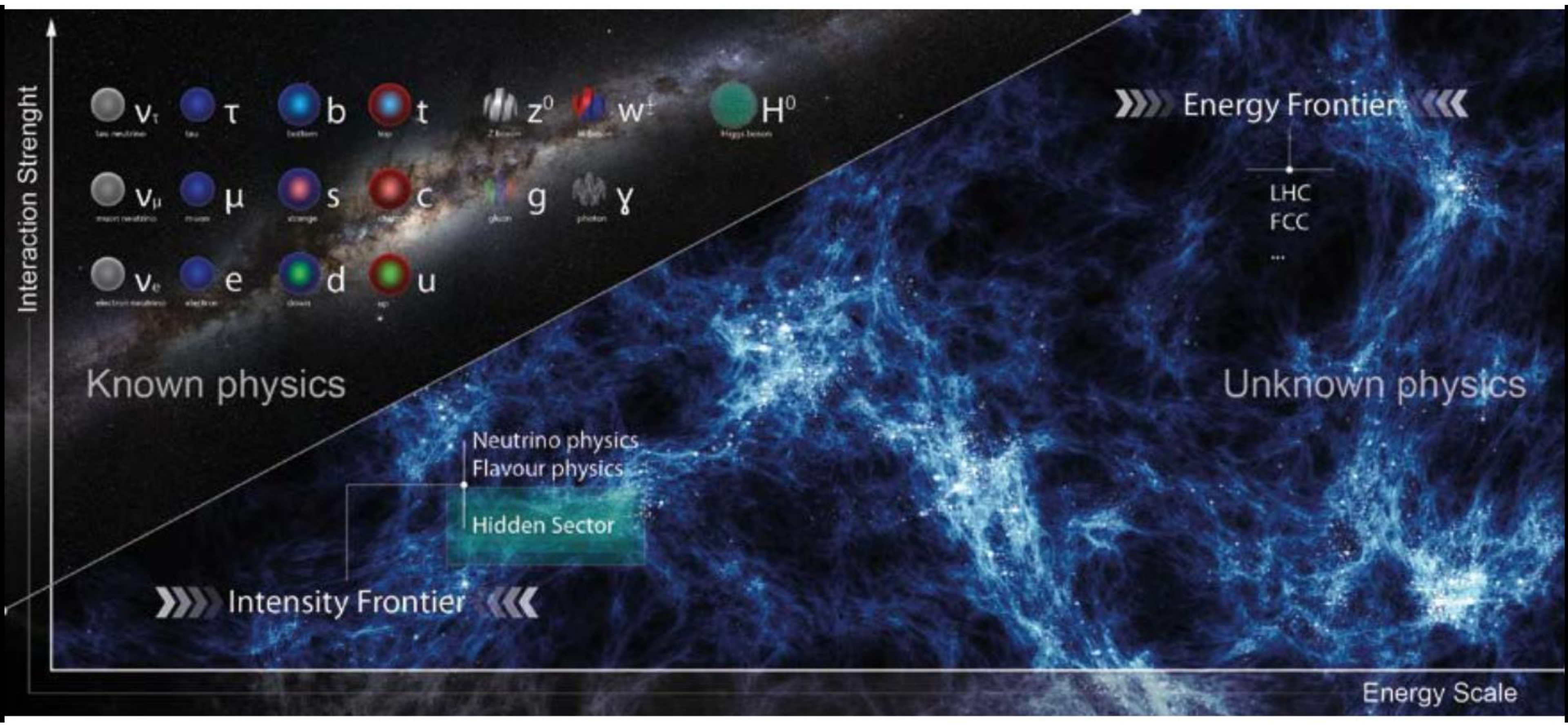
Dark Sector Experiments

Kang Young Lee
GNU

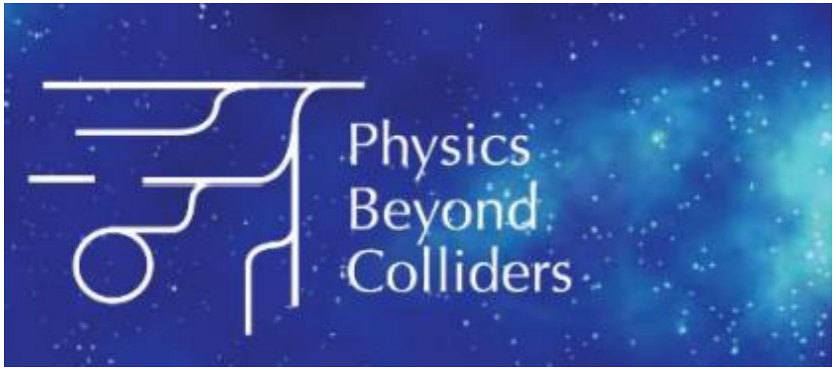
KPS-DPF meeting@SKKU 2022.12.17

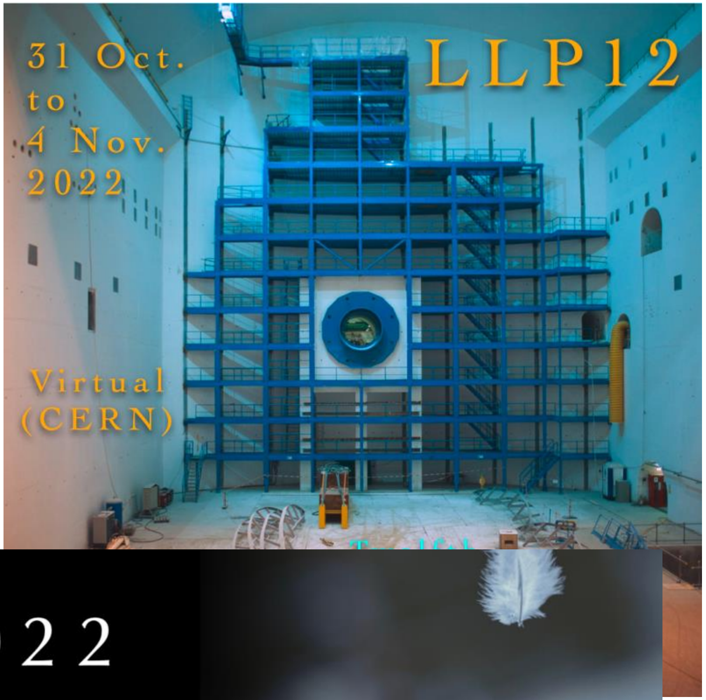
Intensity Frontier vs. Energy Frontier



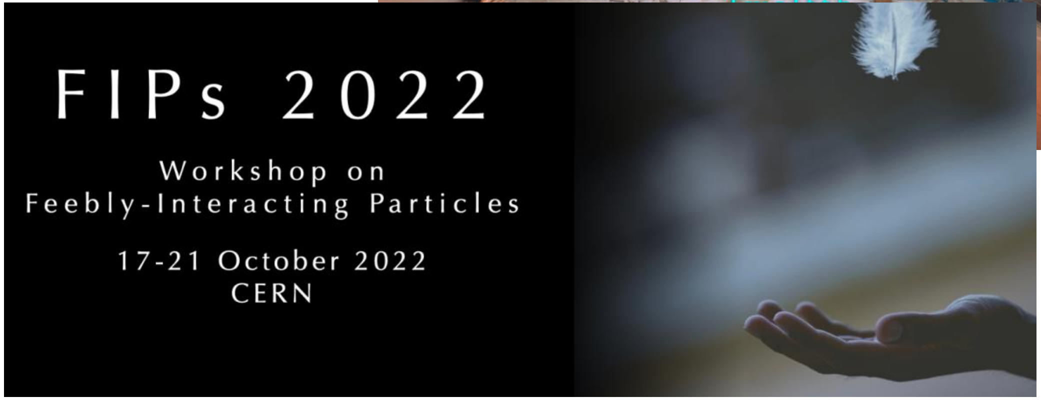
Intensity Frontier

Many Possibilities:
Light Dark Matter,
Light Mediator,
Long-Lived Particles,
...





FPF
Forward Physics Facility



Outline

- BDF/SHiP
- SND@LHC
- FASER/FASERν
- FPF
- NEWSdm
- DAMSA
- MATHUSLA

BDF / SHiP

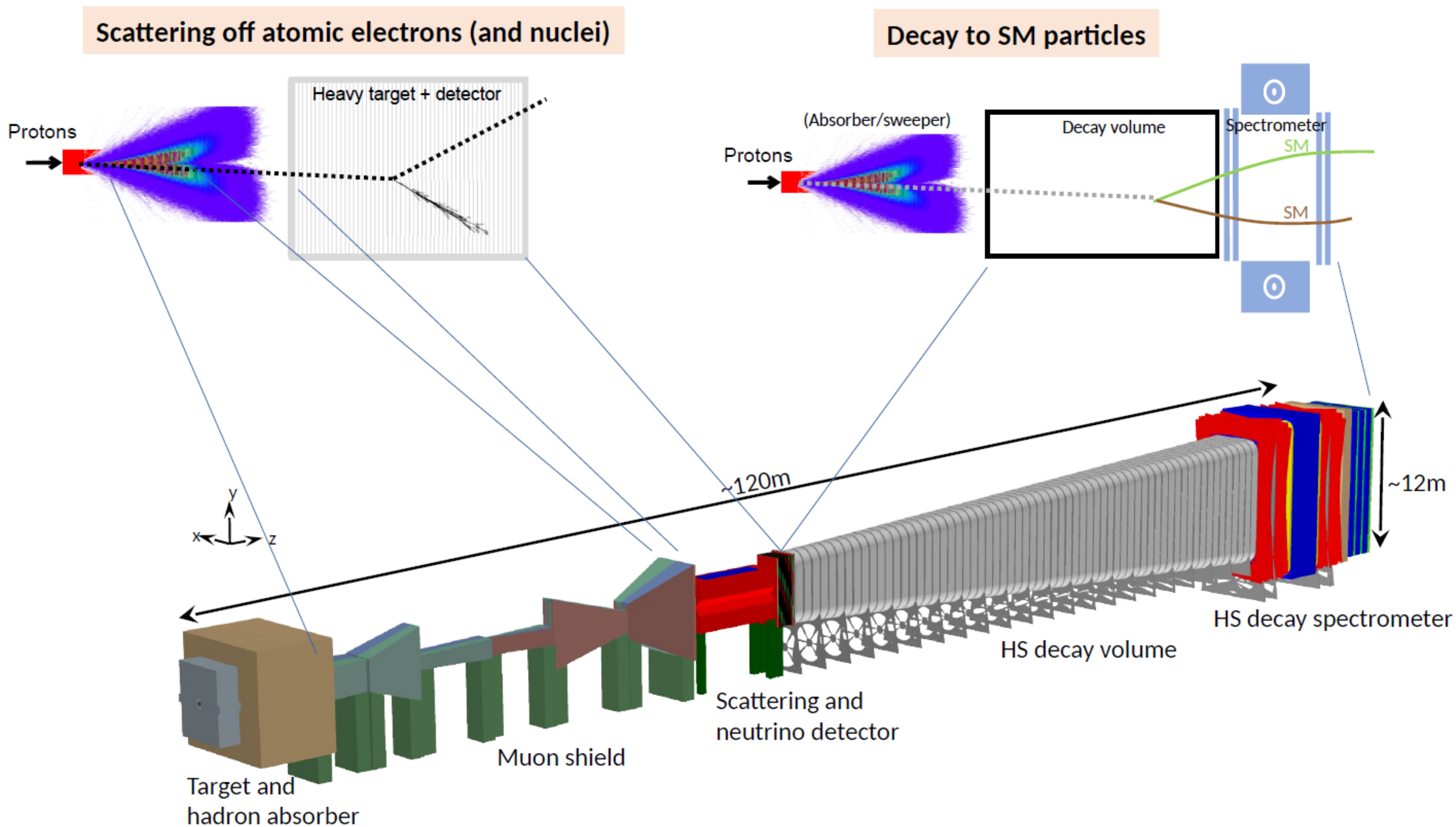

FIPs 2022
Workshop on
Feebly-Interacting Particles
17-21 October 2022
CERN

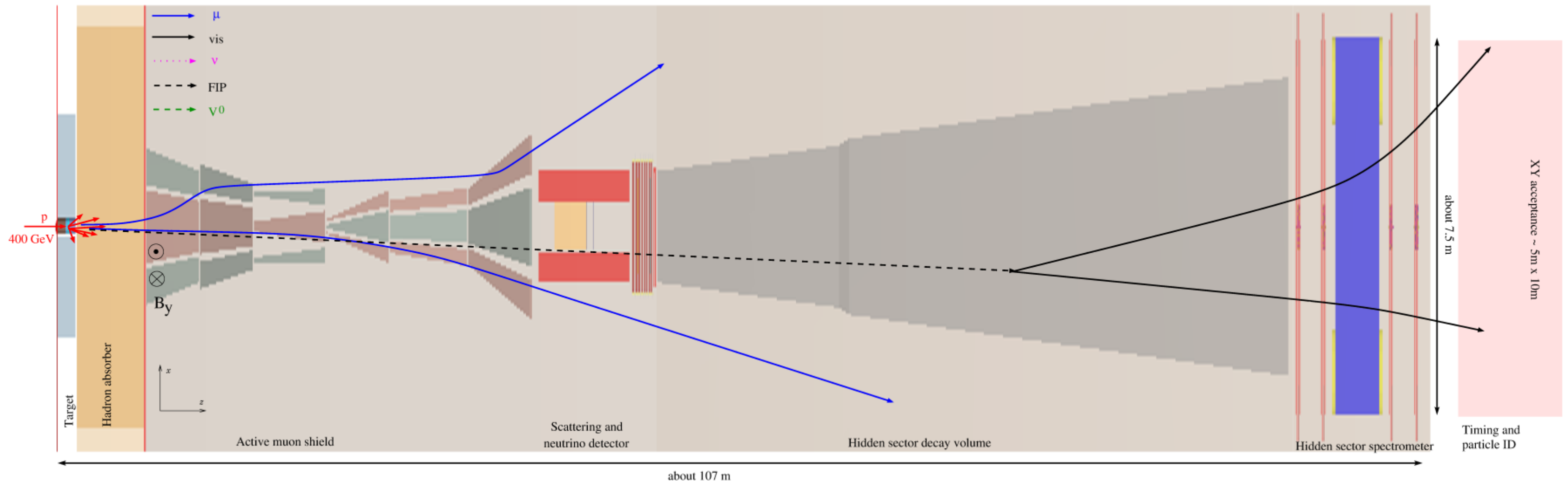

Physics
Beyond
Colliders


31 Oct.
to
4 Nov.
2022
LLP12
Virtual
(CERN)
Twelfth
workshop
of the
Long-Lived Particle Community

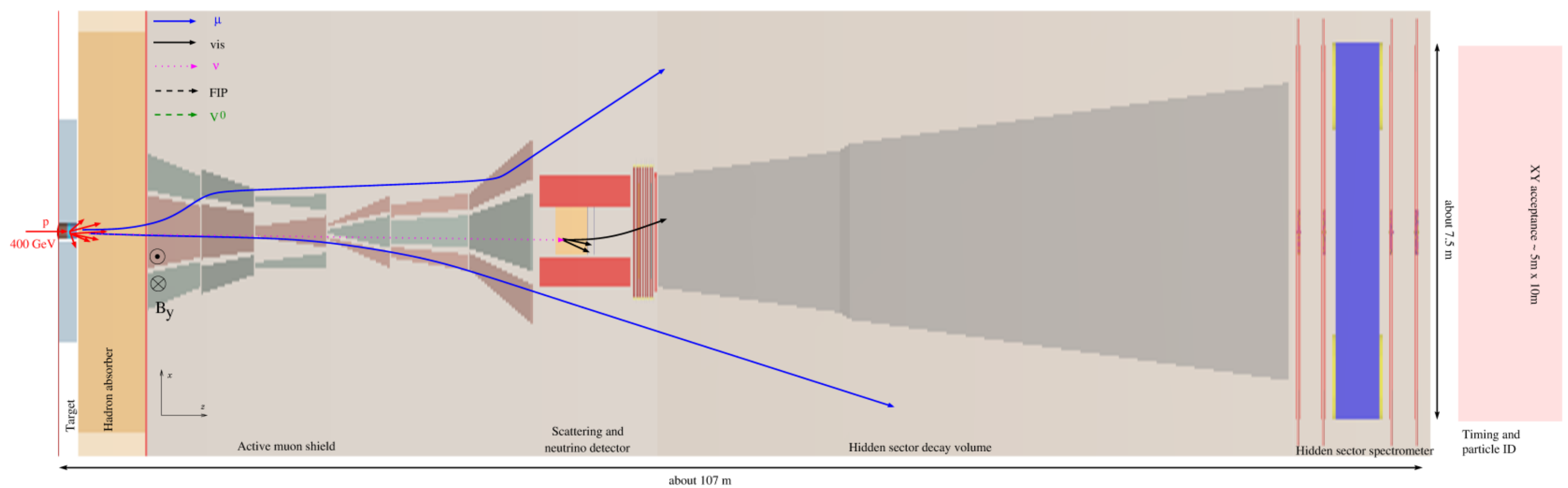
SHiP as presented in CDS(ECN4) report

Dual-platform experiment combining two direct search techniques





μ
vis
ν
FIP
ν0
p
400 GeV
By
Target
Hadron absorber
Active muon shield
Scattering and neutrino detector
Hidden sector decay volume
Hidden sector spectrometer
about 7.5 m
XY acceptance ~ 5m x 10m
Timing and particle ID
about 107 m



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BDF/SHiP @ECN3

- ✓ ***ESPP concluded that BDF/SHiP as one of the front-runners among the larger scale new facilities investigated within CERN PBC.***
- ✓ ***But the project could not be recommended due to financial challenges associated with the other recommendations***

- ✓ *<u>2020 Sep:</u> CERN launches continued BDF R&D with SHiP MoU on top of existing collaboration agreement*

- ✓ *Extensive Layout and Location optimisation study at CERN*
  → BDF/SHiP @ ECN3 provides the best cost-effective solution (Facility cost at the existing ECN3 line is lower than the original cost by a factor)

- ✓ ***<u>2022 July:</u> CERN launches dedicated studies of future programme in ECN3 beam facility & decision process***

CERN-ACC-NOTE-2022-0009
CERN-PBC-Notes-2022-002
1 March 2022

Study of alternative locations for the SPS Beam Dump Facility

Oliver Aberle, Claudia Ahdida, Pablo Arrutia, Kincso Balazs, Johannes Bernhard, Markus Brugger, Marco Calviani, Yann Dutheil, Rui Franqueira Ximenes, Matthew Fraser, Frederic Galleazzi, Simone Gilardoni, Jean-Louis Grenard, Tina Griesemer, Richard Jacobsson, Verena Kain, Damien Lafarge, Simon Marsh, Jose Maria Martin Ruiz, Ramiro Francisco Mena Andrade, Yvon Muttoni, Angel Navascues Cornago, Pierre Ninin, John Osborne, Rebecca Ramjiawan, Pablo Santos Diaz, Francisco Sanchez Galan, Heinz Vincke, Pavol Vojtyla

CERN, CH-1211 Geneva, Switzerland

Keywords:

Summary

As part of the main focus of the BDF Working Group in 2021, this document reports on the study of alternative locations and possible optimisation that may accompany the reuse of existing facilities with the aim of significantly reducing the costs of the facility. Building on the BDF/SHiP Comprehensive Design Study (CDS), the assessment rests on the generic requirements and constraints that allow preserving the physics reach of the facility by making use of the 4×10^{19} protons per year at 400 GeV that are currently not exploited at the SPS and for which no existing facility is compatible. The options considered involve the underground areas TCC4, TNC, and ECN3. Recent improvements of the BDF design at the current location (referred to as 'TT90-TCC9-ECN4') are also mentioned together with ideas for yet further improvements. The assessments of the alternative locations compiled the large amount of information that is already available together with a set of conceptual studies that were performed during 2021.

The document concludes with a qualitative comparison of the options, summarising the associated benefits and challenges of each option, such that a recommendation can be made about which location is to be pursued. The most critical location-specific studies required to specify the implementation and cost for each option are identified so that the detailed investigation of the retained option can be completed before the end of 2022.

