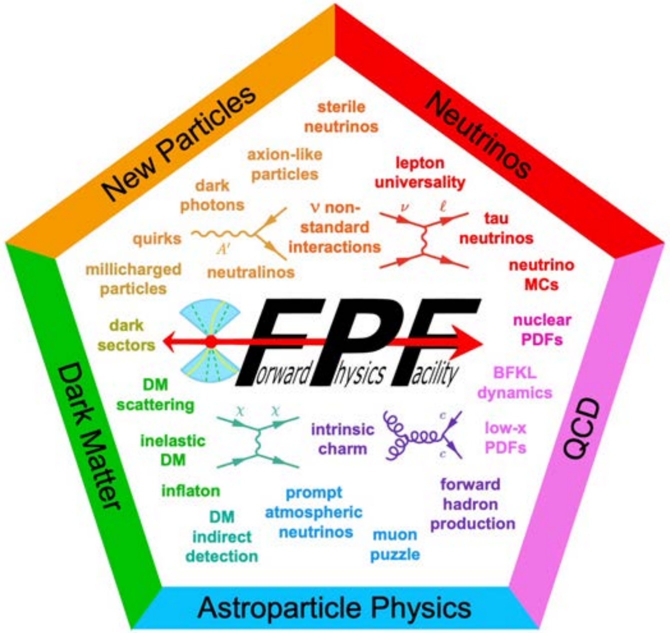
The Forward Physics Facility

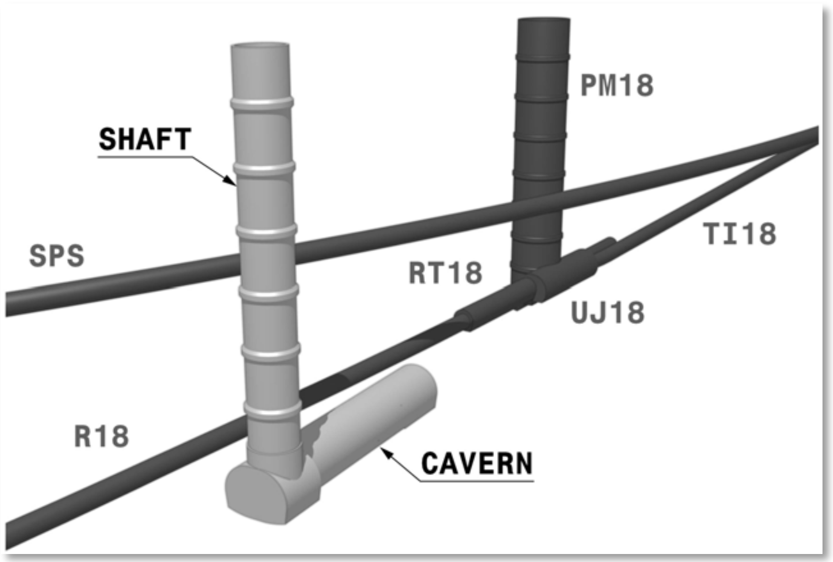
LLP13 workshop at CERN

June 21st 2023

Jamie Boyd (CERN)

