Forward Physics Facility

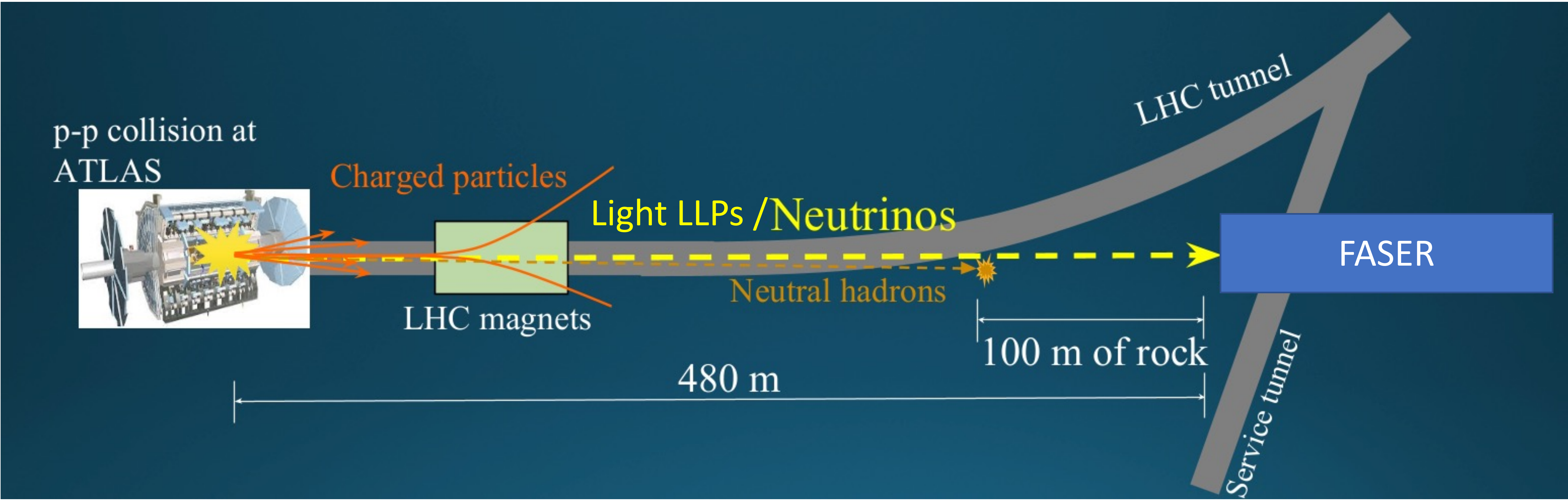
Alan Barr

ICHEP 2024

See also at **ICHEP24**:
FASER TeV Neutrino Results: **Sergey Dmitrievsky**, [Yesterday, 18:15]
FASER BSM physics search results: **Jack MacDonald** Sat 16:45, South Hall 1A

With thanks to Jamie Boyd and Felix Kling for material

Introduction



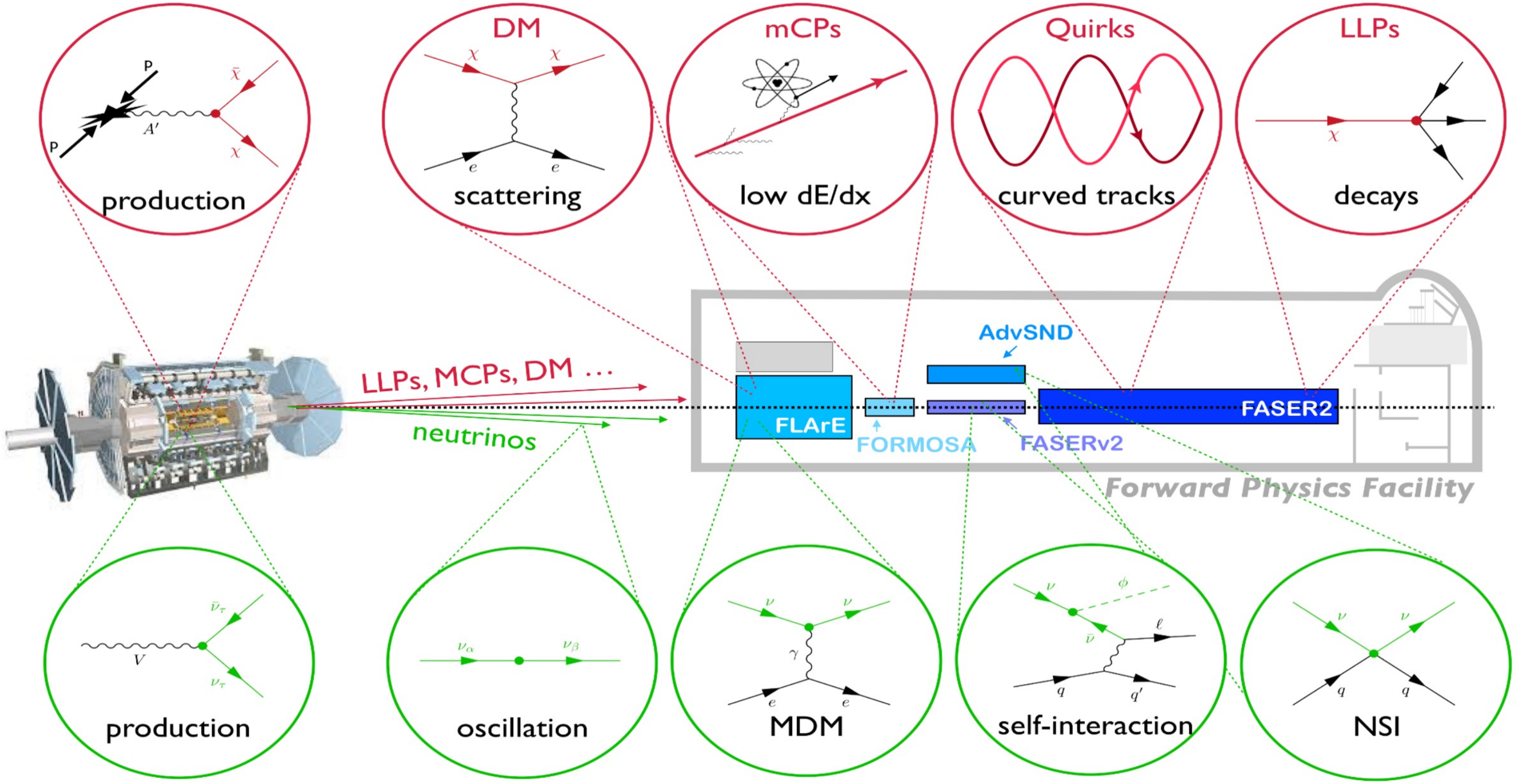
FASER designed to search for new, light, long-lived particles (**LLPs**), and study **neutrinos**.

These are produced in the **decay of light hadrons** which are produced in the LHC collisions.

Light hadron production is very peaked in the **forward direction**, extremely collimated with the beam collision axis line of sight (LOS), hence even small detectors covering the angular region less than a miliradian around the LOS have good physics sensitivity.

Physics Motivation

- The **Forward Physics Facility** has a rich and **broad** physics programme
- Three main physics motivations
  - Beyond Standard Model (BSM) "dark sector" searches
  - Neutrino physics
  - QCD physics



Physics Motivation

- The **Forward Physics Facility** has a rich and **broad** physics programme
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Neutrino physics
  - QCD physics

- In order to fully benefit from the increase in luminosity from the HL-LHC, the FPF will allow:
  - **Longer detectors** to increase target/decay volume
  - **Wider detectors** to increase sensitivity to heavy flavour produced particles
  - Space for **new detectors** with complementary physics capabilities

BSM Physics

- The FPF experiments have **strong sensitivity** in all of the dark sector PBC benchmark models
- In some of these the sensitivity is not as strong as that of SHiP
- There are several classes of models where the FPF is **more powerful than SHiP**

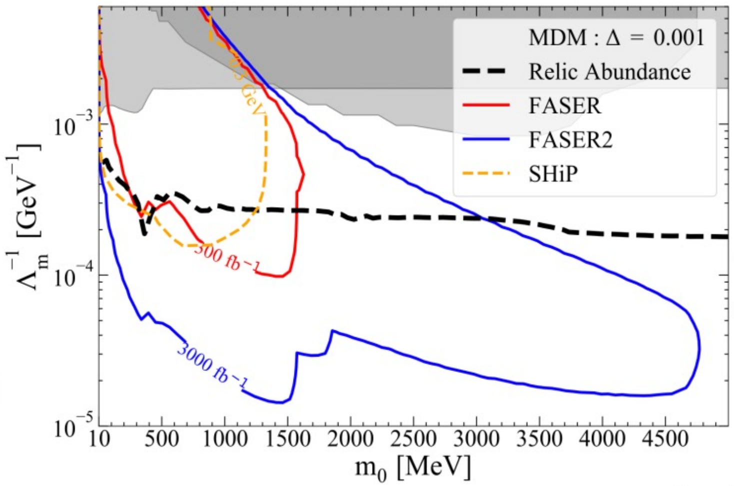
LLPS FROM COMPRESSED SPECTRA

- LLPs can result from weak couplings.
- But they can also arise generically from compressed spectra (e.g., inelastic DM), where decays are phase-space suppressed by degeneracies.
- In this case, decays $\chi_1 \to \chi_0 \gamma$ lead to very soft photons that can be difficult to detect.
- But these are boosted at the LHC by $\gamma \sim 1000$, FASER2 can detect GeV particles with even ~MeV mass splittings, thermal relic target.
- Difficult at SHiP (sensitivity contour assumes E_γ threshold of 300 MeV, 2 10^{20} POT).

m_1, m_0, 0: $\chi_1 \to \chi_0 \gamma$

$$\Delta \equiv \frac{\Delta m}{m_0} \equiv \frac{m_1 - m_0}{m_0}$$

$$\mathcal{O}_m = \frac{1}{\Lambda_m} \bar{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$