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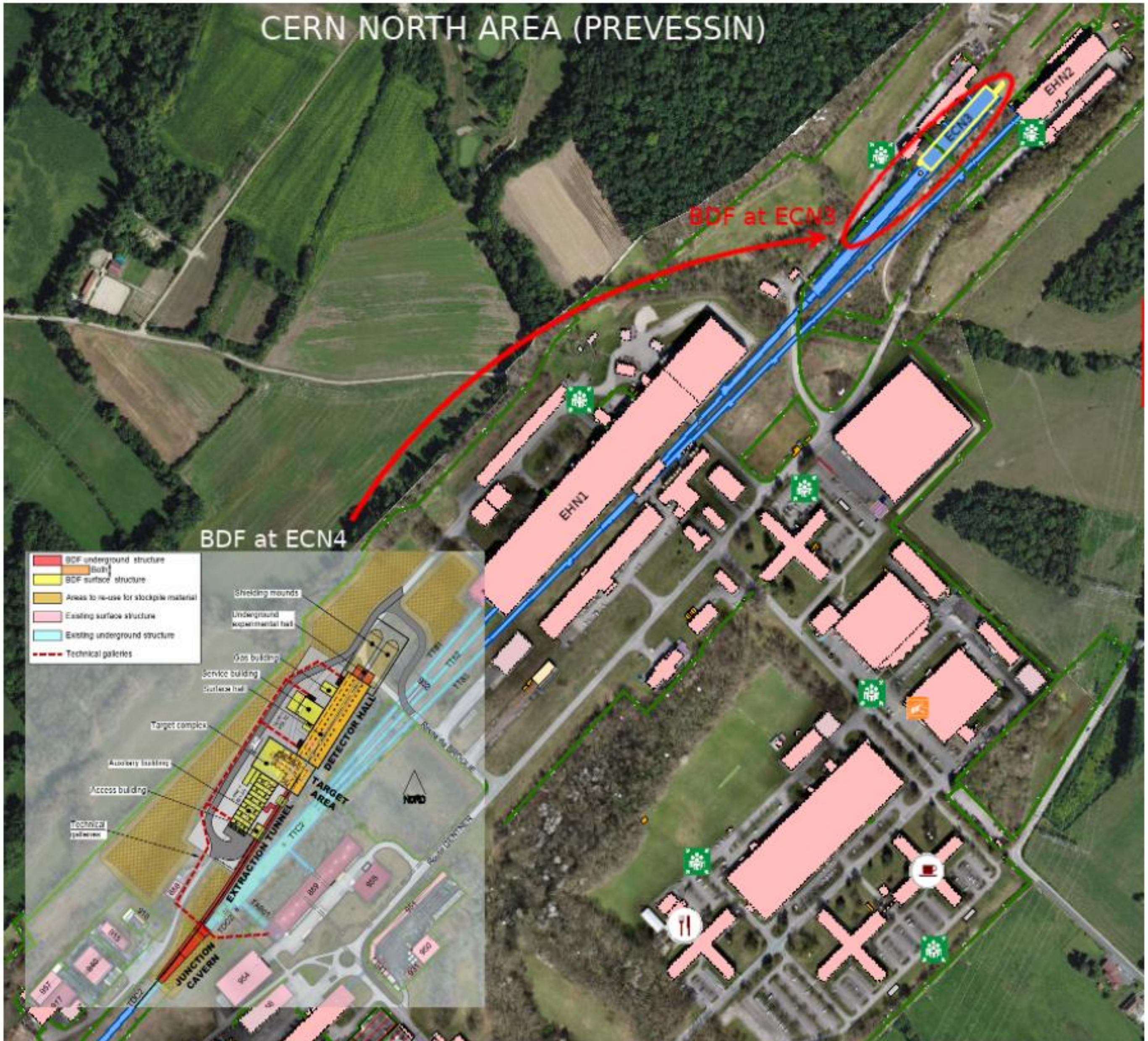
CERN/SPSC-2022-009 / SPSC-SR-305
01/03/2022

H. Lacker@PBC

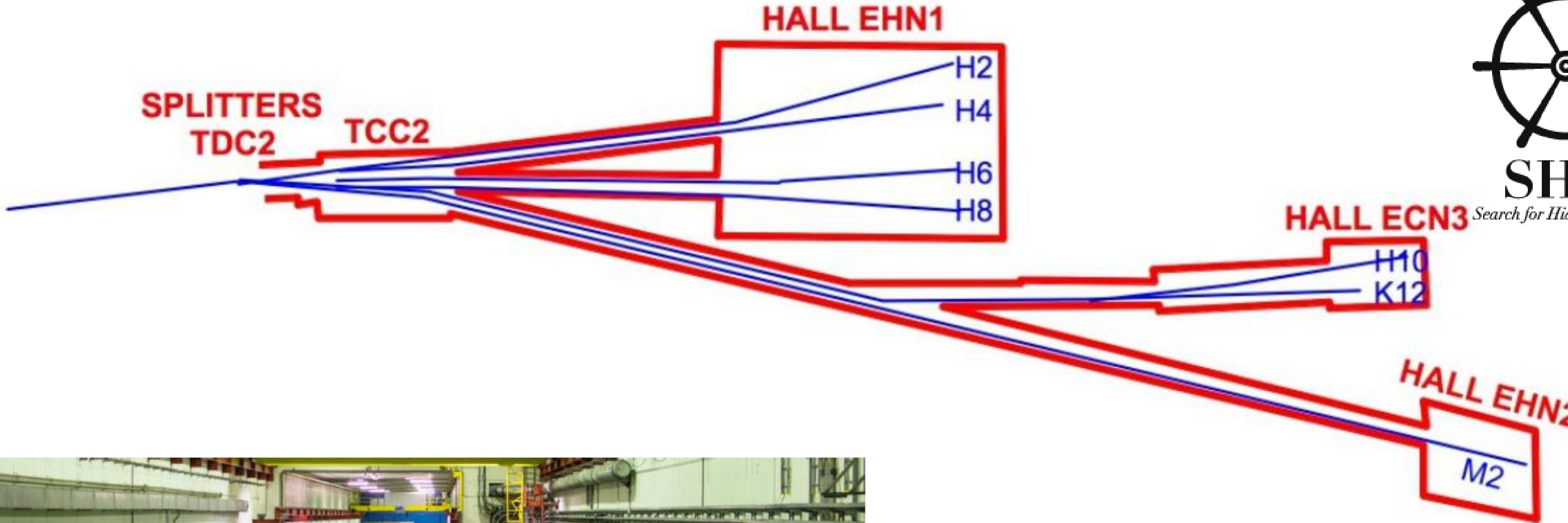
An alternative location for BDF/SHiP ?



Considerable cost reduction

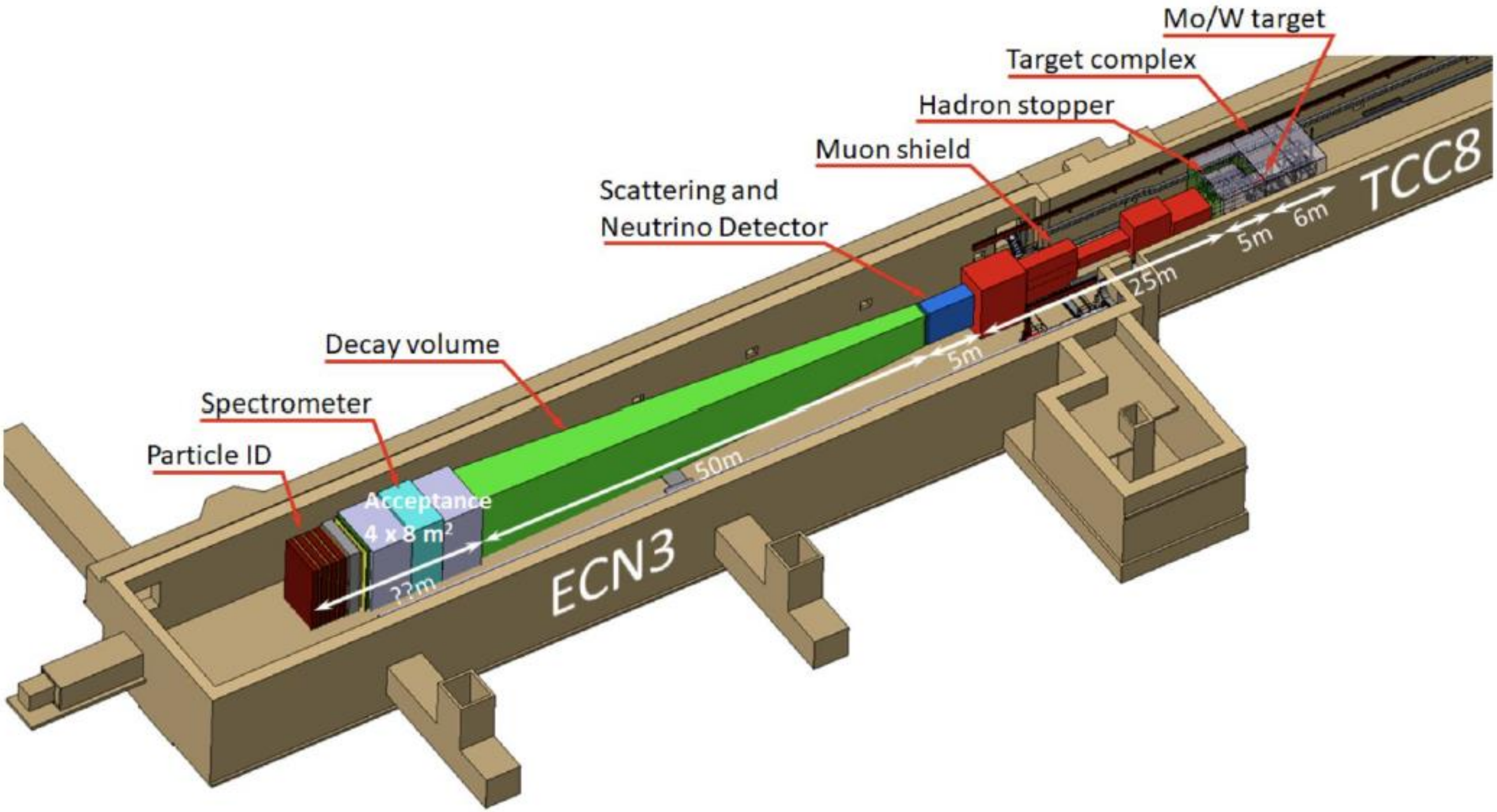
ECN3!

at
North Area



- Now hosting NA62 experiment : rare Kaon decay measurement
- $K \to \pi \nu \nu$
- NA62 will proceed till the LHC LS3.
- 100m in length, 16m wide.
- No additional beamline is needed for the BDF.

SHiP@ECN3

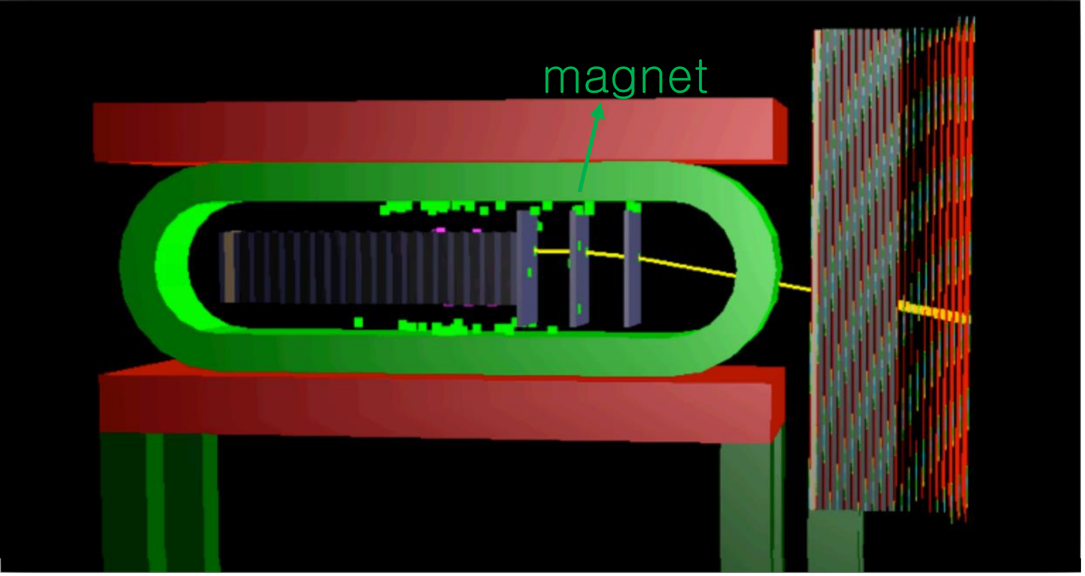


Mo/W target
Target complex
Hadron stopper
Muon shield
Scattering and
Neutrino Detector
Decay volume
Spectrometer
Particle ID
Acceptance
4 x 8 m²
??m
50m
5m
25m
5m
6m
TCC8
ECN3

Issues being studied

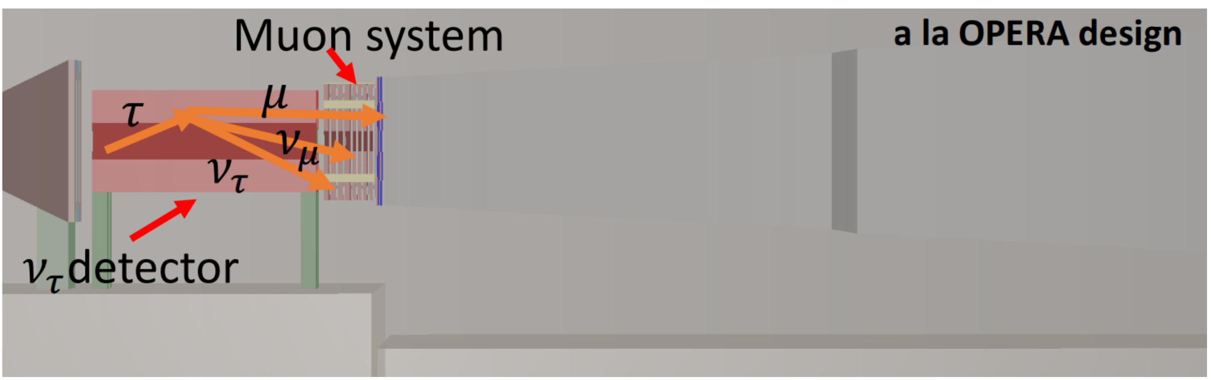
- Target system and hadron stopper identical
- Muon shield shorter (35m→30m)
- SND shorter and more narrow, no room for magnet
- Decay vessel with same length but proportionally smaller transverse dimensions
- Spectrometer with reduced dimensions
- Increase of backgrounds - more studies

- Same sensitivity achievement as SHiP CDS?



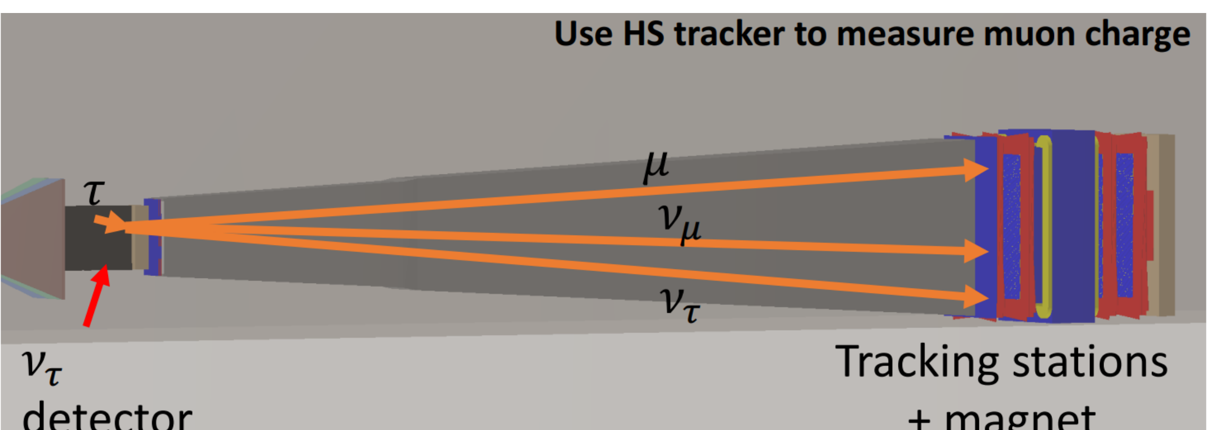
CDS design:

SND is inside the magnet to determine the flavor of ν_τ in both hadronic and muonic τ decays

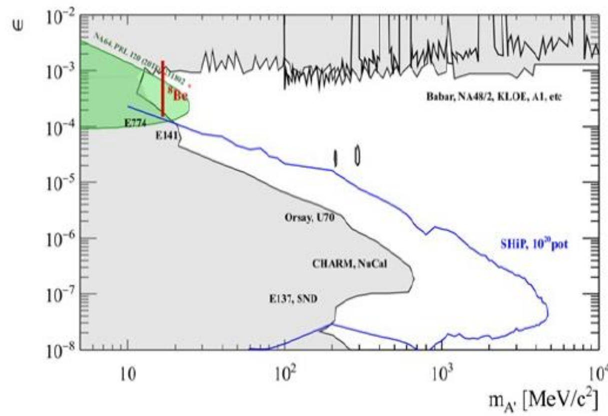


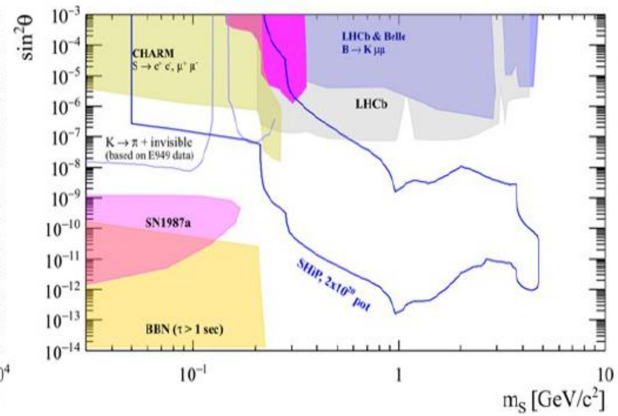
At ECN3:

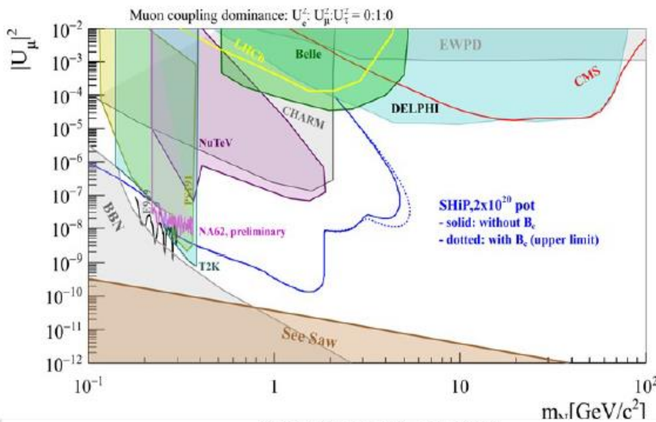
- No space for the magnet
- Use exclusively muons from τ
- Consider two options for the muon charge measurement
  - OPERA type
  - use HS spectrometer

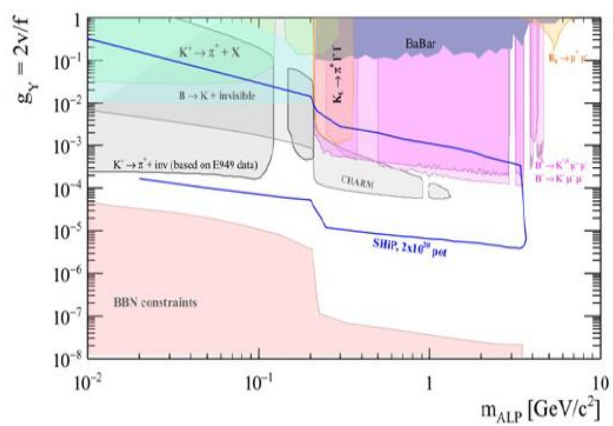


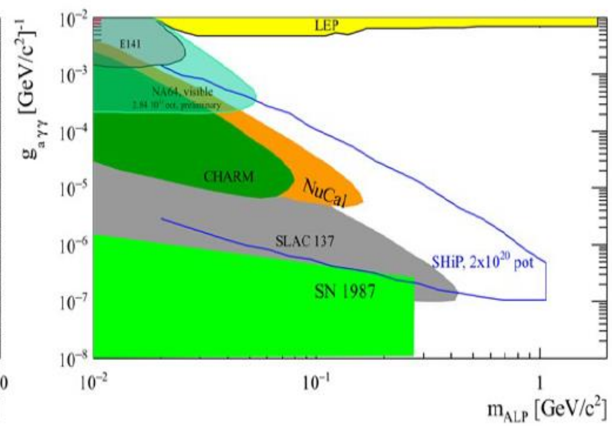
Excellent news: ECN3 sensitivities very close to ECN4 sensitivities

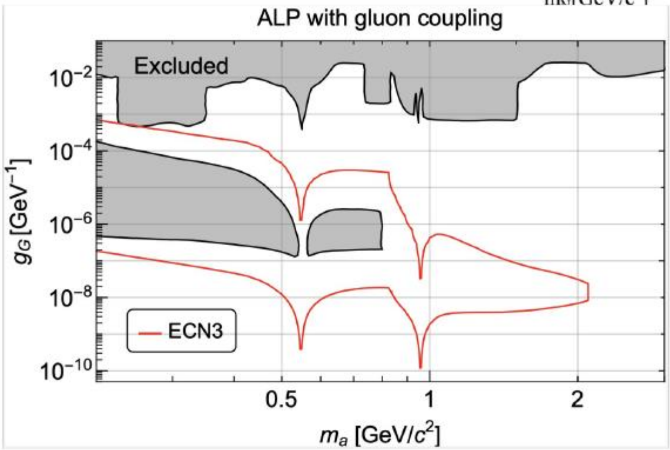




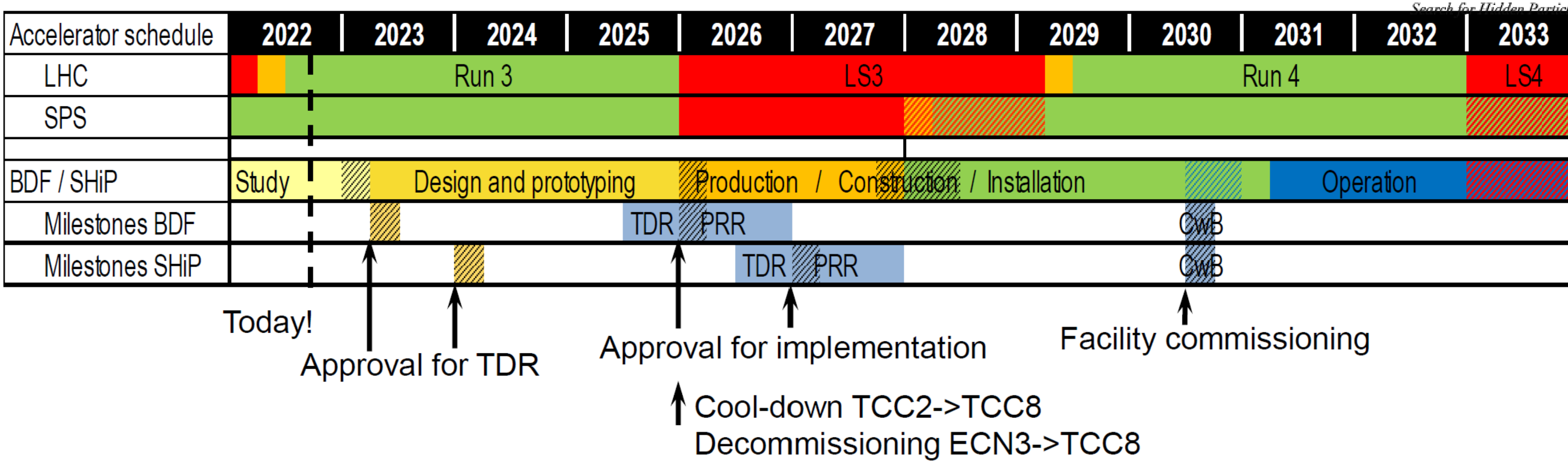








BDF/SHiP Global Schedule



LOI submitted

CERN-SPSC-2022-XXX

5 October 2022

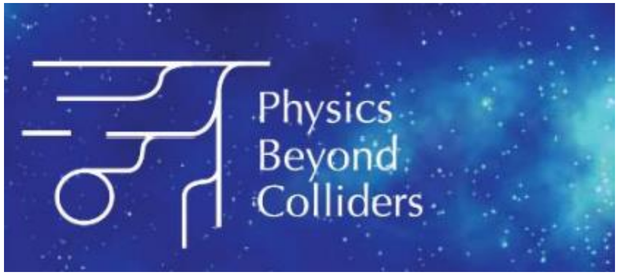
SHiP experiment at the SPS Beam Dump Facility