Physics Beyond Colliders

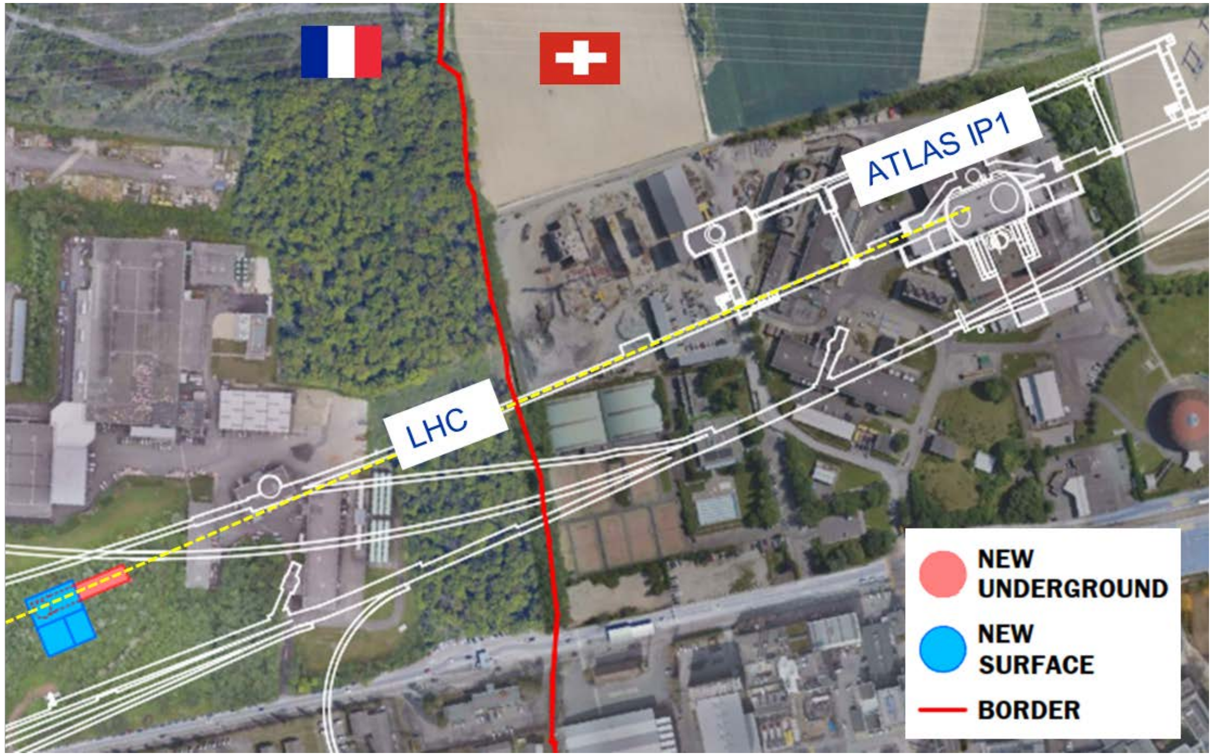




Introduction

- Studies on the physics potential for FASER/SND@LHC has highlighted there is a huge potential for larger detectors with improved capabilities to be placed on the collision axis line of sight at the LHC
- This has led to the proposal of the Forward Physics Facility (FPF) as a new dedicated facility to house such experiments
- The FPF has been studied in the context of the CERN Physics Beyond Colliders effort for the last 3 years with excellent progress across all fronts:
    - Physics studies
    - Design of experiments
    - Design of facility
- Strong, first results from pathfinder FPF experiments FASER and SND@LHC strengthen the physics case
    - See FASER and SND@LHC talks tomorrow!
- 2 weeks ago we held the 6th FPF workshop at CERN with lots of interesting results shown and many nice discussions!
    - https://indico.cern.ch/event/1275380/
- Recent documents on the FPF:
    - https://www.osti.gov/biblio/1972463
        - Summary for P5 US funding process
    - https://cds.cern.ch/record/2851822
        - Update on technical facility studies

Workshop photo:



FPF Location

- ~600m from ATLAS IP
- On CERN land (SM18 area)
- In France
- 10m minimum distance from facility to LHC