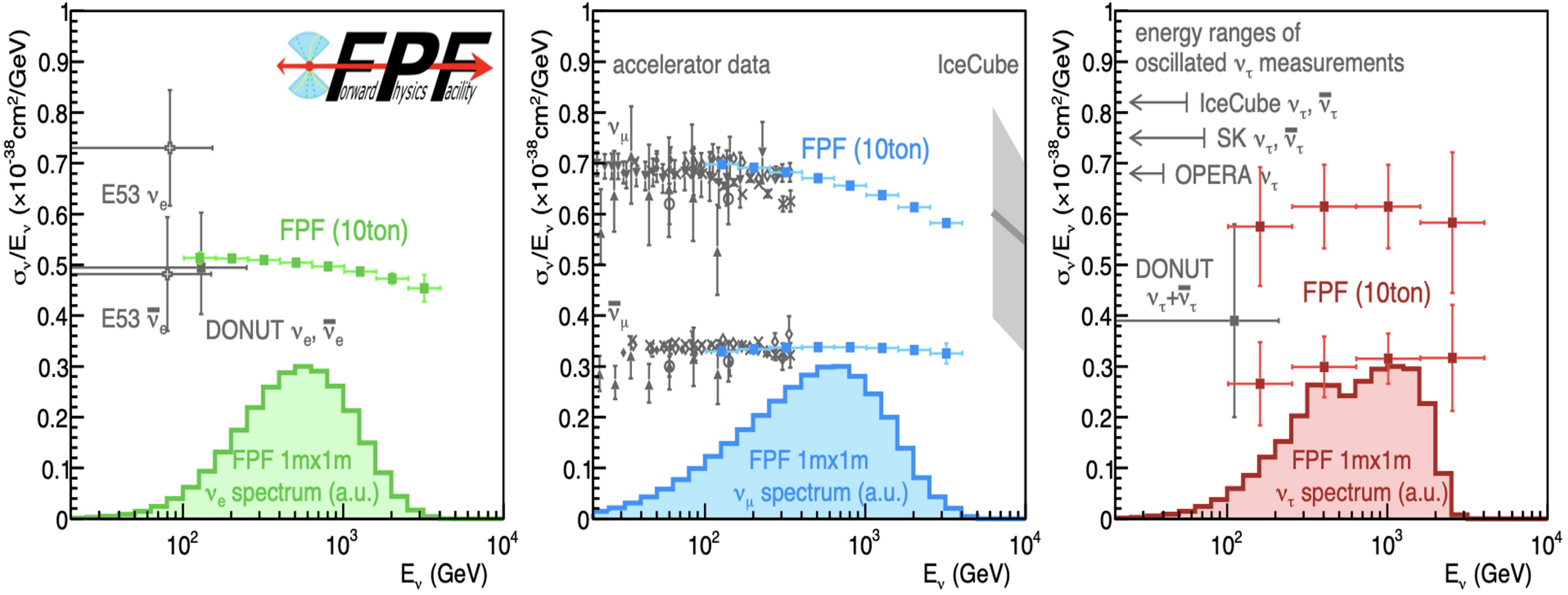
Dienes et al. (2023)

25 March 2024 Feng 7

Further examples in the backup slides

Neutrinos at the FPF

LHC provides a **strongly collimated** beam of **TeV energy neutrinos** of **all three flavours** in the far forward direction.



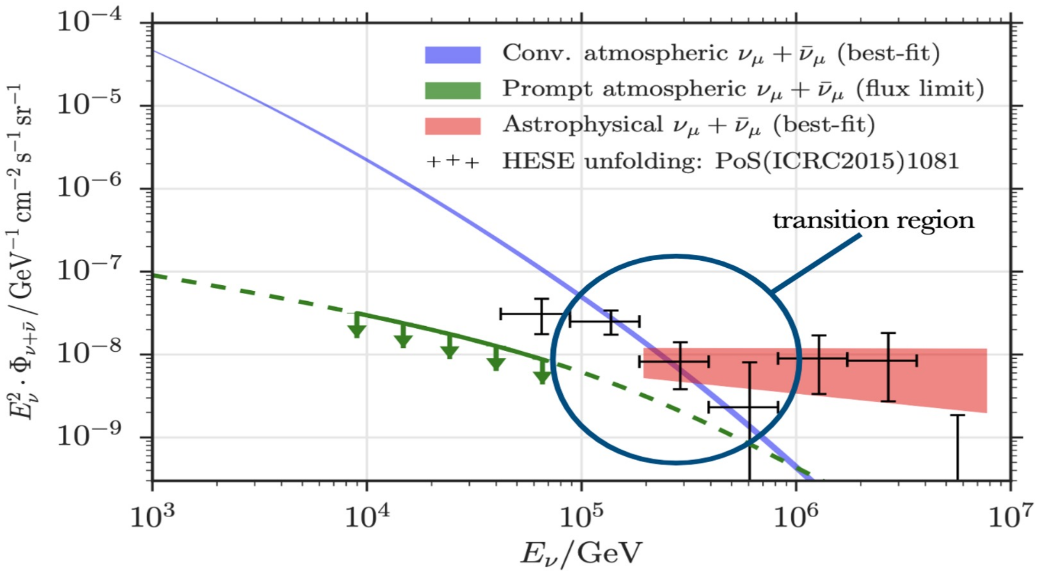
Proposed FPF experiment have potential to detect O(1M) neutrinos:
O(10^6) muon neutrinos, O(10^5) electron neutrinos, O(10^4) tau neutrinos

Application: Astroparticle Physics

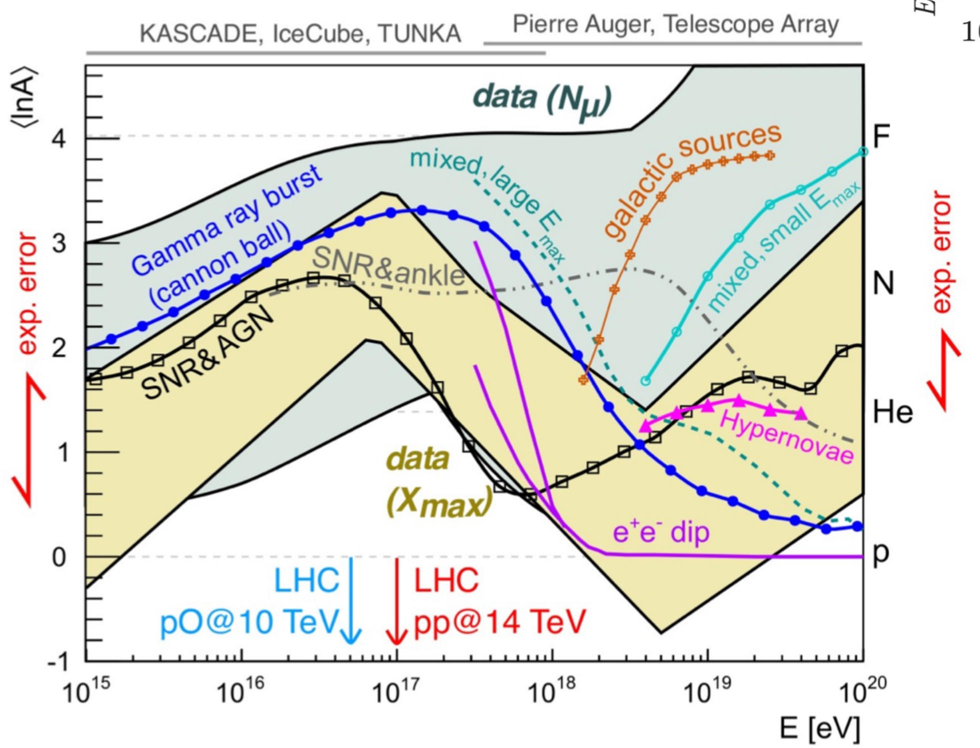
Forward **charm** production at the LHC

↓

Constraints on **prompt atmospheric neutrino flux** at IceCube



https://arxiv.org/pdf/1201.0018



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

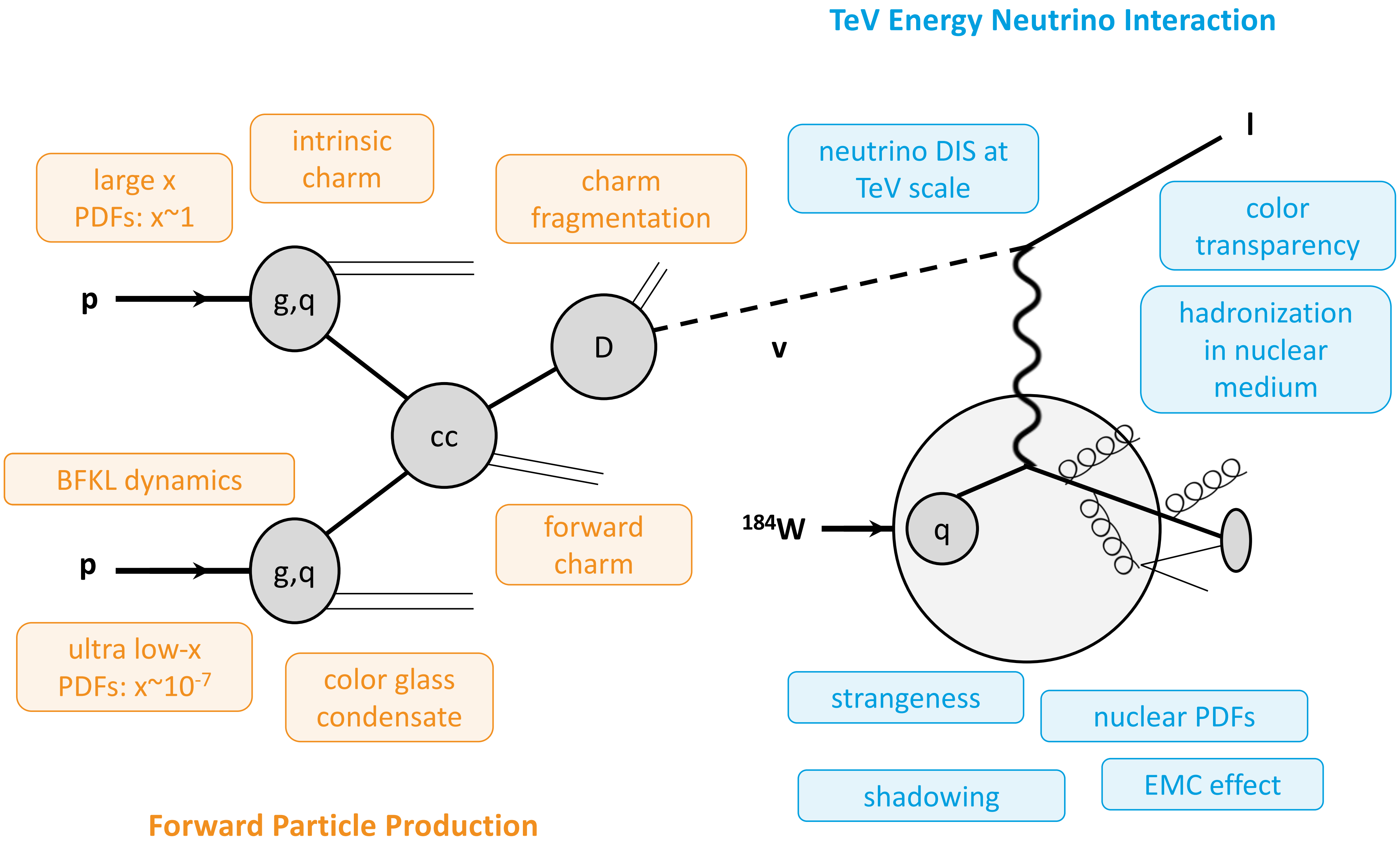
cosmic ray muon puzzle:

observed excess of muons compared to hadronic interaction models

forward pion/kaons fluxes will provide crucial input

More information on astro links: CERN Seminar by **Subir Sarkar**

Application: QCD



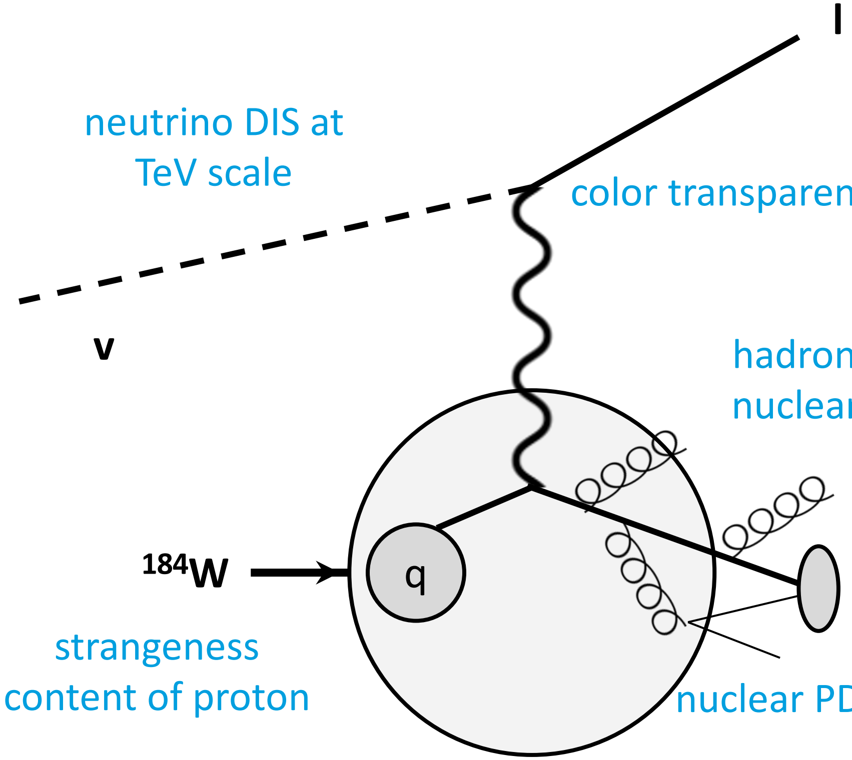
Neutrino DIS at the FPF

Collider Neutrino Experiments
are a **Neutrino-Ion Collider**
at EIC center of mass energies

neutrino DIS at
TeV scale

color transparency

hadronization in
nuclear medium



strangeness
content of proton

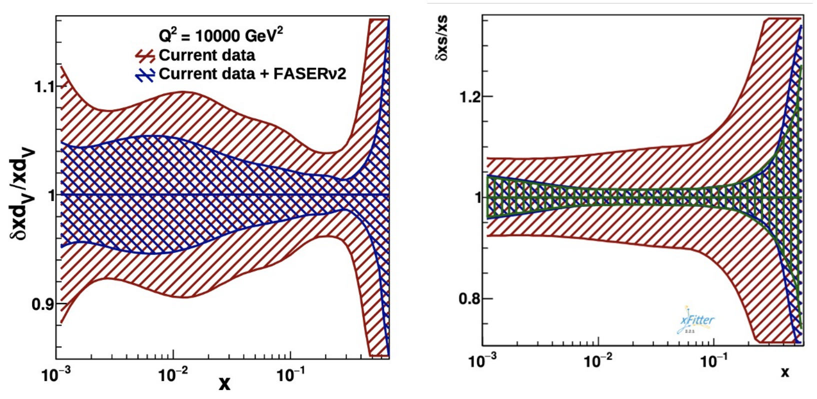
nuclear PDFs

shadowing

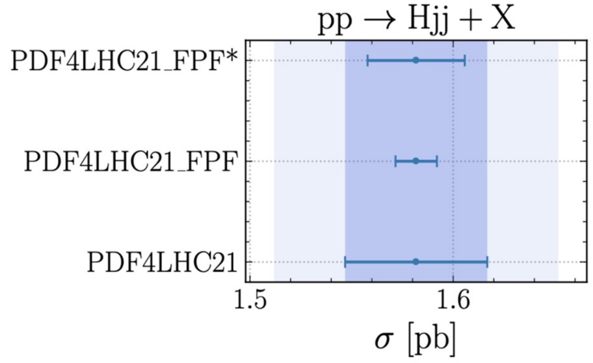
EMC effect

neutrino DIS data will **improve PDFs**

[FPF, P5 Input] [Cruz-Martinez et al. 2309.09581]



reduced PDF uncertainties for
many LHC processes

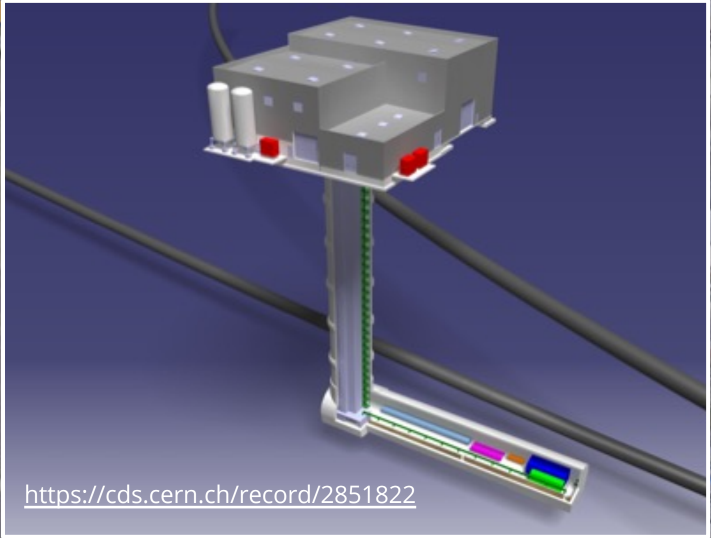


breaks PDF/BSM degeneracy for main LHC experiments

[Rojo, FPF7 Talk]

FORWARD PHYSICS FACILITY

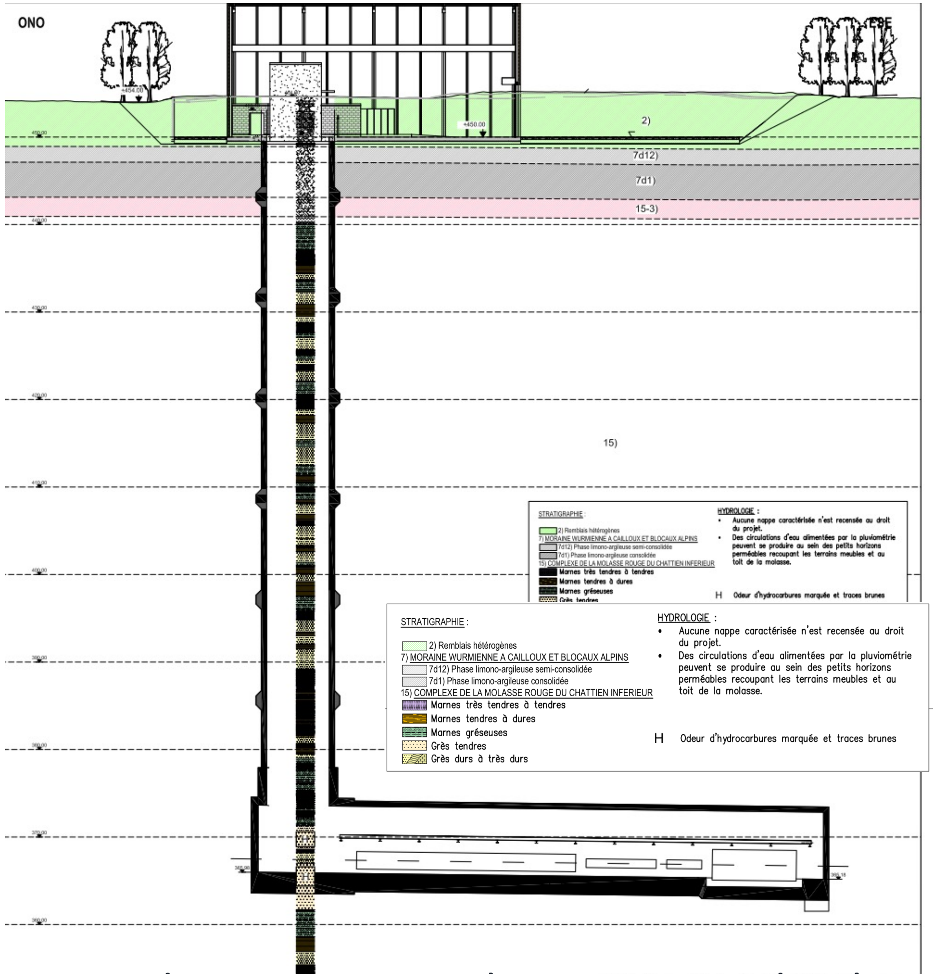
- A comprehensive site selection study by the CERN Civil Engineering group has identified an ideal location ~600 m west of ATLAS.

