FASER: Recent Results and Prospect (FASER2 & FASERν2)

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University of Washington

DPF FPF Symposium
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References from Jamie Boyd, Josh McFayden (FASER2 Contact), Akitaka Ariga, Tomoko Ariga (FASERν2 contact) and Olivier Salin in FPF7 and PBC Mar 24

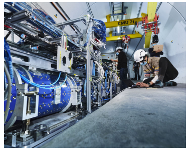
Timeline

Now

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC Run 2				LHC Run 3							LHC Run 4				

FASERν

pilot run



First candidate of collider neutrino
PRD 104, L091101 (2021)

First observation of collider neutrinos
PRL 131 (2023) 3, 031801

First measurements of collider ν_e & ν_μ
arXiv:2403.12520

(talk by Ali Garabaglu)

Dark Photon search
PLB 848 (2024) 138378

Axial-like particles search
CONF-2024-001

(talk by Ansh Desai)

Timeline

Now

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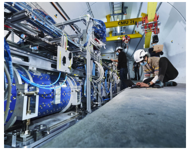
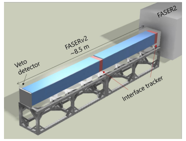
FASERν pilot run



2203.05090 (Snowmass)

PBC review

LOI **TDR**



Data taking

First candidate of collider neutrino
PRD 104, L091101 (2021)

First observation of collider neutrinos
PRL 131 (2023) 3, 031801

First measurements of collider ν_e & ν_μ
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(talk by Ali Garabaglu)

Precision neutrino measurements, ν_τ , lepton flavor universality, etc.

Dark Photon search
PLB 848 (2024) 138378

Axial-like particles search
CONF-2024-001

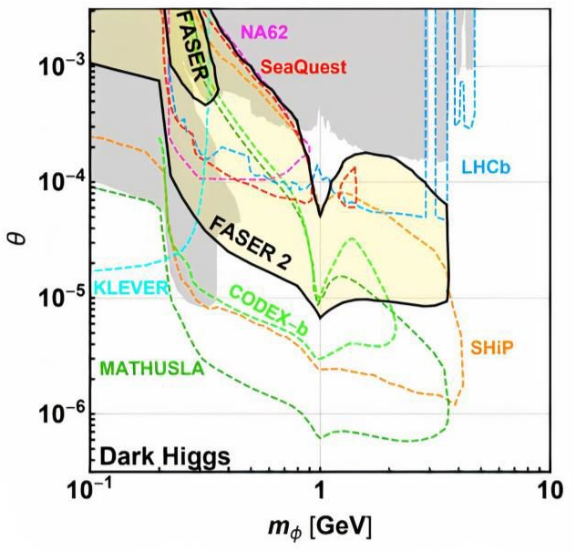
(talk by Ansh Desai)

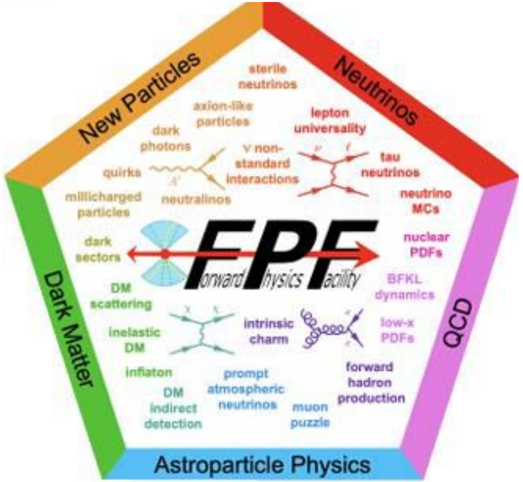
Comprehensive Long-lived particle search

Broad Physics Program

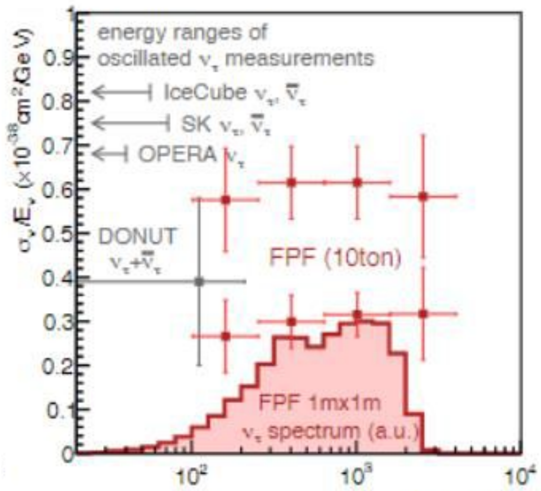
- Beyond Standard Model Physics
  - Dark photon, Dark Higgs, ALP, Heavy Neutral Leptons
    (Talk by Alec Hewitt, Misa Toman, Roshan Mammen Abraham)

- Standard Model Physics
  - Neutrino factories, PDF
  - studies 10^3−10^4 ν_τ interactions
    (Talk by Max Fieg, Jesus Miguel Celestino, Diego Lopez Gutierrez)



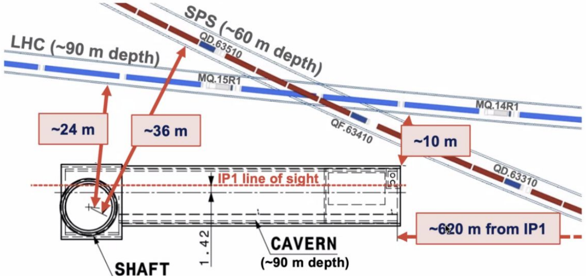


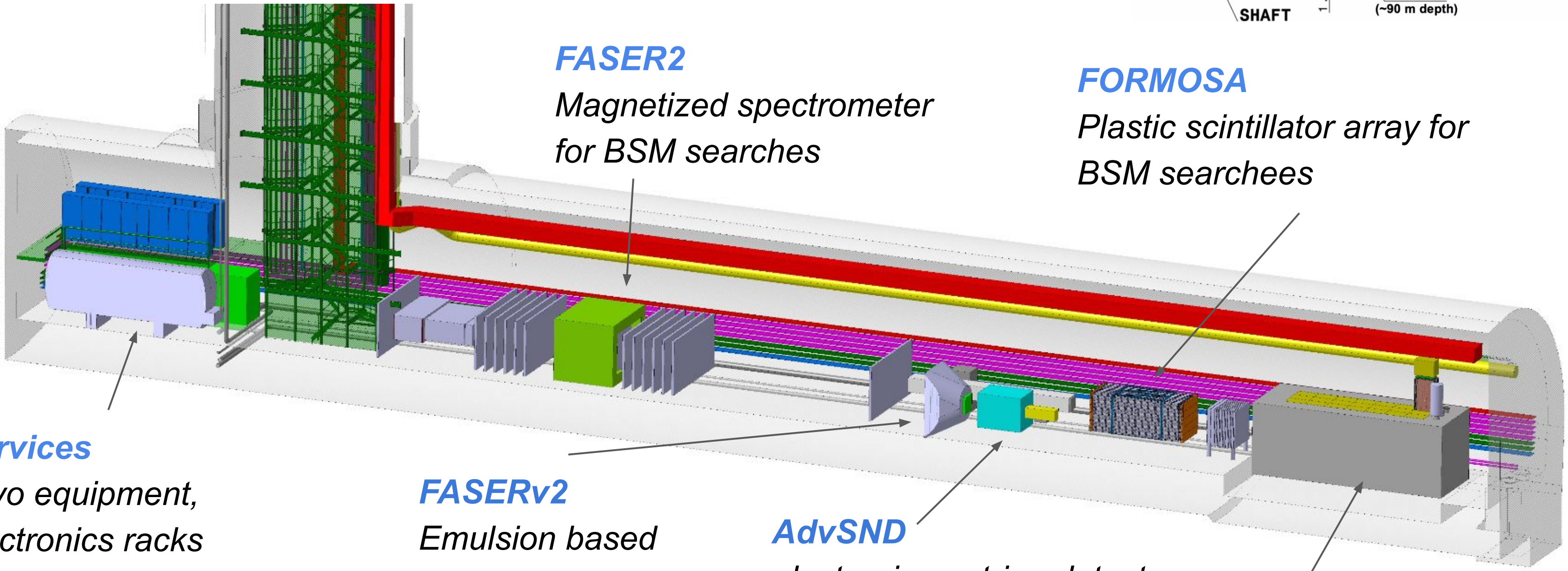
https://arxiv.org/abs/2203.05090
(Snowmass 2021)