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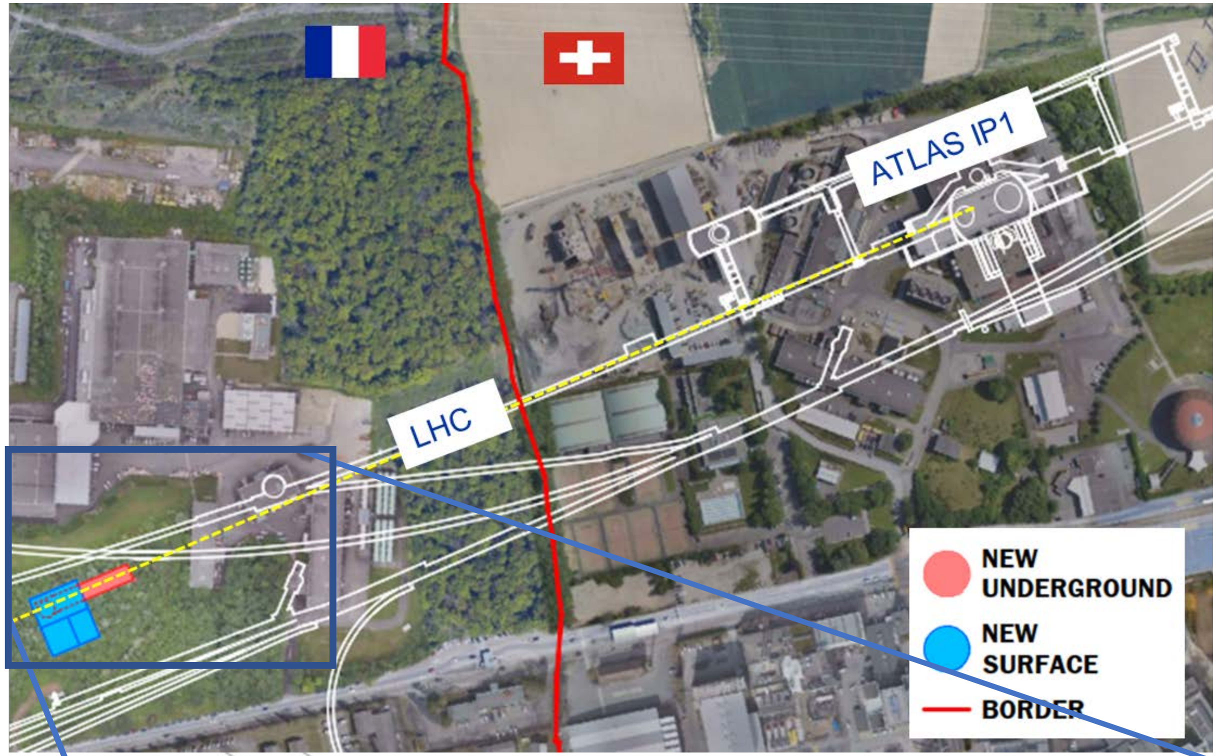
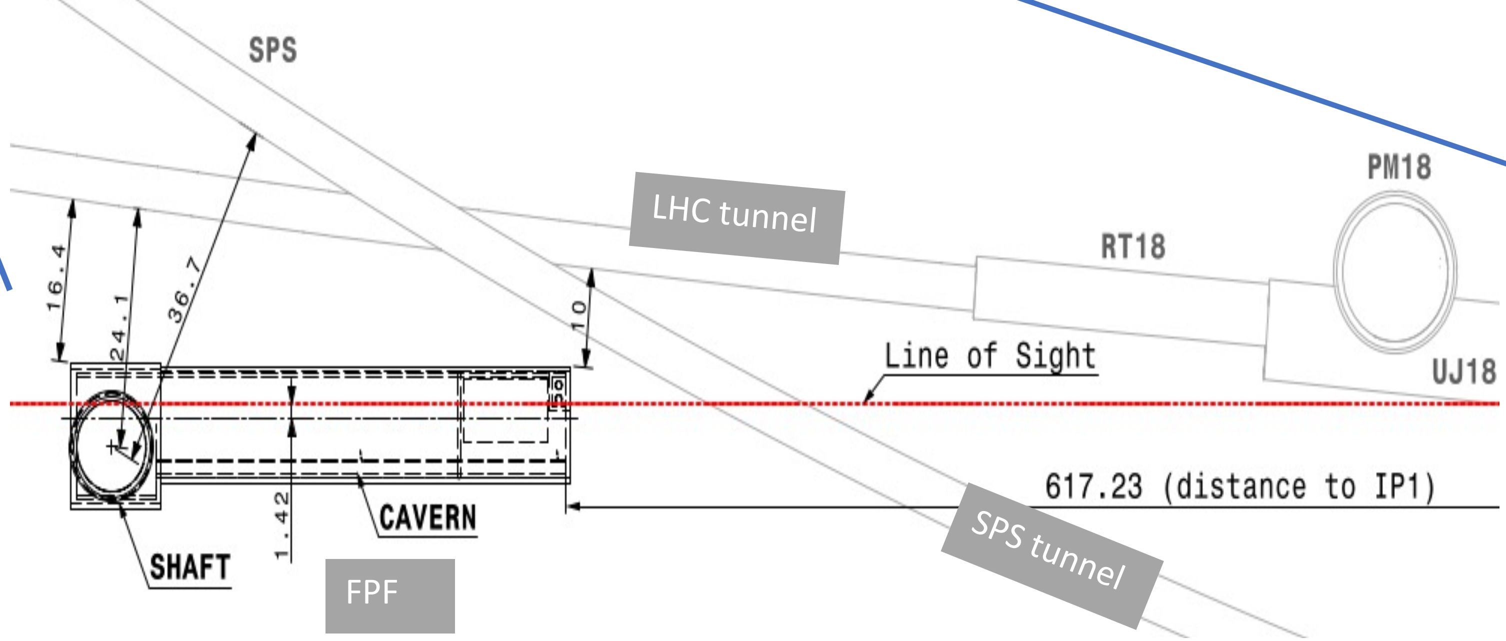
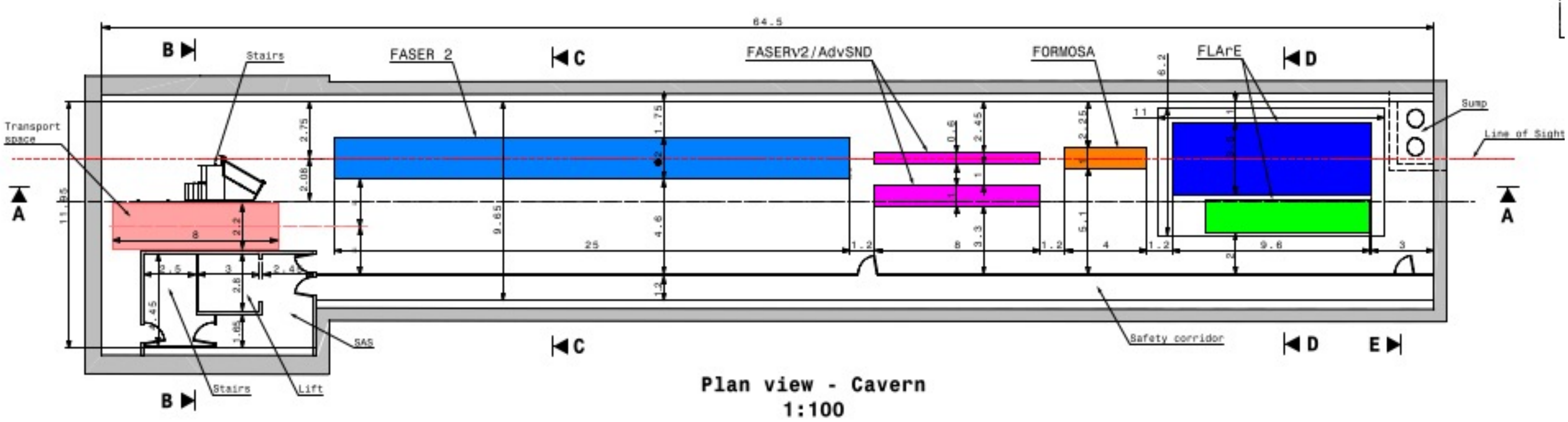




