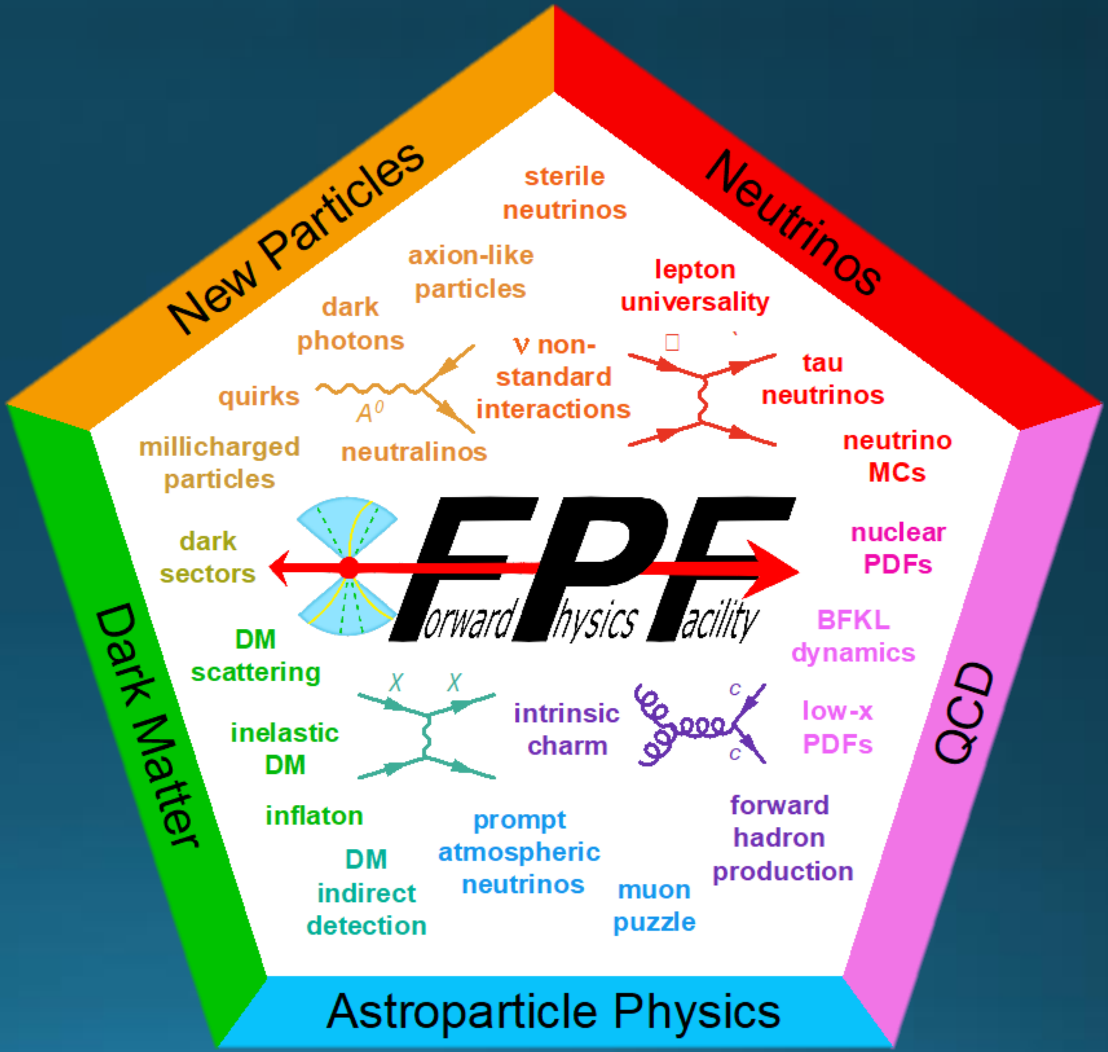
The Forward Physics Facility at the LHC

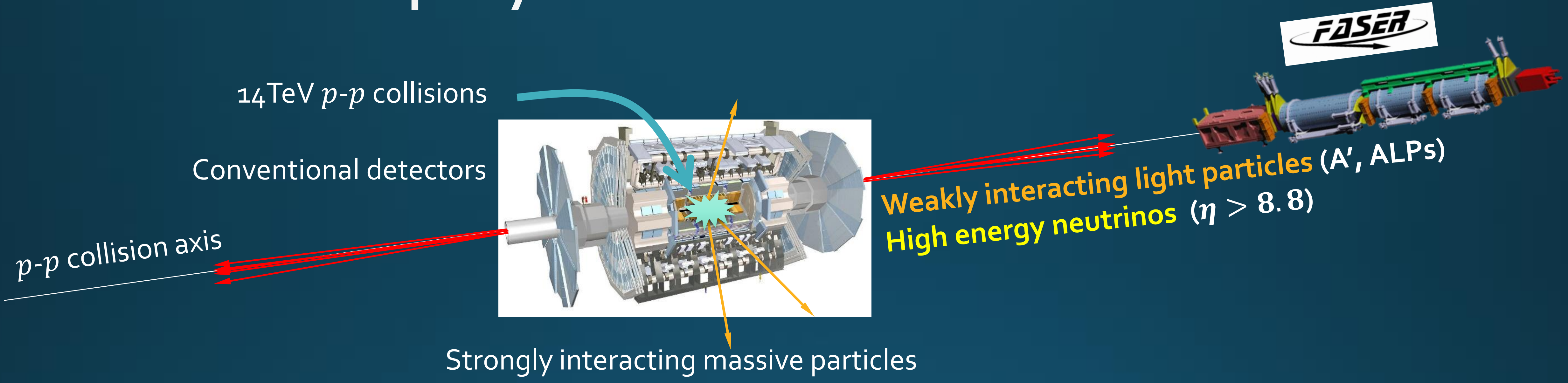
Akitaka Ariga
University of Bern and Chiba University
on behalf of the FPF community

FASER FLArE FORmosa

Physics Beyond Colliders



Forward physics at colliders



- In just a few years, our view of forward physics at colliders has completely changed.
- Now: We know the forward region holds rich physics, both SM and BSM, addressing all of our top science drivers.
- The discovery of collider neutrinos marks the start of multi-messenger collider physics.
- To fully explore what the LHC can offer, the **Forward Physics Facility (FPF)** is being proposed for the HL-LHC — to host a set of detectors that can unlock this exciting new physics.

Pathfinder experiments

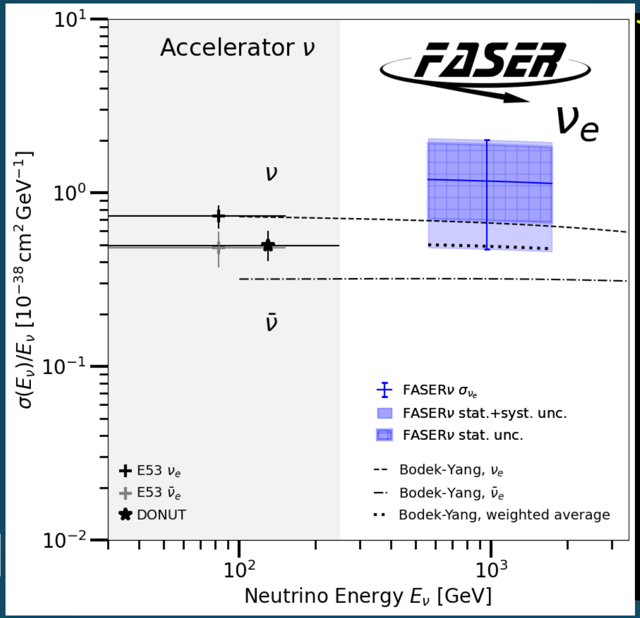
- *Proof of concepts*: collecting data and validating designs/DAQs through Run 3
    - FASER (FASERν), SND@LHC, FORMOSA demostrator

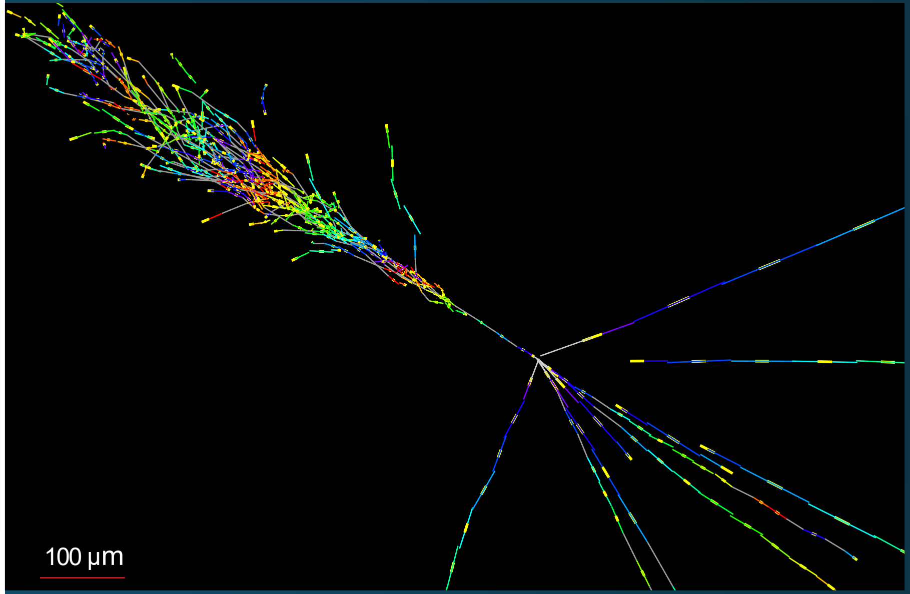
SND@LHC

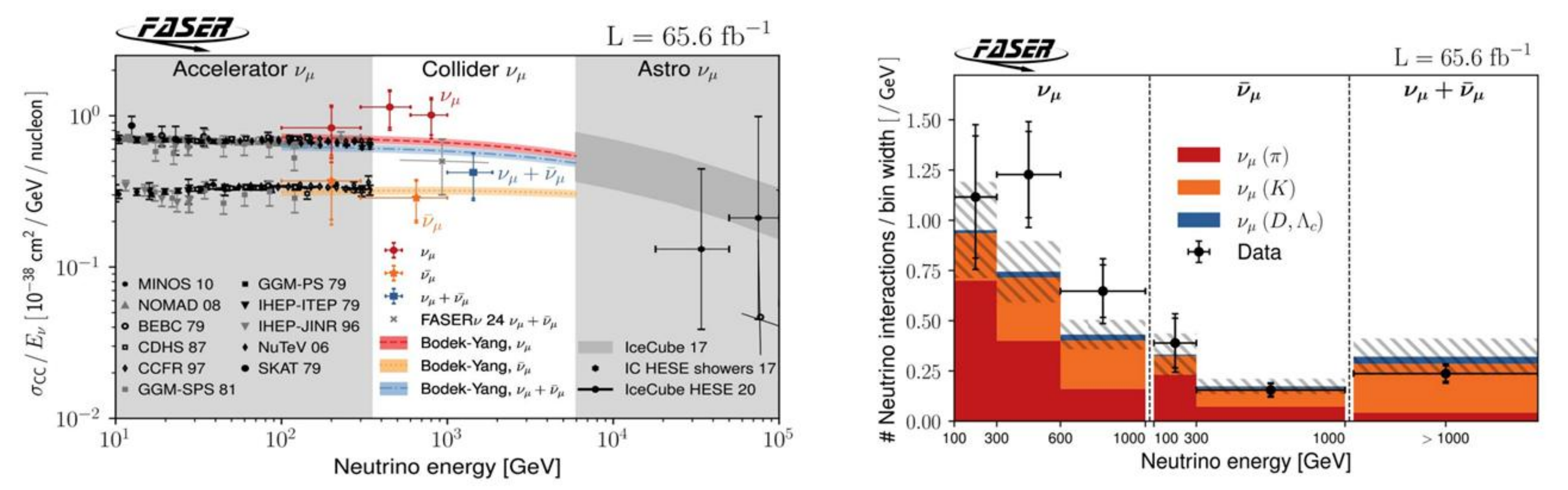
See FASER neutrino talk in EPS-HEP by A. Ariga
https://indico.in2p3.fr/event/33627/contributions/154587/

Collider neutrino results

- ν candidates in 2021 [PhysRevD.104.L091101]
- Collider ν detection established in 2023 [PhysRevLett.131.031801]
- ν_e and ν_μ cross sections in 2024 [PhysRevLett.133.021802] [nature]
- Differential measurements 2024 [PhysRevLett.134.211801]





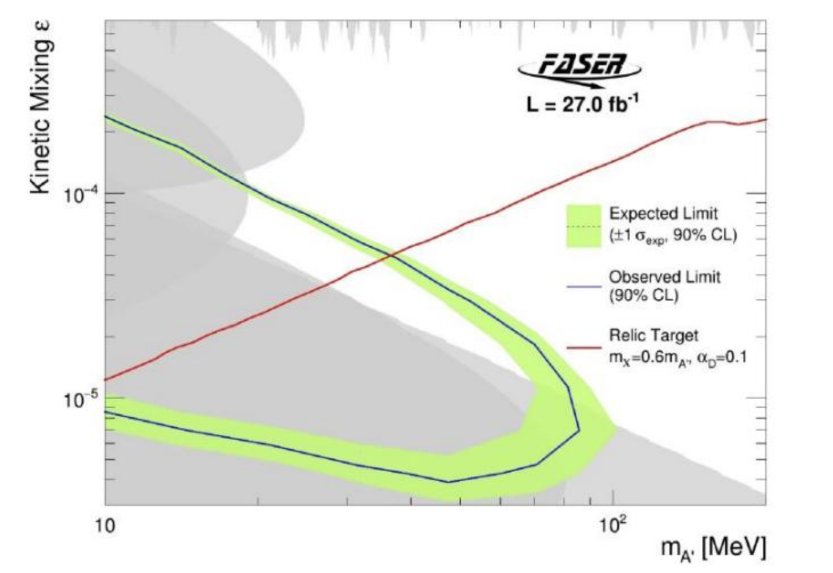


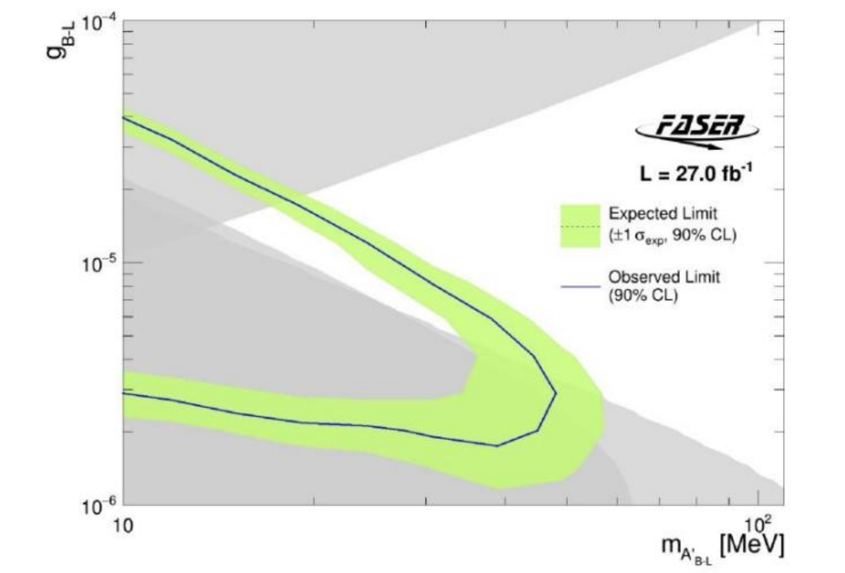
BSM particle searches

See FASER LLP searches in EPS-HEP by X. Ai
https://indico.in2p3.fr/event/33627/contributions/154654/

Dark photon (A')

$B-L$ gause boson (A'_{B-L})

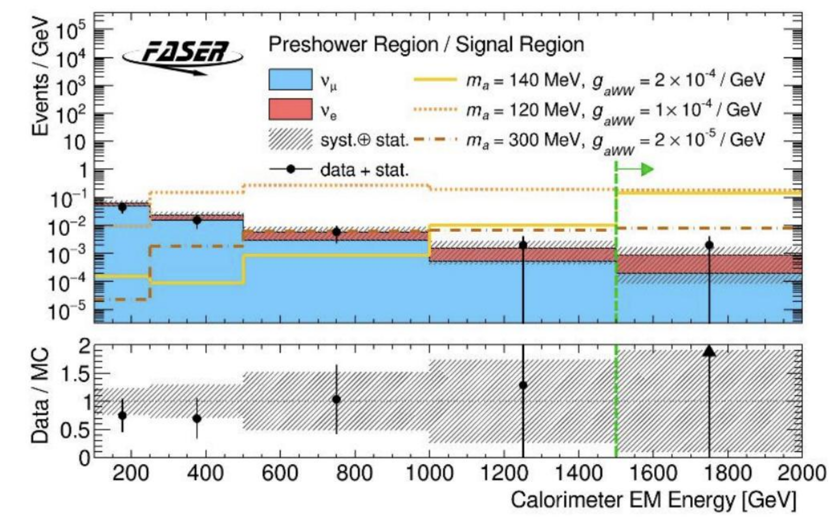


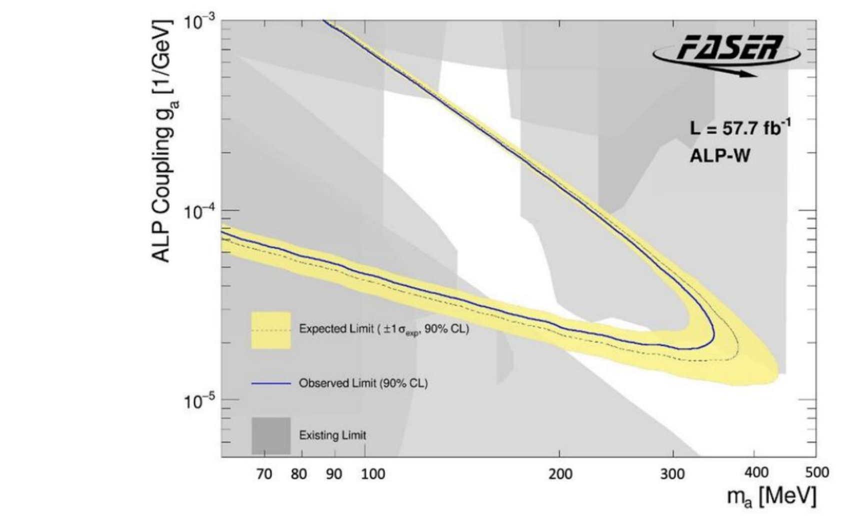


Dark photon search with 2022 data (27 fb^(−1))
j.physletb.2023.138378

Axion-like particles search with 2022/2023 data (57.7 fb^{-1})