Statistical error only

Experiments in **F**orward **P**hysics **F**acility





FASER2
Magnetized spectrometer for BSM searches

FORMOSA
Plastic scintillator array for BSM searchees

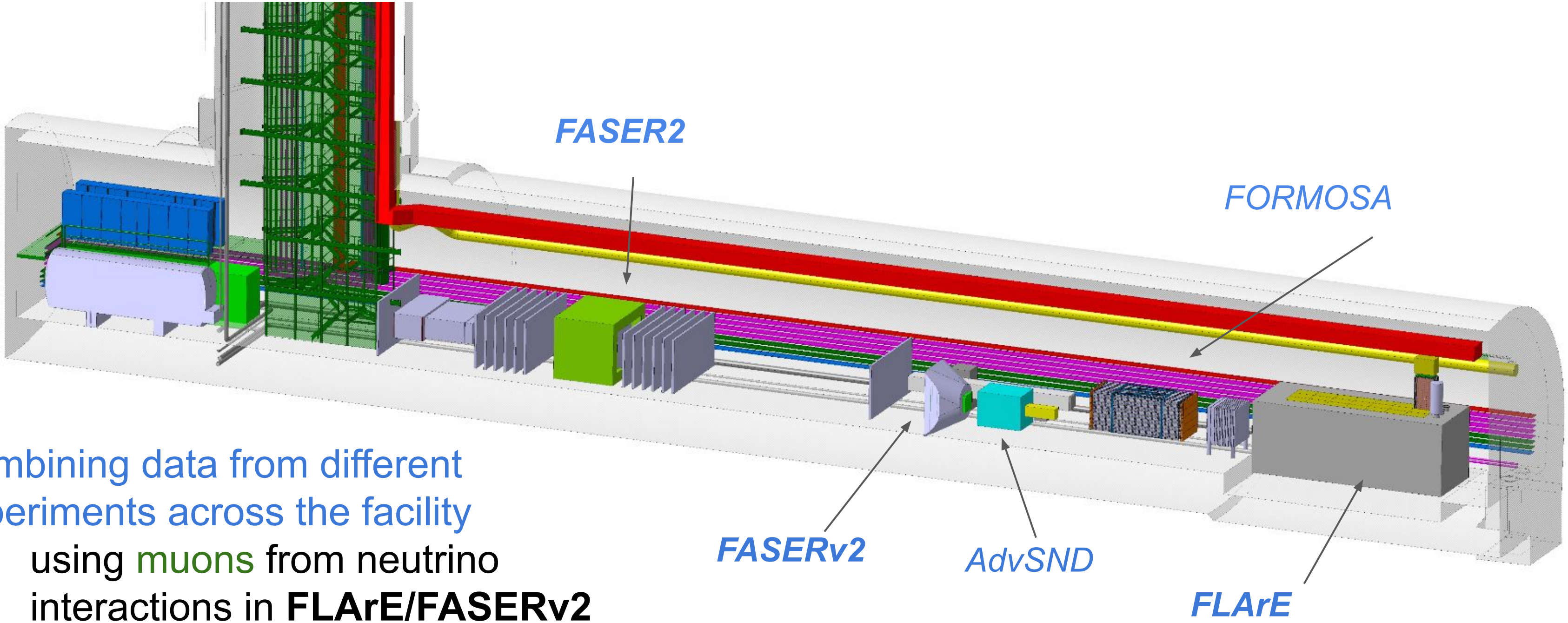
Services
Cryo equipment, electronics racks etc…

FASERv2
Emulsion based neutrino detector

AdvSND
electronic neutrino detector (Consider in TI18 while reserving space for it.)

FLArE
LAr based neutrino detector

Optimal experimental configuration

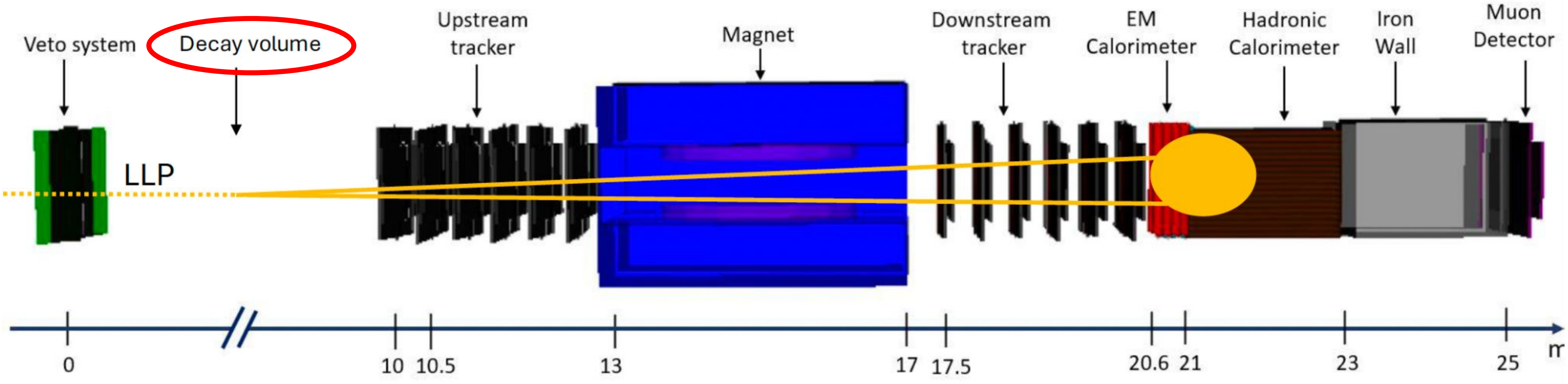


Combining data from different experiments across the facility

- using muons from neutrino interactions in **FLArE/FASERv2** measured in the **FASER2** spectrometer.

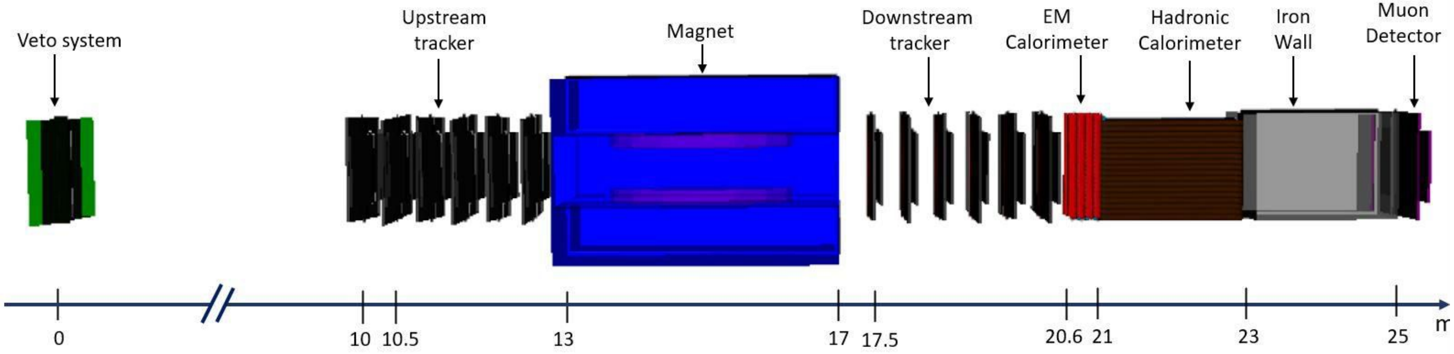
FASER2

FASER2 baseline detector



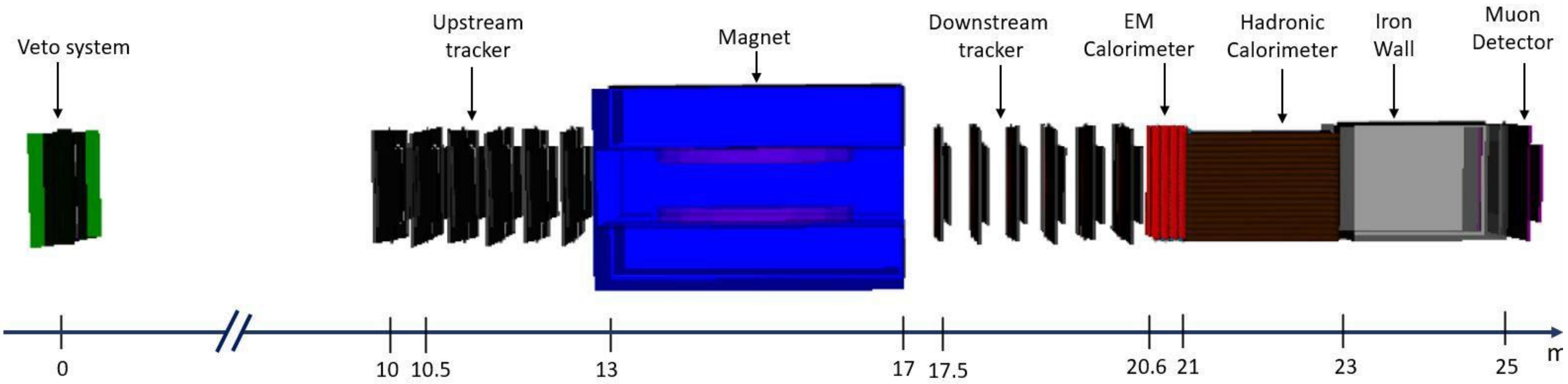
- **Decay volume ~650X**
  - from 0.03 m^2x 1.5 m (FASER) to ~3 m^2 x 10 m (FASERν)