FPF Design

- 65m long cavern
- ~9m wide/hide
- 88mm below surface (same height as LHC in this area)
- Access shaft
- Surface buildings



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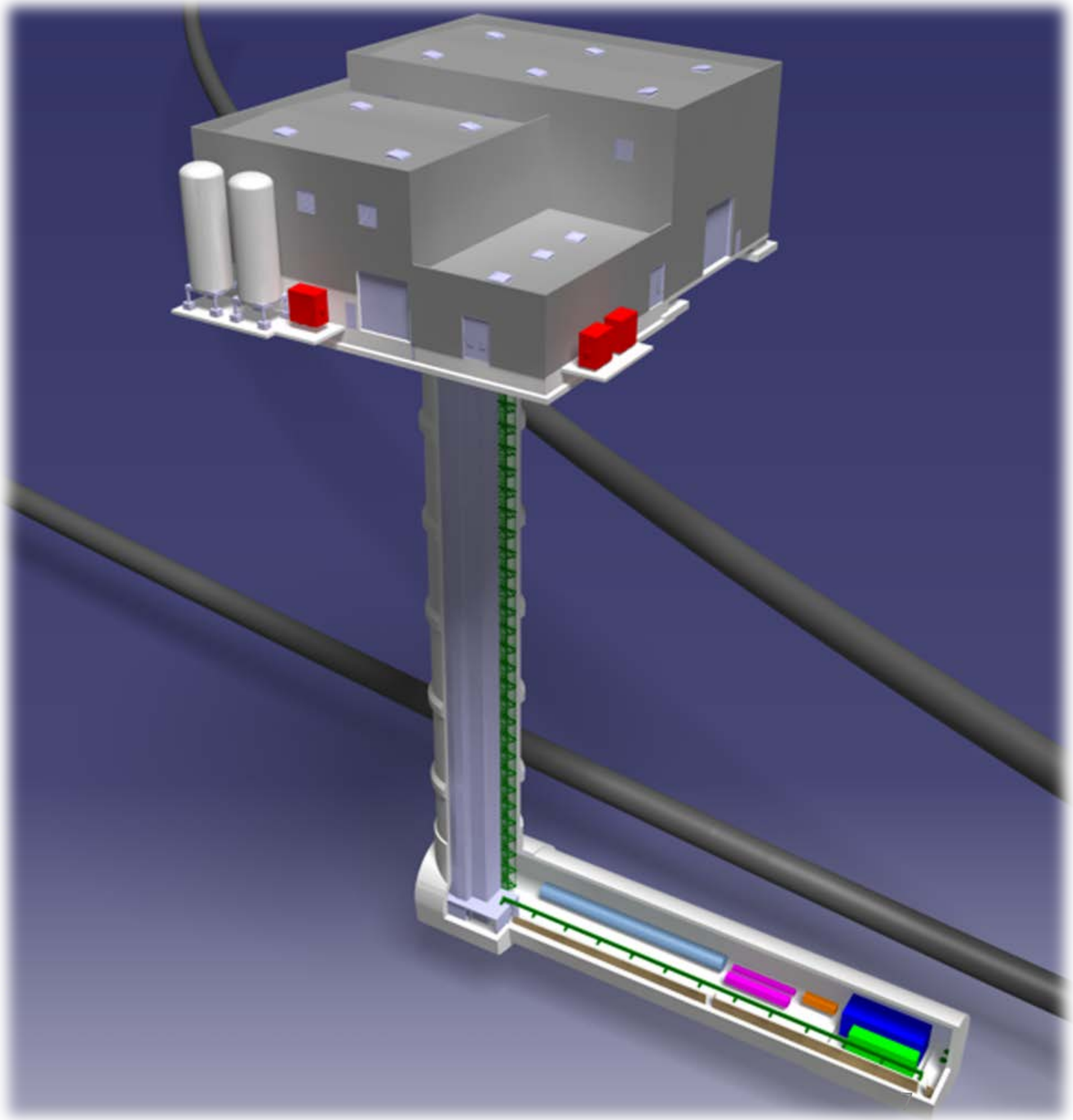
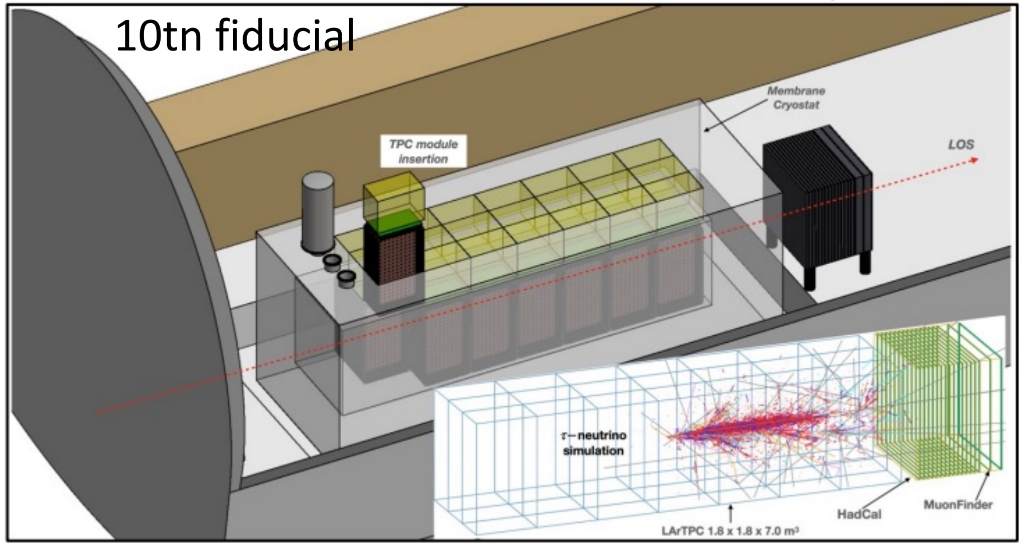
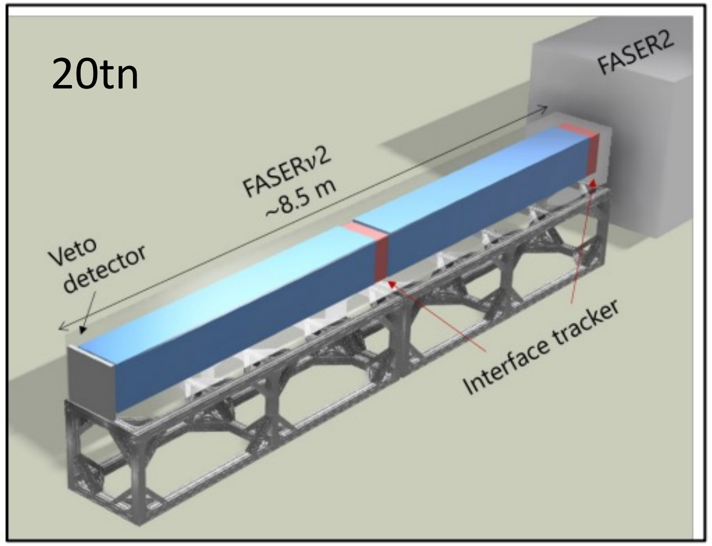