JHEP01(2025)199



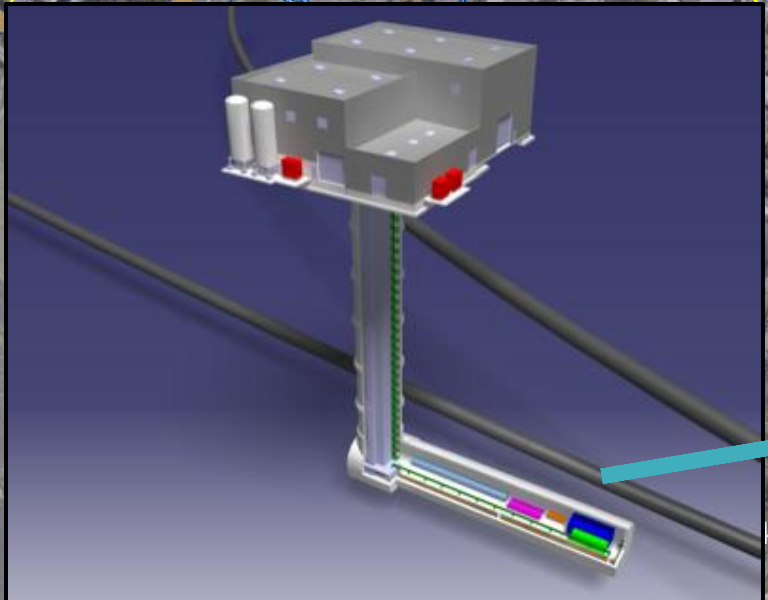


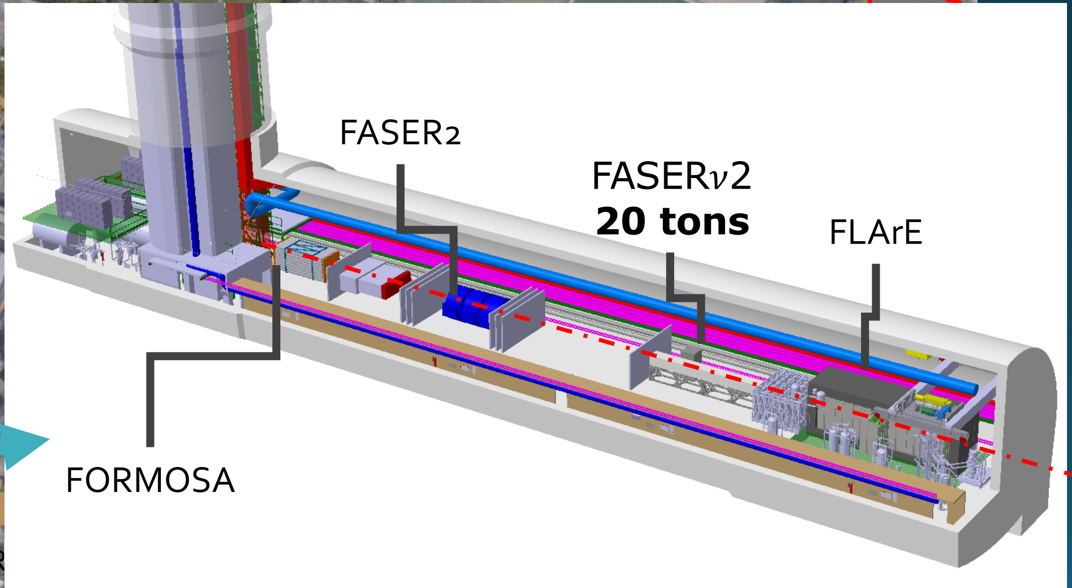
Forward Physics Facility at the HL-LHC

HL-LHC provides x20 proton collisions

Extending sensitivities for new particle searches and neutrino physics by **2 to 4 orders of magnitude**

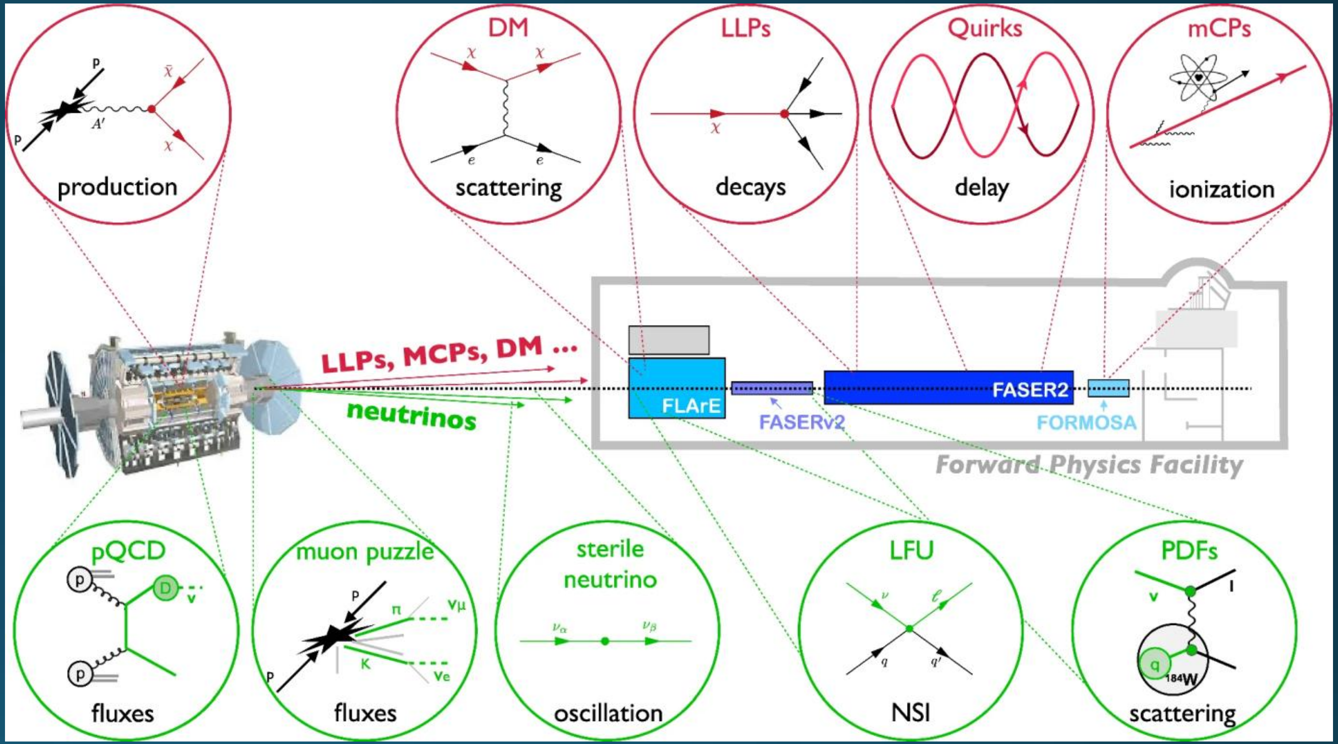
New shaft and hall





Physics objectives and experiments

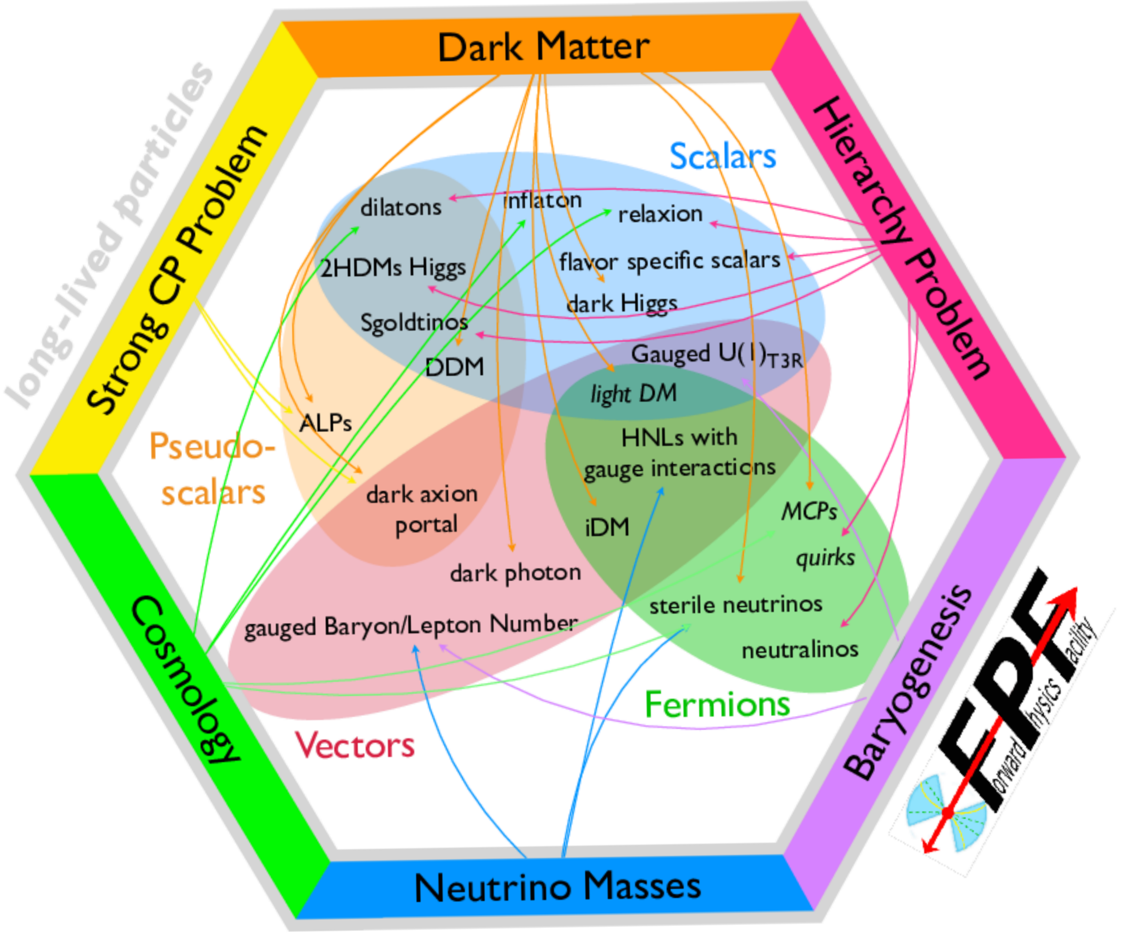
- Neutrino physics at TeV energies
- Neutrino precision physics
- FPF as neutrino-ion collider
- Unique probe of small-x QCD
- Impact for Astroparticle Physics
- Dark matter and mediators
- Millicharged particles
- Other opportunities for new particle searches
- See FPF's input to **ESPPU**!

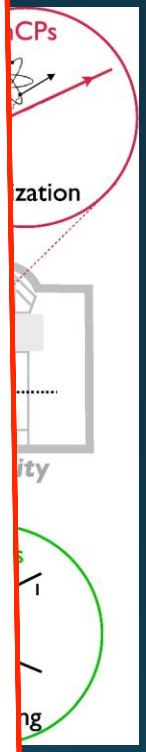


Physics objectives and experiments

- Neutr
- Neutr
- FPF as
- Uniqu
- Impac
- Dark r
- Millich
- Other
- See FP

FPF experiments have discovery potential in every one of the PBC benchmark scenarios!





Neutrinos at FPF

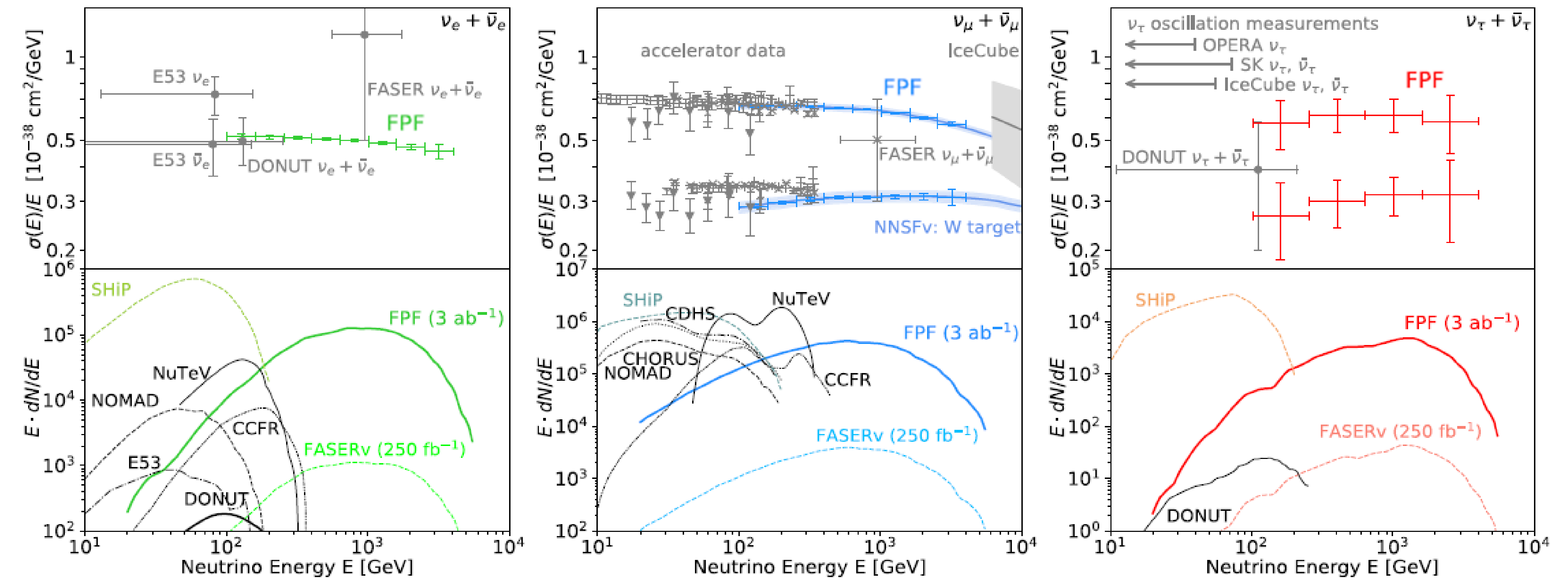
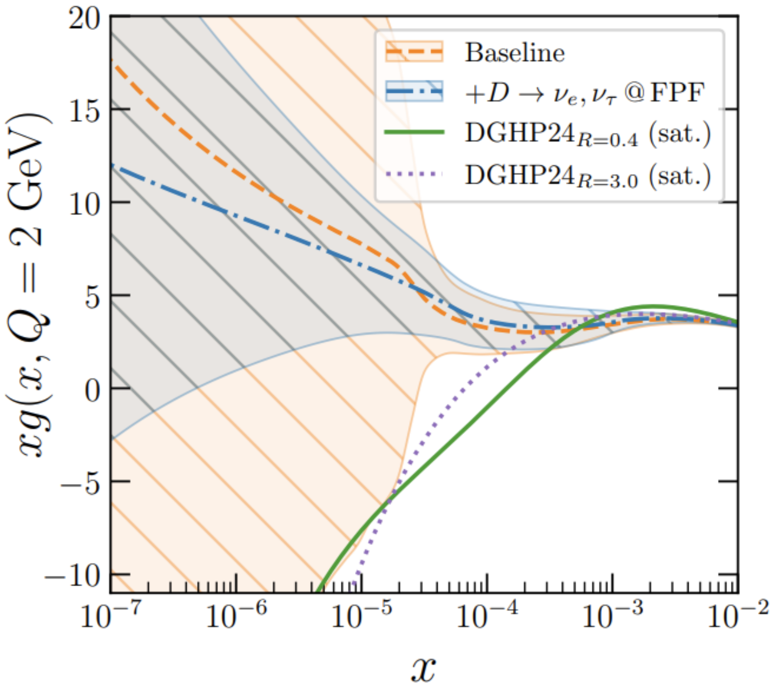
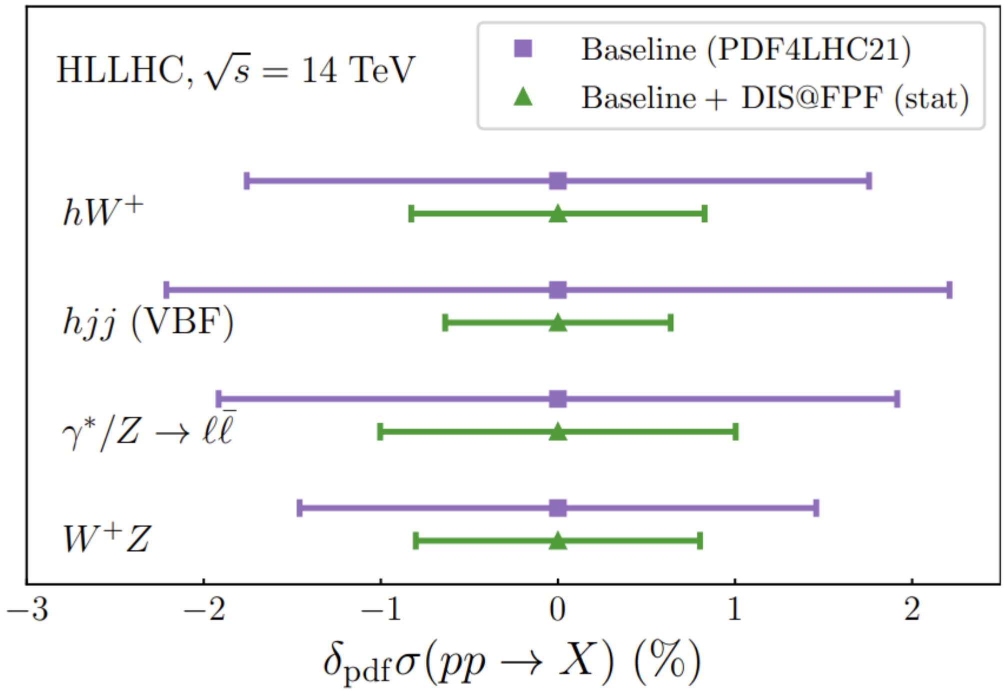