FASER2 baseline detector: general consideration



- **Detector Requirement and Performance**
  - Maintain high physics sensitivity for a variety of physics benchmarks.
- **Motivation for Detector Design with** less granularity and magnetic field at the edge
  - Near Line of Sight (LOS): particles are highly boosted (around 1 TeV),
  - At 1m from LOS: significant reduction in boost
- **Motivation for Square-Shaped Detector:**
  - Muon background increases with distance from LOS in the horizontal plane
  - A square-shaped detector (e.g., 1.7m x 1.7m) is preferred over rectangular shapes (e.g., 3m x 1m)

FASER2 baseline detector



Tracker:

- Based on LHCb's SciFi tracker
- SiPM and scintillating fiber design
- Detector resolution: ~80 μm

Magnet:

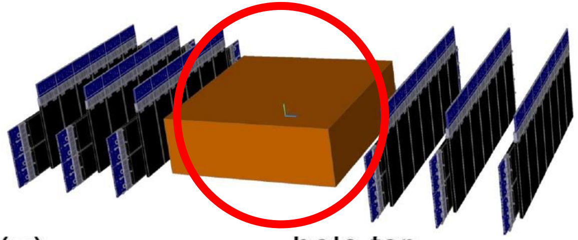
- Based on the SAMURAI style
- Large aperture
- 3m wide x 1m gap
- Superconducting technology
- Magnetic Field : 2-4 Tm

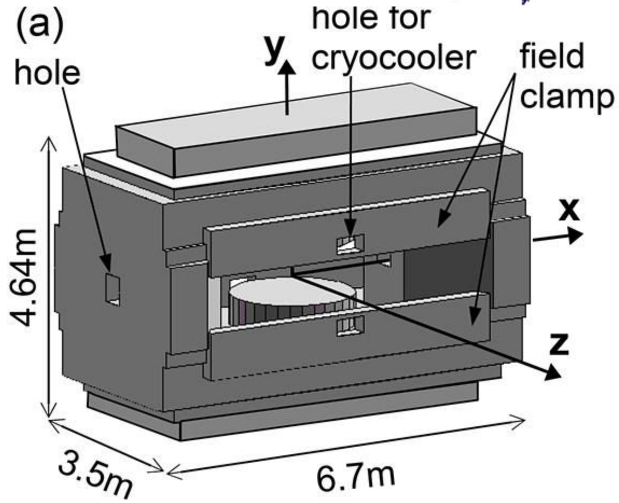
Calorimeter:

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

FASER2 Magnet: SAMURAI style magnet

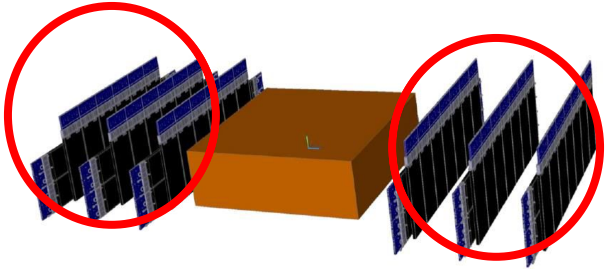
- Based on SAMURAI
  - **Dimension**: 3m wide X 1m gap X 4m along LOS
  - **Integrated field**: 4 Tm
  - **Stored energy:** 7 MJ
  - **Power consumption:** 36.2 kW
  - **Superconducting:** Cryogenic infrastructure needed
- On going study to optimise magnet design:
  - Reduce field strength: 2 Tm
  - Enlarging pole gap to 2 m with reduced width



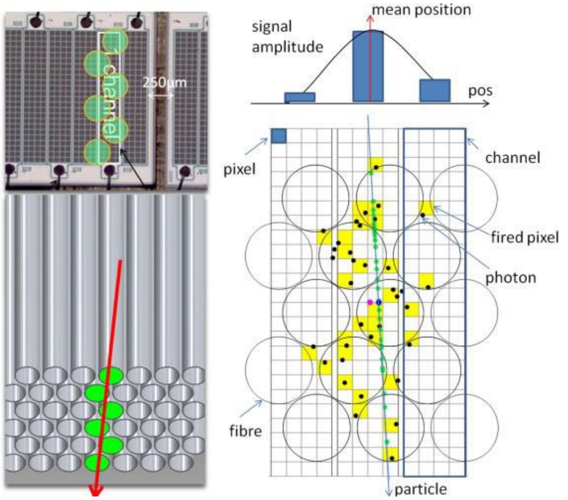


SAMURAI Magnet
made by

FASER2 Tracker: SciFi Technology



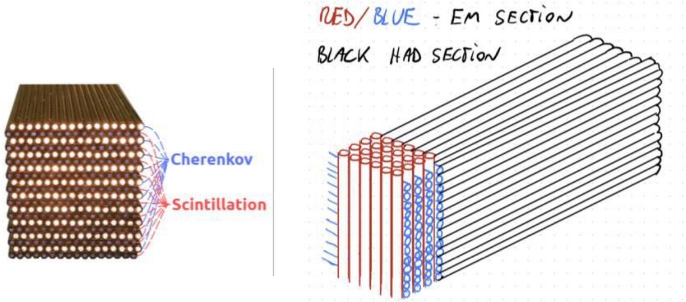
- Based on SciFi detector installed in LHCb in LS2
  - SiPM + Scintillating fiberdesign
  - Resolution ~ 80 μm (fibers diameter 250 μm)
- FASER2 tracking station layout
  - Active area of 3m X 1m
  - Composed of vertical and horizontal fiber layers
  - Stations relatively rotated e.g angle of 1°
- Cost could be reduced by utilizing LHCb, e.g. tooling or available modules

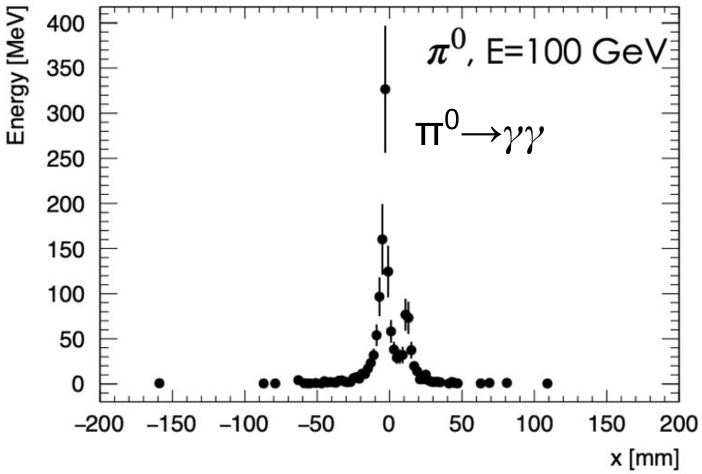


FASER2 Calorimeter: Dual-readout technology

- Design based on dual readout calorimeter prototype
  - Prototypes for Higgs factory detector
  - EM prototype and HiDRa prototype (INFN)
- FASER2 calorimeter design:
  - Fiber diameter 1 mm, 2 mm brass collar
  - Spatial resolution: ~ 5 mm
  - Less granular for outer regions of the detector to reduce number of channels
  - EM energy resolution:

$$\frac{\sigma}{E} = \frac{14.5\%}{\sqrt{E}} + 0.1\%$$

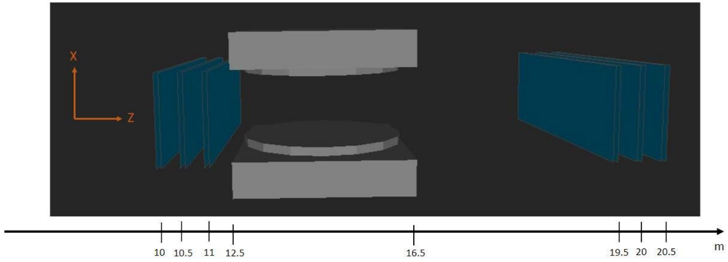


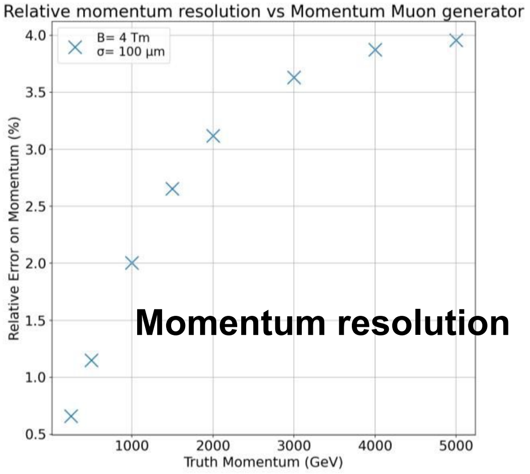


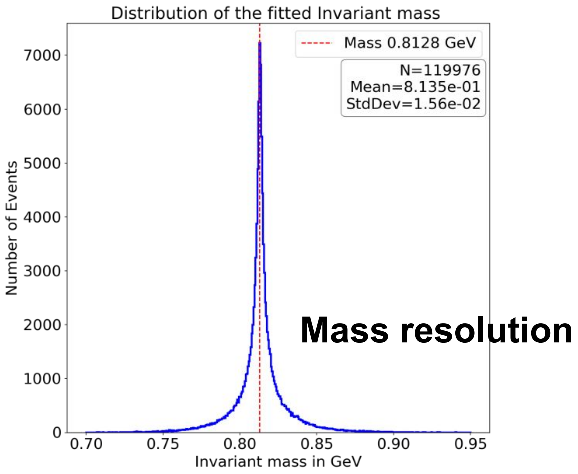
Tracking Performance based on ACTS

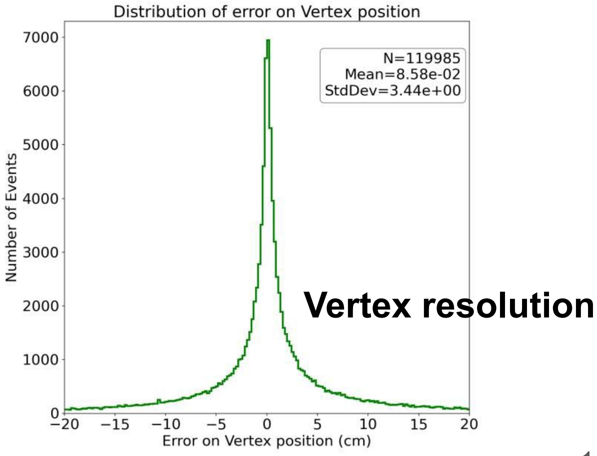
Hypothesis for ACTS implementation:

- Homogeneous material and accurate X0
- Tracker resolution digitized as 100 μm
- Constant magnetic field within the magnet volume
- Truth track finding algorithm







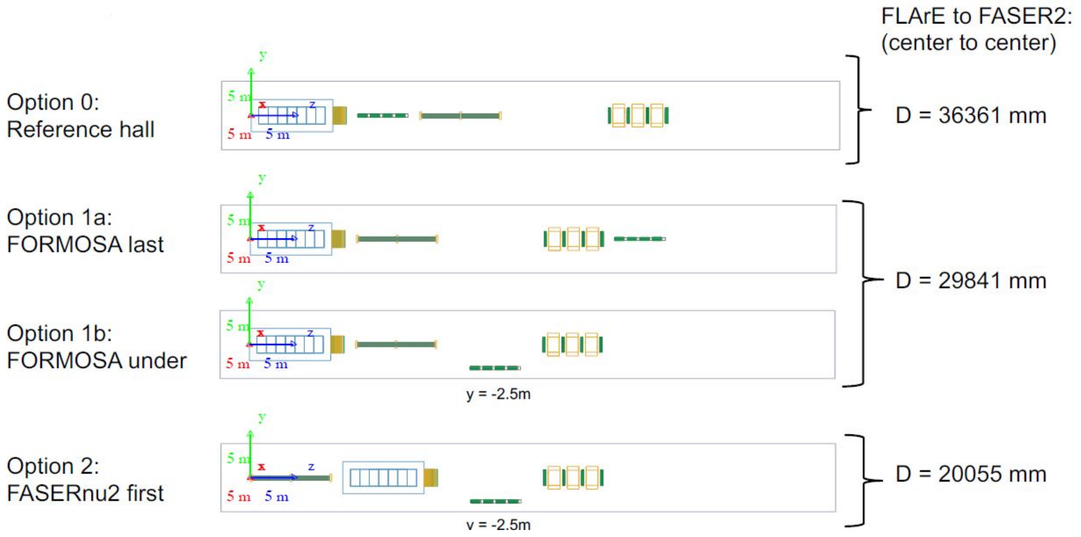


FASER2 muon acceptance from FLArE

Muon from neutrino interaction in FLArE simulated in detailed Geant4 simulation

To maximise the muon acceptance from FLArE(and FASERnu2) into FASER2

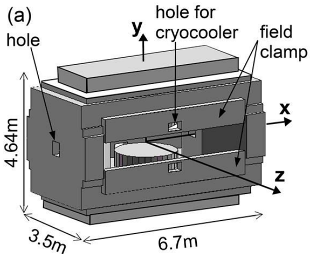
- Minimising distance between FASER2 and FLArE
- Increasing the pole gap of the SAMURAI magnet option is prefered



d	SAMURAI 1 m gap x 3 m	SAMURAI 1.5 m gap x 2 m
37 m	40 %	51%
30 m	45%	56%
17 m	60%	71%

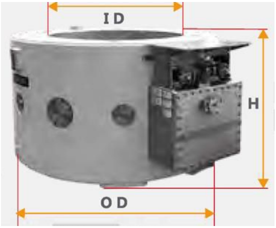
Alternative Technology

Magnet



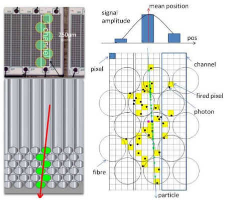
SAMURAI

TESLA Electronics (UK)

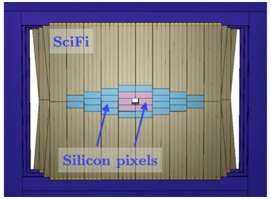


Toshiba (Japan)

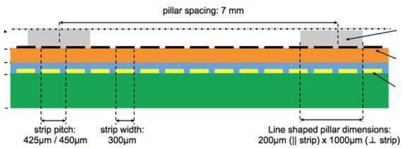
Tracker



SciFi

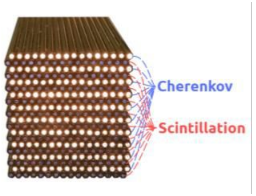


LHCb Run5 Mighty pixel

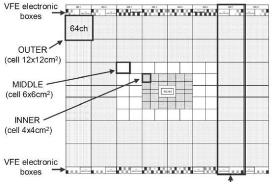


ATLAS Micro Megas

Calorimeter

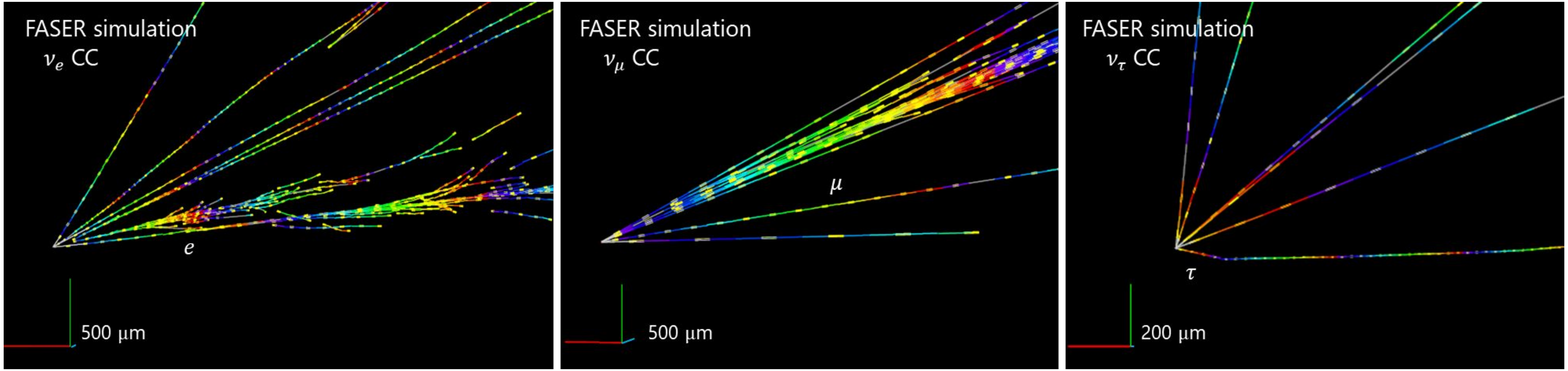


Dual-readout



Reuse LHCb preshower

FASERν2


FASER simulation
ν_e CC
e
500 μm
FASER simulation
ν_μ CC
μ
500 μm
FASER simulation
ν_τ CC
τ
200 μm

