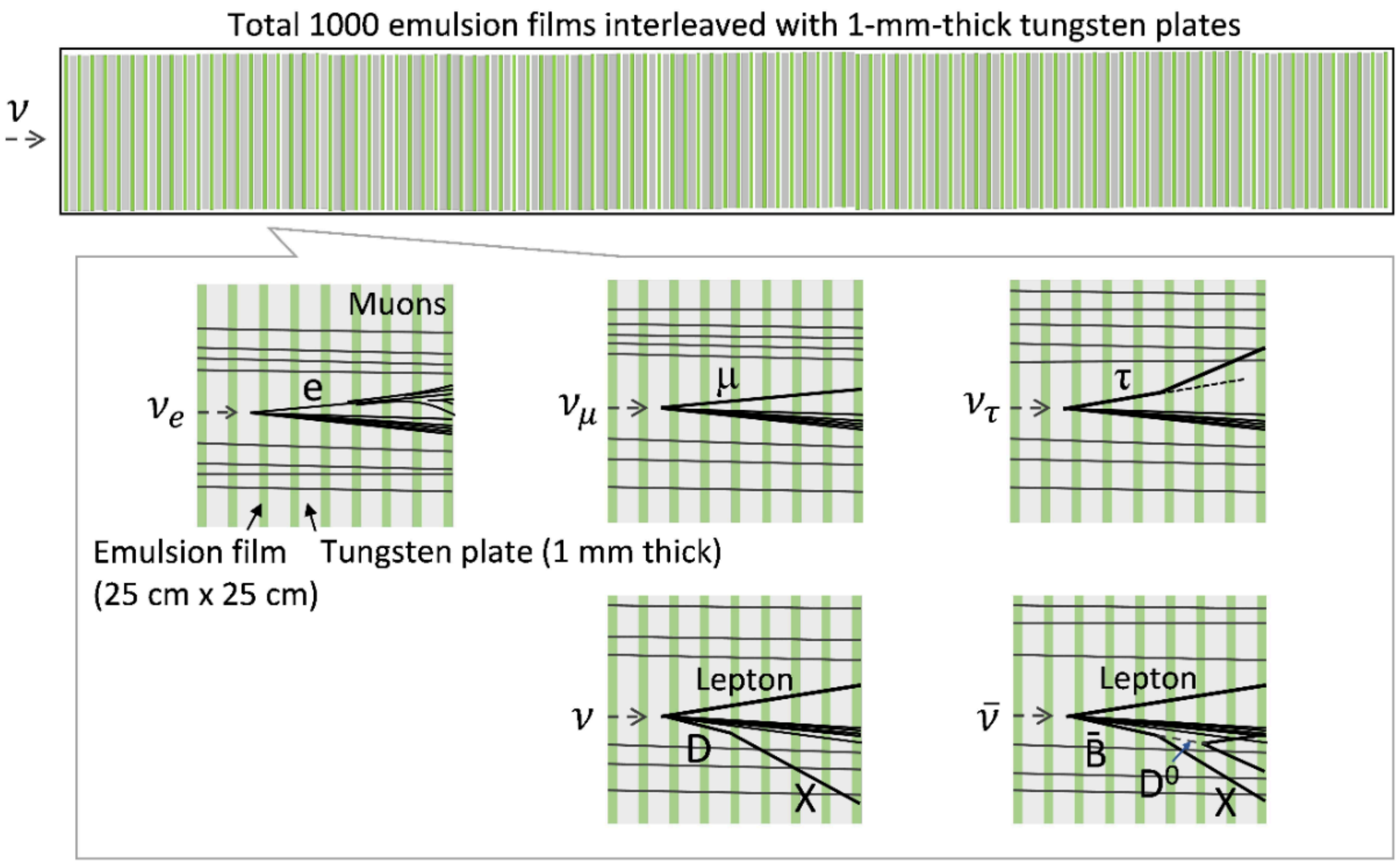
FASERν | Physics case

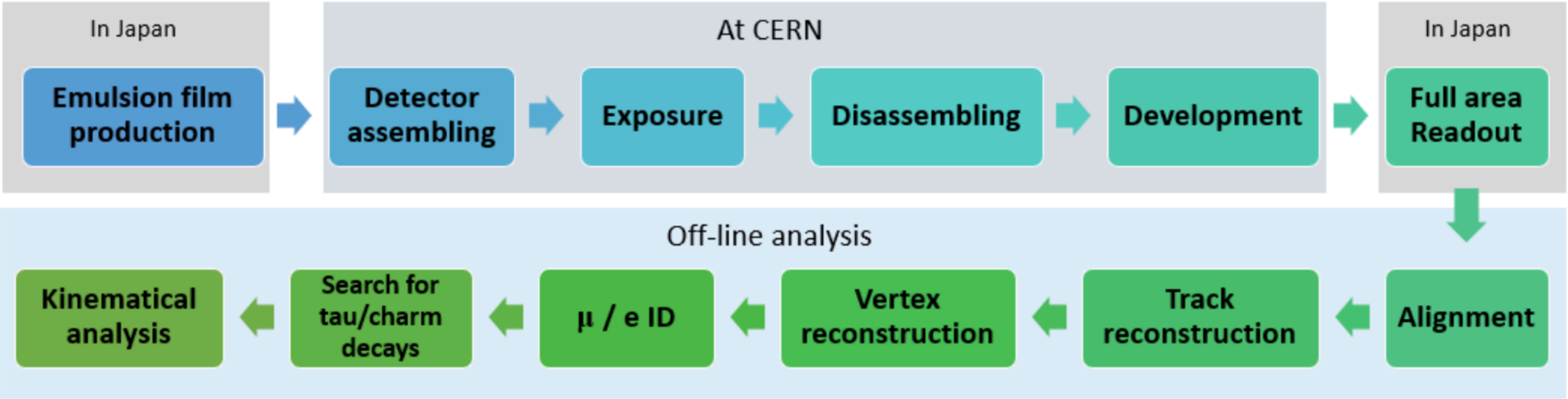
- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb^{-1})
- Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:



FASERν | Detector design

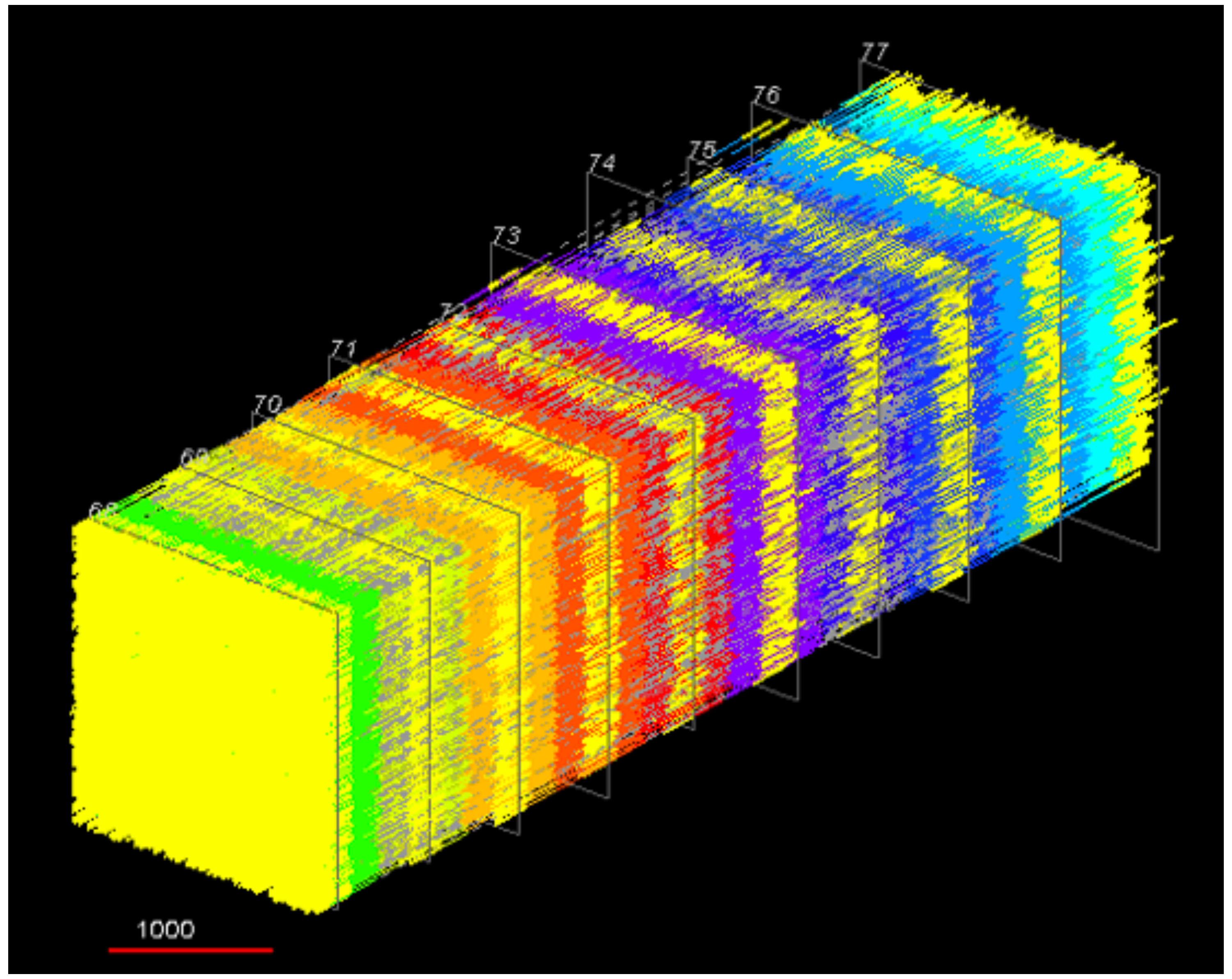
- Emulsion detector with tungsten target
  - 1000 1mm thick tungsten plates interleaved with emulsion film
    - Well understood neutrino detector technology
  - Replace every 20-50 fb^{-1} to maintain track density low
- Challenges:
  - Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
    - Benefit from transport infrastructure installed in UJ12 and TI12 to install FASER detector
  - Procedure well developed for production and offline analysis:

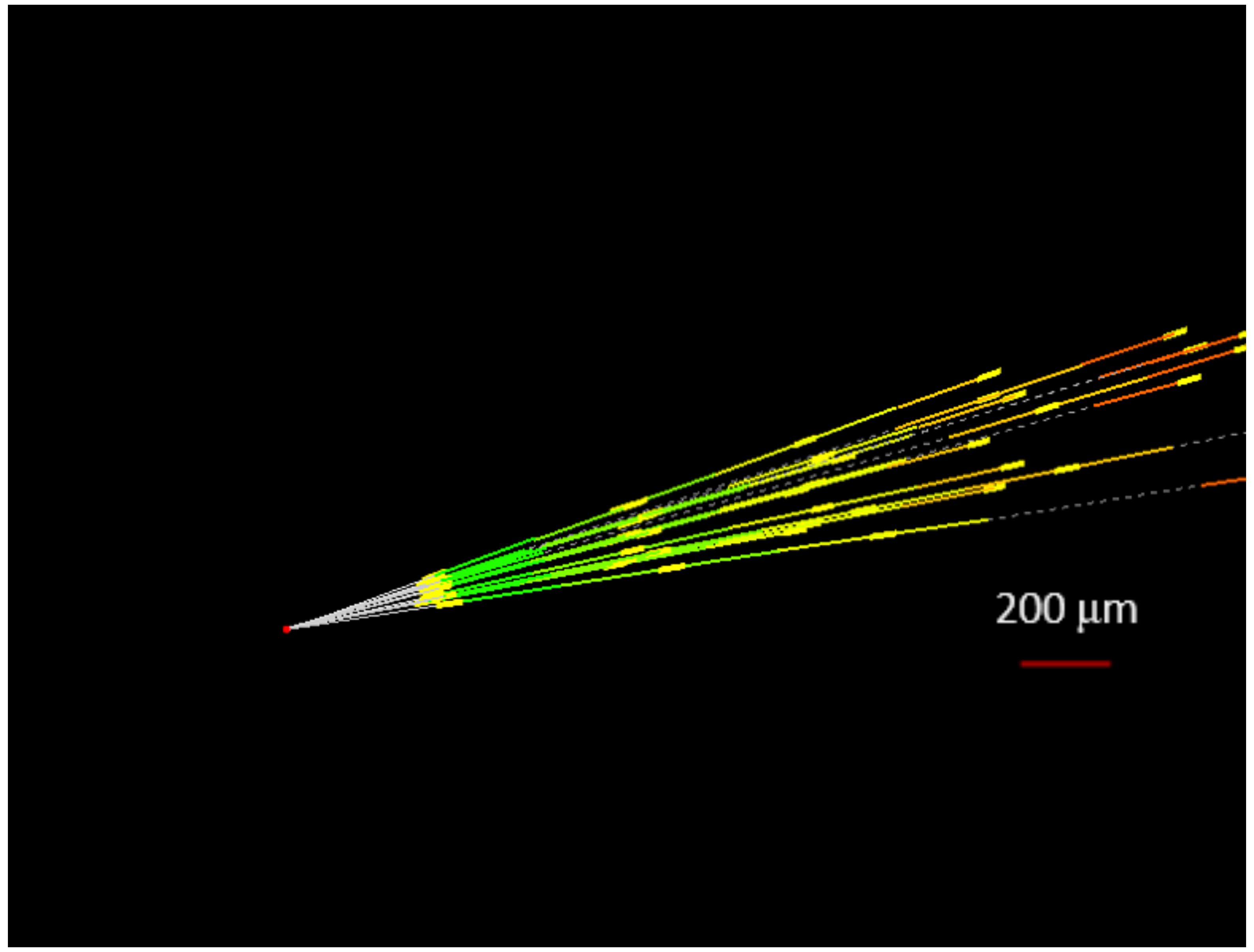




FASERν | Pilot neutrino detector

- A 30 kg detector was installed in TI18 in 2018
- 12.5 fb^{-1} of data was collected
  - ~30 neutrino interactions in the detector expected to have occurred
- Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
  - Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons





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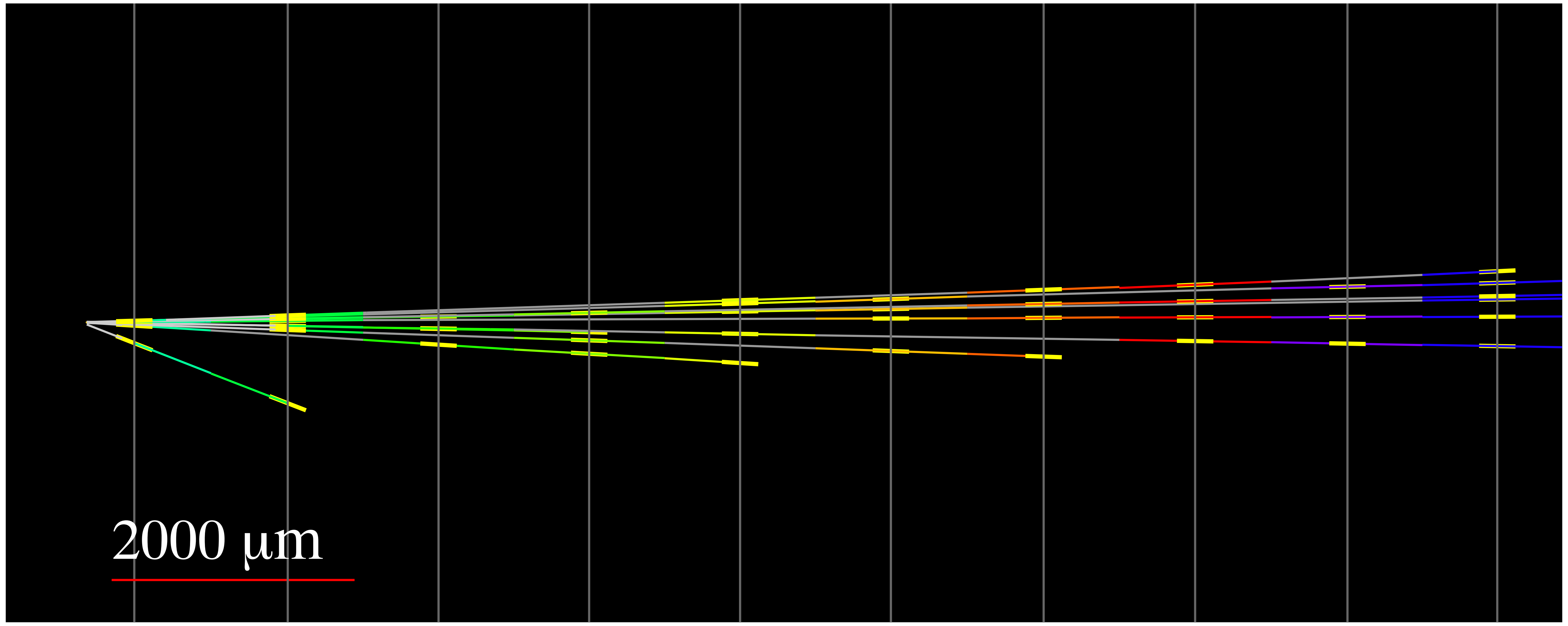

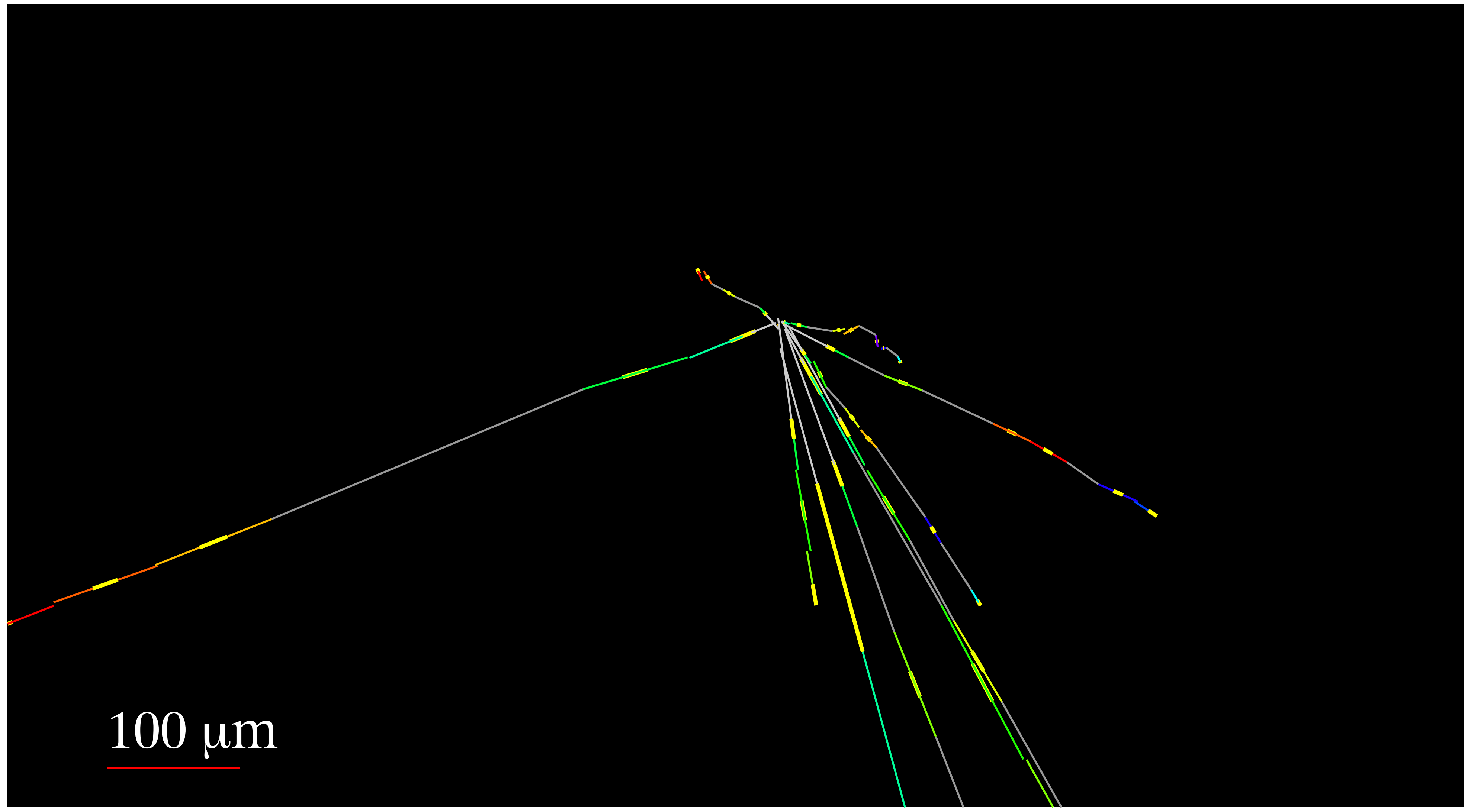

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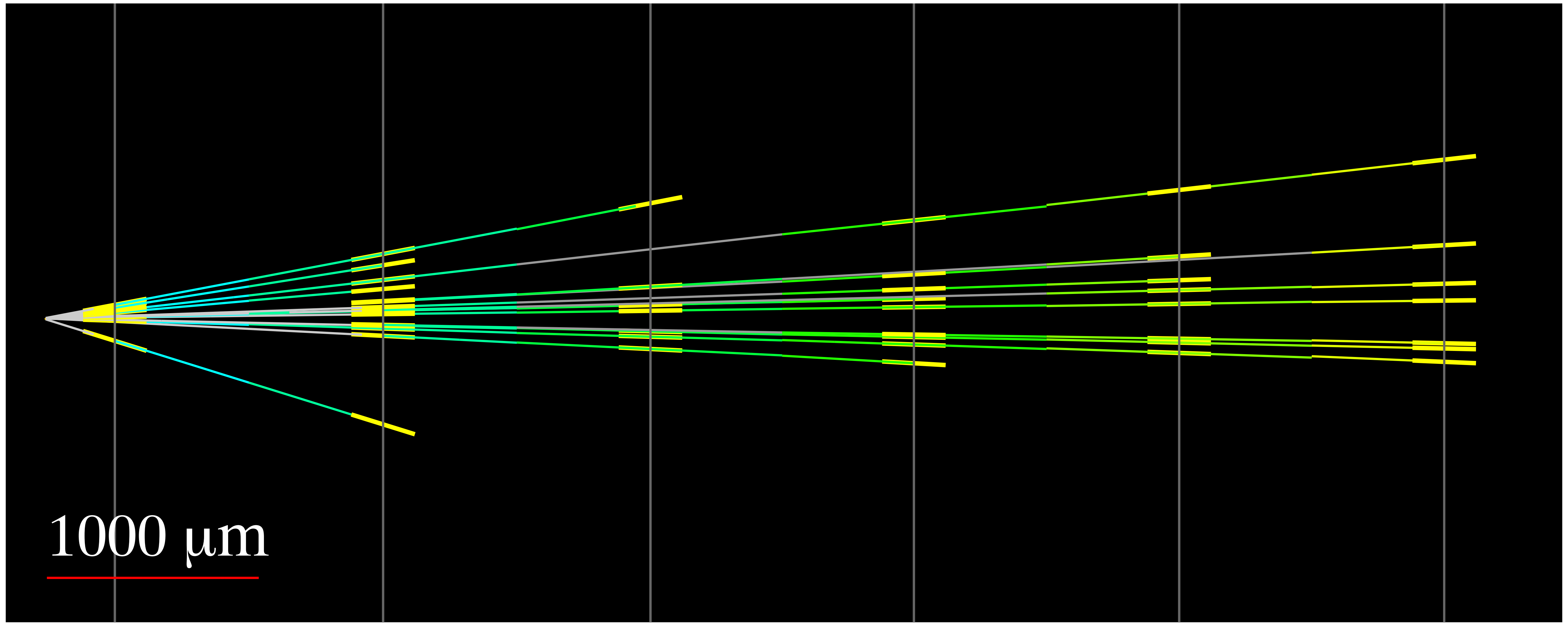

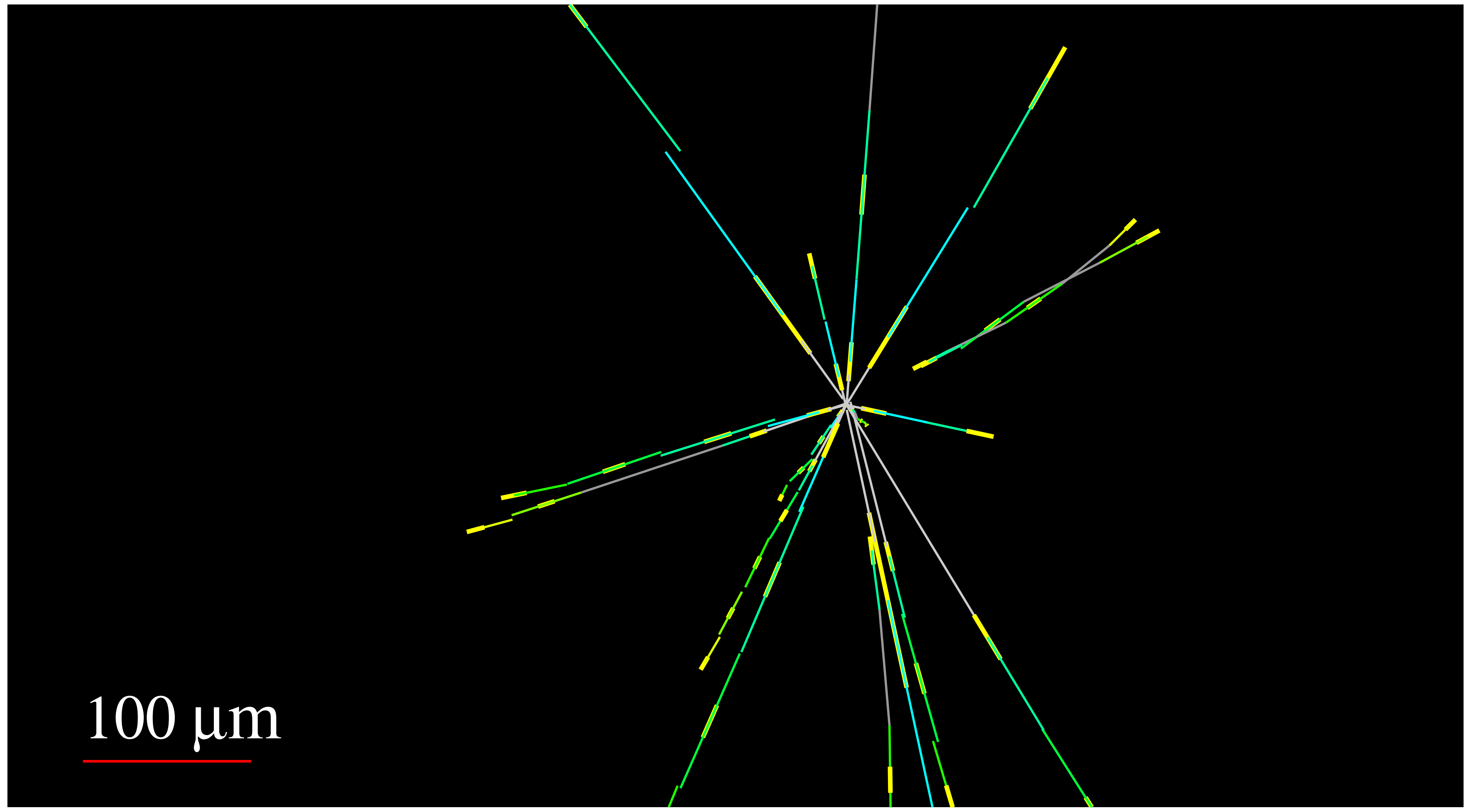

FASERν | Pilot neutrino detector

UNIVERSITY OF SUSSEX

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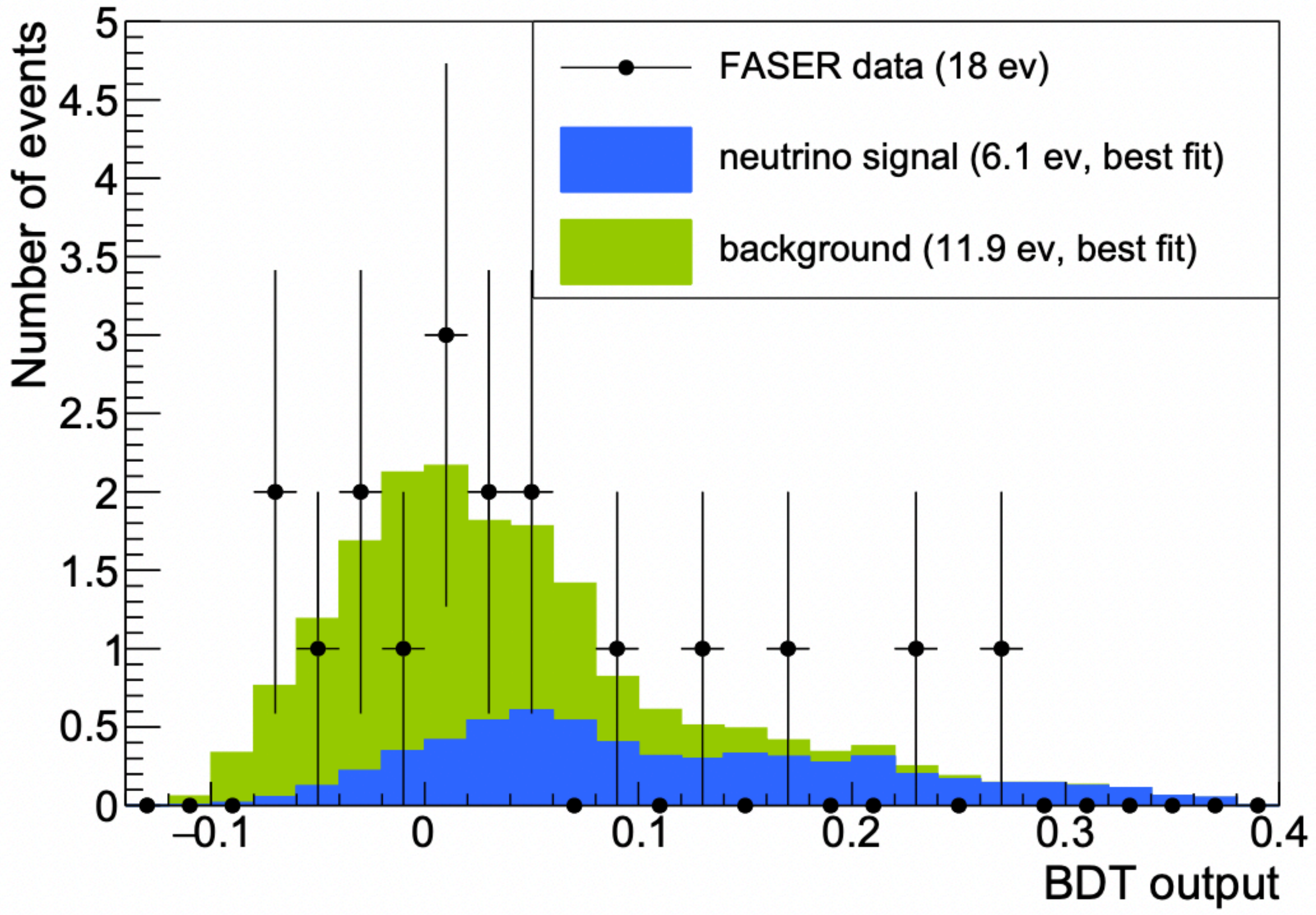
  - Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons

- Paper now out! arXiv:2105.06197
  - BDT developed to distinguish neutrino signal from neutral hadron background in the neutral vertex sample.
  - The background-only hypothesis is rejected with significance of 2.7σ.

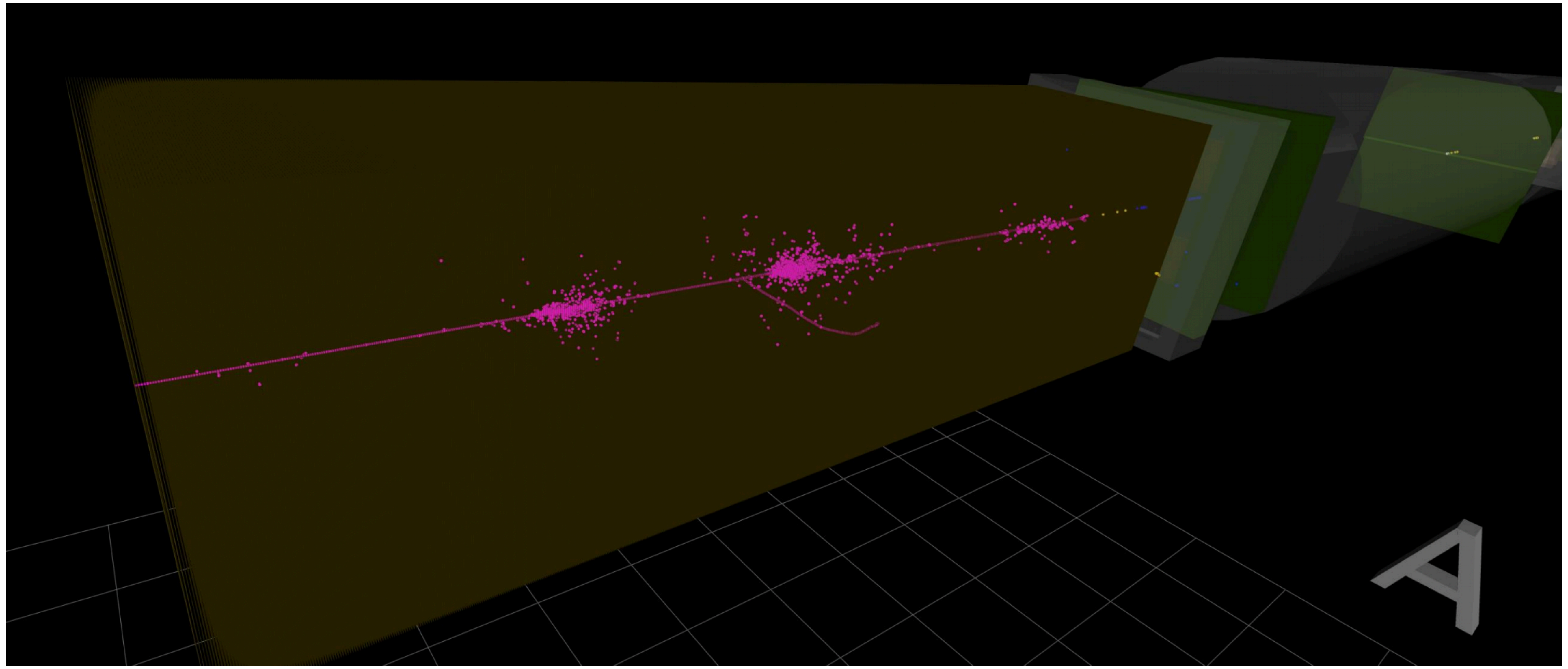


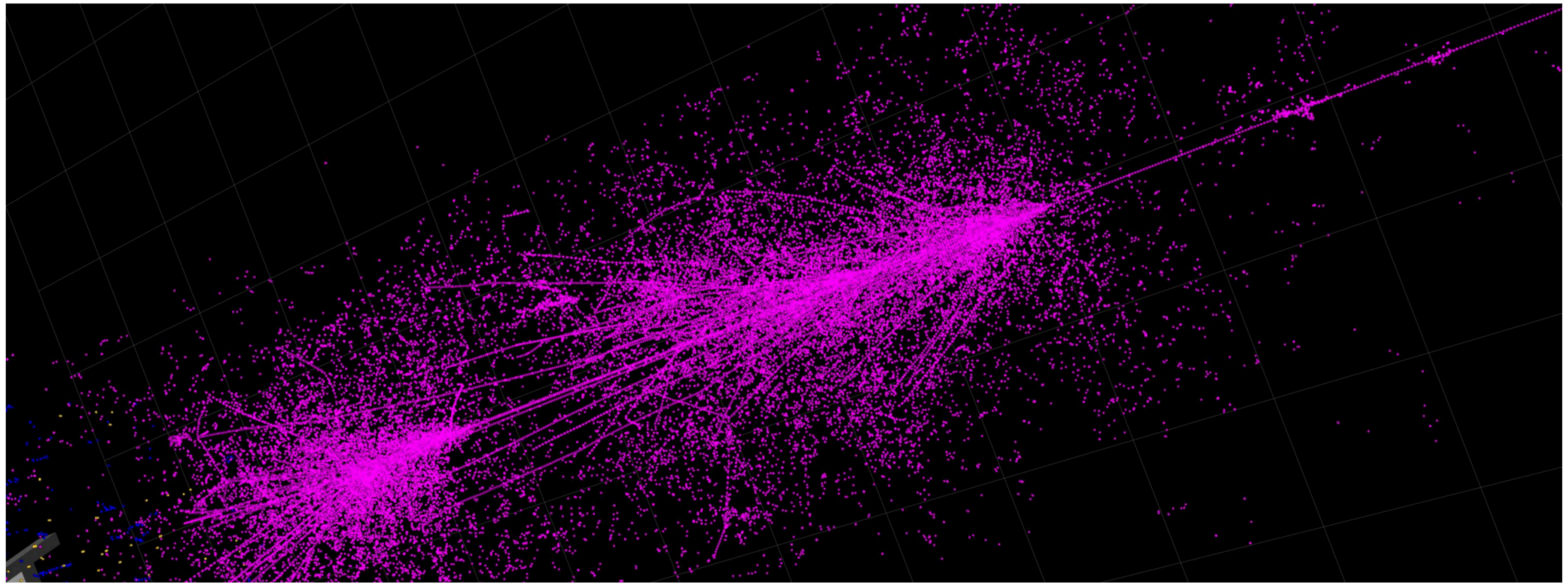
FASERν | Construction

UNIVERSITY OF SUSSEX

FASERν | Offline software

- FASERν geometry and event data model being incorporated into the FASER offline software.
  - First G4 simulations now coming.

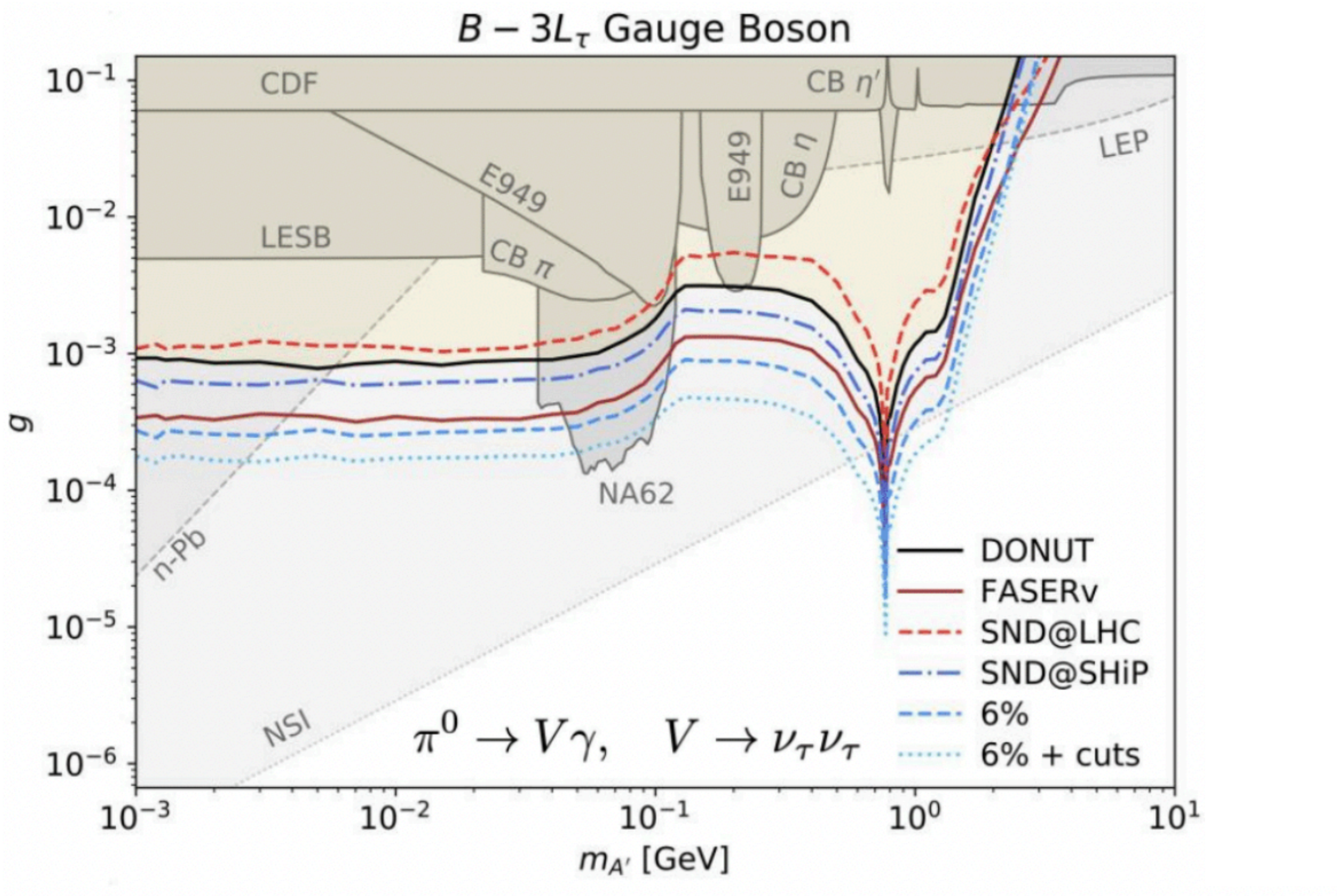


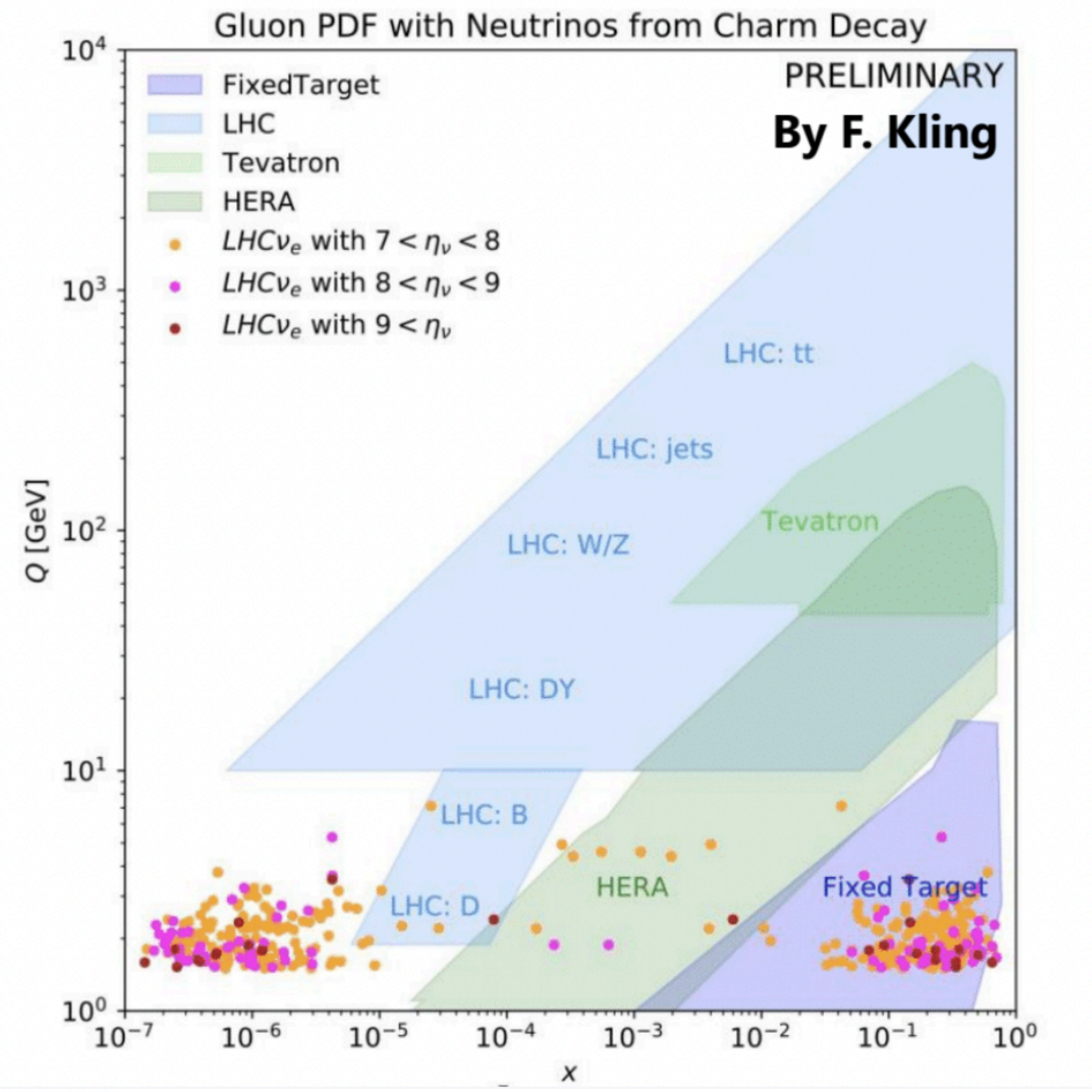


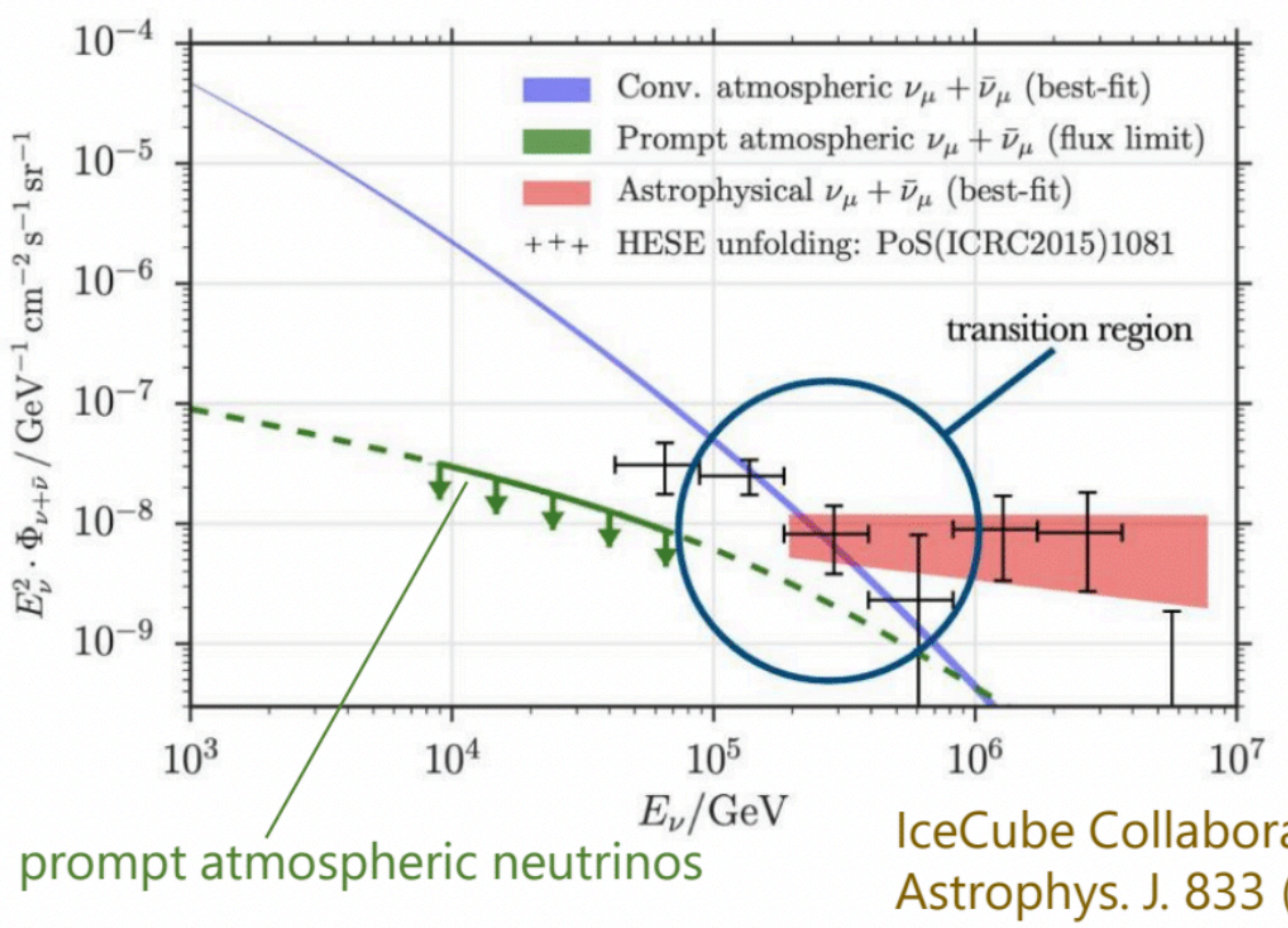
FASERν | Rich neutrino physics program

UNIVERSITY OF SUSSEX

- BSM physics
  - New light weakly coupled gauge boson (→ν_τ) could enhance ν_τ flux.
  - Sterile neutrinos with mass ~40 eV can cause oscillations at FASER
- QCD
  - FASER's neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
  - Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm
- Cosmic rays and neutrinos
  - IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
  - Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes







IceCube Collaboration, Astrophys. J. 833 (2016)

Future

Forward Physics Facility

- FASER, FASERν, and other proposed detectors are currently highly **constrained by tunnels and infrastructure** that was never designed to support experiments.

- At the same time, it is becoming clear that there is a **rich physics program in the far-forward region**, spanning long-lived particle searches, neutrinos, QCD, dark matter, dark sector, cosmic rays, and cosmic neutrinos.

- Strongly **motivates investigating** creation of a dedicated facility to house several far-forward experiments.

Forward Physics Facility

- One of 1578 Snowmass LOIs

- FPF LOI had 240 authors with interest from many communities.
- FPF workshops now on a regular basis.

Thematic Areas

- (EF05) QCD and Strong Interactions: Precision QCD
- (EF06) QCD and Strong Interactions: Hadronic Structure and Forward QCD
- (EF09) BSM: More General Explorations
- (EF10) BSM: Dark Matter at Colliders
- (NF03) BSM
- (NF06) Neutrino Interaction Cross Sections
- (NF10) Neutrino Detectors
- (RF06) Dark Sector Studies at High Intensities
- (CF07) Cosmic Probes of Fundamental Physics
- (AF05) Accelerators for PBC and Rare Processes
- (UF01) Underground Facilities for Neutrinos
- (UF02) Underground Facilities for Cosmic Frontier

Snowmass 2021 Letter of Interest

Forward Physics Facility

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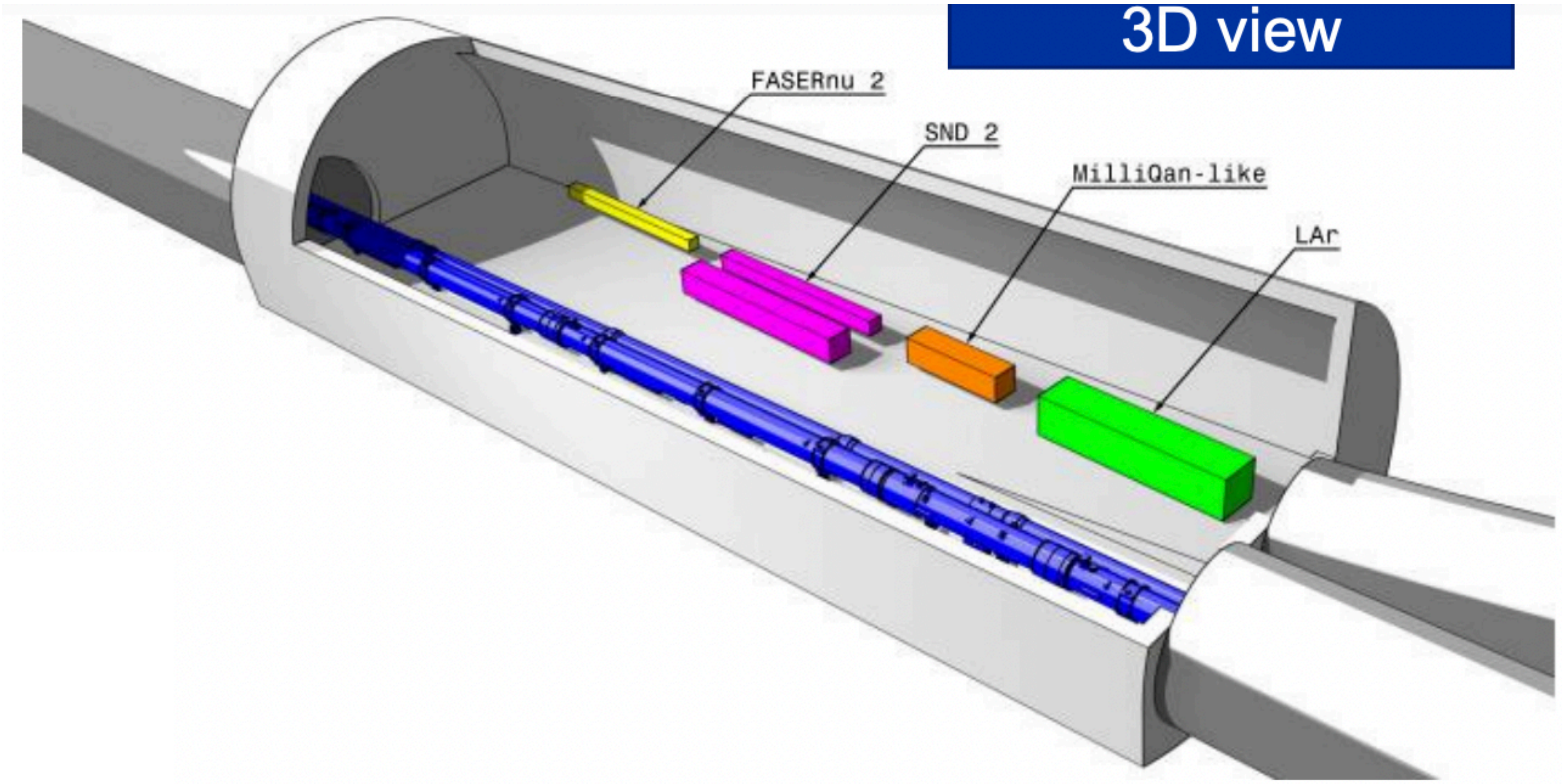
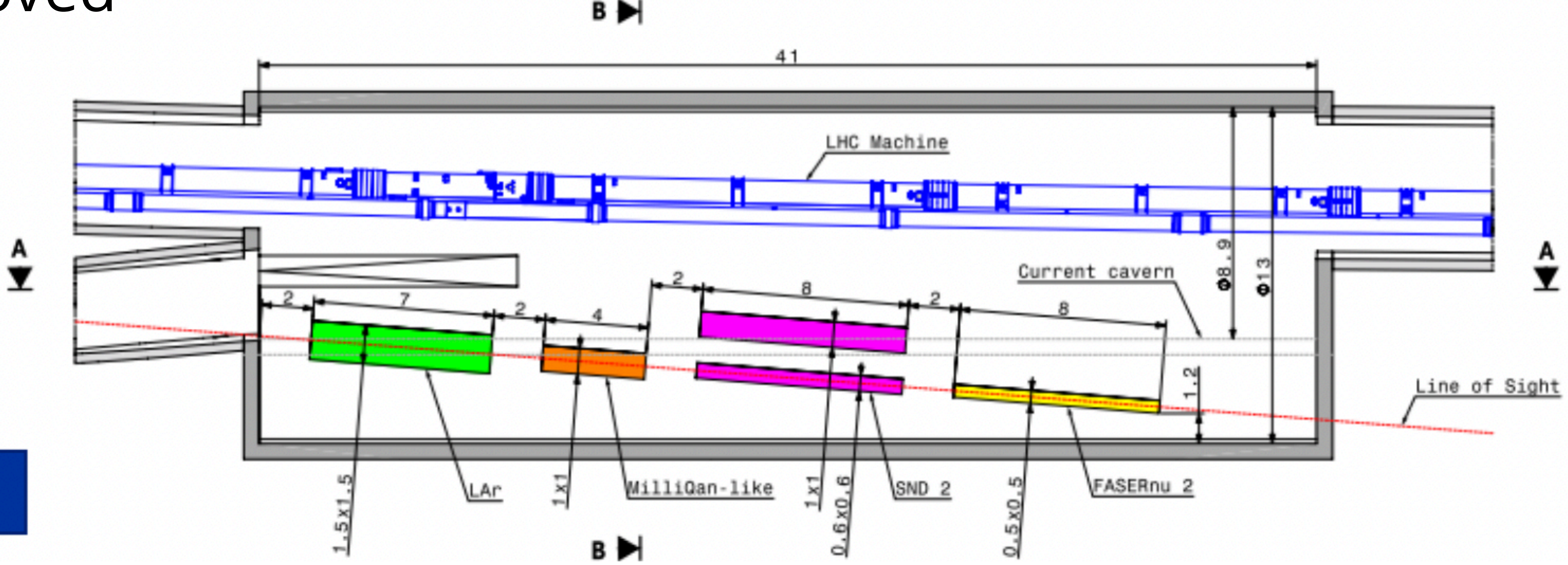
Forward Physics Facility

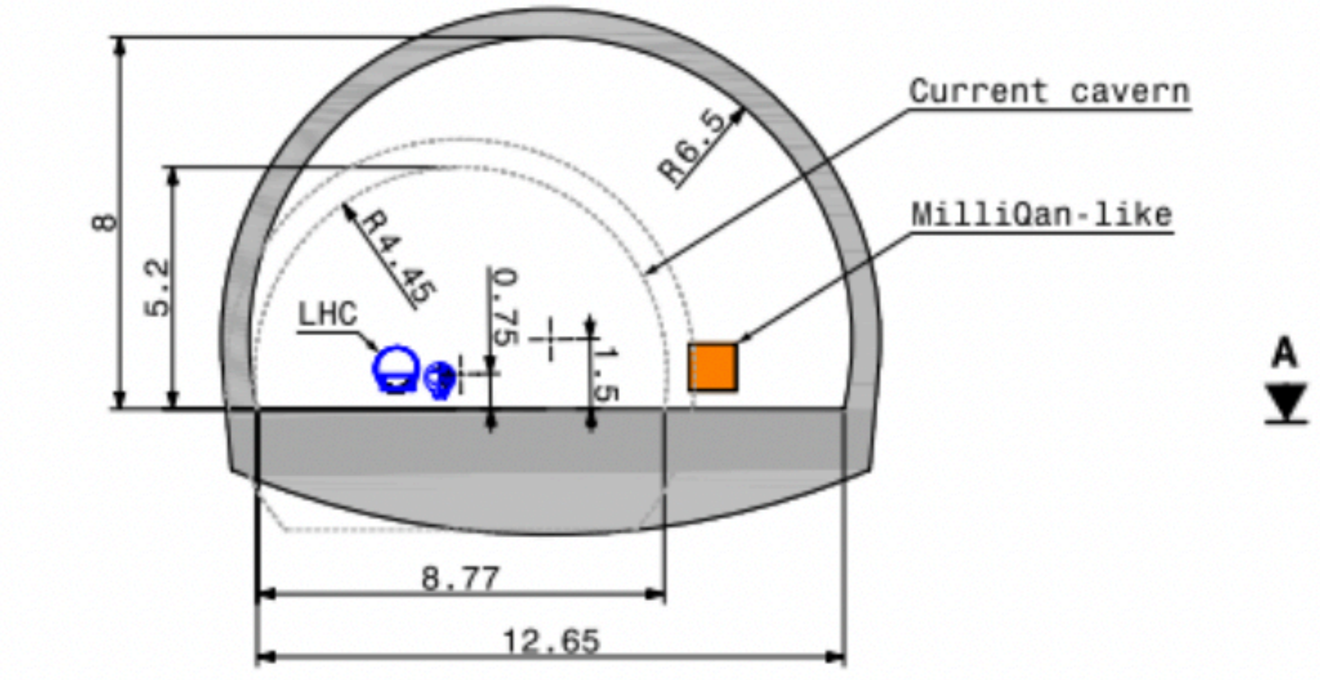
- **Scenario 1: Widening UJ12**
  - Advantages
    - More flexible space along LoS
    - Closer to IP1
  - Disadvantages
    - Major disruption to LHC machine
    - Difficult access for construction
    - All existing services in UJ12 need to be removed

