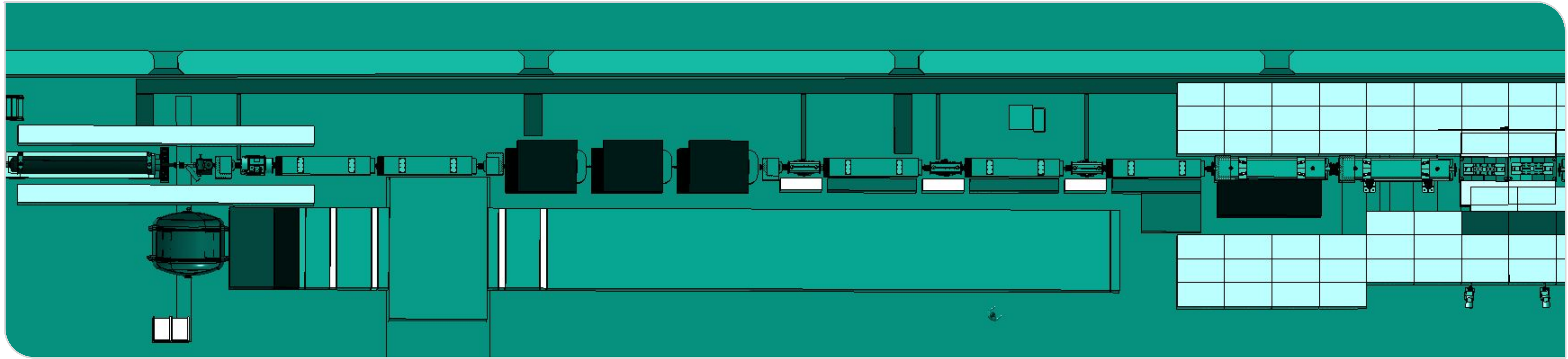
SHADOWS:
Search for **H**idden **A**nd **D**ark **O**bjects **W**ith the **S**PS

Brendan Regnery
on behalf of the SHADOWS Collaboration



The SHADOWS Collaboration

82 Collaborators from 16 Institutions

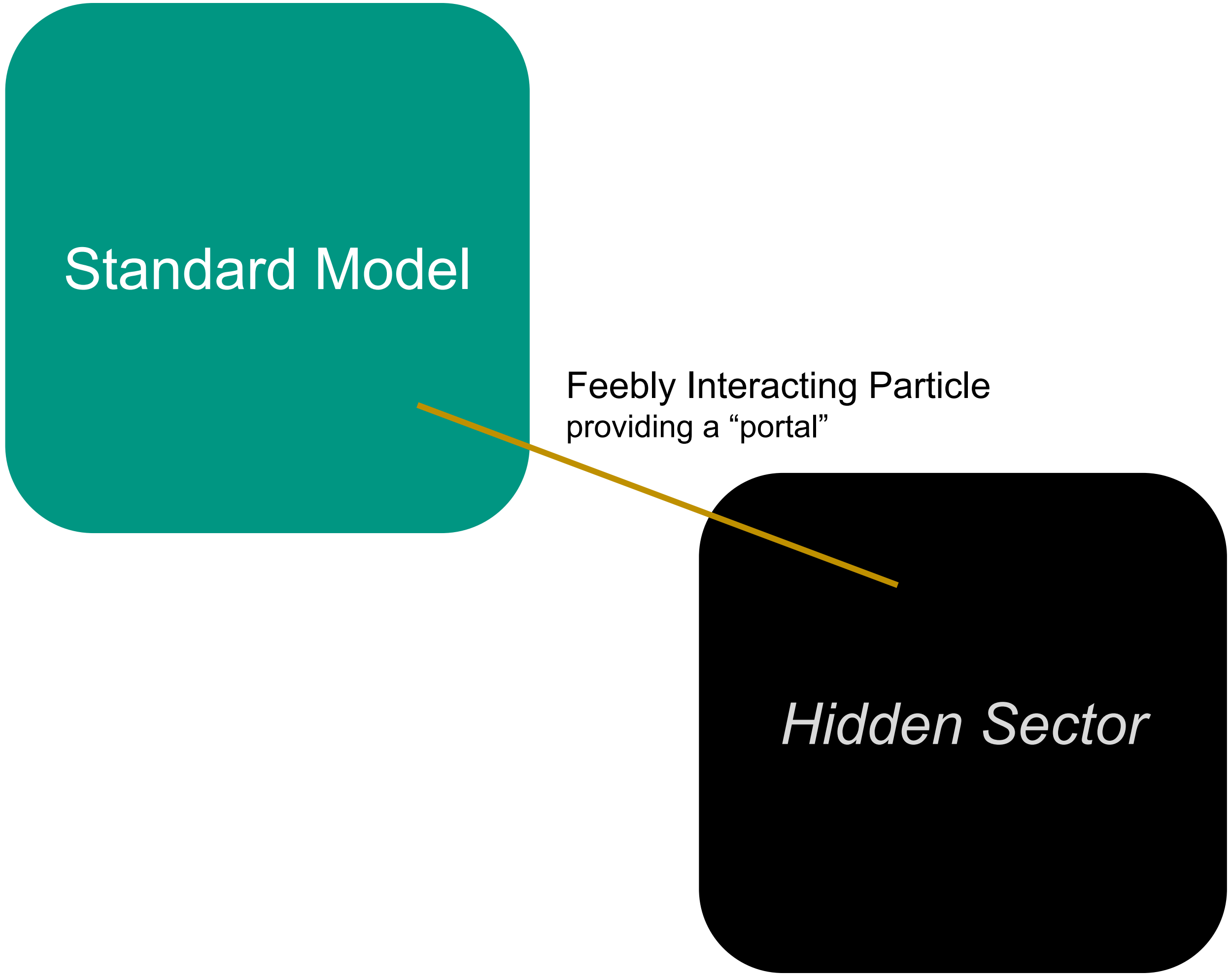
CERN, European Organization for Nuclear Research, Geneva, Switzerland
INFN, Sezione di Napoli, Napoli, Italy
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
INFN, Sezione di Ferrara, Ferrara, Italy
INFN Laboratori Nazionali di Frascati, Frascati (Rome), Italy
INFN, Sezione di Roma III, Roma, Italy
Johannes Gutenberg Universität Mainz, Mainz, Germany
INFN, Sezione di Bologna, Bologna, Italy
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
PARTREC and University of Groningen, Groningen, The Netherland
University of Freiburg, Freiburg, Germany
Charles University, Prague, Czech Republic
Royal Holloway, University of London, UK
INFN, Sezione di Roma 1, Roma, Italy

Overview

- Feebly Interacting Particles
- In SHADOW of HIKE: Searching with SHADOWS
- The experiment and detector technologies
- NaNu: North Area Neutrino subdetector
- The background measurements
- Project organisation
- Conclusions

Feebly Interacting Particles

- Rare interactions with standard model particles
- Axions, heavy neutral leptons, dark photons, dark Higgs, …
- Could provide a portal to a hidden sector with dark matter particles
- Provide explanations to:
  - Strong CP problem
  - Hierarchy of scales
  - Origin of neutrino masses

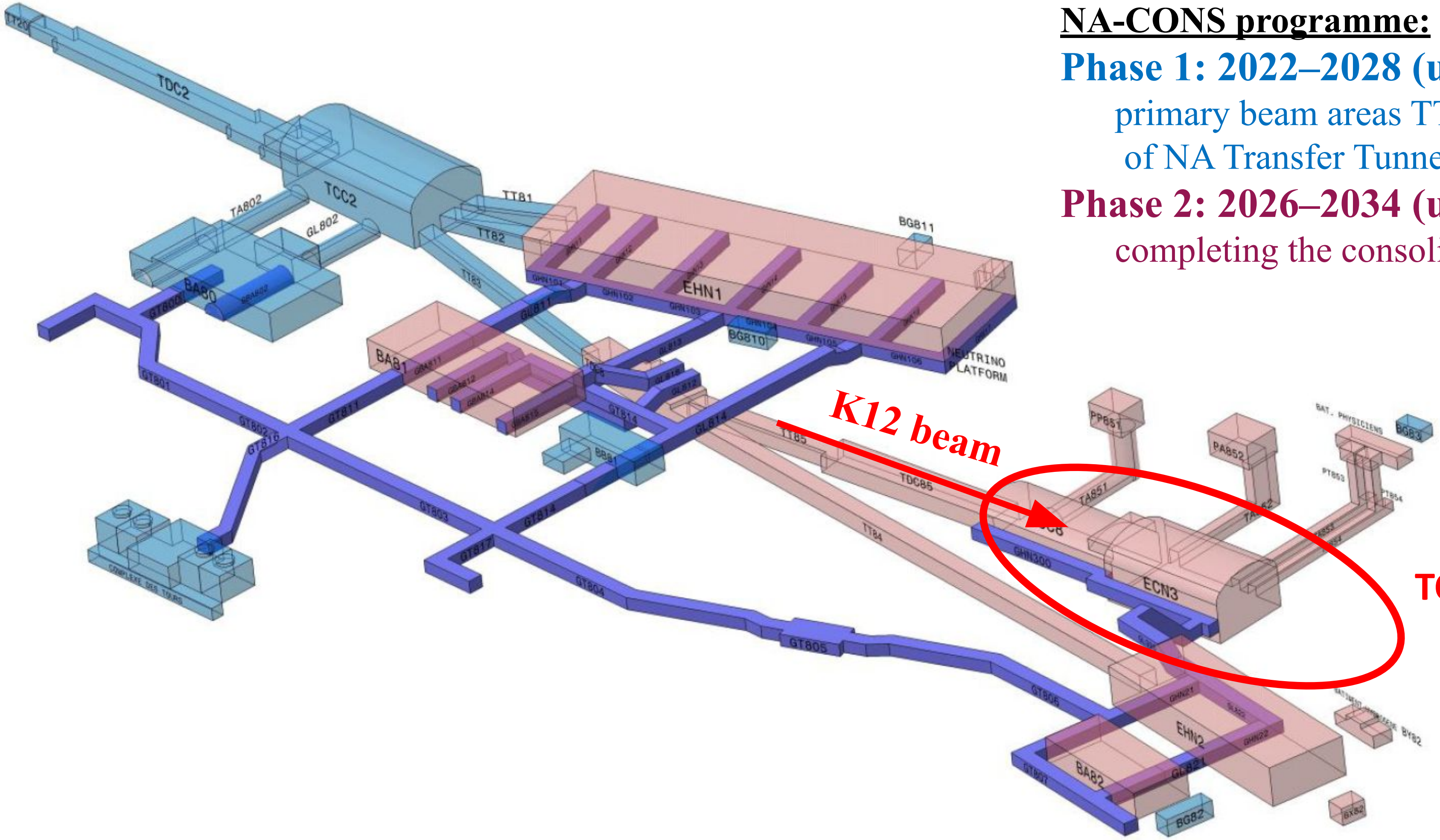


*The **quest for dark matter and the exploration of flavour** and fundamental symmetries are **crucial components of the search for new physics.***

This search can be done in many ways… through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles.

- Recommendations from the European Strategy for Particle Physics

North Area Consolidation programme



<u>NA-CONS programme:</u>

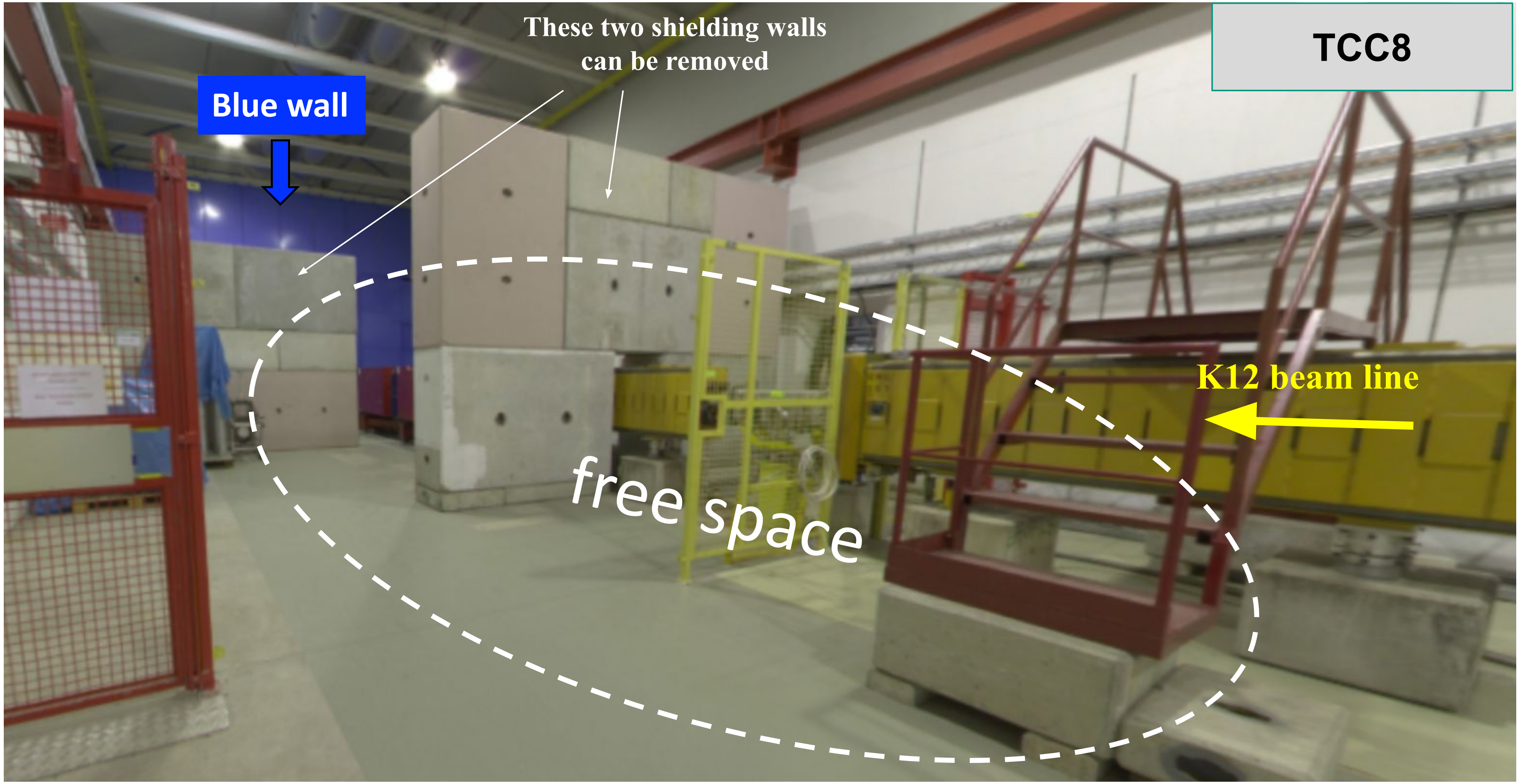
Phase 1: 2022–2028 (up to end LS3),

primary beam areas TT20, TDC2, TCC2 and initial section of NA Transfer Tunnels.

Phase 2: 2026–2034 (up to end LS4),

completing the consolidation of the secondary beam areas.

The First Idea of SHADOWS



How is a new experiment created?

Karlsruhe Institute of Technology

SHADOWS

Search for Hidden And Dark Objects With the SPS

Expression of Interest

W. Baldini[1], A. Balla[2], J. Bernhard[3], A. Calcaterra[2], V. Cafaro[4], N. Charitonidis[3], A. Ceccucci[3], V. Cicero[4], P. Ciambrone[2], H. Danielsson[3], A. De Roeck[3], F. Duval[3], G. D'Alessandro[3], G. Felici[2], L. Foggetta[2], L. Gatignon[5], A. Gerbershagen[3], V. Giordano[4], G. Lanfranchi[2], I. Lax[4], A. Montanari[4], R. Murphy[3], T. Napolitano[2], A. Paoloni[2], G. Papalino[2], T. Rovelli[4], A. Saputi[2], S. Schuchmann[6], F. Stummer[7], G. Torromeo[4], N. Tosi[4], A. Vannozzi[2].

6 Jan 2022

Passo dopo passo

(step-by-step)

Letter of Intent

M. Alviggi[1], S. Bachmann[2], W. Baldini[3], A. Balla[4], M. Biglietti[8], V. Büscher[11], A. Calcaterra[4], V. Cafaro[5], N. Charitonidis[6], A. Ceccucci[6], V. Cicero[5], P. Ciambrone[4], H. Danielsson[6], M. Dellapietra[1], A. De Roeck[6], F. Duval[6], G. Felici[4], T. Ferber[7], L. Foggetta[4], M. Gatta[4], A. Gerbershagen[13], V. Giordano[5], S. Hansmann-Menzemer[2], P. Iengo[1], M. Iodice[8], K. Jakobs[9] M. Klute[7], K. Köneke[9], M. Koval[10], G. Lanfranchi[4], A. Laudrain[11], I. Lax[5], B. Leverington[2], P. Lichard[6], K. Massri[6], A. Montanari[5], R. Murphy[6,12], T. Napolitano[4], F. Neuhaus[11], L. J. Nevay[6] A. Paoloni[4], G. Papalino[4], U. Parzefall[9], S. Ritter[11], T. Rovelli[5,14], A. Saputi[3], B. Schmidt[6], M. Schott[11], H.C. Schultz-Coulon[2], G. Sekhniaidze[1], F. Stummer[6,12], G. Torromeo[5], N. Tosi[5], U. Uwer[2], M. van Dijk[6], A. Vannozzi[4], R. Wanke[11], C. Weiser[9], P. Wertelaers[6], T. Zickler[6]

4 Nov 2022

Technical Proposal

M. Alviggi[1], S. Bachmann[2], W. Baldini[3], A. Balla[4], M. Barth[2], M. Biglietti[5], V. Büscher[6], A. Calcaterra[4], V. Cafaro[7], M. Cavallina[3], A. Ceccucci[8], D. Chouhan[6], V. Cicero[7], P. Ciambrone[4], H. Danielsson[8], M. Della Pietra[1], C. Delogu[6], A. De Roeck[8], L. Dittmann[2], F. Duval[8], G. Felici[4], T. Ferber[9], L. Foggetta[4], E. Gamberini[8], M. Gatta[4], A. Gerbershagen[10], V. Giordano[7], S. Hansmann-Menzemer[2], P. Iengo[11], M. Iodice[11], K. Jakobs[12], J. Kieseler[9], M. Klute[9], K. Köneke[12], M. Koval[13], G. Lanfranchi[4], A. Laudrain[6], I. Lax[87, T. M. Leeflang[2], G. Lehmann Miotto[8], B. Leverington[2], P. Lichard[8], K. Massri[8], A. Montanari[7], T. Napolitano[4], A. Paoloni[4], G. Papalino[4], U. Parzefall[12], B. Ponzio[4], B. Regnery[9], S. Ritter[6], S. Rosati[15], T. Rovelli[16,7], S. Roy[2], A. Saputi[3], B. Schmidt[8], M. Schott[6], D. Schub[2], H.C. Schultz-Coulon[2], G. Sekhniaidze[1], R. Stamen[2], G. Torromeo[7], N. Tosi[7], N. Trevisani[6], U. Uwer[2], A. Vannozzi[4], C. Wang[6], R. Wanke[6], C. Weiser[12], C. Welschoff[2], P. Wertelaers[8]