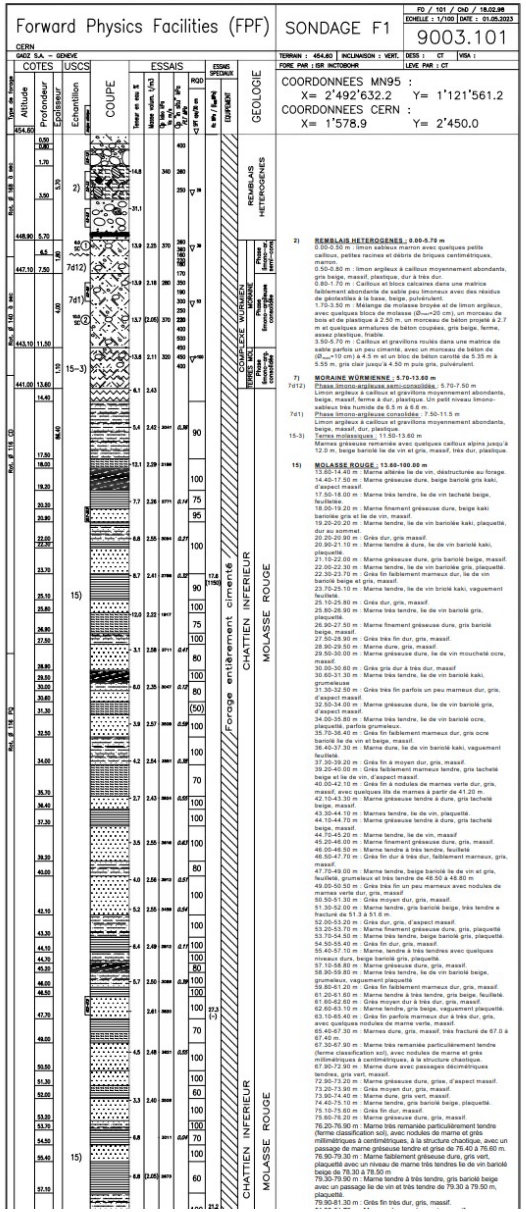


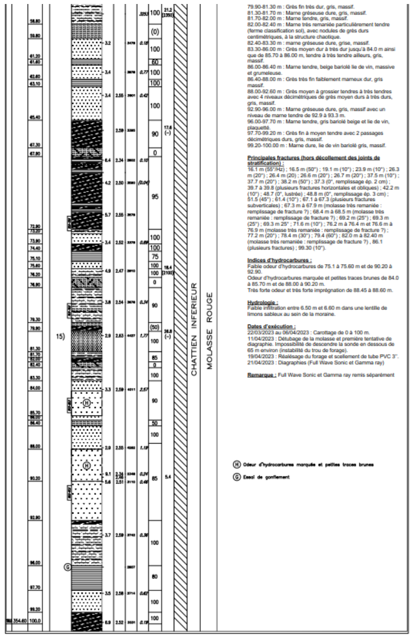
- The site is on CERN land in France
- The cavern is 65 m-long, 9 m-wide/high
- Shielded from ATLAS by 200m of rock
- Disconnected from LHC tunnel
- Cost: ~CHF 40M
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

J. Phys. G 50 (2023) 030501, 1-410
https://cds.cern.ch/record/2851822/

FPF CE Site Investigation Works





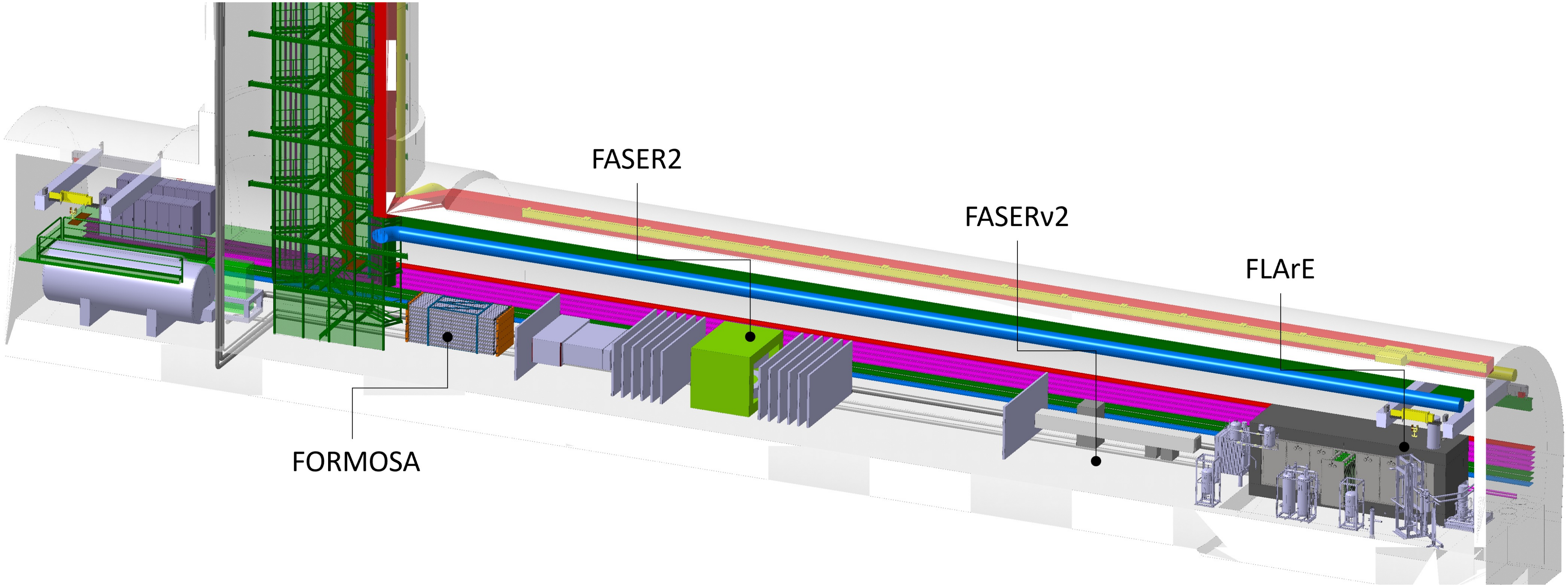


- 20cm diameter core taken to 100m depth at proposed FPF location
- Detailed geological study of core carried out
  - No showstoppers identified
  - Area looks **good for excavation**

FPF Experiments

J. Phys. G 50 (2023) 030501, 1-410

- At present there are **4 experiments** being designed for the FPF
  - Diverse technologies optimized for particular SM and BSM topics
  - FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$
- Experimental layout being optimised
  - Many **opportunities** for new groups

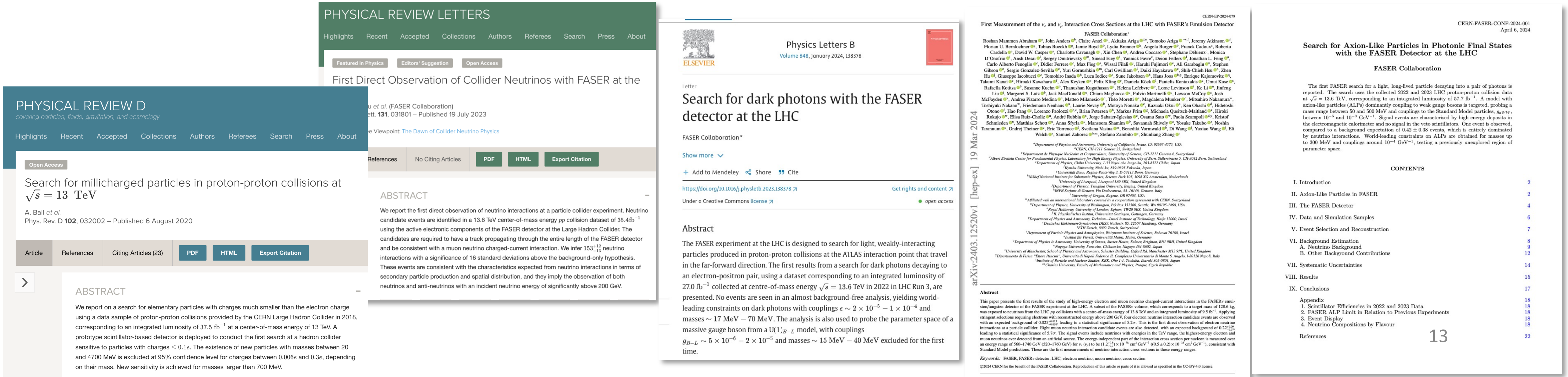


FPF Experiments

J. Phys. G 50 (2023) 030501, 1-410

- At present there are **4 experiments** being designed for the FPF
  - Diverse technologies optimized for particular SM and BSM topics
  - FPF covers η > 5.5, experiments on LOS cover η ≳ 7
- Experiment still in early design phase
  - Many **opportunities** for new groups
- All but one of the proposed FPF experiments have pathfinder versions **already running** at the LHC
  - FASER, FASERν, milliQan
  - Physics results from these experiments give confidence that the FPF physics potential can be realized

Phys. Rev. D **102**, 032002
Phys. Rev. Lett. **131**, 031801
Phys. Let B, **848**, 138378
arxiv: 2403.12520
CERN-FASER-CONF-2024-001



FASERν2 detector overview

Emulsion tungsten neutrino detector, scaled up version of **FASERν**.
20tonne target mass:
- 80x20cm^2 in transverse plane (64x25cm^2 also under consideration)
- 8m long
- 3300x 2mm thick tungsten plates interleaved with emulsion film