3D view



Plan view showing widening required

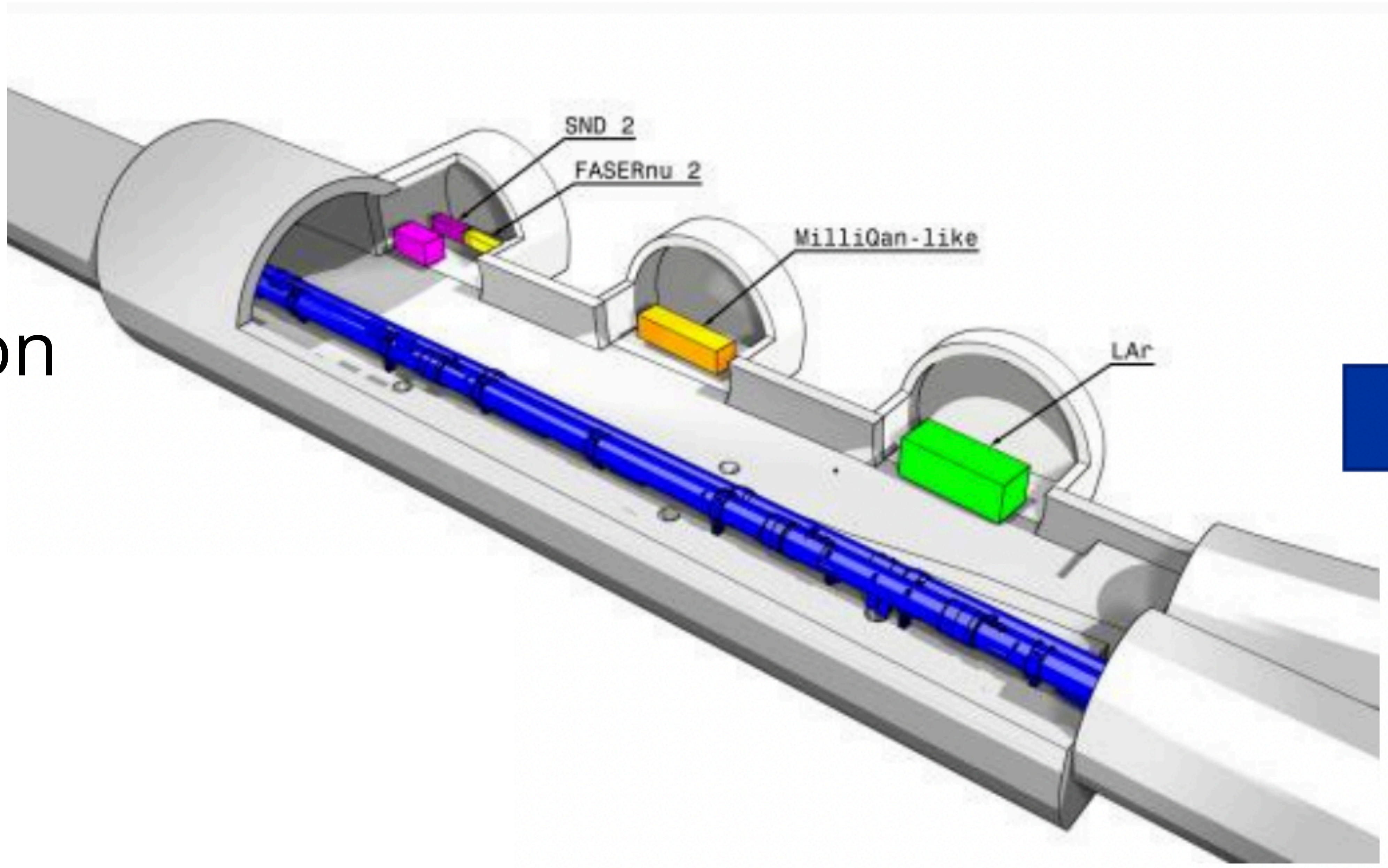




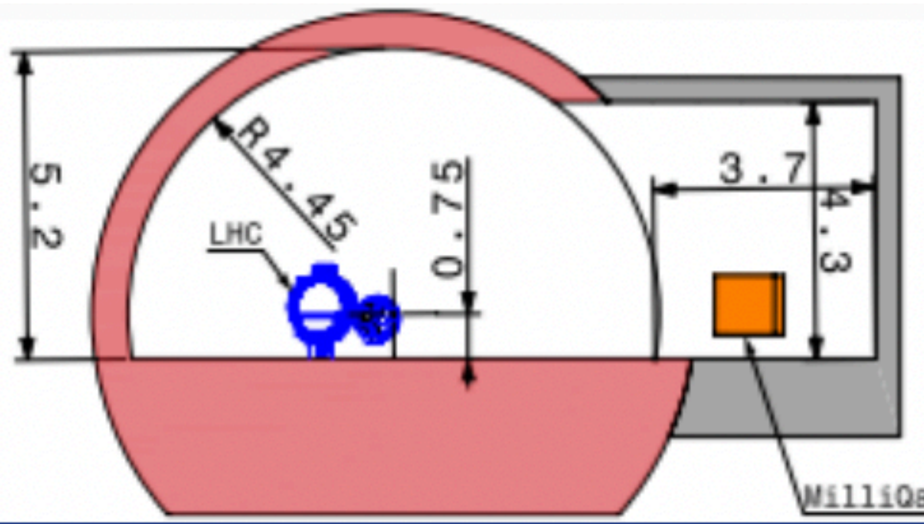
Cross Section at B-B

Forward Physics Facility

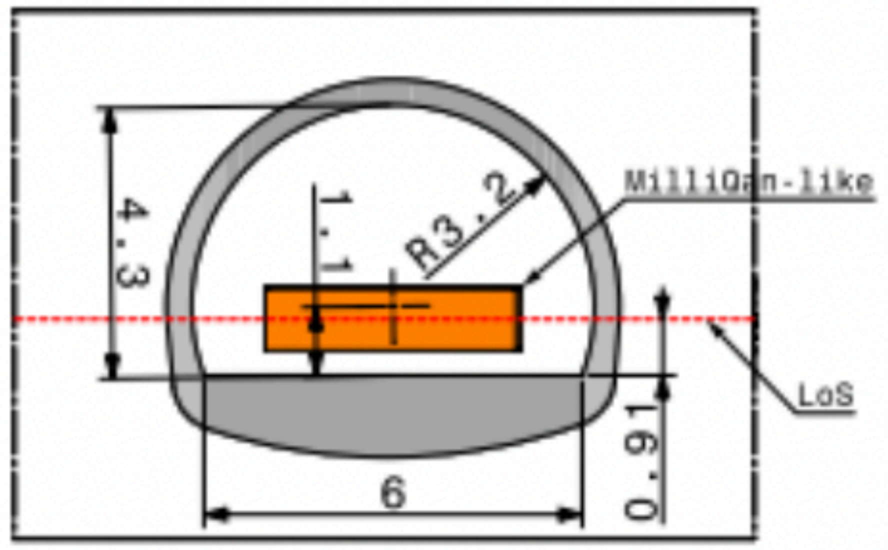
- **Scenario 2: Alcoves**
  - Advantages
    - Lowest cost and disruption
  - Disadvantages
    - Experiments need to be designed around what is possible
    - Likely only 2-3 alcoves possible around 3mØ
    - Stability of existing cavern
    - All existing services in UJ12 need to be removed



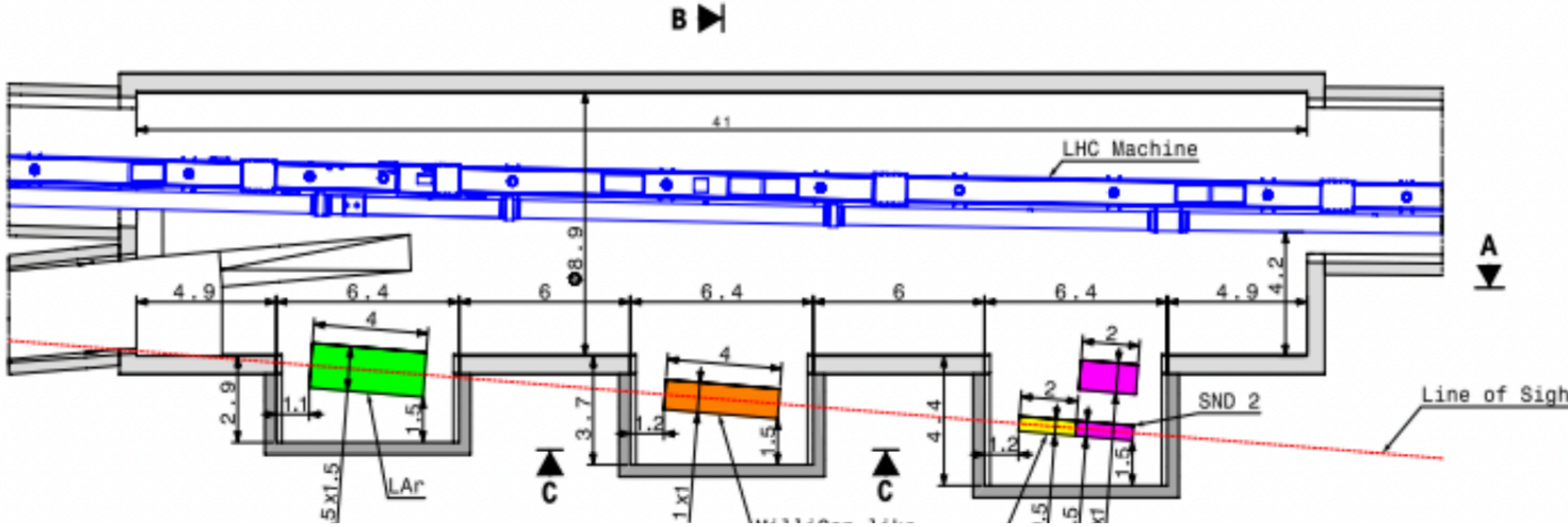
3D view



Alcove Cross Section at B-B



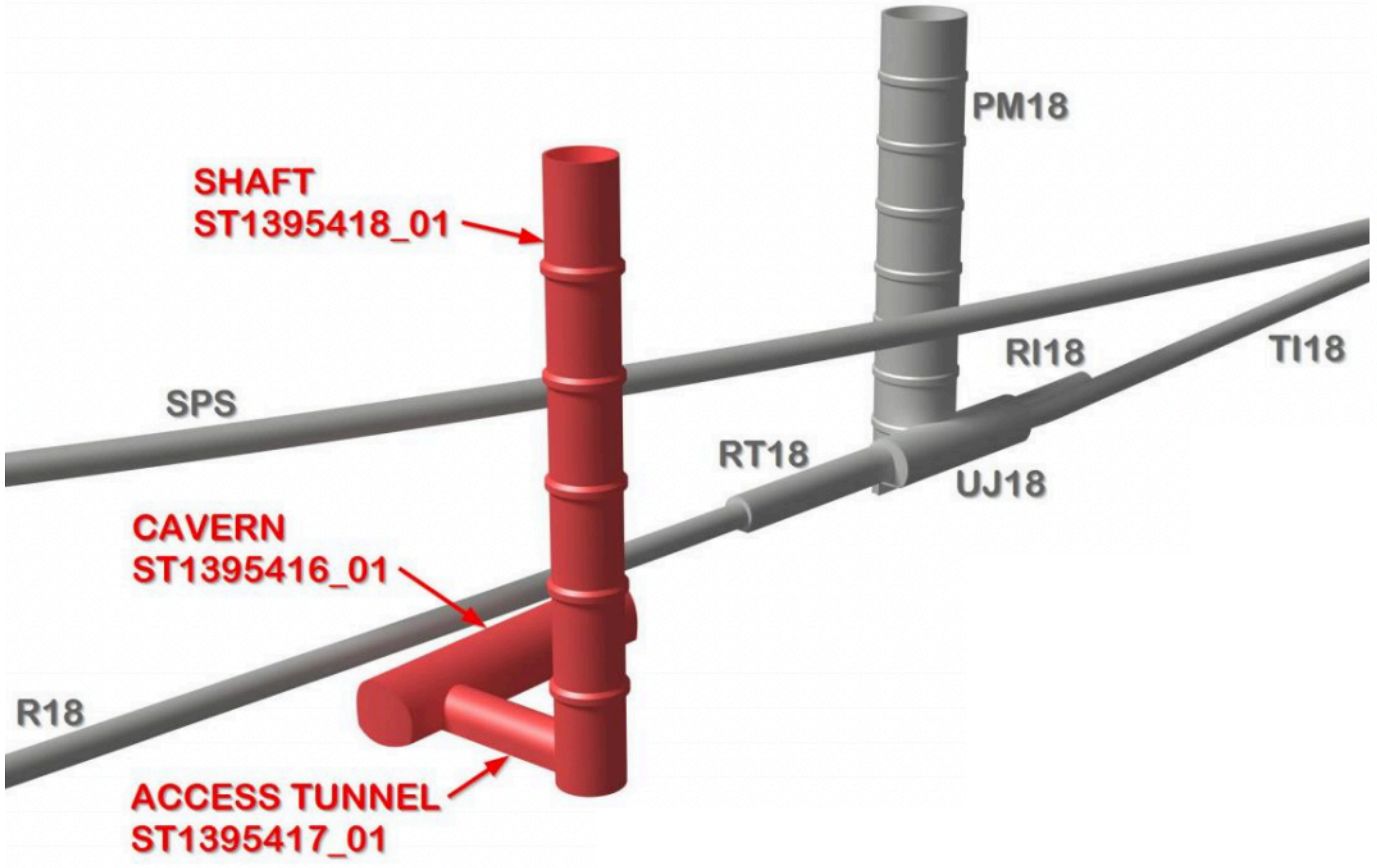
Typical Alcove Cross Section C-C



Typical Alcove Cross Section C-C

Scenario 3: Dedicated new cavern

- Advantages
  - Designed around needs of experiments
  - Construction access far easier
  - Access possible during LHC operation
  - Size/ length not constrained
- Disadvantages
  - More expensive
  - Construction needs to be coordinated with LHC shutdowns
  - Slightly further from IP



Forward Physics Facility

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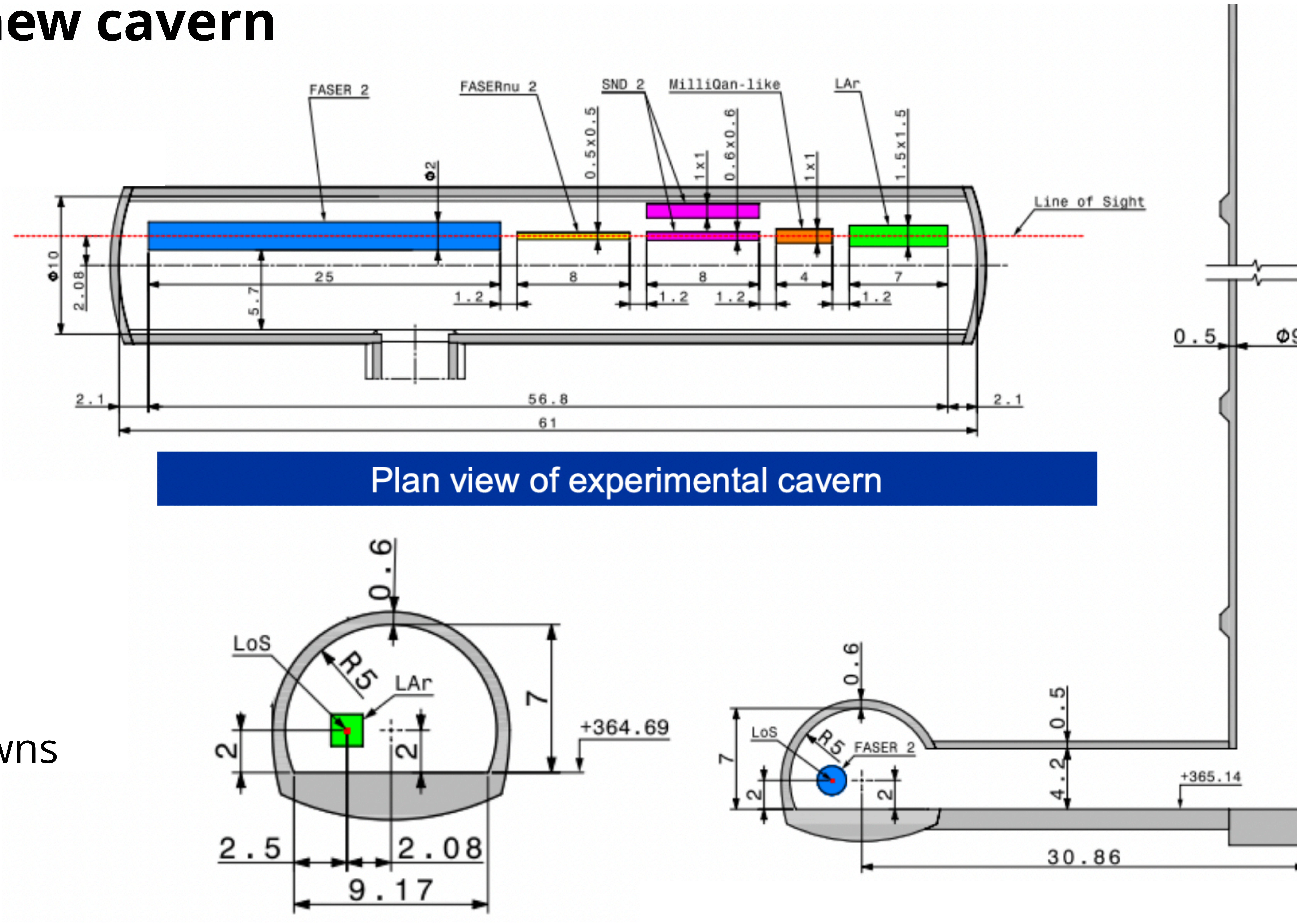


FASER2

- FASER2 (R = 1 m, L = 5-20 m) can discover:
  - All candidates with renormalizable couplings (dark photon, dark Higgs, HNL)
  - ALPs with all types of couplings (ɣ, f, g)
  - and many other particles.
- Among the PBC benchmark scenarios, FASER2's discovery potential extends to all benchmark scenarios
  - Except BC2 and BC3 which can be targeted by other dedicated FPF experiments.

Benchmark Model	FASER	FASER 2
BC1: Dark Photon	√	√
BC1': $U(1)_{B-L}$ Gauge Boson	√	√
BC2: Invisible Dark Photon	–	–
BC3: Milli-Charged Particle	–	–
BC4: Dark Higgs Boson	–	√
BC5: Dark Higgs with hSS	–	√
BC6: HNL with e	–	√
BC7: HNL with μ	–	√
BC8: HNL with τ	√	√
BC9: ALP with photon	√	√
BC10: ALP with fermion	√	√
BC11: ALP with gluon	√	√

FASER2

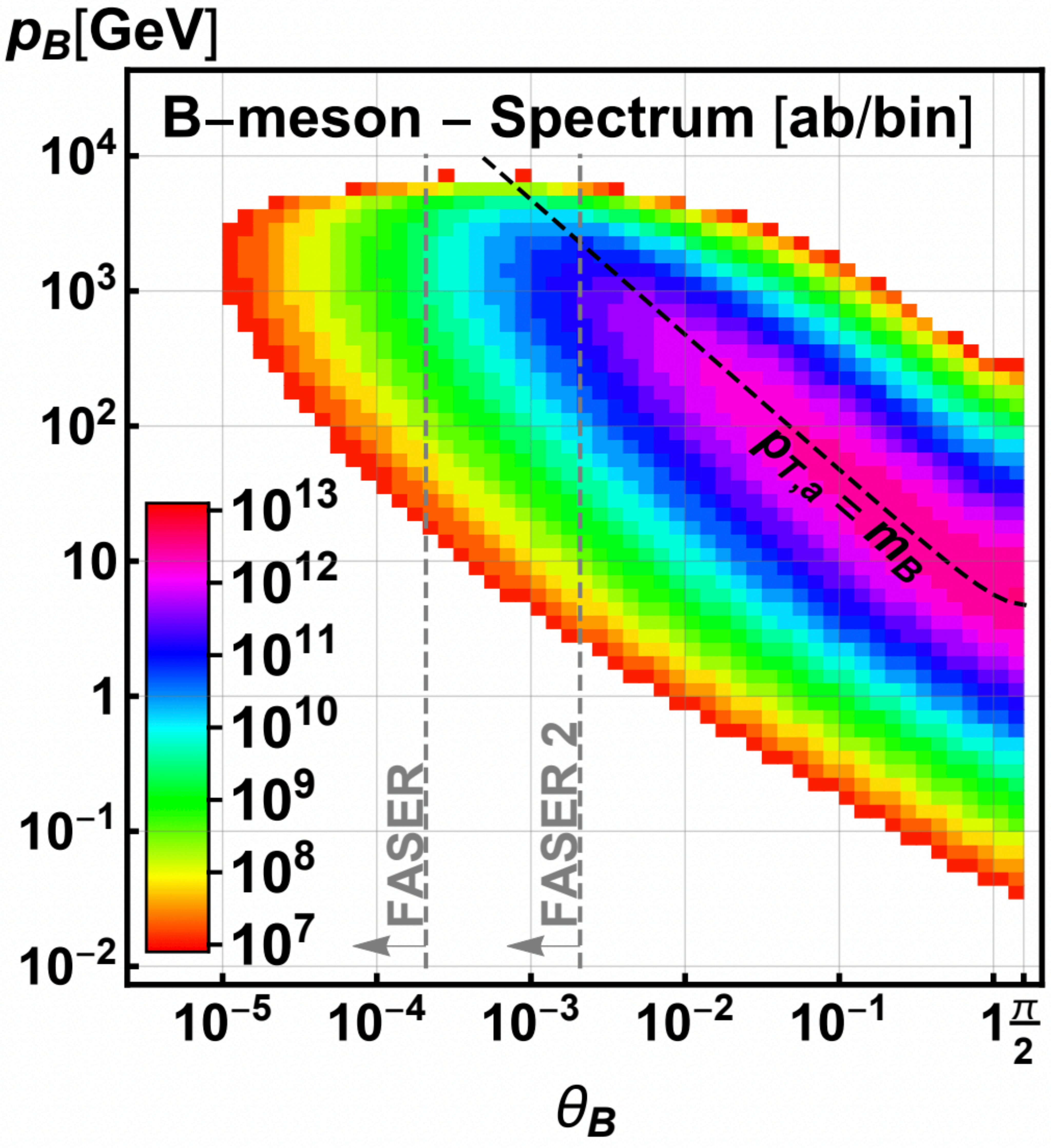
- Due to short timescale for FASER installation - that has been the focus.
  - Have not thought about the design of the FASER 2 detector in detail.
  - Not possible to just scale up the current detector to r=1m
    - for a number of reasons (magnet, SCT modules etc..)

	Radius [cm]	Decay volume length [m]	Integrated luminosity [fb-1]	Timescale
FASER 1	10	1.5	150	LHC Run3 2021-2023
FASER 2	100	5.0	3000	HL-LHC 2026-2035

Benchmark Model	FASER	FASER 2
BC1: Dark Photon	√	√
BC1': $U(1)_{B-L}$ Gauge Boson	√	√
BC2: Invisible Dark Photon	–	–
BC3: Milli-Charged Particle	–	–
BC4: Dark Higgs Boson	–	√
BC5: Dark Higgs with hSS	–	√
BC6: HNL with e	–	√
BC7: HNL with μ	–	√
BC8: HNL with τ	√	√
BC9: ALP with photon	√	√
BC10: ALP with fermion	√	√
BC11: ALP with gluon	√	√

FASER2

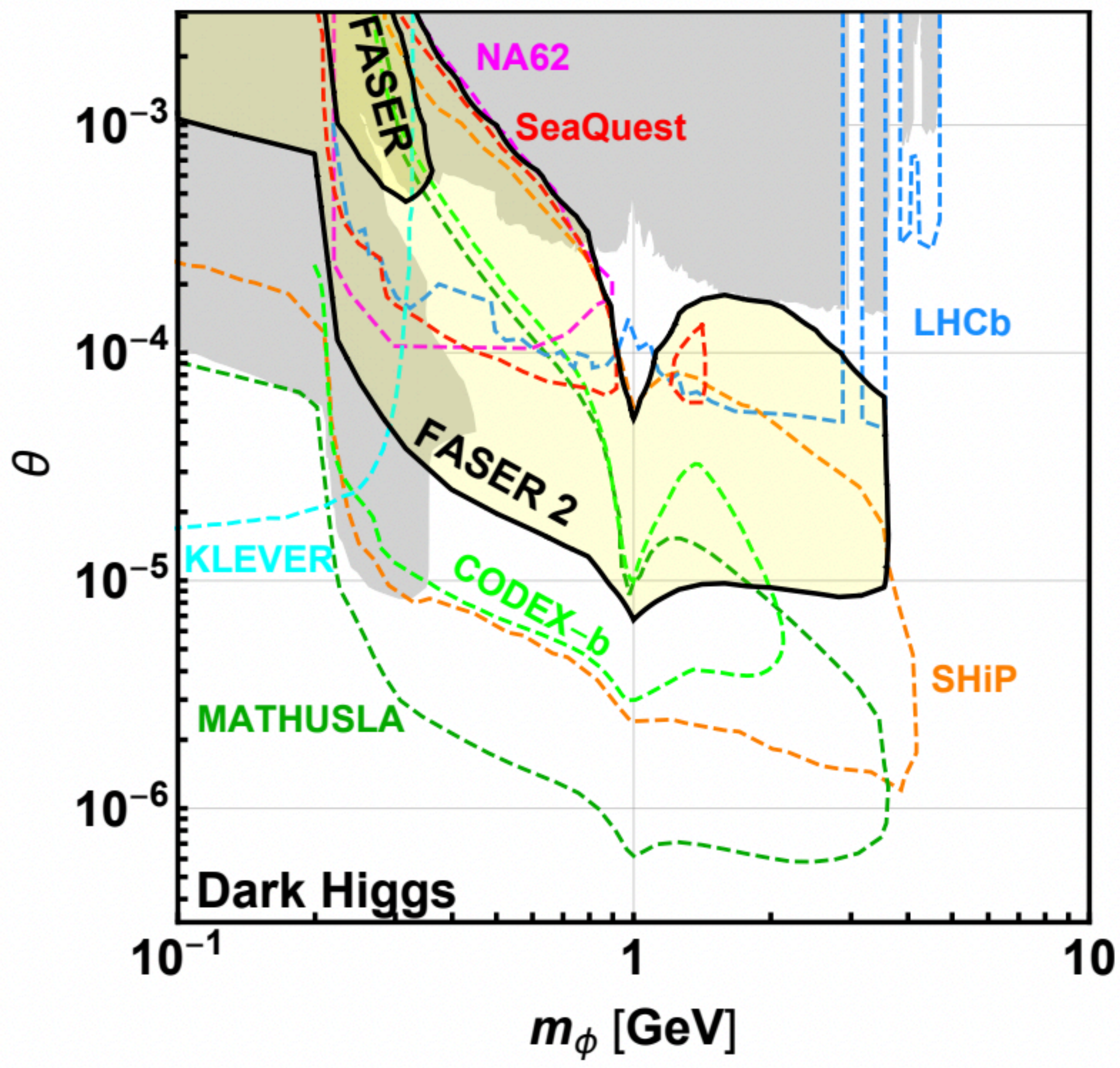
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.



FASER2

- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.

- FASER2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
  - $N_B/N_\pi \sim 10^{-2}$ ($\sim 10^{-7}$ at beam dump expts)



Summary

Summary

- FASER is a new experiment at the LHC complementing the current physics program
- It is a small, fast & cheap experiment being installed now, to take data in Run 3
  - Targeting light, weakly-coupled new particles at low p_T
  - 18 months from theory paper to start of construction!
  - Utilising spare modules from existing experiments
  - Total detector cost <2MCHF - Host-Lab costs from CERN (civil eng., transport, services)
- Detector construction complete on schedule → commissioning ongoing
  - Data-taking in Run 3… we're looking forward to new physics!
- Neutrino physics program with addition of emulsion detectors (FASERν)
  - First measurements of neutrinos produced at a collider & in unexplored energy regime
- Potential to increase sensitivity with FASER2 upgrade for HL-LHC

Thanks for your attention! 🙏

Many thanks to the Simons Foundation, and Heising-Simons Foundation, and to CERN for invaluable support.

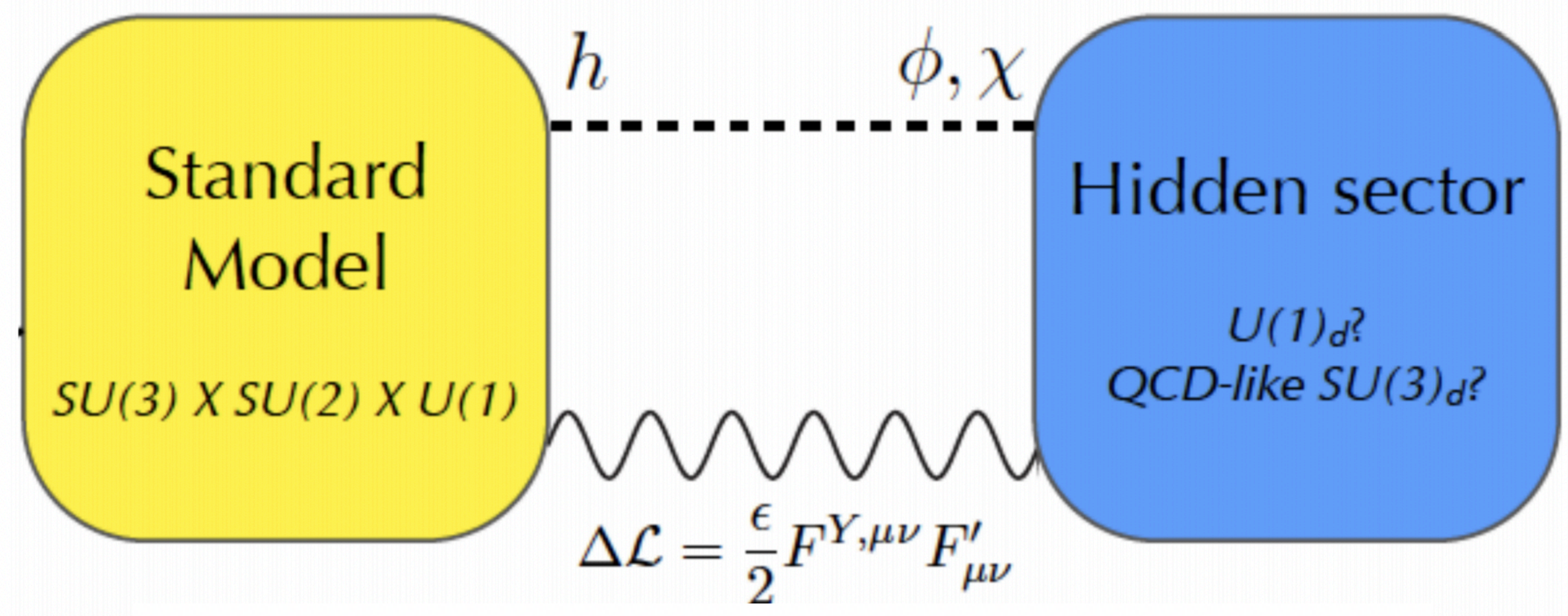
Back-ups

References

- FASER website: https://faser.web.cern.ch/
- Letter of Intent (September 2018): arXiv:1811.10243
- Technical Proposal (December 2018): arXiv:1812.09139
- LLP Physics Reach: Phys. Rev. D 99, 095011 (15 May 2019), arXiv:1811.12522
- FASER Physics Paper/Letter of Intent (August 2019): Eur. Phys. J. C 80, 61 (2020)
- FASER Technical Proposal (November 2019): CERN-LHCC-2019-017

Physics | Dark portal

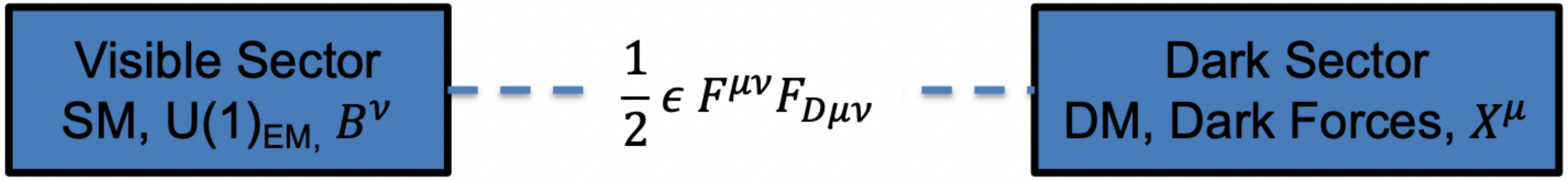
- Hidden sector physics:
  - New mediating particles, couplings to SM via mixing with SM "portal" operator
  - Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations…
  - Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)
- Typically long-lived particles (LLPs) that travel macroscopic distances before decaying to SM particles



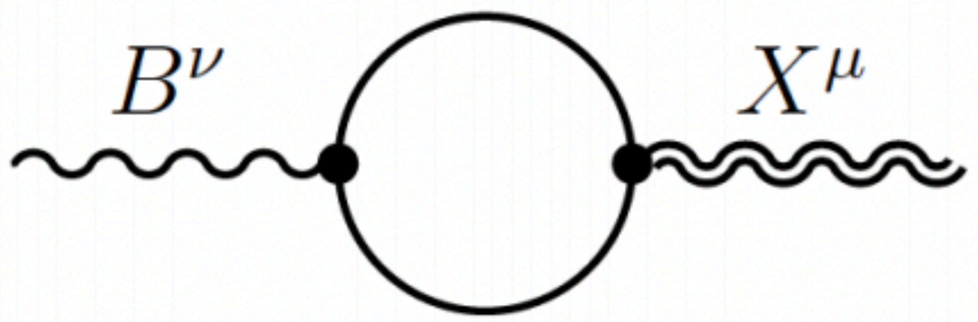
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

- If the dark photon is a portal particle, coupling arises from kinetic mixing:



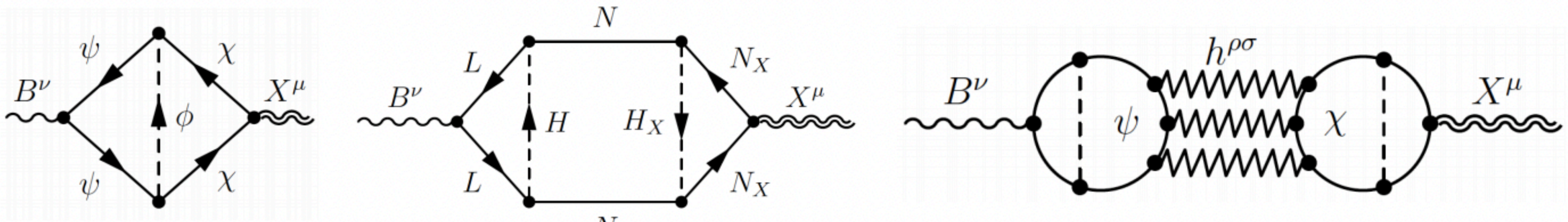
- Mixing can be generated at 1-loop. If 0 at high scale, expect $\epsilon \sim 10^{-3}$



$$\epsilon = -\frac{g' g_X}{16\pi^2}\sum_i Y_i q_i \ln\frac{M_i^2}{\mu^2}$$

Holdom (1986)

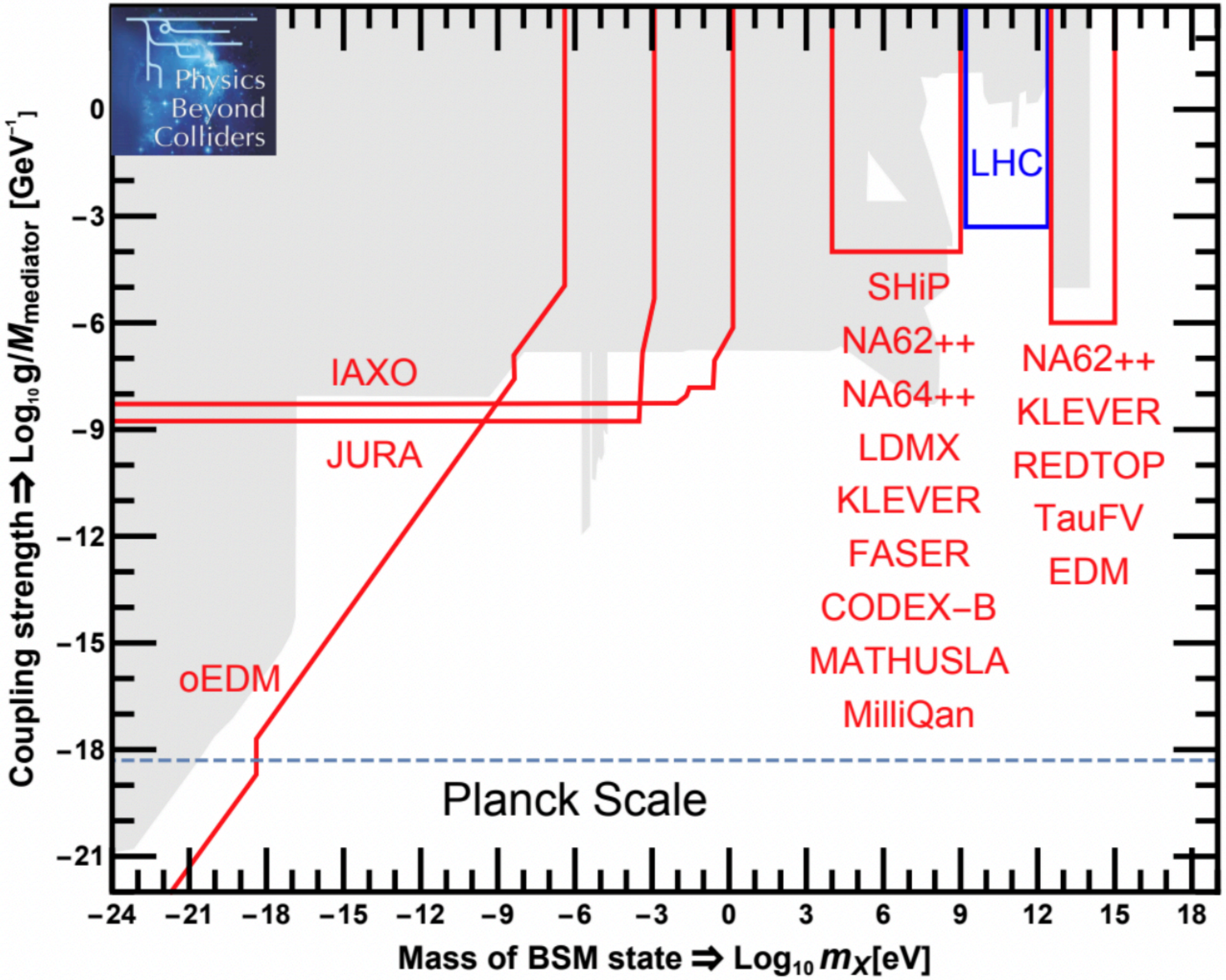
- But there are also theories with mixing generated only at higher loop level



Gherghetta, Kersten, Olive, Pospelov (2019)

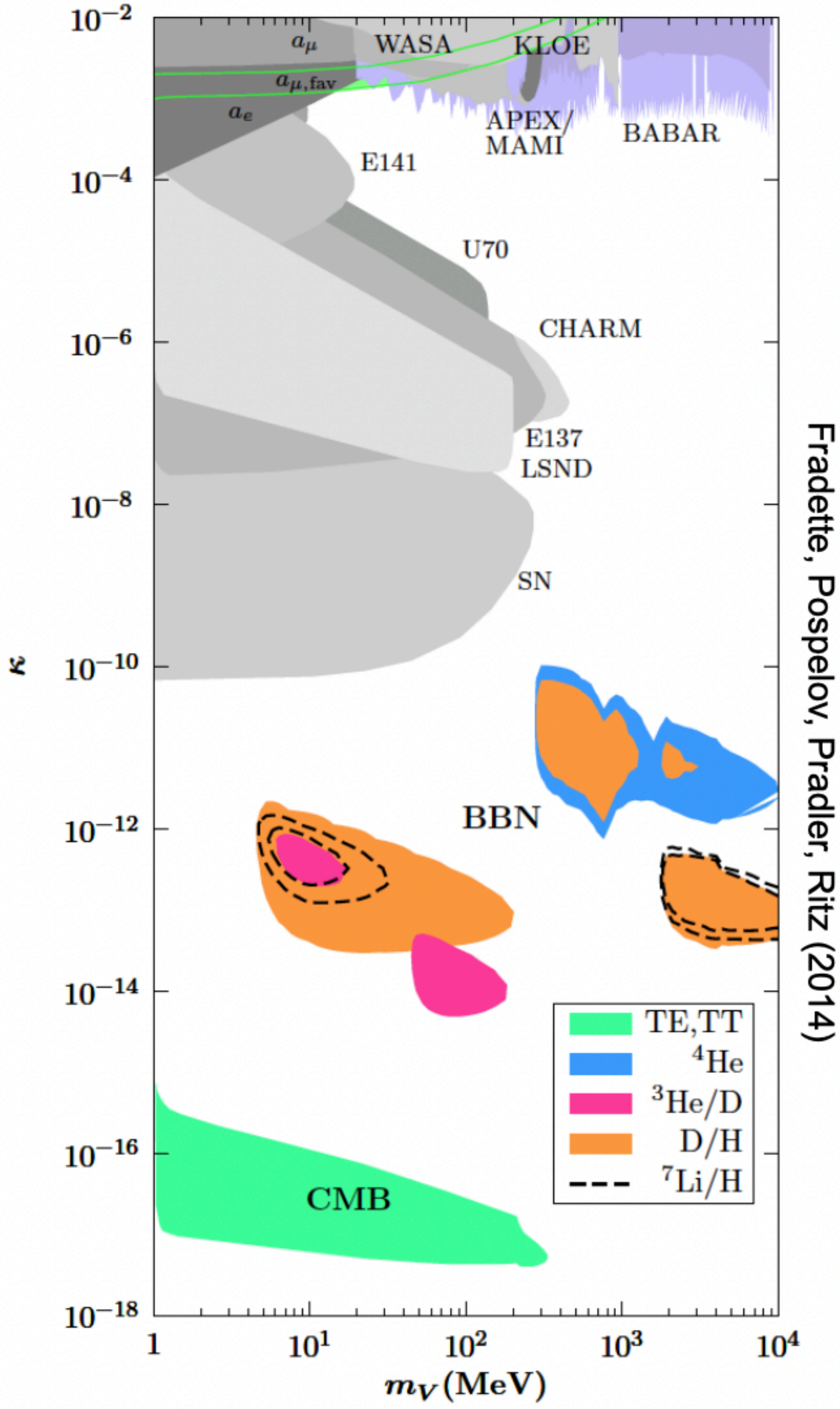
- Other than making us feel ok that $\epsilon > 10^{-3}$ is excluded, models don't provide much guidance about the coupling, and none at all about the mass

Physics Motivation | Landscape



Physics Motivation | Dark photons

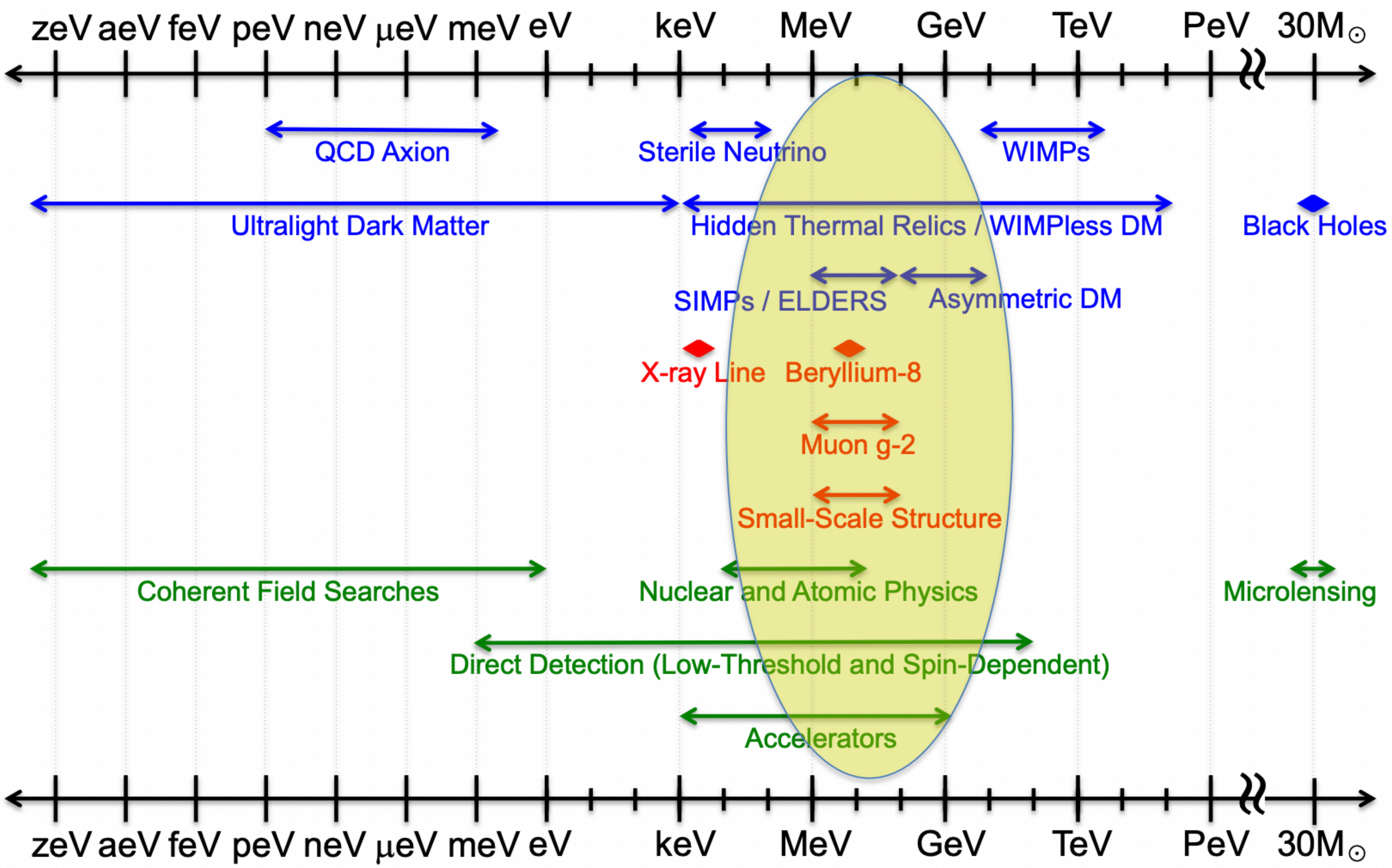
- Dark photons are particularly interesting for FASER as we have fast sensitivity to new regions of phase space
- There is a vast and largely unexplored parameter space
  - "Bump hunts" exclude larger ε
  - Mostly fixed target experiments exclude the gray region
  - Astrophysics (supernova, BBN, CMB) exclude at very low ε
- Overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.
- Dark Sector models don't give us too much guidance on expected mass or coupling strengths.
- Some other intriguing observations…



Physics Motivation | Intrigue…

- Focusing on the mass scale
  - Dark Sector Candidates
  - Anomalies
  - Search Techniques

- We see some interesting things in the ~MeV range



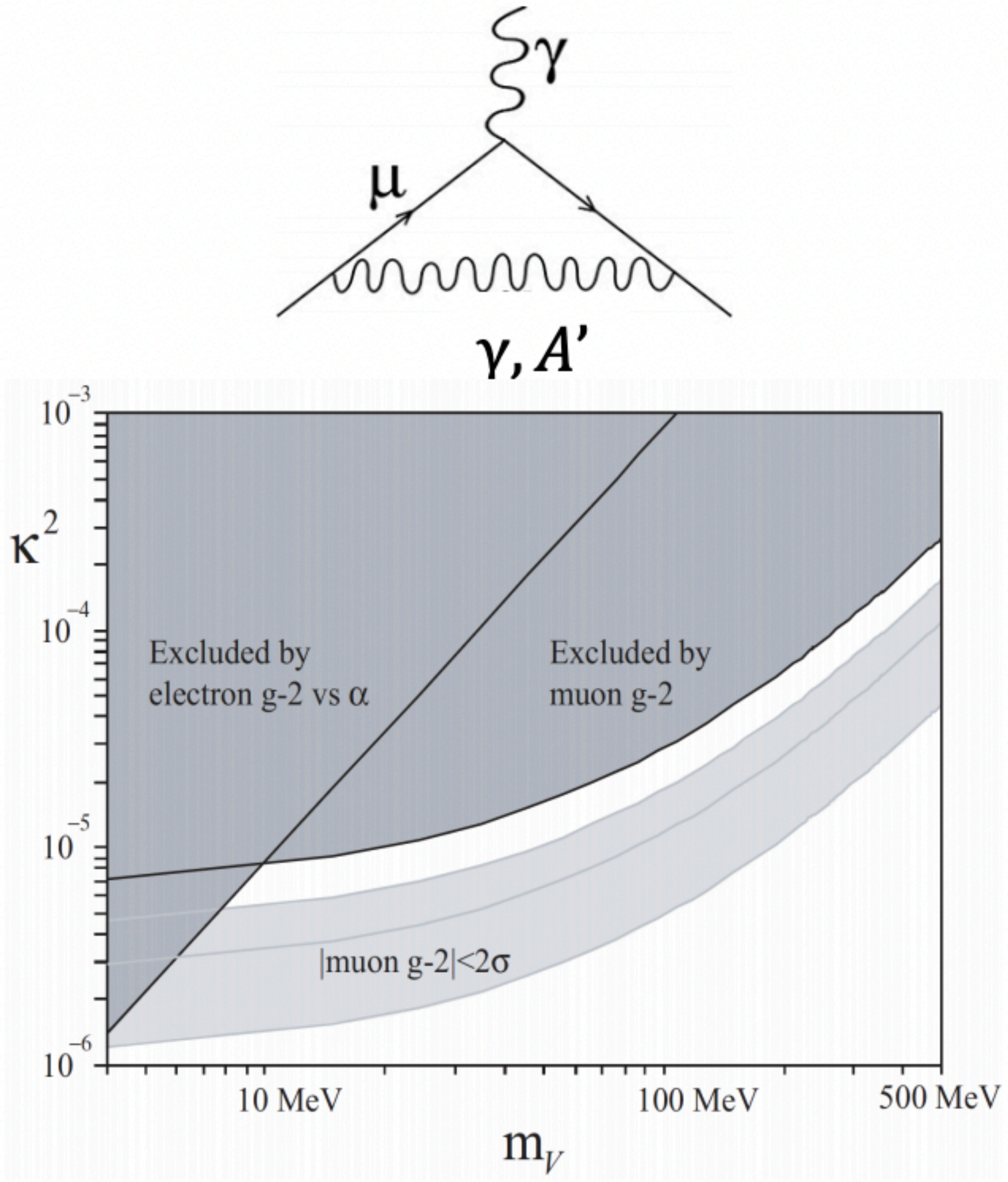
Cosmic Visions Report (2017)

Physics Motivation | g-2

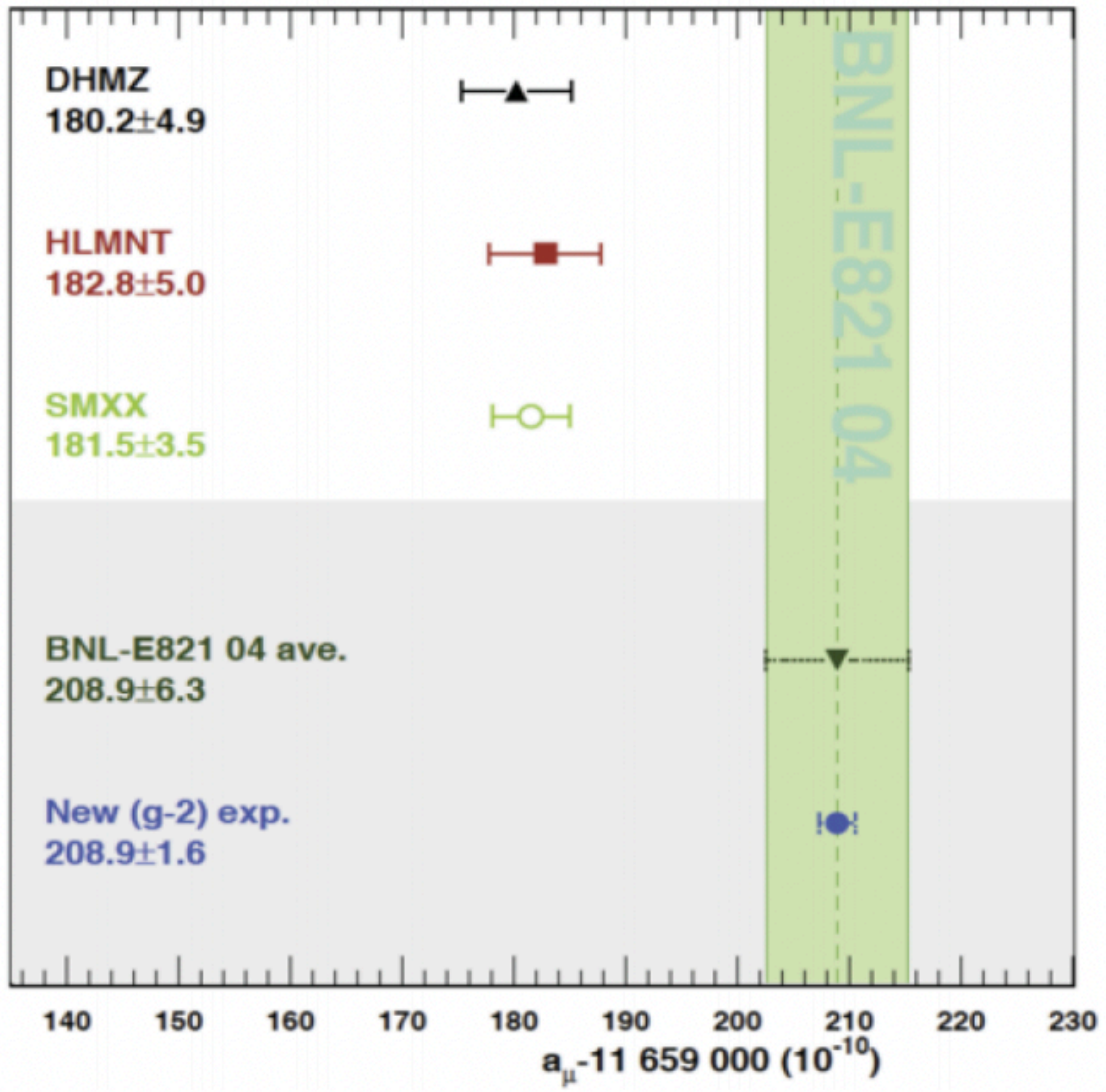
- The 3.7σ discrepancy between the SM and experiment can be resolved by **MeV-GeV particles with $\varepsilon \sim 10^{-3}$**.

- The dark photon is no longer a viable solution

- But other particles with similar masses and couplings are.



Boehm, Fayet (2003)

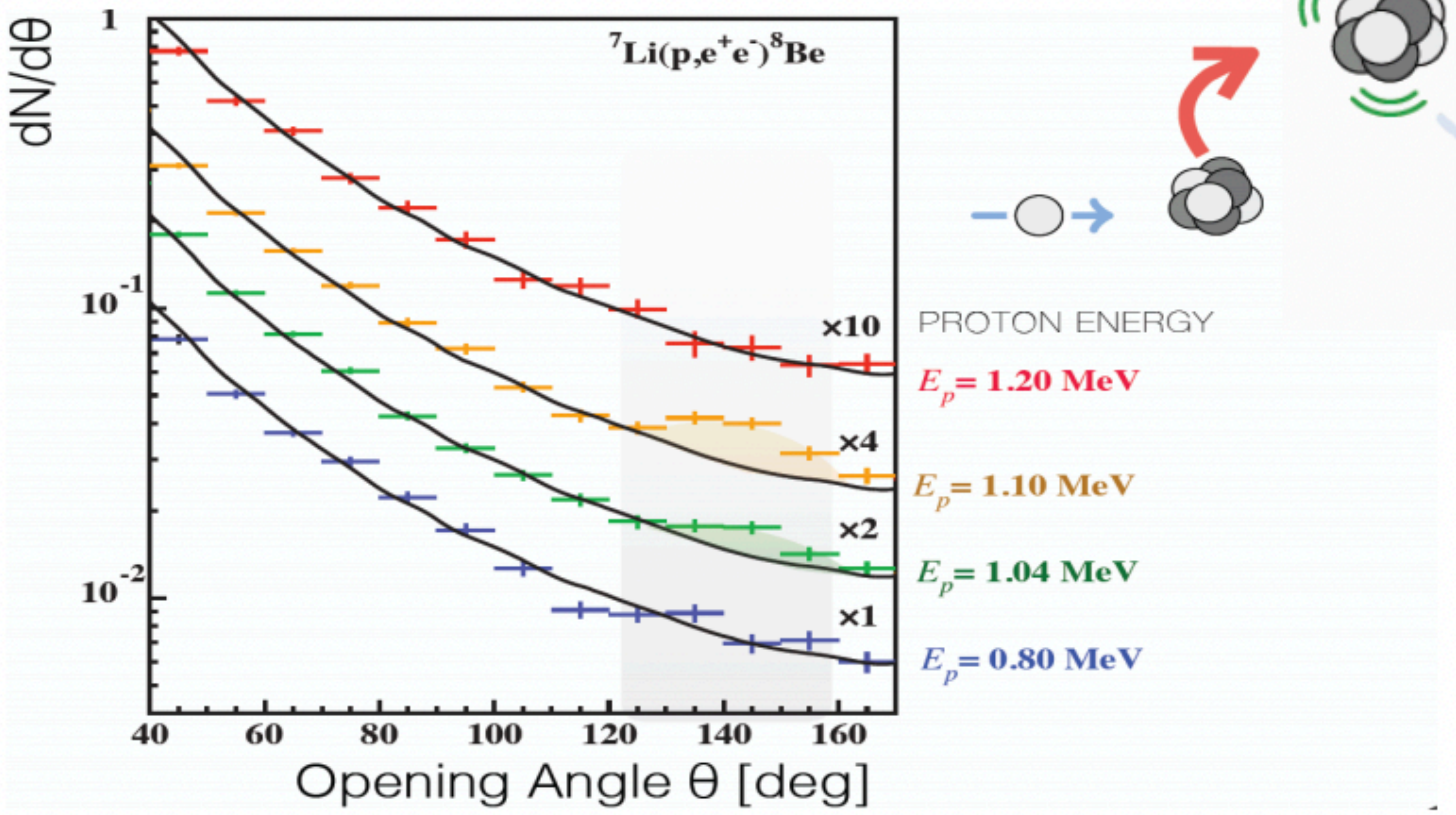


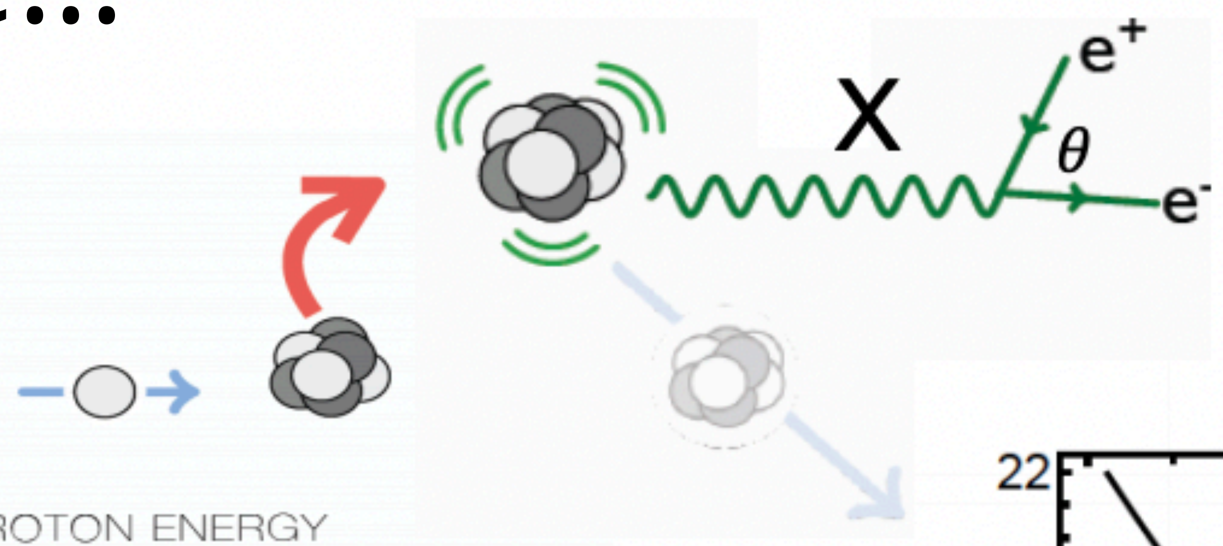
Hagiwara et al. (2017); Aoyama et al. (2020)

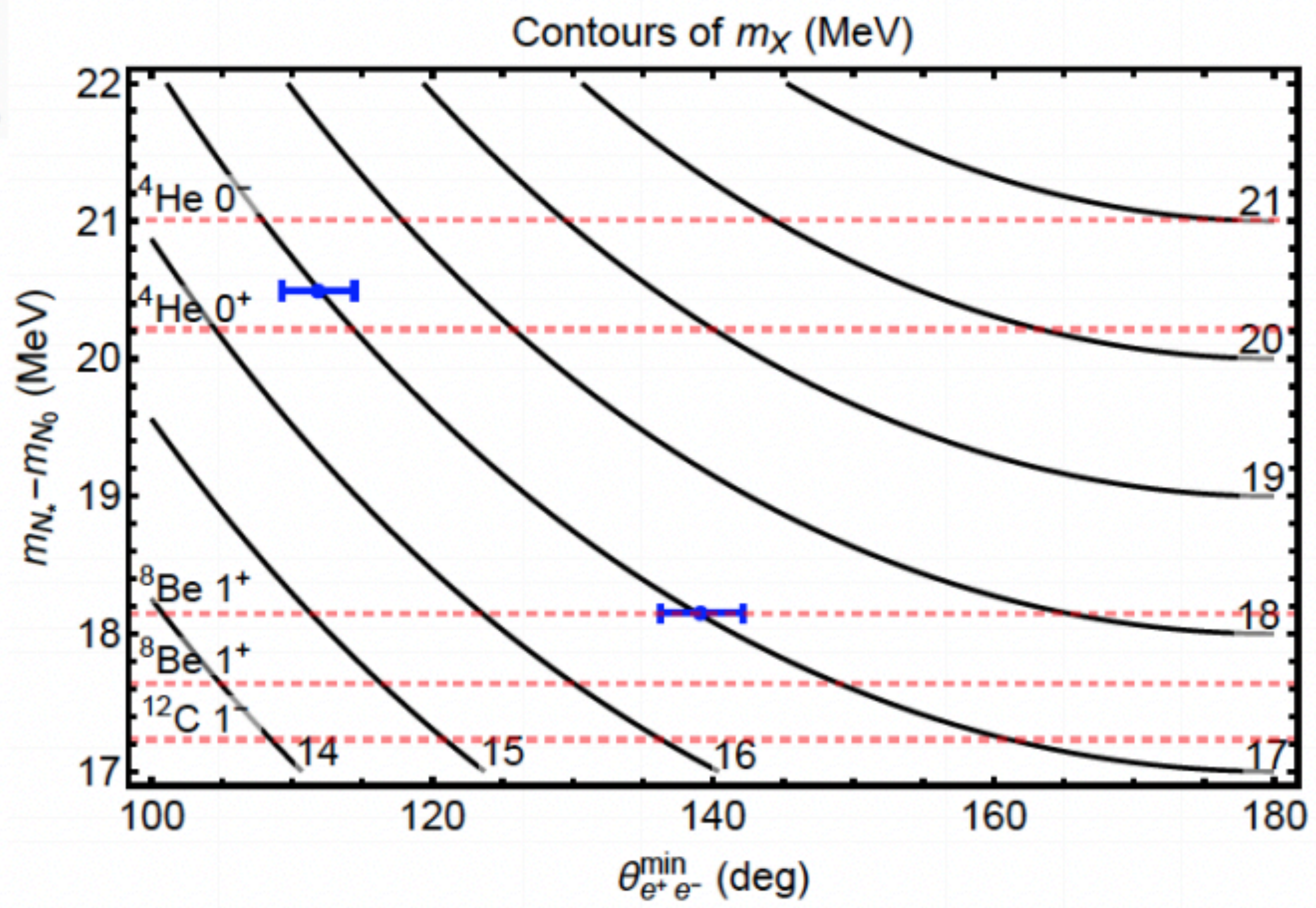
Physics Motivation | He/Be nuclei

UNIVERSITY OF SUSSEX

- 2016: A 7σ anomaly in the decays of excited ^{8}Be nuclei can be explained by a **new particle with mass 17 MeV and couplings ~ 10^{-3} to 10^{-4}**.
- 2019: A new 7σ anomaly in the decays of excited ^{4}He nuclei can be explained by the same new particle…







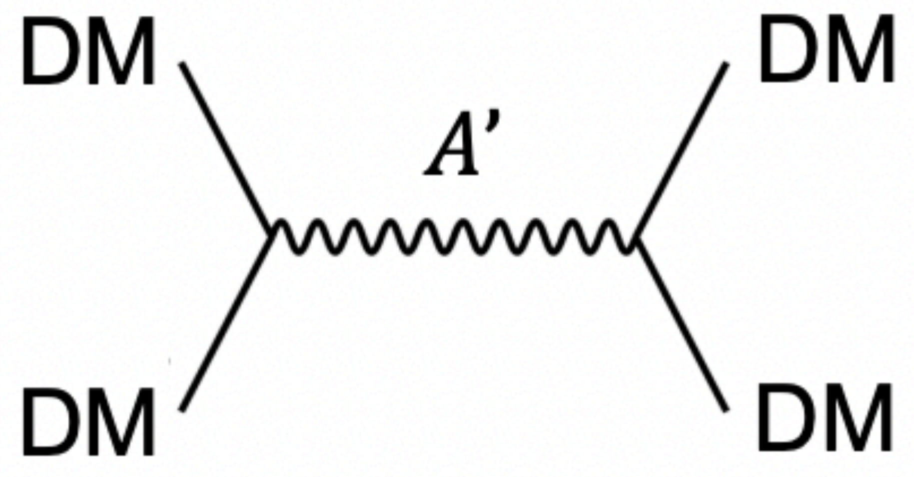
Krasznahorkay et al. (2015, 2019)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)
See also Zhang, Miller (2020)

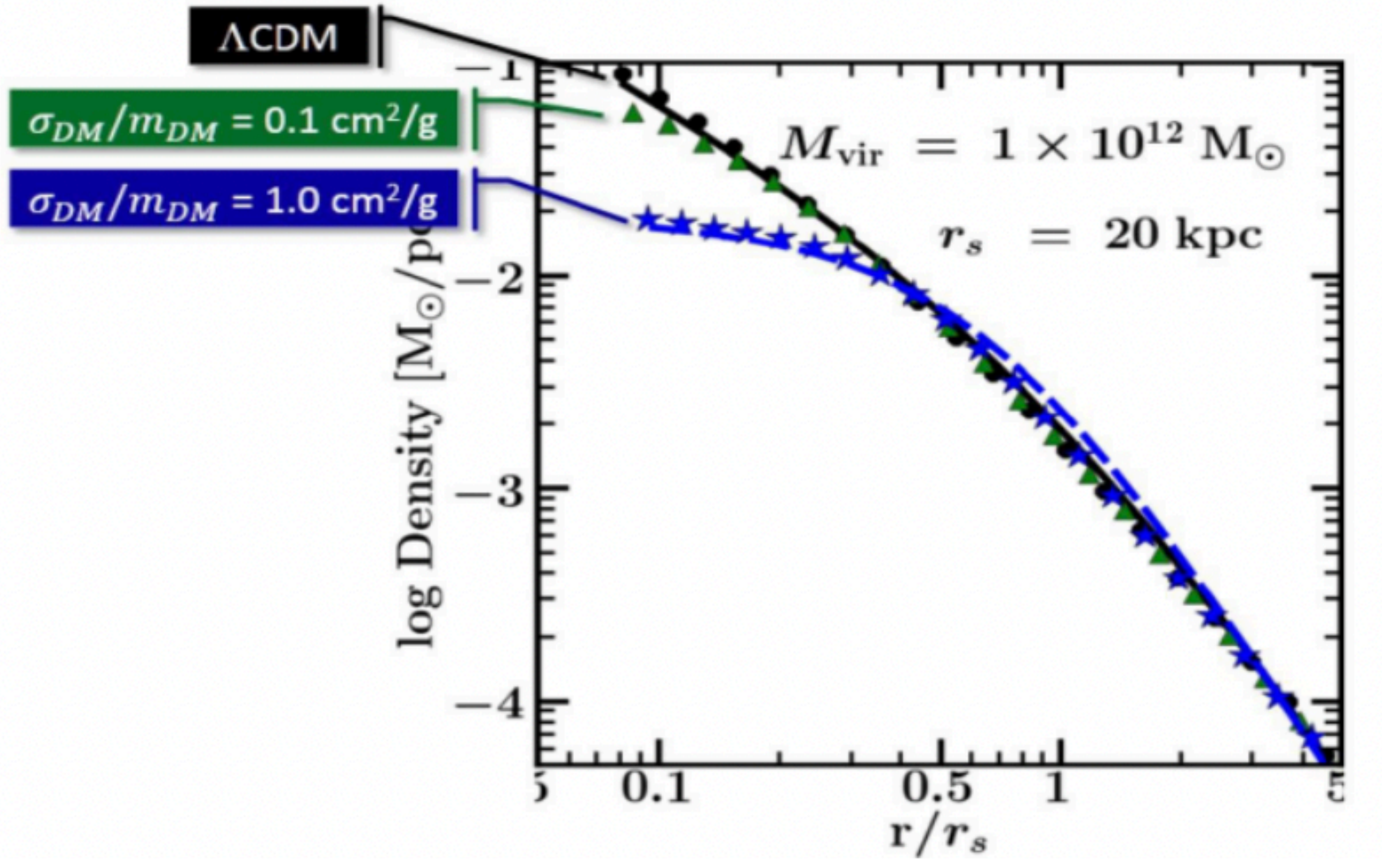
Physics Motivation | Self-interacting DM

- There are indications from small-scale structure that dark matter may be strongly self-interacting.
  - For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted by standard cold dark matter.

