FASER (and FASERν)

Warwick Seminar

4/4/2021

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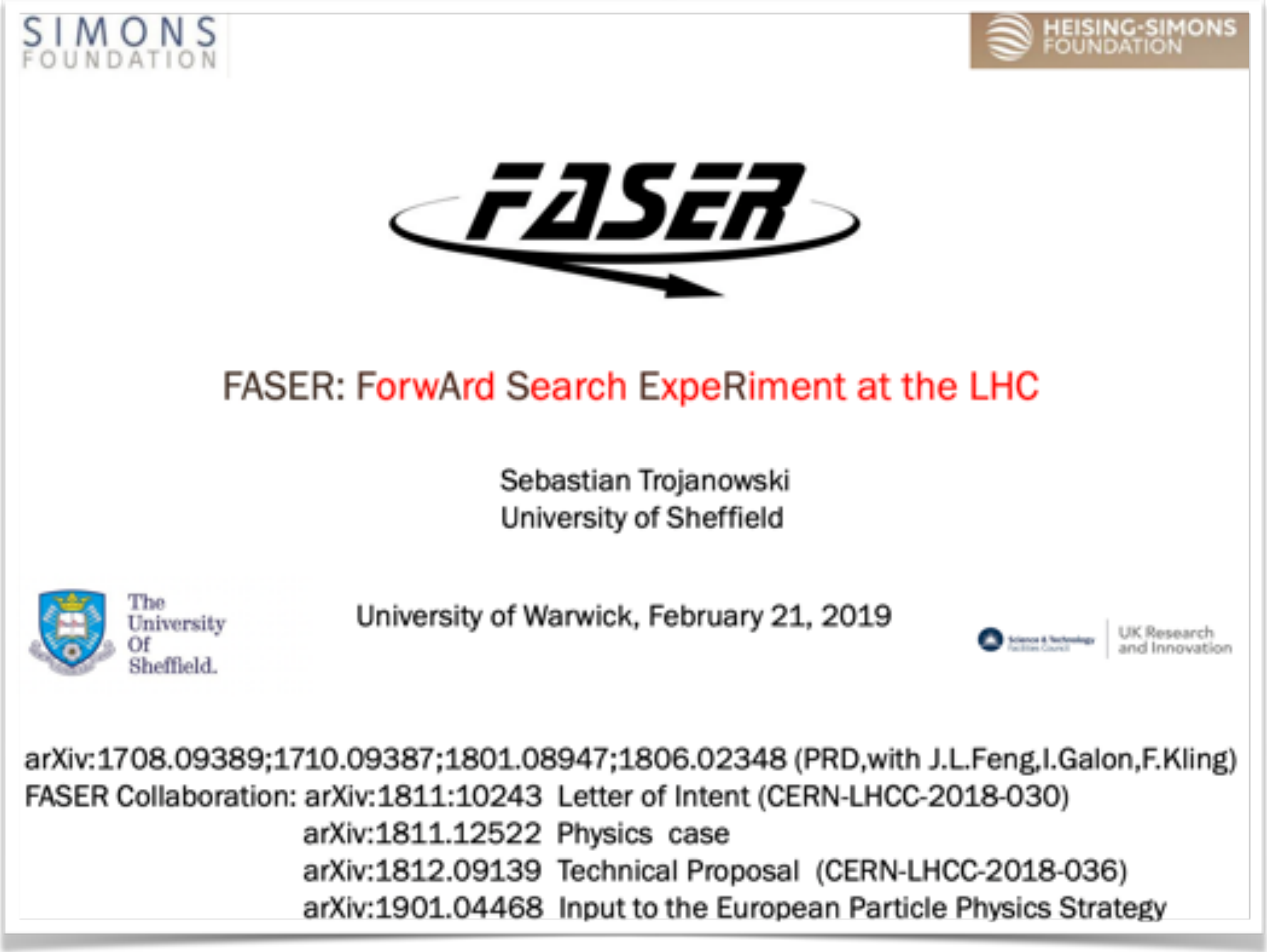
faser.web.cern.ch

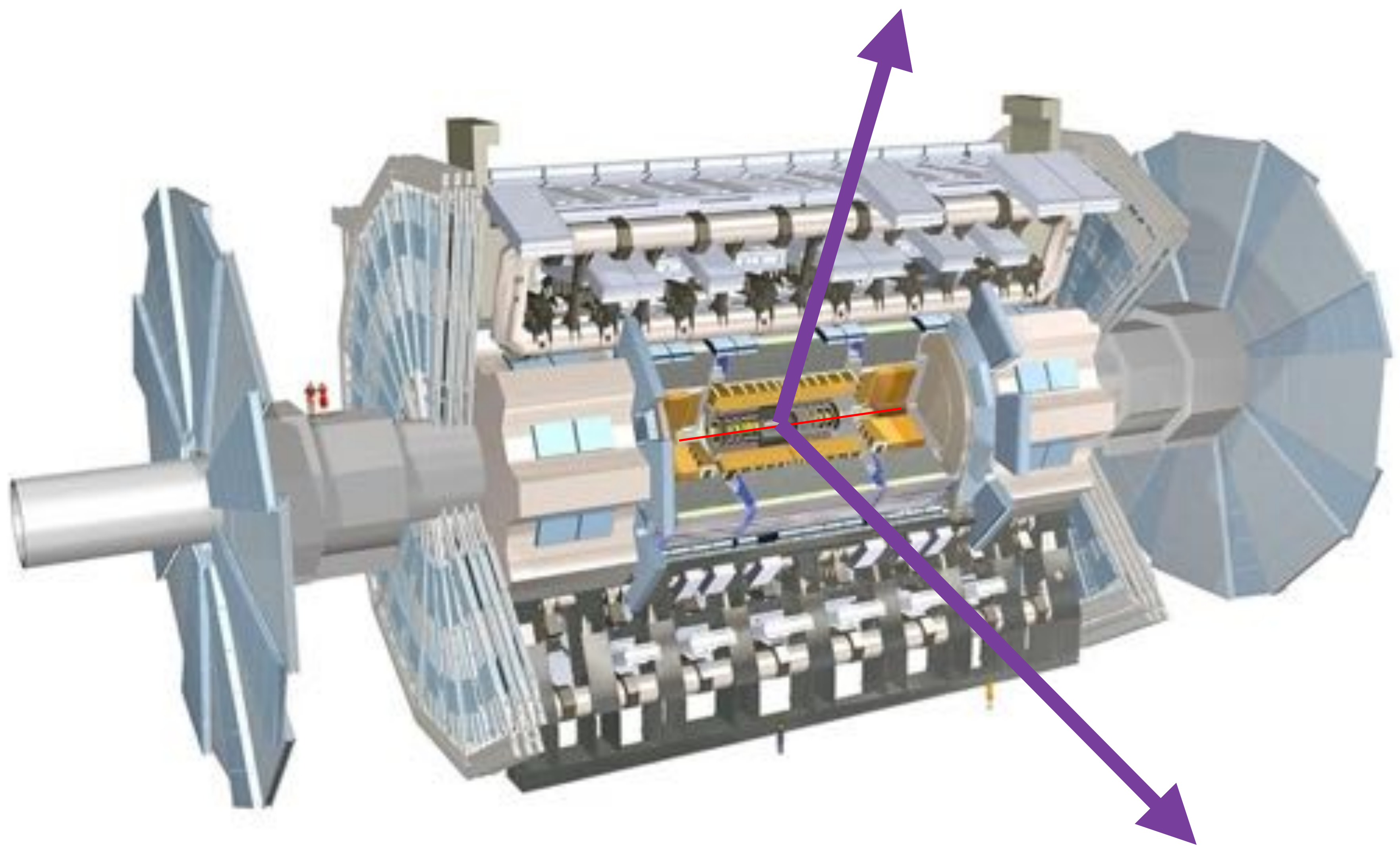
Previous FASER Seminar

- Just over 2 years ago you had a seminar from Sebastian about the plans for FASER
- Today I hope to show you that we've been busy since then…



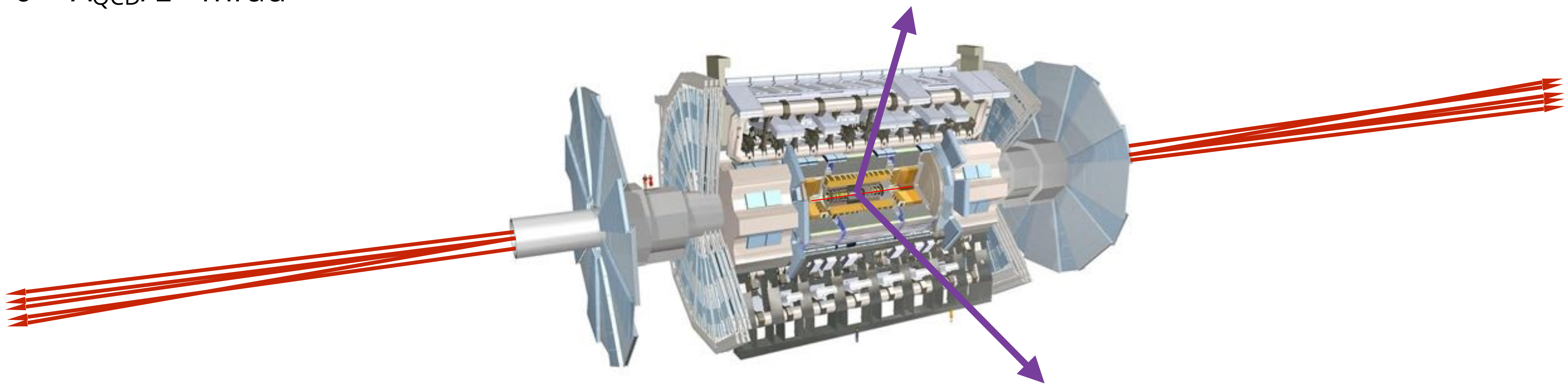
Landscape

- 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



Landscape

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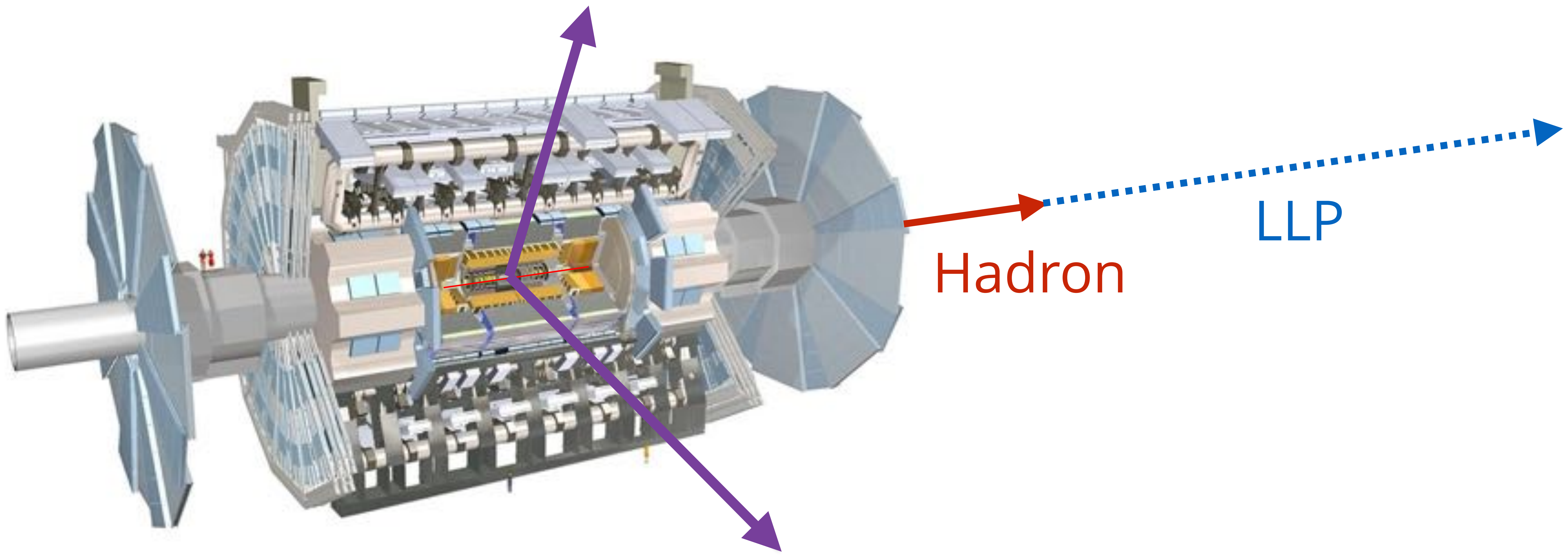
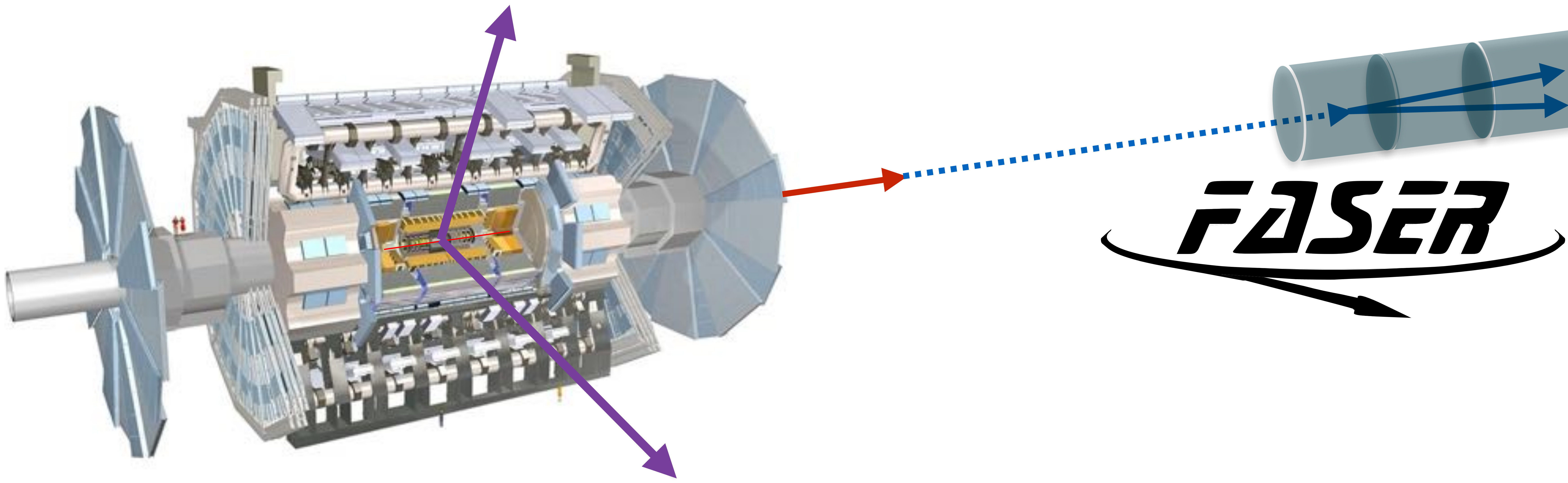
  - **Light meson**: low $p_T \sim \Lambda_{QCD}$ → particles are collimated:
    - $\theta \sim \Lambda_{QCD}/E$ ~mrad
  - Gain sensitivity to **long-lived particles with very weak couplings**.



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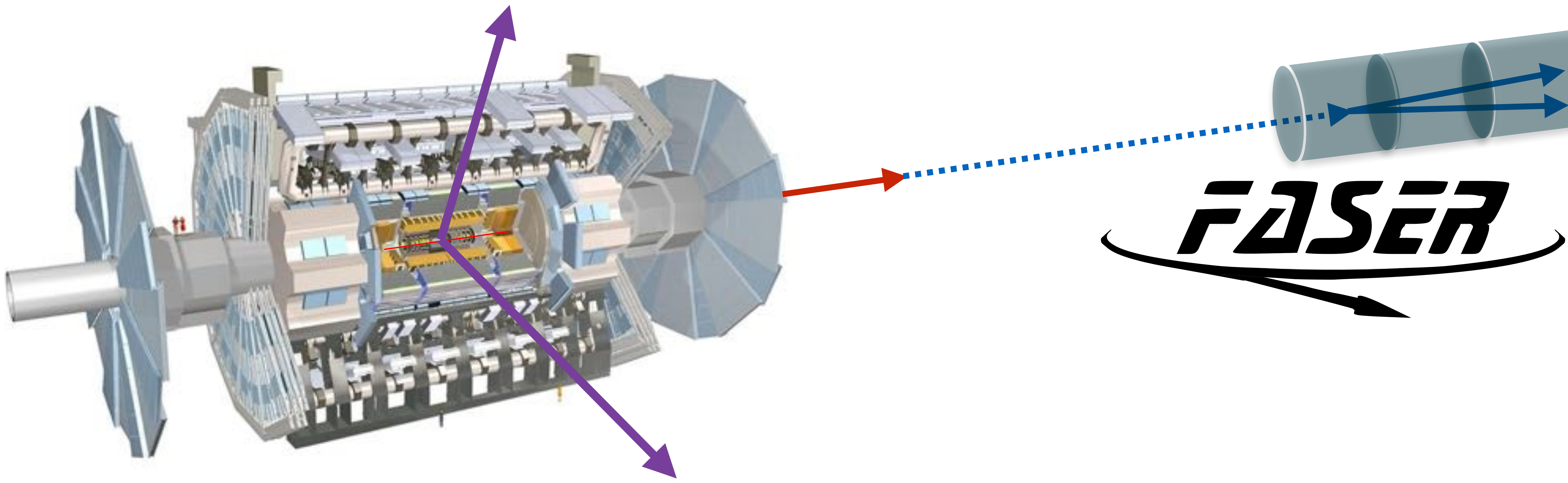
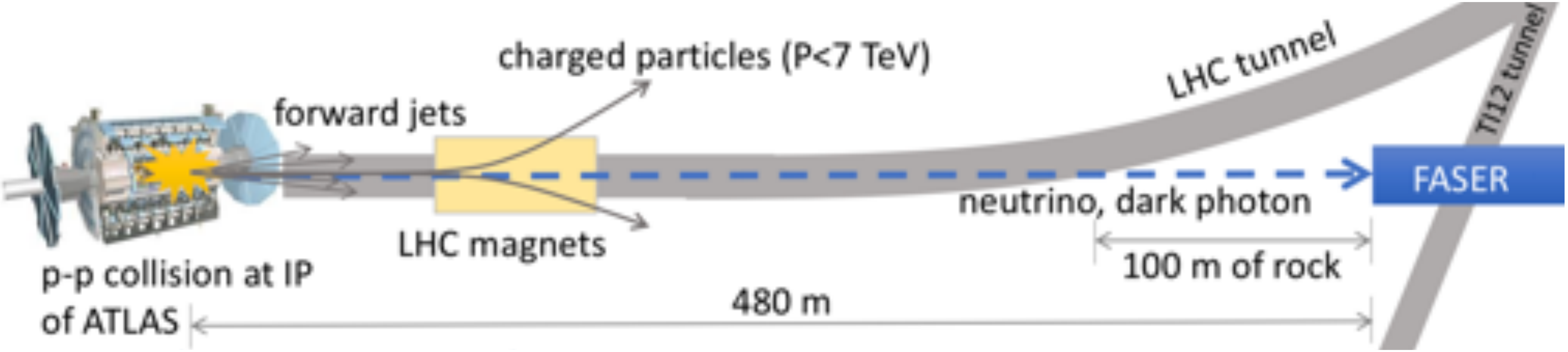
- From only 10^{-8} of solid angle 1% of π_0s are in acceptance.



FASER Location

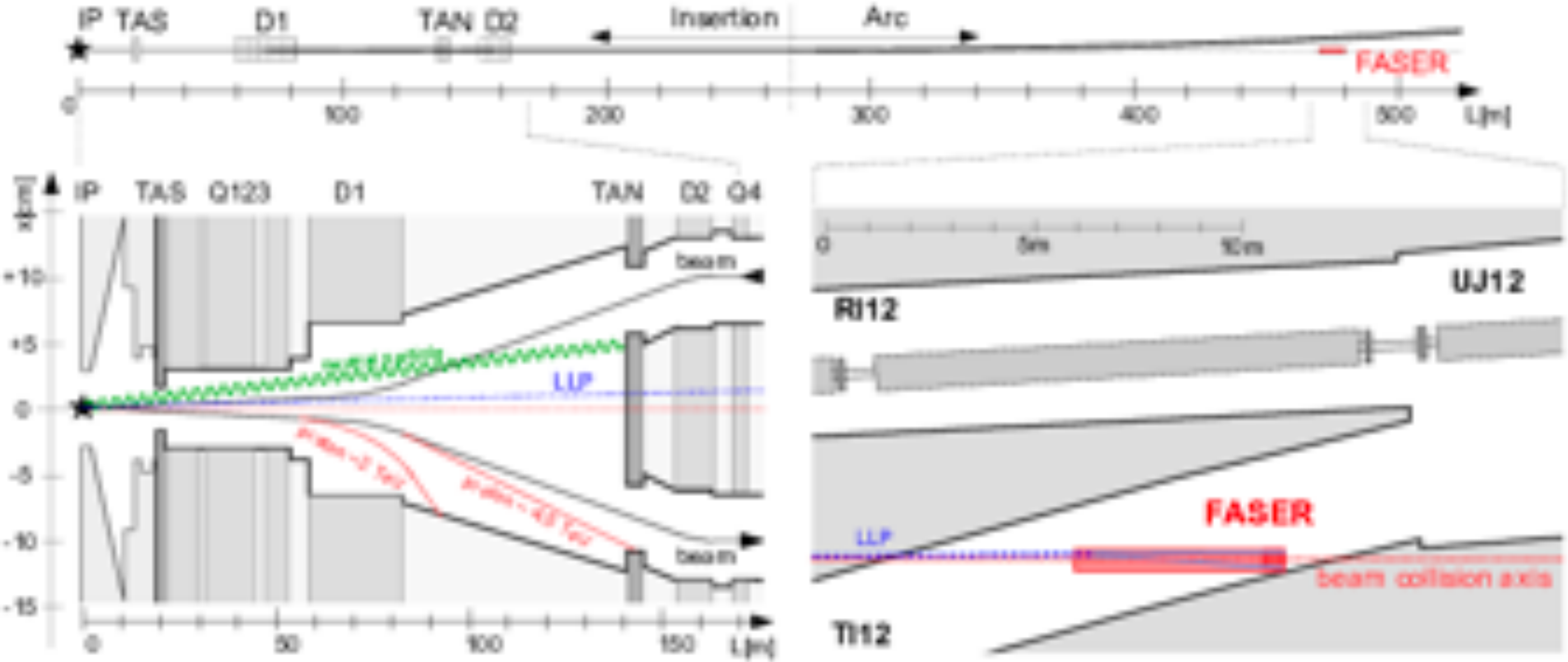
- The TI12 service tunnel just happens to be in just the right place for FASER:



- 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

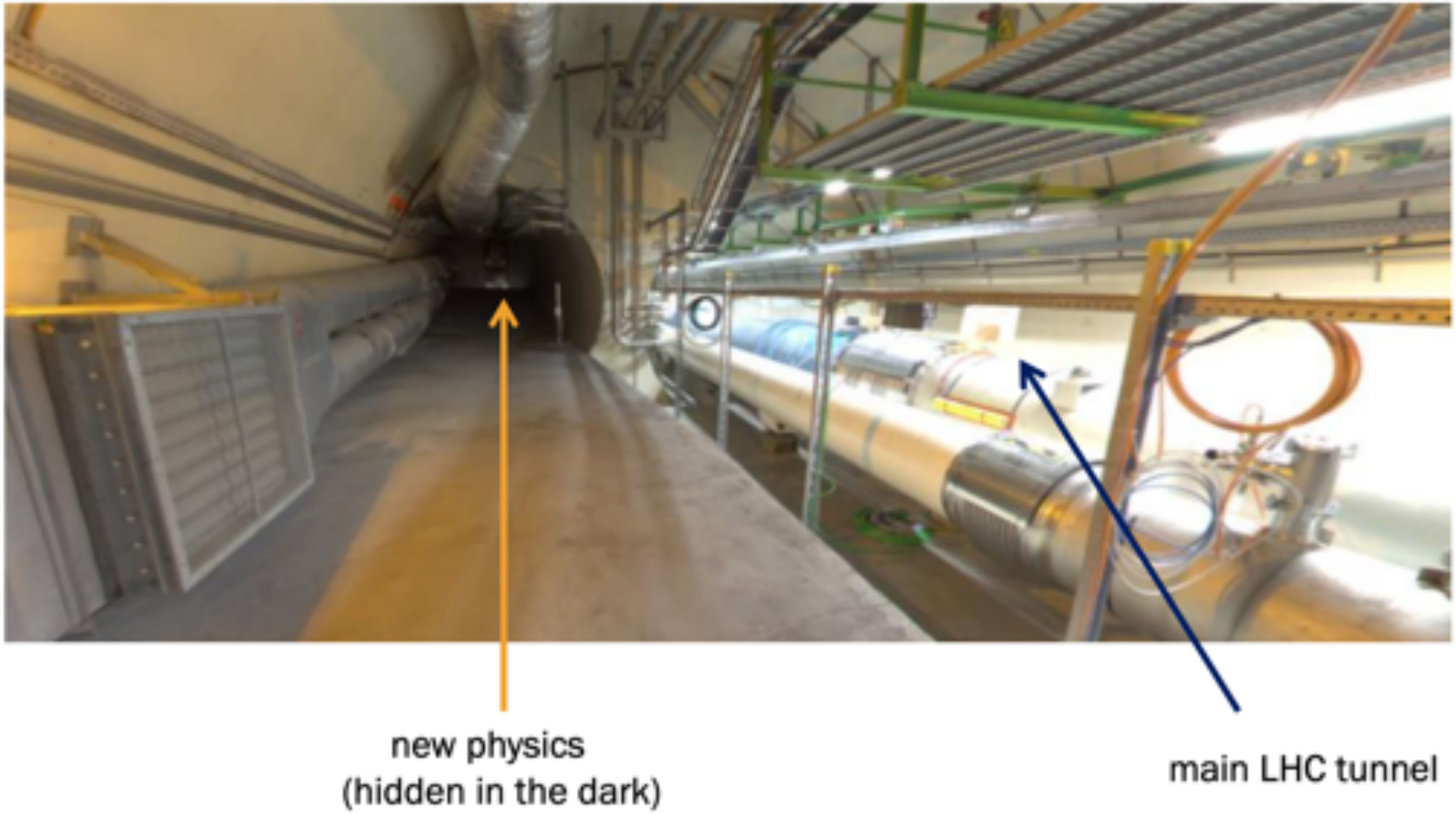
- In relation to ATLAS at Point 1

FASER Location

- Wider setting at the LHC

In real life

- From Sebastian…

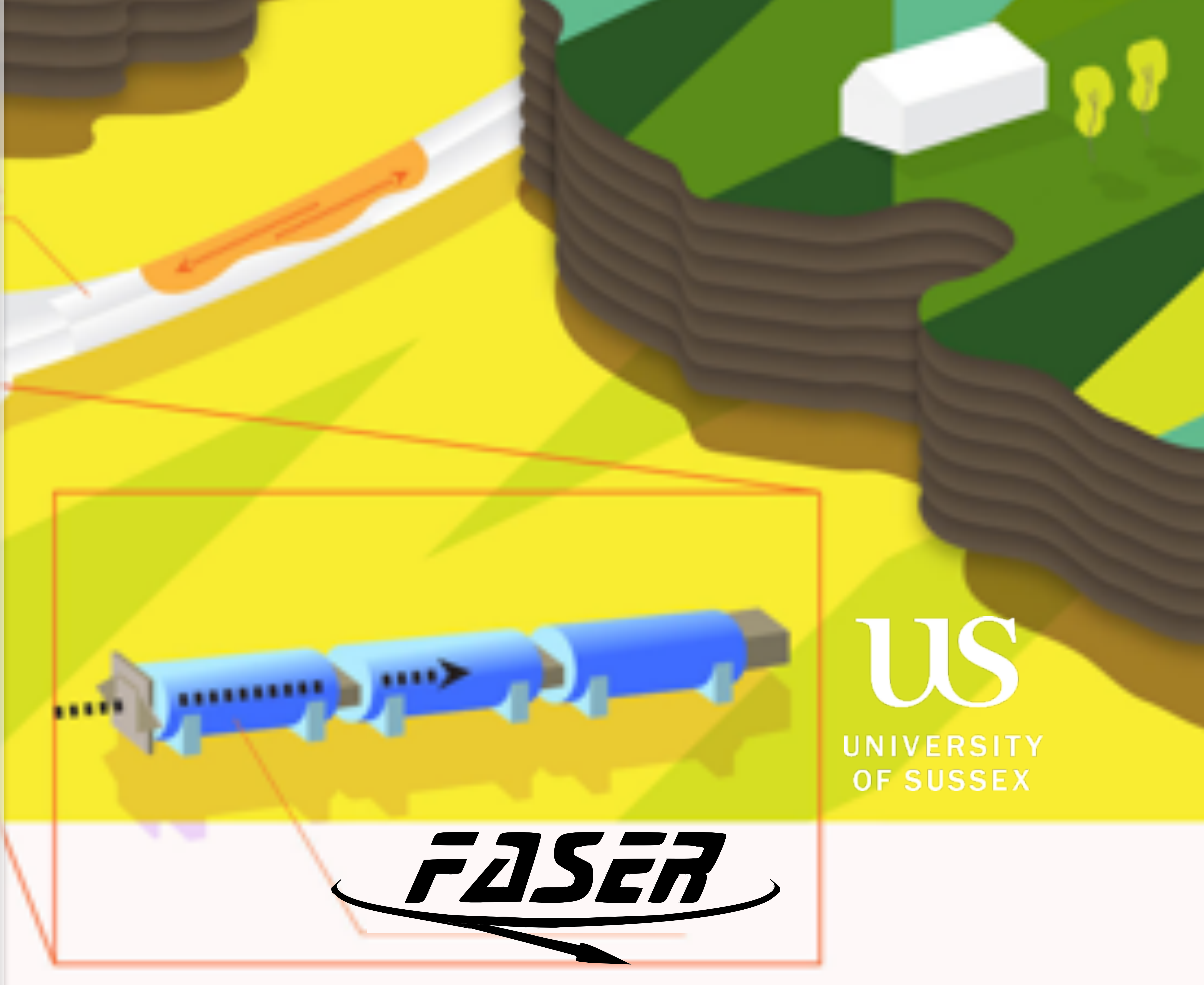


In real life

In real life

Outline

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

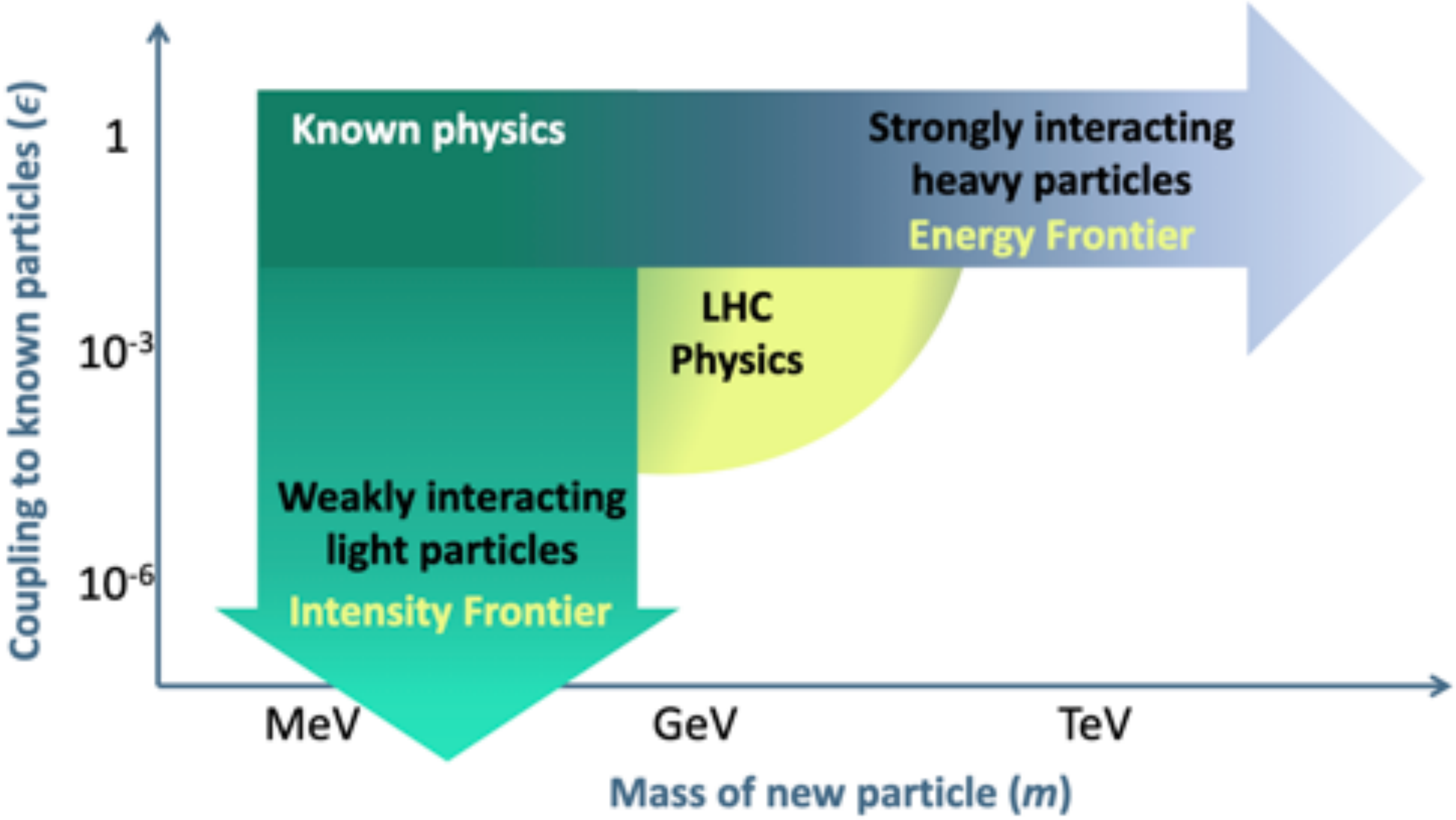


Physics Motivation

Physics Motivation

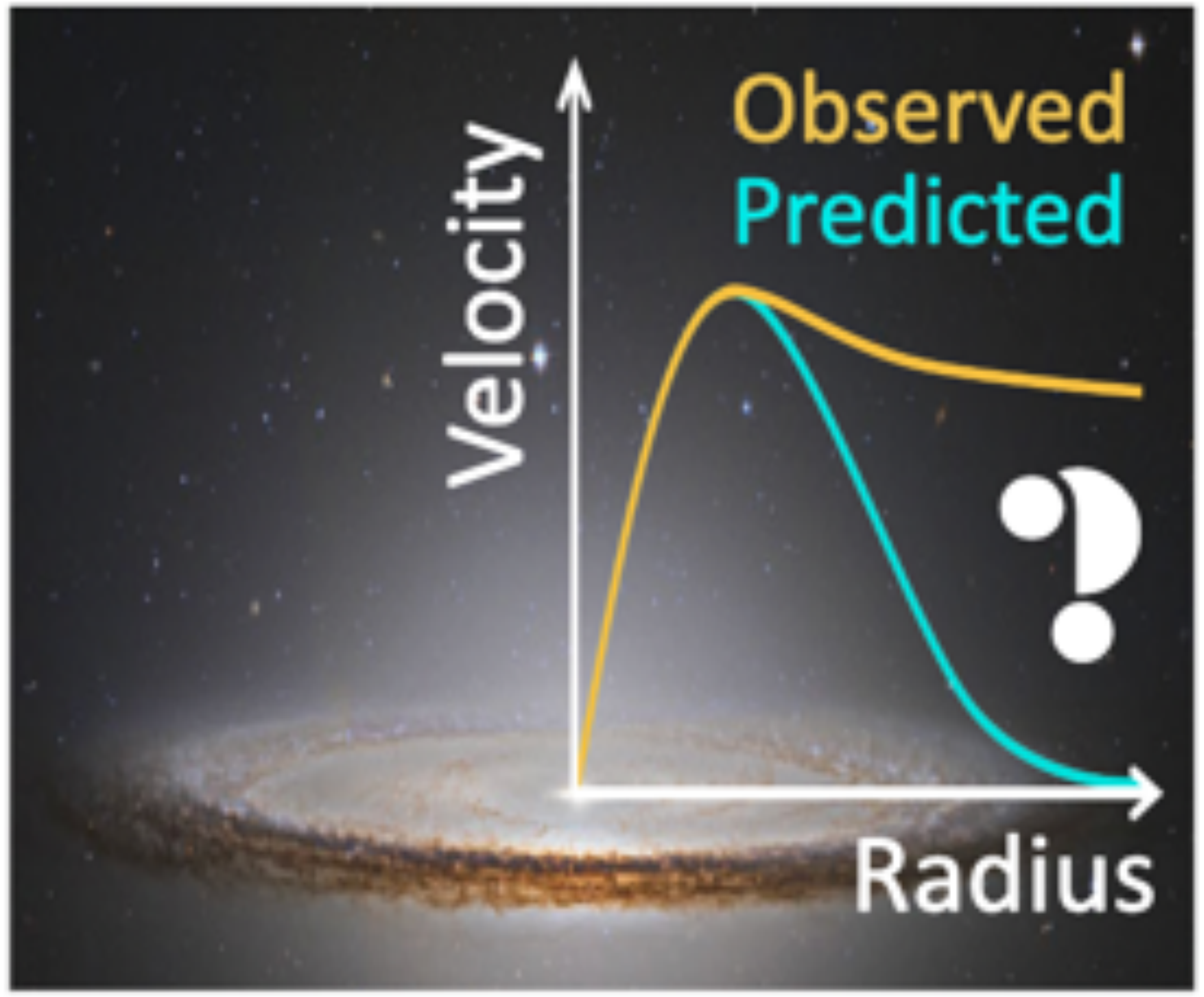
- The **LHC experiments** are producing incredible results, searching in previously unexplored phase spaces and performing increasingly precise measurements.

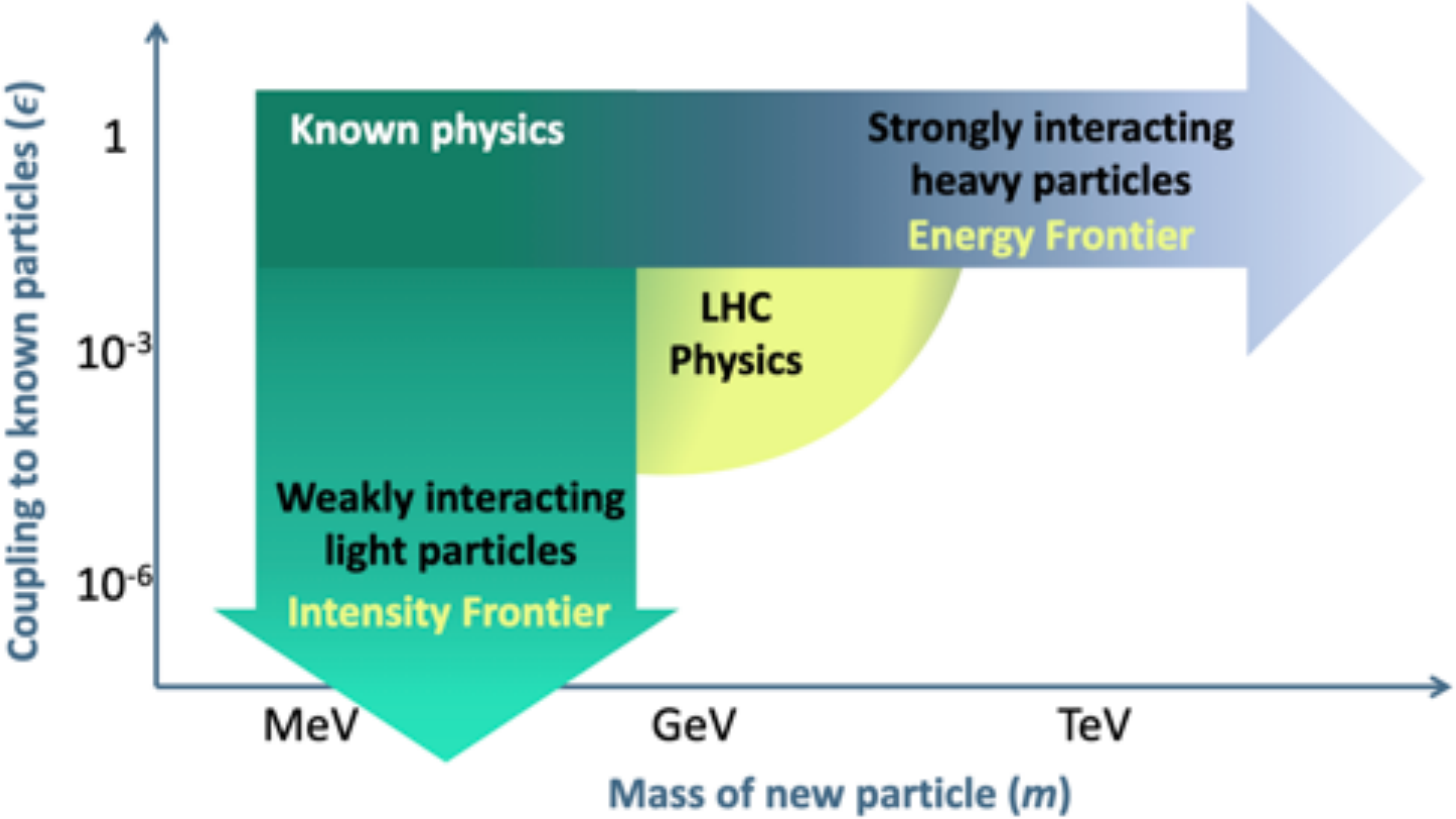
- But the lack of any observation of BSM physics motivates **looking elsewhere** too.



Physics Motivation

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

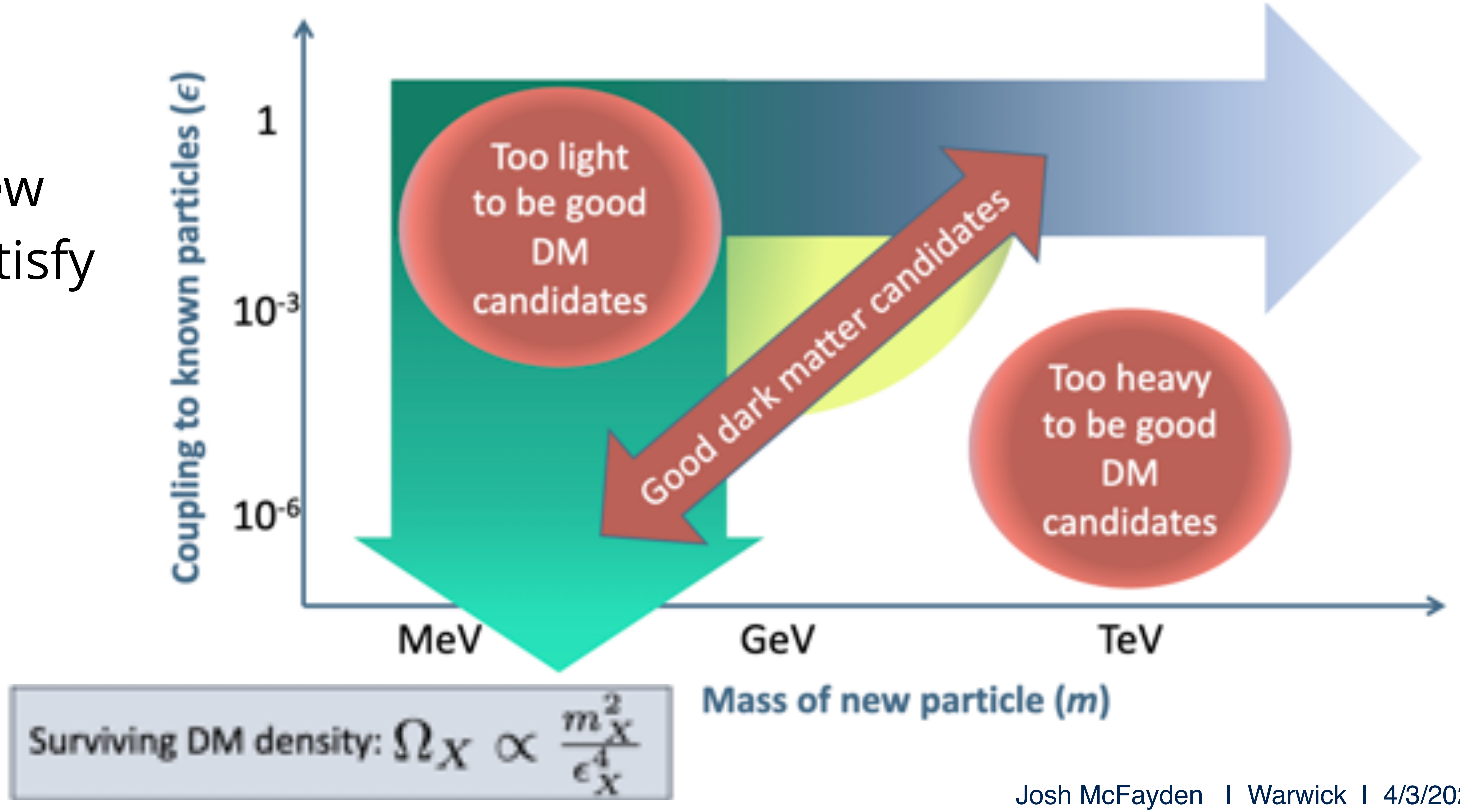




Physics Motivation

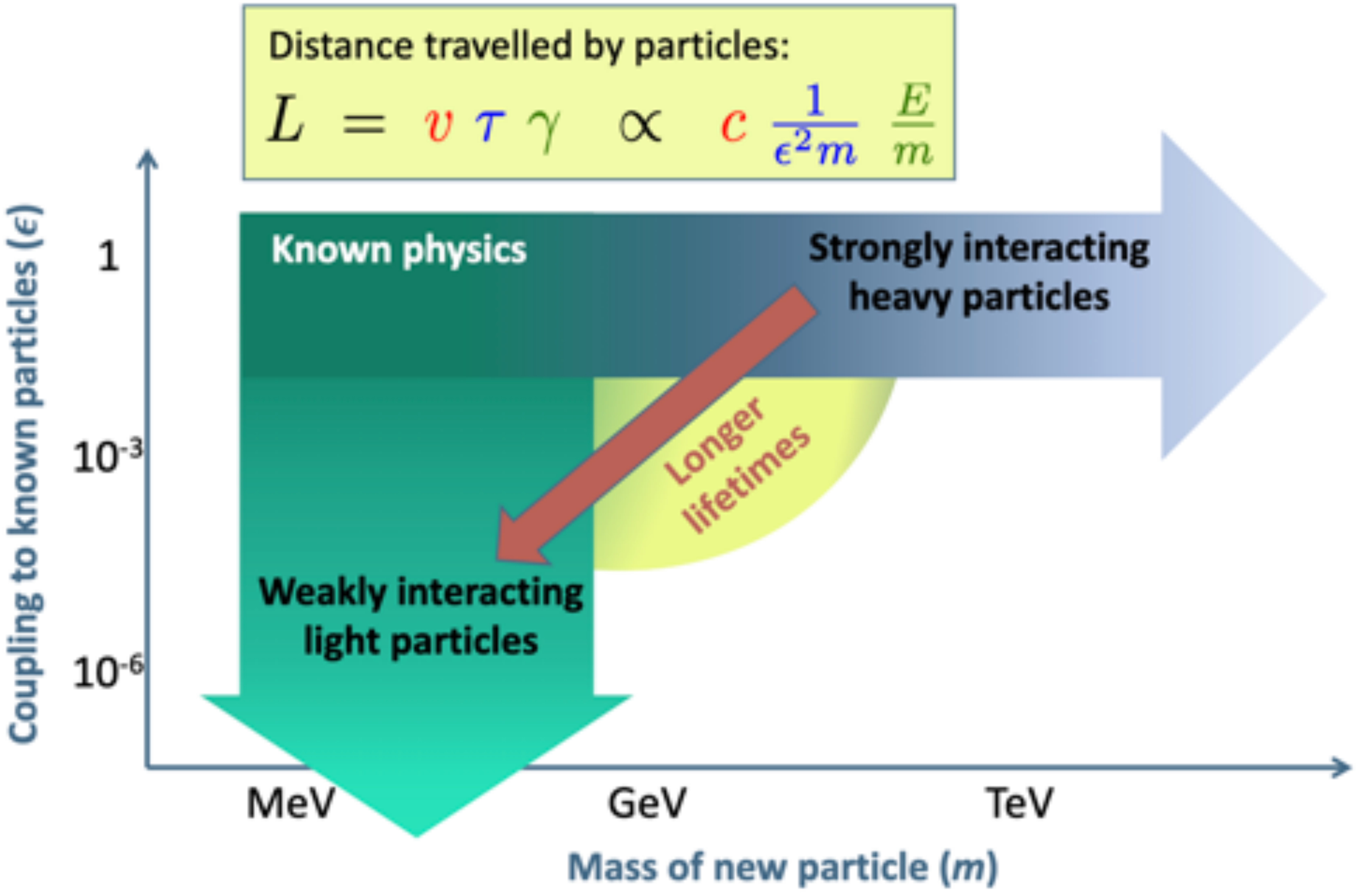
- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

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



Physics Motivation

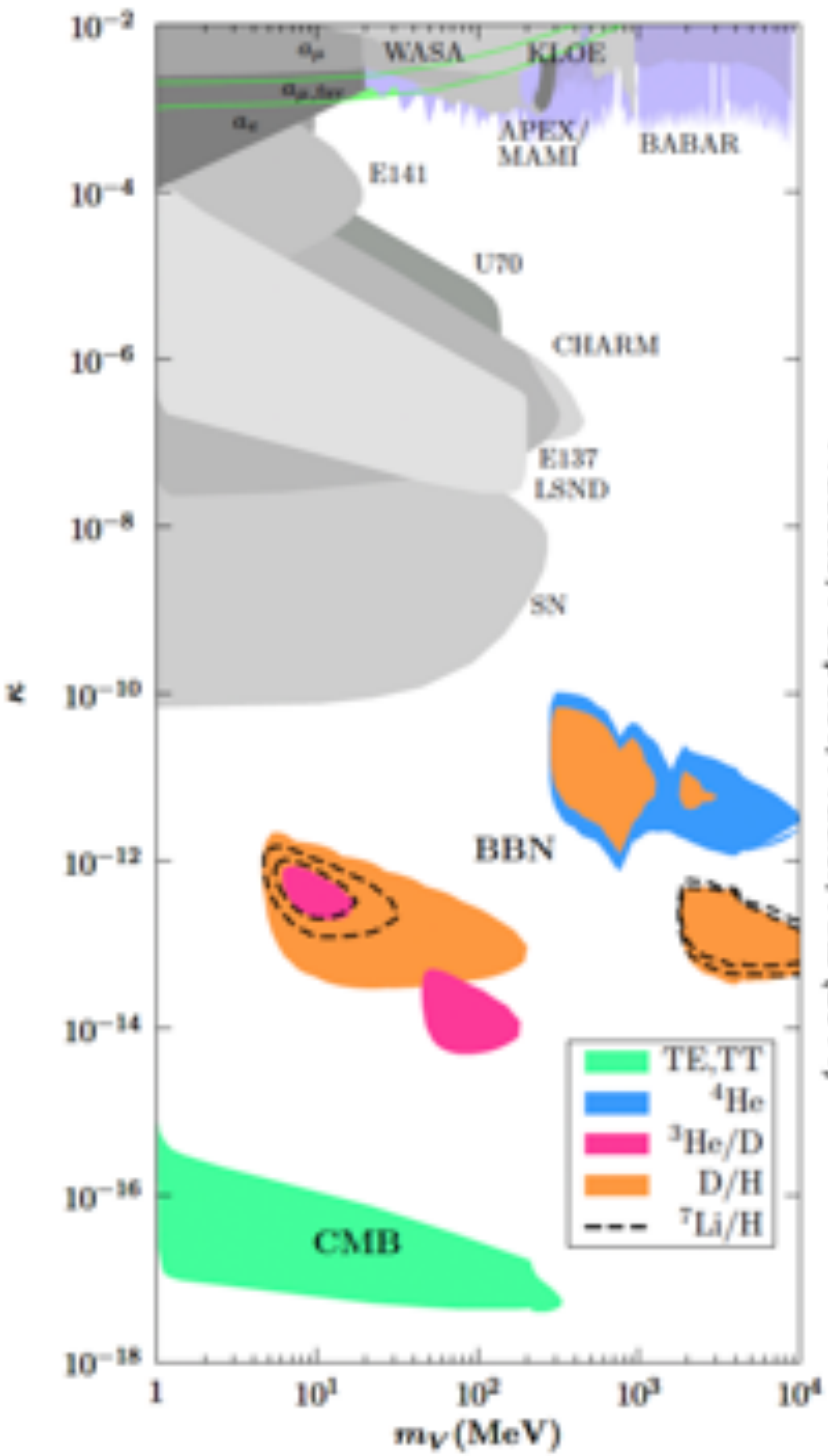
- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- Distinct signatures
- Opportunity for exploration!



Physics Motivation | Dark photons

UNIVERSITY OF SUSSEX

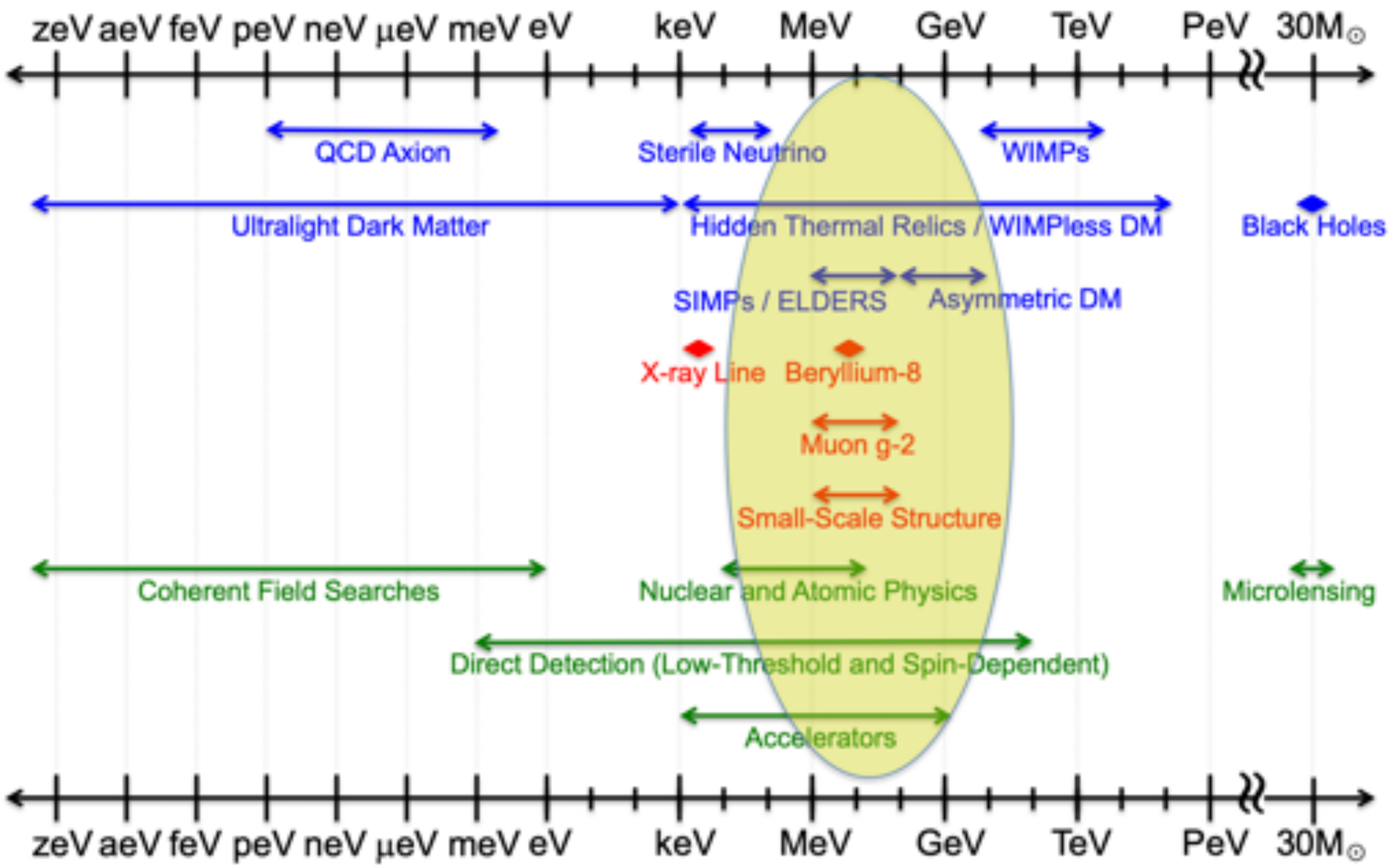
- Dark photons are particularly interesting for FASER as we have fast sensitivity to new regions of phase space
- There is a vast and largely unexplored parameter space
  - "Bump hunts" exclude larger ε
  - Mostly fixed target experiments exclude the gray region
  - Astrophysics (supernova, BBN, CMB) 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…



Fradette, Pospelov, Pradler, Ritz (2014)

Physics Motivation | Intrigue…

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



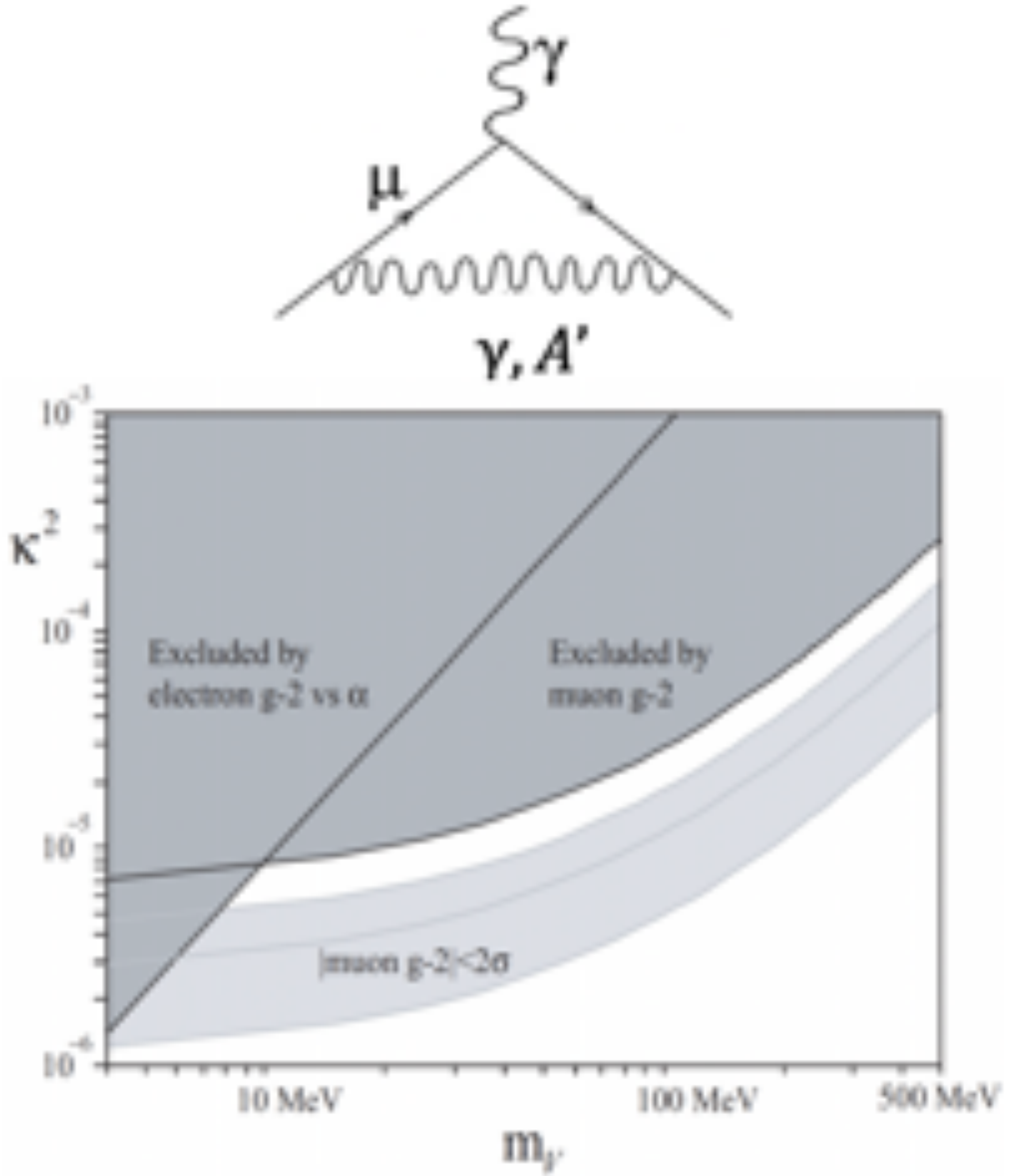
Cosmic Visions Report (2017)

Physics Motivation | g-2

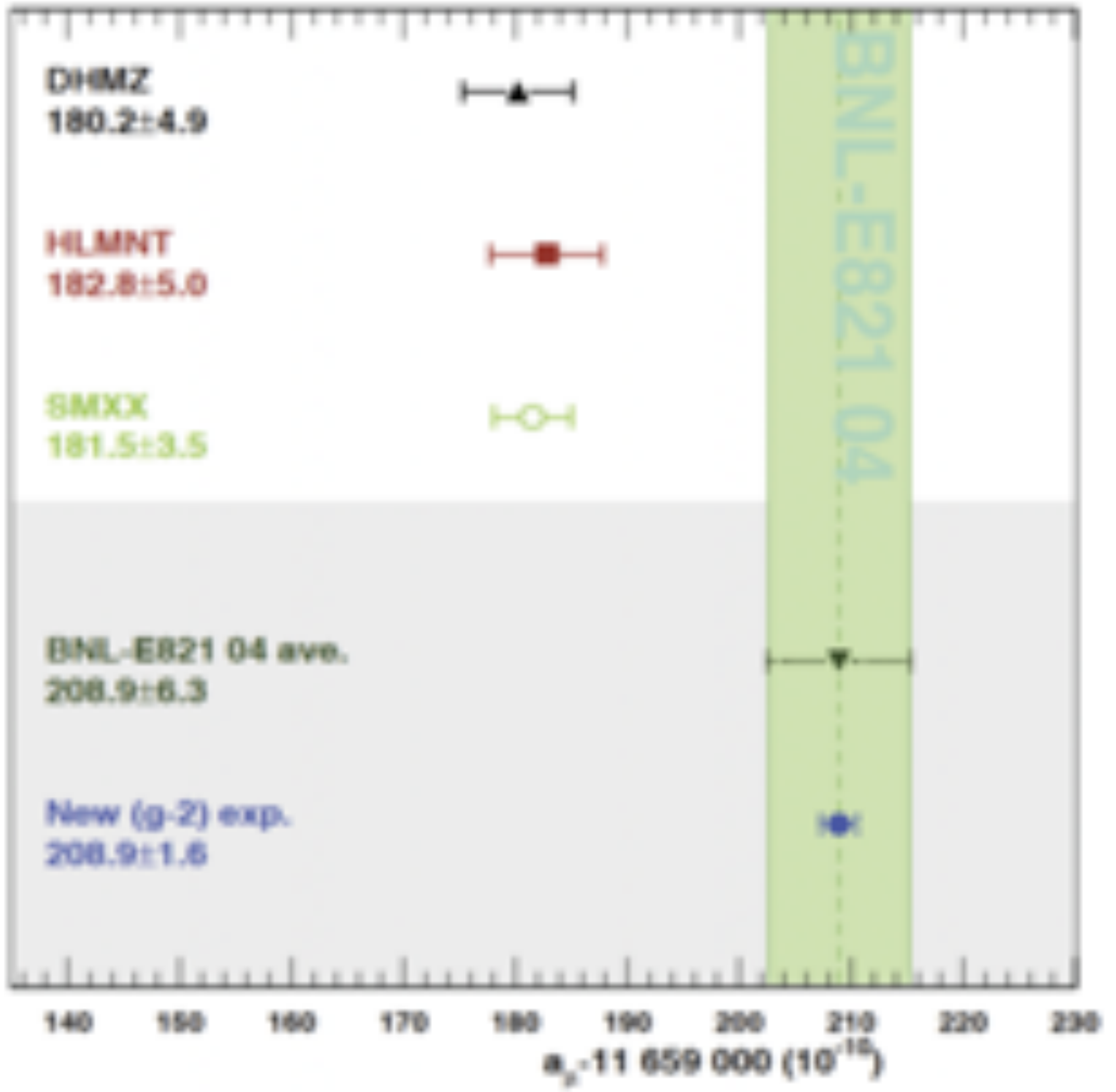
- The 3.7σ discrepancy between the SM and experiment can be resolved by **MeV-GeV particles with ε ~ 10^{-3}**.

- The dark photon is no longer a viable solution

- But other particles with similar masses and couplings are.



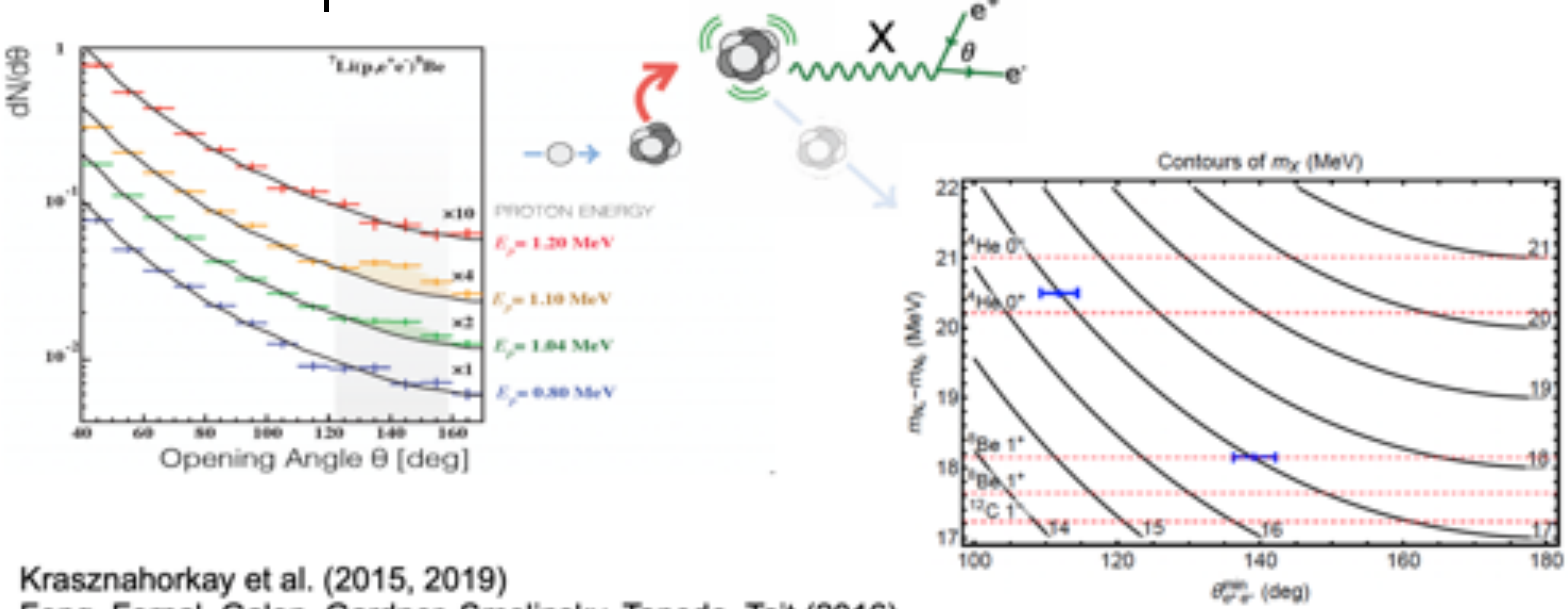
Boehm, Fayet (2003)



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

Physics Motivation | He/Be nuclei

- 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…



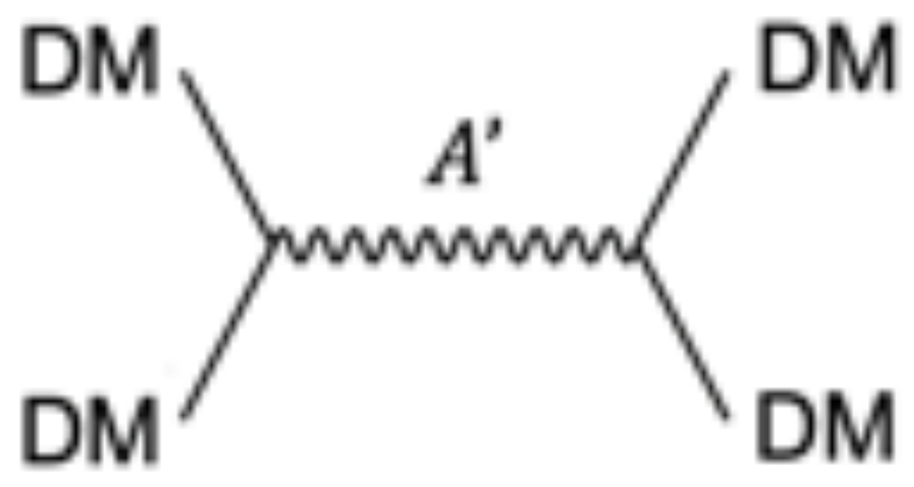
Krasznahorkay et al. (2015, 2019)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)
See also Zhang, Miller (2020)

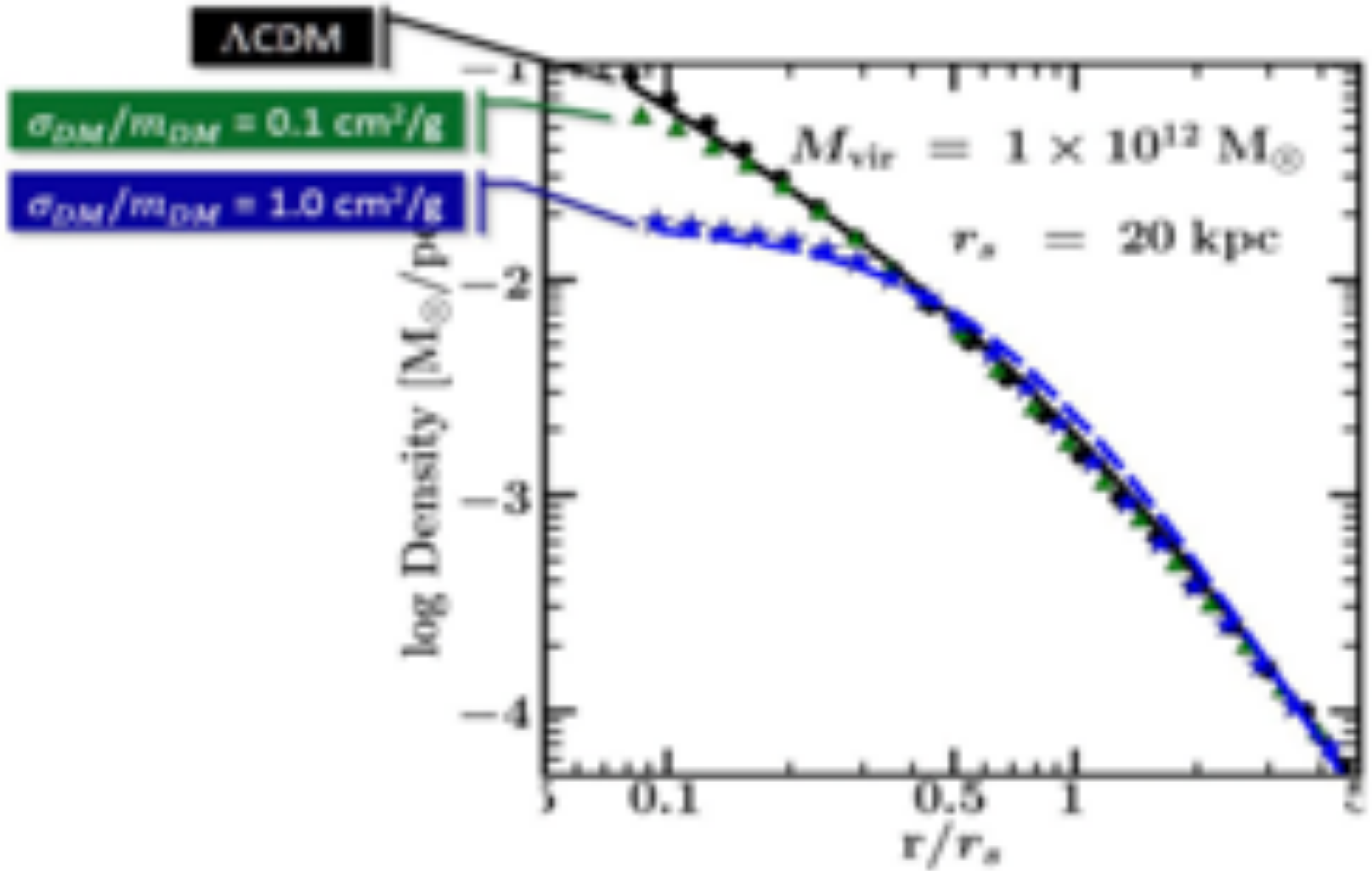
Physics Motivation | Self-interacting DM

- 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**.

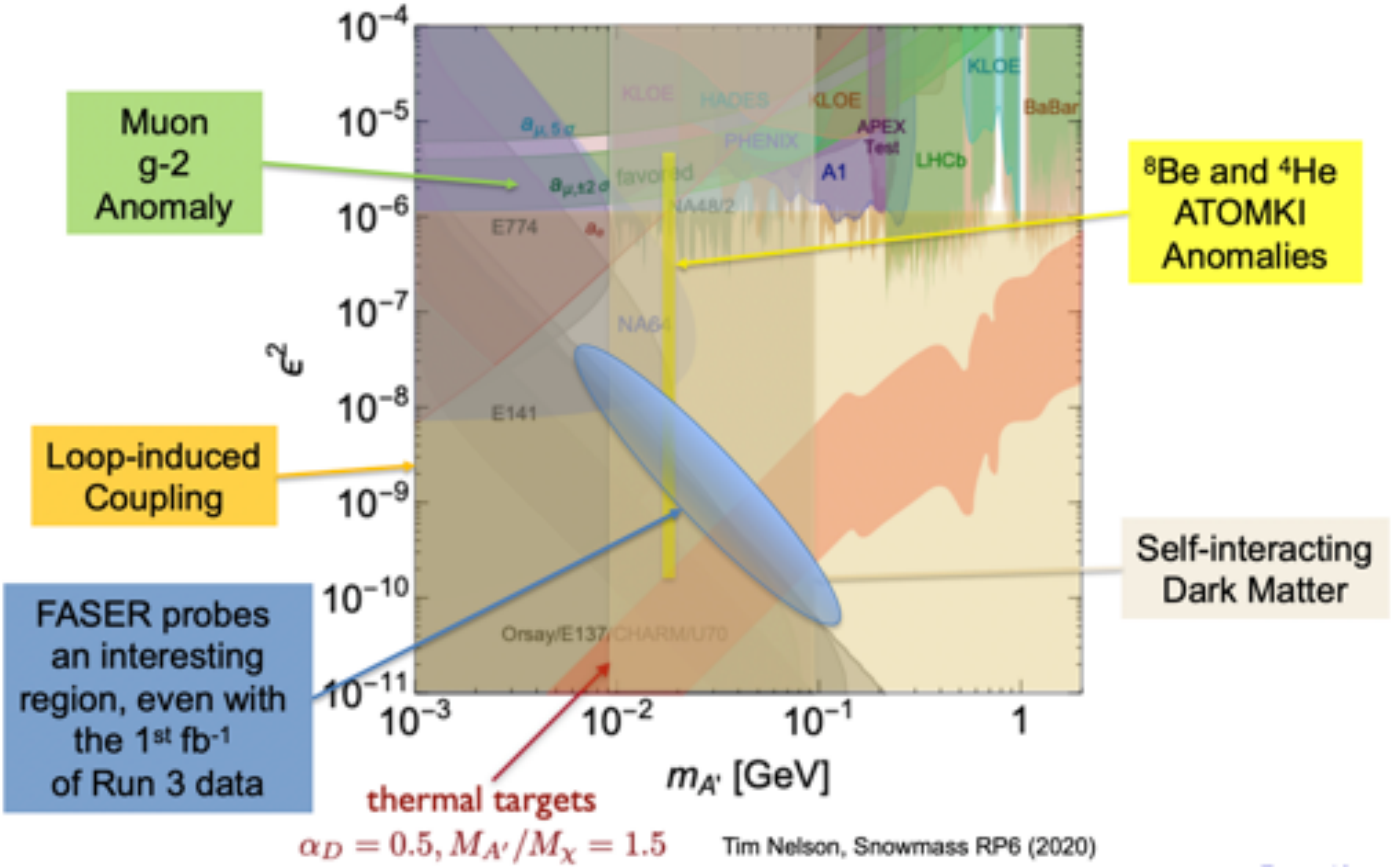
$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$





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.