FASERν and FASERν2: expected number of events

F. Kling and L.J. Nevay, "Forward Neutrino Fluxes at the LHC", Phys. Rev. D 104, 113008 (2021)
J.L. Feng et al., "The Forward Physics Facility at the High-Luminosity LHC, 2023 JPGNPP 50 030501

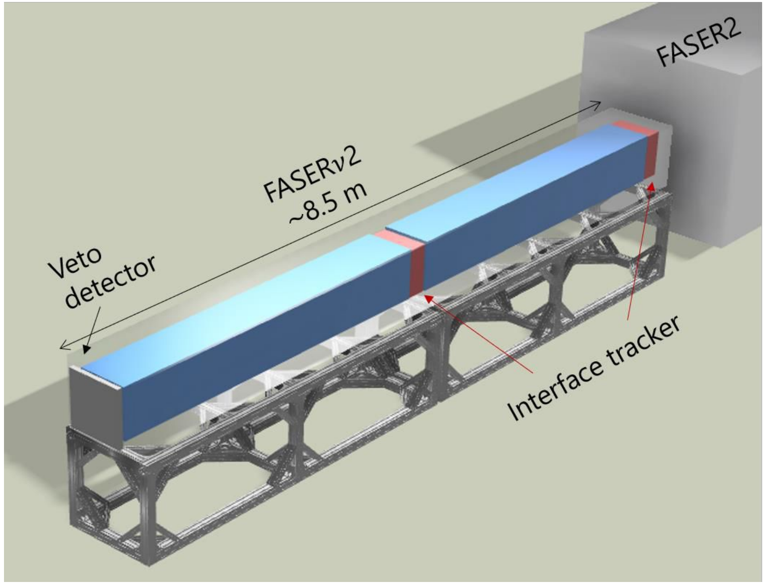
(ν int. rate estimated using **Sibyll 2.3d**) (**DPMJET 3.2017**)

			$\nu_e+\overline{\nu_e}$ CC	$\nu_\mu+\overline{\nu_\mu}$ CC	$\nu_\tau+\overline{\nu_\tau}$ CC		$\nu_e+\overline{\nu_e}$ CC	$\nu_\mu+\overline{\nu_\mu}$ CC	$\nu_\tau+\overline{\nu_\tau}$ CC
FASERν (1.1 tons, 150 fb^{-1})	**ν int.**		**0.9k**	**4.8k**	**15**		**3.5k**	**7.1k**	**97**
	ν int. with charm		~0.1k	~0.5k	~2		~0.4k	~0.7k	~10
	ν int. with beauty		-	~0.05	-		-	~0.1	-
FASERν2 (20 tons, 3 ab^{-1})	**ν int.**		**178k**	**943k**	**2.3k**		**668k**	**1400k**	**20k**
	ν int. with charm		~20k	~90k	~0.2k		~70k	~100k	~2k
	ν int. with beauty		~2	~10	~0.02		~7	~10	~0.2

20x target mass **10x** recorded data → **200x** more neutrinos

Status of FASERν2 tasks

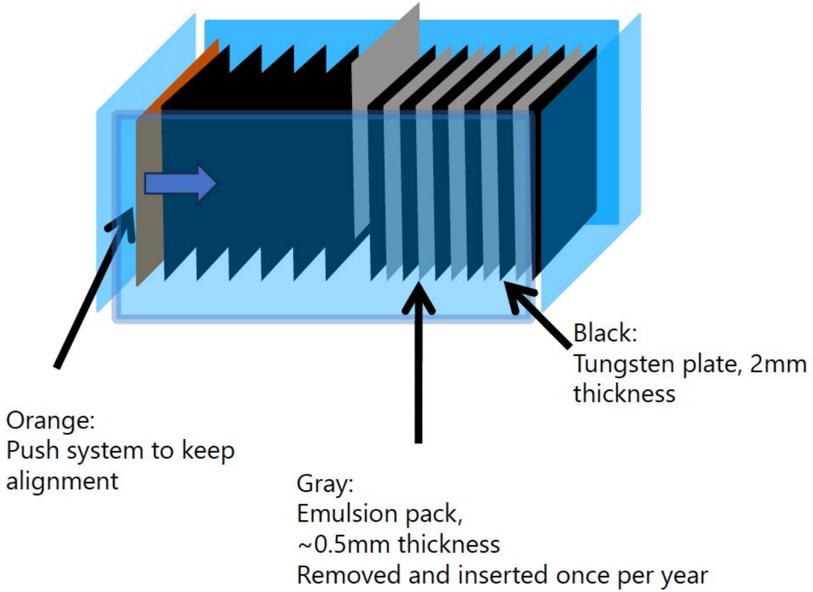
- **Emulsion films** performance tests
- **Tungsten target**
    - 2-mm-thick tungsten plates to reduce number of films
- **Mechanical structure, assembly method, cooling system**
- **Emulsion readout system**
    - 2nd facility in Chiba University in addition to Nagoya University
- **Veto, interface tracker and charge ID**



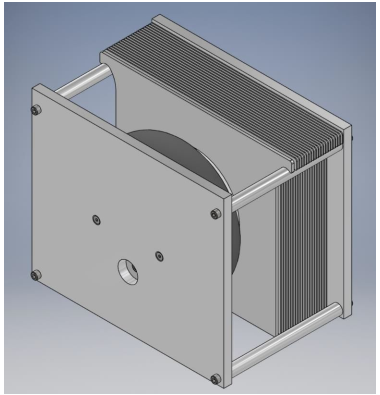
Detector assembling on site

- FASERν assembly (10 days) + transport (1day) approach is **NOT** scalable!
- Idea: Keep the box and tungsten plates always underground, but exchange films only

3 m, 10-tonboxes, 1650 layers per box



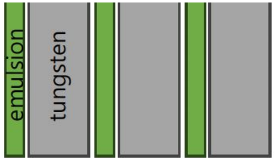
6kg Steel plates x 20



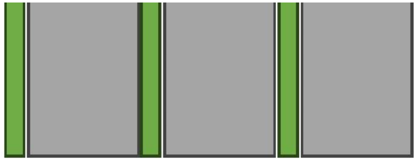
Prototype production / test in Spring –Summer 2024

2 mm thickness films in the FASERνdata

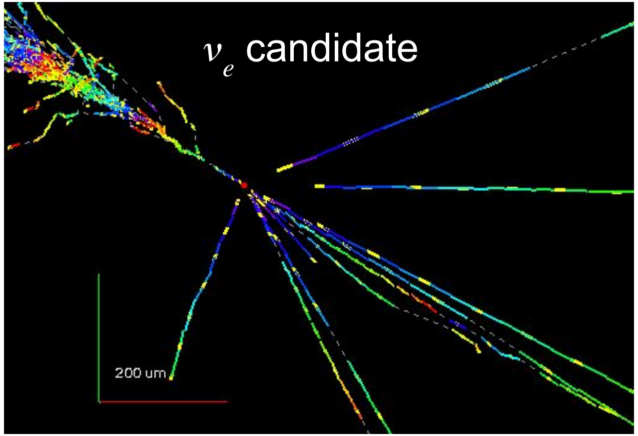
- Reduce the emulsion cost (2M CHF/year→1M CHF/year).