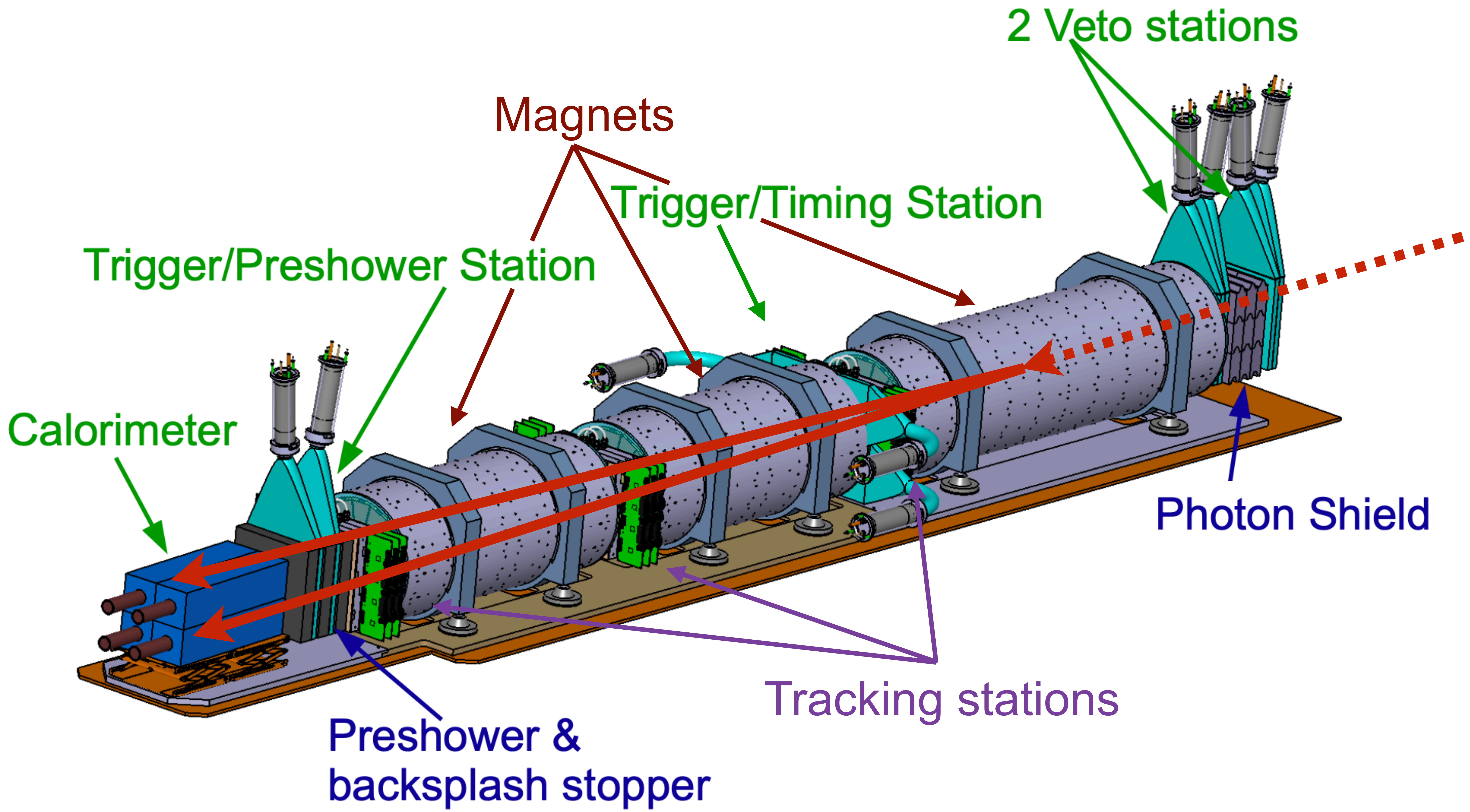
- This can be explained by a characteristic **dark sector mass scale of ~ 10-100 MeV**.

$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$





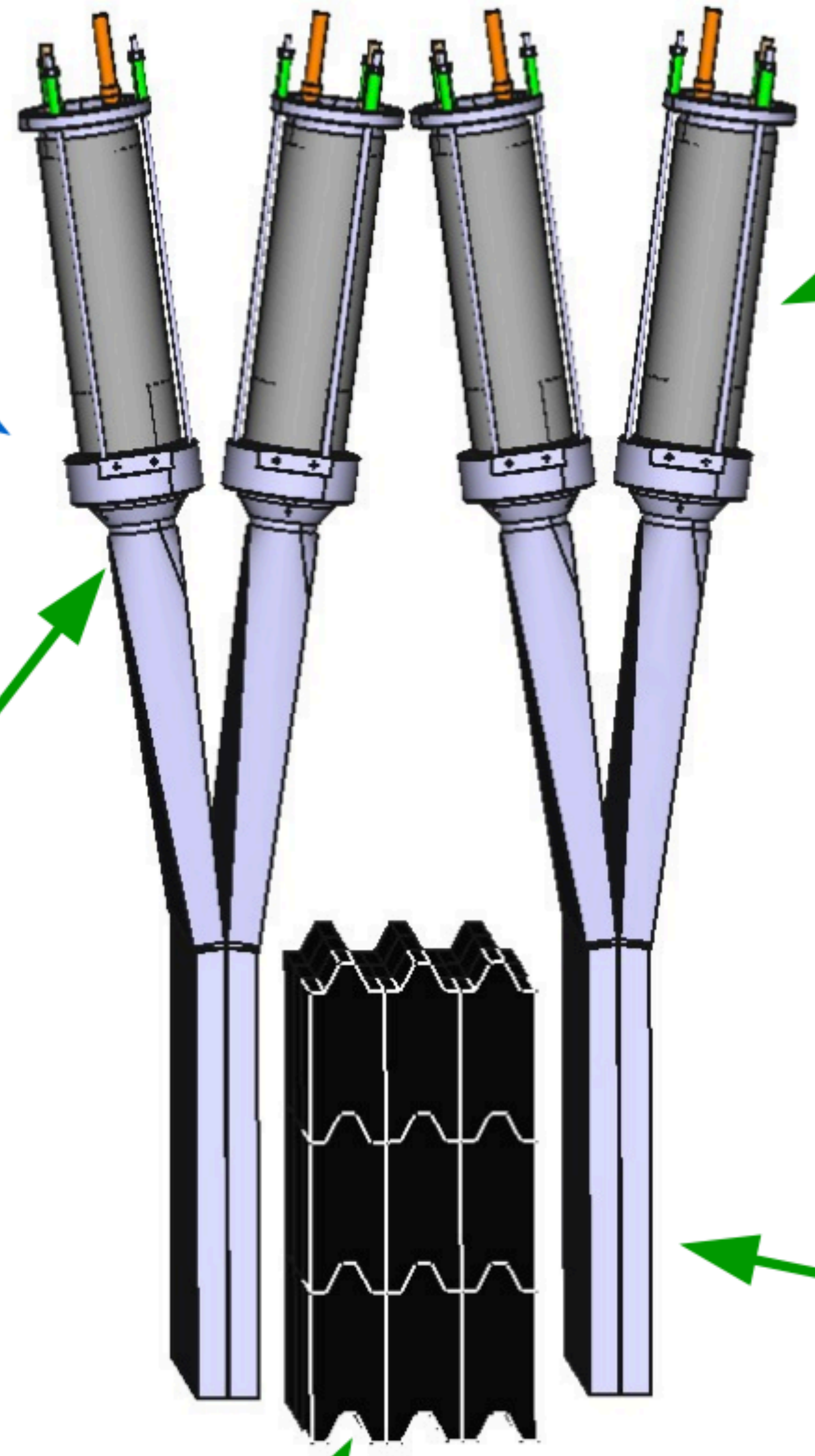
Detector | Details



Scintillators | Veto stations

Final design could be more vertical PMT position

Will have port for LED signal



Hamamatsu H6410 PMTs
- large diameter (46mm)
- large gain 10^6-10^8

Light-guides, PMT-holders and assembly to be done at CERN

Interlocking lead bricks
- ~150x300x300mm³
- exact bricks TBD
- shower/stops photons from upstream muons

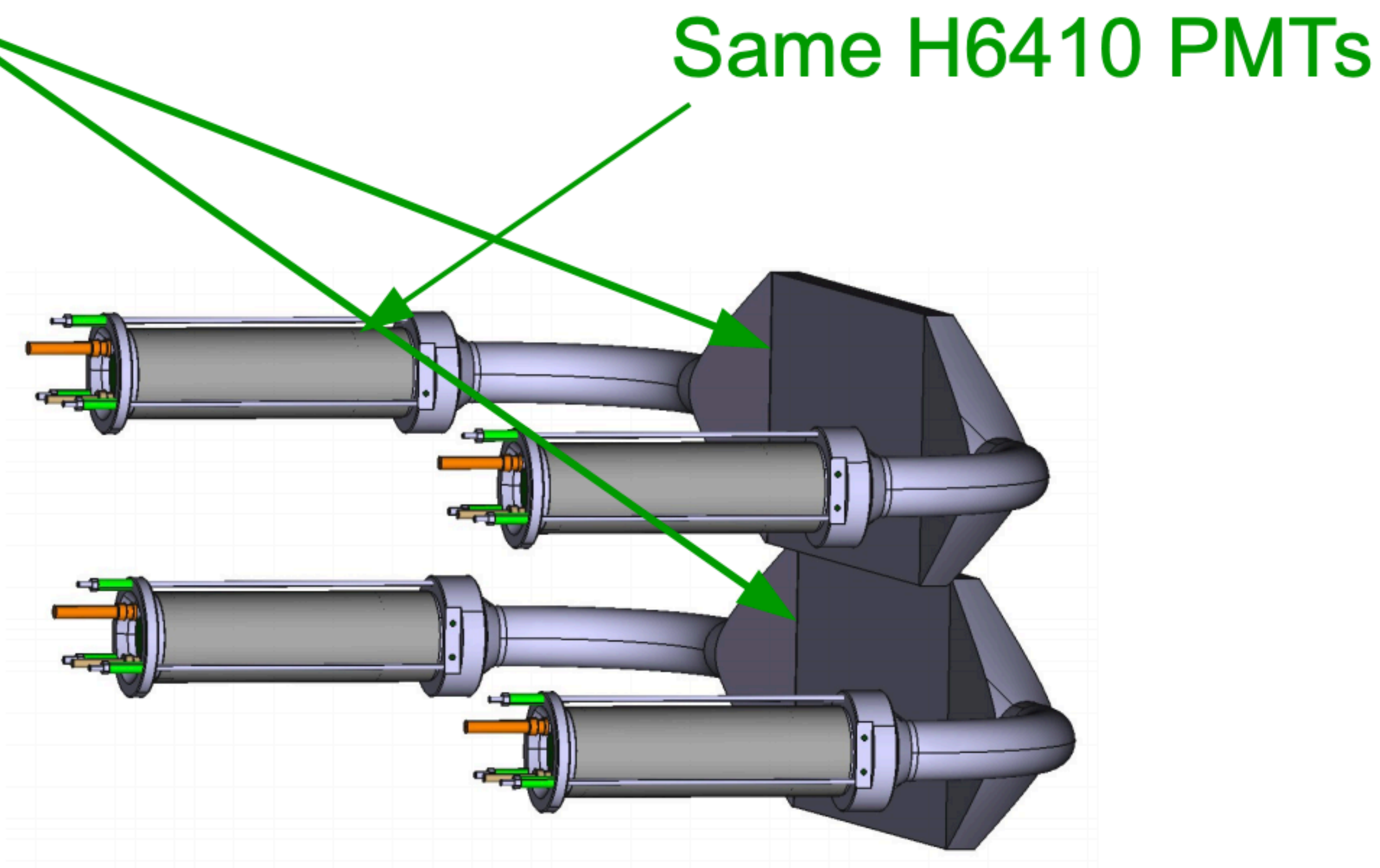
Two independent scintillator layers per station
- 20x300x300mm³
- EJ-200 from Eljen Tech.

PROPERTIES	EJ-200
Light Output (% Anthracene)	64
Scintillation Efficiency (photons/1 MeV e⁻)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5

- expect ~200 photo-electrons per MIP

Scintillators | Trigger/timing station

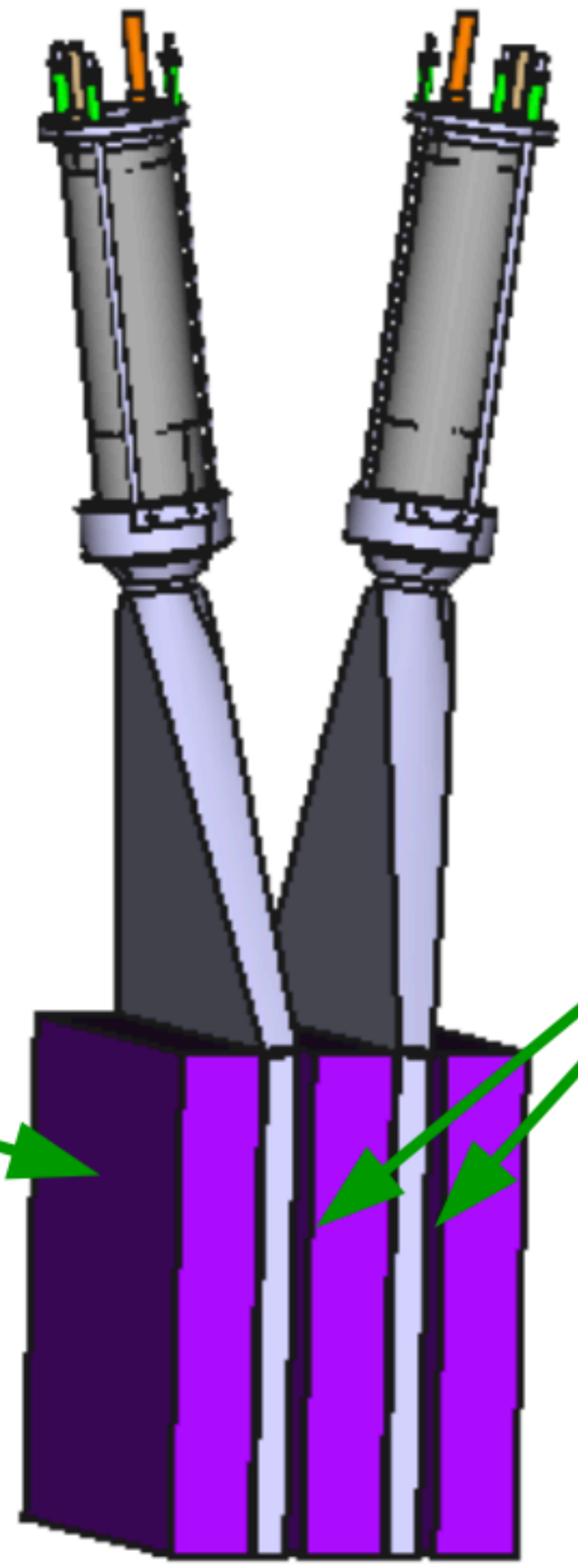
Scintillator layer split in two
- 10X200x400mm^3
- split reduces vertical time-walk and eases construction
- will have small offset and overlap to avoid gap
- again EJ-200 scintillator
- double sided readout:
  1. allows correction for horizontal time-walk
  2. can reduce noise triggers by requiring coincidence
- expect ~80 photo-electrons per MIP
- timing resolution still to be determined (~ns)



Large area to catch muons coming at angle generating showers only seen in last layer/calorimeter, a dominant(?) background for photons-only signal

Scintillators | Trigger/preshower station

Trigger/Preshower station has same scintillator design as veto stations



Carbon fiber (low-Z) blocks between tracker and calorimeter to reduce backsplash from calorimeter

- exact thickness will depend available space after support is designed should be three ~5cm thick blocks

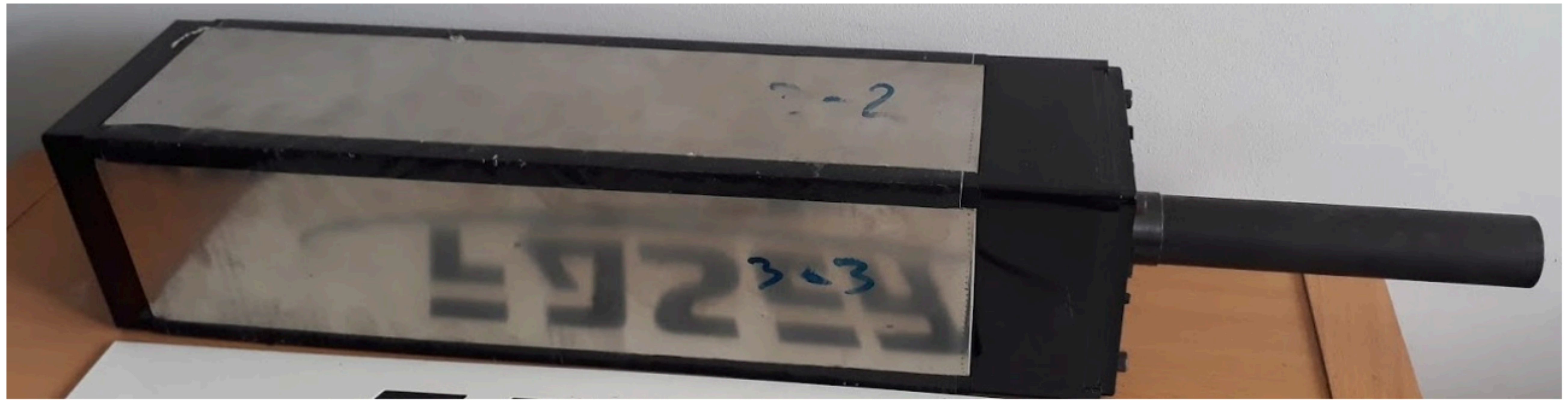
Embed/glue in two 1 radiation length (~5mm) lead plates in front of scintillator layers to start EM shower

- allows to discriminate between incoming di-photon signal and neutrino interactions in calorimeter

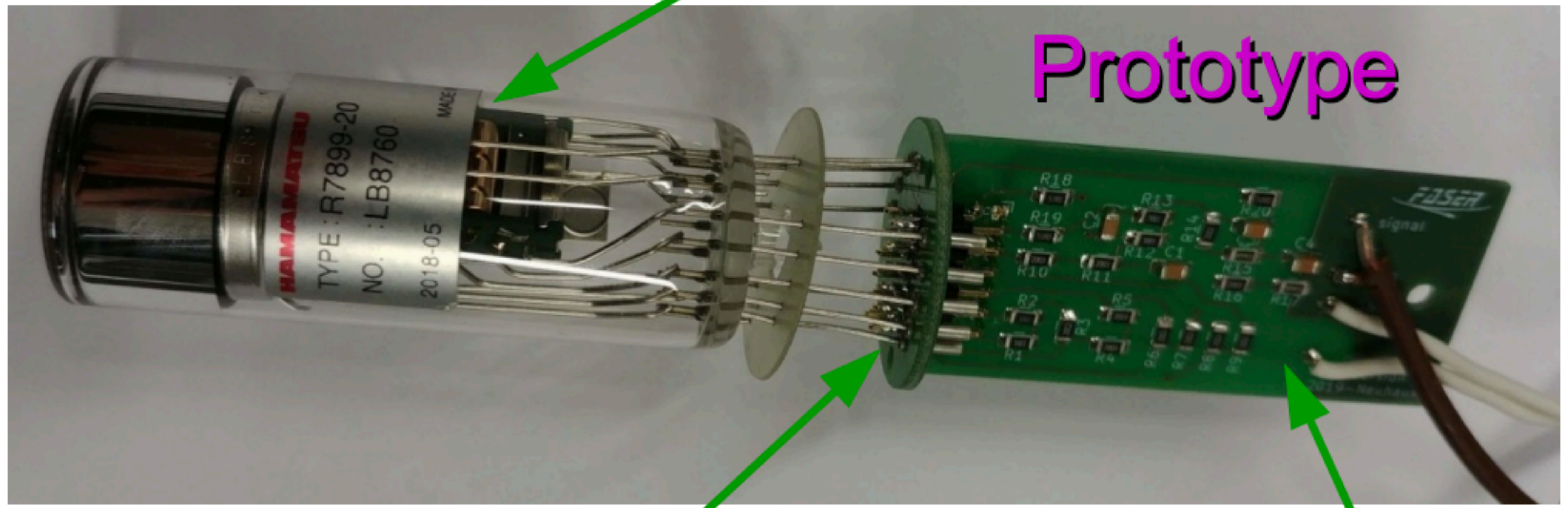
Calorimeter

Using 4 LHCb spare outer ECAL modules for calorimeter (have 8)

Theoretical energy resolution ~1%, but we will be limited by how well we can calibrate and by punch-through



7 R7899-20 Hamamatsu PMT provided by LHCb
- tubes are almost new (from 2018)



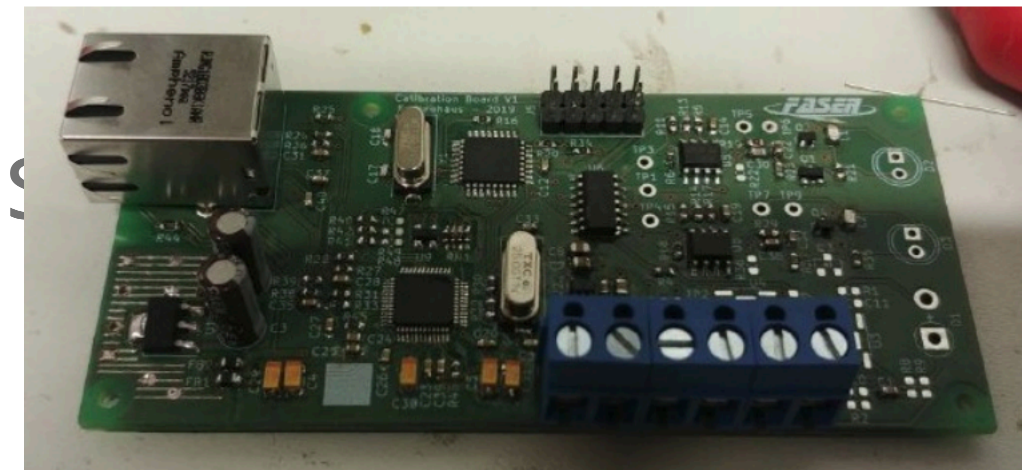
Had to make our own HV base
- done by Friedemann

Have new base with non-solder connection

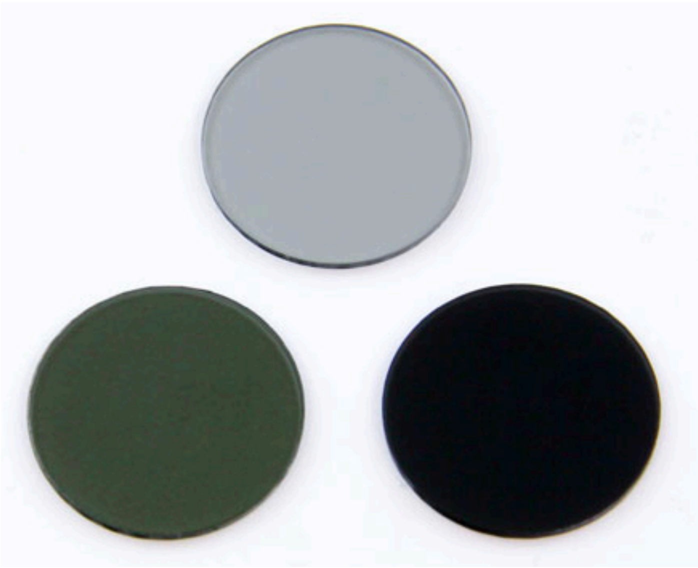
Divider to be shortened to fit in calorimeter tube – waiting for final tests of proto-type

Scintillator and Calorimeter | PMTs

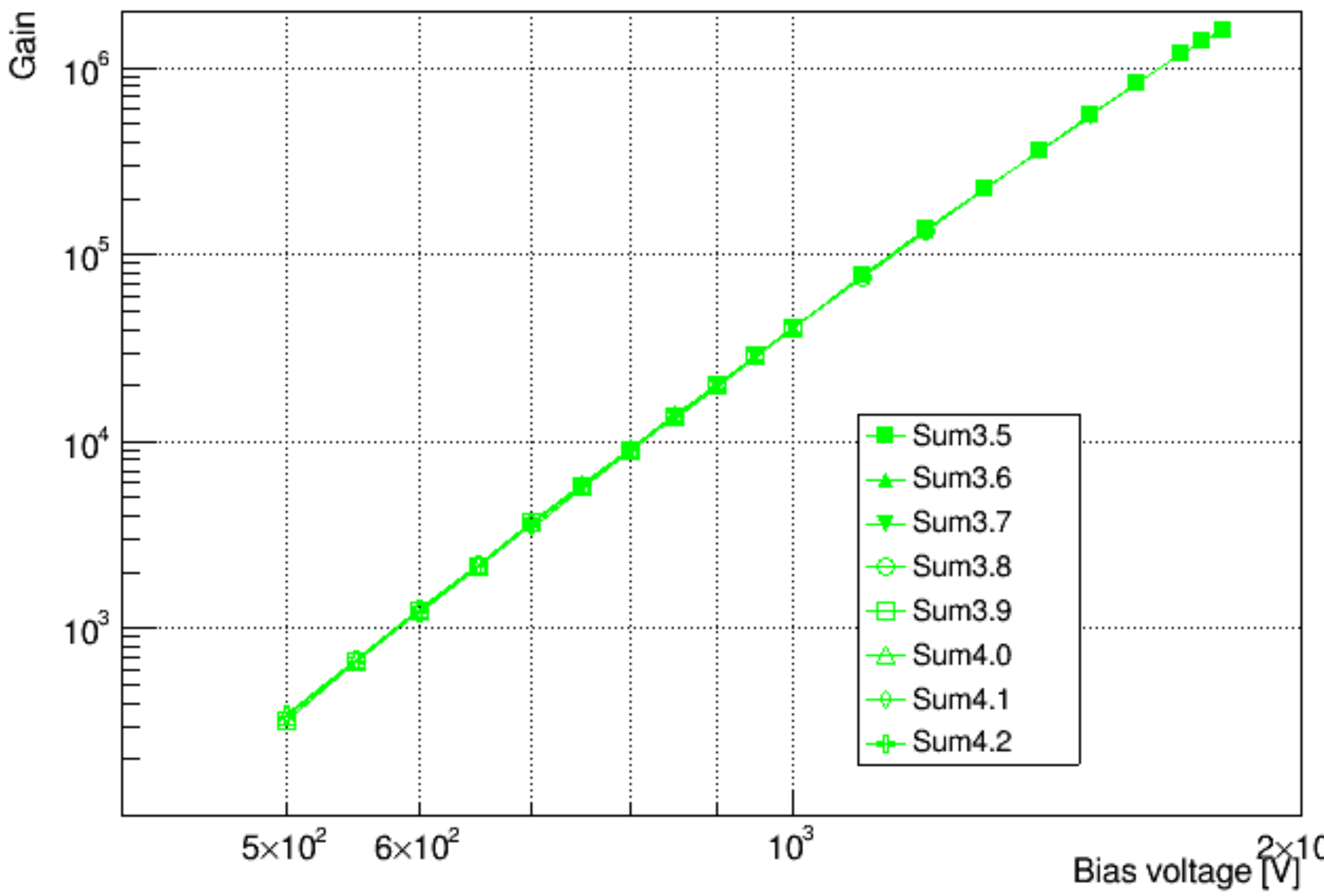
- Have a well developed lab setup for scintillator & calorimeter PMT characterisation
  - Automation of signal pulse and HV settings.
  - PMT signal read-out by digitiser.
  - Well defined procedure to extract gain and linearity measurem
- In-situ calibration
  - Will measure gain vs HV, by pulsing with high intensity LED
  - LED also used to measure stability
  - Circuit designed and first testing in progres



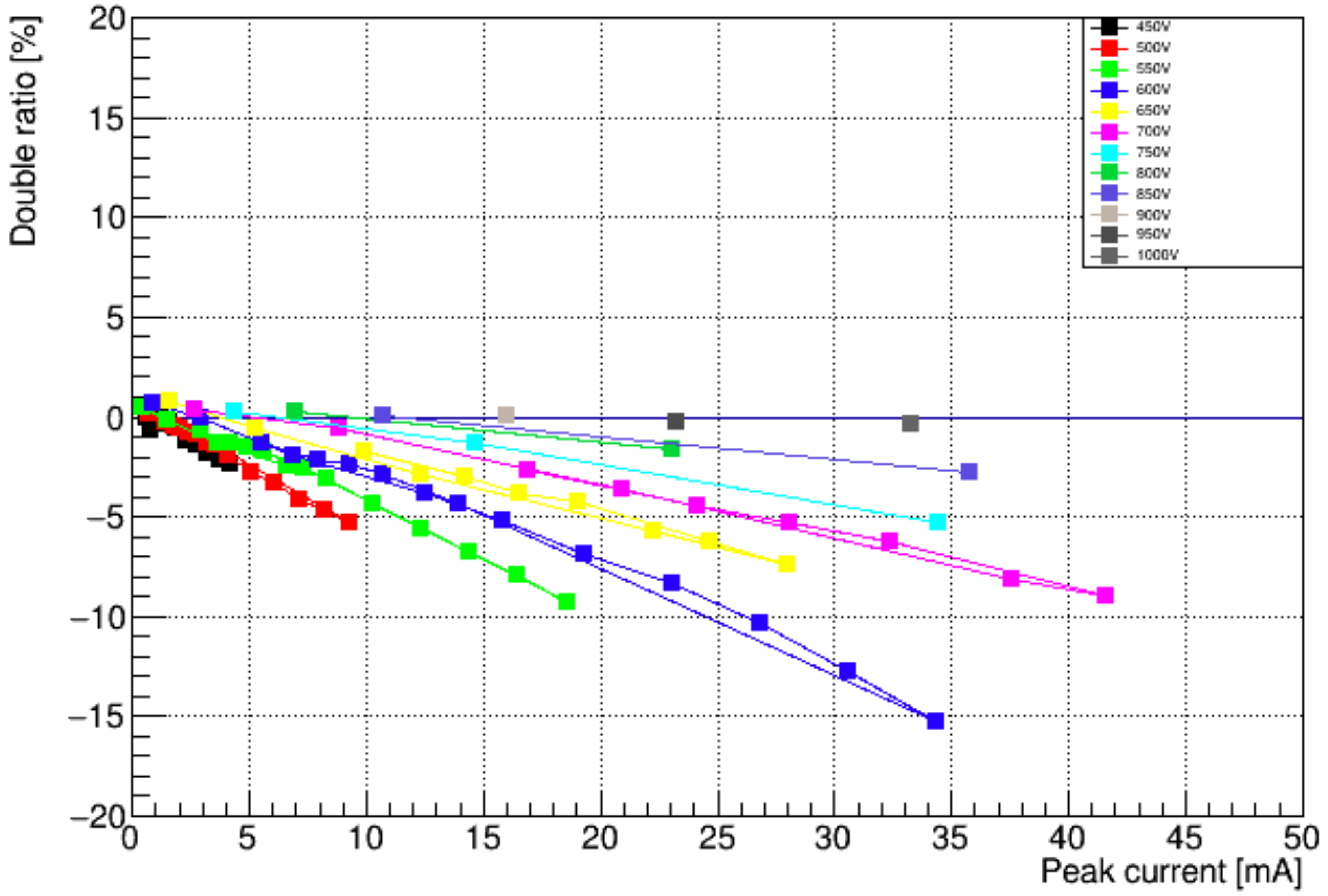
- Optical filters
  - At very low gain PMT is not linear over full range
    - Reduce signal by factor 10 using optical filter
    - Still leaves 100 photo-el. for MIP calibration
    - Other options also being considered.



Gain

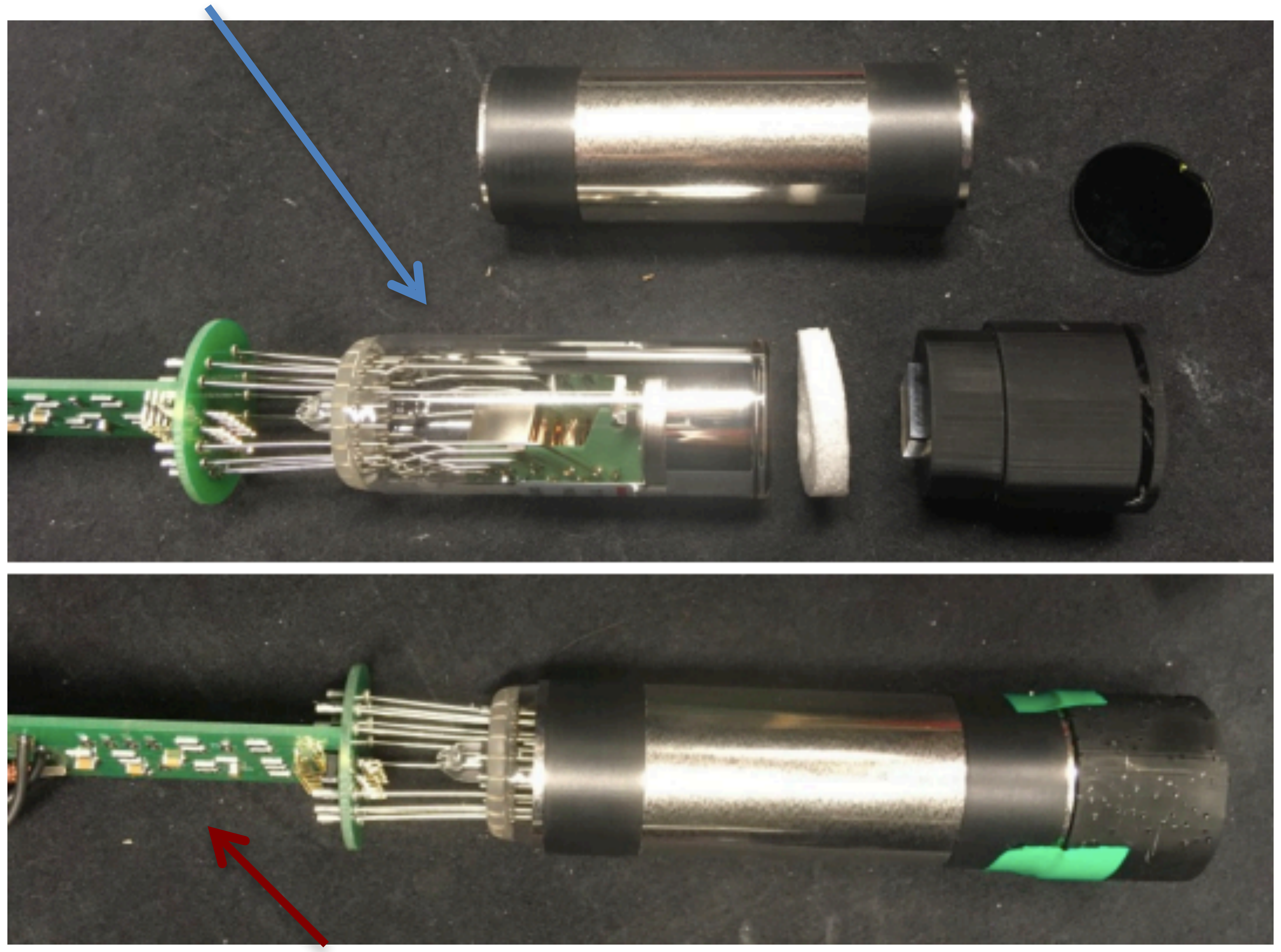


Linearity

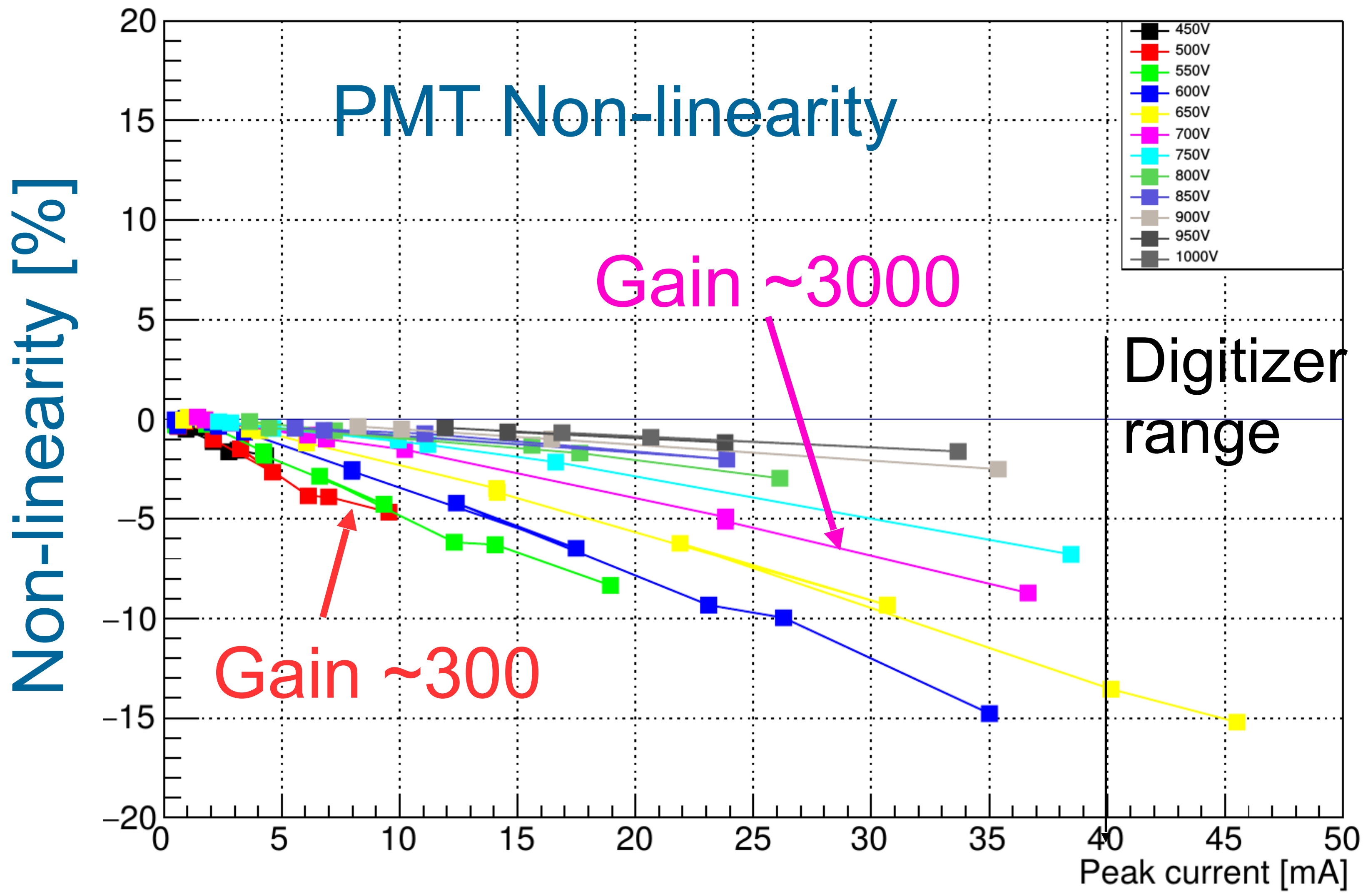


Calorimeter | PMTs

R7899-20 Hamamatsu PMTs provided by LHCb



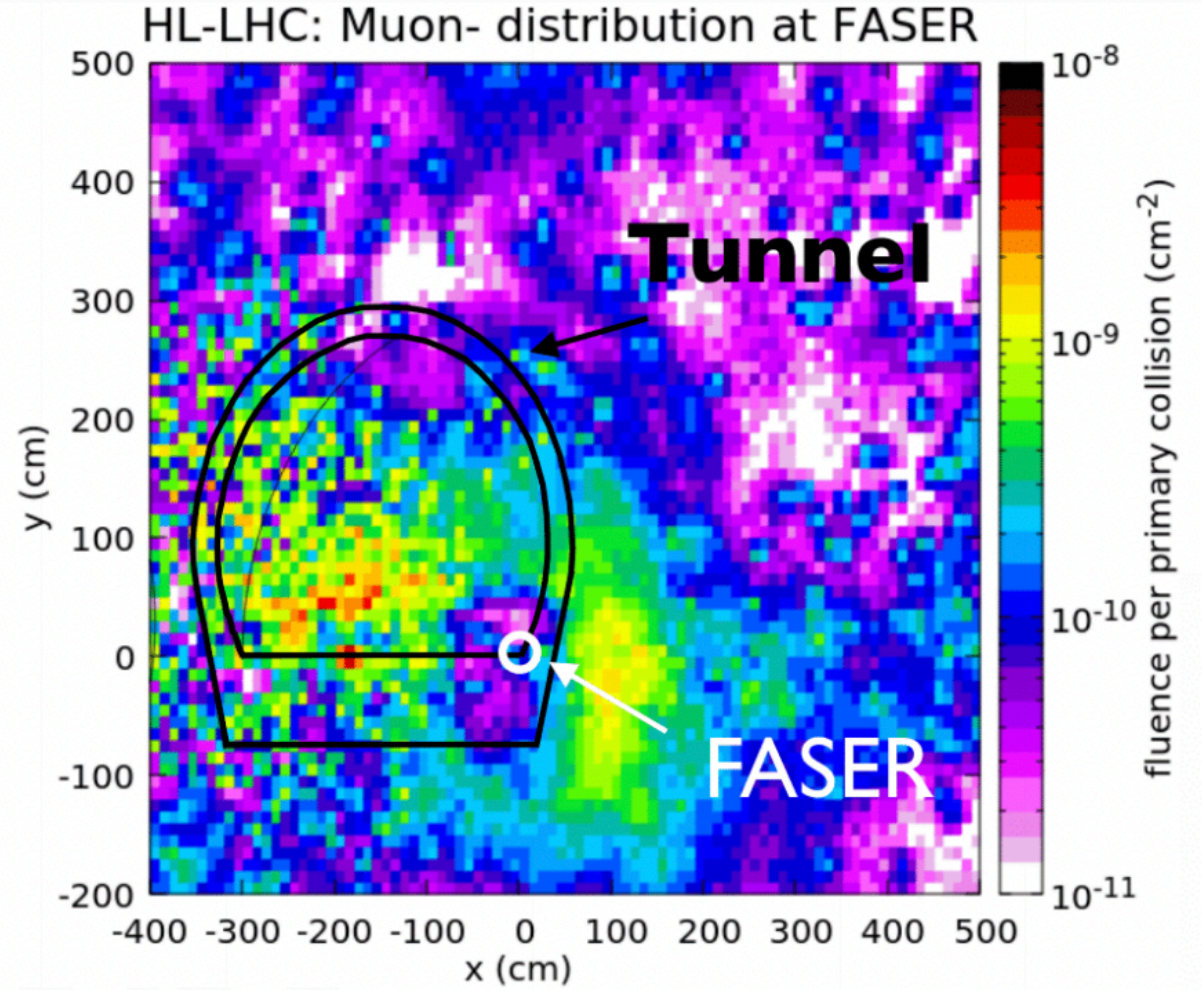
New HV divider

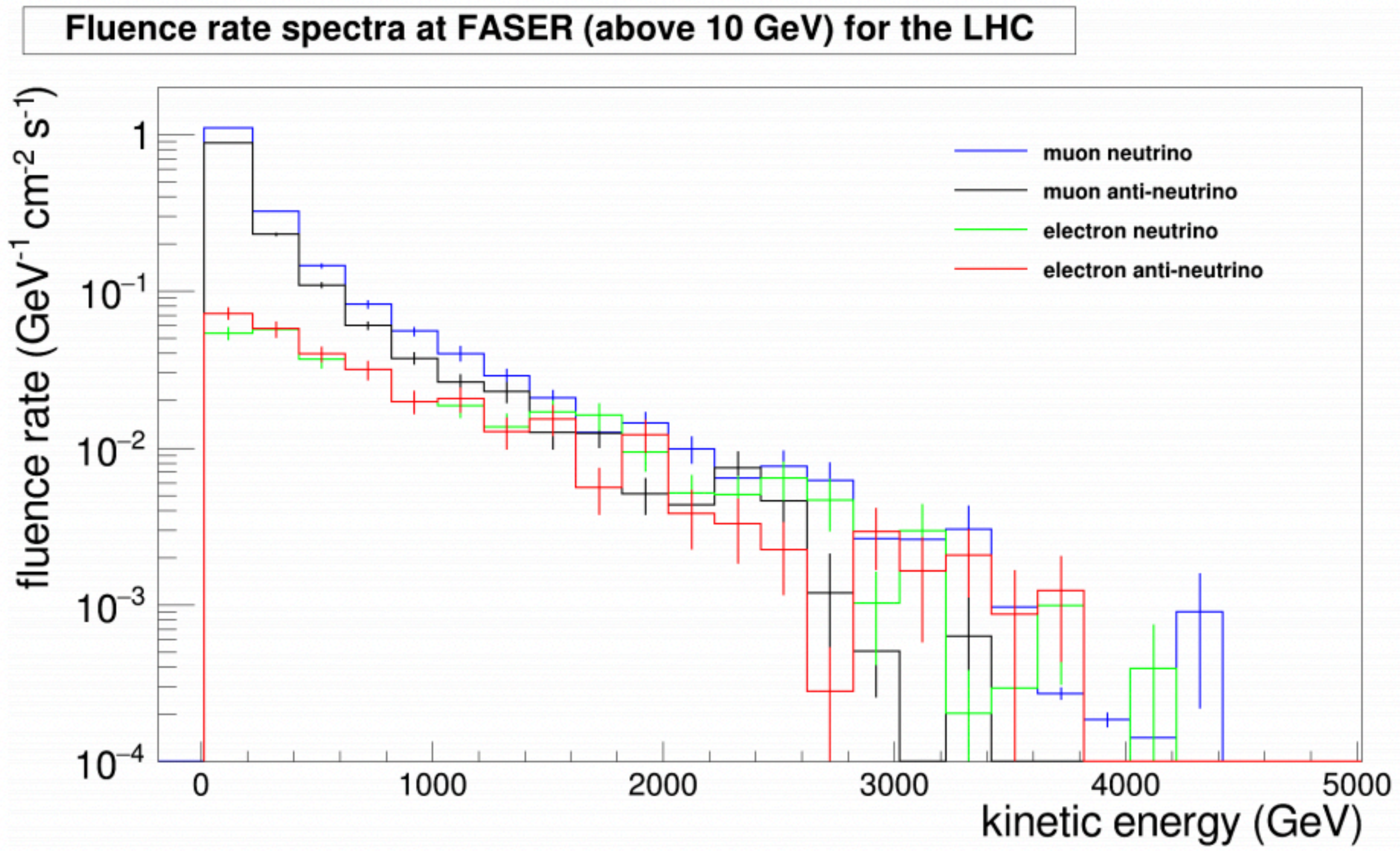


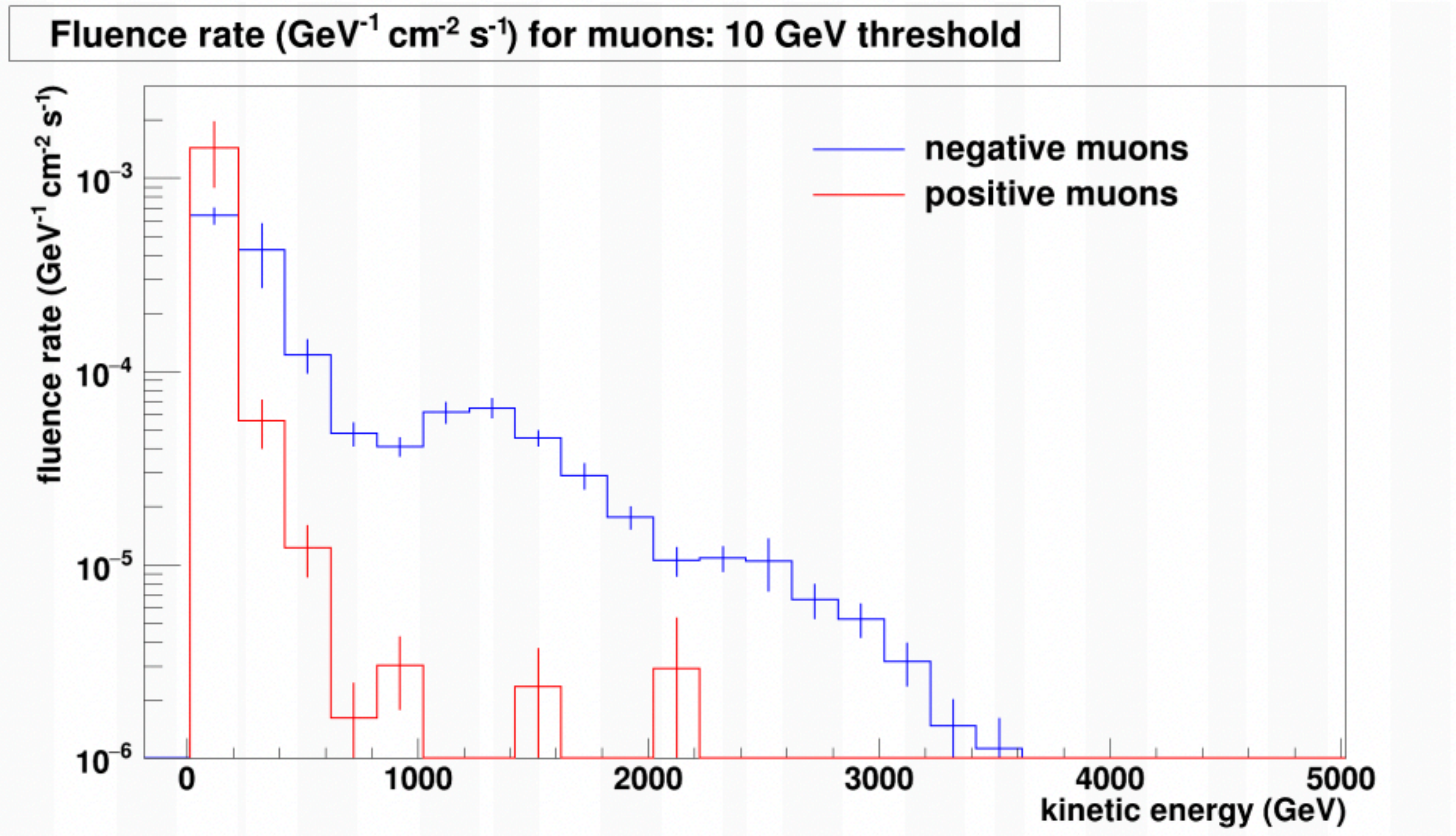
- Testing lab with LED pulser and cosmic ray test stand setup at CERN
- Used to characterize and determine HV working point
- Low gain needed to have sufficient range for largest signals
- Energy calibration:
  - Using *in situ* muons (MIPs)
  - Plan to also have test-beam during Run-3 for spare modules

Conditions | Beam backgrounds

- FLUKA simulations and *in situ* measurements used to assess expected backgrounds.
  - IP1 collisions (shielded by 100m rock)
  - Off-orbit protons hitting beam pipe aperture near TI12 } *Minor*
  - Beam-gas interactions
- Low particle flux along beam axis due to LHC optics.







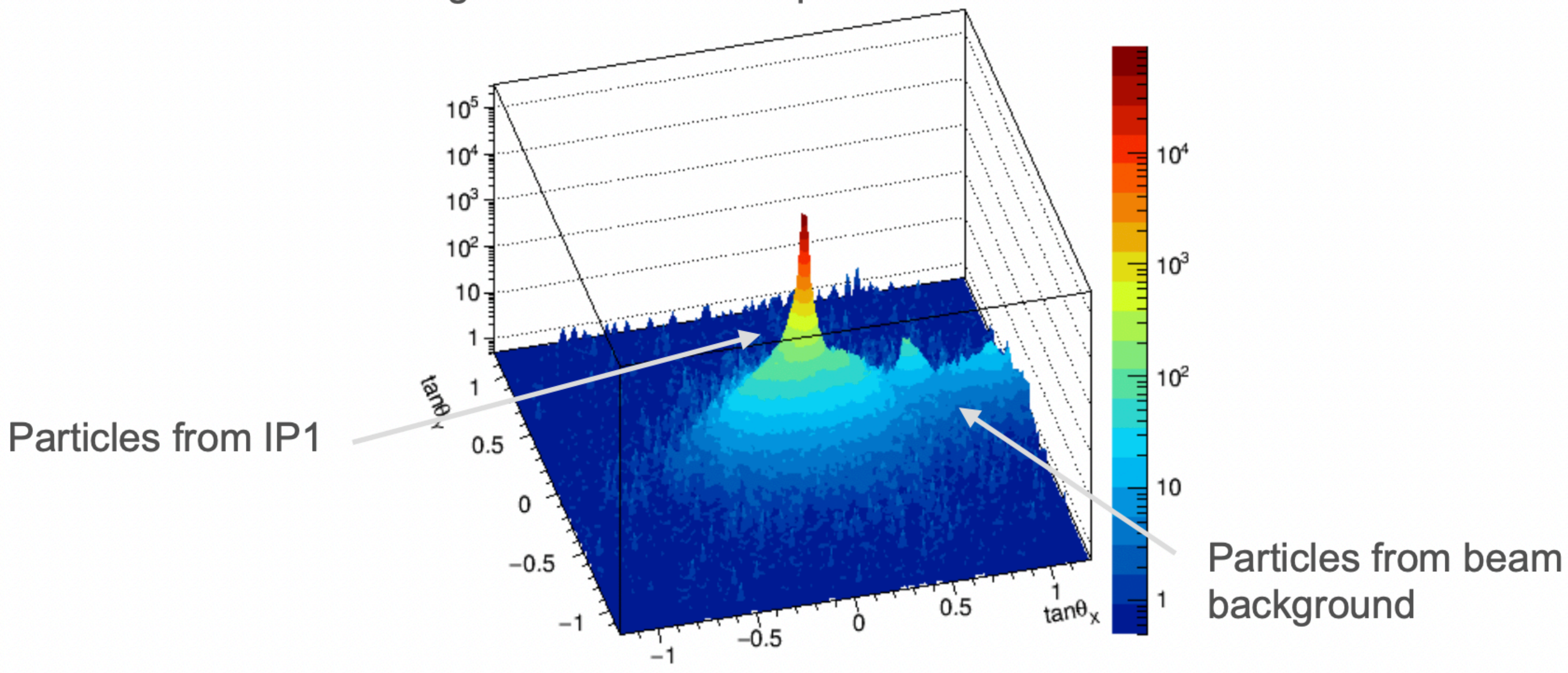
Muon charge asymmetry due to LHC magnets

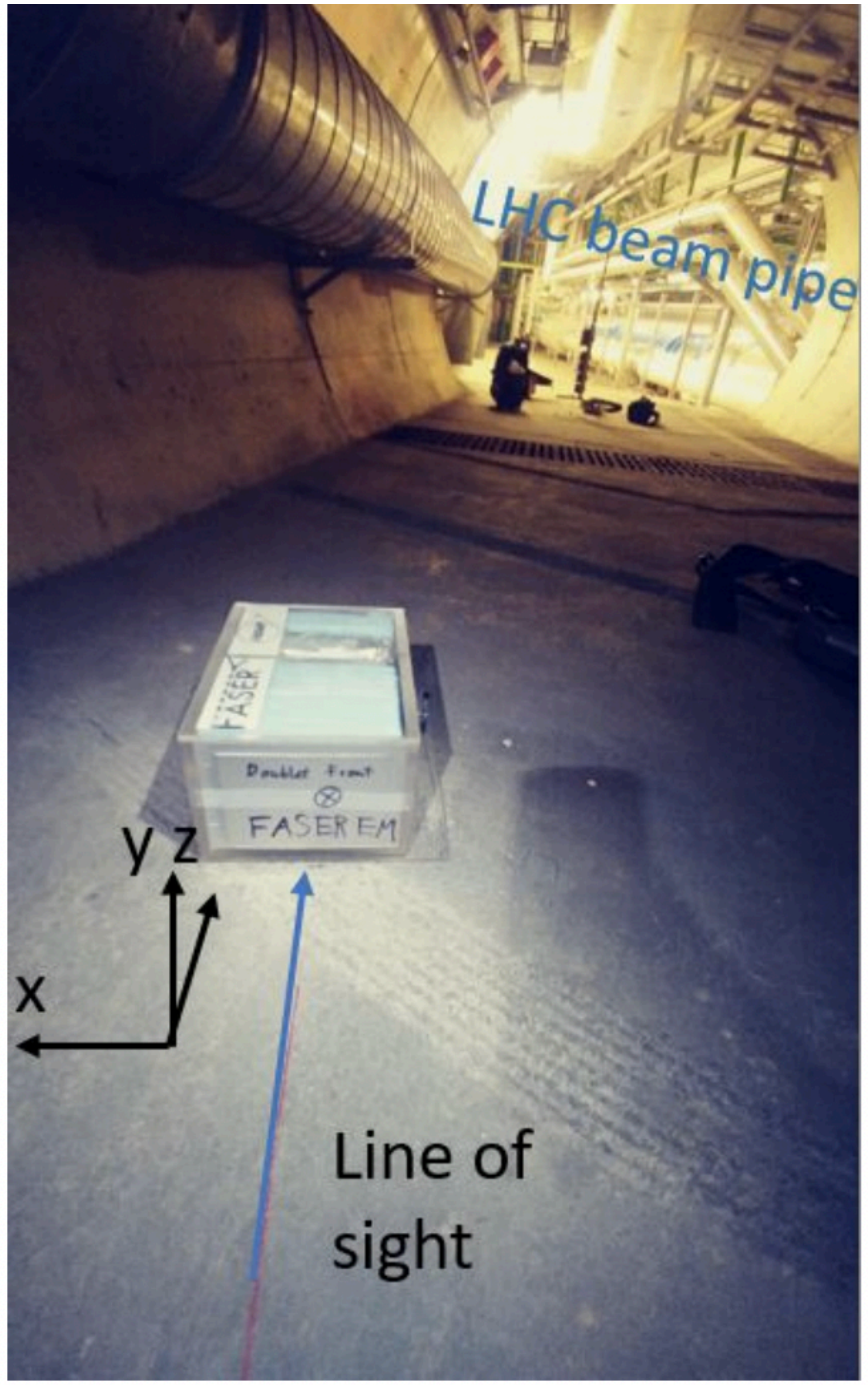
Muons (@L=2x10^{-34} cm^{-2} s^{-1})	
Energy threshold [GeV]	Charged Particle Flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

Conditions | Beam backgrounds

- *In situ* measurements using emulsion detectors and TimePix BLM in TI12 in 2018 confirm expected particle flux, and correlation with IP1 luminosity.