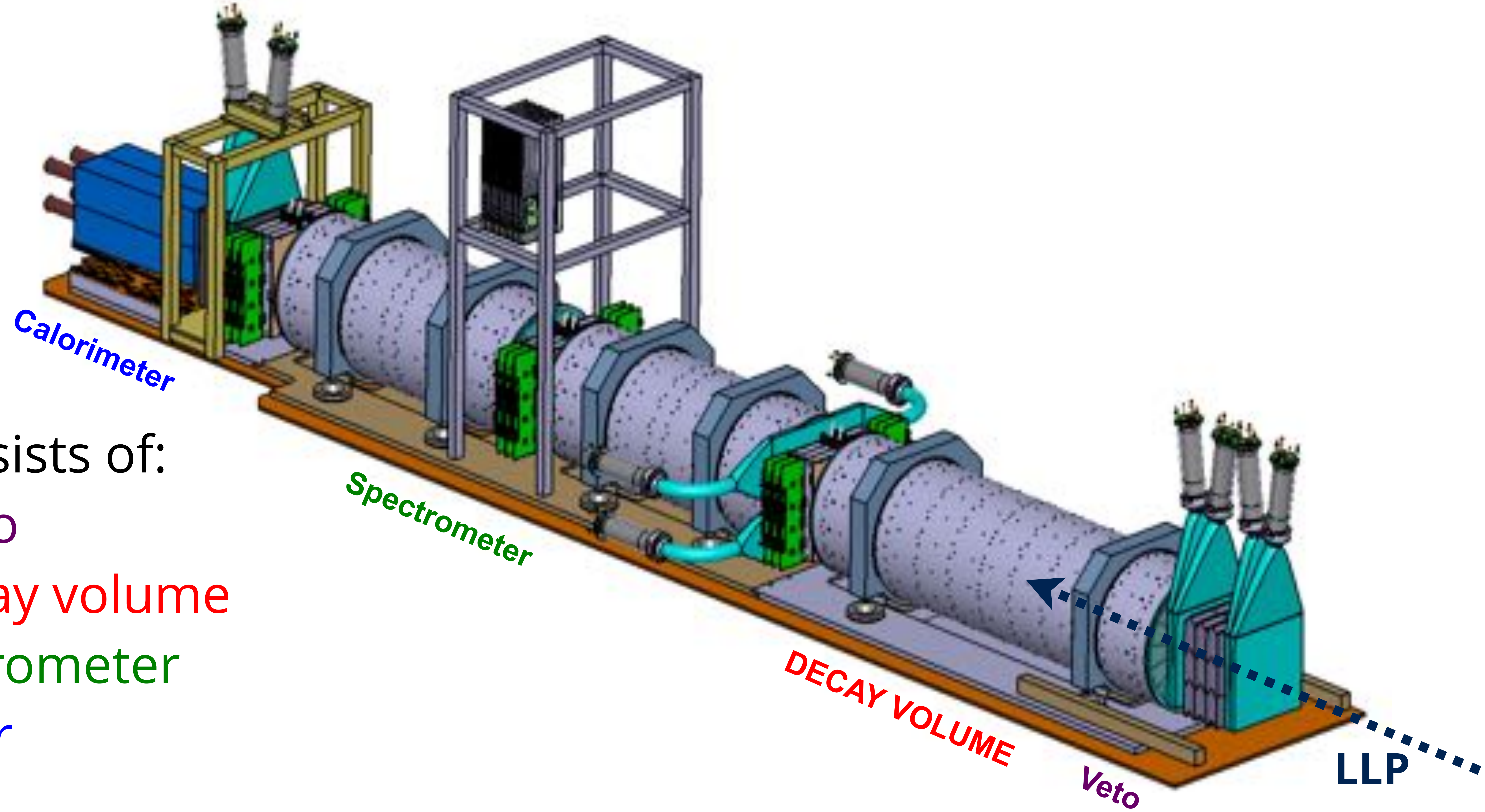


FASER Detector

FASER Collaboration

- 70 collaborators, 19 institutions, 8 countries:

Detector | Brief overview



The detector consists of:

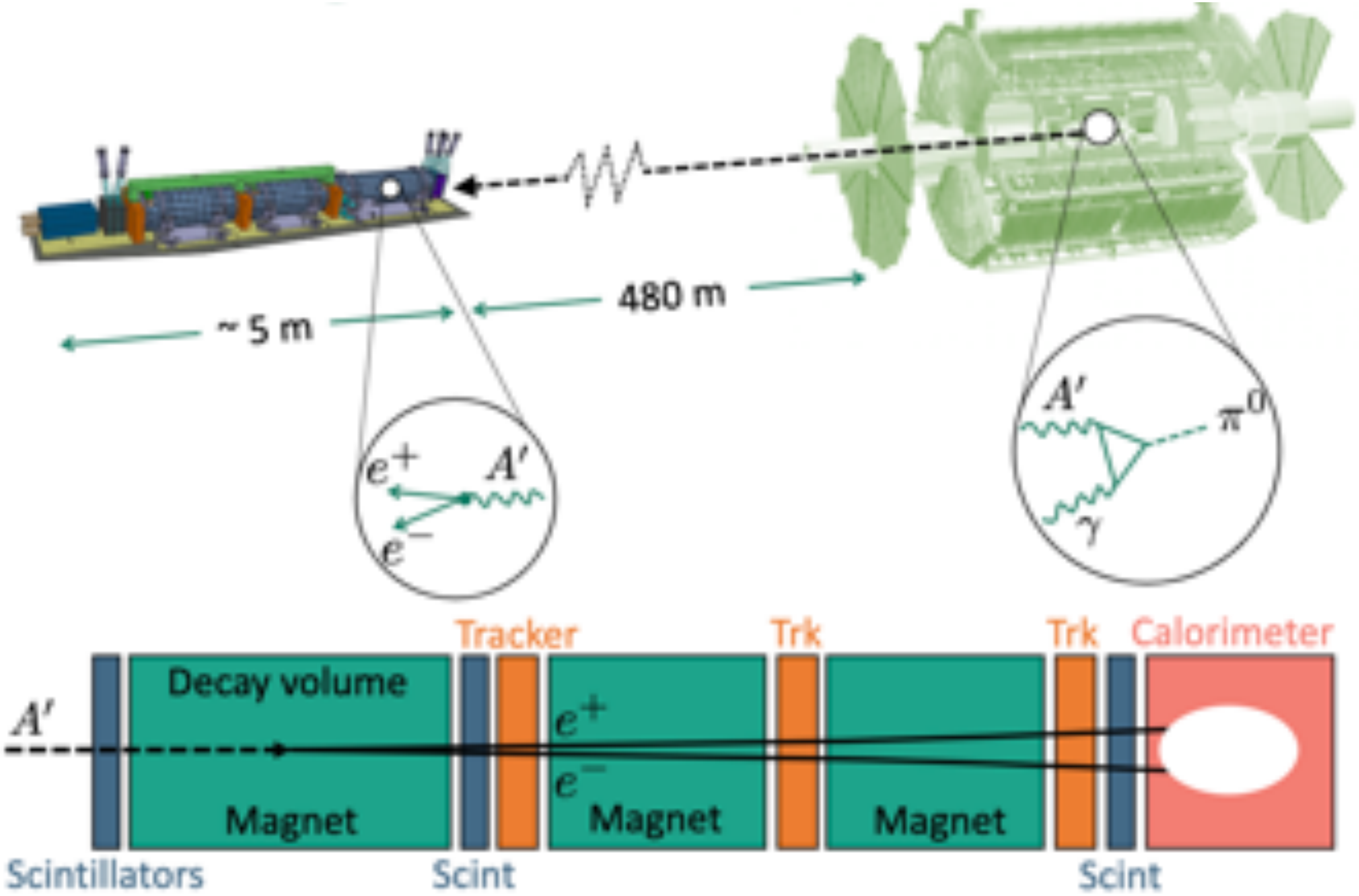
- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

Detector | Philosophy

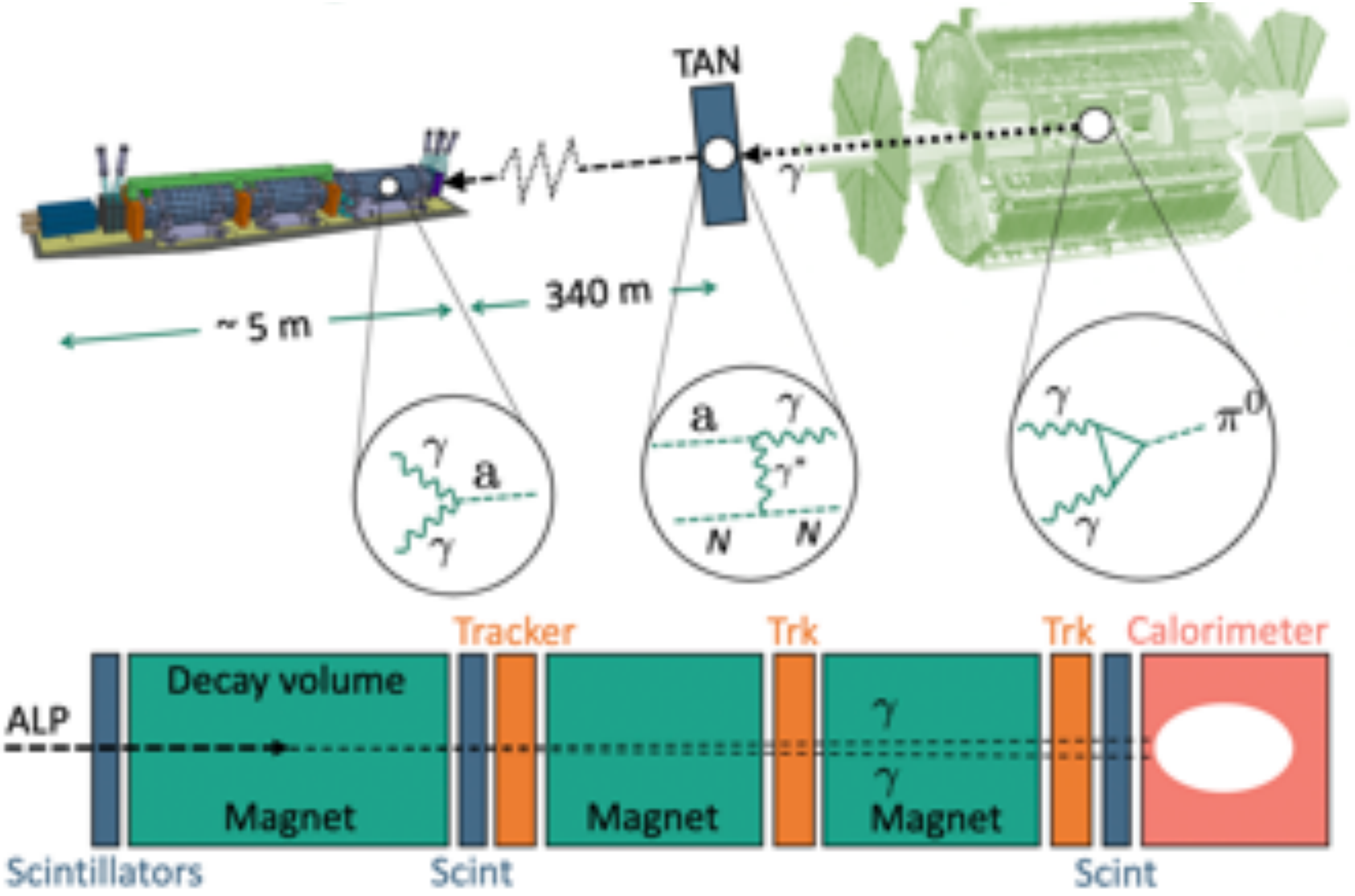
- Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:
  - Detector that can be constructed and installed quickly & cheaply
  - Have tried to re-use existing detector components where possible
  - Aimed for a simple, robust detector (access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

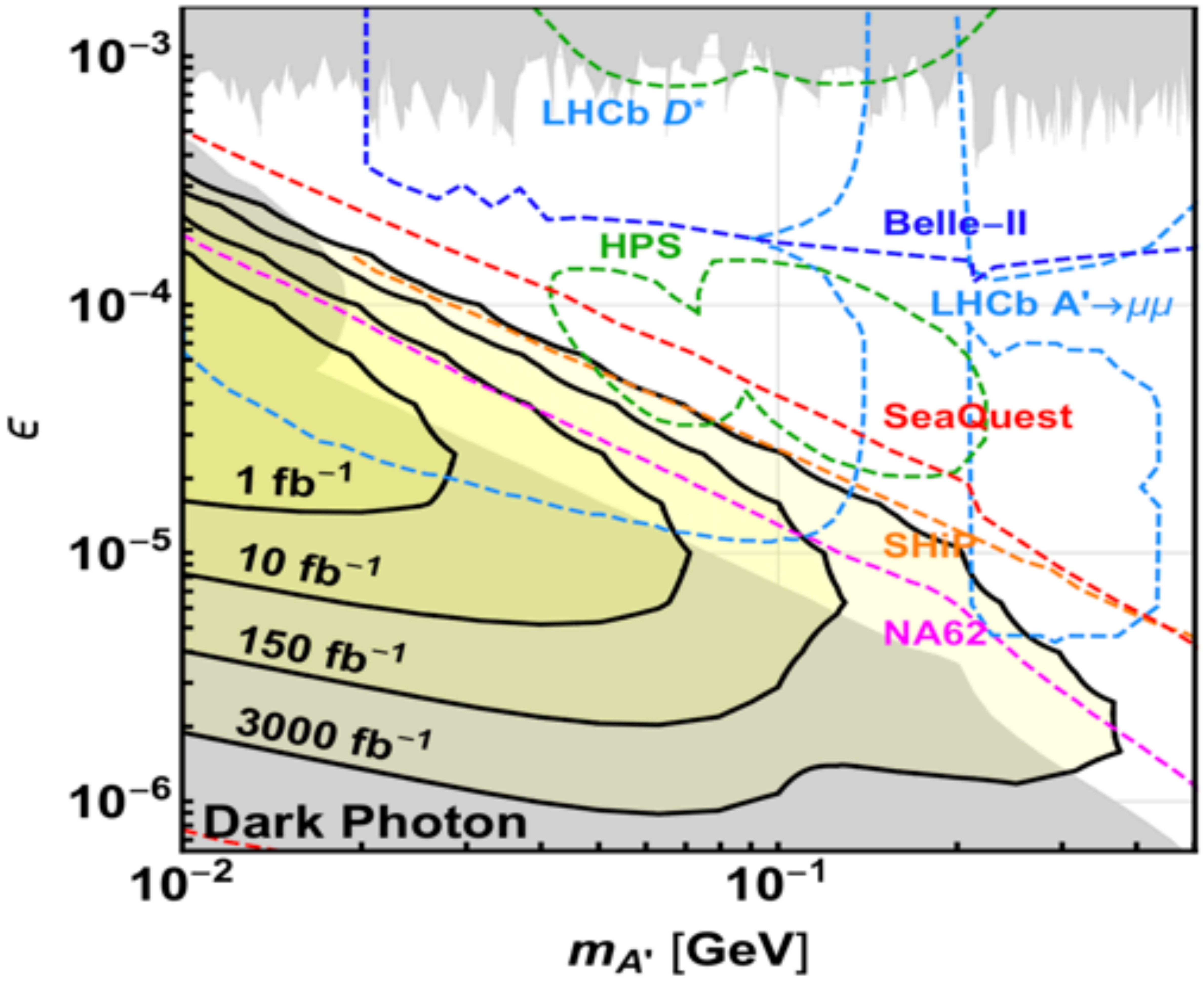


Target scenarios | Axion-like particles



Target scenarios | Dark photon

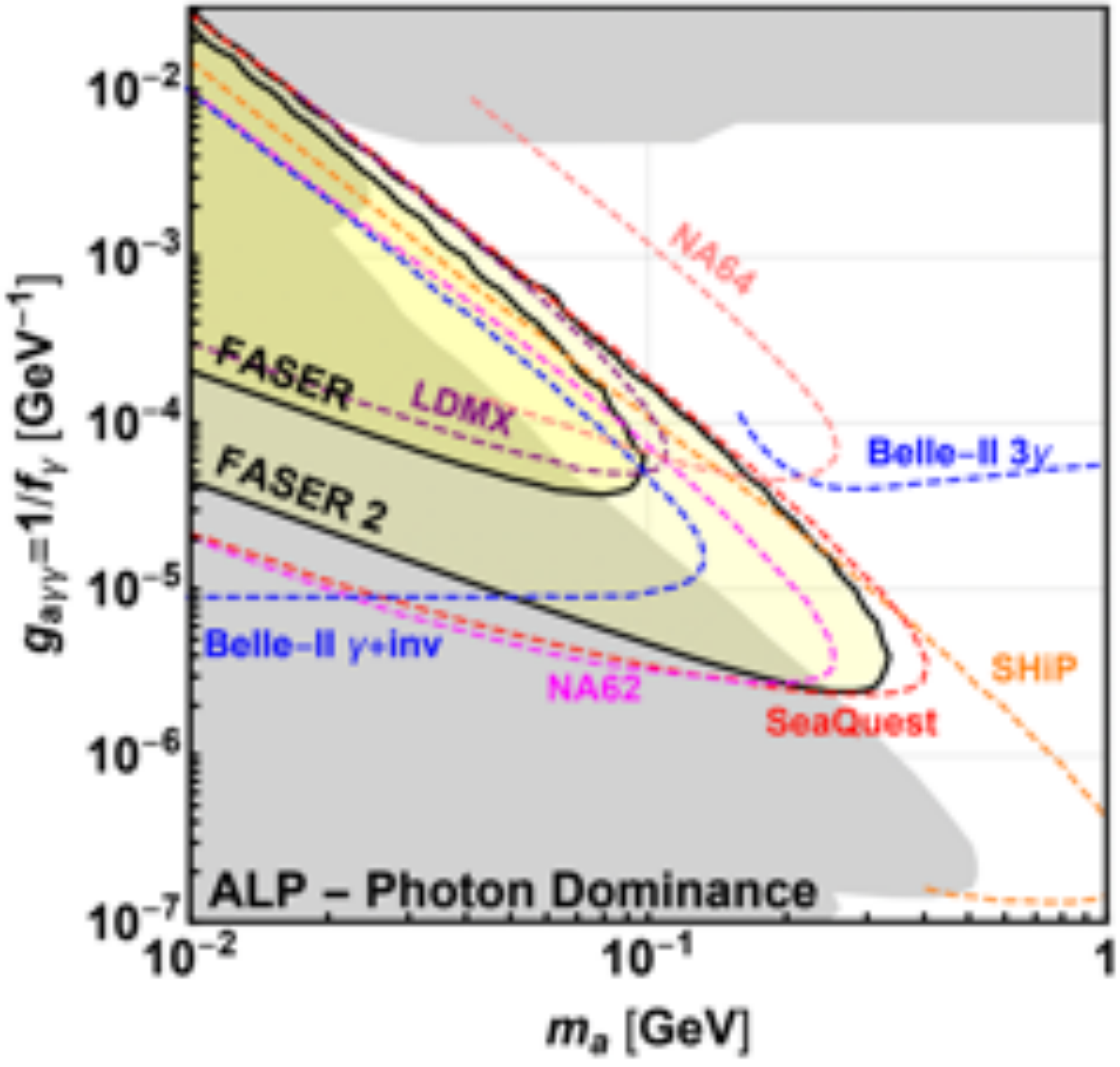
- Expected sensitivity of FASER for **dark photons**
- Detector signature:
  - A′ → e+e-
  - Charged tracks appearing in decay volume
  - Opposite charges separate through detecto
  - Significant energy deposit in calorimeter
- Sensitivity
  - Considers all production channels
    - Assumes no background, 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**

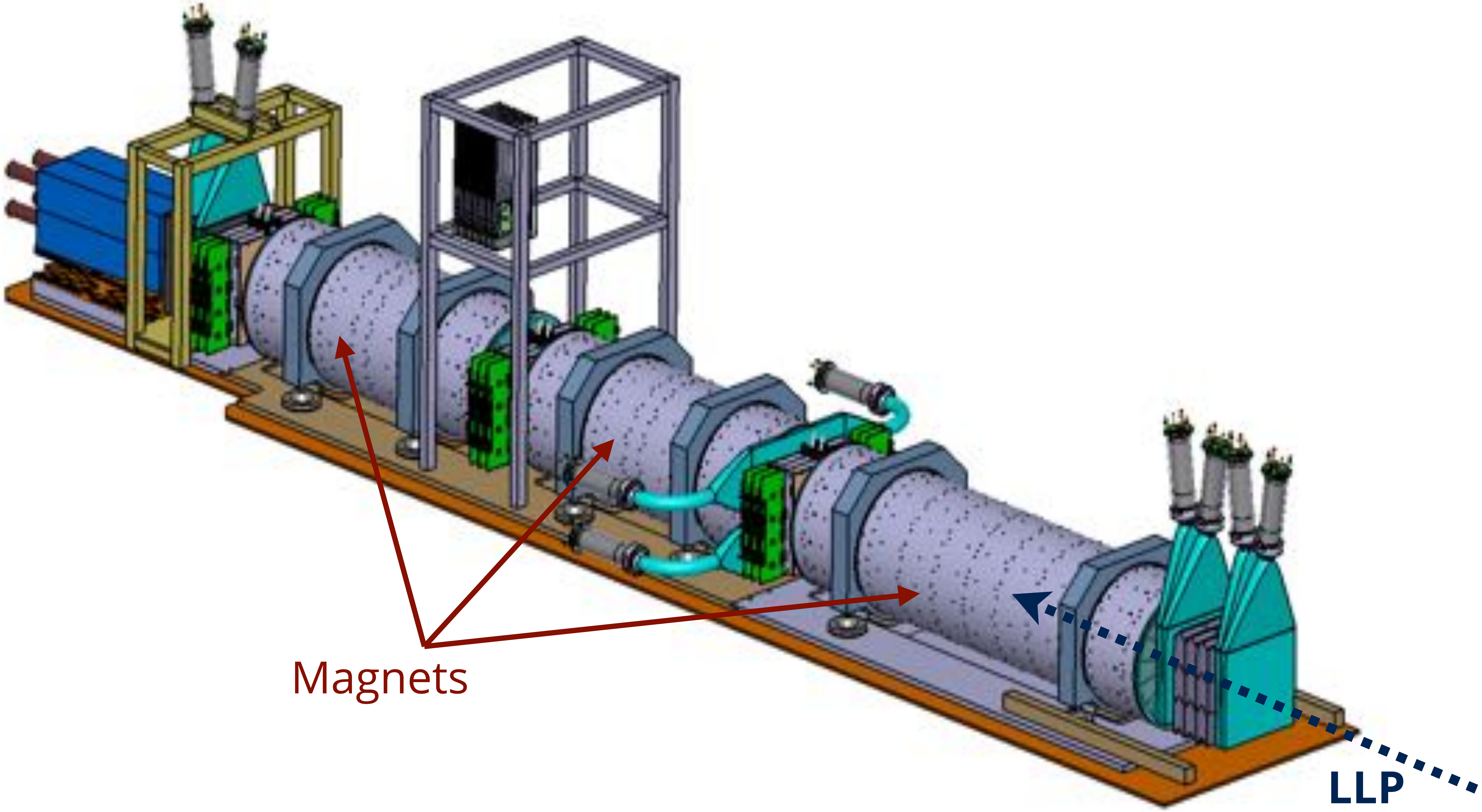
Target scenarios | Axion-like particles

- 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)



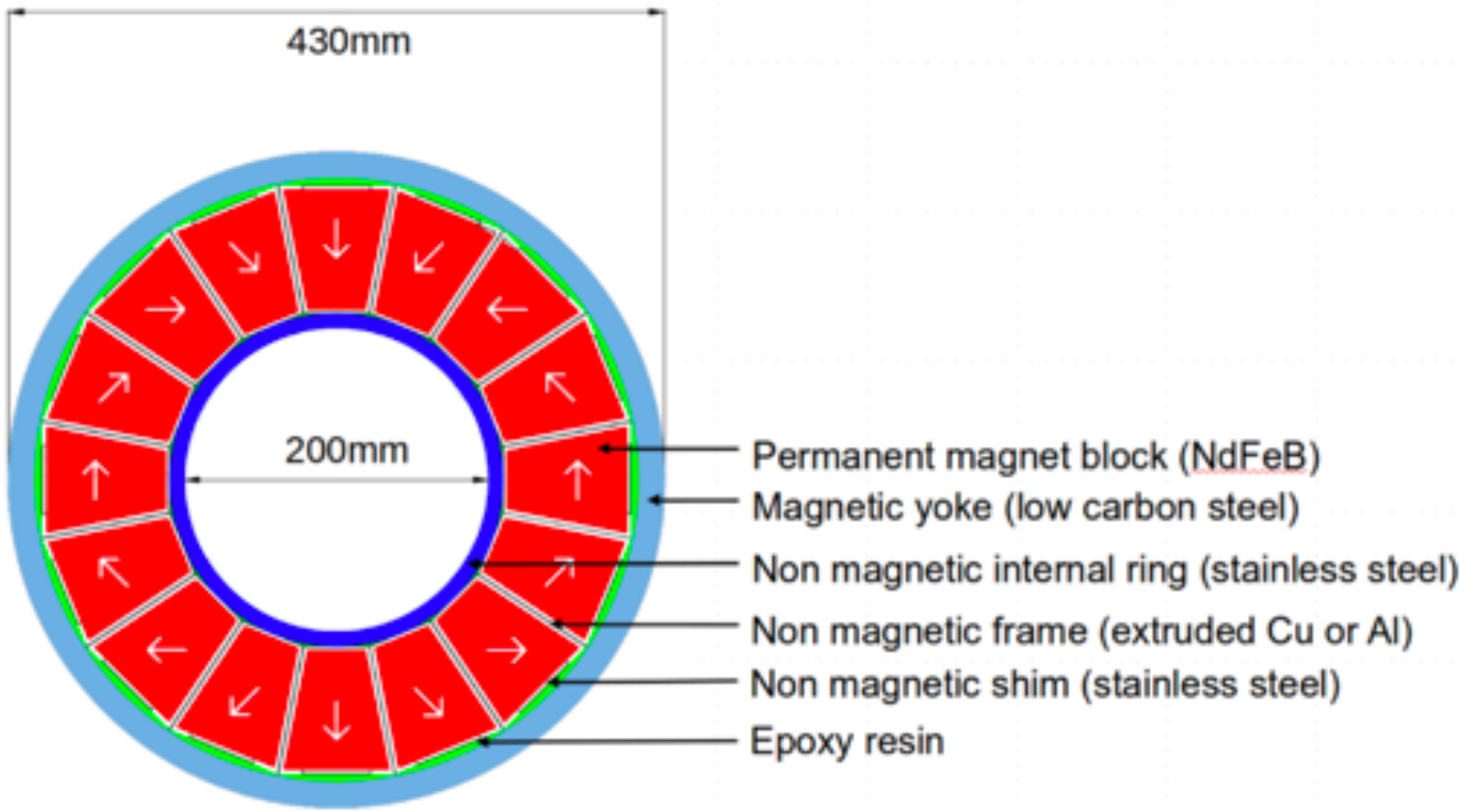
- **Can probe currently unconstrained parameter space.**

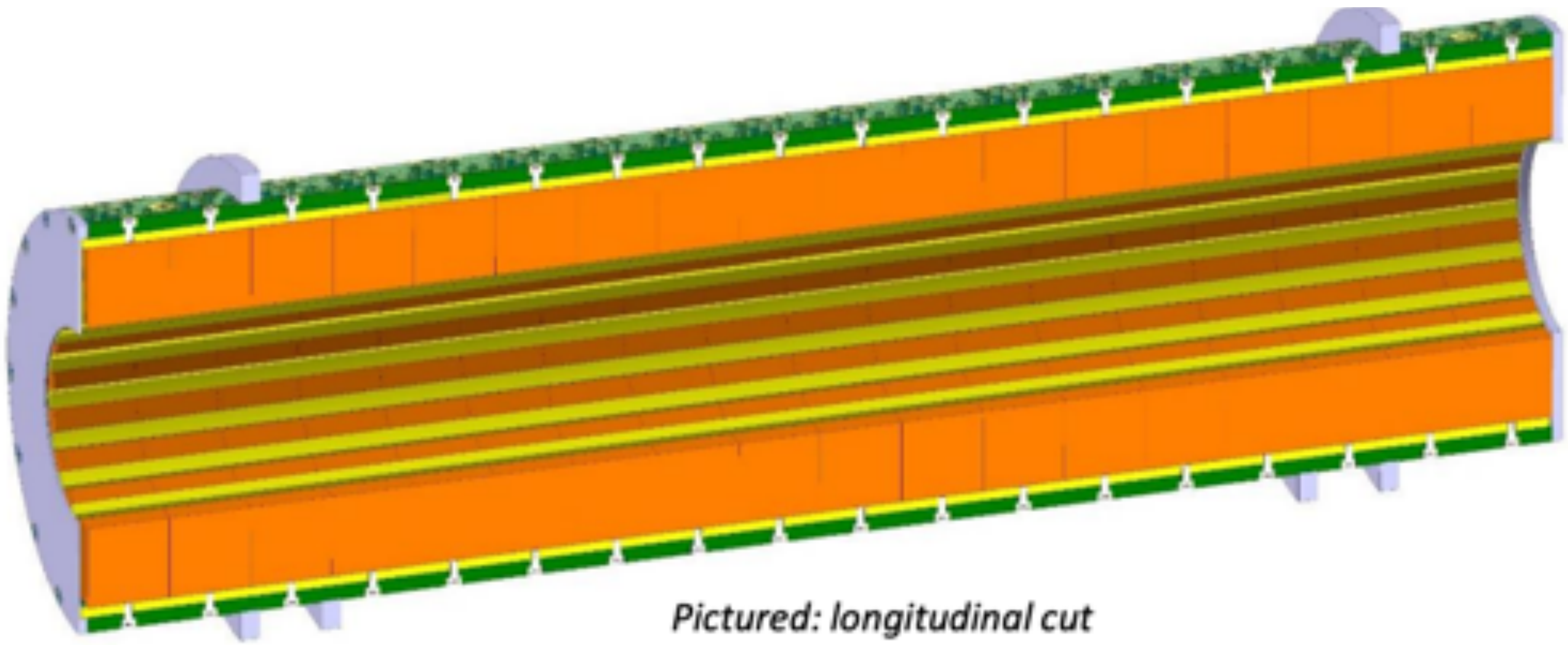
Magnets



Magnets | Overview

- The FASER magnets are 0.55T 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

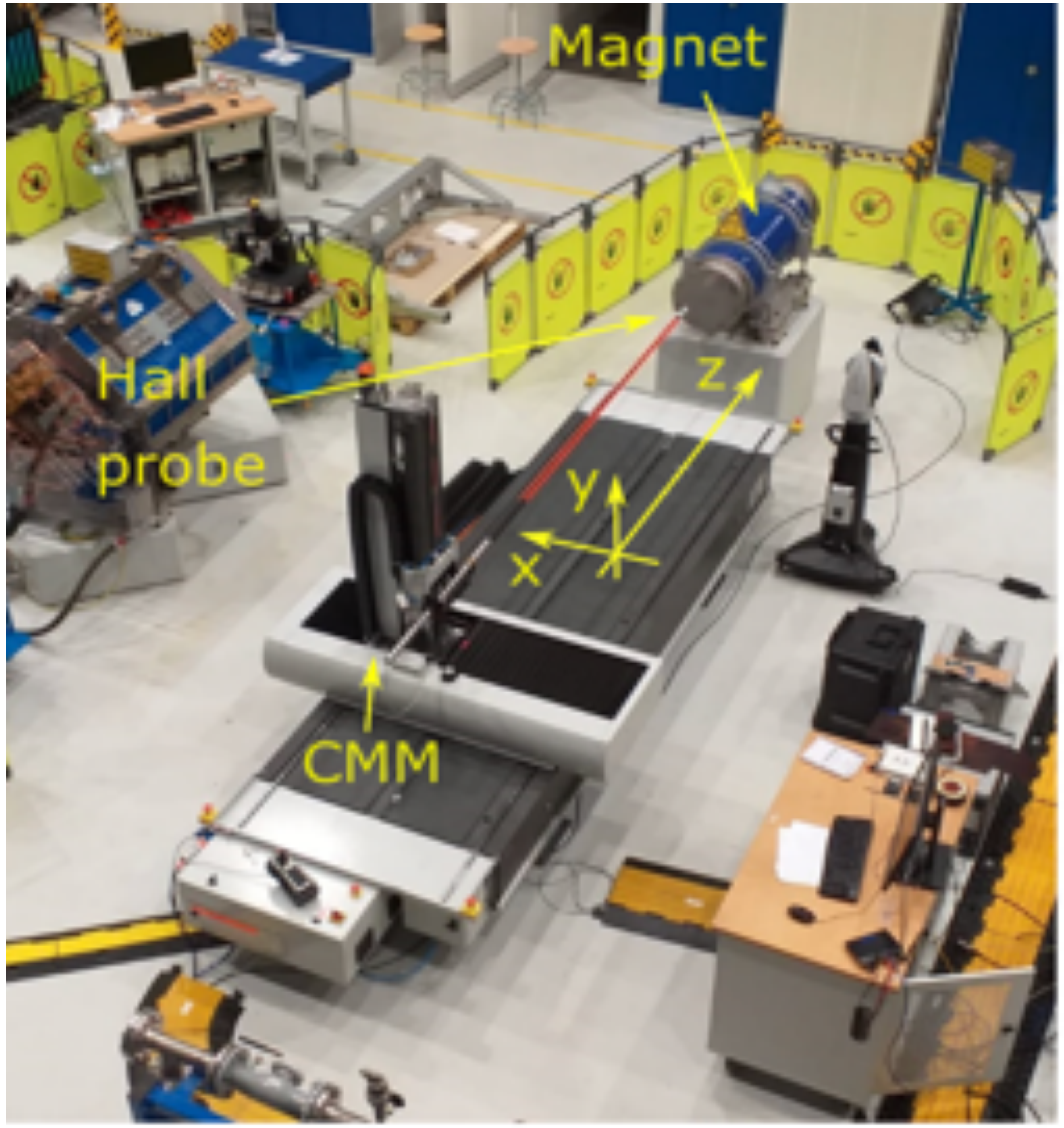


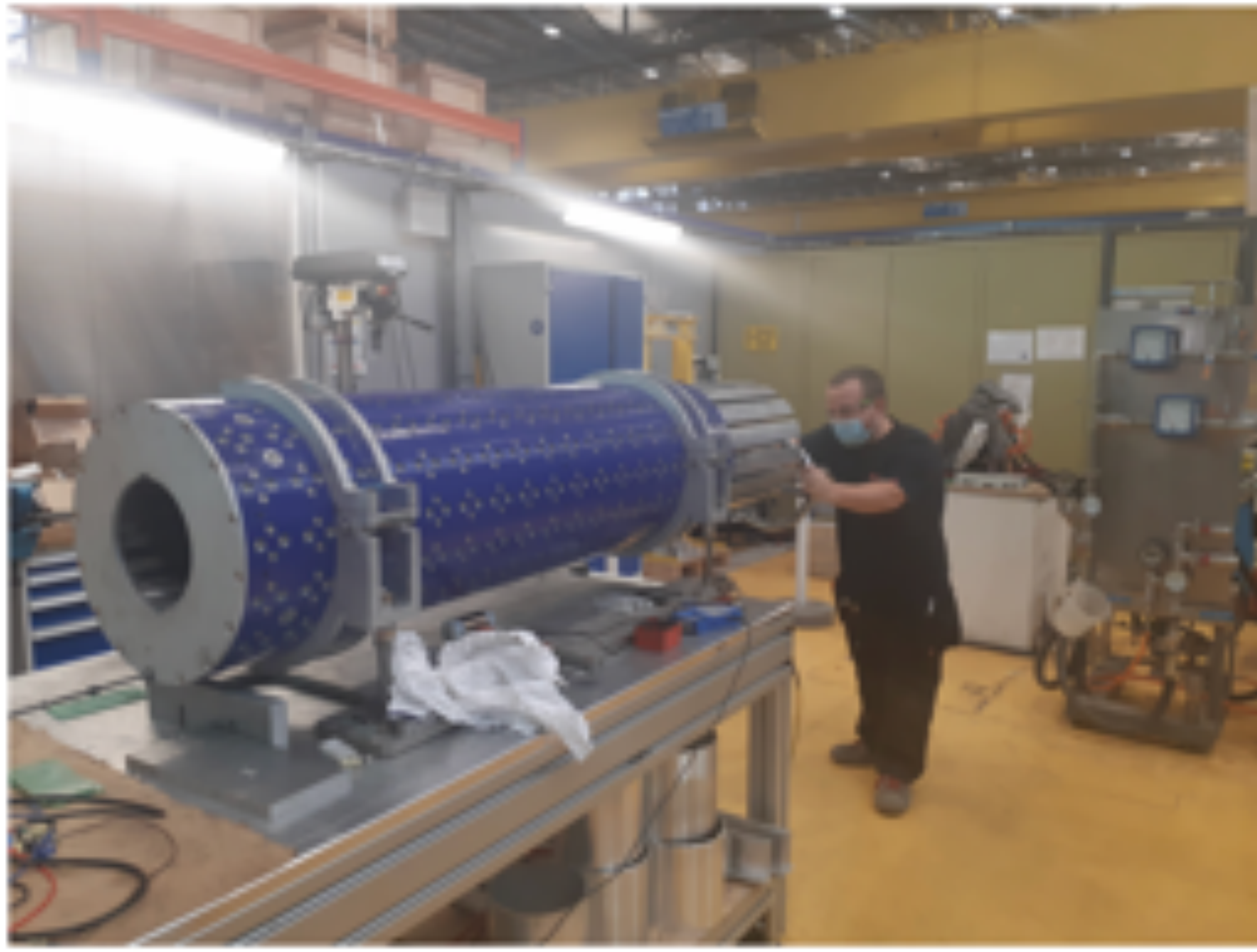


Pictured: longitudinal cut

Magnets | Construction and testing

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

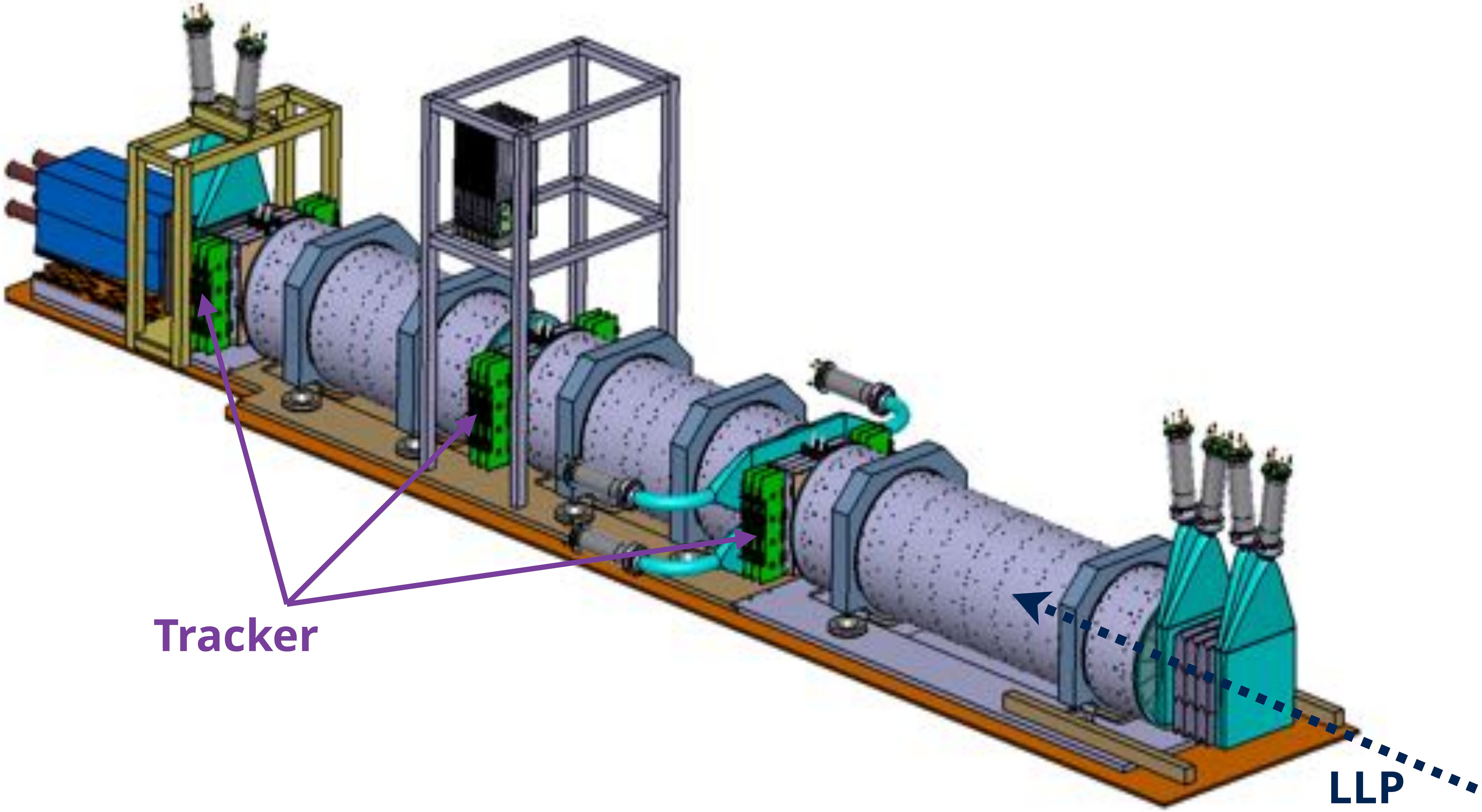




Magnets | Installation

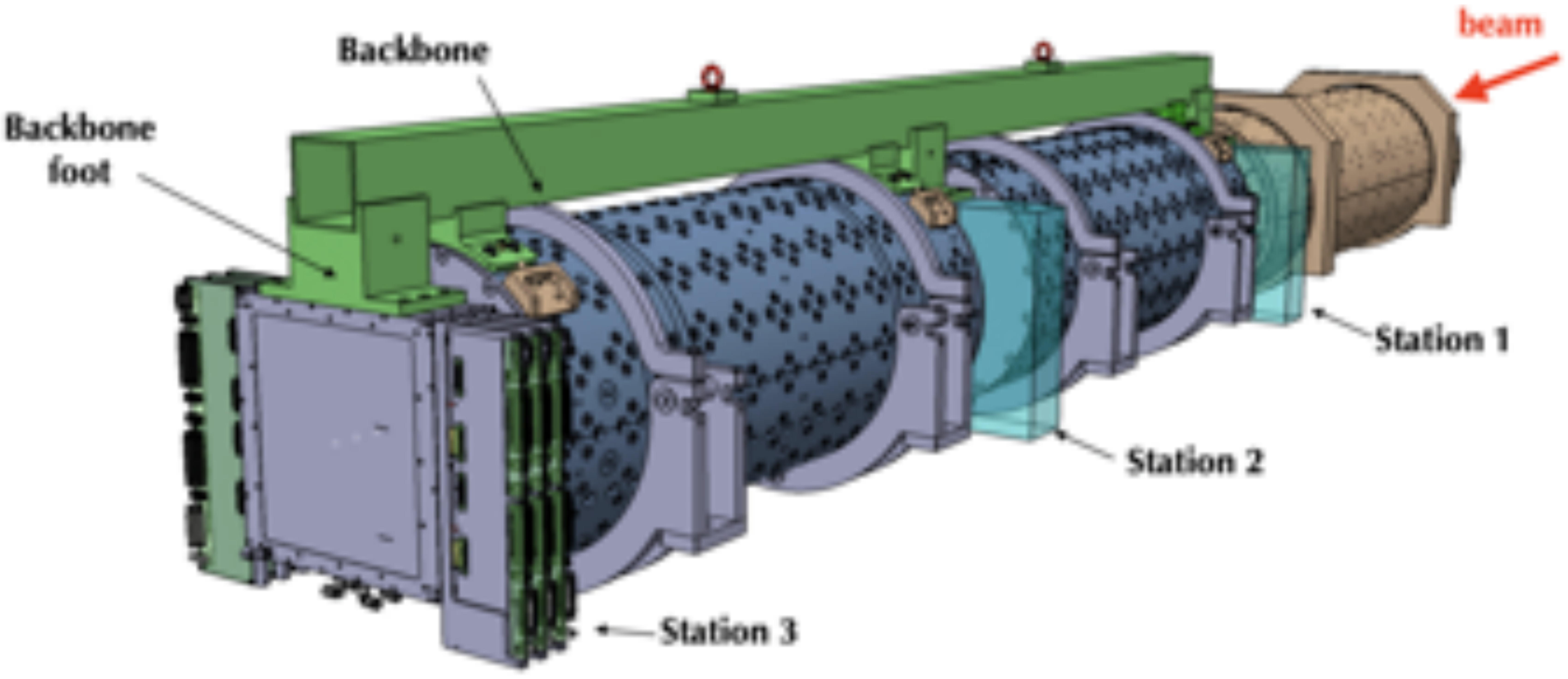
- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN
- Measured field quality well within specifications.
- All magnets now installed underground!

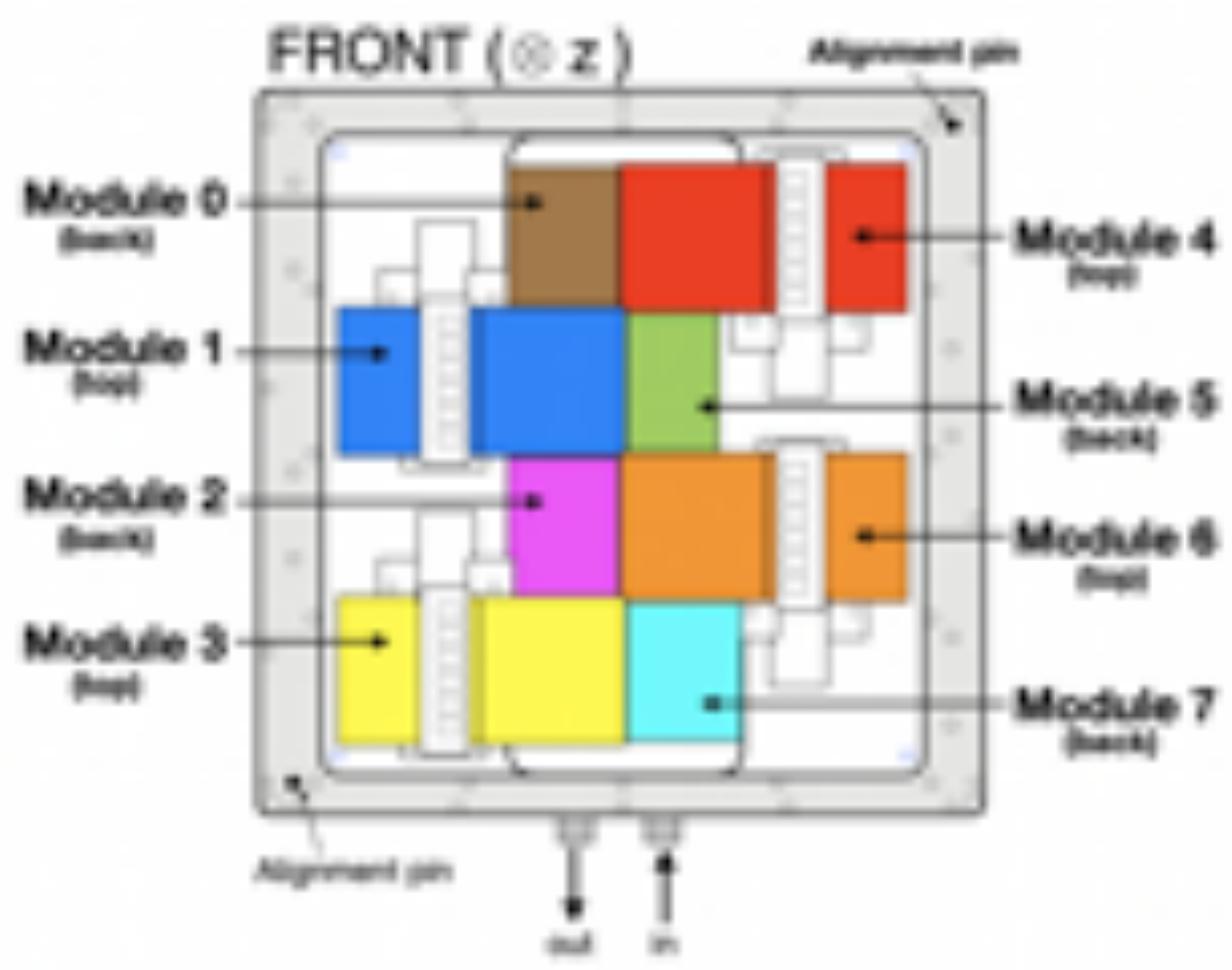
Tracker



Tracker | Overview

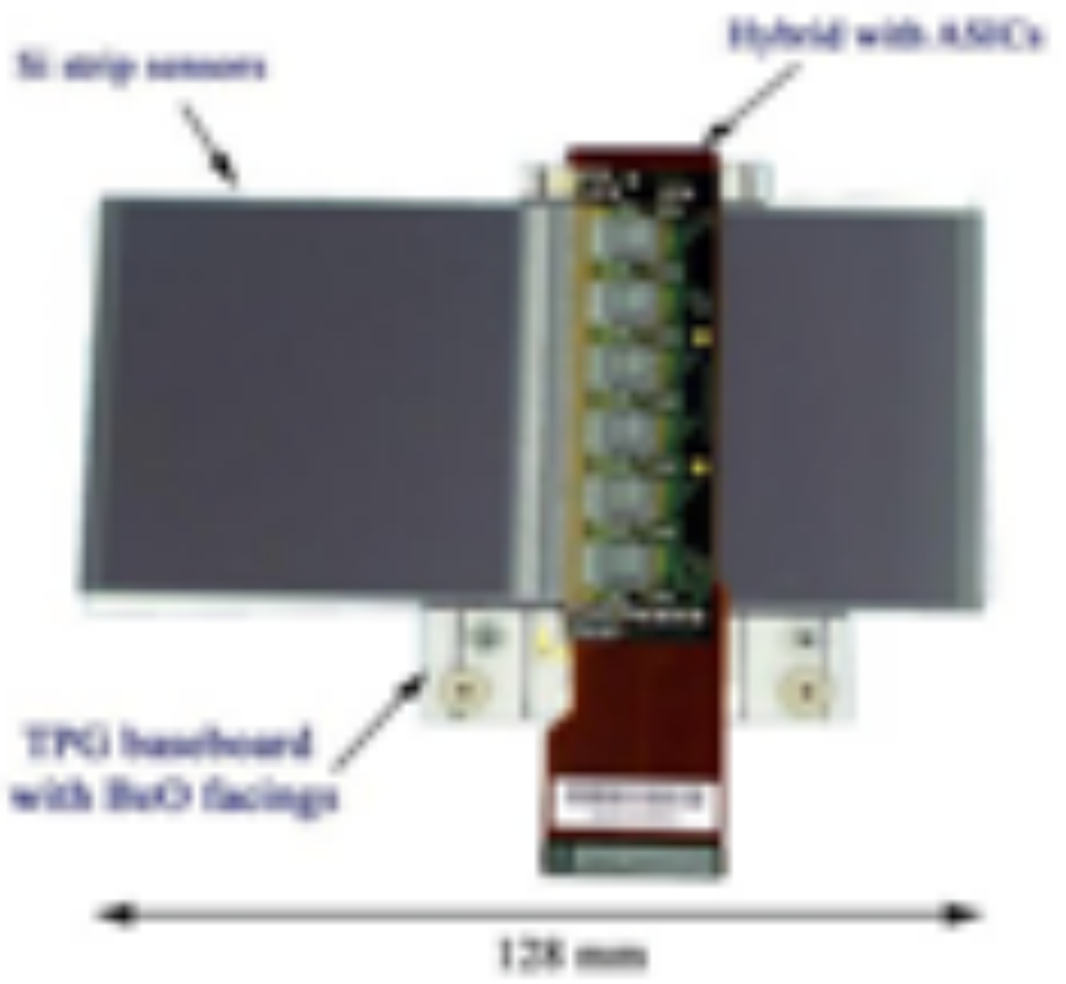
- Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 3 tracking stations.
- Each stations has 3 layers of 8 modules.



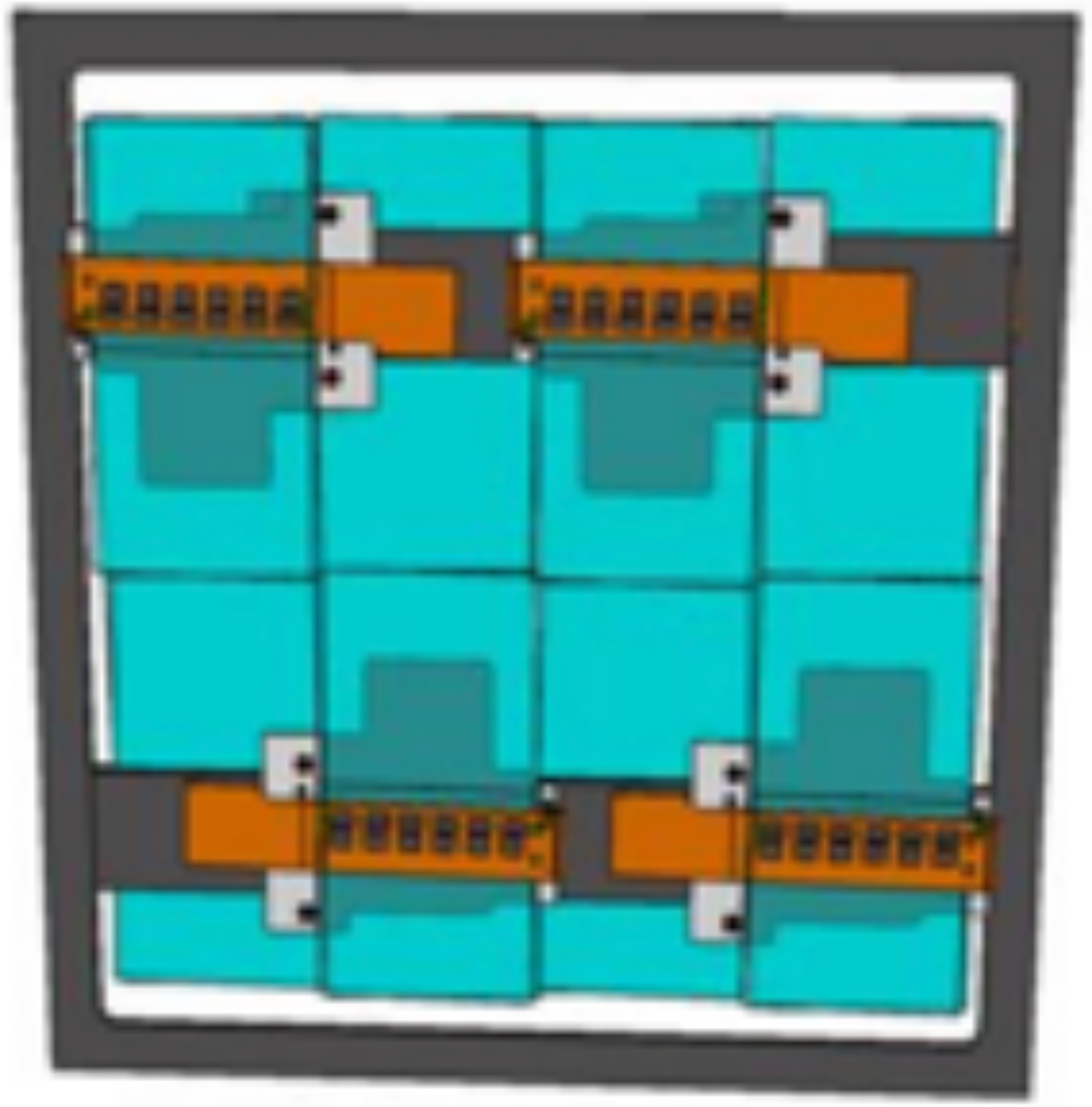


Tracker

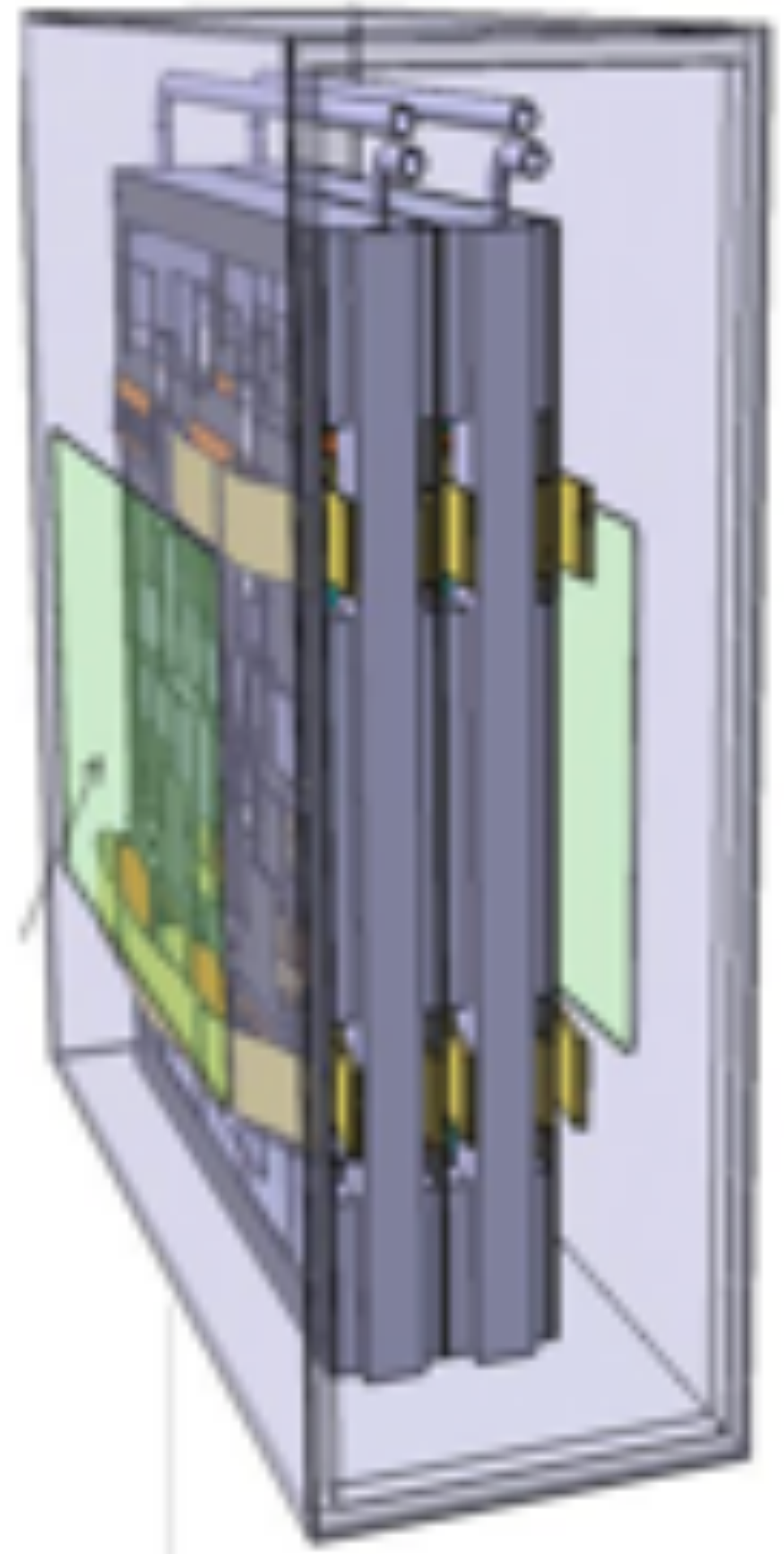
- From Sebastian…



SCT module



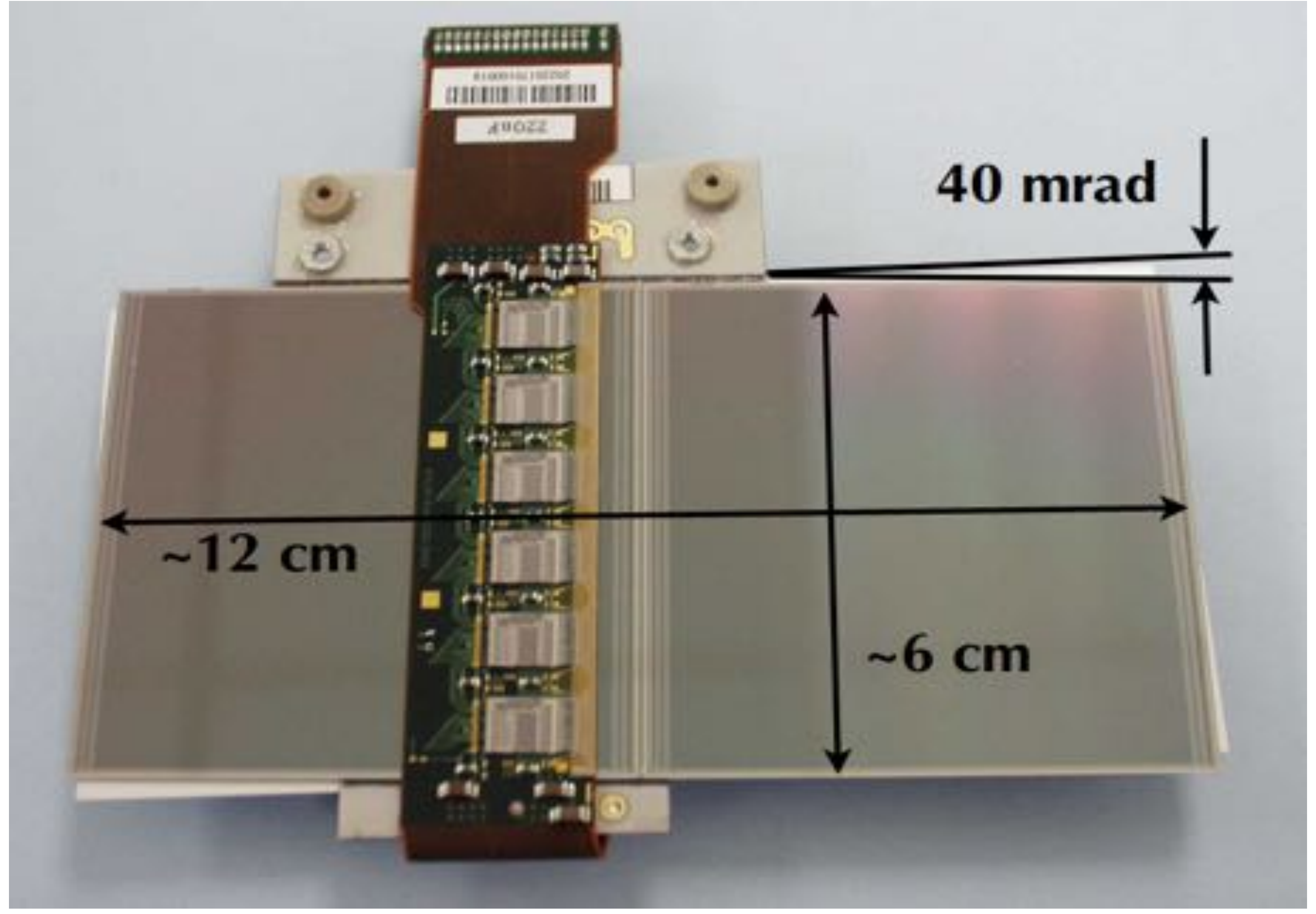
Tracking layer

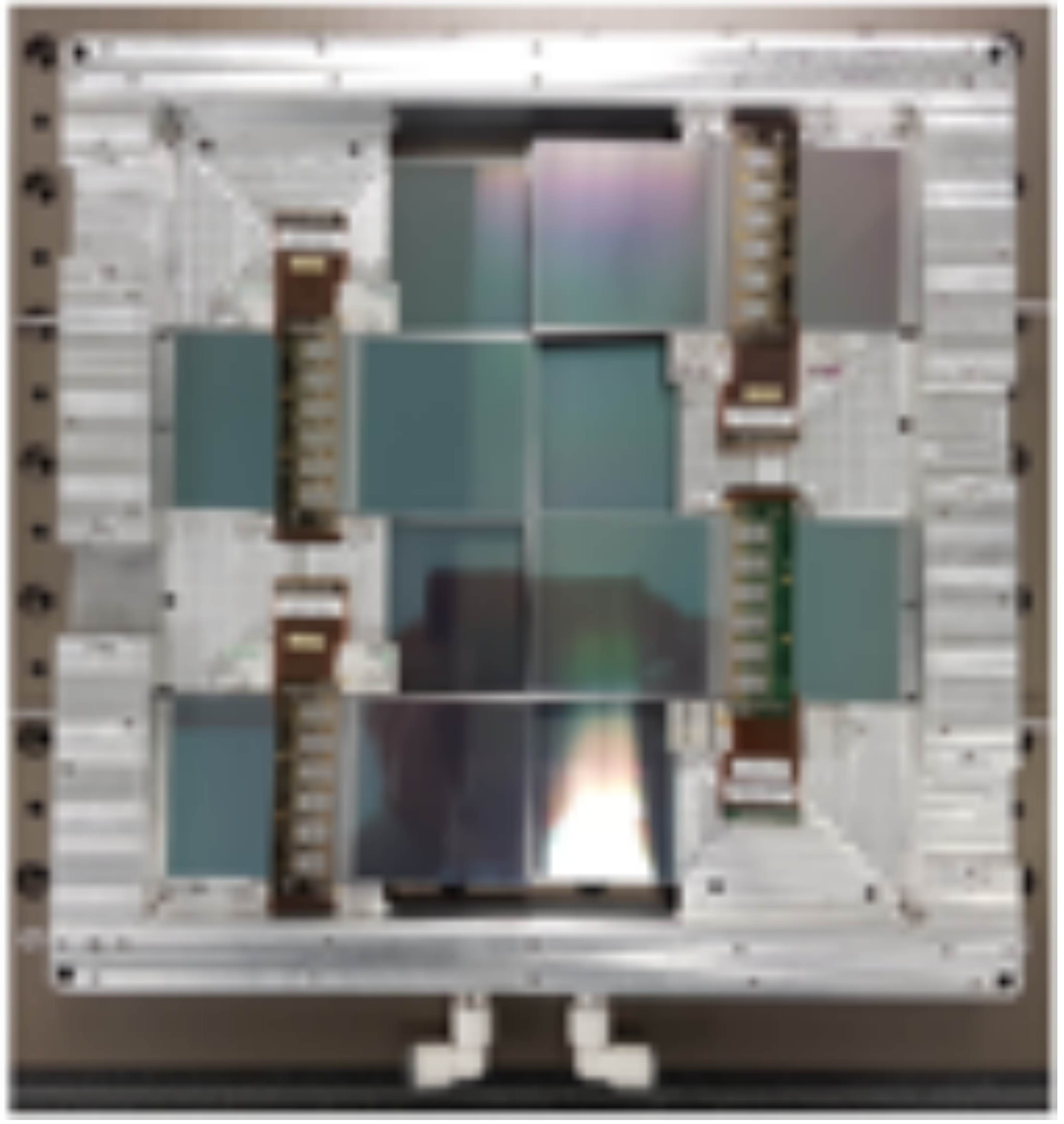


Tracking station

Tracker

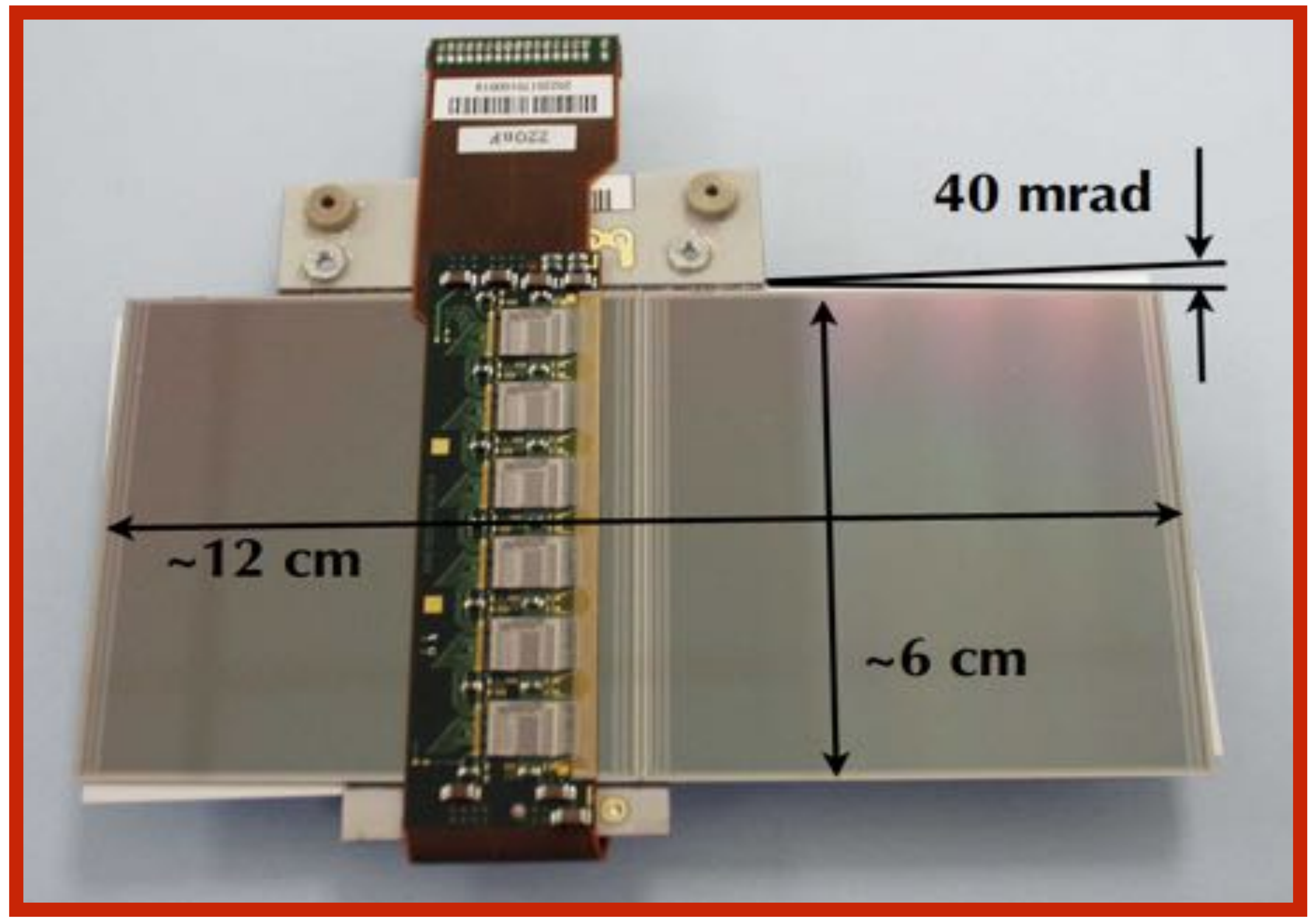
- Today…

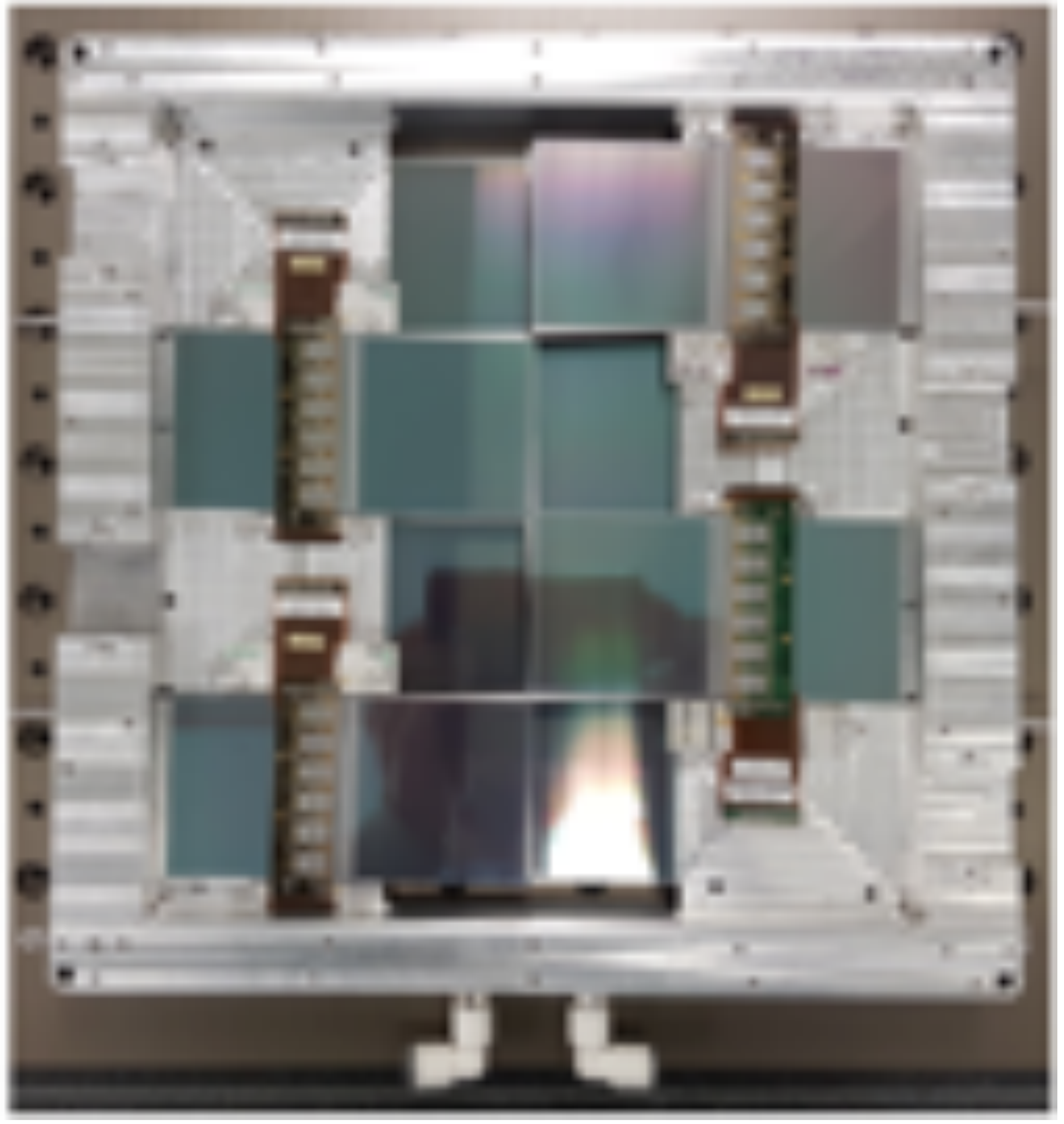




Tracker | Modules

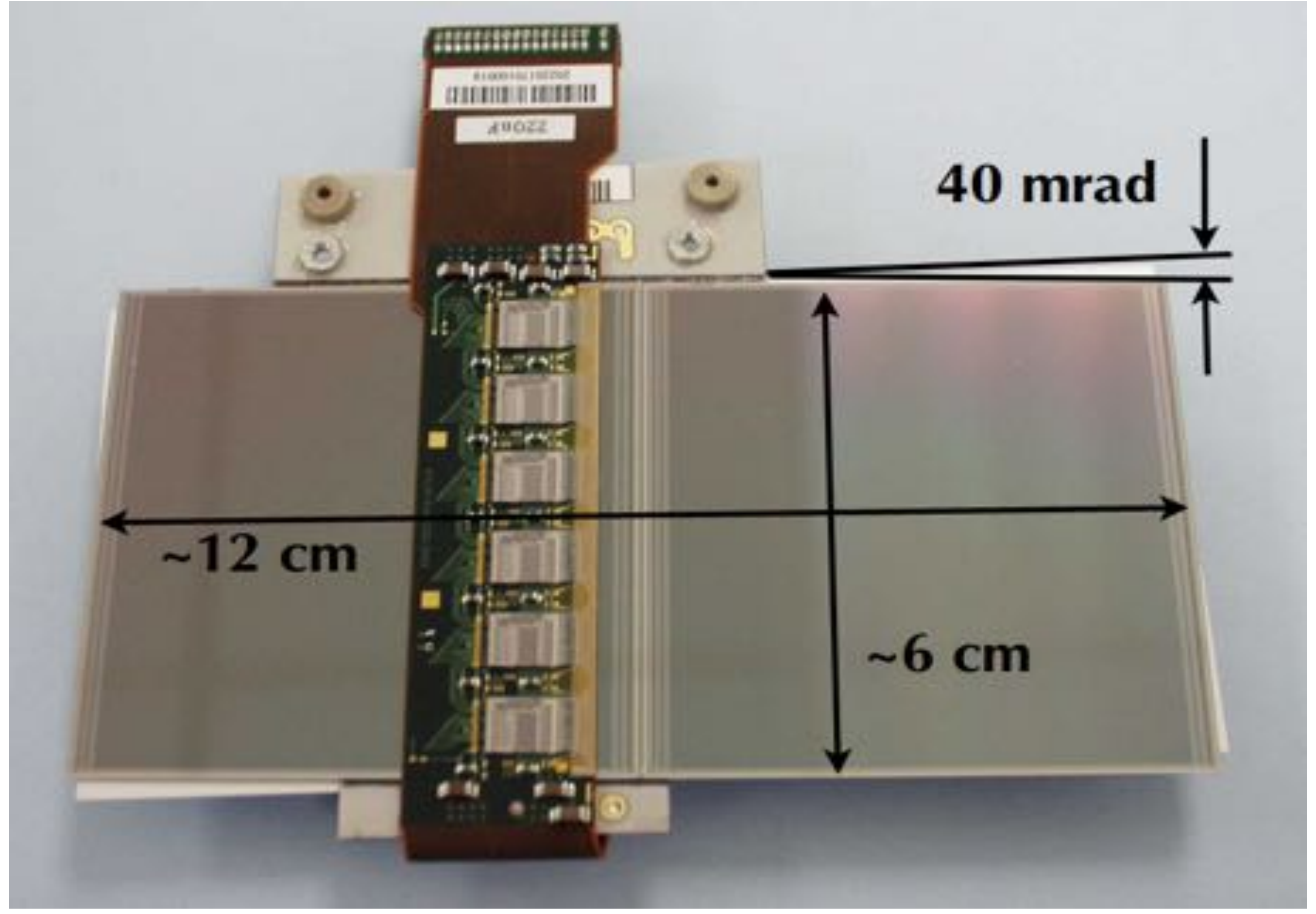
- Spare ATLAS SCT modules are used
  - 80μm strip pitch, 40mrad stereo angle (17μm / 580μm resolution)
    - precision measurement in bending (vertical) plane
  - Many thanks to the ATLAS SCT collaboration!

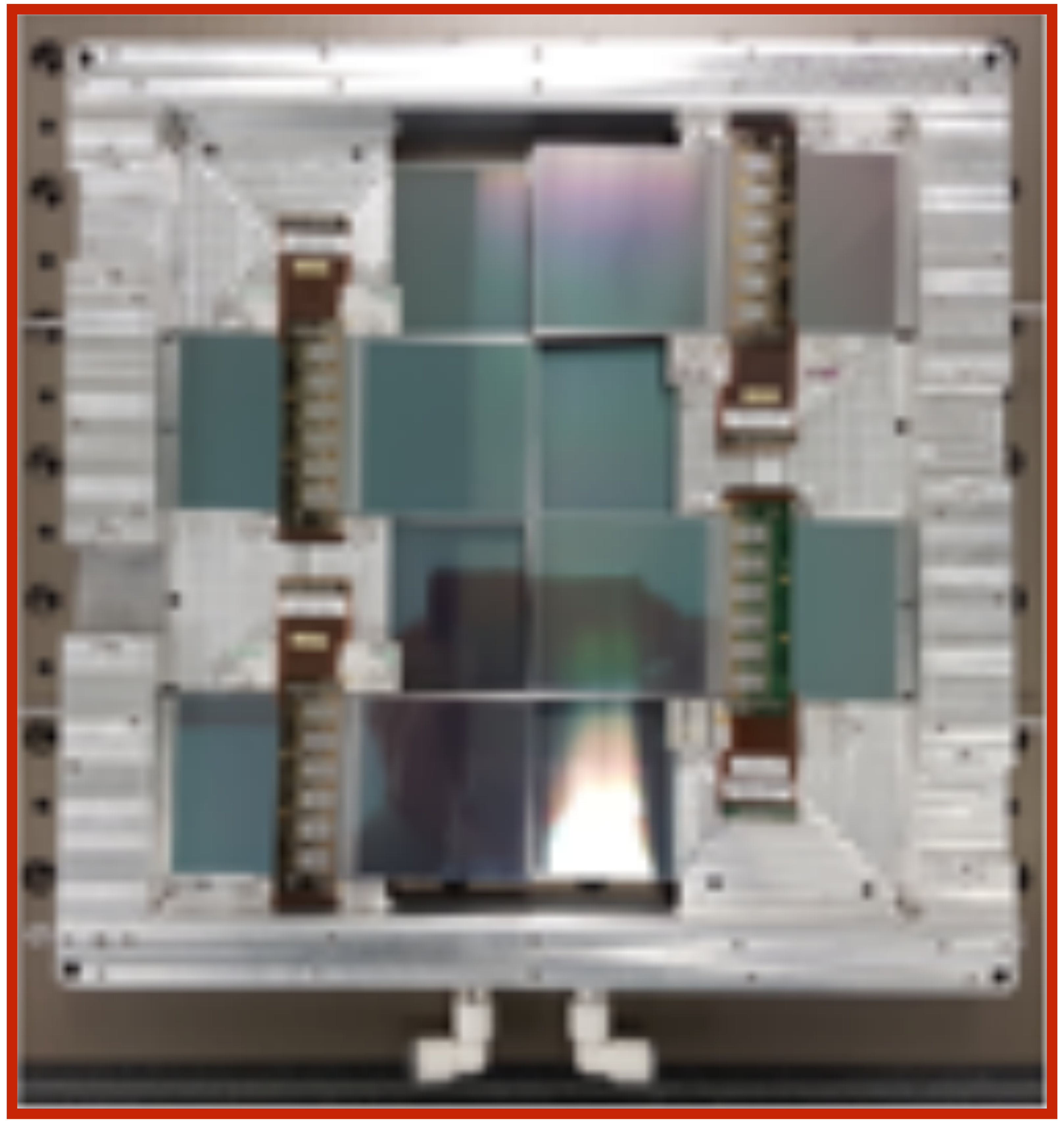




Tracker | Layers

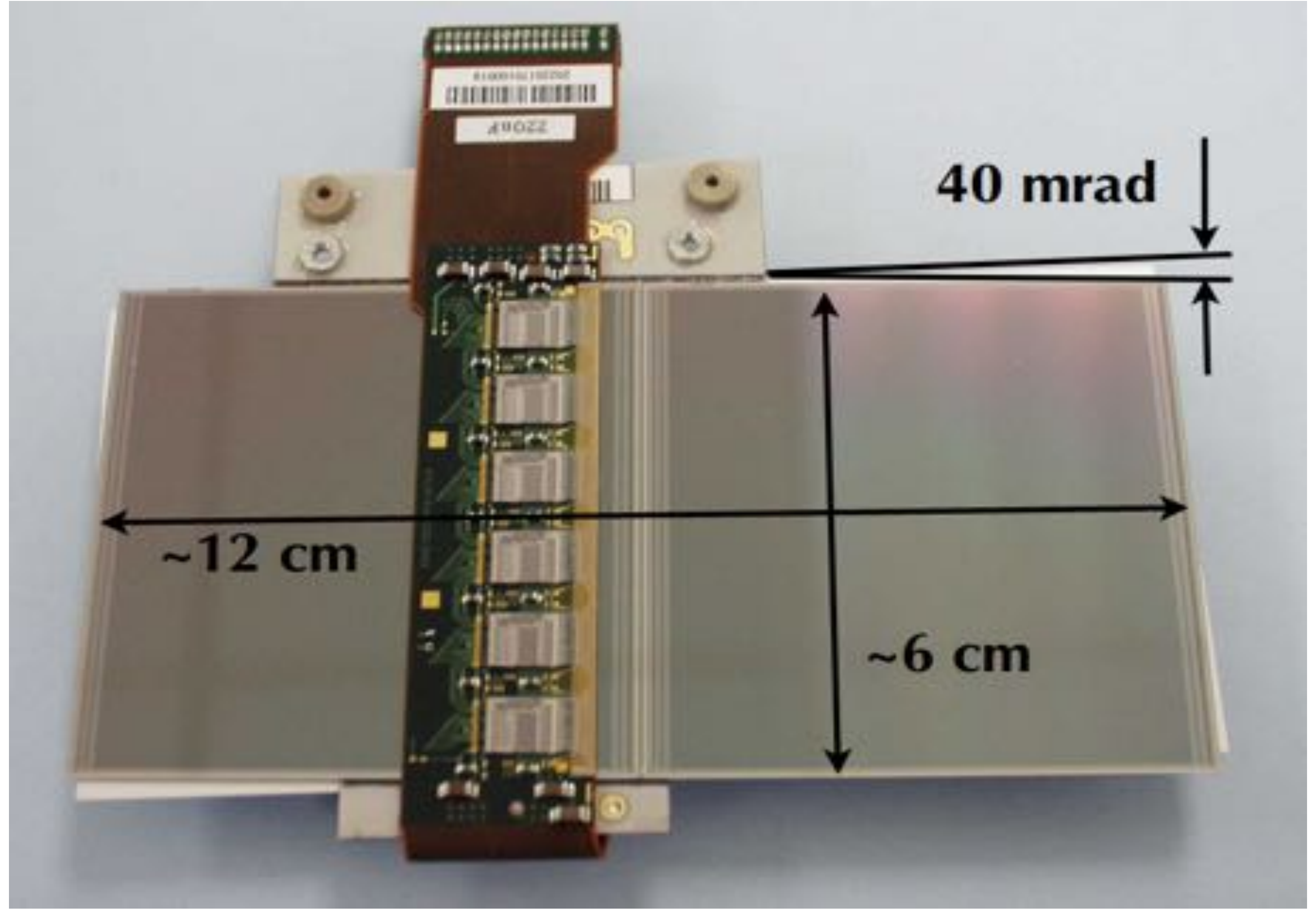
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) → 72 SCT modules needed for the full tracker

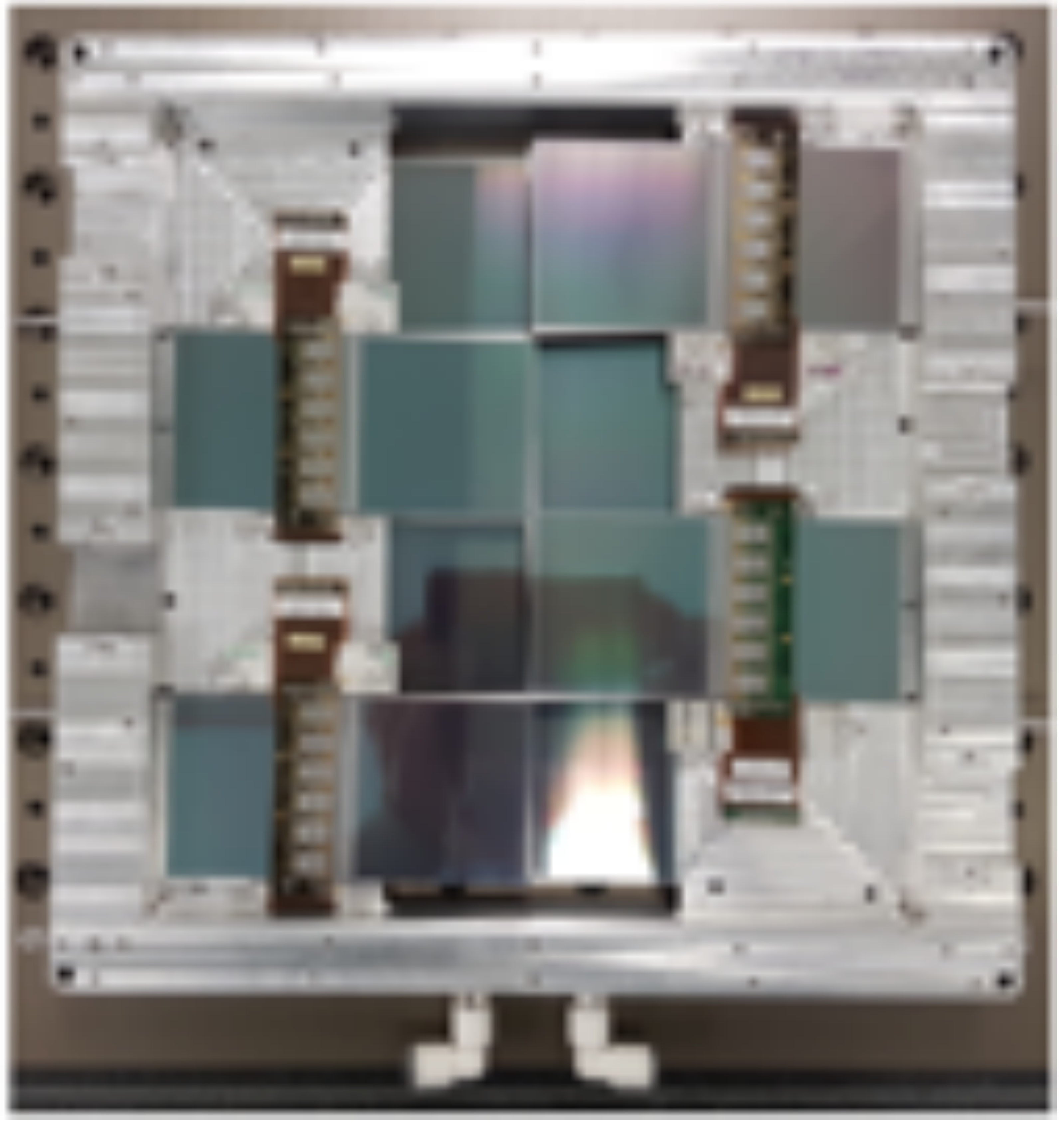





Tracker | Stations

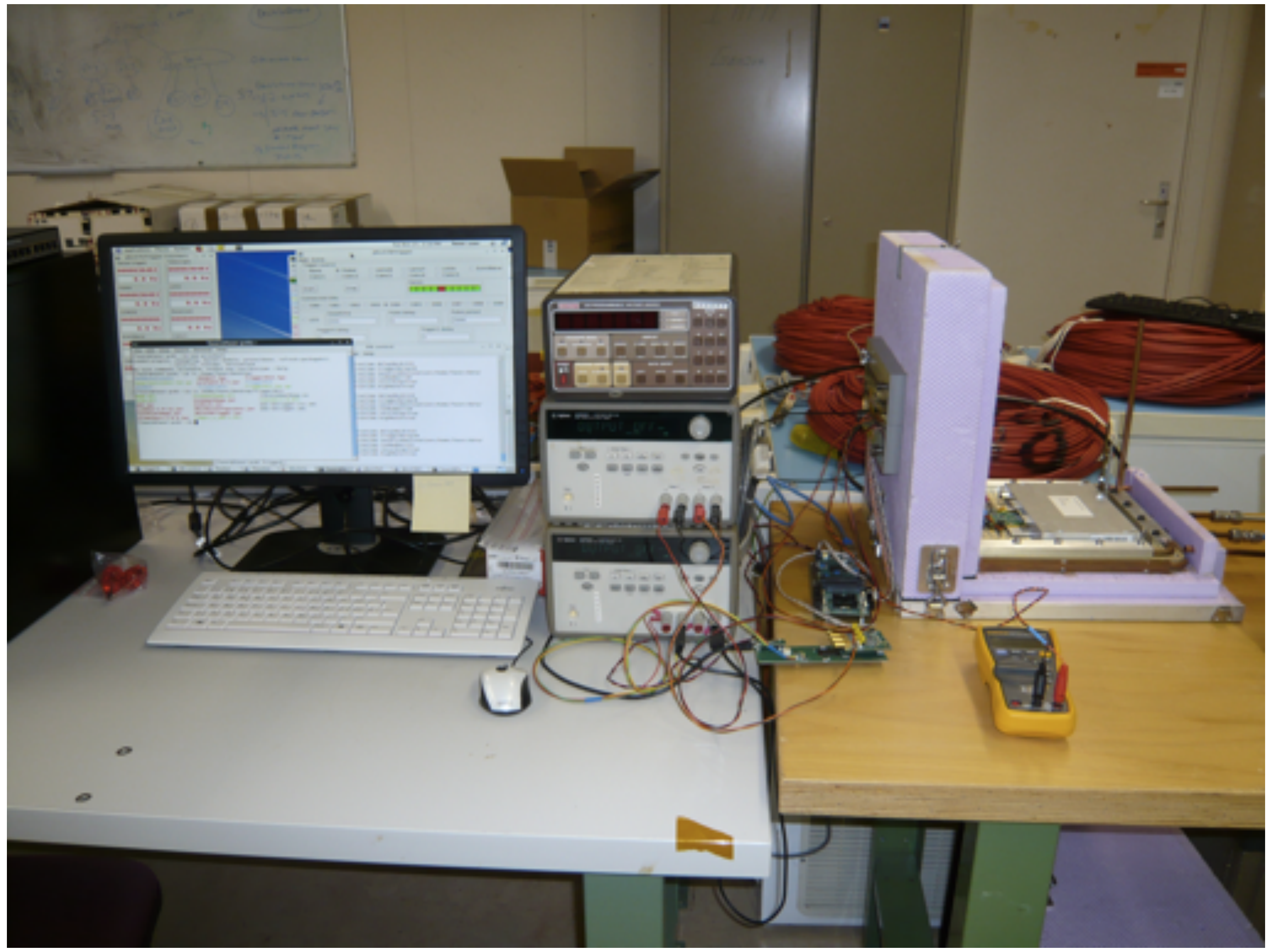
- Low radiation levels in TI12 allows silicon to be operated at room temp.
  - But the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)

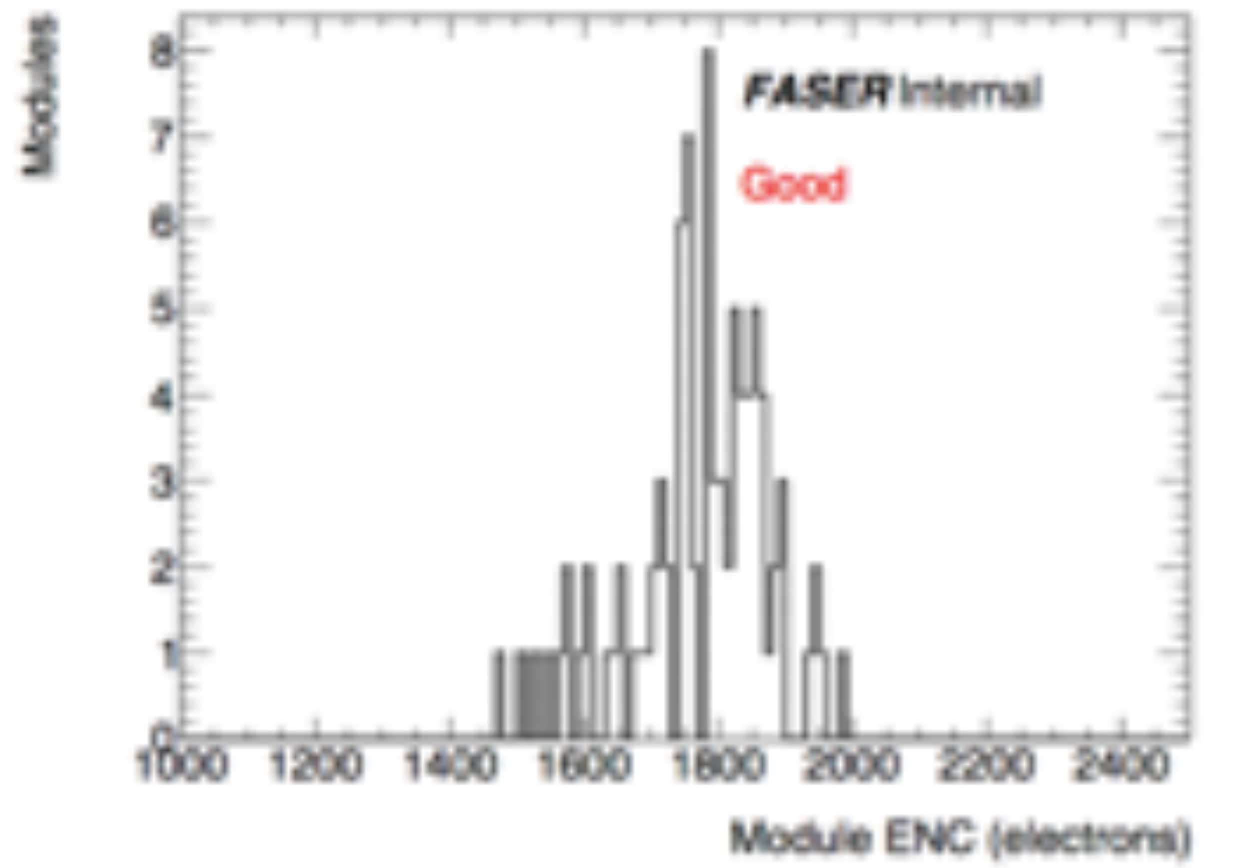


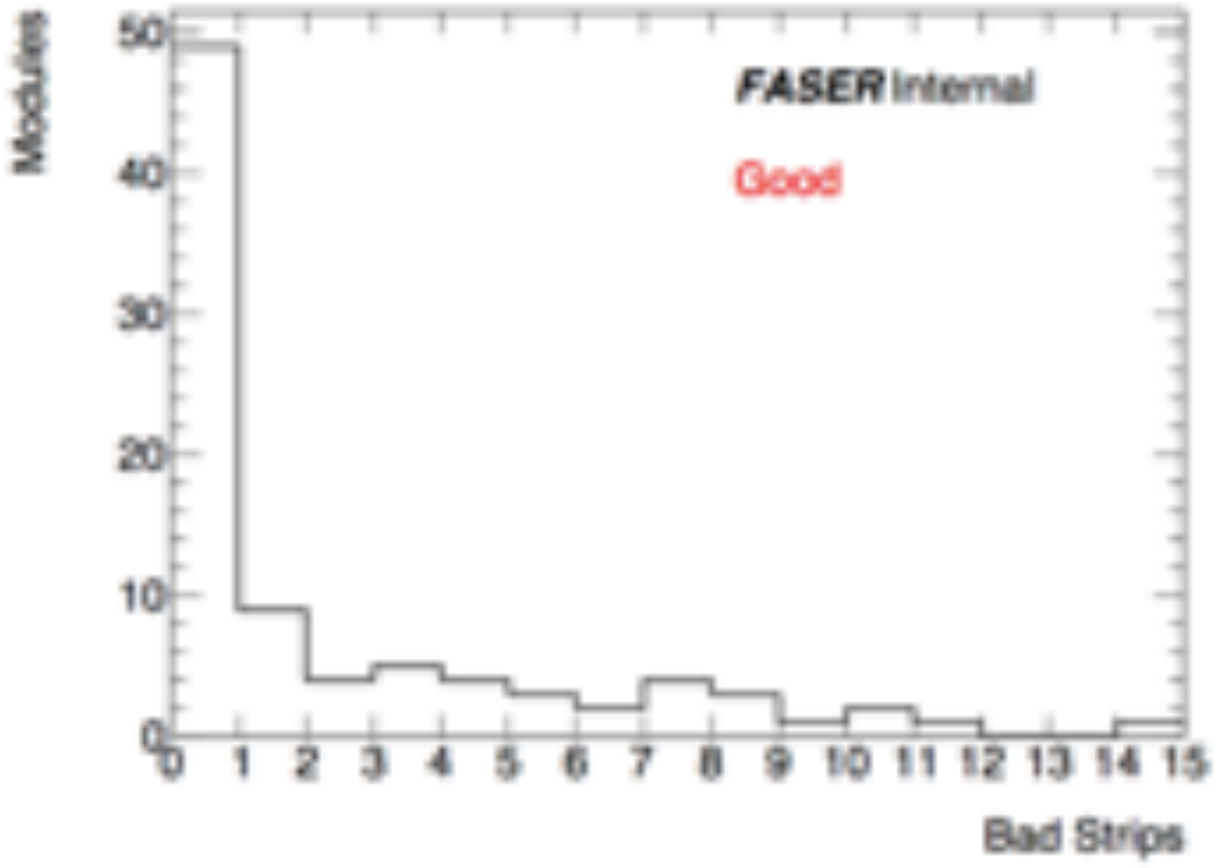


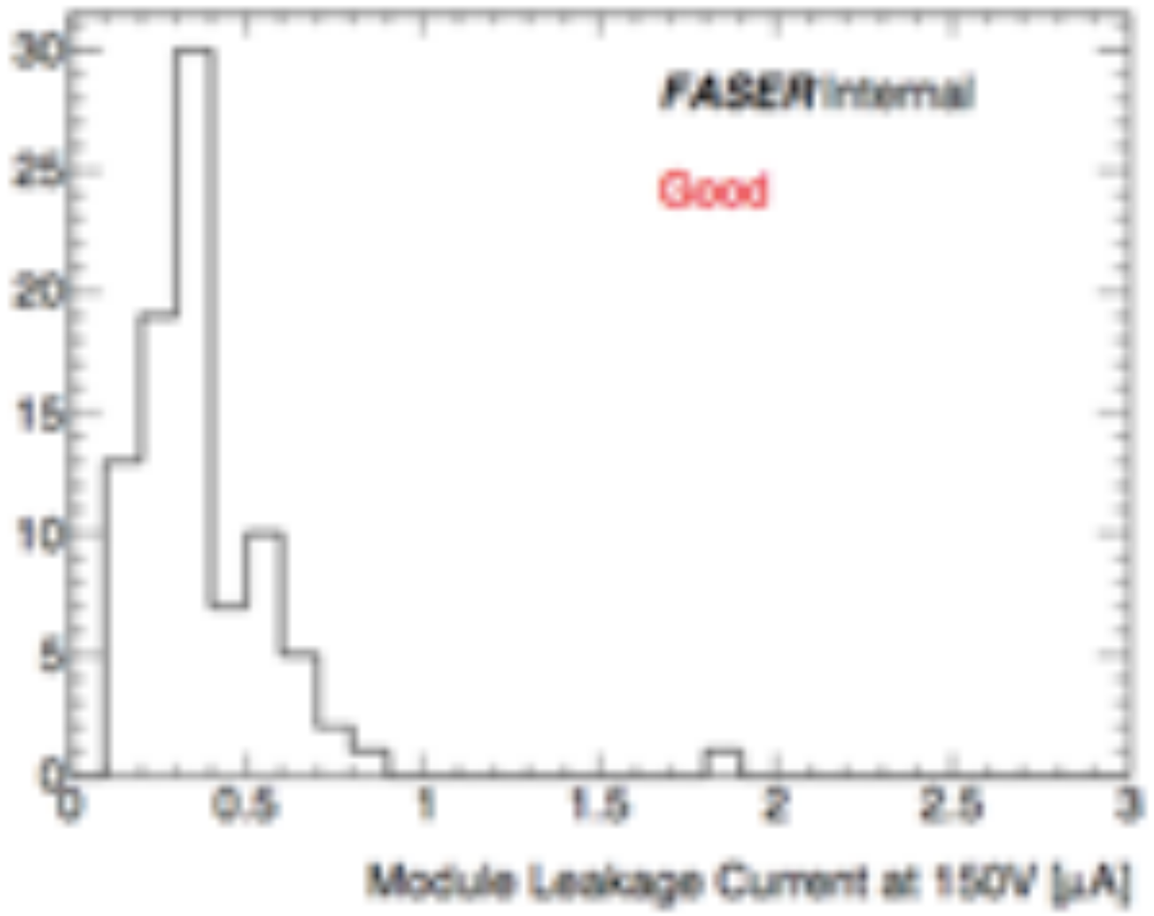
Tracker | Module QA

- 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.