18 Aug 2023

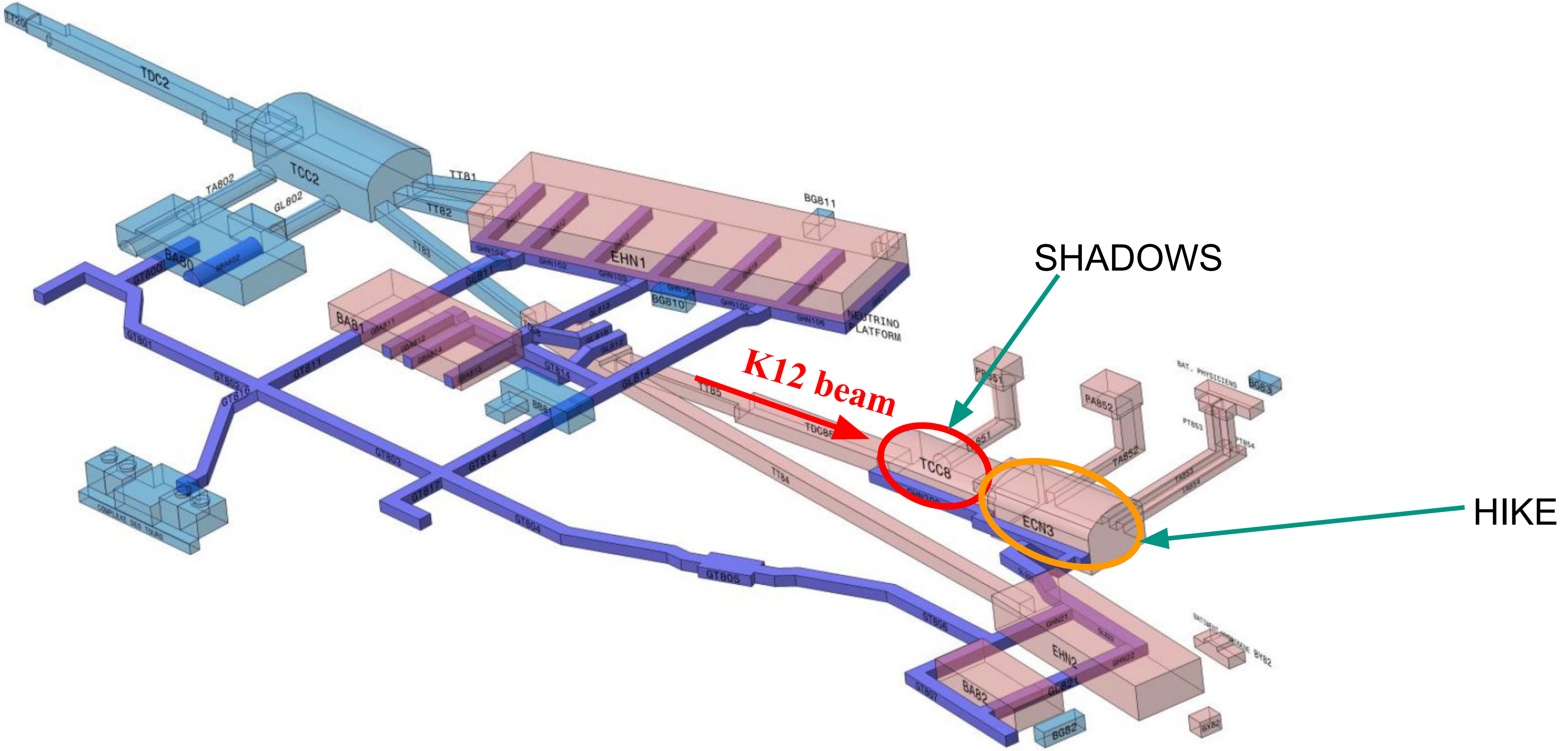
Available on CDS 31 Oct 2023

20 months

Expression of Interest to Proposal

Collaboration nearly tripled in size

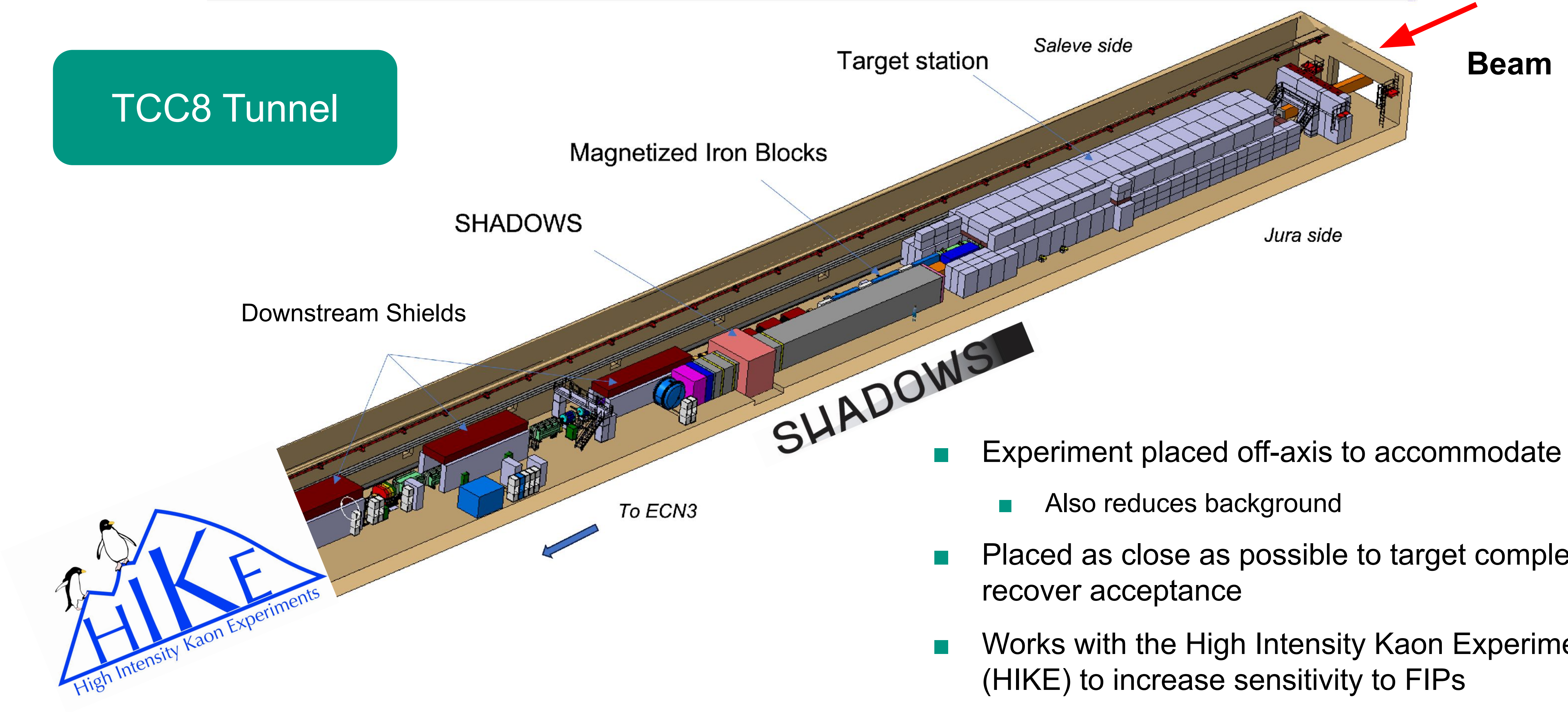
In the shadow of HIKE: Searching with SHADOWS



SHADOWS

In the shadow of HIKE: Searching with SHADOWS

TCC8 Tunnel

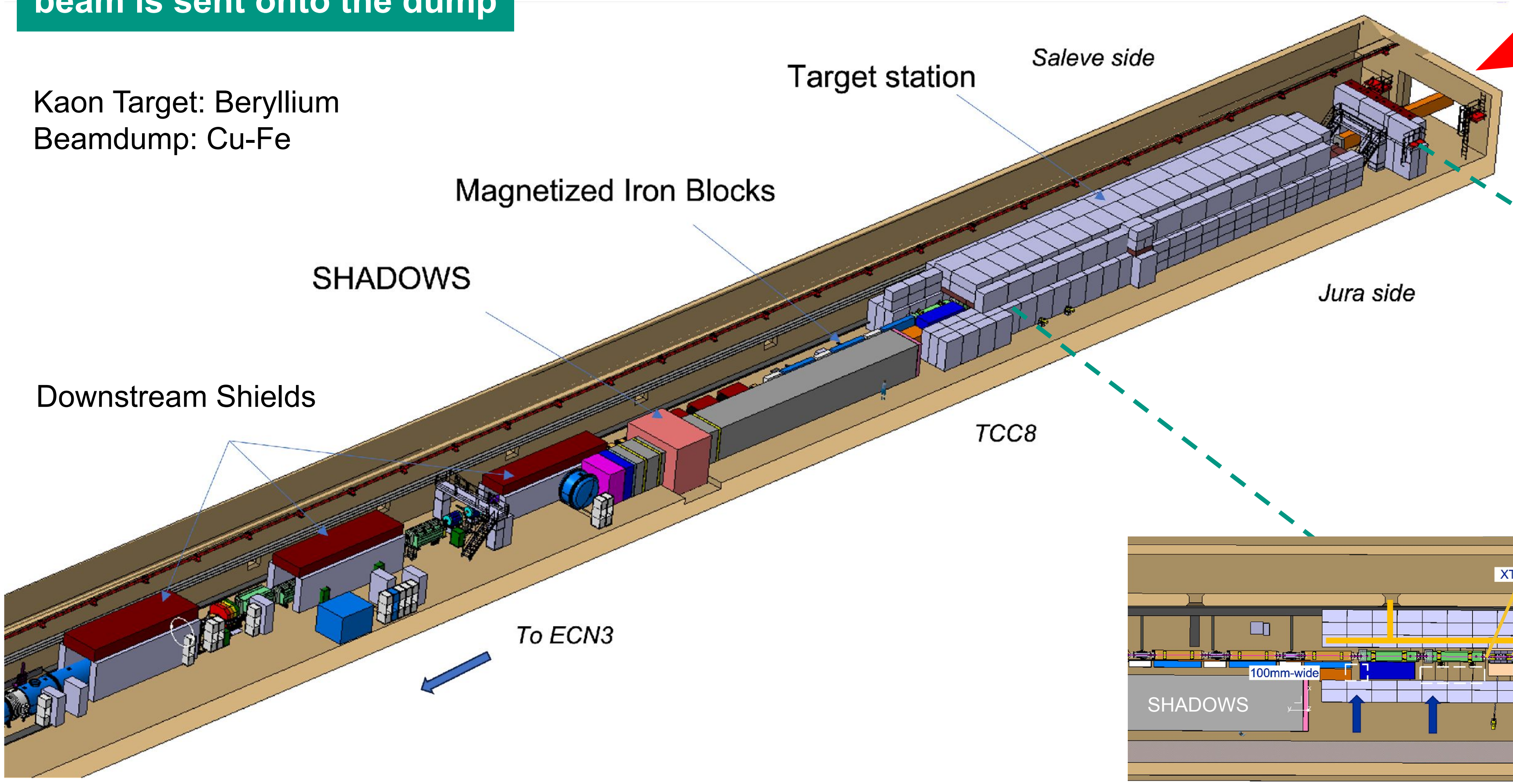


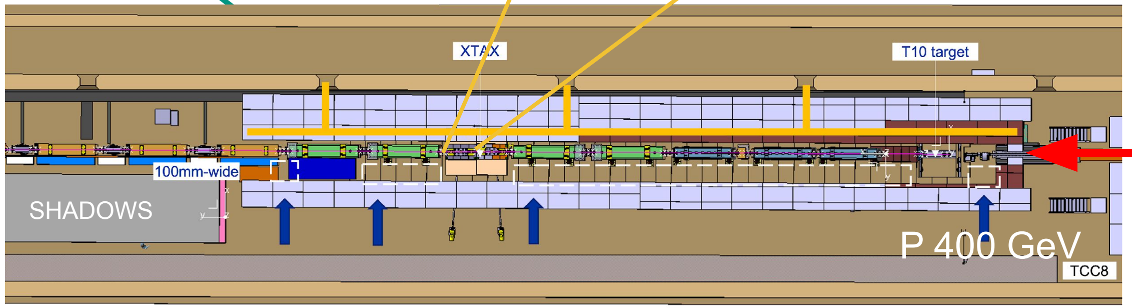
- Experiment placed off-axis to accommodate HIKE
  - Also reduces background
- Placed as close as possible to target complex to recover acceptance
- Works with the High Intensity Kaon Experiments (HIKE) to increase sensitivity to FIPs

Kaon mode and Beamdump mode

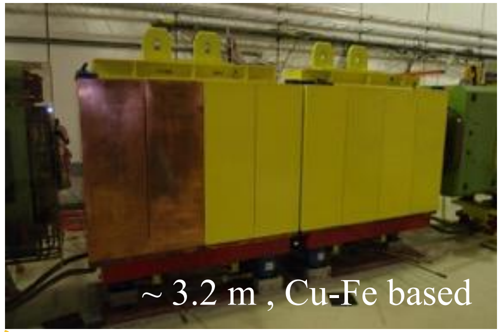
Kaon (T10) target is lifted and the 400 GeV proton beam is sent onto the dump

Kaon Target: Beryllium
Beamdump: Cu-Fe





NA62 dump system



Will be upgraded to withstand higher (7x) intensity

SHADOWS + HIKE: The possible future

- Designed to detect a large number of FIP decays
  - Full list available in SHADOWS proposal… soon available on CDS
- Examples: sensitivity to light dark scalar and heavy neutral leptons
  - More available in the proposal
- Designed with well established technologies
  - Ready for operation by 2030

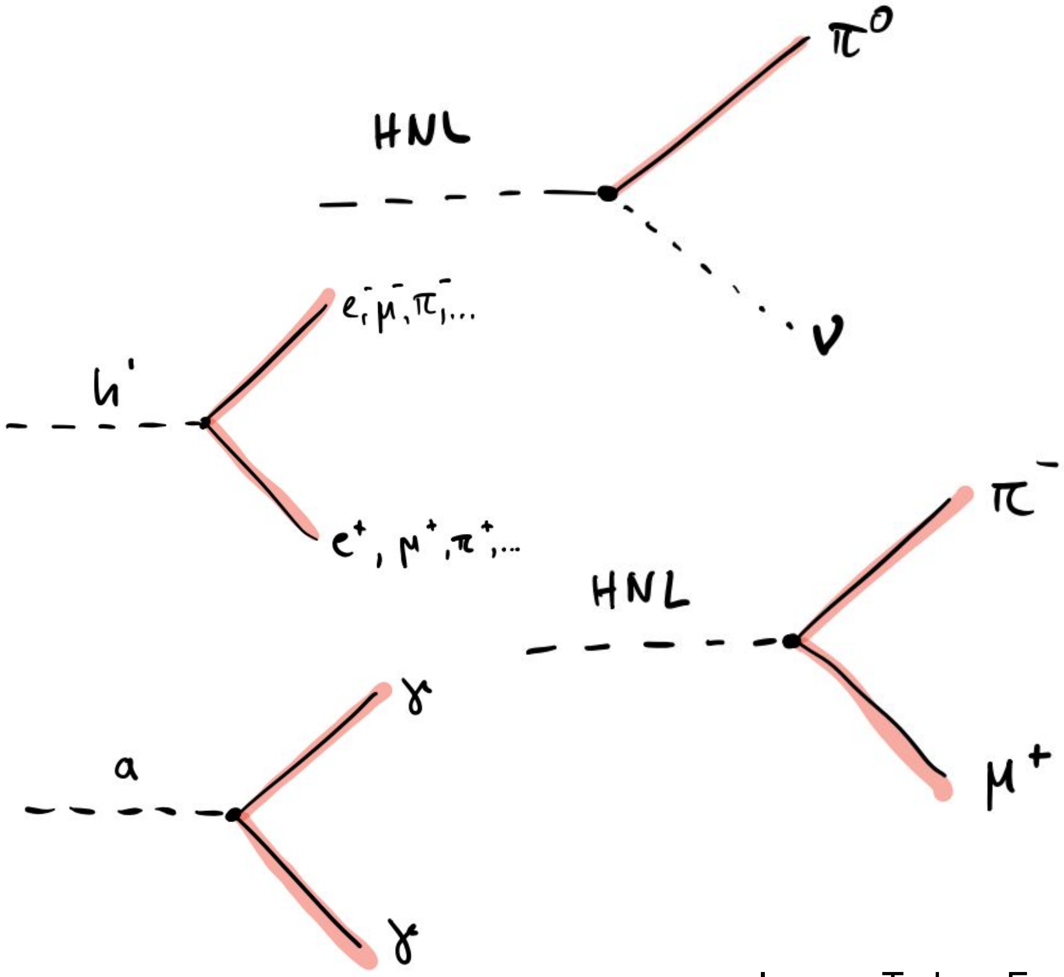
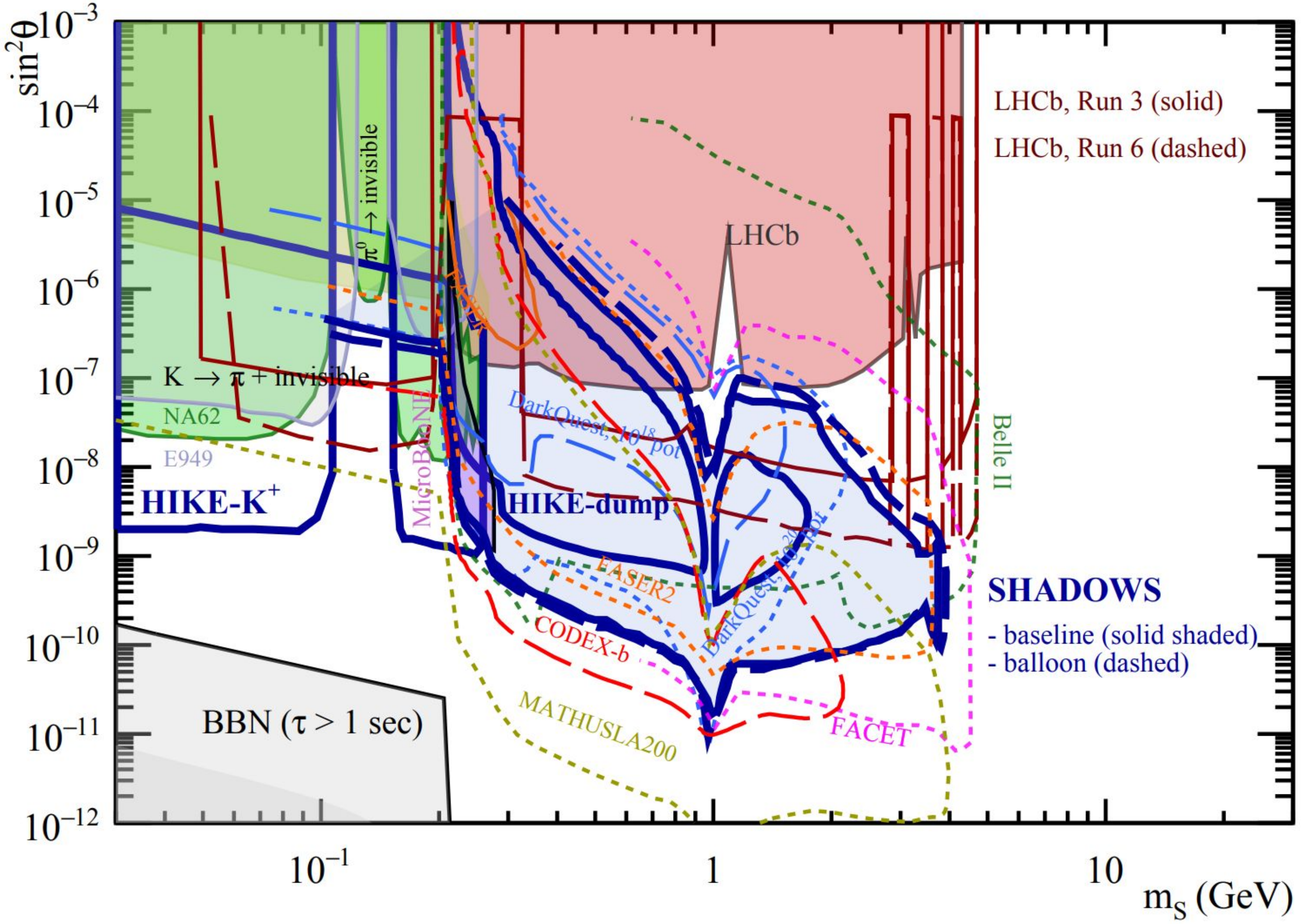