Angular distribution of particles in emulsion detector





Conditions | Beam backgrounds

The FLUKA simulation tracks particle production, deflection, and energy loss with a detailed model of the geometry of the LHC tunnels, including the LHC material map and magnetic field layout. The simulation includes three potential sources of background at the FASER location:

- Particles produced in the *pp* collisions at the IP or by particles produced at the IP that interact further downstream, e.g., in the TAN neutral particle absorber.
- Particles from showers initiated by off-momentum (and therefore off-orbit) protons hitting the beam pipe in the dispersion suppressor region close to FASER.
- Particles produced in beam-gas interactions by the beam passing FASER in the ATLAS direction (for which there is no rock shielding).

Always co-linear with accompanying muons

- $10^5 \rightarrow 10$ with veto

Minor

Conditions | Radiation levels

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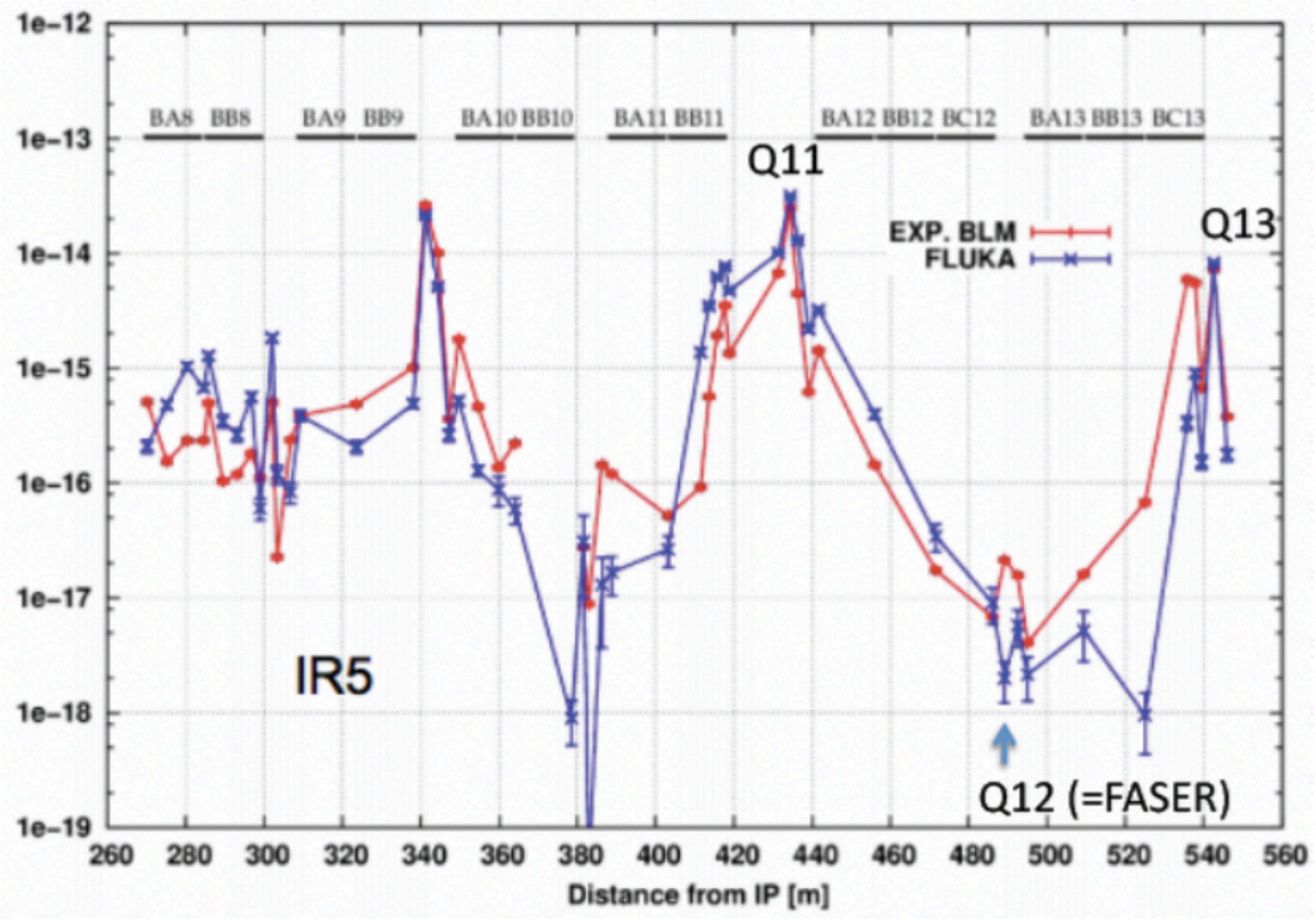
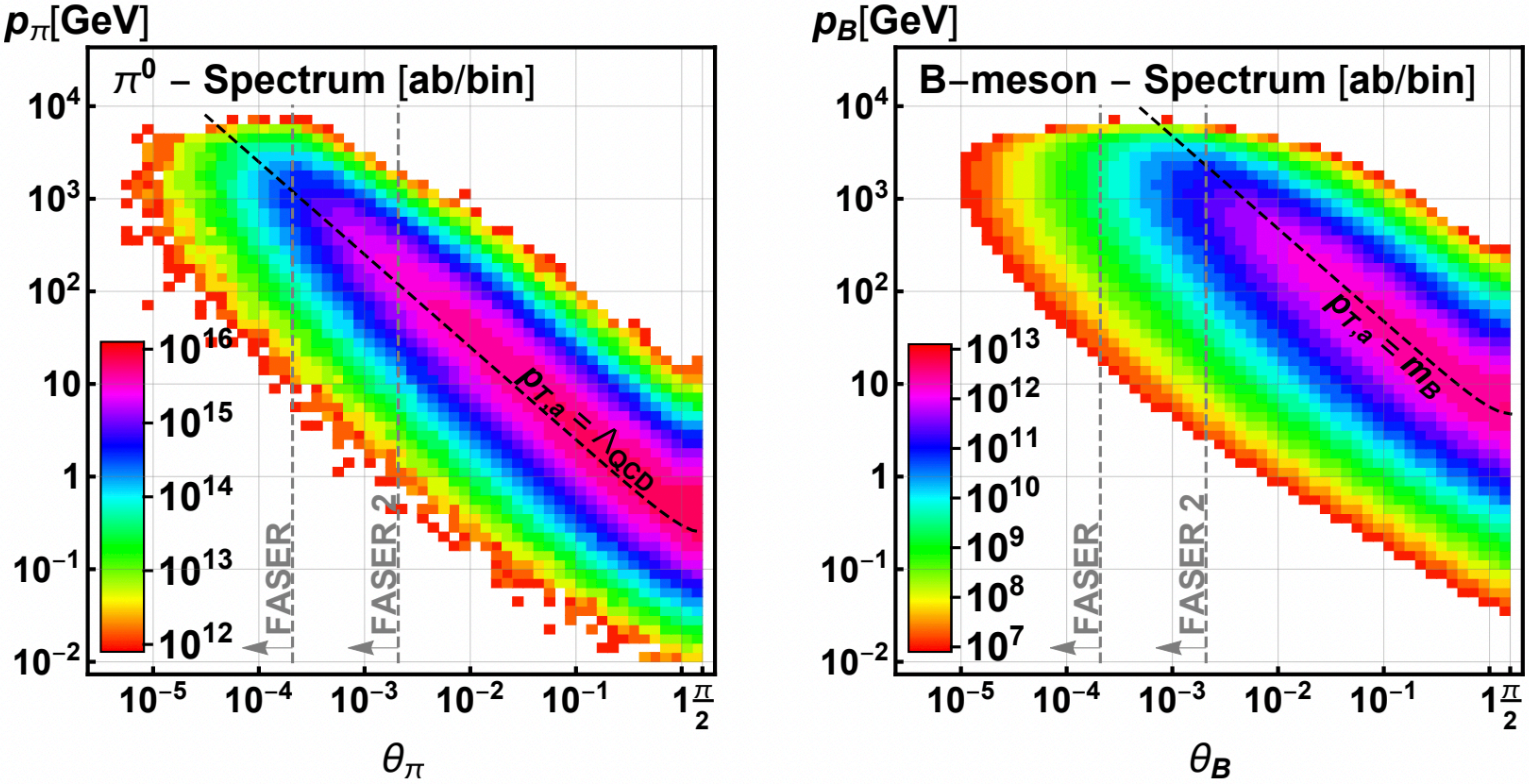
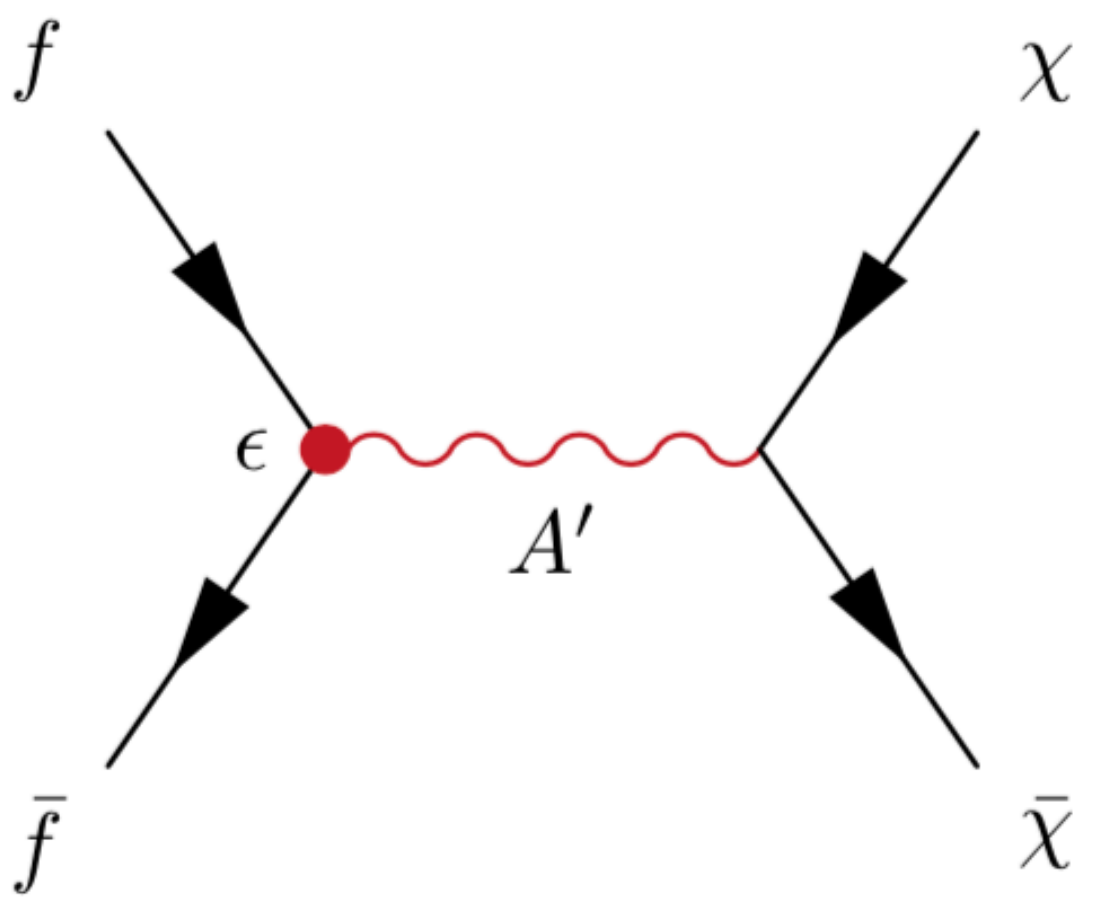
- Radiation level predicted to be very low in TI12 due to dispersion function of LHC at TI12.
- Measurements using BatMon radiation monitor in 2018 confirm FLUKA expectations:
    - less than 5 x 10^{-3} Gy/year
    - less than 5 x 10^{7} 1 MeV neutron equivalent fluence/year
- **FASER detector does not need radiation hard electronics**



Particle spectra



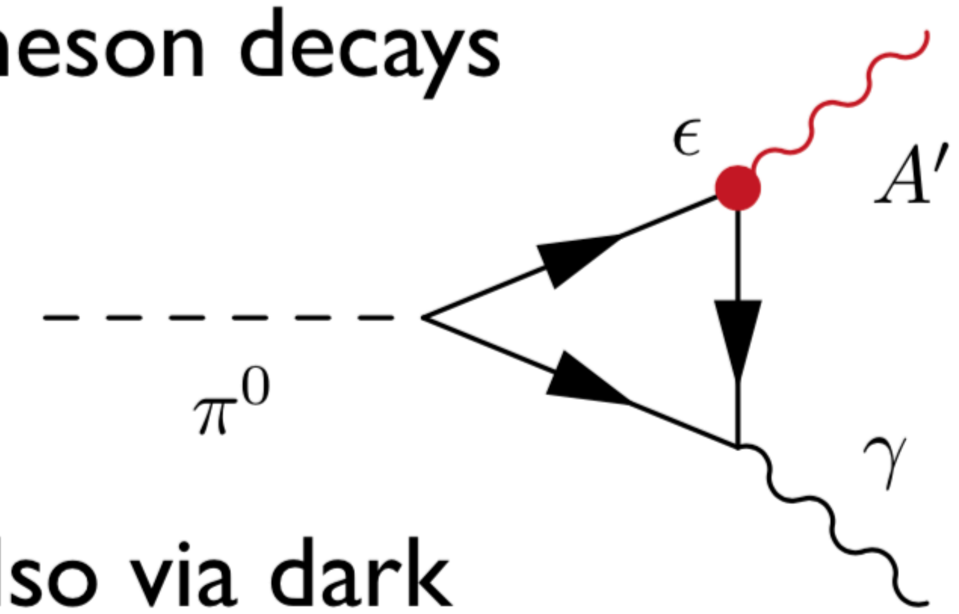
Overview | Dark photons



$$\mathcal{L} = \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu + \sum \bar{f}(i\,\partial\!\!\!/ - \epsilon e q_f A\!\!\!/') f$$

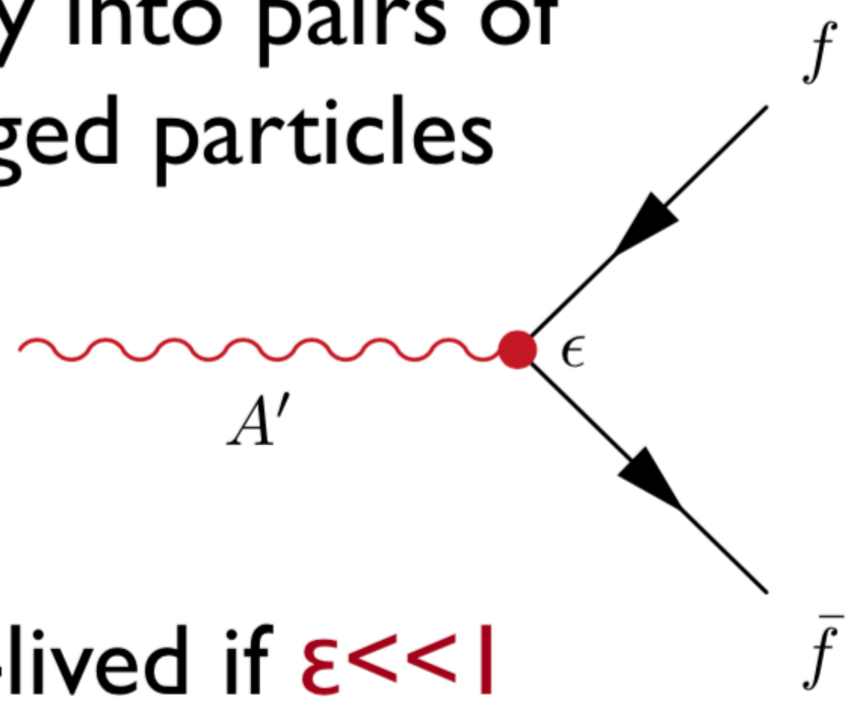
Dark Photons at FASER

- produced for example in meson decays



- also via dark Bremsstrahlung at large $m_{A'}$

- decay into pairs of charged particles



- long-lived if ε<<1

Overview | Dark photons

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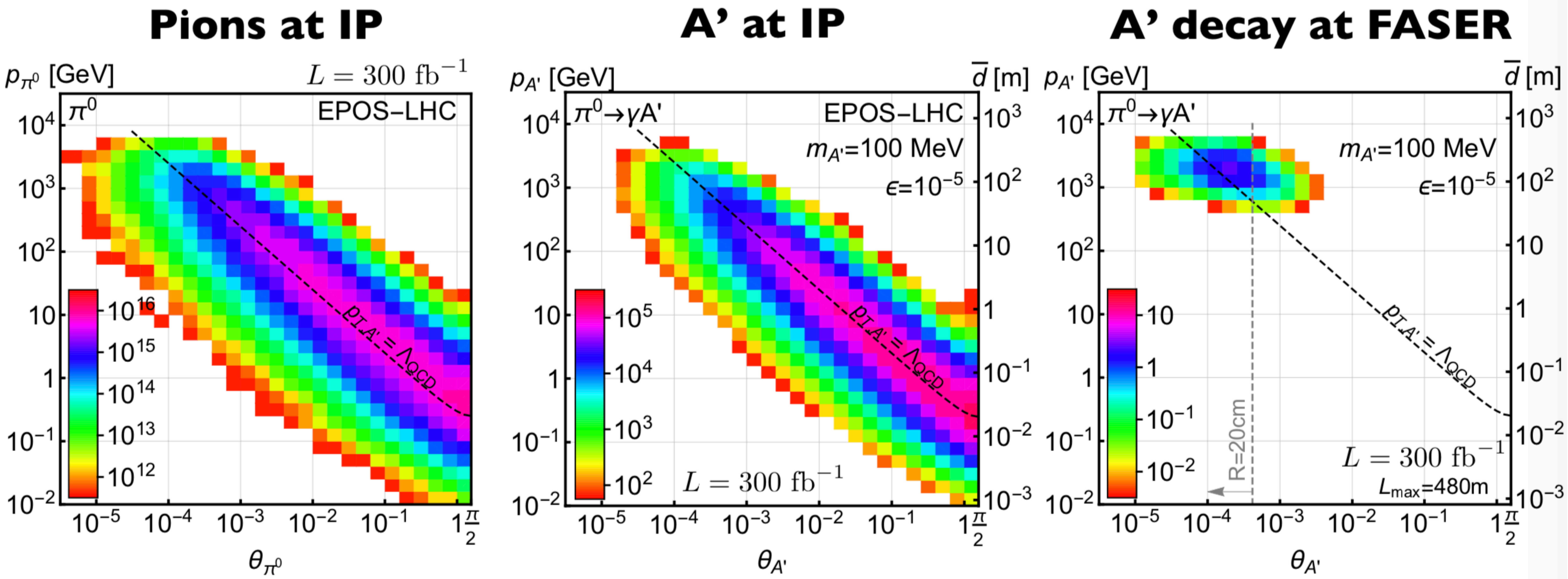


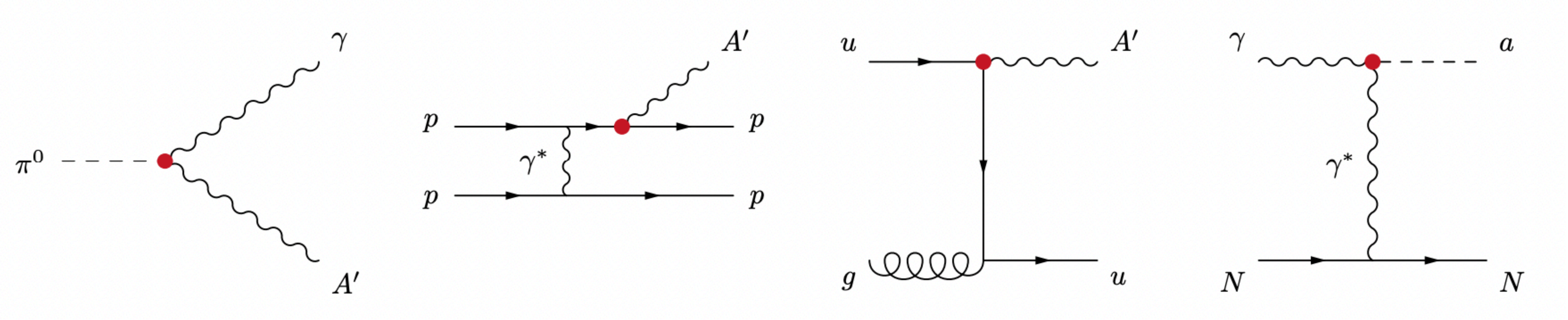
- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ Λ_{QCD}
- enormous event rates N ~ 10^{15} per bin

- production peaks at pT~ Λ_{QCD}
- rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- still rates N~10^5 per bin: LHC could be dark a photon factory

- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

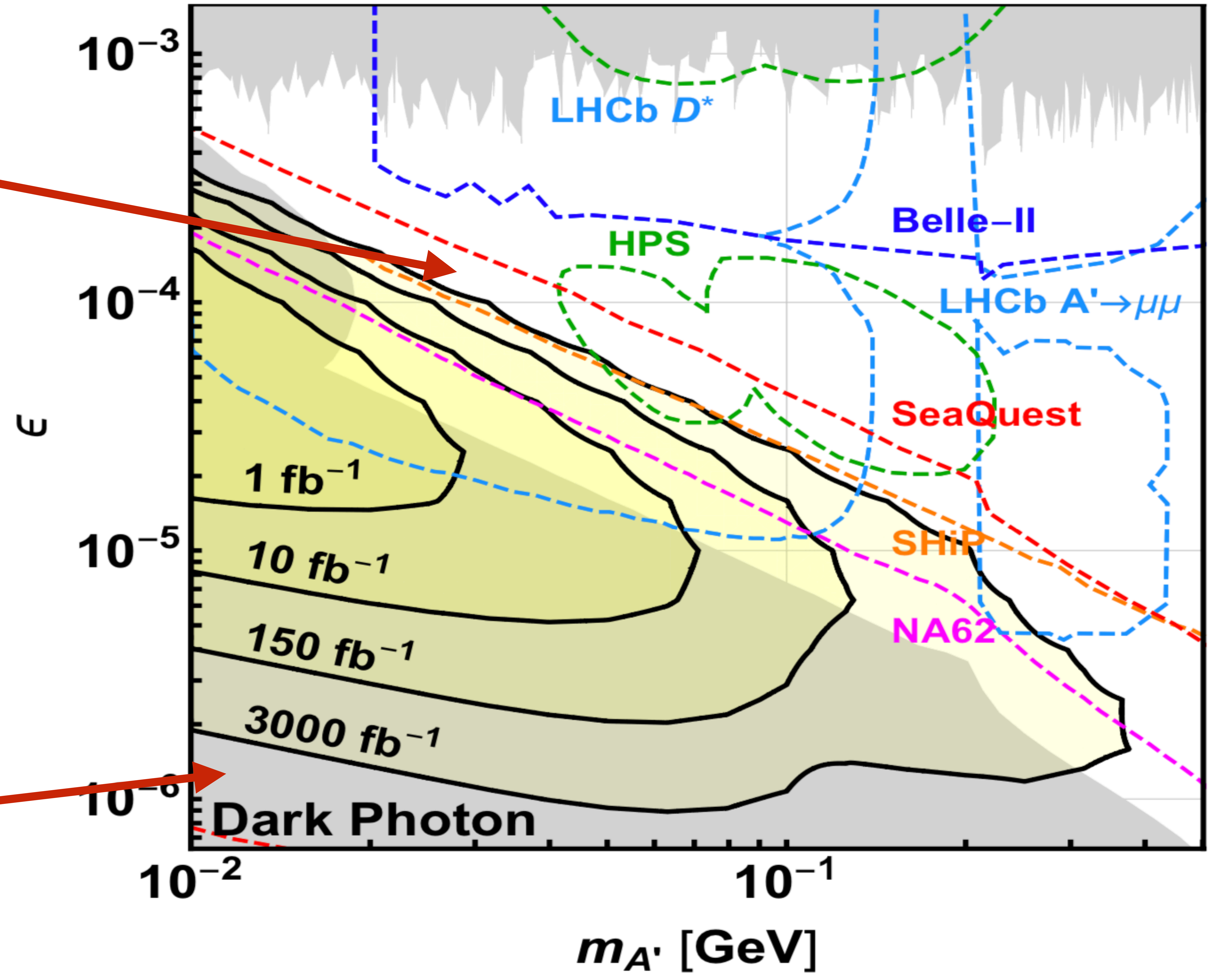
19

Overview | LLP production modes



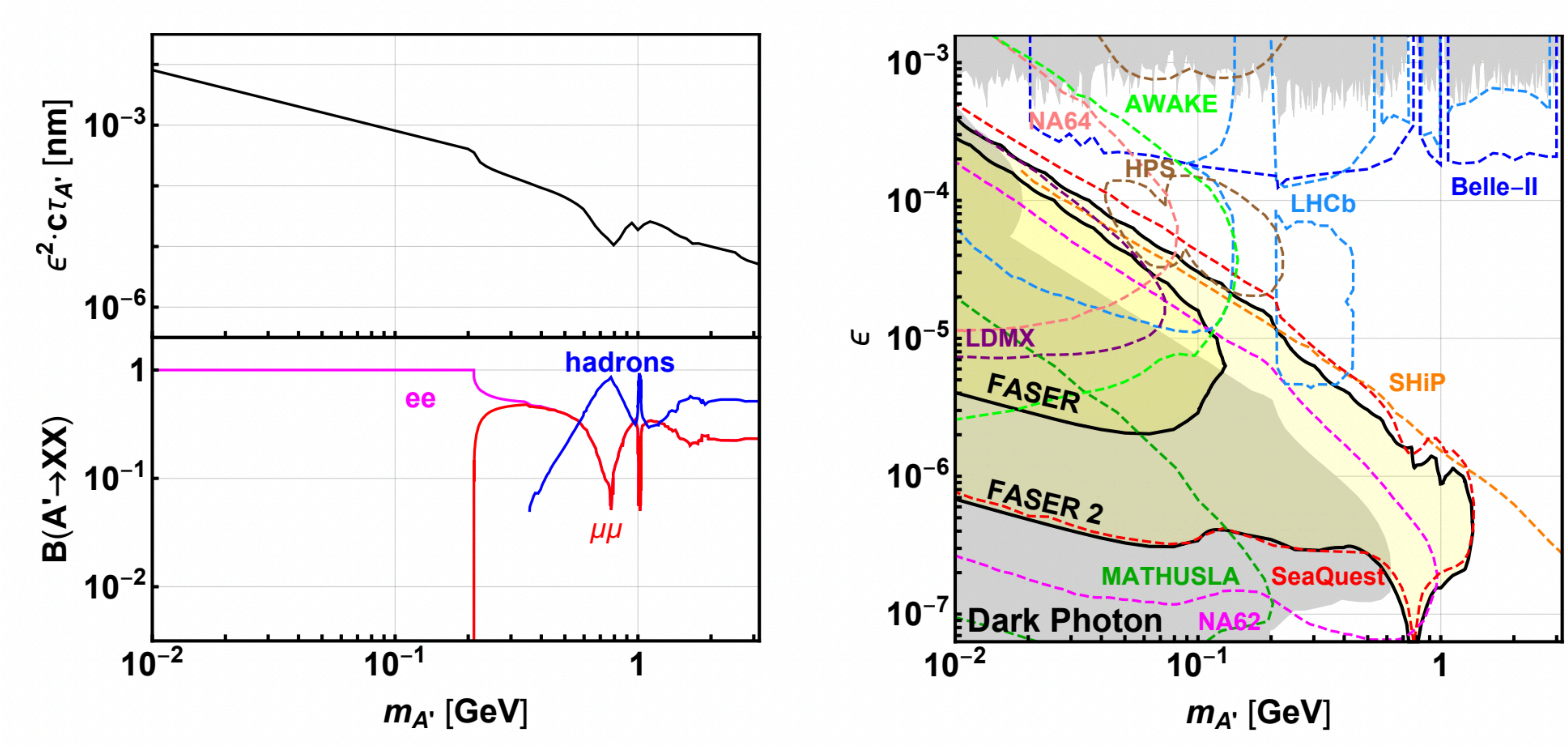
Overview | Dark photon reach

For lower lifetime the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector

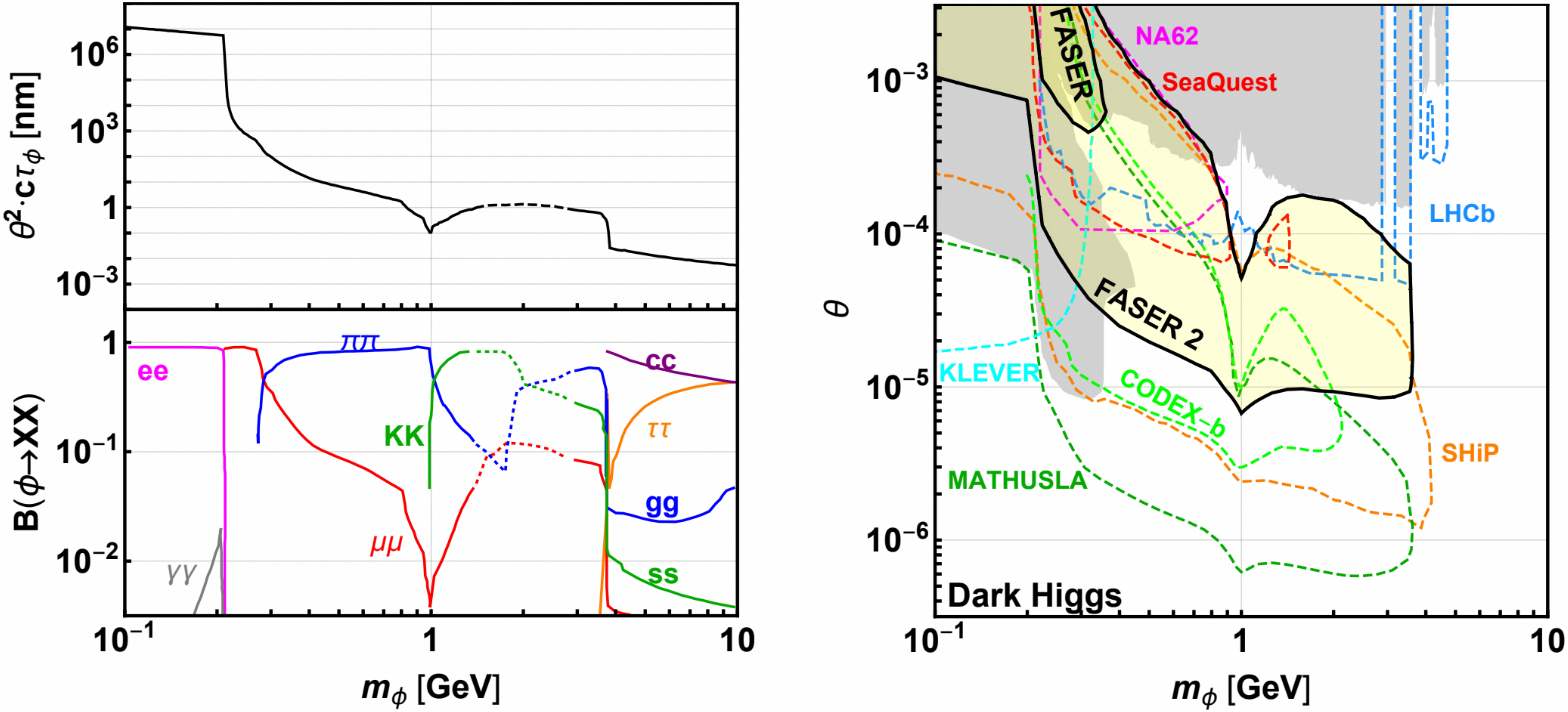


Combining dependence in both production rate and decay width, total number of signal events in the detector scales as ε^4

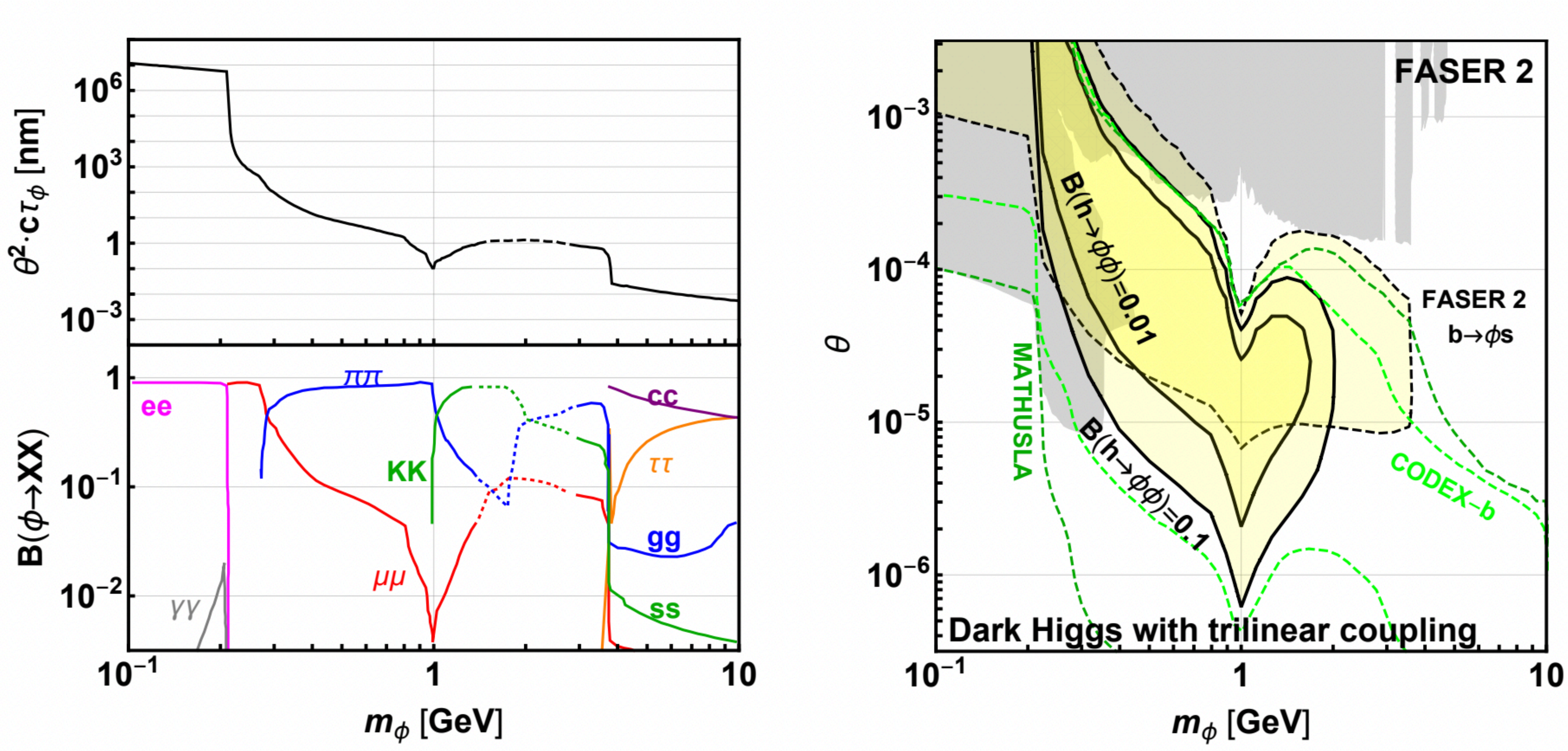
Target scenarios | Dark Photon



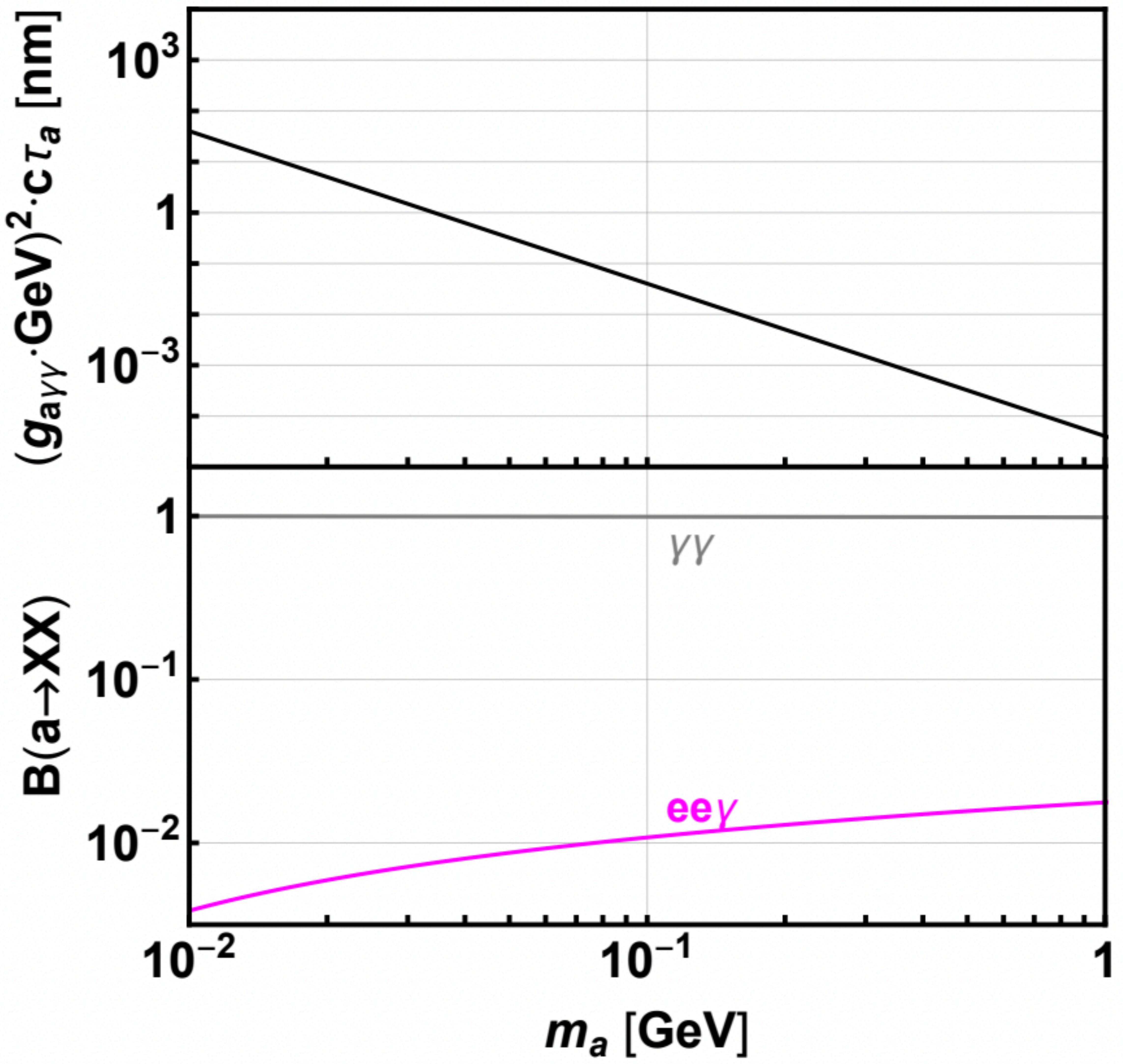
Target scenarios | Dark Higgs

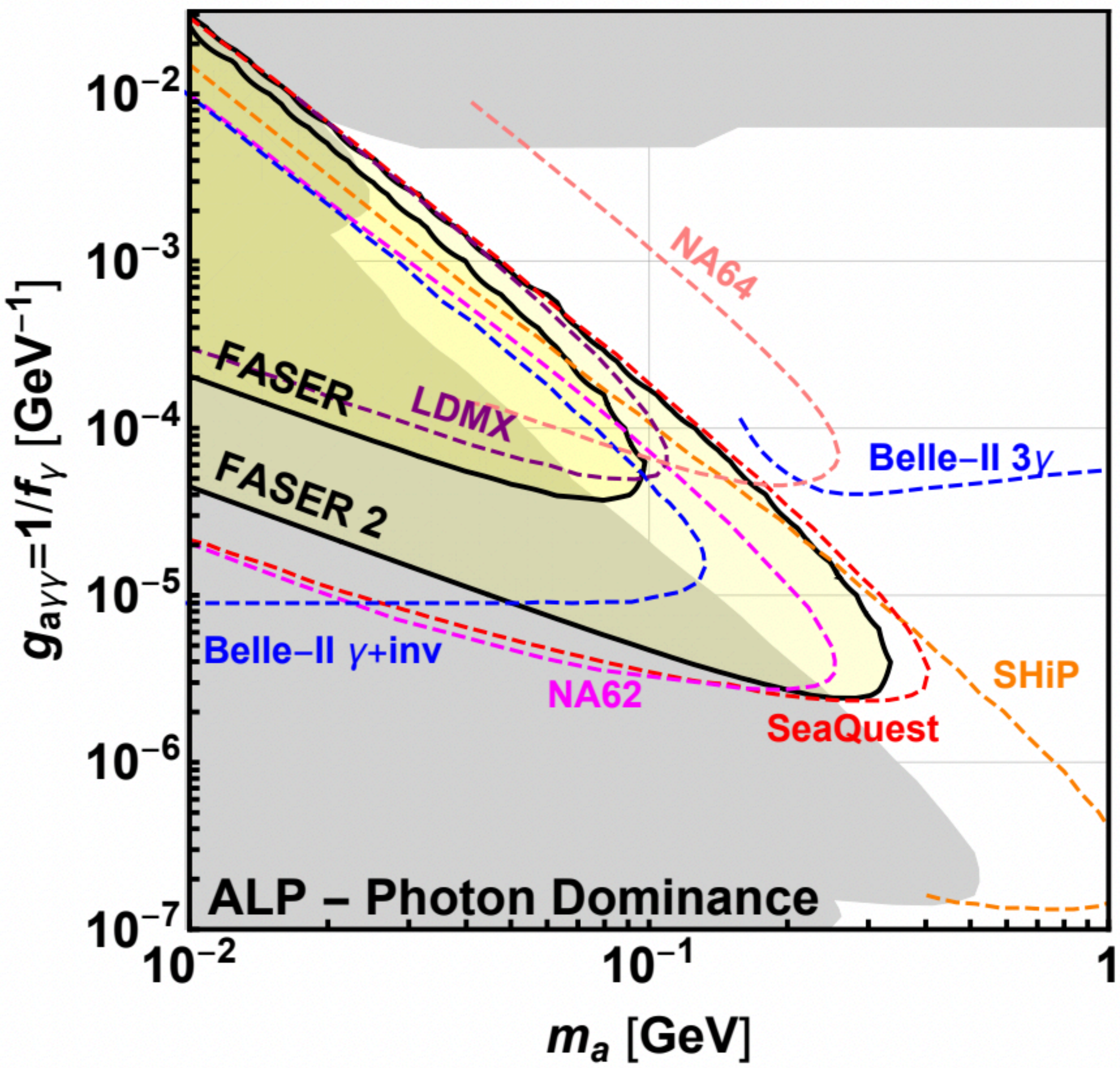


Target scenarios | Dark Higgs

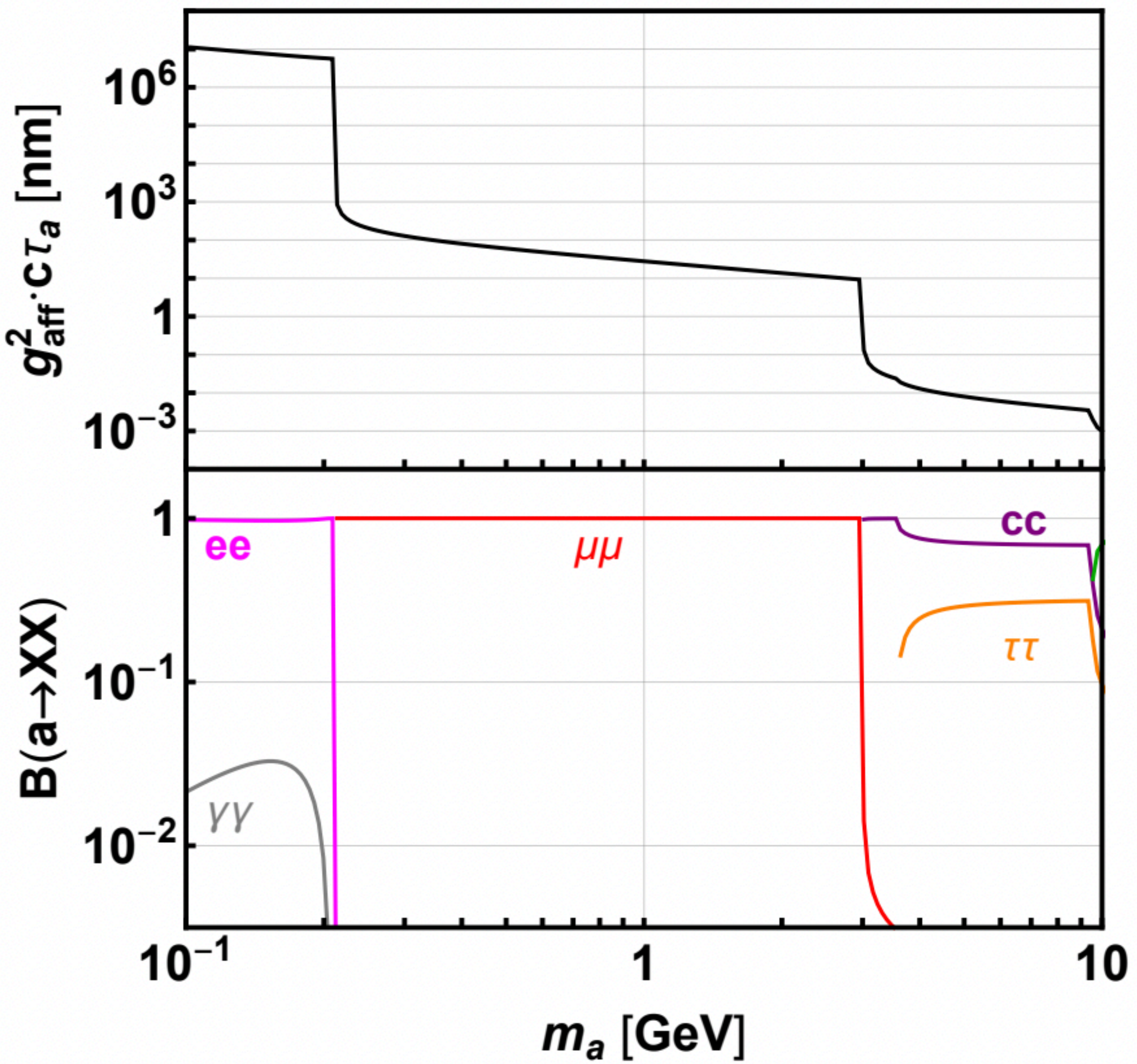


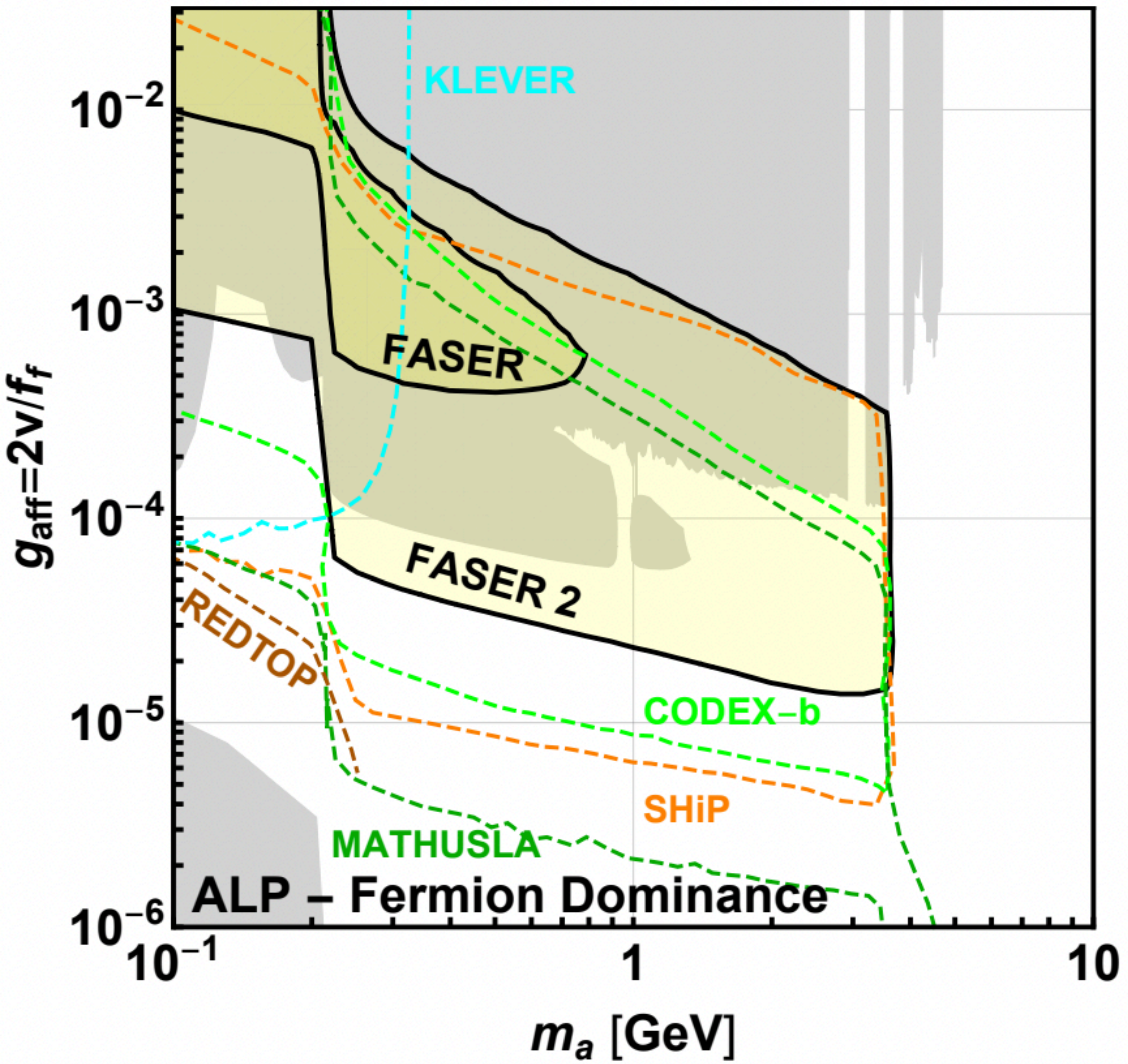
Target scenarios | ALP





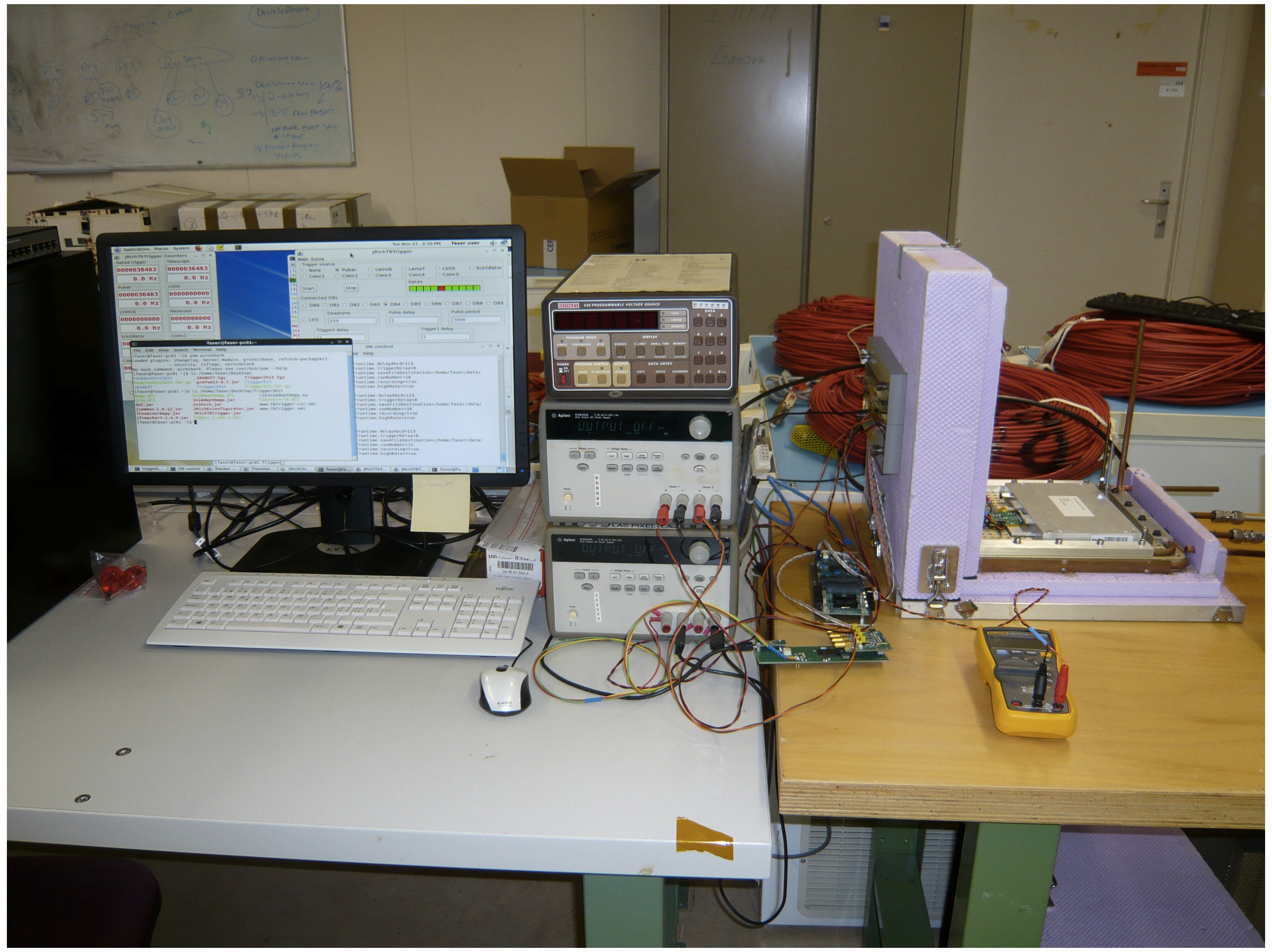
Target scenarios | ALP

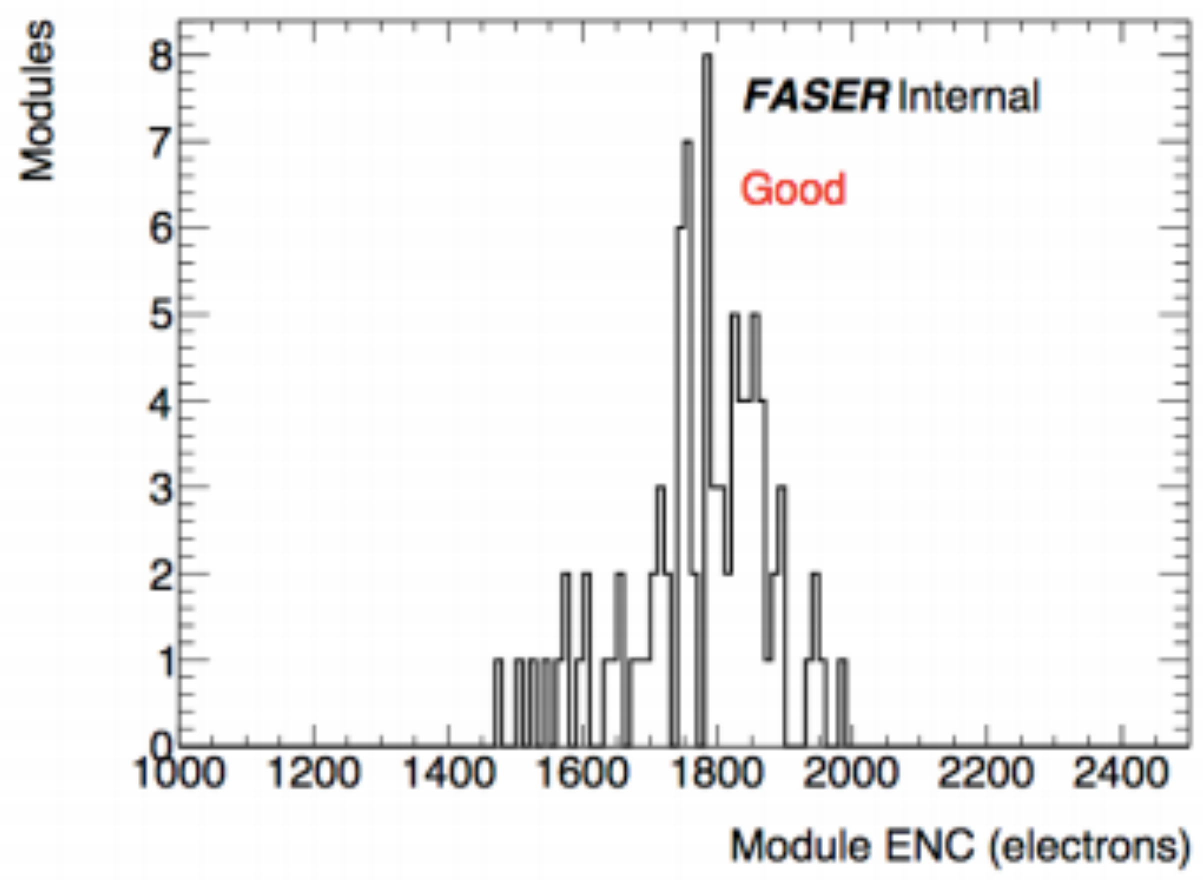


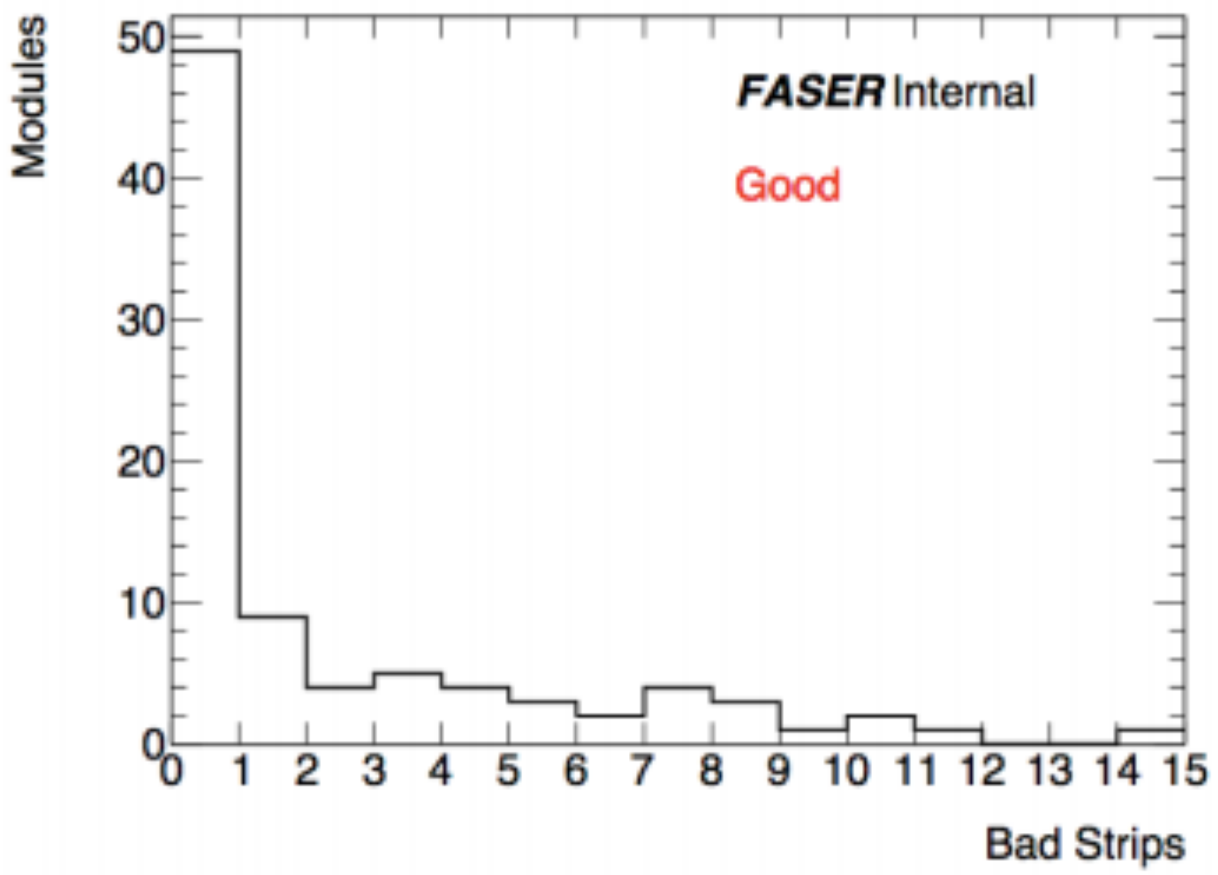


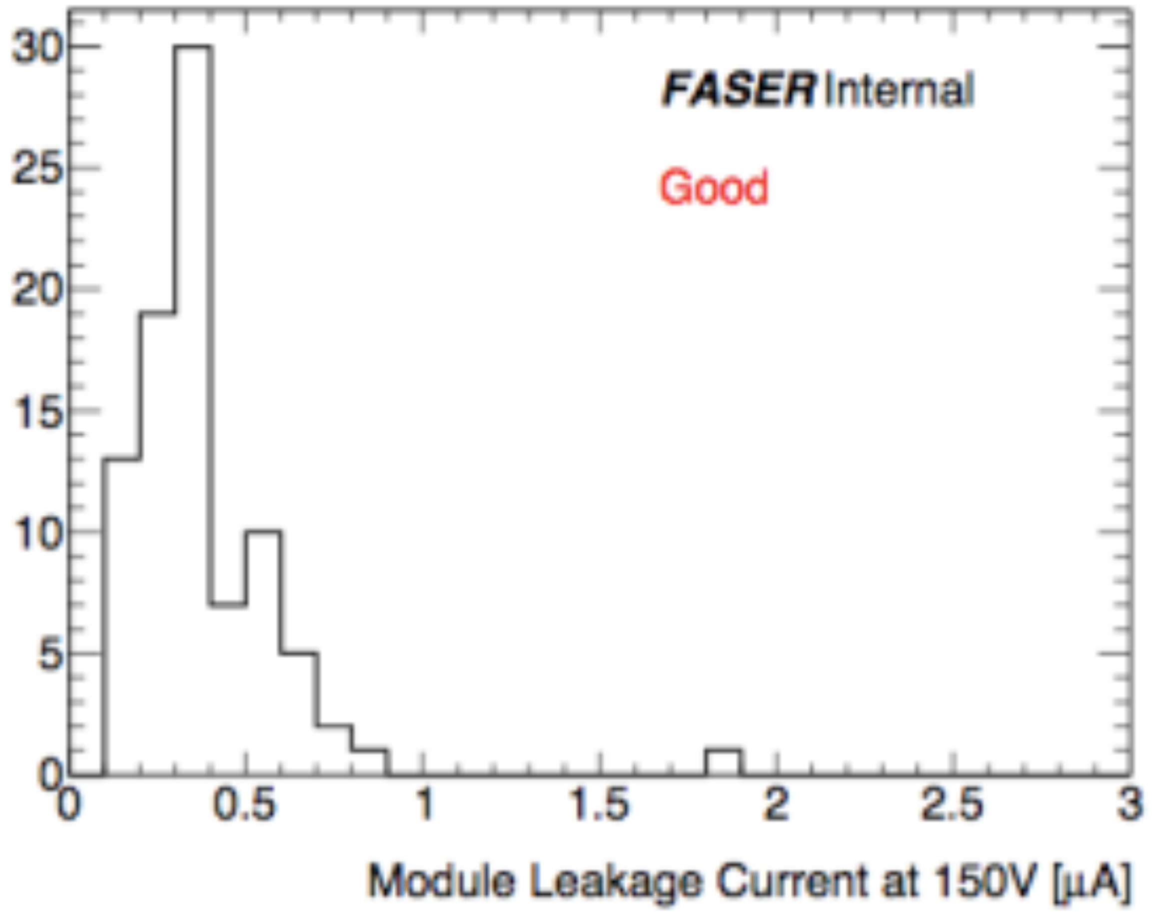
Tracker | Module QA

- SCT modules used had passed ATLAS QA in ~2005 and then been kept in storage.
  - Important to test their functionality.
- SCT module QA at CERN in March 2019. Identified > 80 good spare modules – more than enough for FASER needs.
  - Performance seems not to be degraded by long term storage/age.