Fig. 6 Neutrino yields and cross sections at the FPF. The expected precision of FLArE measurements of neutrino interaction cross sections (top, statistical errors only) and the combined spectrum of neutrinos interacting the FPF experiments (bottom) as a function of energy for electron (left), muon (middle), and tau (right) neutrinos. In the case of muon and tau neutrinos, separate measurements of the neutrino and anti-neutrino measurement can be performed using muons passing through the FASER2 spectrometer, where a 17% branching fraction of taus into muons was considered. Existing data from accelerator experiments [63], IceCube [64], and the recent FASERν result [65] are also shown, together with the prospects for SHiP

QCD and enhancing HL-LHC discovery potential





FPF measures the **gluon probability (PDF)** at low momentum fractions

Improves predictions of **Higgs-** and **weak gauge-boson** cross sections at the HL-LHC

LLPs searches at the FPF

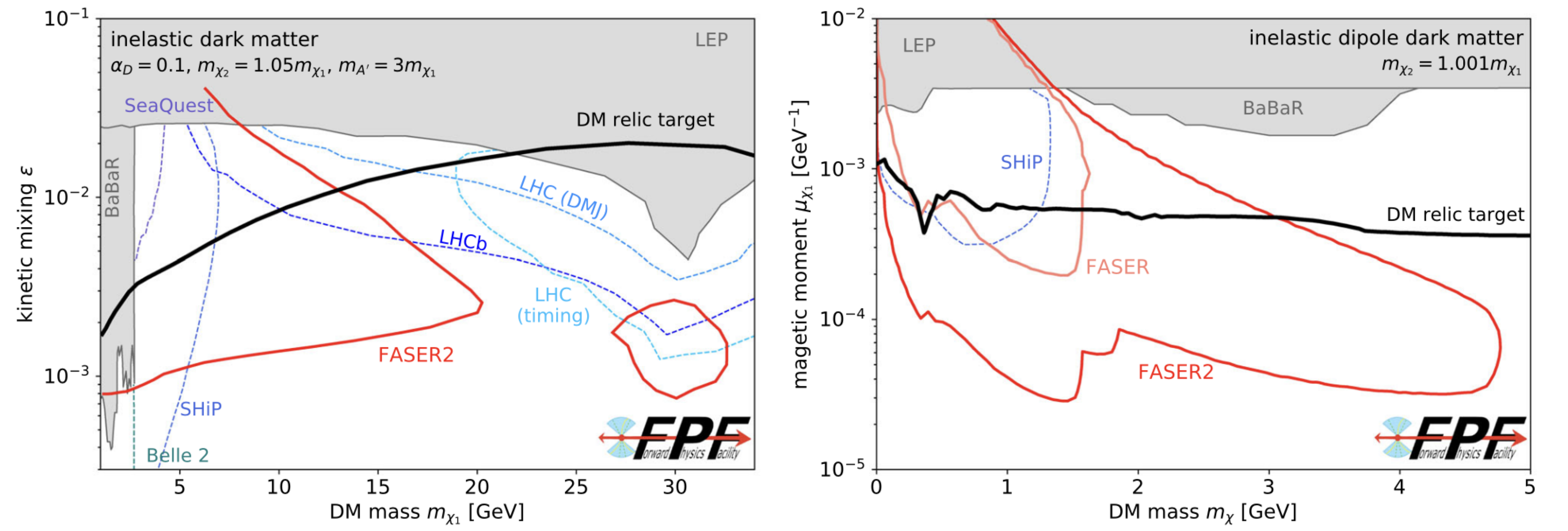


Fig. 4 Inelastic dark matter searches at the FPF. The discovery potential of FASER2 and other experiments for two different realizations of inelastic DM. The left panel considers a the case of heavy inelastic DM interacting via a dark photon portal, as introduced in [15], where the high energy of the LHC allows FASER2 to probe masses up to tens of GeV. The right panel considers the case of light inelastic DM with very small mass splittings that is mediated by a dipole portal as introduced in Ref. [16], where the large LHC energy boosts the signal to observable energies. In both scenarios, the reach of FASER2 extends beyond all other experiments, including direct and indirect DM searches, LHC experiments, and beam dump experiments, such as SHiP. It also covers the thermal DM relic target (solid black lines), that is the cosmologically-favored parameter space where the model predicts the observed dark matter relic abundance as produced through thermal freeze-out. For comparison, we have shown the leading constraints provided by BaBaR [17] and LEP [18,19], as well as projections from a number of other proposed searches, including those for displaced muon jets (DMJ) and delayed particles (timing) at the main LHC experiments [20,21] as well as displaced particle searches at LHCb [22–24], SHiP [25], Belle 2 [26], and SeaQuest [27]

From FPF's input to **ESPPU**

LLPs with unusual propagation patterns

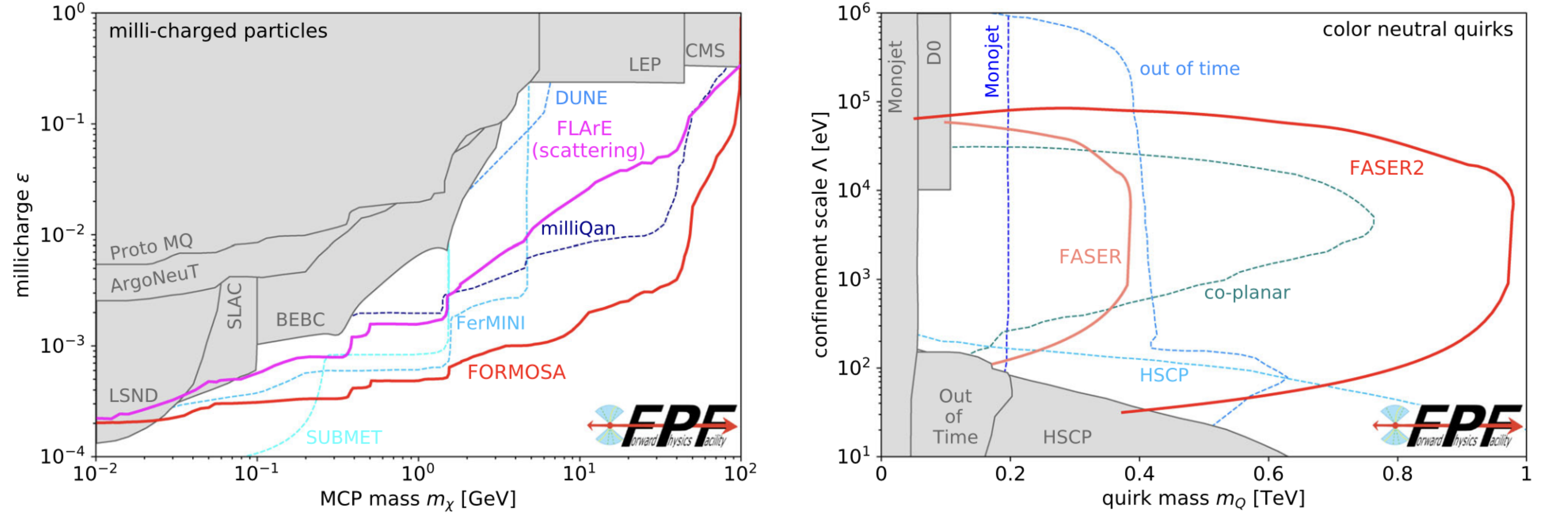
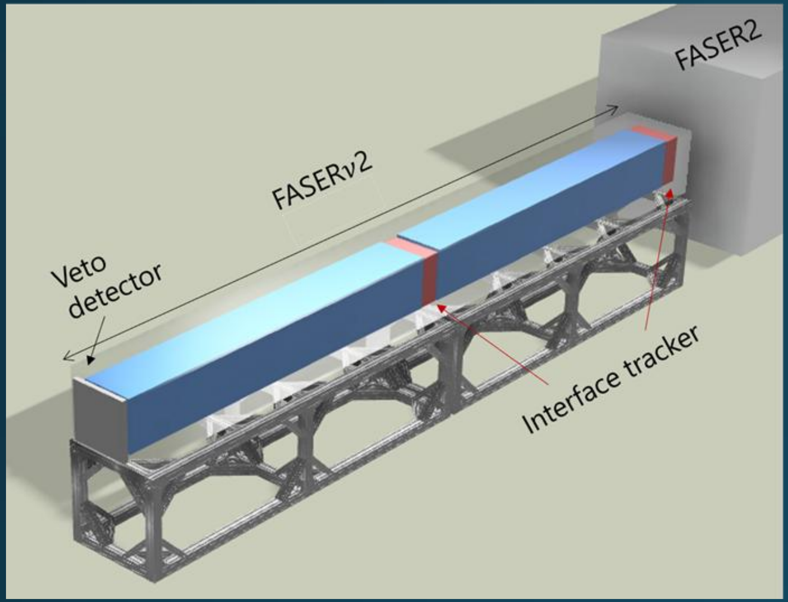
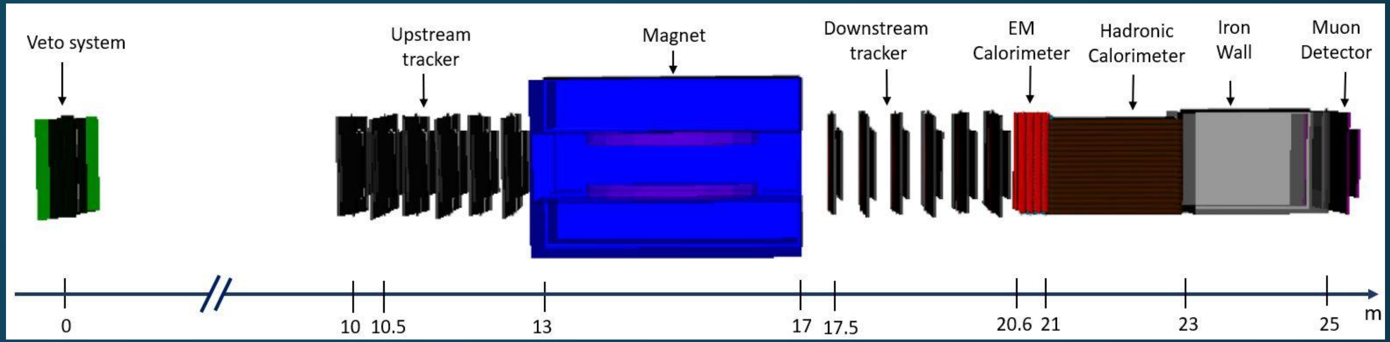


Fig. 5 New particle searches at the FPF. Left: The discovery reach of FORMOSA and FLArE for millicharged particles [14,31]. Right: The discovery reach of FASER and FASER2 for color-neutral quirks [32]. In both panels, we also show existing bounds (gray shaded regions) and projected sensitivities of other experiments (dashed contours), including BEBC [33], SLAC [34], LEP [35,36], CMS [37,38], LSND [39], ArgoNeuT [40], Proto-milliQan [41], milliQan [42], FerMINI [43], SUBMET [44], monojet searches [45–47], quirk searches at D0 [48], heavy stable charged particle searches (HSCP) [45,49,50], co-planar hits searches [51], and out-of-time searches [52,53]

From FPF's input to **ESPPU**

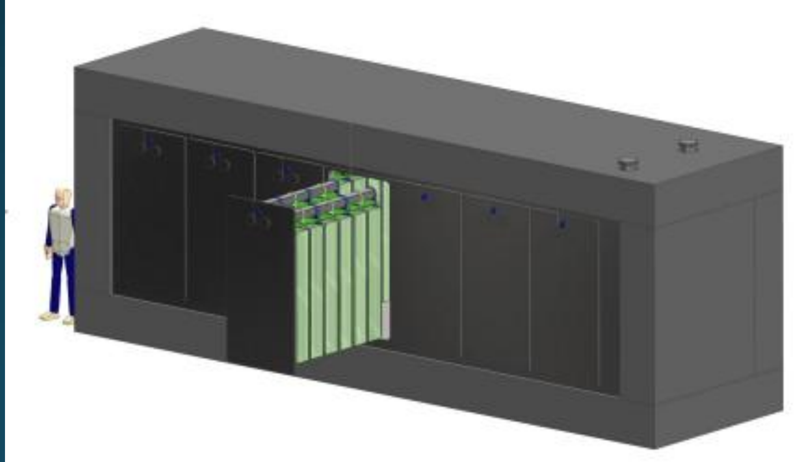
Tailored detectors at the FPF

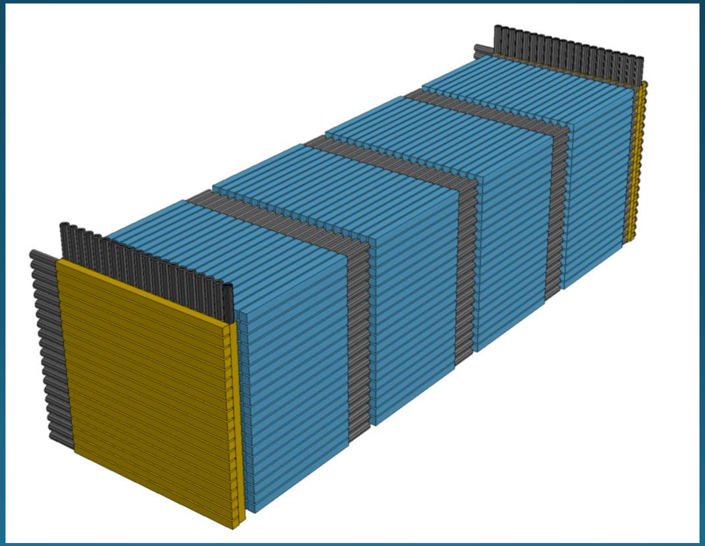




FASER2: tracking spectrometer for LLP searches and muon charge ID

FASERν2: emulsion detector for neutrinos



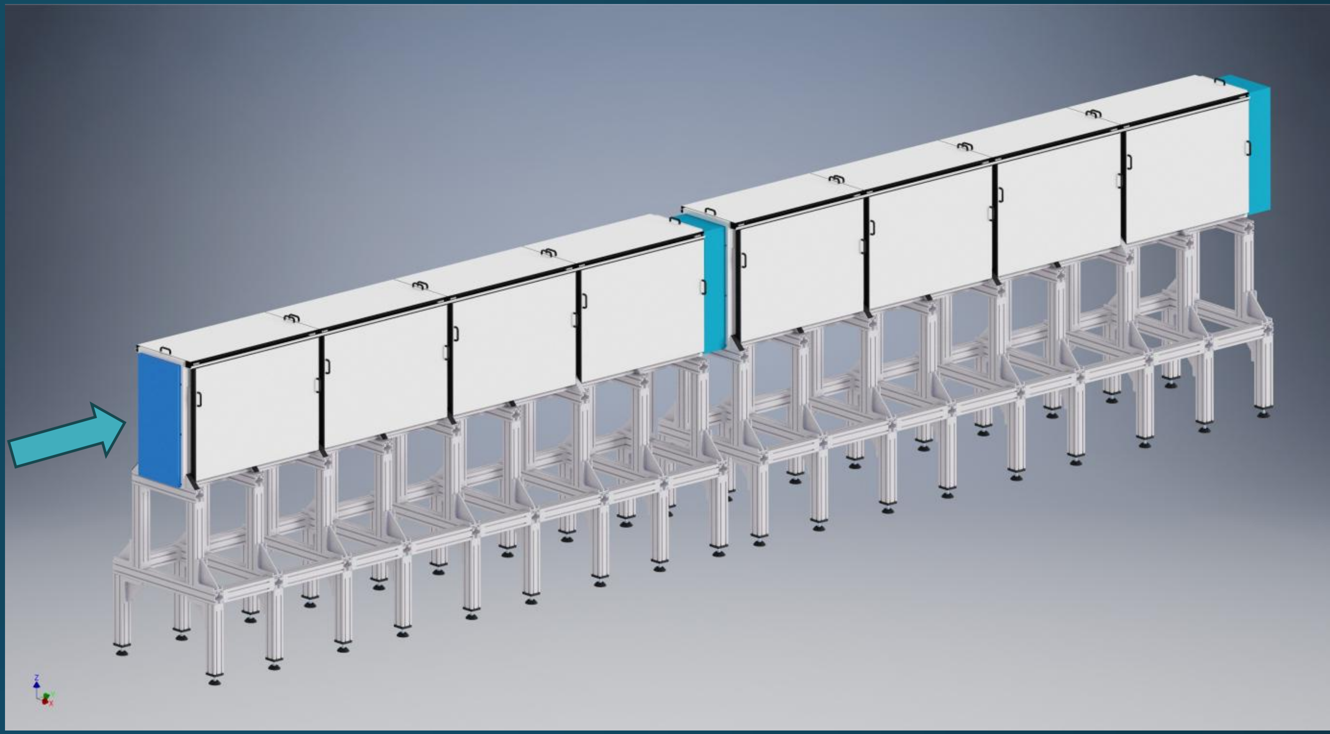


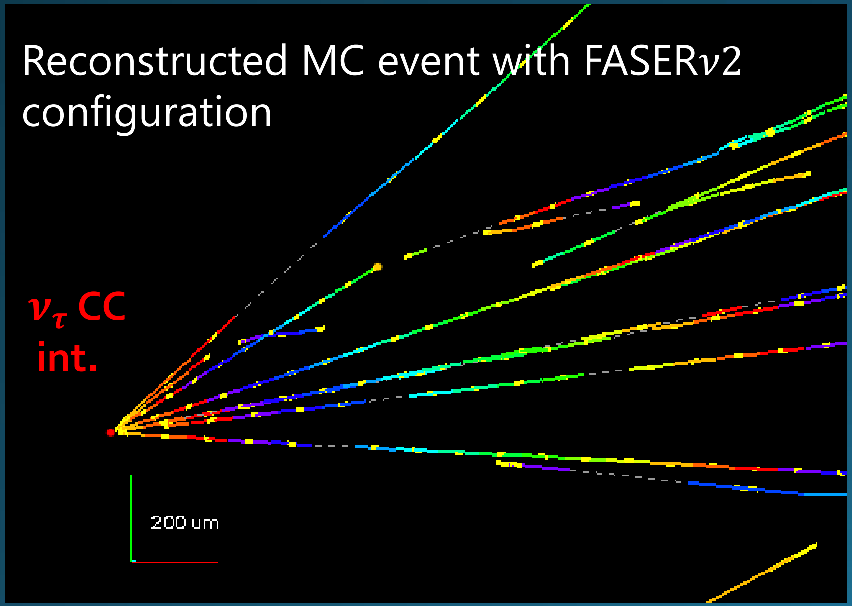
FLArE: LAr TPC for neutrino detection

FORMOSA: plastic scintillator array for mCPs

FASERν2

- 20-ton tungsten-emulsion detector
  - Tungsten target: 64 cm x 25 cm x **2 mm** X 3300 plates
  - Sensitivity to ν_e, ν_μ, ν_τ
  - $\mu^\pm$ charge ID with FASER2
- Performance proven by FASERν
- High statistics ν_τ studies and test lepton flavor universality