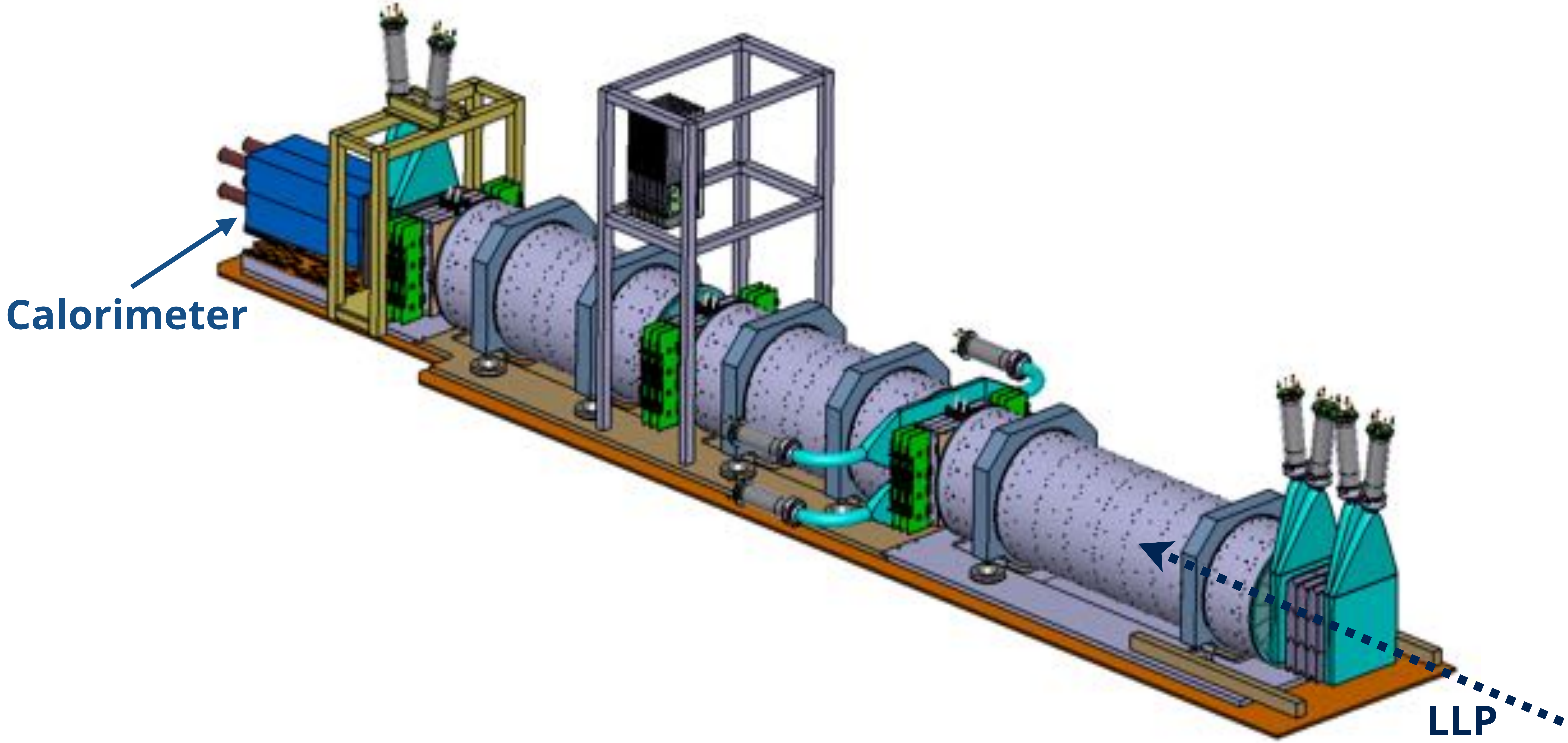






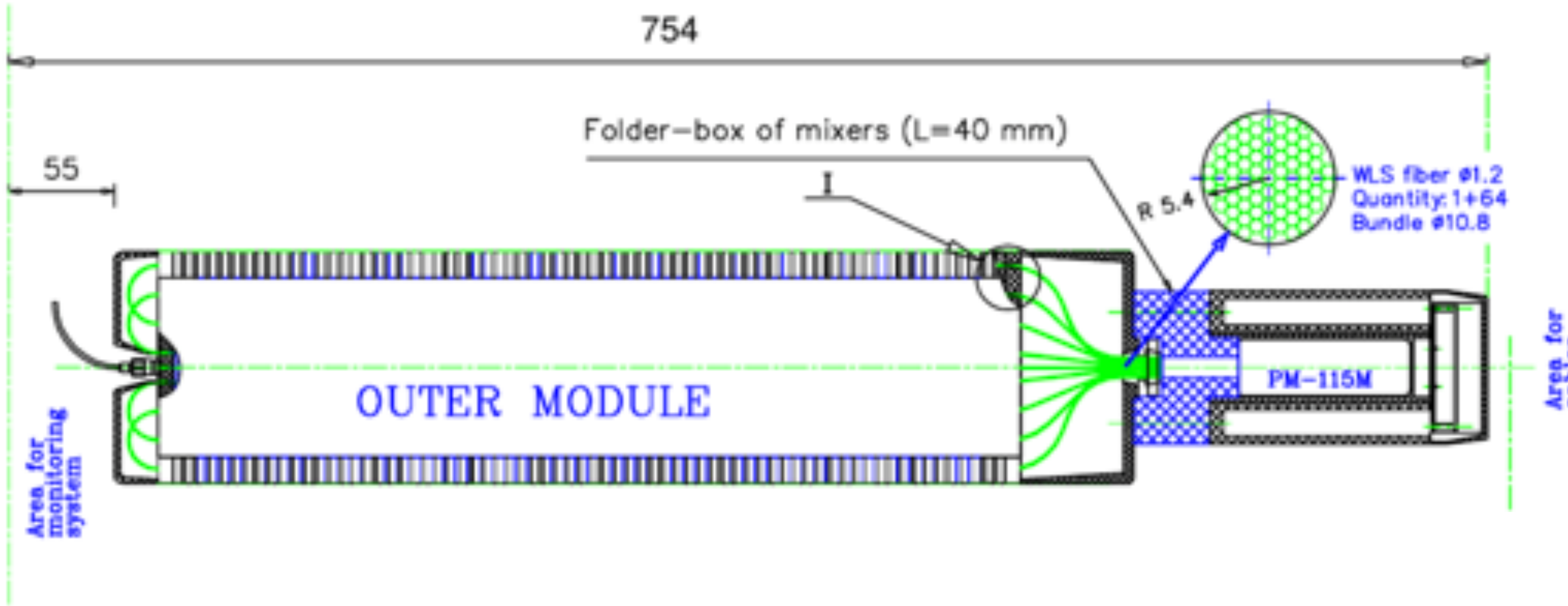


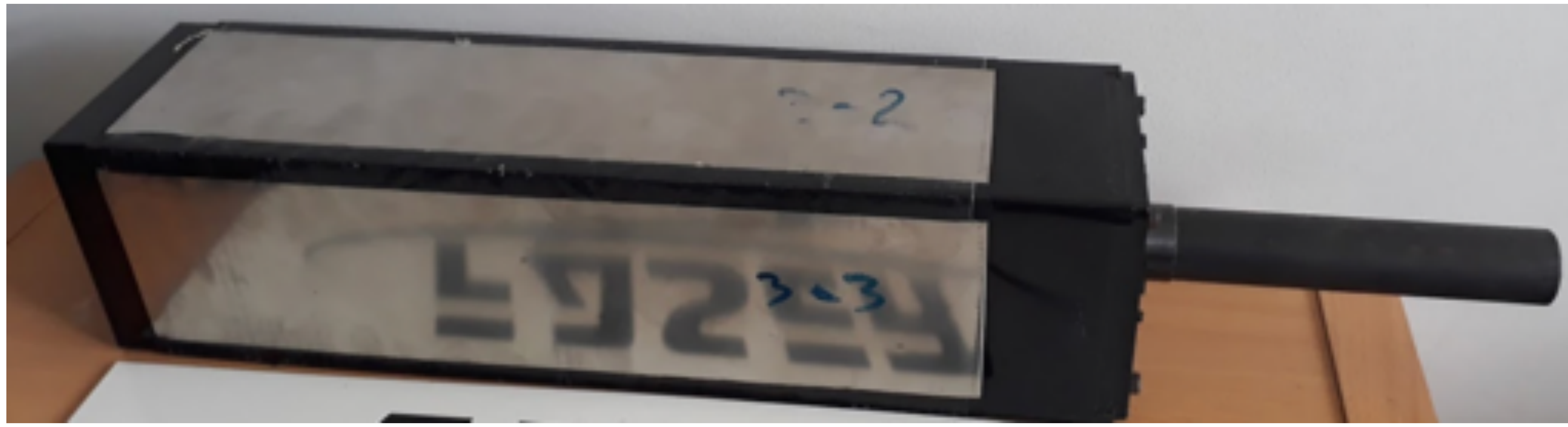
Calorimeter



Calorimeter

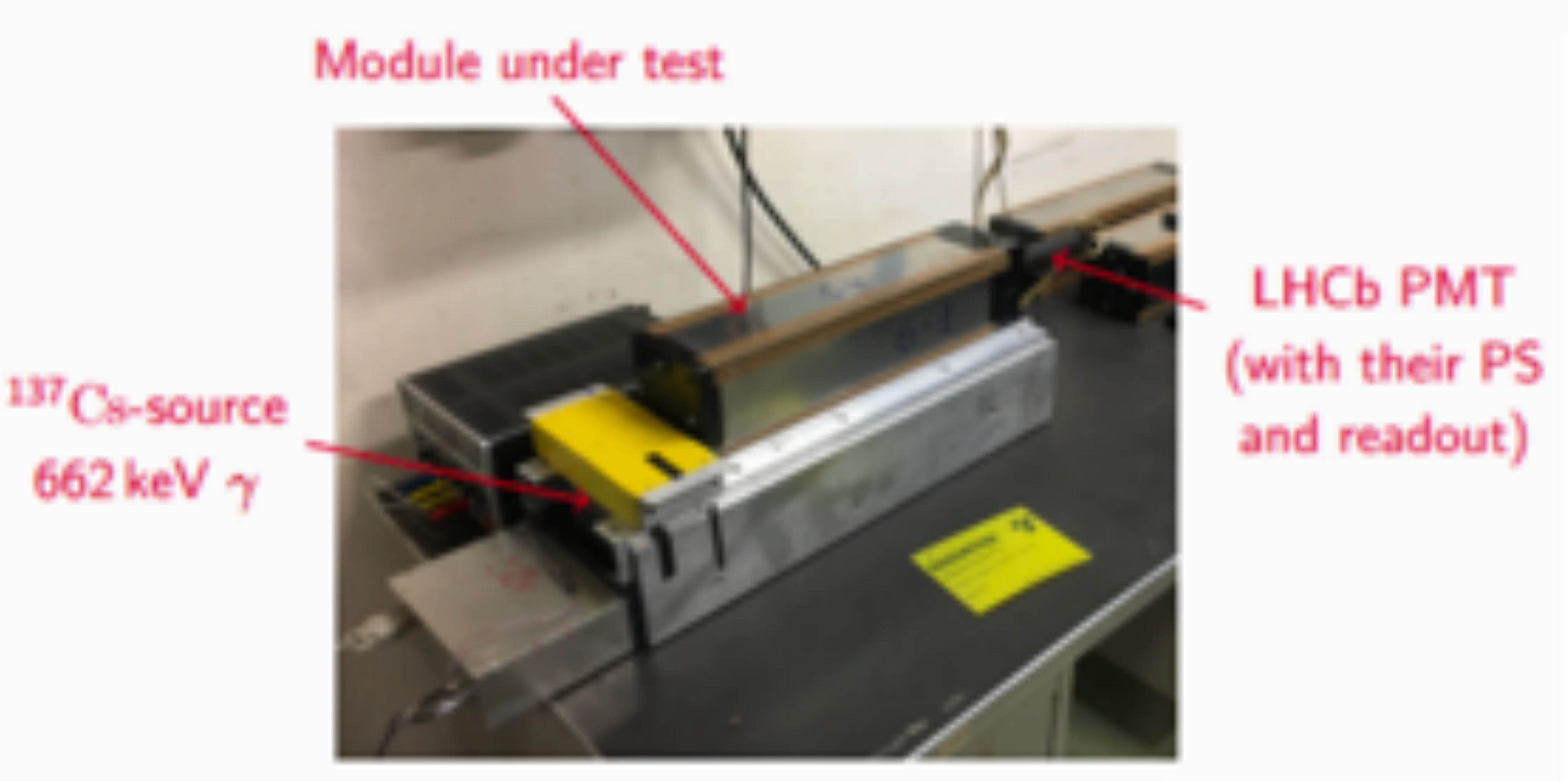
- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Uses 4 spare LHCb outer ECAL modules
  - Many thanks to LHCb for the use of these!
    - PMTs also from LHCb, but needed new voltage divider
  - 66 layers of lead/scintillator, light out by wavelength shifting fibres
    - 25 radiation lengths long
  - Readout by PMT (no longitudinal shower information)
    - Only 4 channels in full calorimeter
  - Dimensions: 12cm x 12cm – 75cm long (including PMT)
  - Provides ~1% energy resolution for 1 TeV electrons

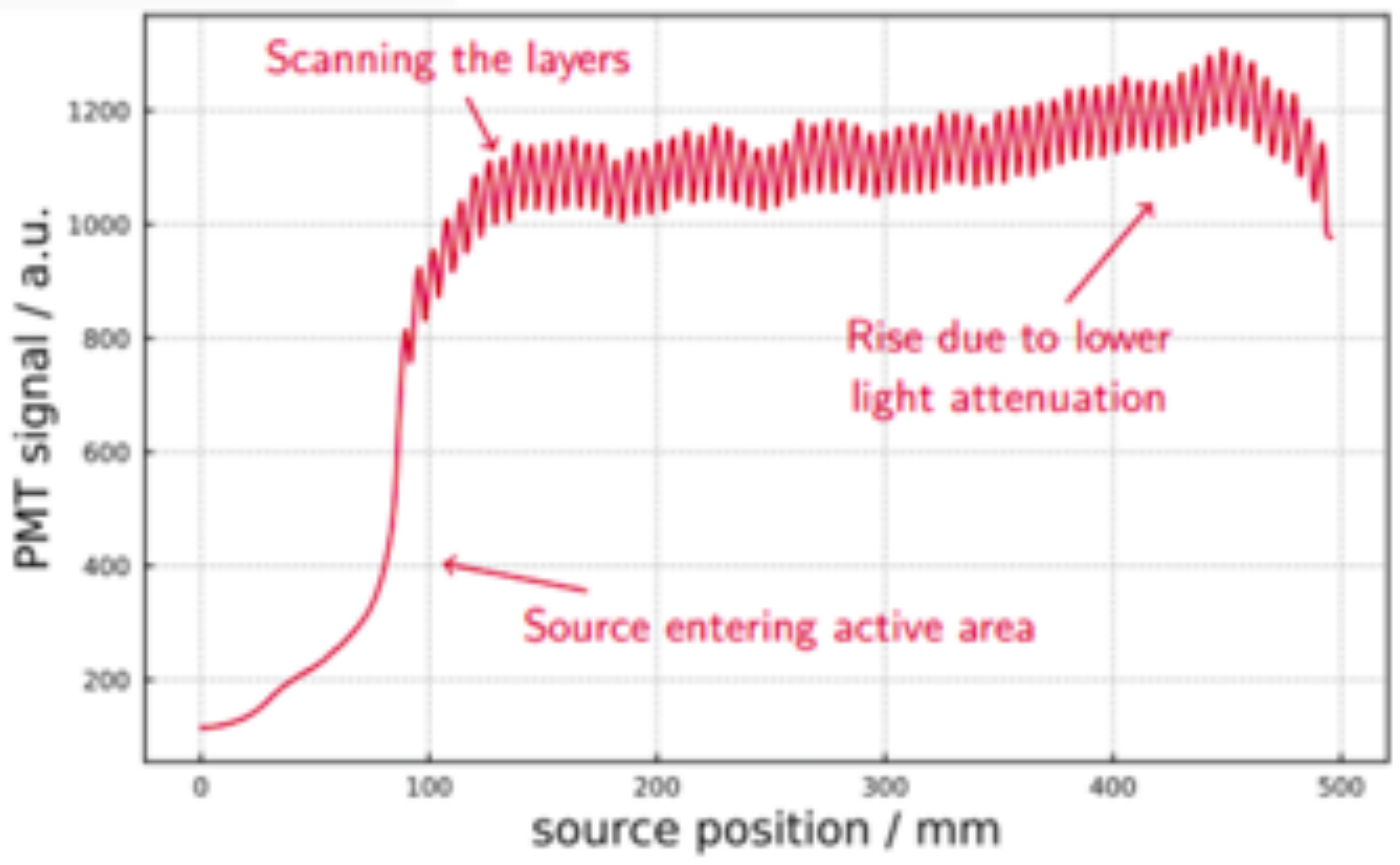




Calorimeter | Testing

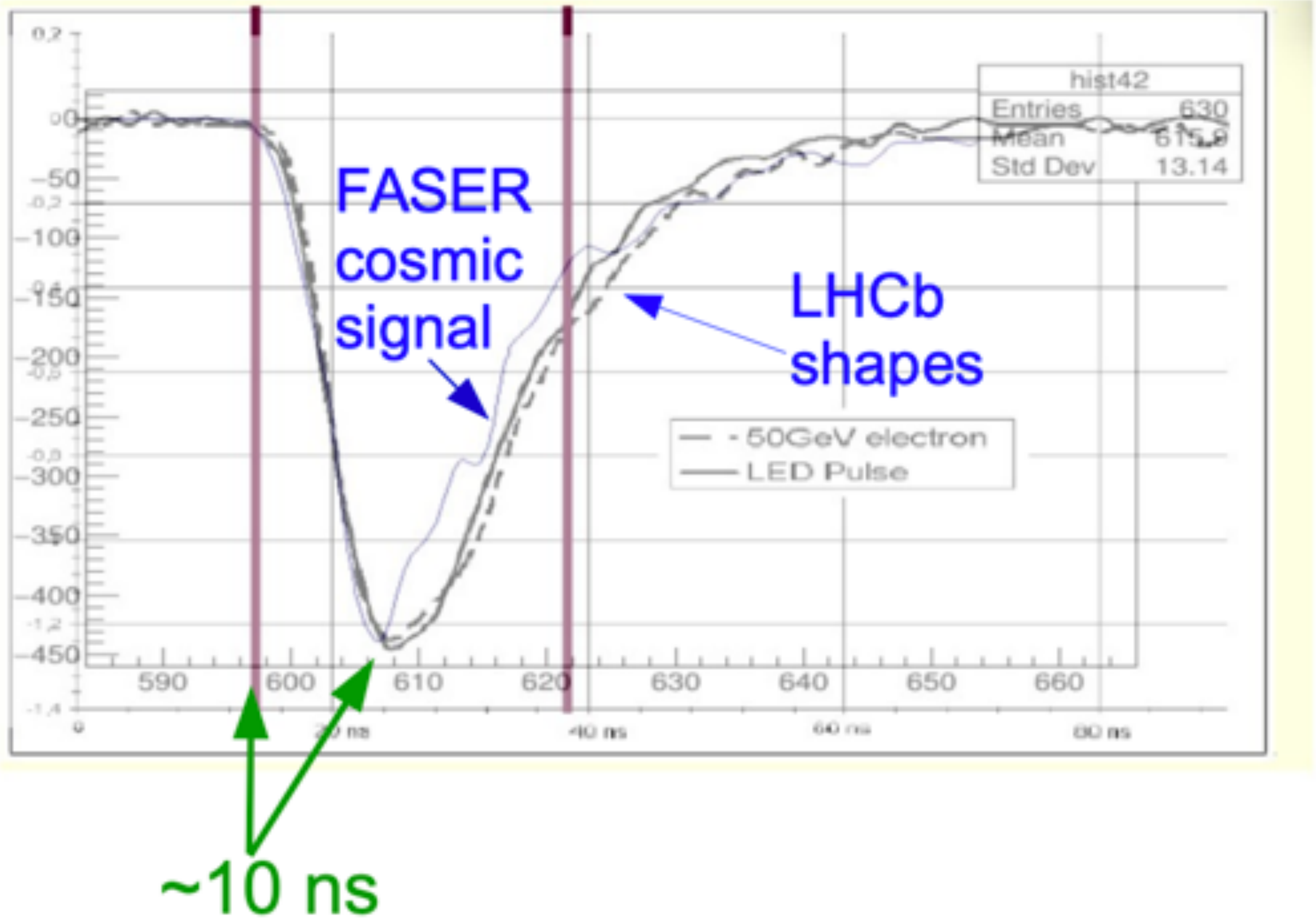
- Early testing performed at CERN
- Caesium source used to check response in all available modules.
- Modules performed as expected.

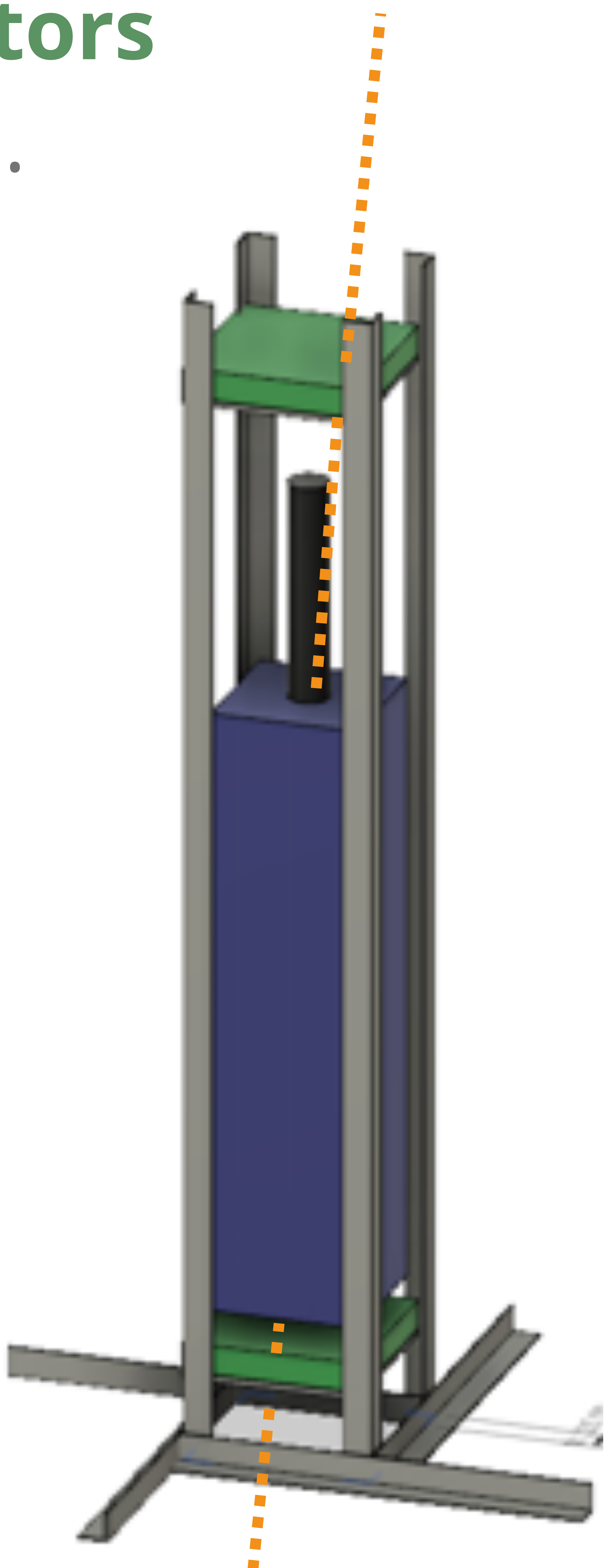


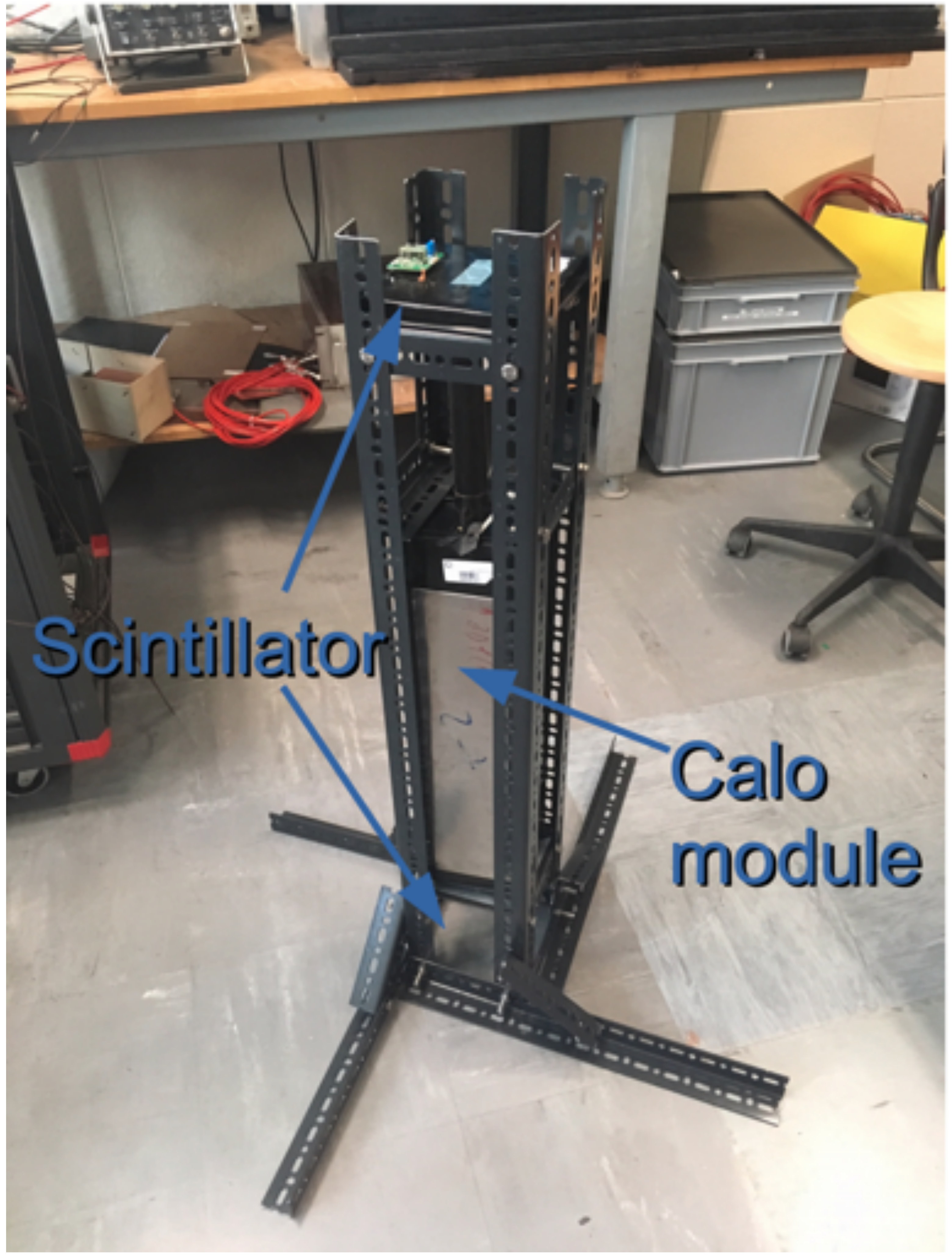


Calorimeter | Cosmic ray test stand

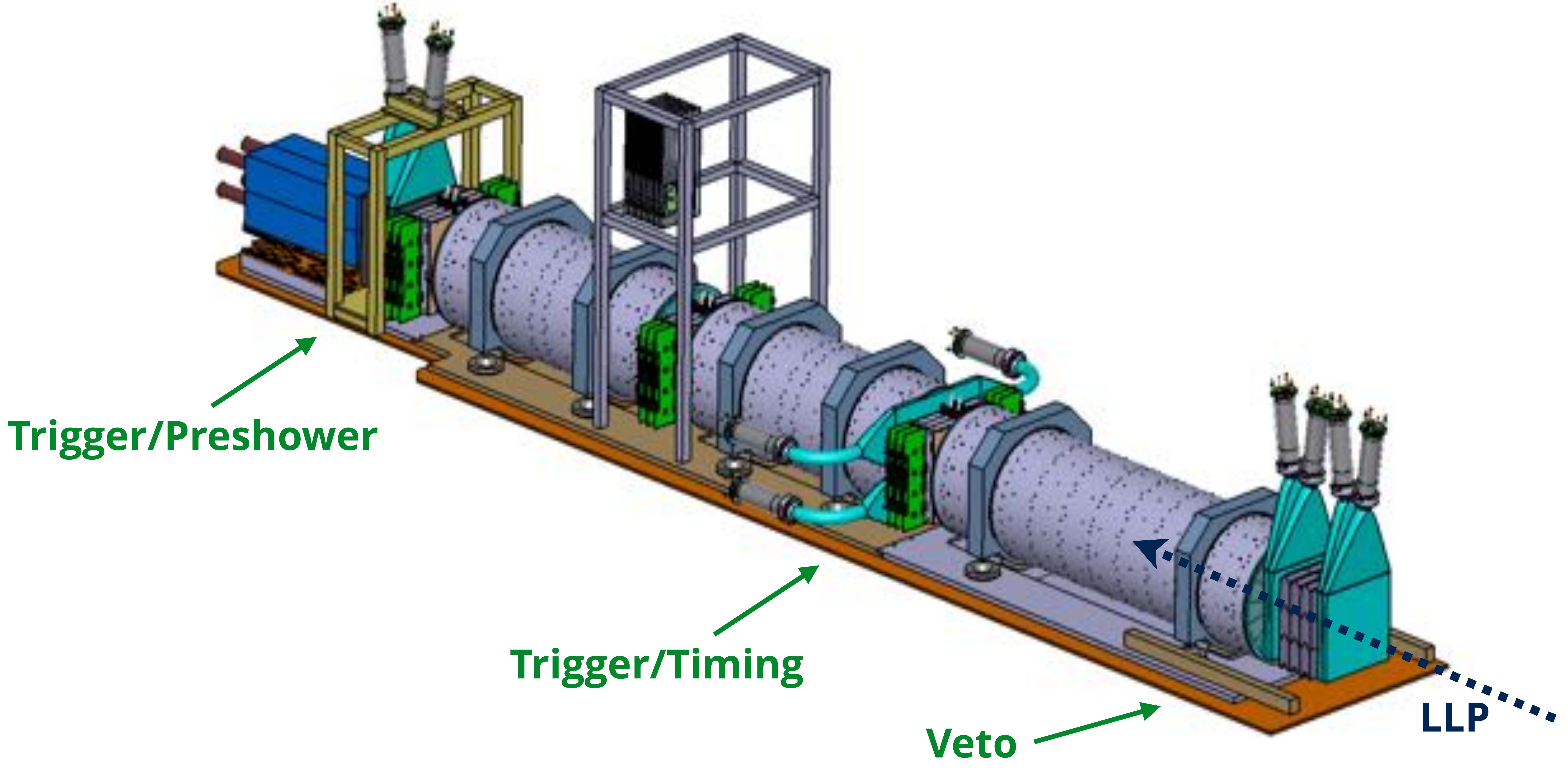
- Cosmic ray test stand used to test calorimeter response and calibrate PMTs.
  - **Calorimeter** signal is read when **scintillators** see coincident signals from **cosmic muon**.
  - Read-out very close to final design
- Good agreement with LHCb pulses observed:





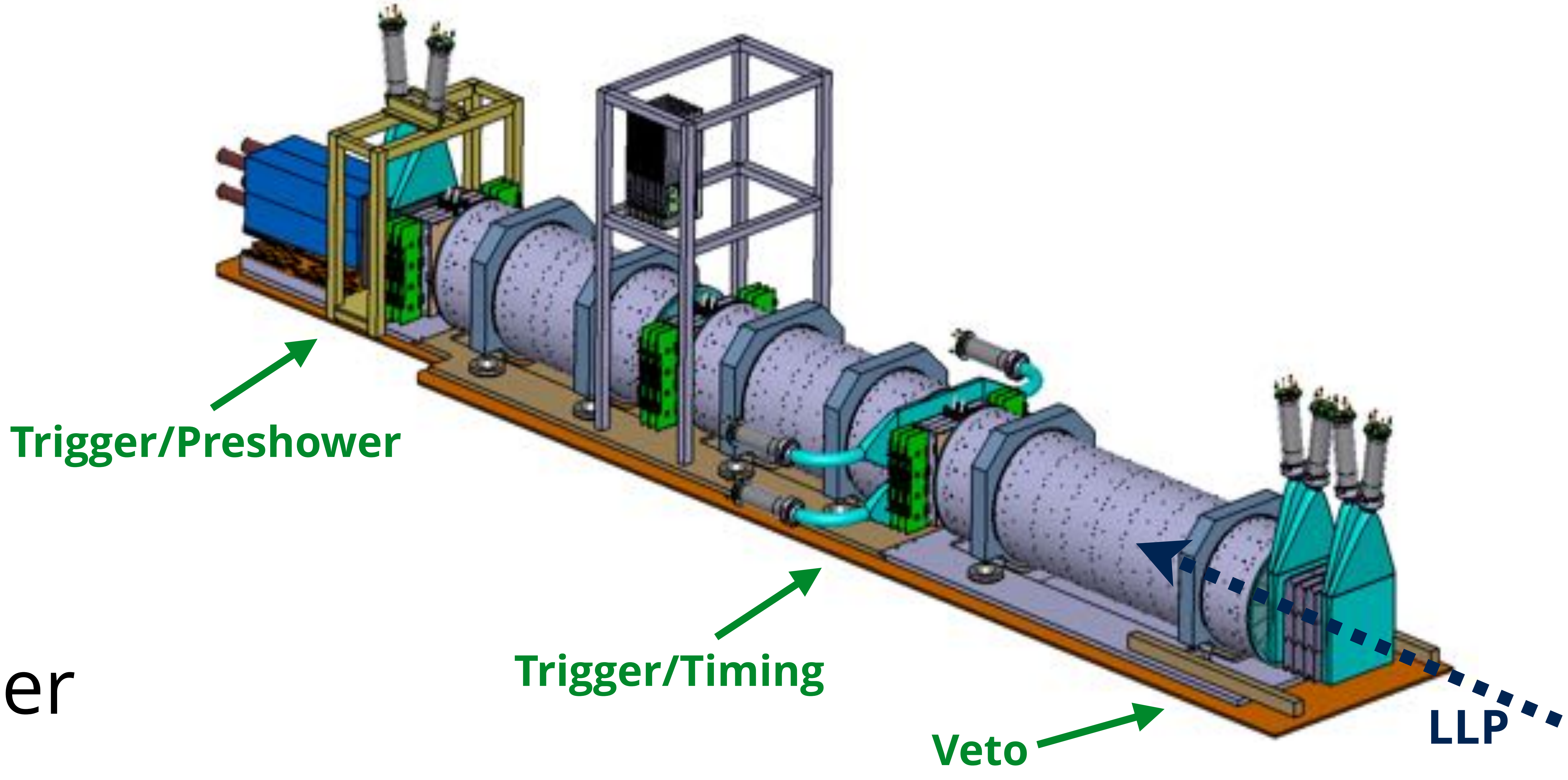


Scintillators



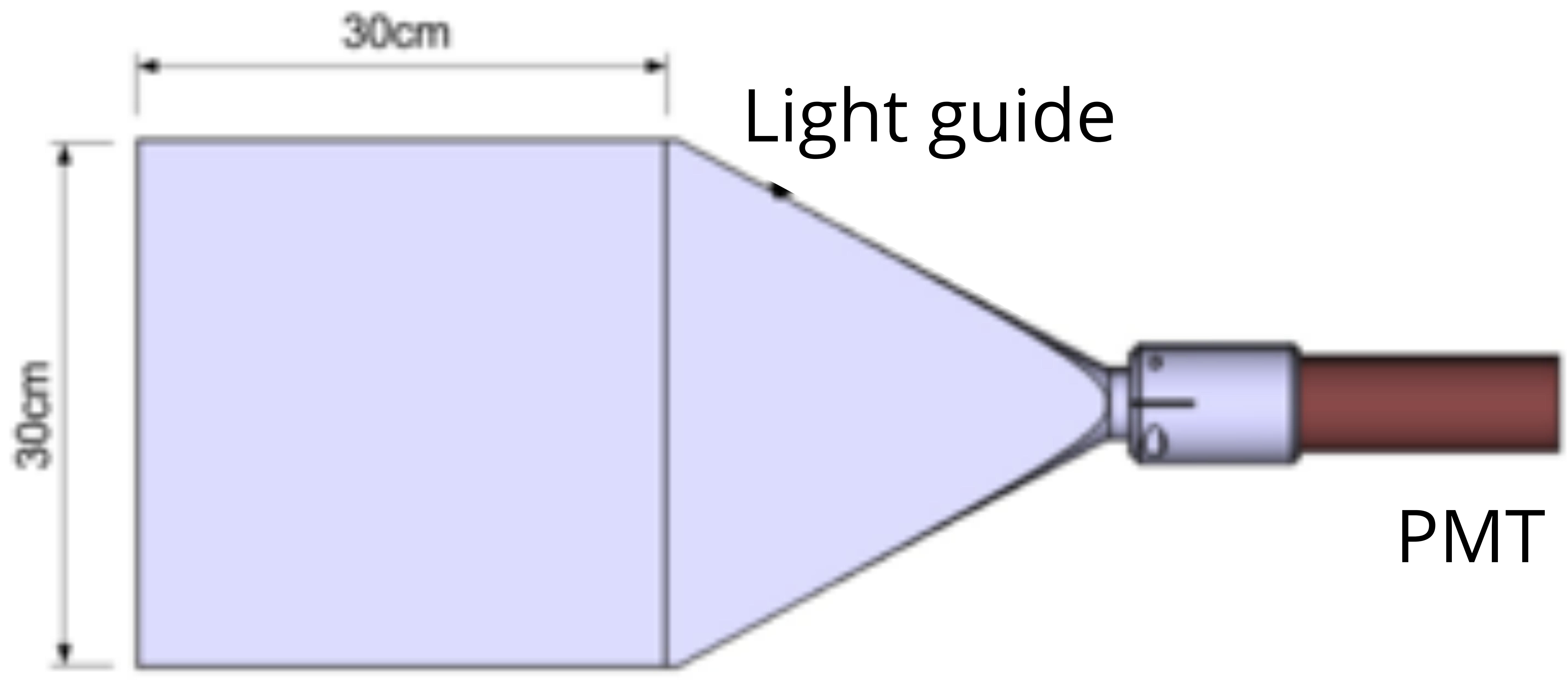
Scintillators

- 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



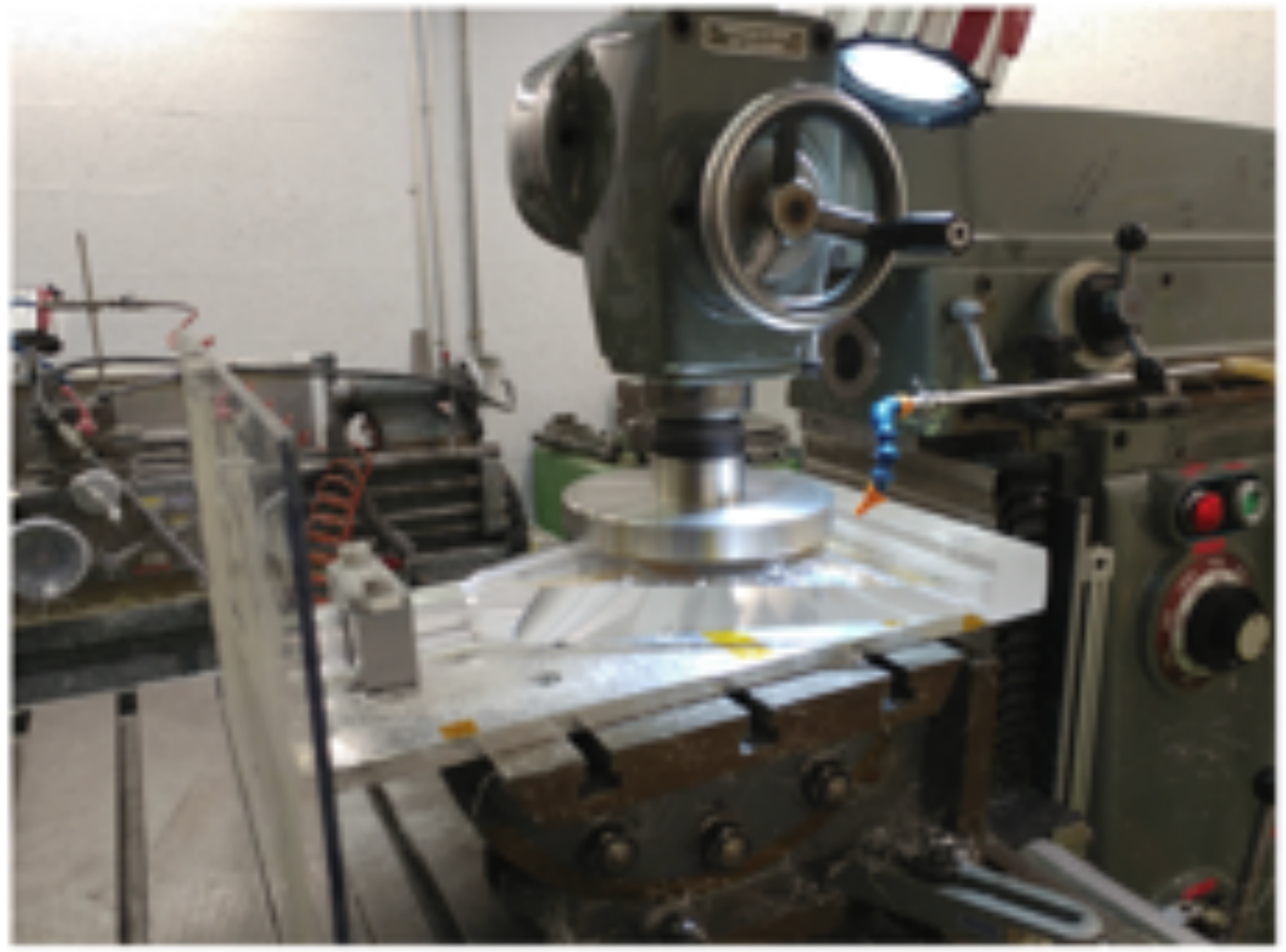
Scintillators

- Last time from Sebastian…



Scintillators | Construction

- Many thanks to the CERN scintillator lab for producing the scintillators and light guides.
- Use cosmic muons to measure the scintillator response & inefficiency • Efficiency >99.9% measured – Within specification

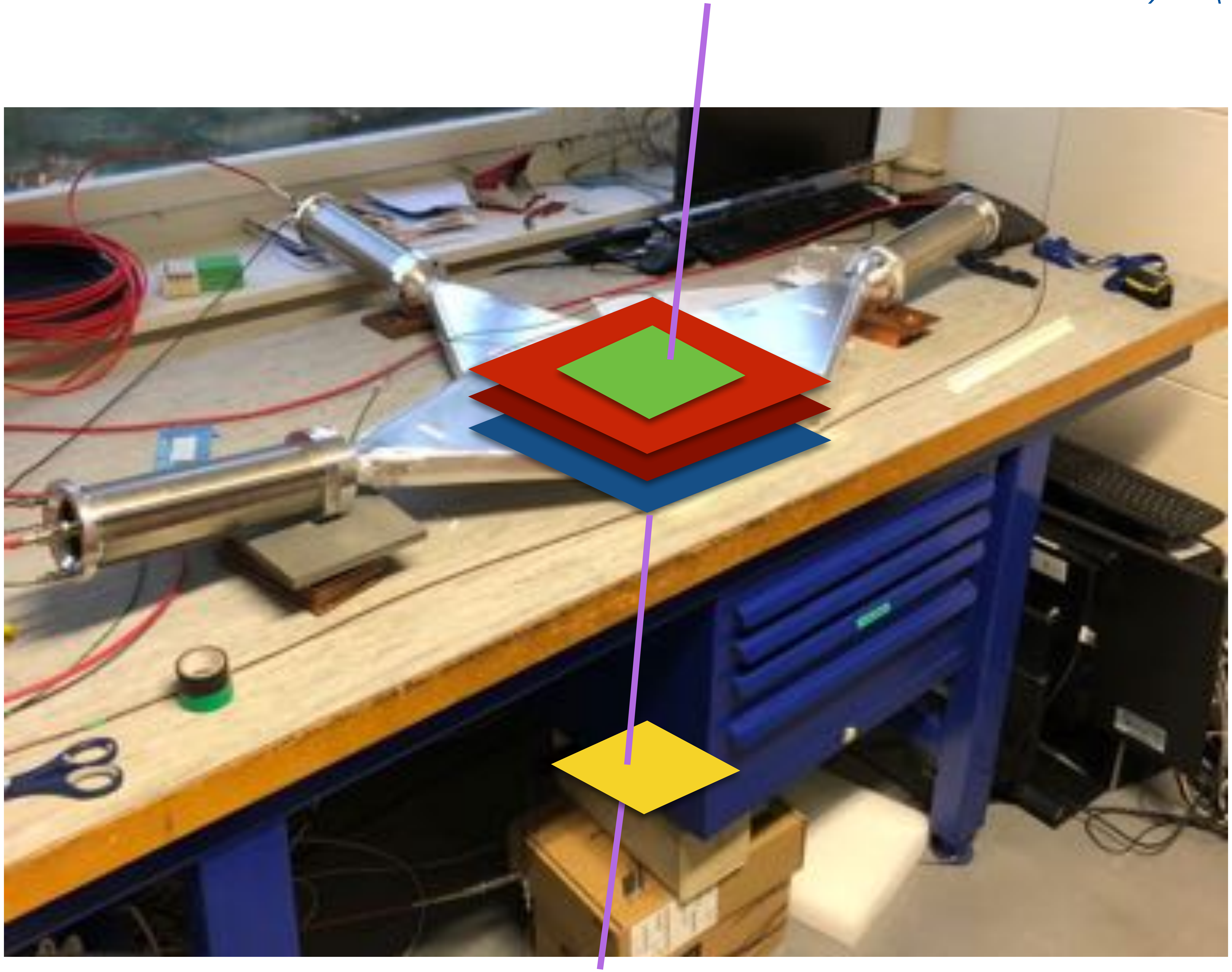


Scintillators | Characterisation

- Use cosmic muons to measure the scintillator response & inefficiency

Scintillator | Characterisation

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



Scintillator | Characterisation

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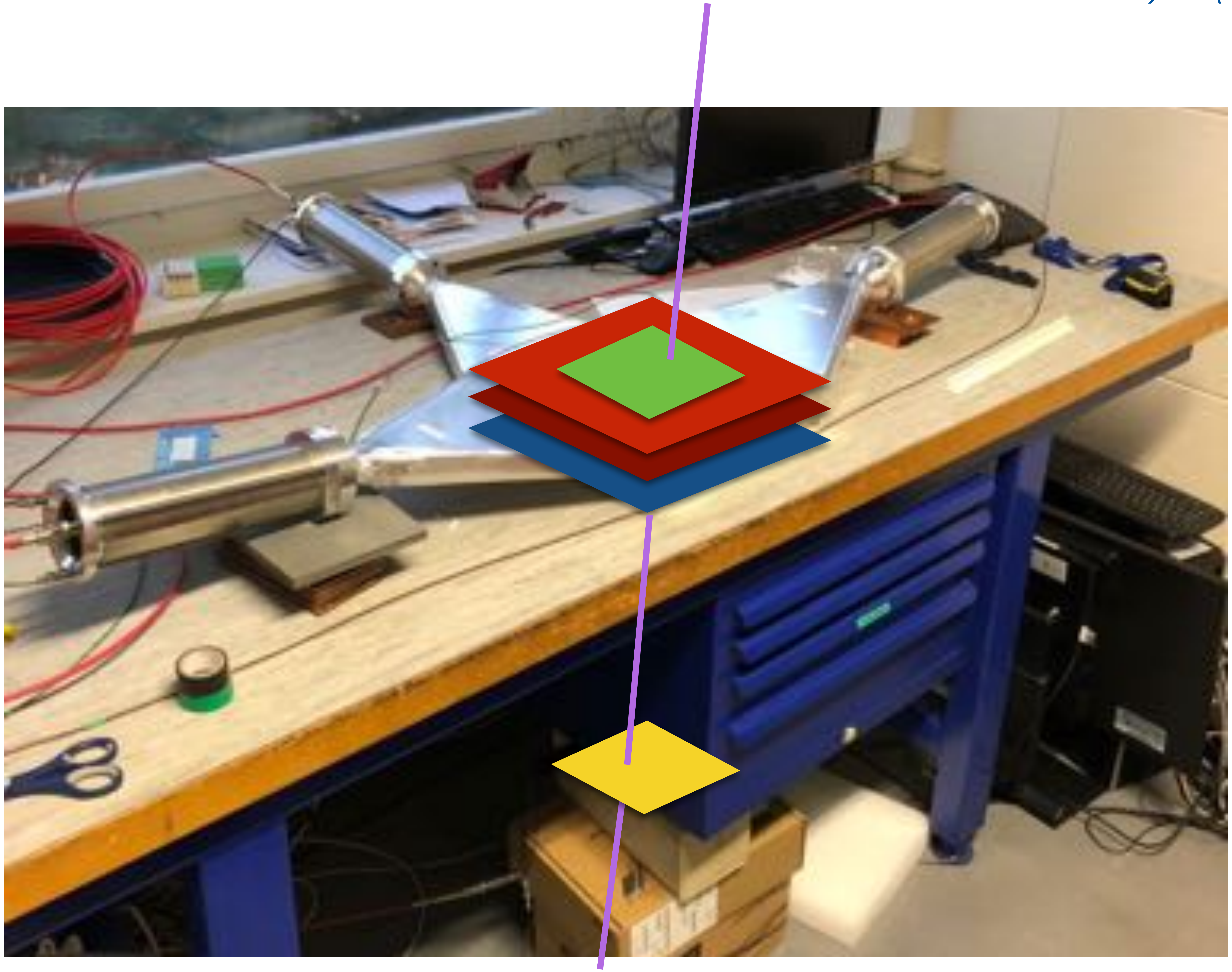
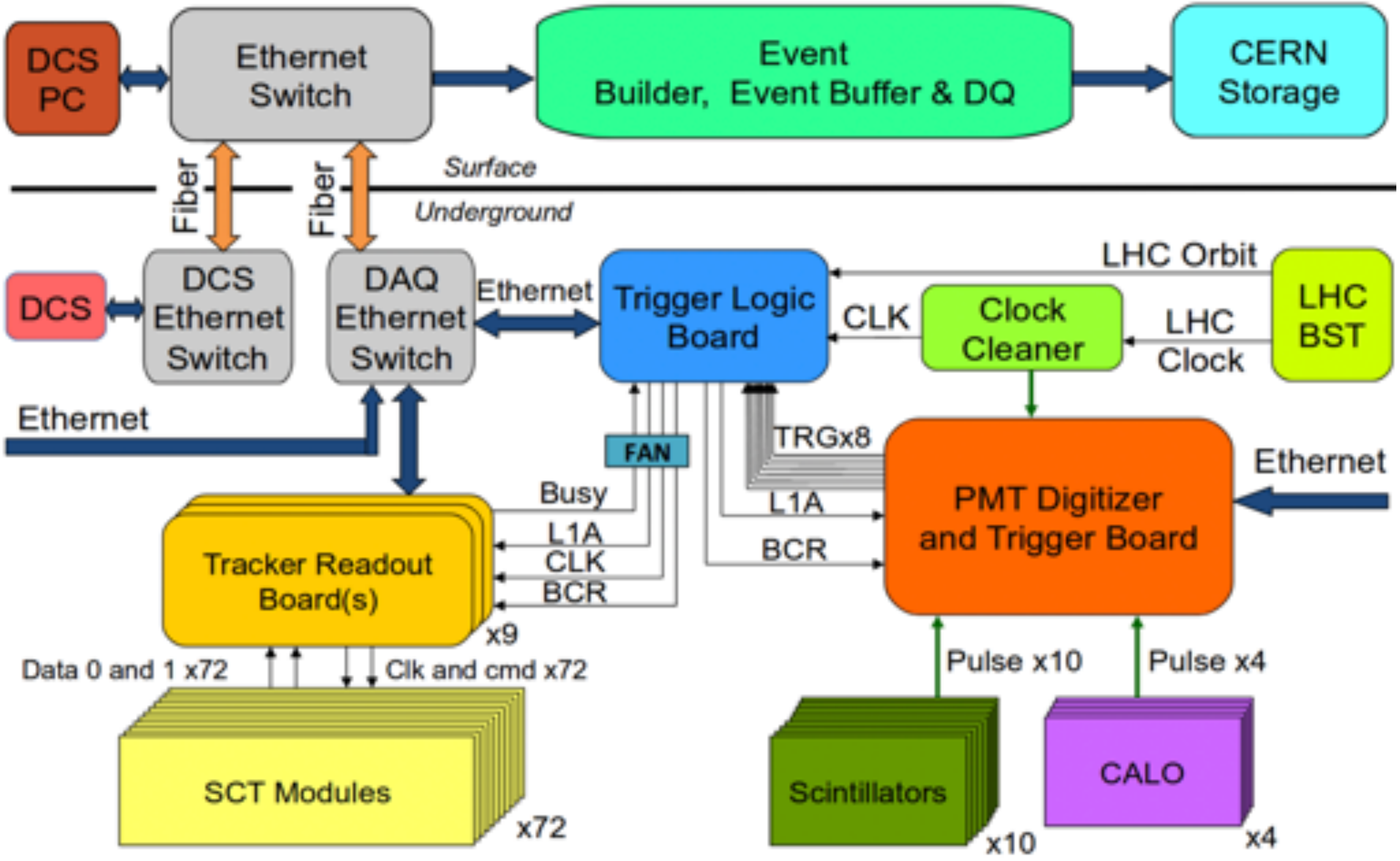
  - Within specification



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)
- Trigger Logic Board is same general purpose FPGA board as Tracker Readout Board but with different firmware/adapter-card.
- 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

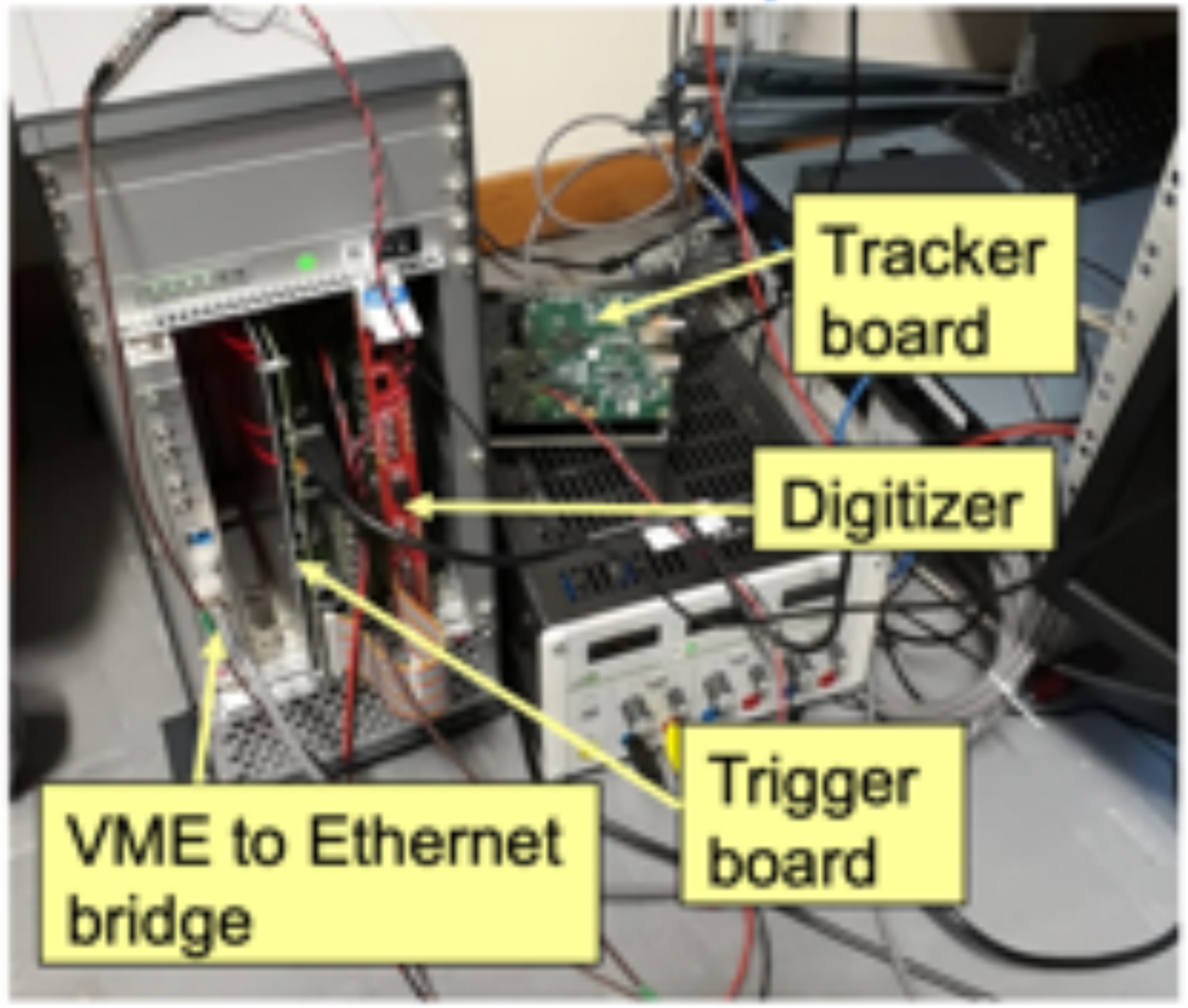
TDAQ | Schematic



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

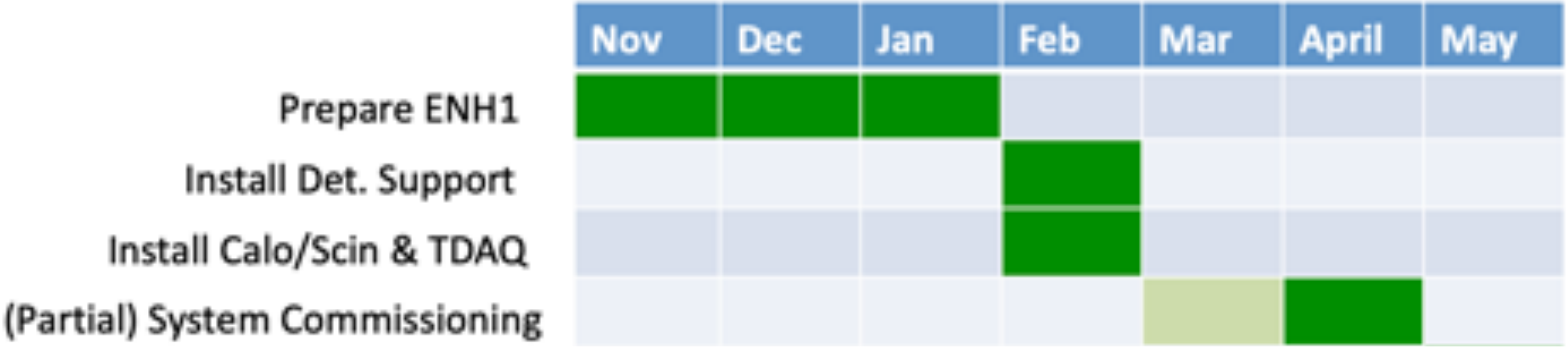
TDAQ test setup



Web-based run-control

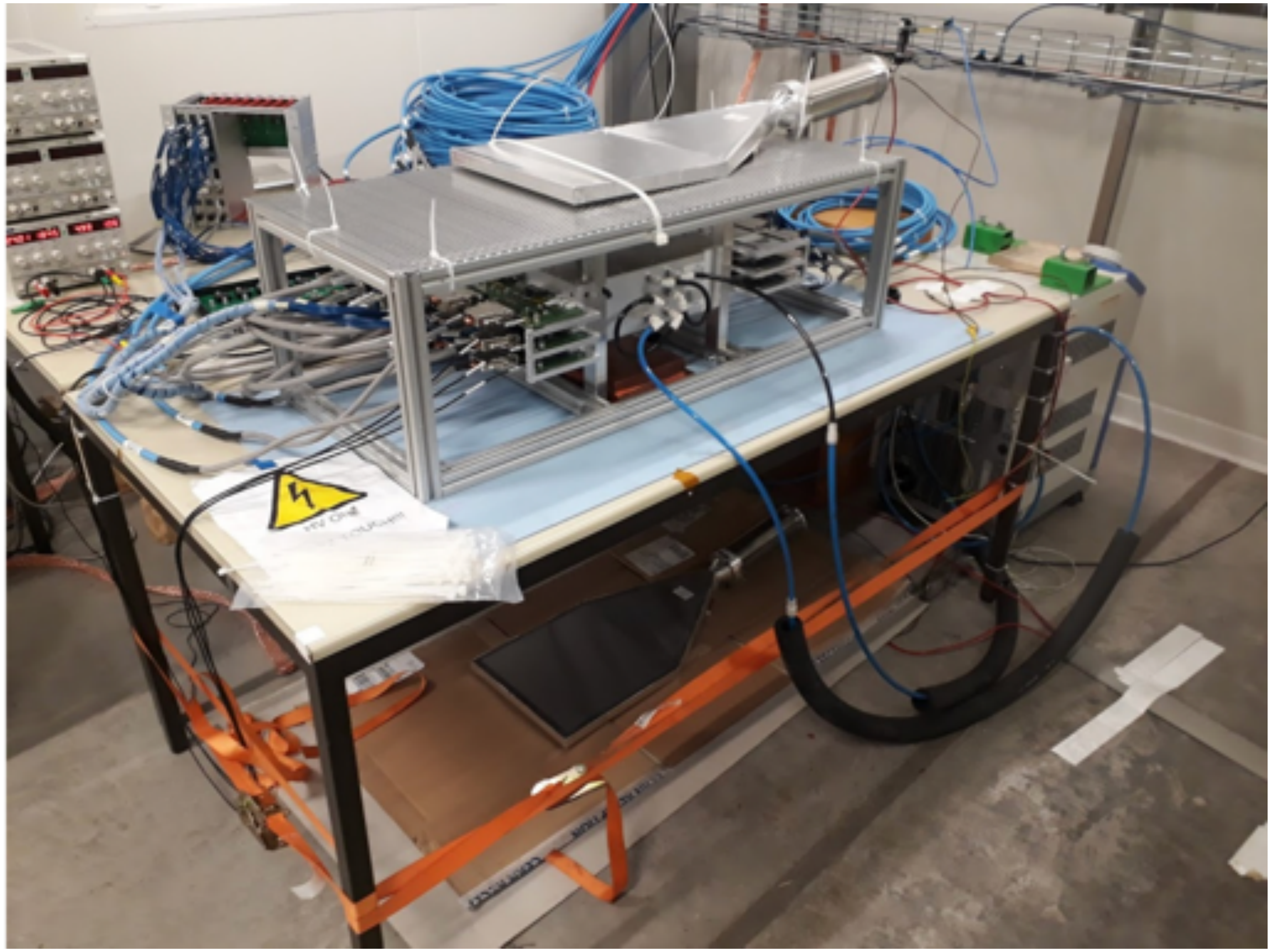
Overground testing

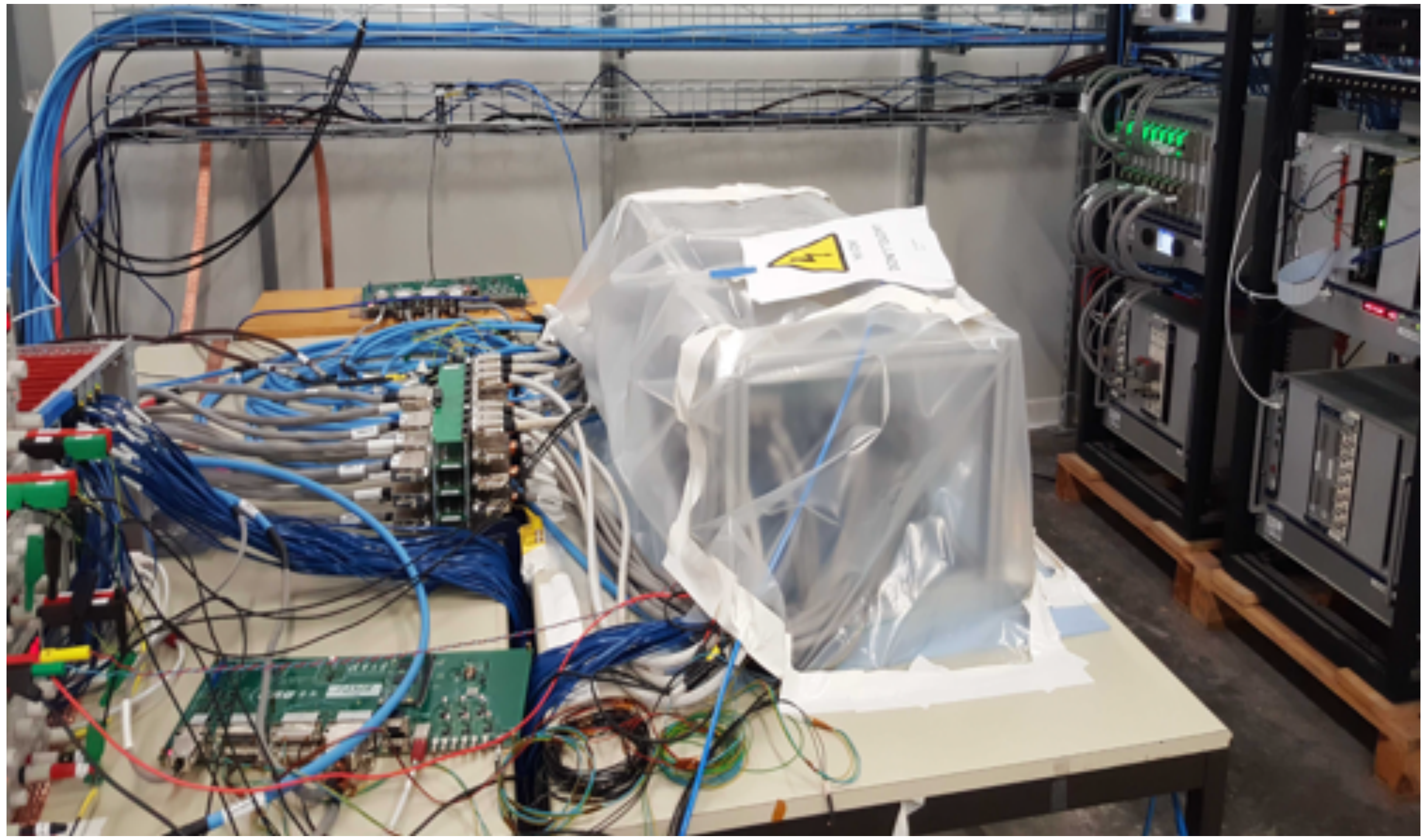
- Have space at CERN Prevessin site (same building as Neutrino Platform)
- Used for dry run above ground
  - Assembly took place in Feb-April 2020
    - Test mechanical assembly
  - Commissioning from March 2020
    - Detector installation
    - Alignment procedures
    - Cabling
    - Cooling
    -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



Overground testing | Tracker

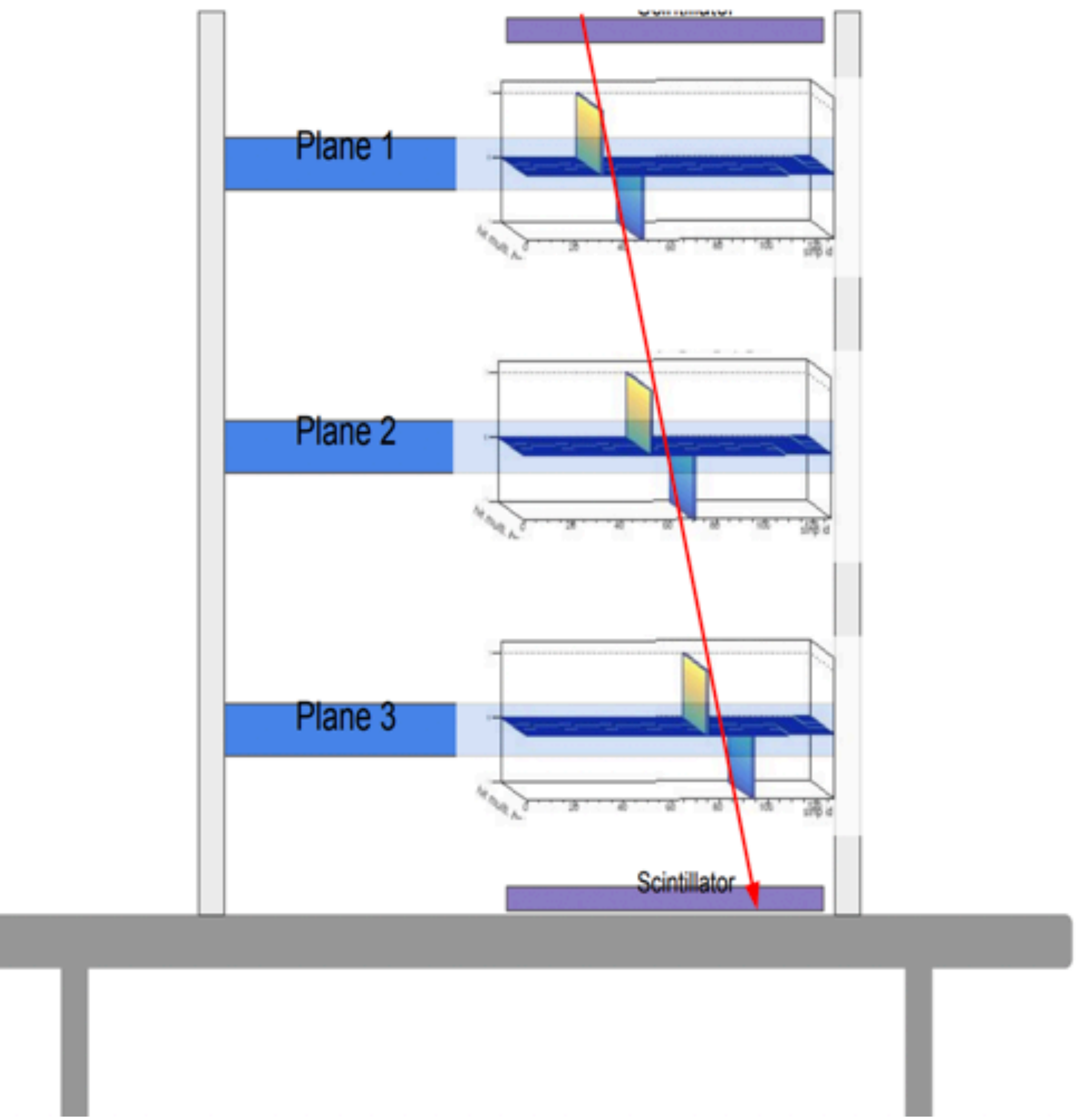
- Cosmic data taking with station on its side, and a scintillator on top/btm.
- Use full FASER TDAQ system to take data.
  - Operational experience
  - Tracker efficiency, resolution and alignment studies
  - Offline s/w debugging

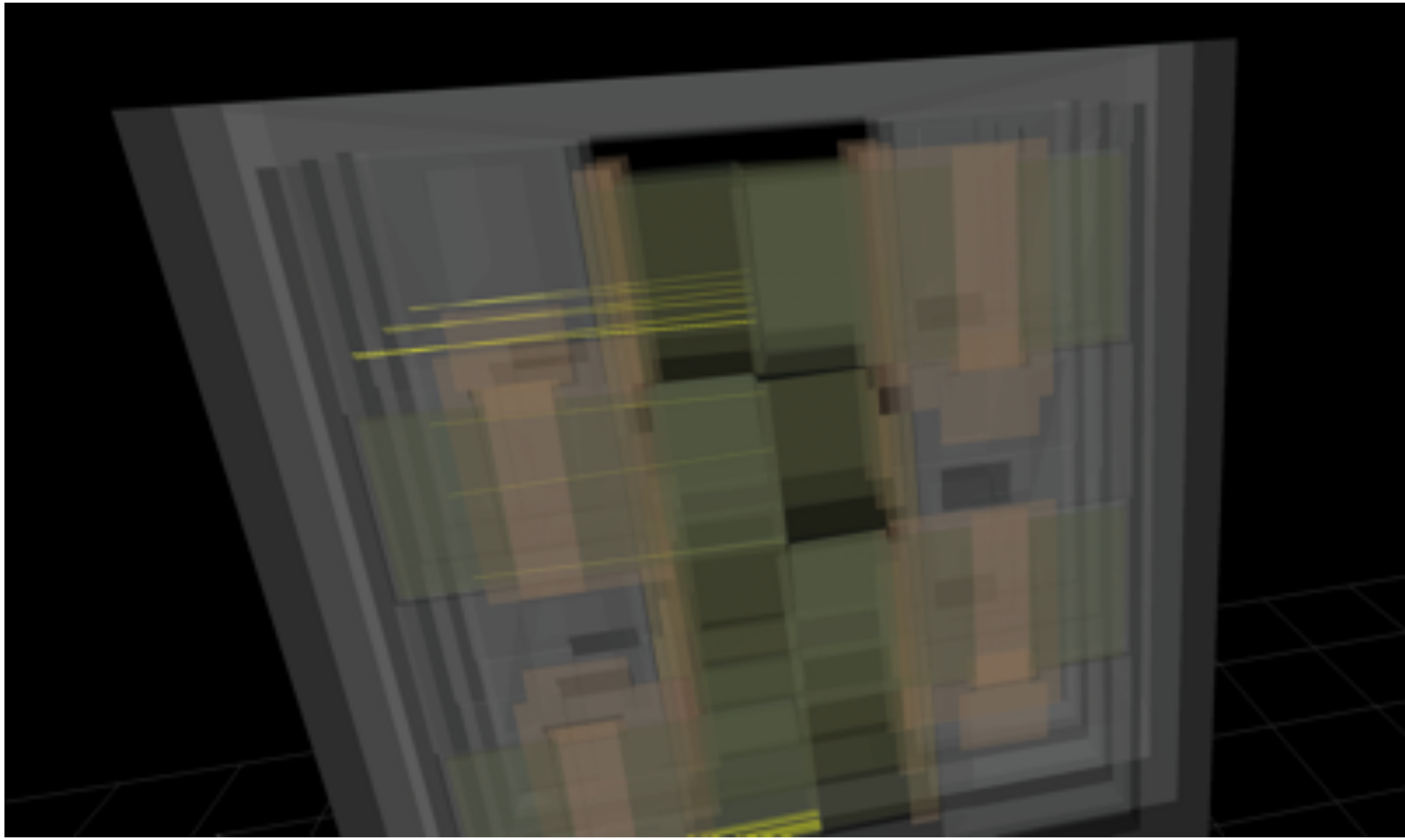




Overground testing | Tracker

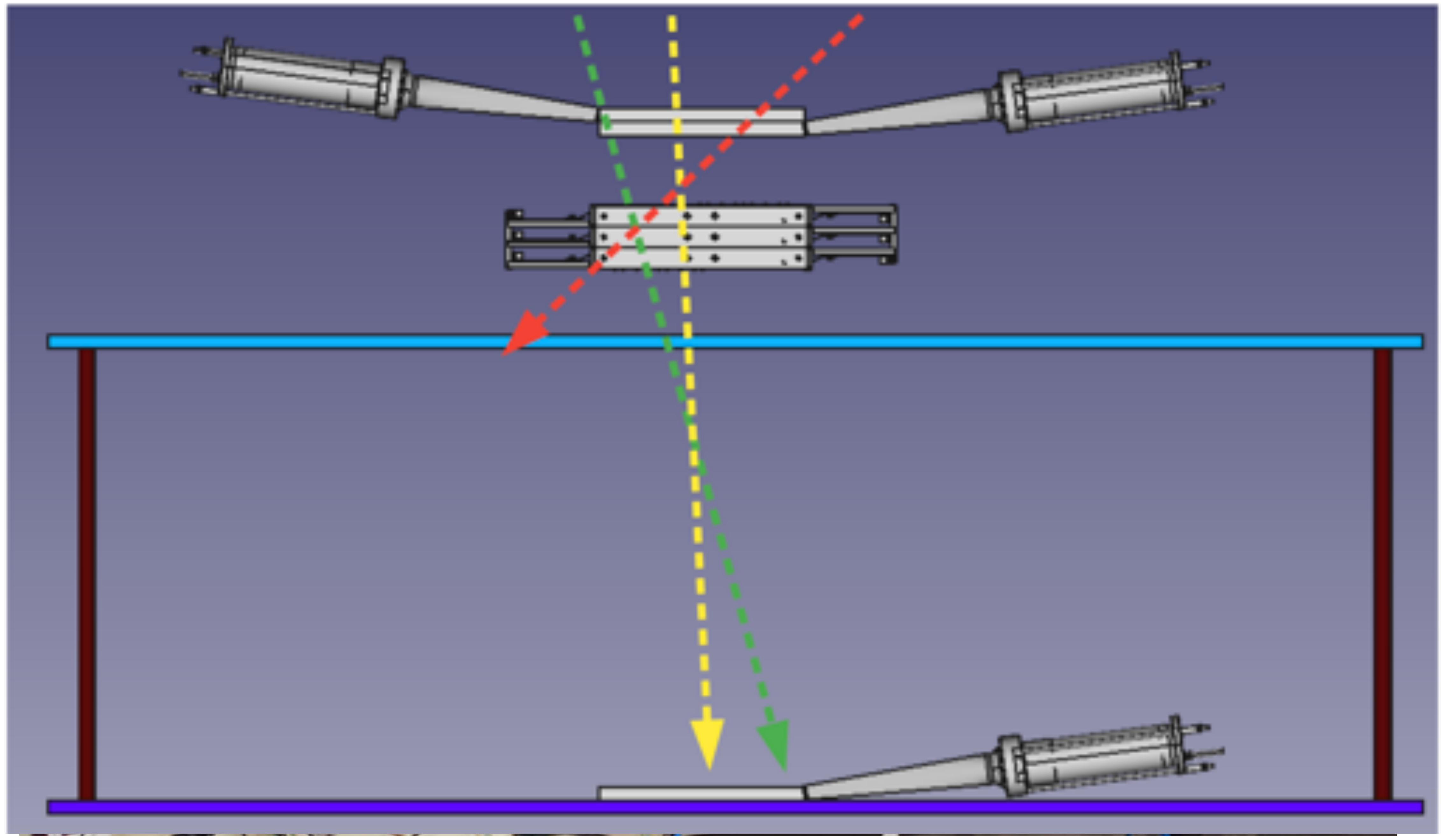
- Straight track candidate along with event display:

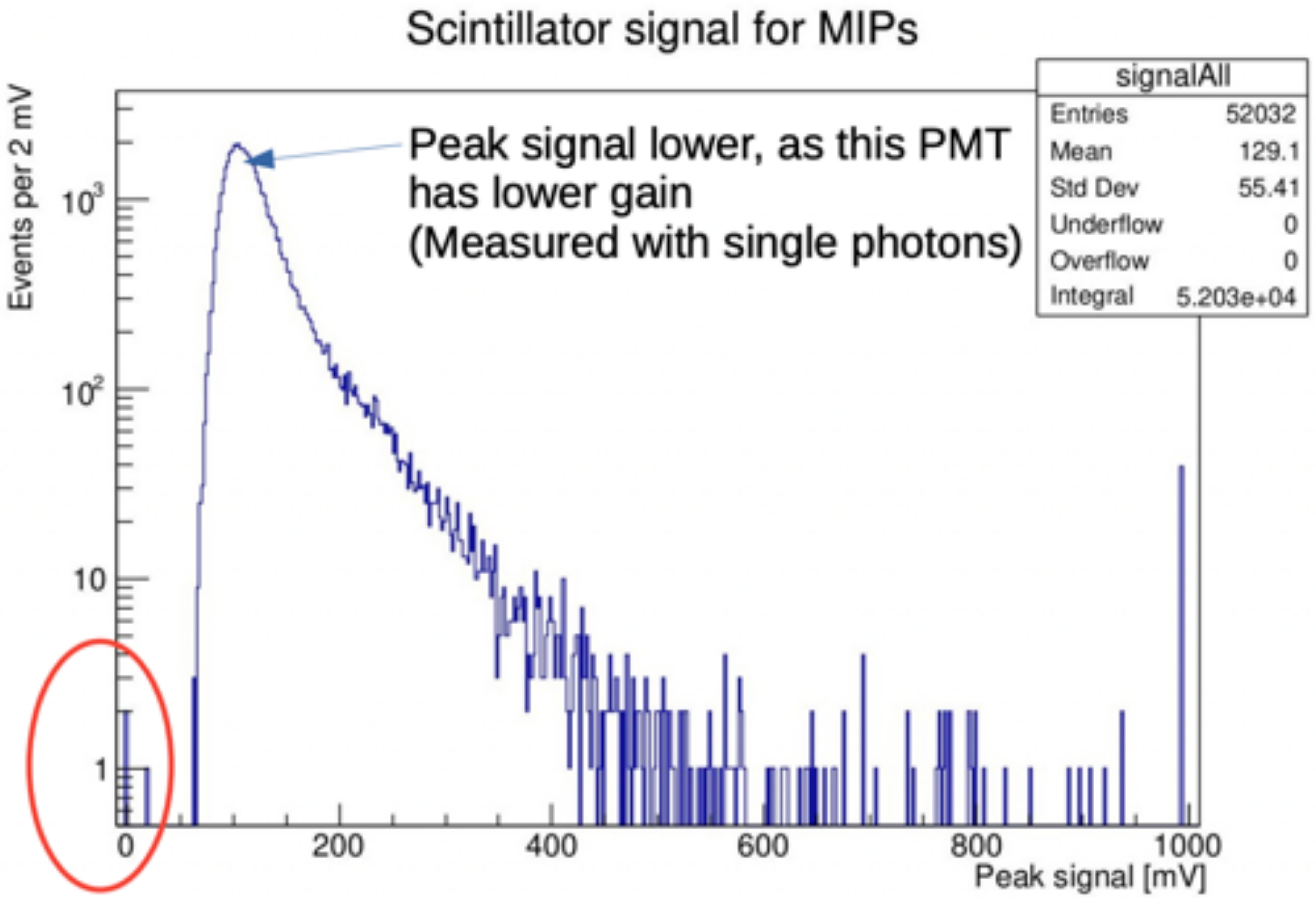




Overground testing | Scintillator

- Also used this data to study the scintillator performance
- Cosmics confirmed by tracker station provides cleaner single track sample
  - After long run only 3 tracks with low signal
    - Efficiency is [99.985:99.998]% at 95% CL





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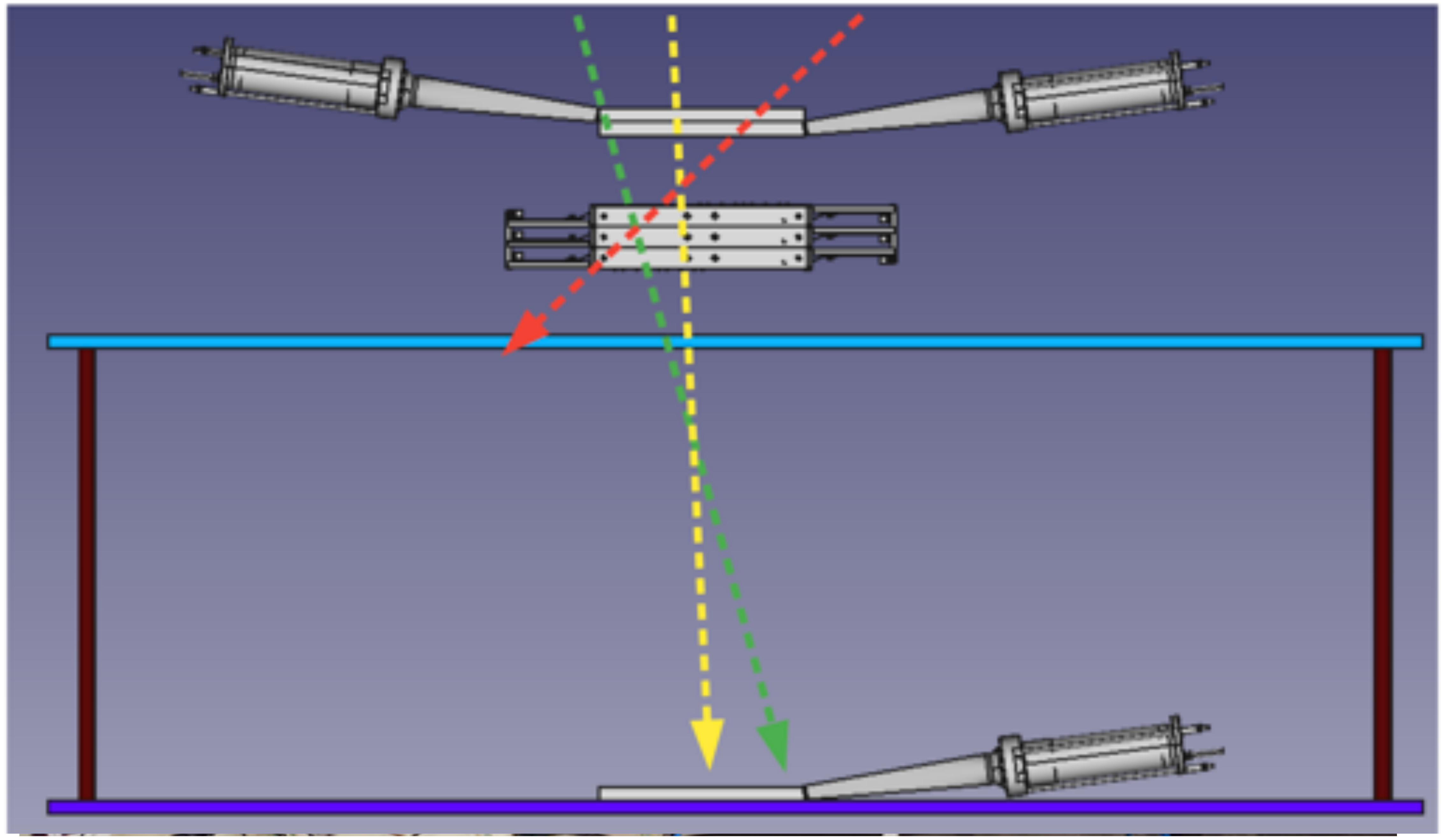
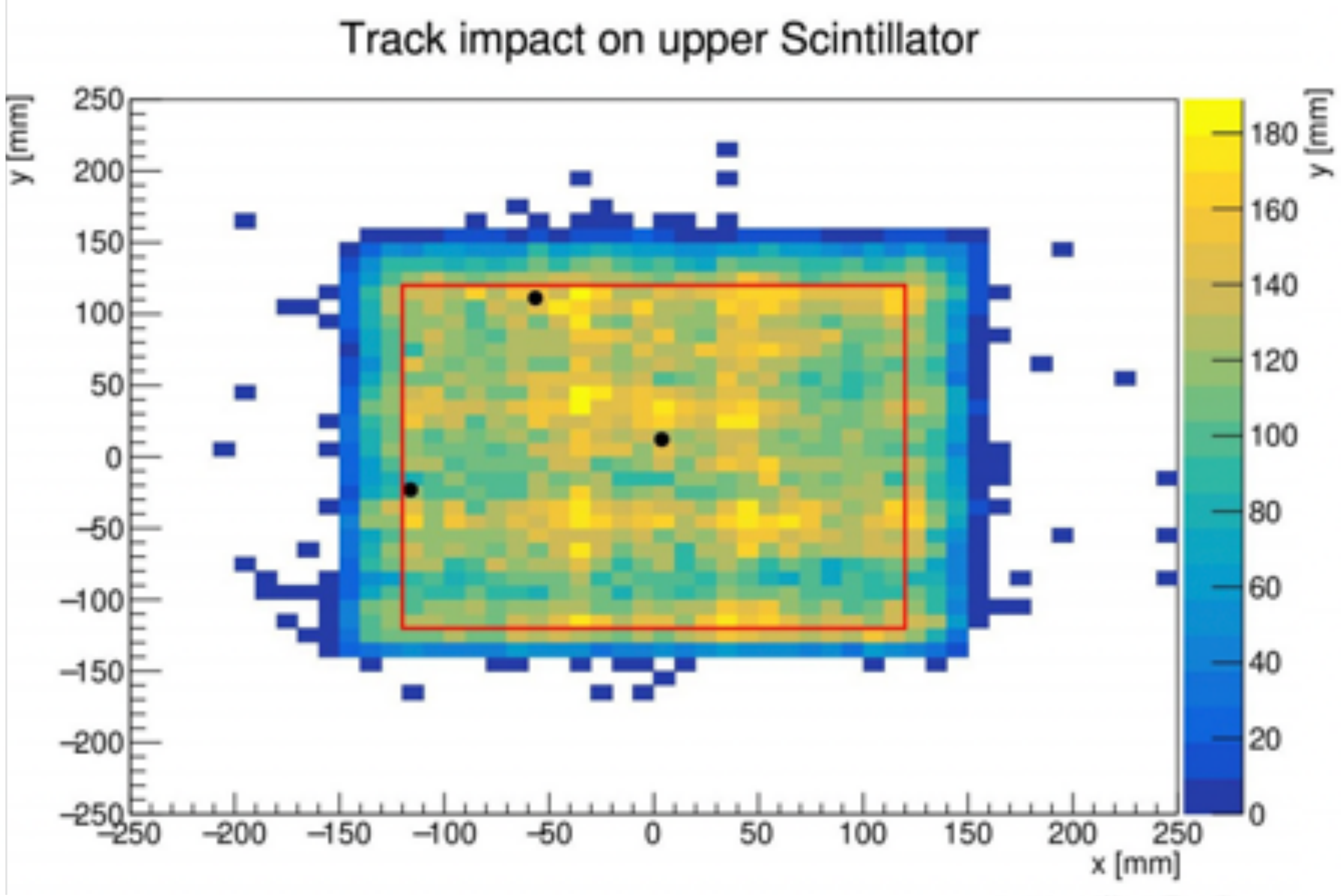
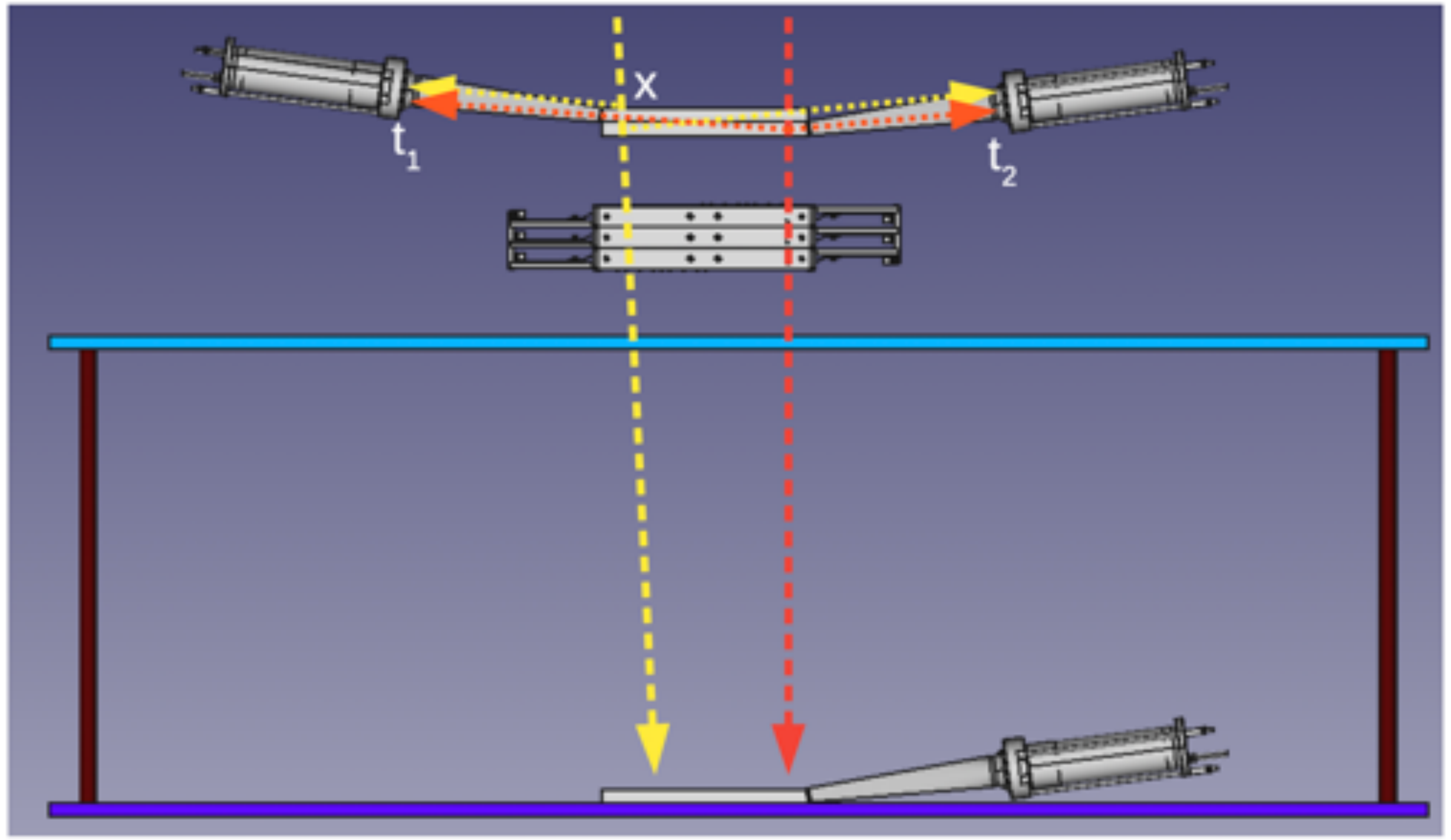
- Cosmics confirmed by tracker station provides cleaner single track sample
  - After long run only 3 tracks with low signal
    - Efficiency is [99.985:99.998]% at 95% CL
  - 2/3 tracks close to scintillator edge.



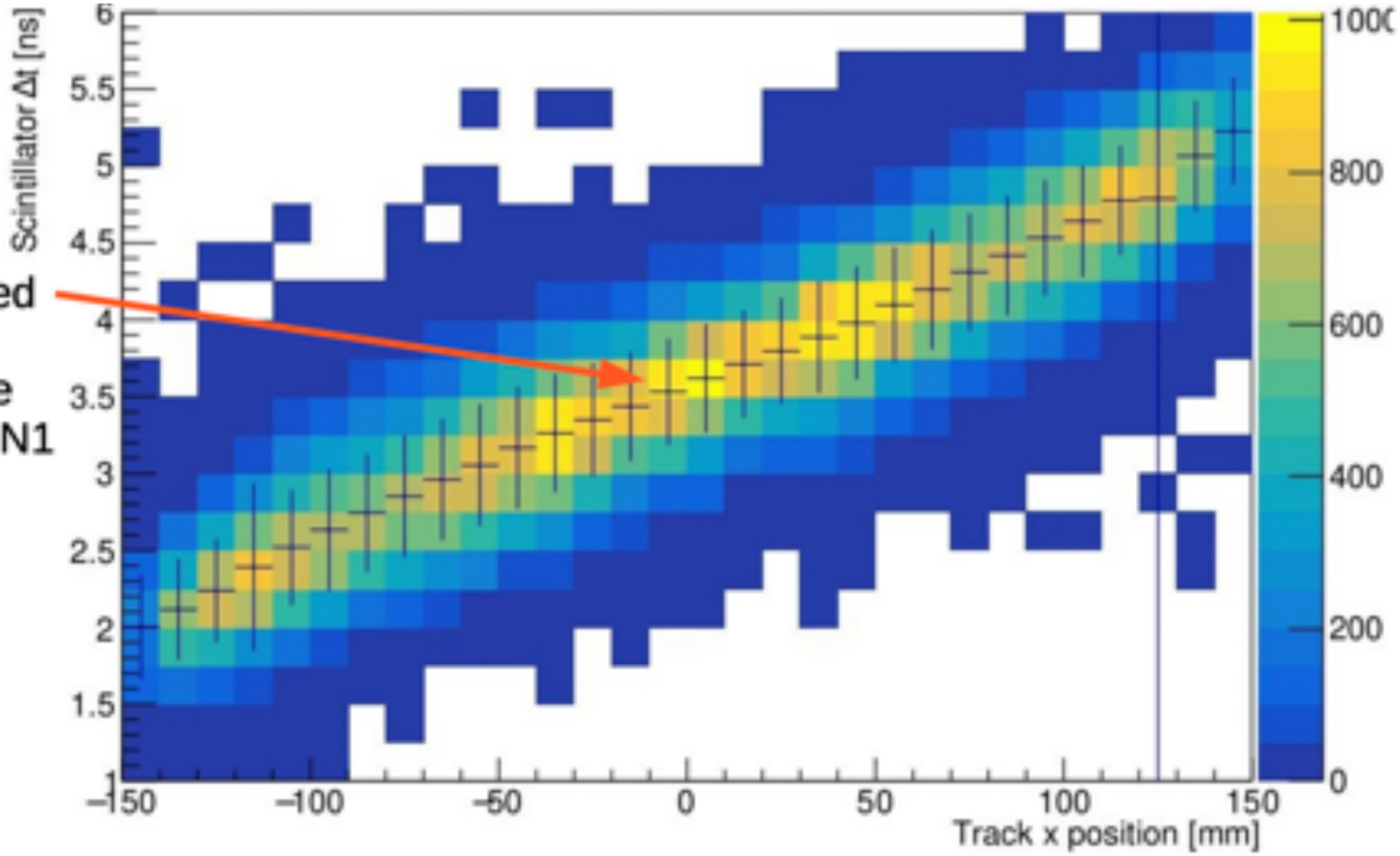


Overground testing | Scintillator

- 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.

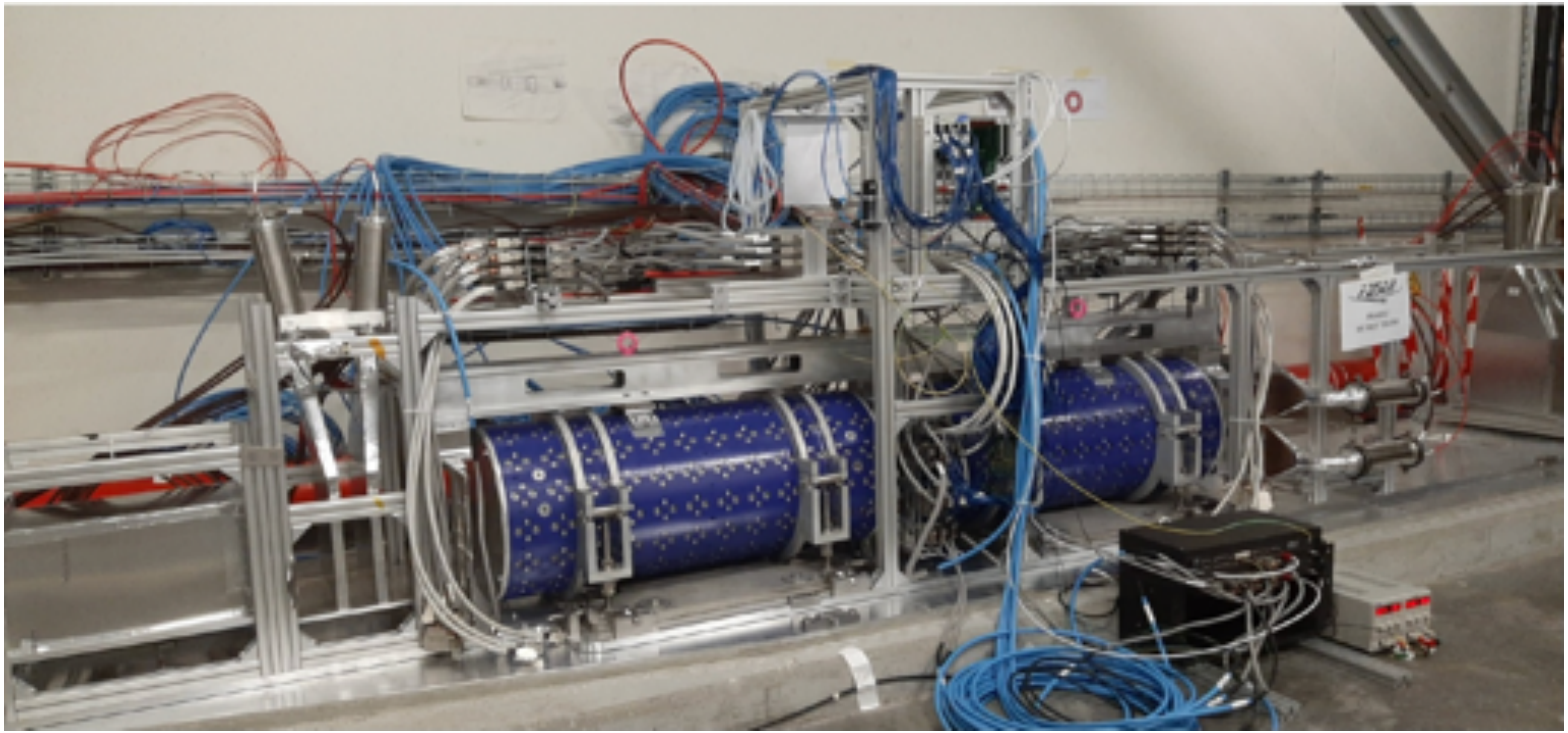


Δt not centered at 0ns due to different cable lengths in EHN1 test setup



Commissioning | Overground

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



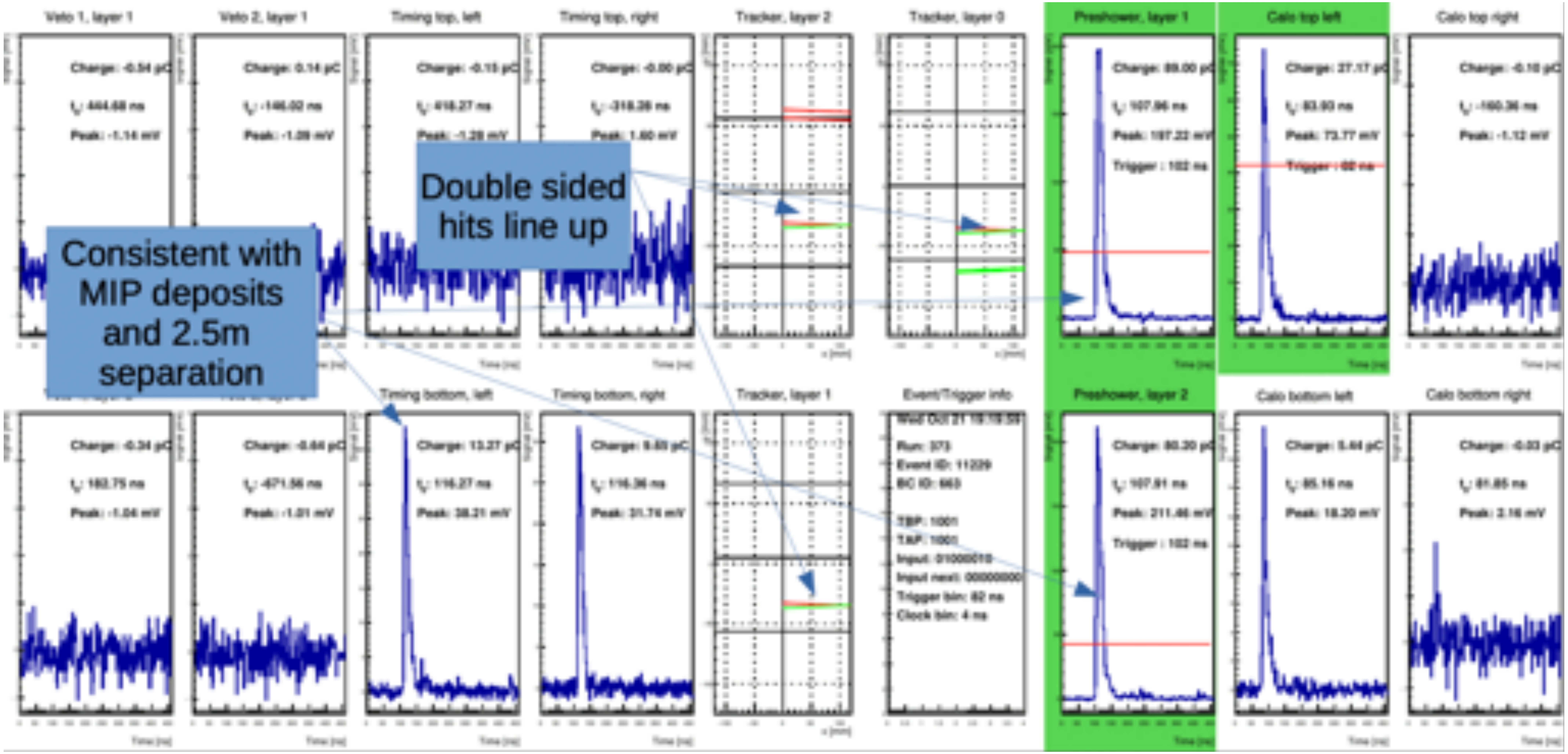
Commissioning | Overground

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

- In just one week before disassembly started:
  - Common clock provided by Technion clock card (40.08 MHz)
  - Triggering on cosmic showers/random triggers
  - Reading out full detector
  - Tracker readout-timed in with respect to trigger signals
  - Ran with FASER DAQ system, run control GUI and monitoring
  - Data recorded to local disk and copied to EOS

Commissioning | Overground

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

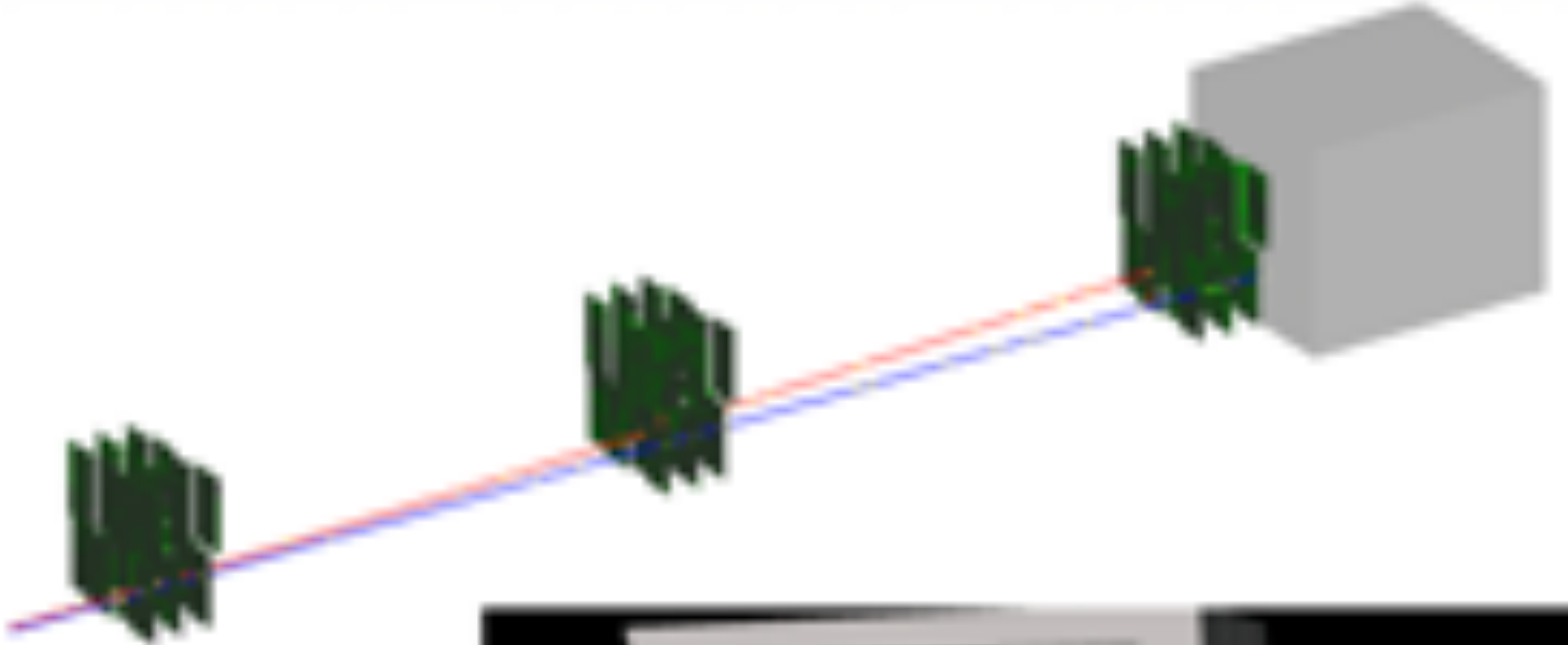


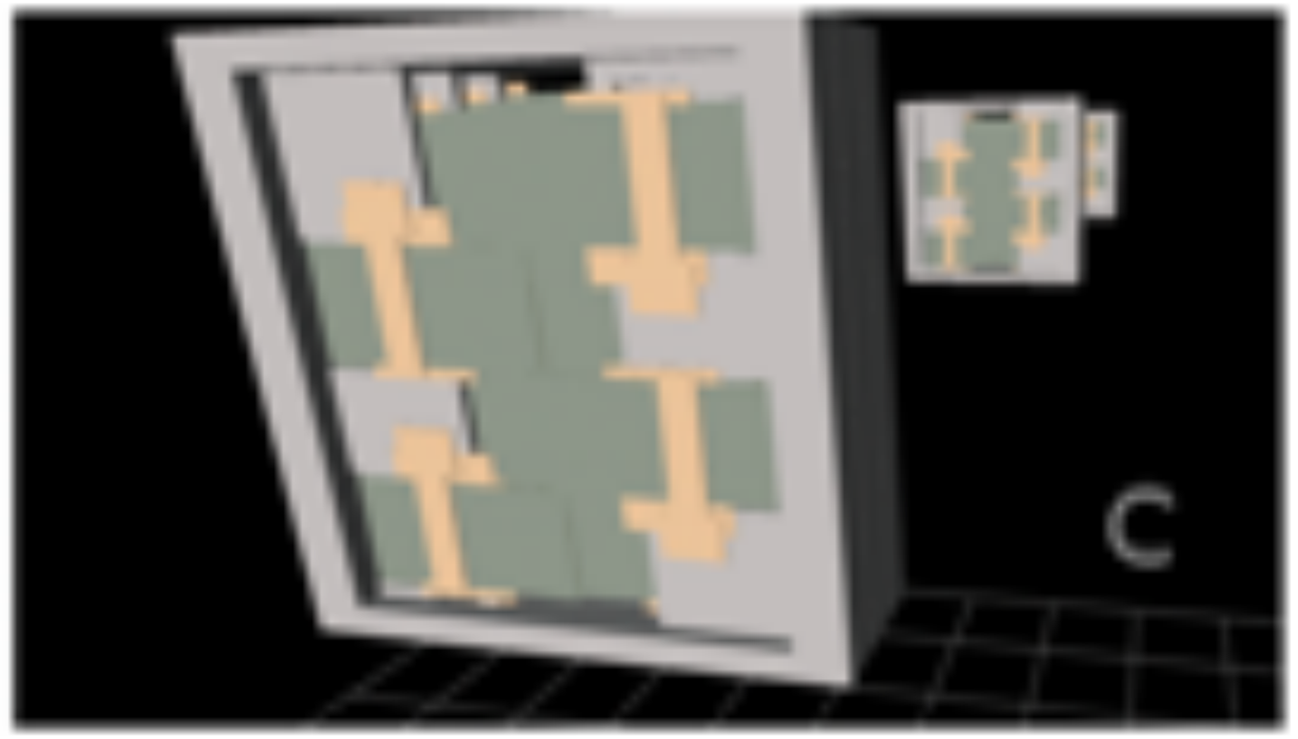
Commissioning | Overground

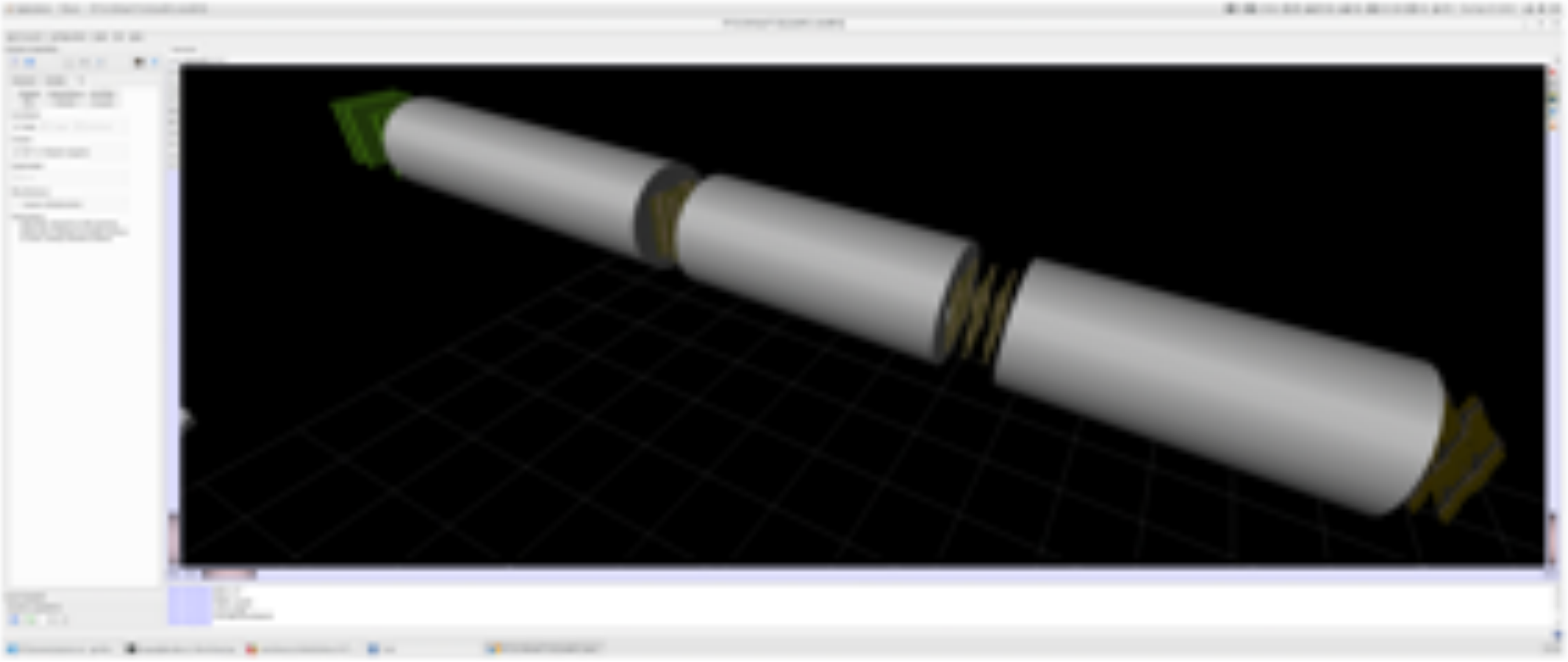
- Simple online event display in progress:

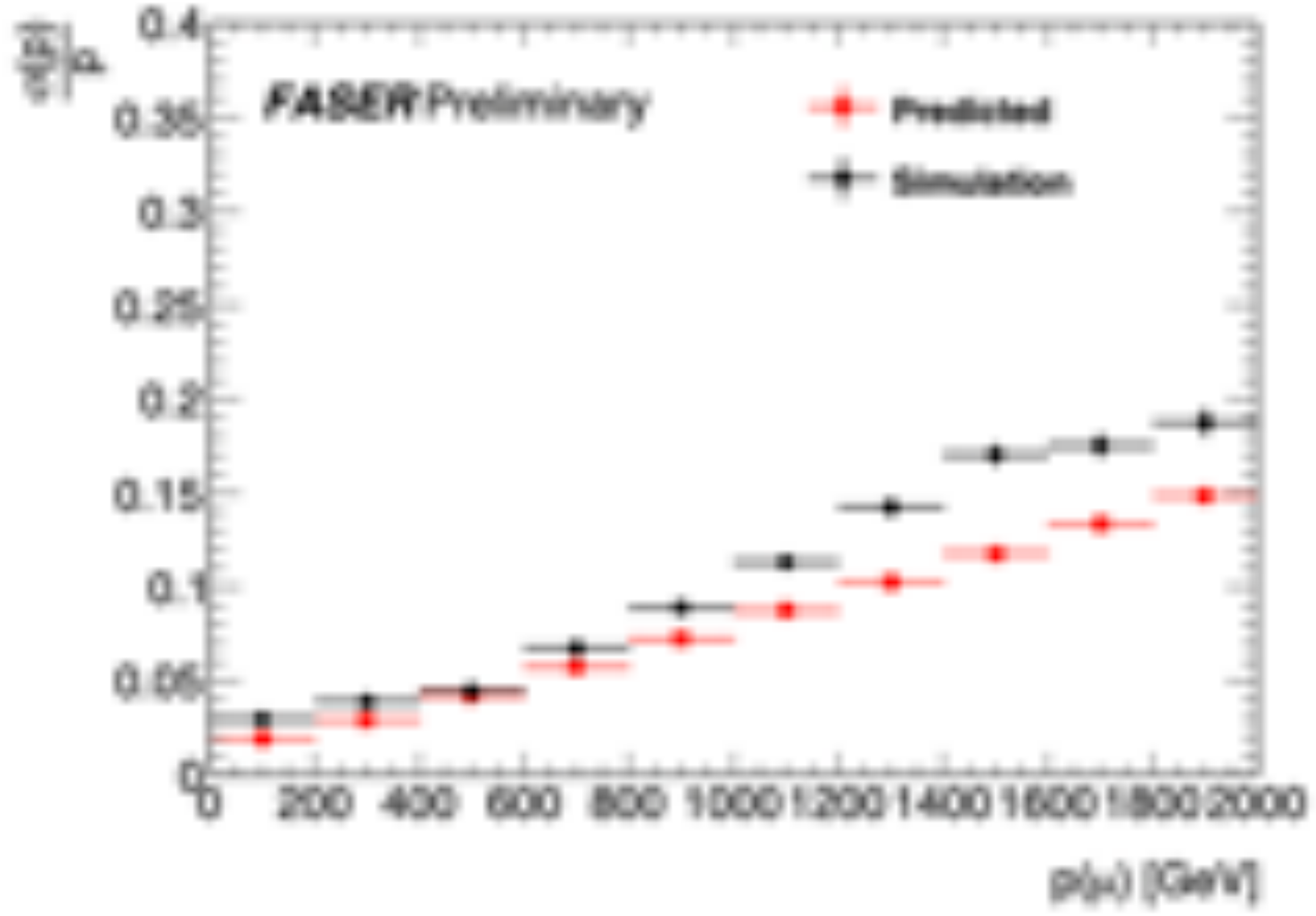
Offline software and Simulation

- 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





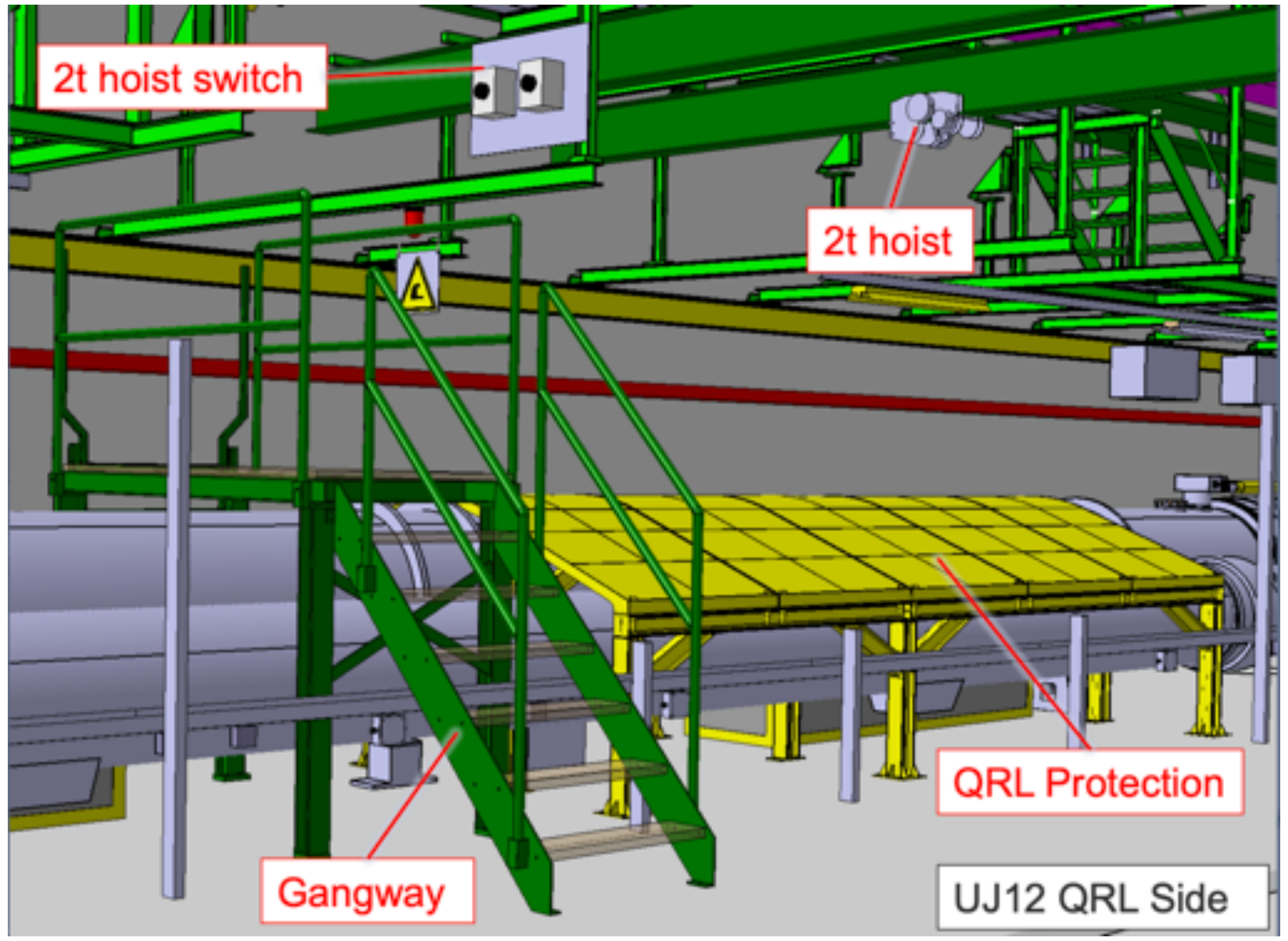


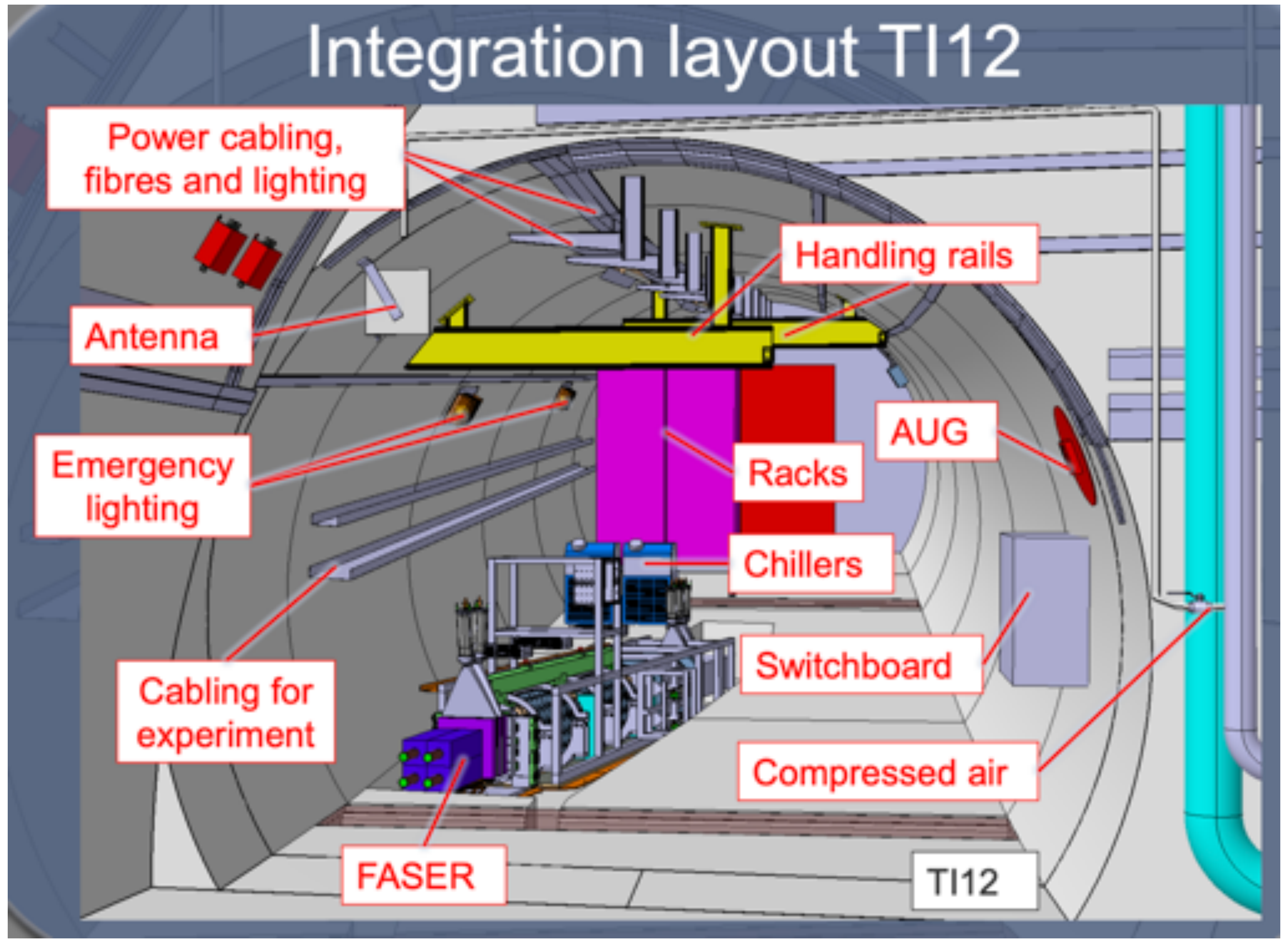


Underground preparations

Preparation for FASER

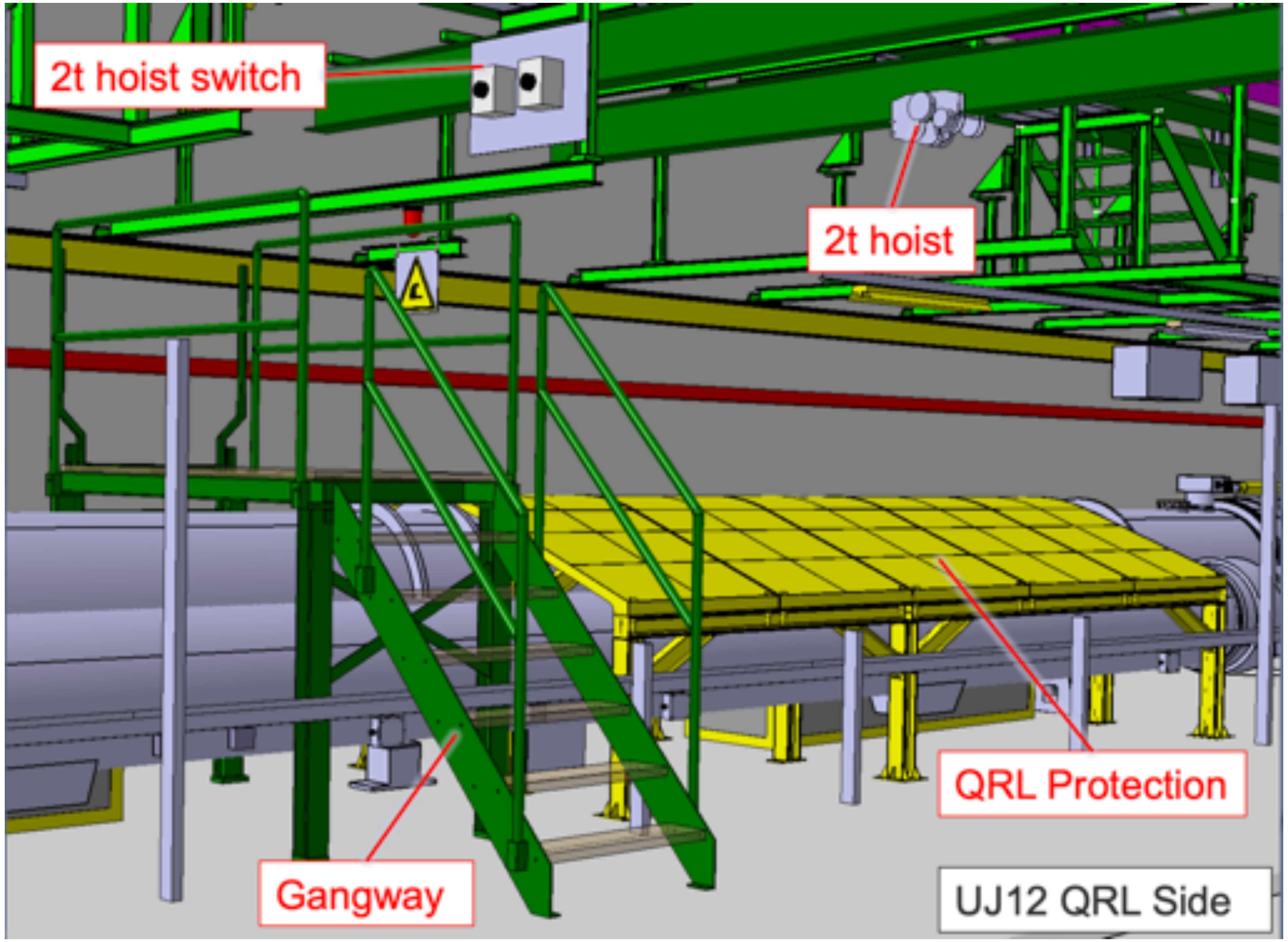
- Civil engineering work in TI12 to allow FASER installation finished on schedule, just before CERN shutdown!
- Significant cleanup work in TI12 before digging could begin.
- Many constraints in planning this:
  - Strong requirement on no dust in the LHC during LS2
  - Little available time for doing 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**



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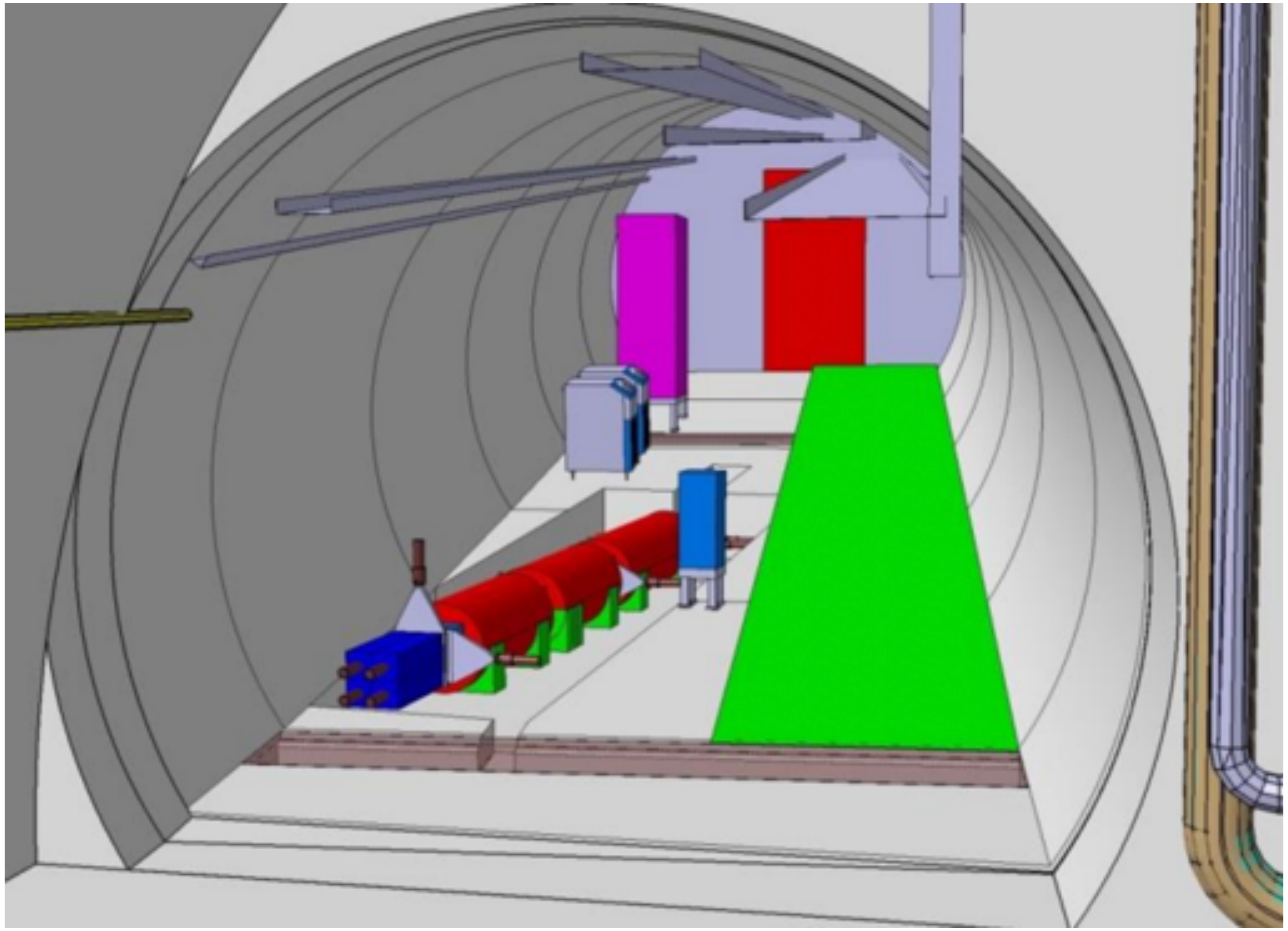
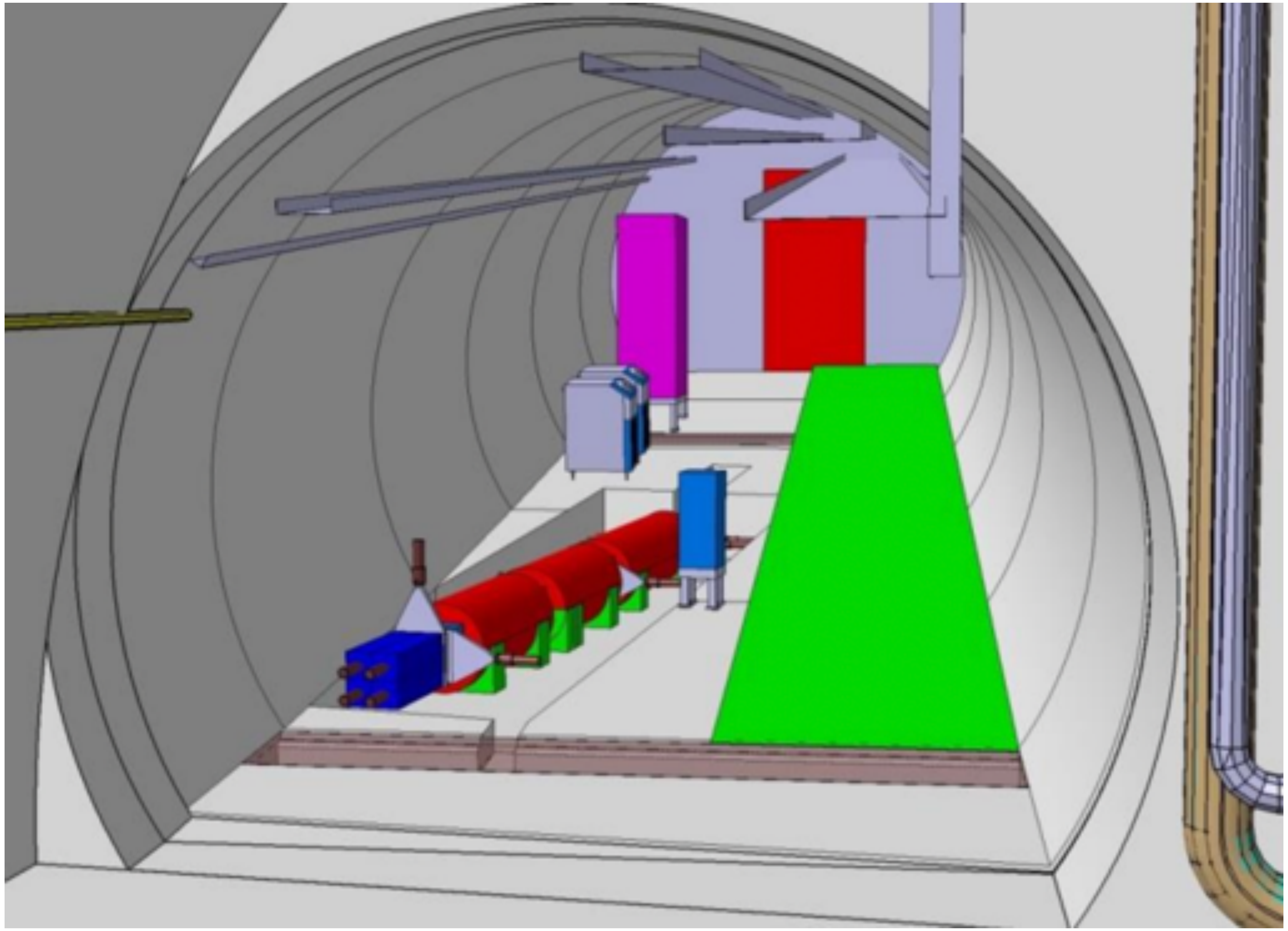
Preparation of TI12

- Last time from Sebastian…



Preparation of TI12

- Main work required
  - 50cm deep trench to get on LOS
  - Various infrastructure
    - Lights
    - Racks
    - Power
    - Network
  - Detector transport
  - Cooling Unit



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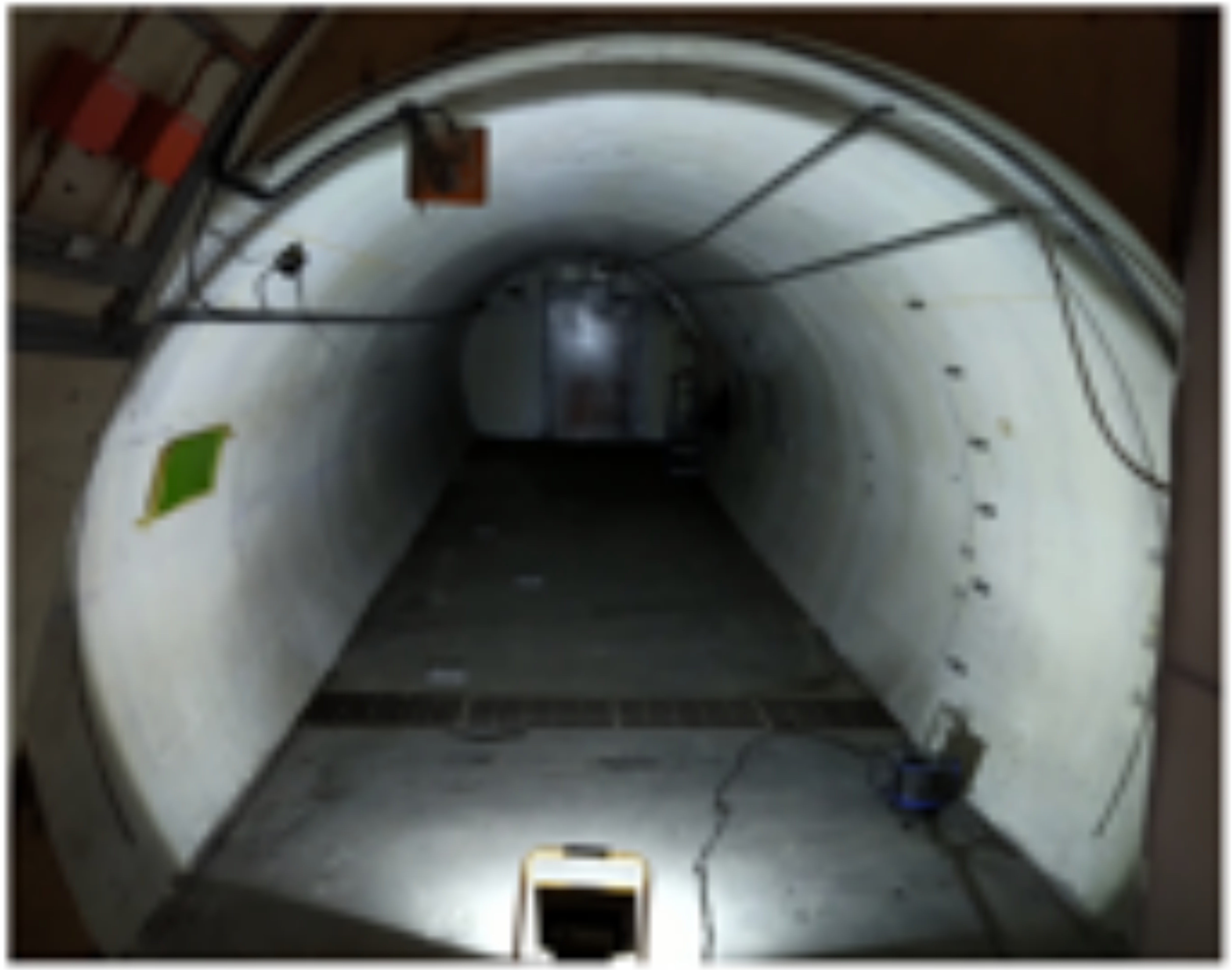

August 2019

Preparation of TI12

- Main work required
  - 50cm deep trench to
  - Various infrastructur
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    - Racks
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  - Detector transport
  - Cooling Unit

December 2019

Preparation of TI12

- Main work required
  - 50cm deep trench to get on LOS
  - Various infrastructure
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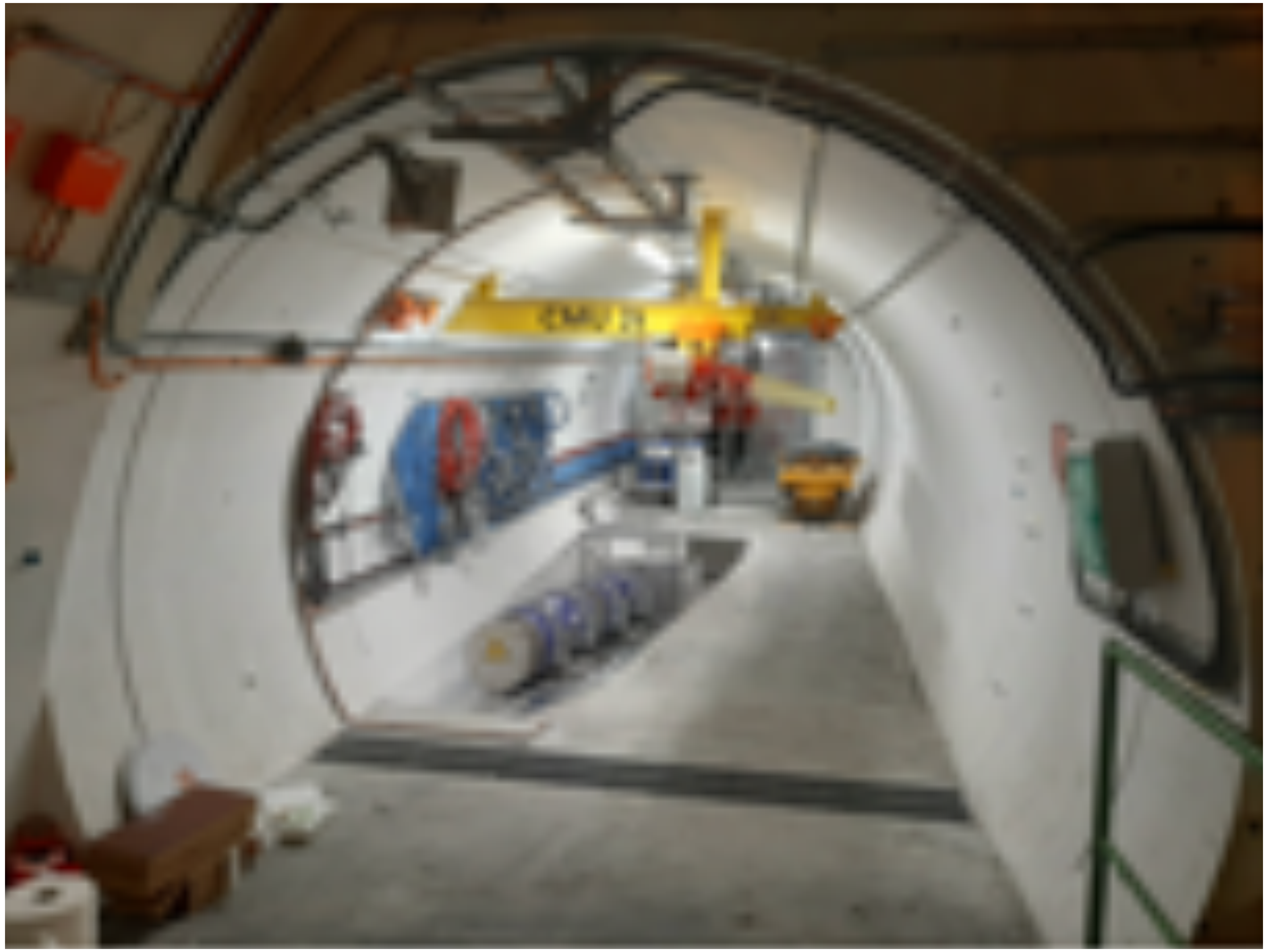
  - Cooling Unit

March 2020

Preparation of TI12

- Main
  - 50cn ... s
  - Vario
    - Ligh
    - Rack
    - Pow
    - Netv
  - Dete
  - Cool



March 2020

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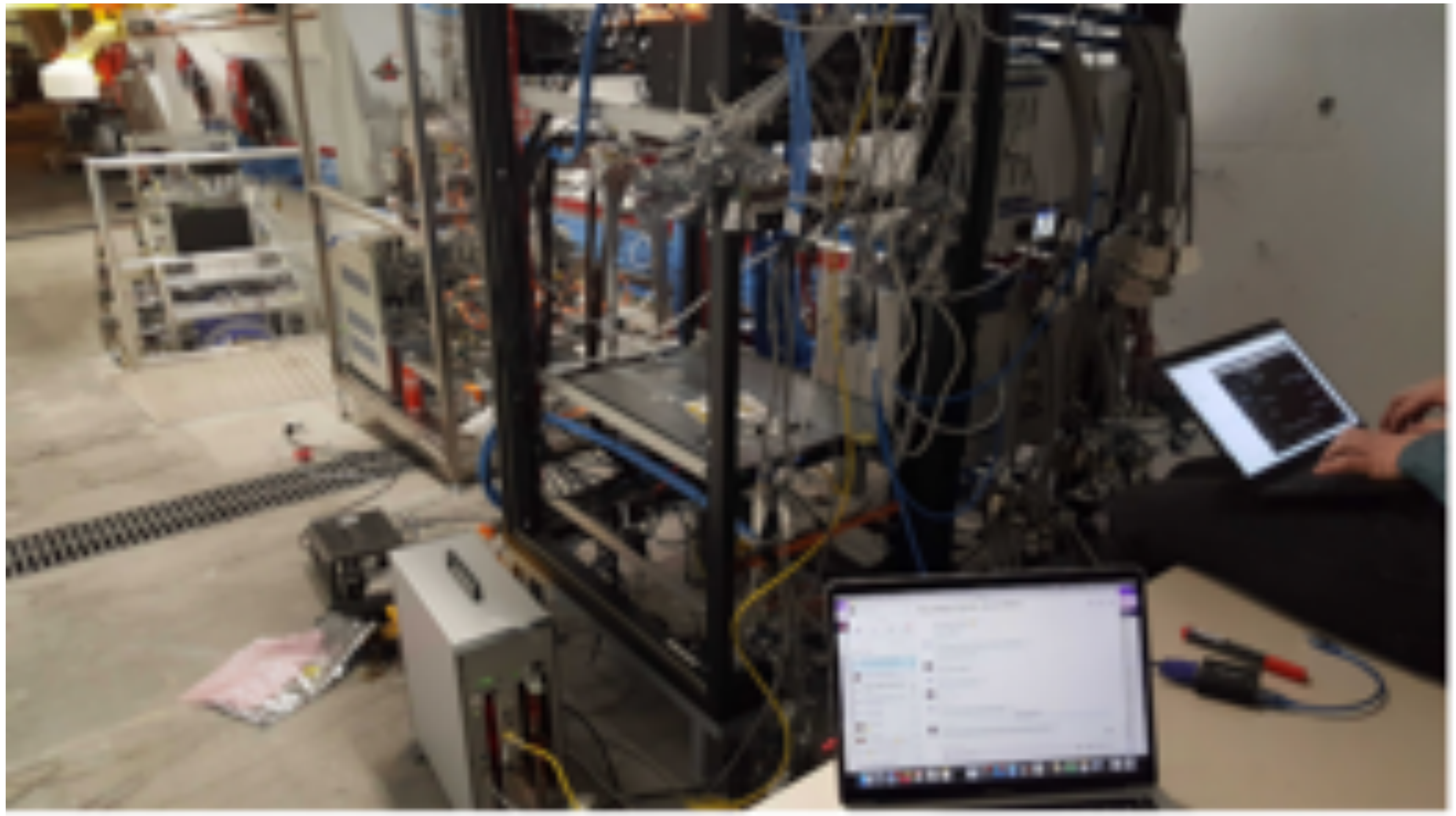
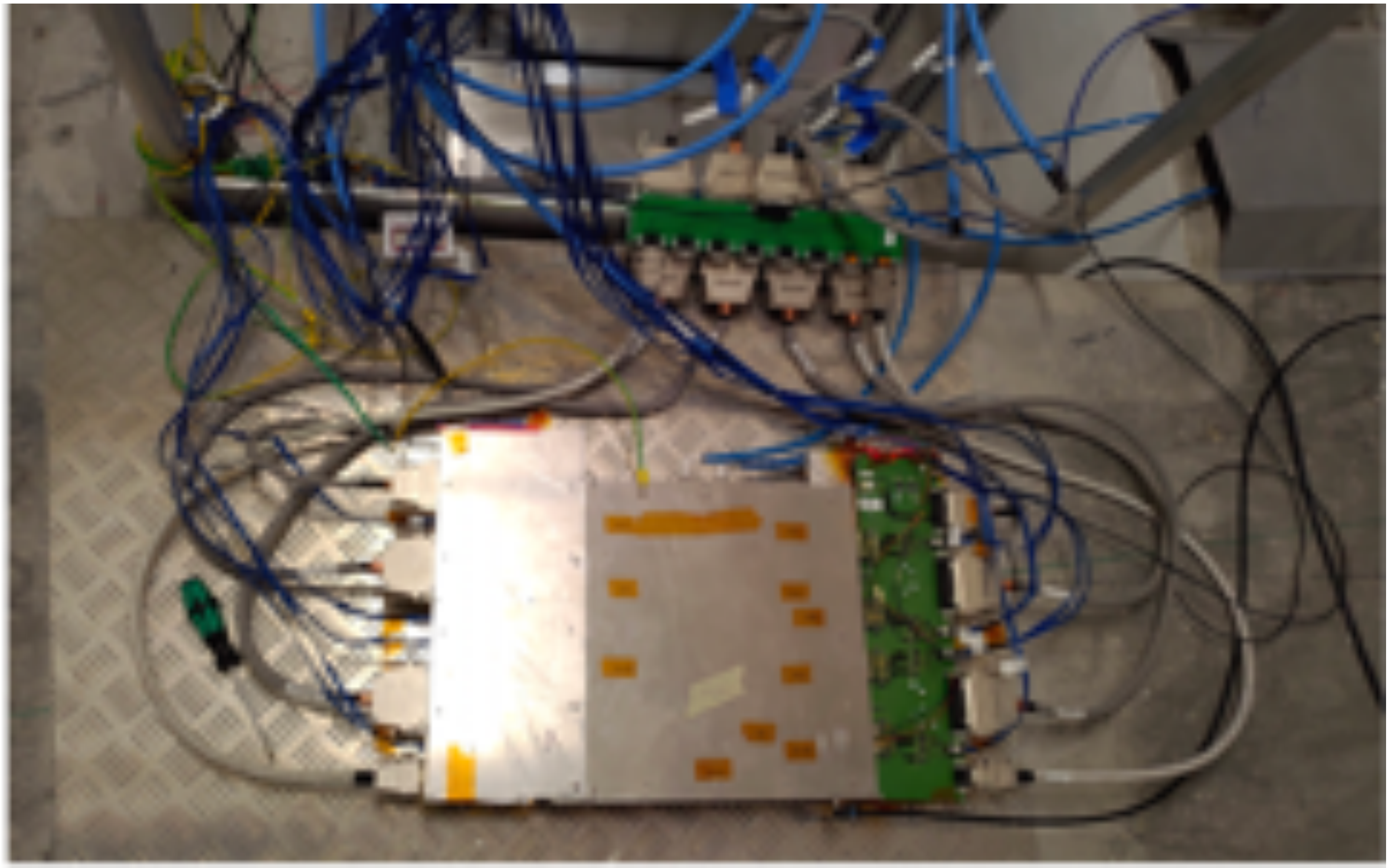
Acknowledge great support from many CERN teams:
SMB-FS, EN-ACE, EN-EA, EN-EL,EN-HE, EN-CV, HSE
– also Physics Beyond Colliders

Commissioning | Underground

- 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.

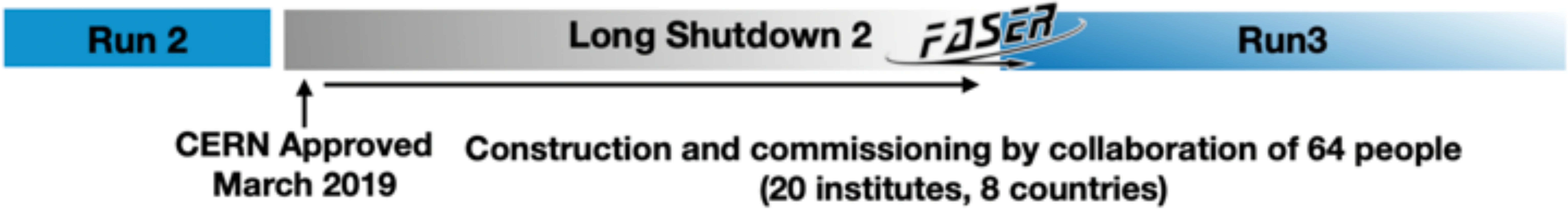




Commissioning to data taking

- Full detector installation to be finished this month!
  - Loss of access from April 2021
  - Will perform remote running at various stages in March.
- Run-3 during 2022-2024
  - Expecting 150/fb at 13(4) TeV

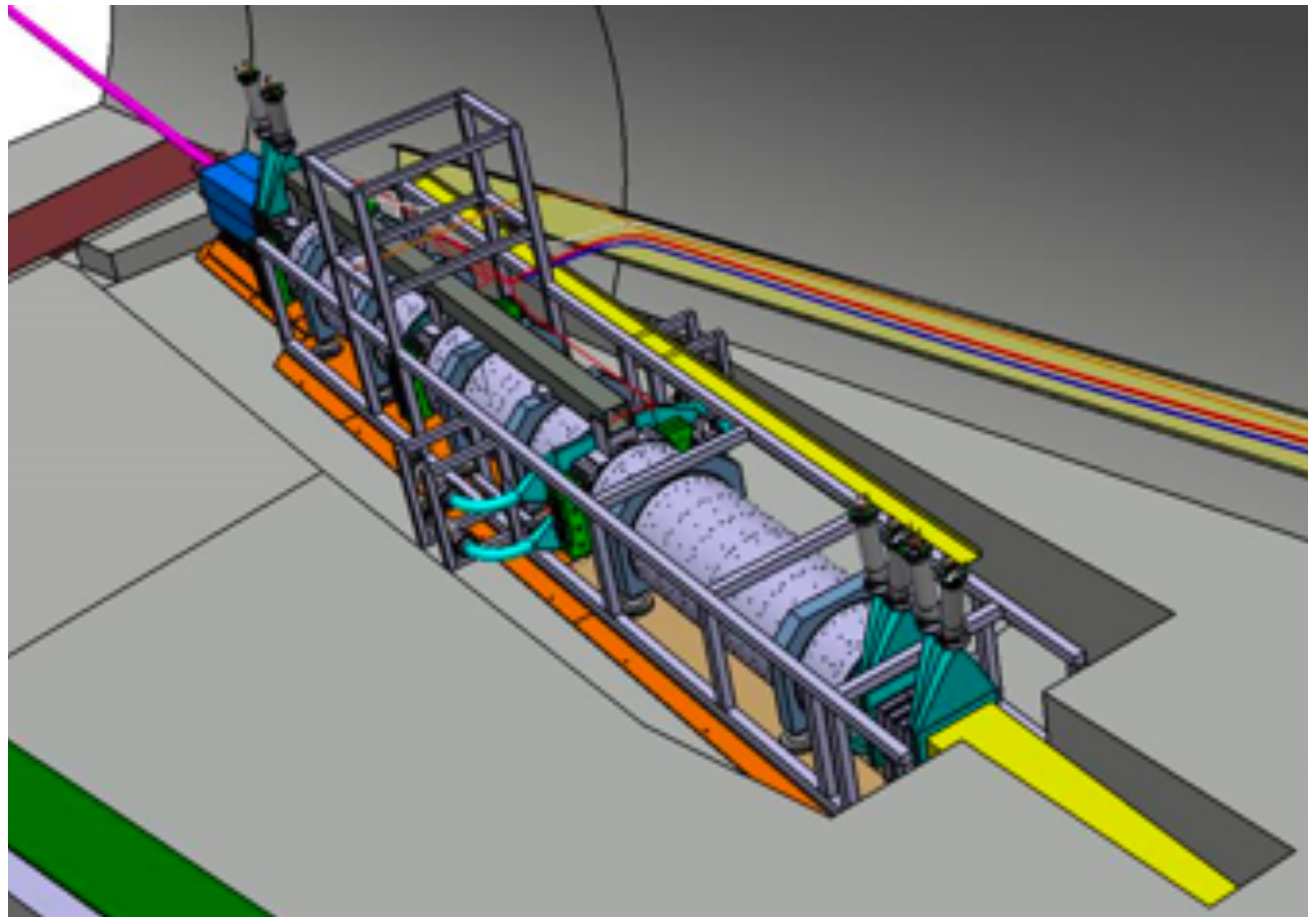
Milestone	Where	When	
Individual component commissioning	CERN labs	July	
Detector commissioning	EHN1	September	2020
Installation of magnets	EHN1	September	
Surface commissioning – part 1	EHN1	October	
Detector installation – part 1	TI12	November	
Surface commissioning – part 2	EHN1	February	
Detector installation – part 2	TI12	March	2021
In-situ dry commissioning	TI12	During 2021	

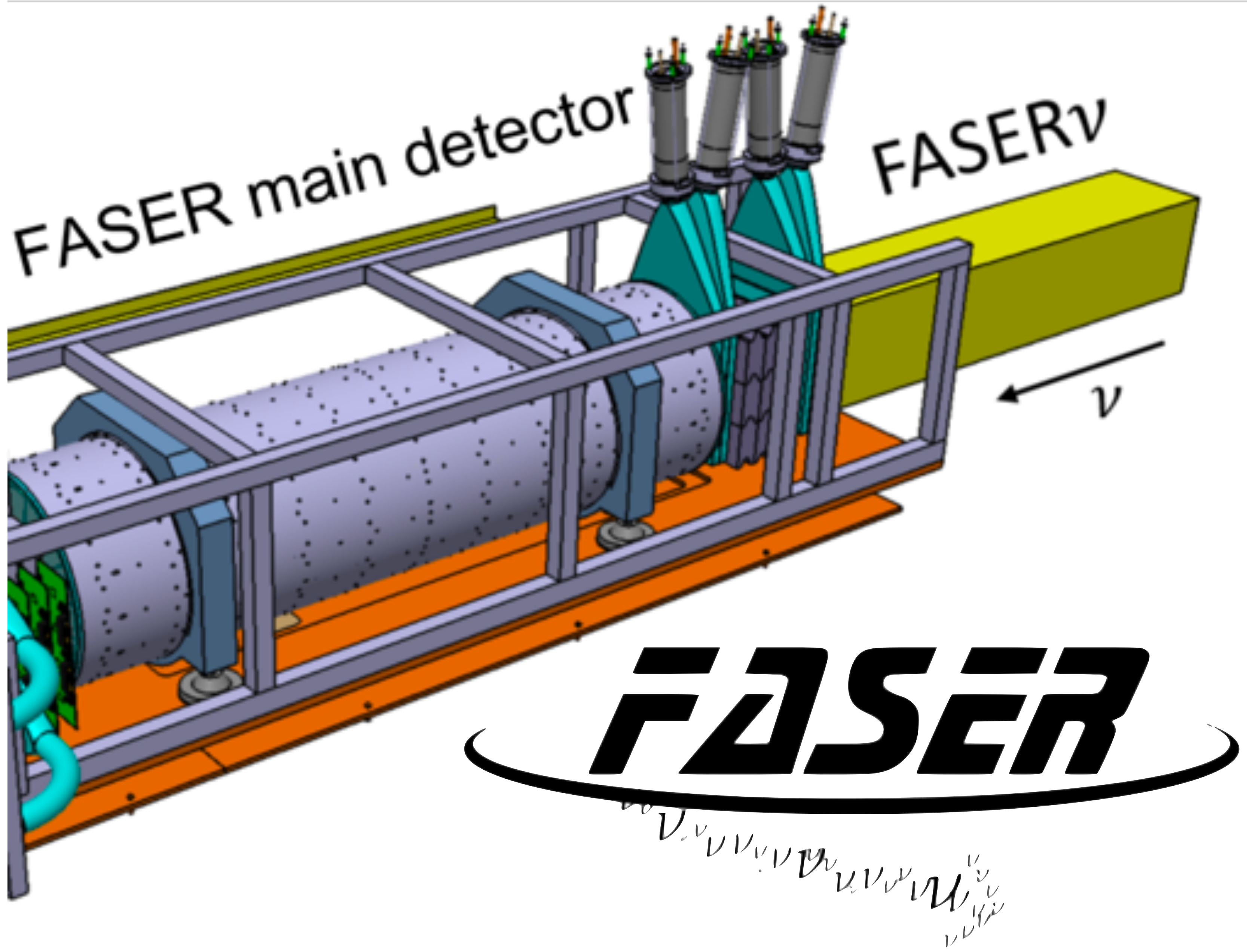


FASERν

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.