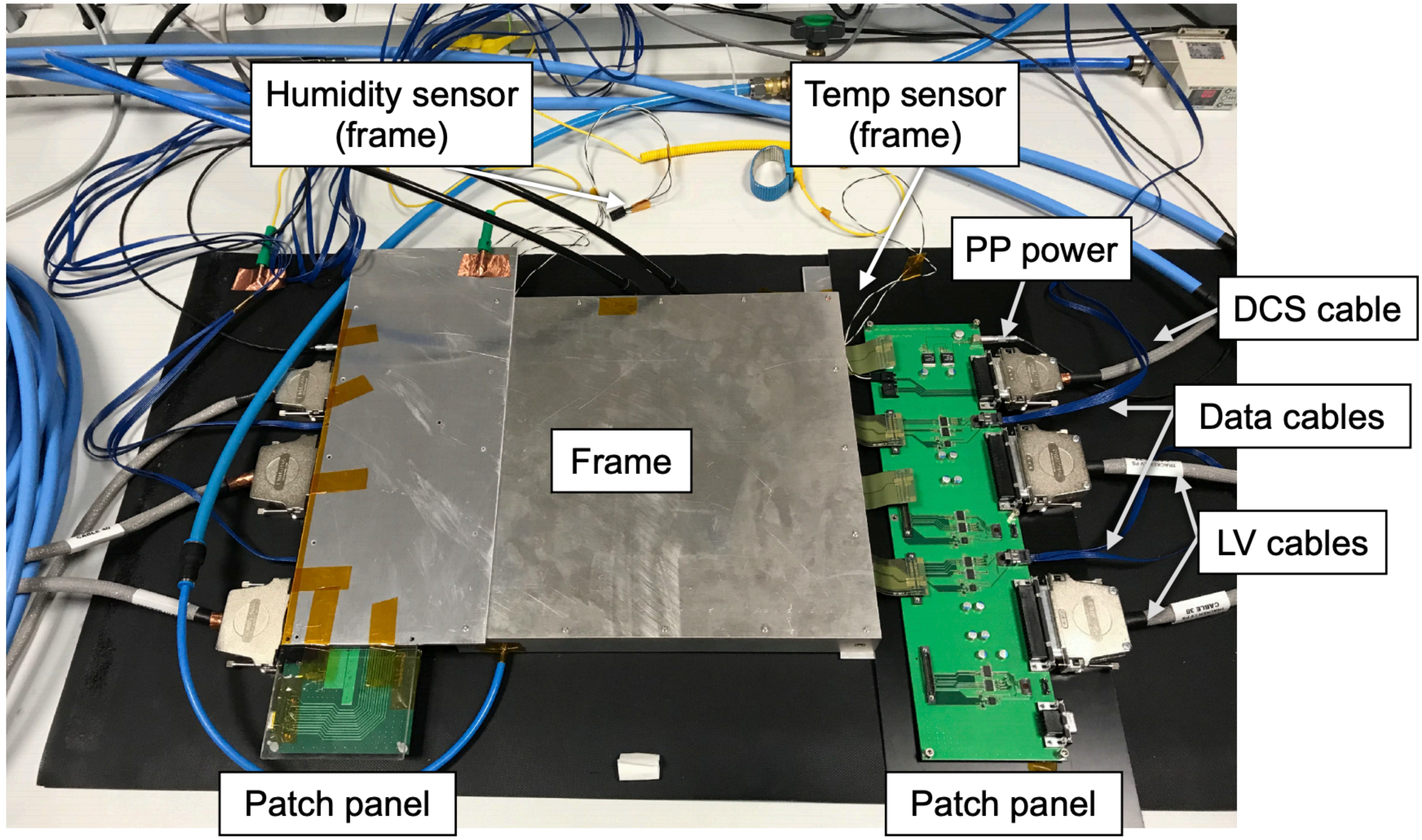


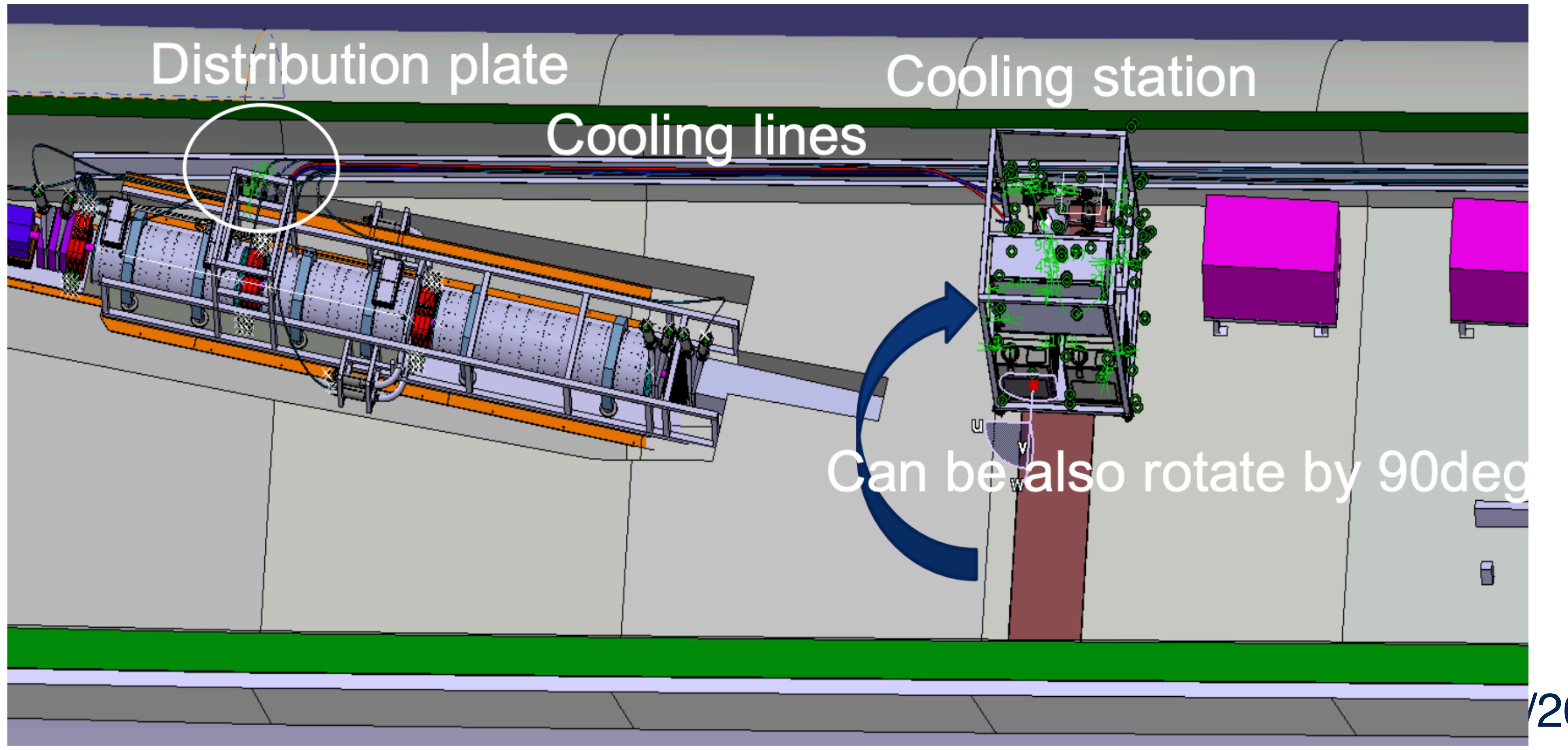




Tracker | Cooling

- Due to low radiation – silicon operated at room temperature. Still need to remove heat from on detector ASICs (5W/module => 360W for the detector). Use simple water chiller (temp ~10-15degrees) – cooling pipe around outside of aluminium frame. Thermal properties validated with FEE simulation and measurements.





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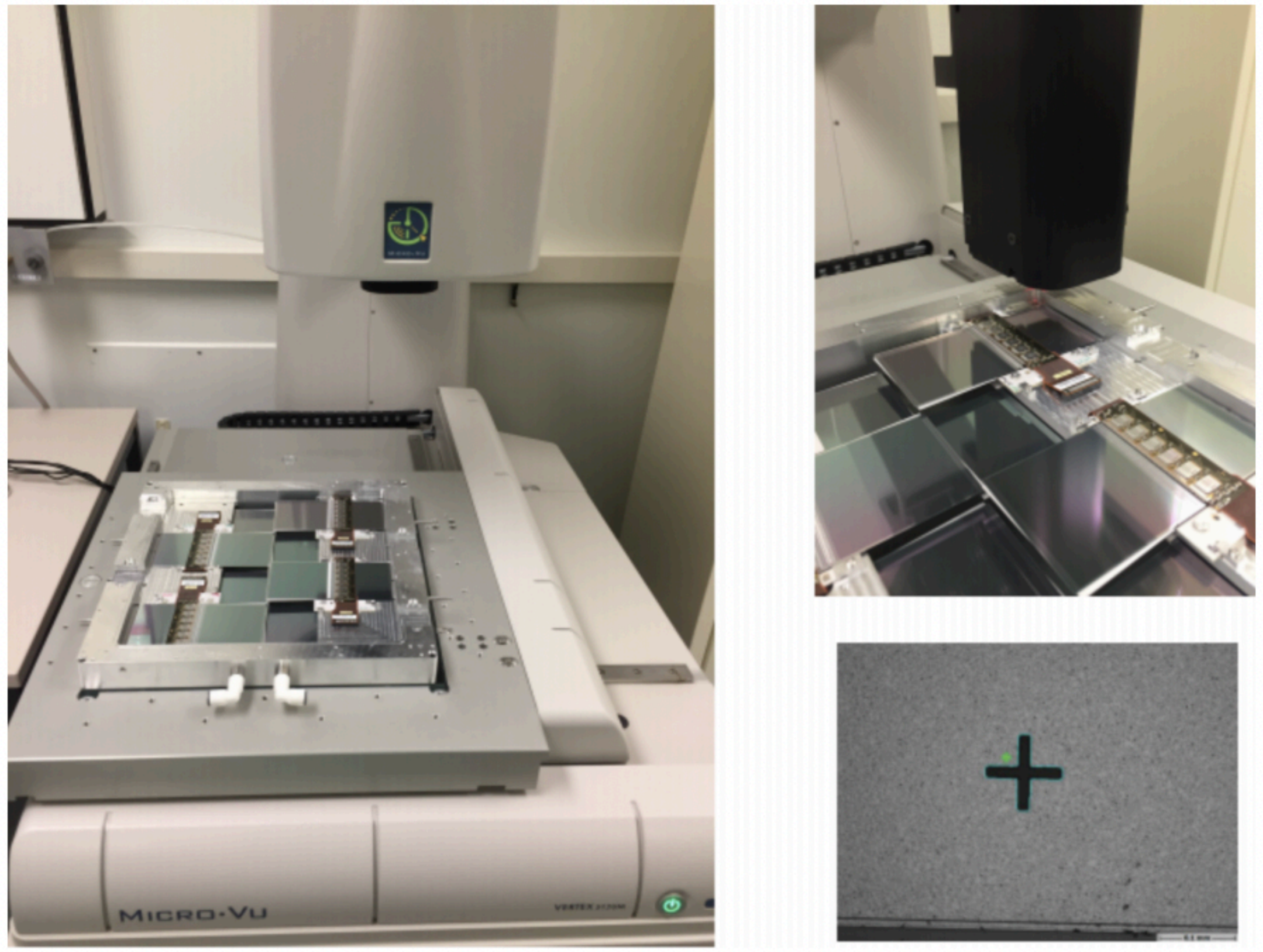
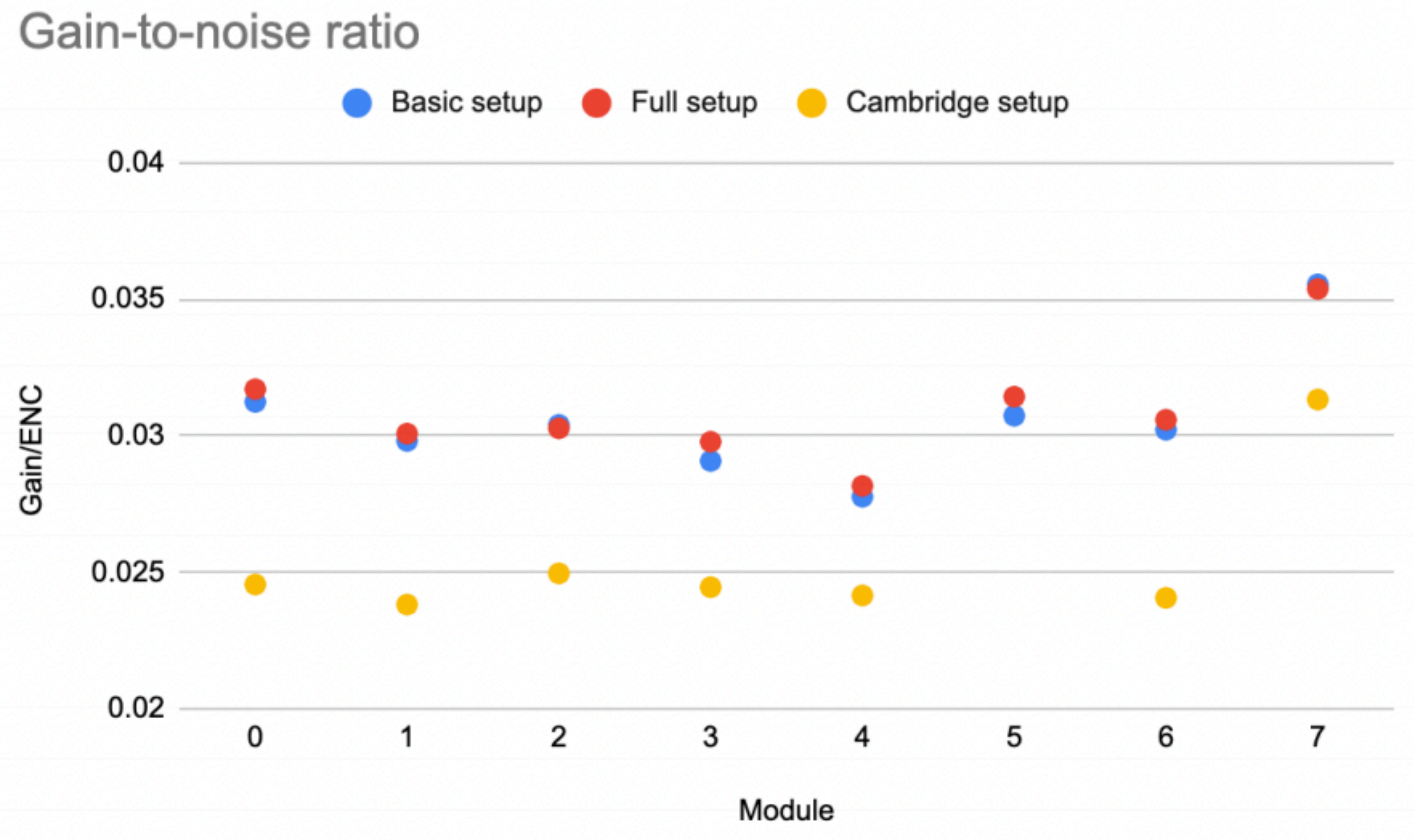
FASER cooling unit, designed/constructed by CERN EN-CV group. Has 2 water chillers for redundancy, and control logic to monitor and remotely switch between them as needed.

Tracker | Prototype layer

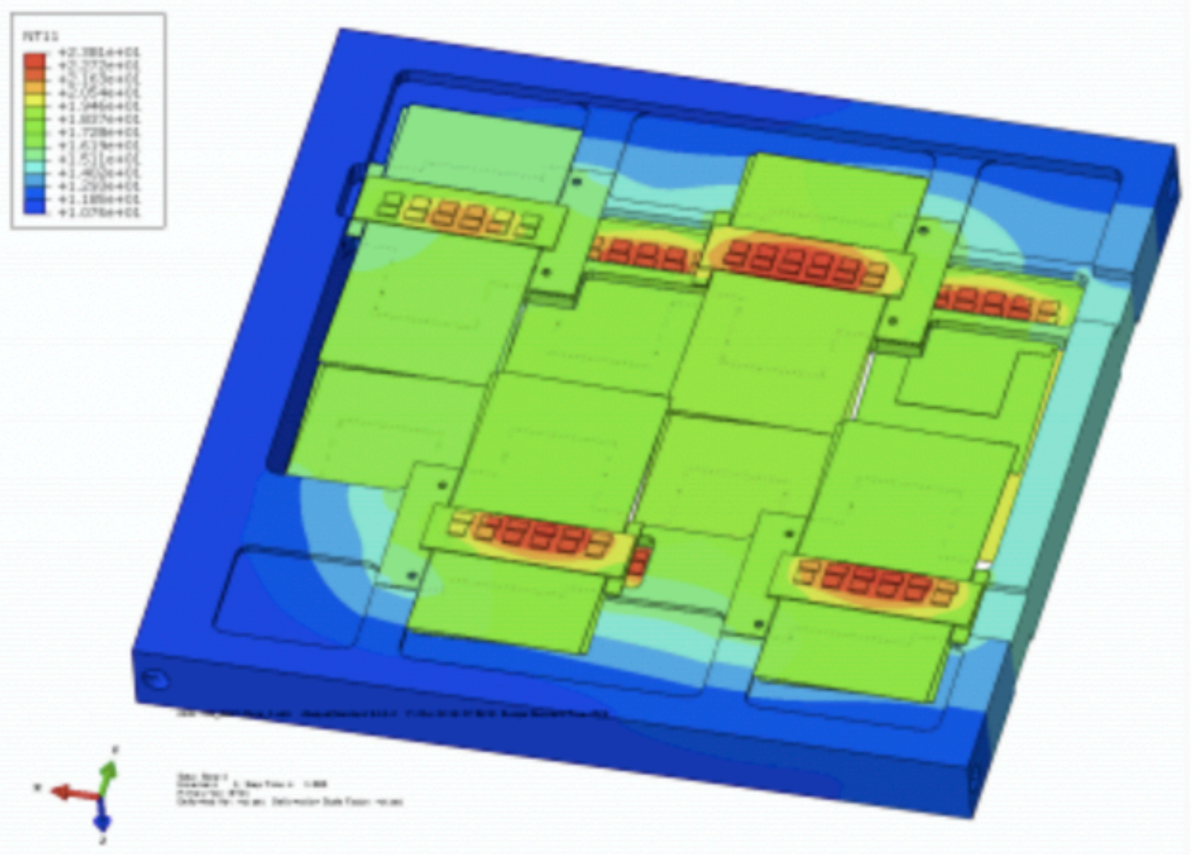
- Thermal measurements
- Readout tests (calibrations/scans) and noise measurements
- Metrology for pre-alignment (~ few microns precision)



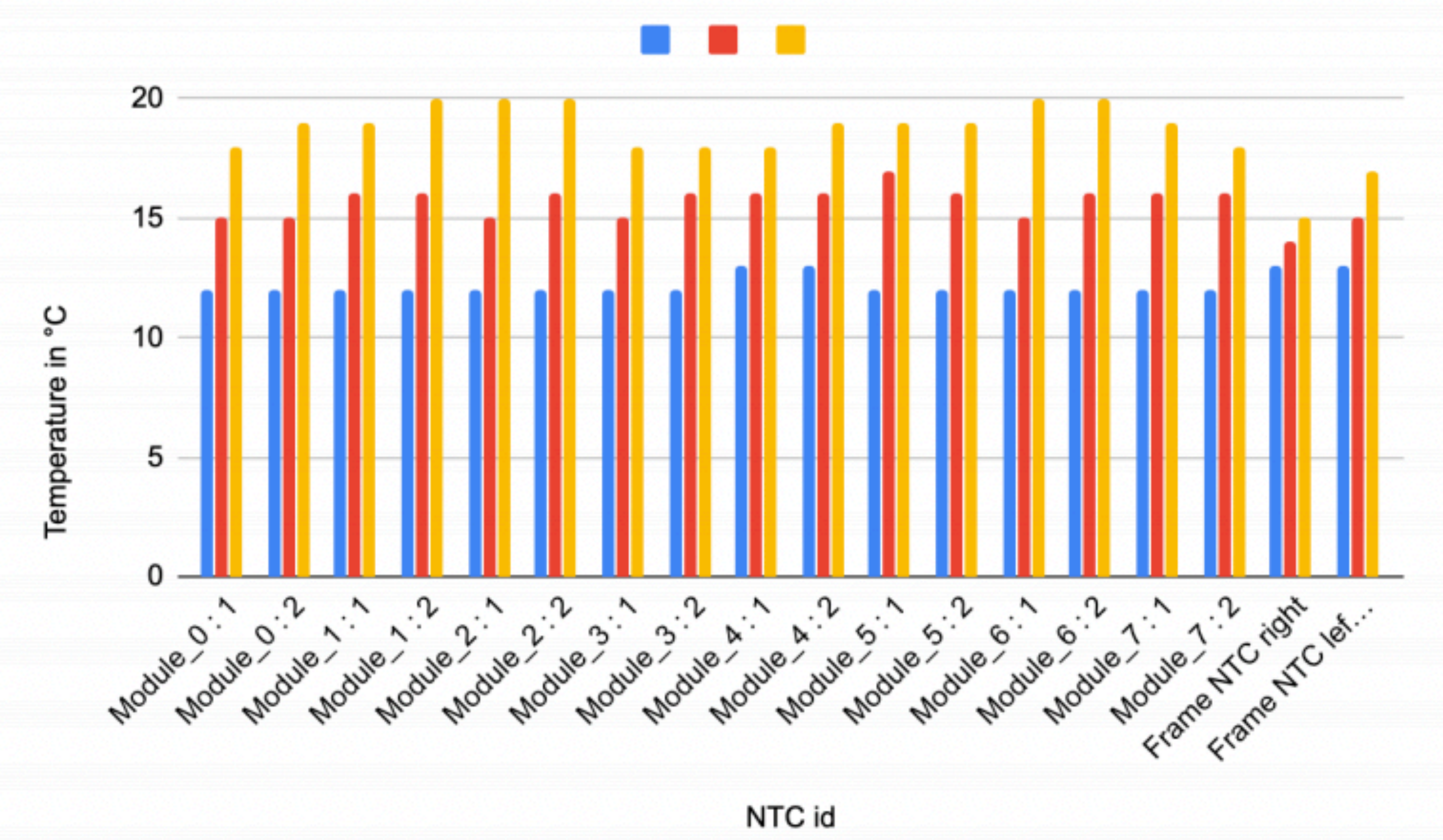
Metrology studies



Gain/noise measurements



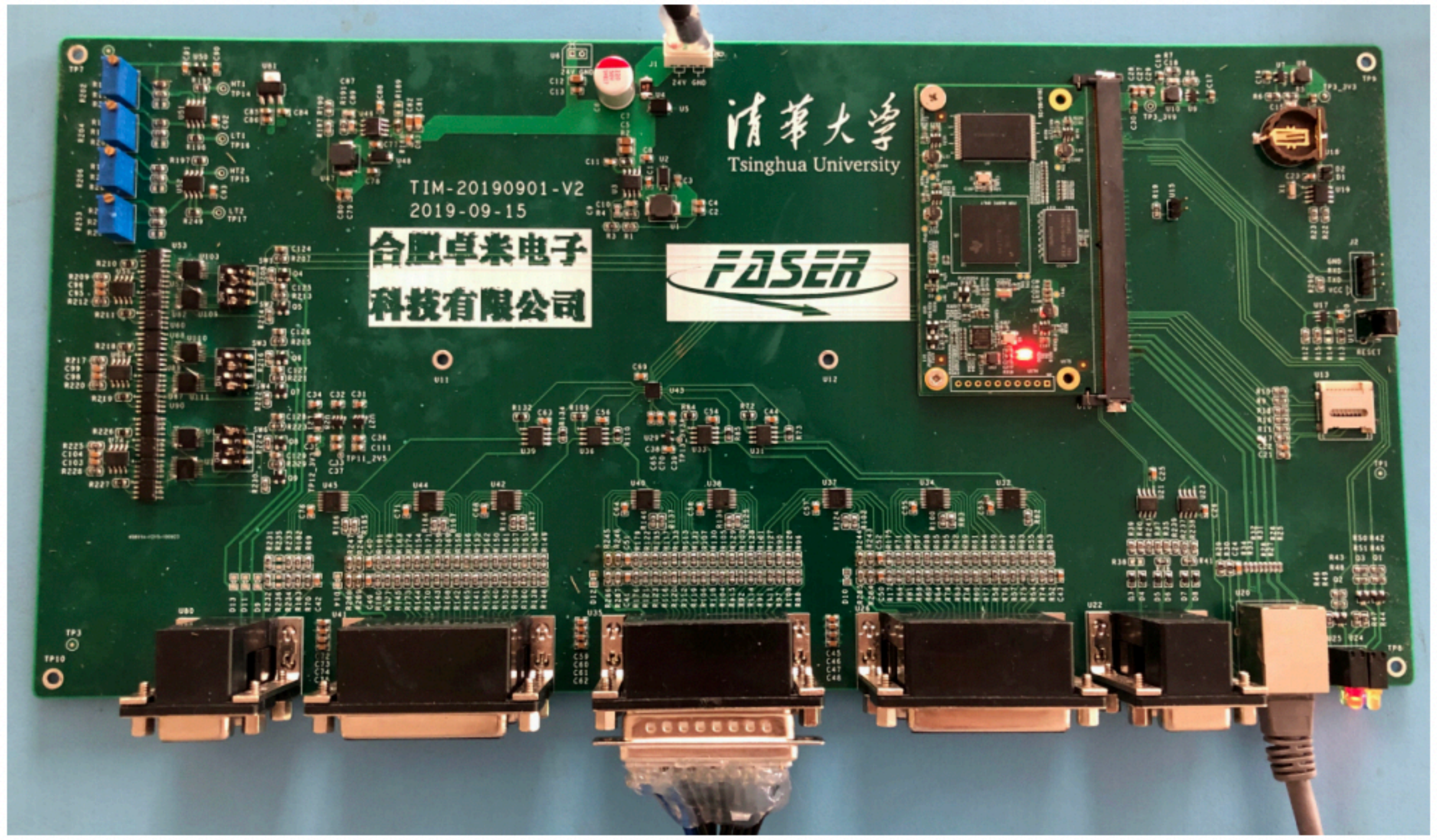
FEA simulation

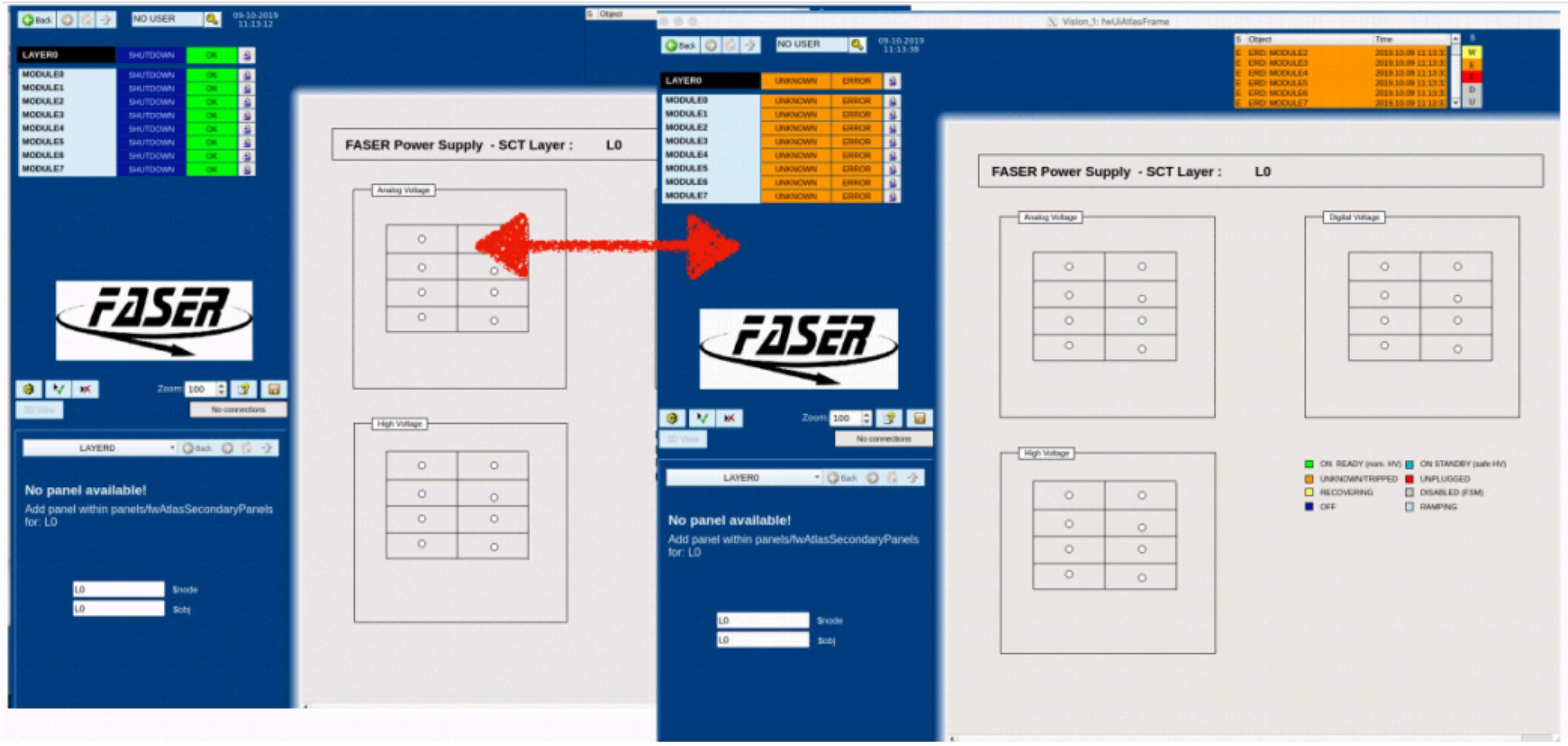


Thermal measurements

Tracker | Monitoring, cooling & power

- Low radiation environment → simple water chiller at ~ 15 °C sufficient to cool ASICs
- Dry air in tracking stations (avoid condensation)
- WIENER system for power supply
- Custom board for tracker interlock & monitoring (TIM)
- Detector Control System (DCS) under development.





Scintillator & Calorimeter

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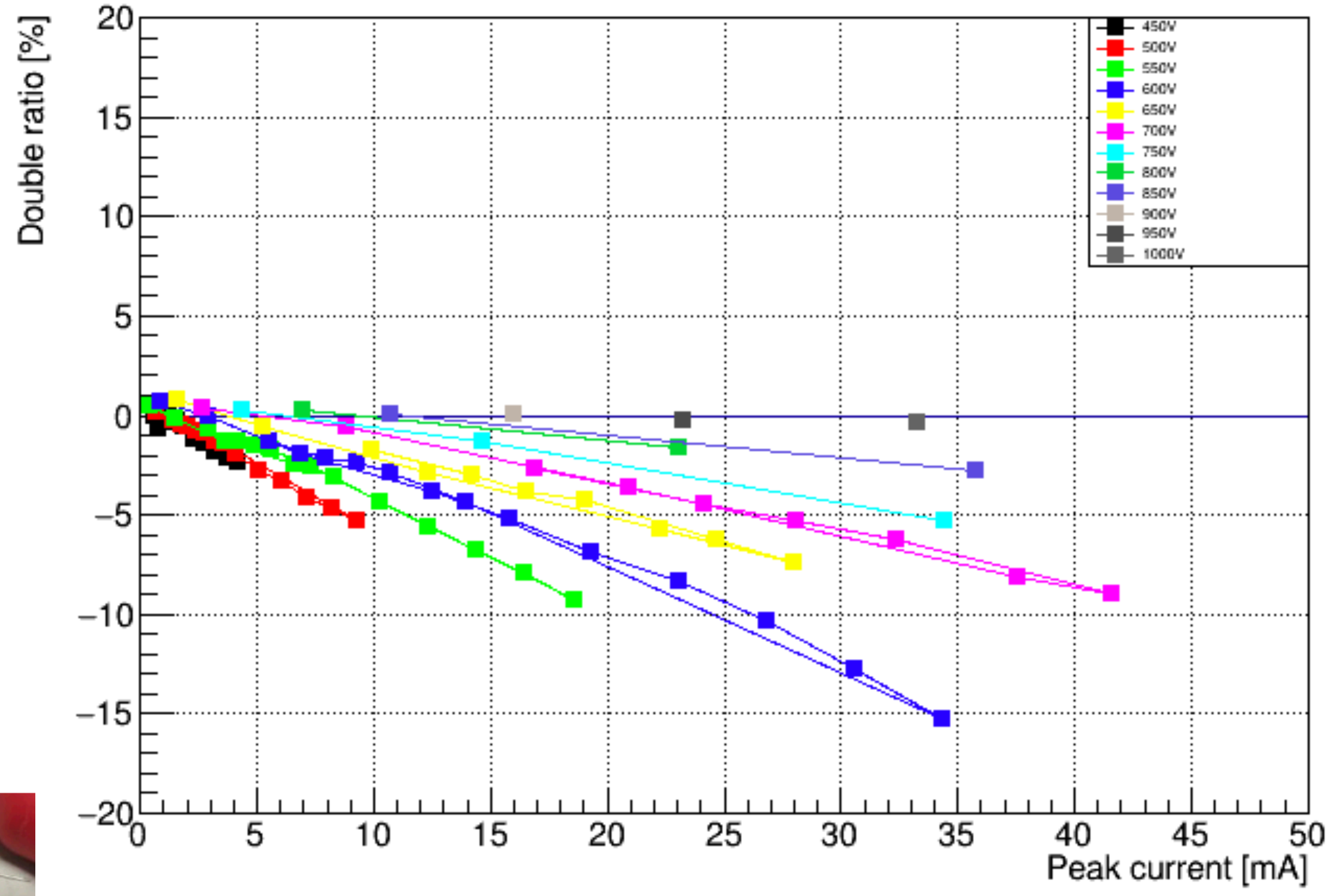
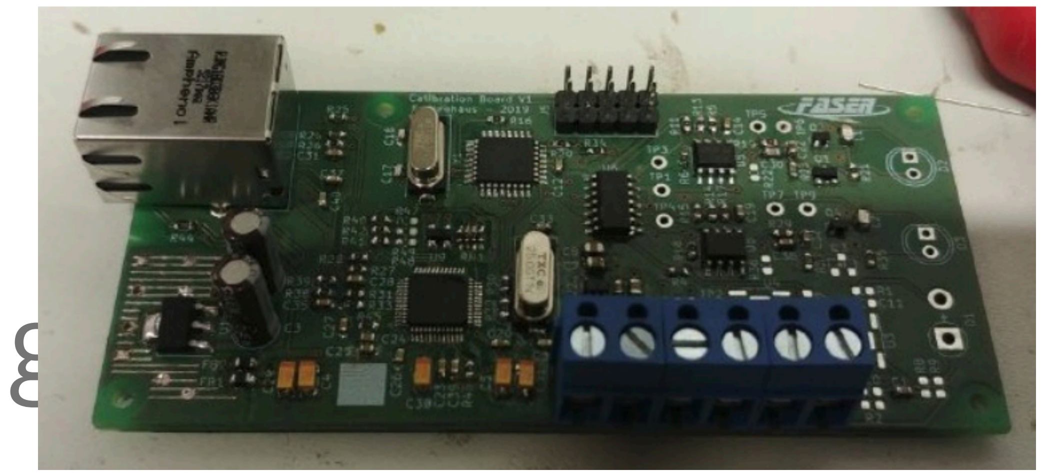
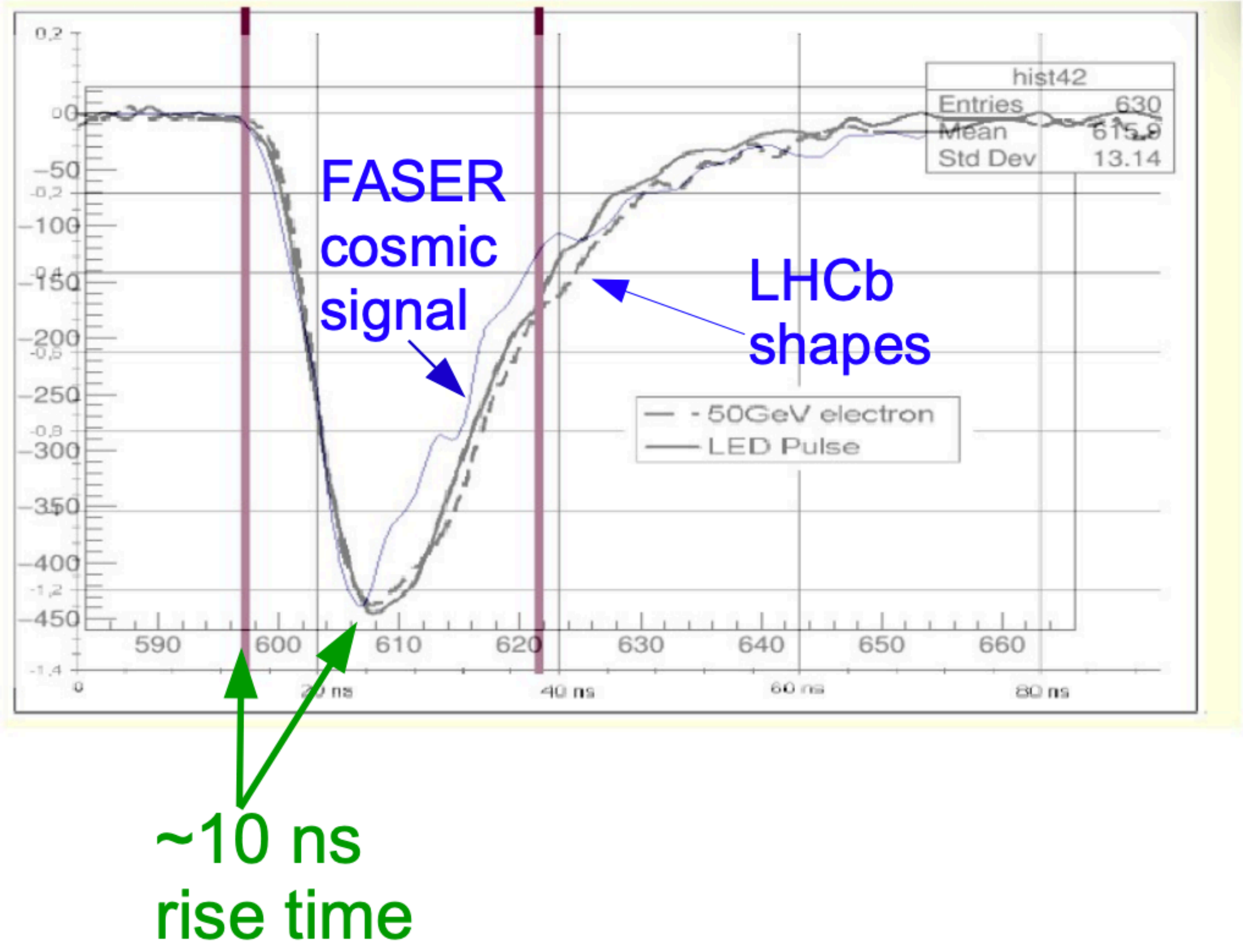
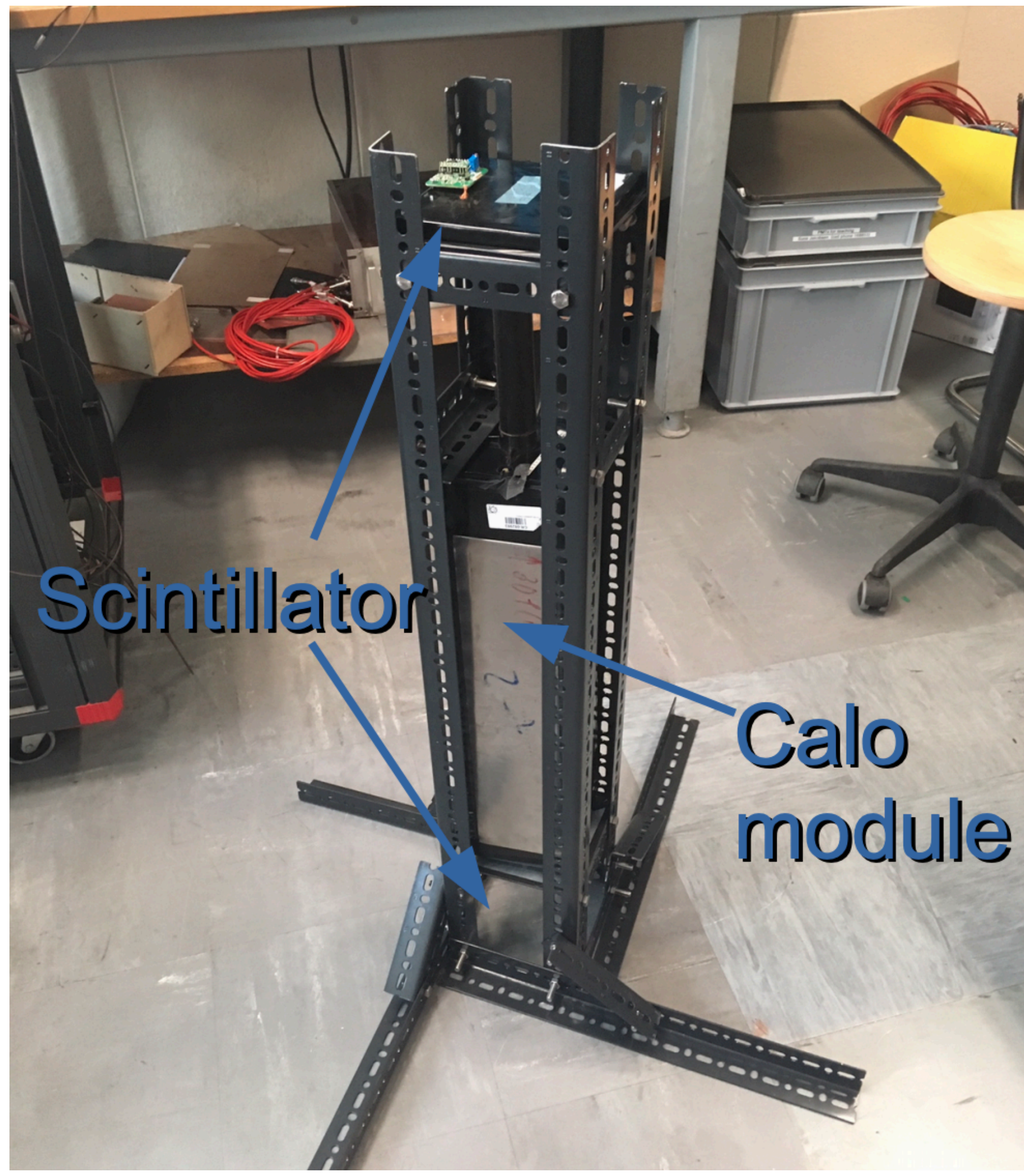
  - PMT signal read-out by digitiser.
  - Well defined procedure to extract gain and linearity measuremen
- In-situ calibration
  - Will measure gain vs HV, by pulsing with high intensity LED
  - Circuit designed and first testing in progress
- Optical filters
  - At very low gain PMT is not linear over full rang
    - Reduce signal by factor 10 using optical filter
    - Still leaves 100 photo-el. for MIP calibration
- Cosmic ray test stand
  - Testing calorimeter response & PMT calibratior
  - Read-out very close to final design
  - Good agreement with LHCb pulses observed

Linearity





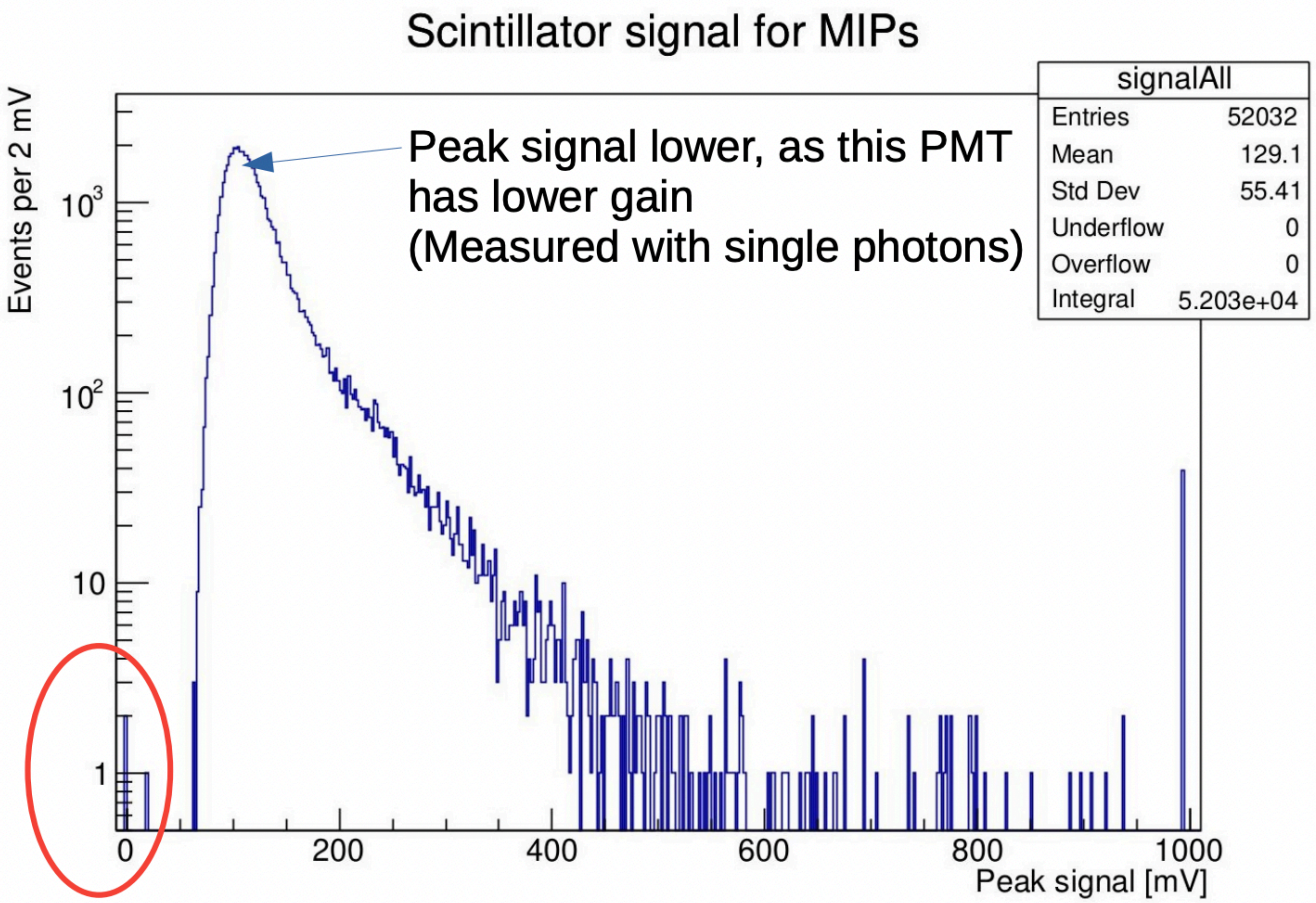




Scintillator | Characterisation

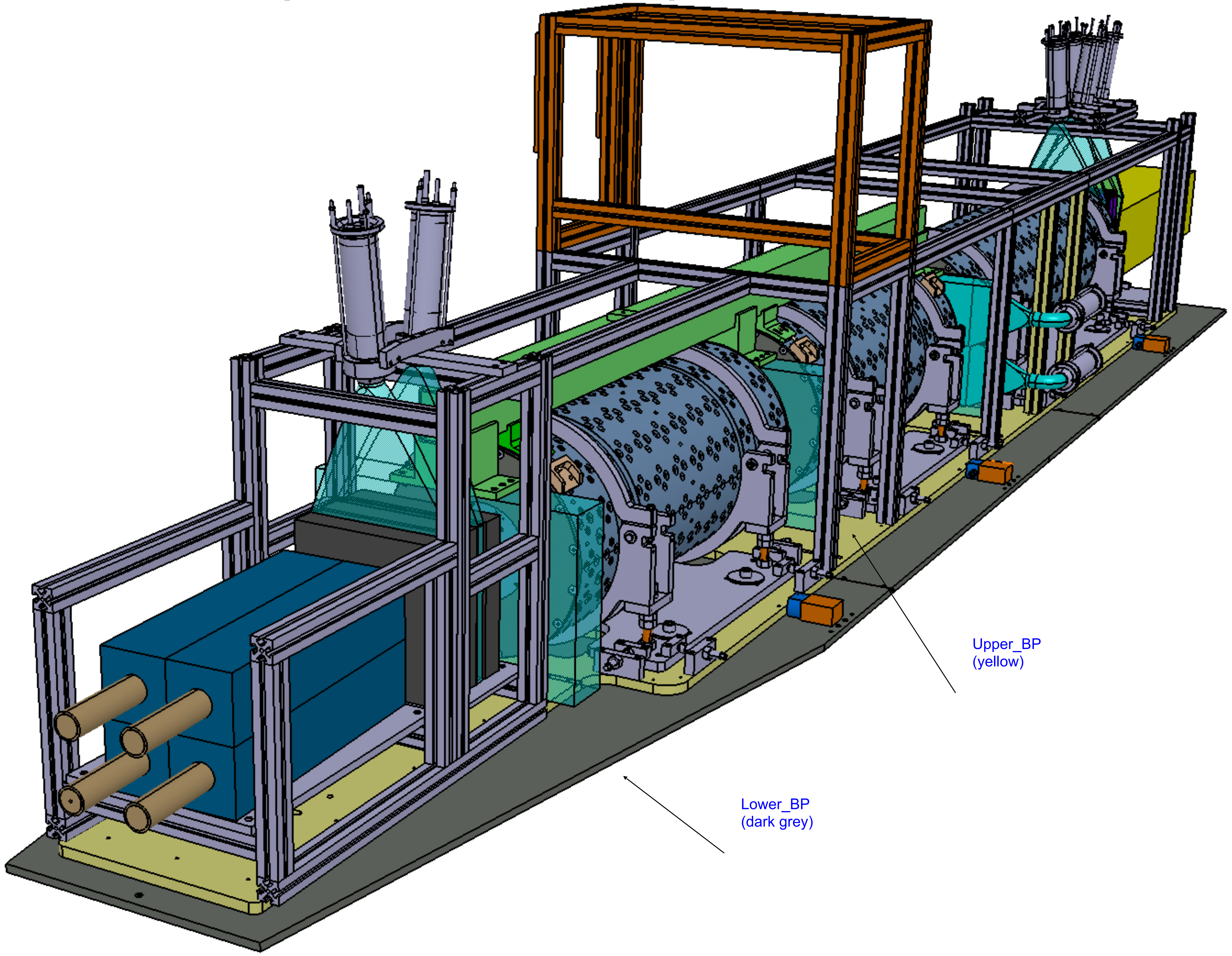
- Large light signal observed
  - ~100s of photons
- For middle sector we ran high stats (50k events) runs over night

Efficiency is [99.985:99.998]% at 95% CL



Frame

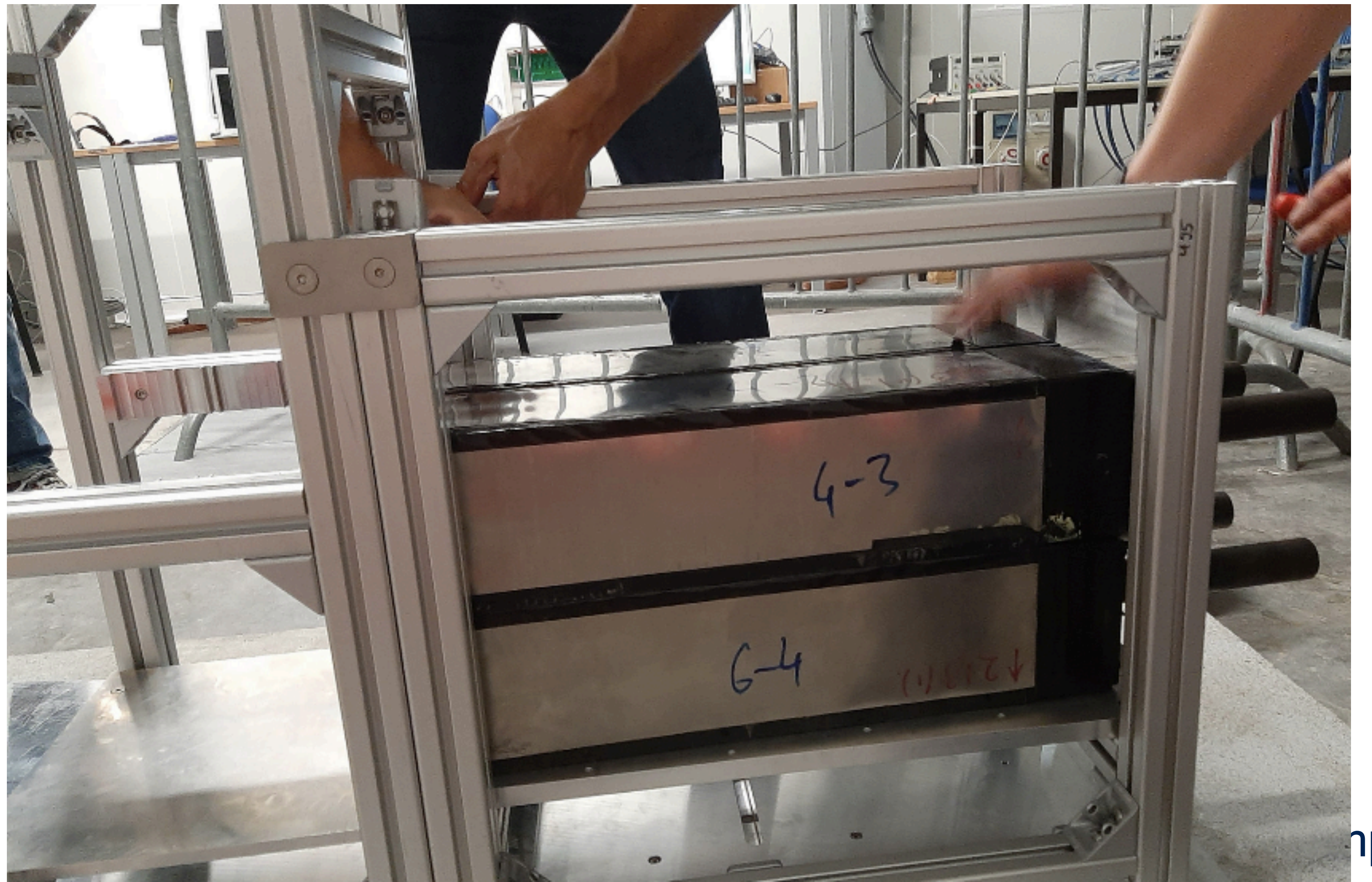
- Main requirements of detector support:
- Keep tracking stations well aligned in vertical plane (O(100μm))
- Align magnets to each other and LOS within a few mm
- Allow detector to follow changes in LOS due to changing crossing angle in IP1
  - Crossing angle moves LOS by ~7cm
  - Crossing direction can change in YETS



Calorimeter/Scintillators | Mounting

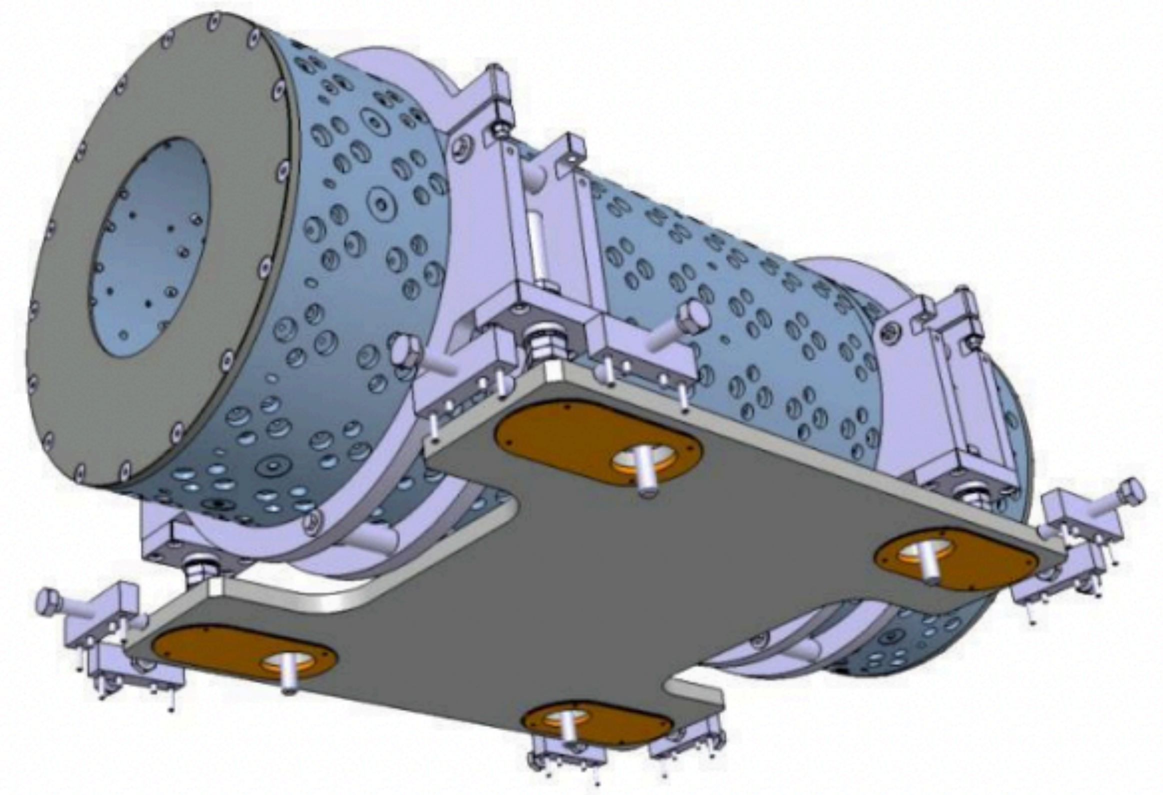
Scintillators mounted in their support.

Calorimeter modules mounted in their support.