Image: Torben Ferber

SHADOWS+ HIKE : The possible future

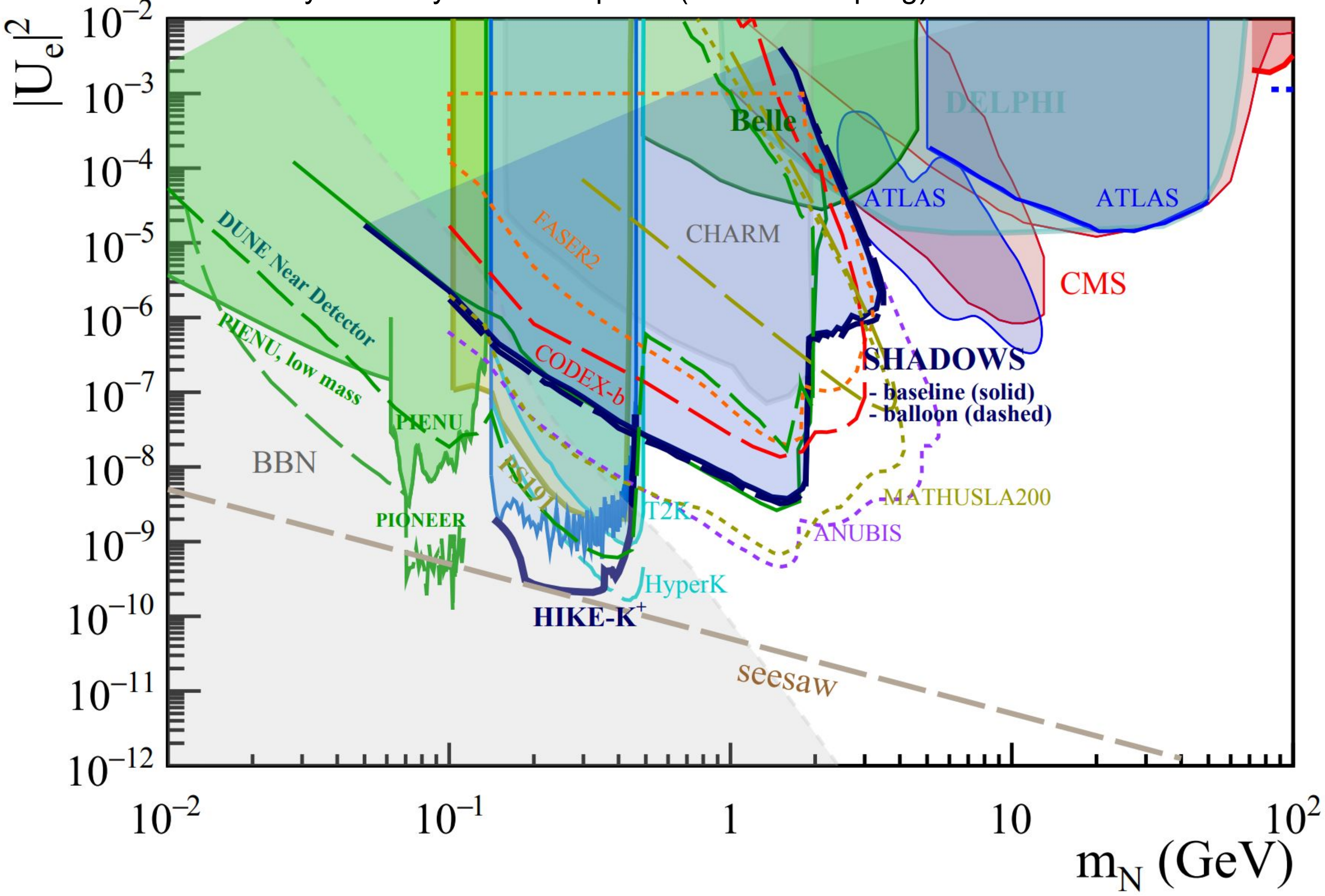
Sensitivity to Light Dark Scalar



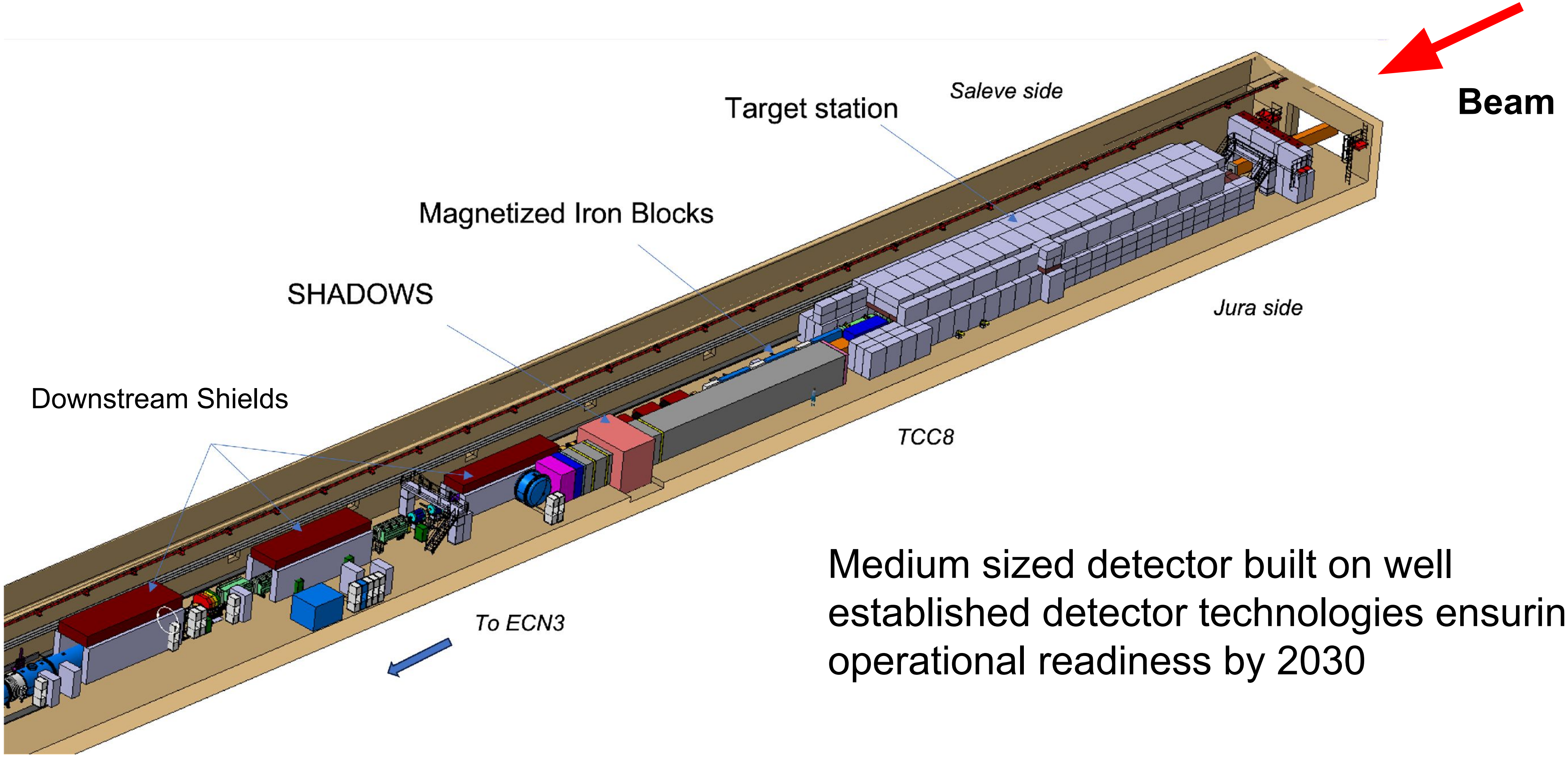
SHADOWS

SHADOWS+ HIKE : The possible future

Sensitivity to Heavy Neutral Leptons (electron coupling)

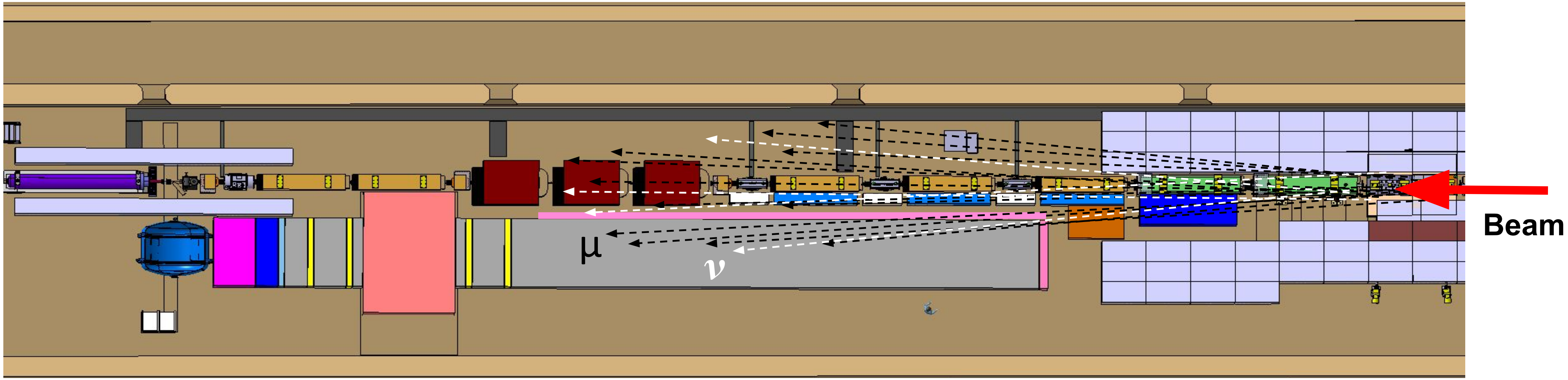


SHADOWS Overview



Medium sized detector built on well established detector technologies ensuring operational readiness by 2030

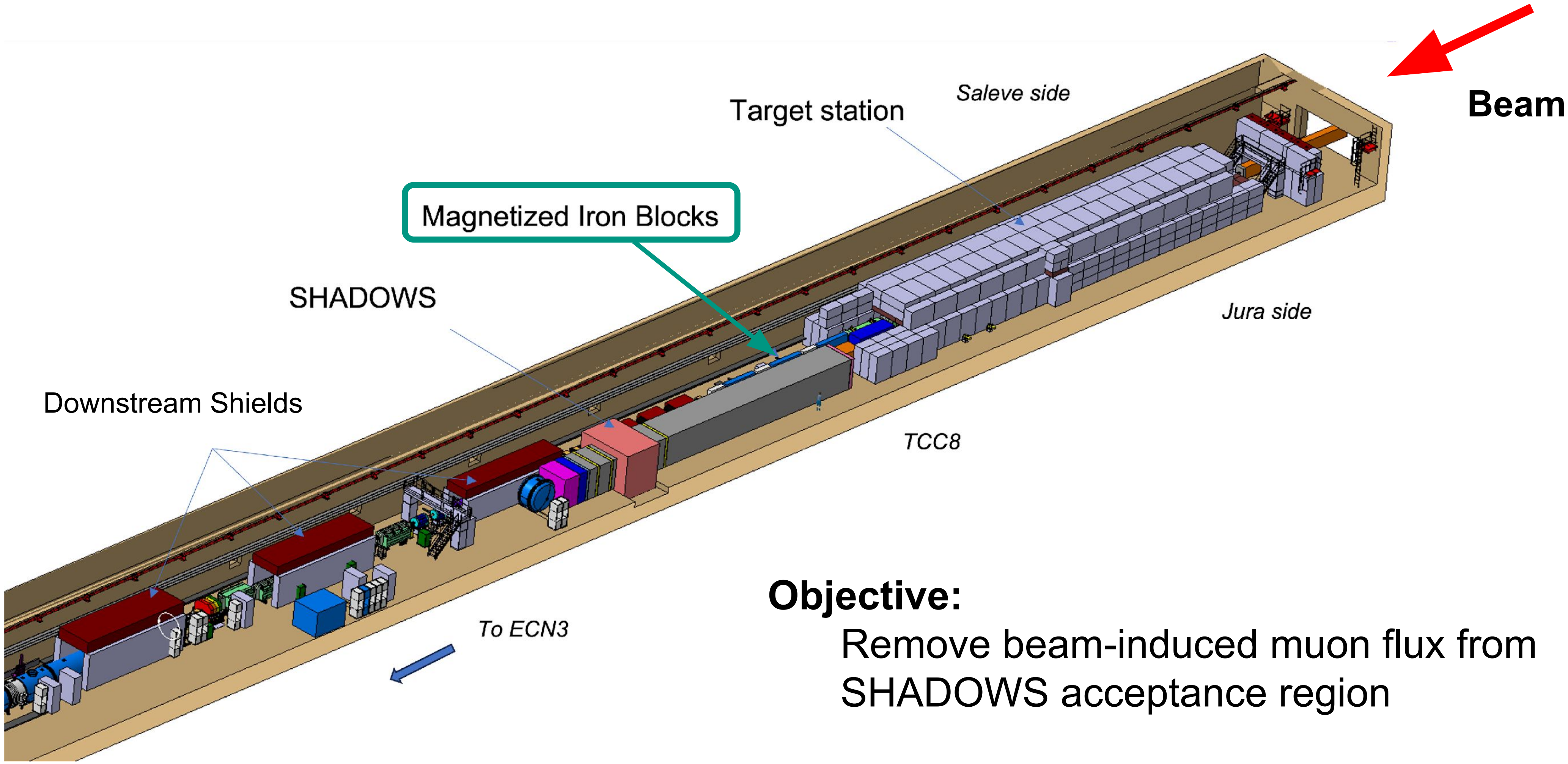
SHADOWS Backgrounds



Objective: remove as much background as possible, leaving only FIPS

Main backgrounds: muons and neutrinos emerging from the dump

MIB: Magnetized Iron Blocks

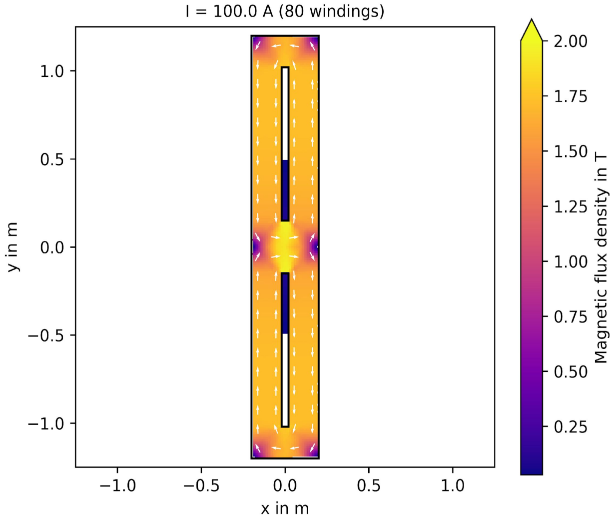


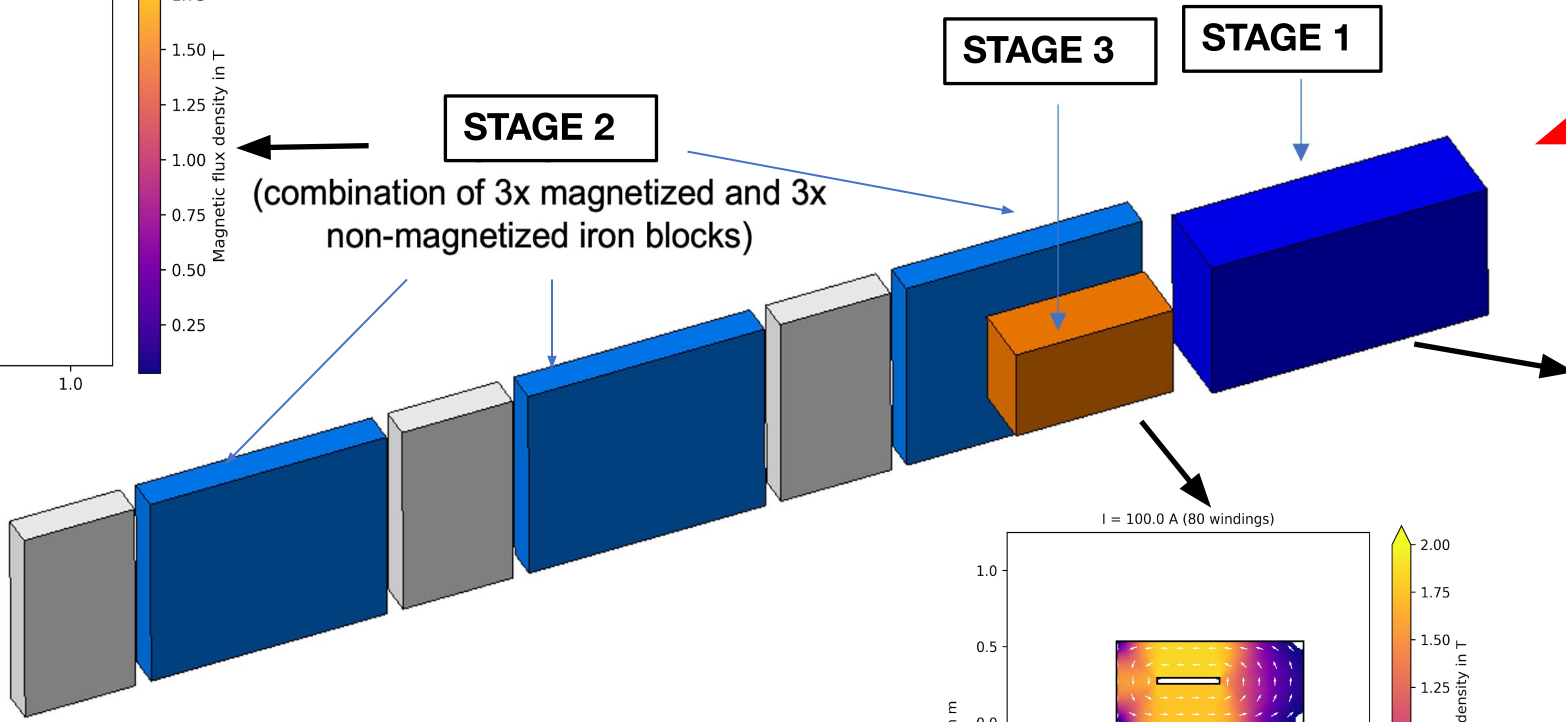
Objective:

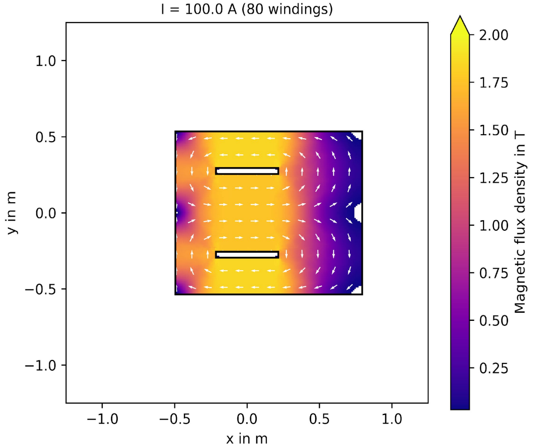
Remove beam-induced muon flux from SHADOWS acceptance region

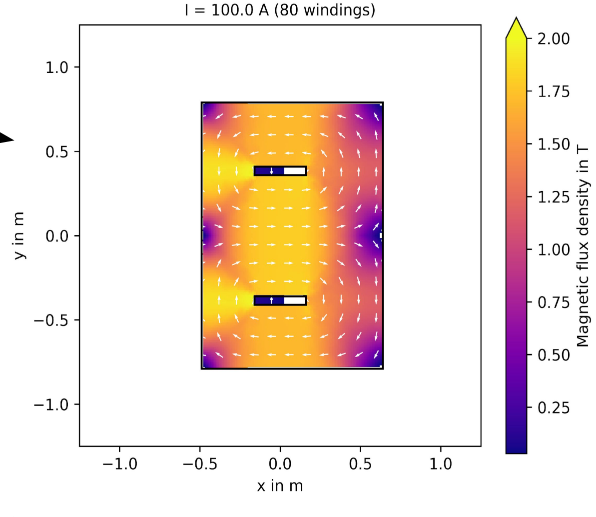
MIB: Magnetized Iron Blocks

Karlsruhe Institute of Technology









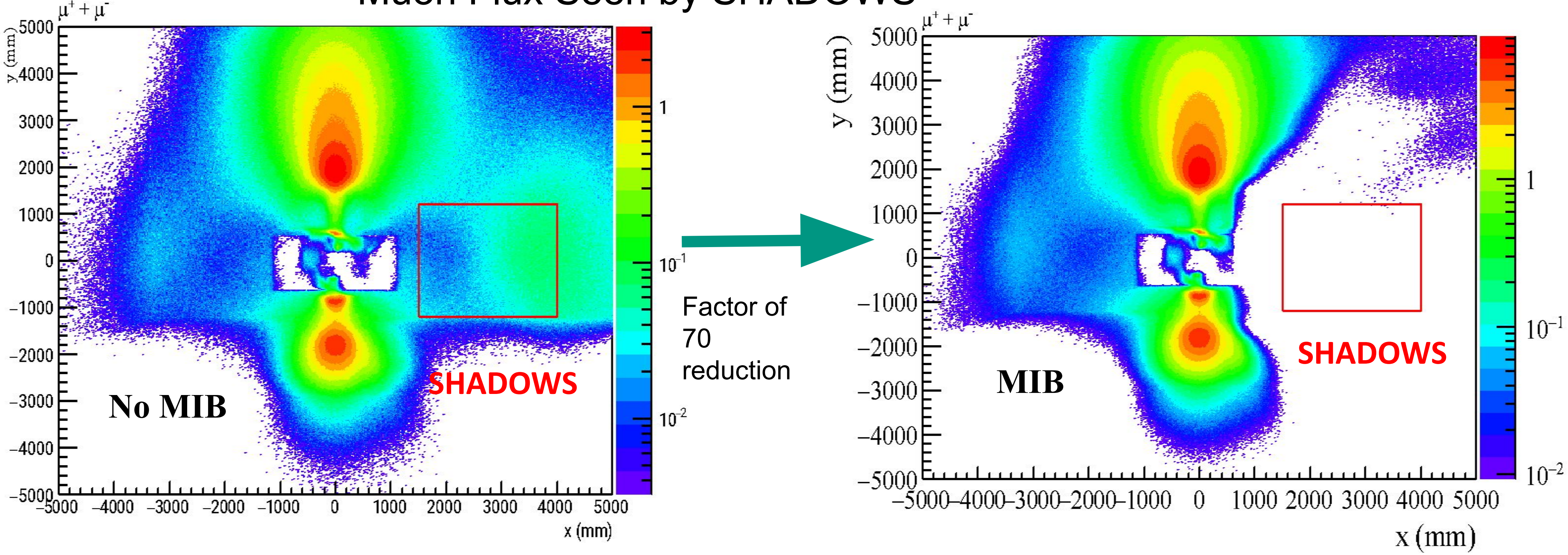
System of electromagnets to prevent background muons from entering SHADOWS

CERN BE-EA-LE
Florian Stummer

MIB Performance

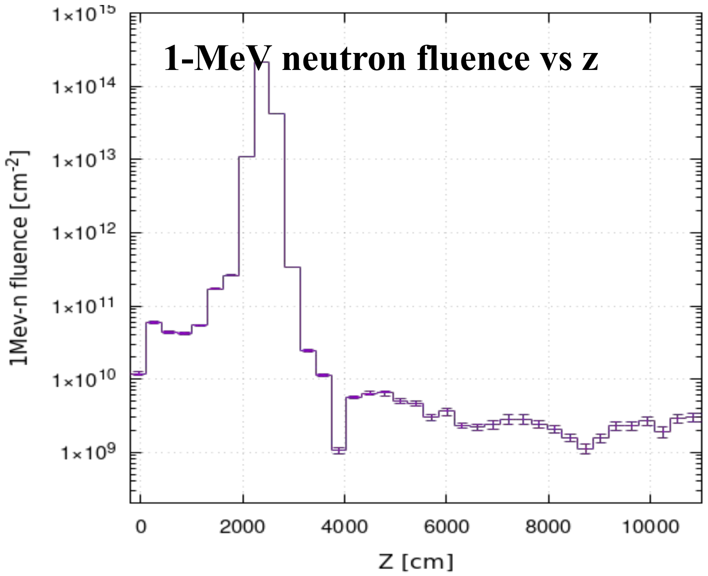
	$\mu^+ + \mu^-$	μ^+	μ^-
rate without MIB	147 MHz	81 MHz	66 MHz
MIB reduction factor	~ 70	~ 58	~ 94
rate with MIB	2.1 MHz	1.4 MHz	0.7 MHz