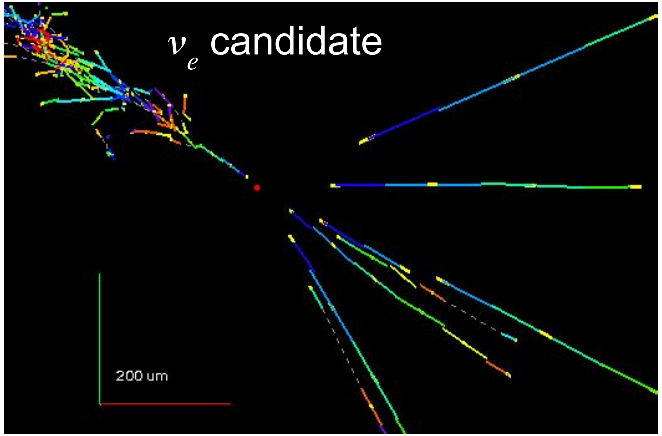


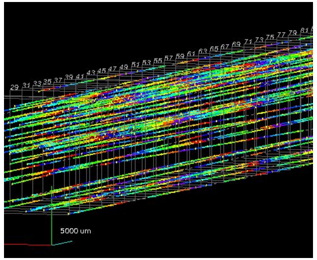
FASERν, 1.1 mm thick



FASERν2, 2 mm thick



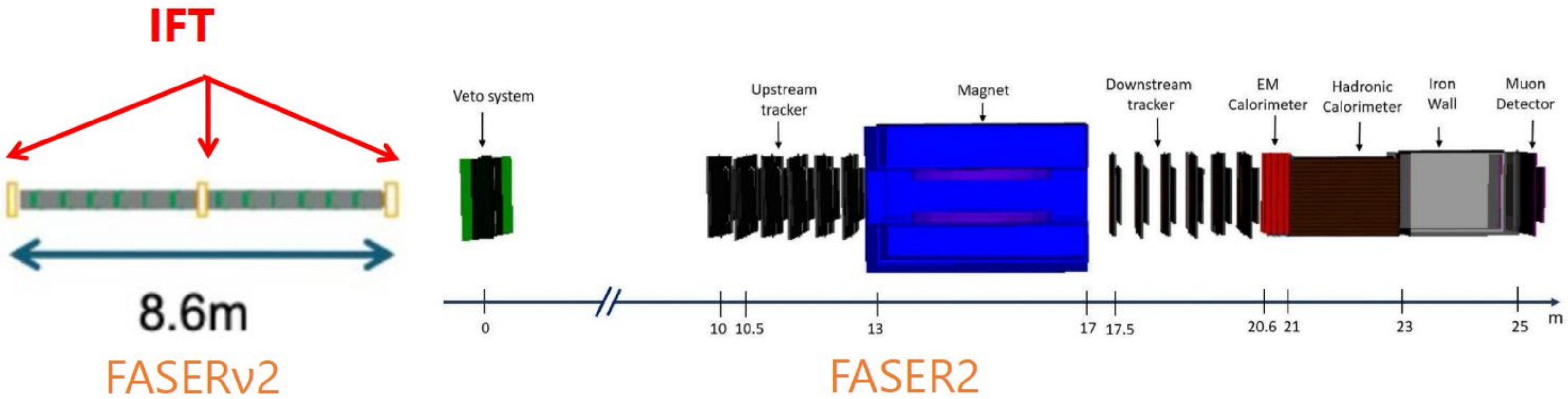




Bkg (~$10^5\,\mu/cm^2$)

Interface Tracker (IFT)

- Goal: Identify charge of muons $\nu_\mu, \nu_\tau \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$
  - Interface FASERν2 and FASER2
  - Three technical options are currently considered: SciFi, Gaseous, Silicon Strip



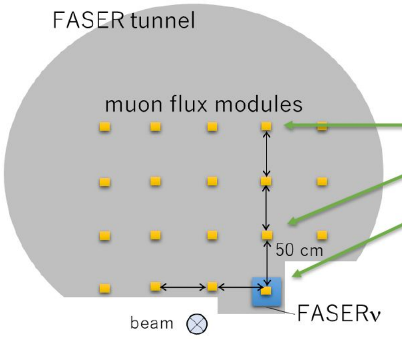
Summary

- FASER2 increases ~650x FASER decay volume
  - Magnet: Finalize transverse shape of magnet with SAMURAI (baseline) and alternatives as well as considering acceptance of muons from neutrinos
  - Tracker: Assess suite of possible tracker technologies SciF (baseline) and alternatives
  - Calorimeter: Design and costing from existing prototype
- FASERν2 aims ~200× FASER ν interaction statistics
  - Long term performance test with Test Beam 2023 (also TB 2024)
  - Prototypes to test assembling scheme
  - Reconstruction with reduced segmentation demonstrated
  - Choice of interface detector
- Work toward the PBC document (summer 2024)
  - Physics studies with benchmark models to assess detector performances
  - Detector options with more or less cost/complexity

Backup

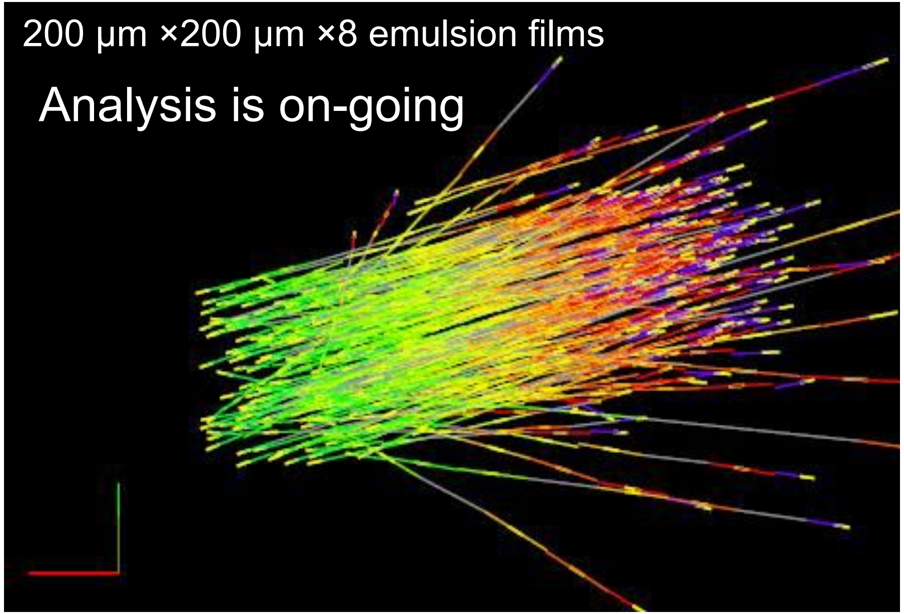
Muon flux map measurement

To validate the FLUKA/BDSIM simulations, emulsion data were collected in the region ~2 m from the LOS



FASERν preliminary

	track density (/cm²/fb⁻¹) (within 10 mrad from the peak)
height=150 cm	5.1×10^4
height=50 cm	1.5×10^4
height=0 cm	1.0×10^4
FASERν 1st module	1.2×10^4



19 small emulsion detectors

9.5 fb^{-1} , July-Sep 2022

Contents

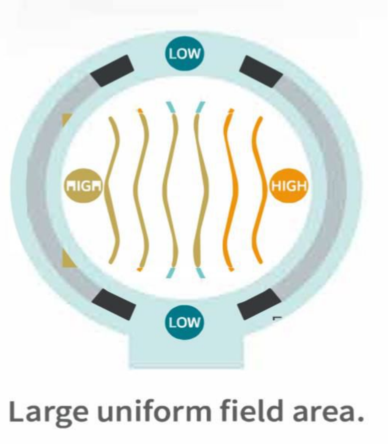
- FASER2 physics studies and detector performance documentation in preparation
  - Requirement for the detector
  - Summarise performance studies
  - Sensitivity plots, Track reconstruction, neutrino acceptance
  - Benchmark detectors performances comparison
- Basis of our input for PBC document (summer 2024) and FPFLoI

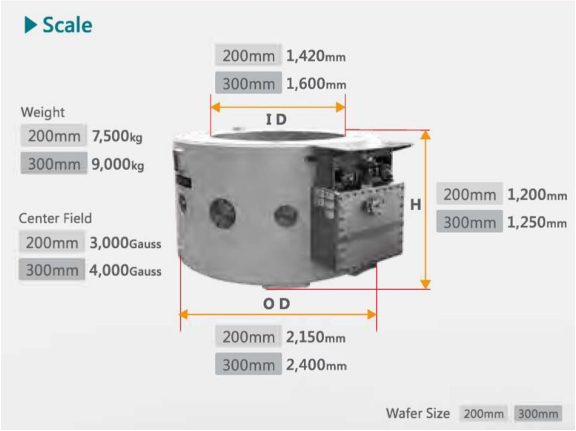
FASER2 Alternative design: Crystal puller magnet

Possibility to use off-the-shelf crystal puller magnets with similar sensitivity to SAMURAI

1. Both of those Industrial Crystal puller magnet:Central field of 0.4 - 0.5 T
2. Can be chained together to have increased integrated magnetic field
3. Aperture diameter of 1.6 m (up to 2 m)
4. **Advantages**:Off the shelf, no R&D needed, cryo system integrated into design

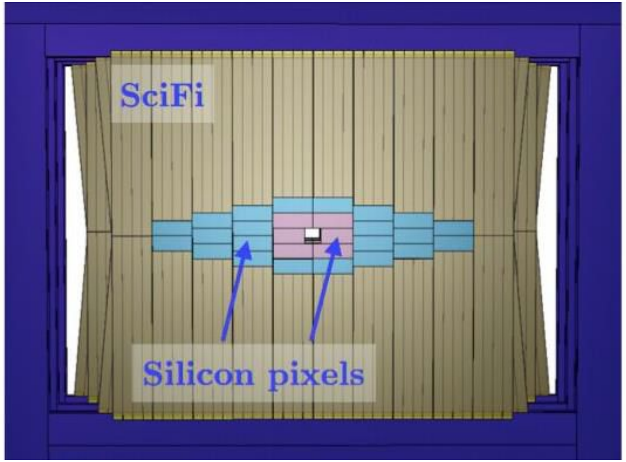
- **TESLA Electronics (UK)**
- **Toshiba (Japan)**