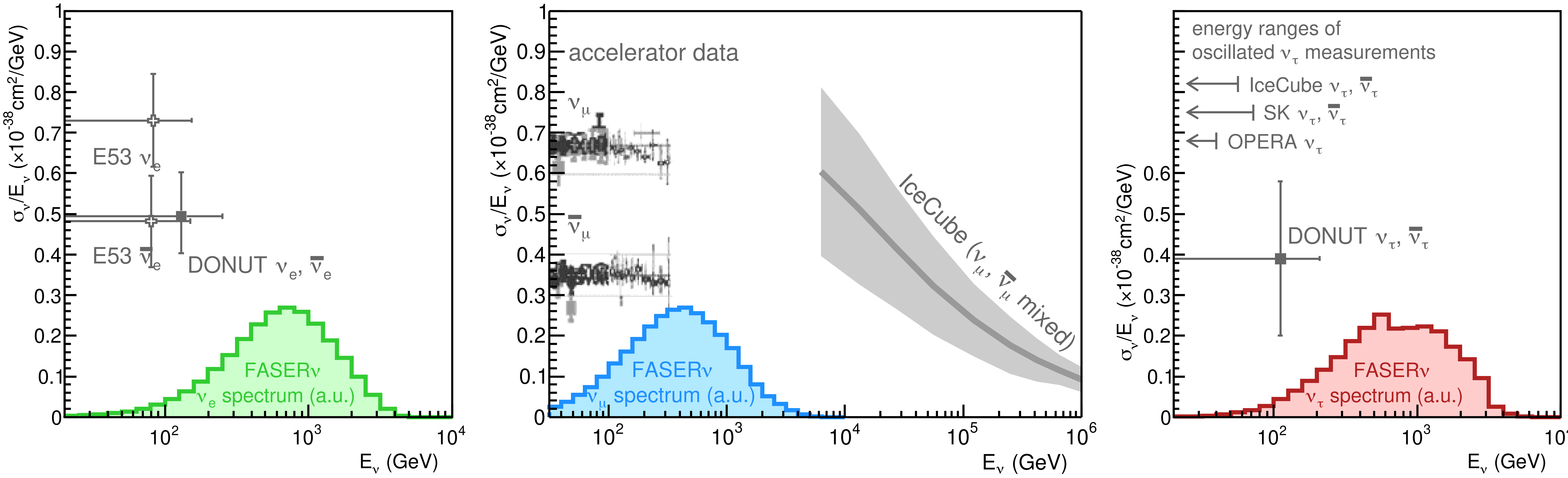




150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERν 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERν (1.2tn Tungsten)	~1300	~20000	~20

FASERν | Physics case

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

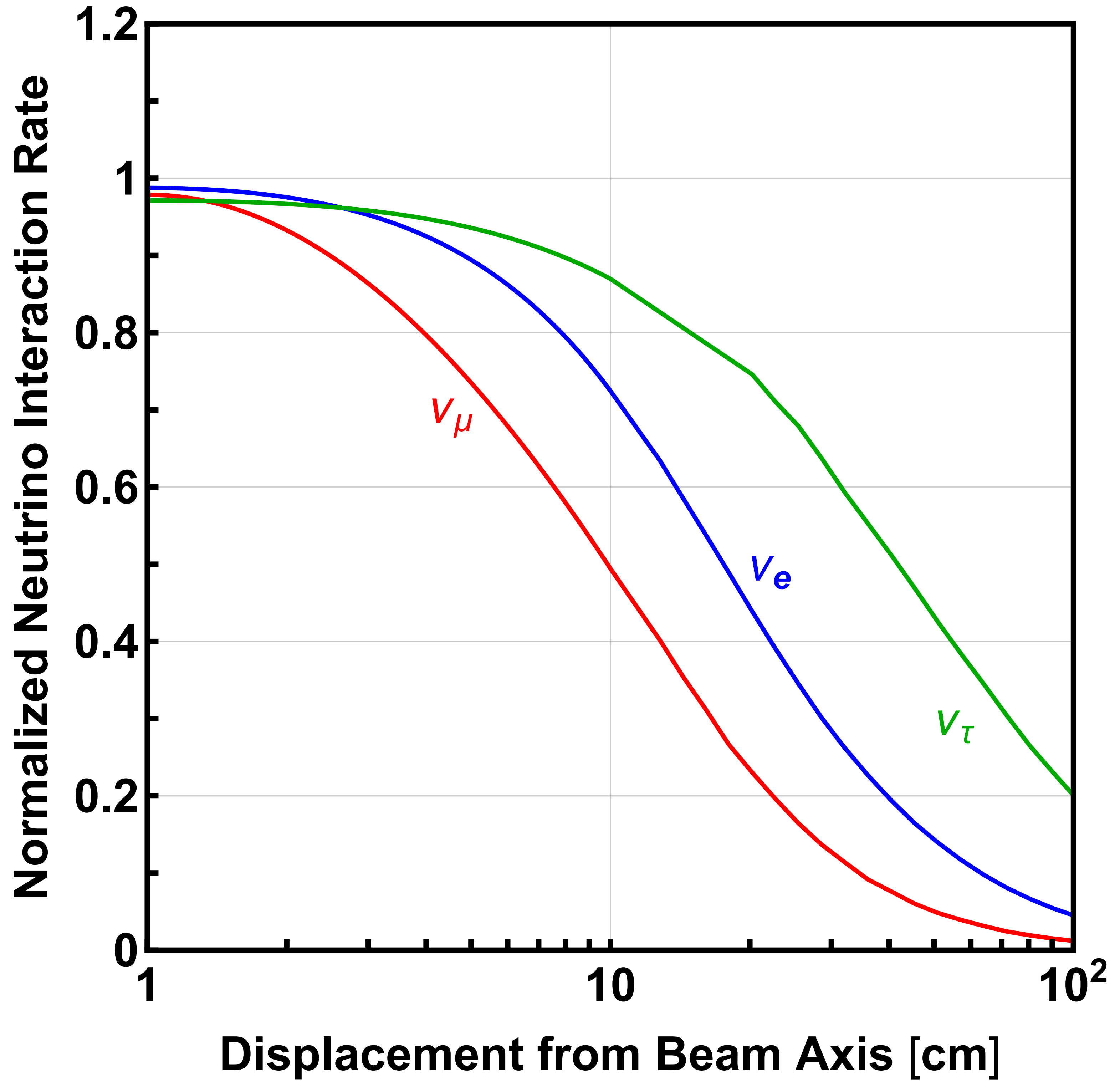


FASERν | Physics case

- 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).

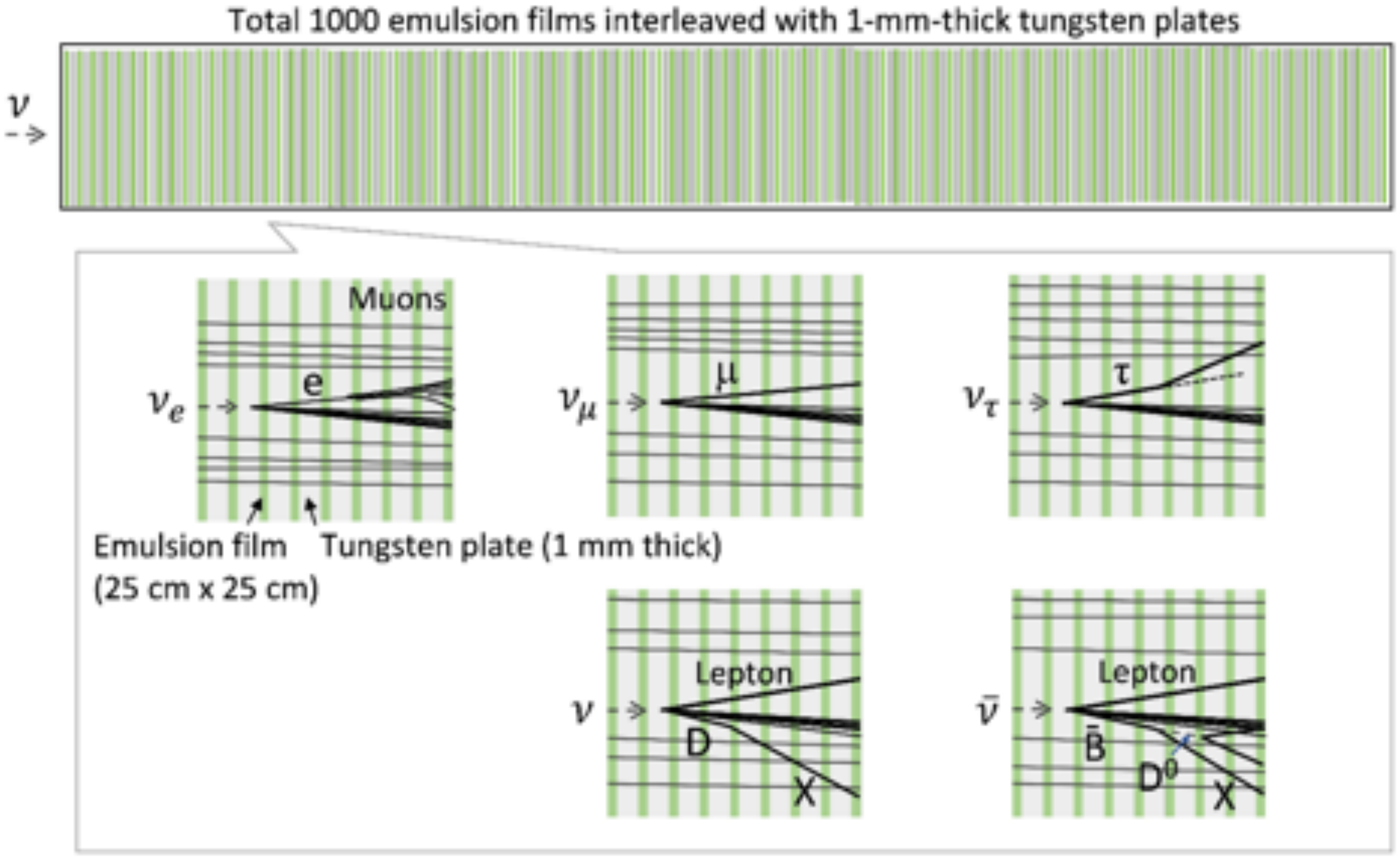
FASERν | Physics case

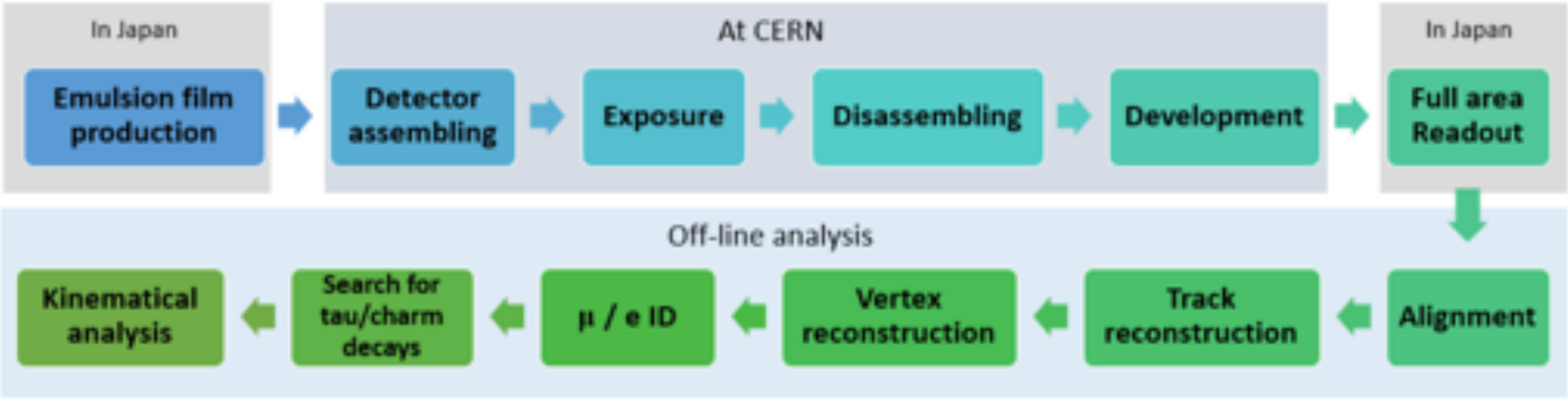
- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb^{-1})
- Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:



FASERν | Detector design

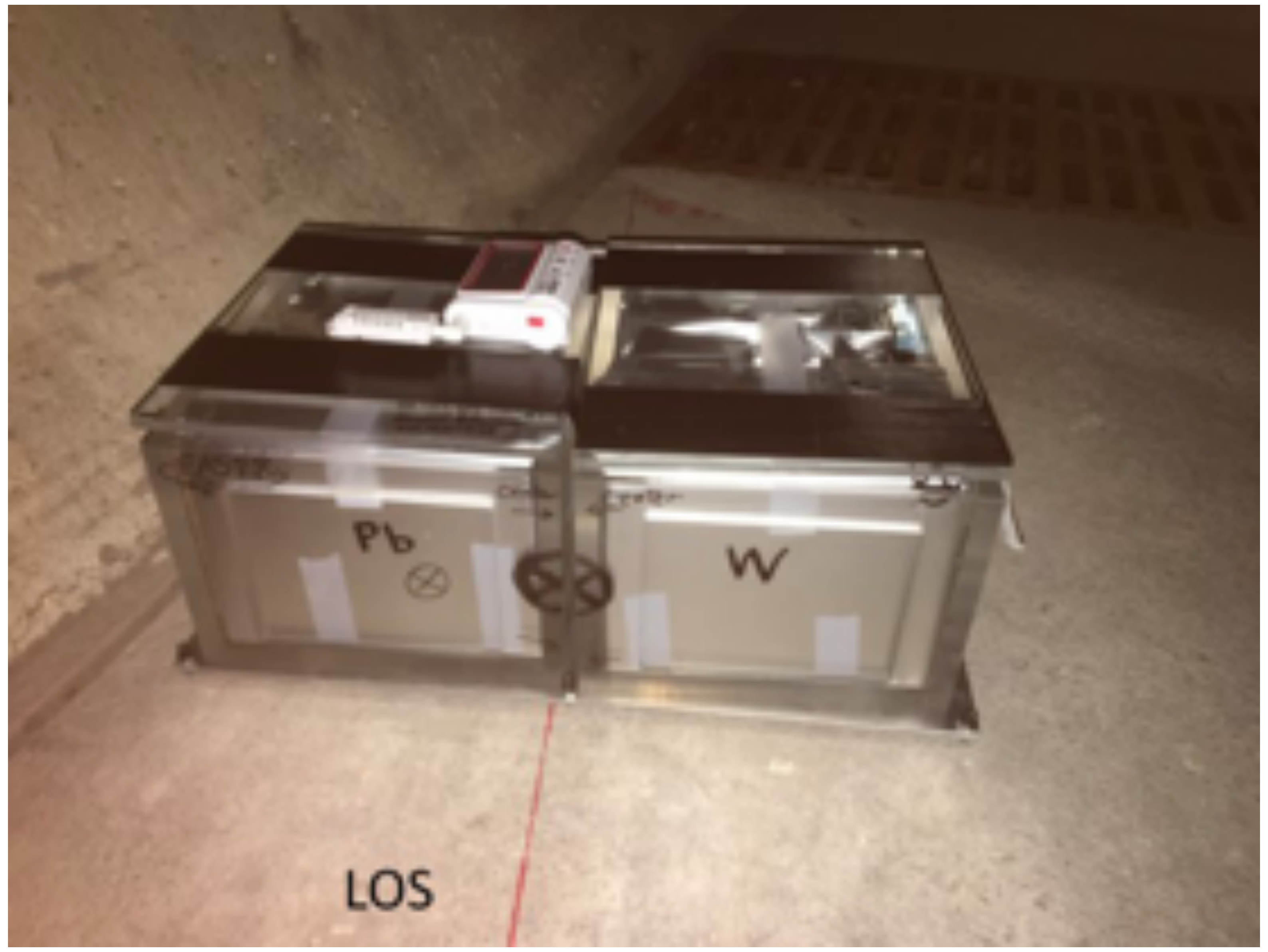
- Emulsion detector with tungsten target
  - 1000 1mm thick tungsten plates interleaved with emulsion film
    - Well understood neutrino detector technology
  - Replace every 20-50 fb^{-1} to maintain track density low
- Challenges:
  - Logistics to transport and replace the 1-ton-scale detector every 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:

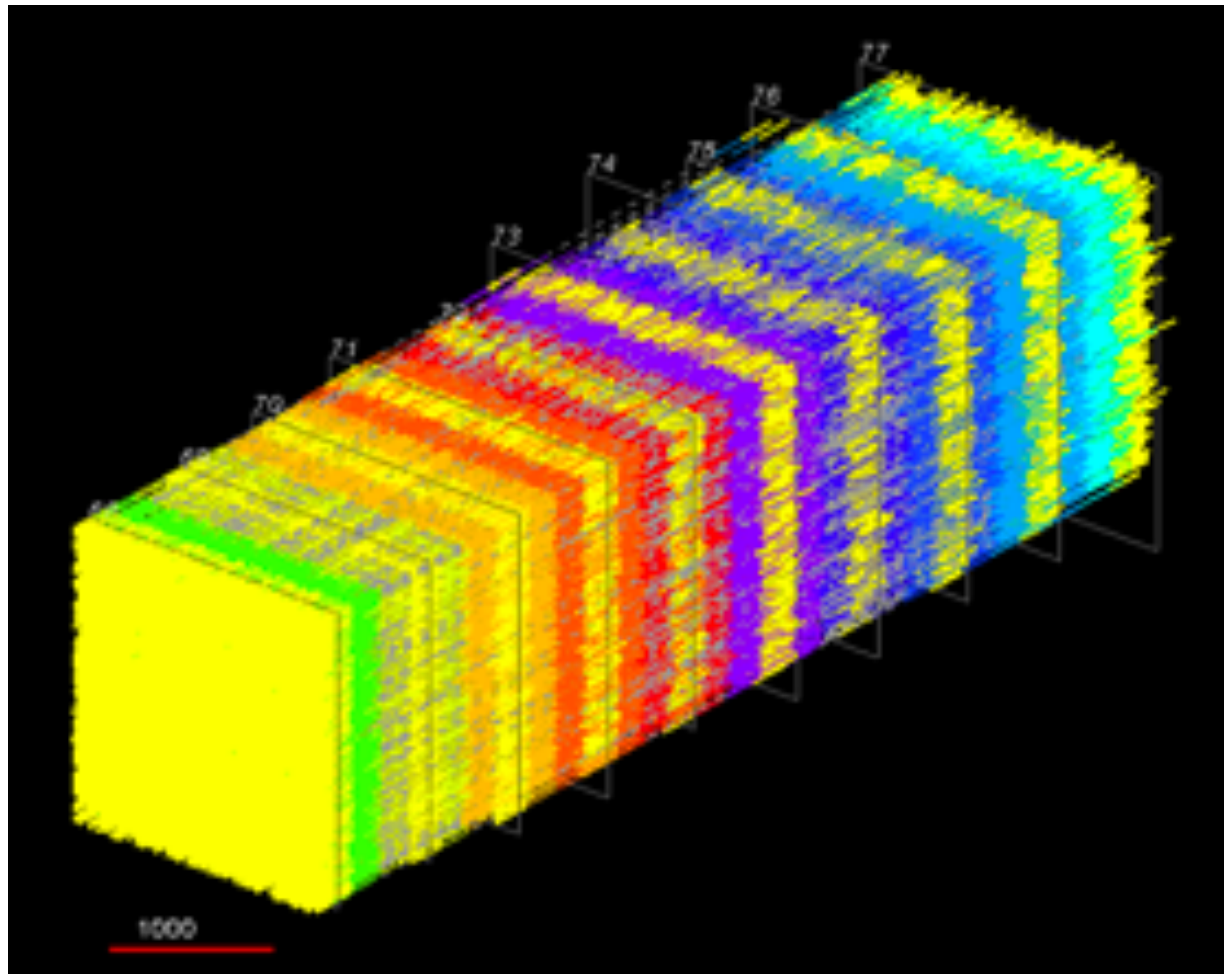


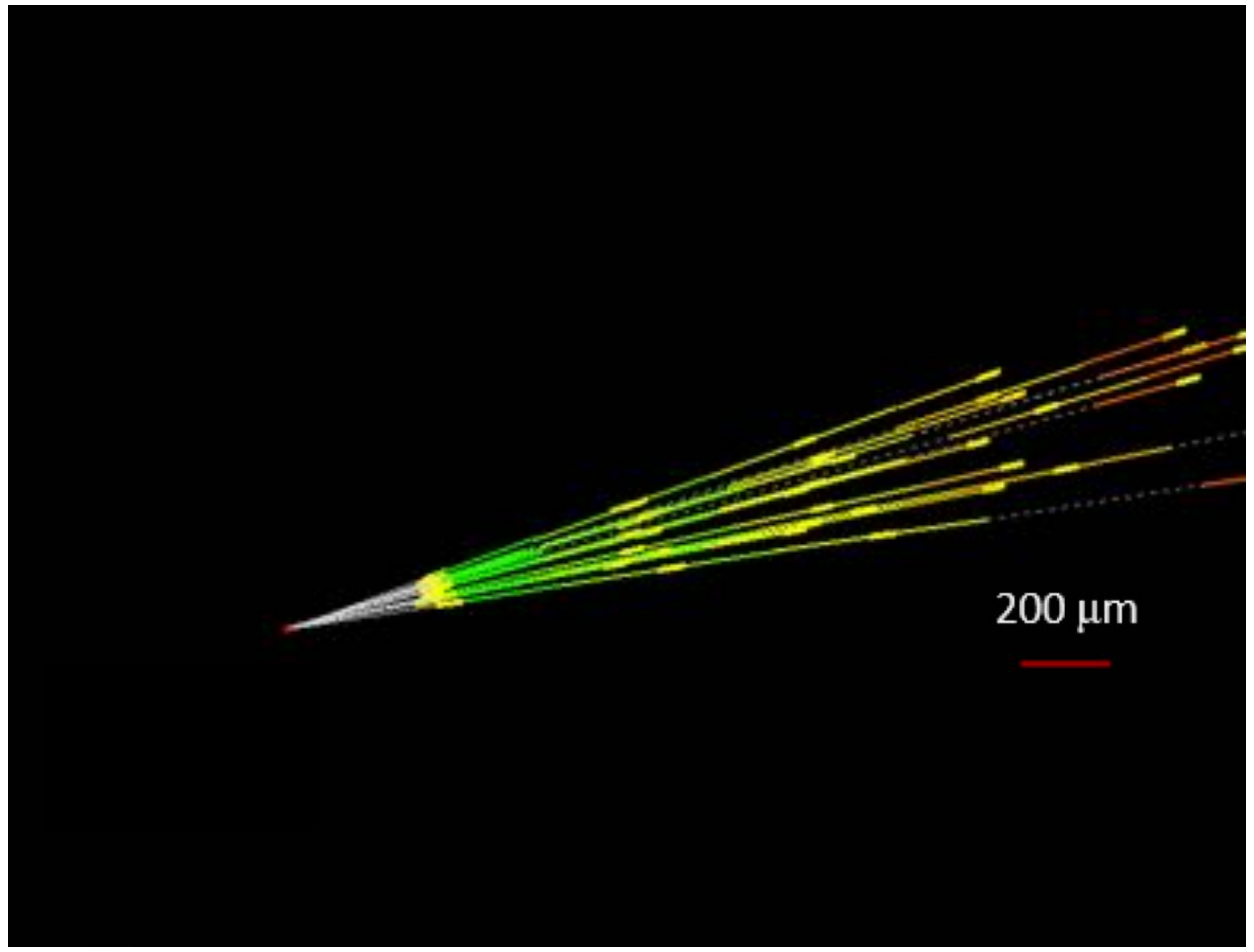


FASERν | Pilot neutrino detector

- 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
- Emulsion data developed, reconstructed and analysis ongoing
- 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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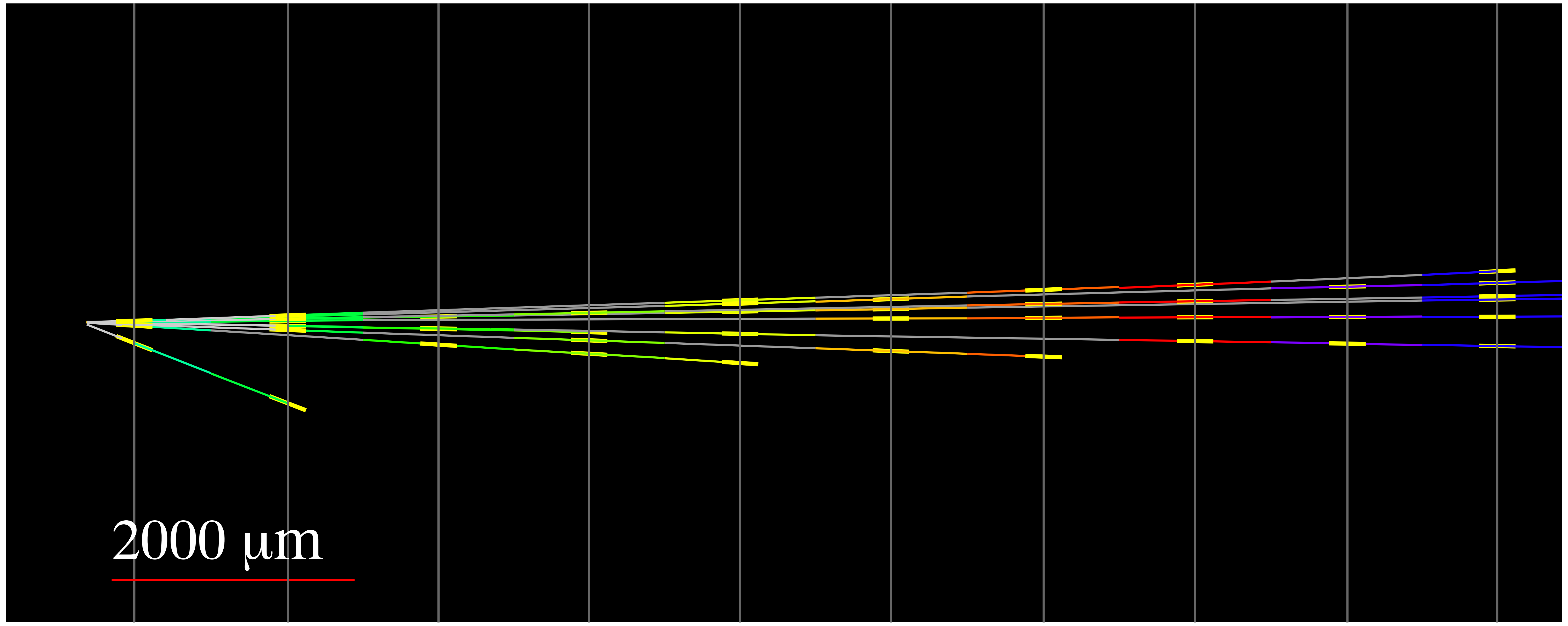

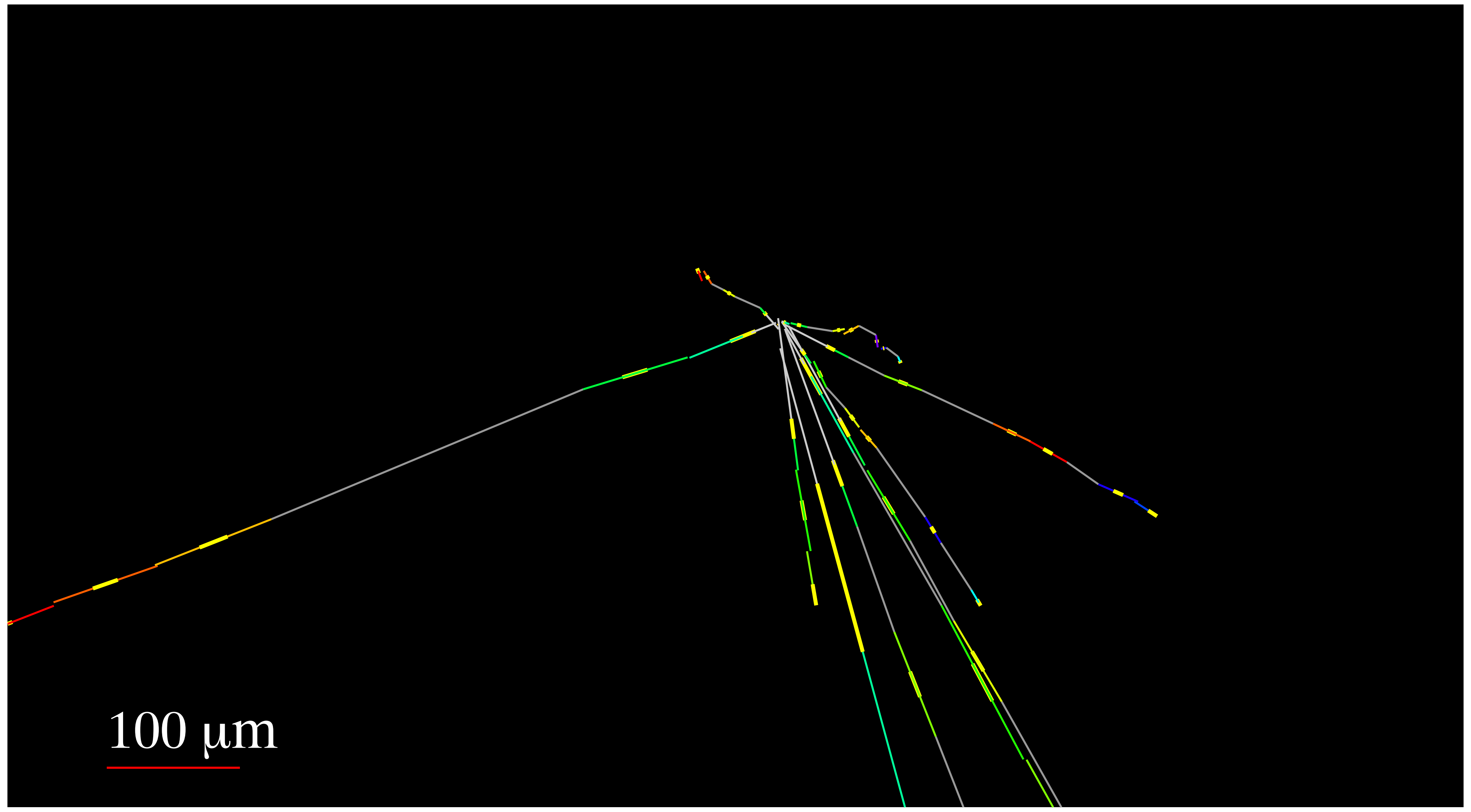

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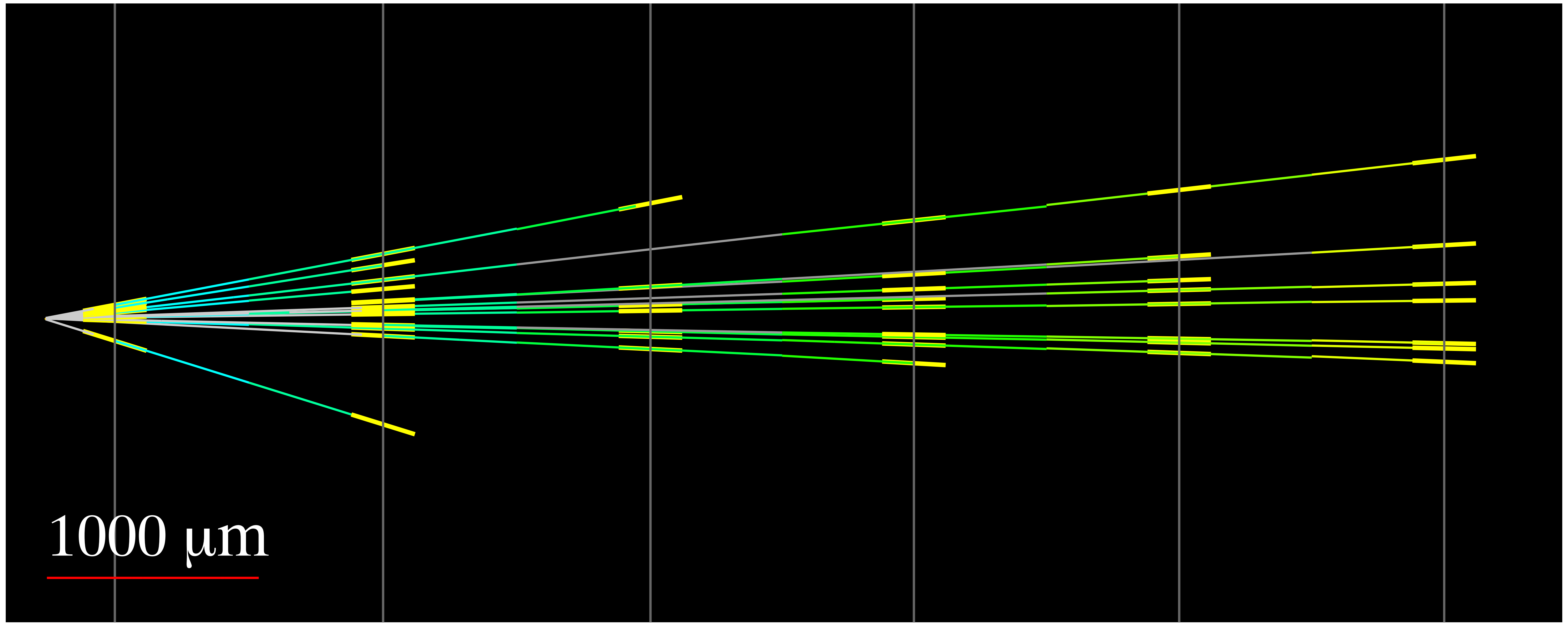
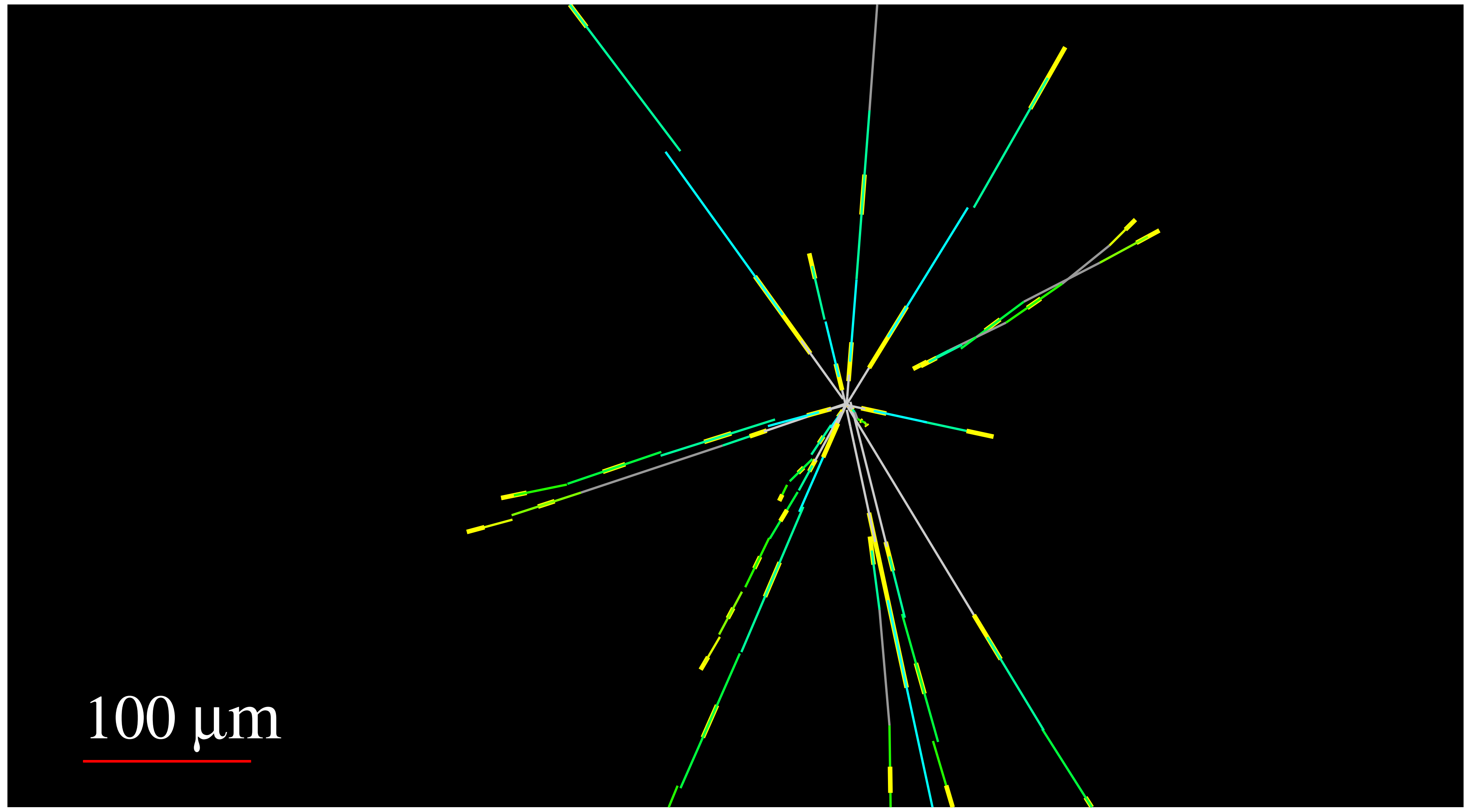
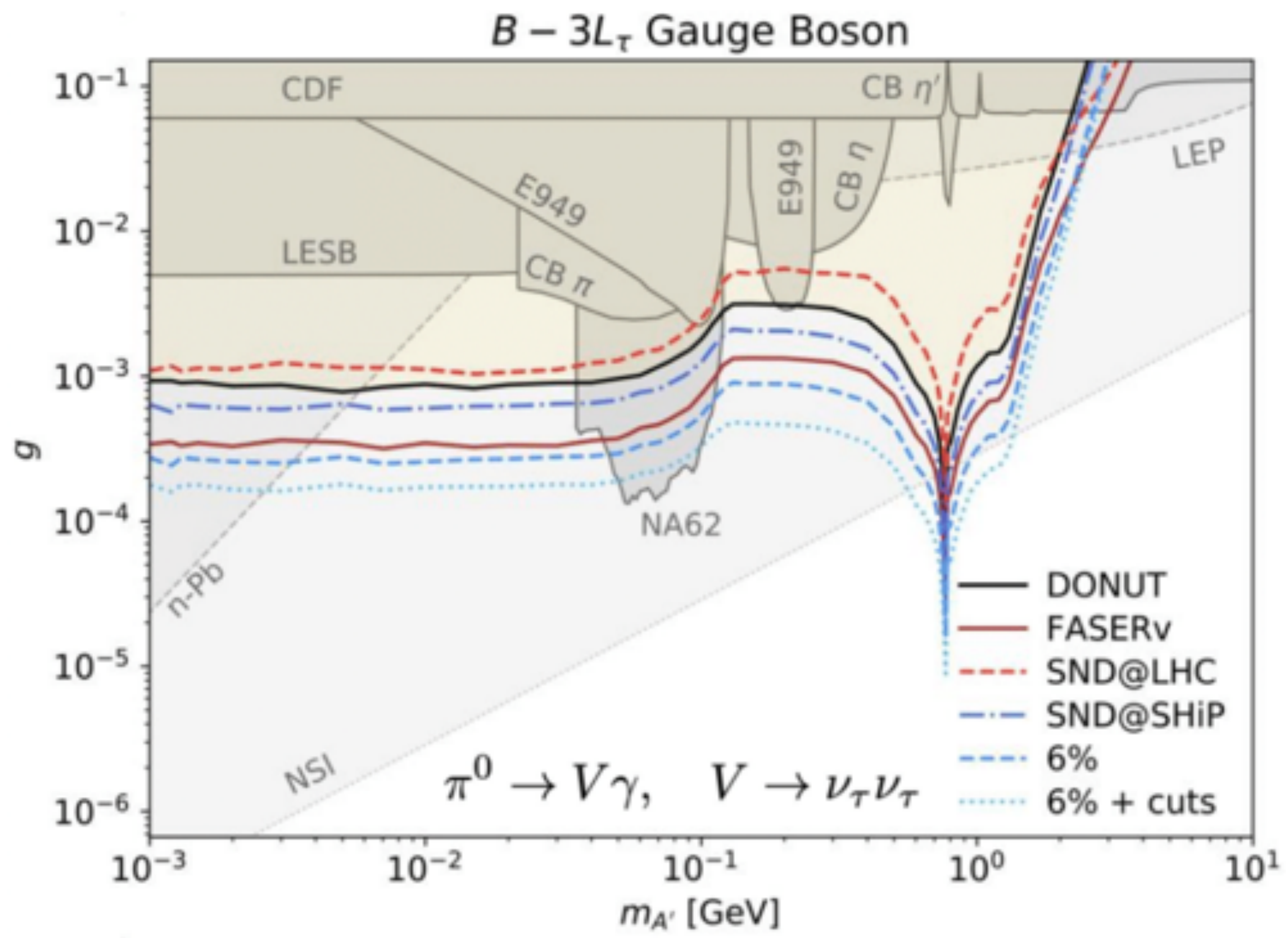
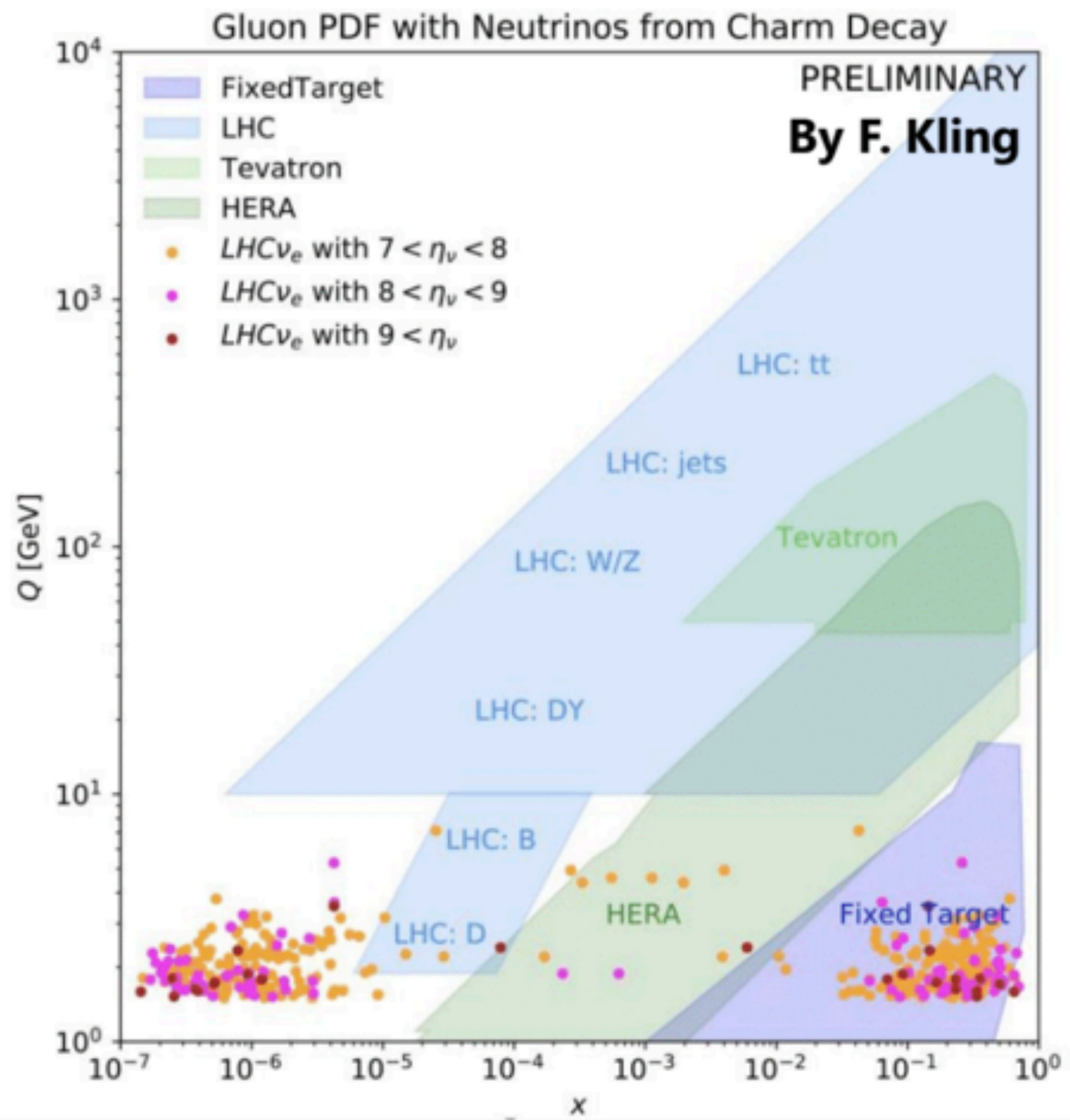


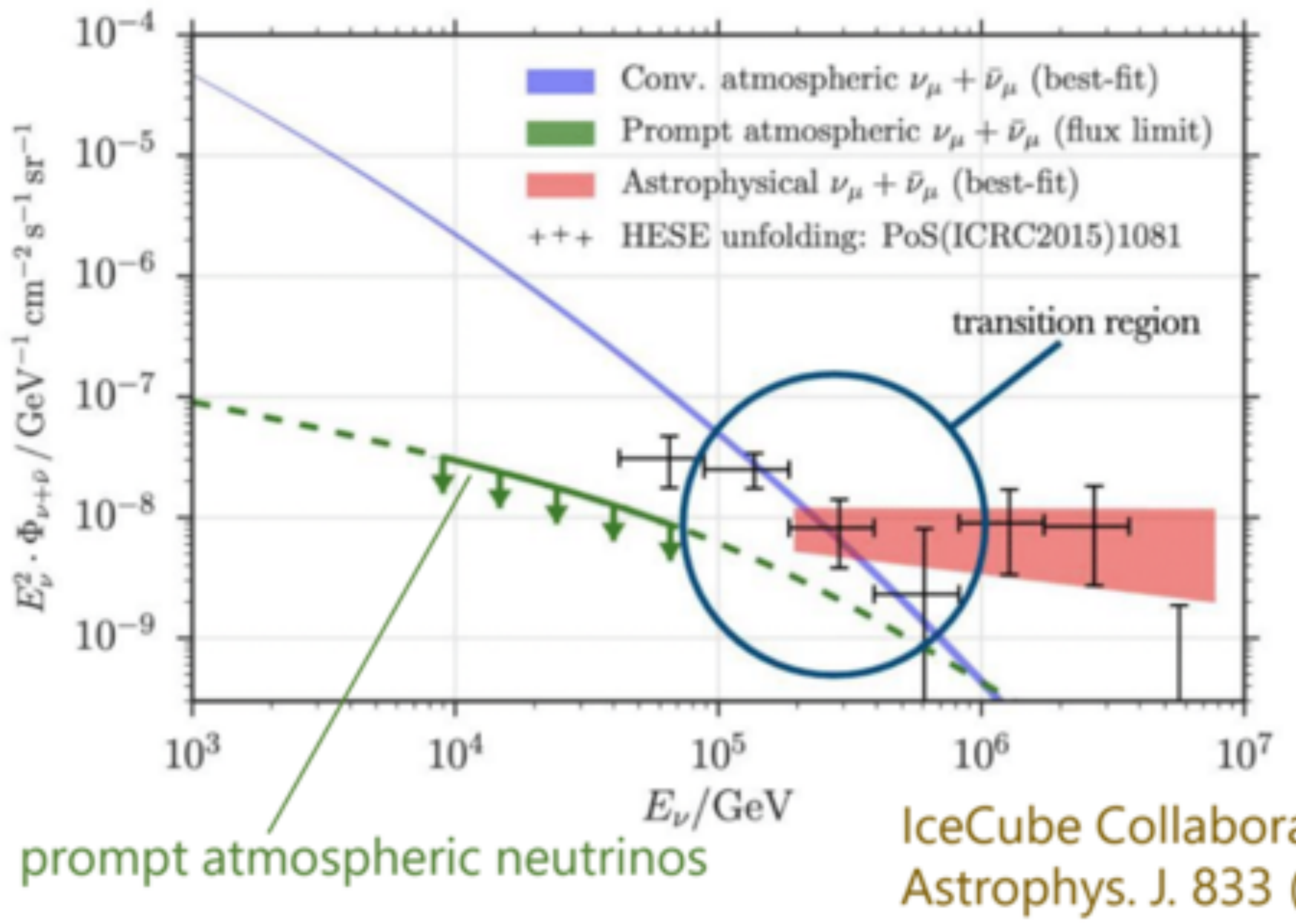


FASERν | Rich neutrino physics program

- 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

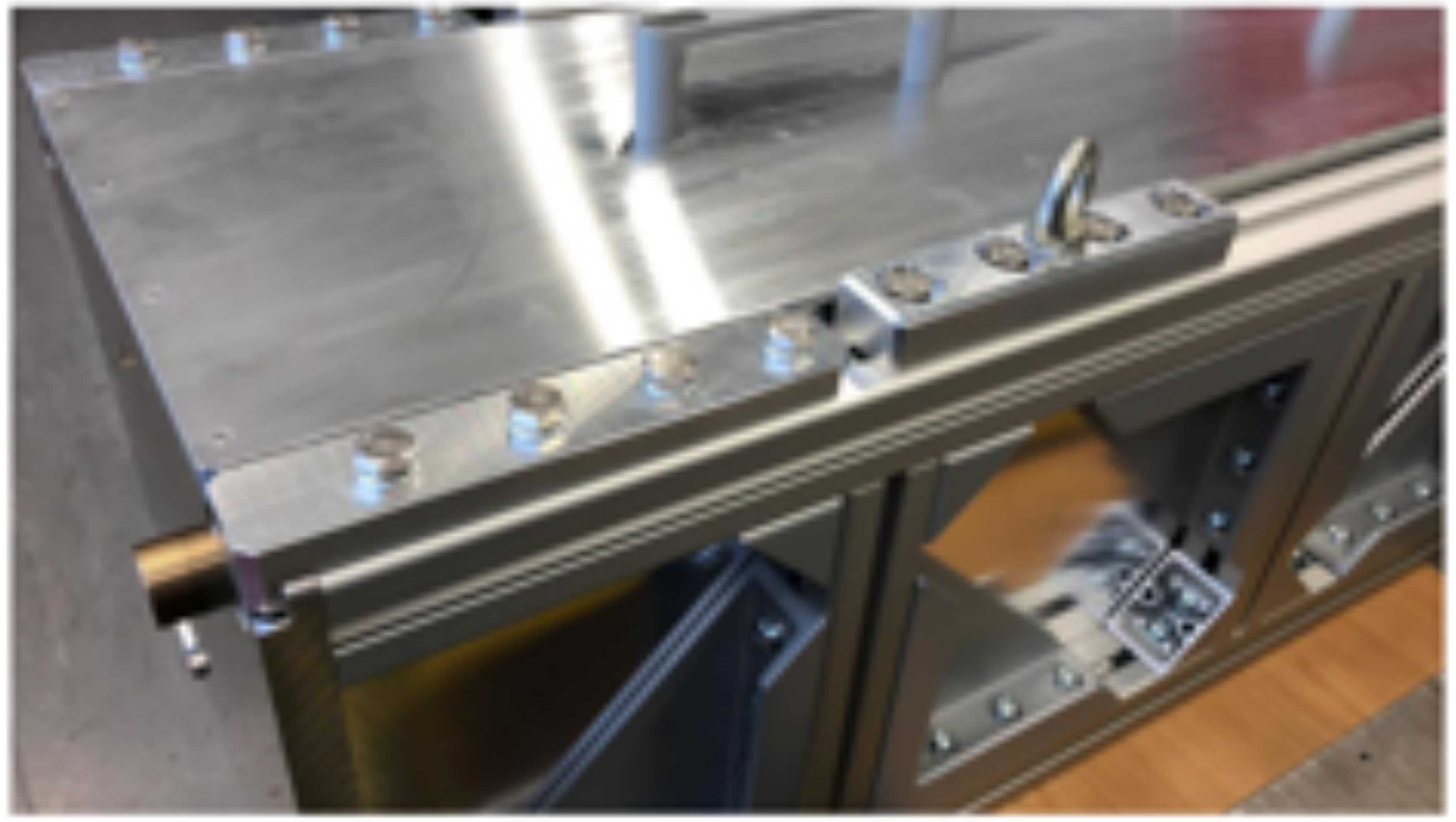


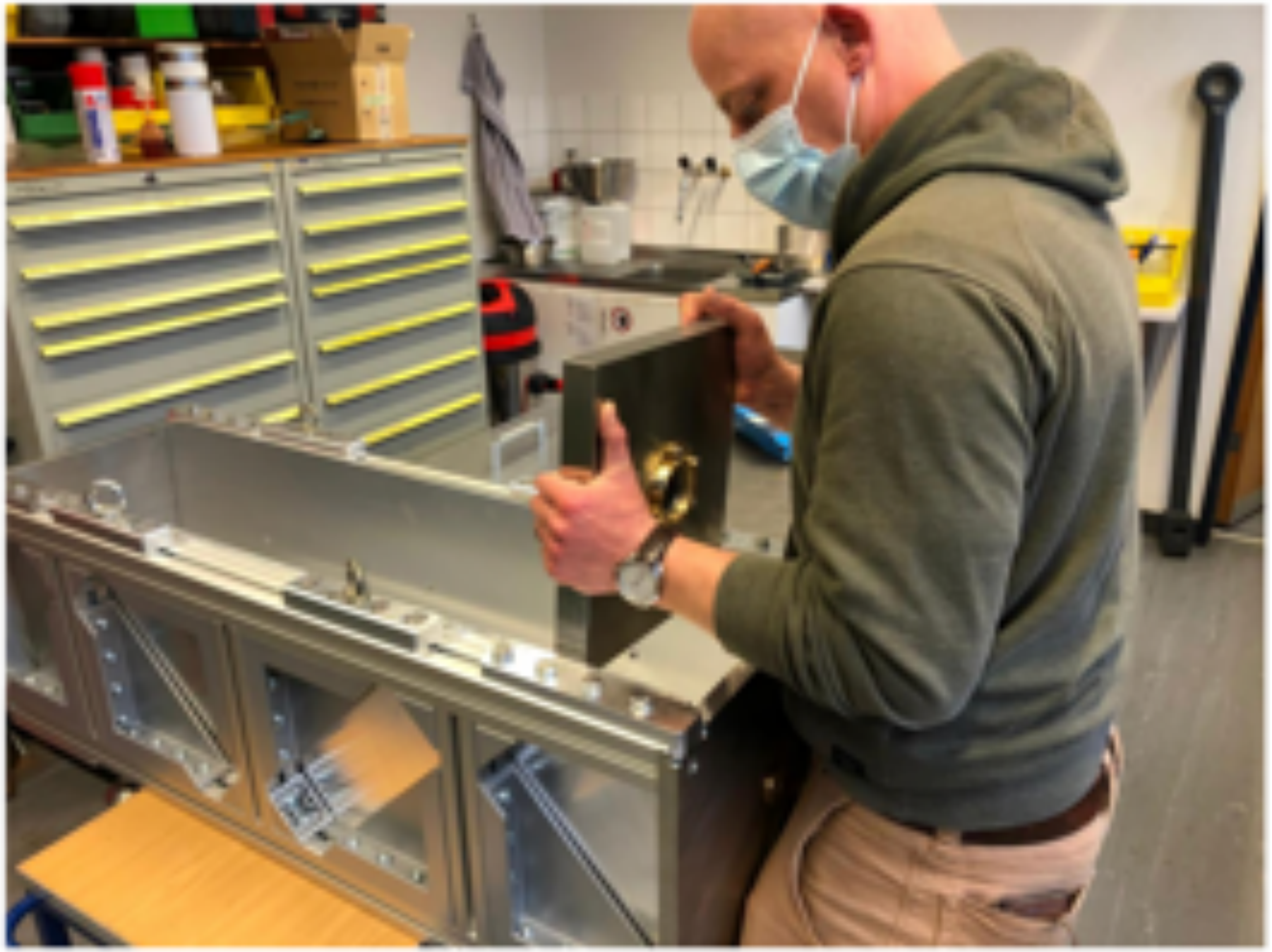




IceCube Collaboration, Astrophys. J. 833 (2016)

FASERν | Construction





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 enlarging UJ12 (or UJ18) to create 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. An FPF workshop is being planned for the coming months.

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

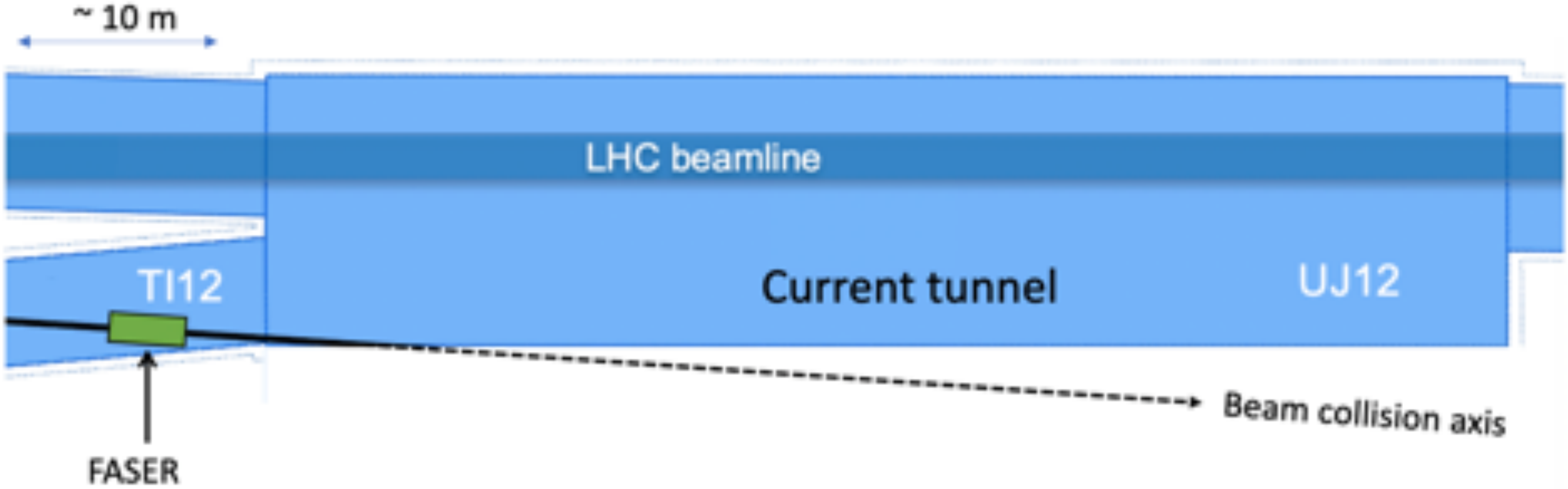
Snowmass 2021 Letter of Interest

Forward Physics Facility

Roshan M. Abraham,[1] Henso Abreu,[2] Yoav Afik,[2] Sanjib K. Agarwalla,[3] Juliette Alimena,[4] Luis Anchordoqui,[5] Claire Antel,[6] Akitaka Ariga,[7] Tomoko Ariga,[8] Carlos A. Argüelles,[9] Kento Asai,[10] Pouya Bakhti,[11] Akif B. Balantekin,[12] Victor Basiles,[13] Brian Batell,[14] James Beacham,[15] John F. Beacom,[4,16,17] Nicole F. Bell,[18] Florian Bernlochner,[19] Atri Bhattacharya,[20] Tobias Boeckh,[19] Jamie Boyd,[21] Lydia Brenner,[21] Mauricio Bustamante,[22] Franck Cadoux,[6] Mario Campanelli,[23] David W. Casper,[24] Grigorios Chachamis,[25] Spencer Chang,[26] Xin Chen,[27] Michael L. Cherry,[28] James M. Cline,[29] Ruben Conceição,[30] Andreas Crivellin,[31] Matthew Citron,[31] Andrea Coccaro,[32] Yanou Cui,[33] Mohamed R. Darwish,[34] Carlos P. de los Heros,[35] Patrick deNiverville,[36] Peter B. Denton,[37] Albert De Roeck,[21] Frank F. Deppisch,[23] Jordy de Vries,[38] Claudio Dib,[39] Caterina Doglioni,[40] Monica D'Onofrio,[41] Liam Dougherty,[21] Candan Dozen,[27] Marco Drewes,[42] Bhaskar Dutta,[43] Tamer Elkafrawy,[44] Sebastian A. R. Ellis,[45] Rouven Essig,[46] Glennys R. Farrar,[47] Yasaman Farzan,[11] Yannick Favre,[6] Anatoli Fedynitch,[48] Deion Fellers,[26] Jonathan L. Feng*,[24] Didier Ferrere,[6] Patrick Foldenauer,[49] Saeid Foroughi-Abari,[50] Jonathan Gall,[21] Iftah Galon,[51] Maria V. Garzelli,[52] Stefano Giagu,[53] Stephen Gibson,[54] Francesco Giuli,[55] Bhawna Gomber,[56] Victor P. Goncalves,[57] Sergio Gonzalez-Sevilla,[6] Yury Gornushkin,[58] Sumit Ghosh,[43] Claire Gwenlan,[59] Carl Gwilliam,[41] Jan Hajer,[42] Francis Halzen,[11,60] Juan Carlos Helo,[61] Christopher S. Hill,[4] Martin Hirsch,[62] Samuel D. Homiller,[46] Matheus Hostert,[43,44] Shih-Chieh Hsu,[65] Zhen Hu,[27] Pham Q. Hung,[66] Giuseppe Iacobucci,[6] Philip Ilten,[67] Tomohiro Inada,[48] Hiroyuki Ishida,[68] Ayu Ishihara,[69] Ahmed Ismail,[1] Ameen Ismail,[70] Sune Jakobsen,[21] Yu Seon Jeong,[21] Yongsoo Jho,[71] Krzysztof Jodłowski,[72] Enrique Kajomovitz,[2] Kevin J. Kelly,[73] Maxim Yu. Khlopov,[74,75,76] Valery A. Khoze,[49] Doojin Kim,[43] Jongkuk Kim,[77] Teppei Kitahara,[78] Felix Kling*,[45] Joachim Kopp,[21,79] Umut Kose,[21] Piotr Kotko,[80] John Krizmanic,[81] Susanne Kuehn,[21] Suchita Kulkarni,[82] Jason Kumar,[83] Alexander Kusenko,[84] Krzysztof Kutak,[85] Greg Landsberg,[86] Luca Lavezzo,[4] Rebecca K. Leane,[45] Hye-Sung Lee,[87] Helena Lefebvre,[54] Benjamin V. Lehmann,[88] Lorne Levinson,[89] Ke Li,[65] Shirley W. Li,[45] Shuailong Li,[90] Benjamin Lillard,[91] Jinfeng Liu,[27] Wei Liu,[92] Zhen Liu,[93] Steven Lowette,[94] Chiara Magliocca,[6] Brandon Manley,[4] Danny Marfatia,[83] Ioana Maris,[95] Josh McFayden,[21] Sam Meehan,[21] Sascha Mehlhase,[96] David W. Miller,[97] Dimitar Mladenov,[21] Vasiliki A. Mitsou,[62] Rabindra N. Mohapatra,[93] Mitsuhiro Nakamura,[98] Toshiyuki Nakano,[98] Marzio Nessi,[21] Friedemann Neuhaus,[79] Kenny C. Y. Ng,[99] Koji Noda,[48] Satoshi Oda,[100] Nobuchika Okada,[13] Satomi Okada,[13] Yasar Onel,[101] John Osborne,[21] Hidetoshi Otono,[8] Carlo Pandini,[6] Vishvas Pandey,[102] Hao Pang,[27] Silvia Pascoli,[49] Seong Chan Park,[71] Brian Petersen,[21] Alexey A. Petrov,[103] Tanguy Pierog,[104] Francesco Pietropaolo,[21] James L. Pinfold,[105] Markus Prim,[19] Michaela Queitsch-Maitland,[21] Meshkat Rajaee,[11] Digesh Raut,[106] Federico L. Redi,[107] Peter Reimitz,[108] Mary Hall Reno,[101] Filippo Resnati,[21] Adam Ritz,[50] Thomas Rizzo,[45] Tania Robens,[109] Christophe Royon,[110] Jakob Salfeld-Nebgen,[21] Osamu Sato,[98] Paola Scampoli,[7,111] Kristof Schmieden,[21] Matthias Schott,[79] Pedro Schwaller,[79] Manibrata Sen,[112] Dipan Sengupta,[113] Anna Sfyrla,[6] Qaisar Shafi,[106] Takashi Shimomura,[114] Seodong Shin,[115] Savannah Shively,[24] Ian M. Shoemaker,[116] Carlos V. Sierra,[117] Torbjörn Sjöstrand,[118] Yotam Soreq,[2] Huayang Song,[90] Jordan Smolinsky,[103] John Spencer,[65] David Stuart,[31] Shufang Su,[90] Wei Su,[119] Antoni Szczurek,[120,121] Dai- suke Takahashi,[100] Yosuke Takubo,[122] Ondřej Theiner,[6] Serap Tilav,[106] Charles Timmermans,[117,123] Eric Torrence,[26] Sebastian Trojanowski,[124] Yu-Dai Tsai,[73] Serhan Tufanli,[21] Paolo Valente,[125] Benedikt Vormwald,[21] Carlos E. M. Wagner,[97,126] Di Wang,[27] Zeren S. Wang,[127] Tao Xu,[128] Tianlu Yuan,[12,60] Tevong You,[21] Shigeru Yoshida,[69] Dengfeng Zhang,[27] Gang Zhang,[27] Yue Zhang,[129] and Yi-Ming Zhong[130]

* Contact Information: Jonathan L. Feng ([illegible]), Felix Kling ([illegible])

Forward Physics Facility



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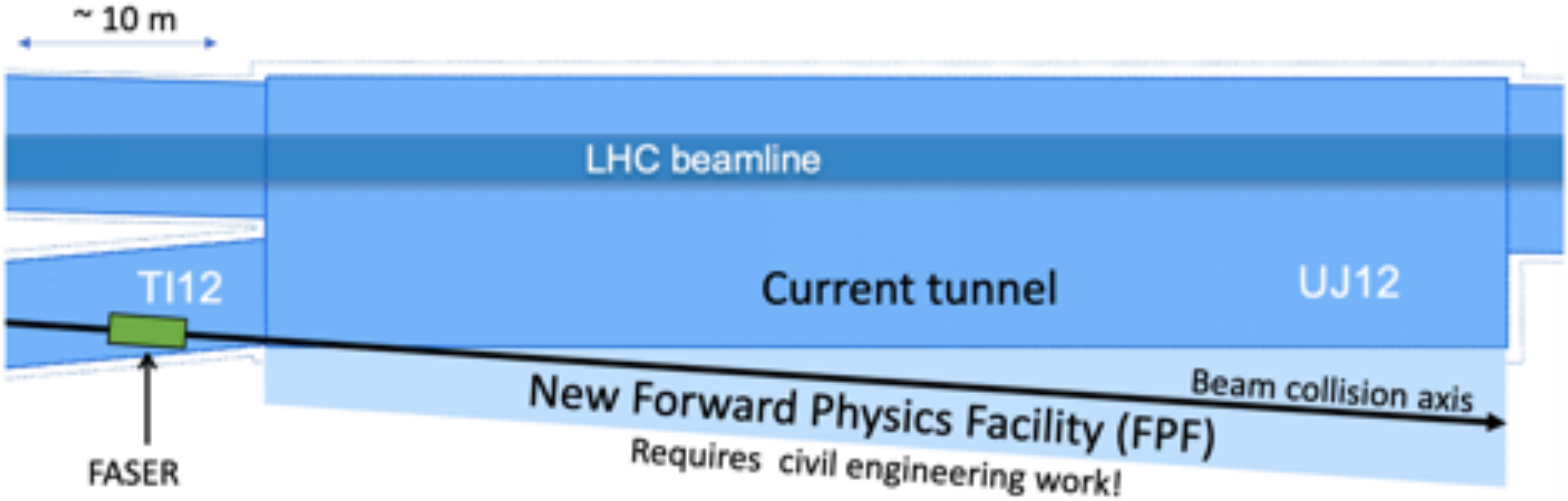
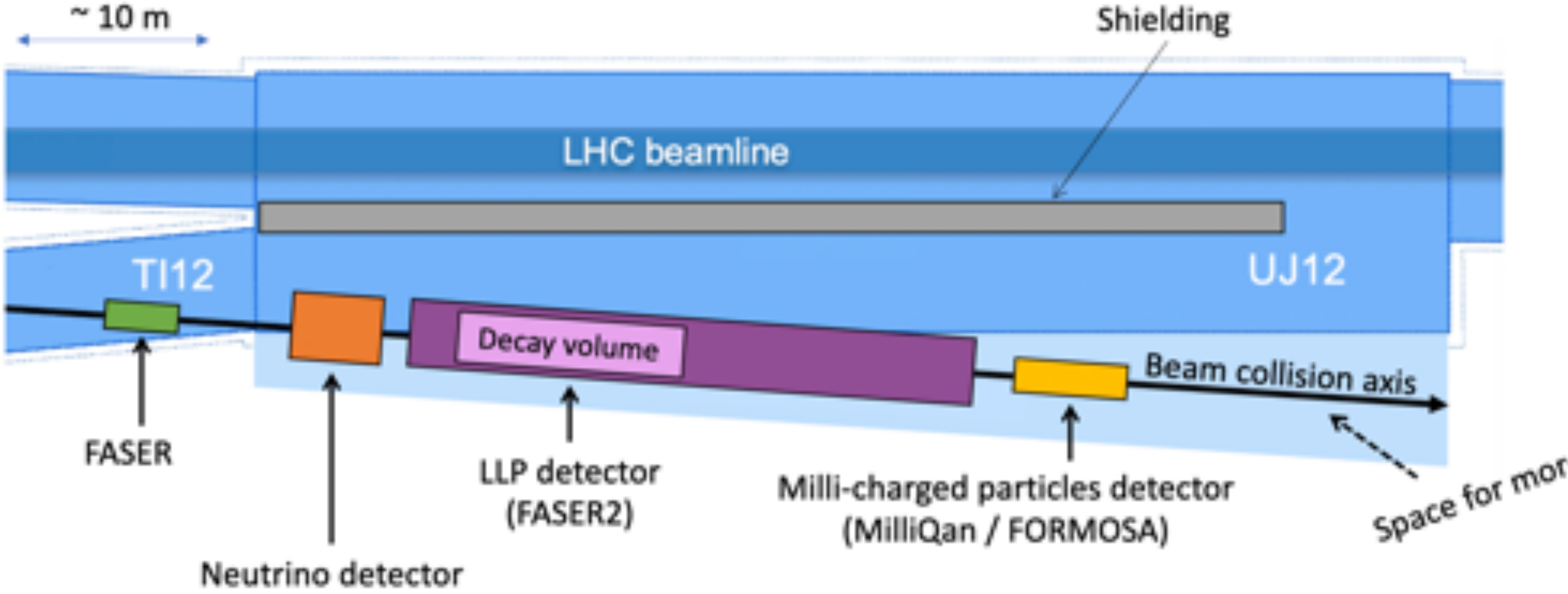


Forward Physics Facility



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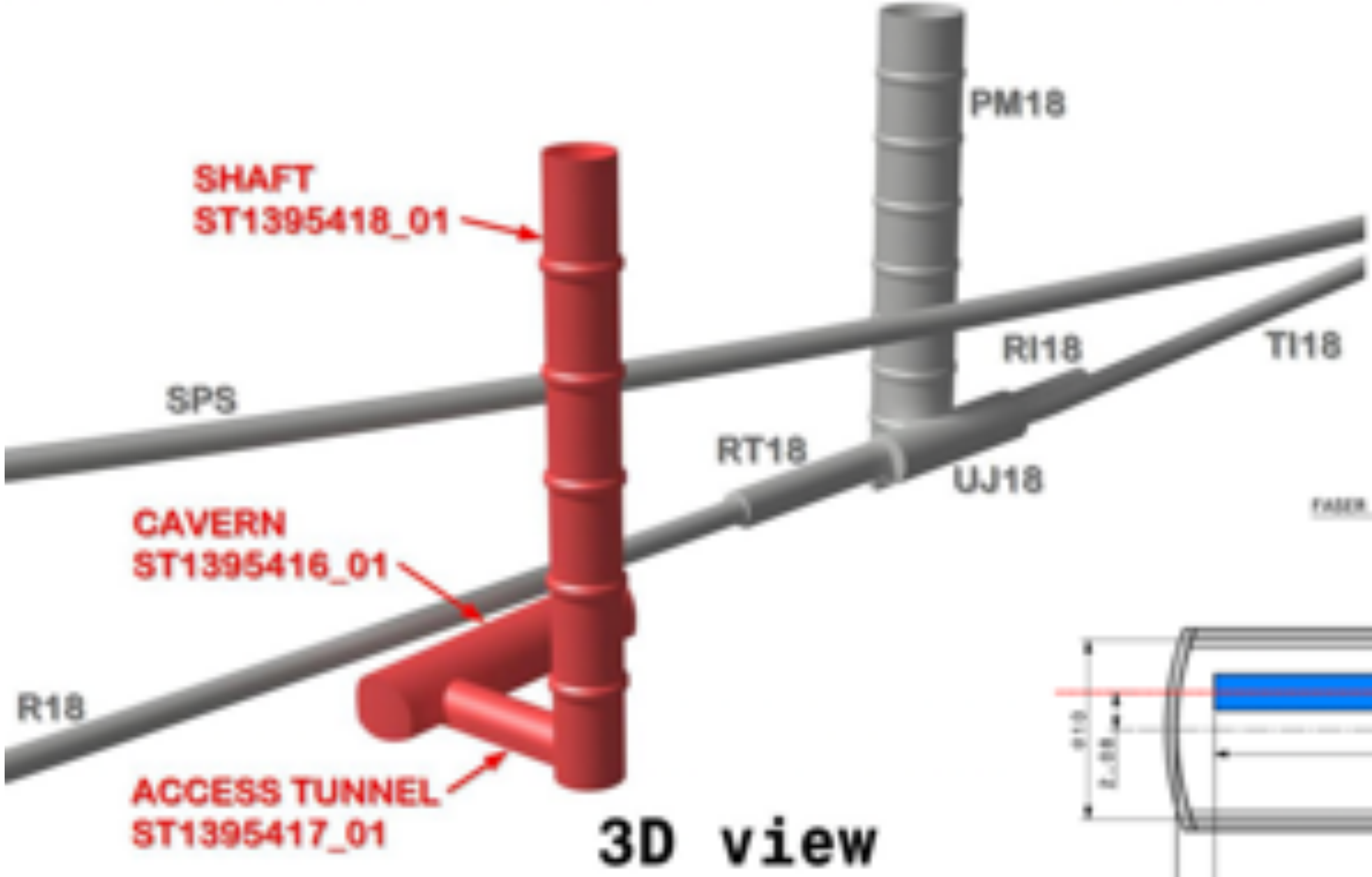
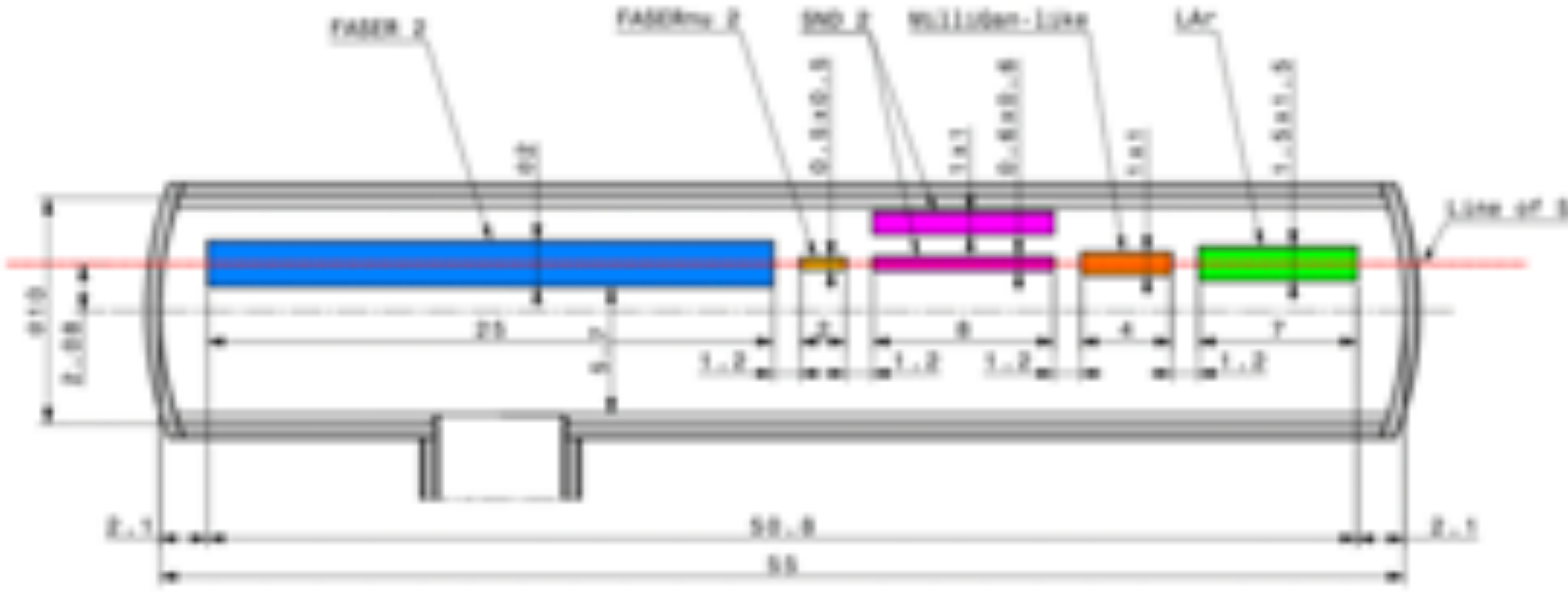


Jonathan Gall, CERN CE study in progress for a dedicated cavern, 612 m from ATLAS IP



Plan view of experimental cavern

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.

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	√	√
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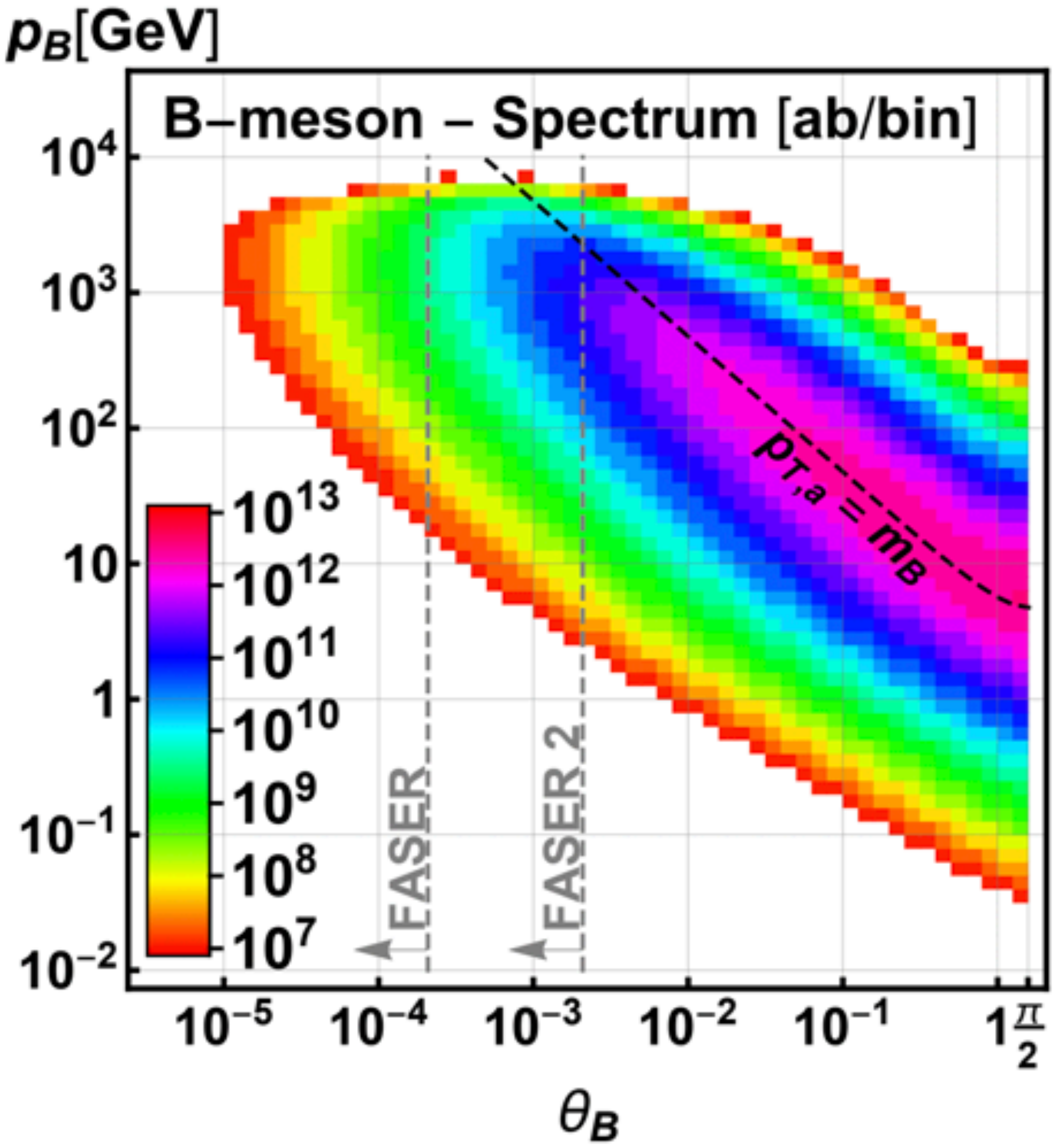
FASER2

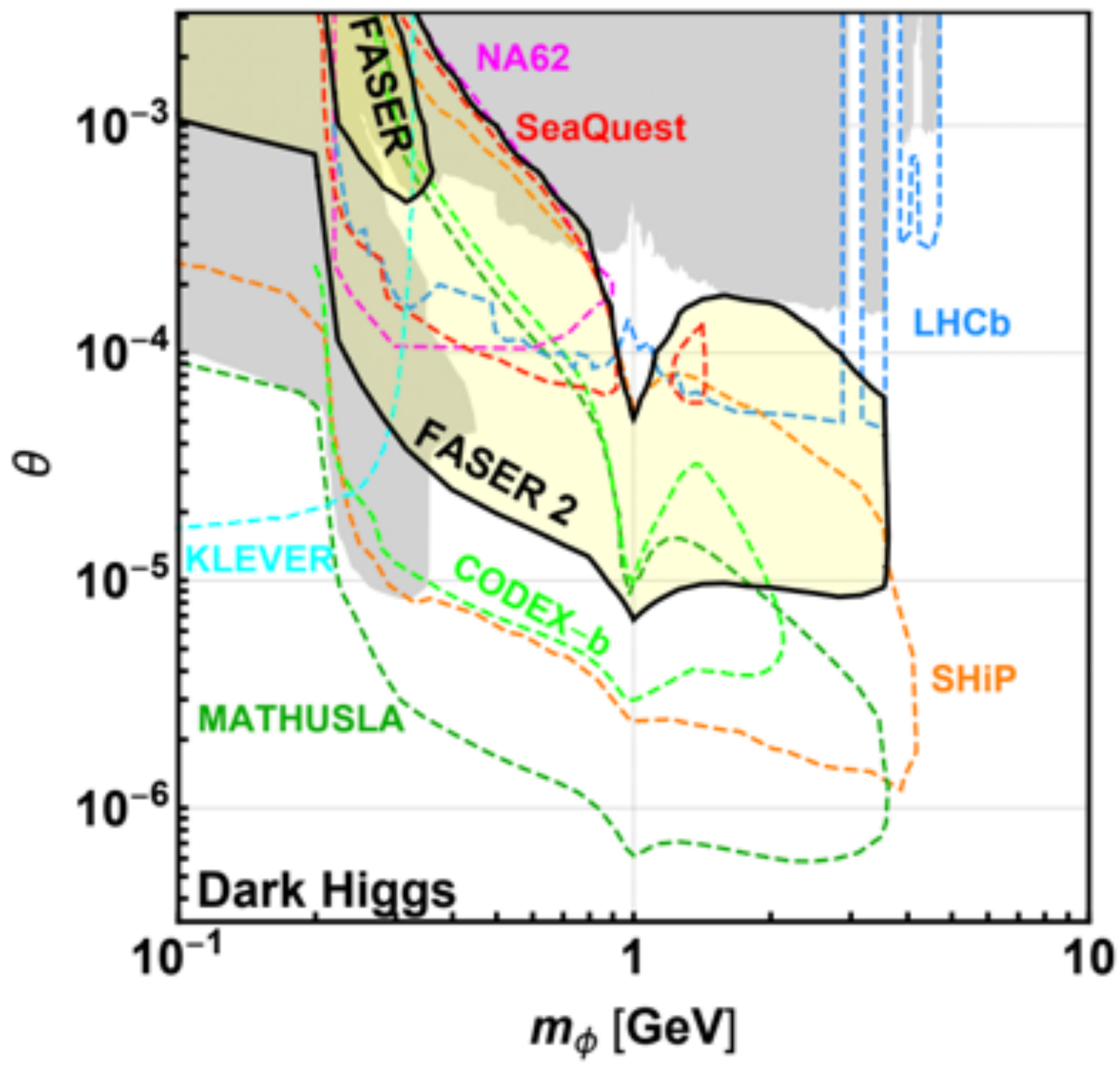
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.