Letter of Intent for implementation in ECN3

[1]BDF Working Group, SHiP Collaboration

Scattering and Neutrino Detector
at the LHC

SND@LHC



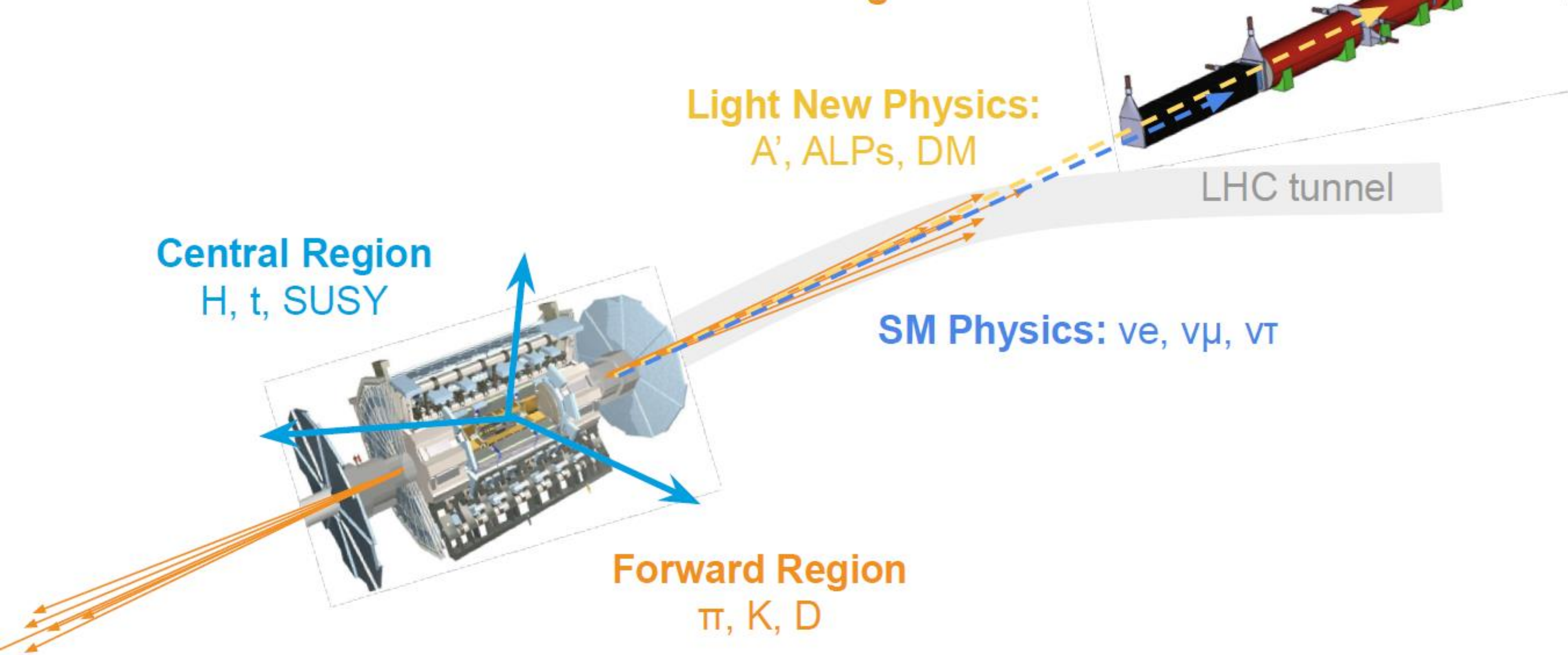
One Slide of Motivation.

LHC
Scattering and Neutrino Detector at the LHC

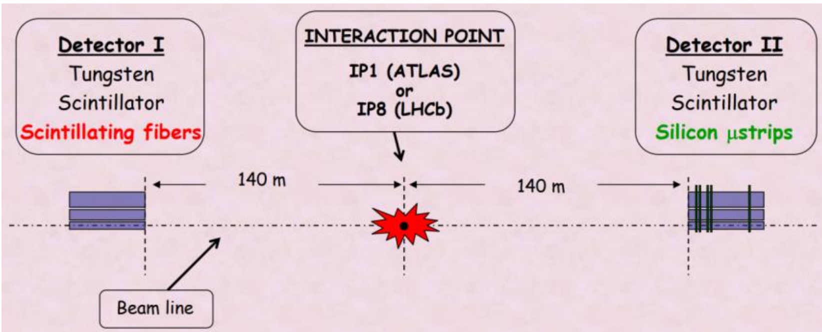
The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

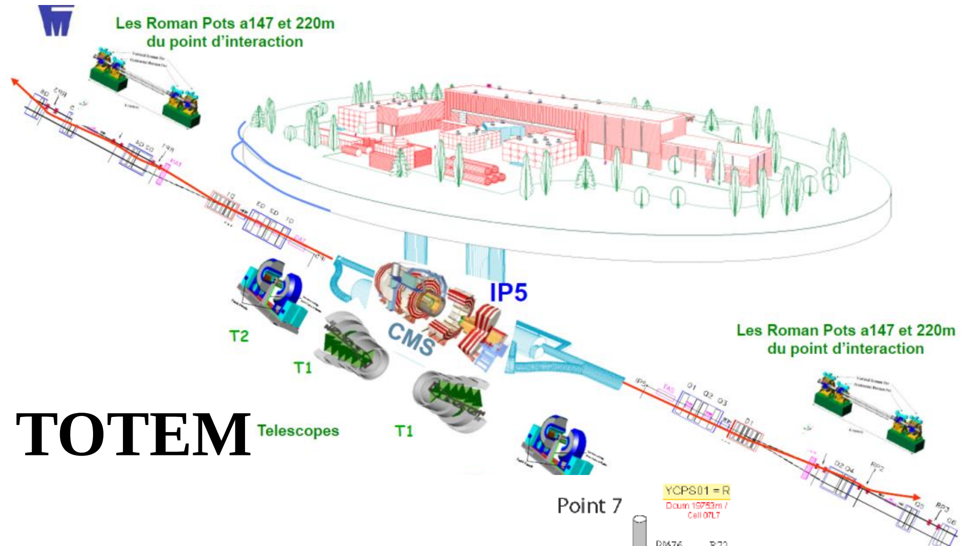
Can we do something with that?



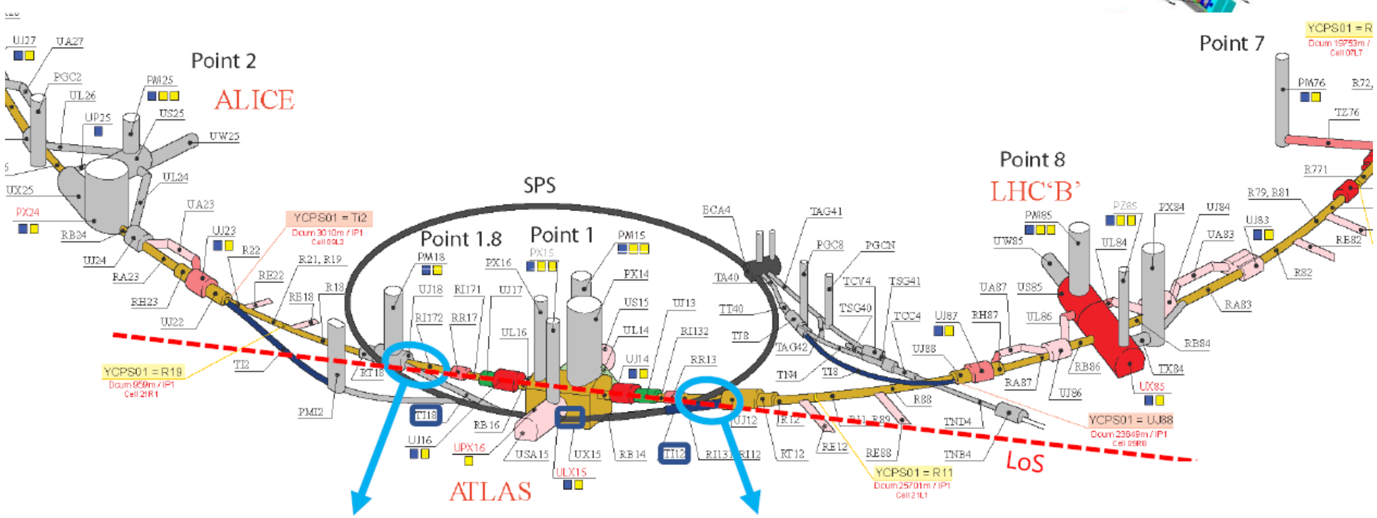
Forward Experiment of LHC



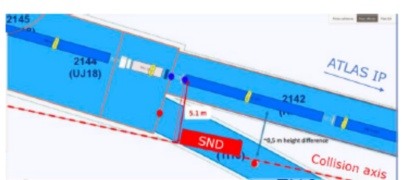
LHCf

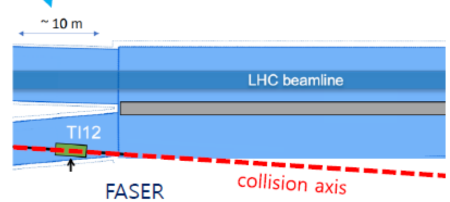


TOTEM



SND@LHC

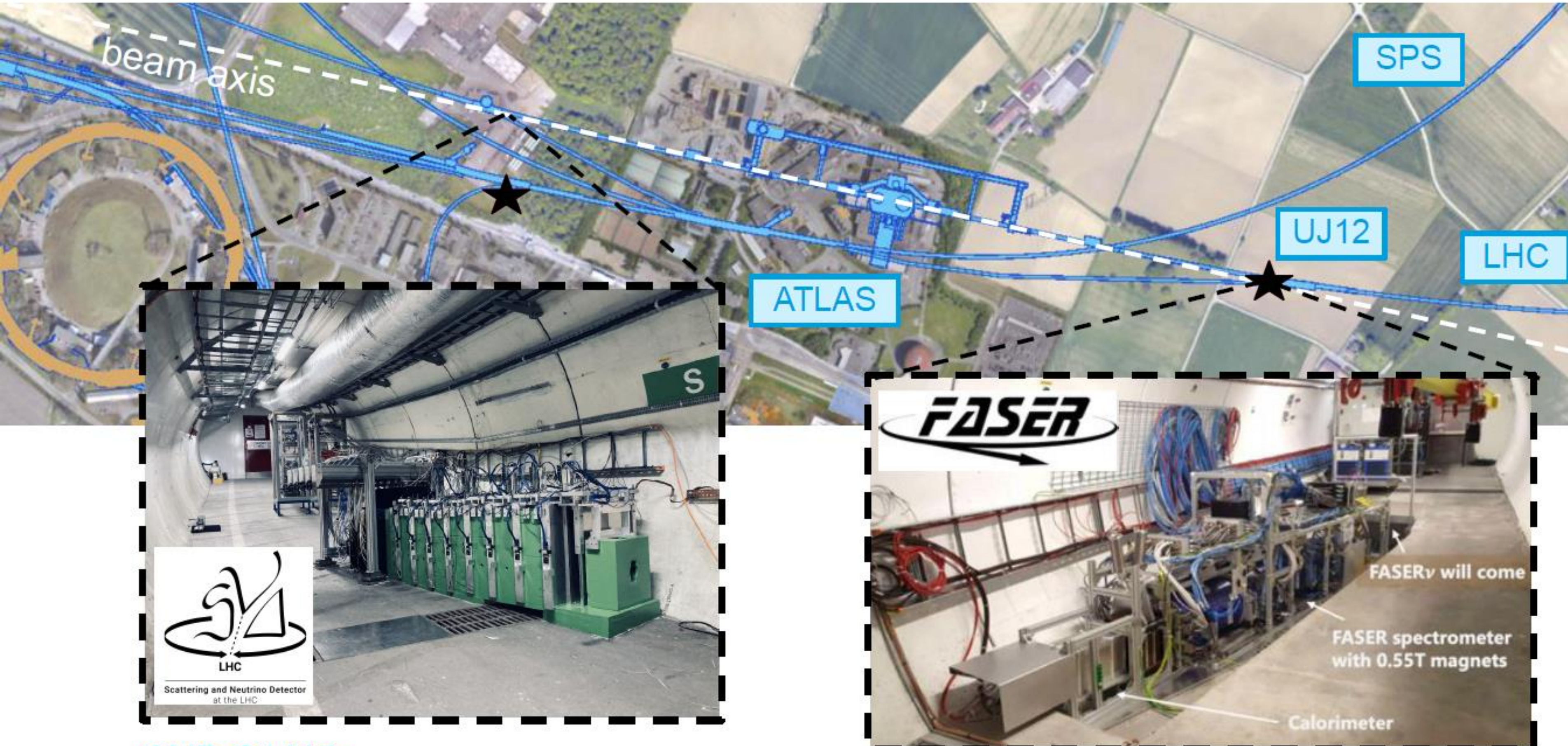




FASER

Run3: FASER and SND@LHC.

Two new experiments have started their operation with the start of LHC Run 3:
SND@LHC and **FASER** (including **FASERν**).

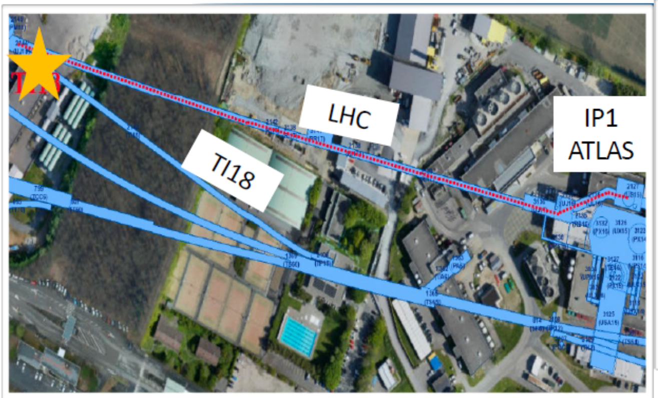


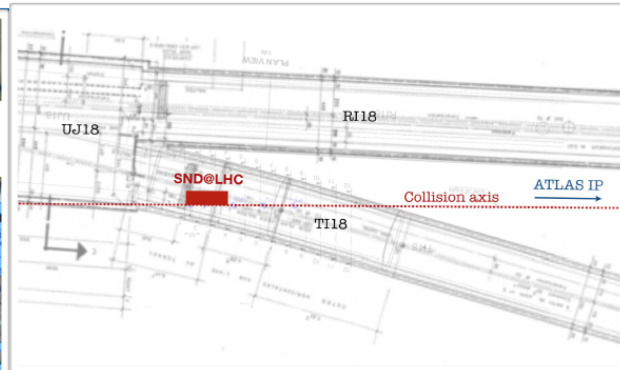
SND@LHC:
Martina Ferrillo's talk

FASER:
Charlotte Cavanagh's talk

FASERν:
Hiroaki Kawahara's talk

SND@LHC REFRESHER

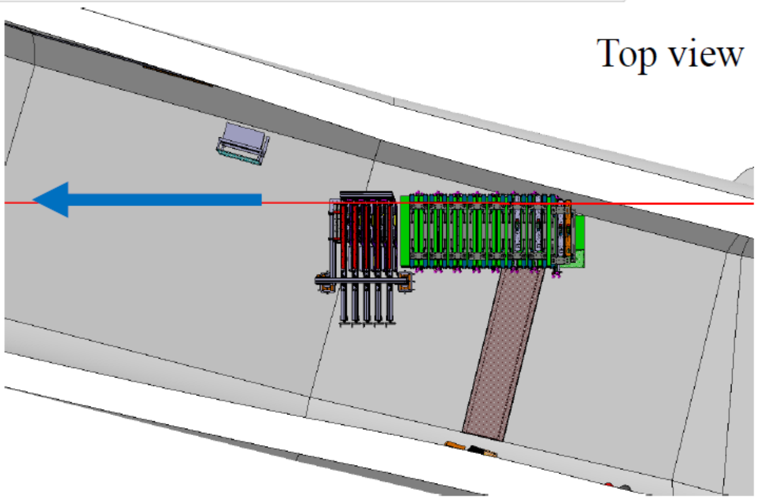


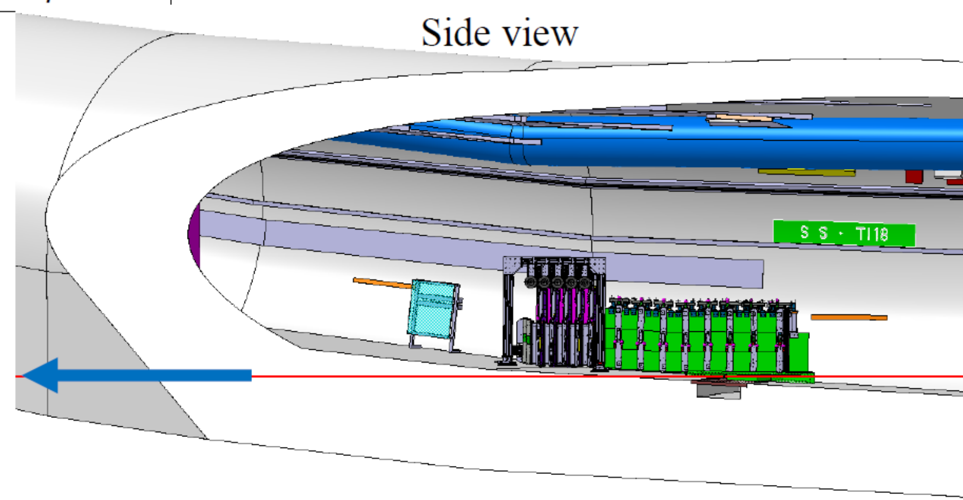


Physics motivation

- Study neutrino interactions of all flavours at unexplored energy range
- Probe heavy flavour production with neutrinos at unexplored rapidity range
- LFU with neutrino interactions
- Search for recoil signatures of FIPs (e.g. HS mediators, LDM,…)

$7.2 < \eta < 8.4$





Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

VETO PLANE:

tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:

- Emulsion cloud chambers (60 emulsion films, each 300μm thick, interleaved by 1mm thick tungsten plates)

E.M. CAL

- 250μm Scintillating fibres for timing information and e.m. energy measurement

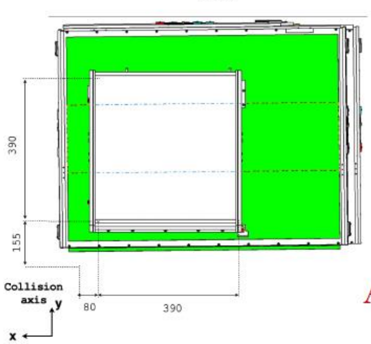
HADRONIC CALO:

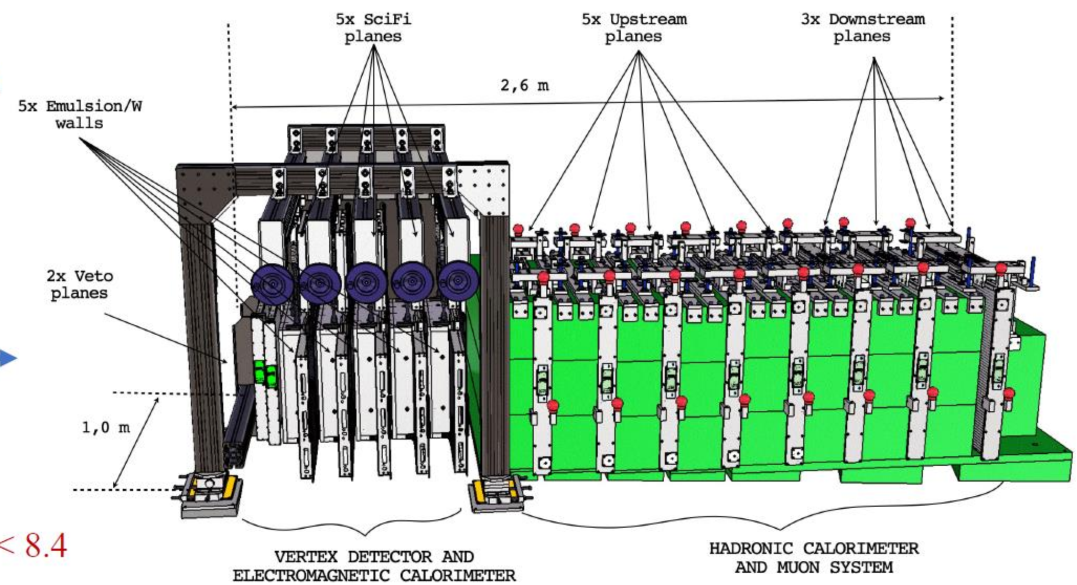
iron walls interleaved with plastic scintillator planes for ~11 λ