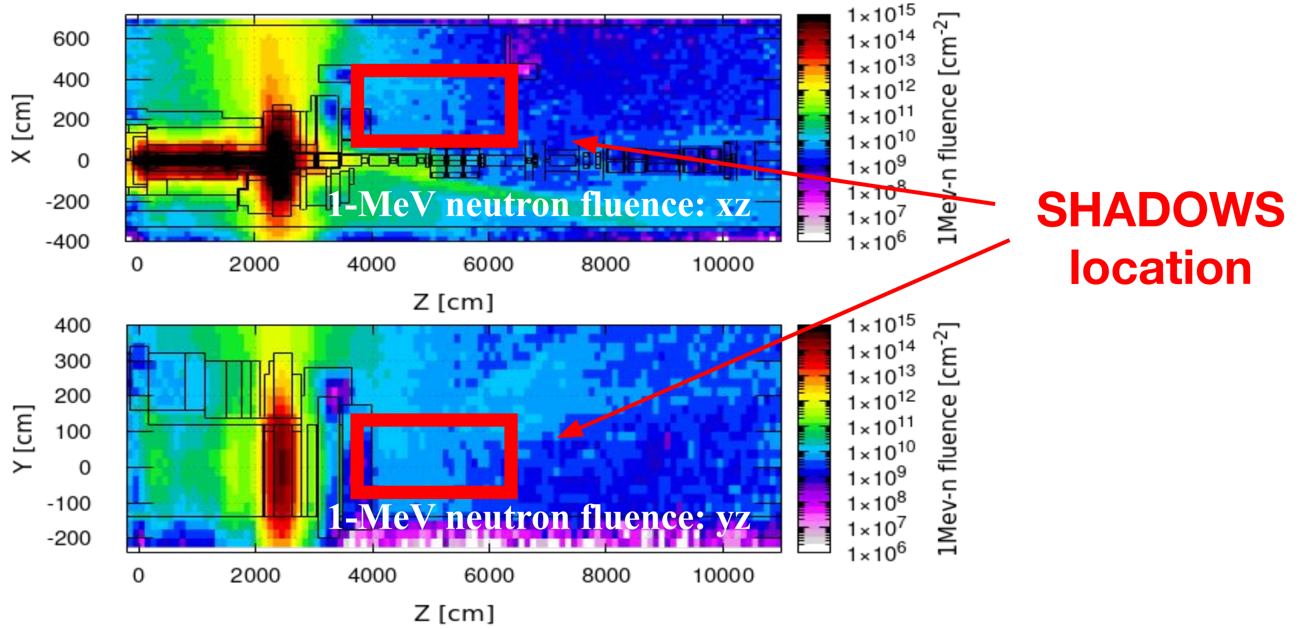
Muon Flux Seen by SHADOWS



- Muon flux reduction in SHADOWS acceptance from 150 MHz to 2 MHz

Radiation Levels



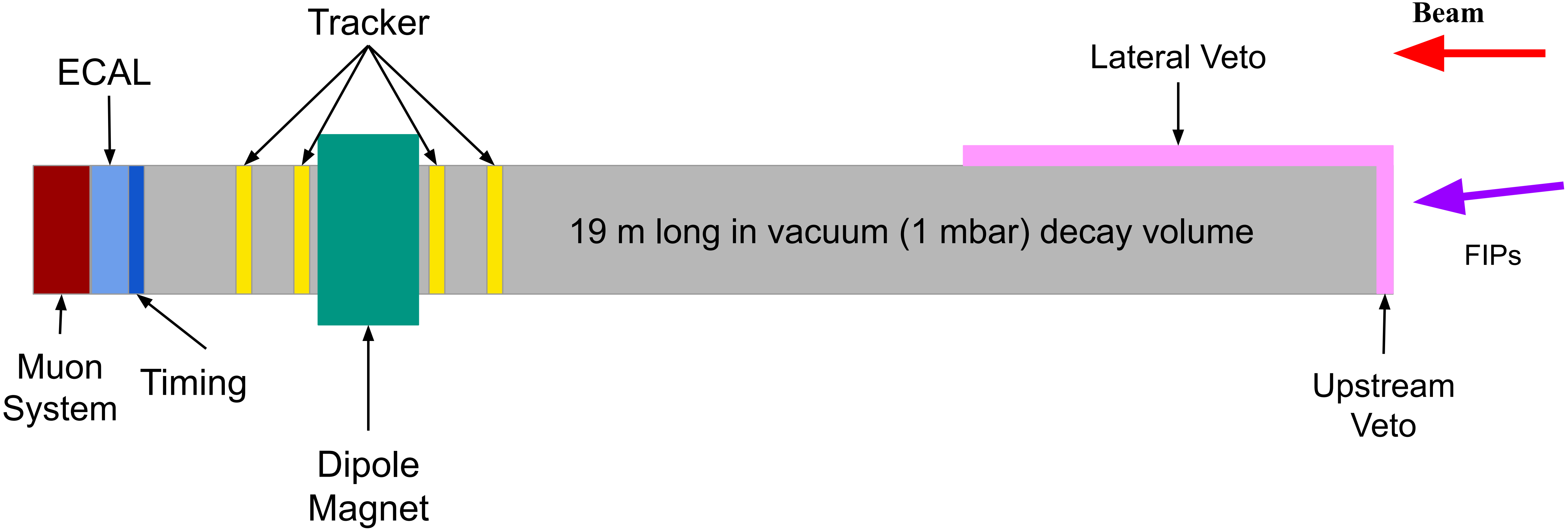


- **SHADOWS can be operated in radiation levels near the beam**
- On-electronics must be *radiation tolerant*
  - SiPMs available that tolerate the levels
- Off-detector electronics protected in radiation shielded alcoves

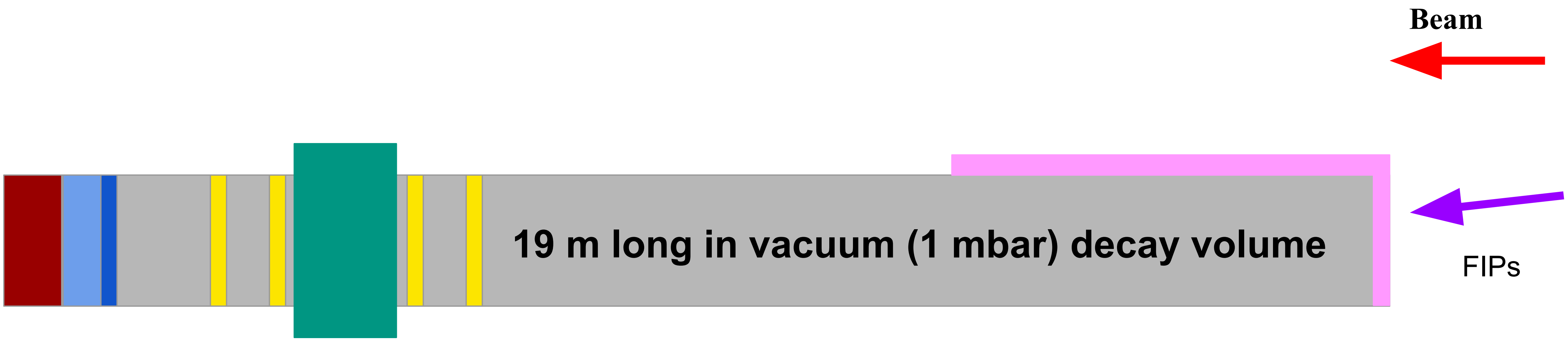
Quantity	Detector location	R2E safe
Total Ionising Dose (Gy)	0.1-1 per year	< 10
1-MeV neutron equivalent fluence (cm^{-2})	10^{9-10} per year	$< 10^{11}$
High-Energy Hadron eq. fluence ($cm^{-2}year^{-1}$)	few 10^9	$< 3 \times 10^6$
Th. neutron eq. fluence ($cm^{-2}year^{-1}$)	$< 5 \times 10^{10}$	$< 3 \times 10^7$

CERN PBC ECN3 Task Force, C. Ahdida, L. Esposito, S. Niang, E. Nowack

The SHADOWS Detector



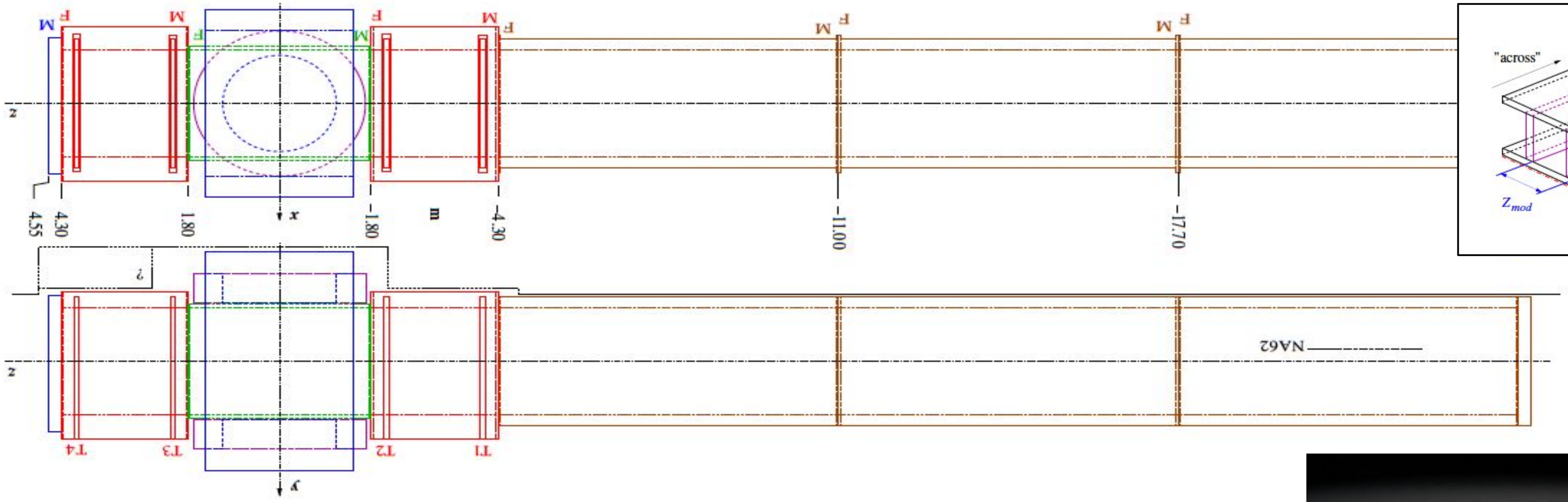
Decay Volume

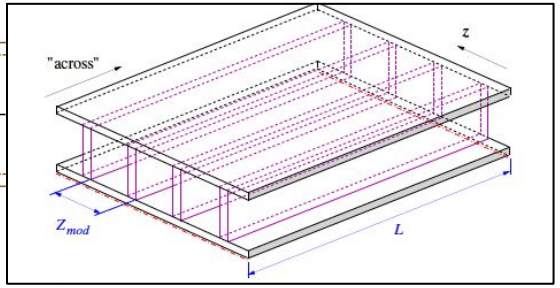


Objective:

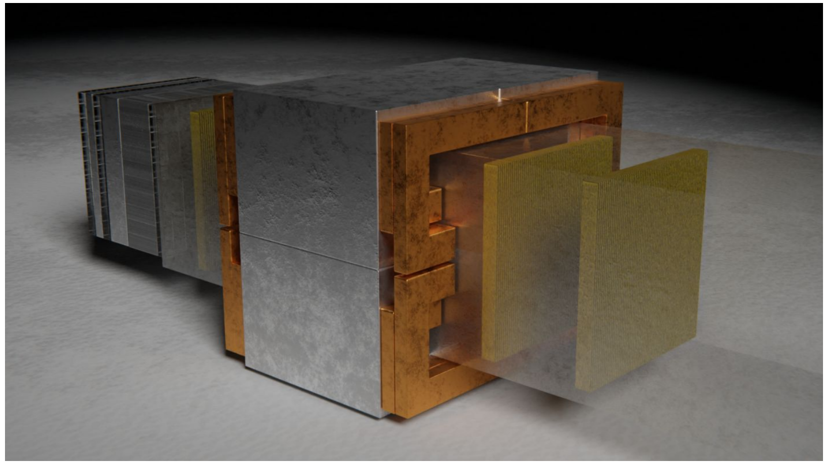
Allow FIPs to decay into standard model particles

Decay Volume



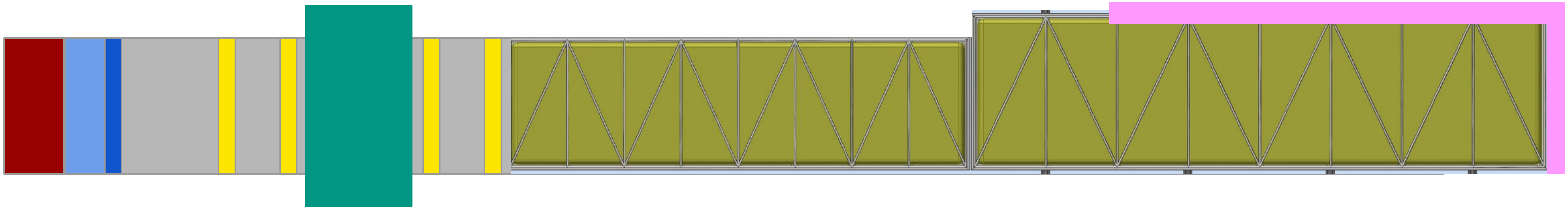


EP-DT CERN
Piet Wertelaers

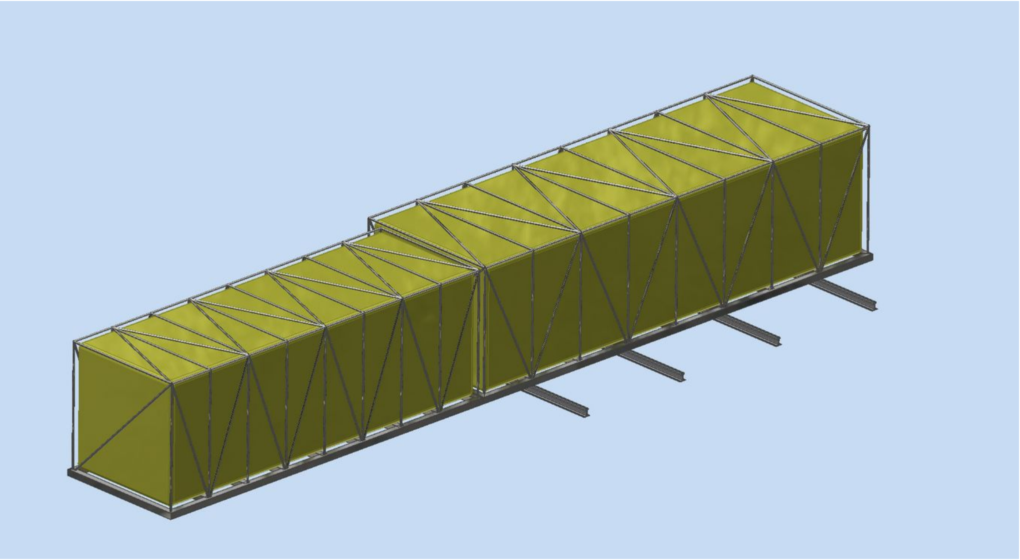


- In vacuum decay vessel (1 mbar)
- Modules supported by stainless steel
  - Design makes the vessel easily transportable
- Anchored to dipole magnet
- Containing the tracking system

Alternative: Helium filled decay vessel



- Helium filled balloon
- Several advantages:
  - Recover part of acceptance (placed closer to beam)
  - Prevent inelastic interactions within the vessel
  - Reduce the cost
- Will be studied for TDR



INFN Ferrara
Alessandro Saputi

Lateral and Upstream Vetoes

Objective:

Veto muons (and any other particle) that enter the decay volume

Lateral and Upstream Vetoes

- Two layers of resistive pad micromegas satisfying SHADOWS requirements
  - Efficiency > 99.8%
  - Spatial resolution: *O*(1) mm
  - Temporal resolution: *O*(10) ns
  - Rate capability: up to 10 MHz /cm^2
- Resistive layer suppresses discharge probability
- Similar to design used in ATLAS experiment
- Small scale prototype produced by INFN in 2023
- Large scale prototype to be prepared in 2024

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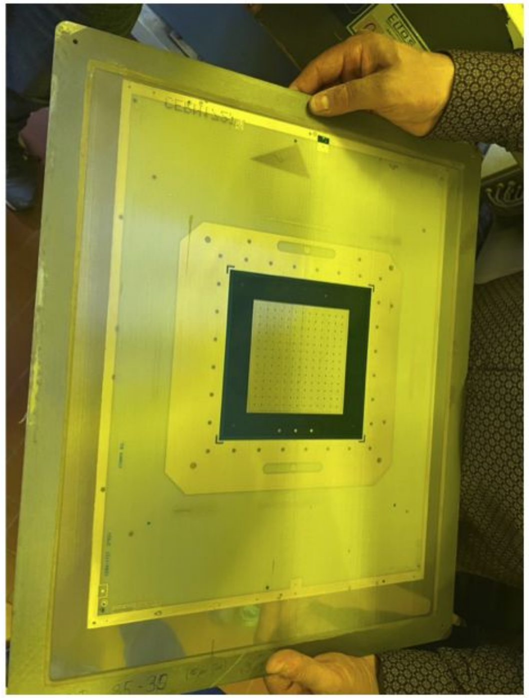
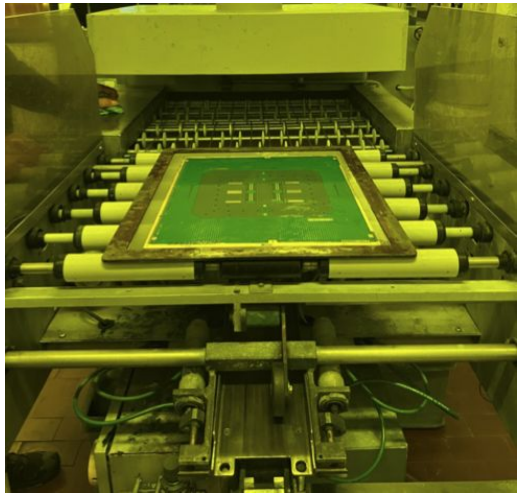
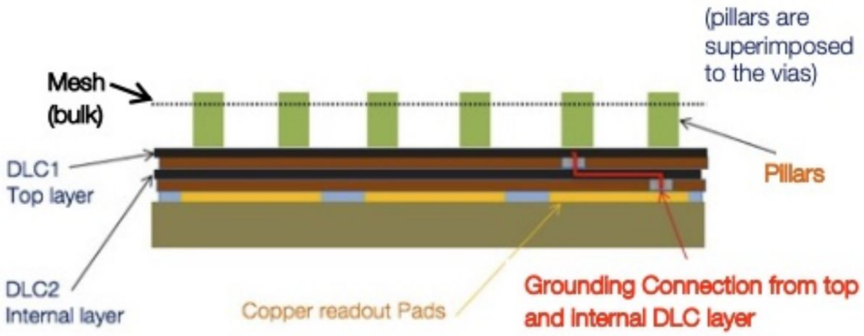
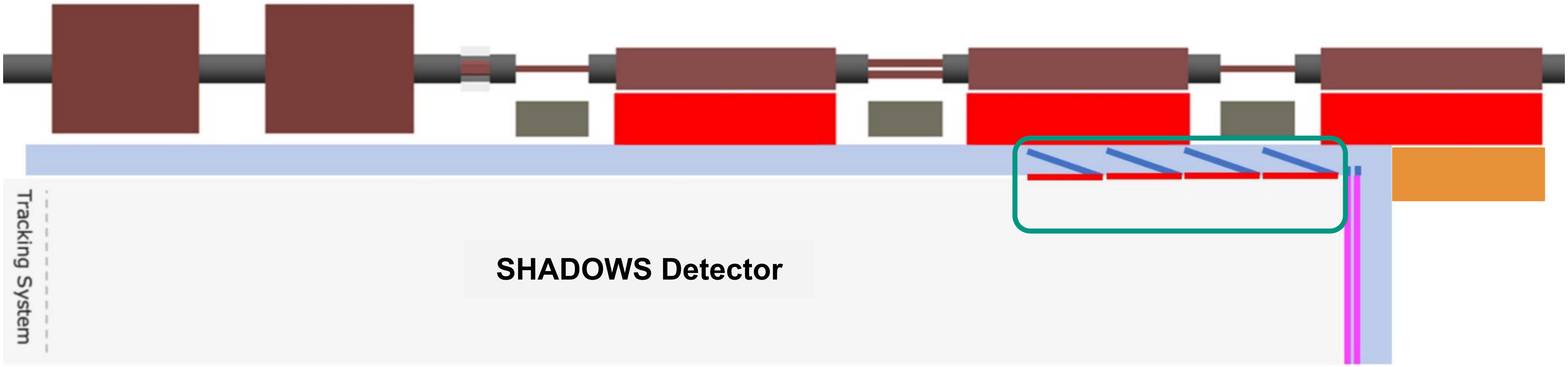






INFN Rome III, INFN Napoli

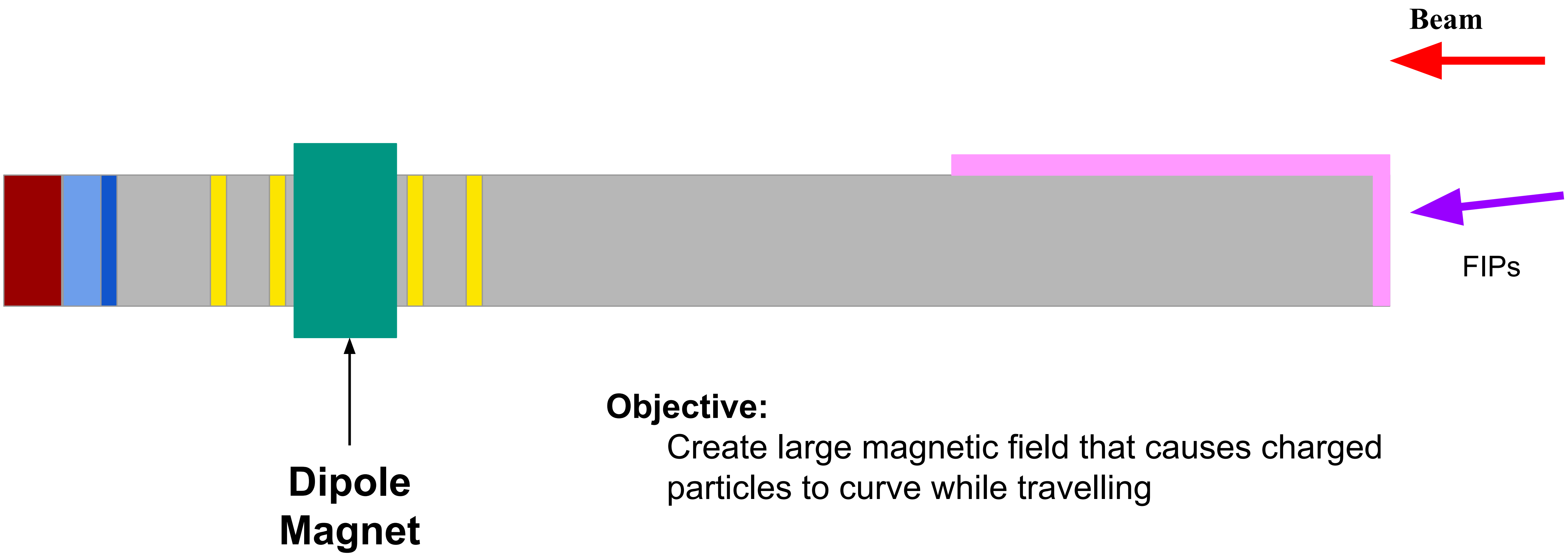
Lateral and Upstream Vetoes



- Lateral veto will tilt in for operation and close when interventions are needed
- Currently being studied

INFN Rome III, INFN Napoli

Dipole Magnet



Objective:

Create large magnetic field that causes charged particles to curve while travelling

Dipole Magnet

- **Requirements:**
  - Integrated Field of ~ 1 Tm
    (similar to NA62 dipole magnet MNP33)
  - Low power consumption
  - 2.7 x 2.7 m^2 aperture

Two possibilities:

- Warm option (baseline):
  - Dissipated power: 287 kW
    (10x less than MNP33 NA62 dipole)
  - Copper coil, iron yoke
- Superconducting option:
  - Collaboration between CERN ATS sector and EP department
  - Compelling idea - will be studied for the TDR.