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)

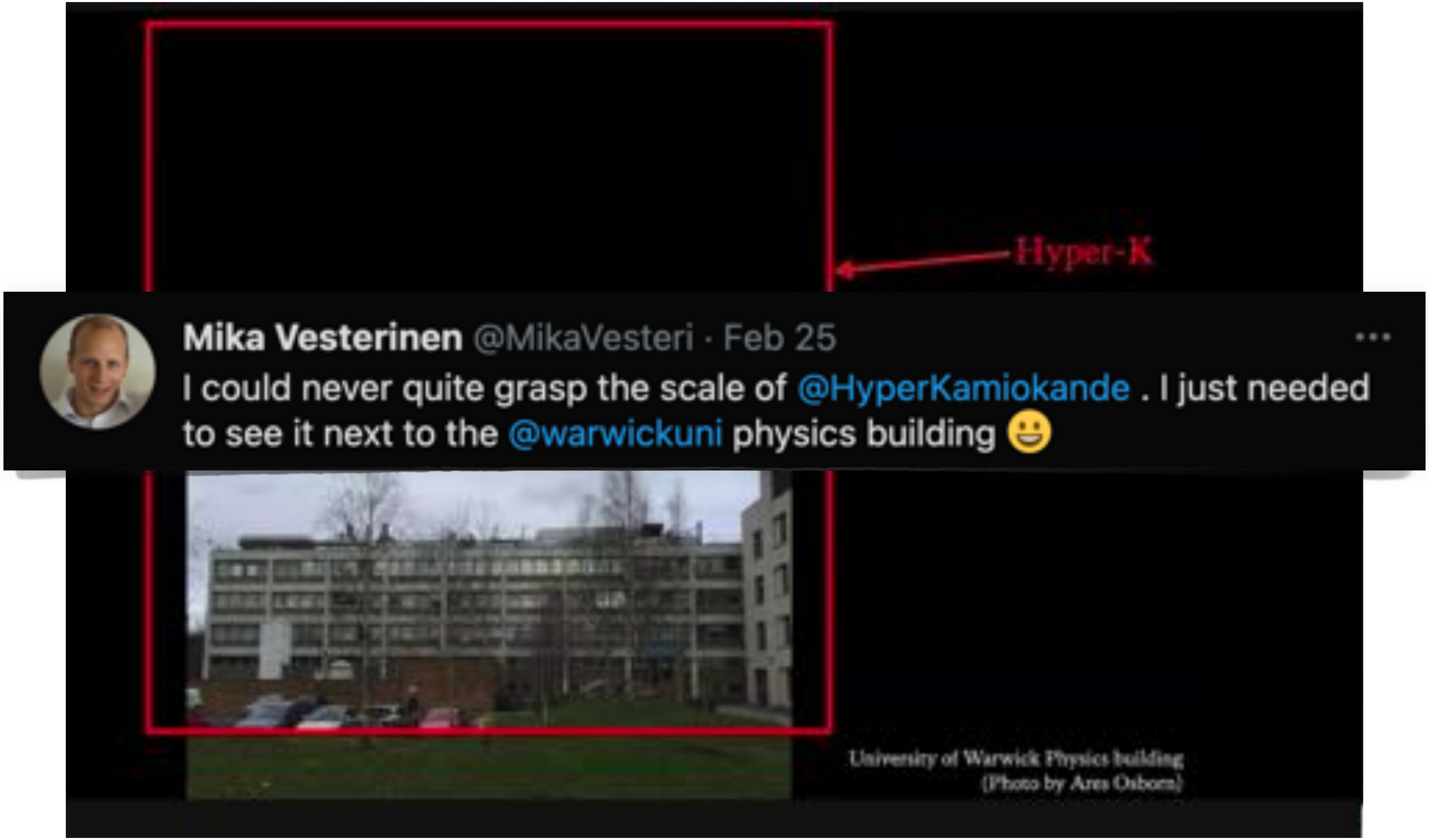


Summary

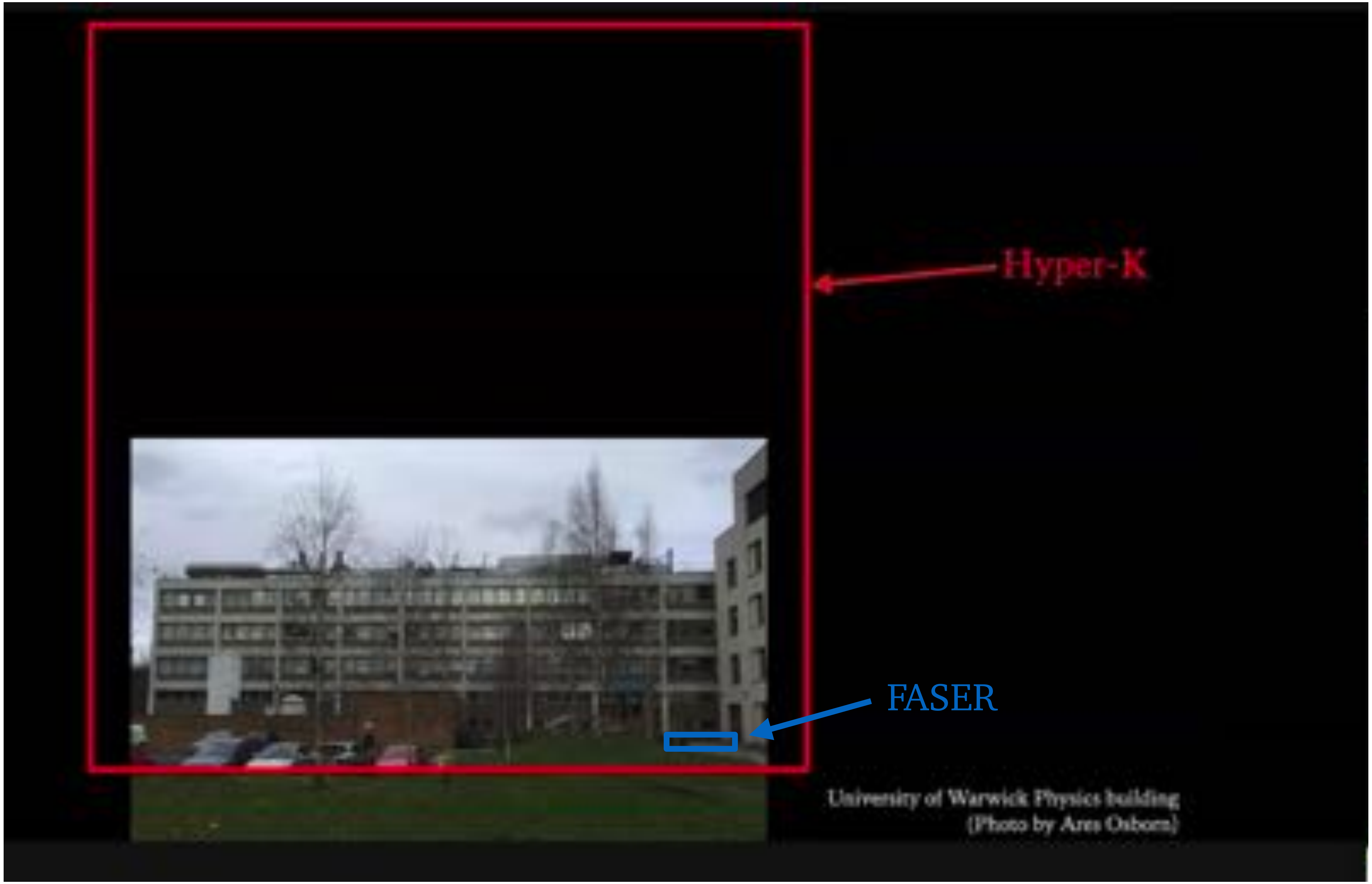
Summary

- 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 design, construction & testing progressing well → LS2 installation on track
  - Data-taking begins soon… 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

Summary


Hyper-K
Mika Vesterinen @MikaVesteri · Feb 25
I could never quite grasp the scale of @HyperKamiokande . I just needed to see it next to the @warwickuni physics building 😃
University of Warwick Physics building
(Photo by Ares Osborn)

Summary



Hyper-K
FASER
University of Warwick Physics building
(Photo by Ares Osborn)


Thanks for your attention! 🙏

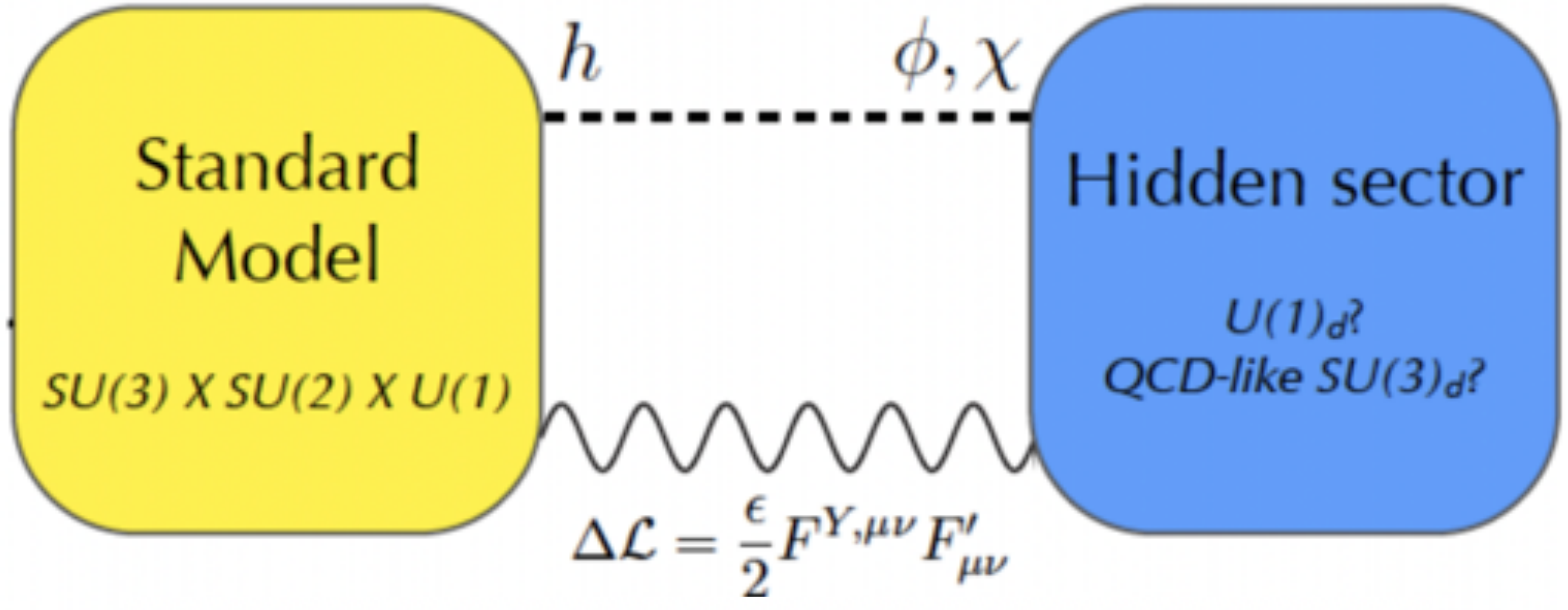
Back-ups

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

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

- 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



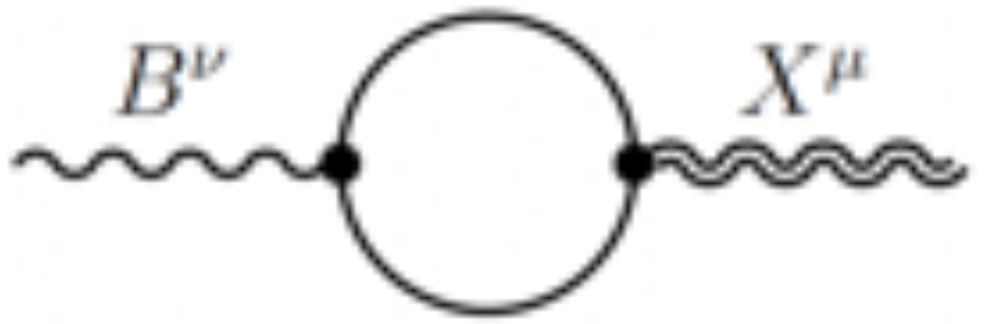
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

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:

Visible Sector
SM, $U(1)_{EM}$, B^{ν} - - - $\frac{1}{2}\epsilon F^{\mu\nu}F_{D\mu\nu}$ - - - Dark Sector
DM, Dark Forces, X^{μ}

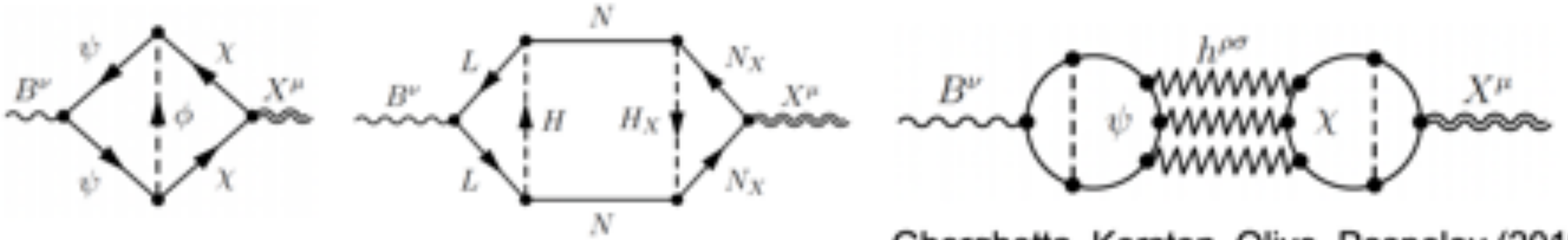
- Mixing can be generated at 1-loop. If 0 at high scale, expect $\epsilon \sim 10^{-3}$



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

Holdom (1986)

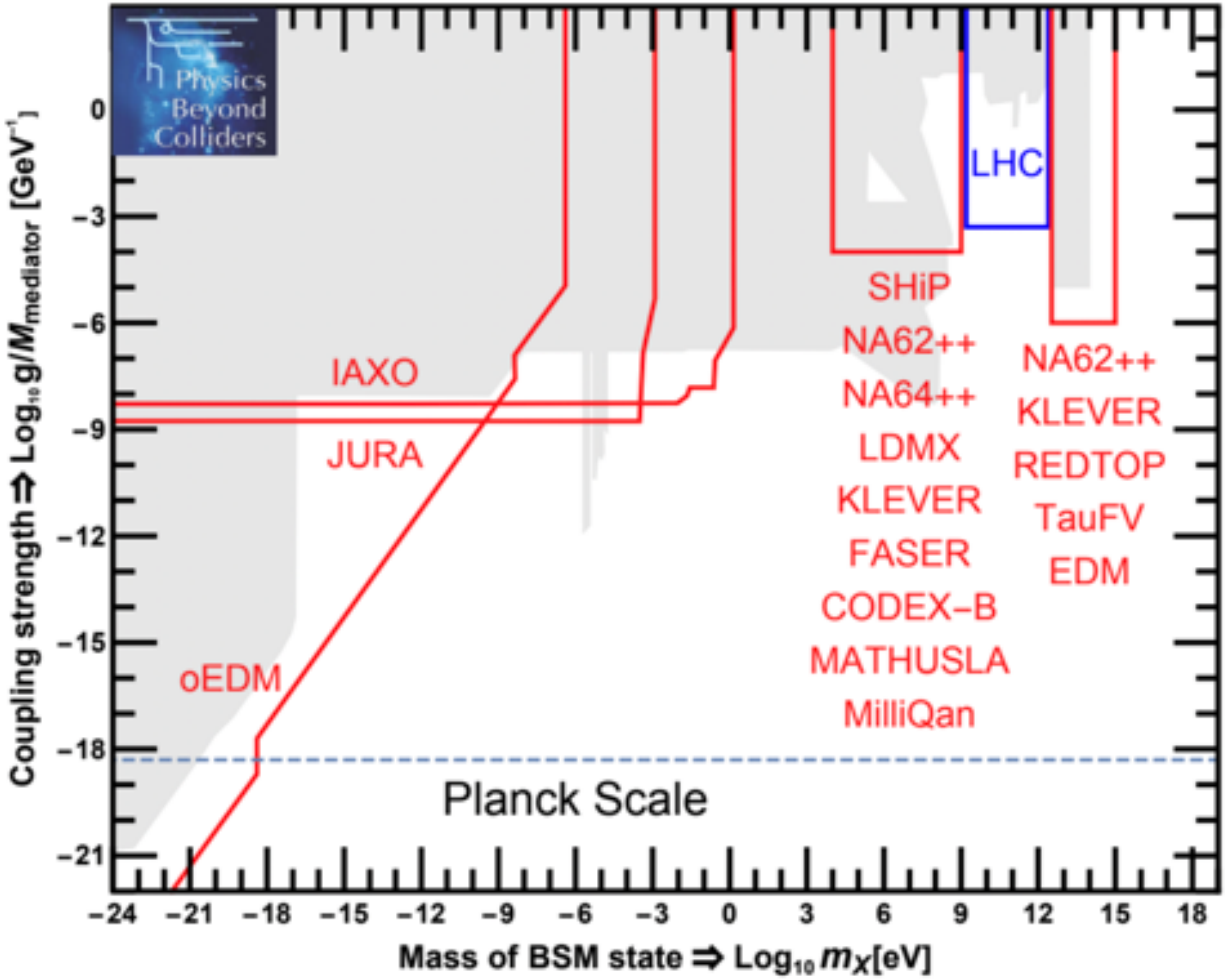
- But there are also theories with mixing generated only at higher loop level



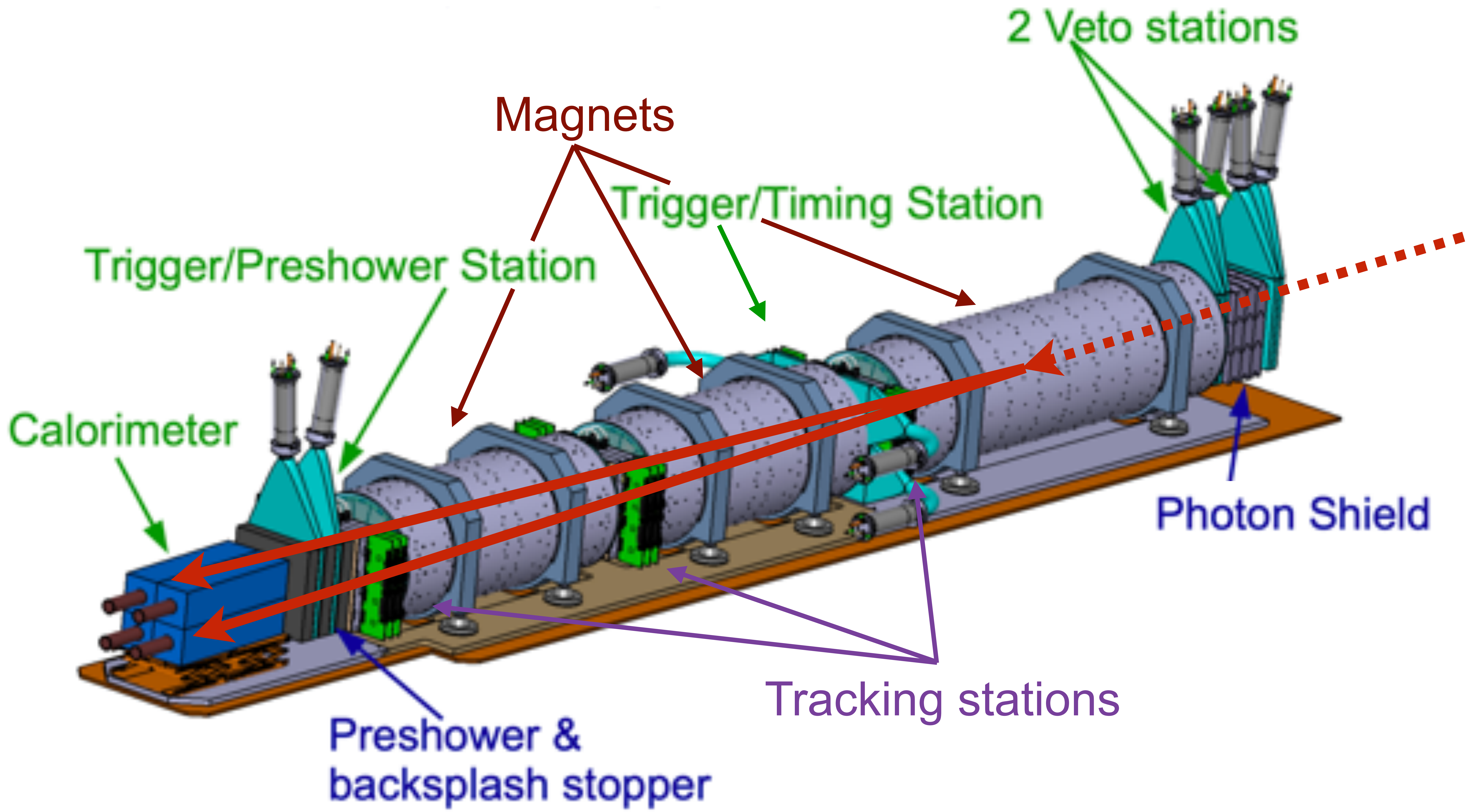
Gherghetta, Kersten, Olive, Pospelov (2019)

- 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



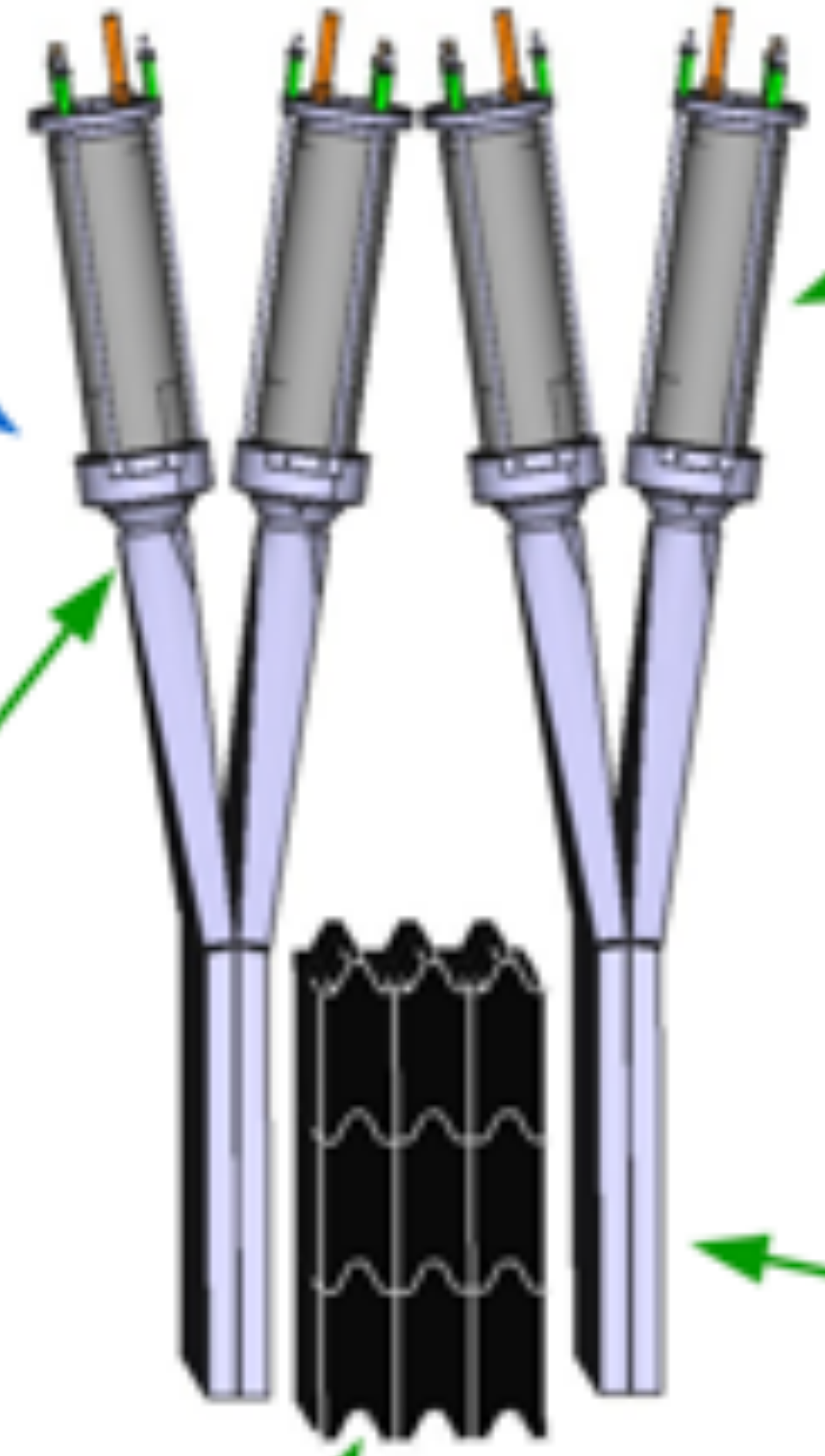
Detector | Details



Scintillators | Veto stations

Final design could be more vertical PMT position

Will have port for LED signal



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

Interlocking lead bricks
- ~$150 \times 300 \times 300 mm^3$
- exact bricks TBD
- shower/stops photons from upstream muons

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

Two independent scintillator layers per station
- $20 \times 300 \times 300 mm^3$
- EJ-200 from Eljen Tech.

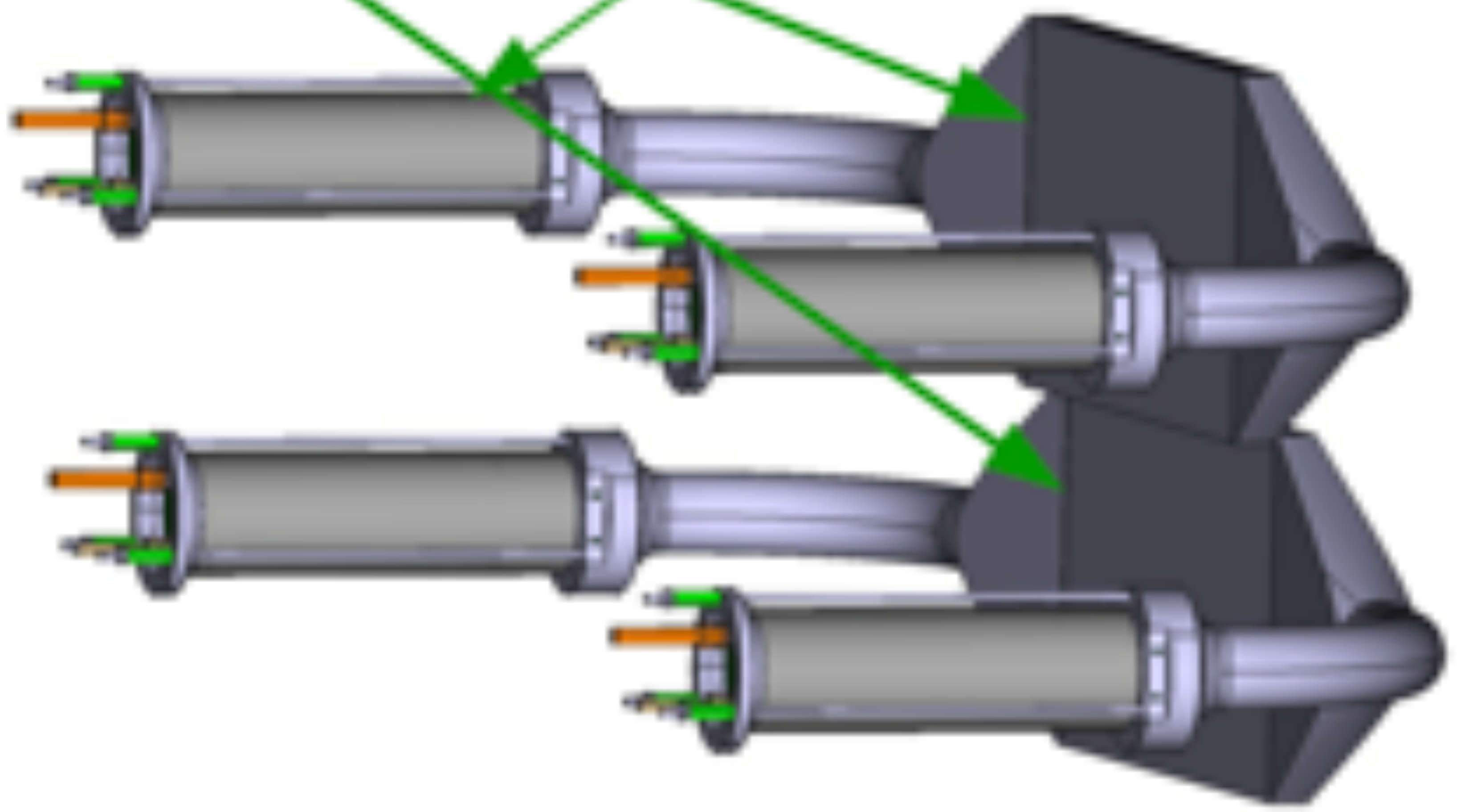
PROPERTIES	EJ-200
Light Output (% Anthracene)	64
Scintillation Efficiency (photons/1 MeV e^-)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5

- 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)

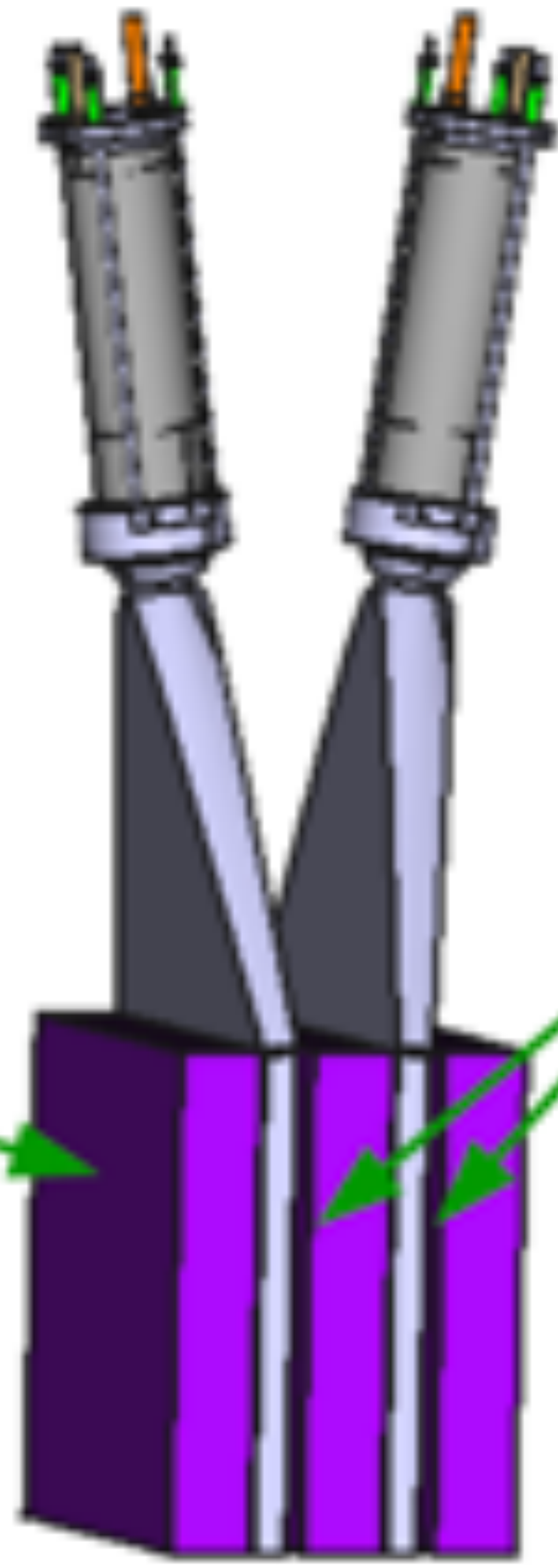
Same H6410 PMTs



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

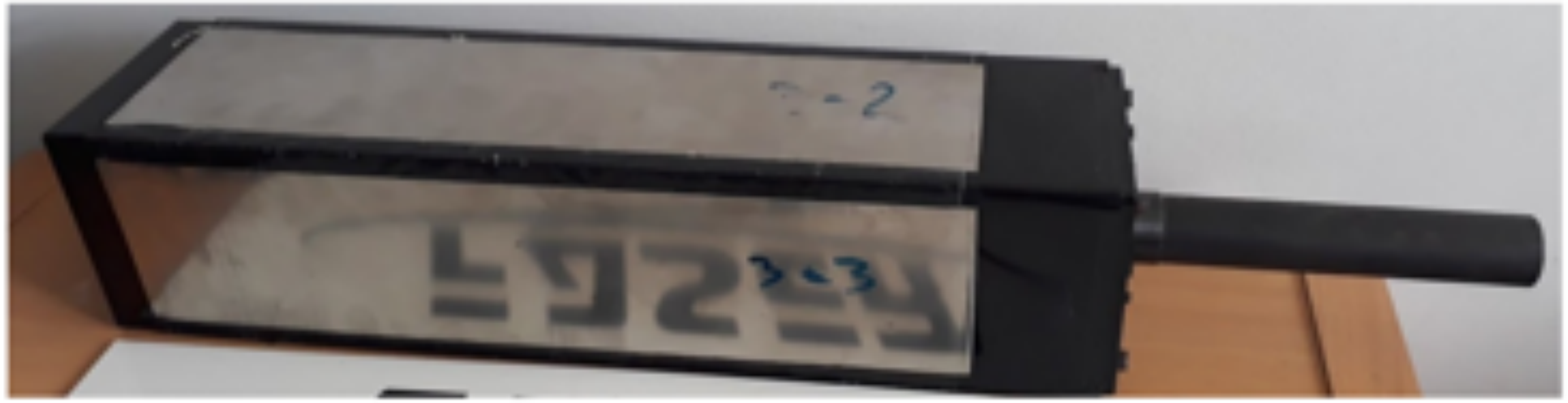
Embed/glue in two 1 radiation length (~5mm) lead plates in front of scintillator layers to start EM shower

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

Calorimeter

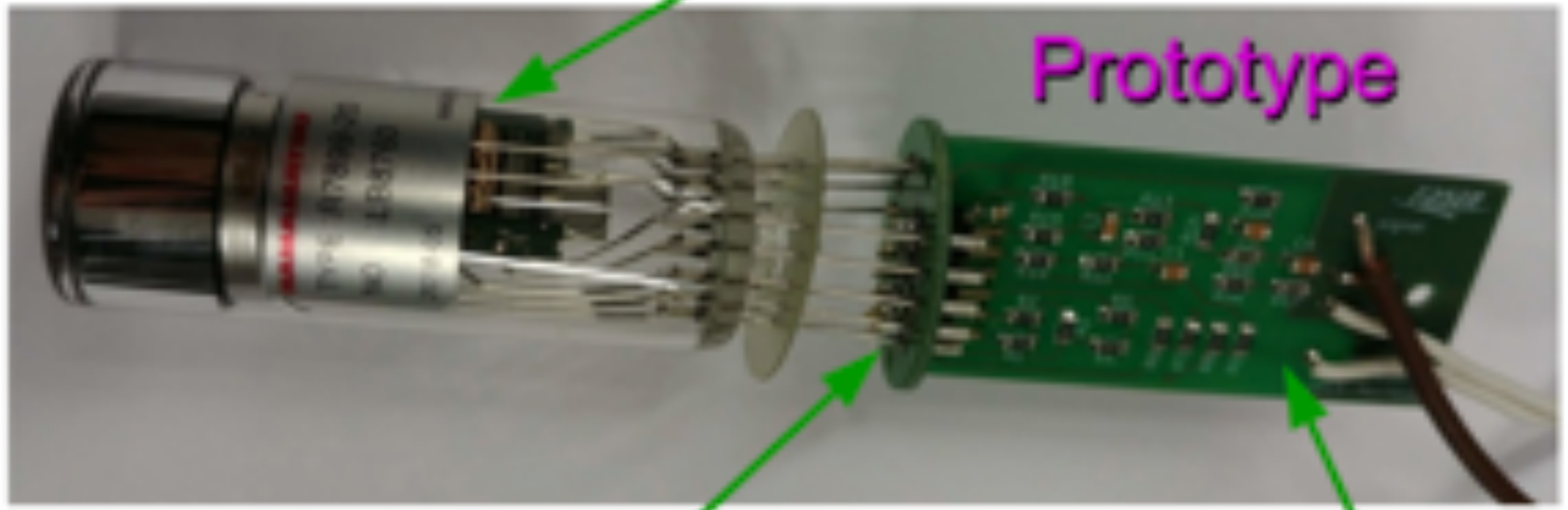
Using 4 LHCb spare outer ECAL modules for calorimeter (have 8)

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)



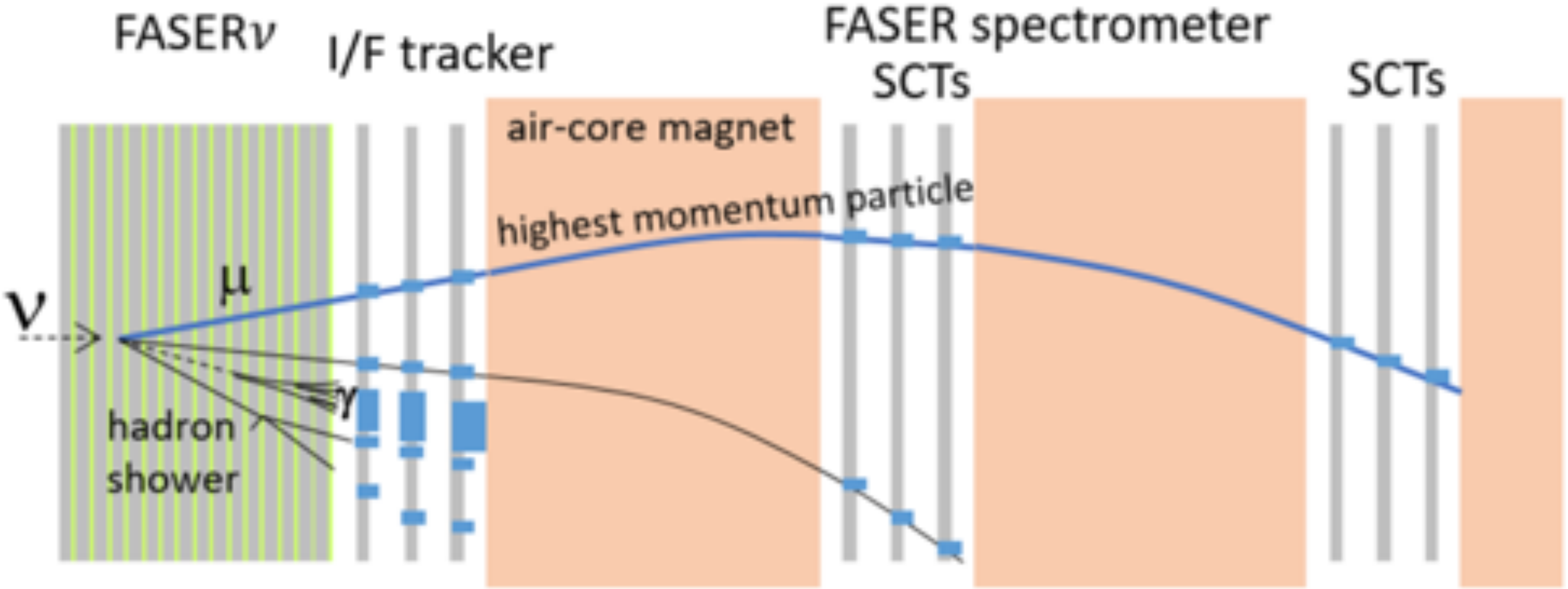
Had to make our own HV base

- done by Friedemann

Have new base with non-solder connection

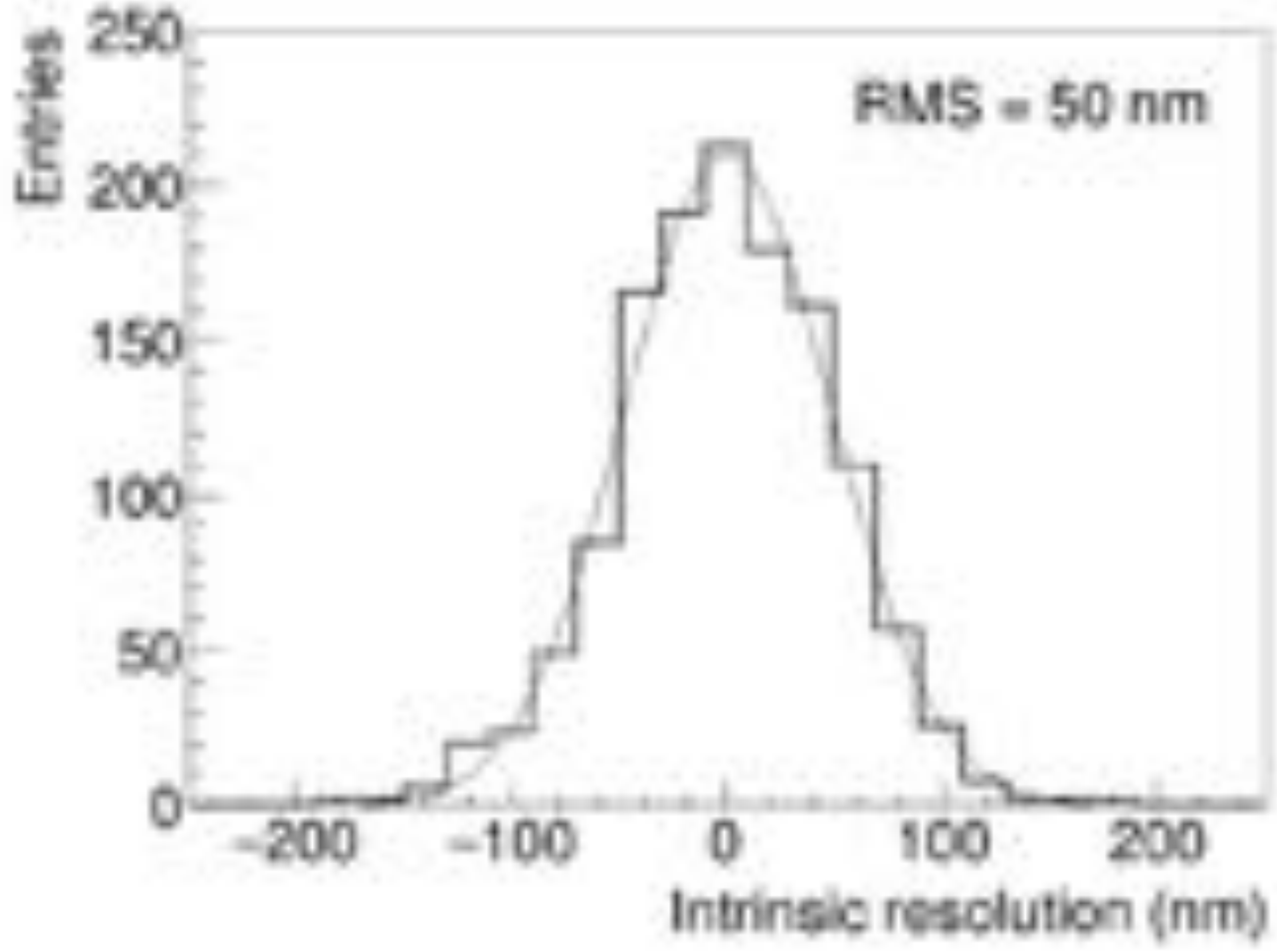
Divider to be shortened to fit in calorimeter tube – waiting for final tests of proto-type

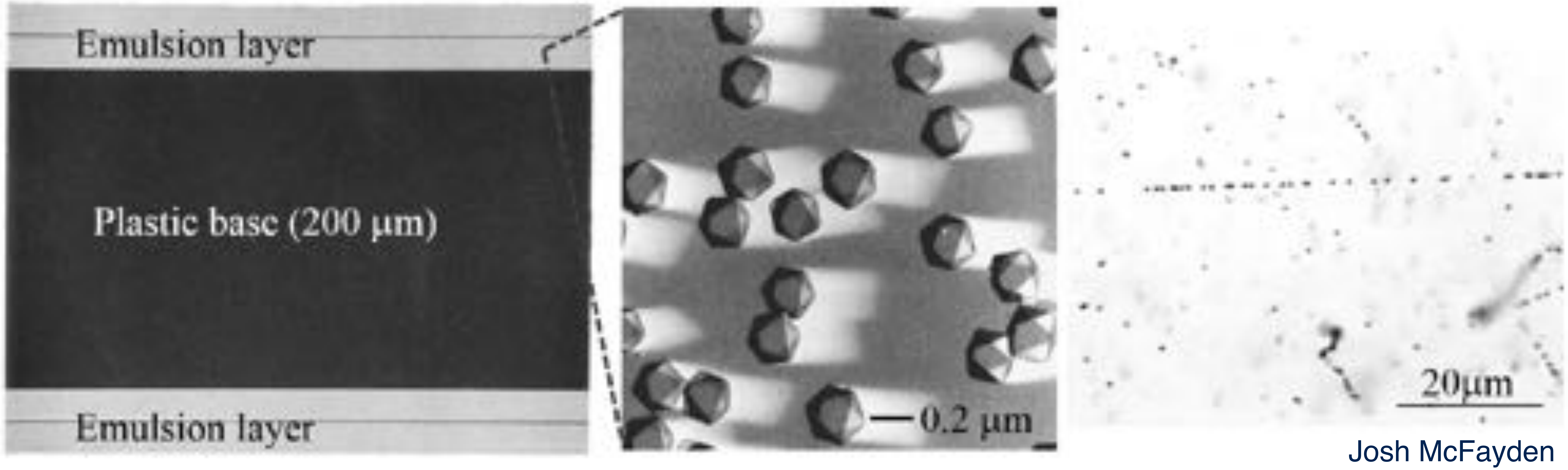
FASERν | Interface detector



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!

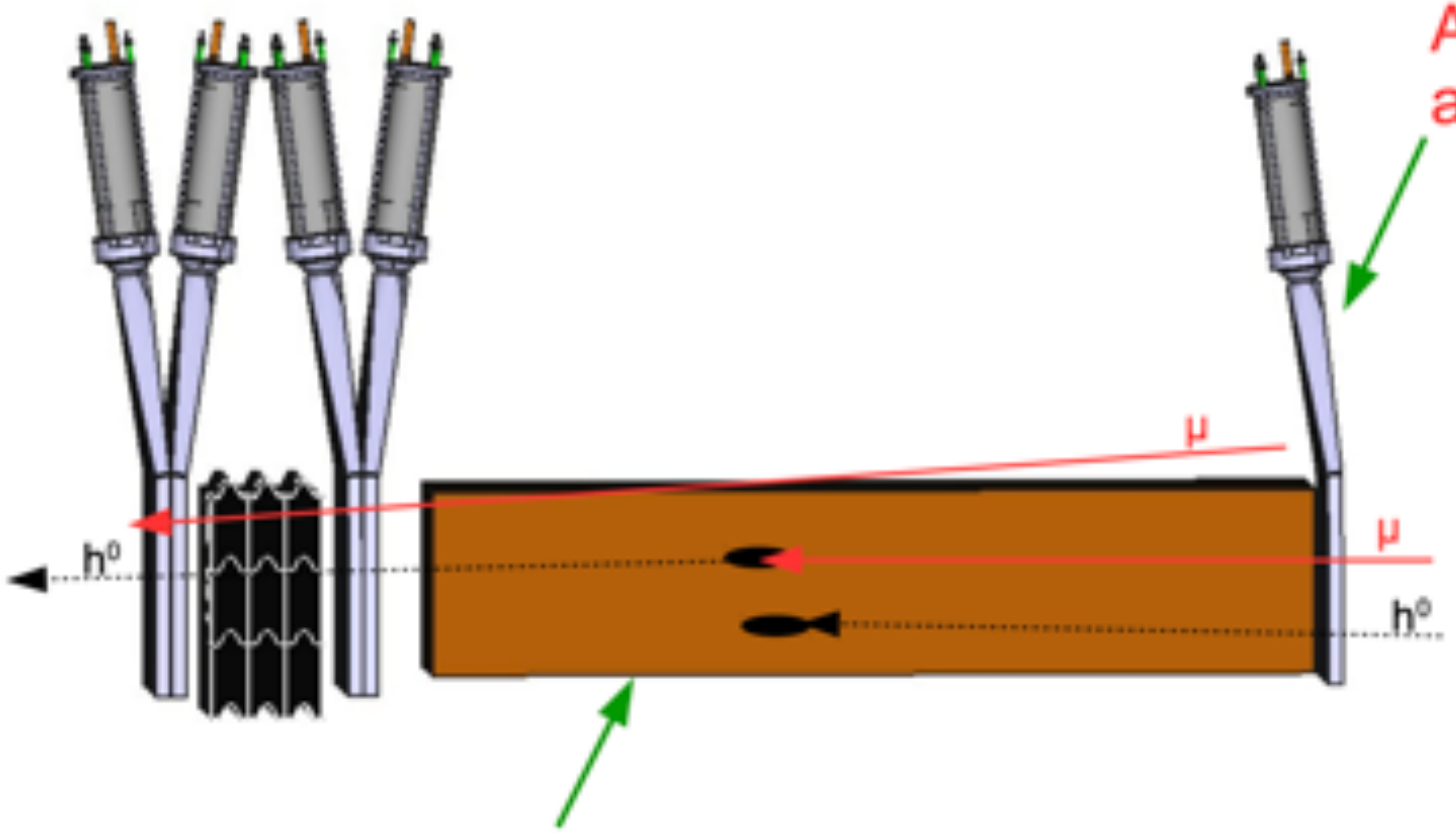




FASERν | Interface detector

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

FASERν | Neutrino flux estimates

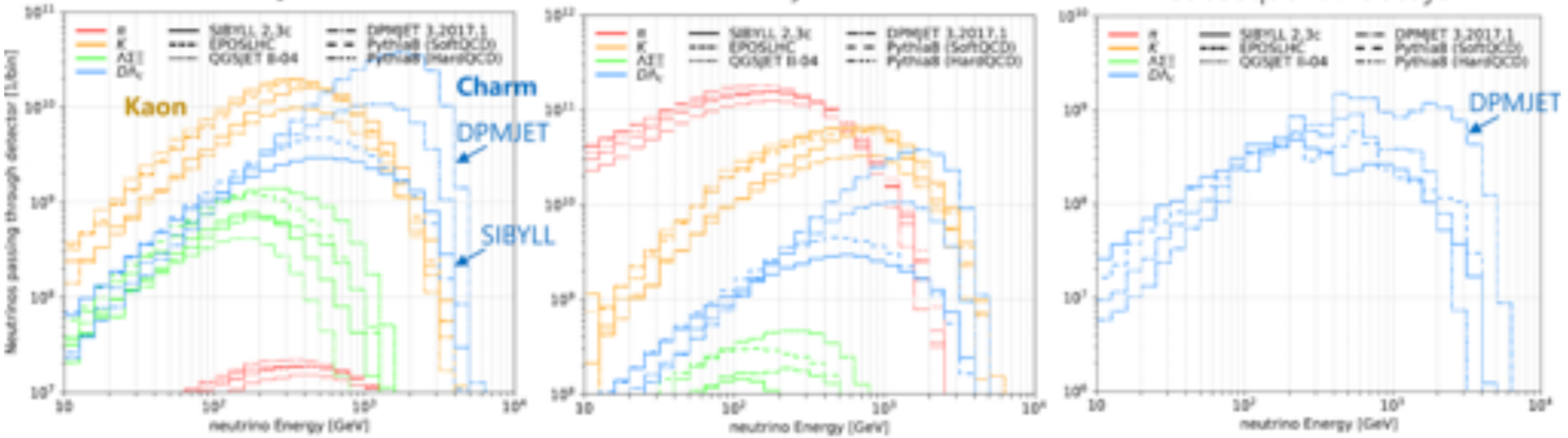
- Checking three simulations.
  - FLUKA (by F. Cerruti's group)
  - BDSIM (by H. Lefebvre, L. Nevay)
  - RIVET-module (by F. Kling)

- **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

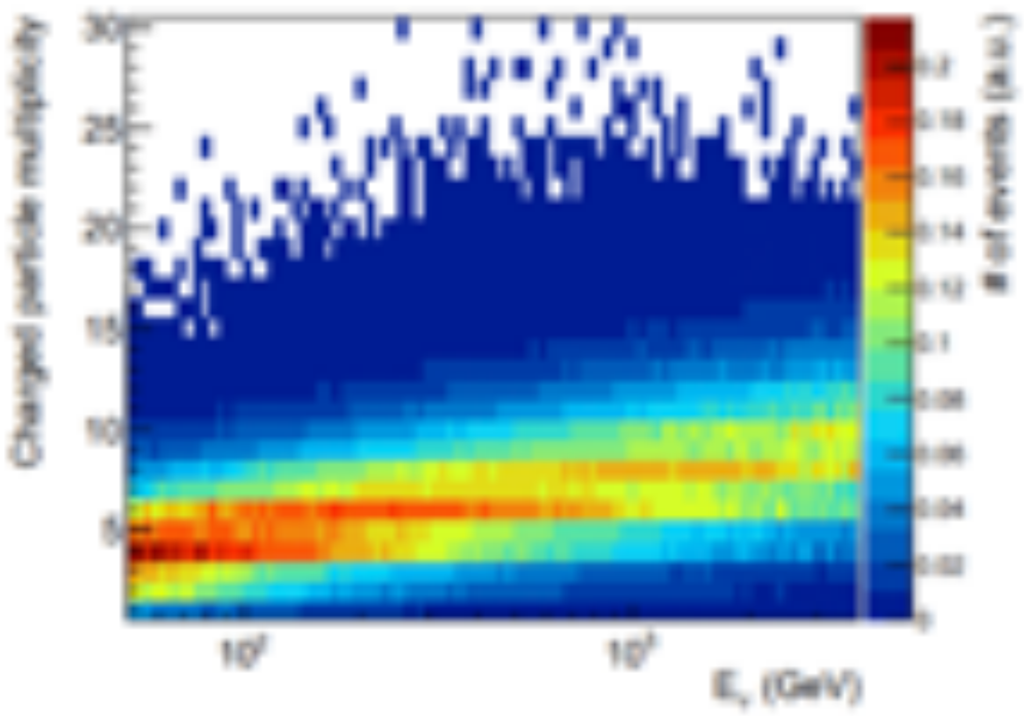


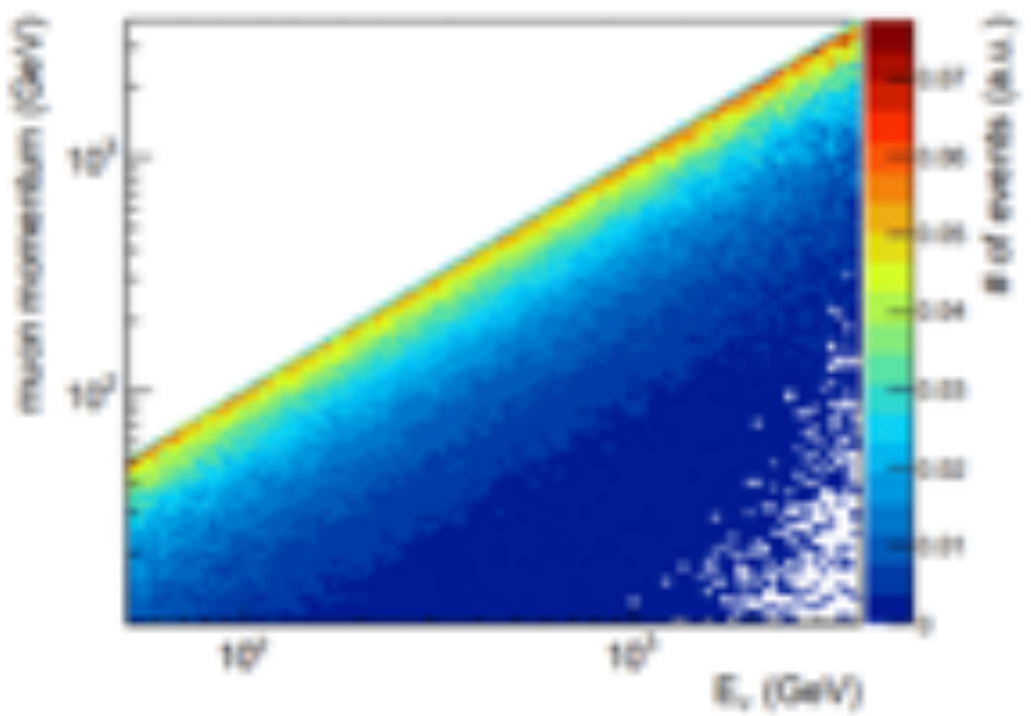
FASERν | Neutrino energy reconstruction

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

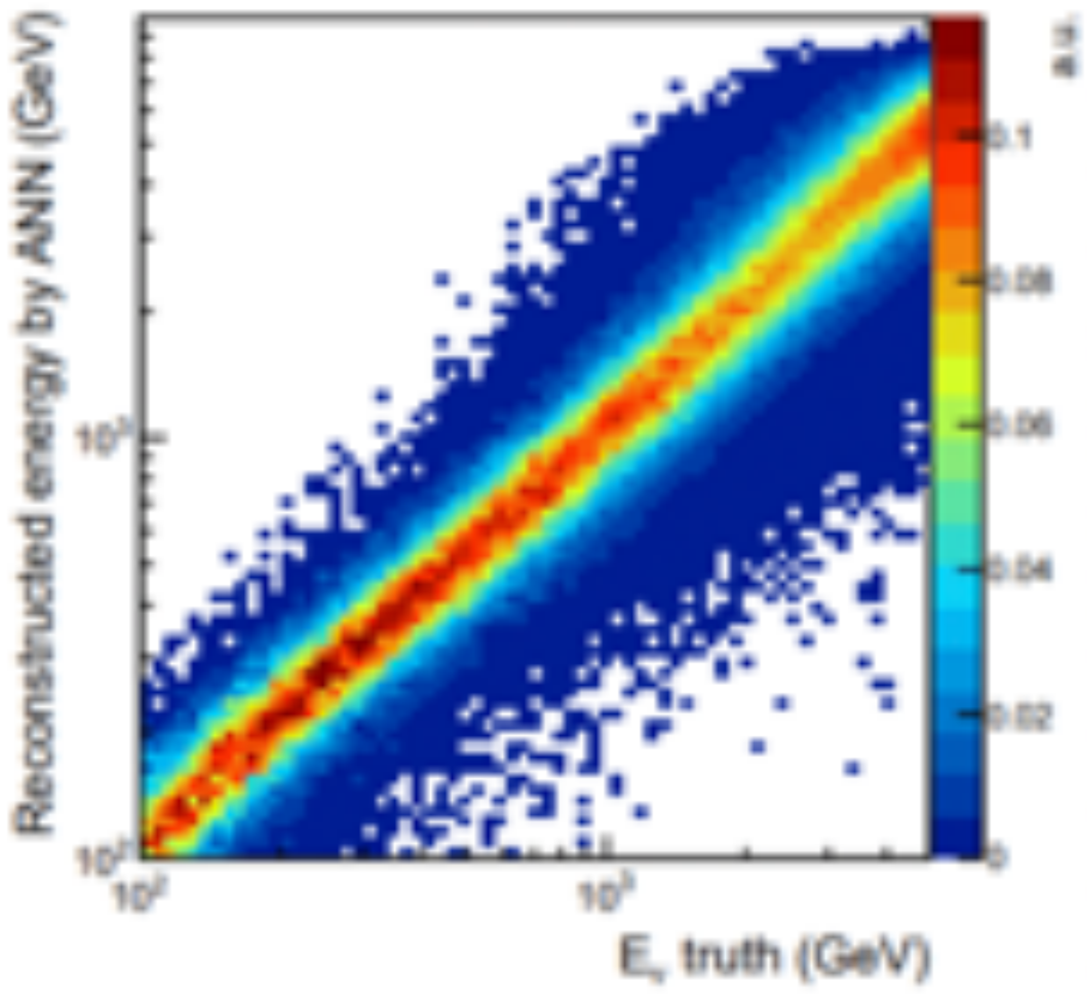
An ANN algorithm was built with
topological variables
- # of charged tracks → E_h
- # of γ showers → E_h
- inverse of lepton angle → E_l
- sum of inverse of hadron track angles → E_h
- inverse of median of all track angles → E_h, E_l

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





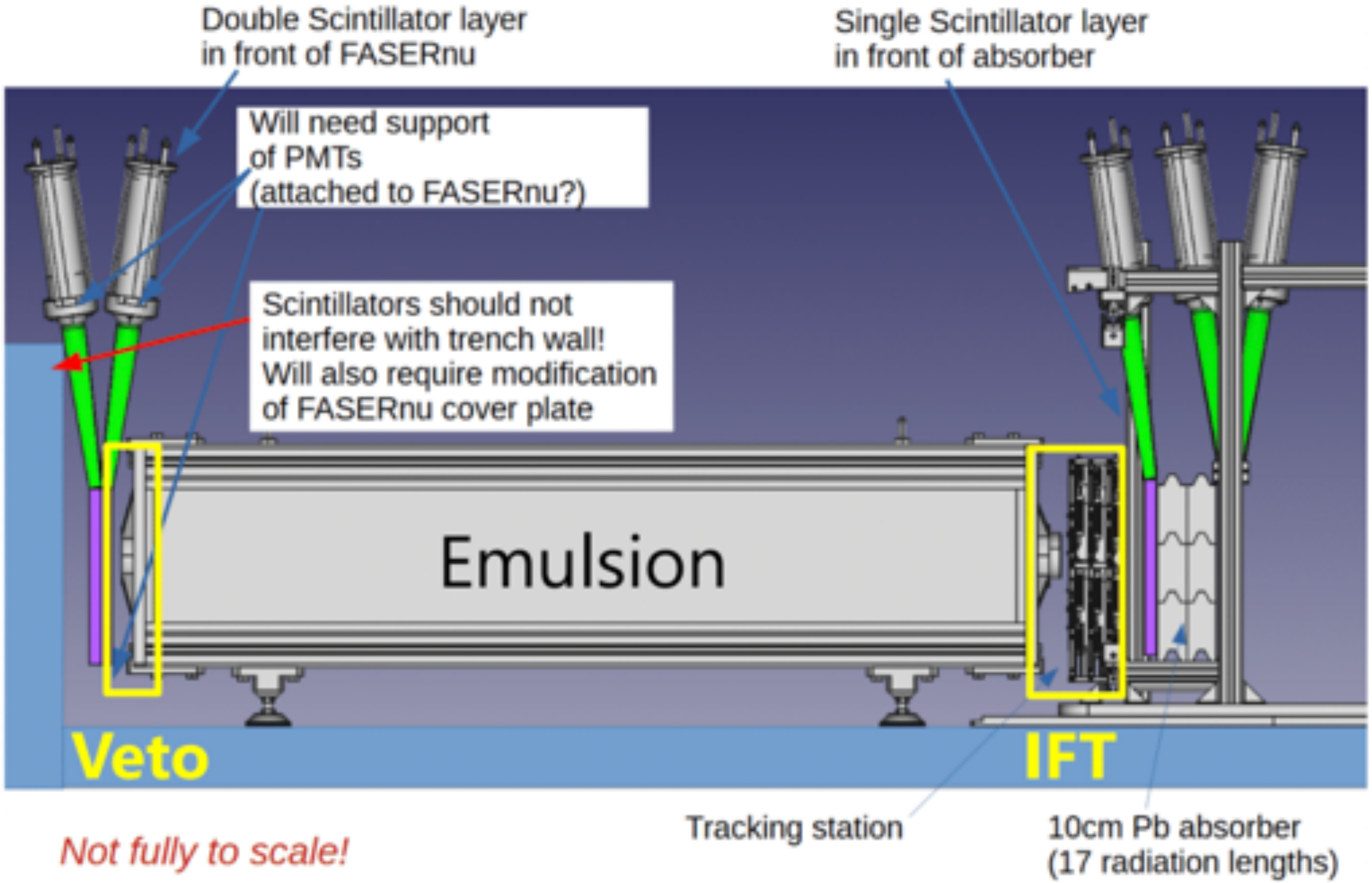
$E_\nu - E_{ANN}$



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

FASERν | Interface to FASER

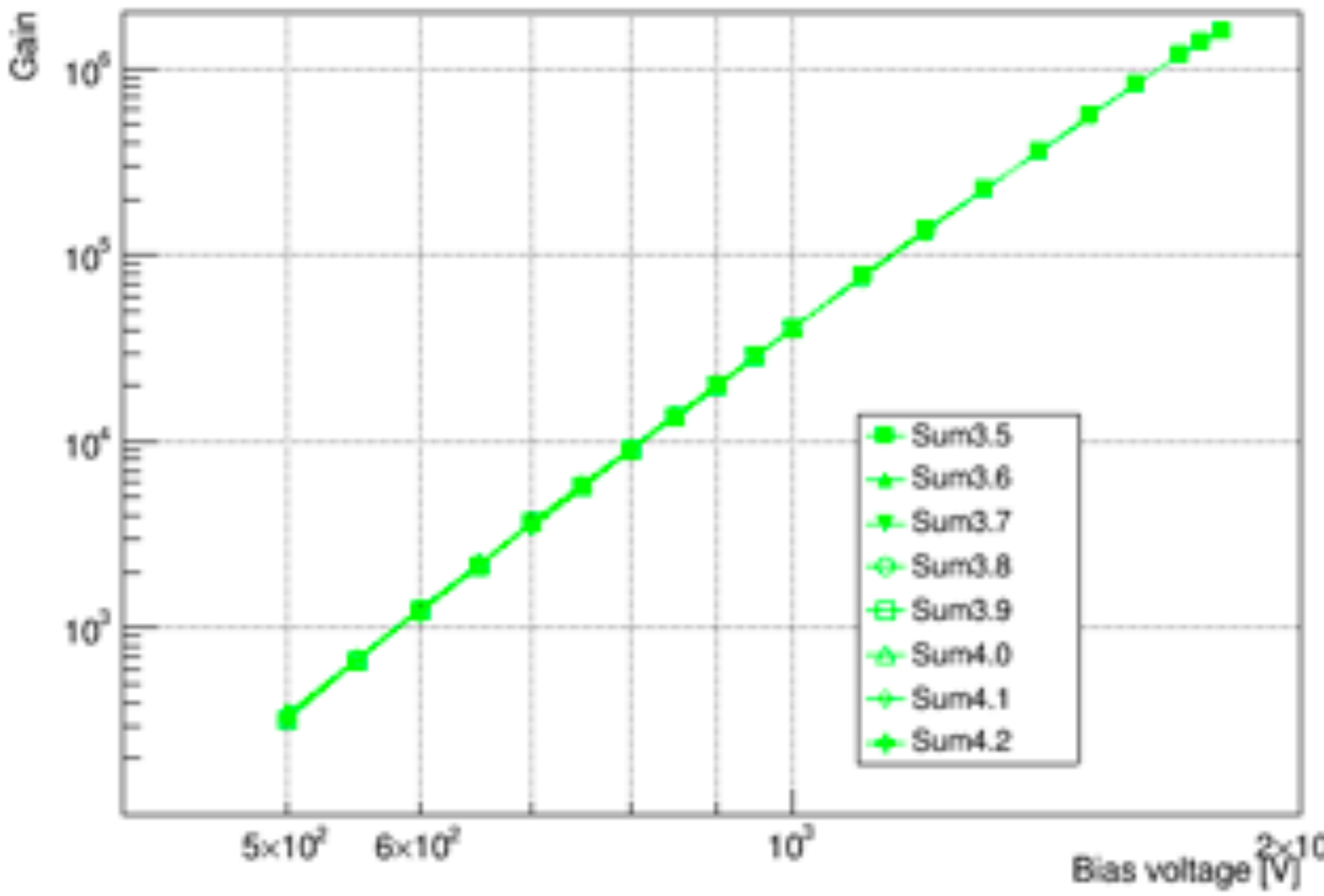
- To connect muon tracks from νμ interactions for charge identification etc.
  - Interface tracker (IFT) with 3 layers of silicon strip detector. A copy of FASER tracker station.
  - Veto station consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle coming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

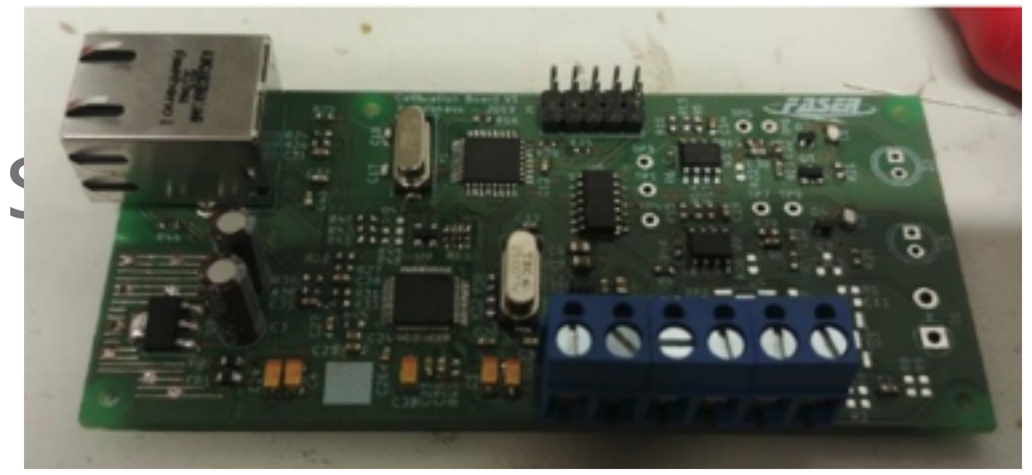


Scintillator and Calorimeter | PMTs

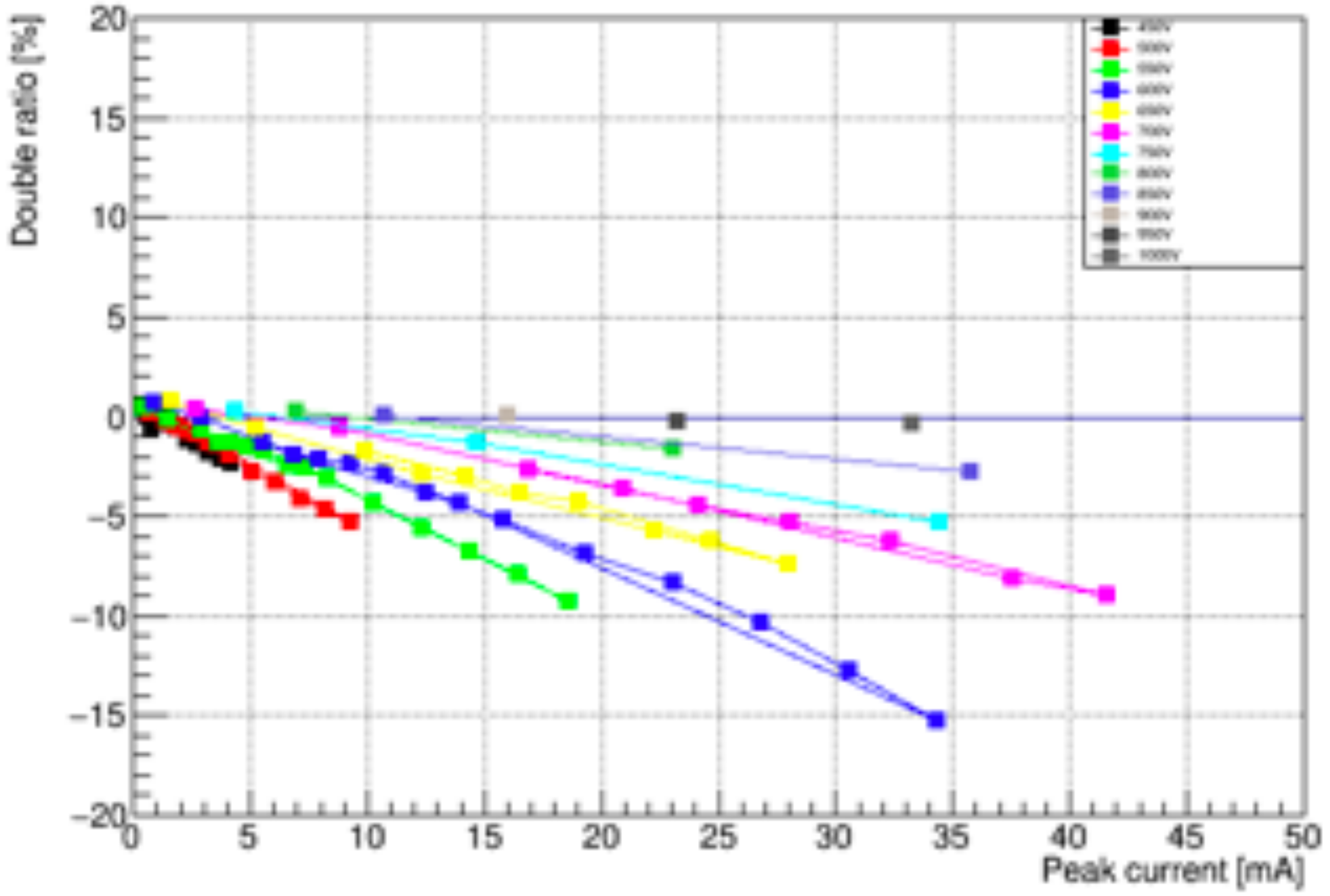
- Have a well developed lab setup for scintillator & calorimeter PMT characterisation
  - Automation of signal pulse and HV settings.
  - PMT signal read-out by digitiser.
  - Well defined procedure to extract gain and linearity measurem
- In-situ calibration
  - Will measure gain vs HV, by pulsing with 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.

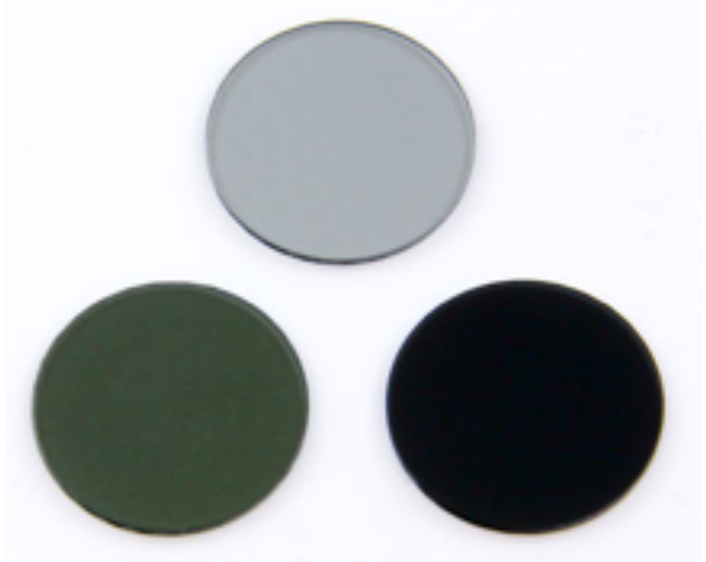
Gain





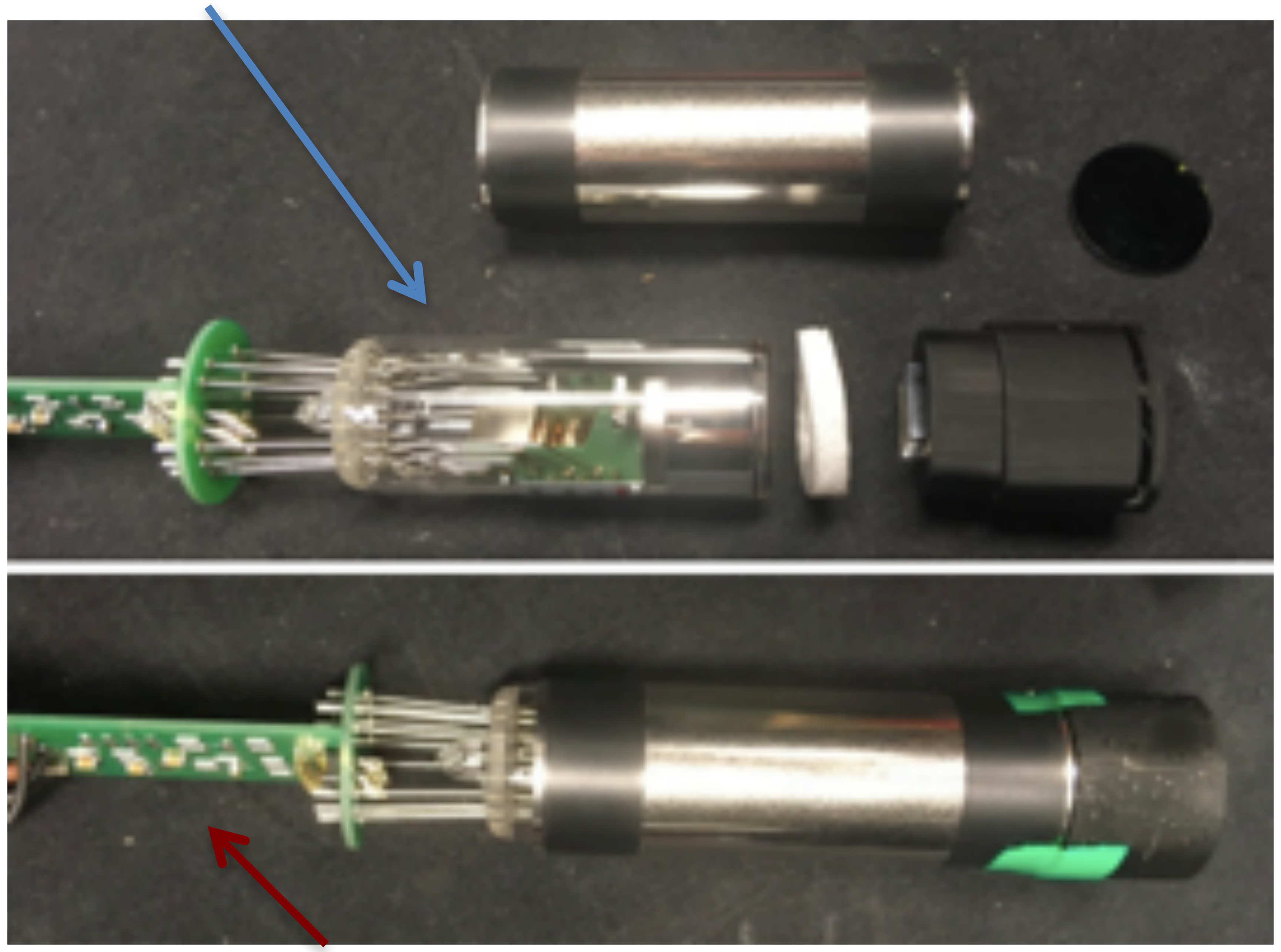
Linearity



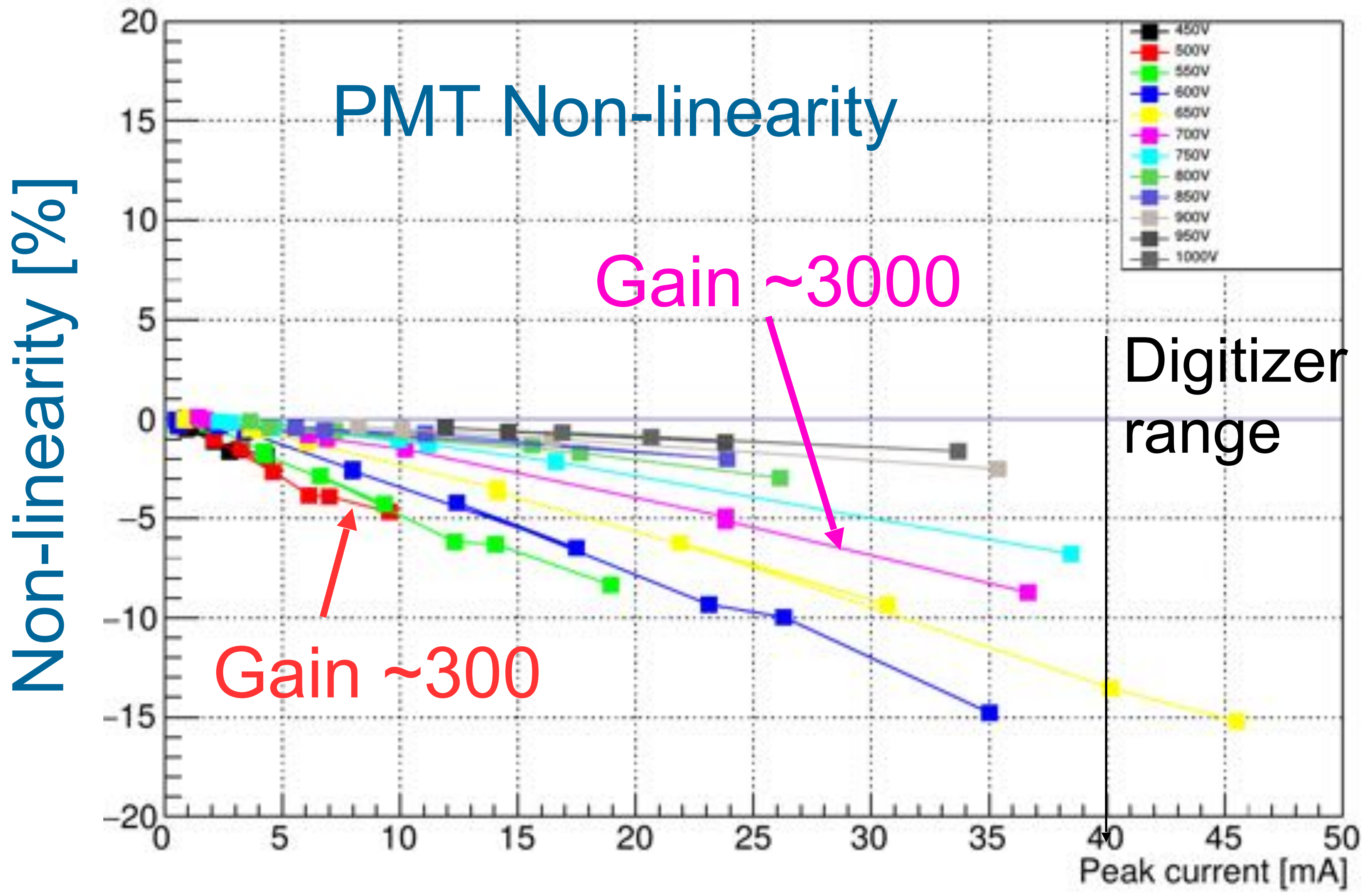


Calorimeter | PMTs

R7899-20 Hamamatsu PMTs provided by LHCb



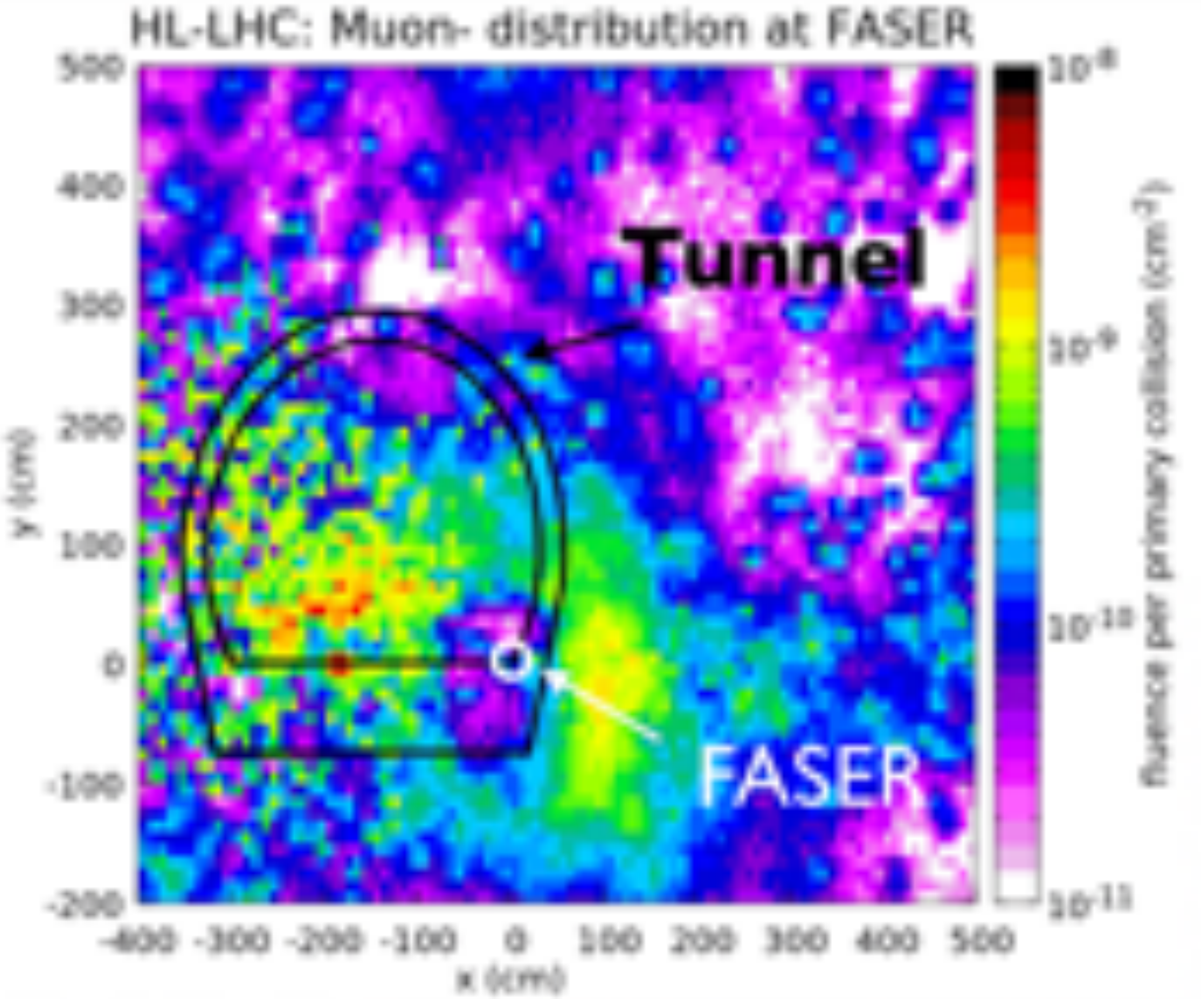
New HV divider

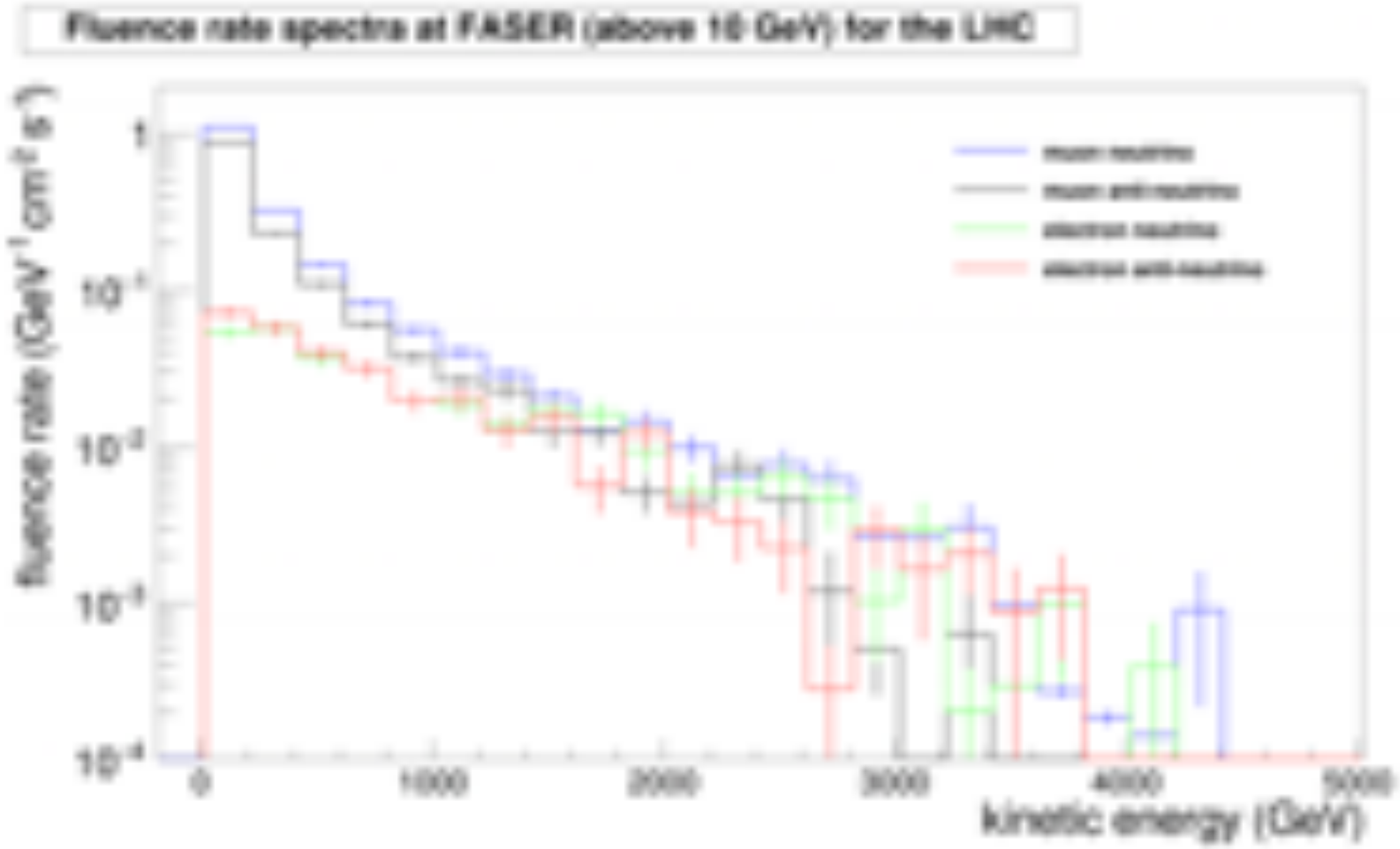


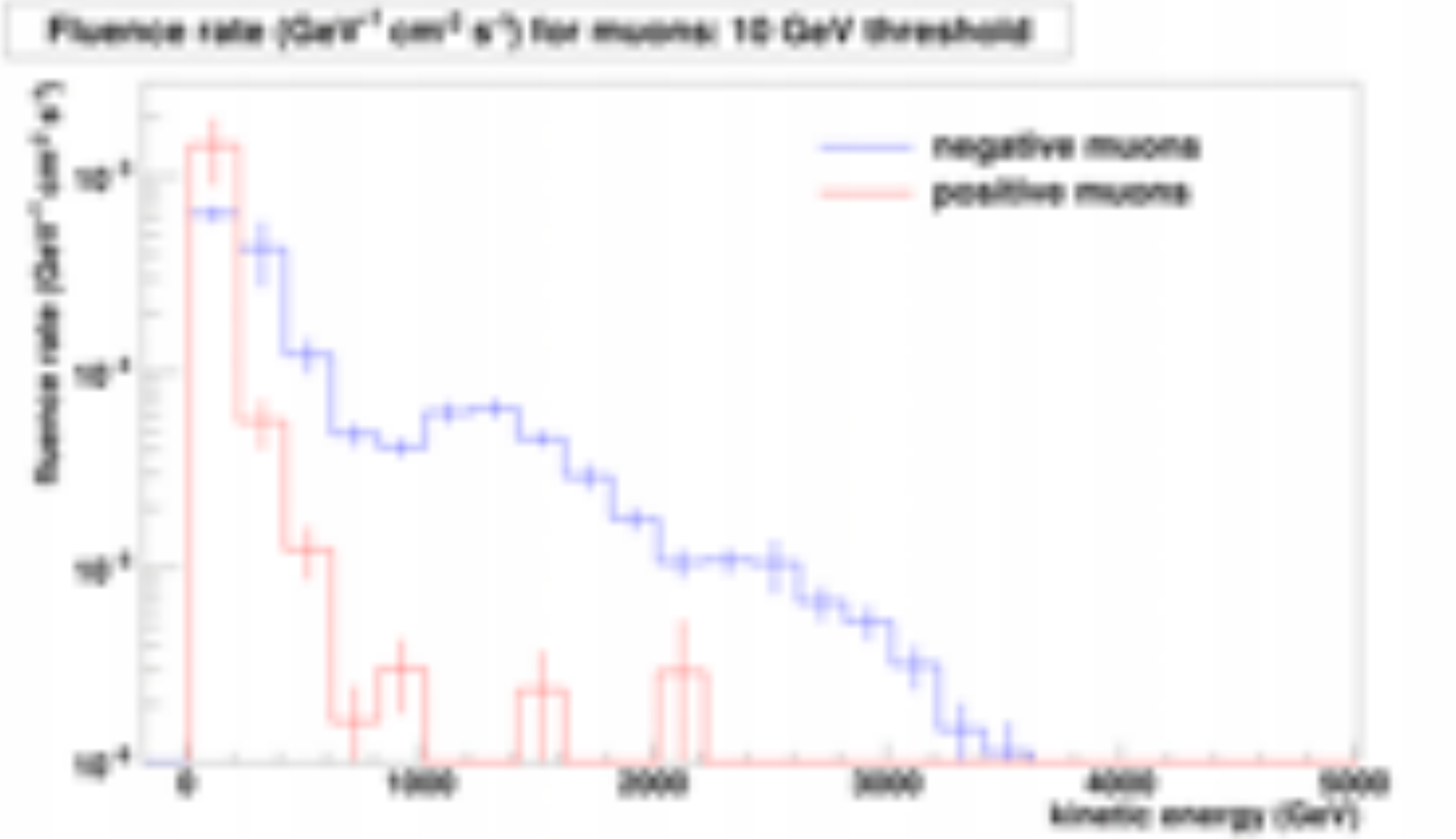
- Testing lab with LED pulser and cosmic ray test stand setup at CERN
- Used to characterize and determine HV working point
- Low gain needed to have sufficient range for largest signals
- Energy calibration:
  - Using *in situ* muons (MIPs)
  - Plan to also have test-beam during Run-3 for spare modules

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 } *Minor*
- Low particle flux along beam axis due to LHC optics.