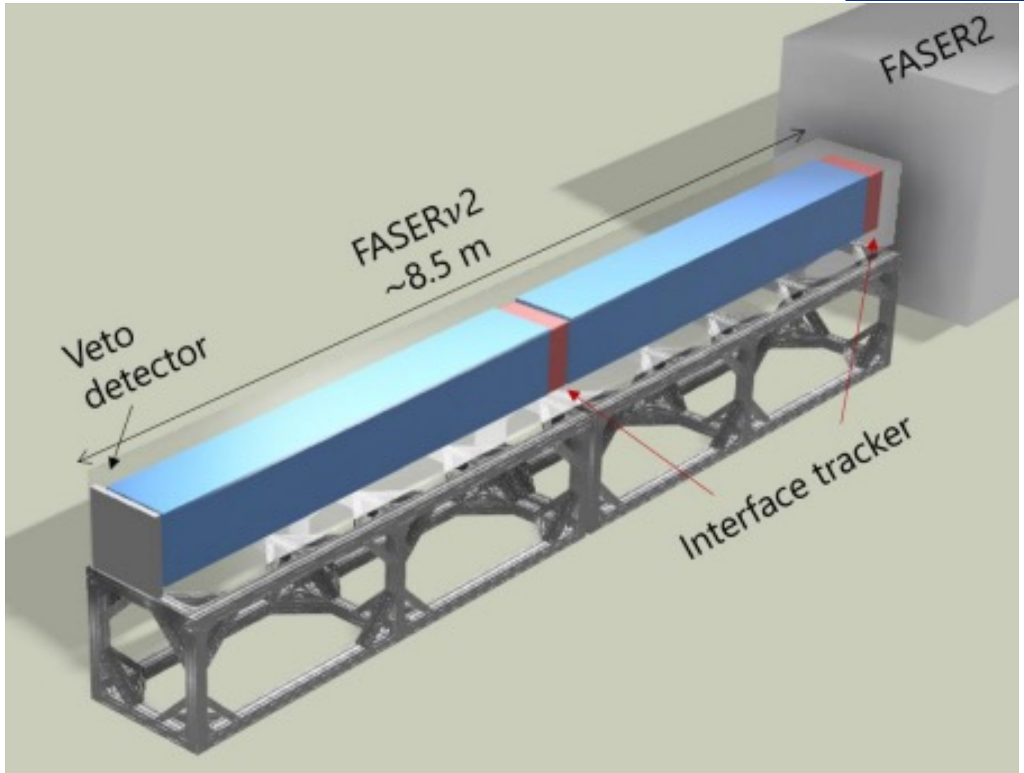
Electronic detectors to allow to **timestamp** events and connect muons from neutrino interactions with those reconstructed in the FASER2 spectrometer (for charge/momentum measurement).

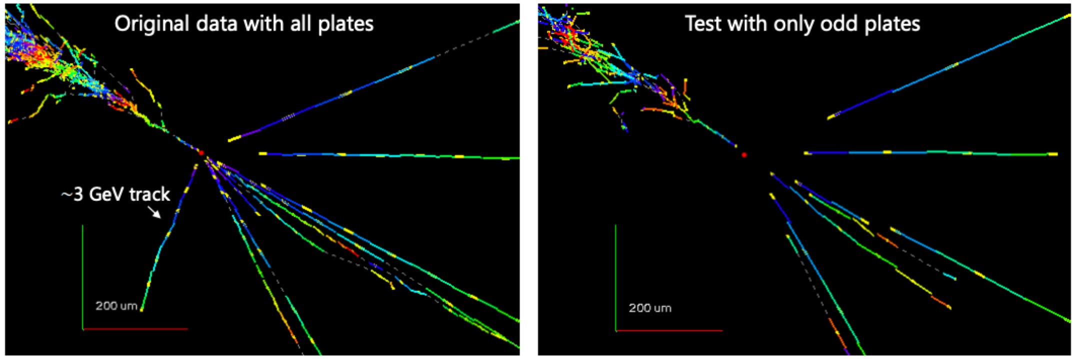
Emulsion needs to be **replaced** with track occupancy of O(10^5) tracks/cm^2 (about 2months of HL-LHC running)

To save cost would like to improve this to have one set of emulsion per year:
- reduce track multiplicity by factor of 3 with **sweeper magnet**,
- or **improve tools** to allow analysis with higher occupancy

Under study…

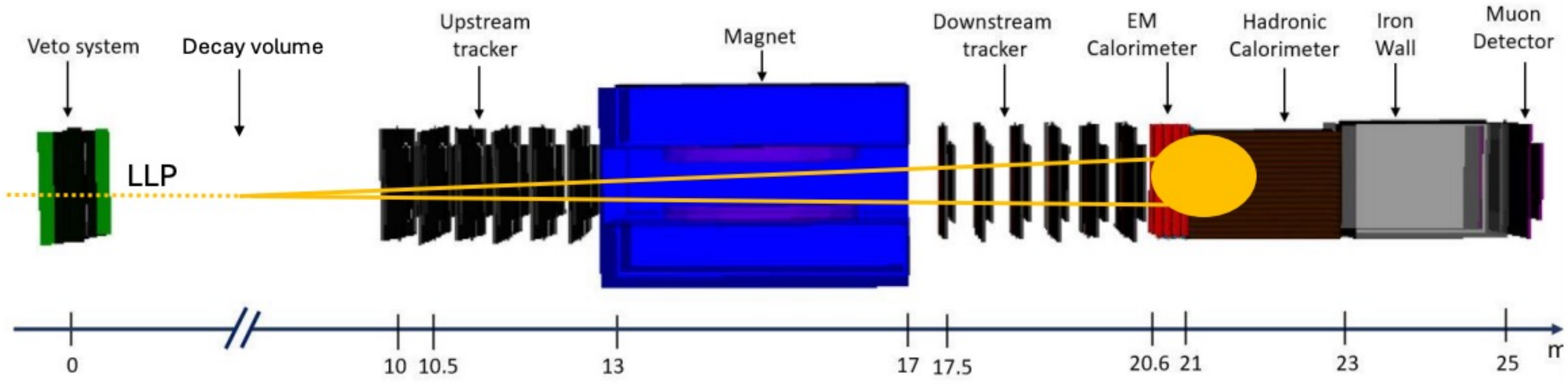
Several testbeam studies and R&D ongoing related to:
- Detector assembly
- Emulsion film optimization (long term operation, higher track occupancy)
- Analysis tools (re-reconstruct FASERν data skipping every-other-film to mimic 2mm thick tungsten)





FASER2 detector overview

FASER2 scaled up version of **FASER** experiment.
Designed to search for decaying **BSM LLPs** (**100x larger** transverse size to FASER, and 7x longer decay volume) and to measure charge/momentum of muons from **neutrino interactions** in FLArE and FASERv2)

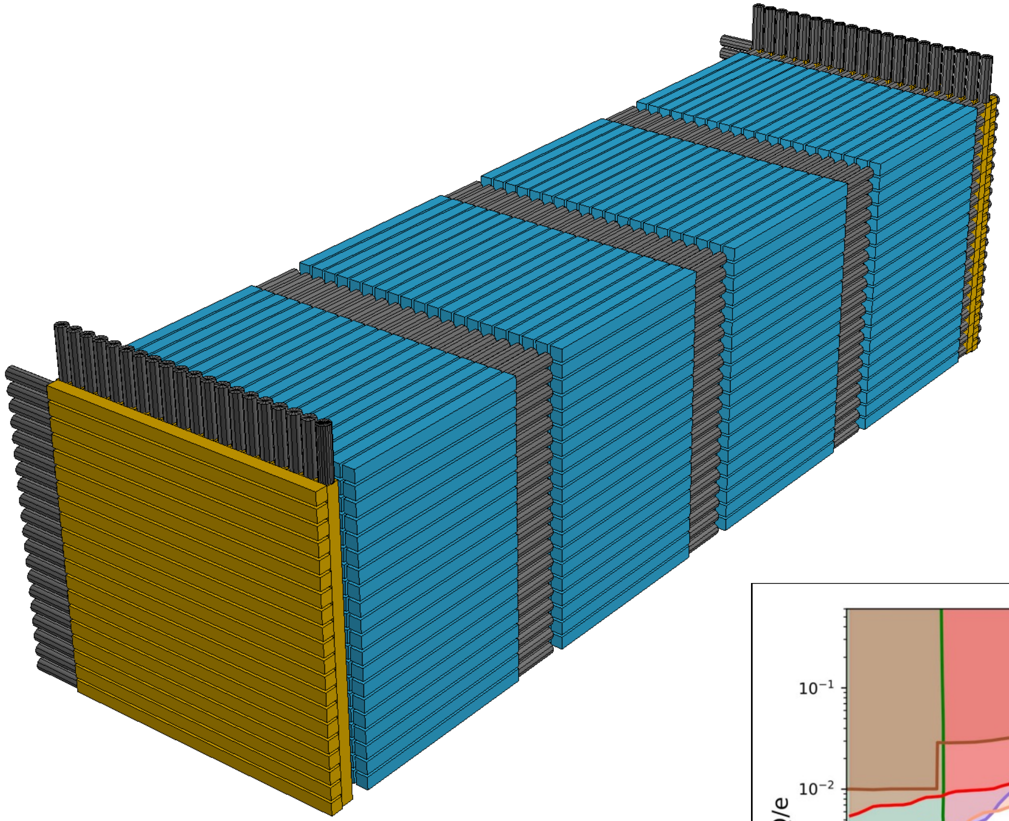


Larger transverse size => need to use to different technologies than in FASER:
Investigated different options for tracking detector technology and magnets.
Baseline tracker – **SciFi tracker** (maybe able to re-use LHCb modules removed in LS3 depending on timing).
Two options for magnet:

- Custom made **super-conducting dipole** (2Tm bending power 1.7x1.7m^2 square air-core apperture):
    - Prelimiary quote from Toshiba: 4.1MCHF 3-4y lead-time
- 4 off-the-shelf **crystal-puller magnet** units (2Tm (central) bending power 1.6m diameter air-core apperture):
    - Prelimiary quote from Toshiba: 2.3MCHF 1-2y lead-time