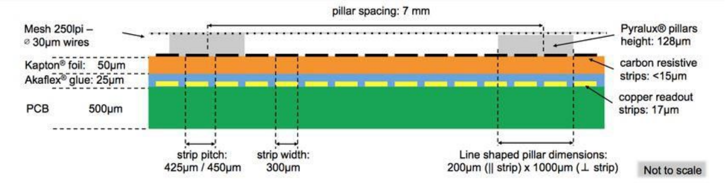


FASER2 Alternative design:Tracker proposals

- **Pixel Mighty tracker (LHCb Run 5)**
  - Mighty pixels modules in central region of tracking layers
  - Achieve better resolution on layer before magnets ~ 50 μm
  - Better separation for close-by tracks in central region



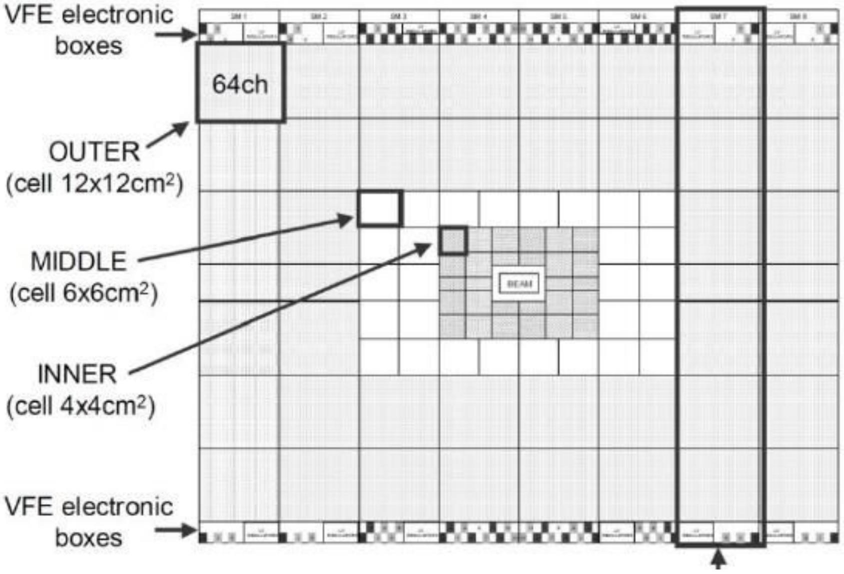
- **Gaseous trackers**
  - MPDG tracker option for FASER2:ATLAS Micro Megas, CMS GEM, μ-RWELL
  - Less than 1 MCHF for 10 layers
  - Less than 1 MCHF for the electronics
  - For MGTD option discussion within RD51 collaboration
  - Studies needed for reconstruction of closely separated tracks



ATLAS Micro Megas

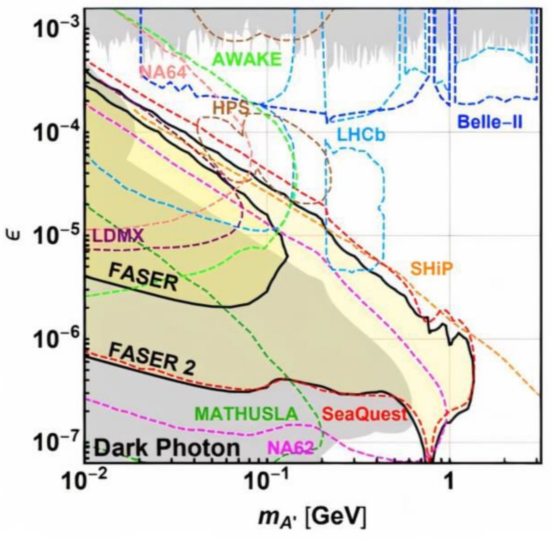
FASER2 Alternative design: LHCb preshower

- Possibility to reuse old LHCb Preshower and Scintillating Pad Detector for part of the FASER2 calorimeter (outer region of the calorimeter)
- Considerable possible cost saving
- Simulation studies in progress to investigate feasibility and performance