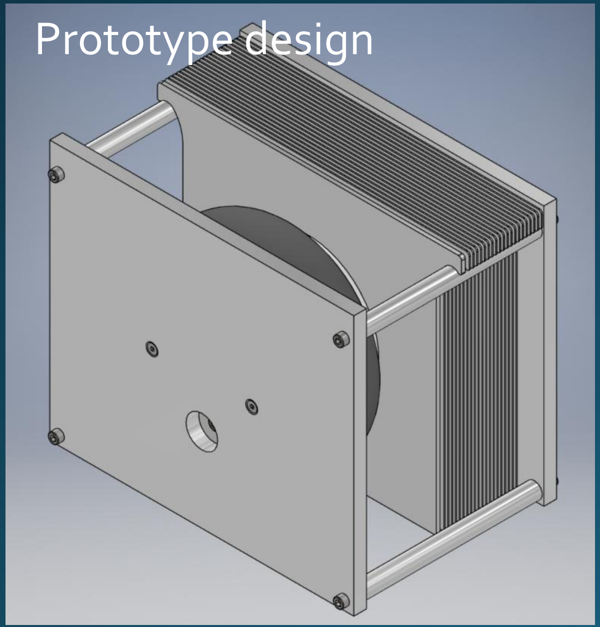
ν int. rate estimated based on **Sibyll 2.3d**

		$\nu_e+\bar{\nu}_e$ CC	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_\tau+\bar{\nu}_\tau$ CC
FASERν (1.1 tons, 150 fb^{-1})	**ν int.**	**0.9k**	**4.8k**	**15**
	ν int. with charm	~0.1k	~0.5k	~2
	ν int. with beauty	-	~0.05	-
FASERν2 (20 tons, 3 ab^{-1})	**ν int.**	**178k**	**943k**	**2.3k**
	ν int. with charm	~20k	~90k	~0.2k
	ν int. with beauty	~2	~10	~0.02

FASERν2 detector structure

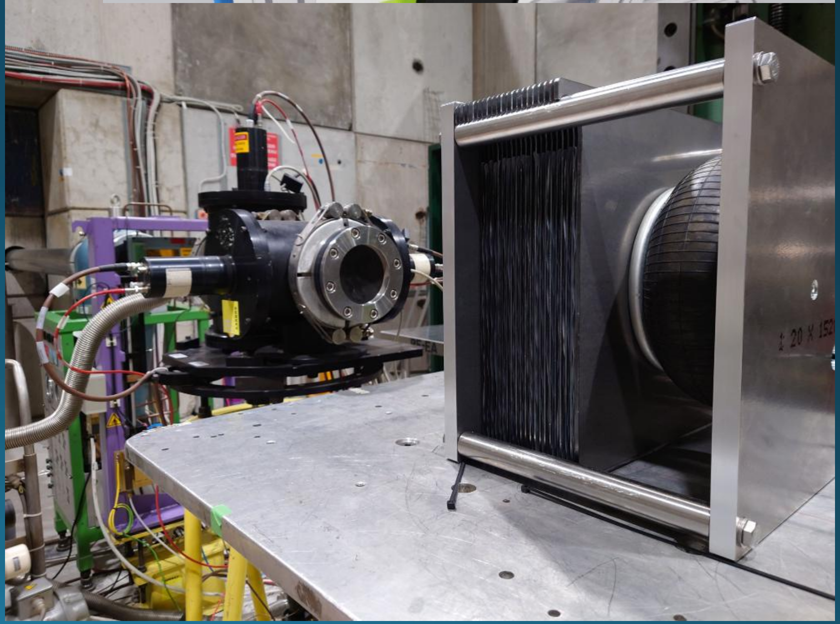
- Assembling a 20-ton detector in dark is technically challenging → Assembling in FPF
  - Light-tight-packed emulsion film
- The scheme was tested in test beam at SPS-H8 in 2024

Prototype design, T-shirt shape iron plates on a rail, pushed by compressed-air pressure

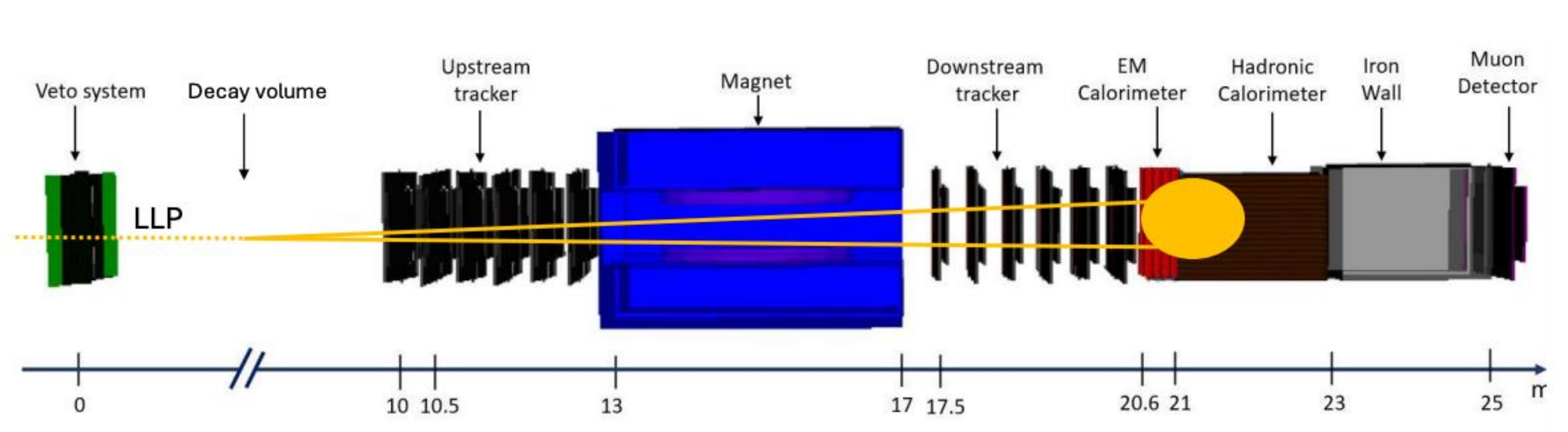


Prototype design

Test at SPS-H8



FASER2



Decay volume:

- 10 m long decay volume

Tracker:

- Based on LHCb's SciFi tracker
- SiPM and scintillating fiber design
- Detector resolution: ~ 100 μm

Magnet:

- Large aperture
- 3m wide X 1m gap (*)
- Superconducting technology
- Magnetic Field : 2 Tm
- Based on the SAMURAI magnet

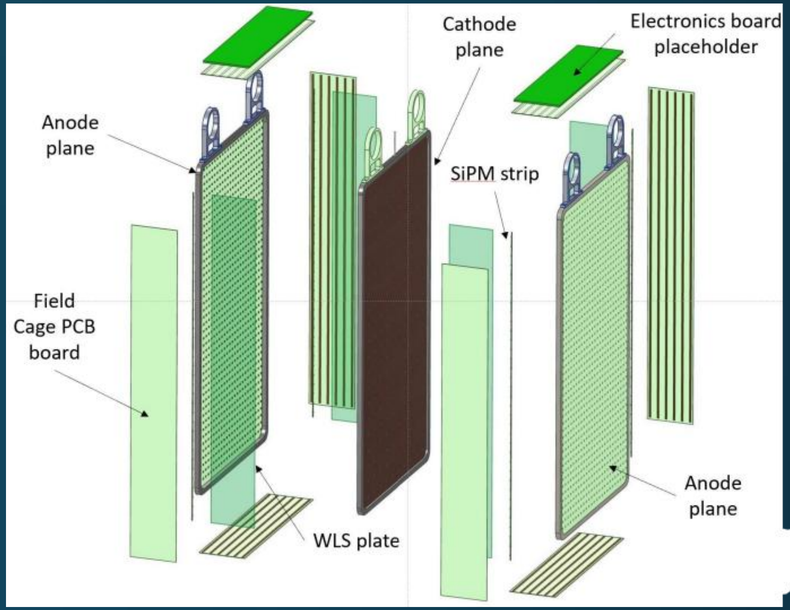
Calorimeter:

- Based on dual-readout calorimetery
- Spatial resolution: 1-10 mm

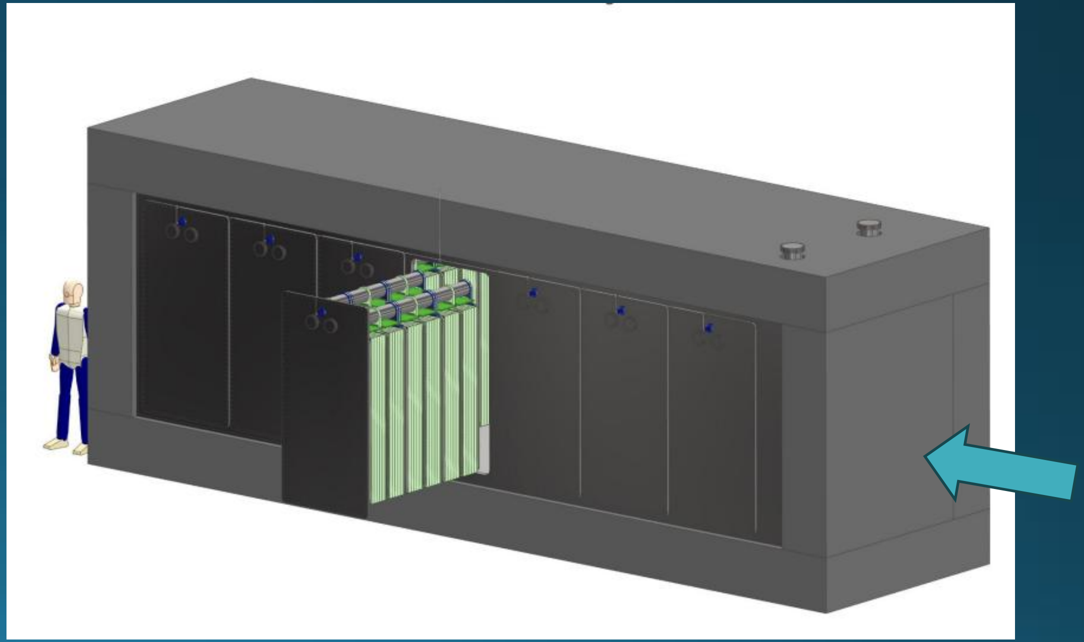
All possible with existing detector technologies

FLArE

Inspired by the DUNE near detector concept (photo in Bern)

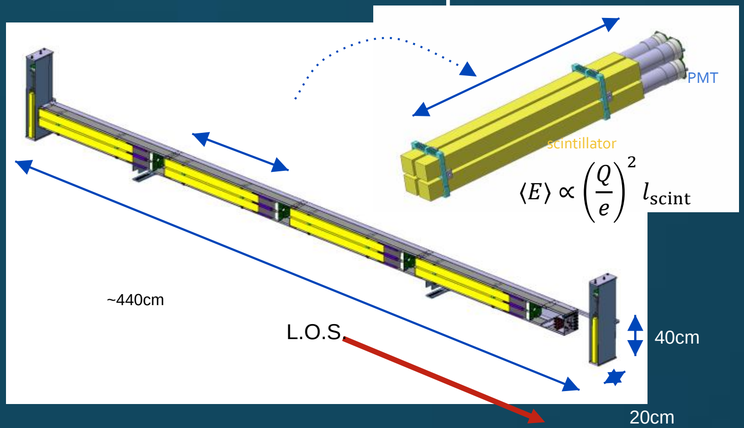


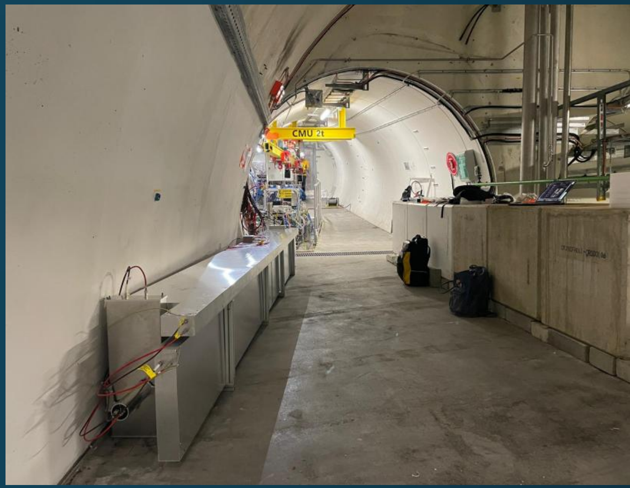
- Liquid Argon neutrino detector
  - Based on DUNE near detector concept
  - 3 x 7 = 21 TPCs
  - 30 tons active volume, 10 tons fiducial volume
- LAr works as precision tracker and calorimeter
- Particle ID, energy measurements from MeV – O(100) GeV
- Study ν_e, ν_μ, ν_τ (statistically)
- $\mu^\pm$ charge ID with FASER2



FORMOSA

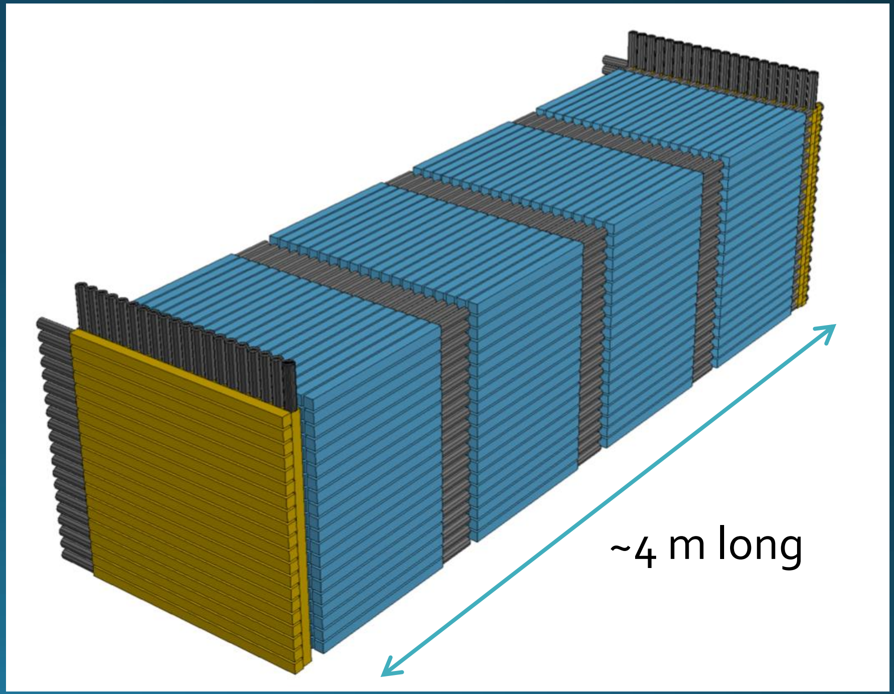
2024





FORMOSA demonstrator as of 2025

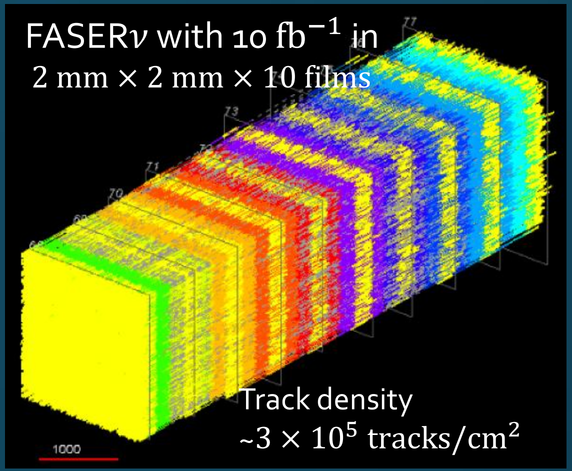
- Direct millicharged particle (mCP) searches at the LHC
- Core concept: Use array of efficient long scintillator bars + PMTs to detect ionization from mCPs.
- Small scale prototype in 2025:
  - 16 scintillator bars
  - Front+back muon panels