FPF Experiments

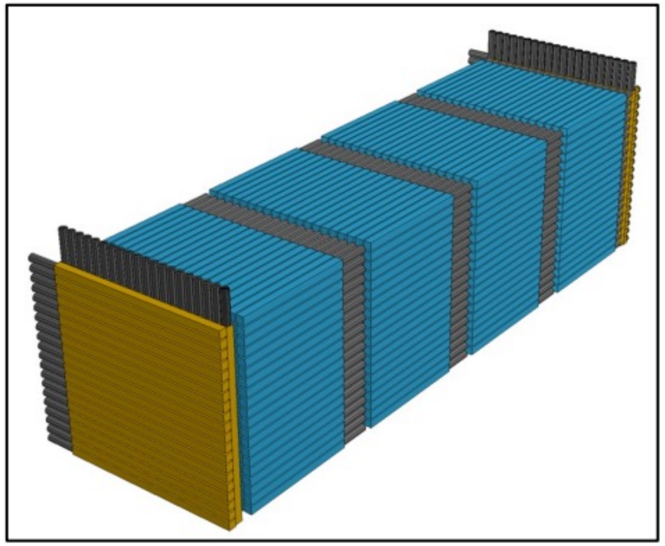
FLArE: LAr TPC (neutrinos + DM scattering)



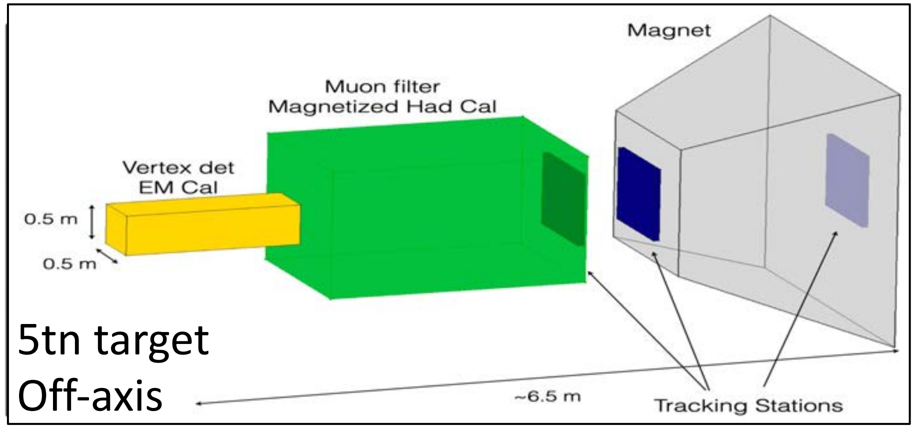
FASERν2: Emulsion (neutrinos)