MUON IDENTIFICATION SYSTEM:

3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking

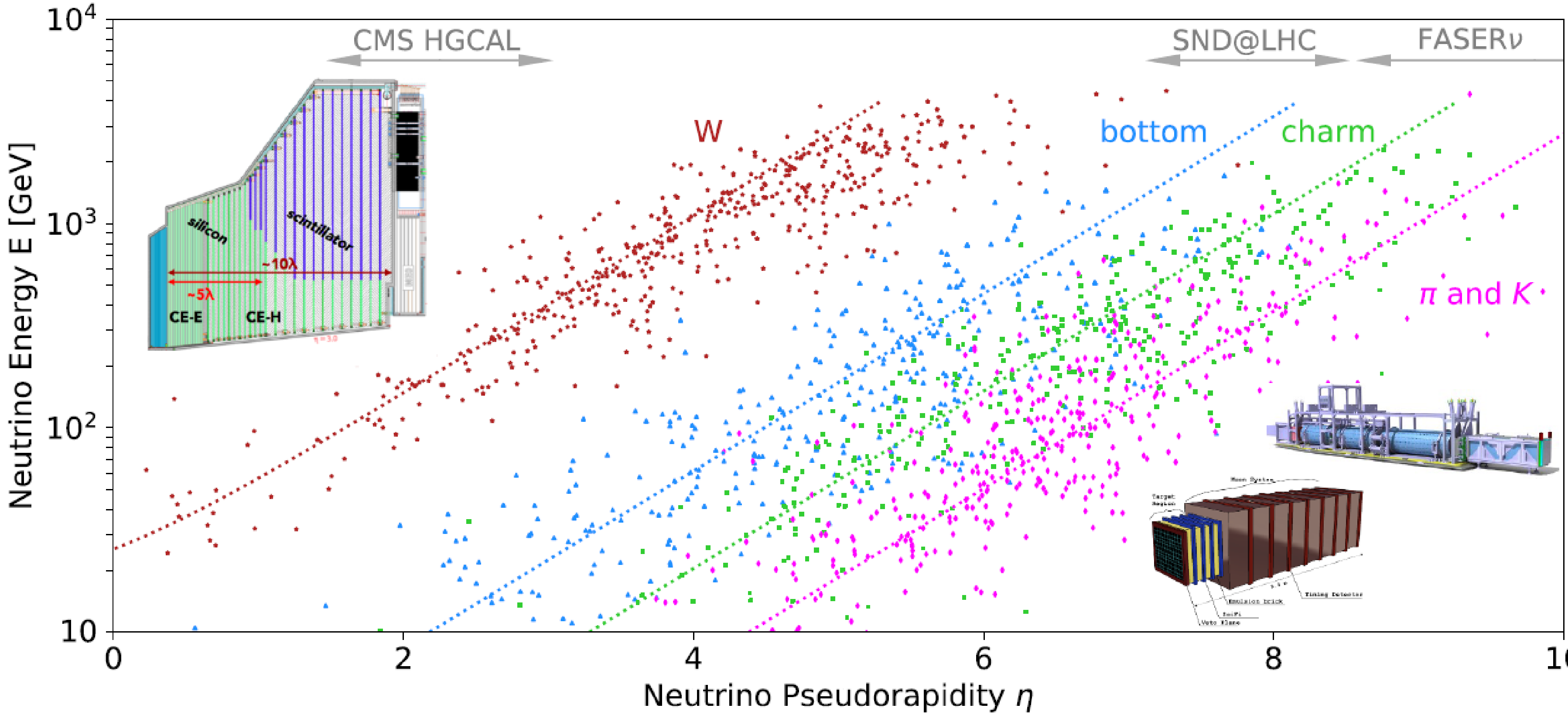
FRONT VIEW





Angular acceptance: $7.2 < \eta < 8.4$

LHC
Scattering and Neutrino Detector at the LHC

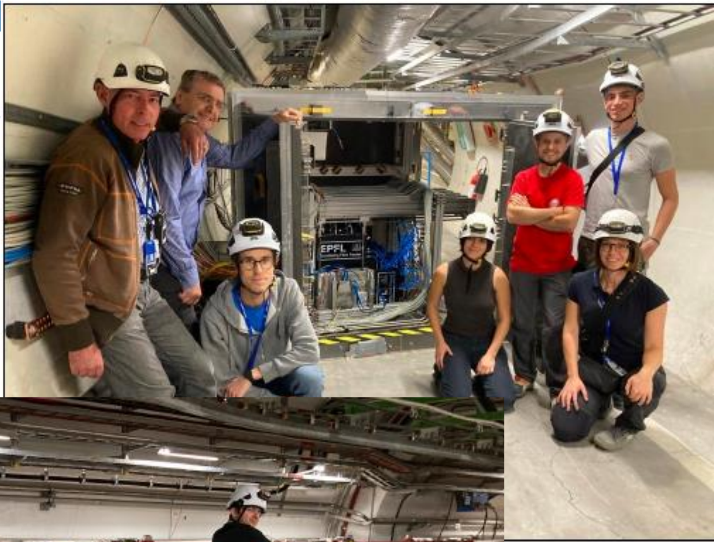


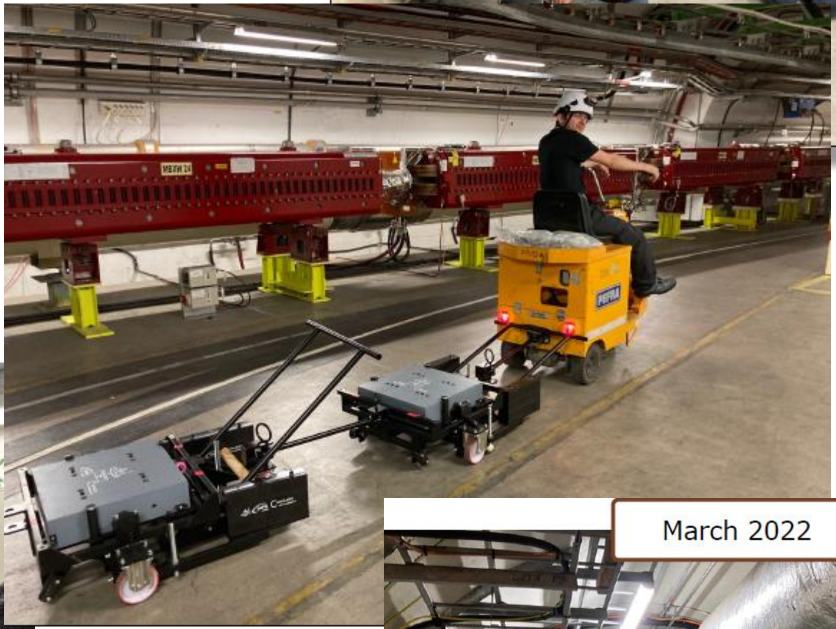
Energy and Pseudorapidity distribution of LHC neutrinos

arXiv: 2108.05370 [hep-ph]

Summary of the experiment main milestones

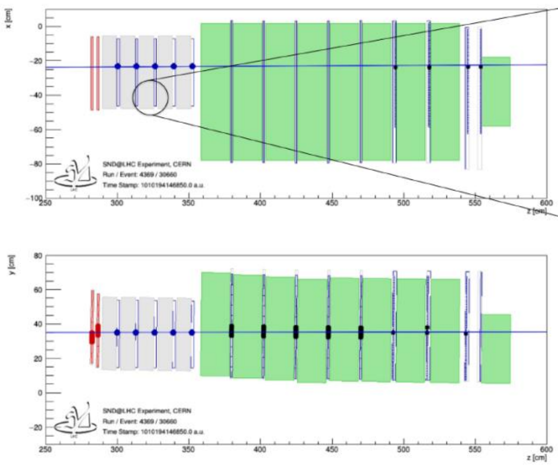
- Letter of Intent: Aug 27^{th}, 2020
- Technical Proposal: Jan 22^{nd}, 2021
- Approval by CERN RB: Mar 2021
- Experimental area & infrastructure: Jun 28 – end Aug
- Detector construction completion: Oct 13
- Detector surface commissioning: Sep - Oct
- Test beams: Sep 1-5, Oct 1-6
- Start of detector installation in TI18: Nov 1
- Turn on and global commissioning: Dec 7
- Detector commissioning and debugging: Jan-Feb 2022
- Installation of the neutron shield: Mar 15
- Installation of the first emulsion films: Apr 7
- First data from "splash"/collision: Apr, May
- First 13.6 TeV collisions: July 5^{th}
- Full target installation: July 26^{th}

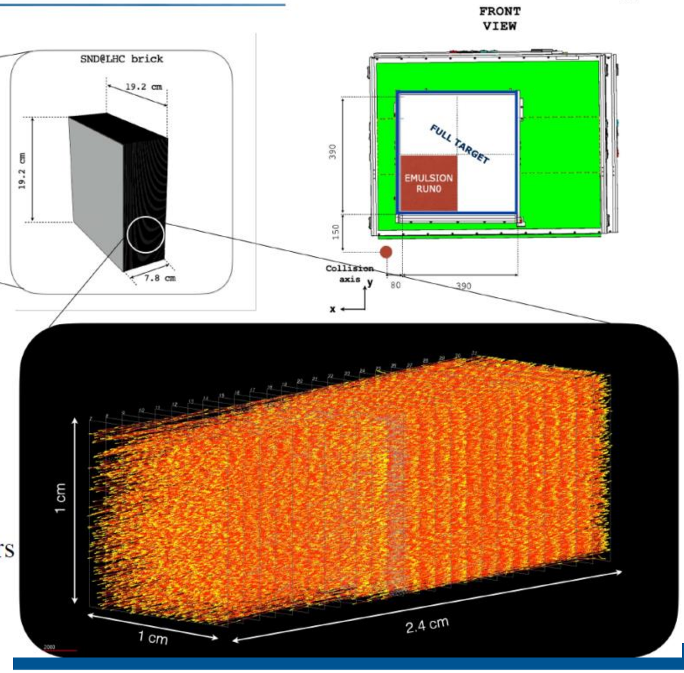




Track reconstruction also with emulsion data

muon track recorded on July 6th from pp @13.6 TeV





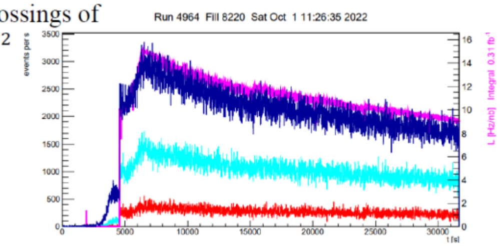
Track rates in emulsion compatible with electronic detectors

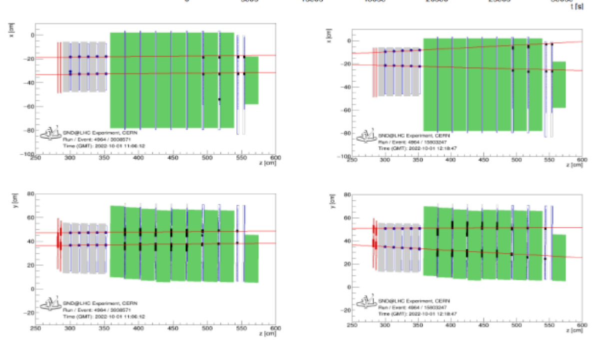
RUN0 from April 7th to July 26th (0.51 fb^{-1})

LHC
Scattering and Neutrino Detector
at the LHC

Multi-track events

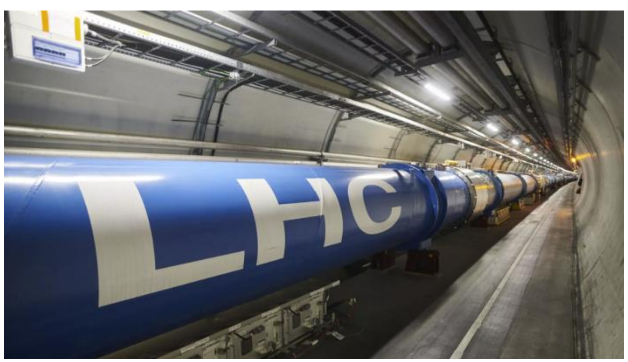
- Run 4964: $\int Ldt = 0.31 fb^{-1}$, $\sigma_{inelastic} = 80\ mb$, 2448 bunch crossings of 3564, $N_{collisions} = 25\times10^{12}$, $T = 26\times10^{3} s$, $N_{xings} = 0.72\times10^{12}$
- Efficiency corrected average over this run: 300 tracks/s
- Single muon per bunch crossing: $\mu = 1.1\times10^{-5}$
- Probability for k-track event from pile-up: $\frac{\mu^k e^{-\mu}}{k!}$
- 2 μ per bunch xing: $p_2 = \frac{1}{2}\mu^2$
- 3 μ per bunch xing: $p_3 = \frac{1}{6}\mu^3$
- Expect $N_{2\ track} = 43$, observed 224
- Additional rate could be due to trident process, muon pair production in rock, concrete, tungsten.
- Hypothesis supported by 3-track events





FORWARD SEARCH EXPERIMENT AT THE LHC

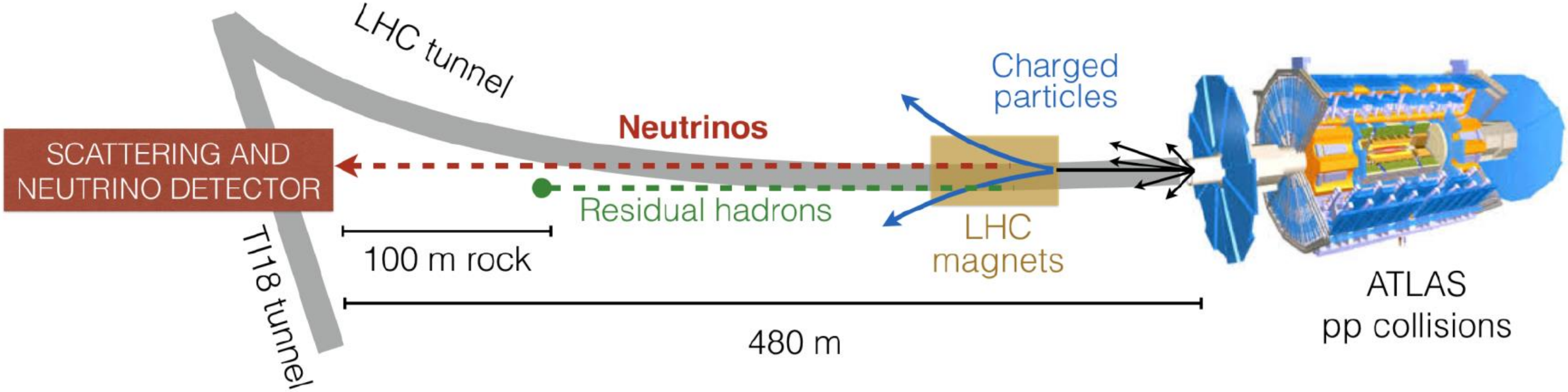
FASER / FASERν



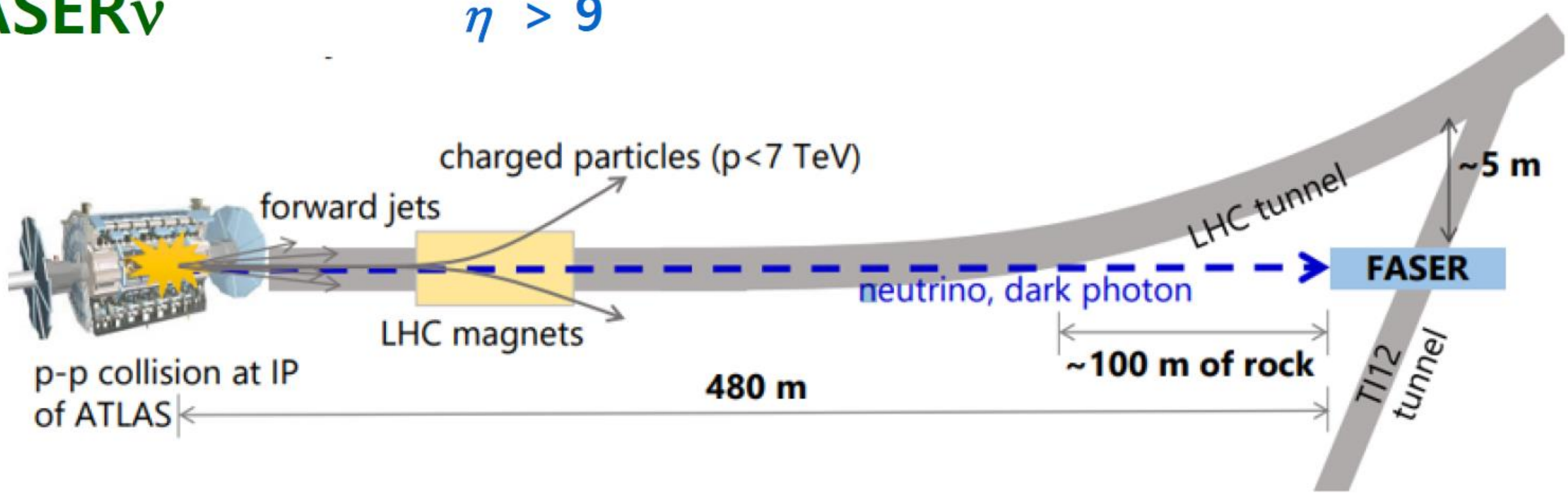
Forward Physics Facility

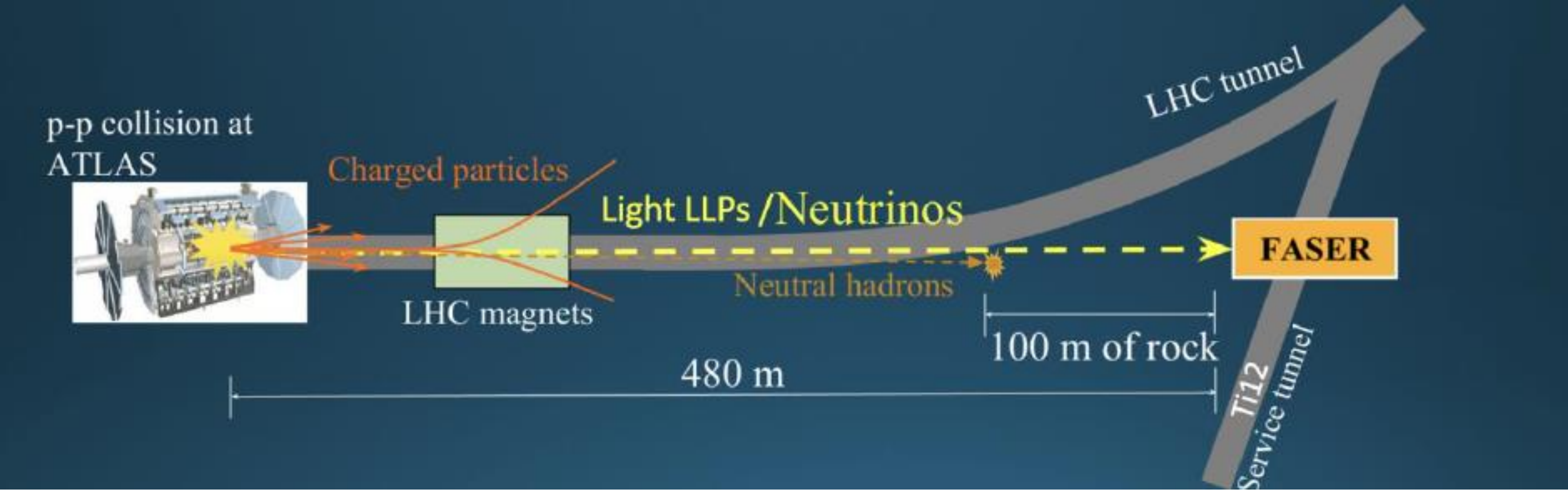
Physics Beyond Colliders

SND@LHC $7.2 < \eta < 8.7$

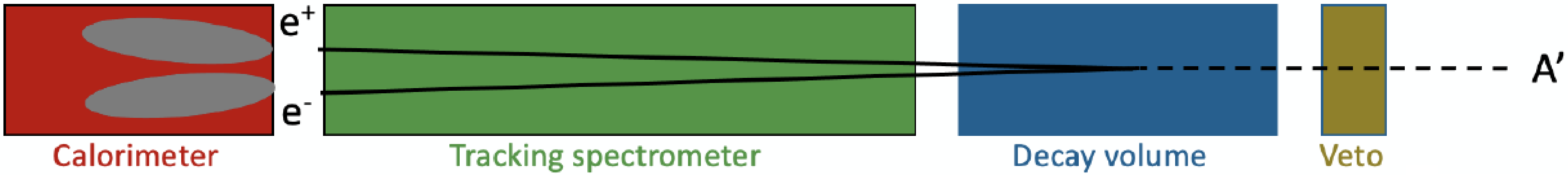


FASERν $\eta > 9$

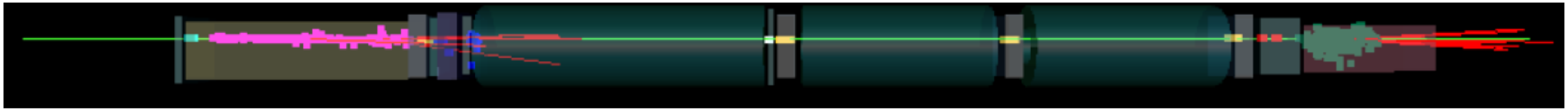




- 10 cm radius, angular acceptance $\theta \lesssim 1$ mrad
- 7 m long, 1.5 m decay volume
- FASER detector paper: https://arxiv.org/pdf/2207.11427.pdf