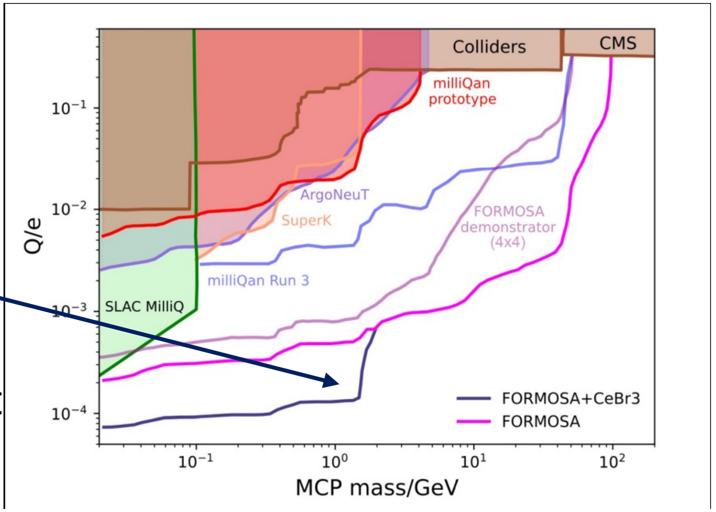
FORMOSA detector overview

FORMOSA is a **scintillator** based **millicharged particle** detector (similar to the running **miliQan** experiment).
Idea is to see low scintillation signal in multiple bars pointing at IP.
Baseline design: 20x20 array of scintillator bars (with surrounding scintillators to veto backgrounds)



At start of 2024 a small **demonstrator detector** was installed in TI12 (FASER location) to study the performance with a large rate of through going muons from the IP. Using this demonstrator the DAQ concept for FORMOSA has been validated.

Team studying updated design with central submodule of CeBr3 scintillator **~35 higher light yield**, allows significant increase in sensitivity for low charges.



FPF Documentation

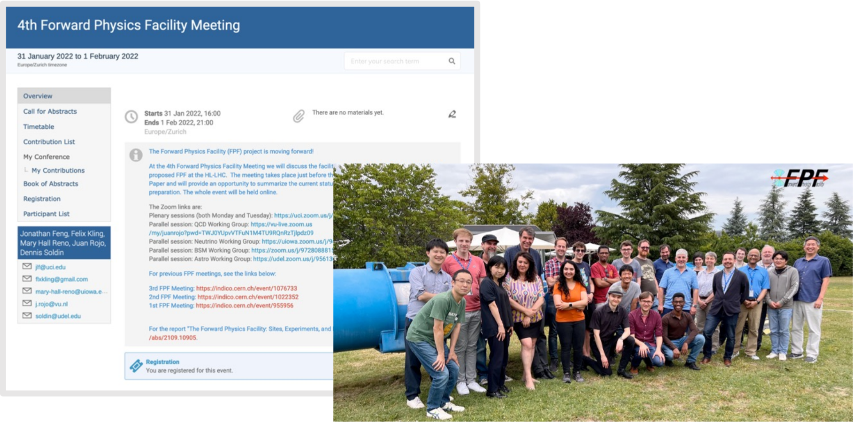
FPF workshop series:
FPF1, FPF2, FPF3, FPF4, FPF5,
FPF6, FPF7, FPF Theory Day

FPF Paper:
2109.10905
~75 pages, ~80 authors

Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

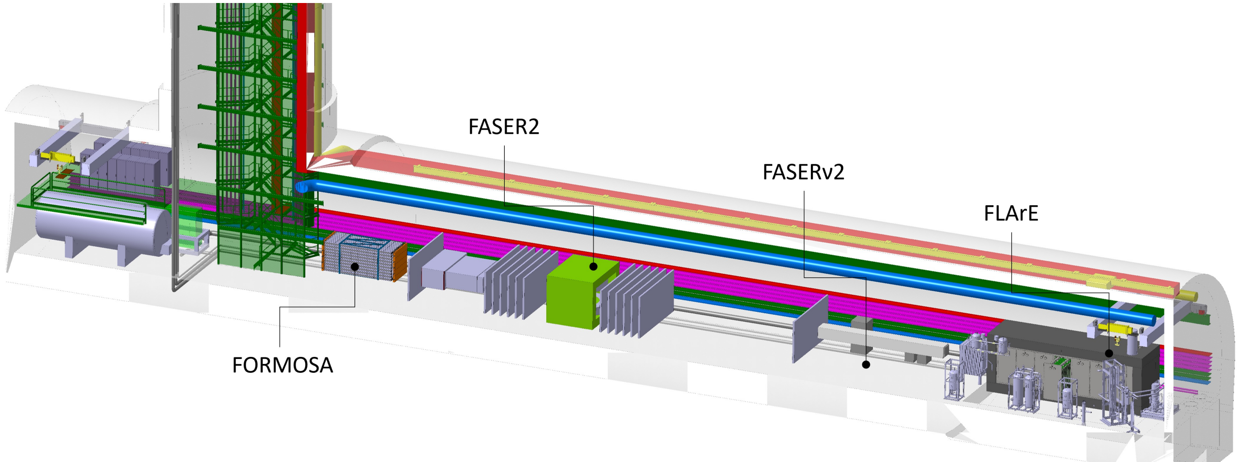
Recent Summary:
FPF Update

Technical Documents:
Facility Technical Study
Muon Flux Study
Vibration Study
Geotechnical Report



Summary

- The FPF greatly **expands the LHC physics progamme**
- The **beam** is there already
- Broad and **interdisciplinary** physics programme
  - Neutrinos, QCD, Cosmic Ray, BSM, …
- The cost is **modest**
- Fully aligned with existing **European strategy**
- Great **test-bed** for new ideas
- Could run in **LHC Run 4**



UNIVERSITY OF OXFORD

- FPF is a proposed **new facility** to house several experiments on the collision axis line-of-sight in the HL-LHC era
  - **Maximise the physics from the HL-LHC**
- The FPF experiments would :
  - Have **world leading sensitivity** in several **BSM models**
  - Study O(1M) **TeV neutrinos** (covering all flavours) with important implications for:
    - **Neutrino physics**
    - **QCD**
    - **Astroparticle physics**
- Following many studies within the PBC we have come-up with a baseline design for the facility that can house the proposed experiments
  - No showstoppers identified for implementing the facility or for operating the experiments
  - Facility cost of **only ~40MCHF**
- Conceptual designs of the experiments are ongoing with **baseline solutions available** for the different detector components
  - More studies will allow better optimizations and improved physics reach
- Plan to submit a proposal for the FPF to the ESPP in Q1 2025
  - If viewed favourably the facility can be implemented to allow **first physics during Run 4**

EXTRAS

CERNCOURIER | Reporting on international high-energy physics

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SEARCHES FOR NEW PHYSICS | MEETING REPORT

Looking forward at the LHC

1 September 2023

New territory 3D rendering of the proposed Forward Physics Facility and its experiments. Credit: A Navascues Cornago

The Forward Physics Facility (FPF) is a proposed new facility to operate concurrently with the High-Luminosity LHC, housing several new experiments on the ATLAS collision axis. The FPF offers a broad, far-reaching physics programme ranging from neutrino, QCD and hadron-structure studies to beyond-the-Standard Model (BSM) searches. The project, which is being studied within the Physics Beyond Colliders initiative, would exploit the pre-existing HL-LHC beams and thus have minimal energy-consumption requirements.

On 8 and 9 June, the 6th workshop on the Forward Physics Facility was held at CERN and online. Attracting about 160 participants, the workshop was organised in sessions focusing on the facility design, the proposed experiments and physics studies, leaving plenty of time for discussion about the next steps.

Documentation on facility studies

CERN-PBC-NOTE 2023-002
https://cds.cern.ch/record/2851822/

CERN-PBC-NOTE 2023-002

7 March 2023
Jamie.Boyd@cern.ch

Update on the FPF Facility technical studies

FPF PBC Working Group:
M. Andreini, G. Arduini, K. Balazs, J. Boyd, R. Bozzi, F. Cerutti, F. Corsanego, J-P. Corso, L. Elie, A. Infantino, A. Navascues Cornago, J. Osborne, G. Peon, M. Sabaté Gilarte
CERN, CH-1211 Geneva, Switzerland

Keywords: FPF

Summary

The Forward Physics Facility (FPF) is a proposed new facility to house several new experiments at the CERN High Luminosity LHC (HL-LHC). The FPF is located such that the experiments can be aligned with the collision axis line of sight (LOS), a location which allows many interesting physics measurements and searches for new physics to be carried out. The status of technical studies related to the FPF, as well as the physics potential were documented in Ref. [1] which was released in March 2022. This note documents updates to the FPF technical studies completed since that time.

1

CERN-PBC-Notes-2024-004
https://cds.cern.ch/record/2904086

CERN-PBC-NOTE 2024-XXX

18 June 2024
Jamie.Boyd@cern.ch

Update of Facility Technical Studies for the FPF

FPF PBC Working Group
K. Balazs, J. Boyd, T. Bud, J.-P. Corso, D. Gamba, A. Magazinik, A. Navascues Cornago, J. Osborne (CERN, CH-1211 Geneva, Switzerland)

Contributors from the FPF Experiments
FLArE: L. Bartoszek (Bartoszek Engineering), Y. Li (BNL), S. Linden (BNL), C. Miraval (BNL), S. Trabocchi (BNL)
FASERν2: S. Bosco (Bern)
FASER2: N. Sumi (KEK), J. Carroll (Liverpool), A. Lowe (Oxford)
FORMOSA: R. Loos (CERN)

Keywords: FPF

Executive Summary

The Forward Physics Facility (FPF) has been proposed to house a set of experiments to detect collider neutrinos and search for new particles in the High-Luminosity LHC era. This report provides an update to the space and infrastructure requirements of the Facility, a result of integration studies carried out by CERN technical teams in conjunction with the FPF experimental community.

Previous radio protection studies showed that access to the FPF cavern during LHC beam operation was expected to be possible. This update includes vibration studies, which indicate that no major disruptions to HL-LHC and SPS performance are expected during FPF excavation works. FPF construction, then, is not expected to interfere with the LHC and can proceed largely independent of the LHC schedule.