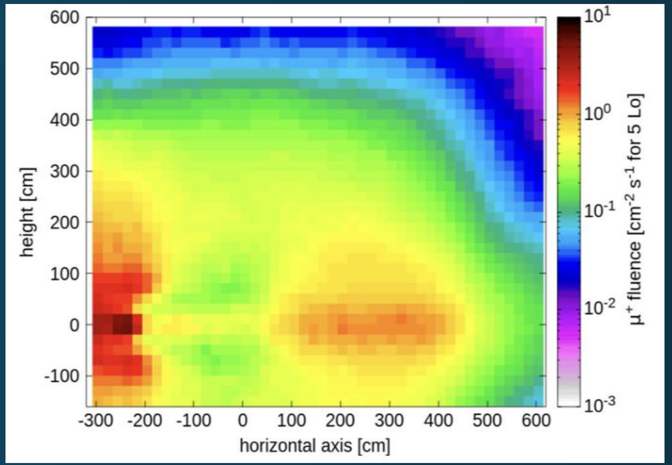


BG muon measures

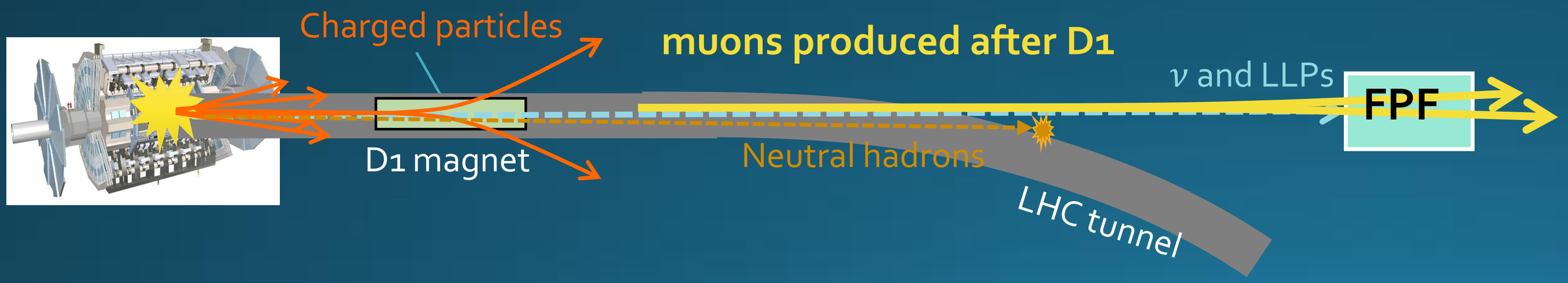
- Background muon limits sensitivities
  - Impacts FASERν2, FLArE, FORMOSA
  - Estimated to be O(1) Hz/cm²
- Reducing muon background would be beneficial for the FPF experiments (particularly FASERnu2)

→Investigating the feasibility of implementing a Sweeper magnet





μ^+ fluence expected in FPF
~O(1) Hz/cm²



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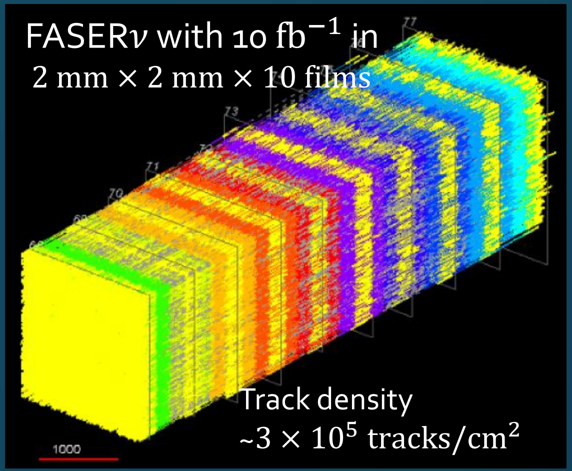
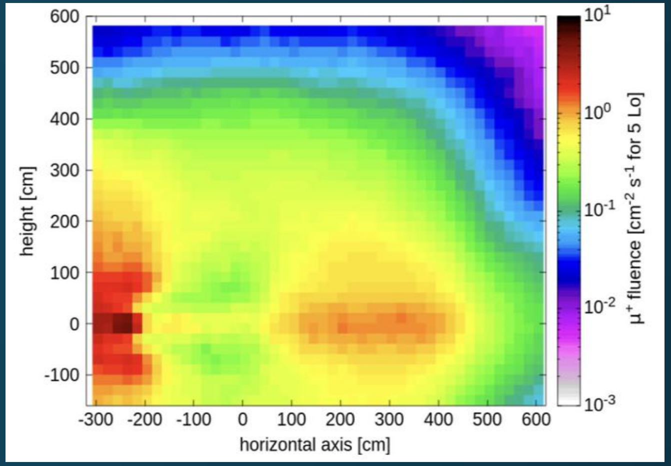
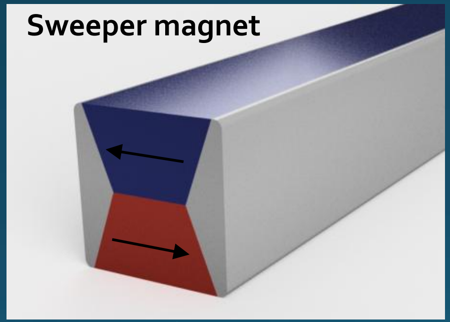
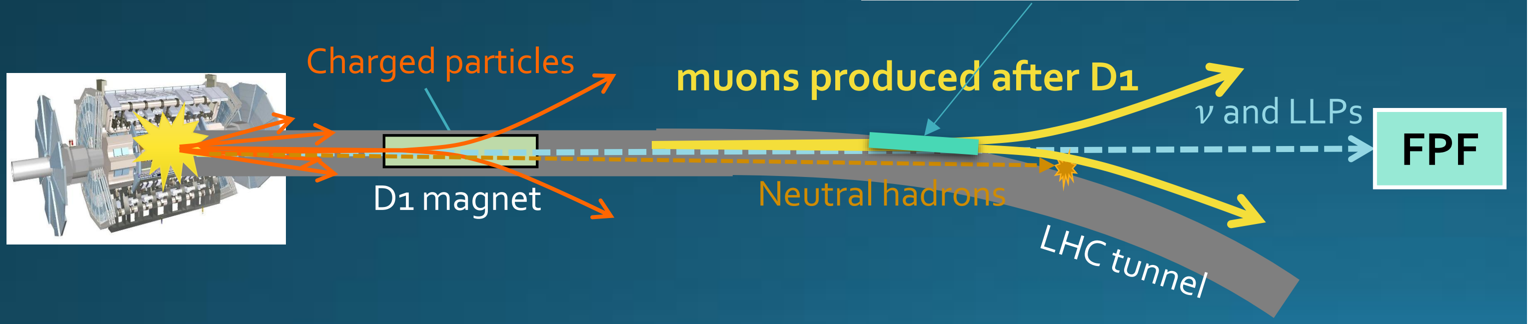




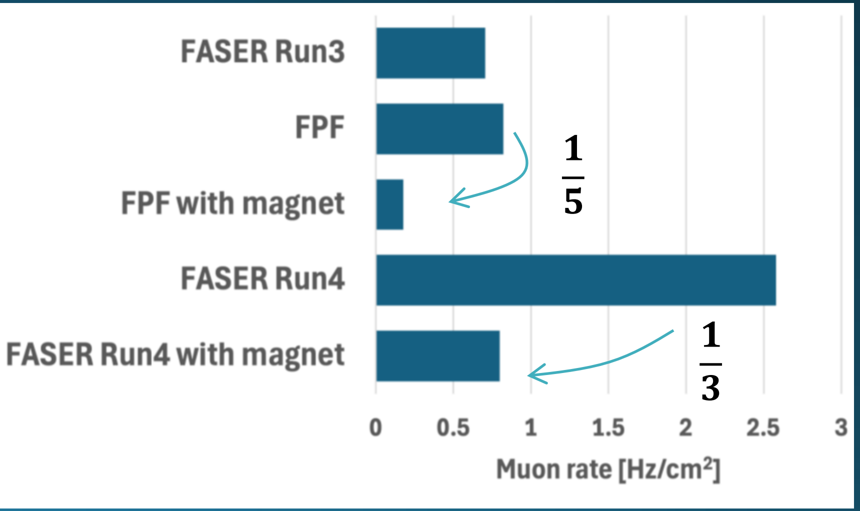
μ^+ fluence expected in FPF
~O(1) Hz/cm²

Place a permanent magnet along the wall of the LHC tunnel
1 T x 40 m long





Simulated muon rates with/without sweeper magnet (preliminary)



FPF documentation

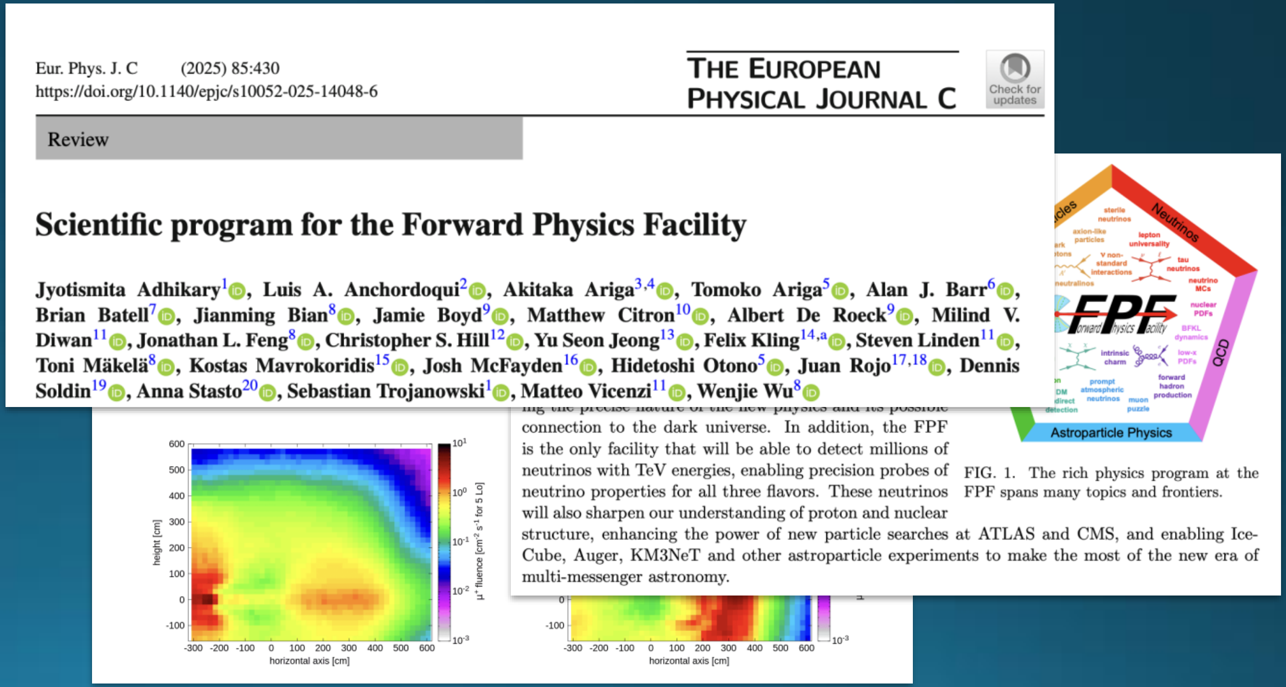
- **FPF workshop series:**
  - FPF1, FPF2, FPF3, FPF4, FPF5, FPF6, FPF7, FPF theory day, FPF8
- **FPF paper:**
  - 2109.10905
- ~75 pages, ~80 authors
- **Snowmass Whitepaper:**
  - 2203.05090
- ~450 pages, ~250 authors
- **Recent Summary:**
  - FPF Update
- **Technical Documents:**
  - Facility Technical Study
  - Muon Flux Study
  - Vibration Study
  - Geotechnical Report

Photo at FPF8 workshop

ESPPU scientific program:

EPJ C: doi.org/10.1140/epjc/s10052-025-14048-6

~25 pages, ~26 authors



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https://doi.org/10.1140/epjc/s10052-025-14048-6

THE EUROPEAN PHYSICAL JOURNAL C

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Review

Scientific program for the Forward Physics Facility

Jyotismita Adhikary[1], Luis A. Anchordoqui[2], Akitaka Ariga[3,4], Tomoko Ariga[5], Alan J. Barr[6], Brian Batell[7], Jianming Bian[8], Jamie Boyd[9], Matthew Citron[10], Albert De Roeck[9], Milind V. Diwan[11], Jonathan L. Feng[8], Christopher S. Hill[12], Yu Seon Jeong[13], Felix Kling[14,a], Steven Linden[11], Toni Mäkelä[8], Kostas Mavrokoridis[15], Josh McFayden[16], Hidetoshi Otono[5], Juan Rojo[17,18], Dennis Soldin[19], Anna Stasto[20], Sebastian Trojanowski[1], Matteo Vicenzi[11], Wenjie Wu[8]

connection to the dark universe. In addition, the FPF is the only facility that will be able to detect millions of neutrinos with TeV energies, enabling precision probes of neutrino properties for all three flavors. These neutrinos will also sharpen our understanding of proton and nuclear structure, enhancing the power of new particle searches at ATLAS and CMS, and enabling IceCube, Auger, KM3NeT and other astroparticle experiments to make the most of the new era of multi-messenger astronomy.

FIG. 1. The rich physics program at the FPF spans many topics and frontiers.