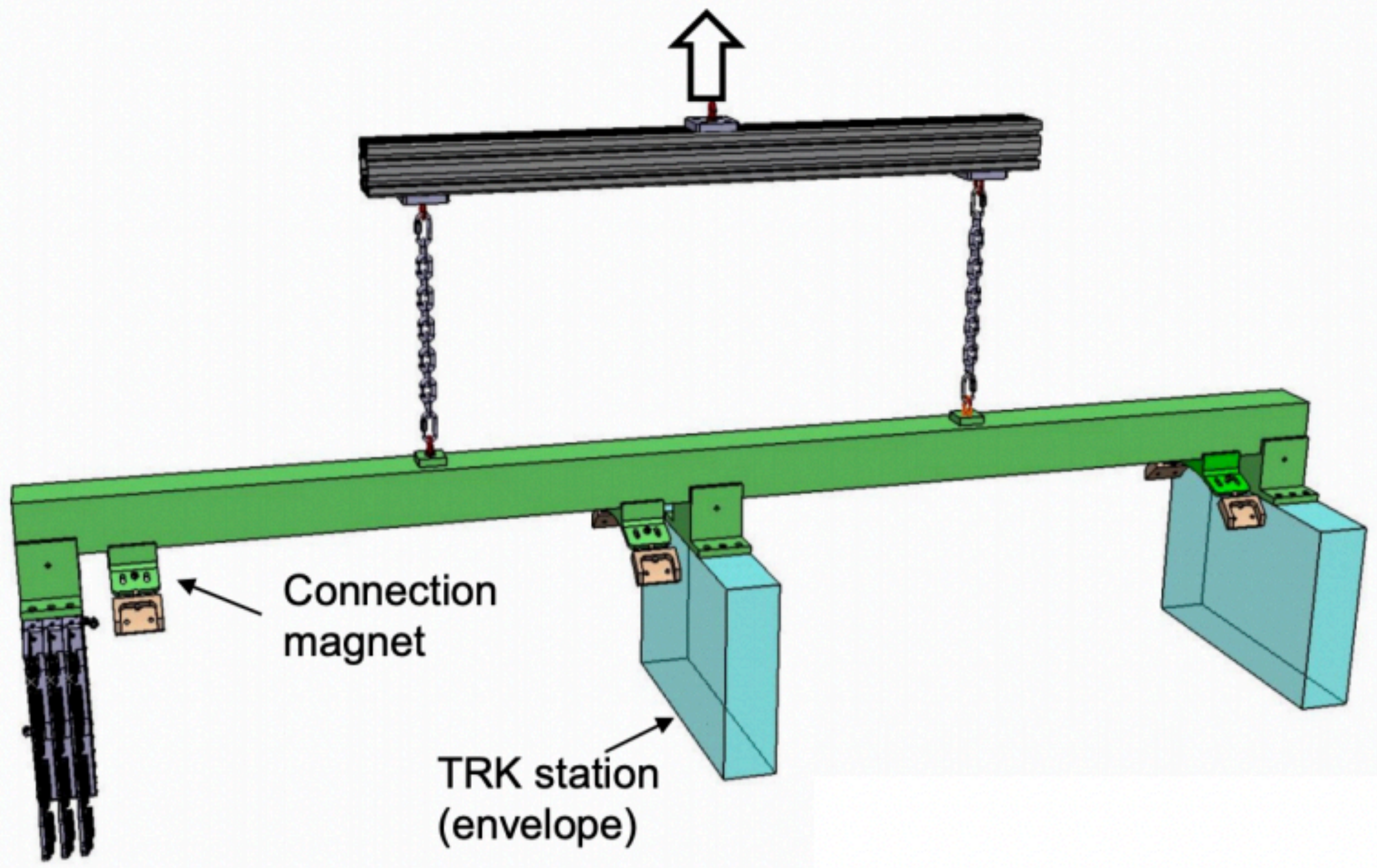
Detector support infrastructure

Magent support frame

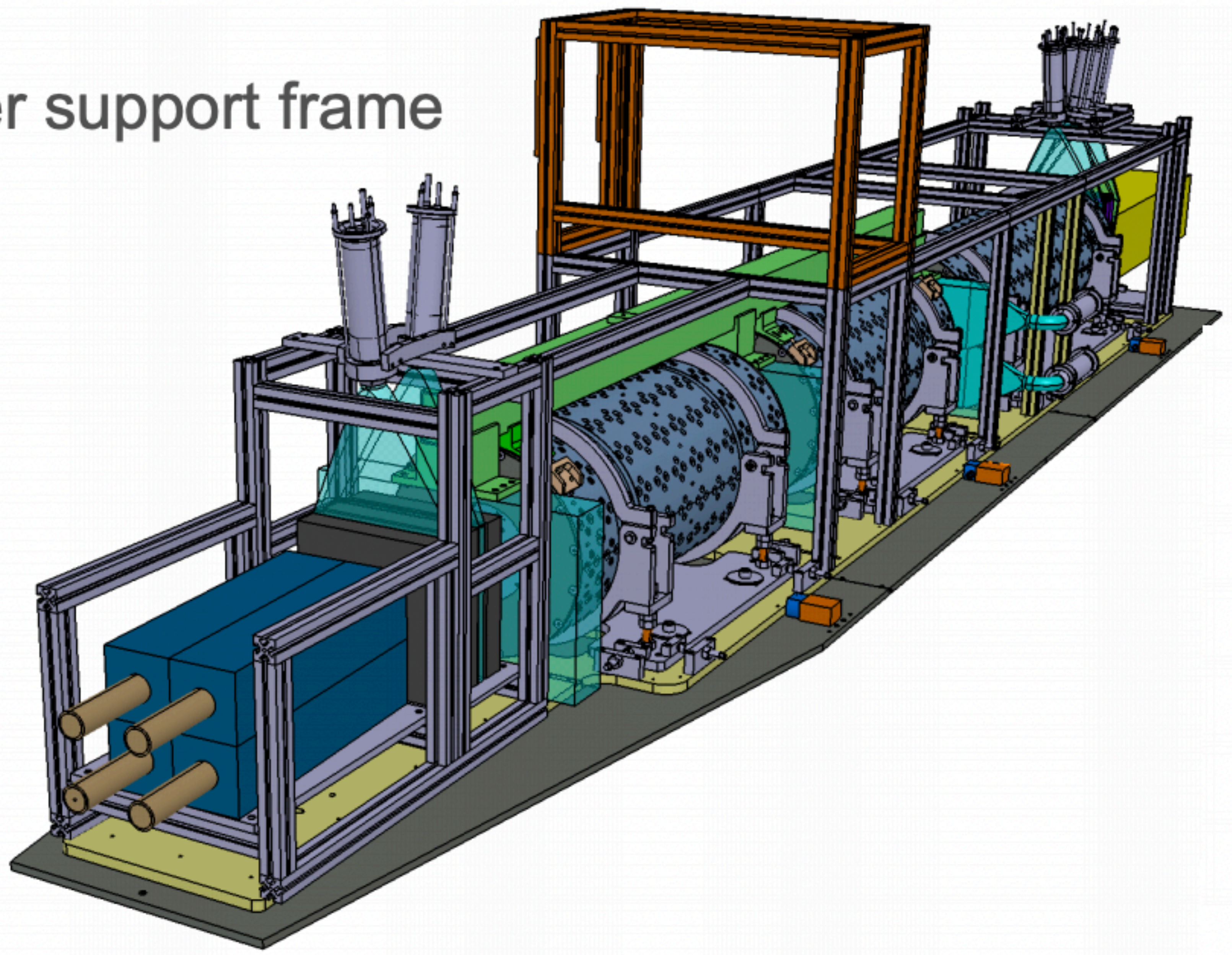


- Detector support structure finalised, in production
- Base plate (fixed with grout) securing permanent magnets
- Tracker stations connected through “backbone", mounted on magn

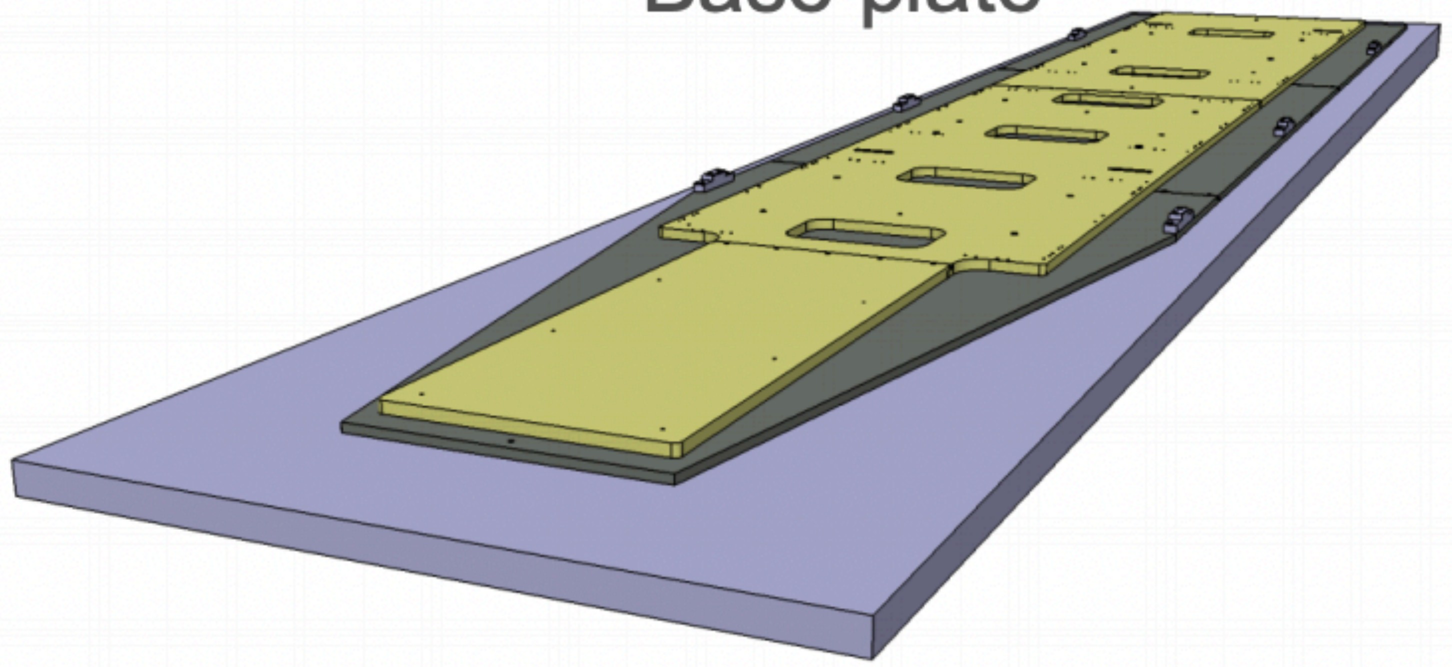
Tracker backbone



Upper support frame



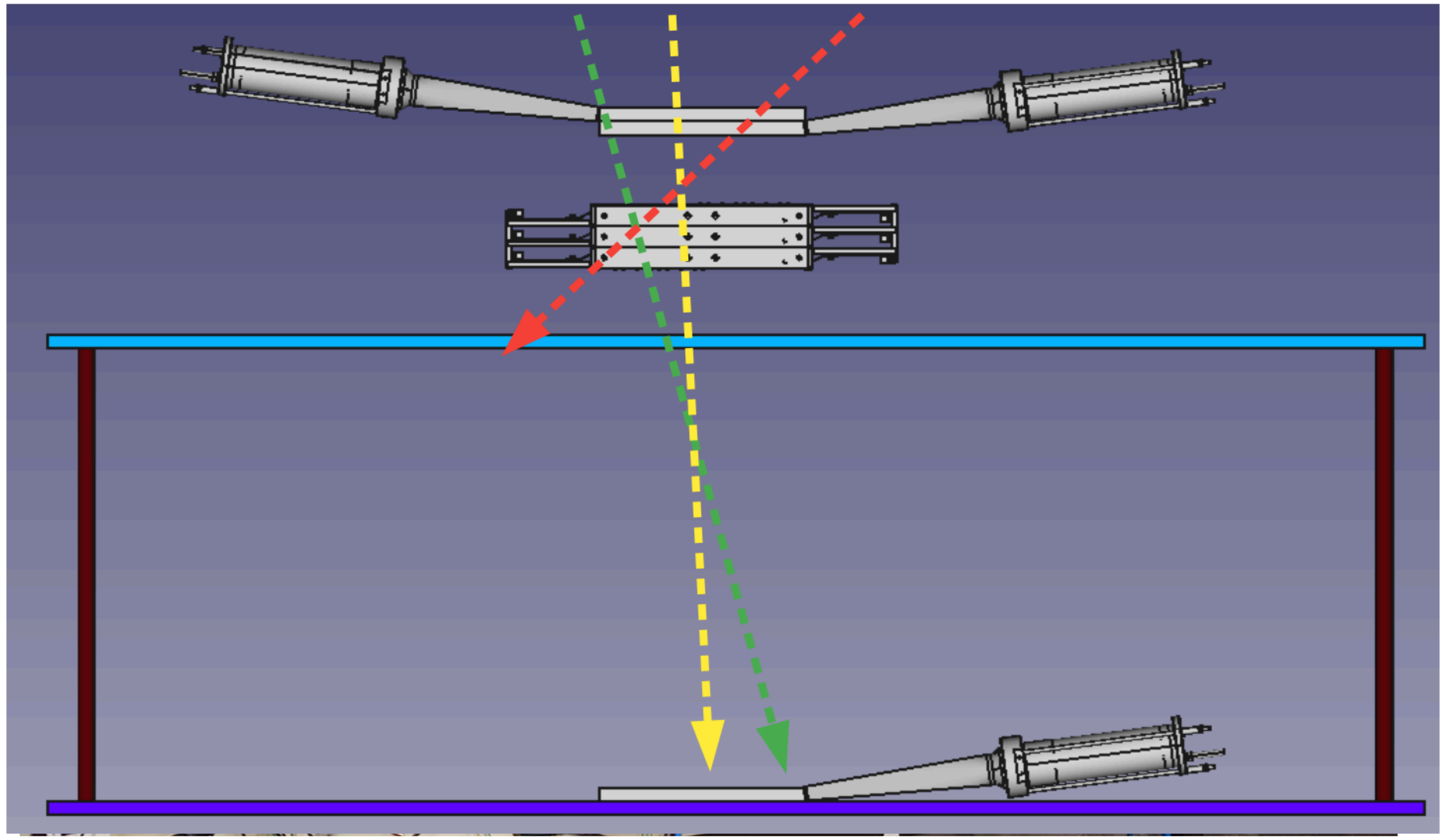
Base plate

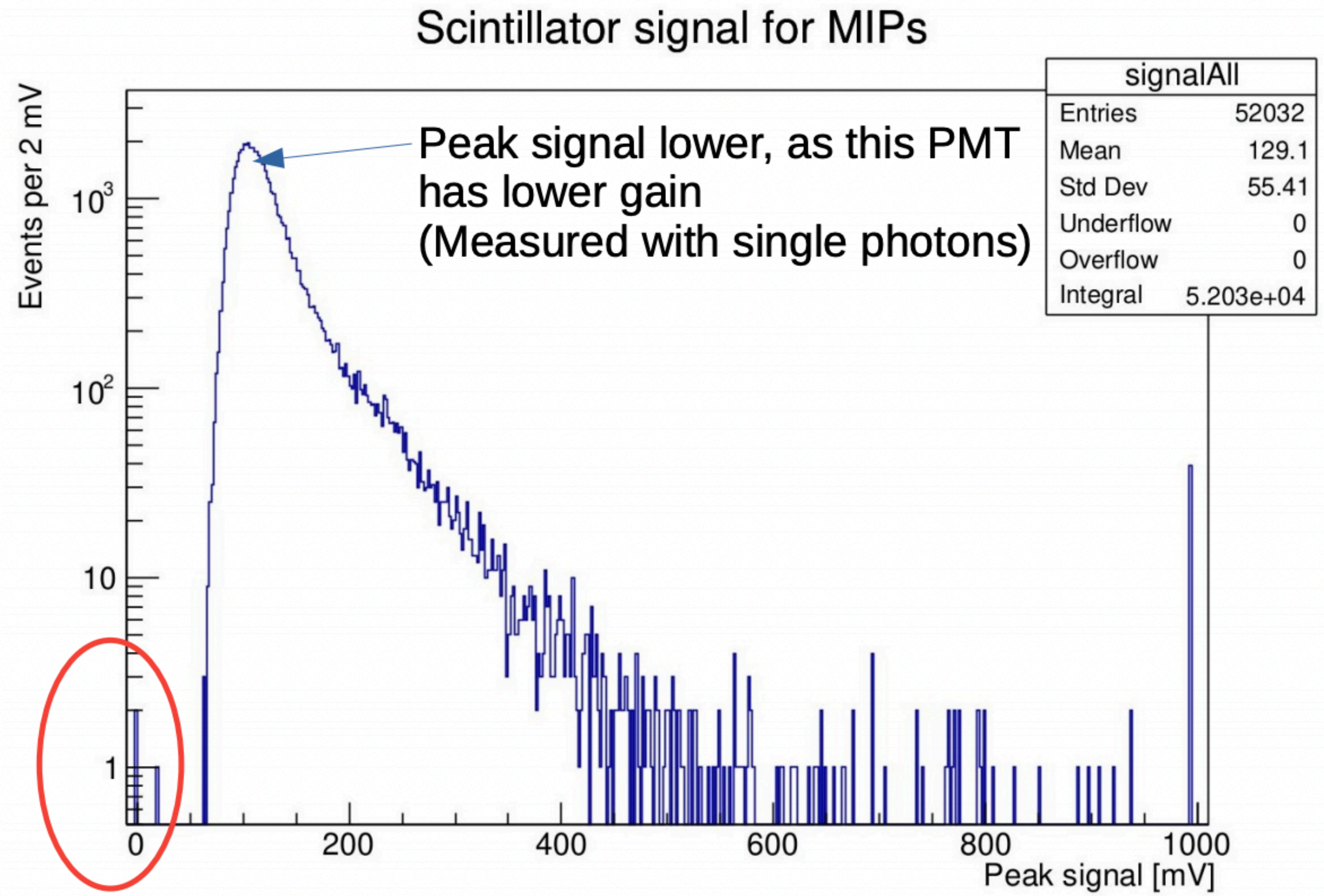


Grout + cement

Overground testing | Scintillator

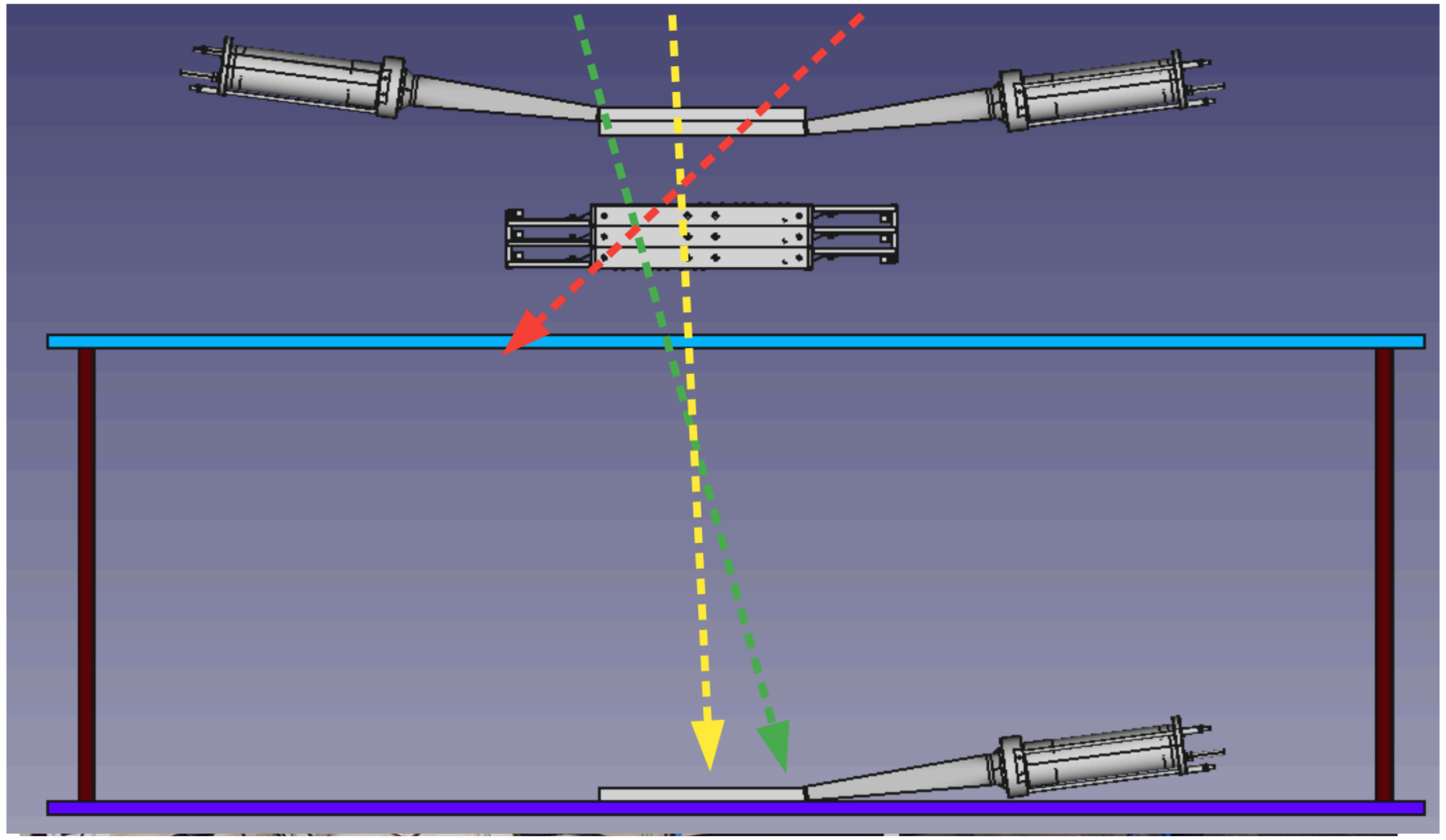
- Also used this data to study the scintillator performance
- Cosmics confirmed by tracker station provides cleaner single track sample
  - Efficiency is [99.985:99.998]% at 95% CL

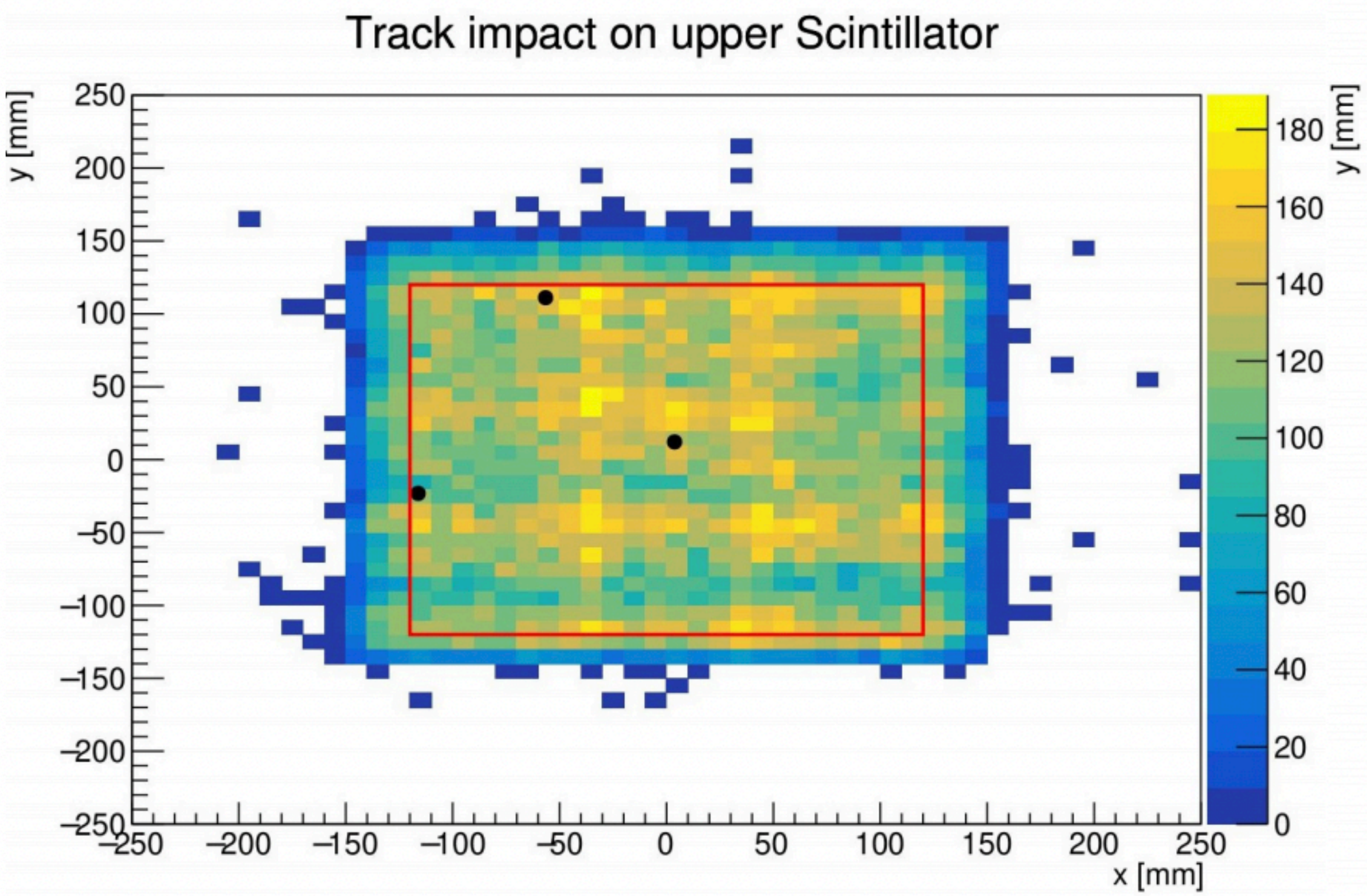




Overground testing | Scintillator

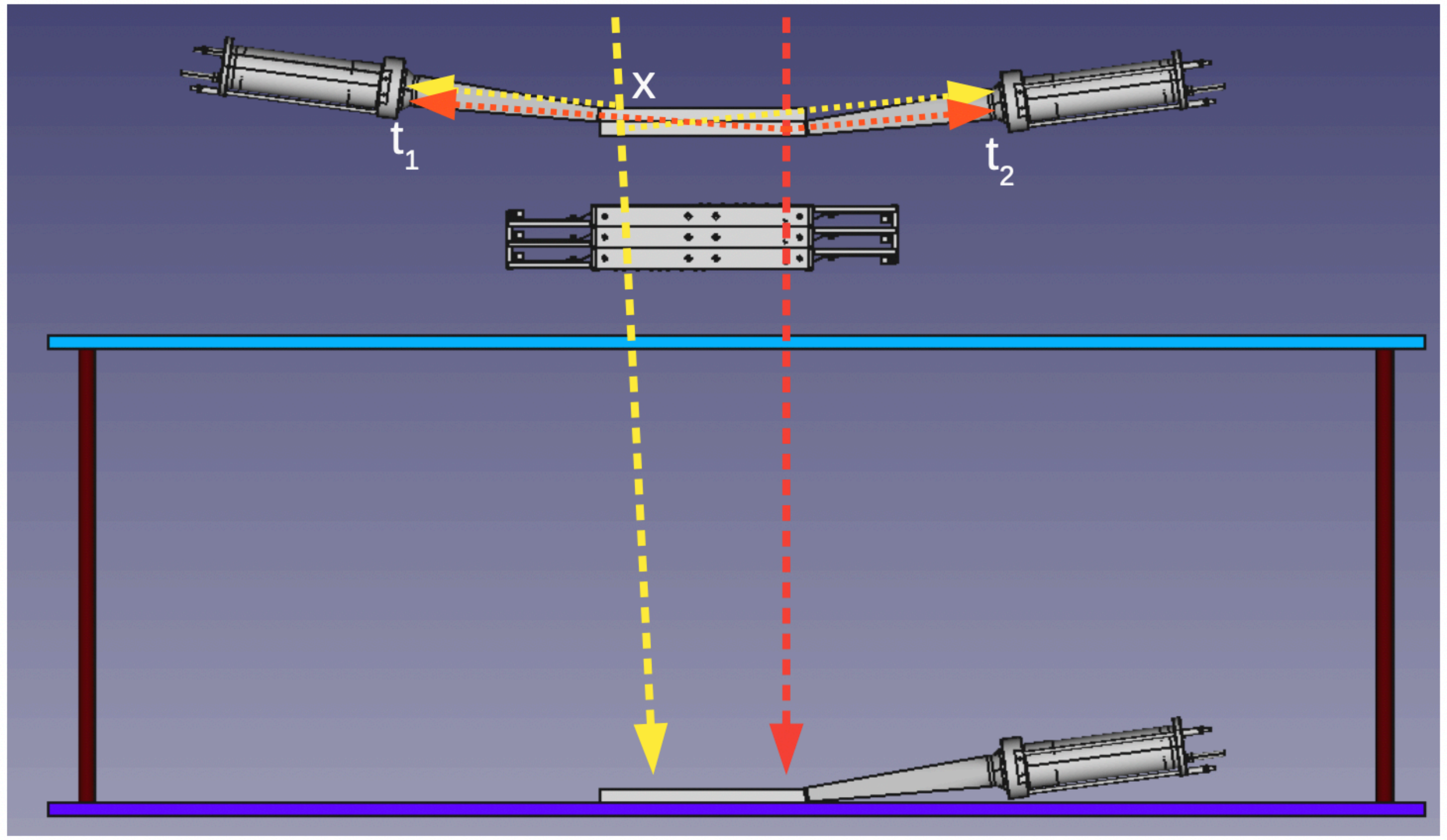
- Also used this data to study the scintillator performance
- Cosmics confirmed by tracker station provides cleaner single track sample
  - Efficiency is [99.985:99.998]% at 95% CL
- 2/3 tracks close to scintillator edge.

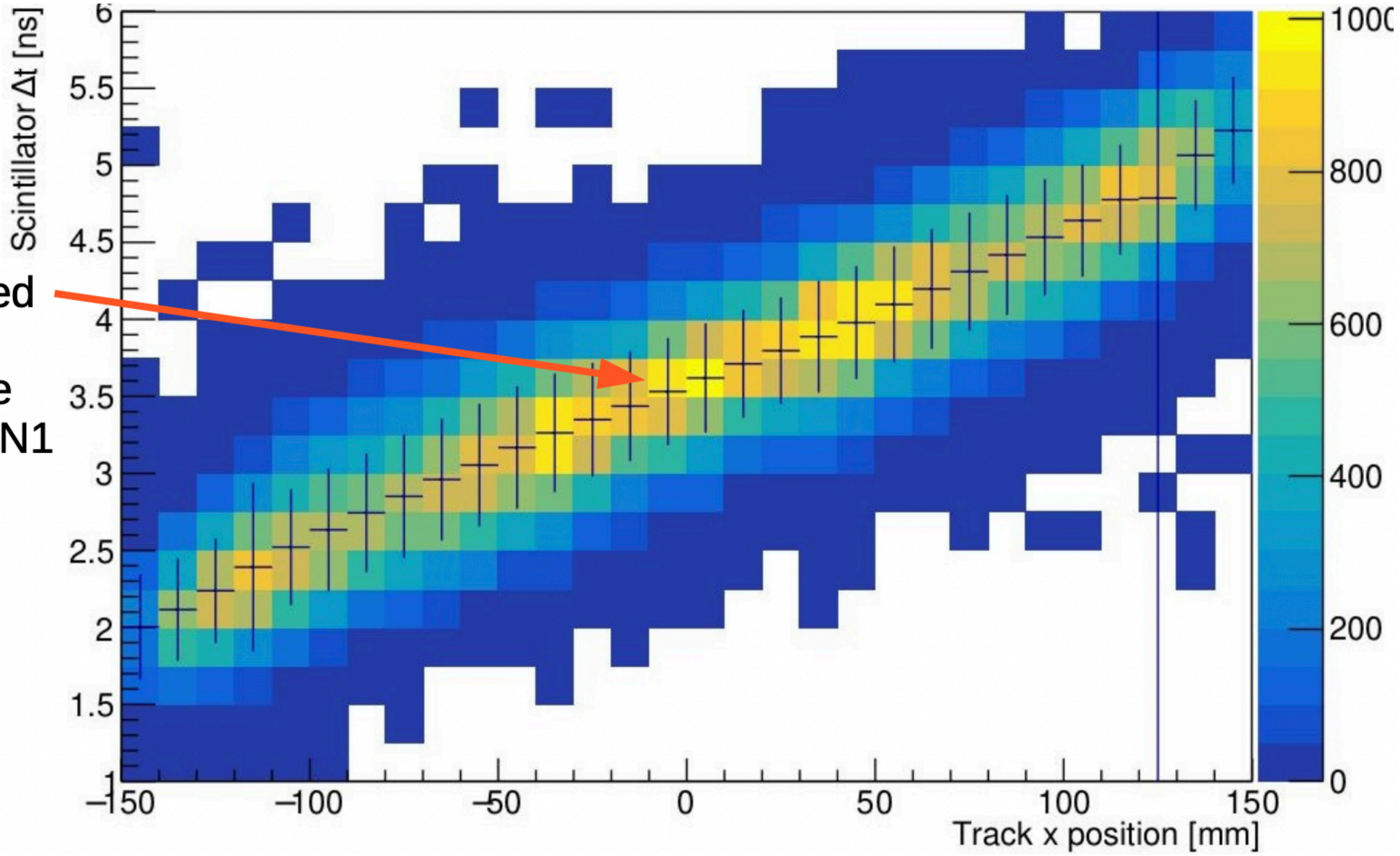




Overground testing | Scintillator

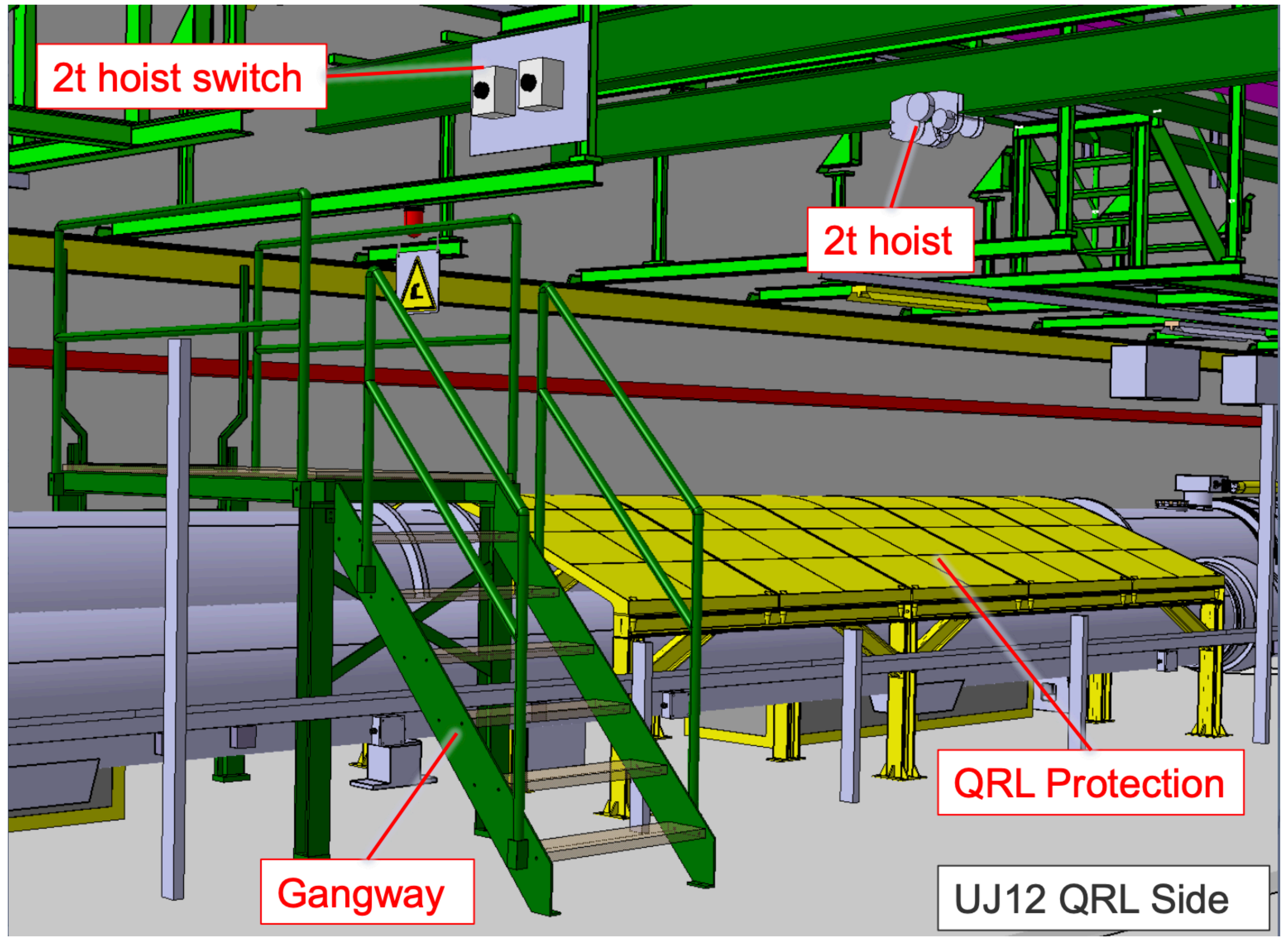
- With two opposite pointing scintillators, can test signal arrival time
  - Propagation time is ~20cm/ns → ±1.5ns
- Selecting events with track in specific location, measure σ(Δt)=0.33-0.4ns
  - Assuming uncorrelated PMT time → single scintillator time resolution of ~0.25ns
- For events with single good track see very good correlation between track position and time difference.

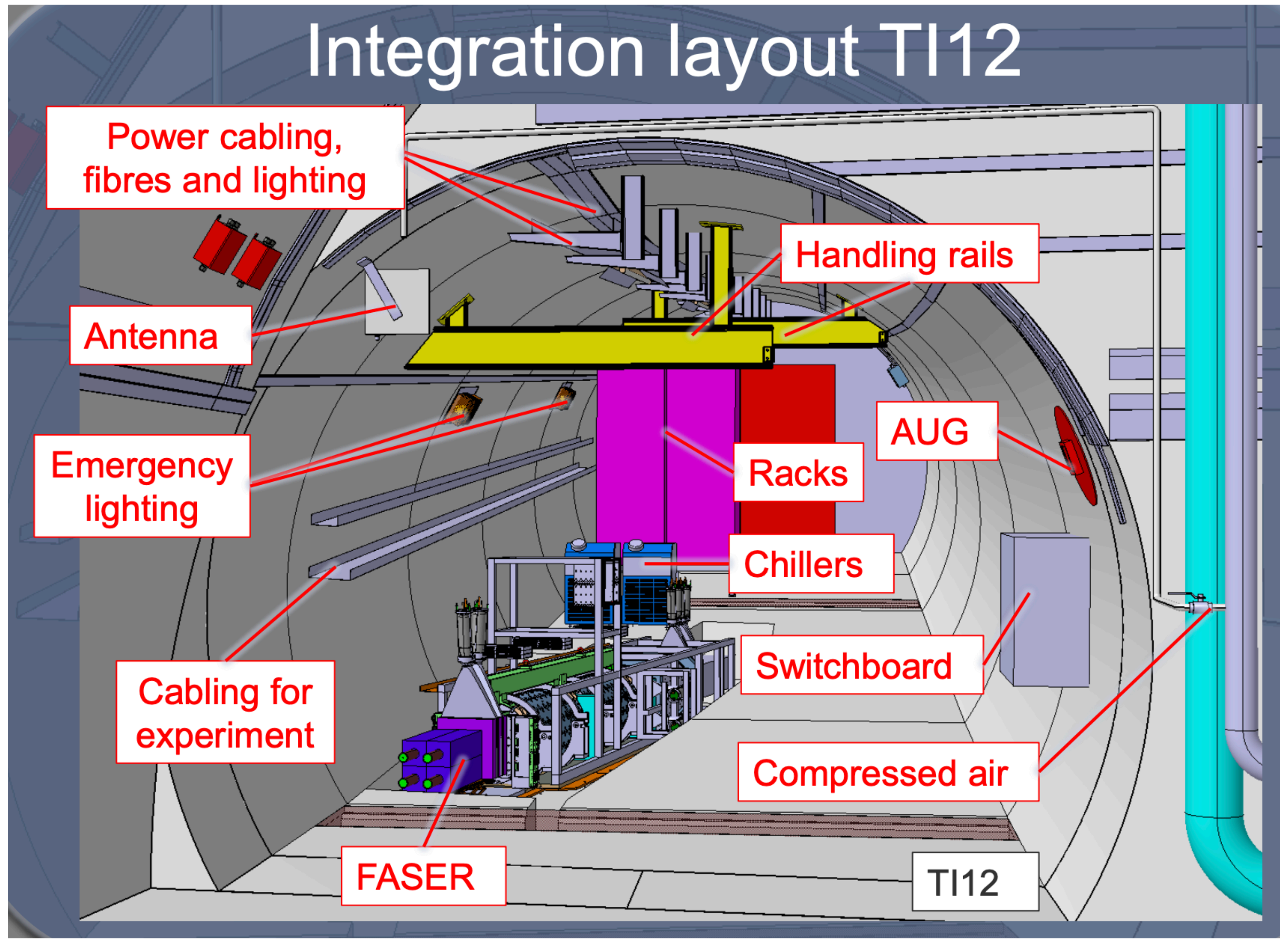




Preparation for FASER

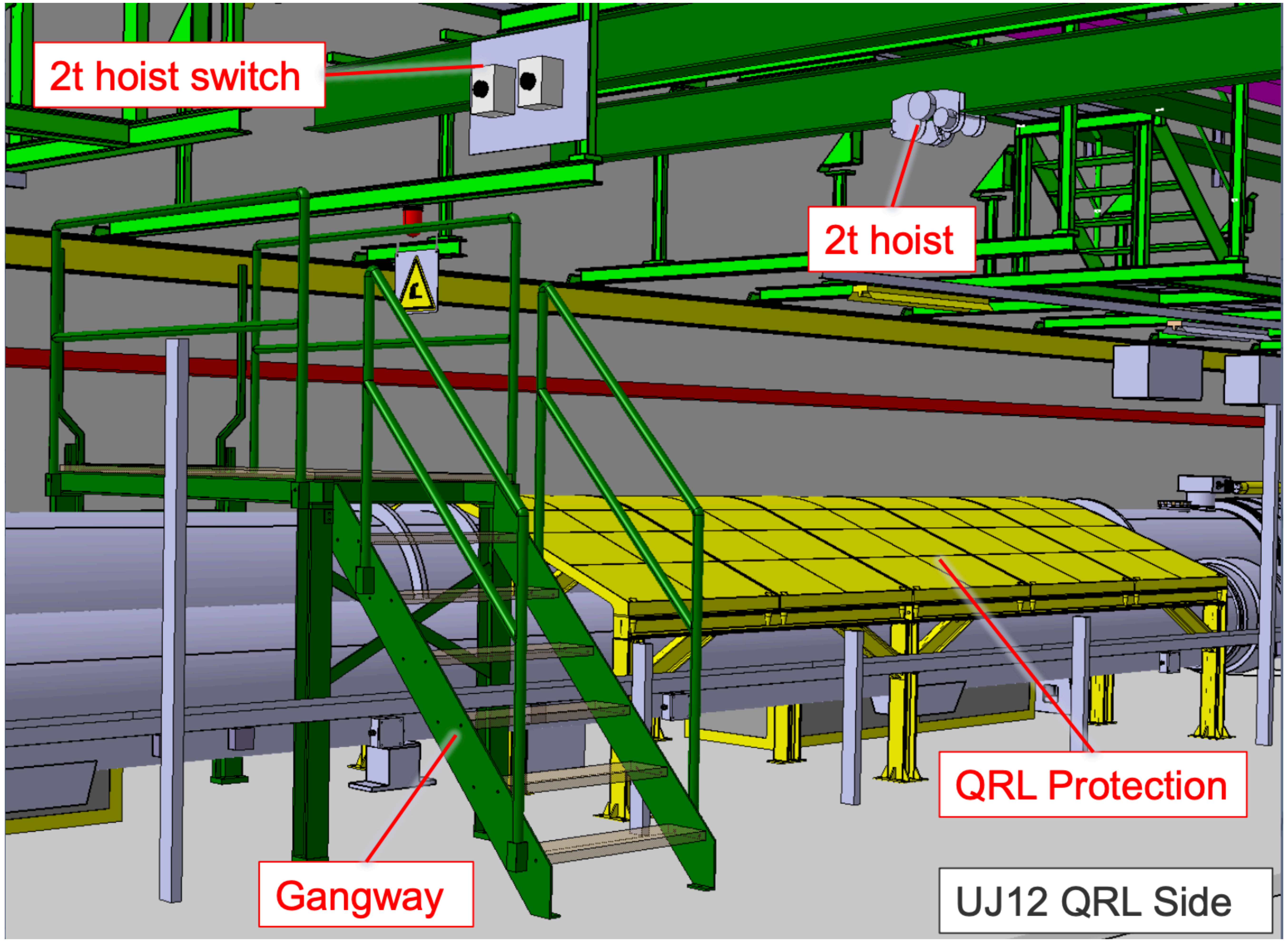
- Civil engineering work in TI12 to allow FASER installation finished on schedule, just before CERN shutdown!
- Significant cleanup work in TI12 before digging could begin.
- Many constraints in planning this:
  - Strong requirement on no dust in the LHC during LS2
  - Little available time for doing the work in LS2
  - Extremely important to not effect the tunnel stability during the works
  - The drainage must be maintained during and after the works





Preparation of UJ12

- Lots of work required in the area where TI12 and the LHC tunnel combine - UJ12
  - Move lighting and cable trays
  - Install gangway
  - Install hoist (including power and switch)
  - Install QRL protection
    - Hoist and QRL protection also important for **FASERν**



Preparation of UJ12

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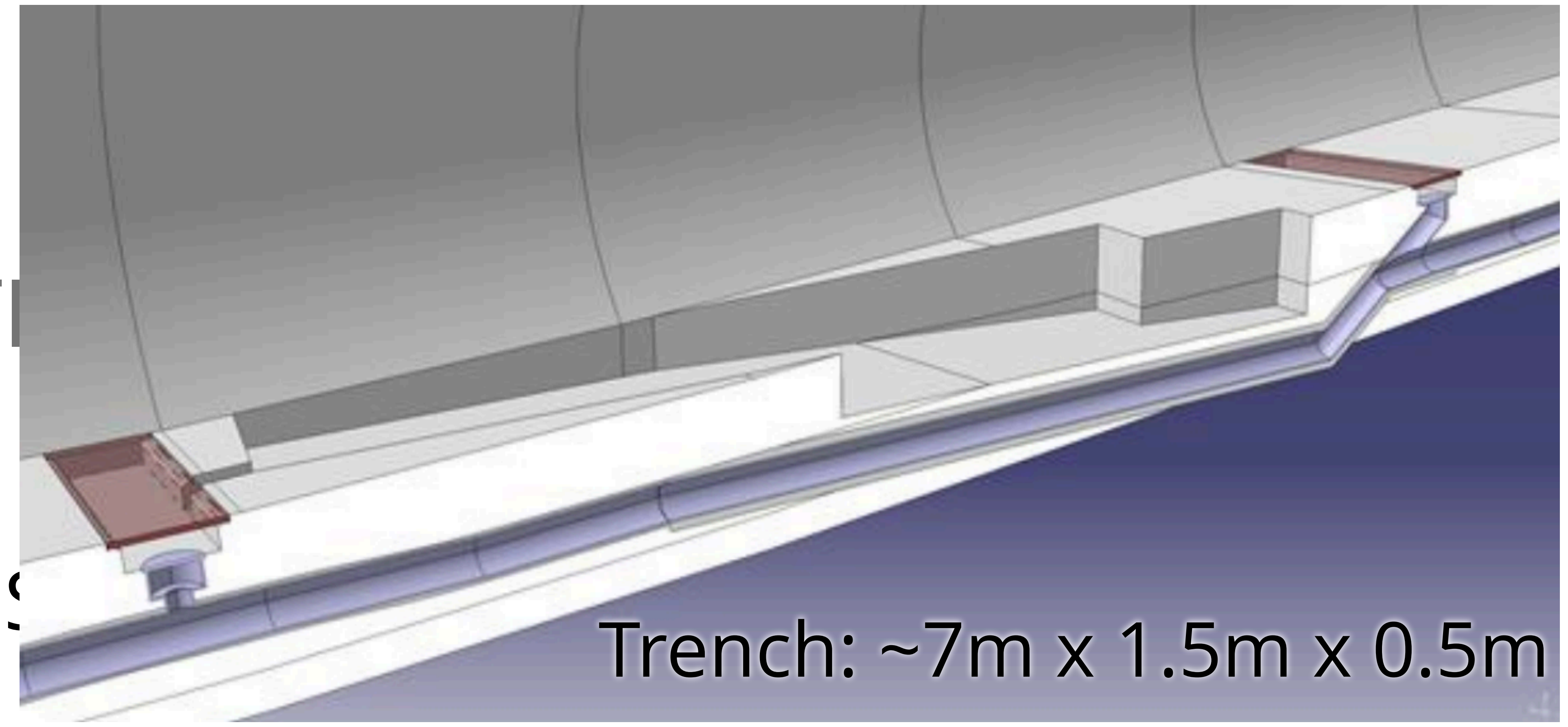
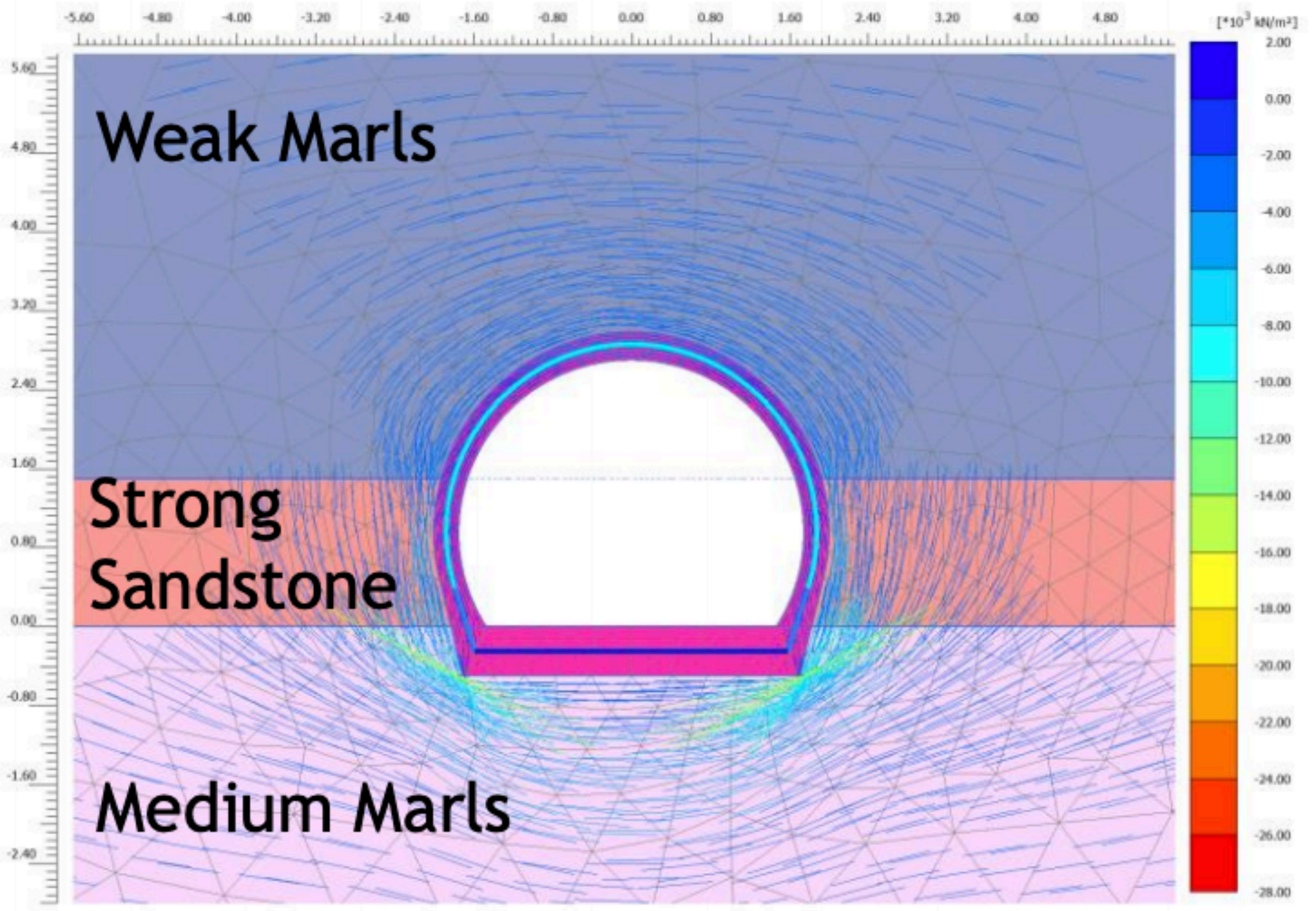
  - Install hoist (including power and switch)
  - Install QRL protection
    - Hoist and QRL protection also important for **FASERν**

Civil Engineering in TI12

- Trench
  - To be aligned with the line-of-sight (LOS) in the vertical direction a shallow (<50cm deep) trench is needed in TI
  - Drain shallower than shown on historical drawings
    - Provided opportunity to increase trench depth - parallel to LOS
  - Plan area increased to allow more space for FASERν



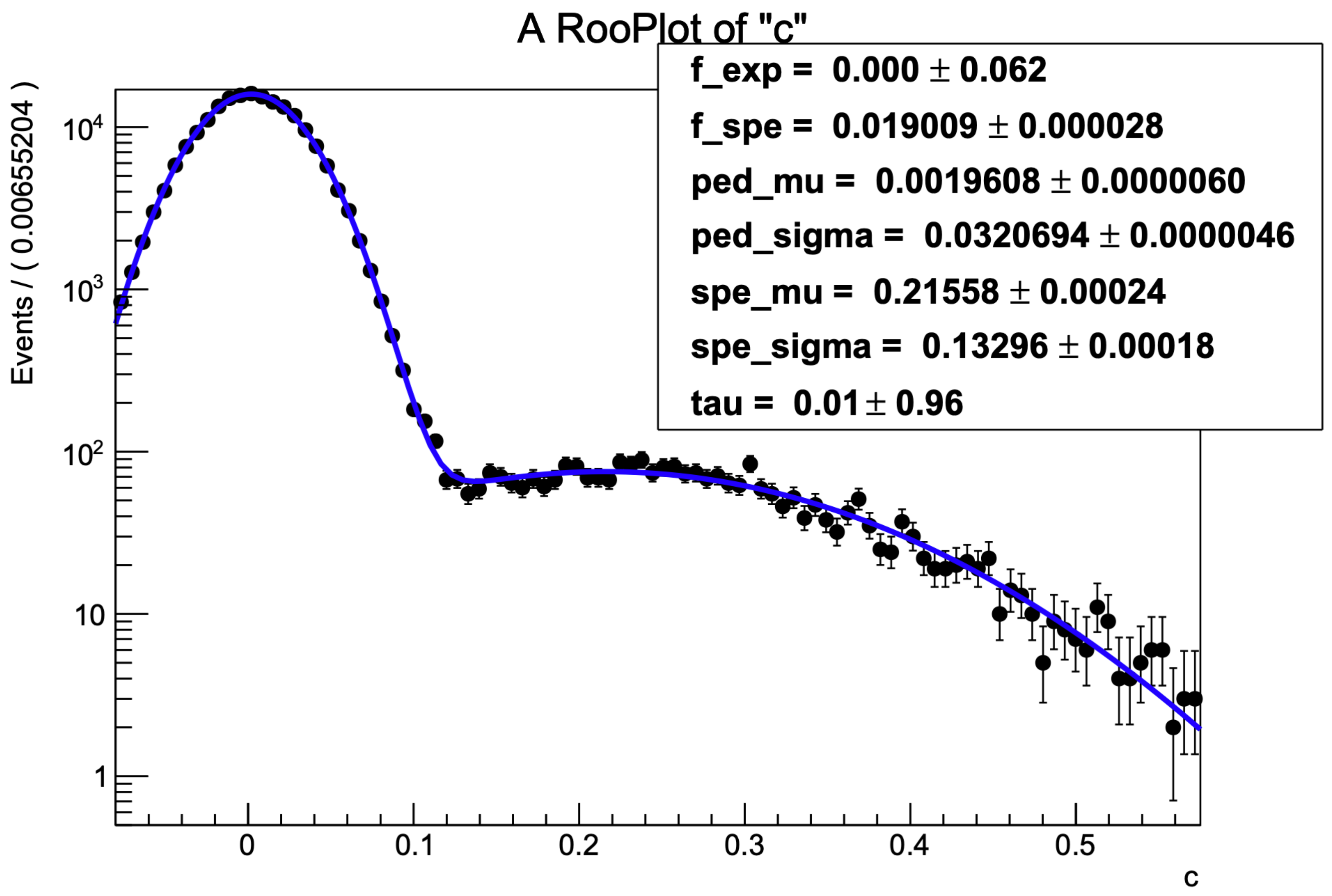
- Trench strengthening
  - Improved rock characteristics enabled removal of steel fra
  - Less complex site works and better ground conditions en

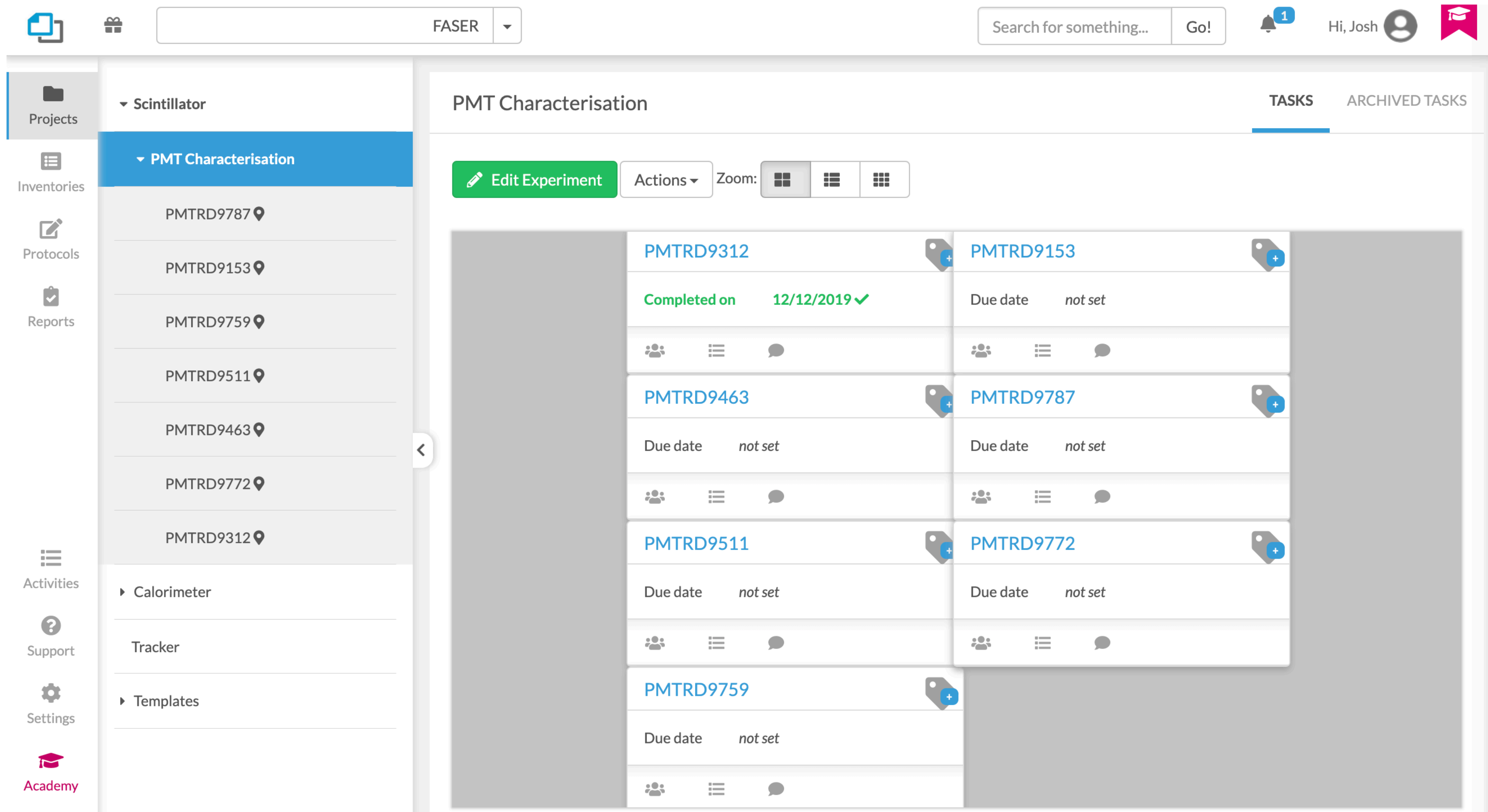


- Next steps:
  - Complete tender process: ~Now
  - Preconstruction planning: End Dec 2019
  - Construction works: Jan-Mar 2020, completion (with redundancy) April 2020

Scintillator | PMT gain measurement

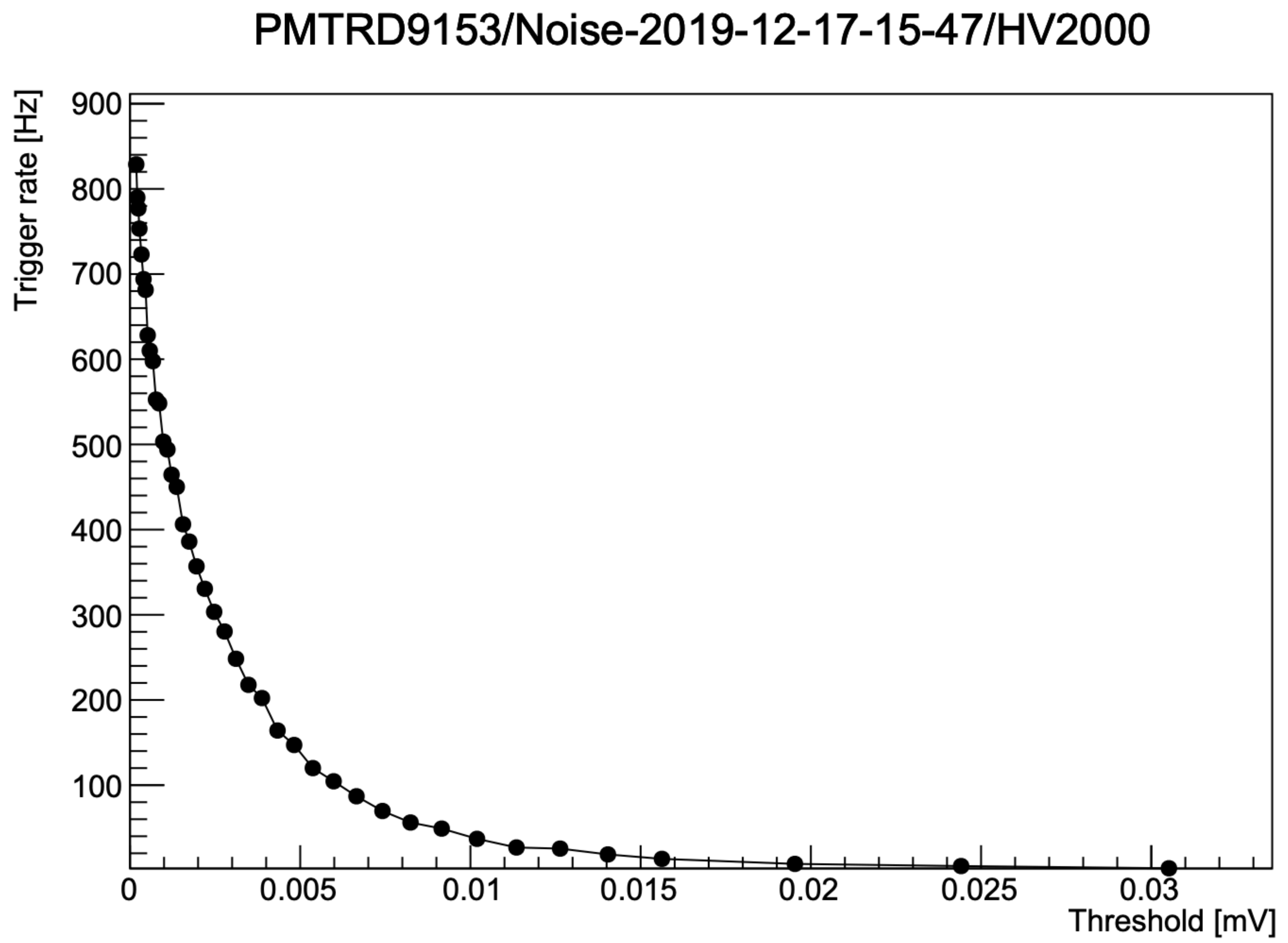
- Have completed single photon gain measurements on 11 (out of 12) PMTs
  - Use low intensity LED pulses to measure charge read out from a single photon at different intensities and High Voltage settings.