Since the last study, a site investigation, where a core was drilled to the depth of the FPF cavern, yielded broadly positive results, confirming the reliability of the Facility design. More detailed considerations of services have been incorporated, leading to a slight increase in size and an accompanying modest increase in cost for the civil engineering compared to previous estimates. The updated timeline for the works shows that the FPF could be constructed within a few years of approval, with no special R&D needed for the Facility design.

1

CERN-PBC-NOTE 2024-003
https://cds.cern.ch/record/2901520/

CERN-PBC-NOTE 2024-003

4 July 2024
davide.gamba@cern.ch

Impact of Vibration to HL-LHC Performance During the FPF Facility Construction

D. Gamba, H. Bartosik, M. Guinchard, J. A. Osborne, K. Pál, C. Vendeuvre, J. Wenninger, K. Widuch
CERN, CH-1211 Geneva, Switzerland

Keywords: excavation, forward physics facility, ground motion, tunnel deformation, vibration, FPF, LHC, HL-LHC, SPS

Summary

The Forward Physics Facility (FPF) is a proposed experimental site intended to be positioned approximately 630 meters from the ATLAS interaction point. It aims to capture long-lived particles and neutrinos that travel along the beam collision axis and fall outside the ATLAS detector's acceptance. The construction of this facility, particularly the excavation of the necessary shaft and cavern, could occur concurrently with beam operations at the CERN accelerator complex. Therefore, it is crucial to ensure that the ground motion resulting from these construction activities does not disrupt the normal functioning of the SPS and LHC. This study details how sensitive the SPS and LHC rings are to vibrations and misalignments close to the FPF construction site. It also examines the expected effects on beam operations, incorporating lessons learned from the HL-LHC infrastructure development near the ATLAS experiment, previous civil engineering projects, and established knowledge of slow ground movements in the vicinity.

1

FPF Organization

Steering Committee: Jamie Boyd, Albert De Roeck, Milind Diwan, Jonathan Feng, Felix Kling

Coordination Panel: Aki Ariga, Alan Barr, Brian Batell, Jianming Bian, Jamie Boyd, Giovanni De Lellis, Albert De Roeck, Milind Diwan, Jonathan Feng, Chris Hill, Felix Kling, Juan Rojo, Dennis Soldin, Anna Stasto

WG0 Facility: Jamie Boyd

Physics WGs

WG1 Neutrino Interactions: Juan Rojo

WG2 Charm Production: Anna Stasto

WG3 Light Hadron Prod: Luis Anchordoqui, Dennis Soldin

WG4 BSM: Brian Batell, Sebastian Trojanowski

Detector WGs

WG5 FASER2: Alan Barr, Josh McFayden, Hide Otono

WG6 FASERnu2: Aki Ariga, Tomoko Ariga

WG7 FLArE: Jianming Bian, Milind Diwan

WG9 FORMOSA: Matthew Citron, Chris Hill

Technical group:

Bringing together experts from CERN, BNL, and an external engineering contractor Bartoszek engineering:

BNL: M. Diwan, S. Linden, Y. Li, C. Miraval + L. Bartoszek

CERN: J. Boyd, J.P Corso (integration), A. Magazinik (integration), F. Resnati (neutrino platform)

Meeting bi-weekly on Fridays.

Strongly Reviewed in Snowmass.

Executive Summary (10 pages)

LHC

The Energy Frontier (Science Drivers 1 – 3 & 5): The Energy Frontier currently has a top-notch program with the Large Hadron Collider (LHC) and its planned High Luminosity upgrade (HL-LHC) at CERN, which sets the basis for the Energy Frontier vision. The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no obvious and unambiguous signal of BSM physics. This implies that new physics either occurs at scales higher than we have probed, must be weakly coupled to the SM, or is hidden in backgrounds at the LHC. The immediate goal for the Energy Frontier is to continue to take and analyze the data from LHC Run 3, which will go on for about three more years, and carry out the 2014 P5 recommendations to complete the HL-LHC Upgrade and execute its physics program. The HL-LHC will measure the properties of the Higgs Boson more precisely, probe the boundaries of the SM further, and possibly observe new physics or point us in a particular direction for discovery.

A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision regions during the normal LHC and HL-LHC running of the ATLAS, CMS, LHCb, and ALICE experiments to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles produced at larger angles but decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.

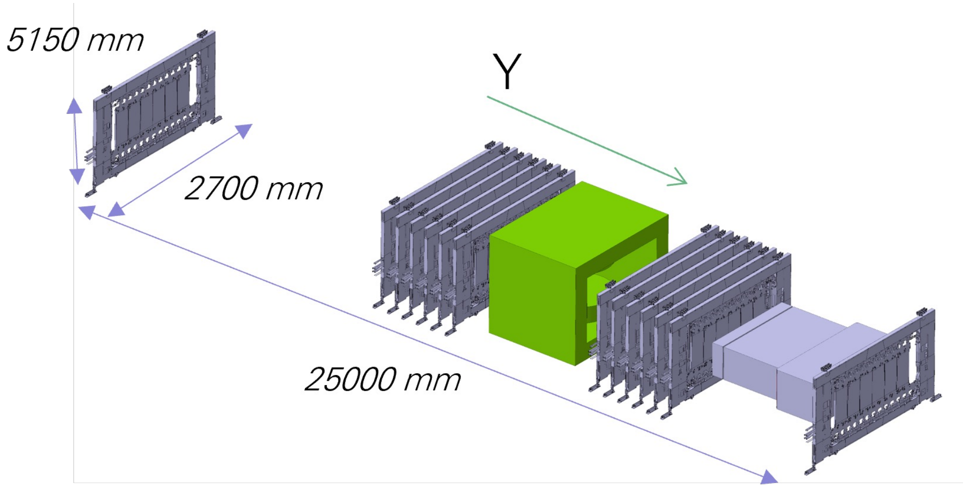
future collider

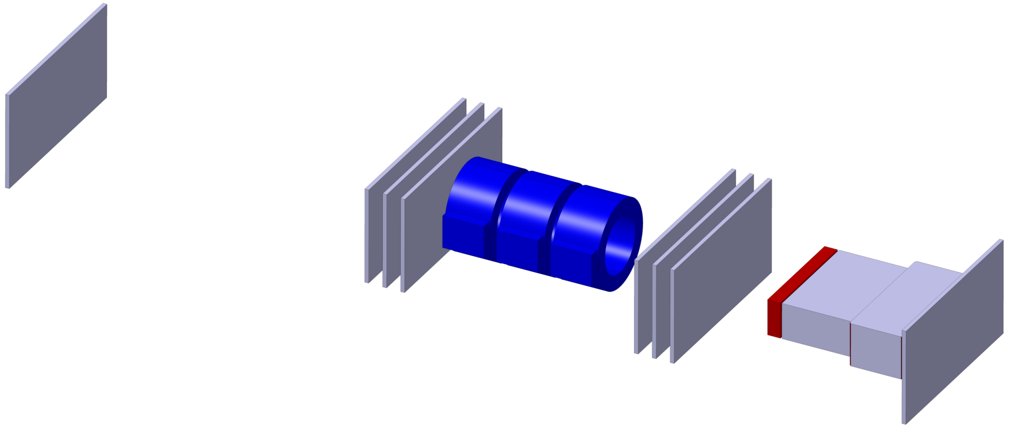
New colliders are the ultimate tools to extend the EF program into the next two decades thanks to the broad and complementary set of measurements and searches they enable. With a combined strategy of precision measurements and high-energy exploration, future lepton colliders starting at energies as low as the Z-pole up to a few TeV can shed substantial light on some of these key questions. It will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond. The EF supports a fast start for the construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs Factory will require an immediate, vigorous, and targeted accelerator and detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.

Finally, the U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with, for example, CERN.

A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision … to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles … decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S. participation … including auxiliary experiments.