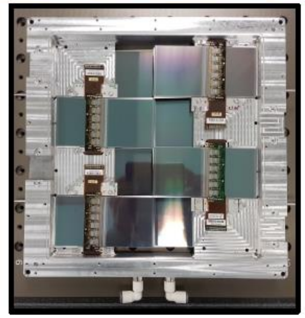


Simulation event display: muon traversing entire detector volume



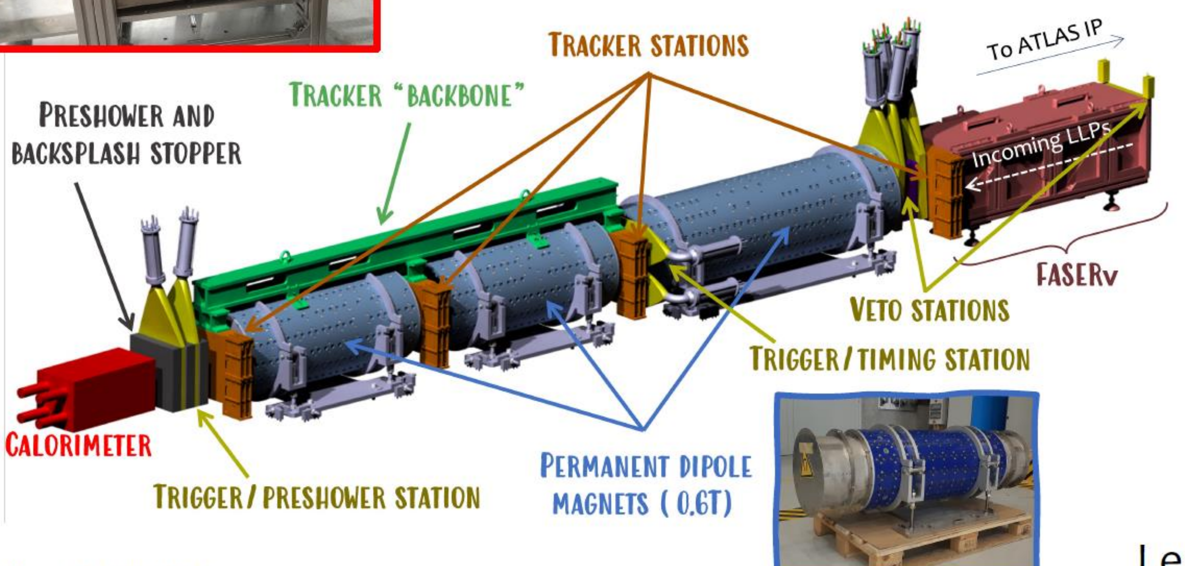
FASER Detector

Calorimeter modules (LHCb) mounted in support



A tracker layer made of ATLAS SCT modules

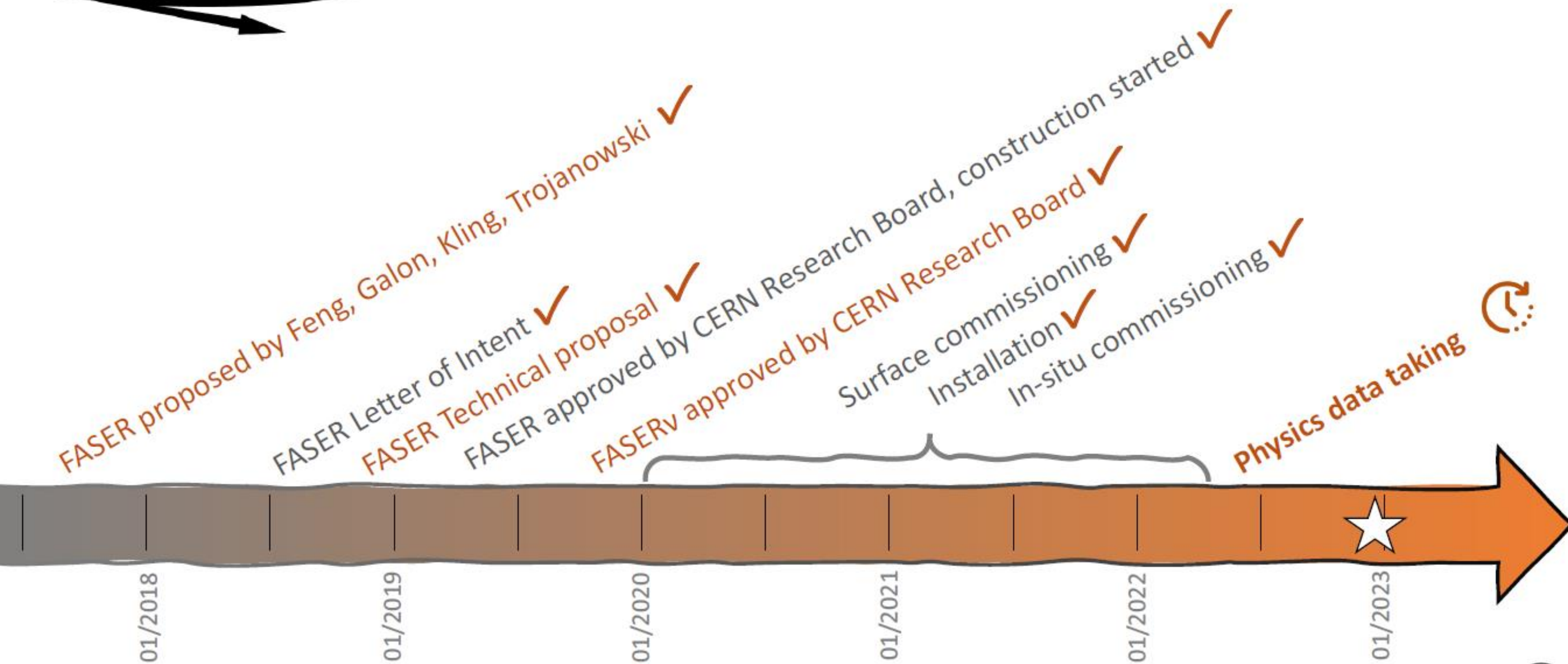
Two stations to veto O(10^9) muons
A timing station, resolution < 1 ns
A preshower station



Length: 7 m
Aperture: 20 cm
Length of decay volume: 1.5 m

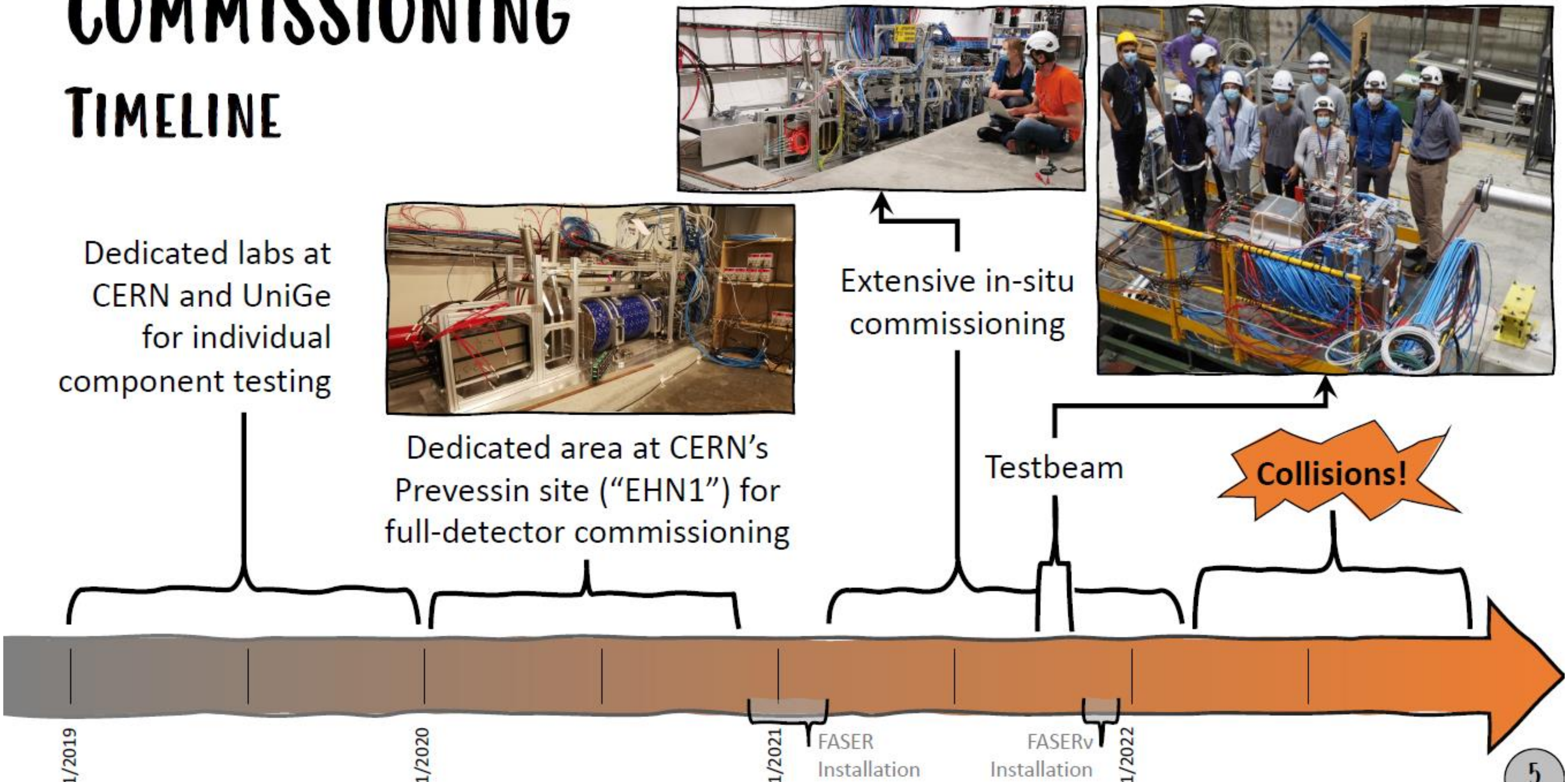
arXiv:2207.11427

FASER Global timeline



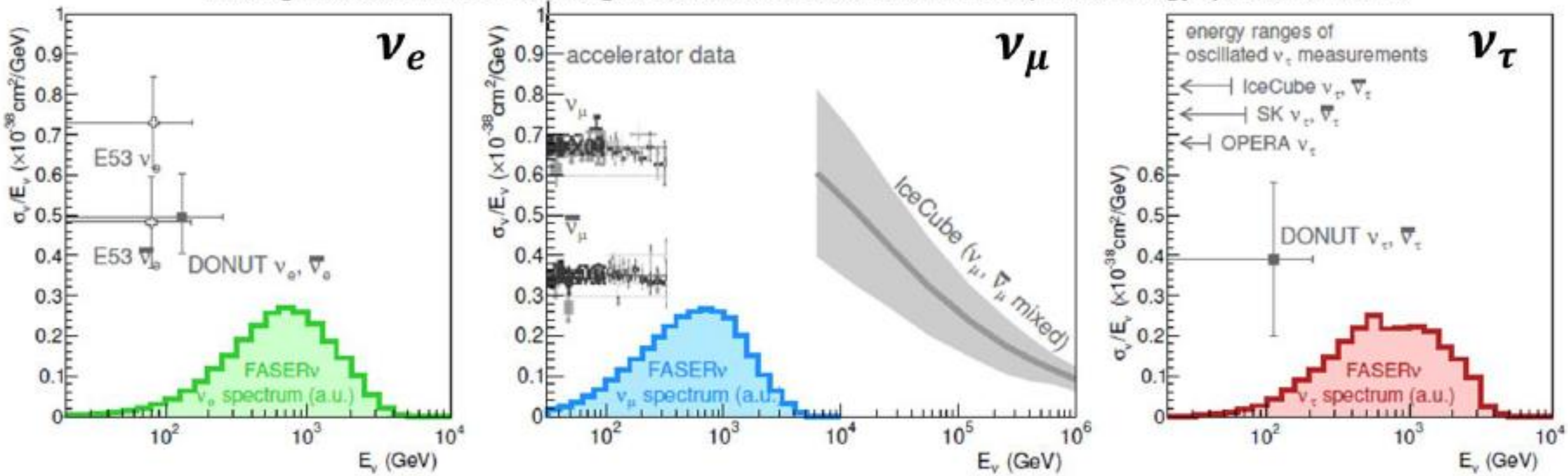
Commissioning

Timeline



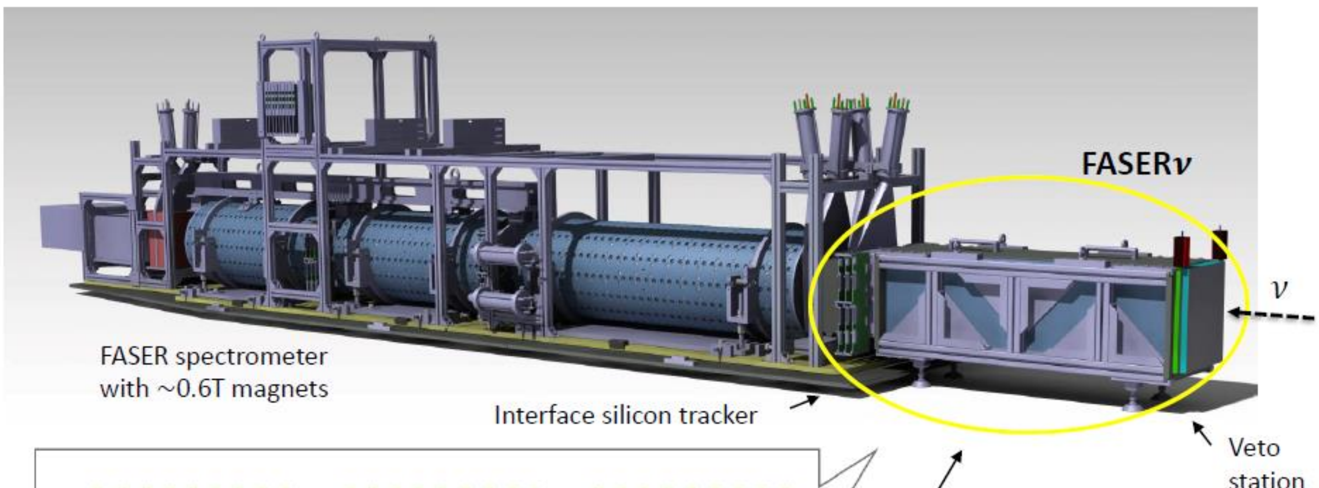
FASER neutrino program

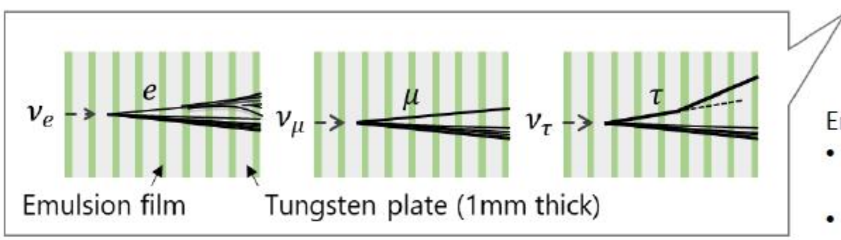
Existing measurements of νN charged-current cross sections and the expected energy spectra for FASERν



The FASERν detector

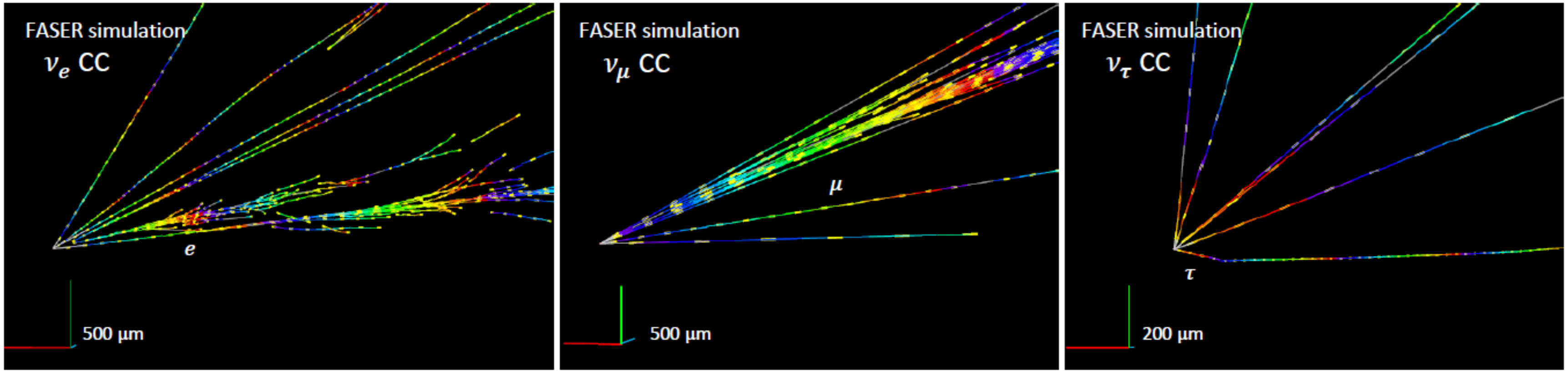
- Emulsion/tungsten detector, interface silicon tracker, and veto station
- Distinguishing all flavor of neutrino interactions
- Muon charge identification with hybrid configuration with the FASER spectrometer
- Neutrino energy measurement by combining topological and kinematical variables





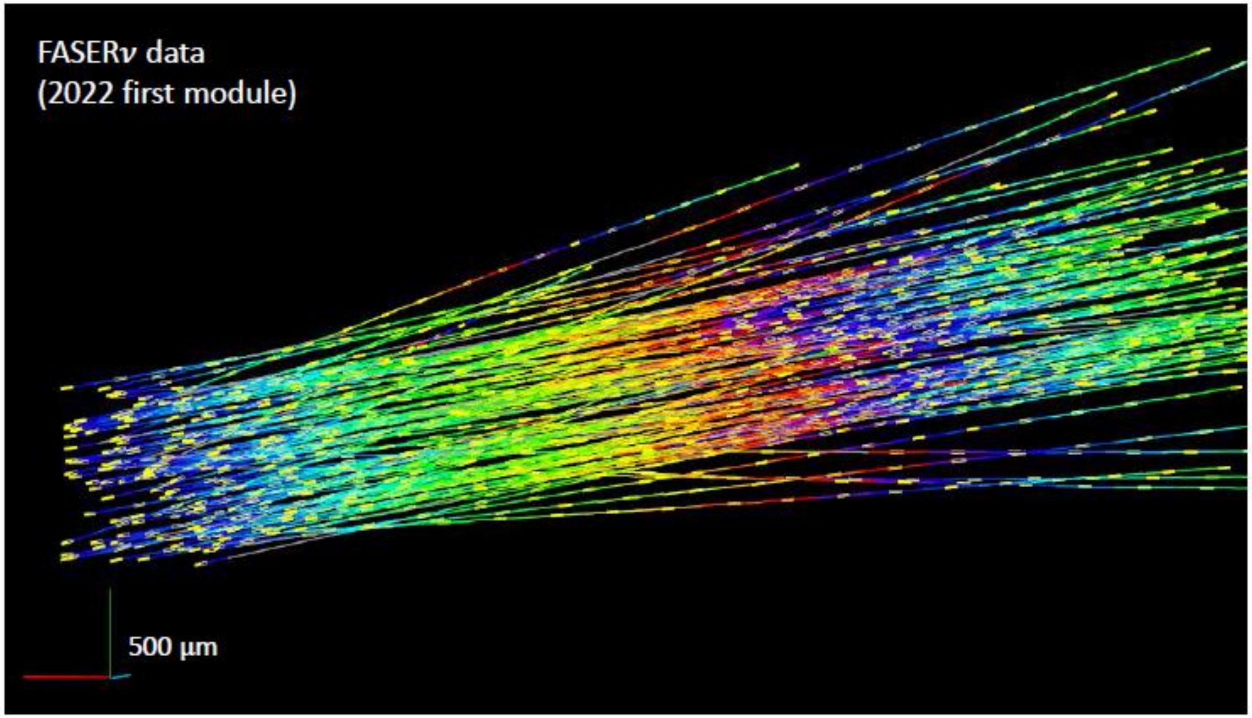
Emulsion/tungsten detector
- 730 1.1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm², 1.1 m long, 1.1 tons

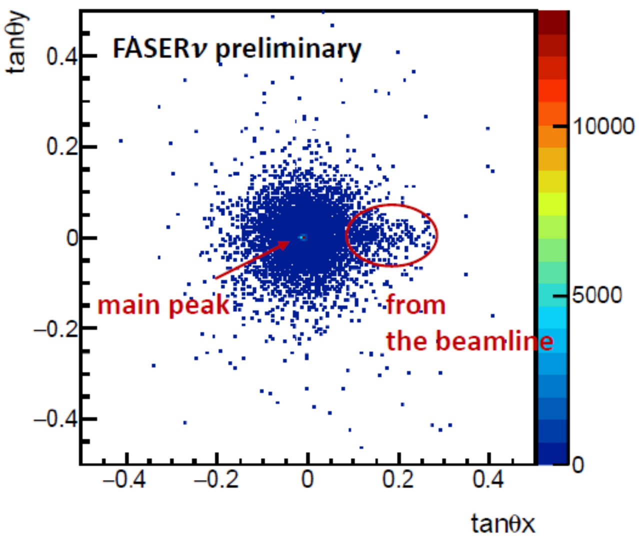
Physics run in LHC Run 3 (2022-2025), ~12 emulsion replacements



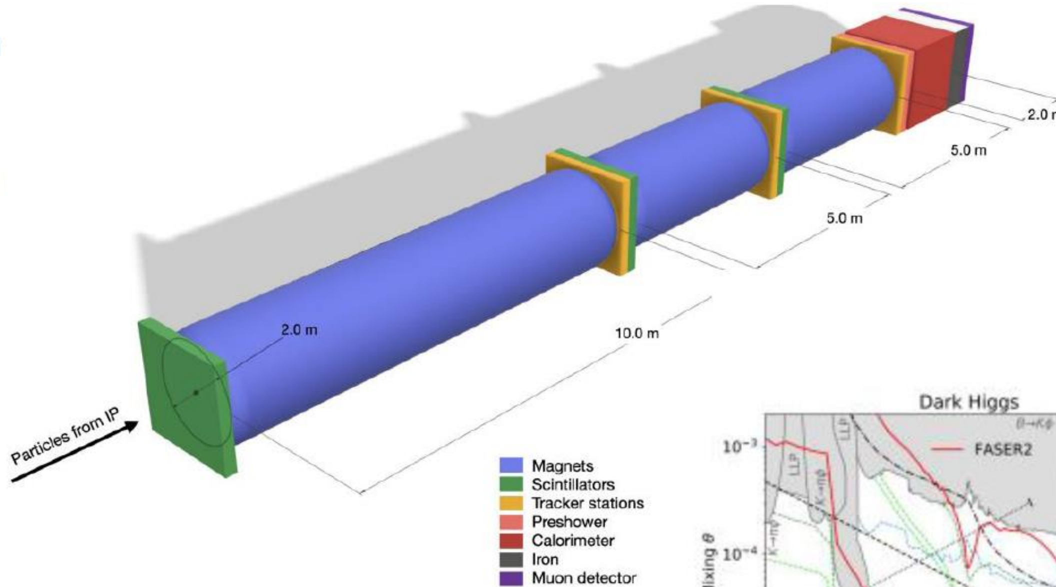
- Event displays of simulated neutrino interaction vertices for 433 GeV ν_e CC, 664 GeV ν_μ CC, and 831 GeV ν_τ CC.