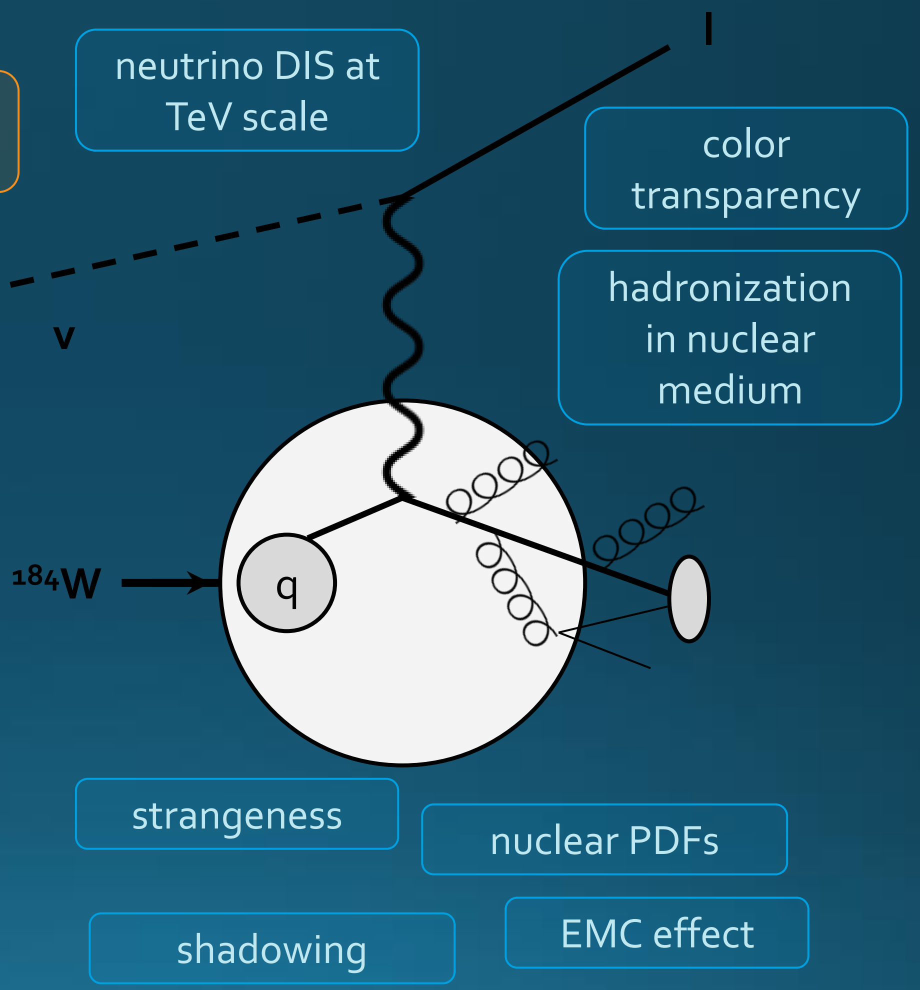
Summary

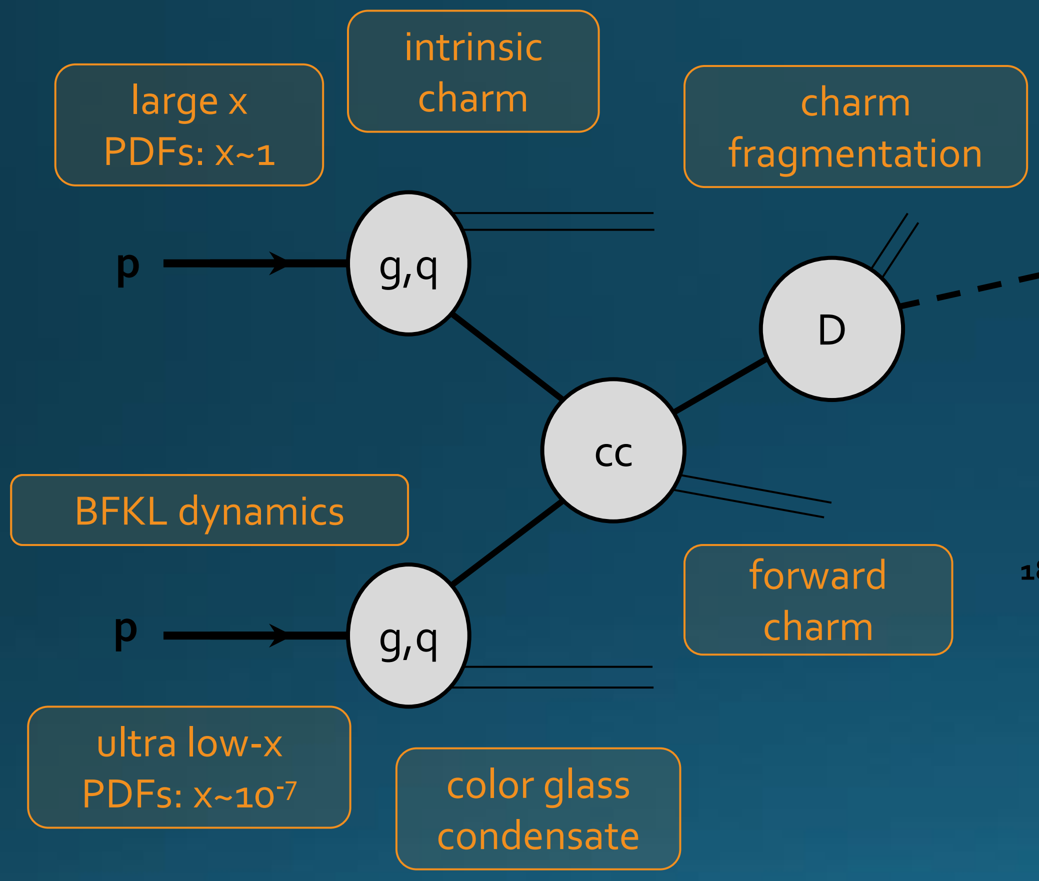
- Forward physics has been found to be a rich playground for exciting physics
  - Pathfinder experiments already reported results in Run 3
- Forward Physics Facility (FPF) has been proposed to exploit the potential of the HL-LHC
  - 4 experiments (FASER2, FASERν2, FLArE, FORMOSA)
  - Study neutrinos and BSM particles
- FPF input to ESPPU summarising physics programme (see **here**)

Detector				CC Interactions		
Name	Mass	Luminosity	Rapidity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
SND@LHC at Run 3	0.8 t	350 fb^{-1}	$7.2 < \eta < 8.4$	300	1.5k	12
FASERν at Run 3	1.1 t	350 fb^{-1}	$\eta > 8.8$	2.3k	12k	40
FASER at HL-LHC	1.1 t	3 ab^{-1}	$\eta > 8.8$	19k	102k	360
SND@HL-LHC	1.3 t	3 ab^{-1}	$6.9 < \eta < 7.6$	2.9k	15k	143
FASERν2 at FPF	20 t	3 ab^{-1}	$\eta > 8.5$	190k	970k	3.5k
FLArE at FPF	10 t	3 ab^{-1}	$\eta > 7.5$	52k	250k	1.5k
FLArE HCAL at FPF	41 t	3 ab^{-1}	$\eta > 6.5$	51k	270k	2.2k

Neutrinos as a probe

TeV Energy Neutrino Interaction





Forward Particle Production

FPF timeline and cost

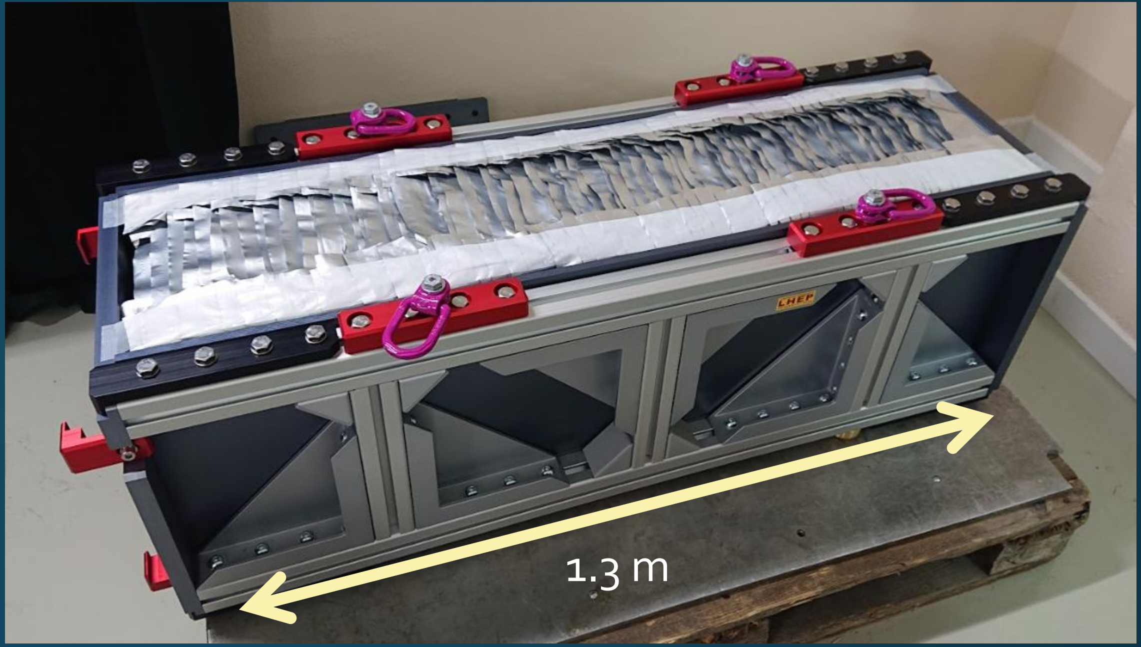
- Vibration study indicates that construction of the FPF possible during LHC operations
- Radiation protection studies indicate work in FPF possible while the LHC is running

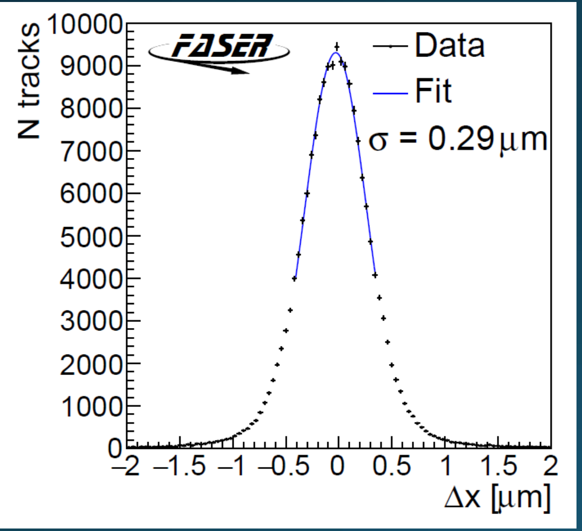
  $\longrightarrow$ not restricted to LS!
- Timeline: construct in LS3/early Run 4, physics starts in late Run 4.
- Capture as much HL-LHC luminosity as possible.
- Cost Estimate: 35 MCHF (class 4)

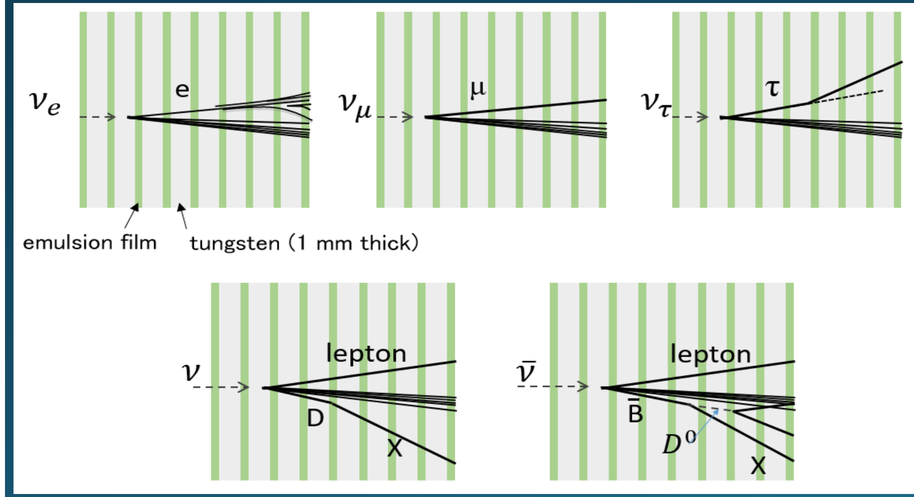
Ref.	Work Package	Cost [CHF]	Percentage of the CE Works
1.	Underground Works	12,392,344.00	35%
1.1	Preliminary activities	1,845,000.00	5.2%
1.2	Access shaft	4,424,143.00	12.5%
1.3	Experimental Cavern	6,123,201.00	17.3%
2.	Surface Works	6,727,231.00	19%
2.1	General items	720,776.00	2.0%
2.2	Topsoil and earthworks	702,227.00	2.0%
2.3	Roads and network	796,122.00	2.3%
2.4	Buildings	4,508,106.00	12.8%
2.4.1	Access building	2,224,786.00	6.3%
2.4.2	Cooling and ventilation building	1,497,350.00	4.2%
2.4.3	Electrical Building	563,689.00	1.6%
2.4.5	External platforms	222,281.00	0.6%
3.	General items	11,815,899.00	33.4%
4.	Miscellaneous	4,397,504.00	12.4%
	TOTAL CE WORKS	35,332,978.00	100.0%

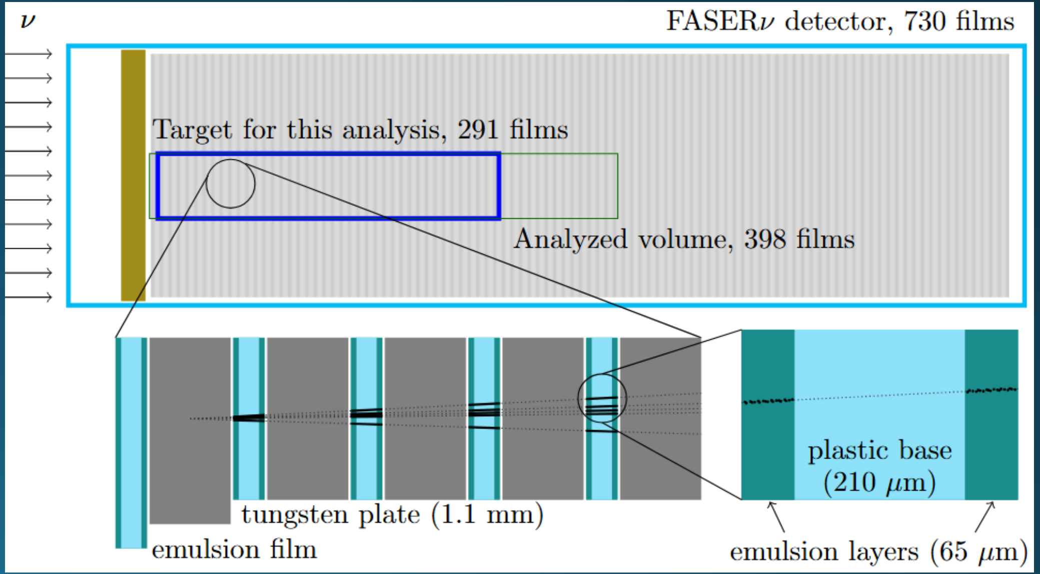
FASERν and current sample

- Emulsion/tungsten neutrino detector
  - 730 emulsion films ~ an exa-channel detector
  - Target mass of 1.1 tons (8 λ_{int}, 220X_0)
  - Typical position resolution, 300 nm
- Data set for the published result:
  - 9.5 fb^{-1} in 2022 run, target mass of 128.6 kg
  - ~1.7% of data collected by 2023



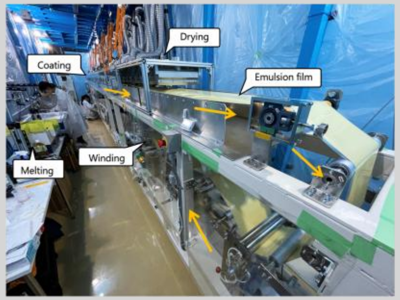






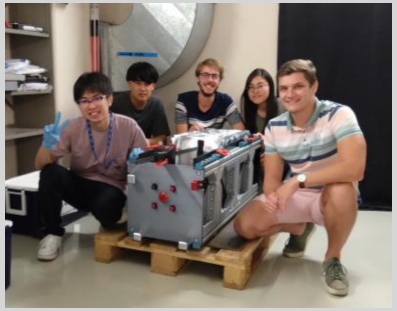
FASERν steps, 3 detectors per year

Japan



Film production

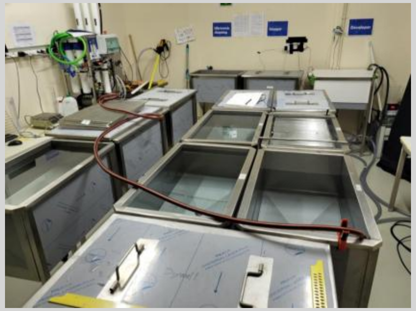
CERN



Assembly

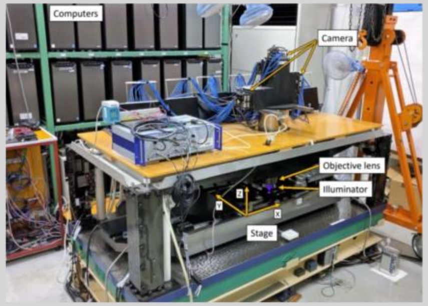
Exposure

Disassembling



Development

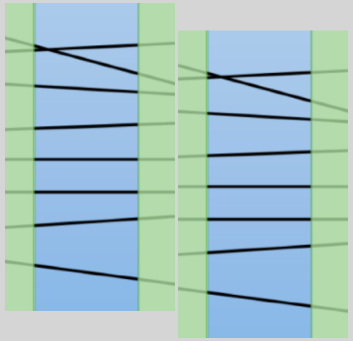
Japan



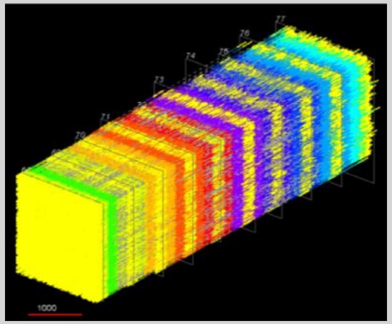
Readout

Offline analysis

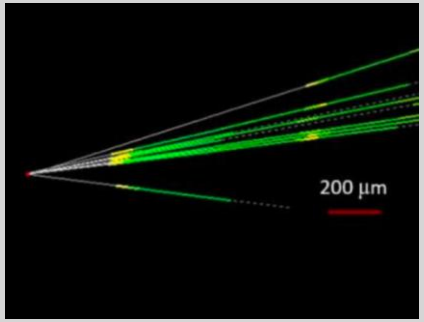
Alignment



Track reconstruction

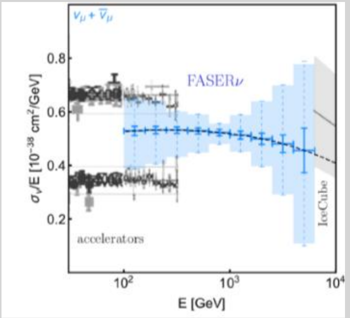


Vertex reconstruction



e, μ ID
τ decay search
charge ID
$E\nu$ reco
charm/beauty
etc.