FASER2 Magnet



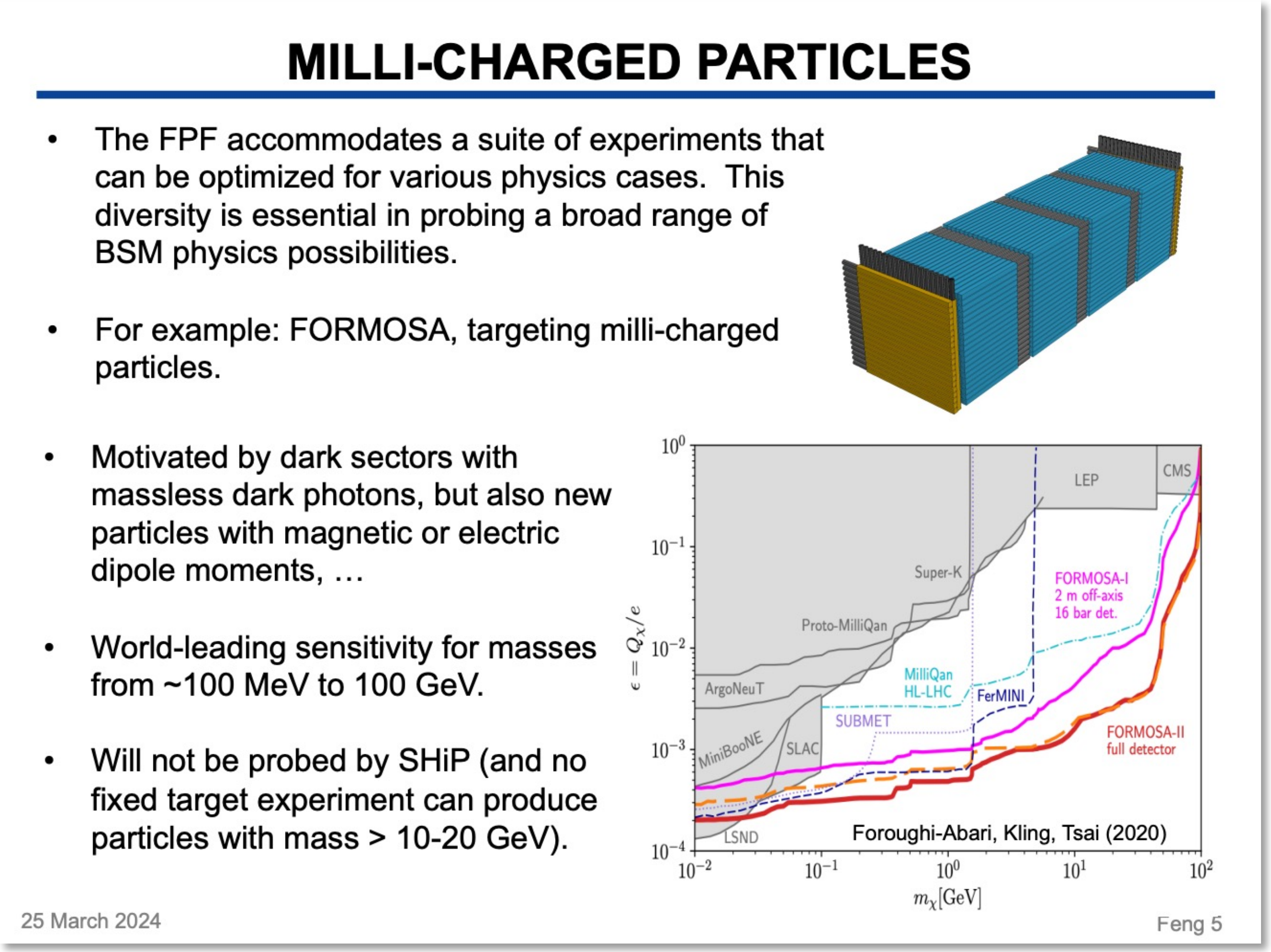


Two possible magnet solutions investigated for the FASER2 magnet:

- Custom made SC dipole based on (descoped) SAMURAI experiment magnet
  - 2Tm bending power, 1.7m x 1.7m apperture
  - SAMURAI magnet built by Toshiba, JP, but similar magnet could be built by TESLA, UK
  - Cost (Toshiba) 730 MJPY (4.1 MCHF today), 3-4y lead-time
- Off the shelf ‘crystal puller’ magnets:
  - 4 units: 0.4T central field 1.25m depth => 2Tm bending power (central region)
  - 1.6m diameter
  - Available from both Toshiba and TESLA
  - Cost (Toshiba) with modified mechanics to operate on side: 400 MJPY (2.3MCHF), 1-2y lead-time

BSM Physics

- The FPF experiments have strong sensitivity in all of the dark sector PBC benchmark models
- In some of these the sensitivity is not as strong as that of SHiP
- There are several classes of models where the FPF is **more powerful than SHiP**



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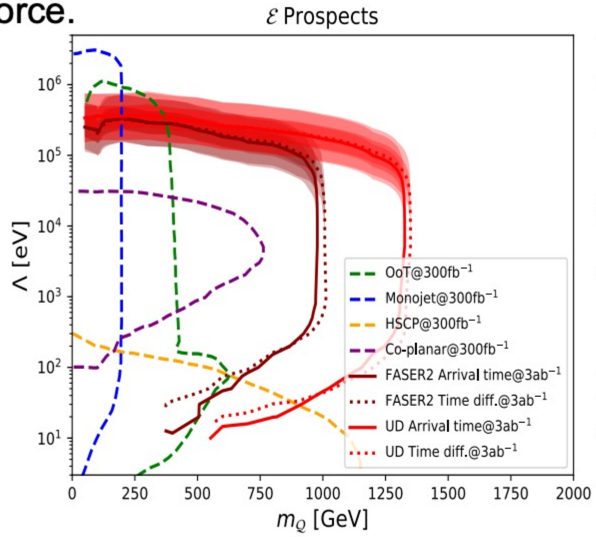
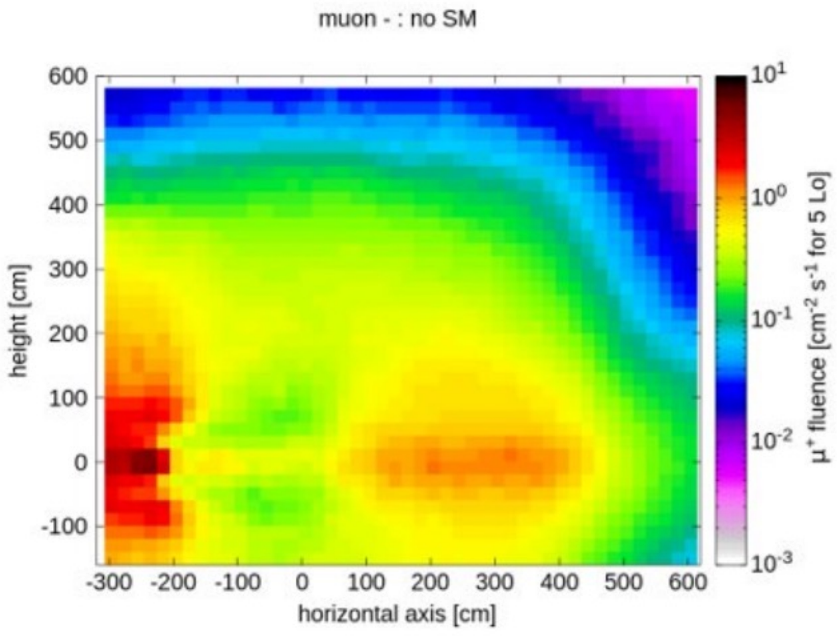
STRONGLY-INTERACTING DARK SECTORS

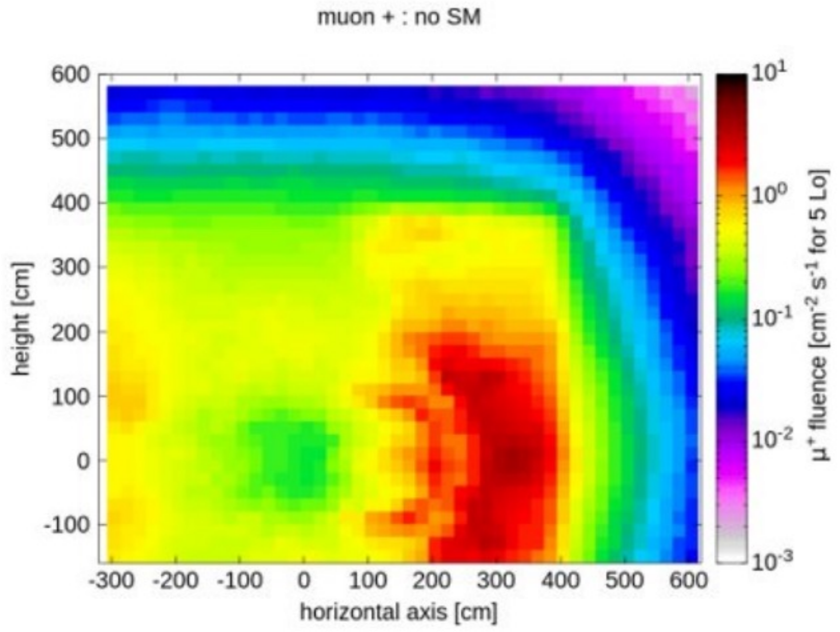
- U(1) dark force → dark photons, milli-charged particles.
- Any other dark force → strongly-interacting dark sector. Dark particles ("quirks") can be pair-produced at the LHC, but then oscillate down the beampipe, bound together by the dark color force.
- FASER2 can discover quirks with masses up to ~TeV, as motivated by the gauge hierarchy problem (neutral naturalness).
- Requires LHC energies to produce new TeV particles, impossible to see at fixed target experiments.



Li, Pei, Ran, Zhang (2021); Li et al. (in progress)

Backgrounds





Muon background flux estimatewd to be 0.6Hz/cm^2 at L=5e34cm^{-2}s^{-1} in region 20cm from LOS.
Muon hotspots horizontally +/- 2m from the LOS.
Reducing the muon flux would be beneficial for some experiments, investigating the possibility of a sweeper magnet to reduce the flux.

Detailed FLUKA simulations used to:
- Estimate muon background
- Estimate radiation levels (RP)
- Estimate radiation to electronics / detector

All look encouraging for implemtning the FPF experiments
FLUKA simulation of Run 3 LHC setup validated at 20% level by FASER/SND@LHC data
(Note for HL-LHC much of the LSS changes => signifciantly reduces estimated muon flux per fb^{-1})

Facility Costing

Please find enclosed the first draft of the updated cost based on the results of the site investigations and the cost review done by ARUP. The estimated cost of the facility based on the existing design is 30.1MCHF, the estimate being a Class 4 (accuracy ranges being -15% to -30% on the low side, and +20% to +50% on the high side).

Ref.	Work Package	Cost [CHF]
1.	Underground Works	10,000,000.00
1.1	Preliminary activities	1,600,000.00
1.2	Access shaft	3,900,000.00
1.3	Experimental Cavern	4,500,000.00
2.	Surface Works	6,120,000.00
2.1	General items	640,000.00
2.2	Topsoil and earthworks	660,000.00
2.3	Roads and network	730,000.00
2.4	Buildings	4,090,000.00
2.4.1	Access building	2,000,000.00
2.4.2	Cooling and ventilation building	1,400,000.00
2.4.3	Electrical Building	490,000.00
2.4.5	External platforms	200,000.00
3.	General items	10,000,000.00
4.	Miscellaneous	4,000,000.00
	TOTAL CE WORKS	30,120,000.00

Assumptions

1. Services not included
2. Technical galleries not included
3. Cranes not included
4. Access building as a conventional steel portal frame structure with cladding, only one floor
5. CV Building as a reinforced concrete building, only one floor
6. Finished floor level at 450m ASL
7. Sectional doors not included

Very preliminary estimate of cost increase to make cavern larger (to accommodate additional infrastructure etc..):

	Additional cost
5m longer cavern	700,000 CHF- 1,000,000.00 CHF
10m longer cavern	1,400,000 CHF - 2,000,000.00 CHF
Increase of the radius of the cavern by 1m	700,000 CHF- 1,000,000.00 CHF

Very preliminary costing of technical infrastructure for cavern at 10MCHF level.

Total cost of facility (no experiments): ~40MCHF