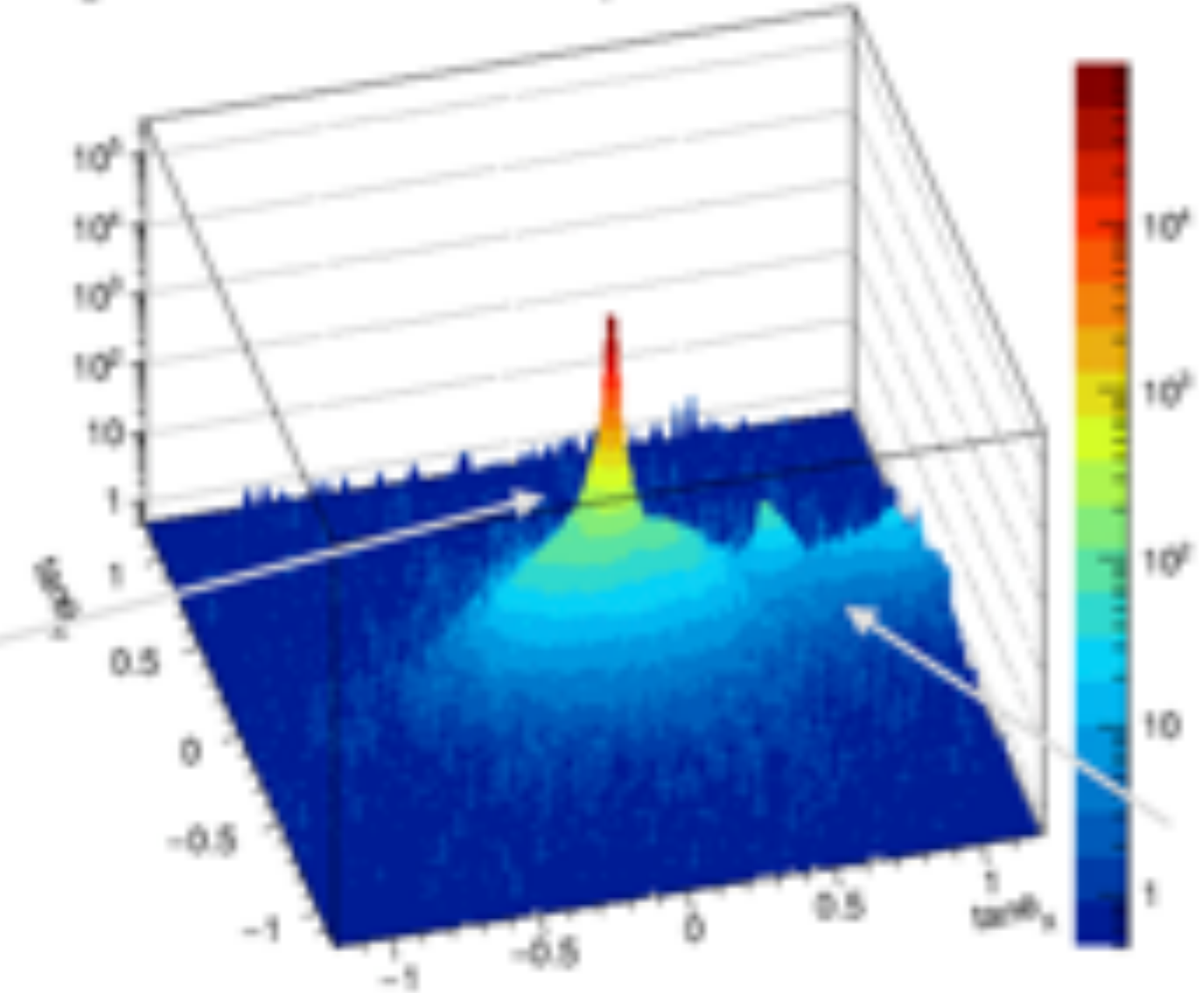


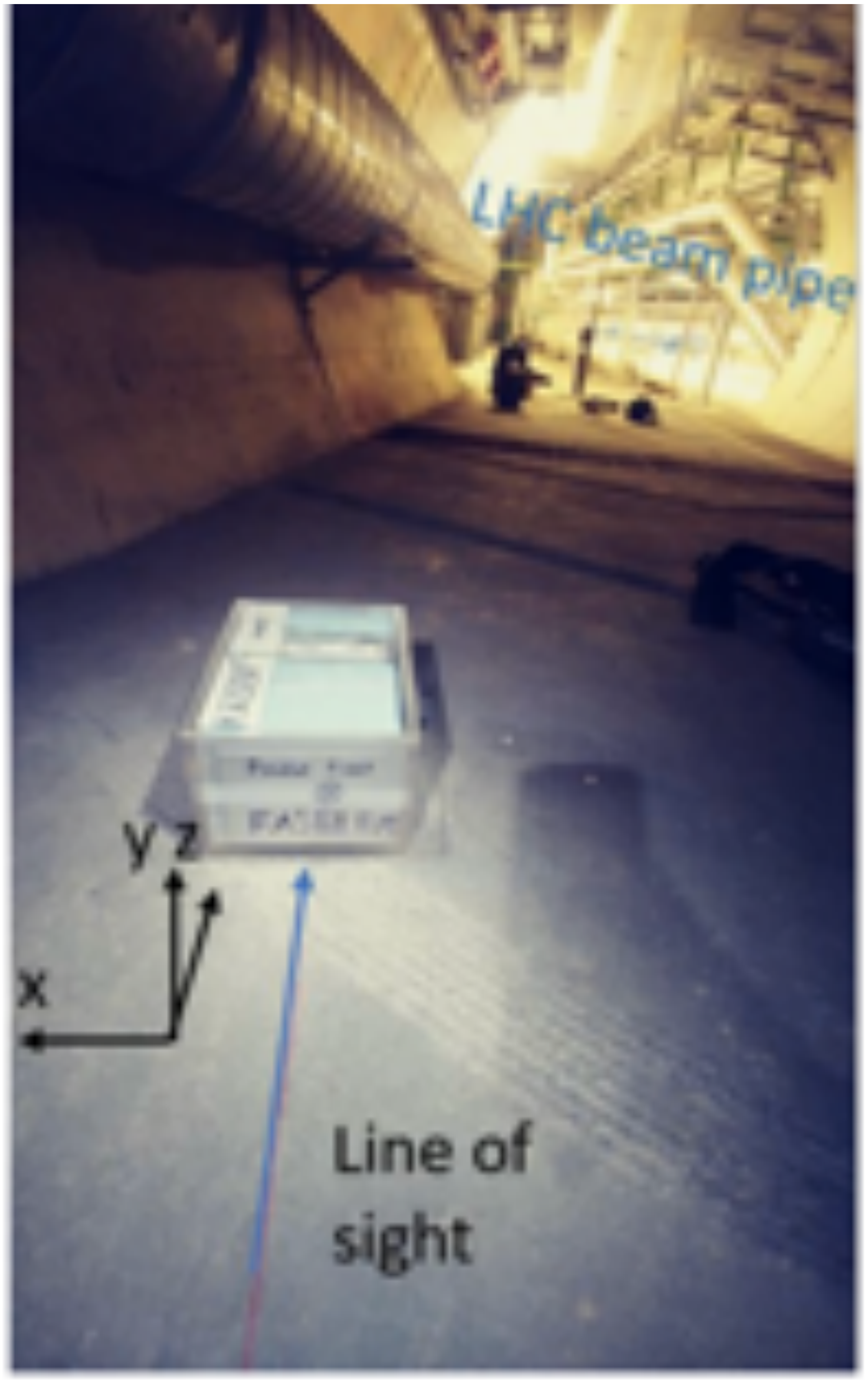
Muon charge asymmetry due to LHC magnets

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

- *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).

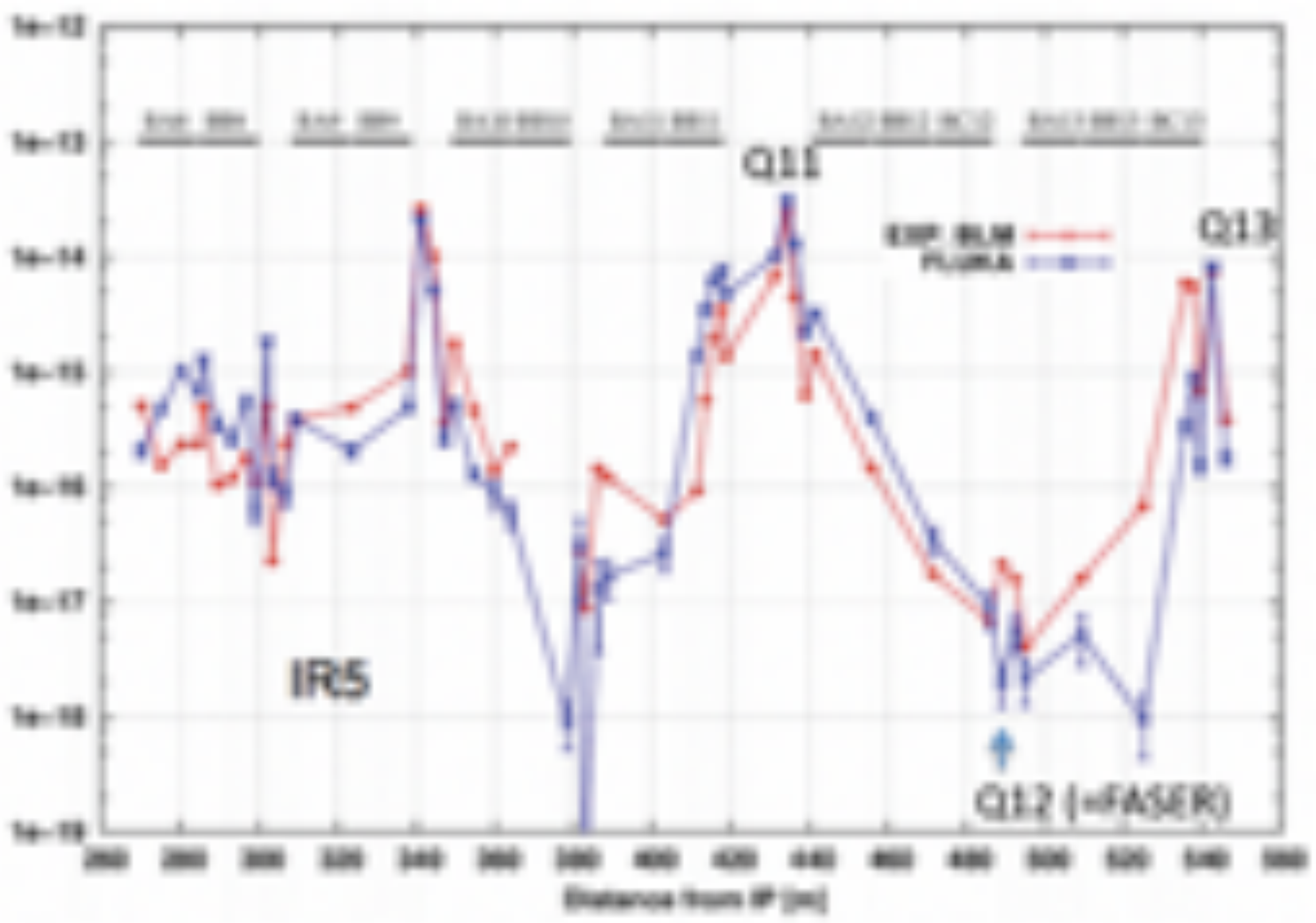
Always co-linear with accompanying muons

- $10^5 \rightarrow 10$ with veto

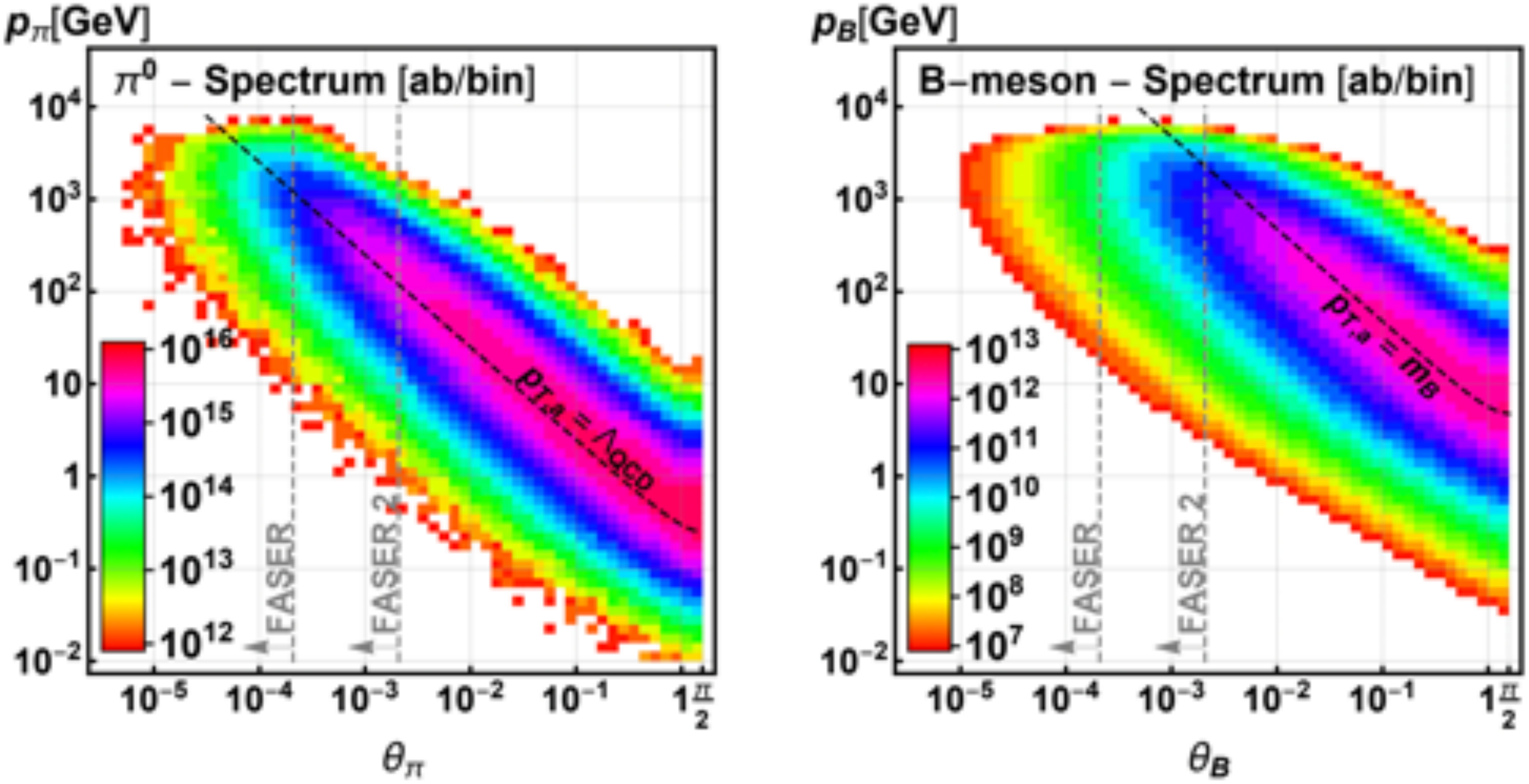
Minor

Conditions | Radiation levels

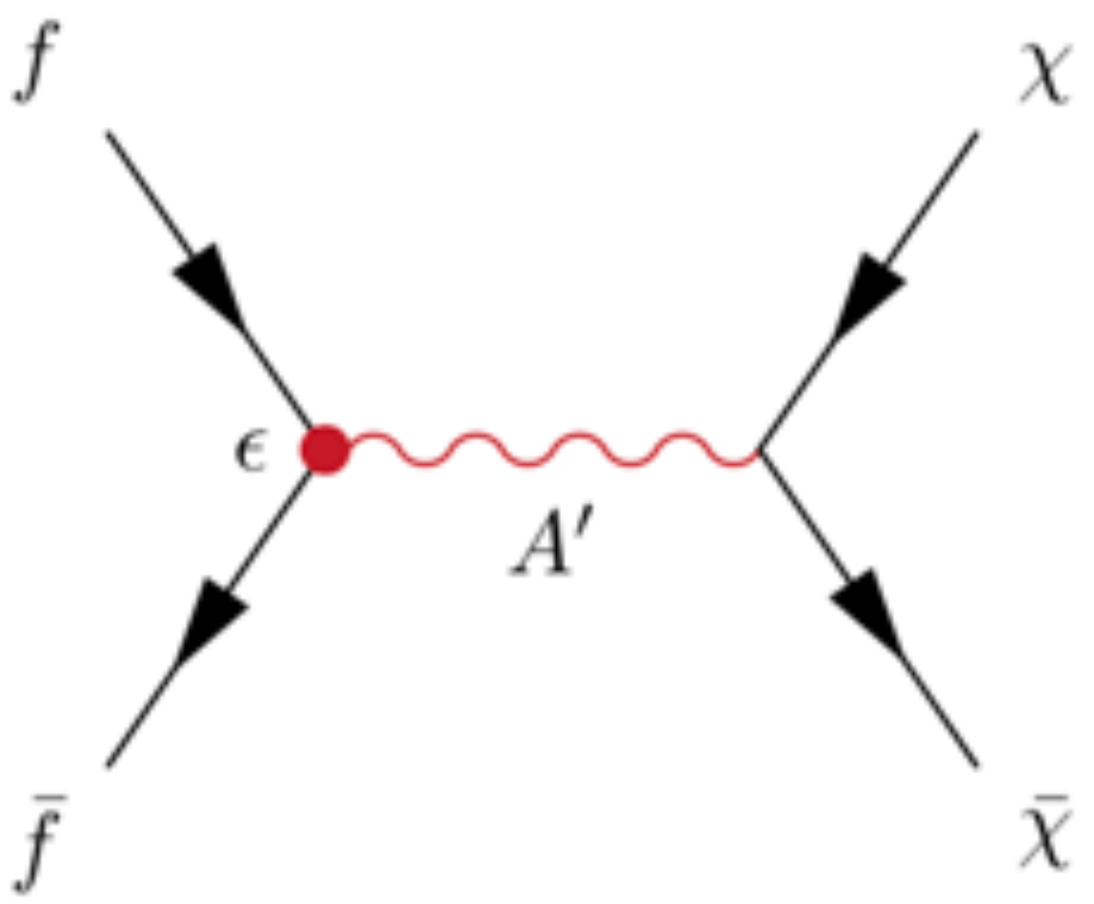
- Radiation level predicted to be very low in TI12 due to dispersion function of LHC at TI12.
- Measurements using BatMon radiation monitor in 2018 confirm FLUKA expectations:
  - less than 5 x 10^{-3} Gy/year
  - less than 5 x 10^{7} 1 MeV neutron equivalent fluence/year
- **FASER detector does not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



Particle spectra



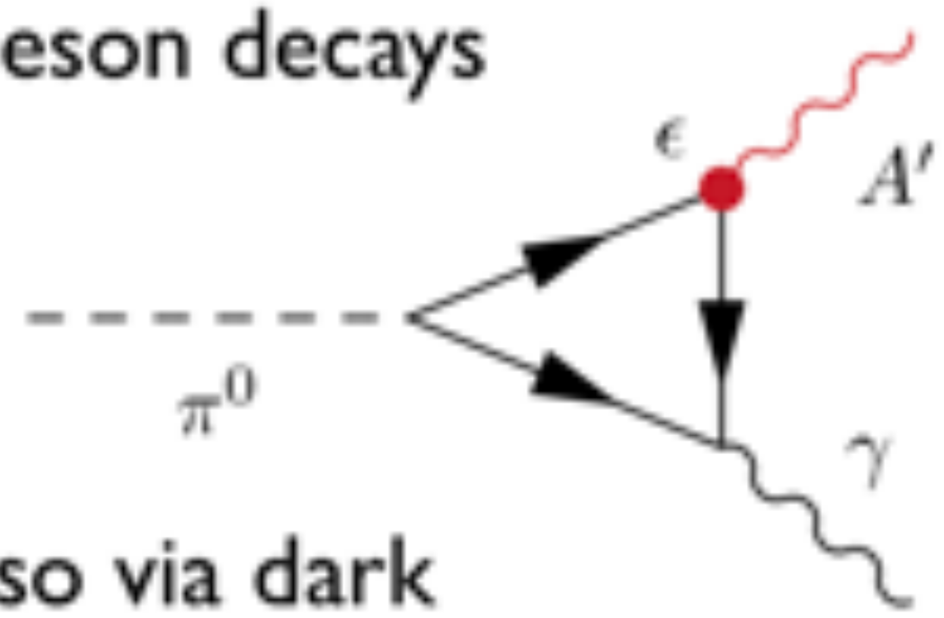
Overview | Dark photons



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

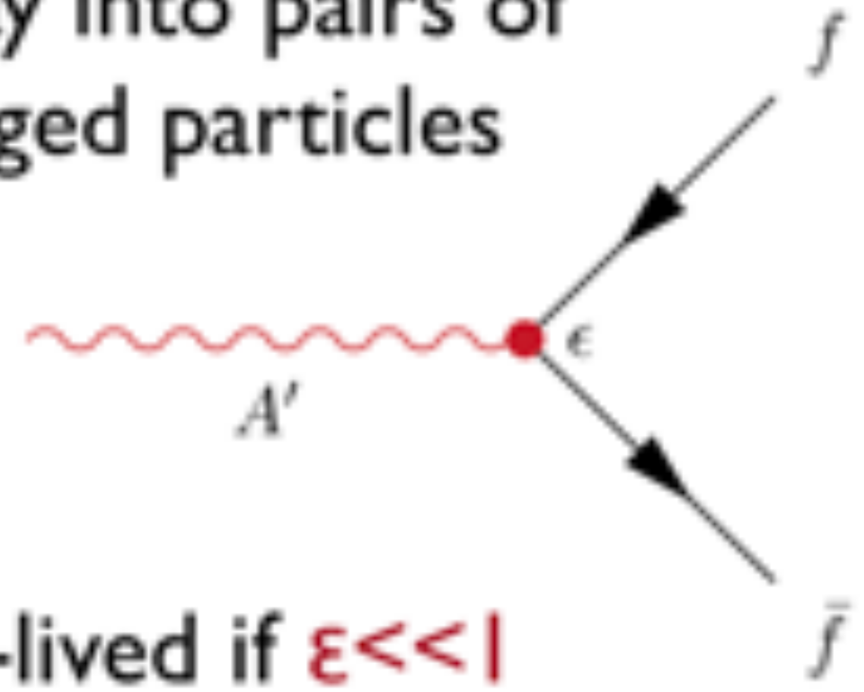
Dark Photons at FASER

- produced for example in meson decays



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

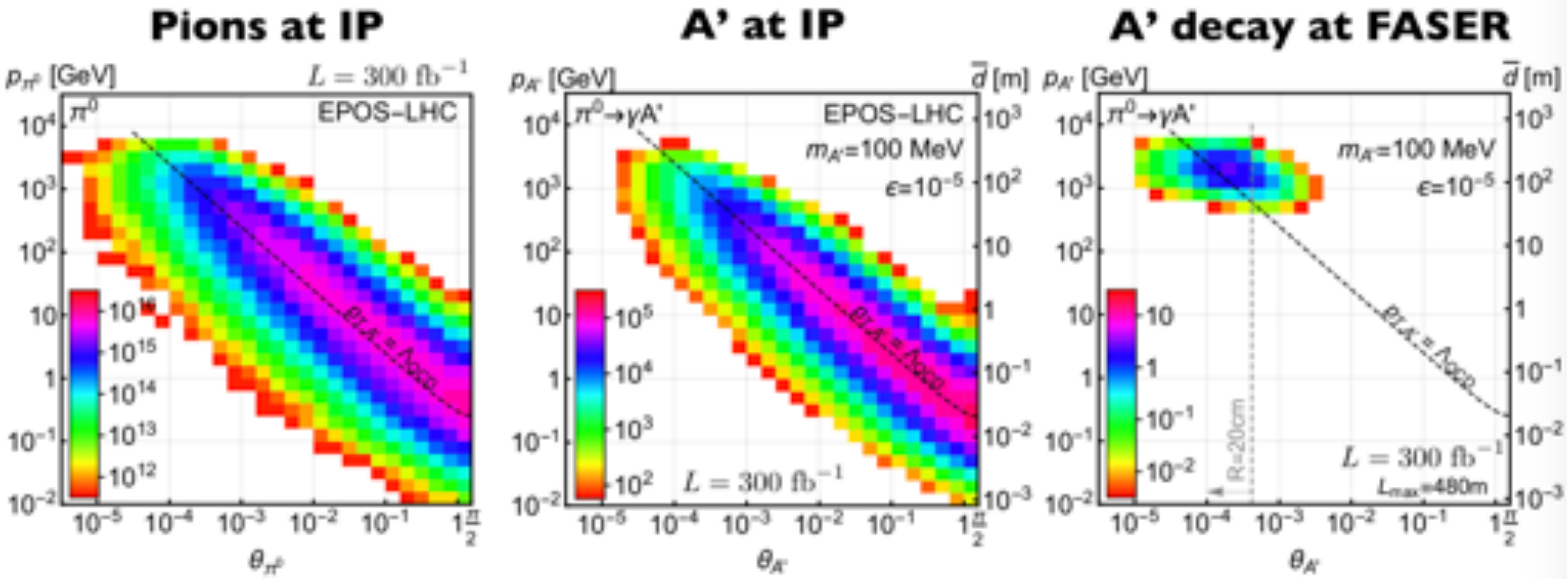
- decay into pairs of charged particles



- long-lived if ε<<1

Overview | Dark photons

UNIVERSITY OF SUSSEX



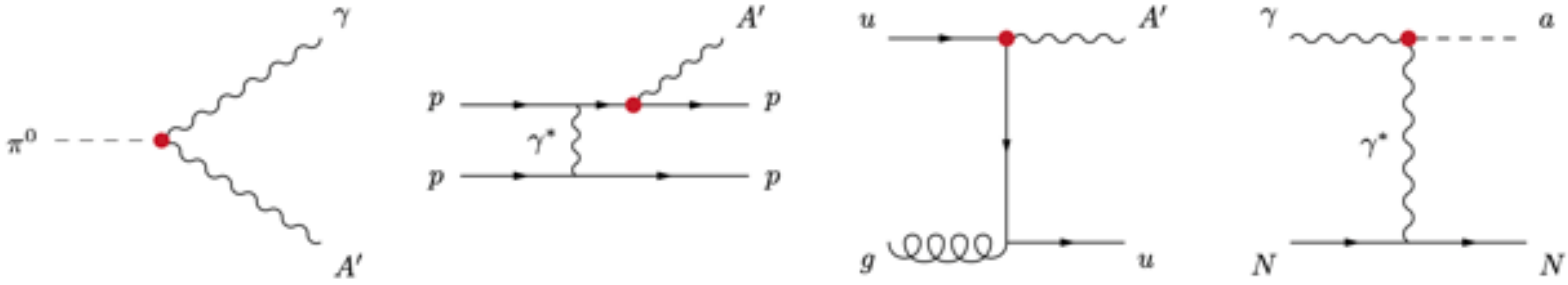
- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ Λ_{QCD}
- enormous event rates N ~ 10^{15} per bin

- 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

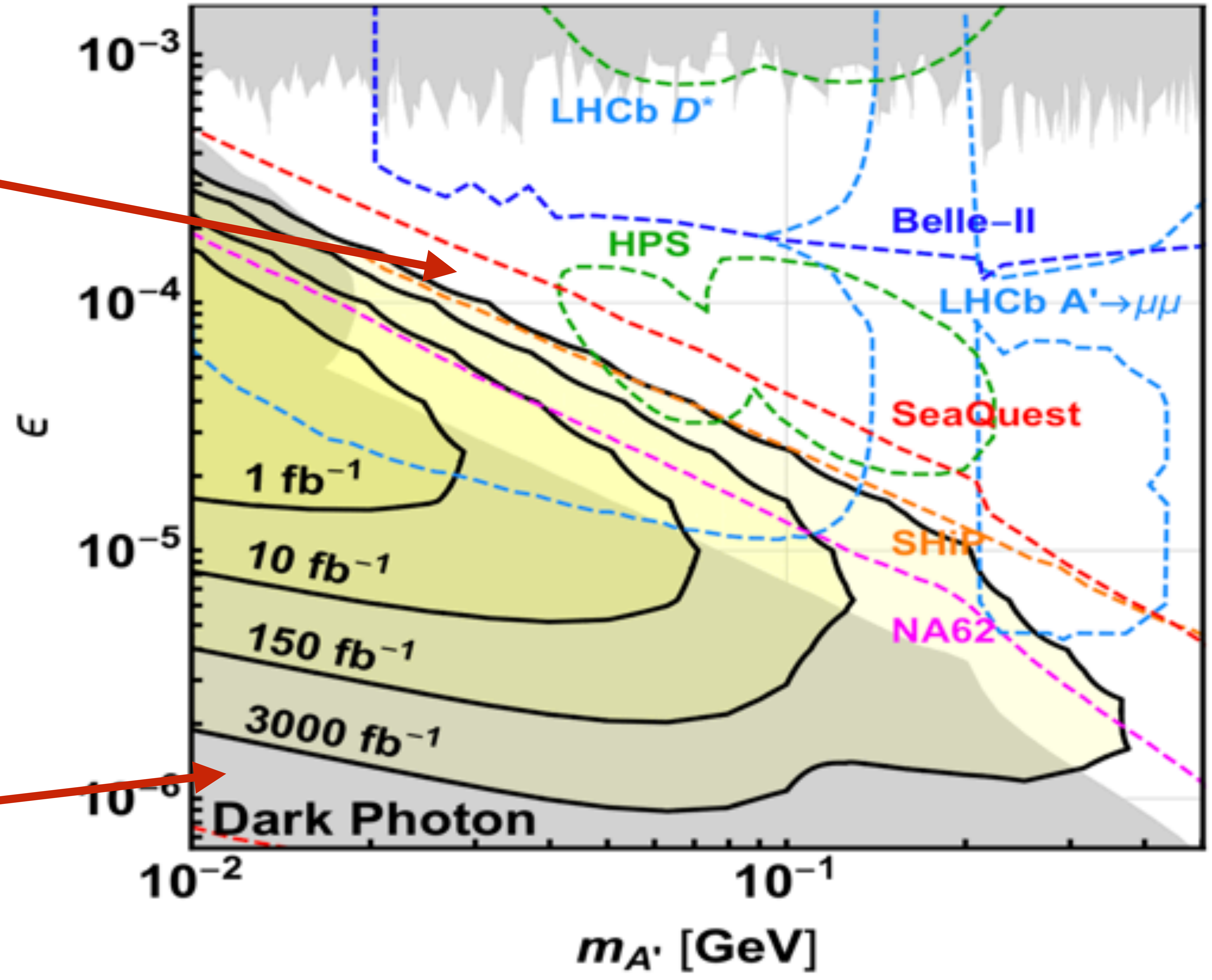
- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

19

Overview | LLP production modes

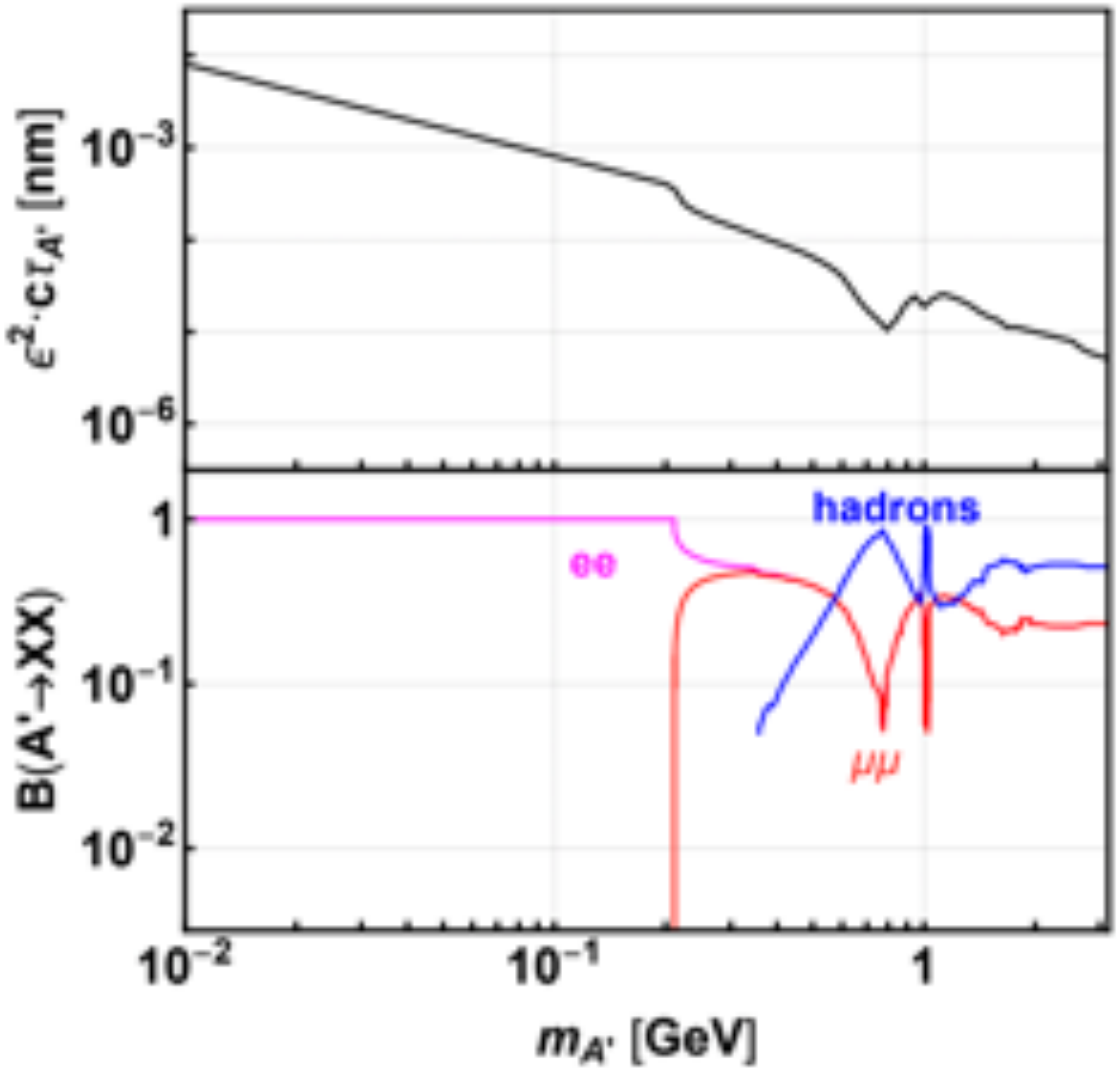


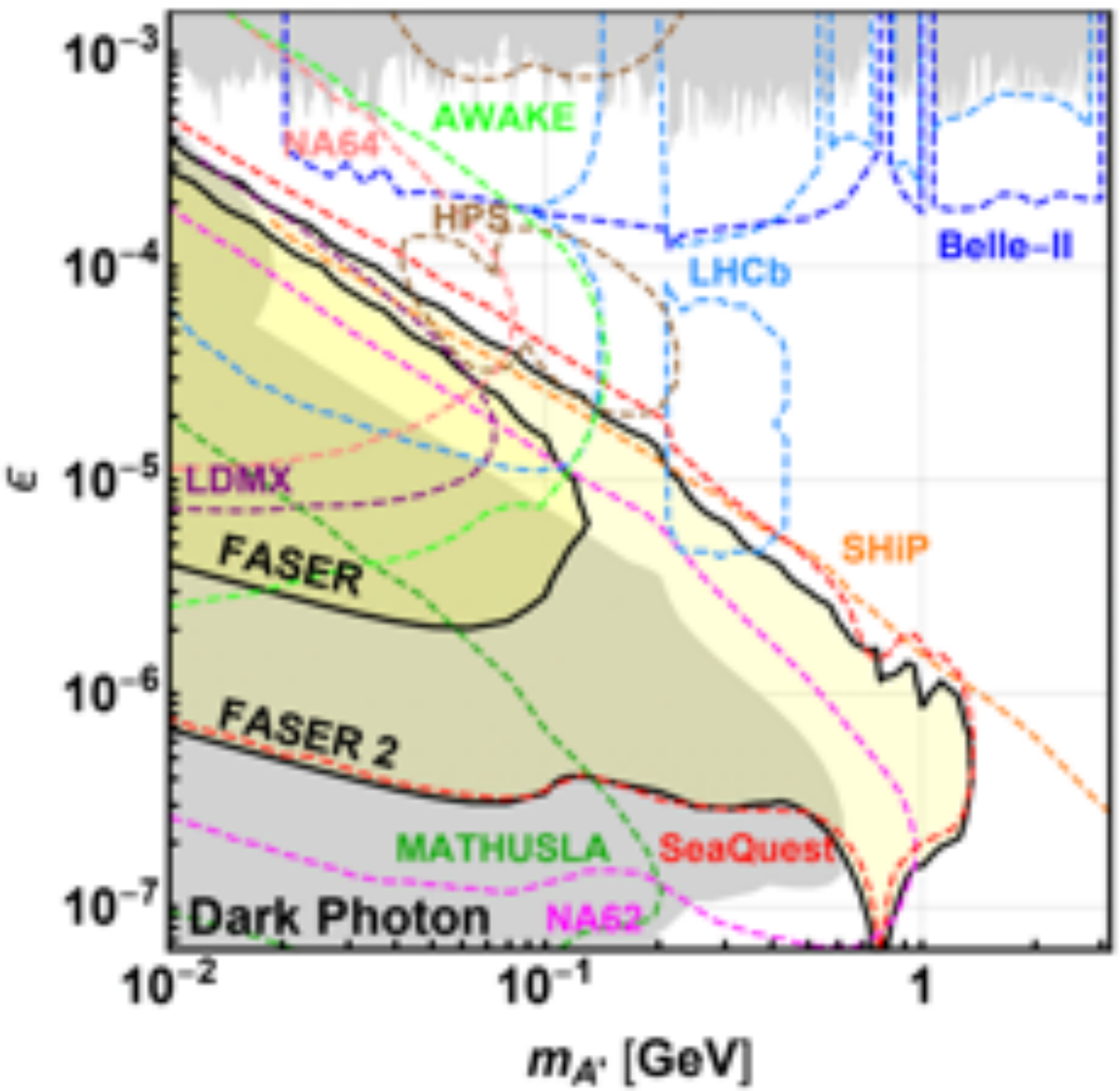
For lower lifetime the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector



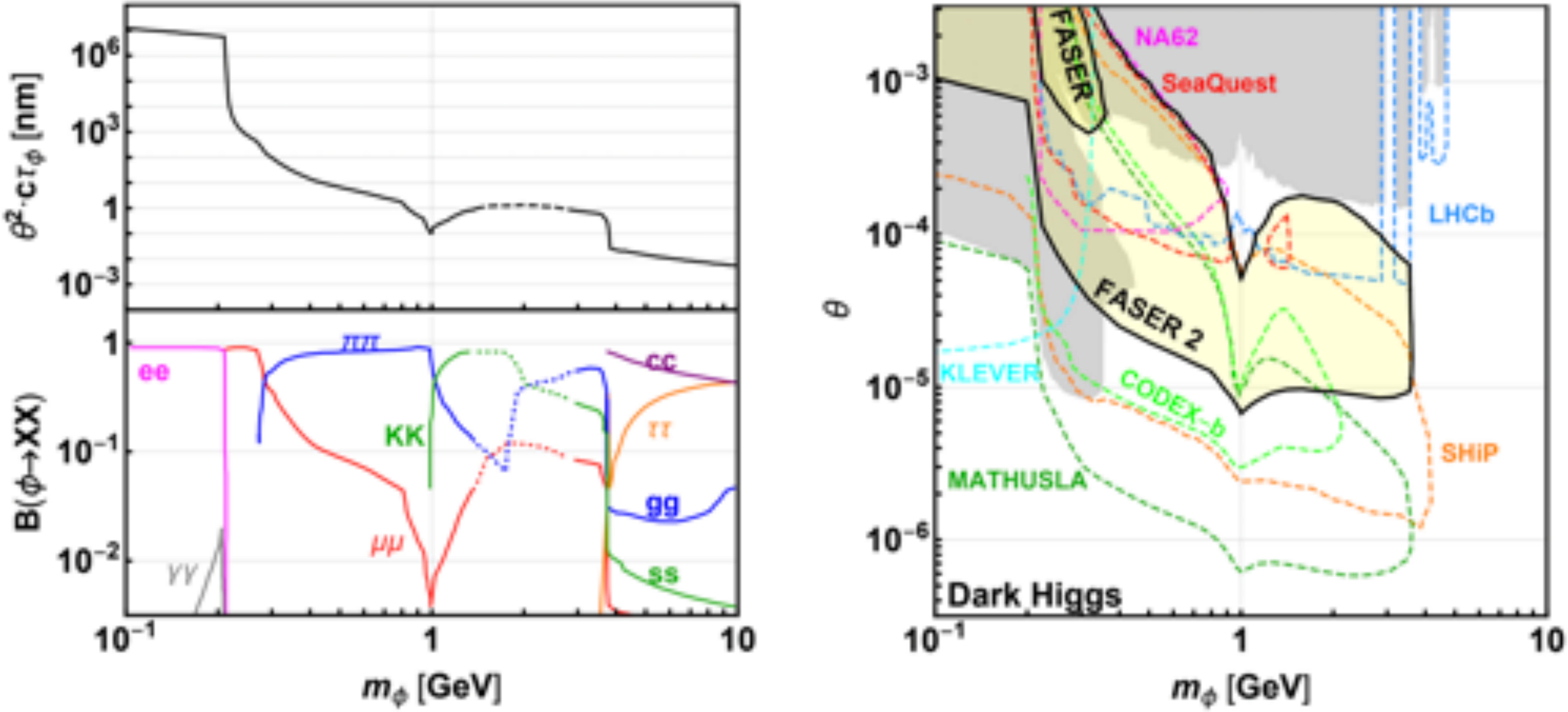
Combining dependence in both production rate and decay width, total number of signal events in the detector scales as ε^4

Target scenarios | Dark Photon

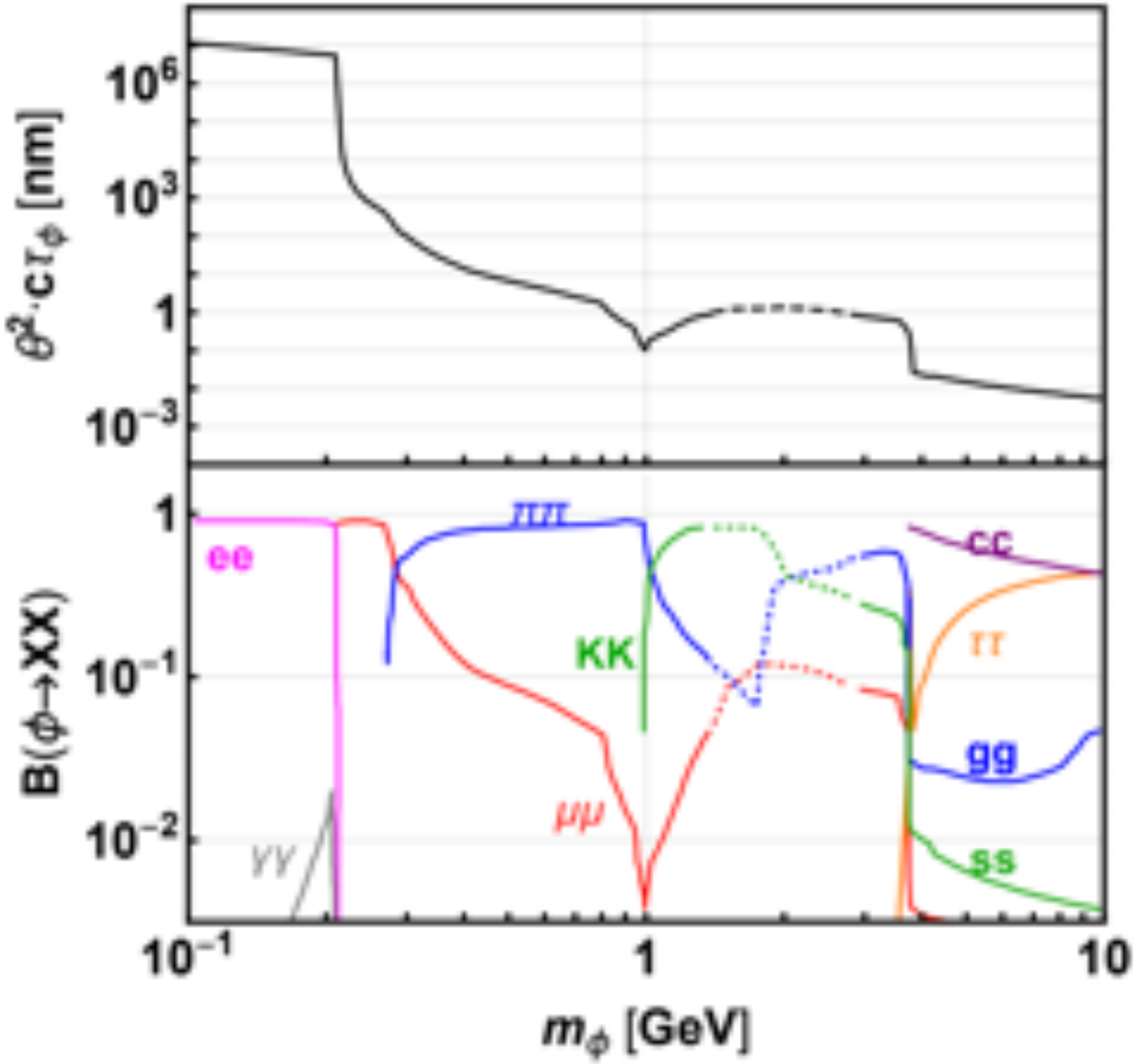


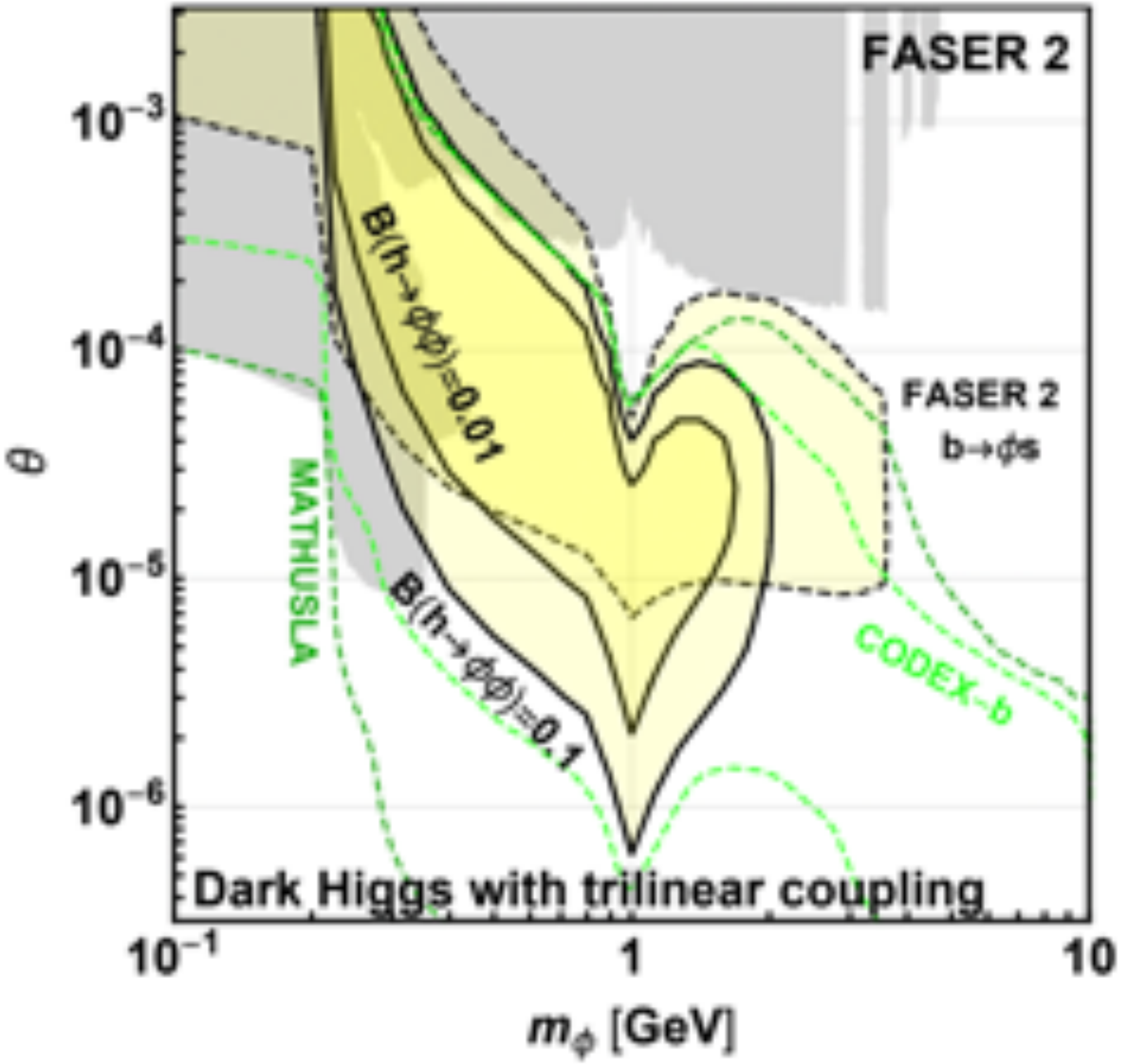


Target scenarios | Dark Higgs

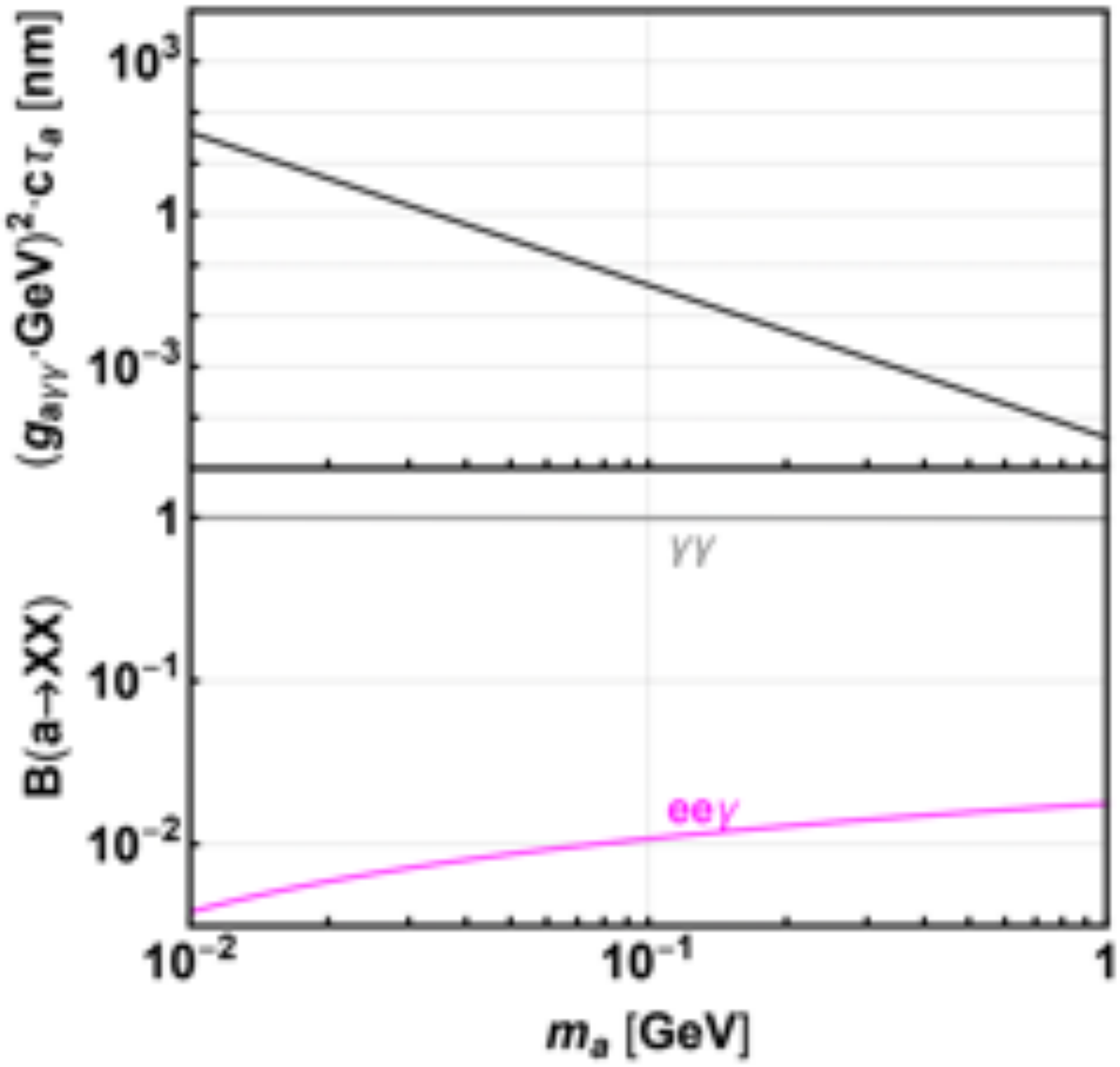


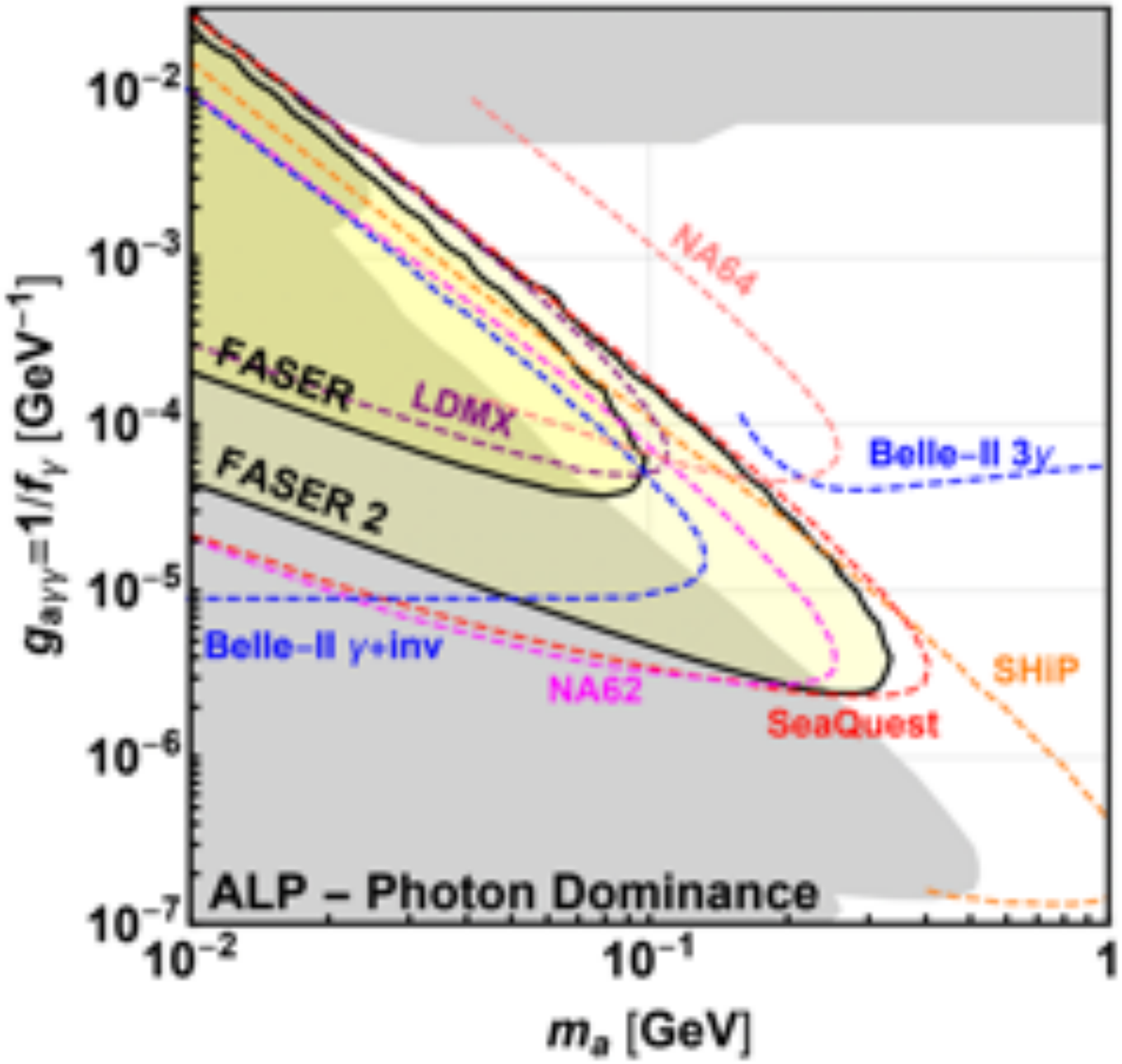
Target scenarios | Dark Higgs



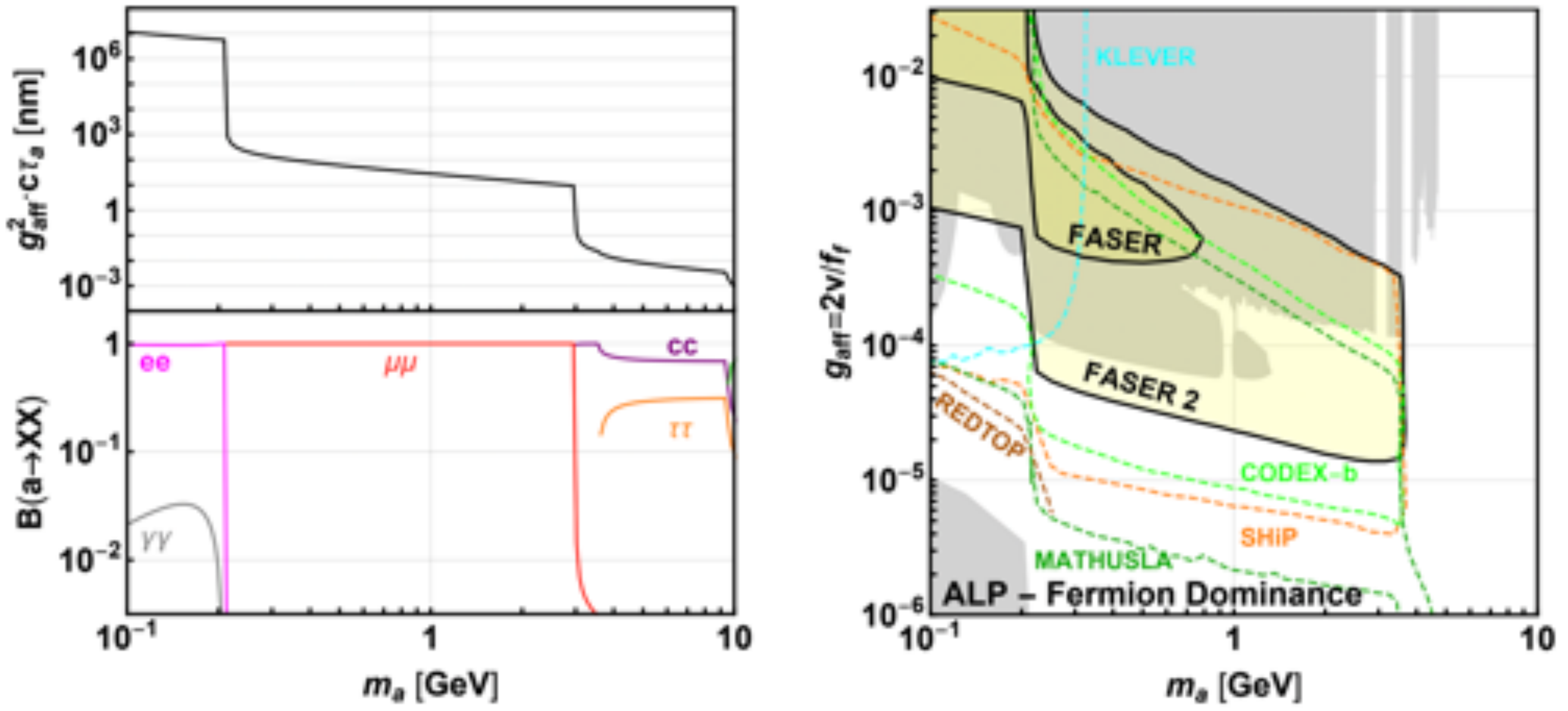


Target scenarios | ALP



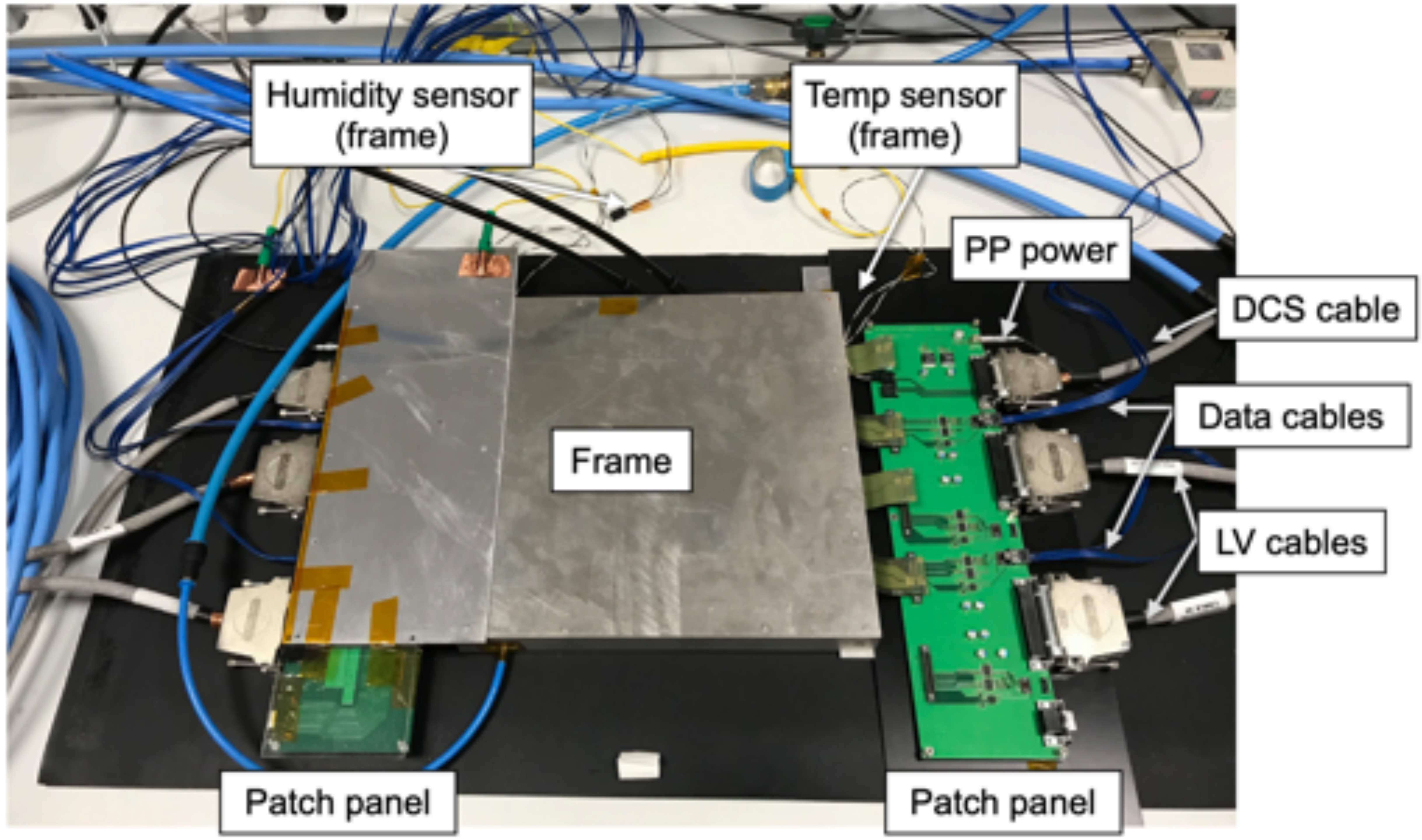


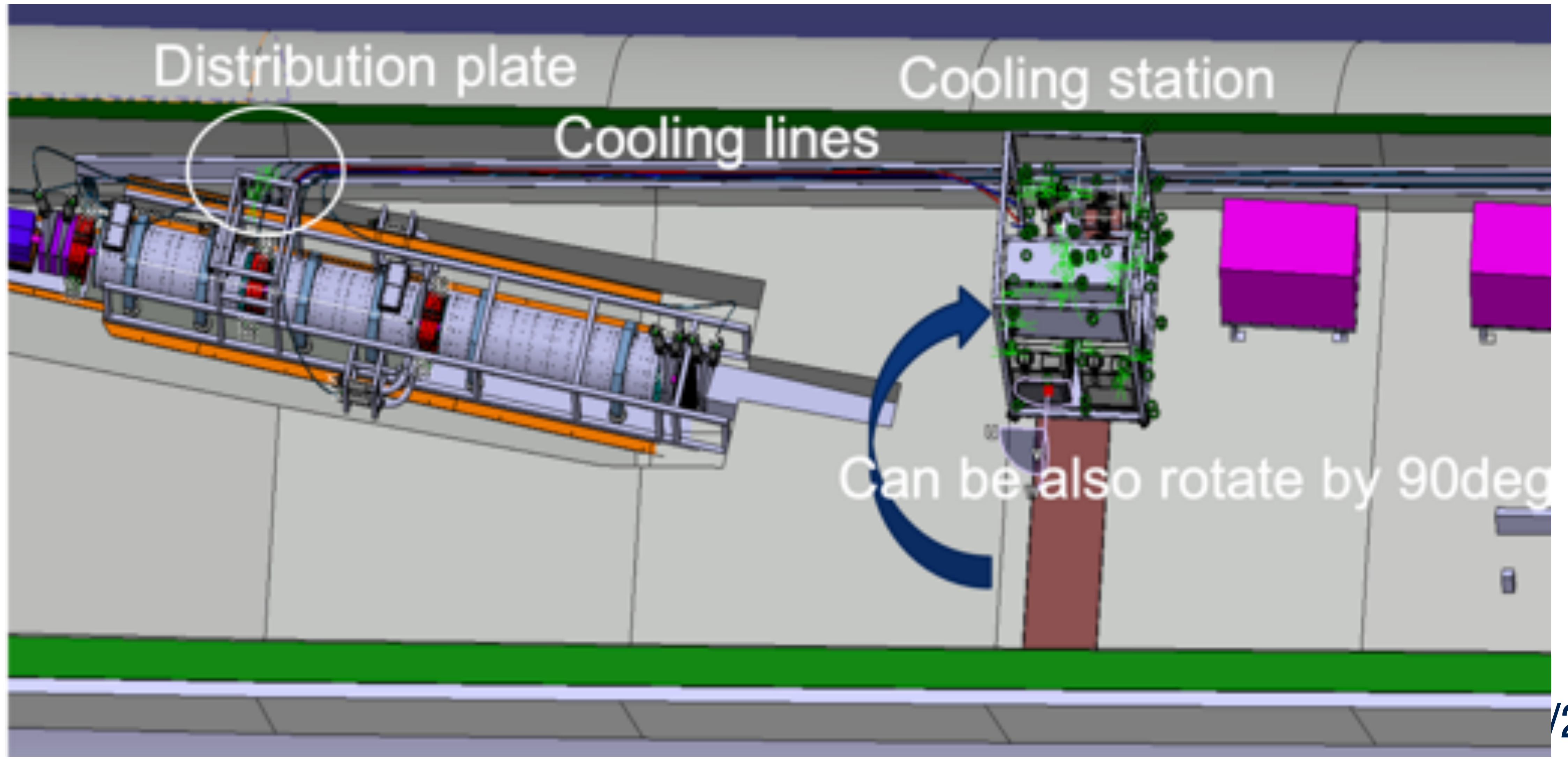
Target scenarios | ALP



Tracker | 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.





Tracker | Cooling

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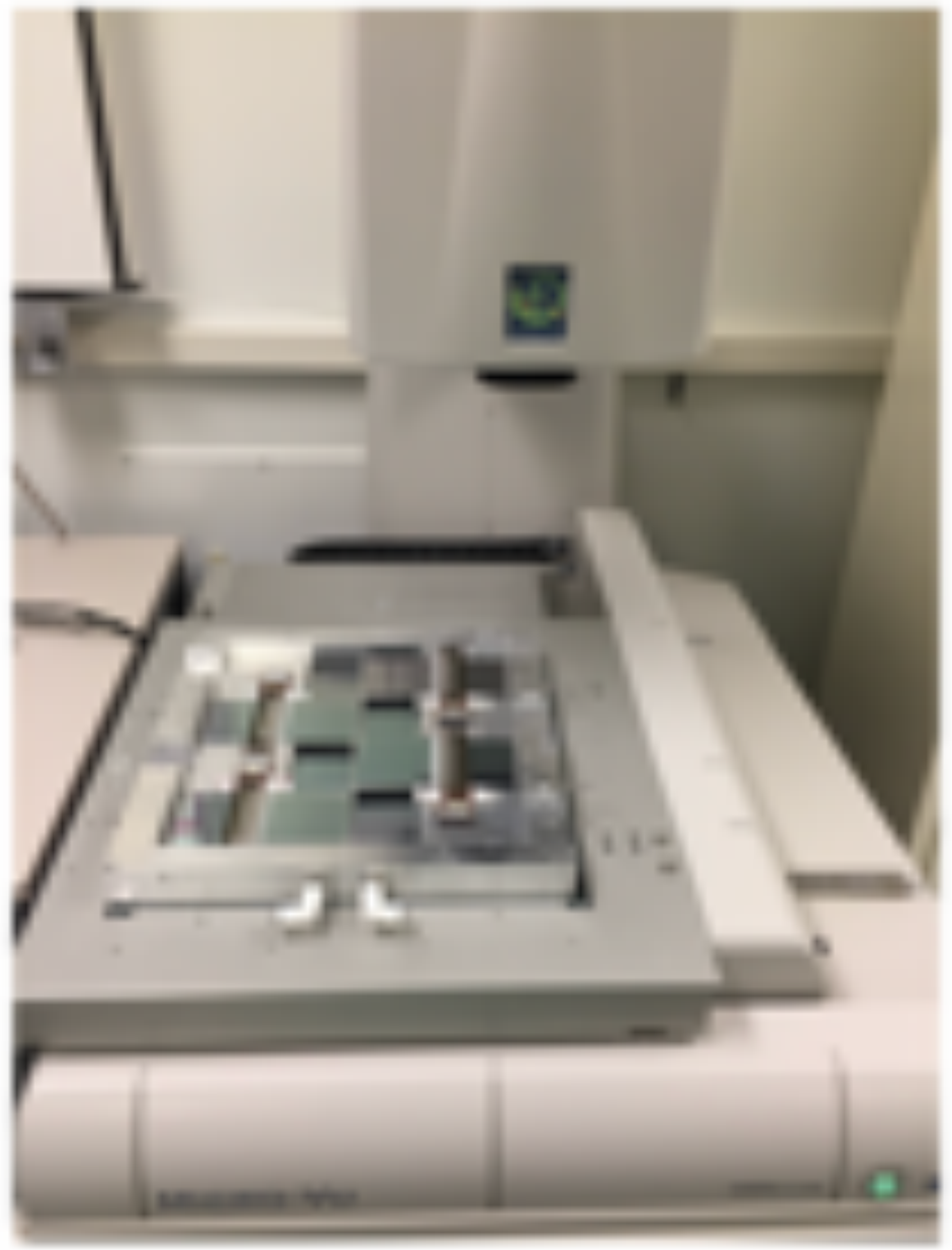
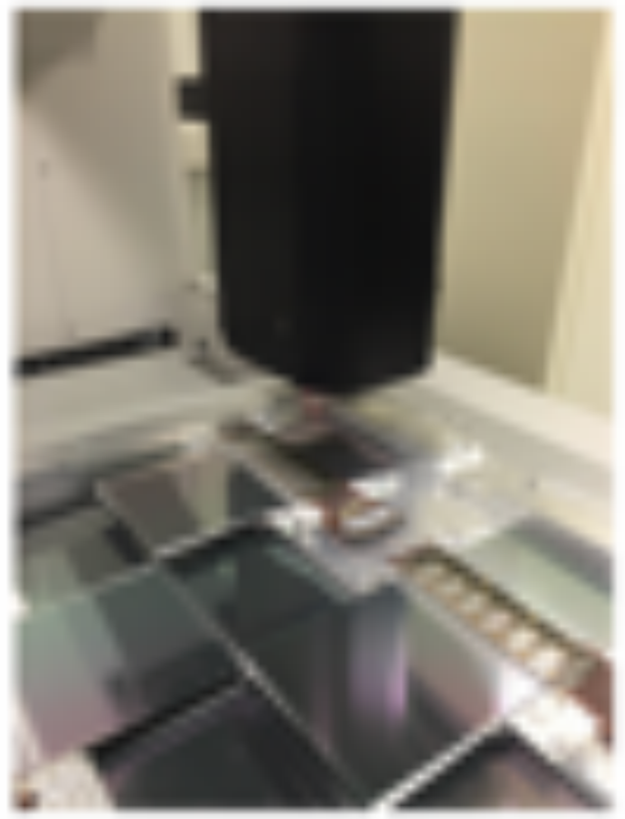
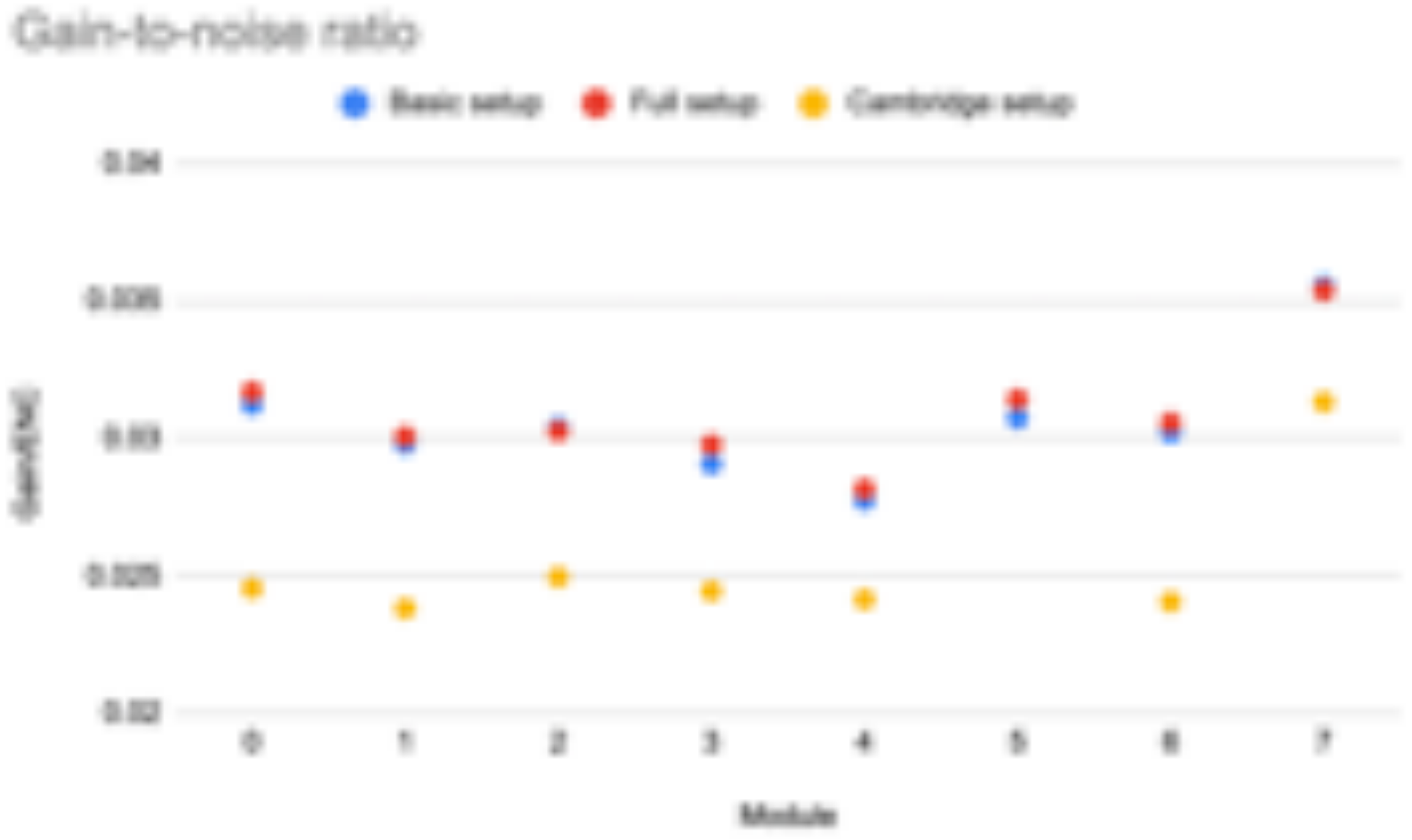
FASER cooling unit, designed/constructed by CERN EN-CV group. Has 2 water chillers for redundancy, and control logic to monitor and remotely switch between them as needed.