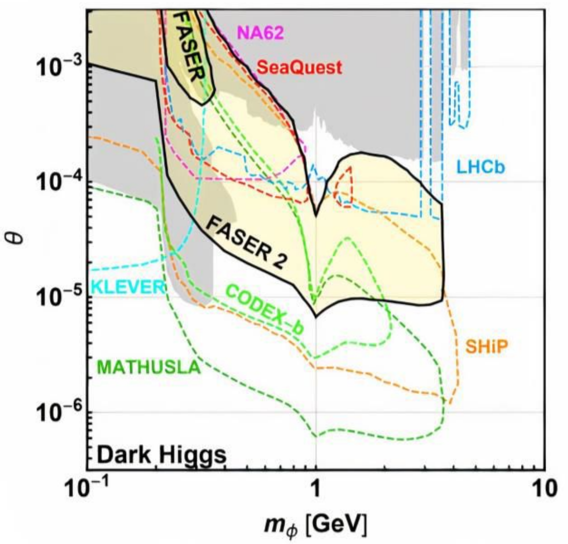


FASER2 BSM Physics

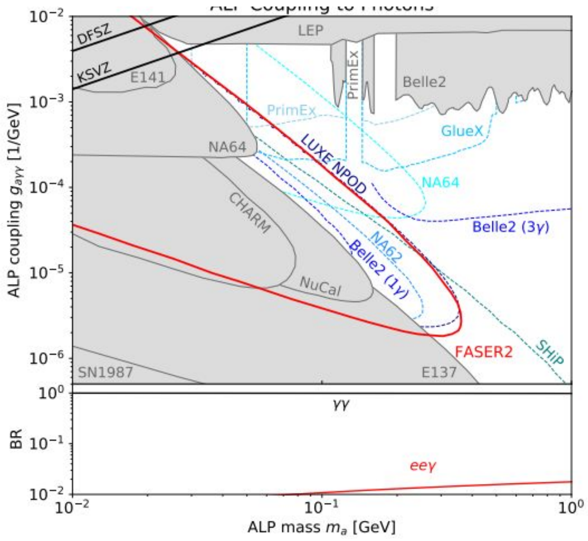
Dark Photons



Dark Higgs

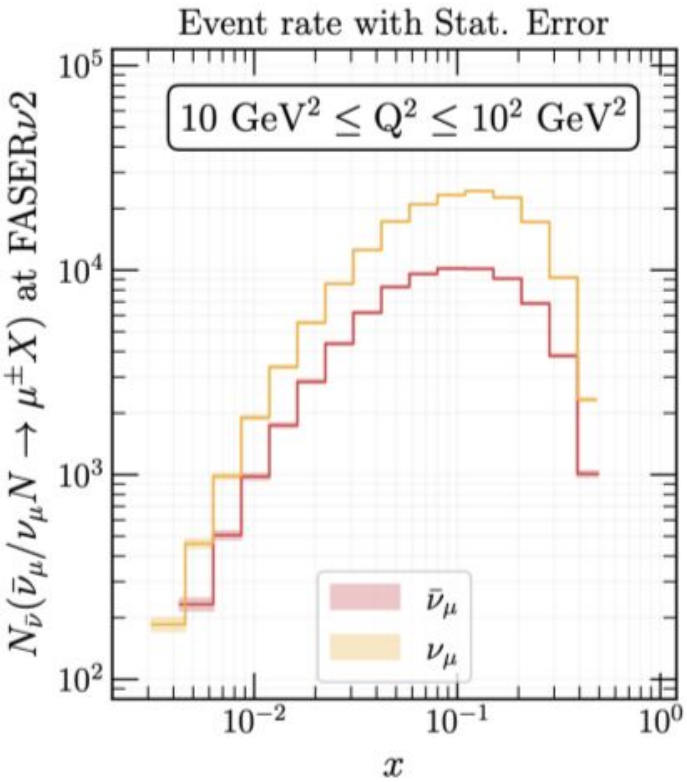


Axion-Like particles

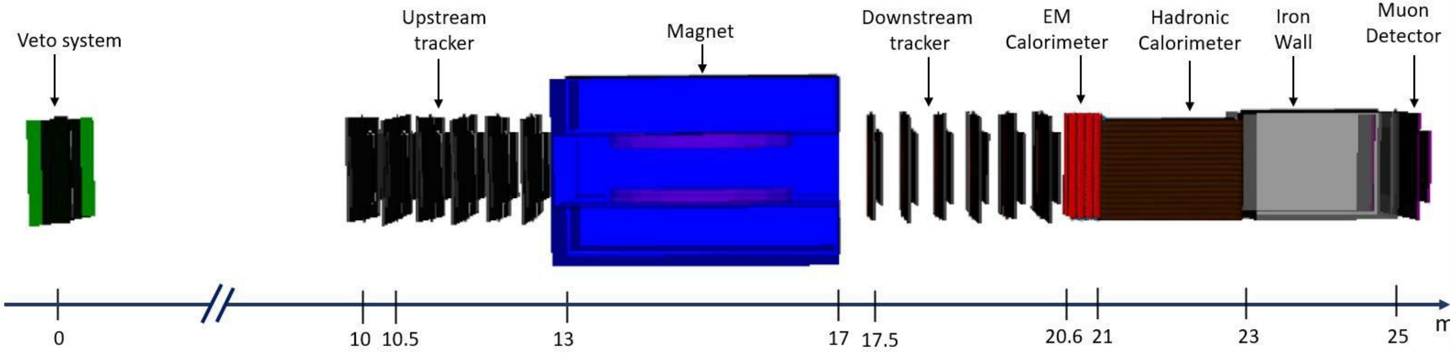


FASER2 SM Physics

Main spectrometer to neutrino experiments for the FPF (FLArE, FASERnu2)



FASER2 baseline detector: costing



- Previous costing estimation in the region of 20 MCHF
  - Cost mainly driven by magnet quotation (10 MCHF)
- Overall cost could be significantly lower than original estimate
  - Updated quotes for magnet is closer to 5 MCHF
  - Investigation for reduced complexity for tracker and calorimeter

Cost

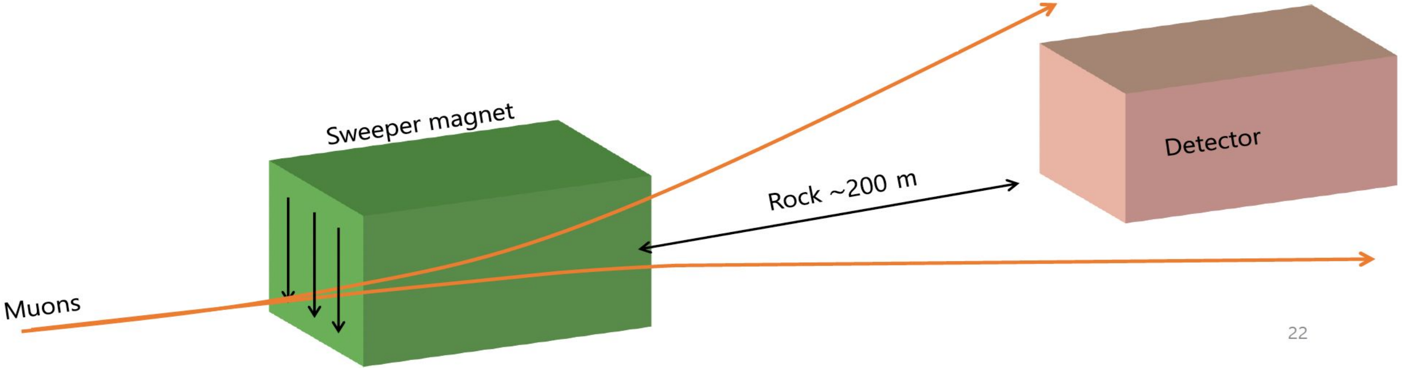
Construction 4.7M CHF. Emulsion 1M CHF/years

Item	Cost (kCHF)	How many years	Sub-total	Comments
Fixed costs				
Tungsten	2000		2000	2-mm-thick 40x40 cm^2, 3300 plates +10%
Emulsion readout	1700		1700	
Expert of the readout system	500		500	
Veto / interface detectors	200		200	
Support structure	400		400	
Cooling system	100		100	
Annual cost				
Emulsion	1000	10	10000	40x40 cm^2, 3300 films
Chemicals for development	50	10	500	
Personnel for scanning	50	10	500	
Total			15900	

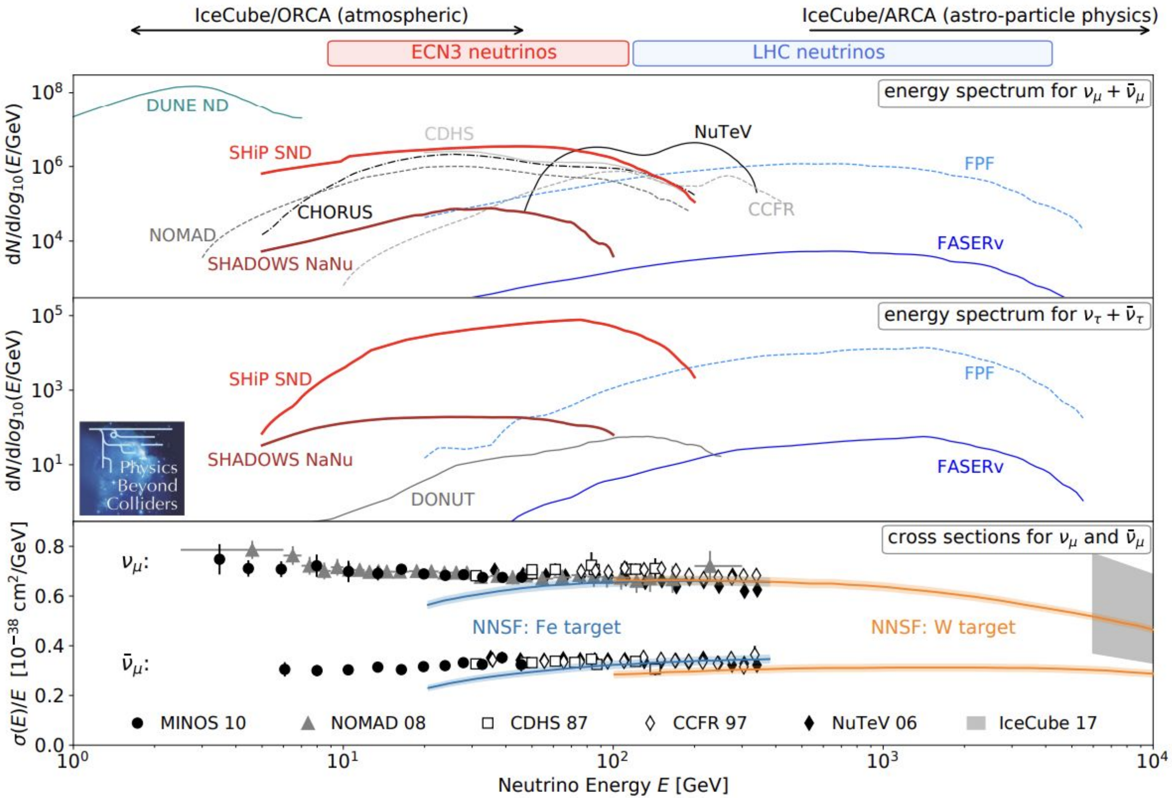
Sweeper magnet to reduce BG muons

To increase the duration of data taking with a FASERν2 detector, a reduction of muon rate is vital

- Maximum track density in emulsion should be kept below ~5x10^5 tracks/cm^2 2 months without muon reduction
- Install a sweeper magnet upstream to reduce the muon flux
- Previous studies by CERN FLUKA team showed a pessimistic result
- Further effort is needed! Simulation studies with BDSim or others



ECN3 decision now made to move forward with SHiP



Other related talks in DPF

- Anesh Desai New Physics at FASER (May 13)
- Ali Garabaglu FASER Neutrino (May 14)
- Alec Hewitt Heavy Neutral Leptons with FASER2 (May 14)
- Max Fieg Neutrino-Ion Collider for PDF with FASER/SND/FPF (May 14)
- Jesus Miguel Celestino FASERnu/nu2 nuon-unitarity of leptonic mixing matrix (May 15)
- Diego Lopez Gutierrez Tau trident in DUNE and FASER (May 16)
- Misa Toman Dark photon Spin correlation at FASER (May16)
- Roshan Mammen Abraham Probing muon g-2 with FASER2 (May 16)

FASER2 Contact: Jamie Boyd, Josh McFayden
https://twiki.cern.ch/twiki/bin/view/FASER/FASER2
FASERnu2 contact: Akitaka Ariga, Tomoko Ariga

FPF7 Feb 29-Mar 1 2024 https://indico.cern.ch/event/1358966/
PBC Mar 25-27 2024 https://indico.cern.ch/event/1369776/
FASER2 https://indico.cern.ch/category/16035/
FASERnu2 https://indico.cern.ch/category/16945/