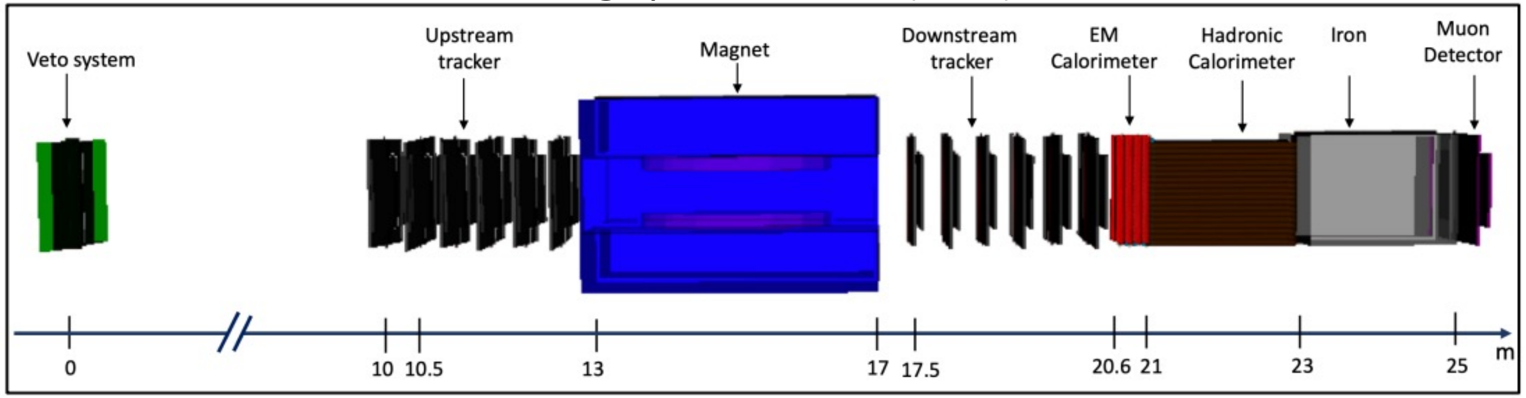
FORMOSA: Scintillators (milicharged



AdvSND: electronic (neutrinos)



FASER2: tracking spectrometer (LLPs)

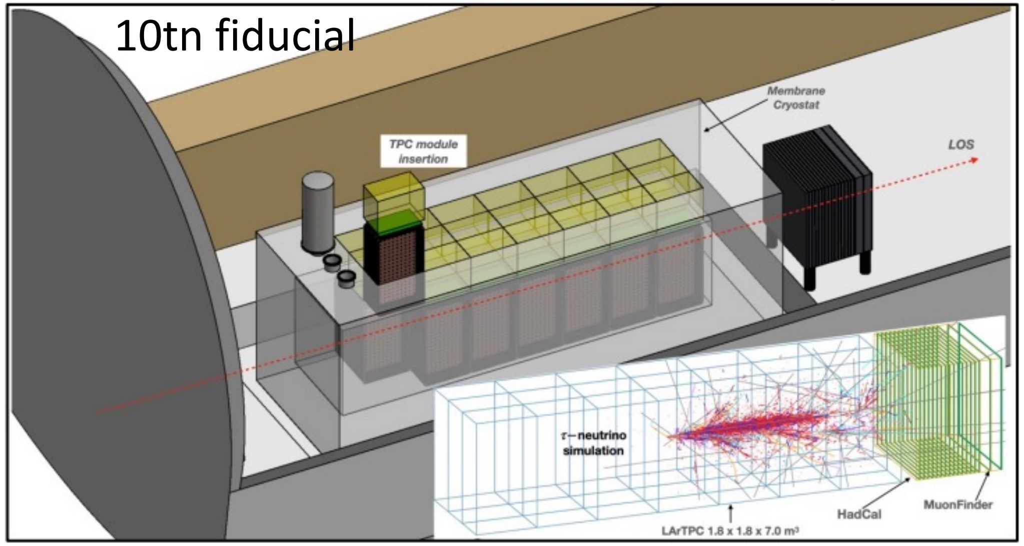


See dedicated talk on FLArE later today

FPF Experiments – pathfinder results

FLArE: LAr TPC (neutrinos + DM scattering)

10tn fiducial



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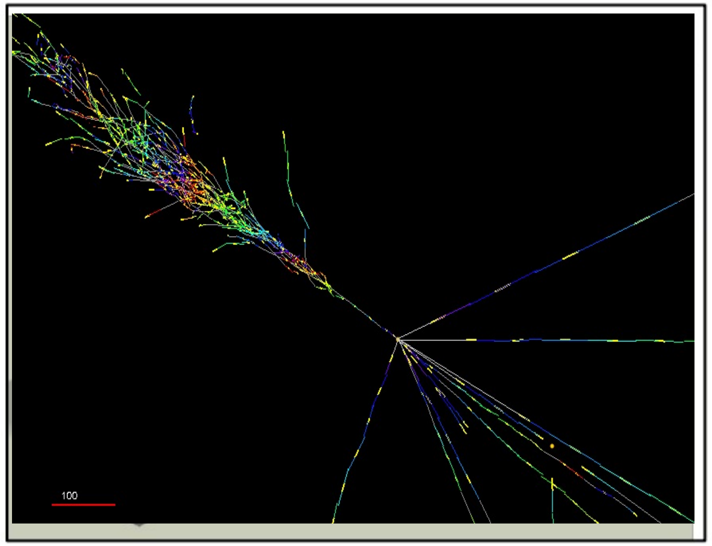