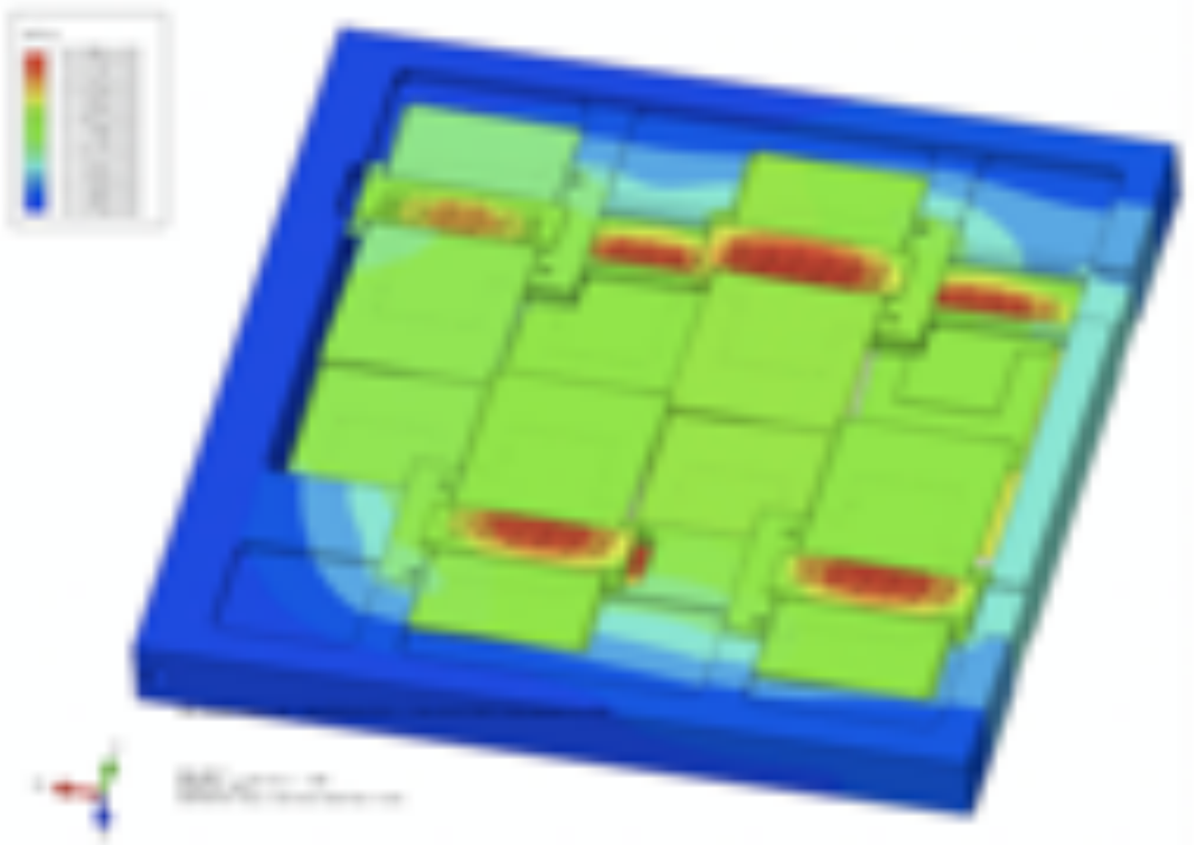
- Thermal measurements
- Readout tests (calibrations/scans) and noise measurements
- Metrology for pre-alignment (~ few microns precision)

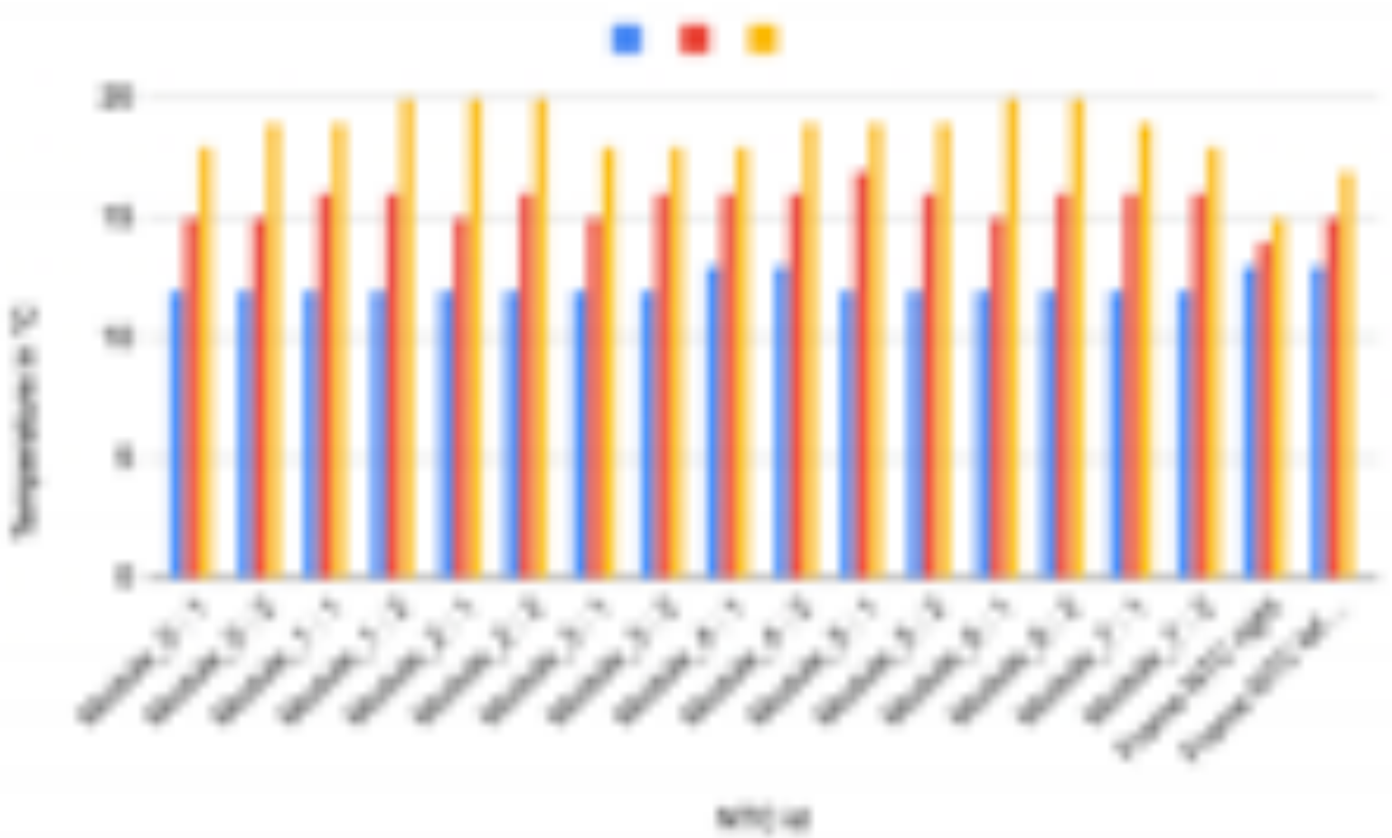

Metrology studies



Gain/noise measurements



FEA simulation



Thermal measurements

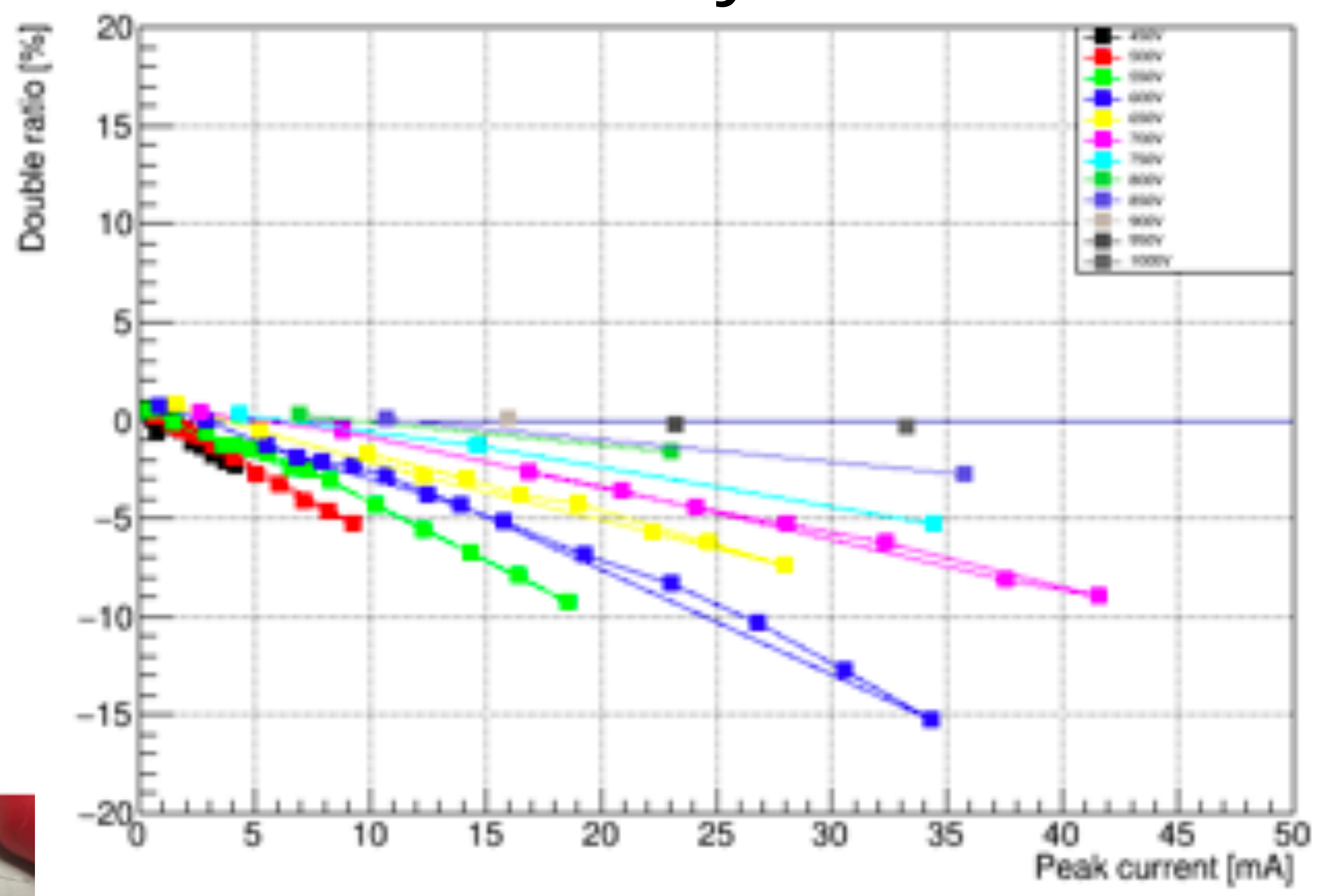
Tracker | Monitoring, cooling & power

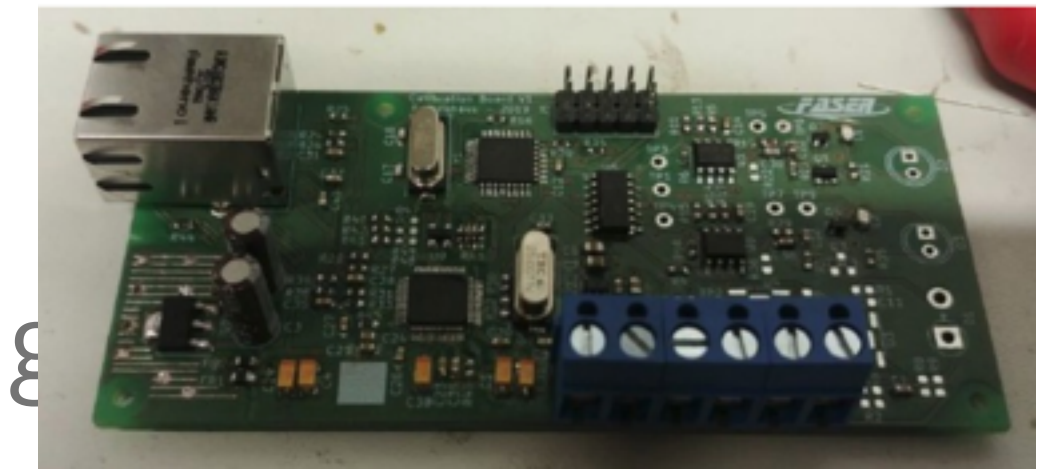
- Low radiation environment → simple water chiller at ~ 15 °C sufficient to cool ASICs
- Dry air in tracking stations (avoid condensation)
- WIENER system for power supply
- Custom board for tracker interlock & monitoring (TIM)
- Detector Control System (DCS) under development.

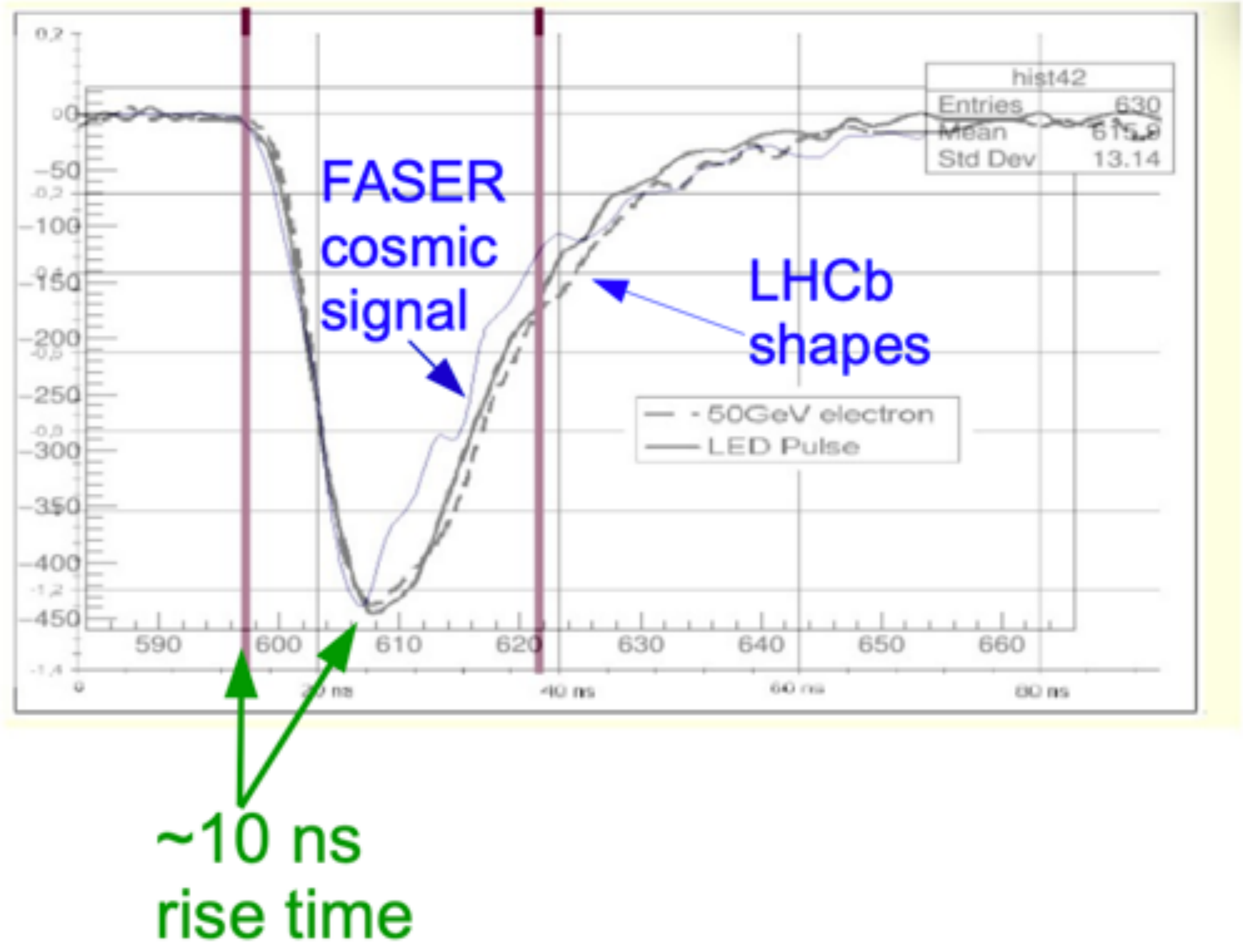
Scintillator & Calorimeter

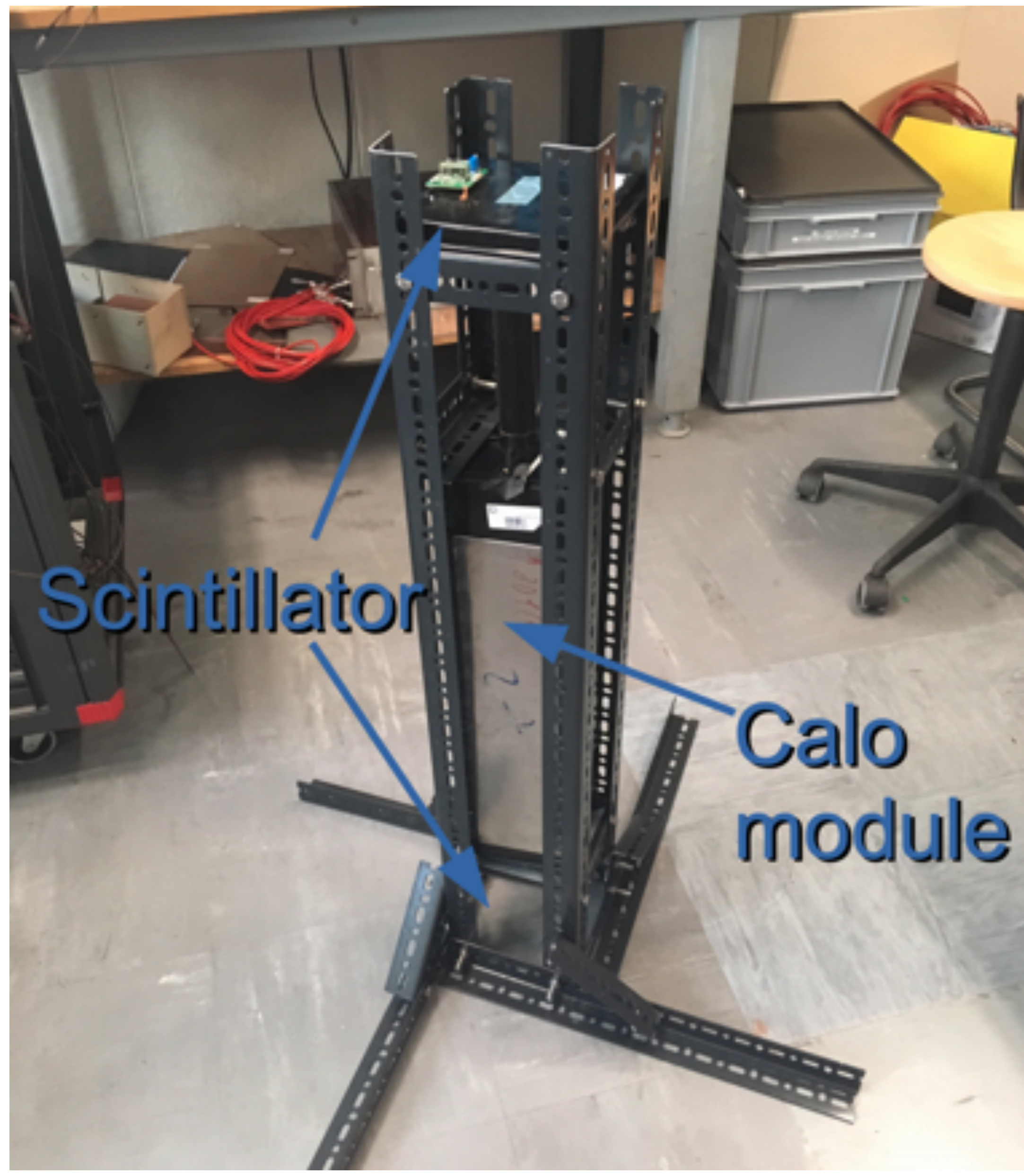
- Have a well developed lab setup for scintillator & calorimet
  - PMT signal read-out by digitiser.
  - Well defined procedure to extract gain and linearity measuremen
- In-situ calibration
  - Will measure gain vs HV, by pulsing with high intensity LED
  - Circuit designed and first testing in progress
- 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





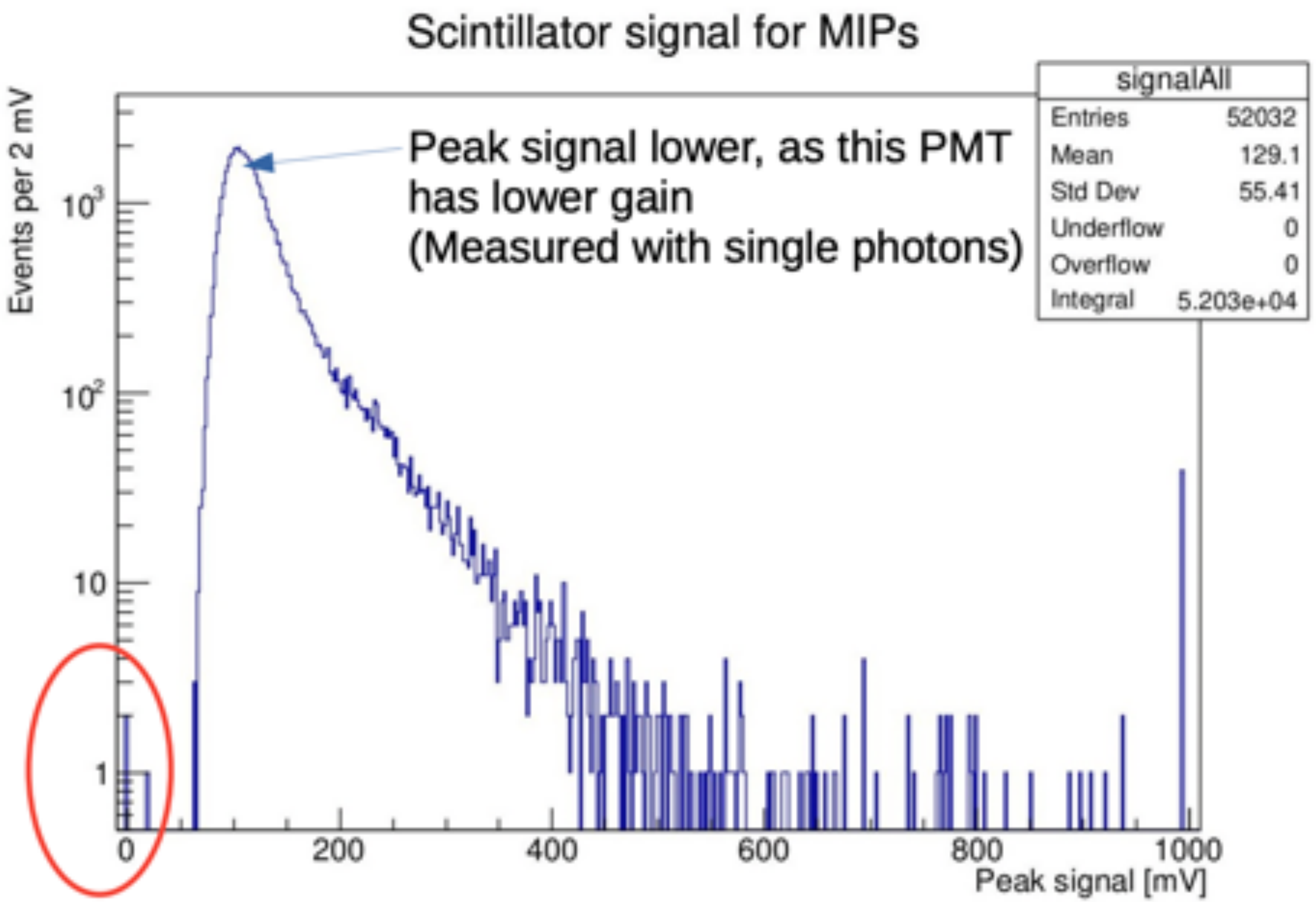




Scintillator | Characterisation

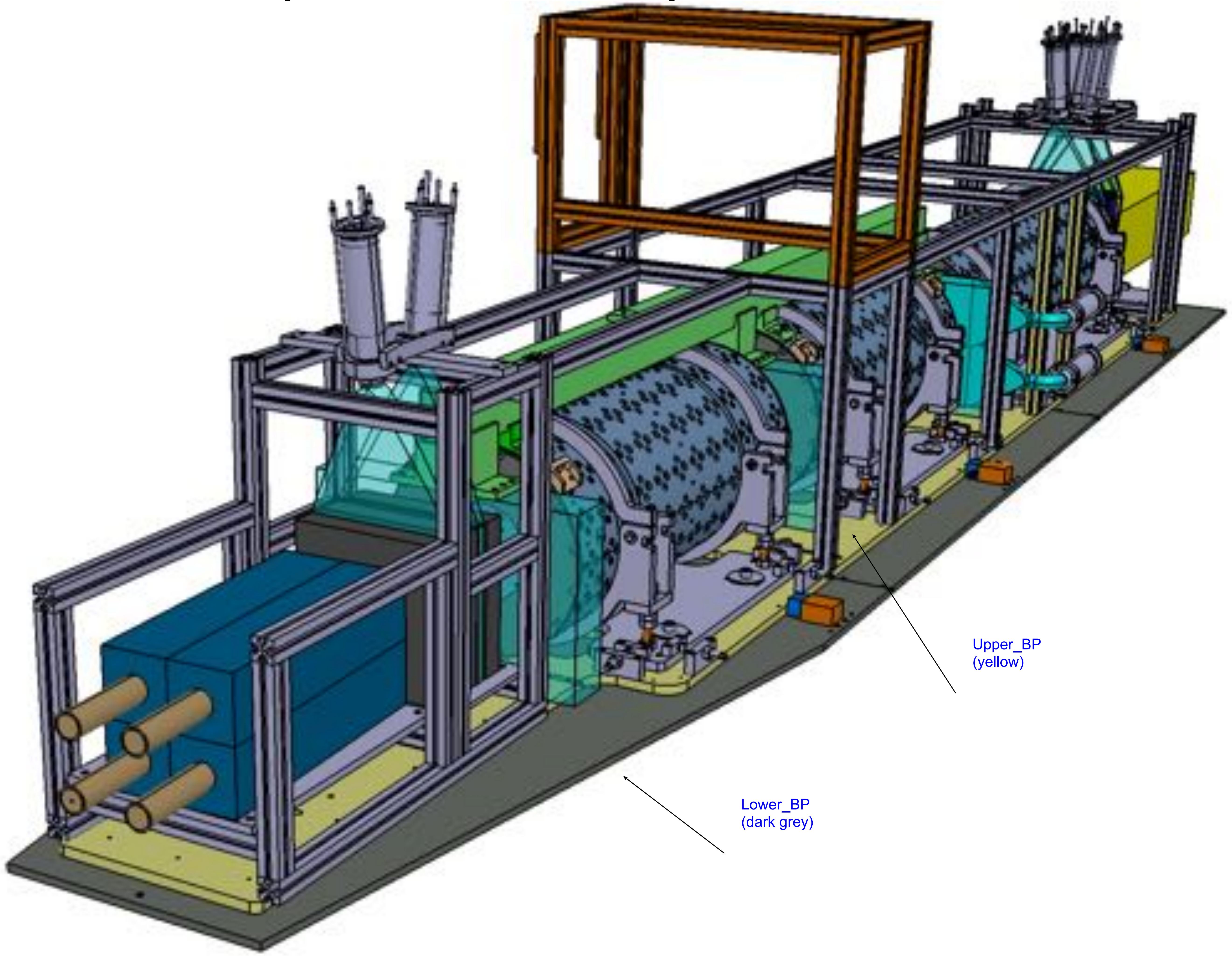
- Large light signal observed
  - ~100s of photons
- For middle sector we ran high stats (50k events) runs over night

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



Frame

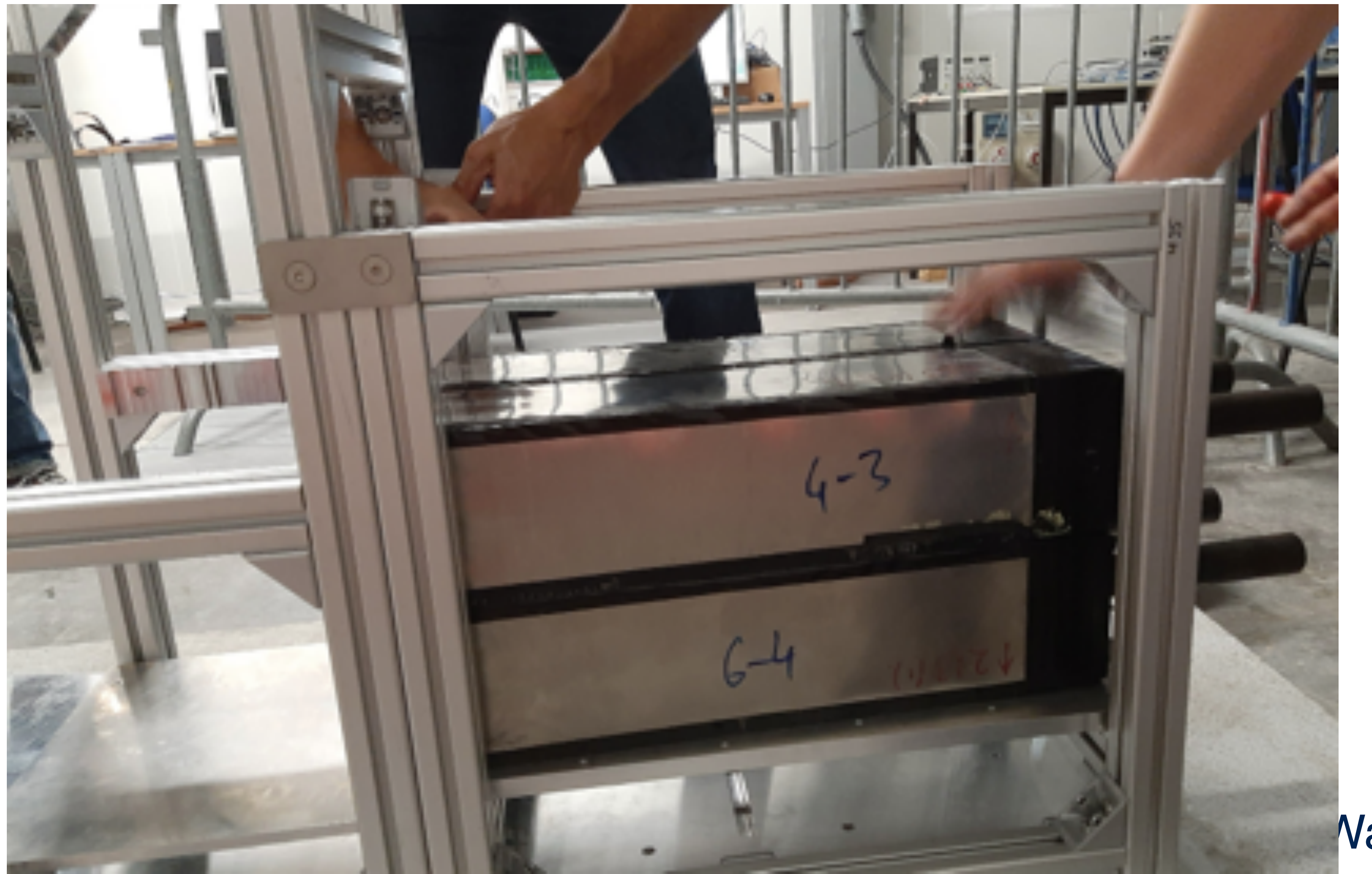
- Main requirements of detector support:
- Keep tracking stations well aligned in vertical plane (O(100μm))
- Align magnets to each other and LOS within a few mm
- Allow detector to follow changes in LOS due to changing crossing angle in IP1
  - Crossing angle moves LOS by ~7cm
  - Crossing direction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



Calorimeter/Scintillators | Mounting

Scintillators mounted in their support.

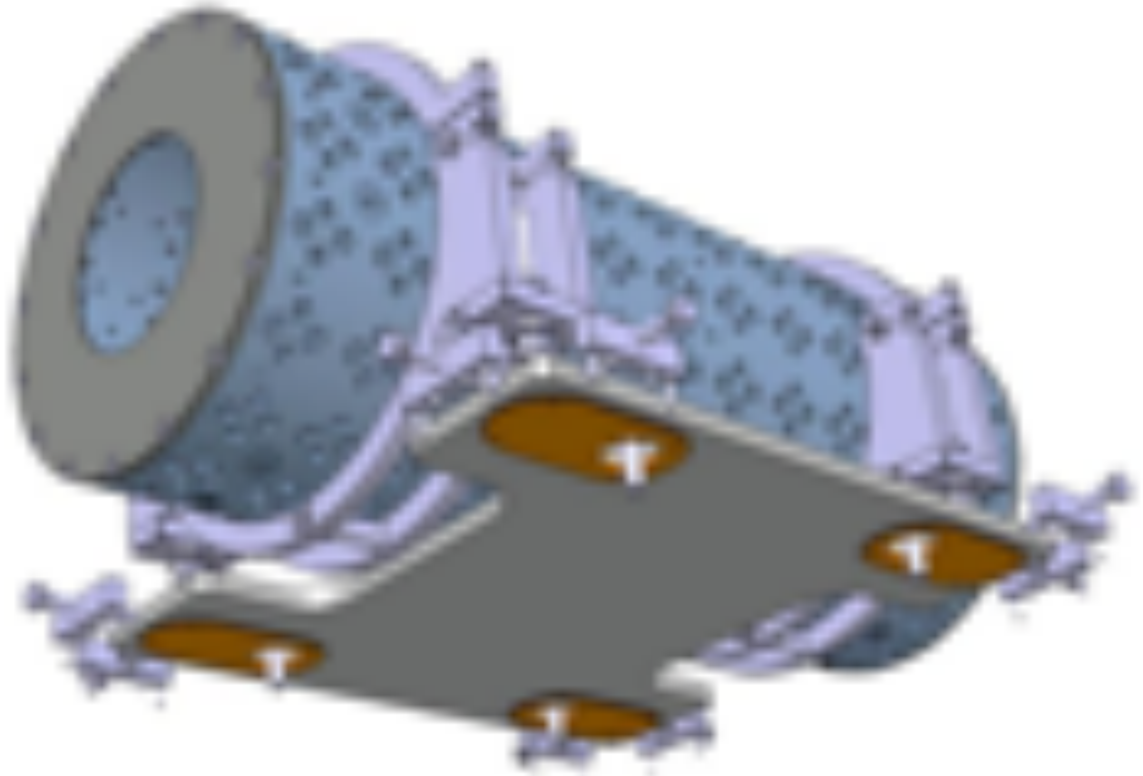
Calorimeter modules mounted in their support.



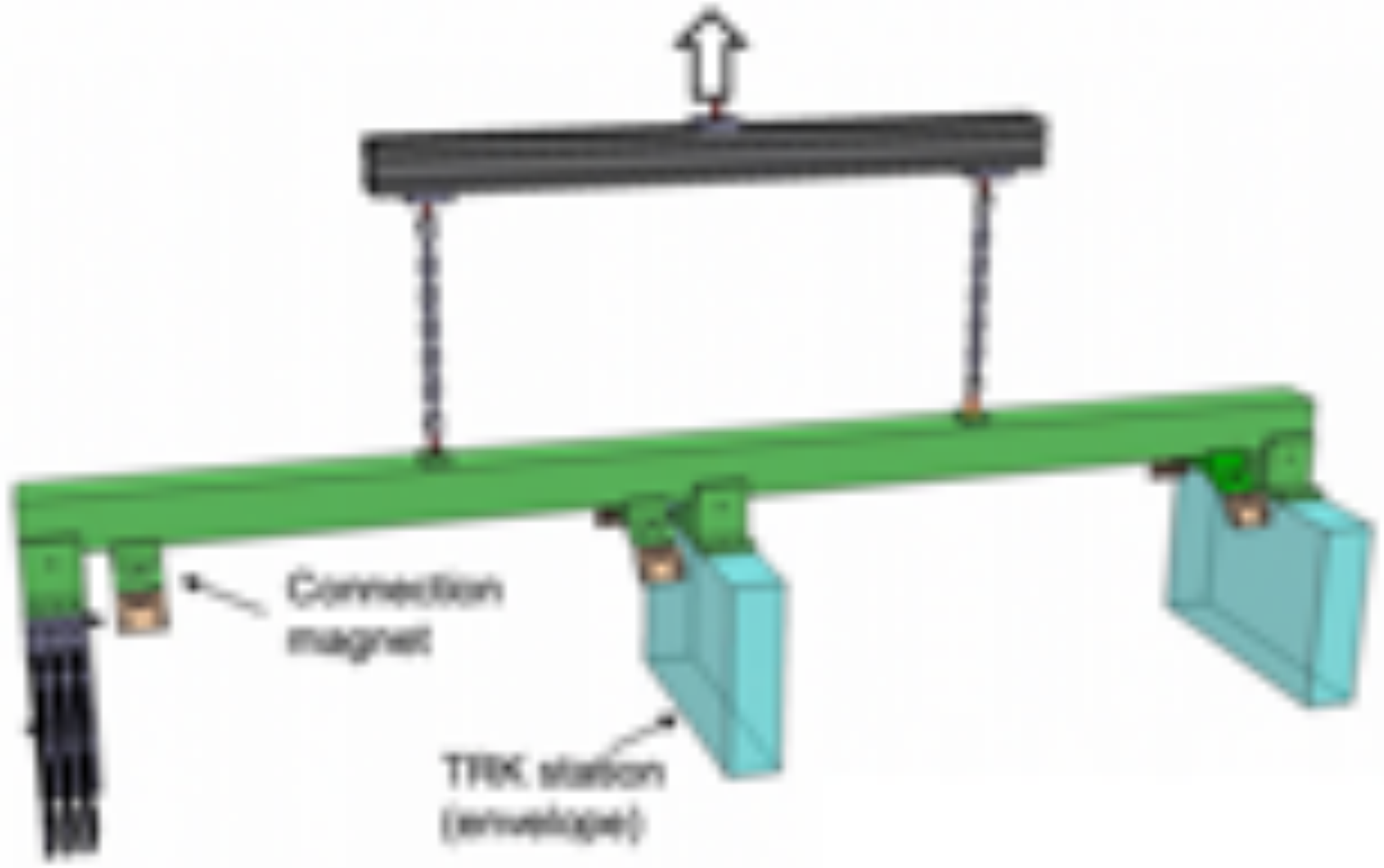
Detector support infrastructure

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

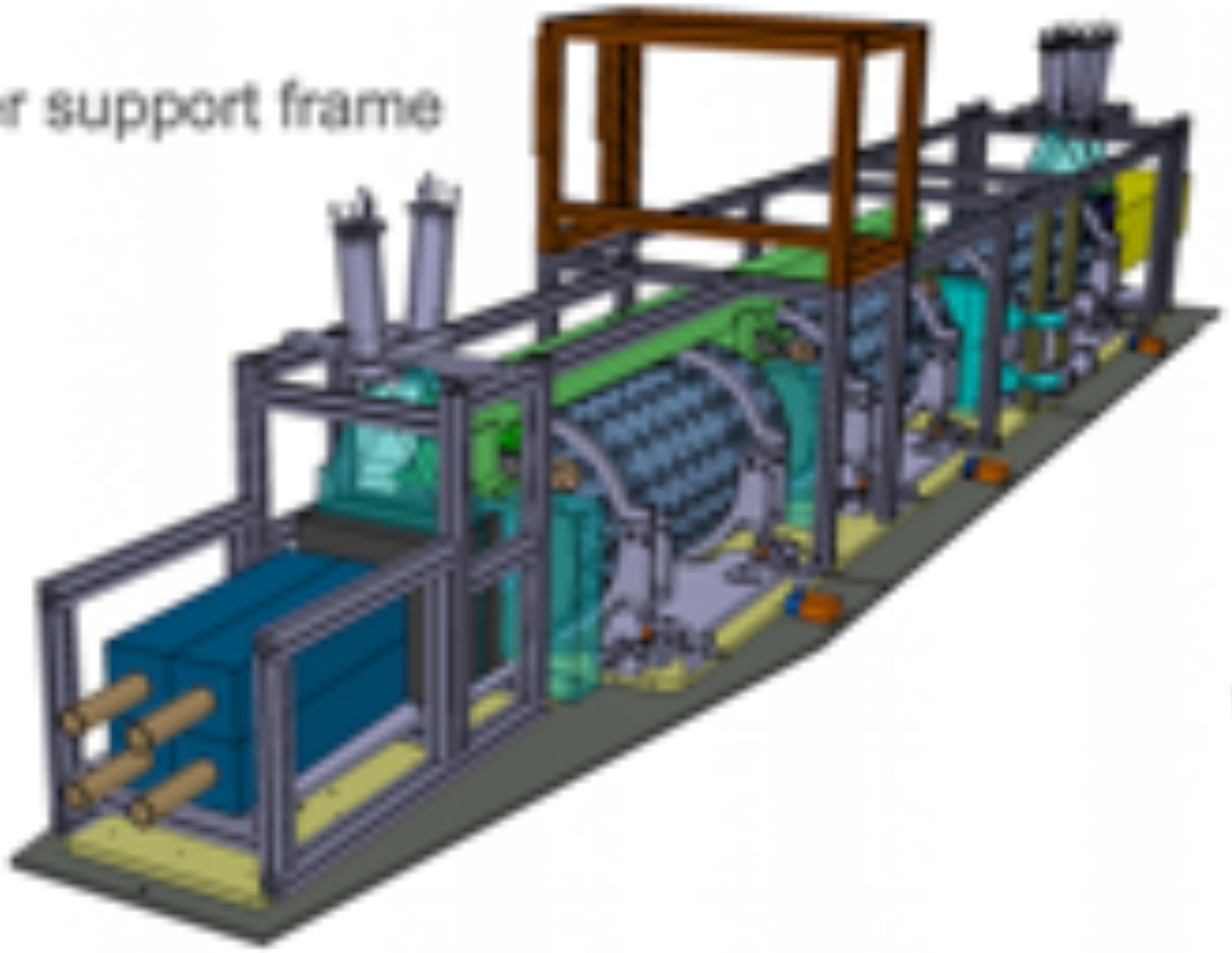
Magent support frame



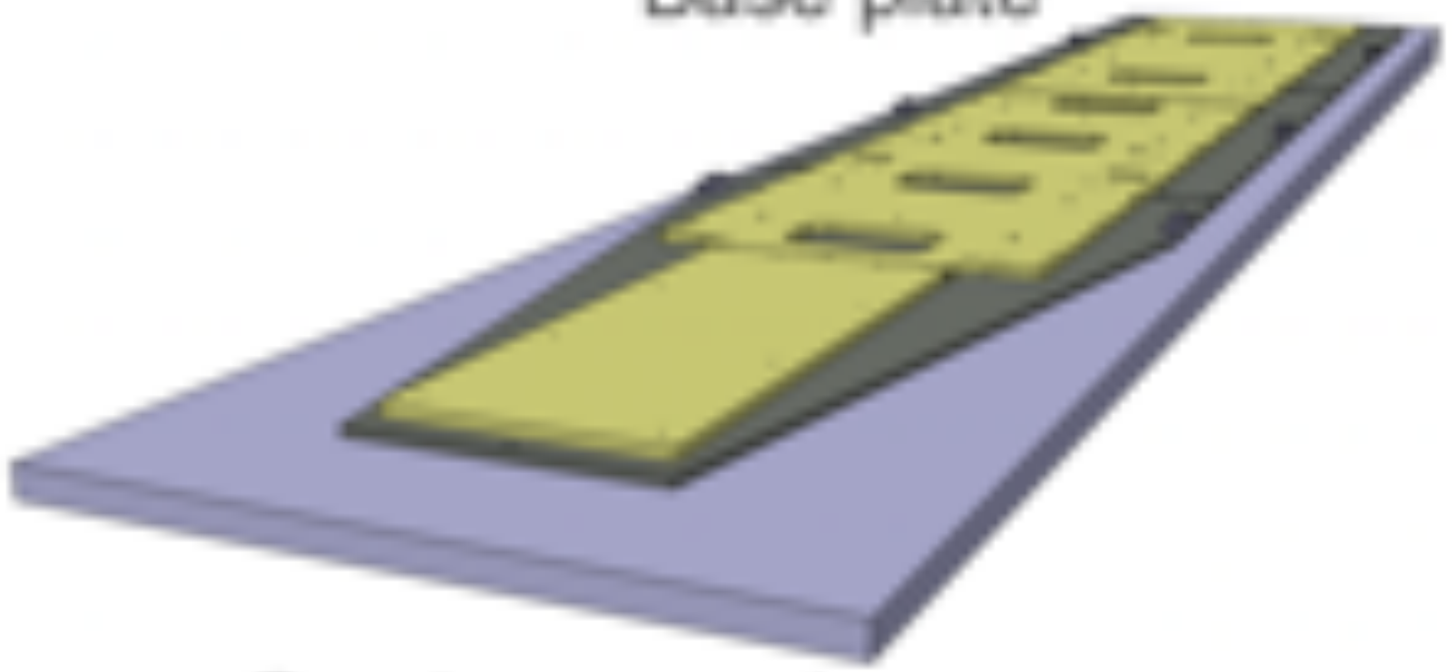
Tracker backbone



Upper support frame



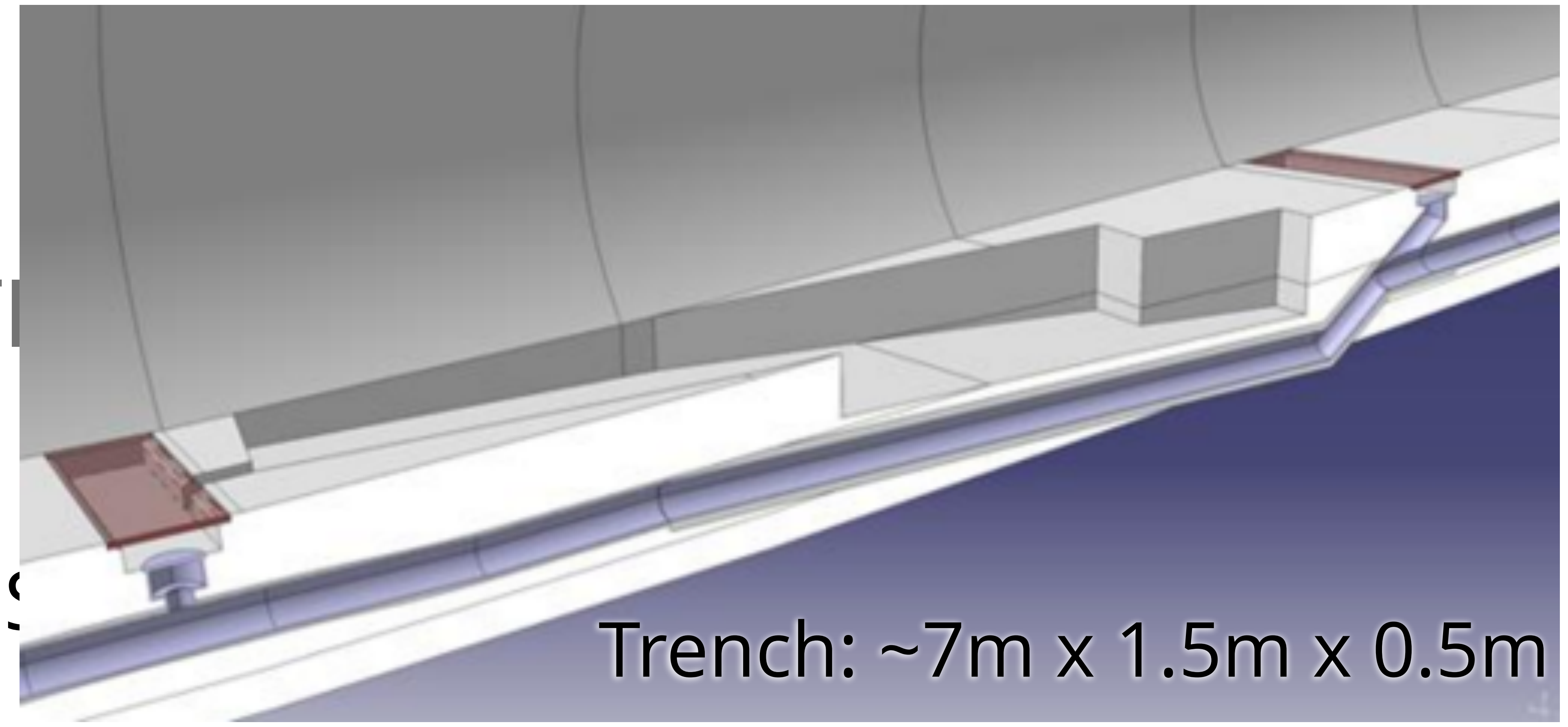
Base plate

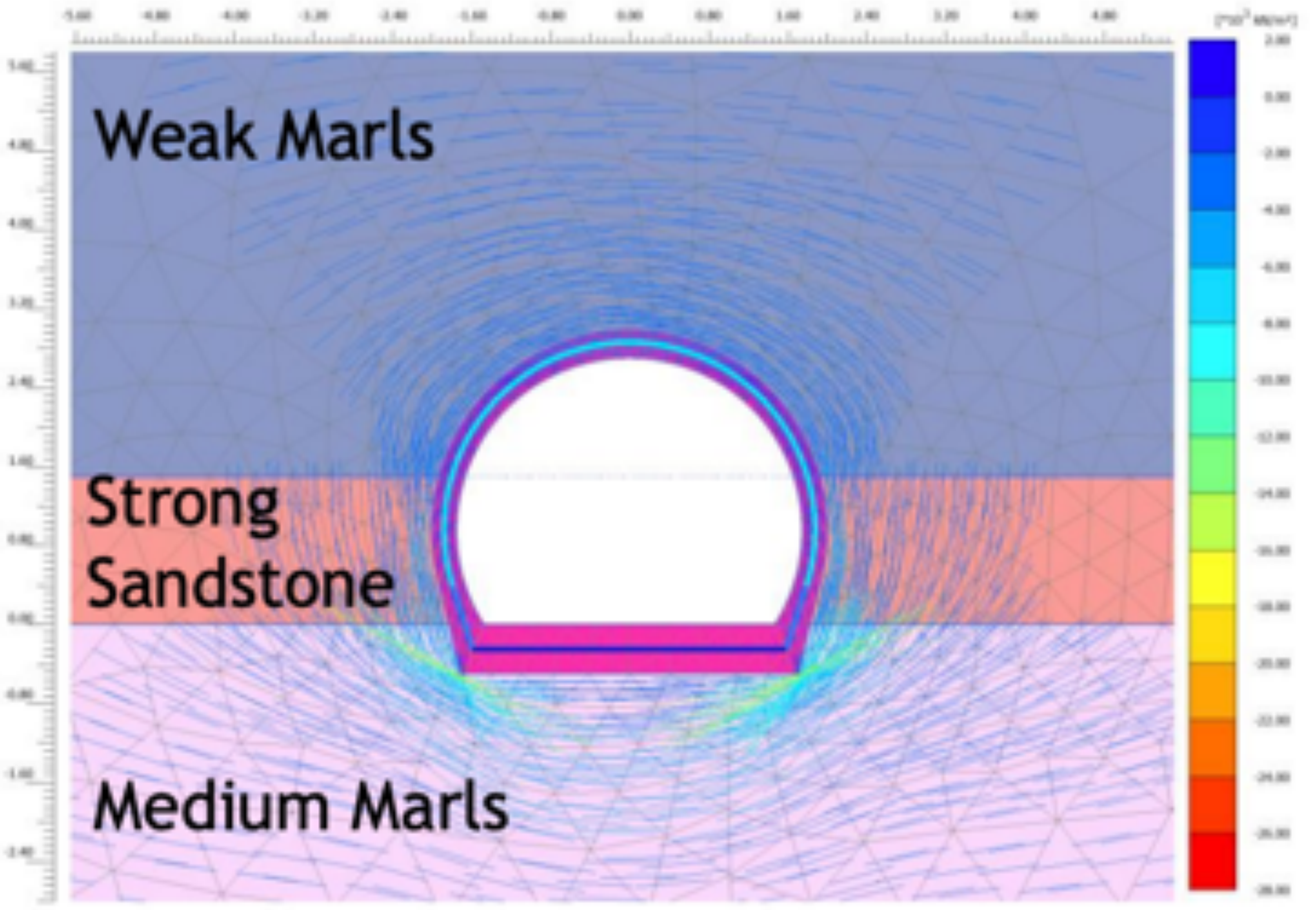


Grout + cement

Civil Engineering in TI12

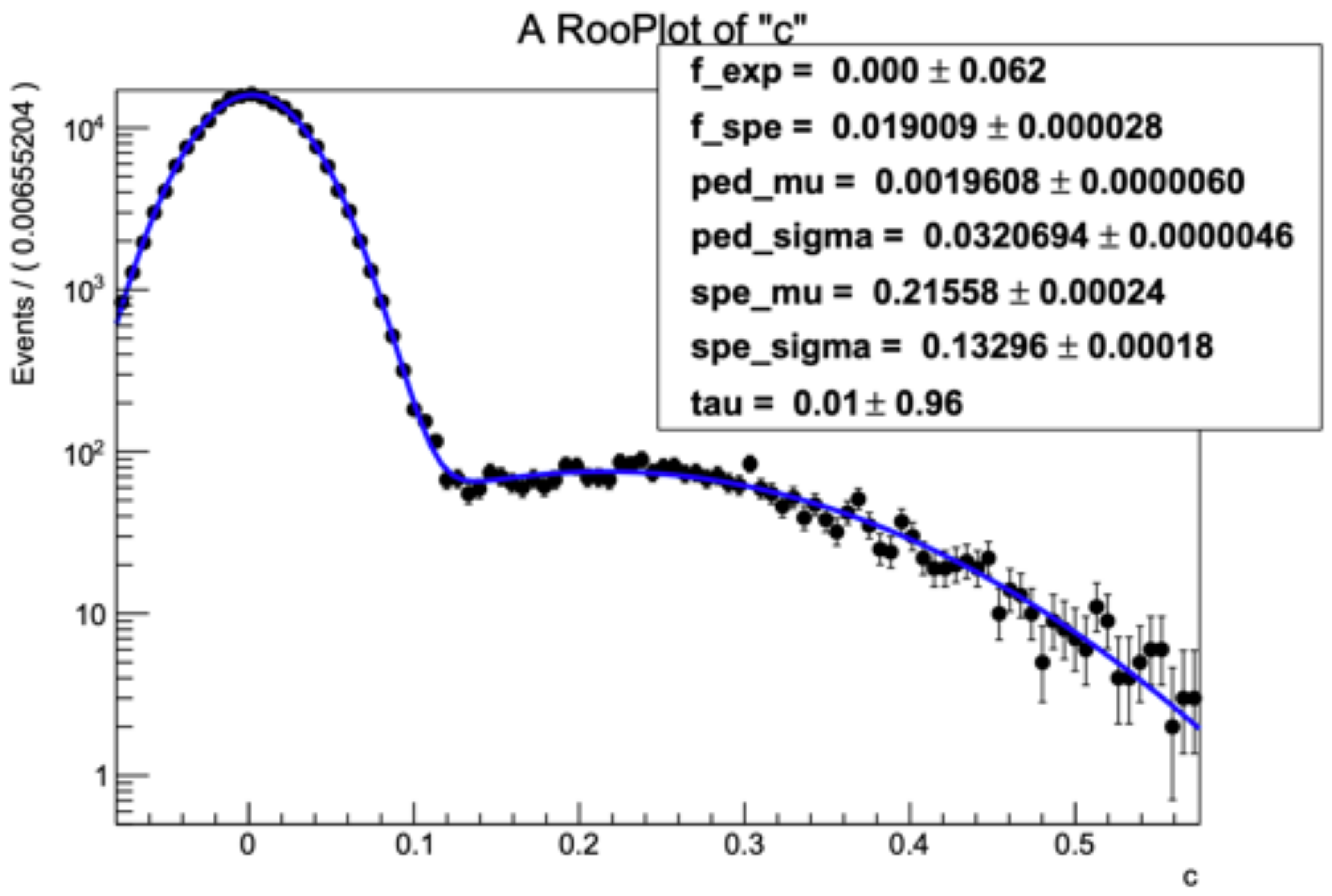
- Trench
  - To be aligned with the line-of-sight (LOS) in the vertical direction a shallow (<50cm deep) trench is needed in TI
  - Drain shallower than shown on historical drawings
    - Provided opportunity to increase trench depth - parallel to LOS
  - Plan area increased to allow more space for FASERν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

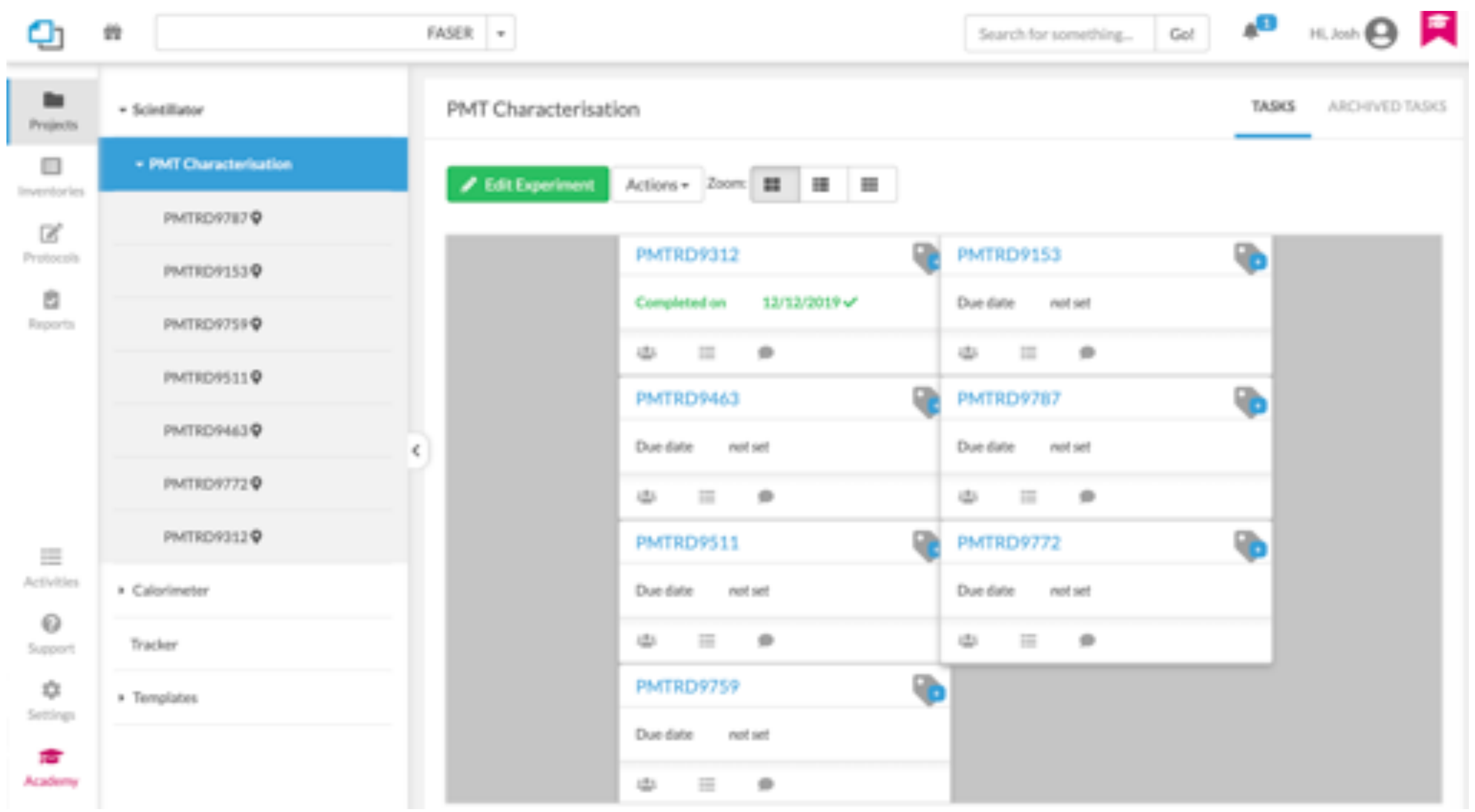




Scintillator | PMT gain measurement

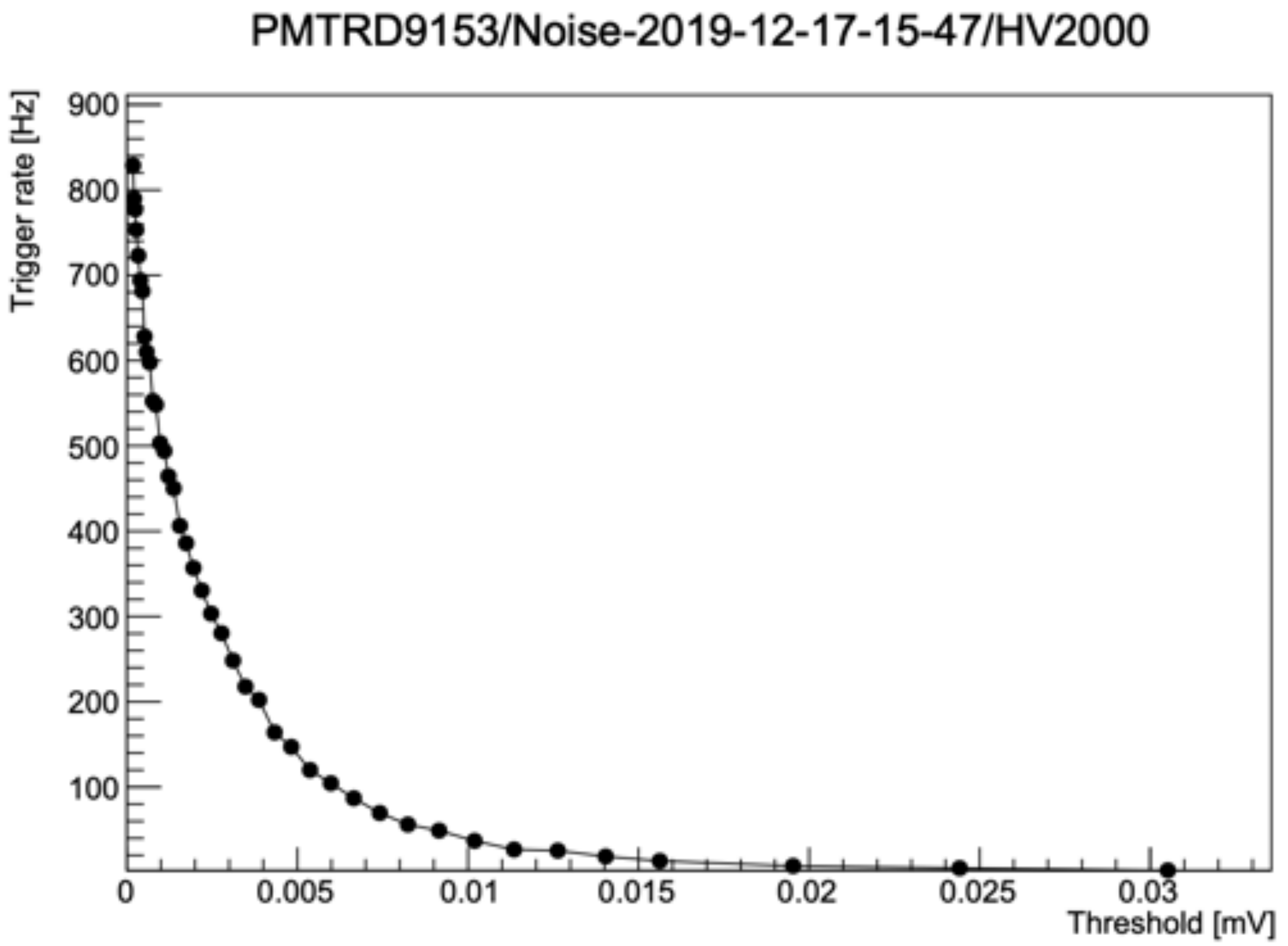
- Have completed single photon gain measurements on 11 (out of 12) PMTs
  - Use low intensity LED pulses to measure charge read out from a single photon at different intensities and High Voltage settings.





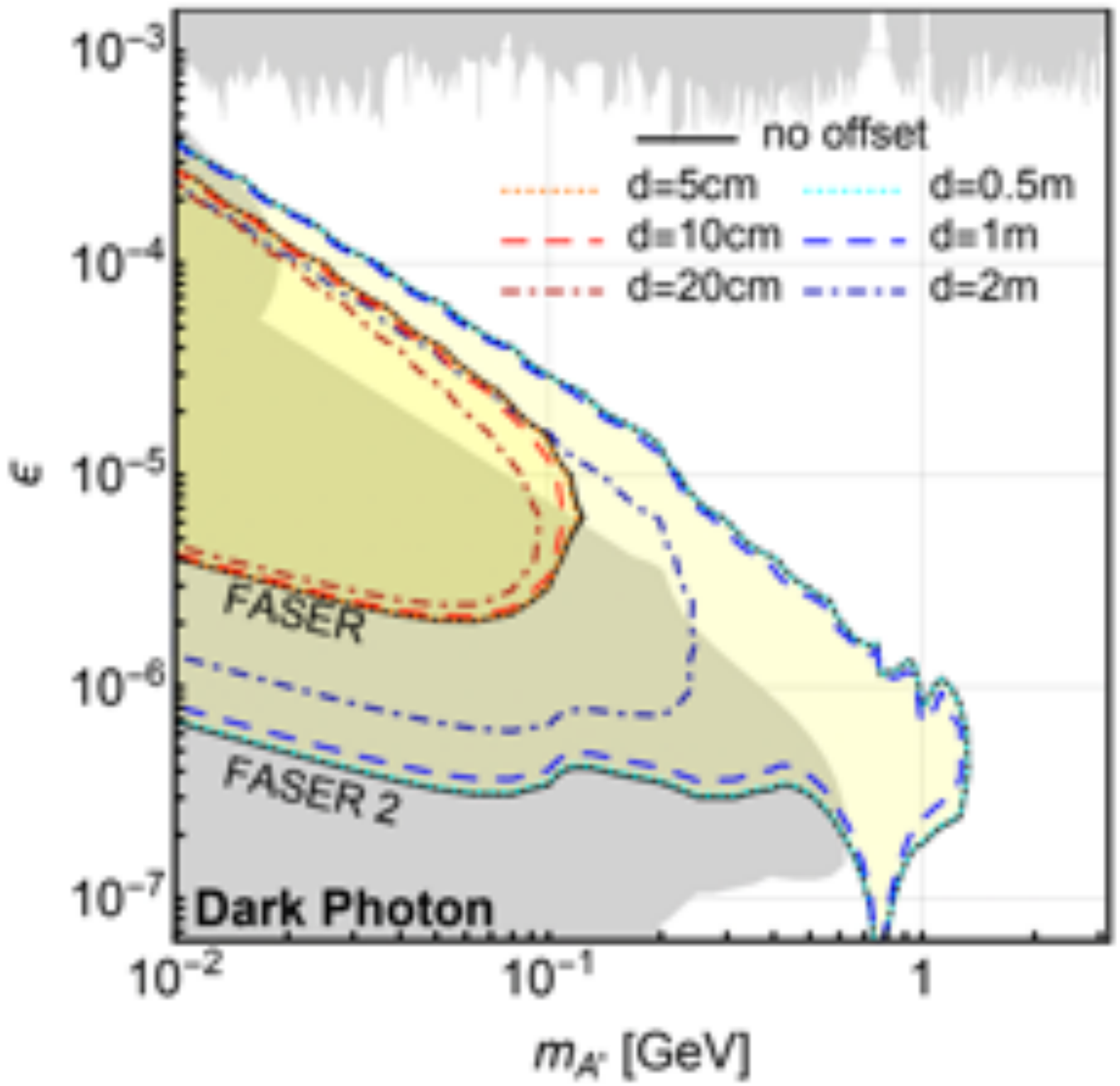
Scintillator | PMT noise measurement

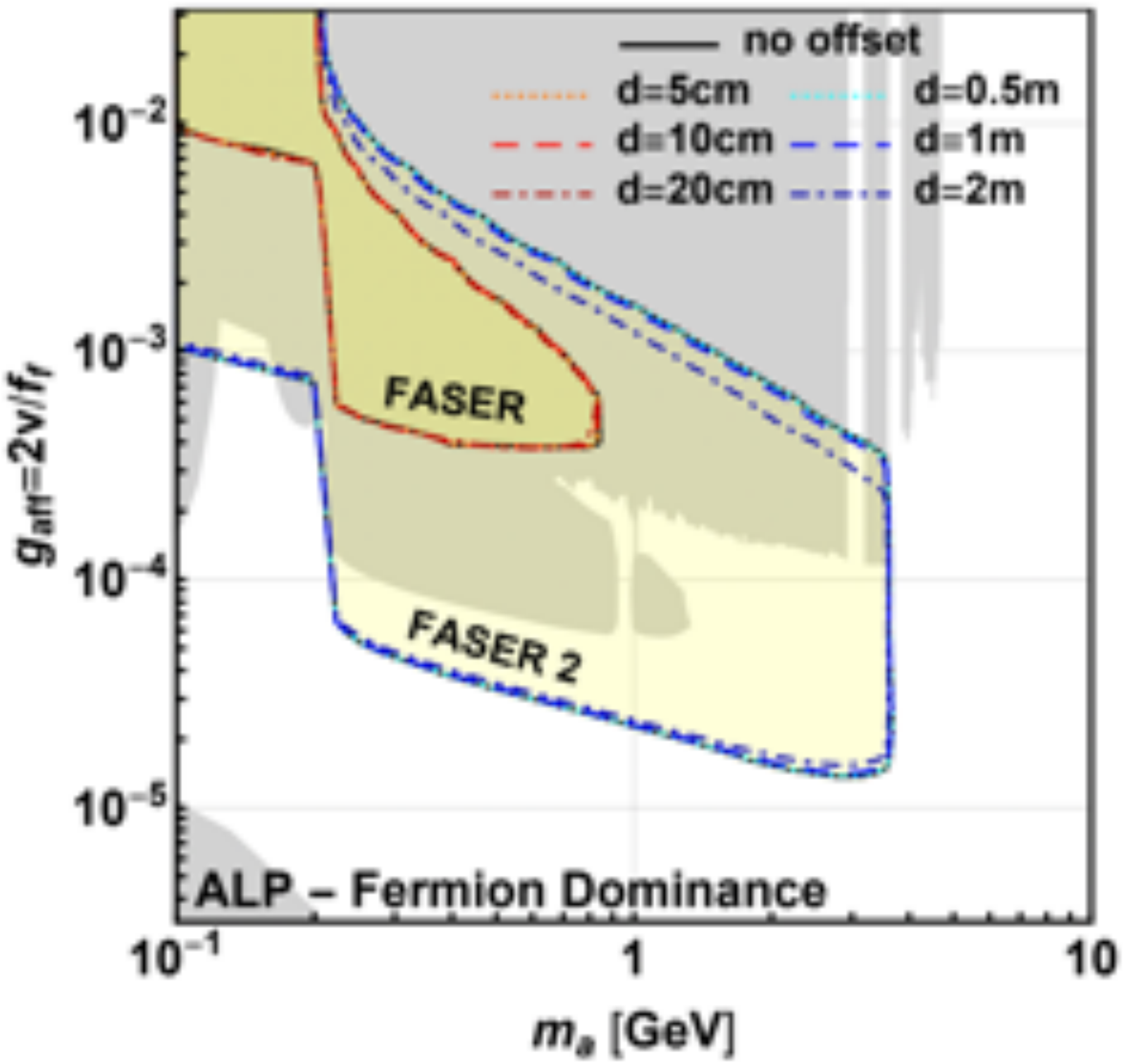
- We also started making noise measurements
  - Want to be sure that expected signal is not going to suffer from significant noise.
- Check the threshold normalised to the gain
  - Seem that the thresholds roughly scale with gain so the equivalent photo-electrons is similar across PMTS.
- For 100 Hz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



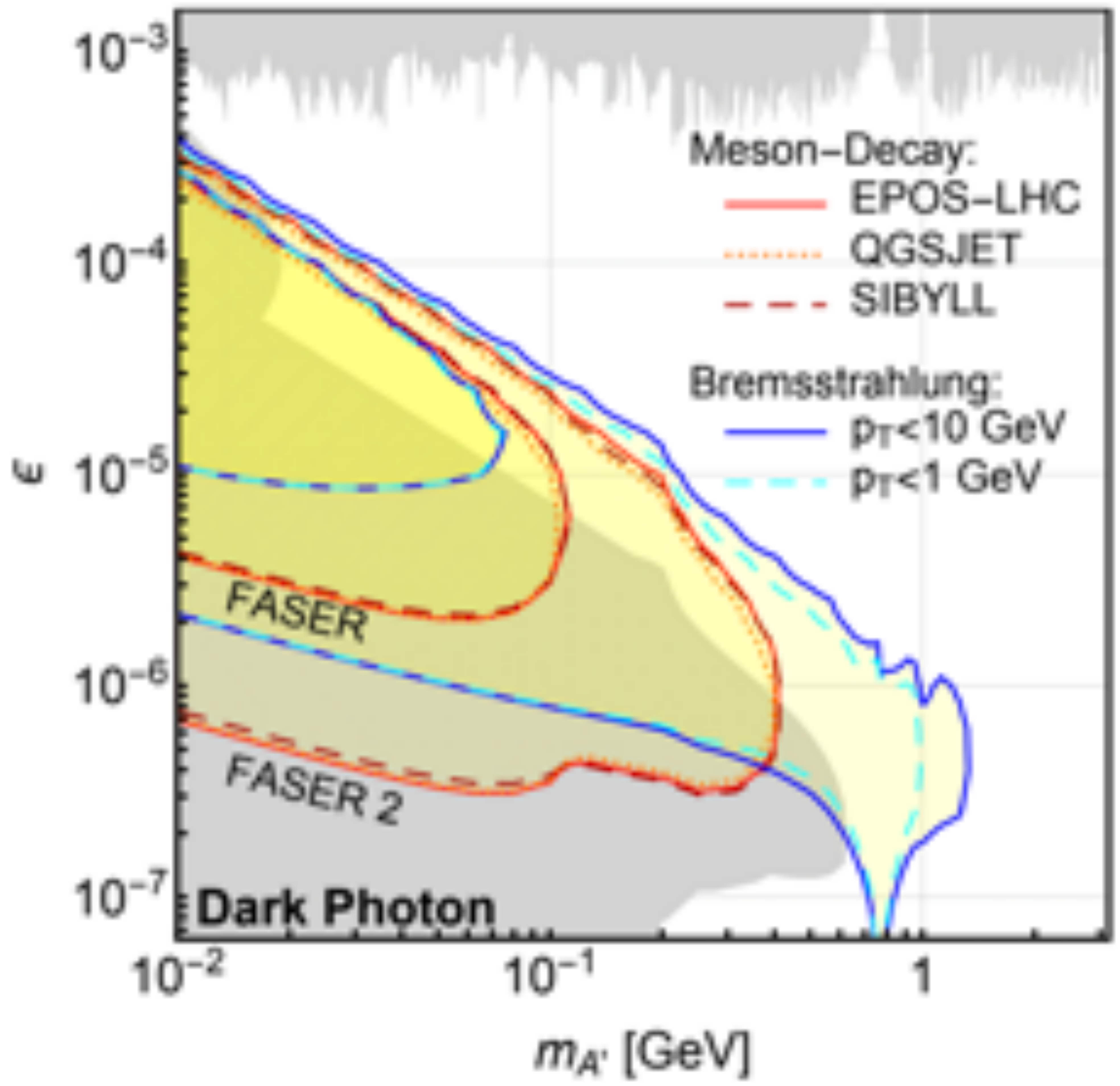
Rate [Hz]	10.0	50.0	100.0	500.0	1000.0
Threshold [mV]	17.91	9.03	6.15	1.02	0.05
Normalized [pE]	0.674	0.340	0.232	0.038	0.002

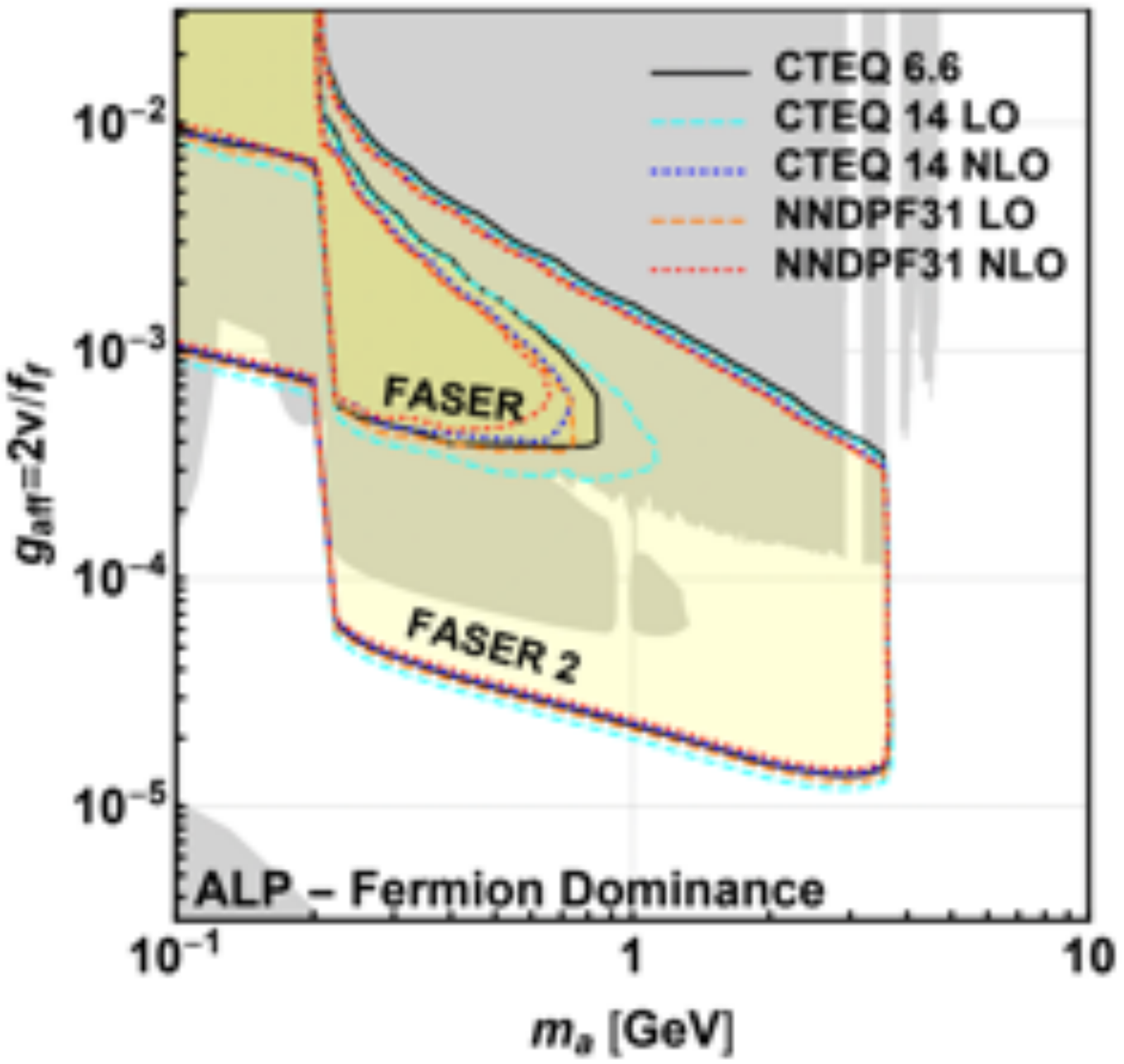
Beam offset


no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
Dark Photon
ϵ
$m_{A'}$ [GeV]

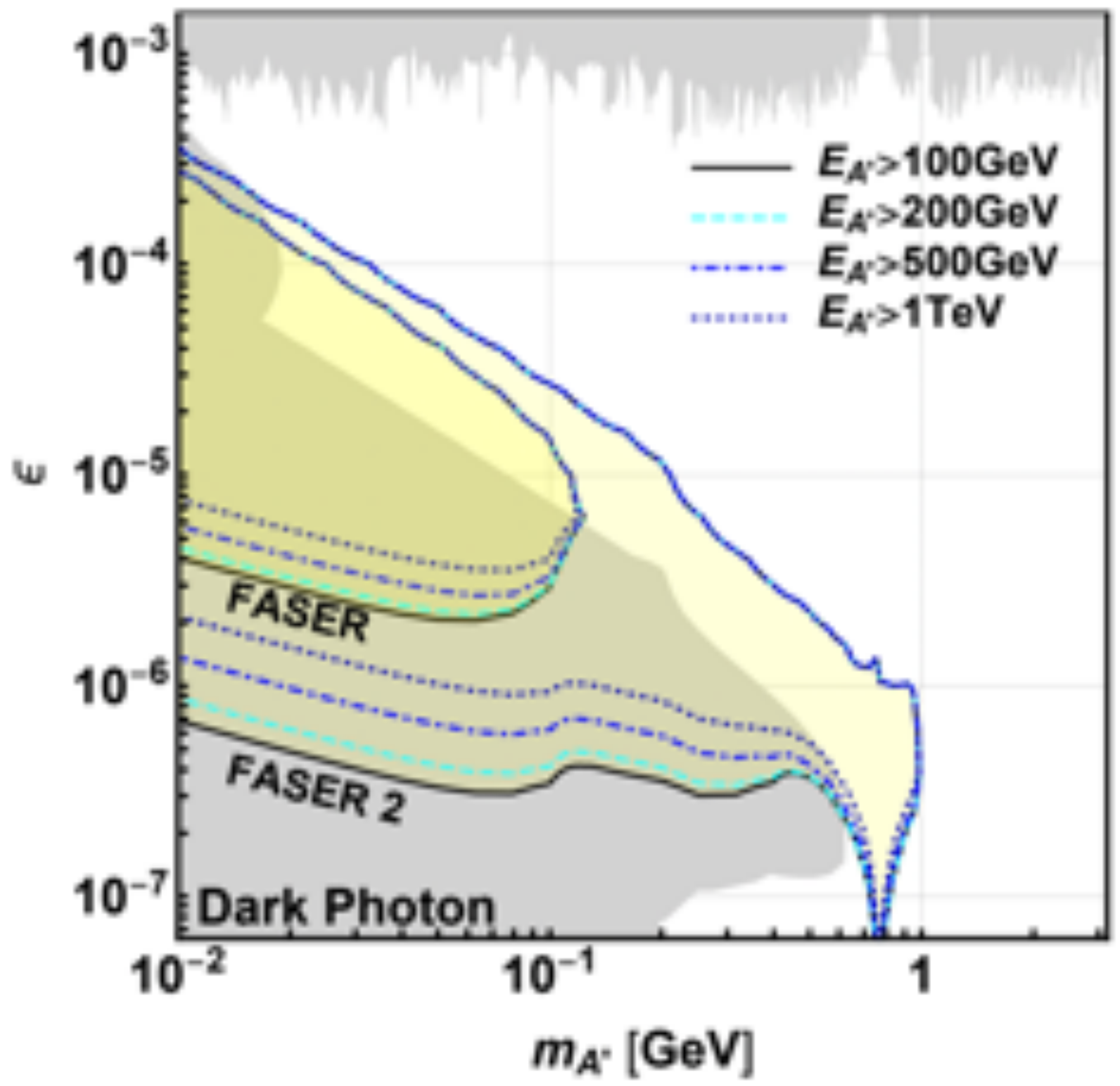

no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
ALP – Fermion Dominance
$g_{aff}=2v/f_f$
m_a [GeV]

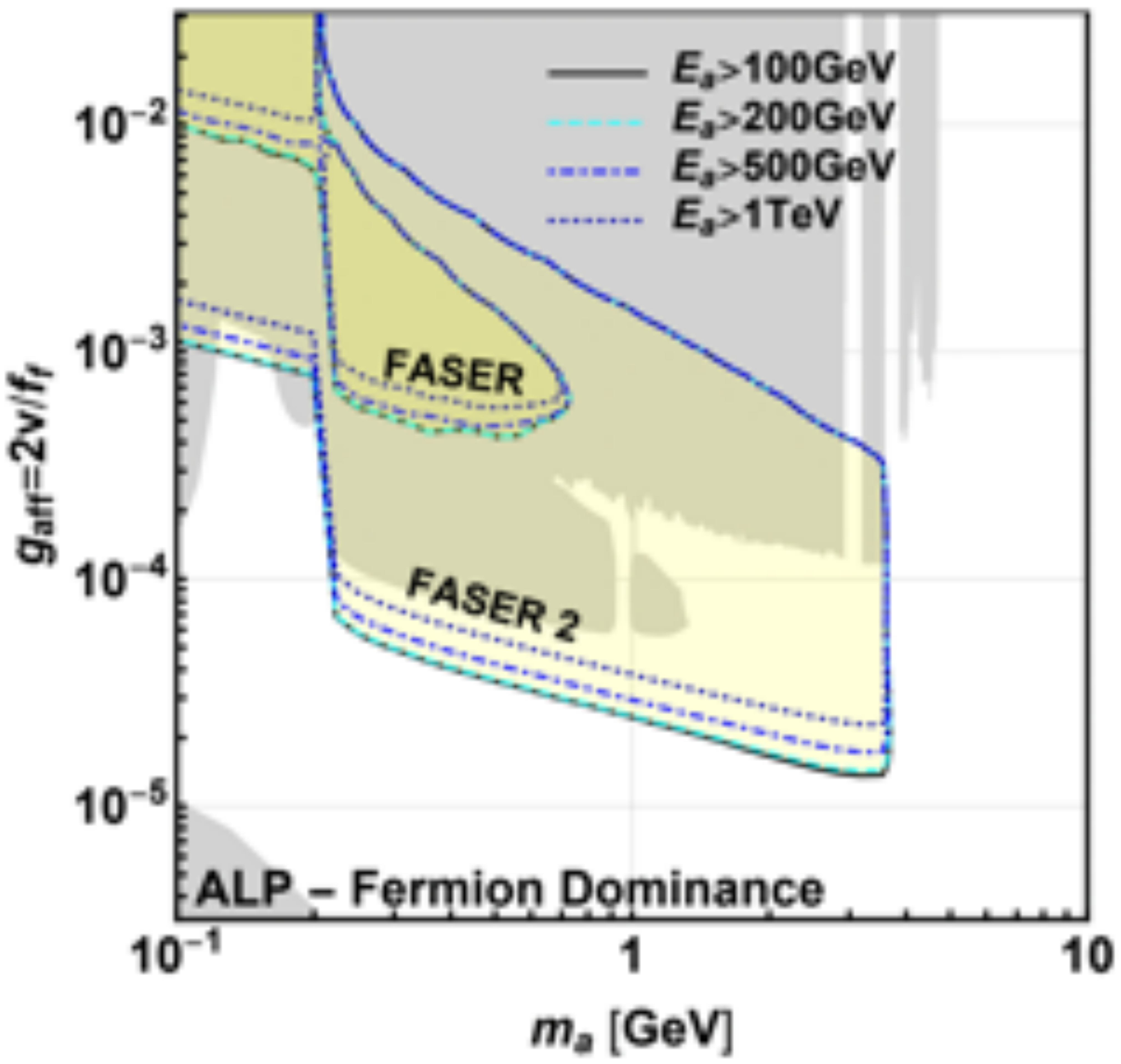
Modelling uncertainties

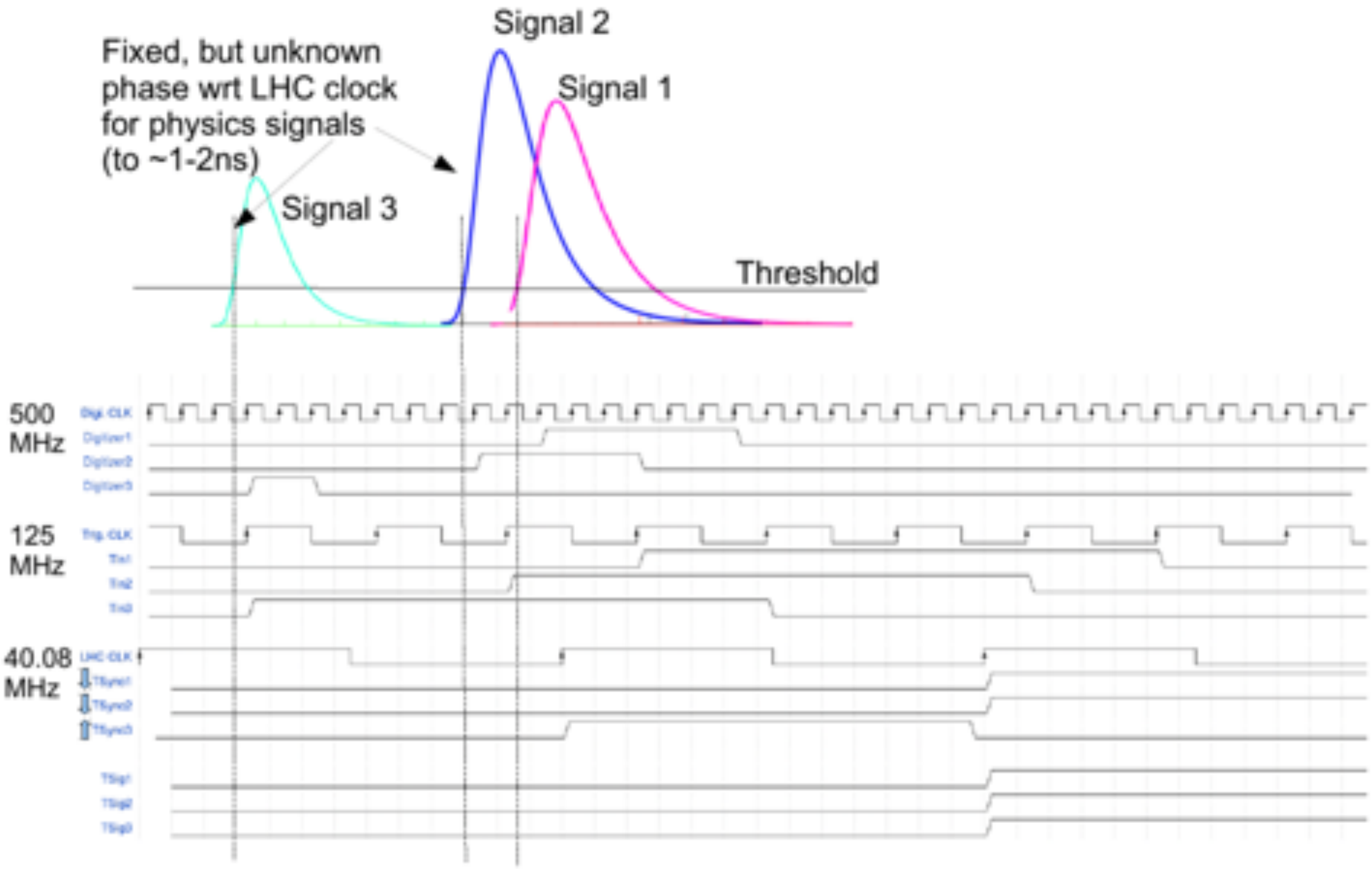




Energy threshold






Fixed, but unknown phase wrt LHC clock for physics signals (to ~1-2ns)
Signal 2
Signal 1
Signal 3
Threshold
500 MHz
125 MHz
40.08 MHz