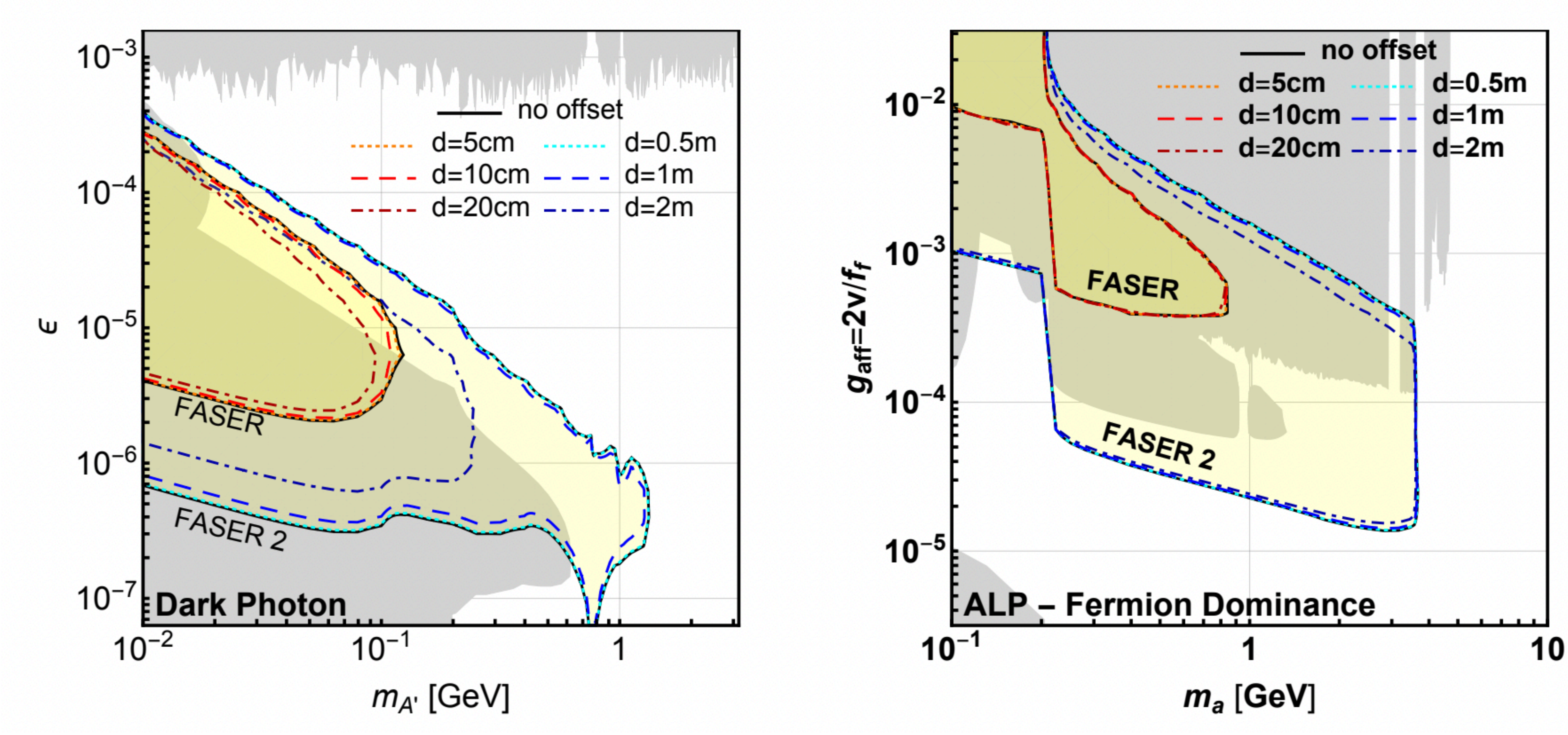
Scintillator | PMT noise measurement

- We also started making noise measurements
  - Want to be sure that expected signal is not going to suffer from significant noise.
- Check the threshold normalised to the gain
  - Seem that the thresholds roughly scale with gain so the equivalent photo-electrons is similar across PMTS.
- For 100 Hz the required threshold corresponds to ~0.25 of a photo-electron - much lower than our expected signal ~10s PEs.



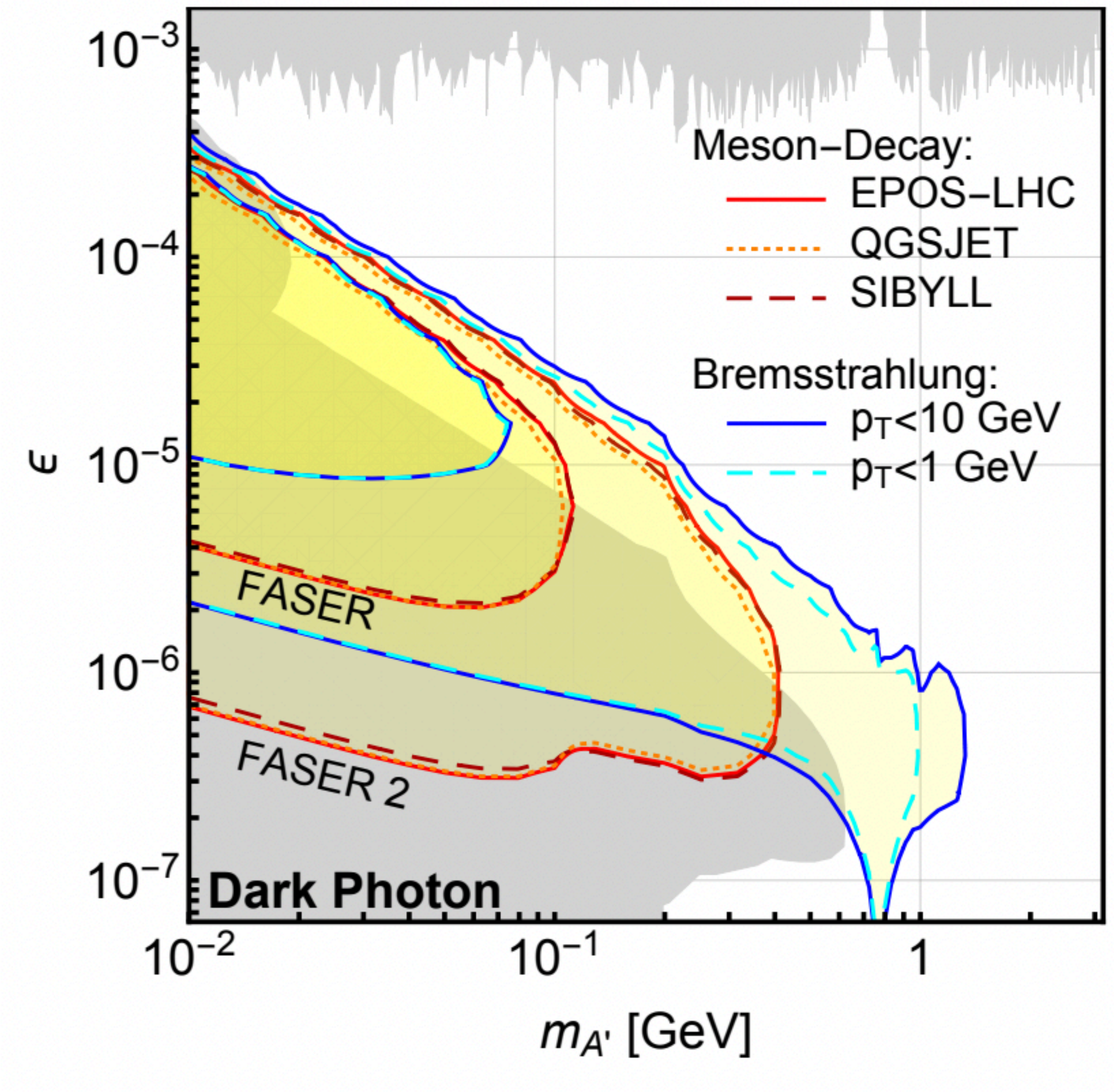
Rate [Hz]	10.0	50.0	100.0	500.0	1000.0
Threshold [mV]	17.91	9.03	6.15	1.02	0.05
Normalized [pE]	0.674	0.340	0.232	0.038	0.002

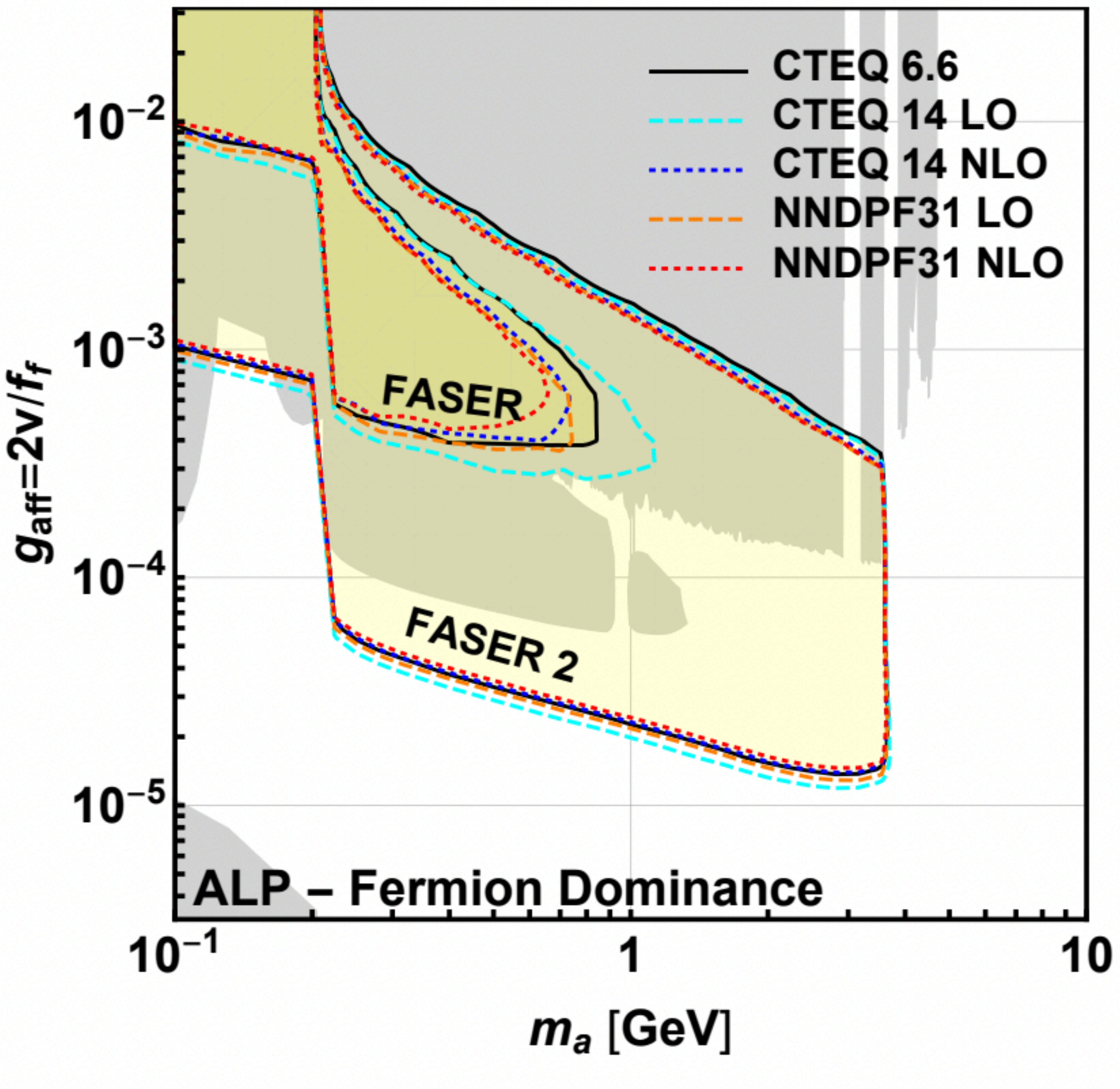
Beam offset



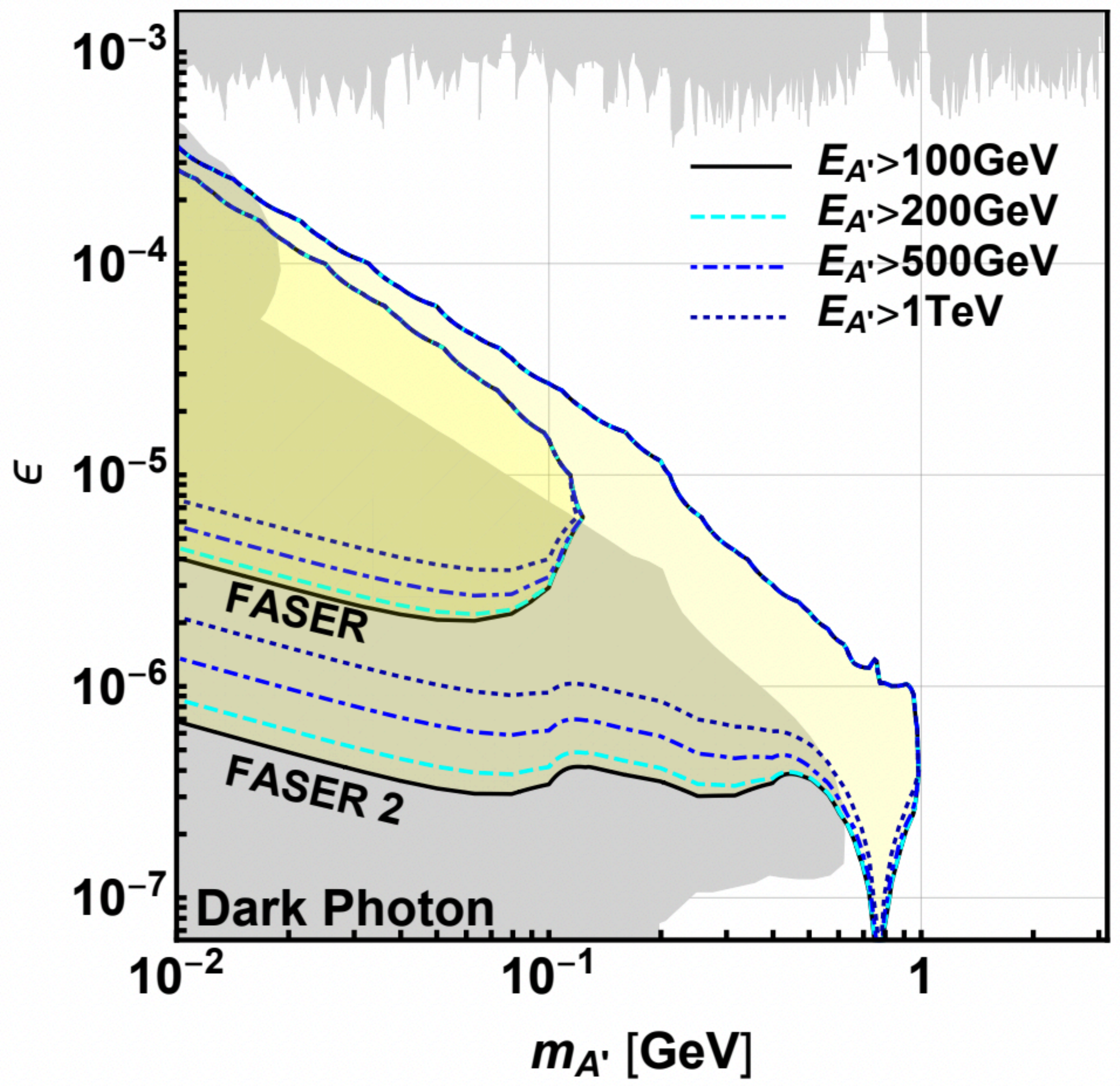
no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
Dark Photon
ϵ
$m_{A'}$ [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
1
ALP – Fermion Dominance
$g_{aff}=2v/f_f$
m_a [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
1
10

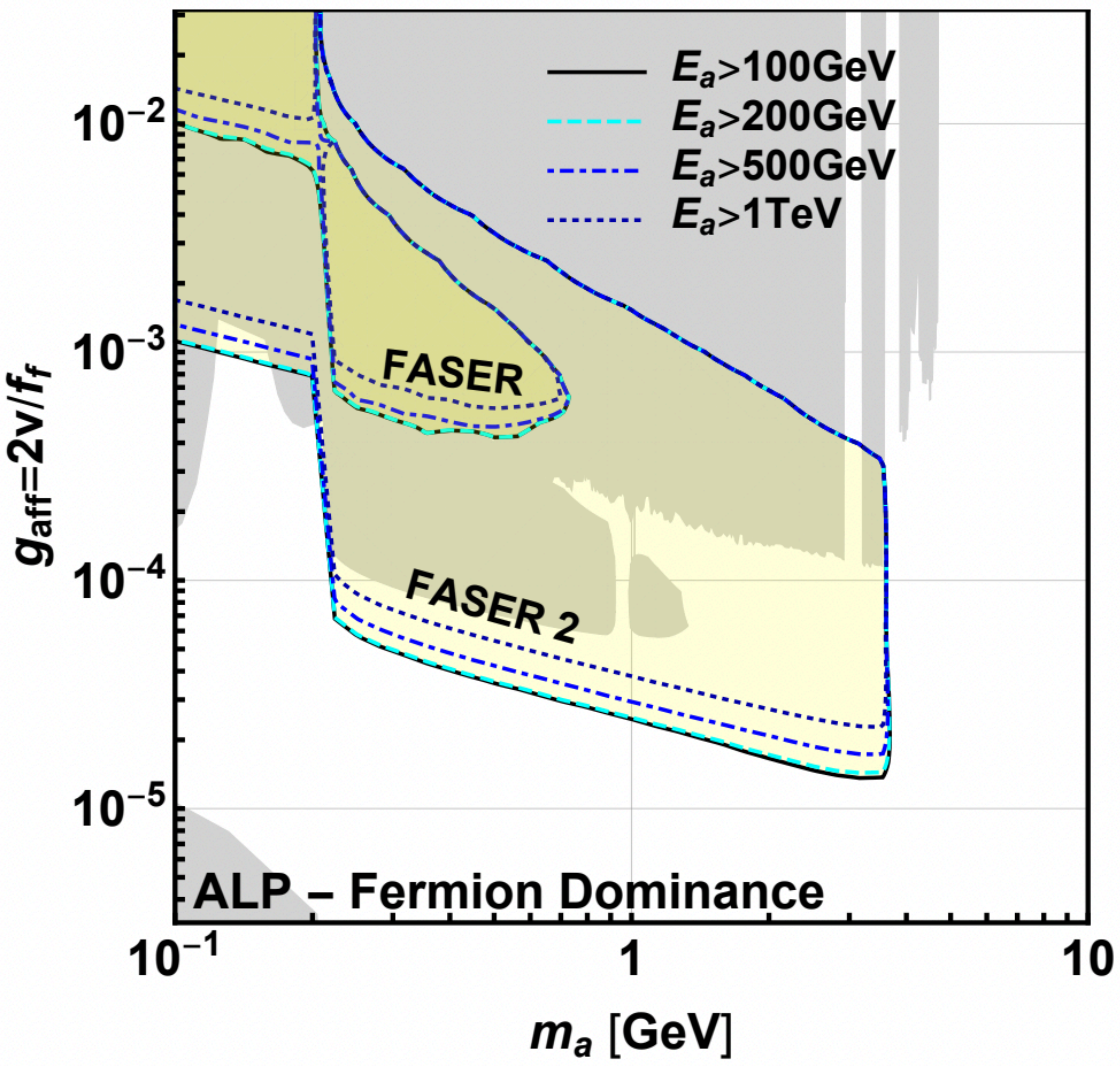
Modelling uncertainties





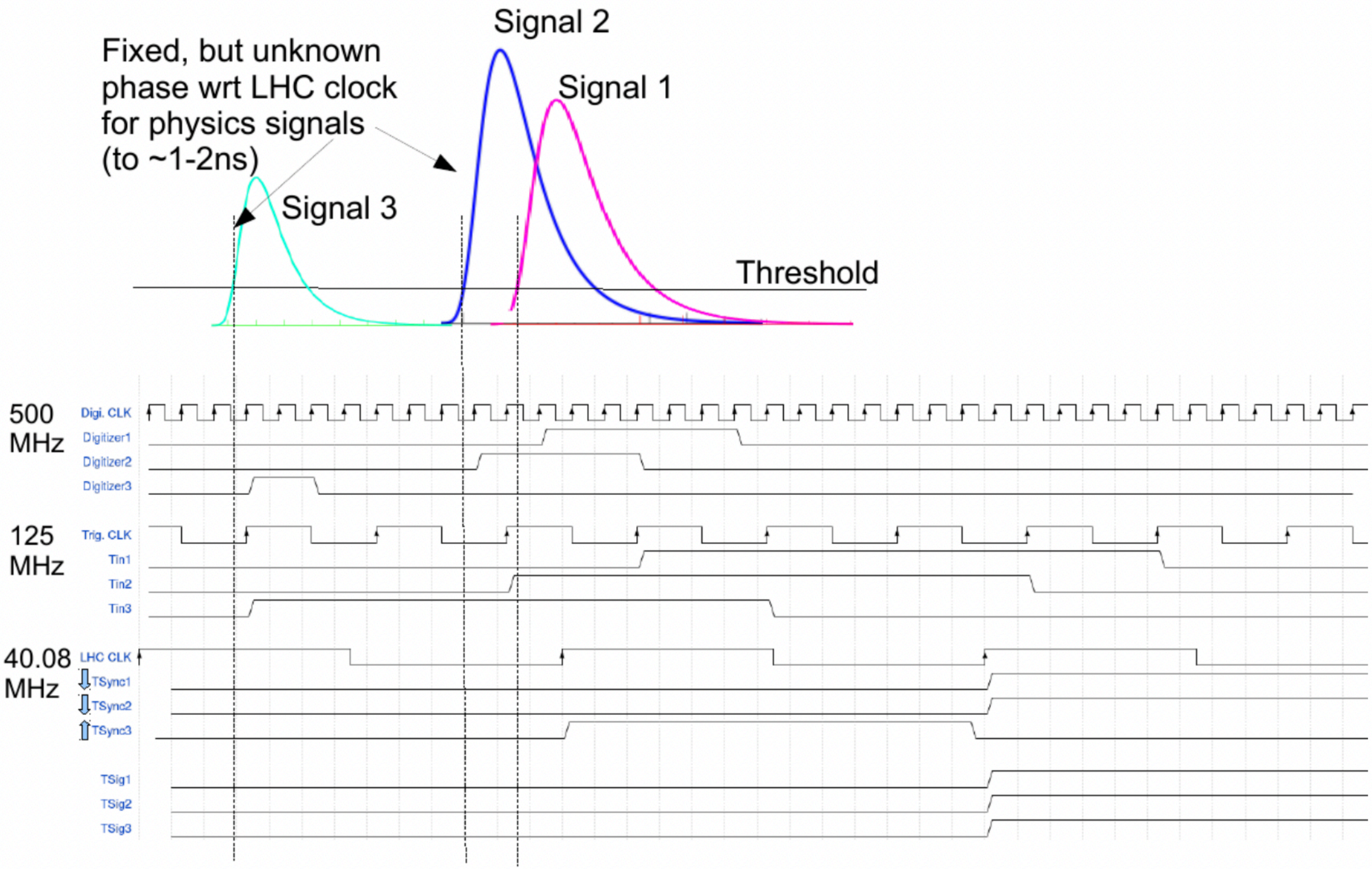
Energy threshold





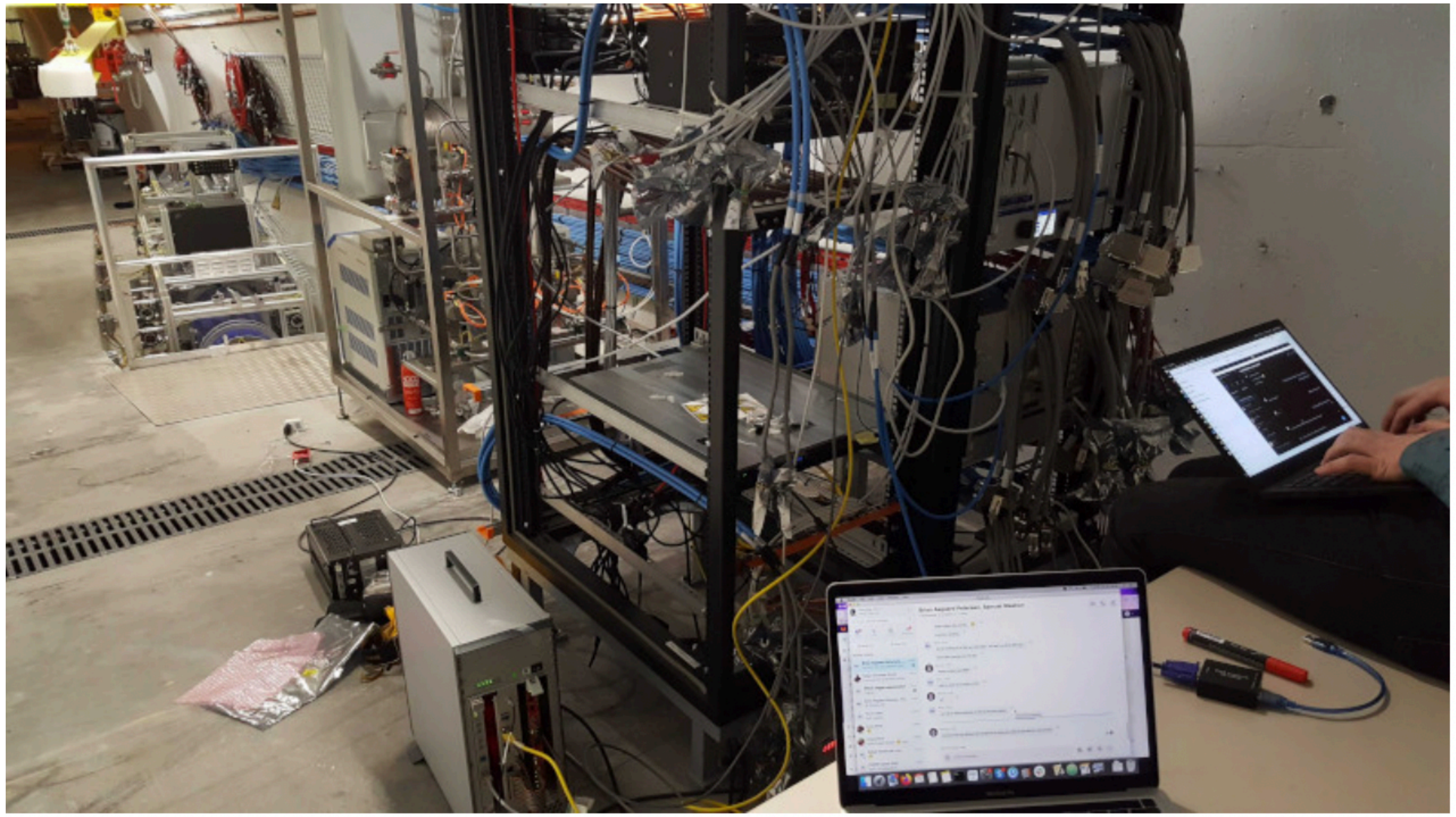
TDAQ | Overview

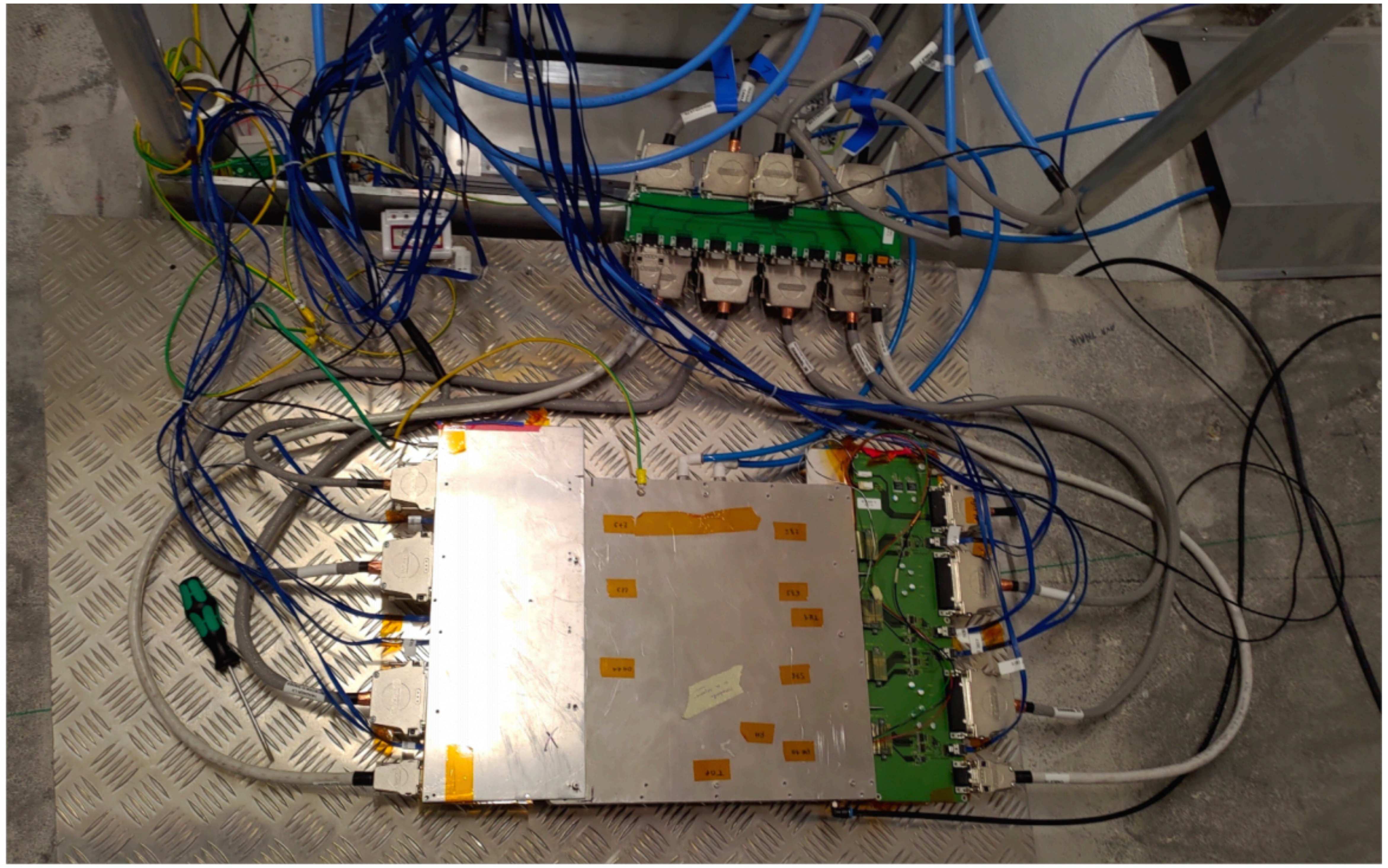
- Trigger an OR of signals from scintillators and calorimeter
  - Plan to trigger on all particles entering FASER, but could pre-scale events with incoming charged particle if needed
- Expected maximum trigger rate ~500Hz from incoming muons
- Expected maximum bandwidth ~15MB/s
  - Event size (~25KB) dominated by PMT waveforms where readout a long time around pulse to allow offline quality checks (configurable)
- Readout and trigger logic electronics in TI12 tunnel
  - Not sufficient time to send signals to the surface and back
  - Event builder and DAQ s/w running on PC on surface (600m away)
- No trigger signals sent/received from ATLAS


Signal 2
Fixed, but unknown phase wrt LHC clock for physics signals (to ~1-2ns)
Signal 1
Signal 3
Threshold
500 MHz
Digi. CLK
Digitizer1
Digitizer2
Digitizer3
125 MHz
Trig. CLK
Tin1
Tin2
Tin3
40.08 MHz
LHC CLK
TSync1
TSync2
TSync3
TSig1
TSig2
TSig3

Commissioning | Underground

- Testing TDAQ in TI12.
  - Took few events from pre-shower scintillators through digitizer.
  - First ‘data’ taken in TI12!
- Testing prototype tracking plane in TI12.
  - Found issue with cooling unit protection – very useful test.





Commissioning | Underground

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Online monitoring - DAQ

Recent Runs

Time	host	runNumber	runType	state	comment
2021-04-15 23:28:02	faser-daq-006	1700	Cosmics	Started	Overnight cosmics run. Typo in Calorimeter threshold corrected
2021-04-15 23:26:47	faser-daq-006	1699	Cosmics	Stopped	Calorimeter channel 'bottom left' has wrong threshold.
2021-04-15 20:19:00	faser-daq-006	1699	Cosmics	Started	Overnight cosmics run
2021-04-15 20:13:37	faser-daq-006	1698	Test	Stopped	Enough statistics
2021-04-15 19:56:23	faser-daq-006	1698	Test	Started	PMT single rate measurement. 2nd reference run at nominal voltage - ~900V

Commissioning | Underground

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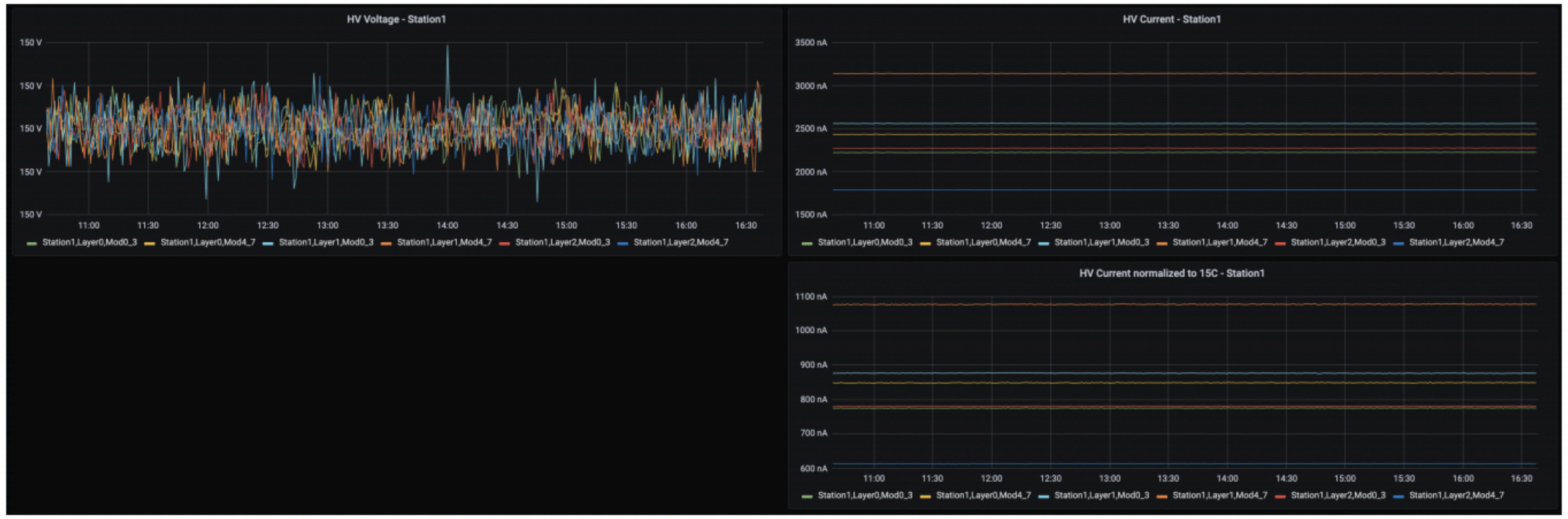
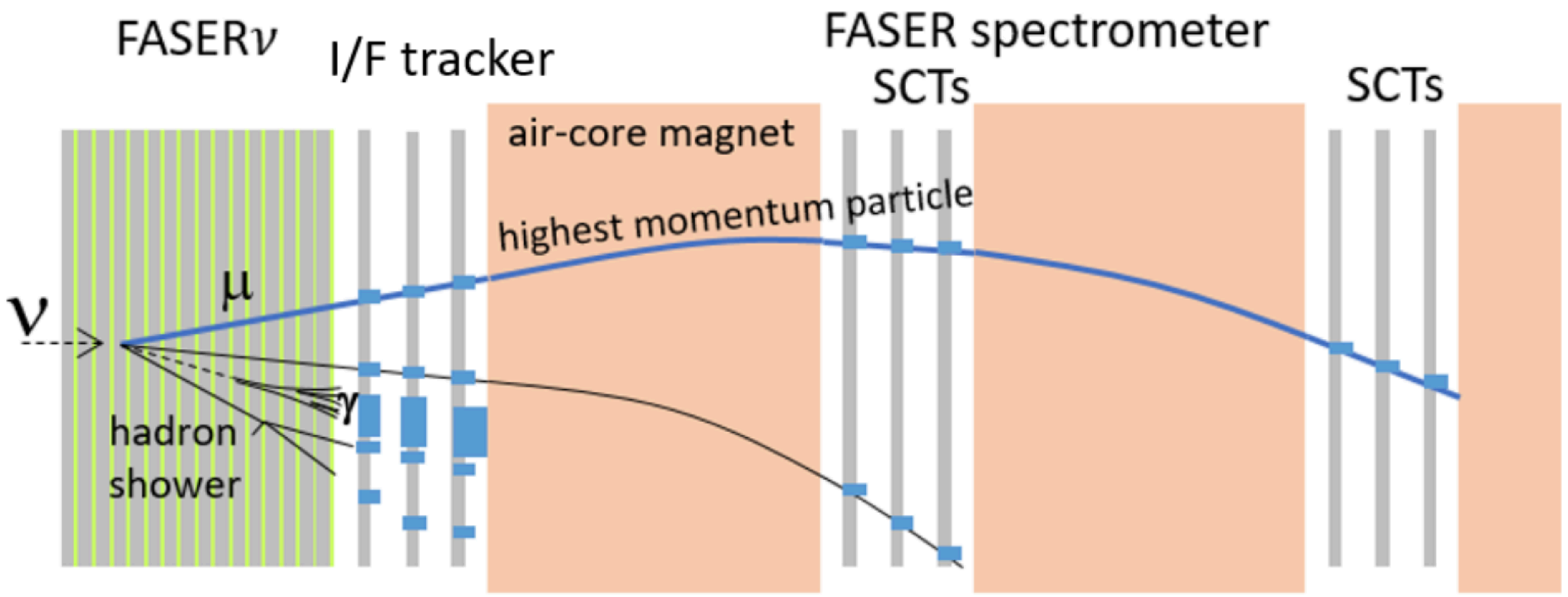
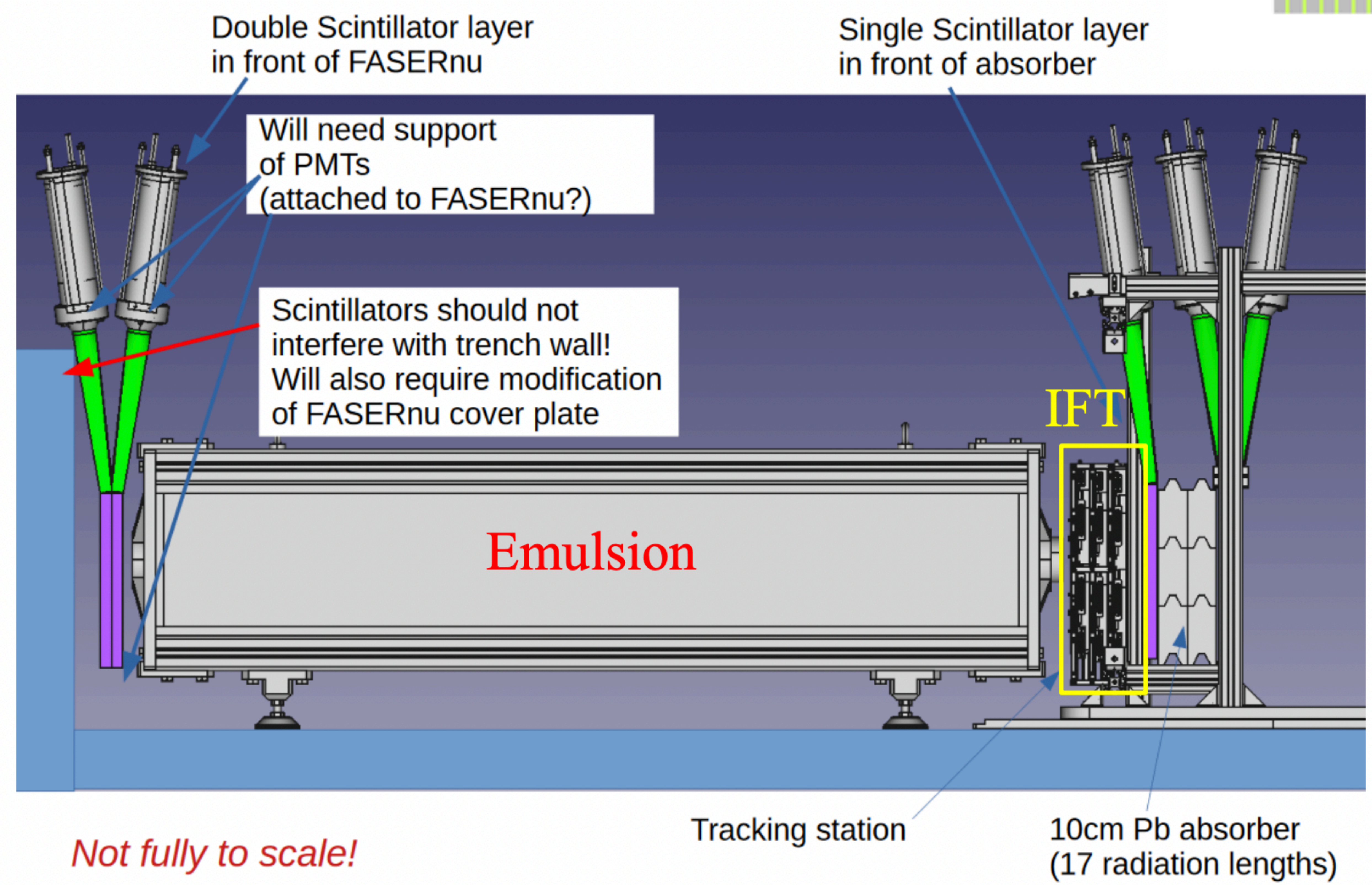
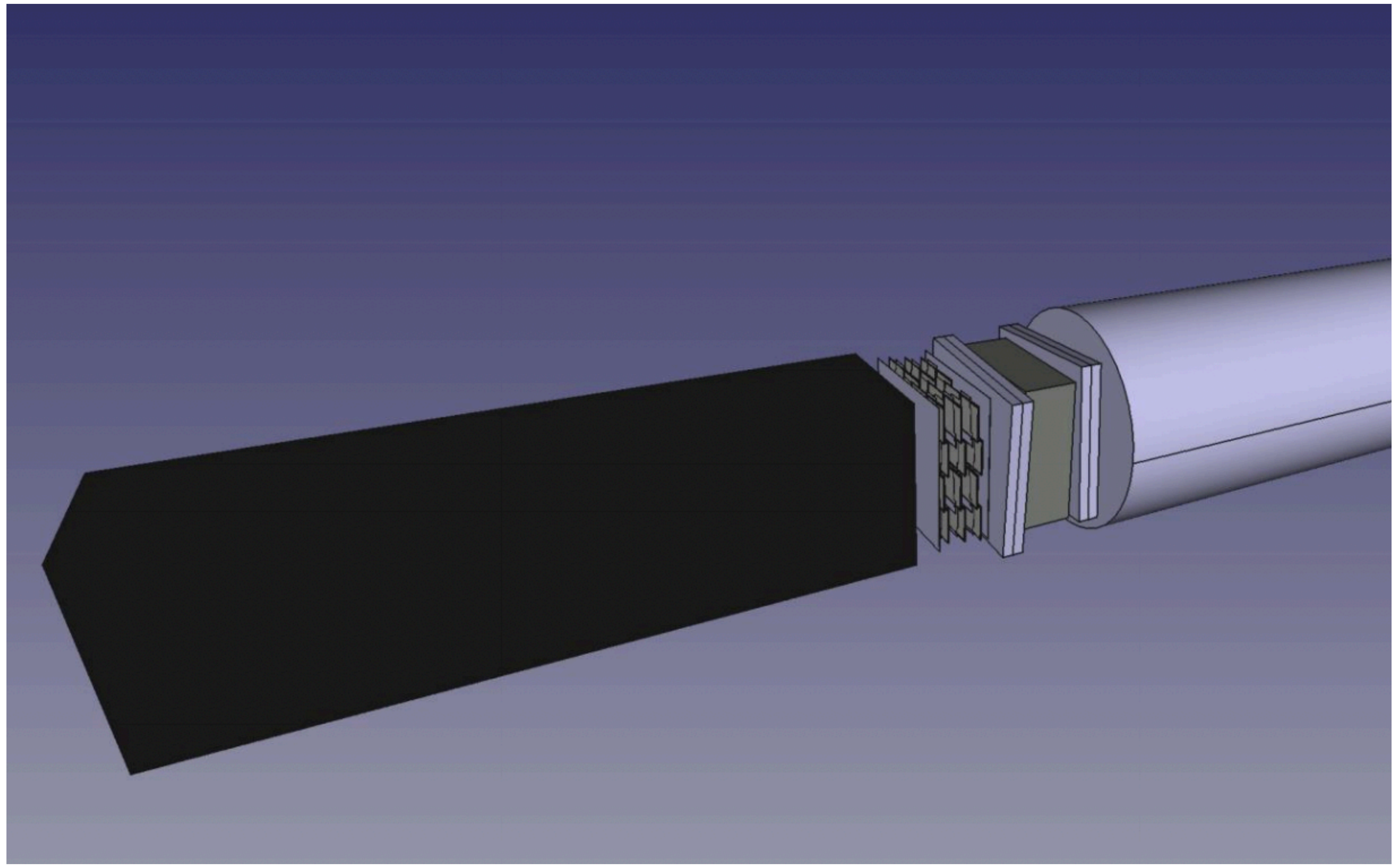
Online monitoring - DCS



FASERν | Interface detector

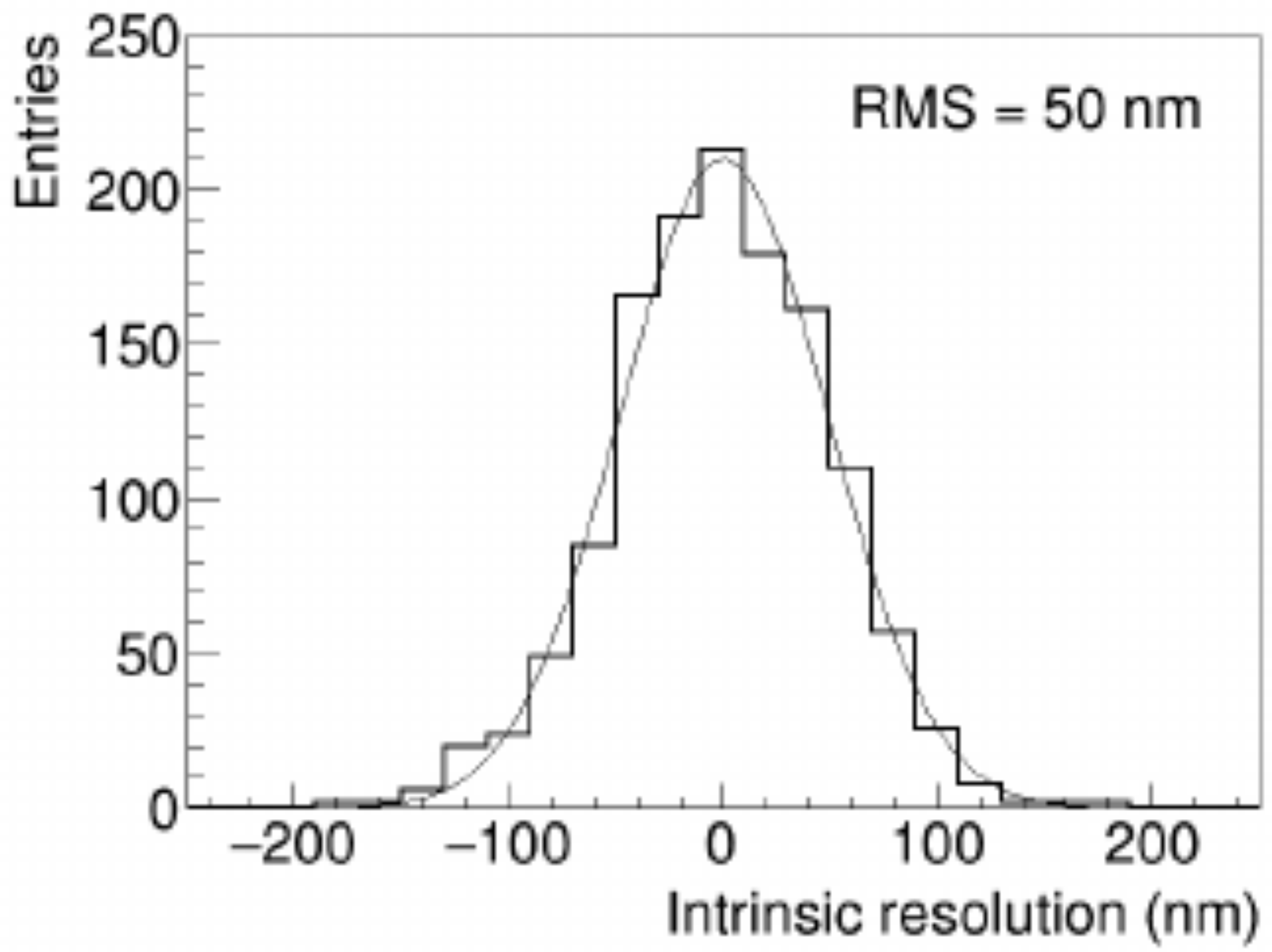


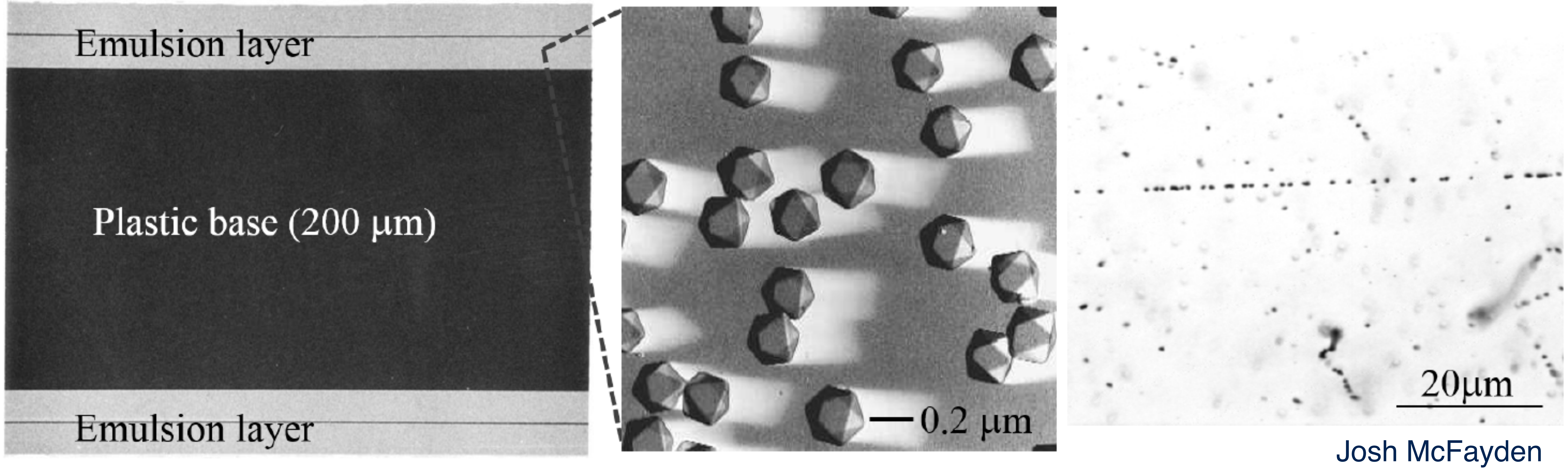




FASERν | Emulsion detection

- Emulsion film made up of ~80μm emulsion layer on either side of 200μm plastic
- Emulsion gel active unit silver bromide crystals (dia. 200nm)
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~50nm, and angular resolution ~0.35mrad
  - But no time resolution!





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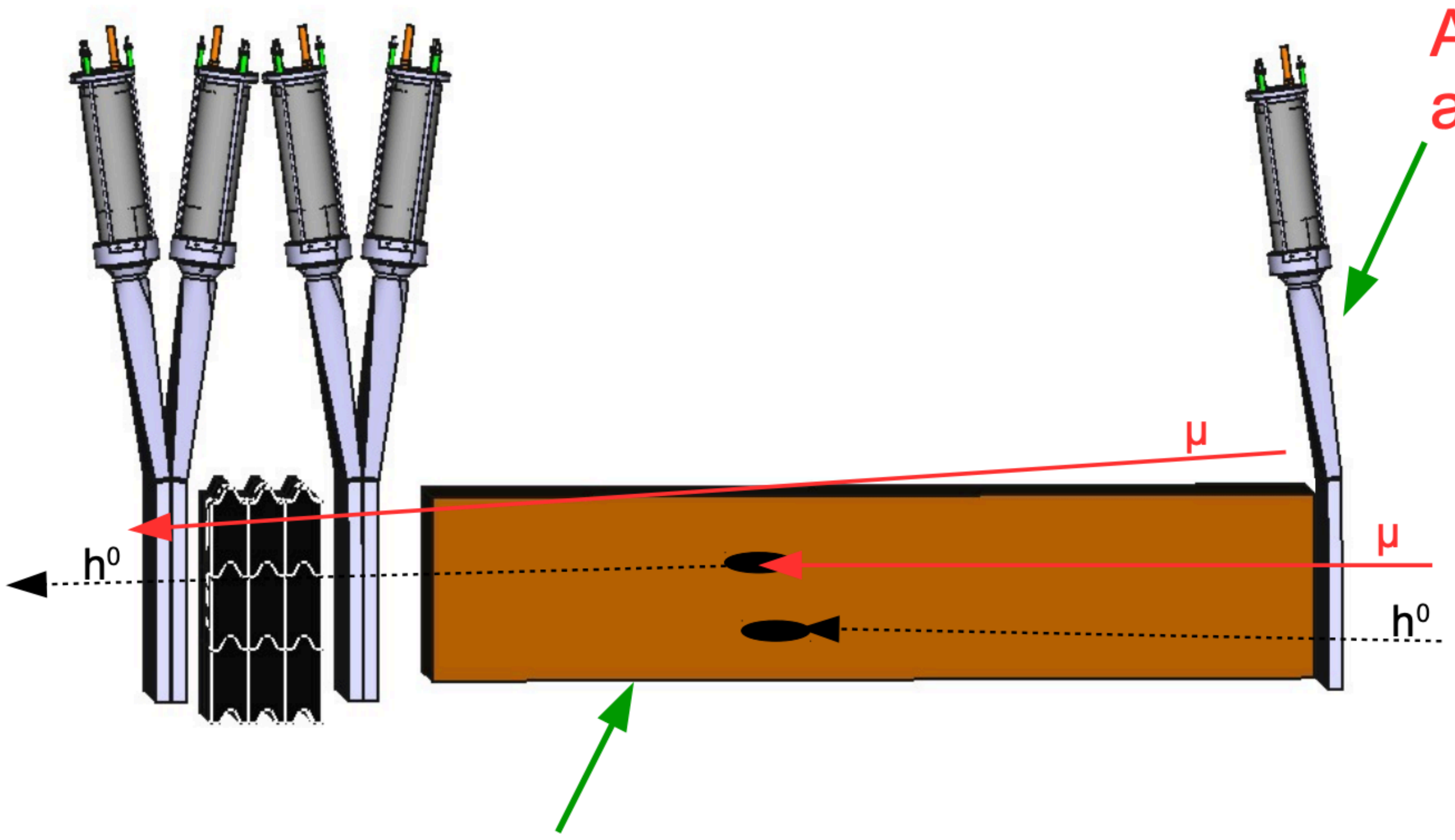
Do we still need shield wall with 1m tungsten installed in front?

- Probably, as we loose angular acceptance if station far apart
- Tungsten detector could function as hadron absorber



Add Scintillator at front?