Physics analysis



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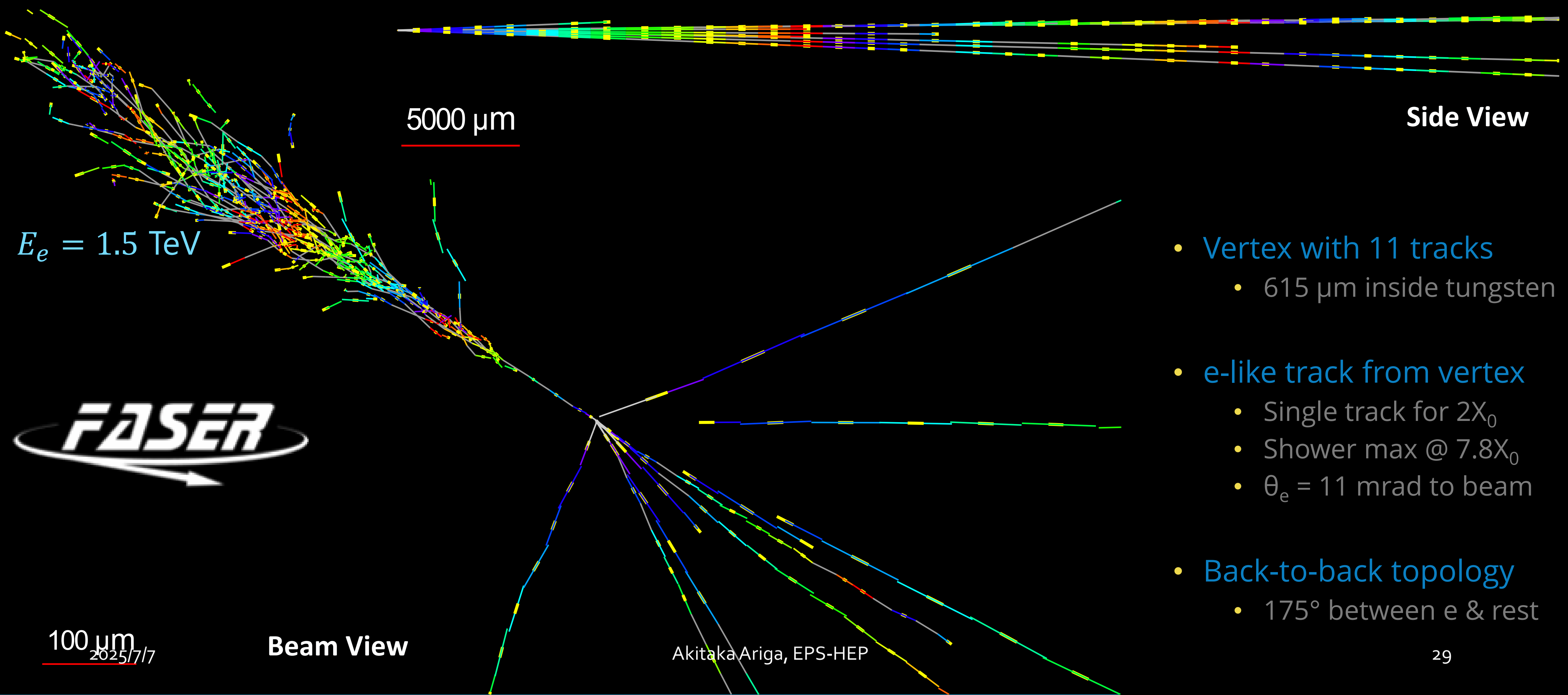
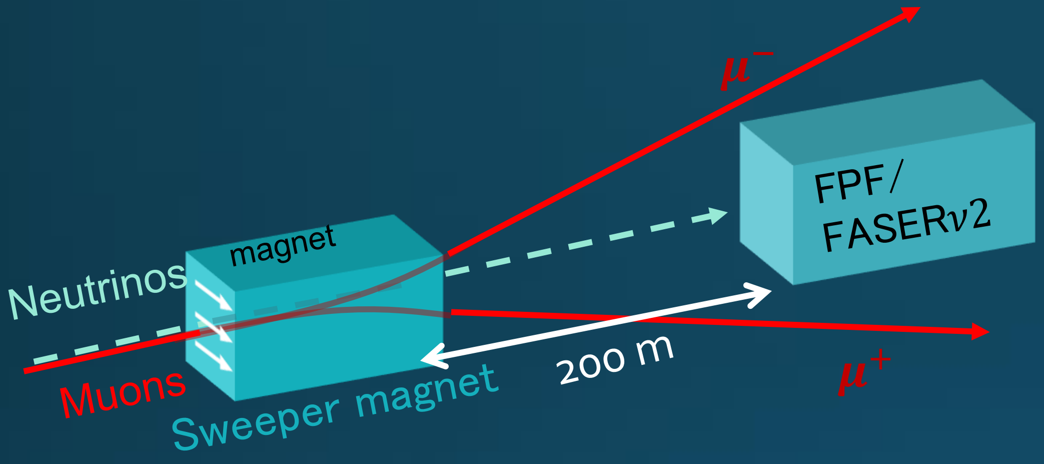
Electron neutrino observation in FASERν

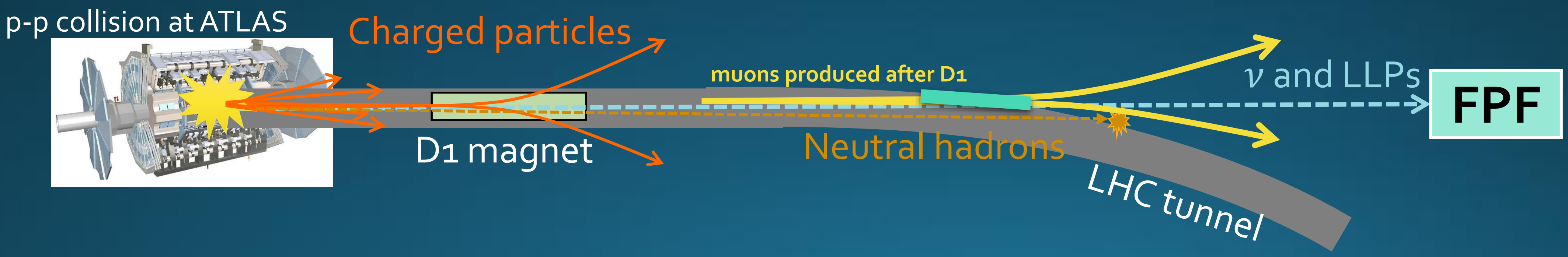
ν_e CC event, "Pika-ν" event



- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest



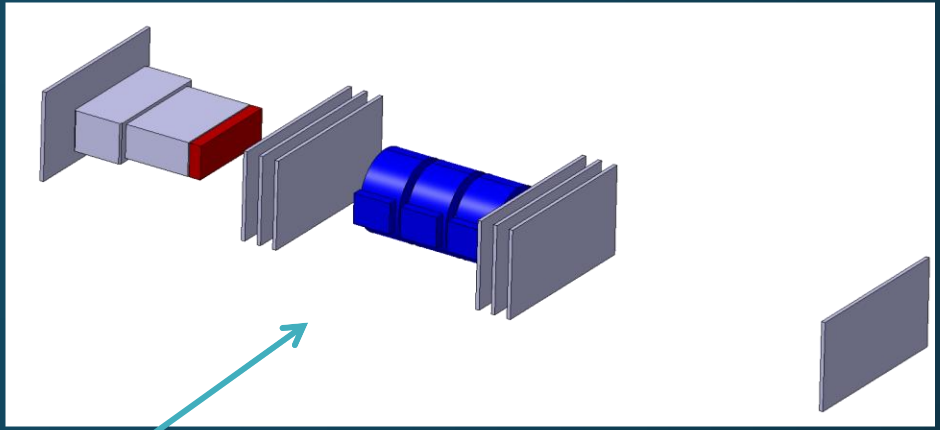
magnet
Neutrinos
Muons
Sweeper magnet
200 m
μ^-
μ^+
FPF/
FASERν2

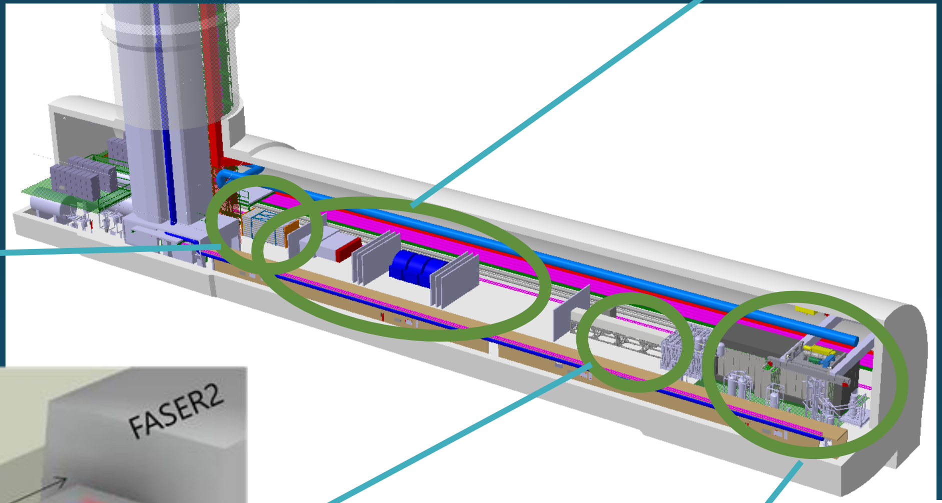


p-p collision at ATLAS
Charged particles
muons produced after D1
ν and LLPs
FPF
D1 magnet
Neutral hadrons
LHC tunnel

FPF detectors

FASER2: Large decay volume and magnetic spectrometer for LLPs

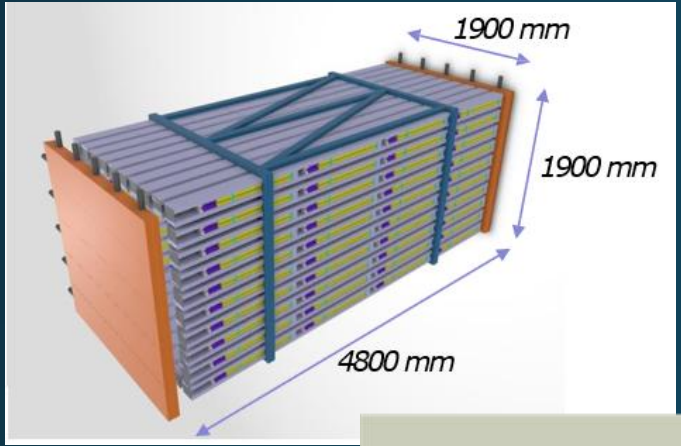




beam

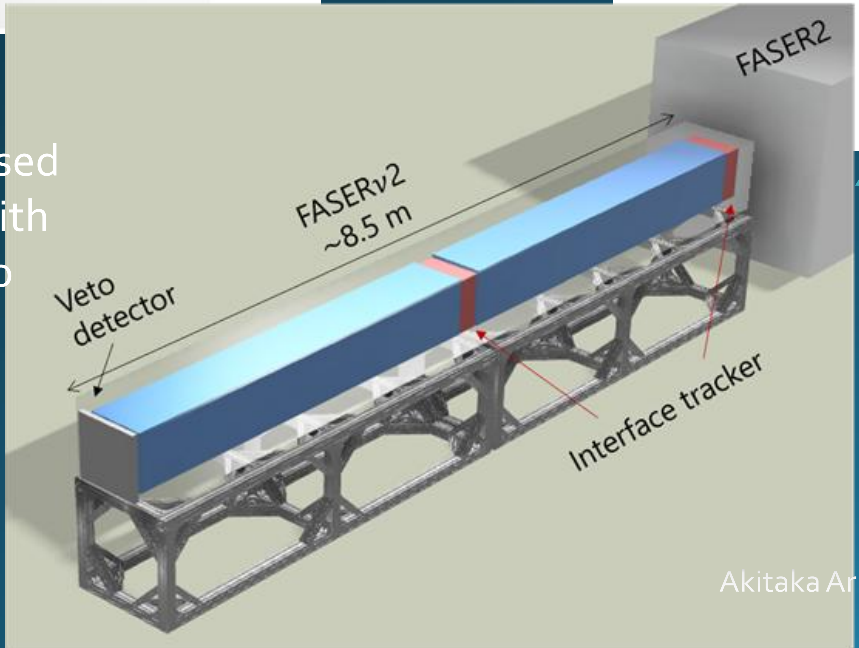
FORMOSA

scintillator array for milli charged particle



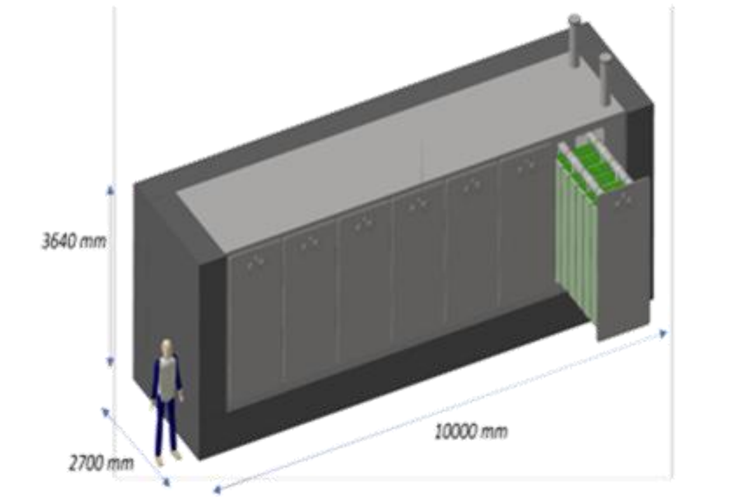
FASERv2

20-ton emulsion-based neutrino detector with interface detector to FASER2



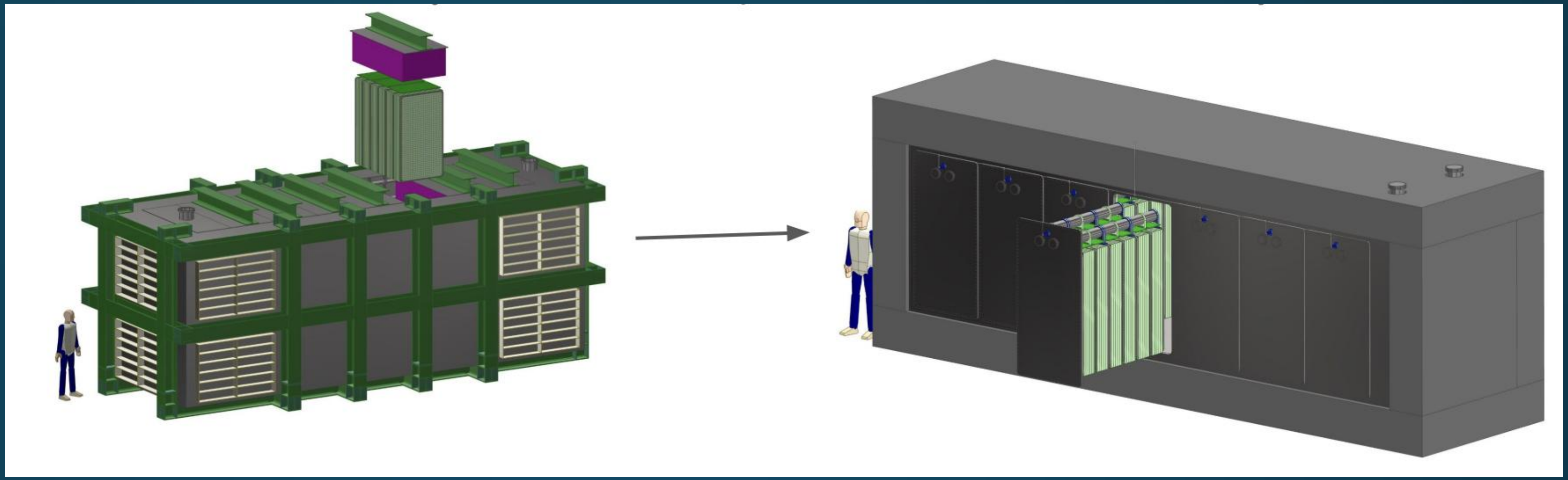
FLArE

100t liquid-Ar neutrino detector
See Milind's talk

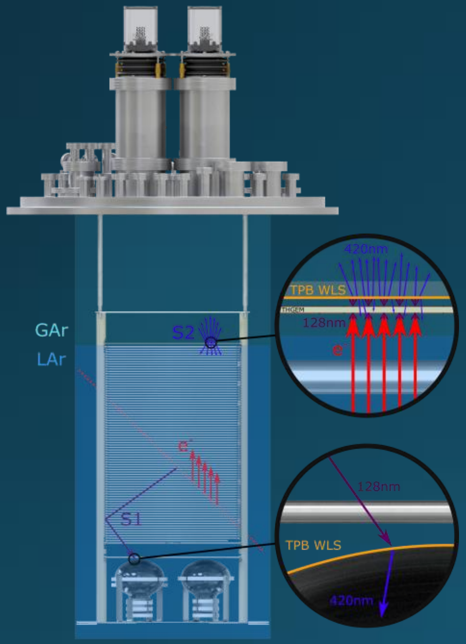


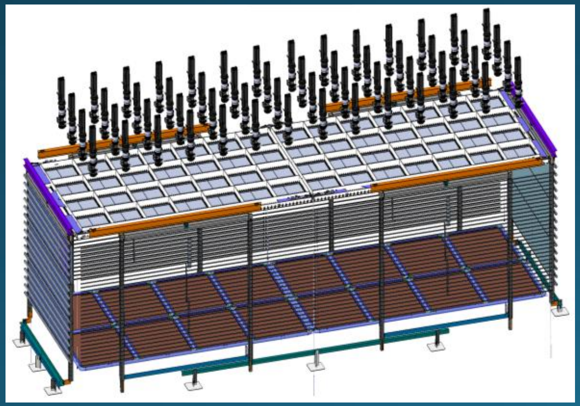
FLArE

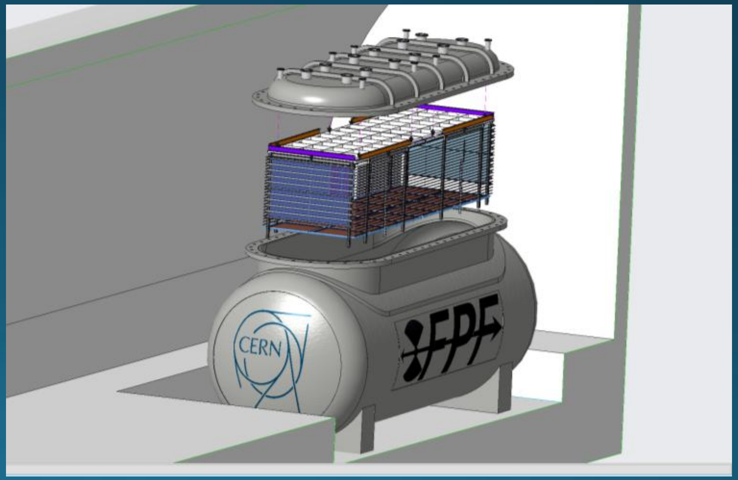
Design evolving considering physics, installation and operation constraints!