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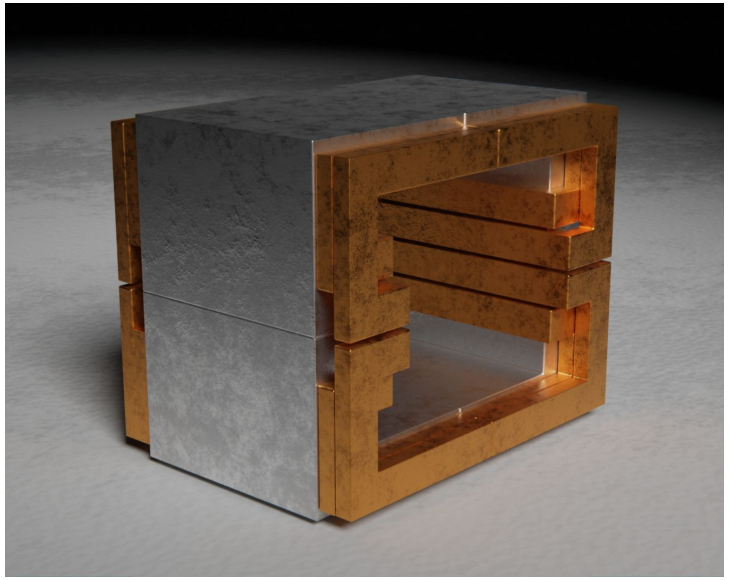
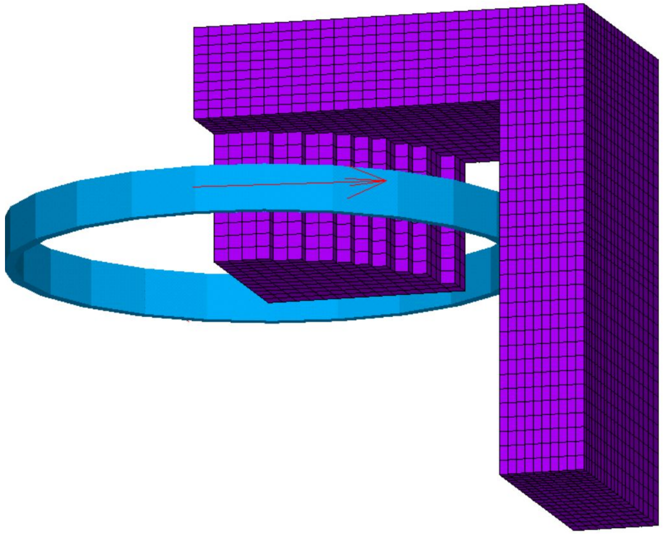


Rendering of the warm option dipole magnet



Conceptual layout of superconducting option

EP-DT CERN
Piet Wertelaers

Dipole Magnet: Warm Option

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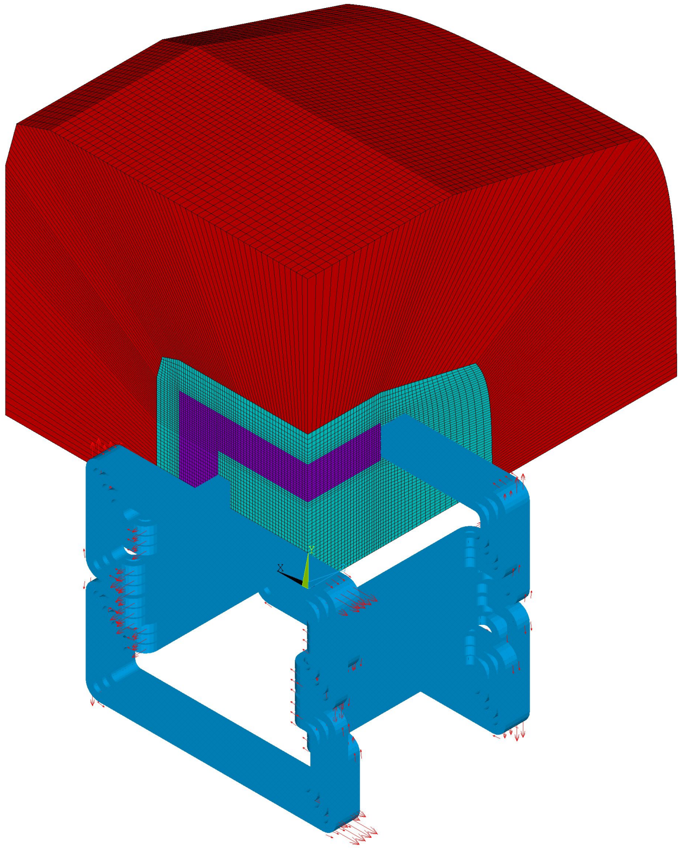
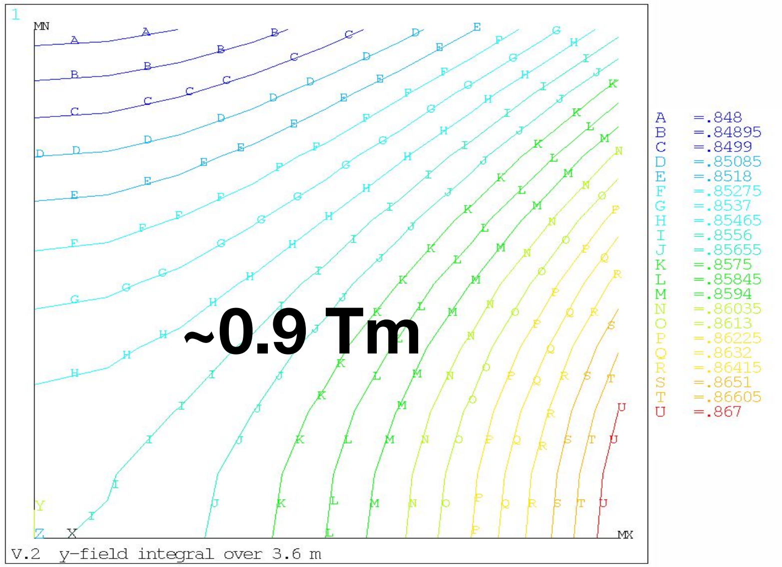
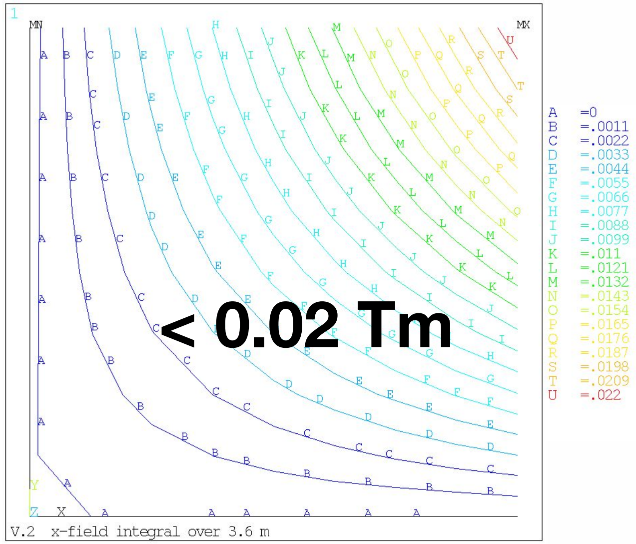


Field integrals (in Tm) in y



Field integrals (in Tm) in x



EP-DT CERN
Piet Wertelaers

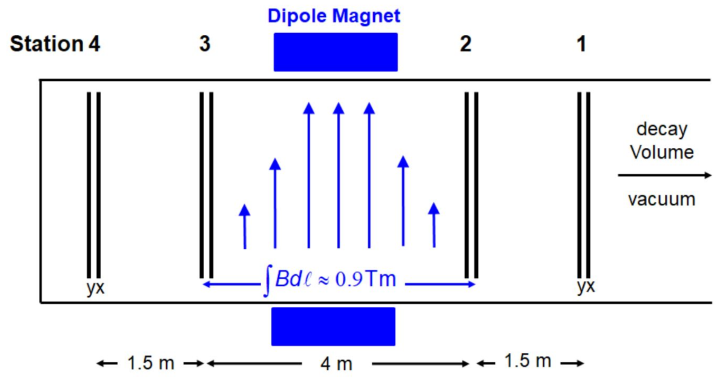
Tracking System

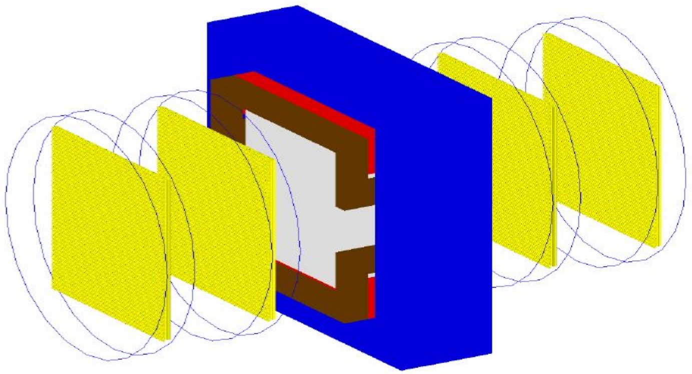
Objective:

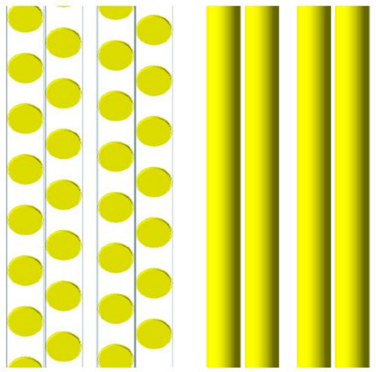
Reconstruct charge particle tracks and reject background with ≥ 2 tracks

Tracking System

- Requirements
  - Vertex resolution of $O(1)$ cm over 20m
  - IP resolution of $O(1)$ cm from 35 m
  - Mass resolution of 1-2 %mass
  - Single hit efficiency > 98 %
  - Rate capability 4 MHz
- Proposed technology
  - Straw drift tubes with $O(1)$ cm diameter
  - 4 tracking stations
  - 2 views (vertical, horizontal) per station
  - 4 layers per view
  - Active area of 2.5 x 2.5 m^2
  - R&D and construction synergistic with HIKE
  - Proven in NA62
- Also investigating scintillating fibers







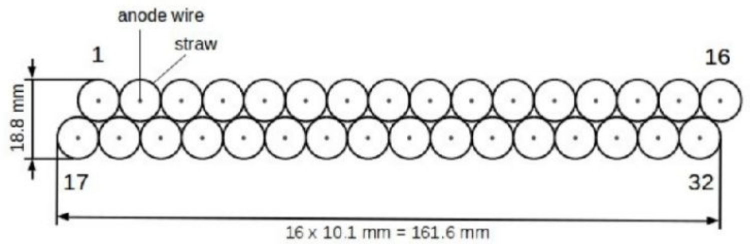
Top left image: NA62

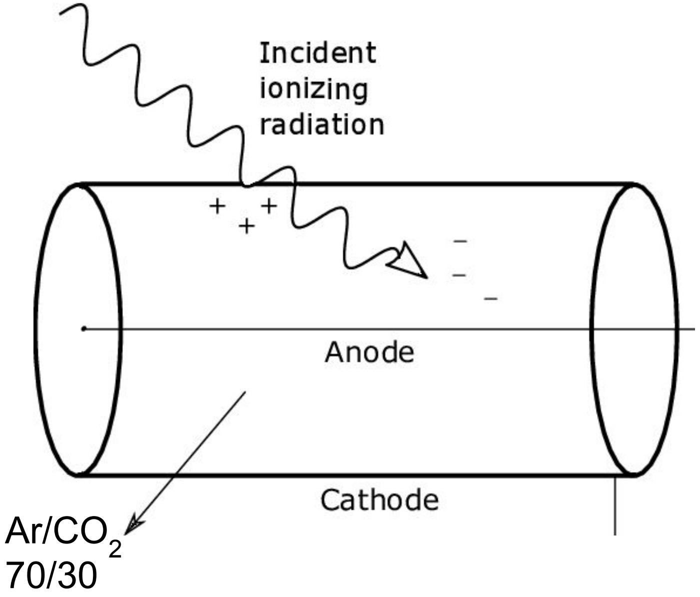
Heidelberg University, CERN

Tracking System

- Baseline design: NA62-like
  - Straw tubes separated by 1 cm
  - Tubes with 1 cm diameter
  - Cathode tube: polyurethane coated with Cu and Au
  - Anode wire: W wire plated with Au
  - 1024 tubes per station - 4096 total
  - Vacuum tightness
    (1 bar overpressure)
- Alternative design: PANDAS-like
  - Hermetic, self supporting structure

Alternative:





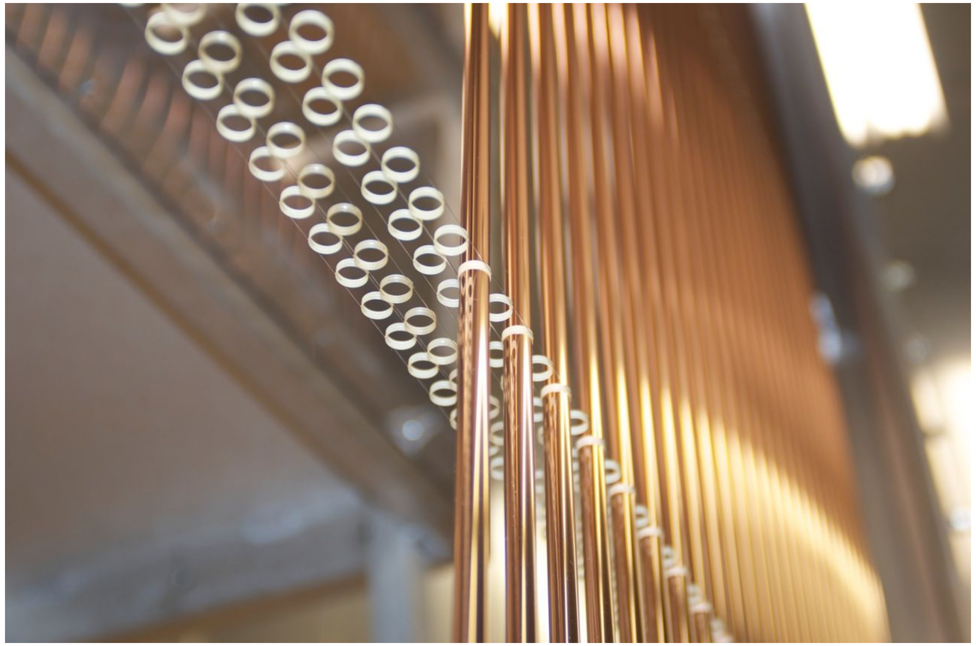


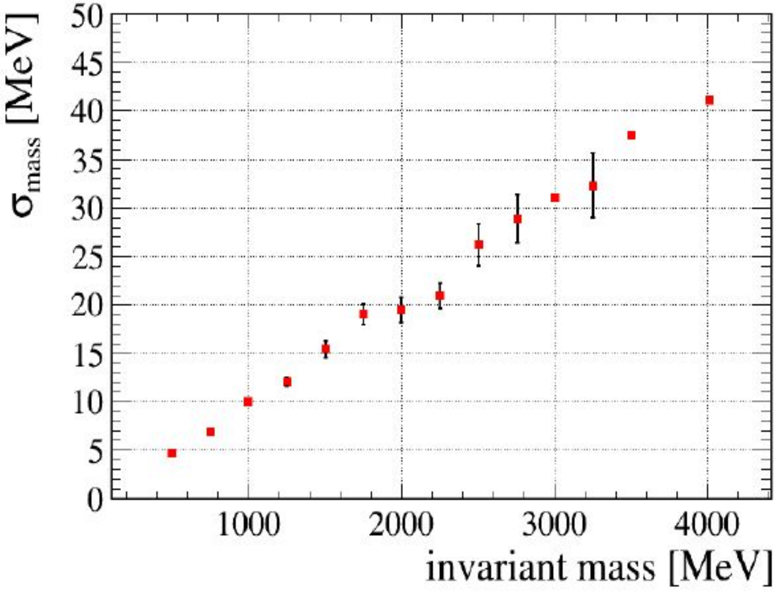
Image: NA62 in CERN Courier

Karlsruhe Institute of Technology

Heidelberg University, CERN

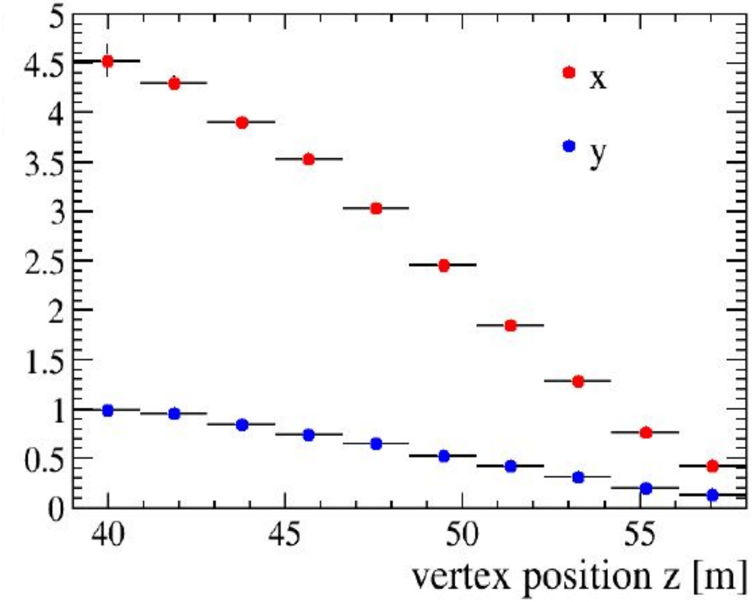
Tracking System

Mass resolution



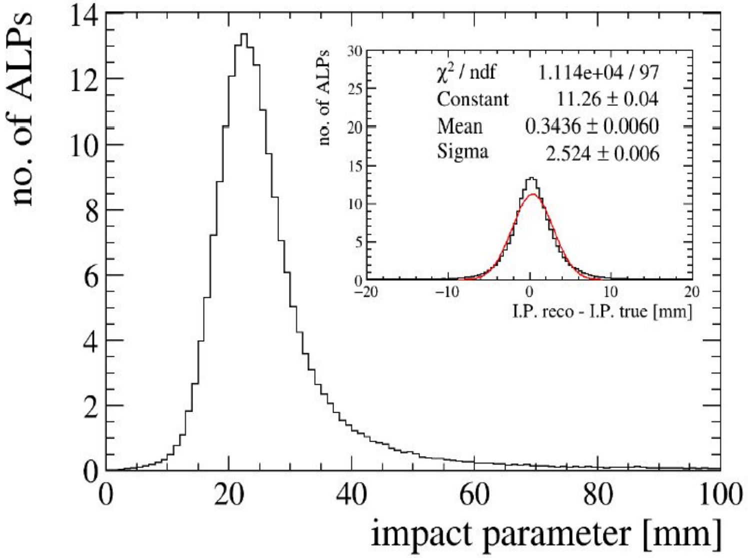
$\sigma(M)/M = 1\%$

Vertex resolution



σ_x(vertex) = 0.5-4.5 mm
σ_y(vertex) = 0.2-1.0 mm

Impact parameter resolution



σ(IP) = 3 mm

From simulation, NA62-like straw drift tubes are good choice

Heidelberg University, CERN

Timing System

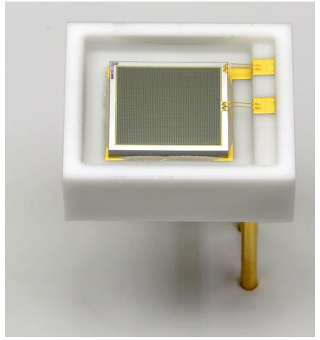
Timing

Objective:

Reject combinatorial muon background

Timing System

- Required time resolution: < 100 ps
- Proposed technology: scintillating bars
  - < 100 ps time resolution
  - Bar size:1.26 m long, 6 cm wide, 1 cm thick
  - SiPM readout
    - Hamamatsu S13360 series
    - 0.6 x 0.6 cm^2 readout w/ pixel pitch of 75 μm
    - 8 SiPMs per scintillating bar -> 1600 total
- First prototypes built by SHiP
- Further R&D still needed



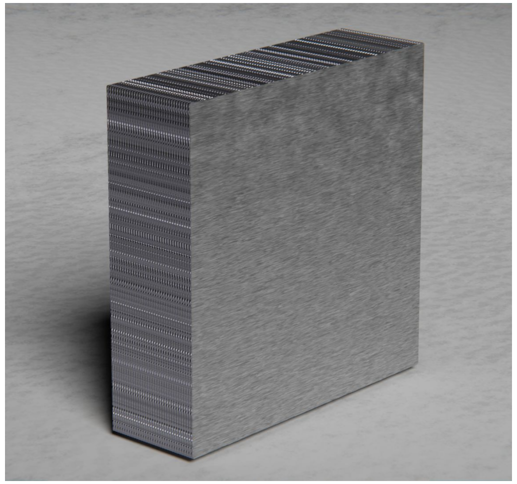
University of Freiburg (DE)

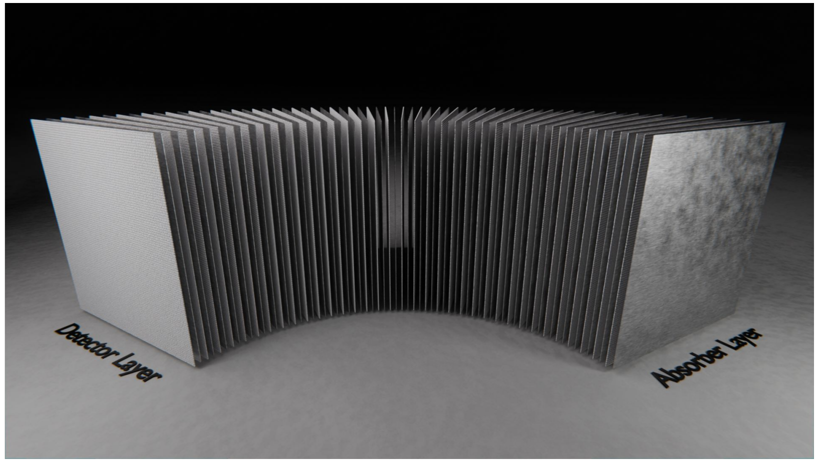
Images: (top left) Hamamatsu, (top right) Eljen Technology, (bottom) University of Freiburg

Electromagnetic Calorimeter

Electromagnetic Calorimeter

- Requirements
  - Pointing capability to discern shower direction
  - Energy resolution 10-15 %
  - Electron identification 99%
  - $\pi^{\pm}$ misidentification 1 %
- Proposed Technology: StripCal
  - 40 layers of 1 cm wide scintillating strips alternating vertical and horizontal
  - Interspersed with 40 layers of Iron absorbers
  - 20 X_0 lengths → 1 m long calorimeter
- Alternative Technologies
  - Hybrid with micromegas (SplitCal)





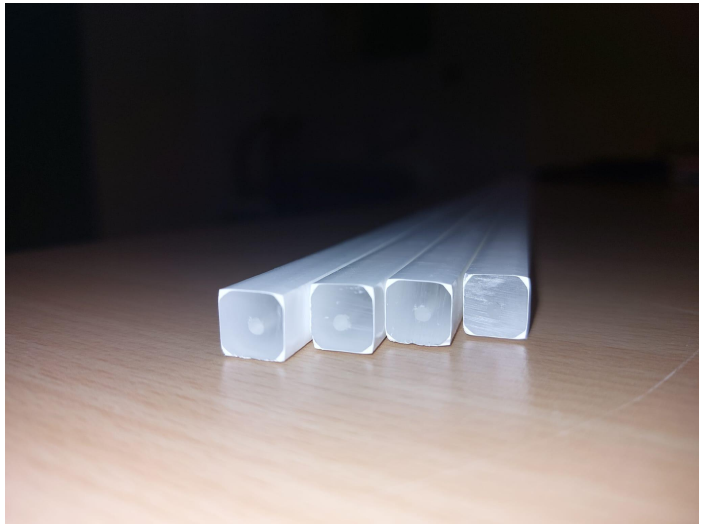
GEANT 4 Rendering of ECAL layers

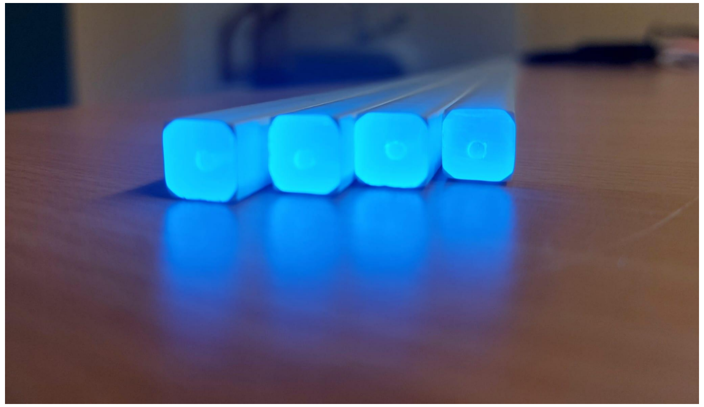
University of Mainz, Karlsruhe Institute of Technology

Electromagnetic Calorimeter

Karlsruhe Institute of Technology

- Similar to the current NA62 MUV1 detector
- 1 ns time resolution
- In total 10,000 scintillating strips readout by 20,000 SiPMs
- Able to discern the shower direction
- Prototype will be assembled in Mainz
  - 9.5 x 9.5 mm^2 scintillating strips
  - Beginning cosmic tests to determine best fiber/SiPM combination

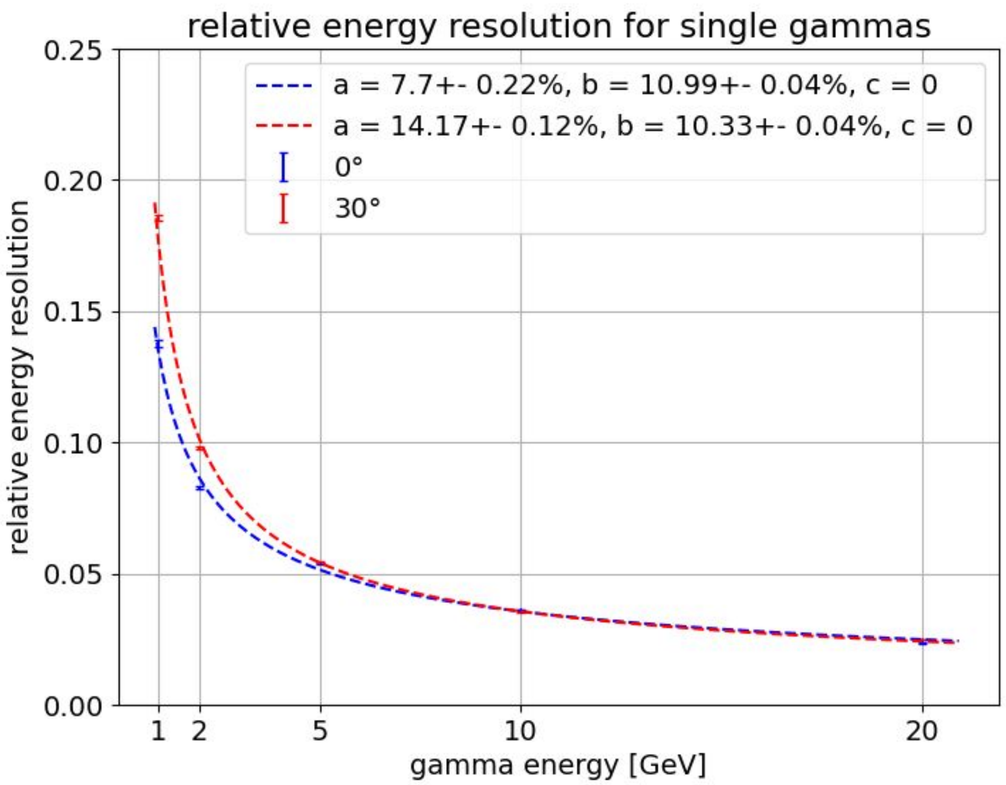


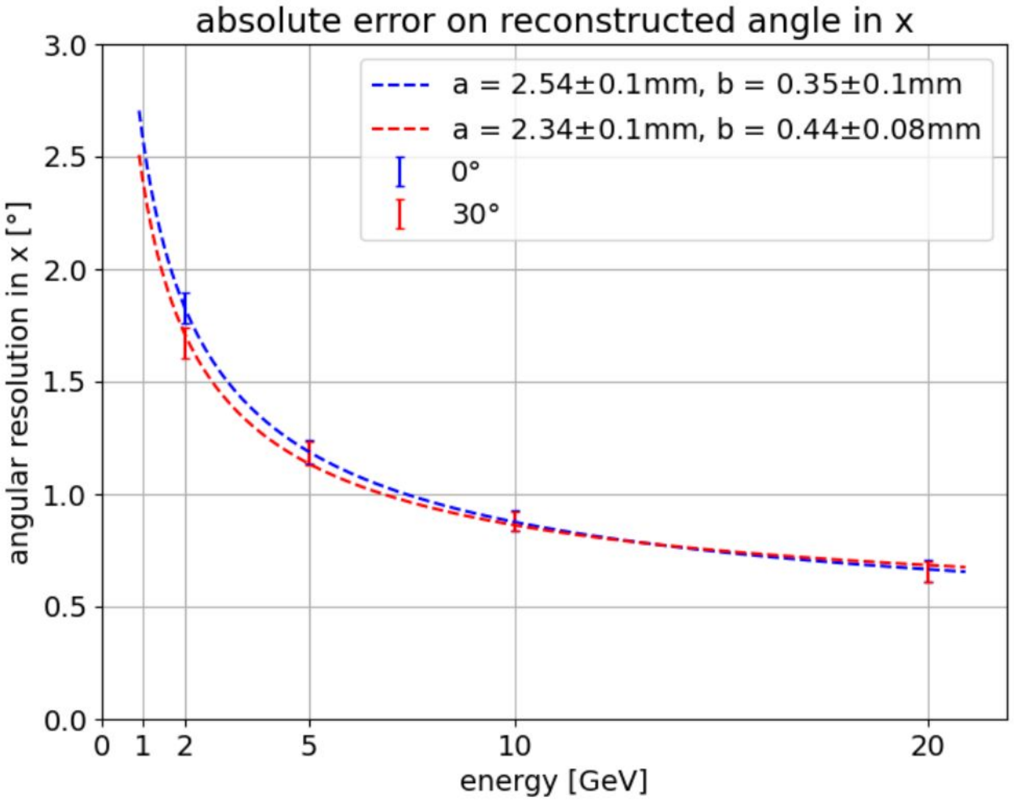


University of Mainz, Karlsruhe Institute of Technology

SHADOWS

Electromagnetic Calorimeter

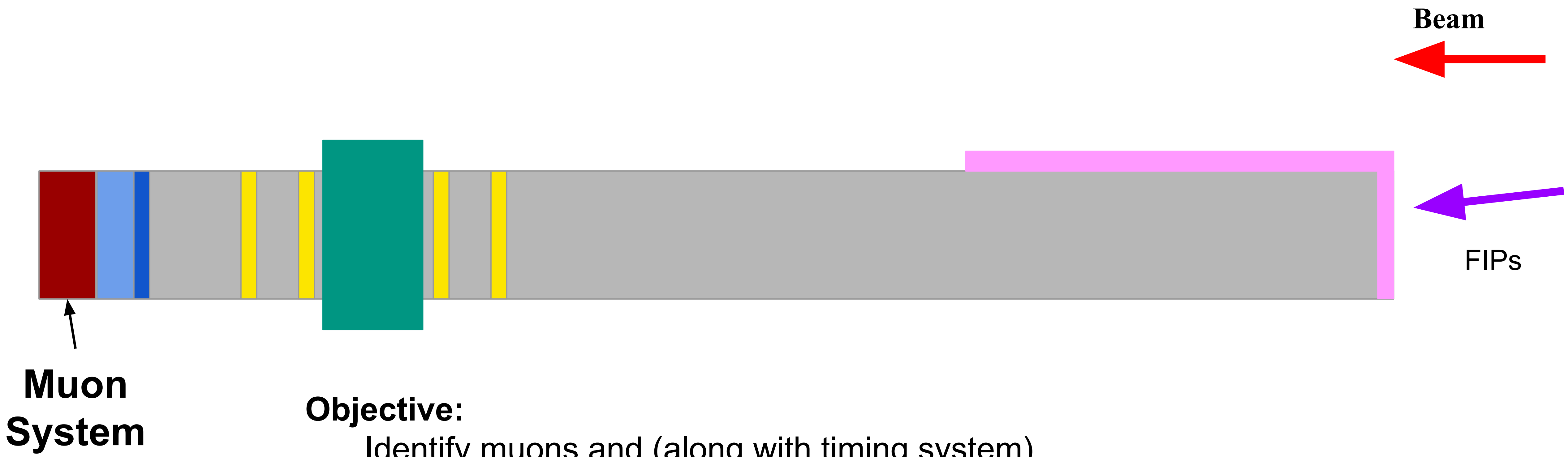




note: symmetric with y

Energy and Angular resolution in StripCal simulation

Muon System

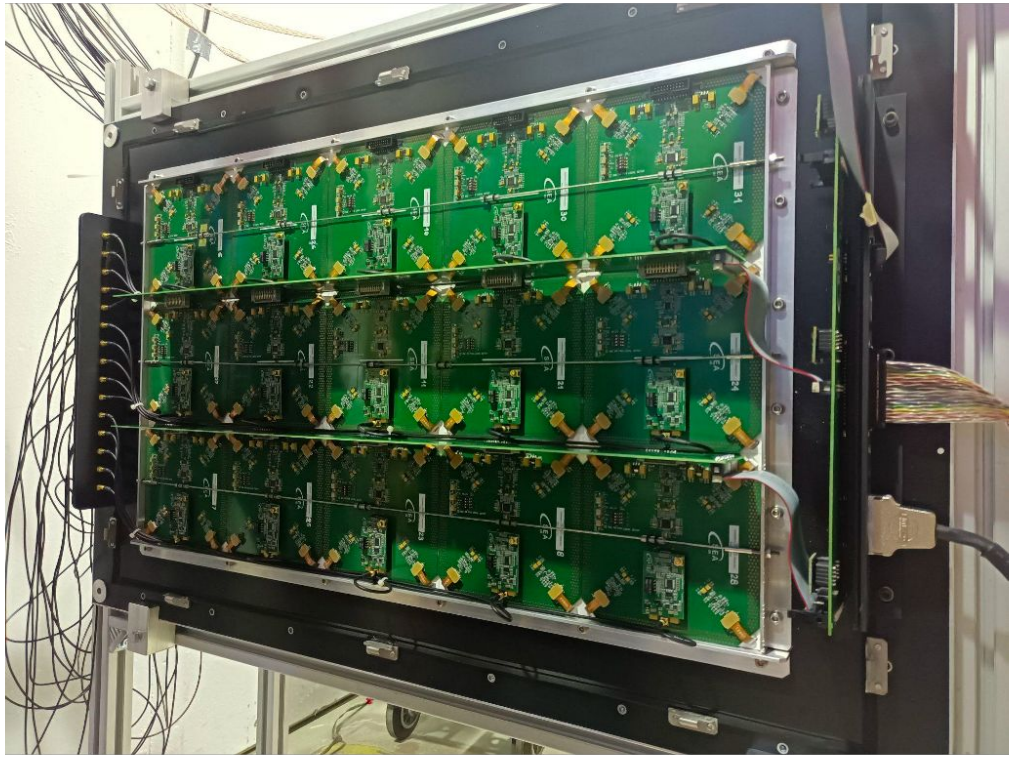


Objective:

Identify muons and (along with timing system) reject combinatorial muon background

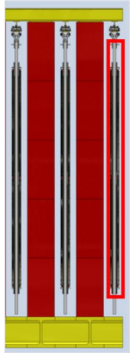
Muon System

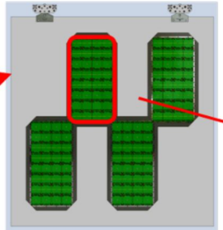
- Three stations of scintillating tiles interspersed with iron absorbers
- 15 x 15 cm^2 tiles with SiPM readout
- 250 ps measured time resolution
- Two full size prototype modules produced by INFN
  - Used in background measurement (see later slides)
- Stations can be easily moved in case of interventions



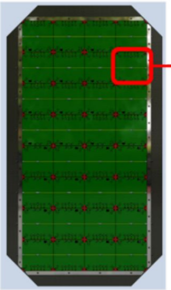
INFN Frascati, INFN Bologna, INFN Ferrara

Muon System

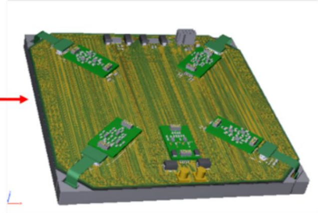




1 station = 8 modules
[same pattern staggered
on the other side of the wall]

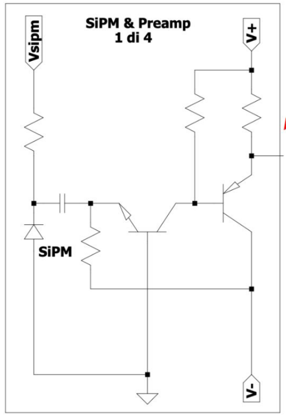


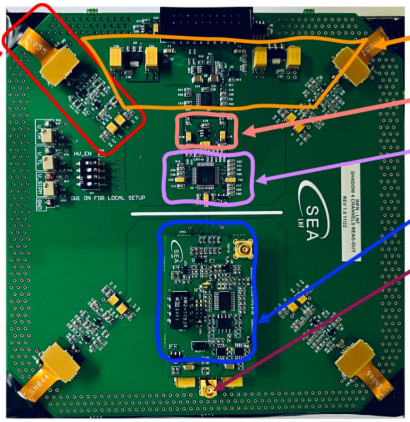
1 module = 32 tiles



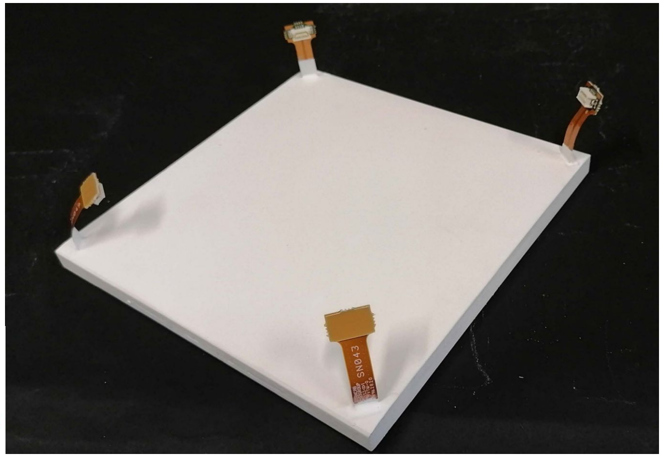
1 tile = $(15x15x1)\,cm^3$

Muon system design





Front-end electronics board

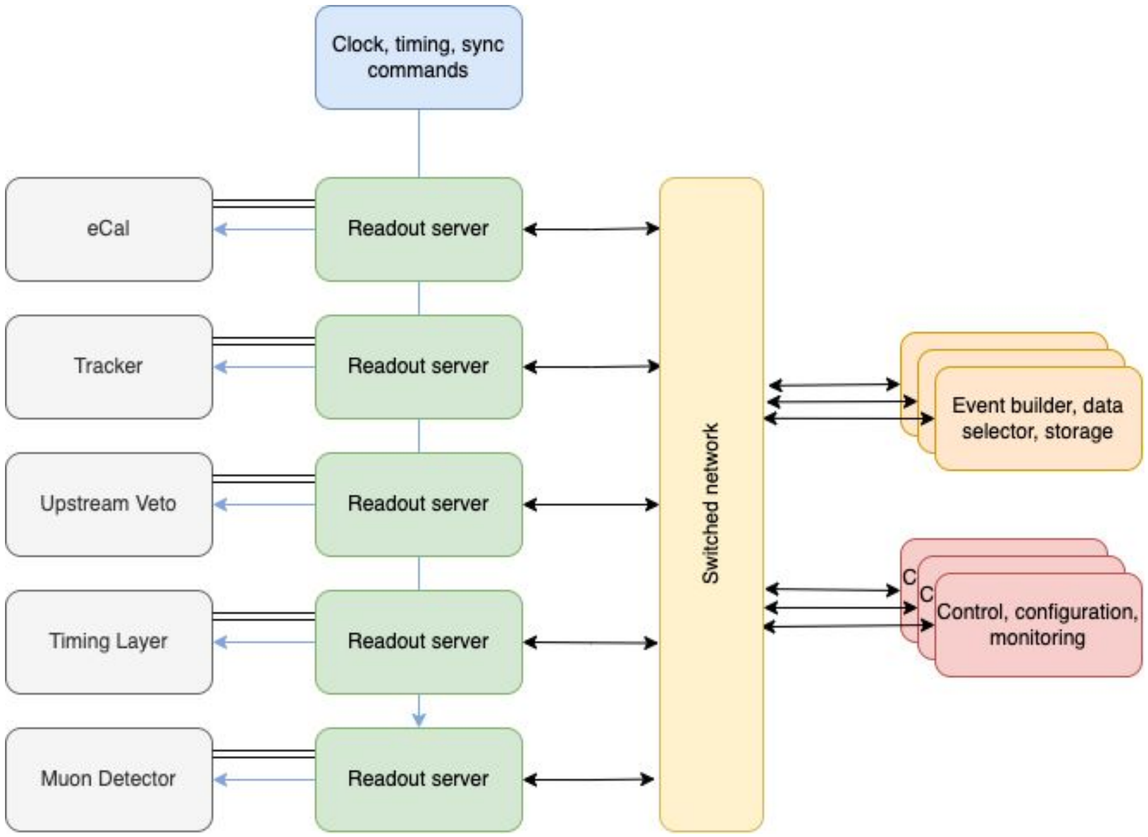


Scintillating tile with 4 SiPMs
(coated in reflective paint)