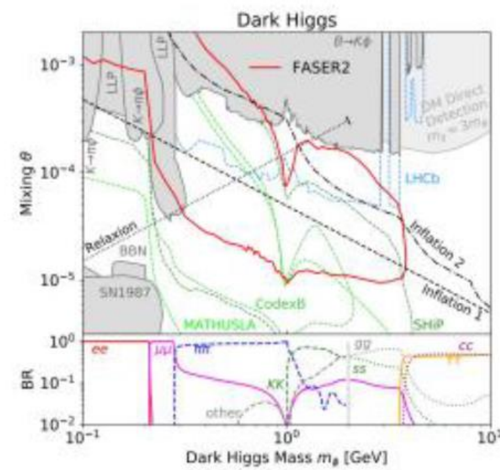
First data: Reconstructed tracks





- FASER2: a scaled up version of FASER with $\sim 100 \times$ the active area
- Broad LLP program probing many models
  - Extending sensitivity to higher masses
- Forward Physics Facility (FPF) will be a dedicated new facility $\sim$ 600 m west of IP1



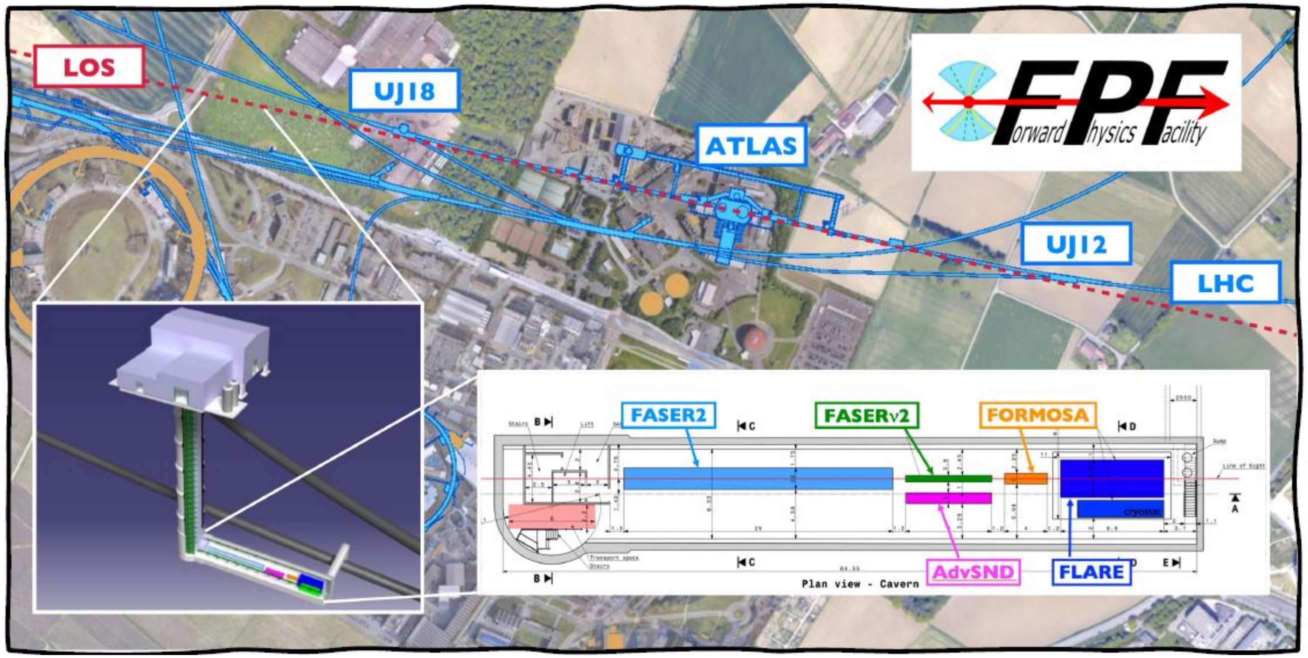


More details on Forward Physics Facility in Felix's Talk

Forward Physics Facility @ LHC

FPF

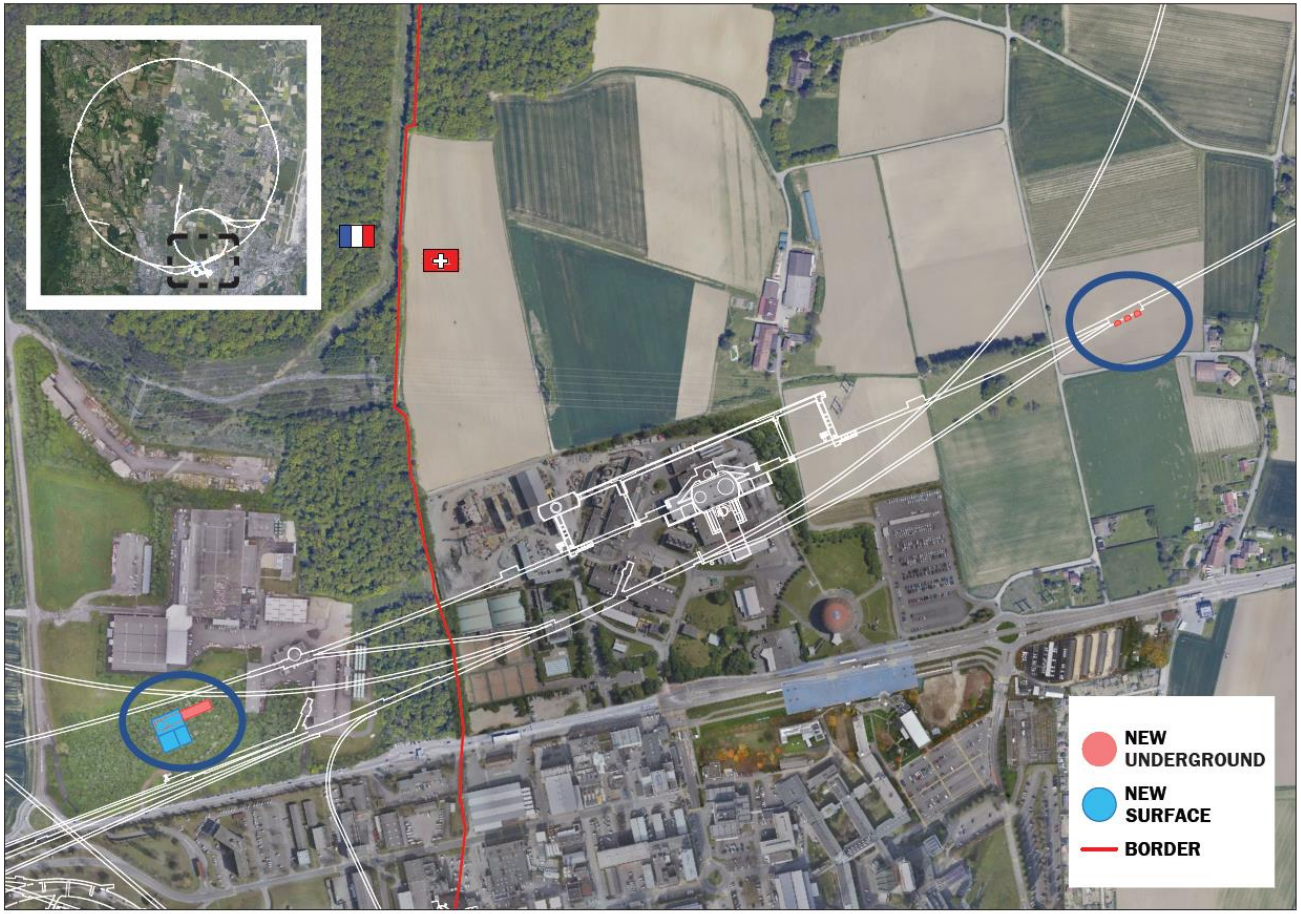
- The Forward Physics Facility (FPF) is a proposed new facility to house several new experiments on the beam collision axis line of sight (LOS) at one of the LHC high luminosity interaction points
- There is a strong and broad physics case for experiments in this location related to:
  - Dark sector searches, neutrino physics and QCD



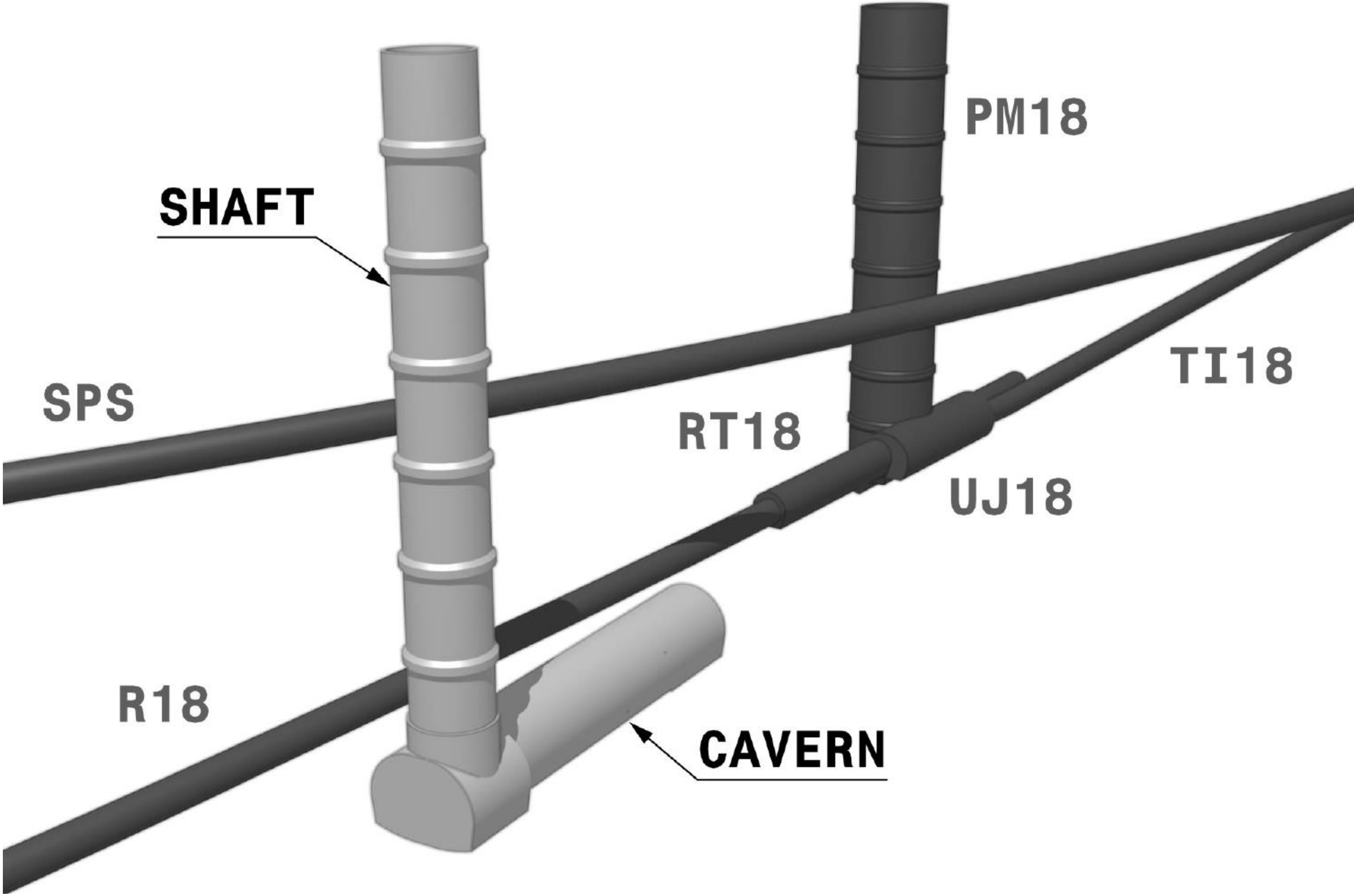
J. Boyd@PBC

Site Selection

K. Balazs, J. Osborne - SCE



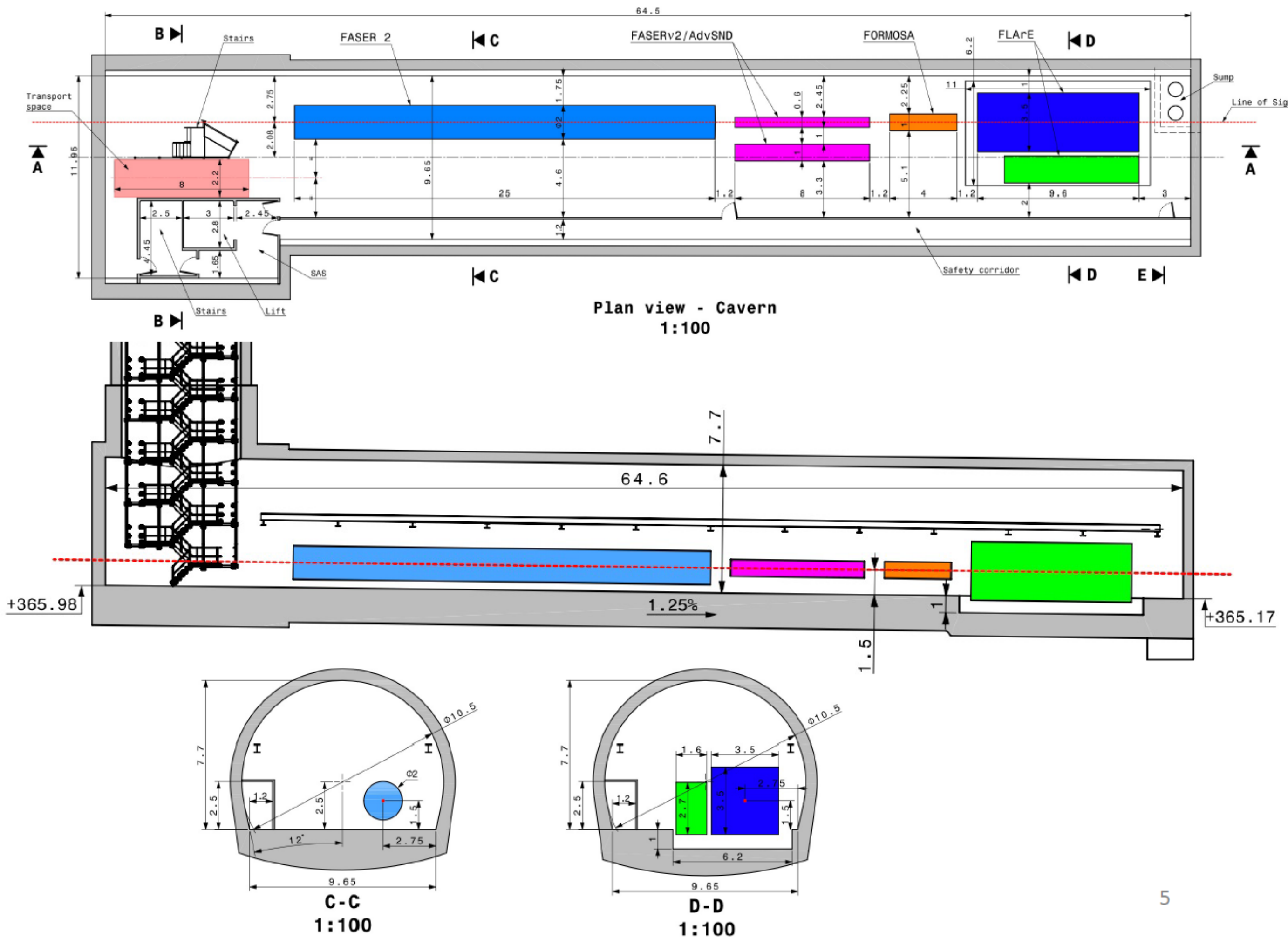
After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points, two options were retained for further detailed study. After a preliminary costing of each we have now converged on the dedicated new facility in the SM18 area as the baseline proposal. This is ~600m from the ATLAS IP (to the west), and is situated on CERN land.



J. Boyd@PBC

FPF Facility:

65m long, 9.7m wide, 7.7m high cavern.
Connected to surface through 88m high shaft (9.1m diameter):
617m from IP1.



J. Boyd@PBC

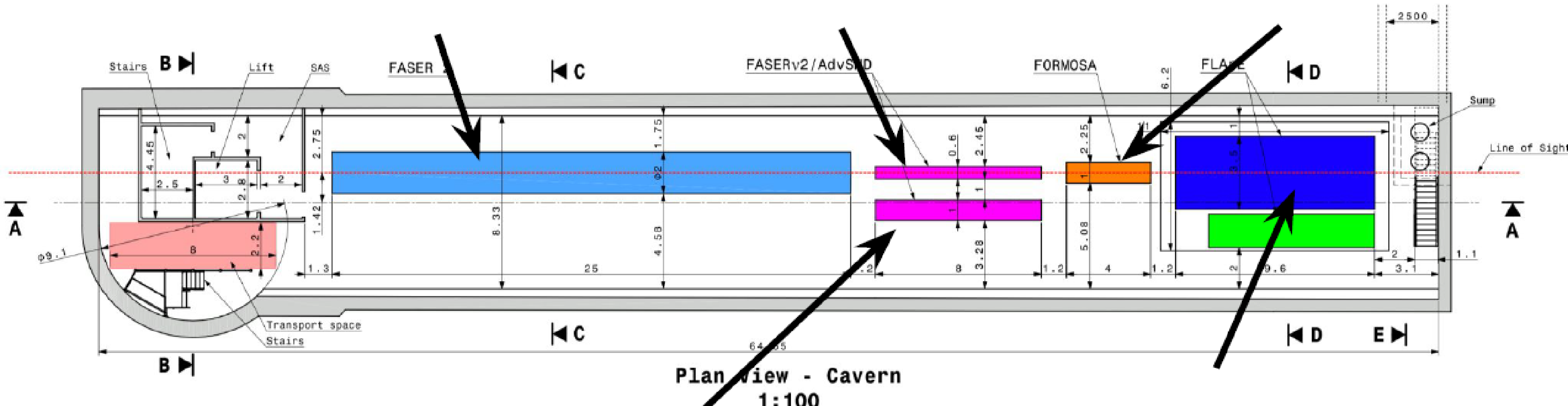
FPF: Experiments.