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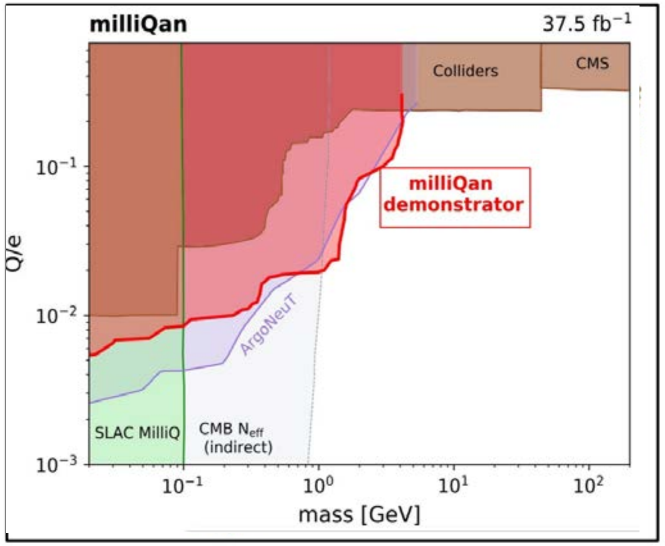

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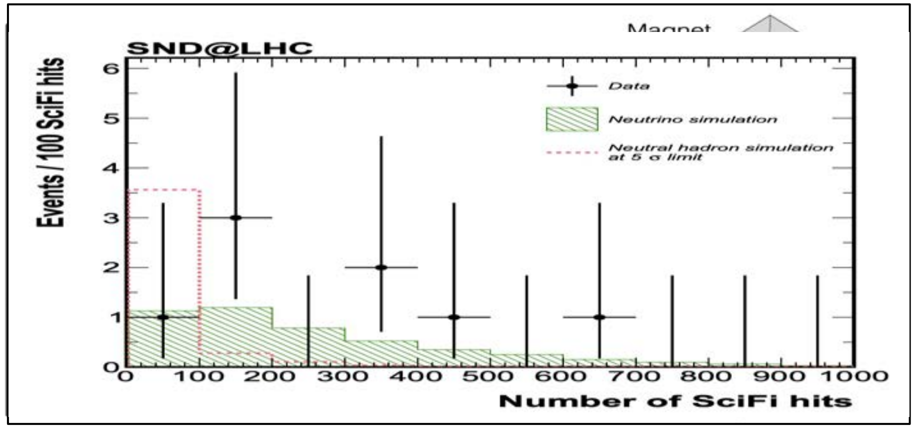

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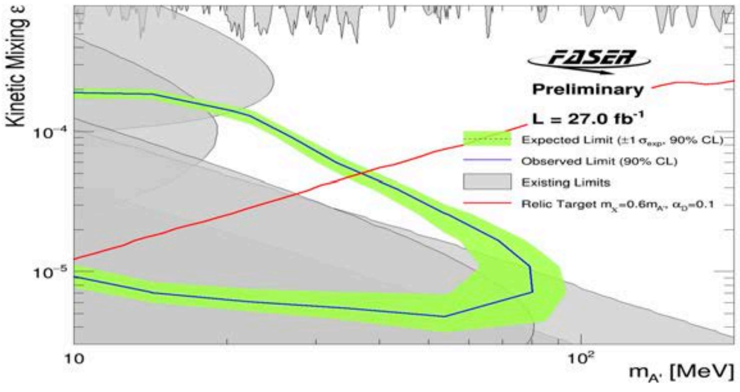
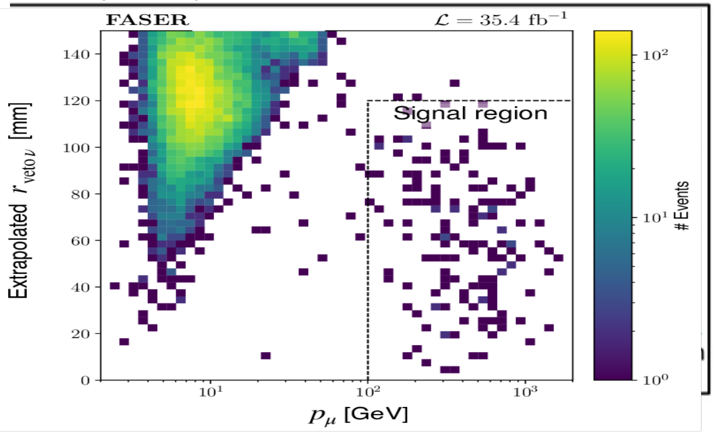




More details in dedicated FASER / SND@LHC and MilliQan talks tomorrow!