INFN Frascati, INFN Bologna, INFN Ferrara

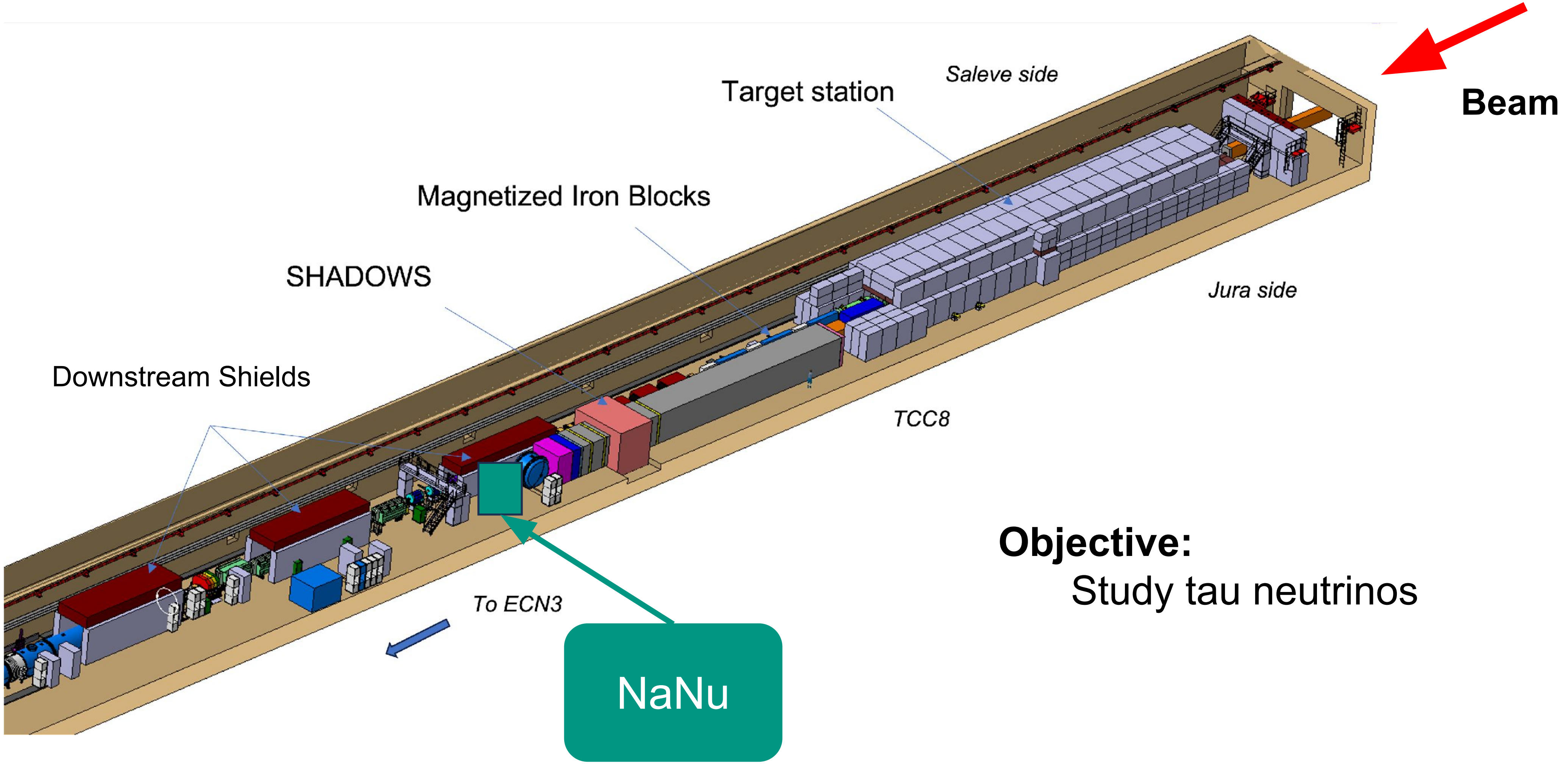
Trigger, Data Acquisition, and off detector boards

- Use triggerless approach
  - Filtering done with software in High Level Trigger
- Low power GBT
  - Send data off detector at rates up to 8.96 Gb/s
- DAQ being developed with HIKE to maximise expertise, share costs, etc.
- Off-detector boards placed in radiation protected alcoves up to 100 m from detector
- DAQ can be placed above ground in bldg 911 or in brand new Prevessin Data Centre



CERN EP-DT Enrico Gamberini and collaborators

NaNu: North Area NeUtrino

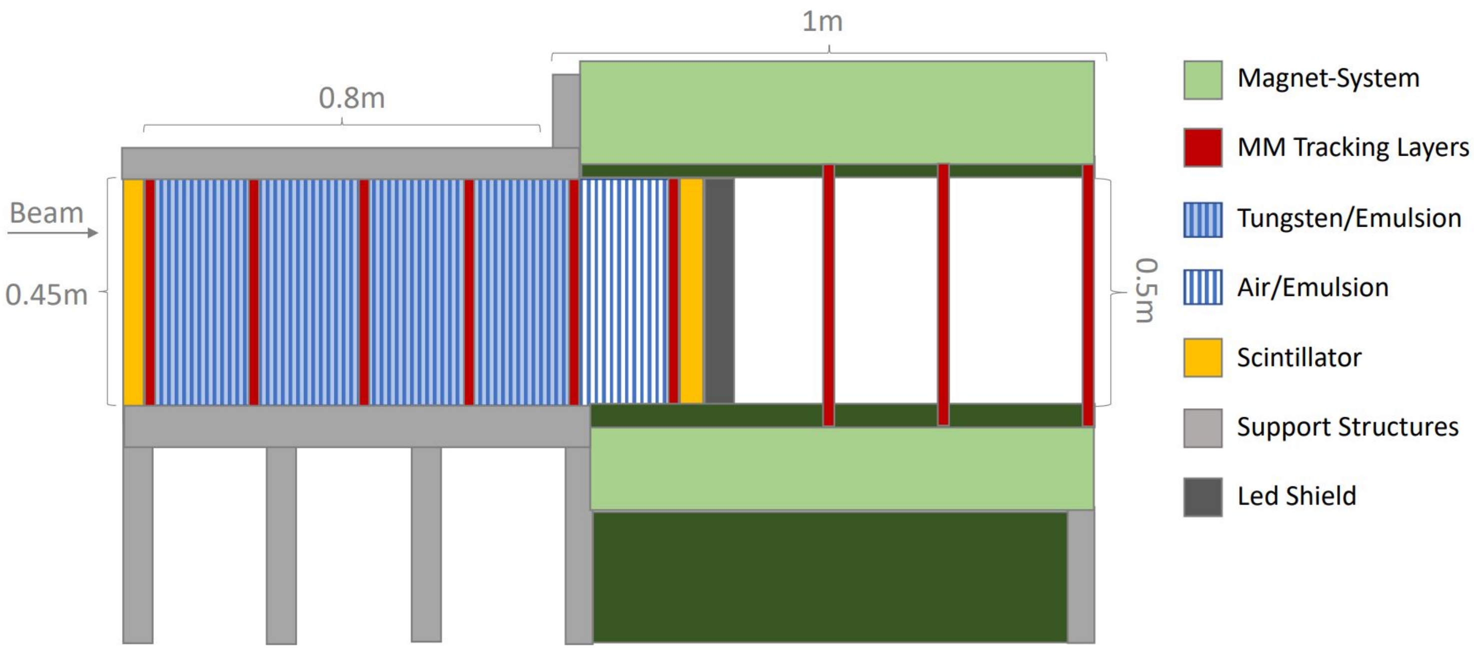


Objective:

Study tau neutrinos

NaNu: North Area NeUtrino

- Tungsten based emulsion detector
- Scintillators used as a vetoes
- MicroMEGAS used as trackers
- Placed inside a 1.4 T dipole magnet
- **Physics Programme:**
  - Deep inelastic scattering $\nu(\mu)$
  - First observation of anti-$\nu(\tau)$
  - $\nu(\tau)$ anti-$\nu(\tau)$ inclusive cross section
  - $\nu(\tau)$ anomalous magnetic moment



Magnet already available at CERN (MNP22)

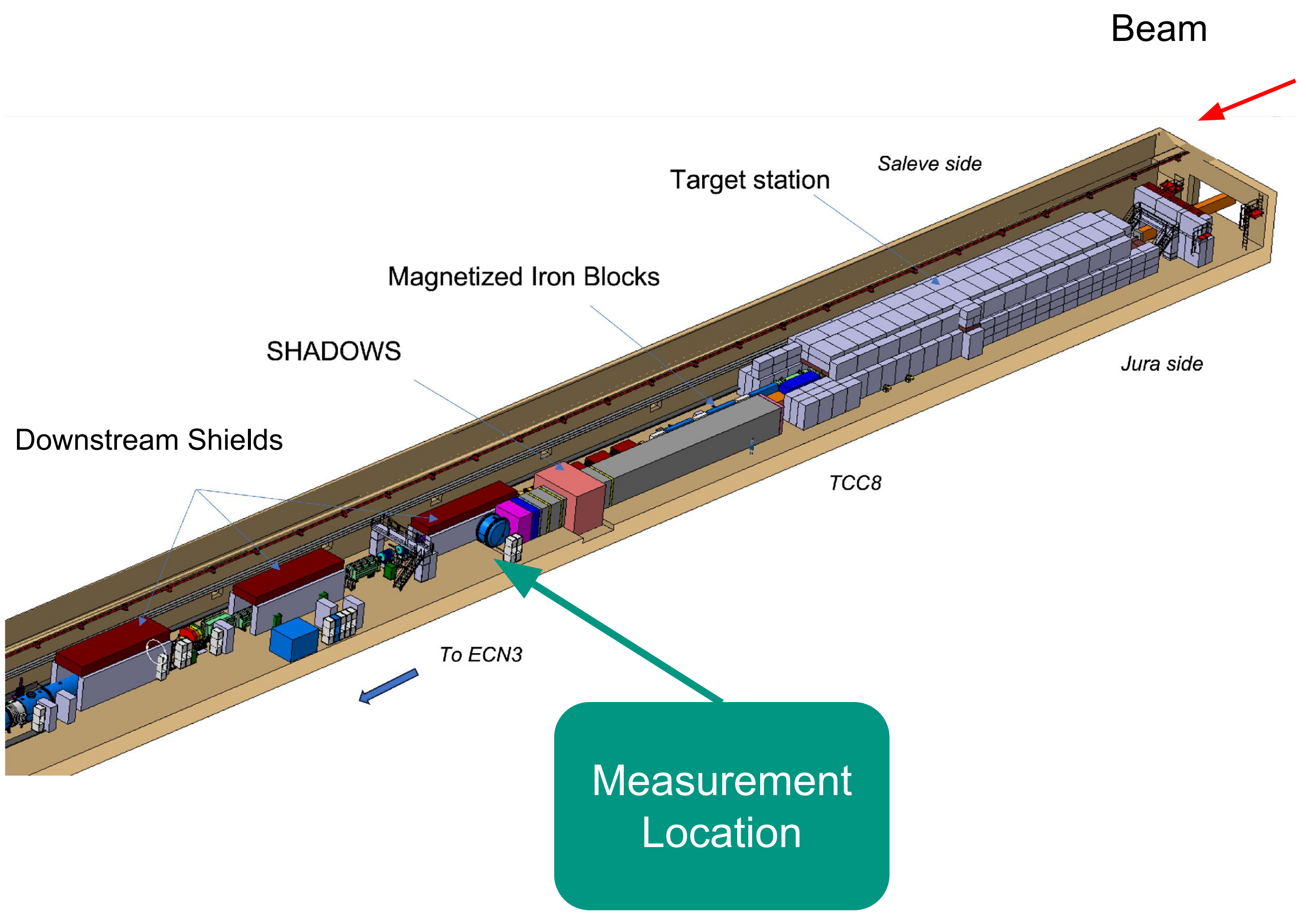
University of Mainz/ University of Bonn

Muon Background Studies

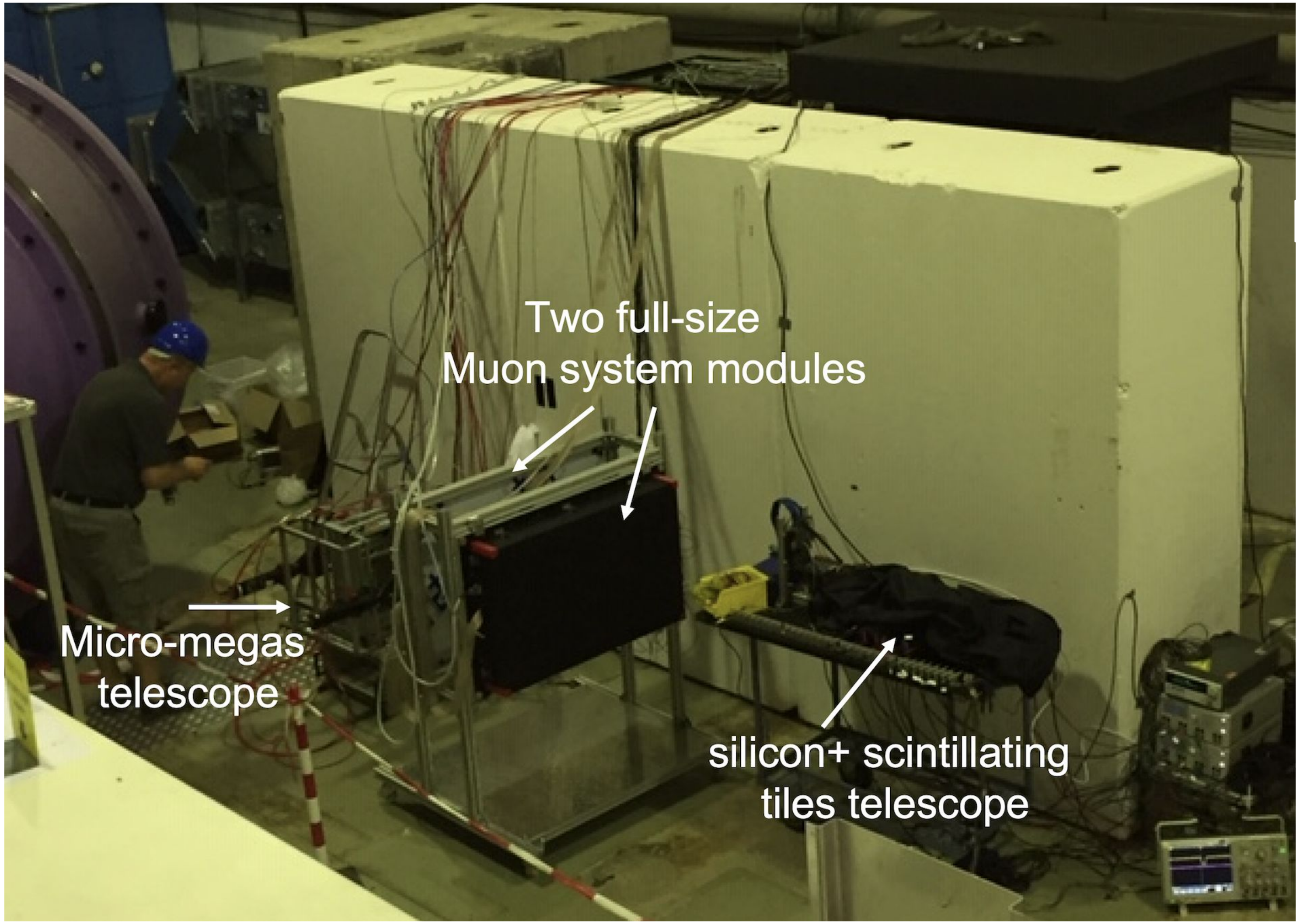
Objective: Measure muon background rate in NA62 cavern and compare to simulation

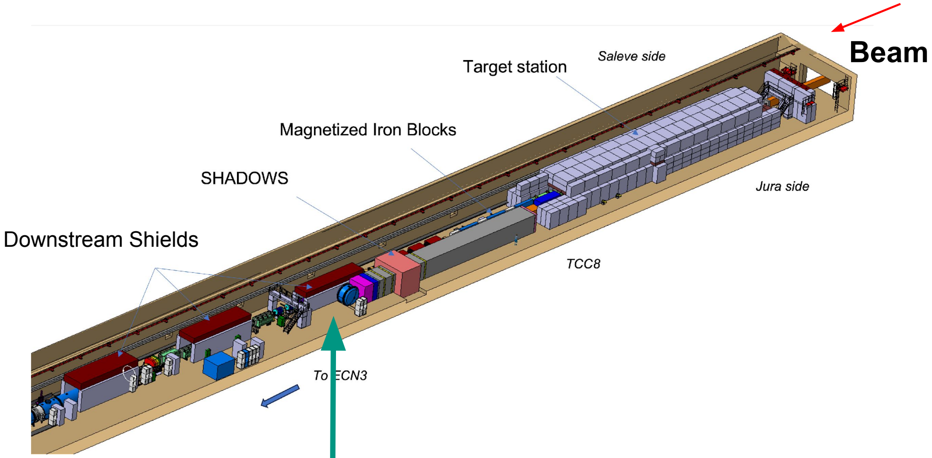
- Switched between beamdump and kaon mode
- Behind blue wall (radiation shielding) in NA62 cavern
- Not final SHADOWS location
- Detector position moved to behind the reservoir

Completed in June 2023



Muon Background Studies: Measurement Devices



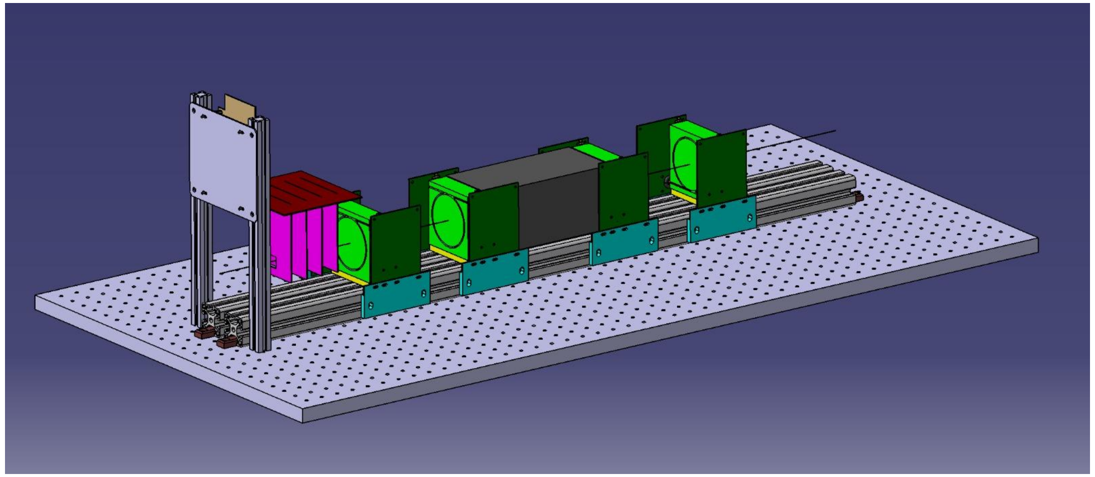


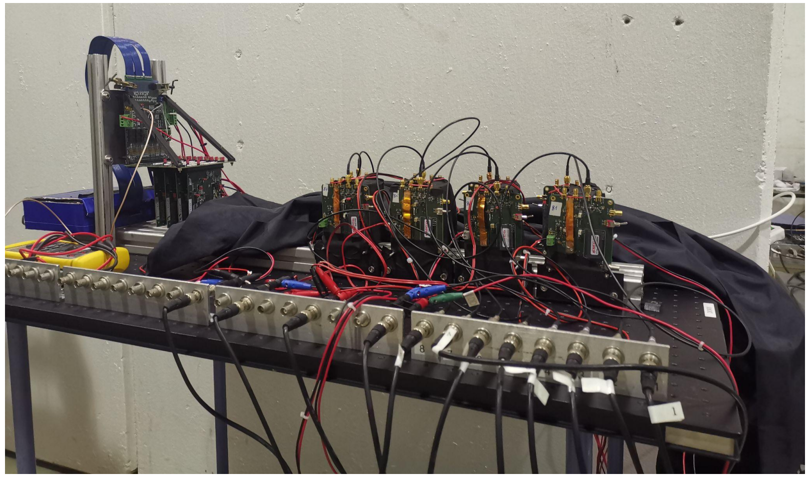
Measurement Location

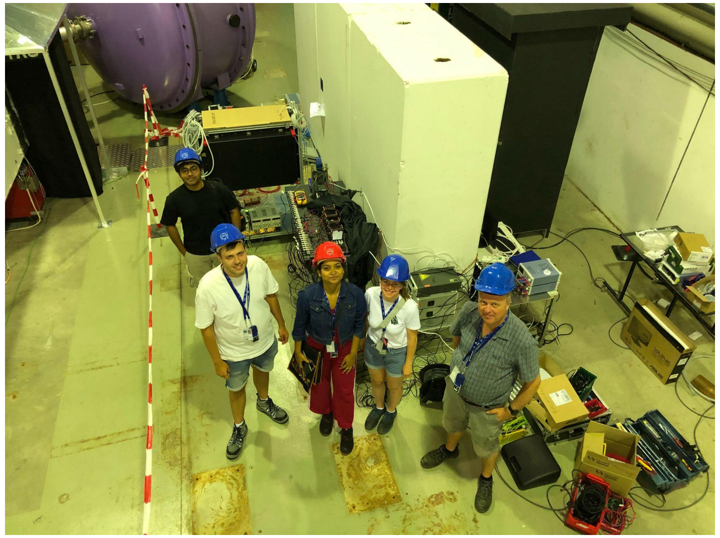
University of Mainz, University of Heidelberg, INFN LNF, INFN Ferrara, INFN Bologna, and KIT