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

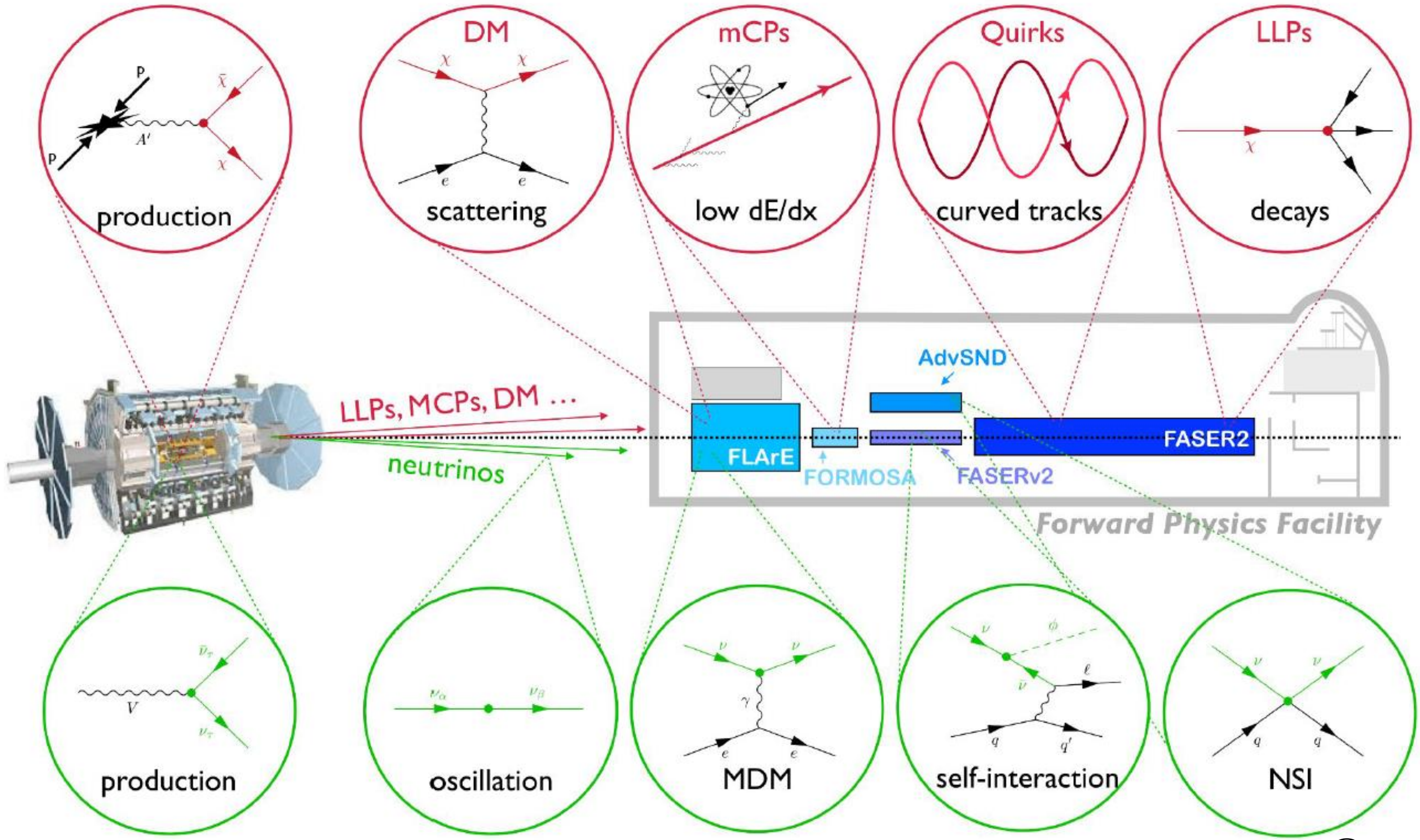
FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

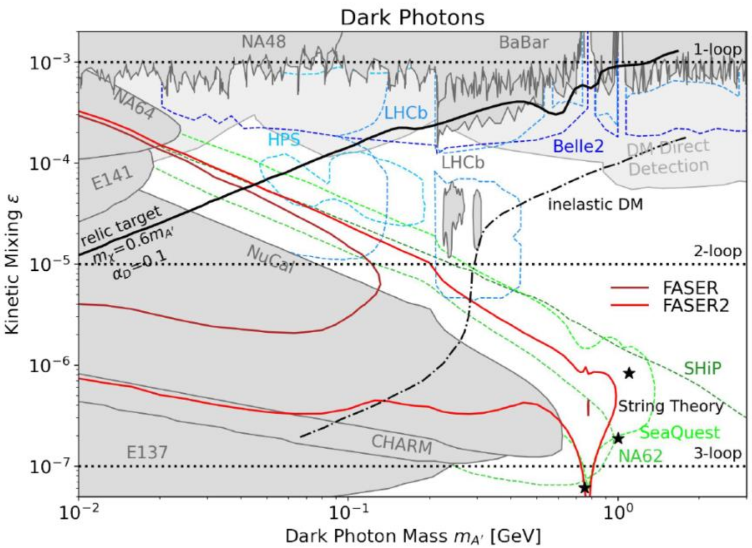
More Searches for BSM Physics



F. Kling@LLP

Long-Lived Particles: Dark Photon.

Dark Photon = gauge boson mixing with photon: $\mathcal{L} \sim -\frac{1}{2} m_{A'}{}^2 A'^2 - \epsilon e q_f \bar{f} \not{A}' f$



Dark Matter Scattering.

mA' > 2mX

↓

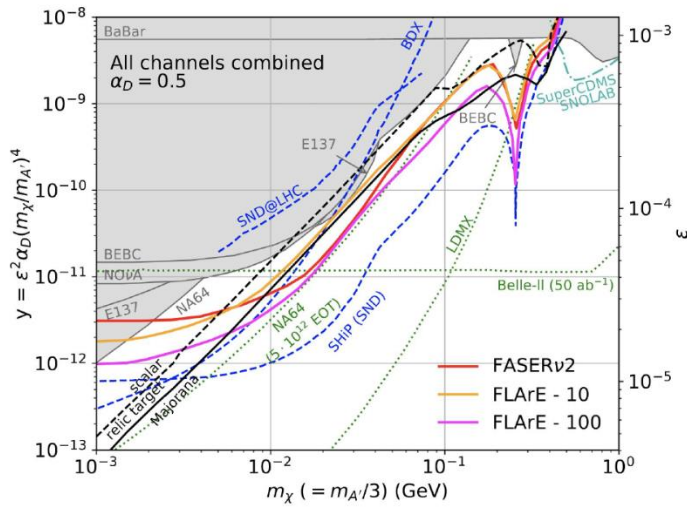
dark photon promptly decays in DM

↓

LHC produces DM beam

↓

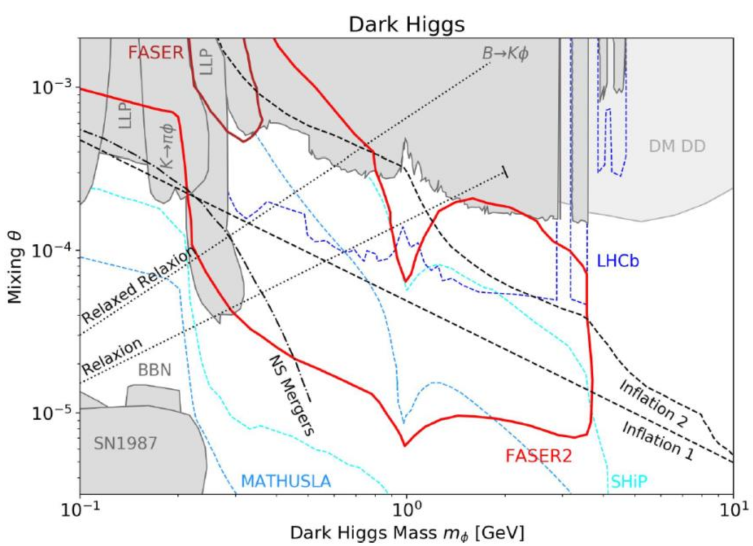
DM scattering in neutrino detector



for more details see: 2101.10338

Long-Lived Particles: Dark Higgs.

Dark Higgs = light scalar mixing with SM Higgs: $\mathcal{L} \supset m_\phi{}^2 \phi^2 + \sin\theta\, y_f \phi \bar{f} f$

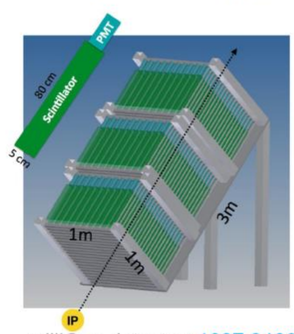


MilliCharged Particles.

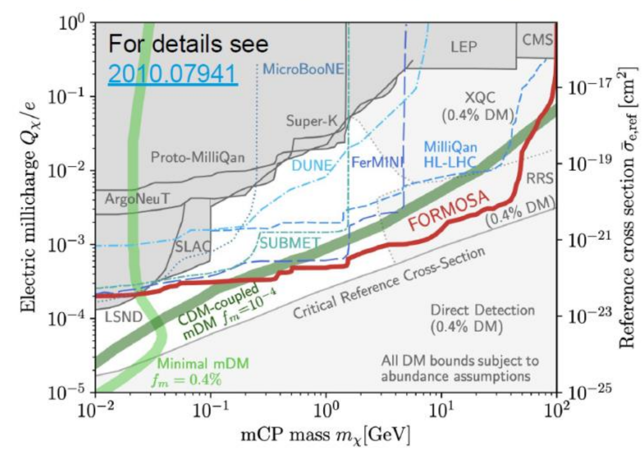
If mA'=0: X is effectively milli-charged with Q=εe → search for minimum ionizing particle with very small dE/dx

MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS

But it was noted that sigal flux is ~100 times larger in forward direction.

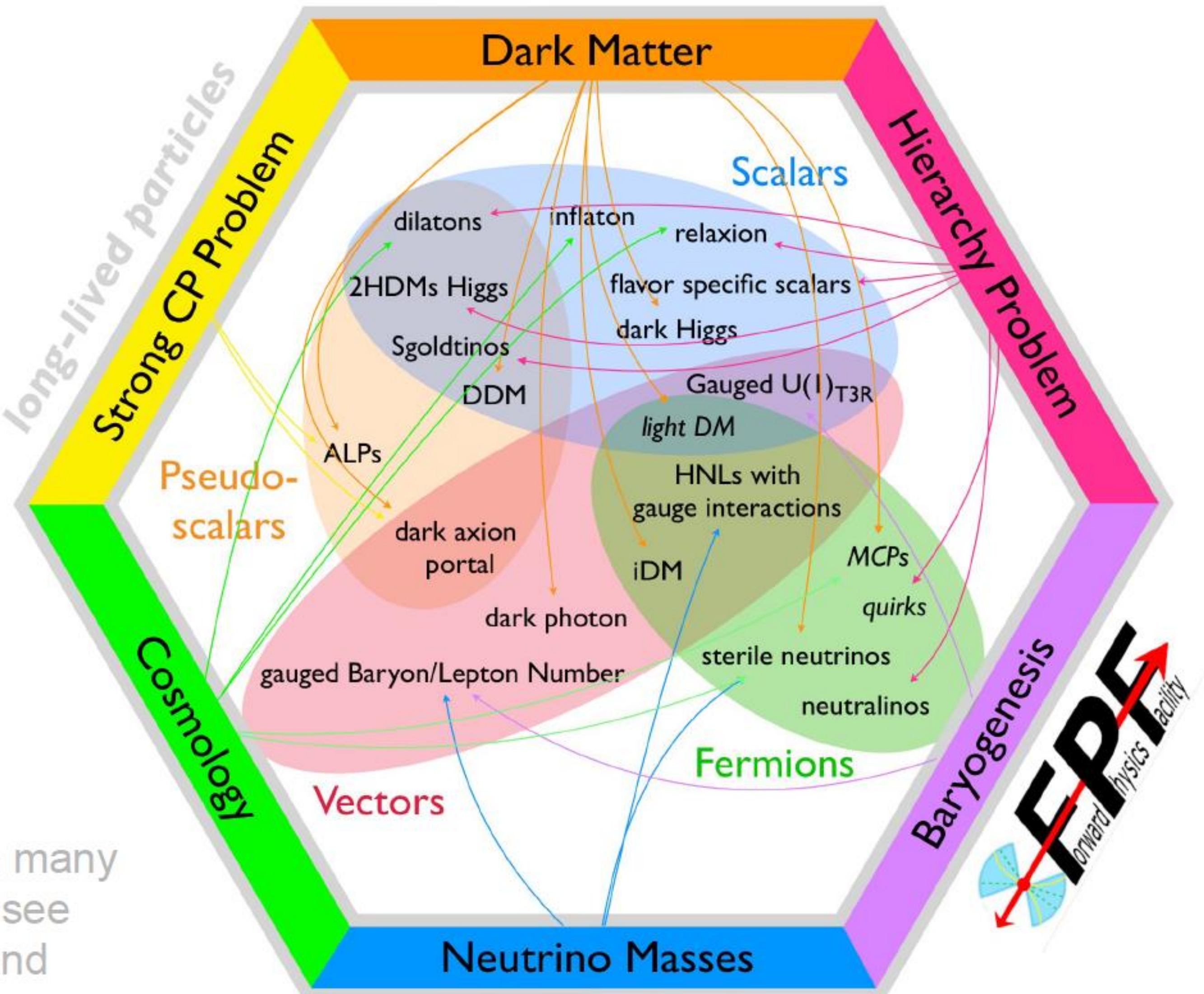


milliQan detector: 1607.04669



F. Kling@LLP

Long-Lived Particles.



For details on many more models see [1811.12522](1811.12522) and [2203.05090](2203.05090).

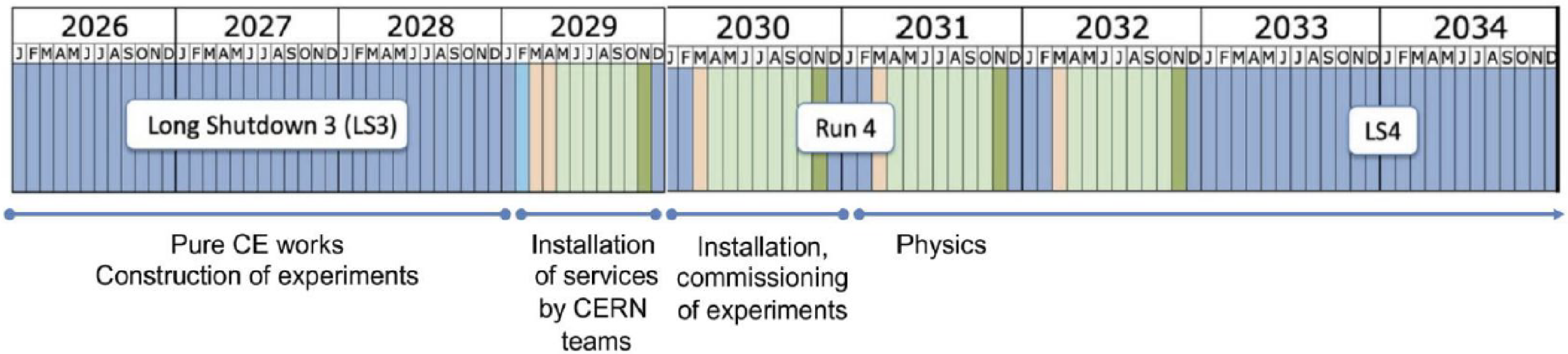
F. Kling@LLP

FPF:Timeline.

radiation protection studies indicate that there is no danger from working in the FPF while the LHC is running

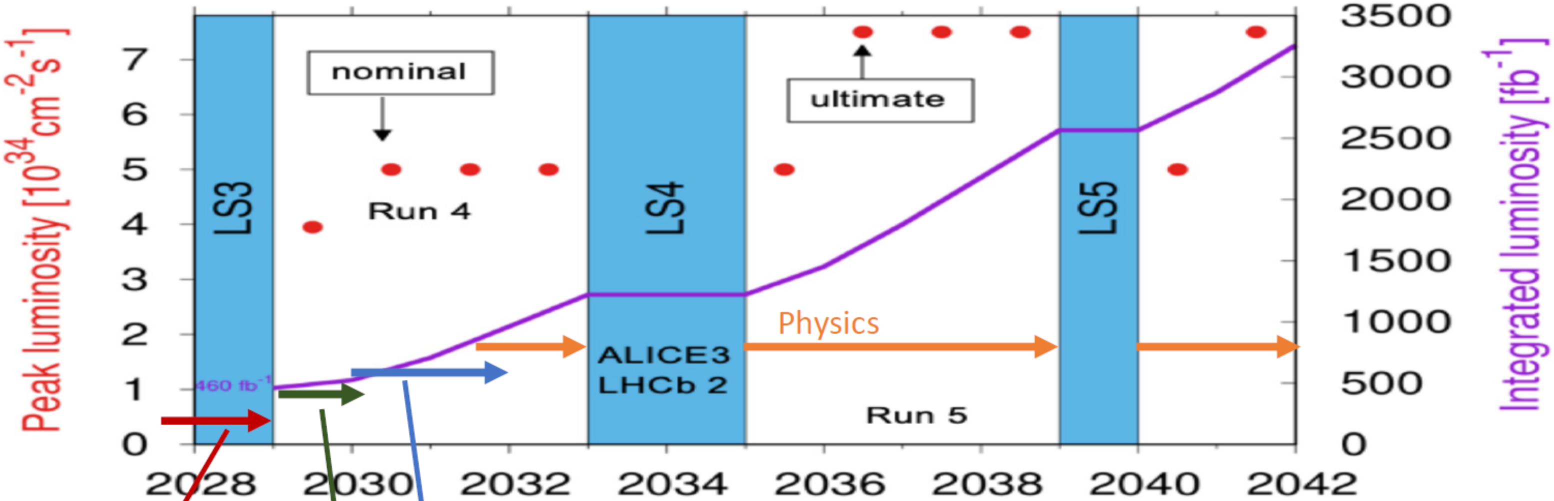
vibration studies indicate that construction of the FPF, installation of services, experiments, will not interfere with LHC operations

possible timeline presented at Chamonix (Jan 2022)



conceptual designs for the FPF and its 5 experiments by mid-2023

Possible FPF schedule



Pure CE works

Installation and commissioning of the experiments

Installation of services (CERN technical teams, busy during LS3)

Such a schedule would:

- Allow physics data taking for most of the luminosity of the HL-LHC
- Not overload CERN technical teams during LS3
- Design of facility would allow different experiments to come online at different times

Time is tight: Need to move fast towards CDR/TDR for funding and approval

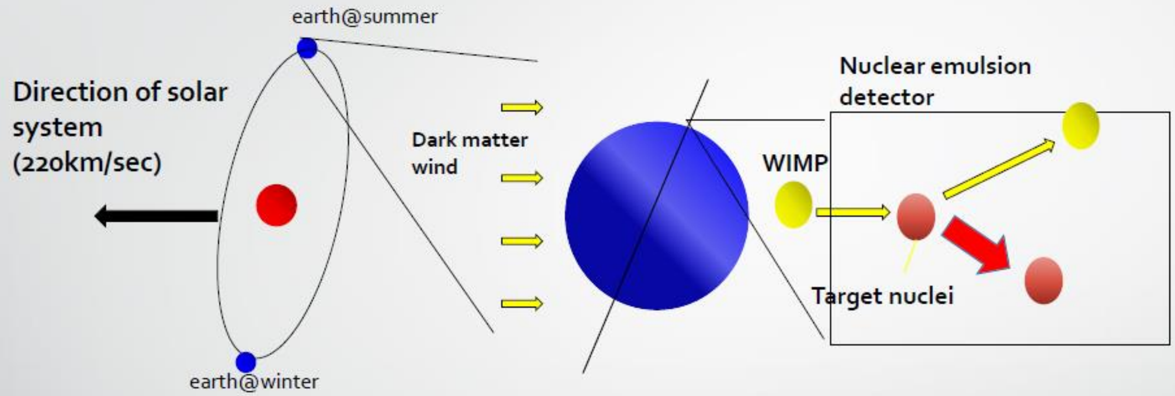
Others

Physics Beyond Colliders

NEWSdm

Nuclear Emulsions for WIMP Search with Directional Measurement

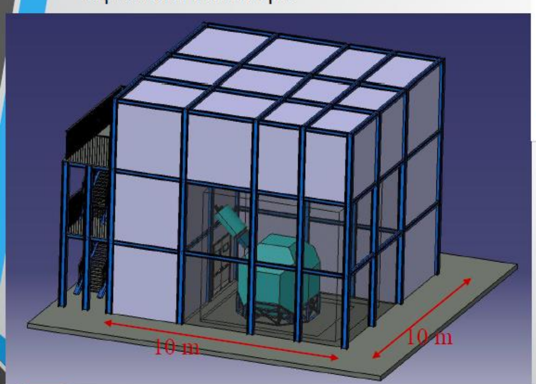
WIMP directional information

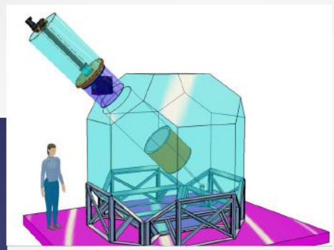


- Direction of the scattered nuclei has strong correlation with WIMP flux and provide a **strong signature** and unambiguous proof of the galactic DM origin
- **Nuclear Emulsion** is a high density solid state media – big mass with a compact detector is possible
- ...rcome the "neutrino floor", ... scattering creates an

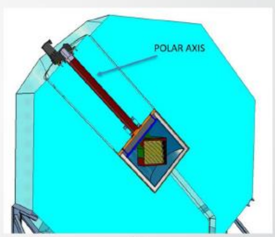
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

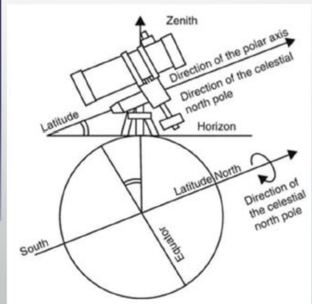


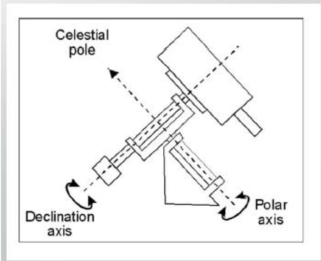


(a)



(b)