- Design changed from TPCs being top-loaded to side-installed “filling cabinet” design



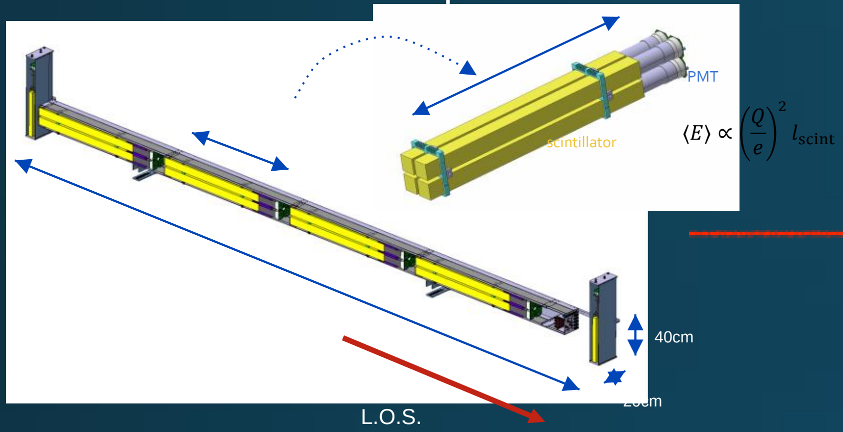




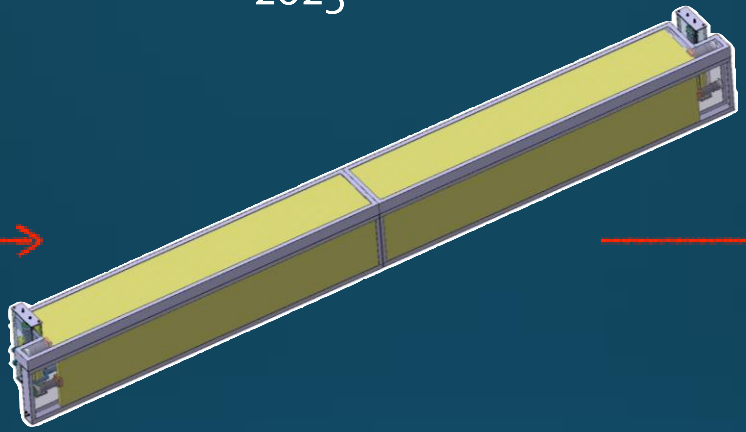
Considering an alternative design using an ARIADNE-style (ARgon ImAging DetectioN chambEr) optical readout

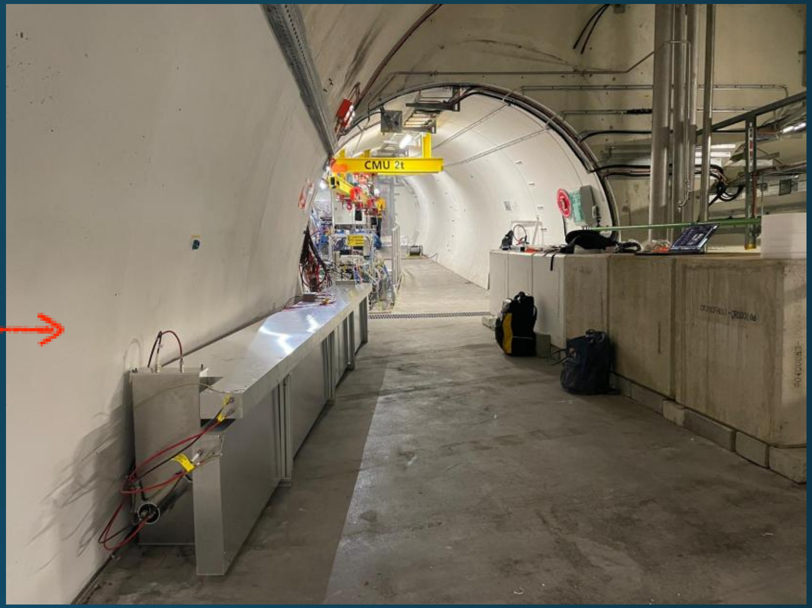
FORMOSA demonstrator, as of 2025

2024



2025

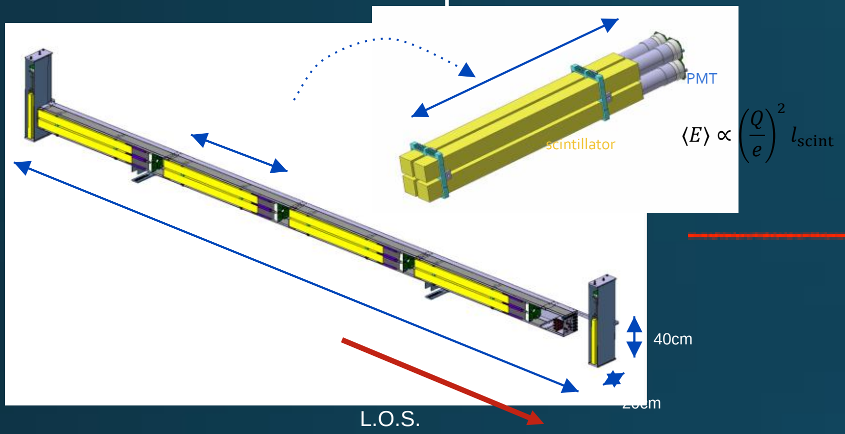




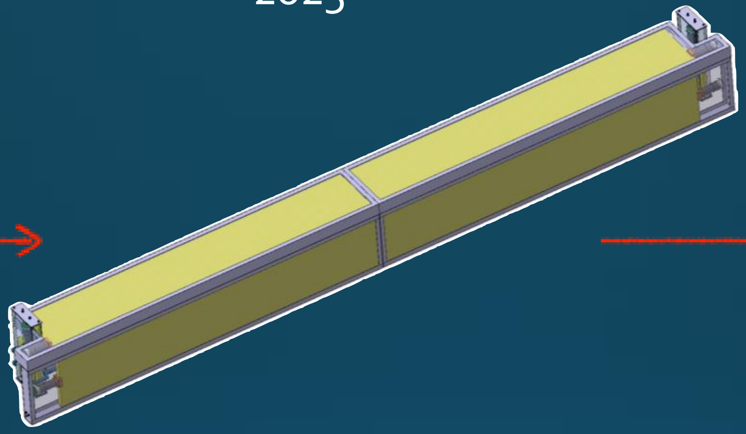
- Small scale prototype of the FPF FORMOSA:
  - The same 16 bars as last year
    - Replacing 4 HV bases (one per layer in the same line-of-sight) as a readout test
  - Same front+back muon panels
  - Hermetic coverage on the LHC-side (to probe radiation) and top (for cosmics)
  - Additional test $CeBr_3$ scintillator module installed
  - Panel between main body and wall installed (to probe for side-showering)

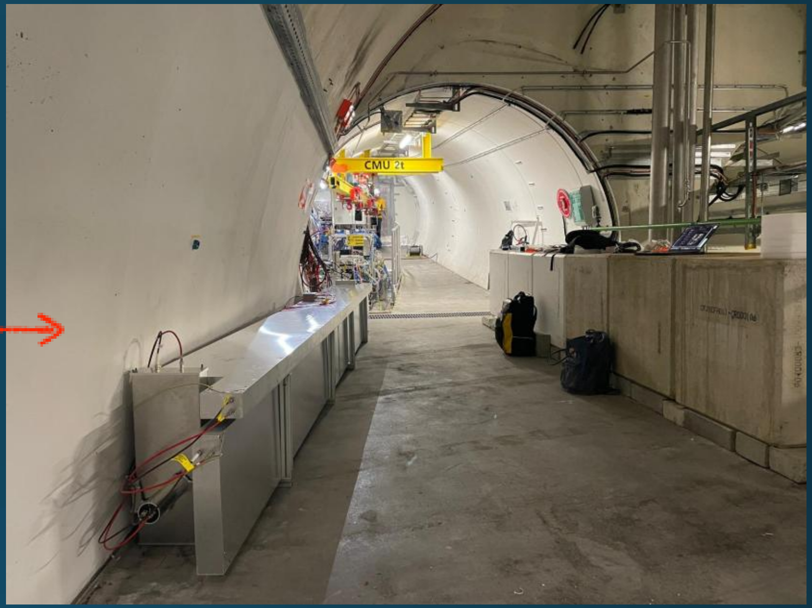
FORMOSA demonstrator, as of 2025

2024



2025





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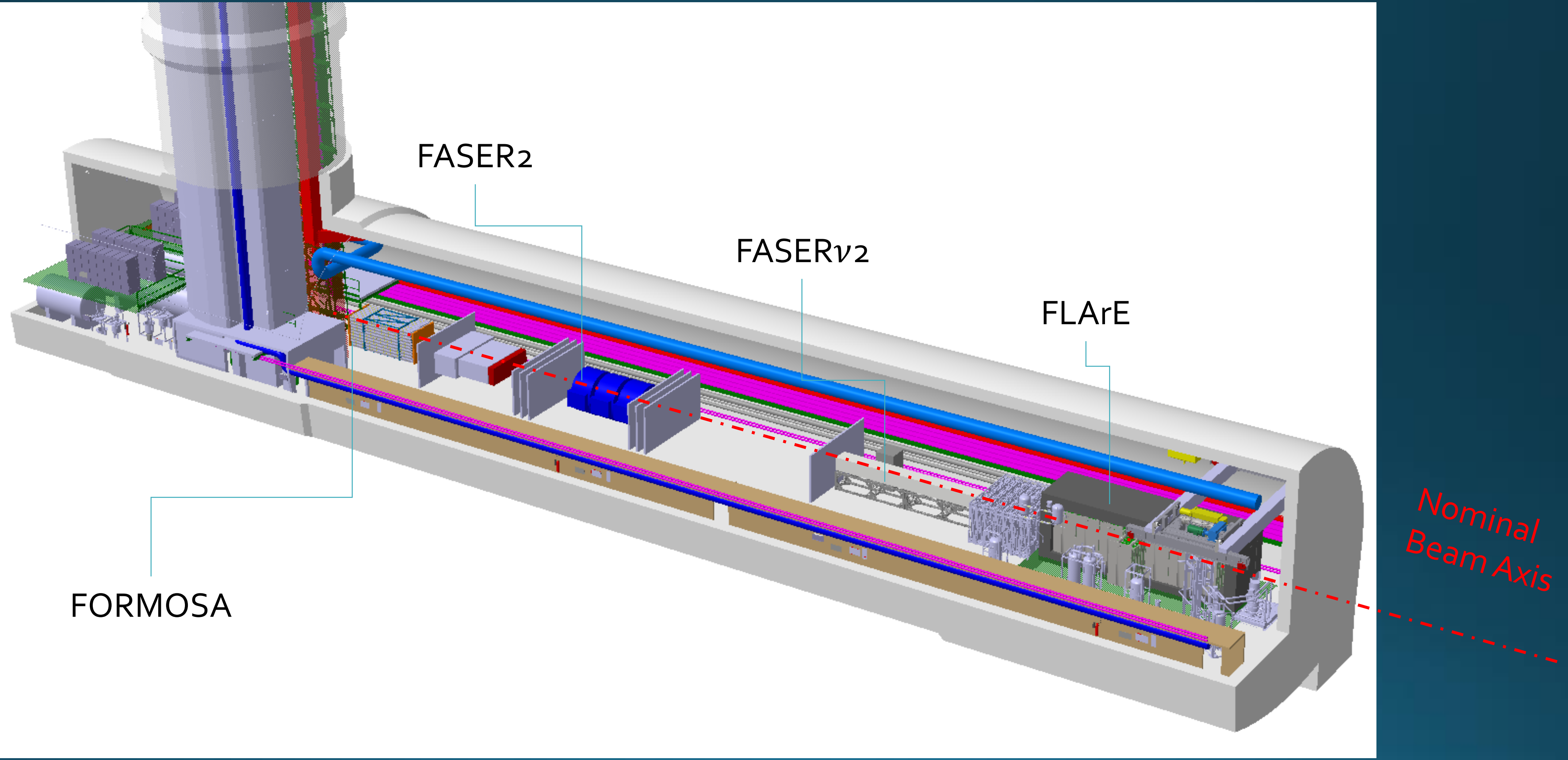
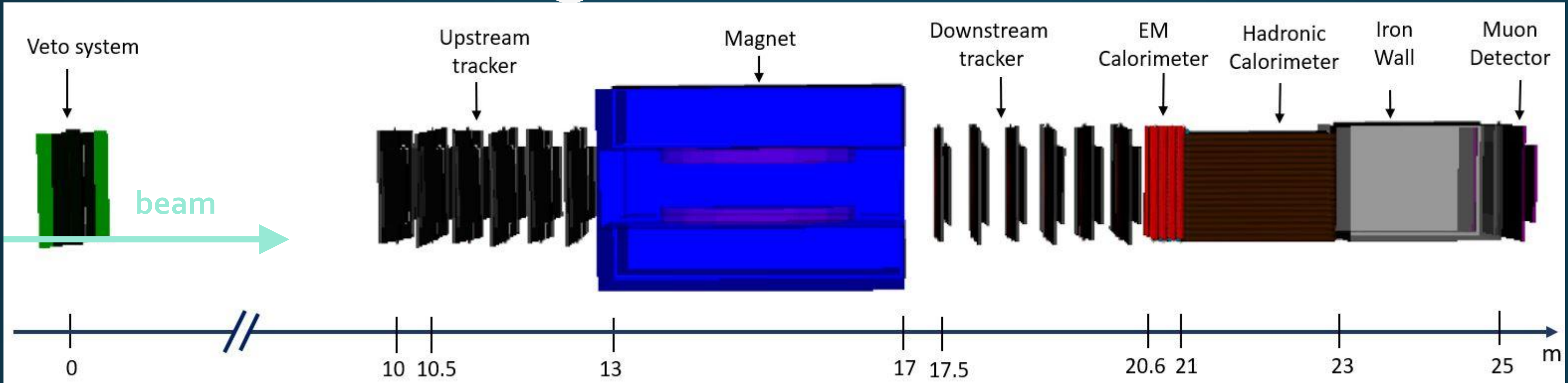
4 proposed FPF experiments, diverse detectors for a broad physics program



FASER2 Design [baseline]



Tracker:

- Based on LHCb's SciFi tracker
- SiPM and scintillating fiber design
- Detector resolution: ~ 100 µm

Magnet:

- Large aperture
- 3m wide X 1m gap (*)
- Superconducting technology
- Magnetic Field : 2 Tm
- Based on the SAMURAI magnet

Calorimeter:

- Based on dual-readout calorimetery
- Spatial resolution: 1-10 mm

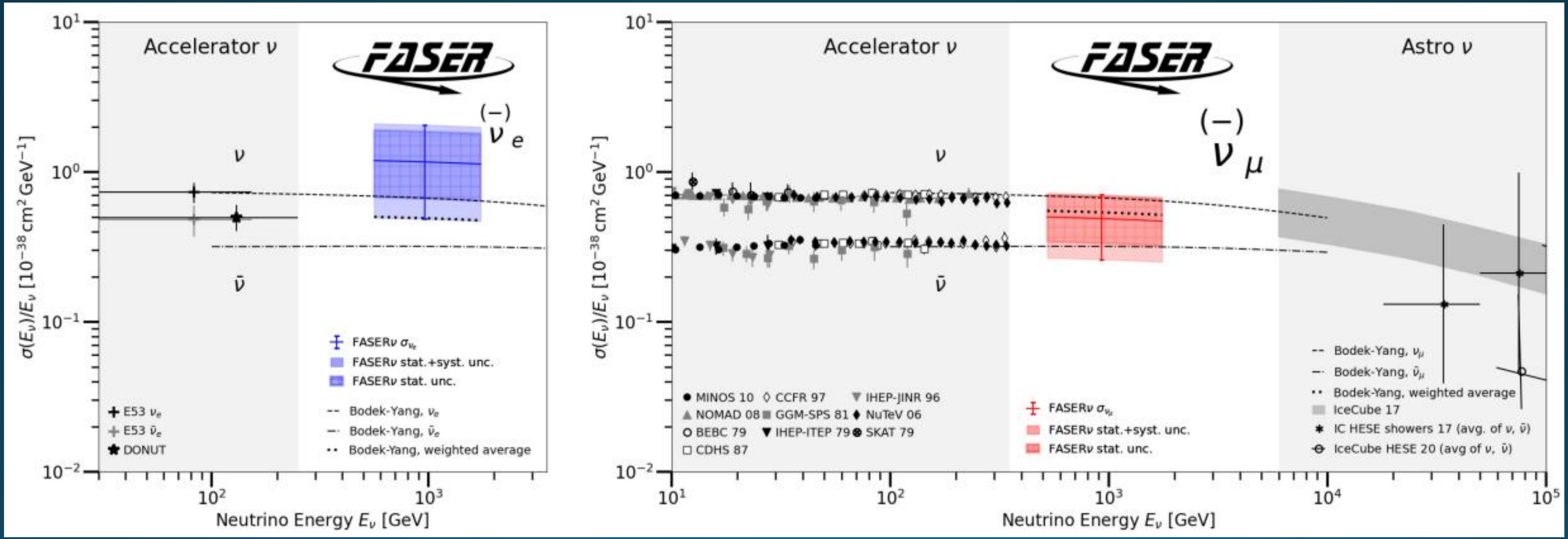
All possible with existing detector technologies

(*) A more square (e.g., 2 m × 1.5 m) aperture is also under consideration, as it improves the acceptance of muons from FLArE by 5-10% without a significant degradation in LLP sensitivity.

First cross section measurements at TeV energies

PhysRevLett.133.021802

4 ν_e and 8 ν_μ observed events with negligible BG, both above 5 σ



Relative measurement wrt theoretical curve.

L=9.5 fb^{-1}, m=128.6 kg