Silicon + Scintillating Telescope

- 4 layer silicon telescope followed by 4 scintillators
  - Scintillating light detected by SiPMs on both sides
- Smaller active area, but capable of powerful measurements



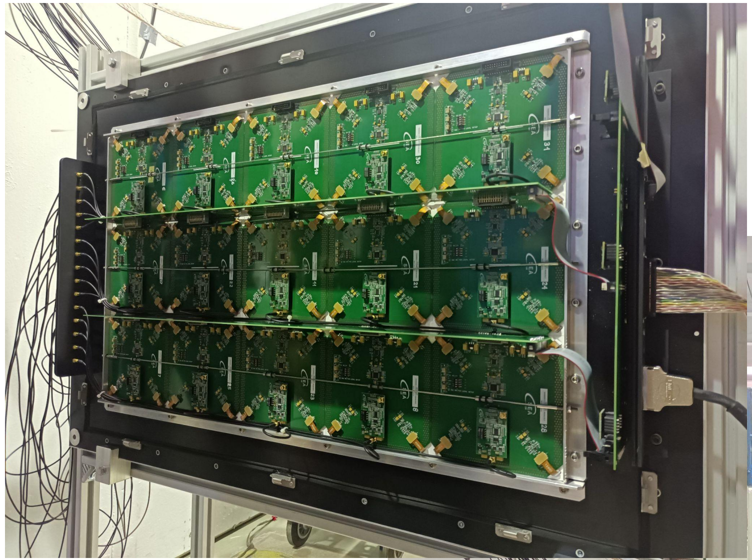




Heidelberg University

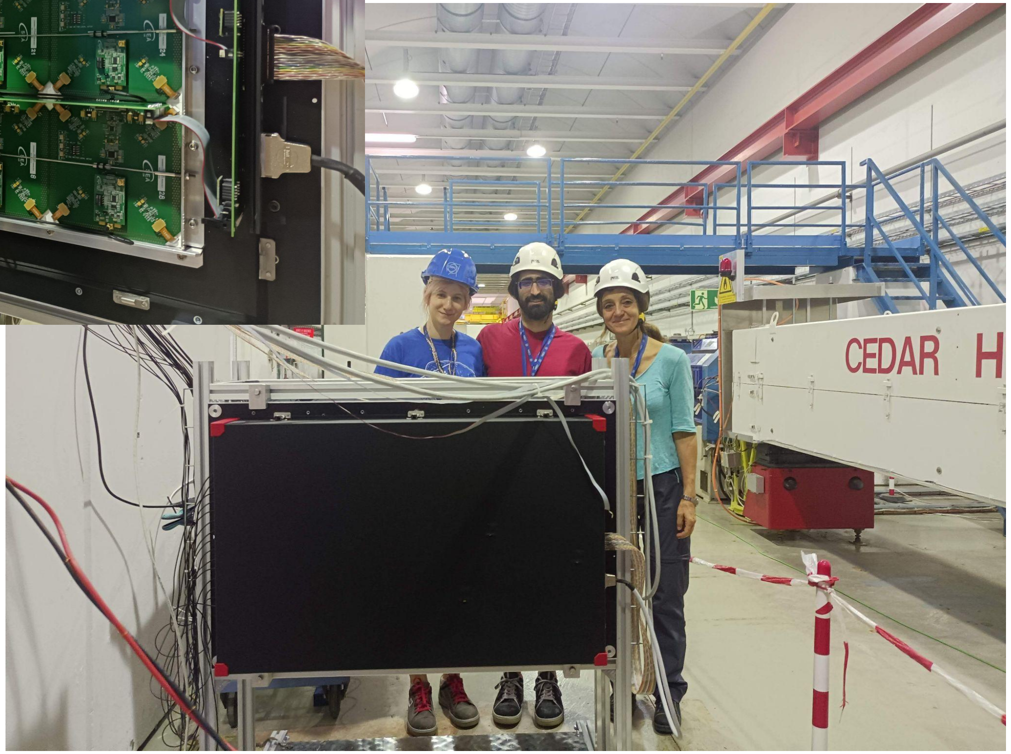
Two Prototype Muon Modules

- 2 prototype modules for SHADOWS muon system
- Measure coincidences as background rate
  - Counting experiment
- Large active area (75 x 45 cm^2)
- One tile not included in measurement
- Additionally, tests future detector components



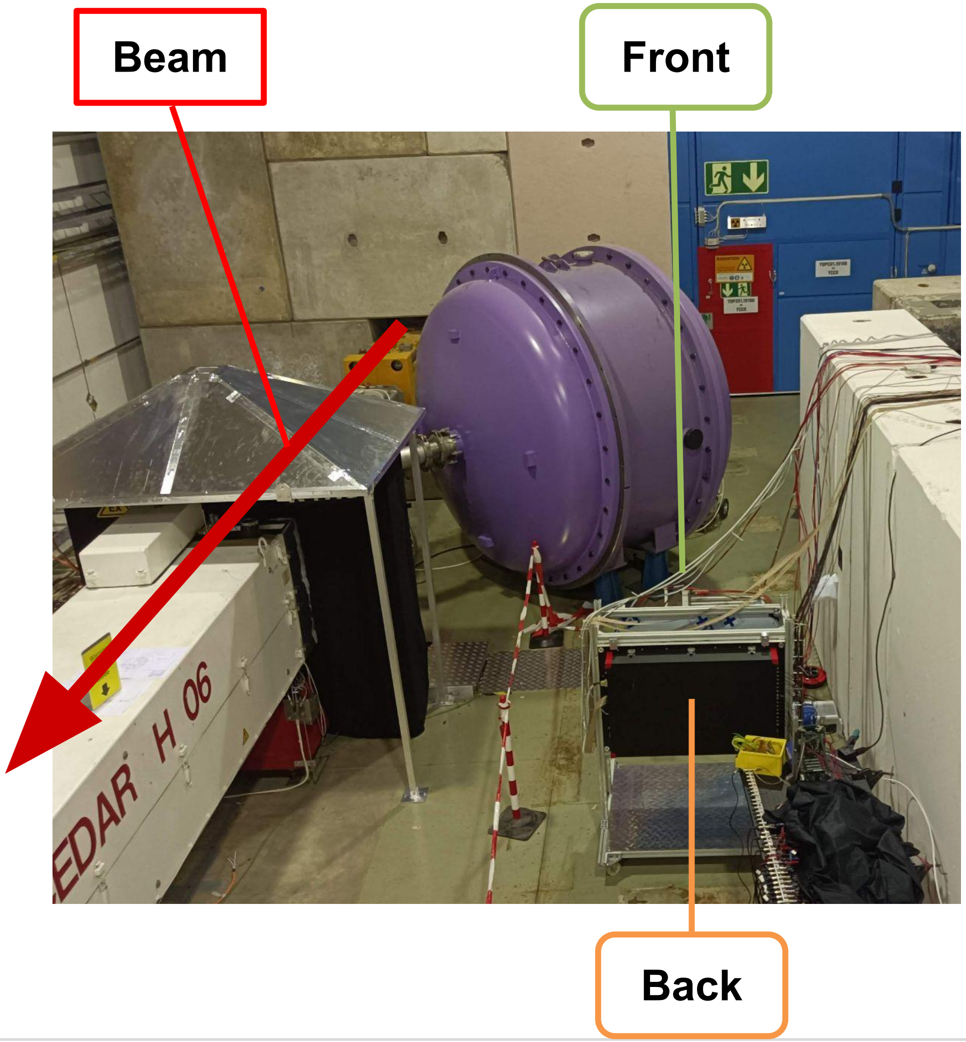
+ Me! But someone needs to take the photos

+ Alessandro Paolini, Giulietto Felici

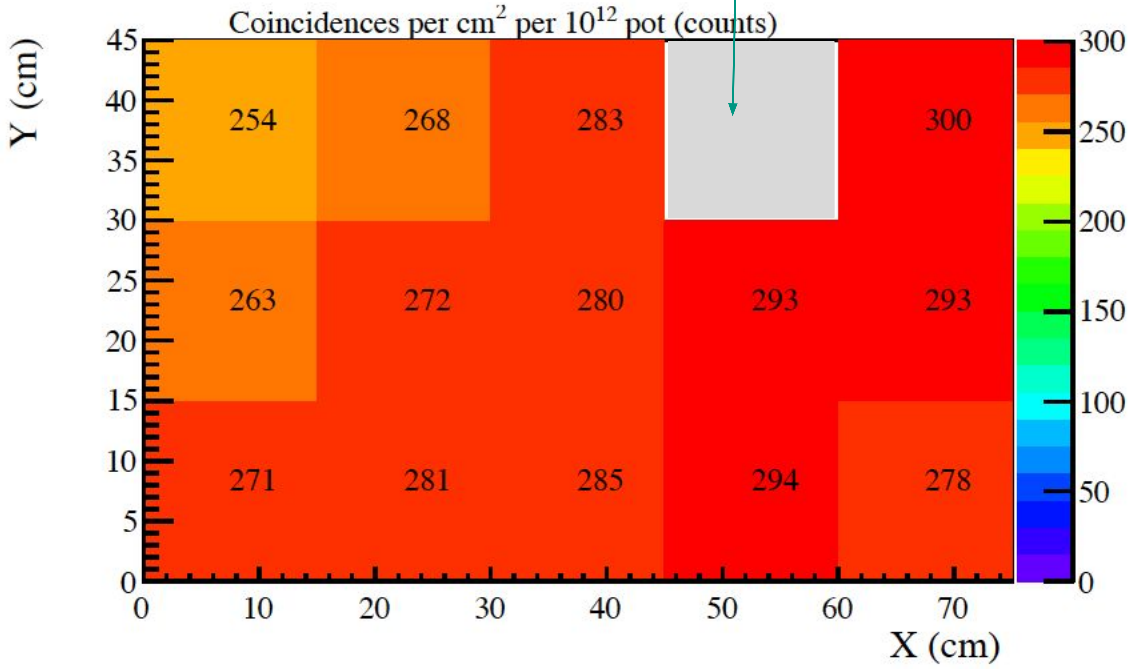


INFN LNF, INFN Ferrara, and INFN Bologna with some help from KIT

Results



electronics issue
with one tile

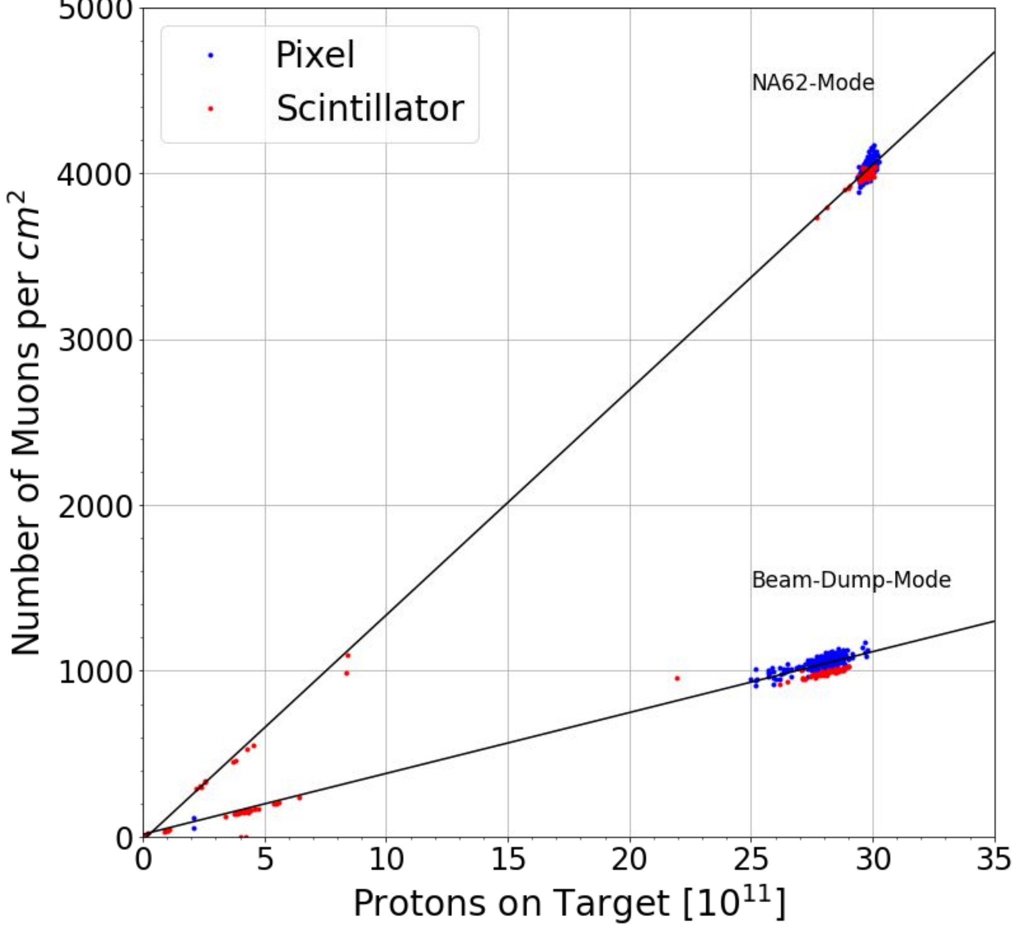


- Coincidences through two scintillating tiles
- Normalized per area and protons on target

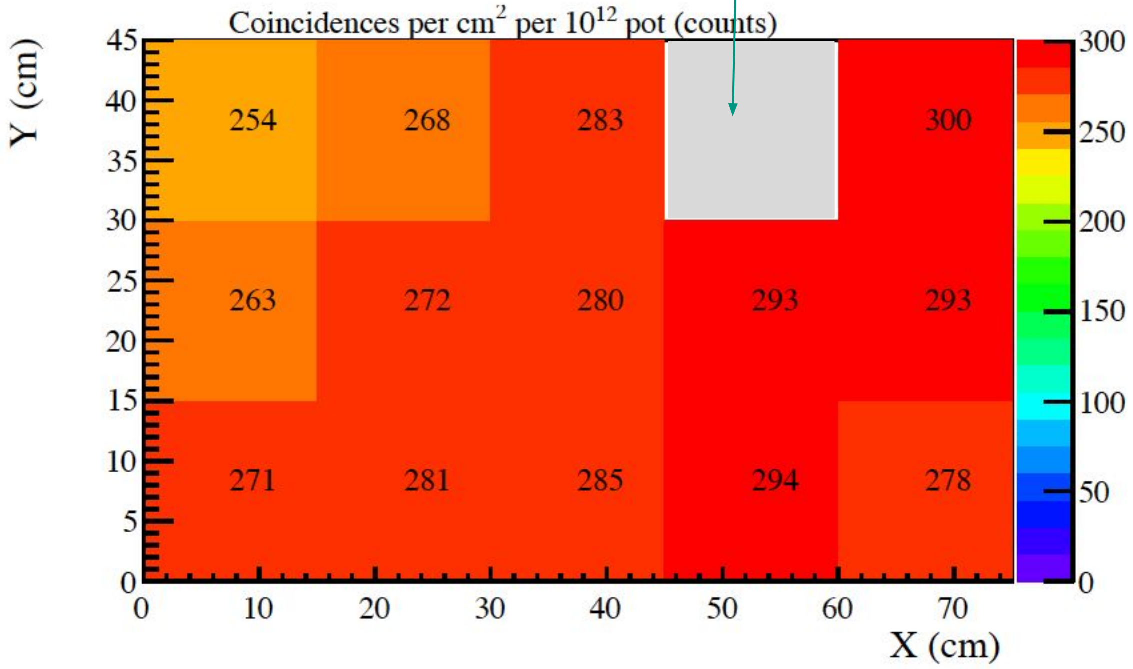
electronics issue
with one tile

Results

Silicon - Scintillator Telescope



Muon Modules Prototype



- **Simulation (rescaled):** 260 ± 20 counts/cm^2/10^{12} pot
- **Measured:** 250-300 counts/cm^2/10^{12} pot
  - Two different measurement devices -> cross validation
- Match expectation

Project organisation: preliminary groups and costs

Item	Technology	Interested groups
MIB system	magnetized	
	iron blocks	CERN, LNF-INFN
Upstream Veto	Micromegas	INFN (Rome3, Naples)
Decay Vessel	in-vacuum	CERN
Dipole Magnet	warm	CERN
Tracker	Straws	Heidelberg
Timing Layer	scintillating bars	Freiburg
ECAL	StripCal	Mainz, KIT
Muon	scintillating tiles	INFN (LNF,Ferrara, Bologna)
Software		INFN-Rome 1, Prague
TDAQ		CERN
NaNu		Mainz/Bonn

Item	Technology	Cost (M€)
MIB system	magnetized	
	iron blocks	0.992
Upstream Veto	Micromegas	0.860
Decay Vessel	in-vacuum	1.0
Dipole Magnet	warm	2.57
Tracker	Straws	1.624
Timing Layer	scintillating bars	0.180
ECAL	StripCal	0.980
Muon	scintillating tiles	1.111
TDAQ		0.250
Total SHADOWS		**9.567**
Total NaNu		**2.840**

Still room for new collaborators!

Cost uncertainty C3 class:
(-(10-20)%, +(10-30)%)

Project Schedule

2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
NA62 Run			LS3	LS3	LS3	ECN3/HI Installation/ commissioning	ECN3/HI Installation/ commissioning	ECN3/HI run
Proposal	TDR	TDR	TDR/PRR	Production	Production	Production/ Installation	Installation/ Pilot Run	SHADOWS run
2032	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
ECN3/HI run	LS4		ECN3/HI Run				LS5	
SHADOWS run	consolidation	SHADOWS run	SHADOWS run	SHADOWS run	SHADOWS run	SHADOWS run	consolidation	SHADOWS run

The schedule through our eyes

Karlsruhe Institute of Technology

Terrifying Moment of Truth
(Proposal decision December 6, 2023)

Discover FIPs
Win Nobel Prize
Etc… etc…

NA62 Run

LS 3 + ECN3 Installation

SHADOWS + HIKE runs

Build, Install, and Commission a brand new experiment

We are here

2030

Conclusions

- SHADOWS is a proposed north area experiment to search for Feebly Interacting Particles
- SHADOWS and HIKE can occupy the TCC8 and ECN3 areas together
  - HIKE + SHADOWS will search for FIPs
  - HIKE will continue the Kaon programme
- Built on well established detector technologies to ensure operational readiness by 2030
- A preliminary, but complete design has been proposed
- Backgrounds are well studied

And now… we wait…. 🤞

Thank you!

On behalf of a young, but very motivated, group of scientists

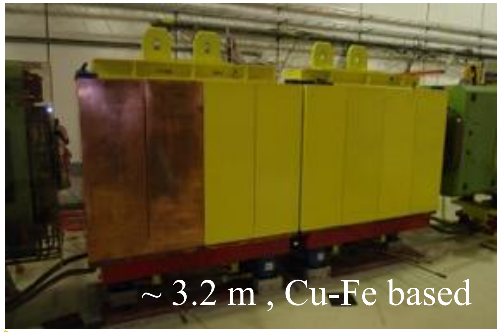
Back-up slides

Kaon mode vs Beamdump mode path

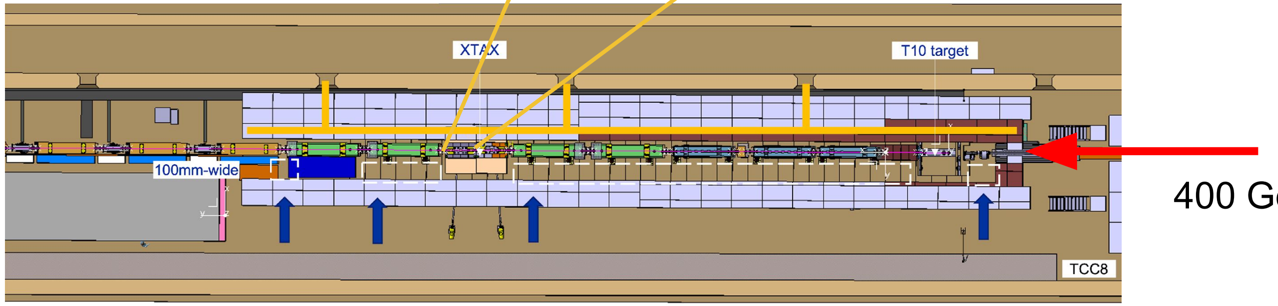
Kaon (T10) target is lifted and the 400 GeV proton beam is sent onto the dump

Kaon Target: Beryllium
Beamdump: Cu-Fe

NA62 dump system



Will be upgraded to withstand higher (7x) intensity



400 GeV Protons

Inside the dump system