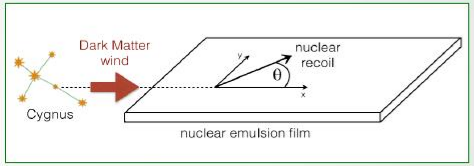


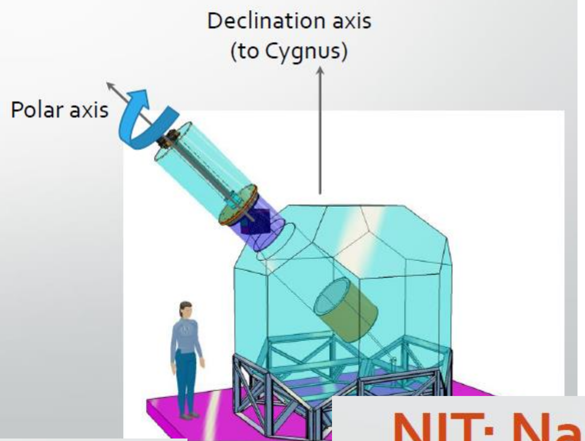


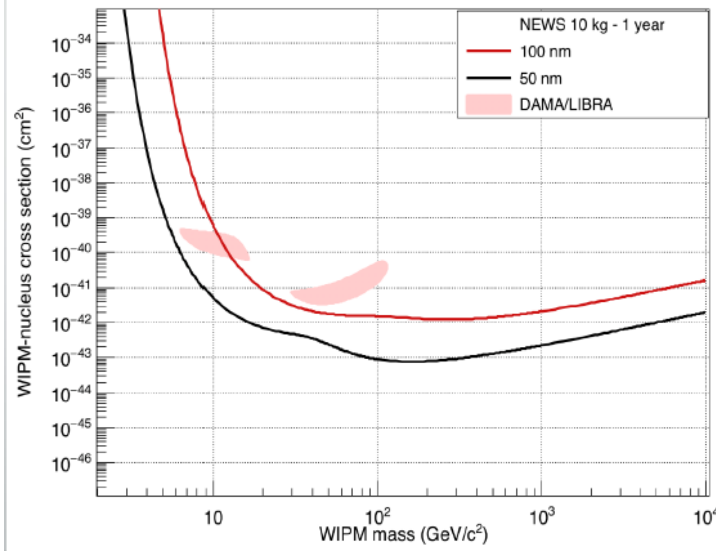
V. Tioukov@Blois

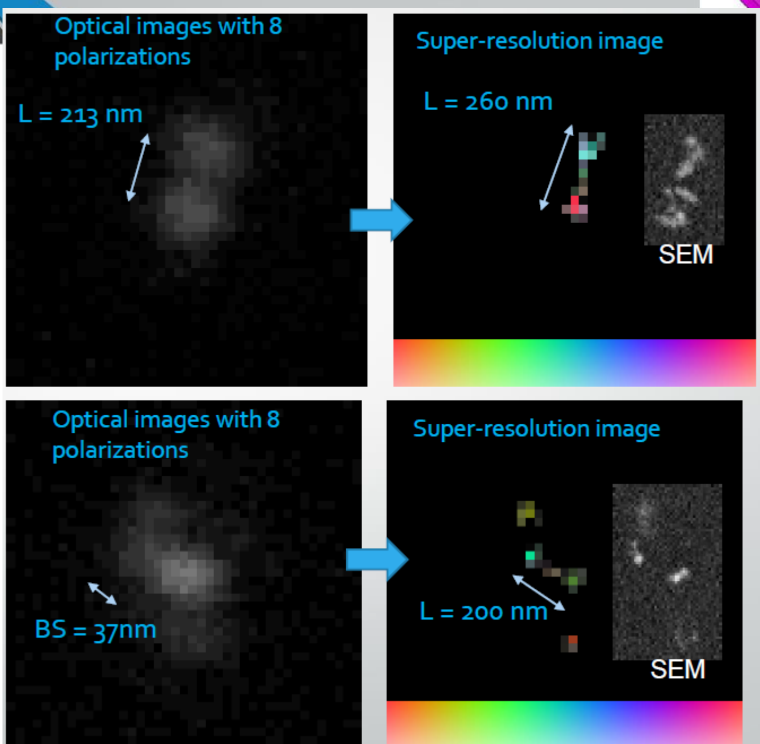
NEWSdm concept

- **Goal**: detect the direction of **nuclear recoils**
- **Target**: nanometric emulsion films acting both as target and tracking detector
- **Background reduction:** neutron **shield** surrounding the target
- **Fixed pointing**: target mounted on **equatorial telescope** pointing to the Cygnus Constellation
- **Location**: underground lab (LNGS)

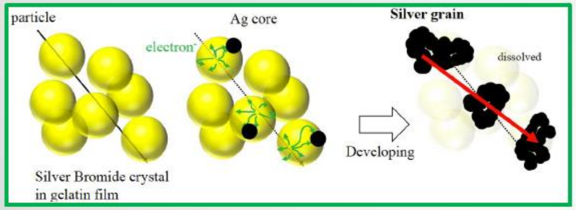








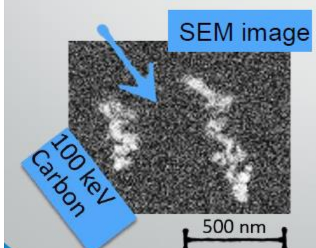
NIT: Nano emulsion Imaging Tracker

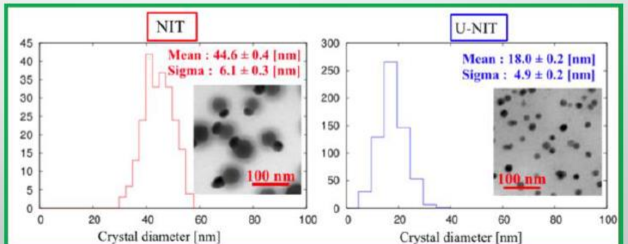


A long history, from the discovery of the **Pion (1947)** to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (**OPERA, PRL 115 (2015) 121802**)

- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce *latent image*
- Chemical treatment make Ag grains visible

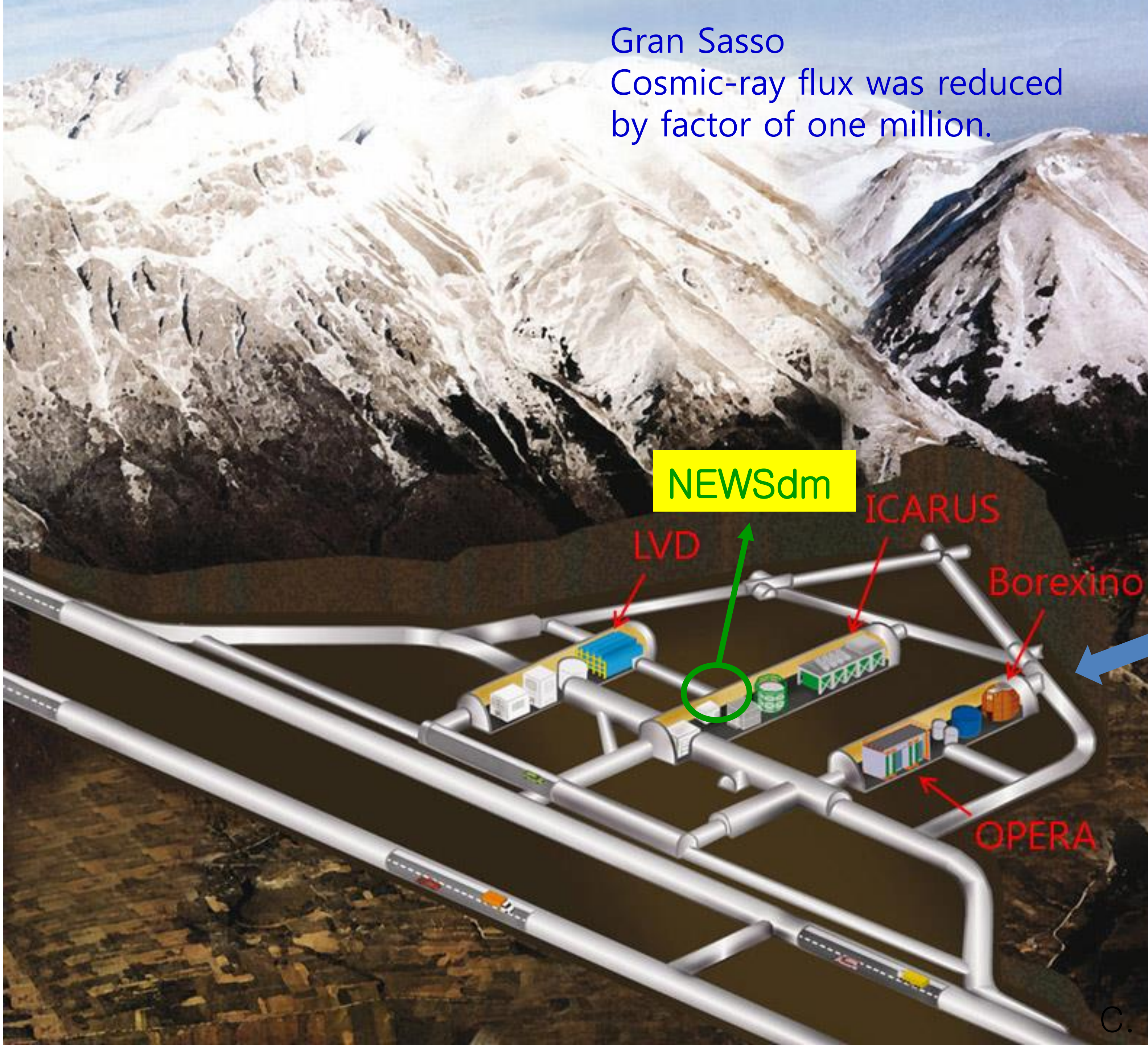
- New kind of emulsion for DM search
- Smaller crystal size





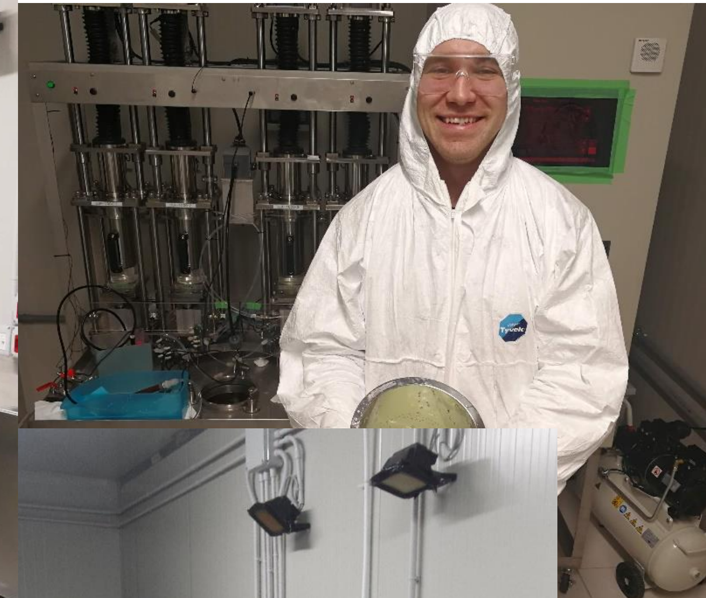
NIT granularity: 71 nm U-NIT granularity: 40 nm

V. Tioukov@Blois



1400 m
underground

CNGS Beam



NIT production test
at Gran Sasso

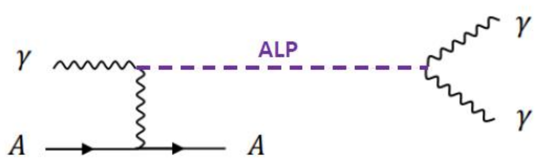
C. S. Yoon@KPS

DAMSA: Dump produced Aboriginal Matter Searches at an Accelerator

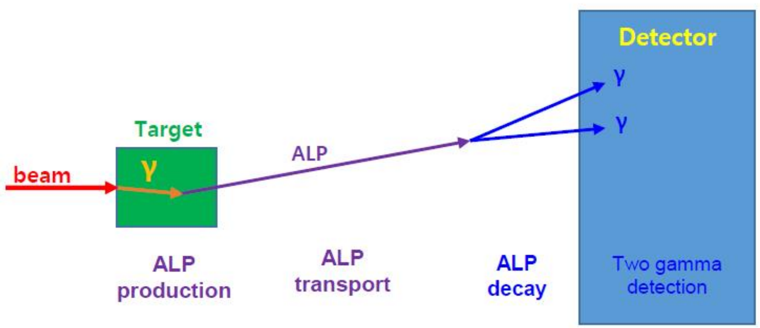
- Fixed target experiment based on intensive proton beam accelerator
- To search for Axion-like Particle (ALP) in sub-GeV energy regime

ALP production by Primakoff process

Production and detection of ALPs



Primakoff process ALP decay



Primakoff process

$$\gamma\,(p_1) + A\,(p_2) \;\rightarrow\; a(k_1) + N(k_2)$$

Production cross-section of ALPs

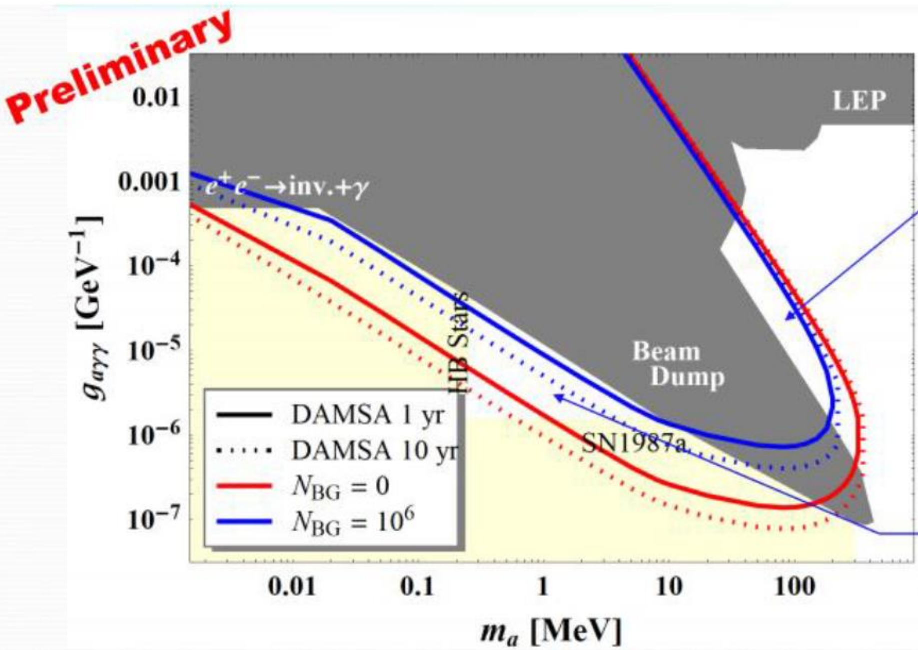
$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$t = (p_1 - k_1)^2 = m_a^2 + E_\gamma (E_a - |\vec{p}_a| \cos\theta)$$

Z: atomic number,
α: fine structure constant
$F(t)$: form factor
$|\vec{p}_a|$: magnitude of the outgoing three-momentum of the ALP at the angle θ relative to the incident photon momentum
E_γ: incident photon energy

Expected ALP sensitivity at DAMSA by Primakoff process

Doojin Kim's talk at Raon User Workshop in 21-23 July 2021, **DAMSA: An Axion-like Particle Search at the RAON Facility**



DAMSA can probe the ALP parameter region that has never been explored.

Short-lived ALPs (high mass)

DAMSA will cover part of the so-called "cosmological triangle" where only (standard) cosmology would constrain.

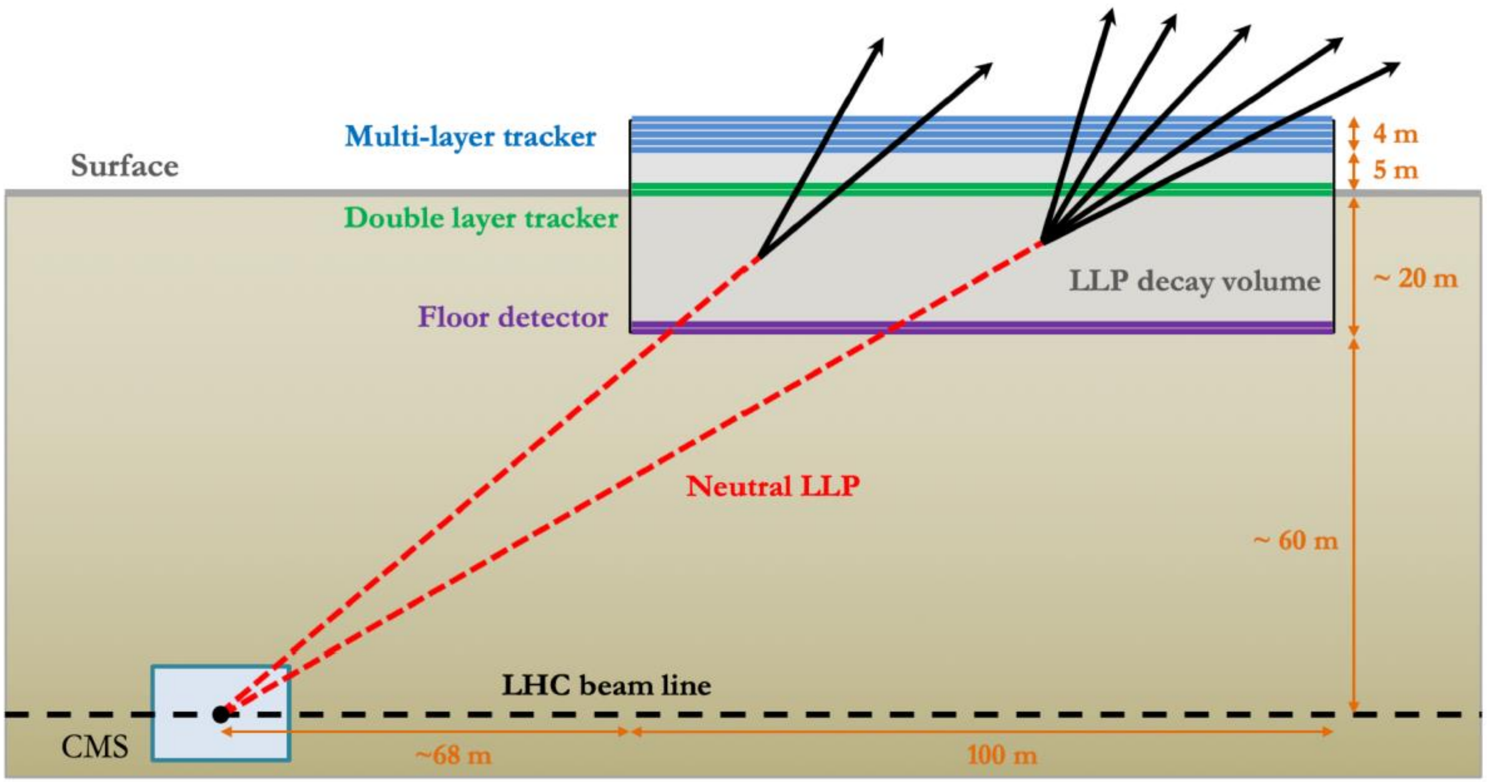
Long-lived ALPs (low mass)

According to above sensitivity, backgrounds treatment is much crucial for low mass ALPs detection.

MATHUSLA

Basic idea

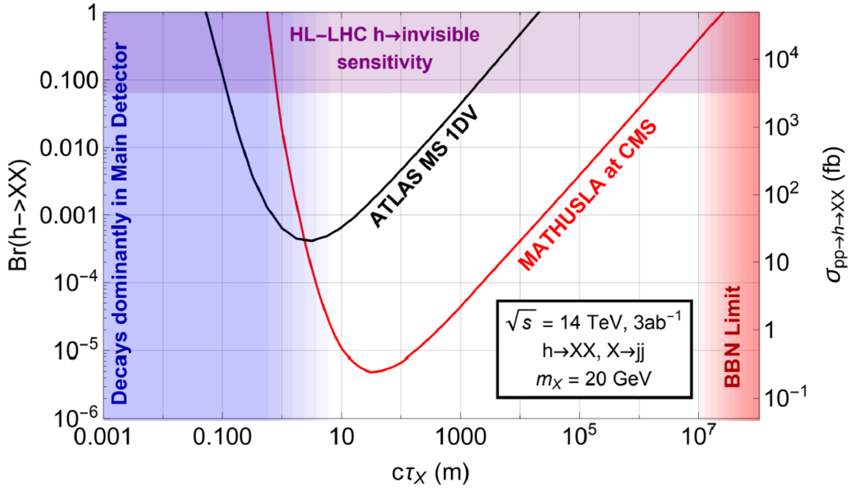
Extremely long-lived, neutral particles need more time to decay than traditional particle detectors can provide



https://mathusla-experiment.web.cern.ch/

Projected sensitivity

SM Higgs boson → neutral, hadronically-decaying LLPs

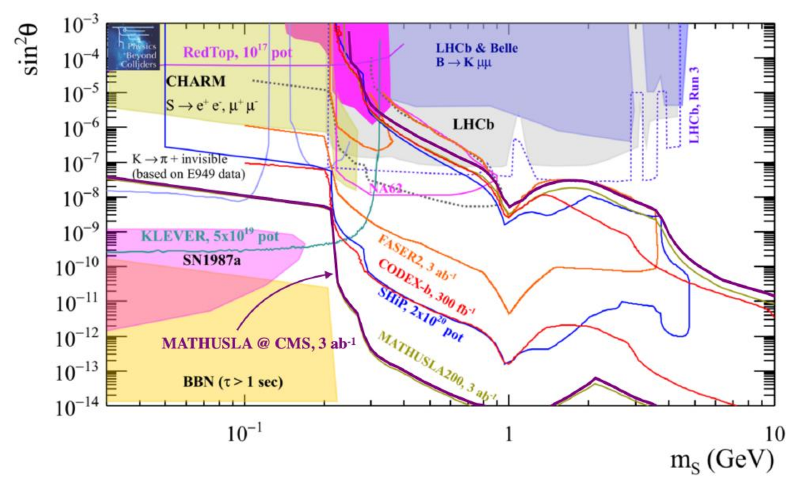


Sensitive to **cross-sections < 1 fb** for lifetimes O(100m)

~1000x increased sensitivity compared to comparable ATLAS searches

Sensitivity comparison

Singlet scalar s mixing with SM Higgs, BR($H \to ss$) = 0.01



Unique sensitivity to **small mixing angles**

especially for larger masses - sensitivity extends out to $m_H/2$

감사합니다.