- Veto events with muon induced neutral hadrons
- potentially help pick events with neutrinos for matching to emulsion

1m tungsten provides 10 nuclear interaction lengths
→ will stop/shower most hadrons

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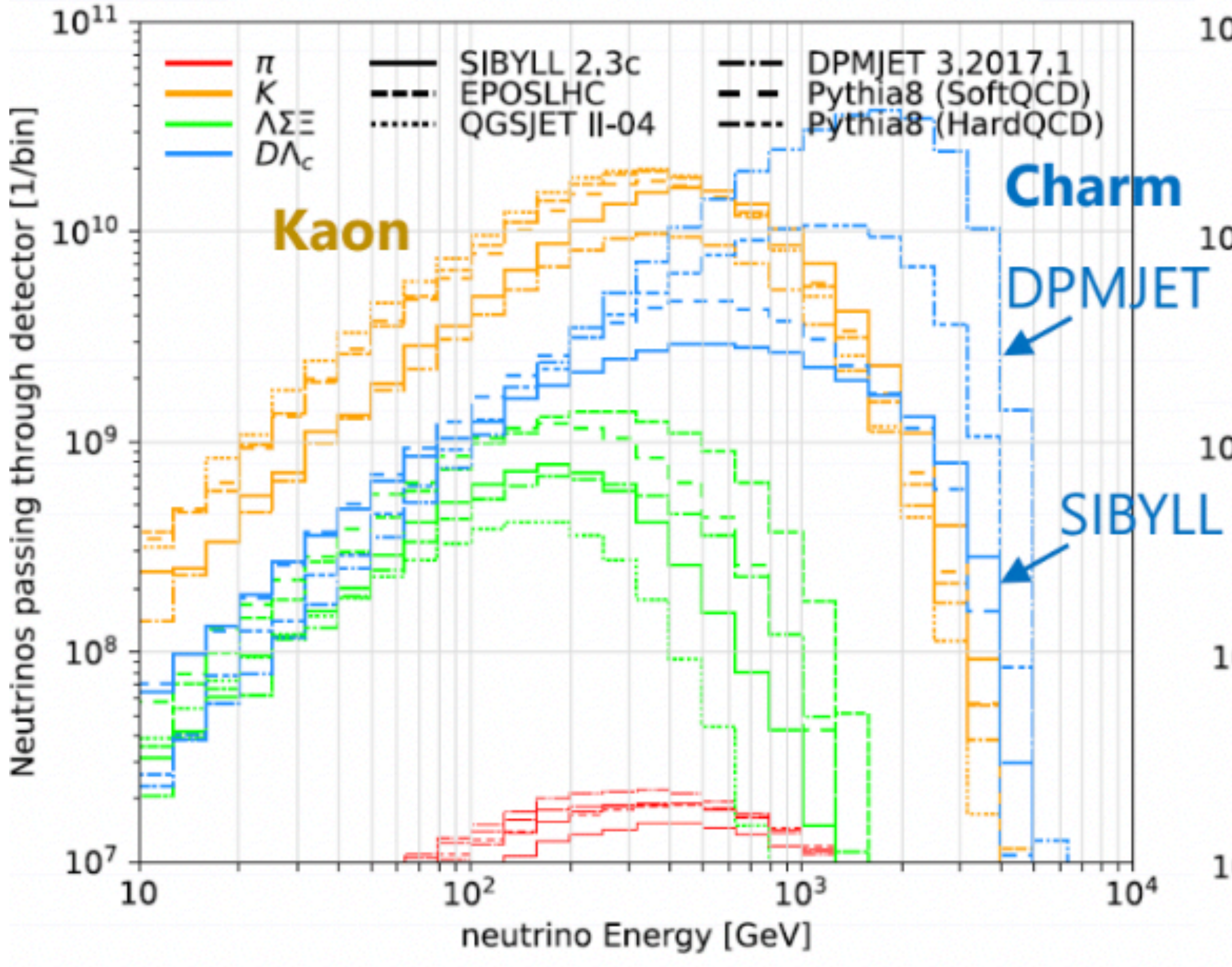
FASERν | Neutrino flux estimates

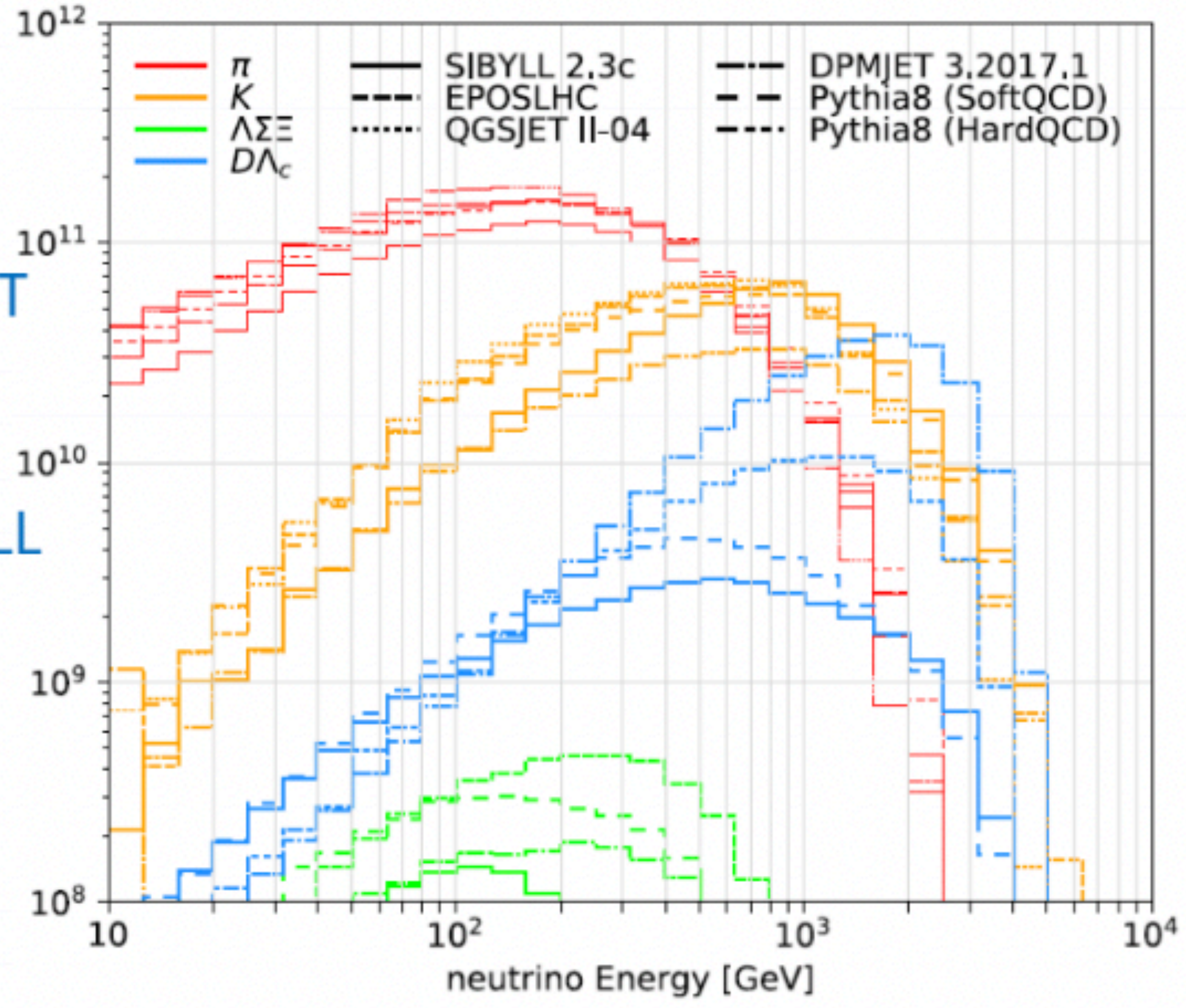
- Checking three simulations.
  - FLUKA (by F. Cerruti's group)
  - BDSIM (by H. Lefebvre, L. Nevay)
  - RIVET-module (by F. Kling)

- **Differences between generators** have been checked with the same propagation model (RIVET-module)

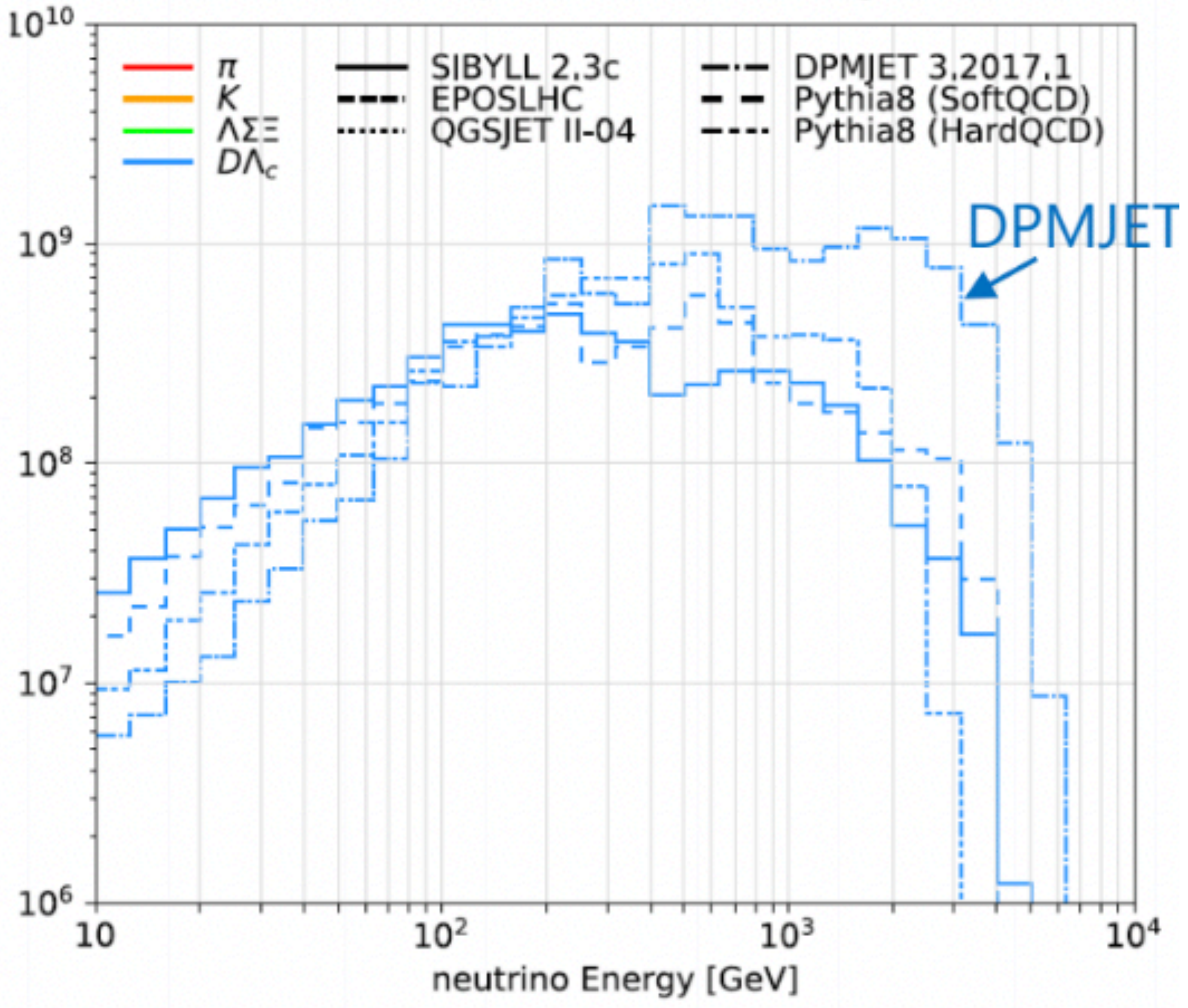
ν_e mainly from kaon and charm decays



ν_μ mainly from pion and kaon decays



ν_τ mainly from D_s and subsequent τ decays



FASERν | Neutrino energy reconstruction

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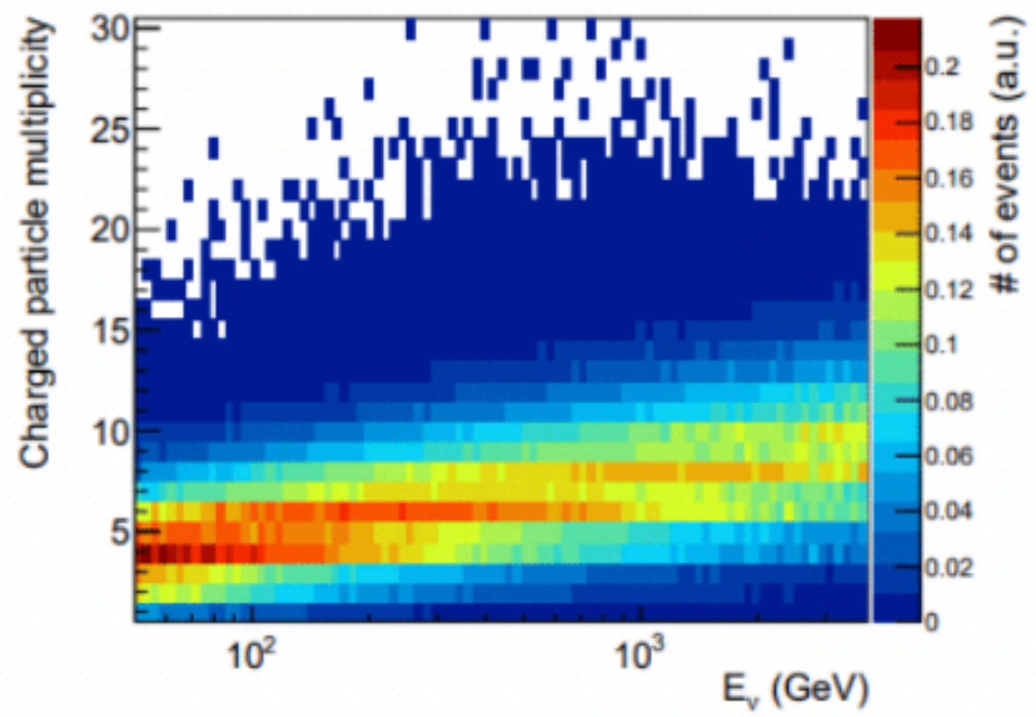
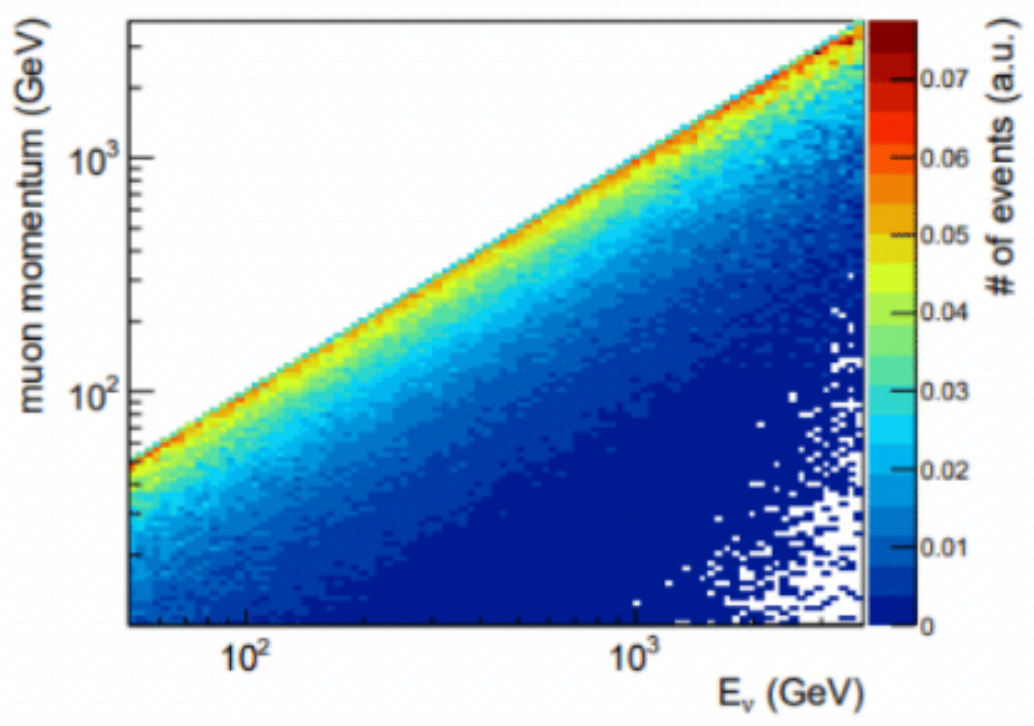
- Neutrino energy will be reconstructed by combining topological and kinematical variables

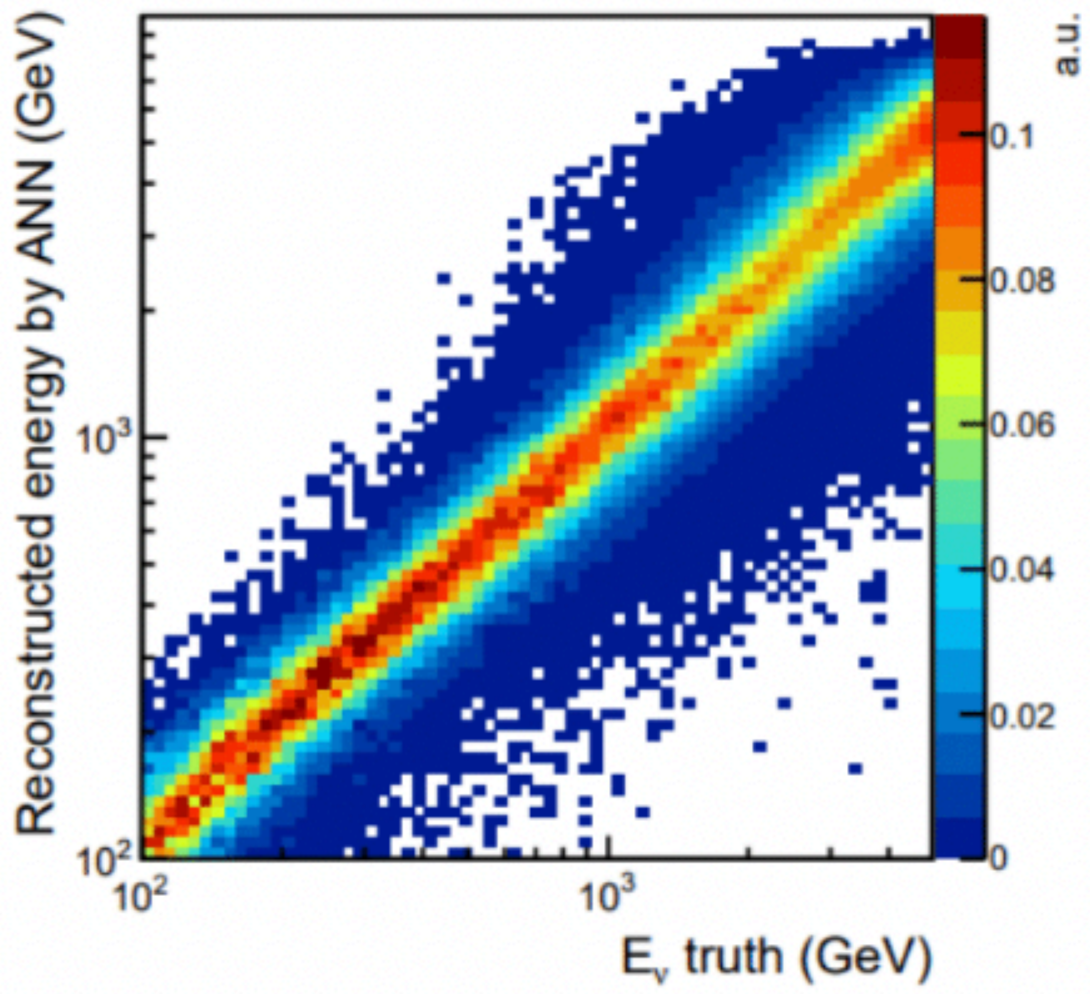
An ANN algorithm was built with
topological variables
- # of charged tracks → E_h
- # of γ showers → E_h
- inverse of lepton angle → E_l
- sum of inverse of hadron track angles → E_h
- inverse of median of all track angles → E_h, E_l

kinematical info (smeared)
- lepton momentum → E_l
- sum of charged hadron momenta → E_h
- sum of energy of γ showers → E_h





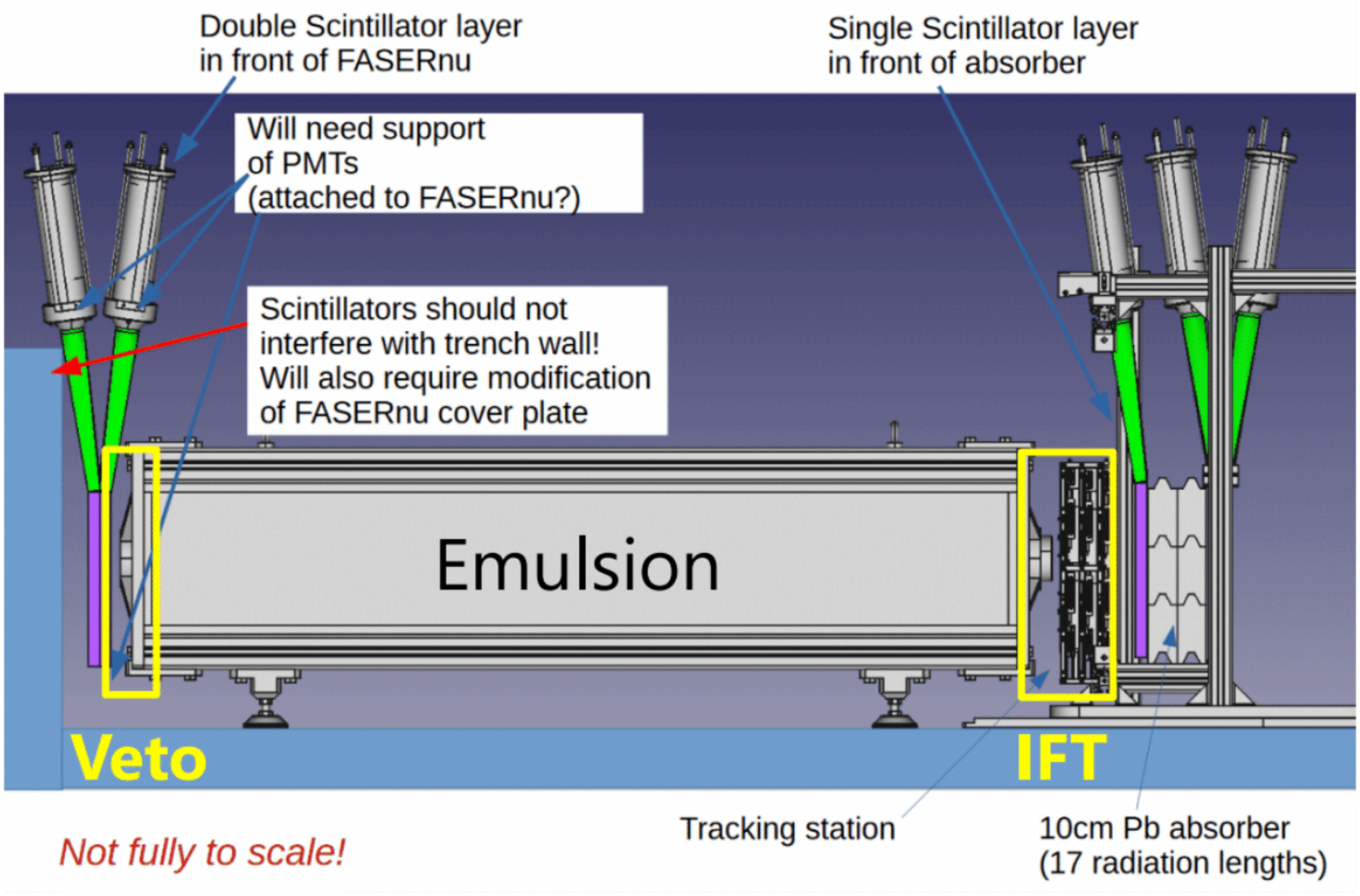
$E_\nu - E_{ANN}$



$$\frac{\Delta E}{E} \sim 30\%$$

FASERν | Interface to FASER

- To connect muon tracks from νμ interactions for charge identification etc.
  - Interface tracker (IFT) with 3 layers of silicon strip detector. A copy of FASER tracker station.
  - Veto station consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle coming from upstream of FASER
  - Construction of the IFT will start in January 2021. Installation at FASER site is planned in fall 2021



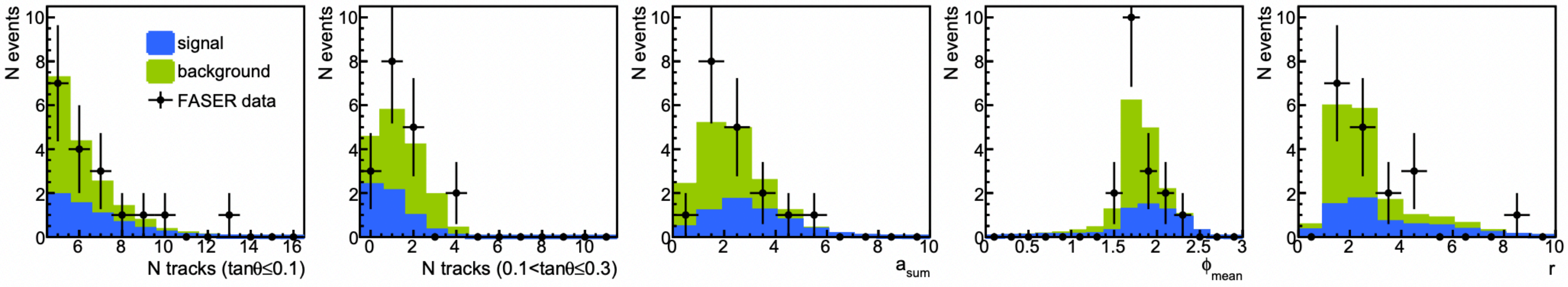


FIG. 4. Monte Carlo simulation distributions of the BDT input variables for the neutrino signal and neutral hadron background. The observed neutral vertices in the data sample are shown in black. The Monte Carlo simulation distributions are normalized to 12.2 fb^{-1}.

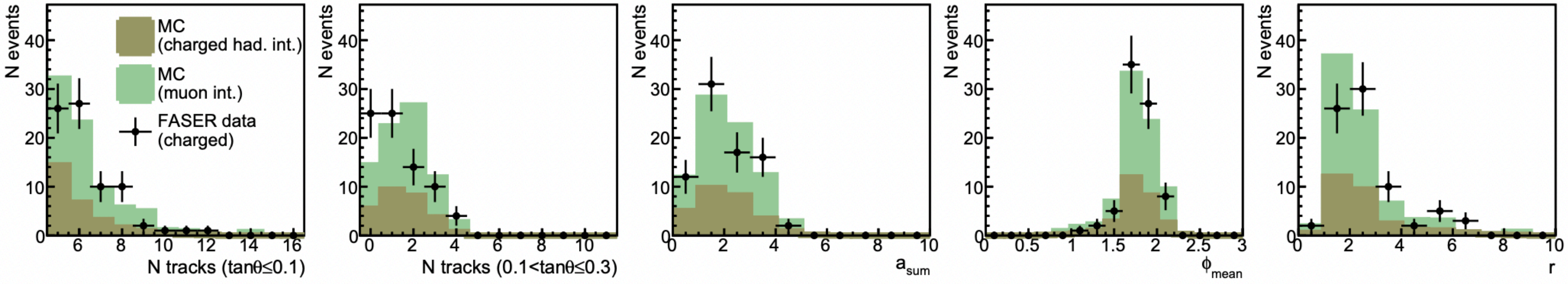


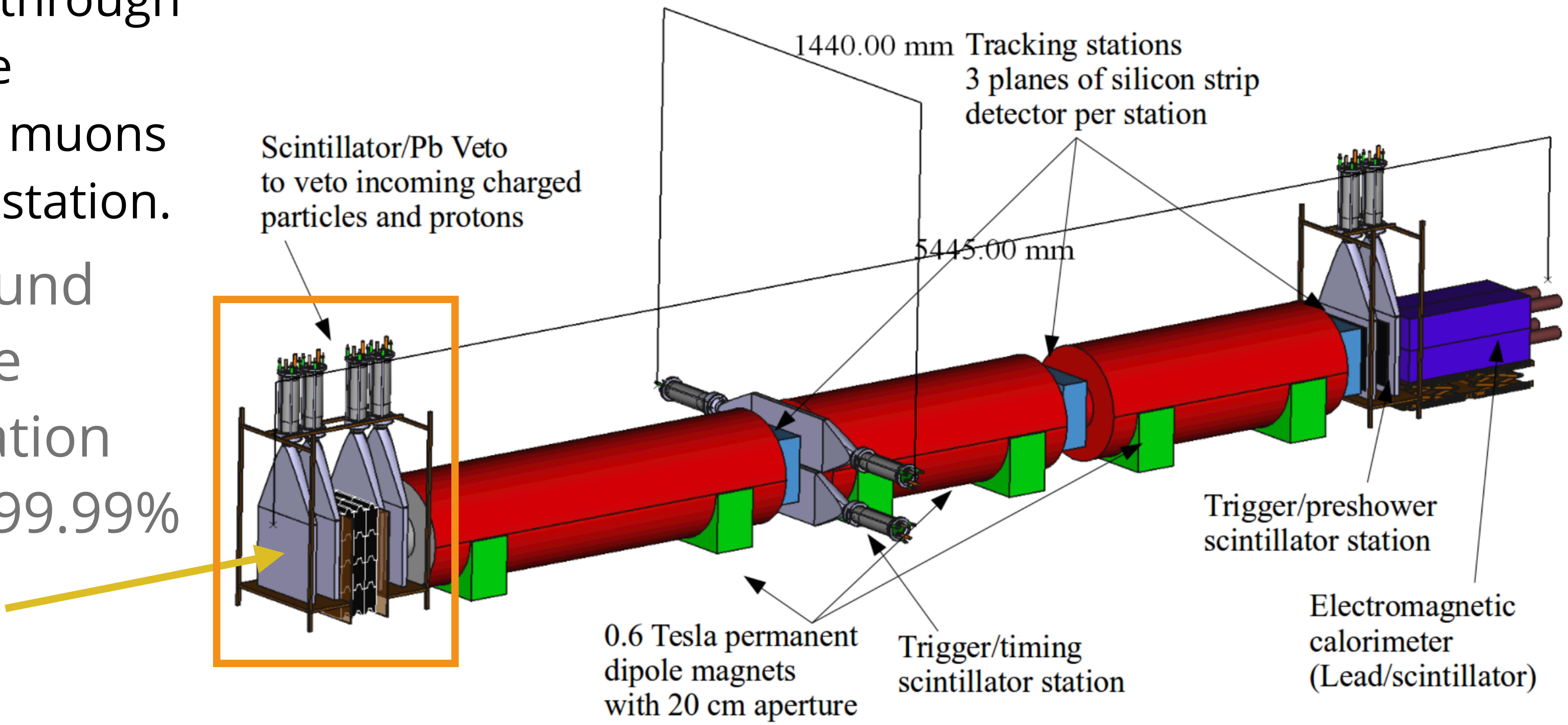
FIG. 5. Monte Carlo simulation distributions of the BDT input variables for charged hadron interactions and muon interactions. The observed charged vertices in the data sample are shown in black. The Monte Carlo simulation distributions are normalized to the data to compare the shapes.

Detector layout

(as per specification document)

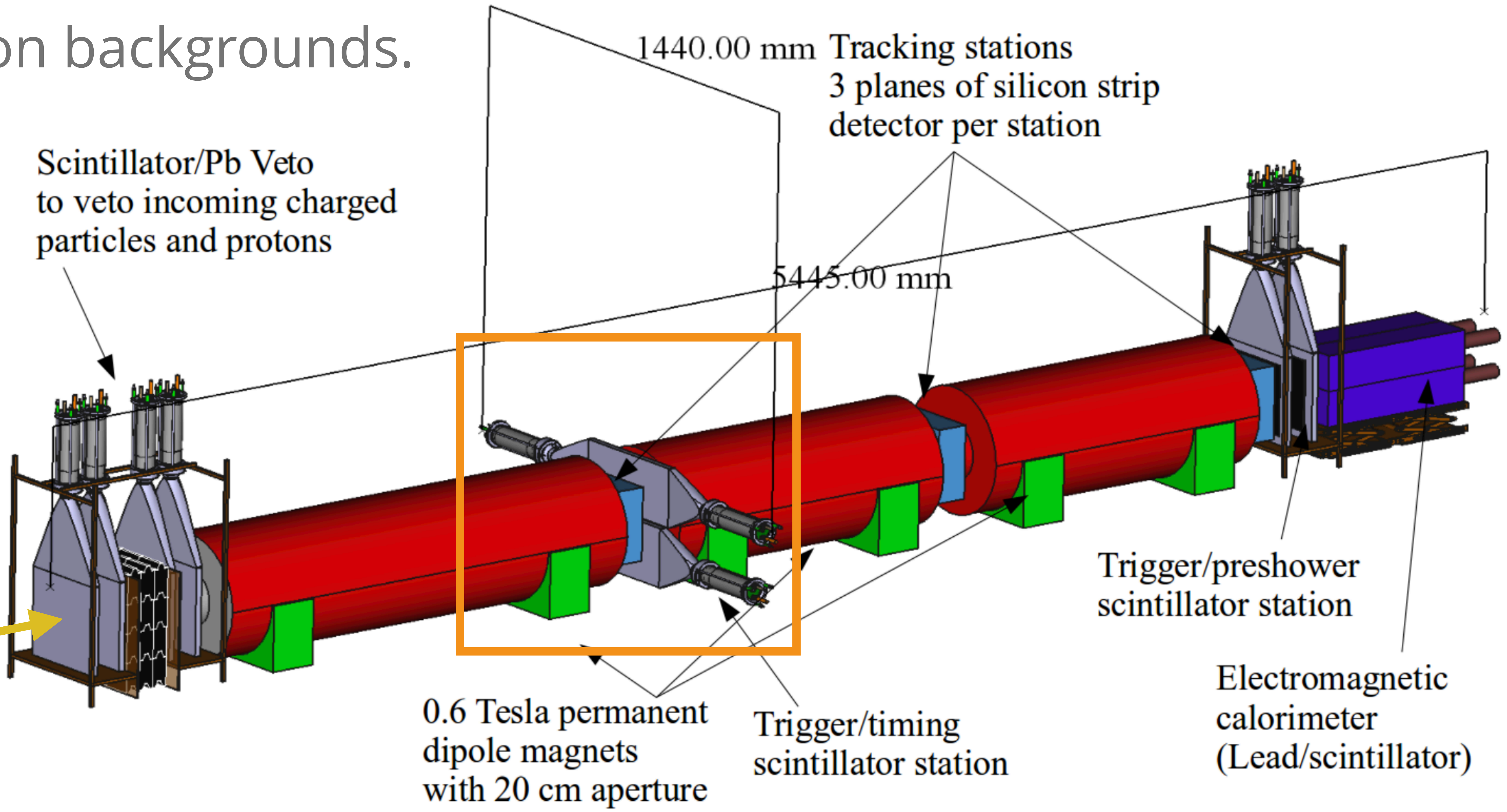
Overview | Veto station

- Used to suppress events with incoming particles, mostly high-energy muons.
  - Lead absorber: contains energetic photons from muon bremsstrahlung before the detector or generates a shower detectable by the second station.
    - High-energy muons passing through the absorber will also radiate photons, but in this case the muons will be detected by the front station.
  - To fully suppress background related to muons from the interaction point, each station should detect more than 99.99% of the incoming muons.



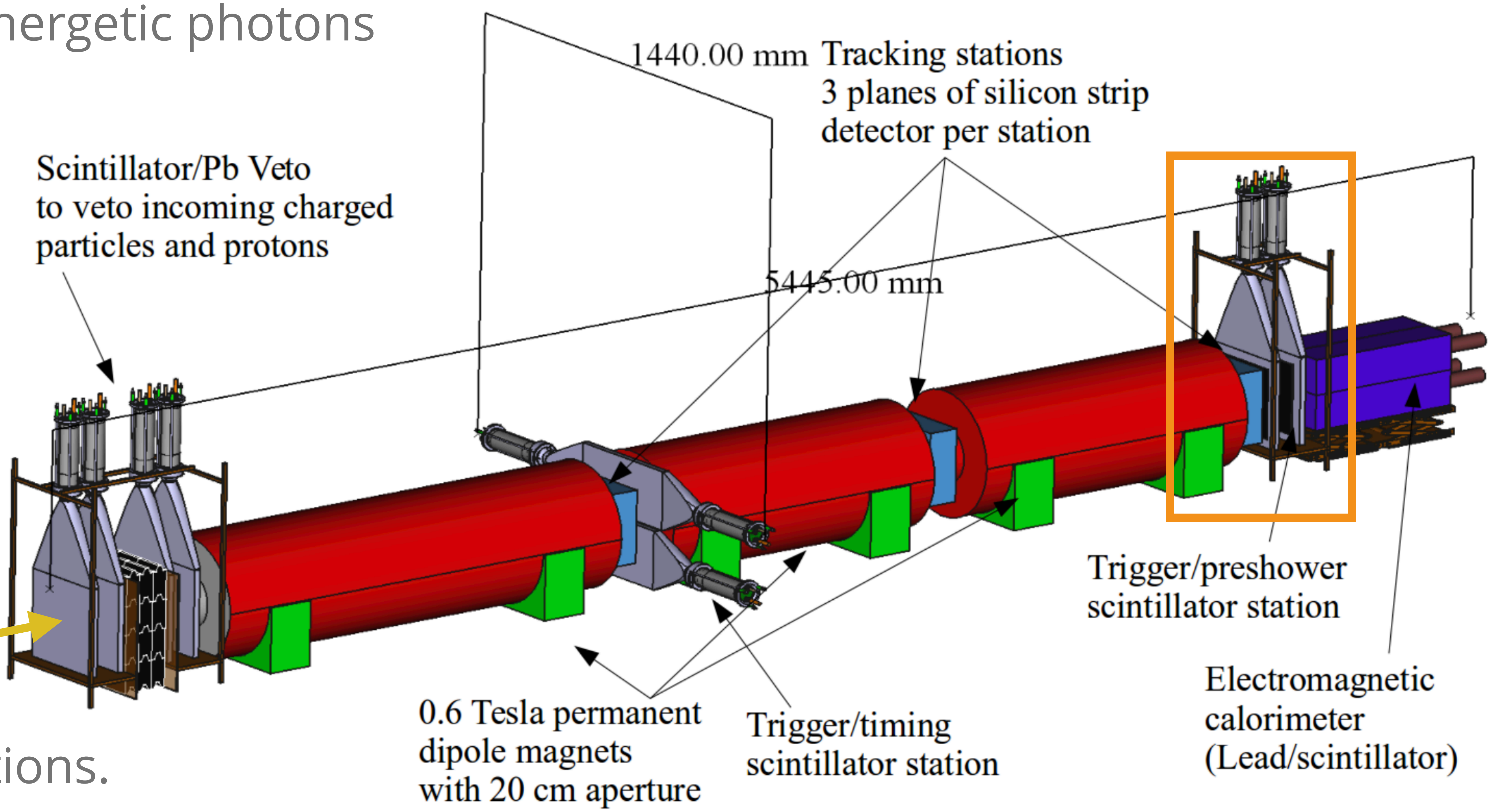
Overview | Trigger/timing station

- Located after the first magnet and first tracking station
- Used to detect the appearance of a charged particle pair from the decay of a LLP in the decay volume of the first dipole magnet.
  - Provides the primary trigger signal and will also be used to precisely measure the arrival time of the signal with respect to the pp interaction at the IP.
  - Precision < 1 ns to suppress non-collision backgrounds.
  - Material should be minimized while maintaining efficiency > 98%.
- Secondary veto
  - Active area large enough to cover most of the magnet front surface.
  - Can detect muons that cause an EM shower missing veto stations and first two tracker stations and mimicking a photon-only signature.



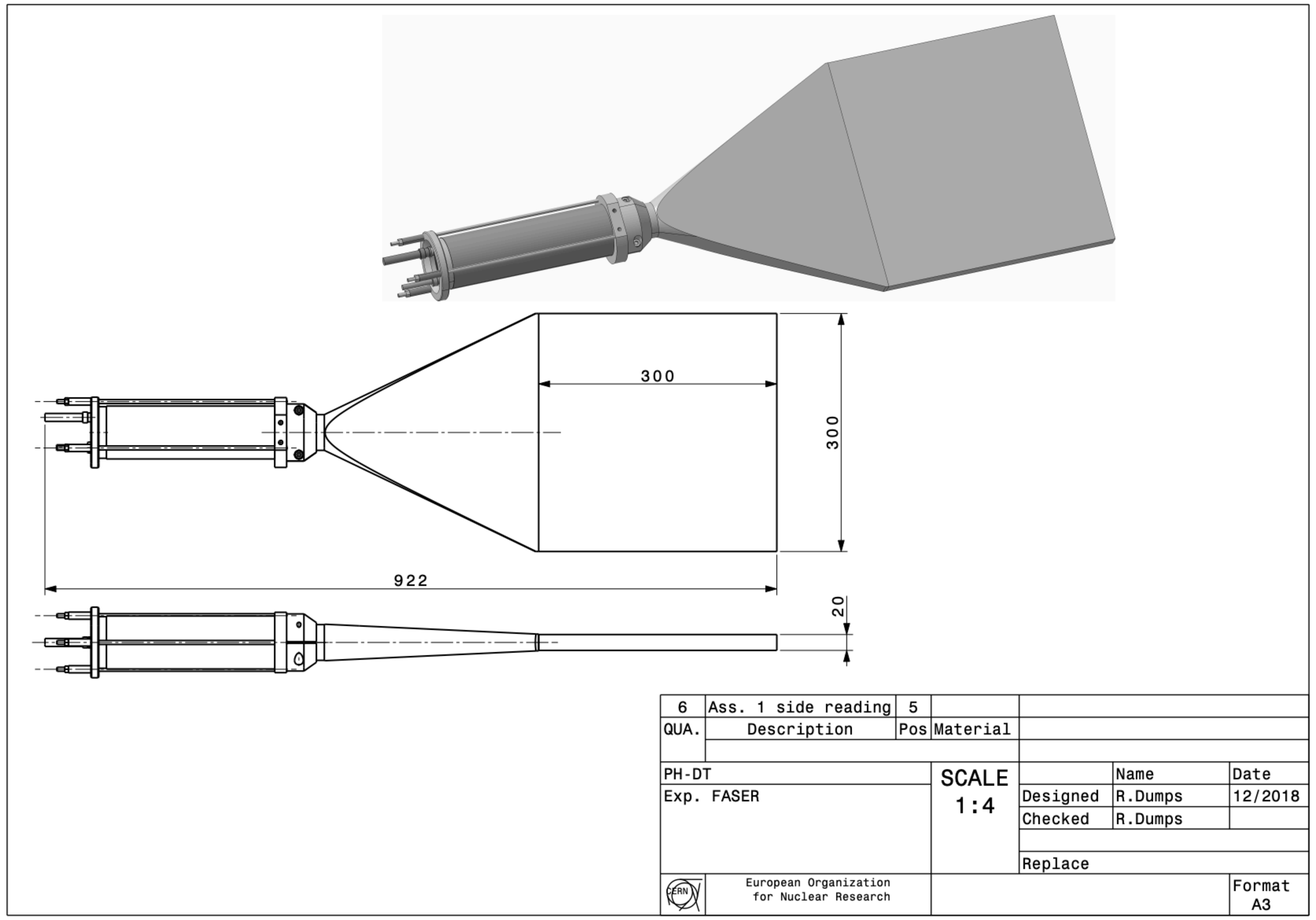
Overview | Trigger/preshower station

- Located just in front of the calorimeter.
- Provides an additional trigger signal which, if needed, can be used in a coincidence with the first trigger station to reduce the rate of non-physics triggers.
- Preshower detector
  - A thin layer of radiator to create simple preshower.
  - Can detect a physics signal of two close-by energetic photons with high efficiency.
    - Helps distinguish this signal, which would otherwise leave only large energy deposition in the calorimeter, from deep inelastic scattering of high energy neutrinos in the calorimeter.
    - Needed because the calorimeter does not have any longitudinal segmentation.
- Low-Z absorber
  - Reduces backsplash from calorimeter and preshower radiator the last tracking station
  - Located between tracker and preshower stations.



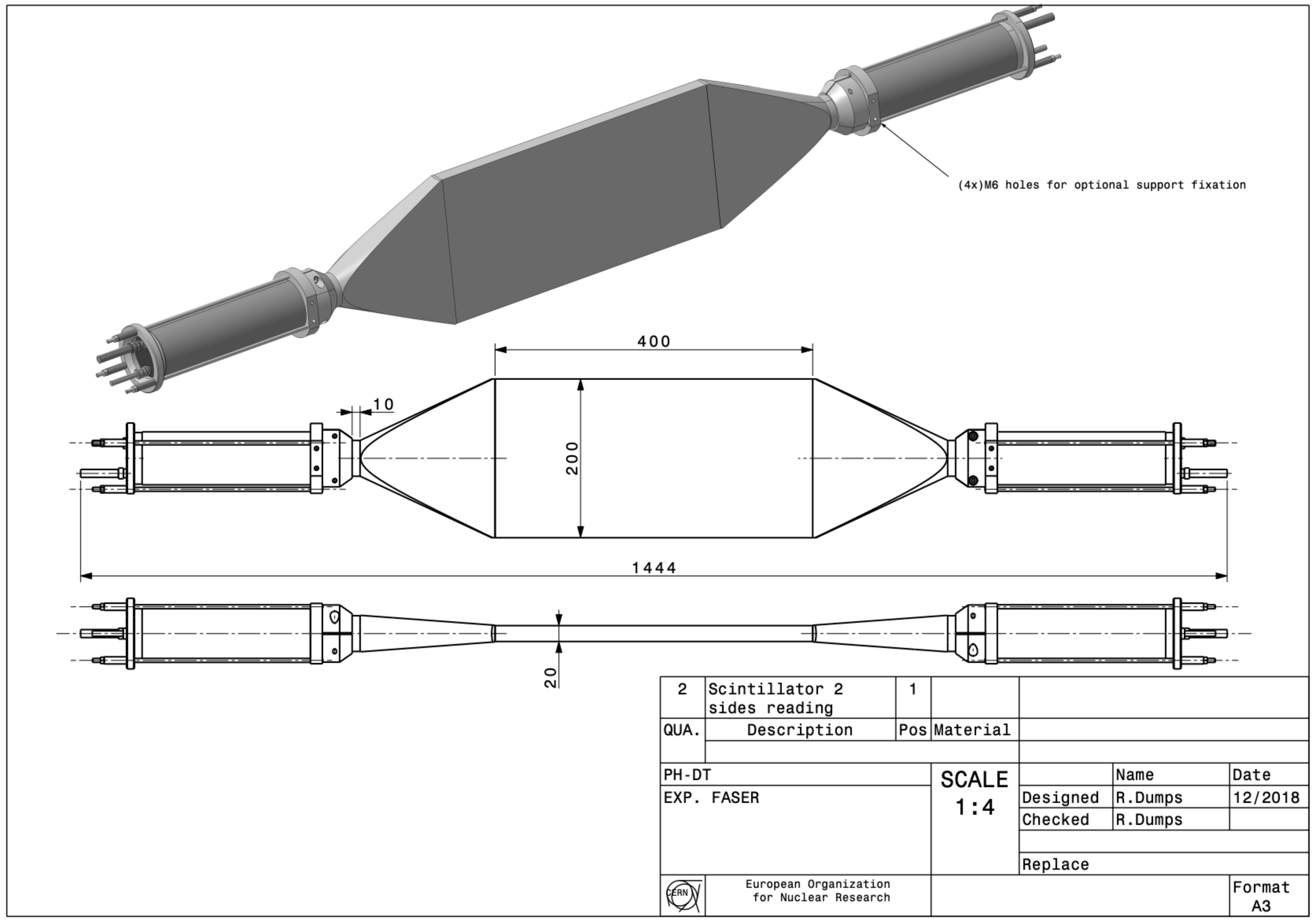
Scintillator design | Veto/preshower

- Veto/preshower stations consist of 2 x 2 cm-thick, 30 cm×30 cm plastic scintillator (Bicron BC 408) connected through a light guide to a Hamamatsu H6410 PMT.
  - Scintillator layer is larger than the magnet aperture to ensure no charged particles can enter undetected
  - 2 cm thickness is chosen to provides a very high single layer detection efficiency (well above 99%).
  - Two independent layers provides redundancy and ensure a very high veto efficiency
    - Can easily be measured in situ, as there should be no correlated inefficiencies.
- The H6410 provides
  - Maximum gain of 3×10^6
  - Typical rise time of 2.7 ns
  - Typical transit time-spread of 1.1 ns (single photo-electron).
- Both layers will be installed with the PMT pointing up to reduce (horizontal) width
- The scintillator layer and light guide will be wrapped in thin aluminium sheets to ensure light tightness and to improve fire safety



Scintillator design | Trigger/timing

- The trigger/timing station consists of a single scintillator layer made from two 20 cm× 40 cm scintillator blocks with a thickness of 1 cm (2.5% radiation length)
- The layer is split into two blocks
  - To reduce the size of the light guide, keep high detection efficiency and improve timing precision (less vertical time-walk)
- The horizontal time-walk is compensated by using the average signal time of the two PMTs
  - The reason for having PMT on each side of the scintillator layer.
- With this setup, the timing resolution will be limited by the precision of the readout electronics.
- Having two blocks will imply a gap of about 1.5 mm between the active parts of the scintillators.
  - To avoid an inefficiency, the two blocks will be offset along the line-of-sight by 1.5 cm, so that a small 1 mm overlap can be introduced.



Light detection

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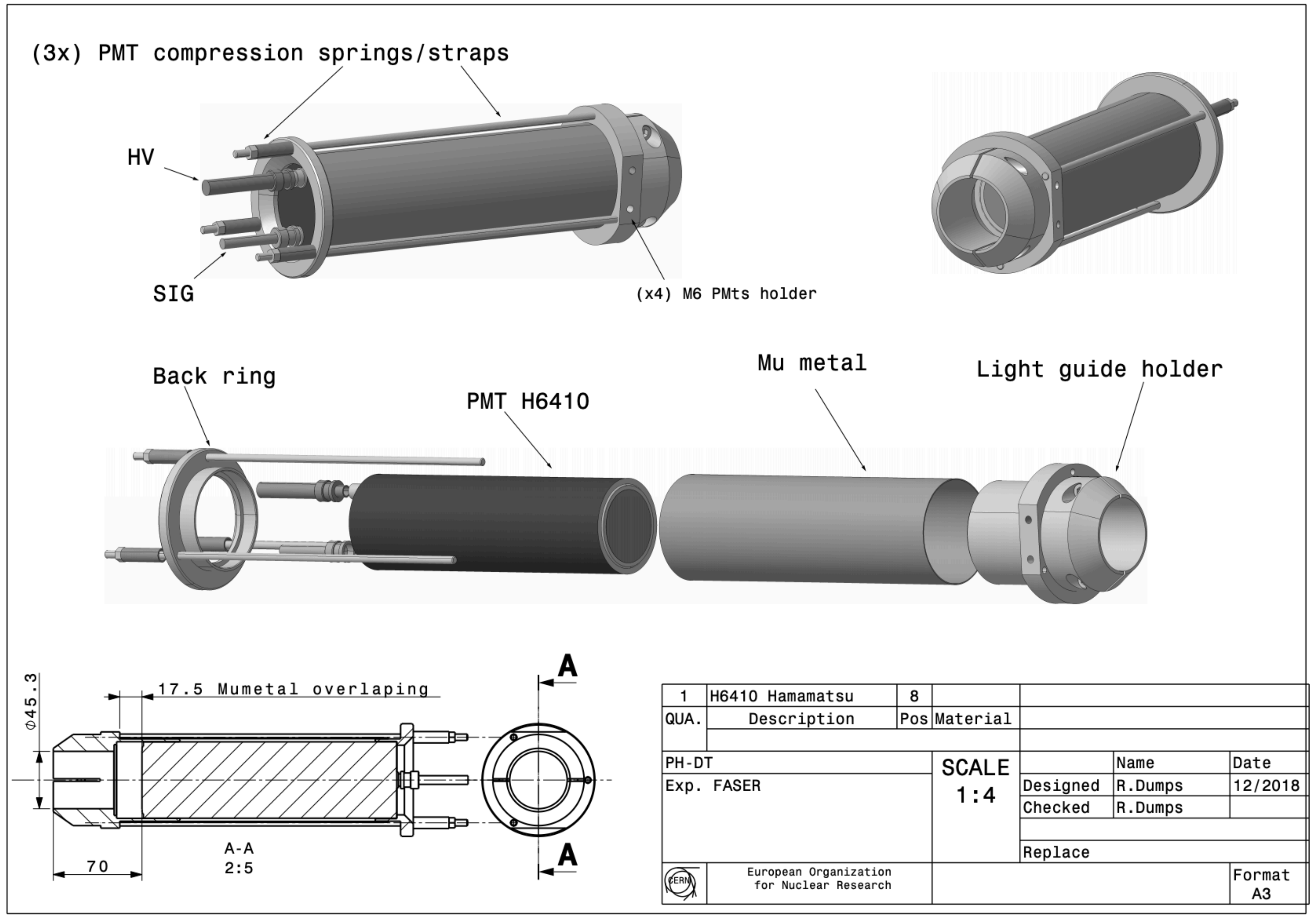
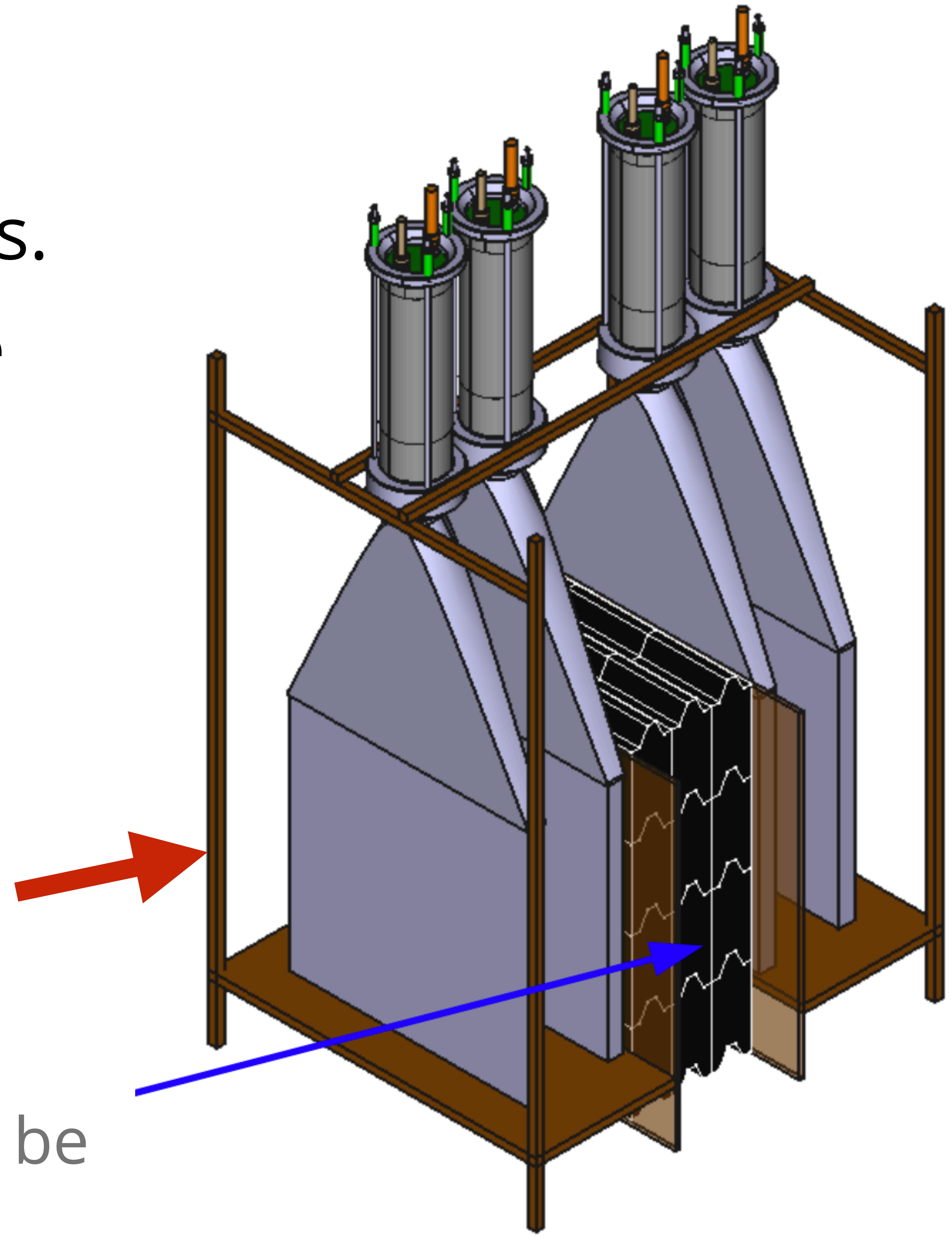
- The PMTs come as a full assembly with
  - the phototube itself
  - voltage divider
  - surrounding mu-metal for magnetic field shielding.
- Will be encased in an additional mu-metal shielding to ensure operation is not affected by magnetic fringe fields (up to 5 mT).
- Need to check efficiency in lab before installation.
- The H6410 has a larger aperture (46 mm), larger gain and better time resolution than the Hamamatsu H3178-51 proposed in the Technical Proposal.



- Operation voltage is ~-2 kV with a maximal voltage of -2.7 kV and a maximum anode current, including the voltage divider, of 0.67 mA.
- Each PMT will have high voltage supplied from its own HV channel
  - Avoids any correlation in efficiency between the PMTs and allows adjusting the HV individually to equalize gains.
- Significant rate of single muons can be used to calibrate the PMT response
  - No in situ calibration system is foreseen.

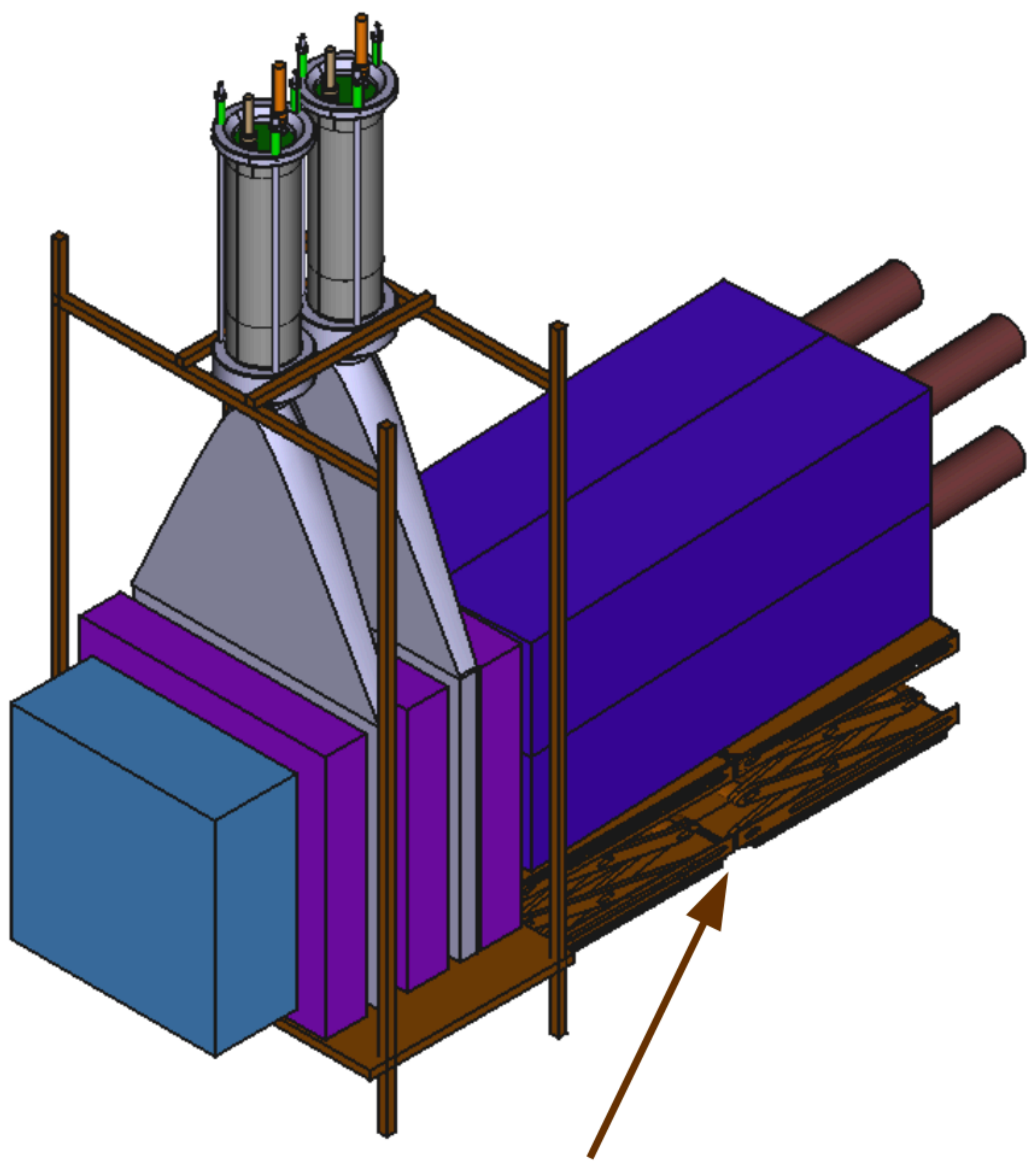
Support structure

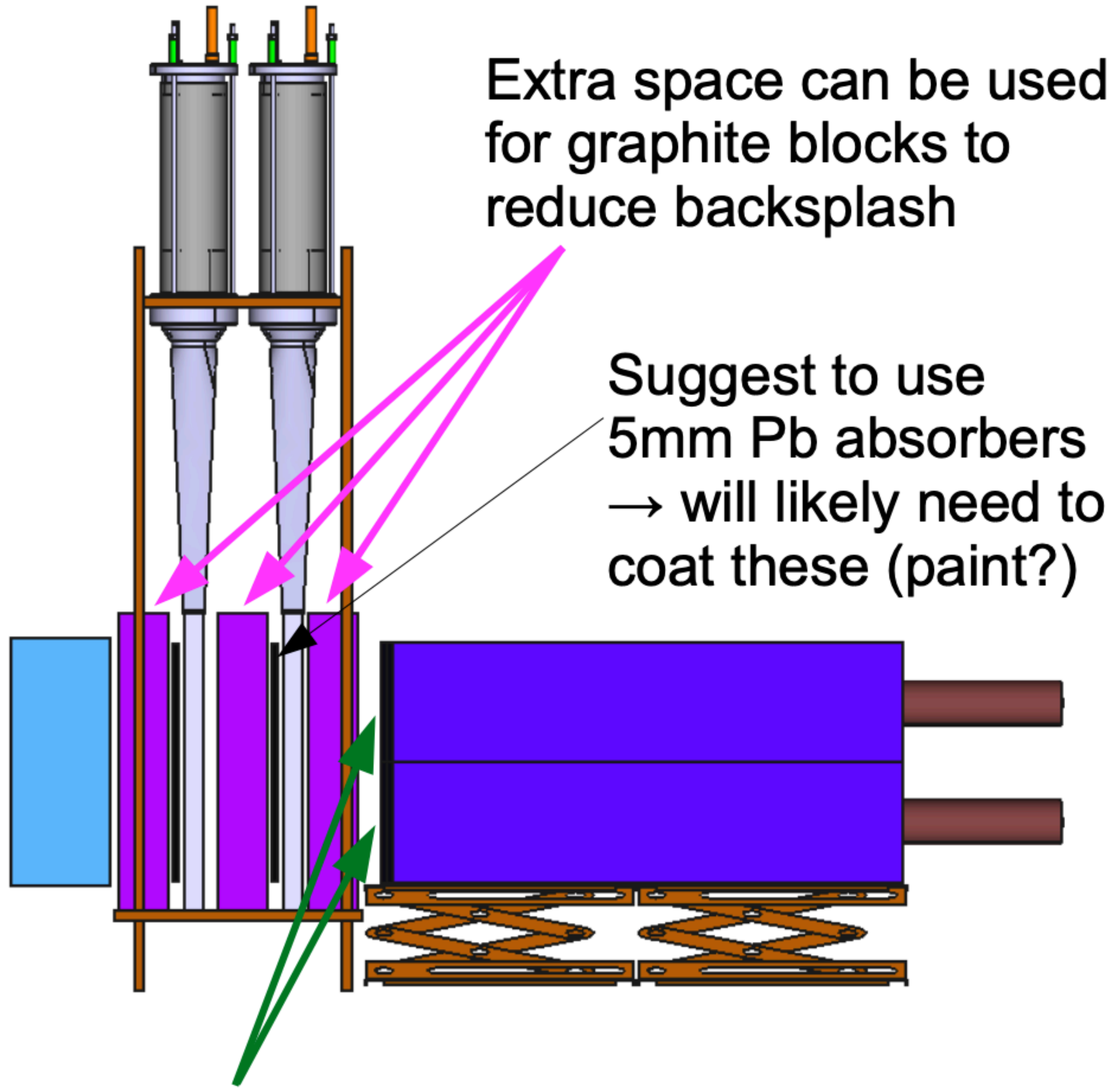
- The scintillator layers will be mounted to a simple vertical (or H-shaped in the case of the vertical layers) **support structure** with M6 screws on the PMT holder
- The layers with only one PMT will need to be supported at the bottom of the layer by resting on a stable surface.
- For the timing layers with PMTs on both side, it will be sufficient to attach the layer to the vertical structure in both PMT holder mounts.
- To align the scintillators, the support structure has to be adjustable
  - Though 1 cm precision should be sufficient given the much smaller active aperture.
  - The only exception is the timing layer, where the two layers have to be adjusted vertical to have a small 1 mm overlap of the active areas (about 2.5mm total overlap).
- Need to get further weight details:
  - Weight of scintillator, light guide and PMT with holder.
  - The scintillators are 1-2 kg, depending on the type and the light guides will be similar or less. PMT with mu-metal is 2 kg?



Pre-shower | Layout and support

- Nominal construction similar to the veto stations except with **layers of absorber** in front of scintillator layers and **graphite blocks** to reduce backsplash
  - Generates characteristic signal for two photons in the scintillators by initiating the EM shower before calorimeter.
  - Addition of graphite blocks to mitigate backsplash
- Layout
  - The two scintillator layers have a single light guide and PMT, pointing upwards for both layers.
  - The layers will be separated by 80 mm
- Support
  - Similar to veto stations with space reserved in front of the first layer and behind the second layer for installing graphite blocks.
  - Blocks can either be stacked on the same structure that support the scintillators from the bottom or be stacked directly on the base plate.
  - The graphite block in front of the calorimeter will need to have openings for the optical fibres for the calibration system to pass through.





Pre-shower | Absorber and Backsplash

- **Absorber**
  - The front face of each scintillator will have a 20 cm×20 cm tungsten or lead plate attac
    place by the support structure) in the middle of the active area.
  - Plates will be ~1 radiation length thick (3.5 mm tungsten or 5.6 mm lead) and weigh 2
    - The thickness of each absorber material should be optimized using simulation.
  - More cost efficient to use lead plates unless someone has a suitable tungsten plate al
- **Backsplash mitigation**
  - EM showers in the two absorber plates and in the calorimeter will produce low energy
    in the opposite direction
    - This will produce unwanted signals in both the preceding scintillator layer and last tracker station
  - To suppress that, put 5 cm thick 30 cm×30 cm blocks of high density graphite (8 kg tot
    in front of the absorber plates and between the last scintillator layer and calorimeter
  - Graphite has a large ionization energy loss compared to its radiation length making it
    good absorber for low energy electrons/positrons.
  - The cost of the graphite plate will depend on the density desired and the size of the g
    - Medium grained (GR-060, density 1.72 g/cm3) ~200 CHF, isomolded (GM-10, density 1.82 g/cm3)