CERN civil engineering

Site Investigation works

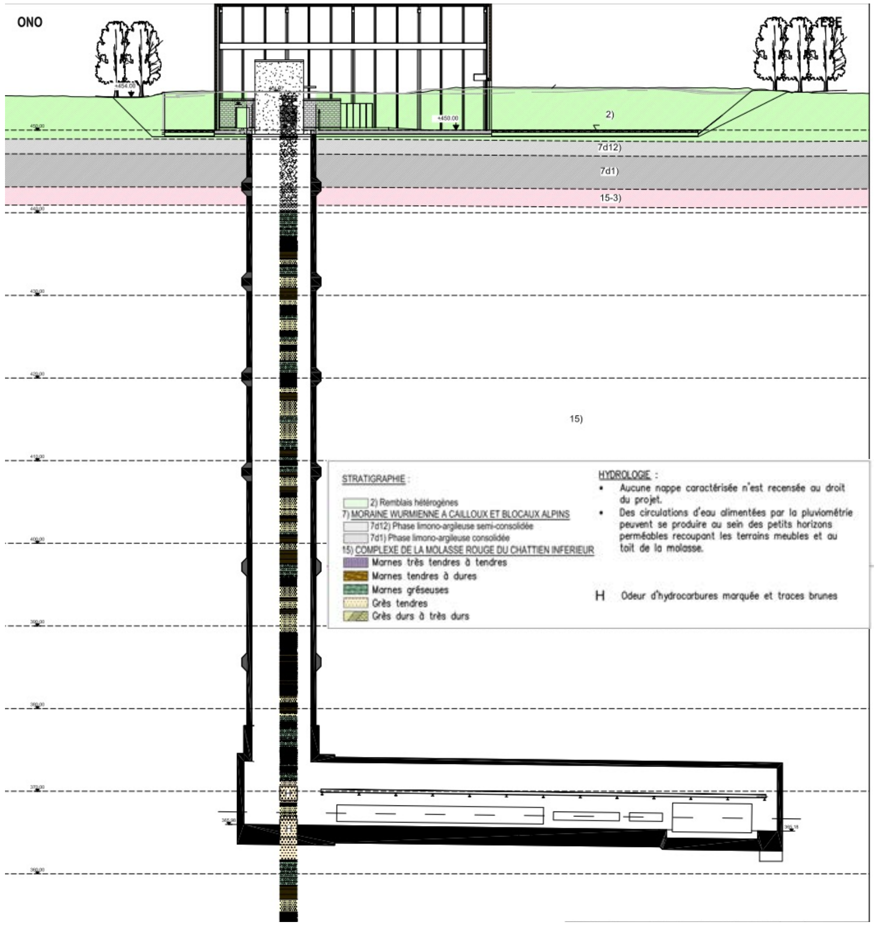
➢ Drilling machine in place

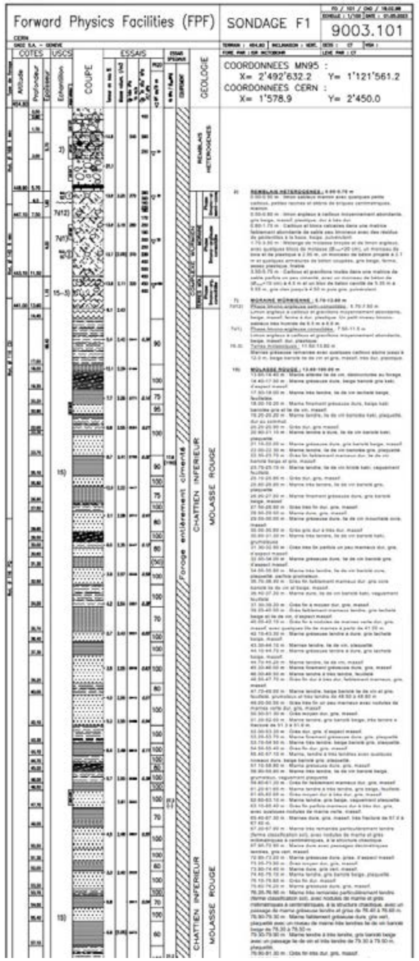
➢ Works started

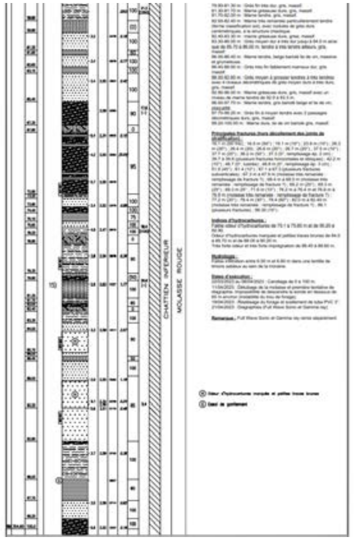
➢ Core samples

CERN civil engineering

Site Investigation works: First Results







- 100m deep core (20cm diameter):
- 0.0 to 5.7m: heterogeneous fill comprising gravel, moraine and molasse rock from former excavations, as well as concrete and metal debris.
- 5.7 to 13.6m: mainly consolidated silty-clay Würmian moraine.
- From 13.6m: red molasse, consisting of alternating marl, sandstone and sandy marl.

No big issues identified in first analysis of the core.
No water table identified - good news, as reduces potential issue from water ingress.

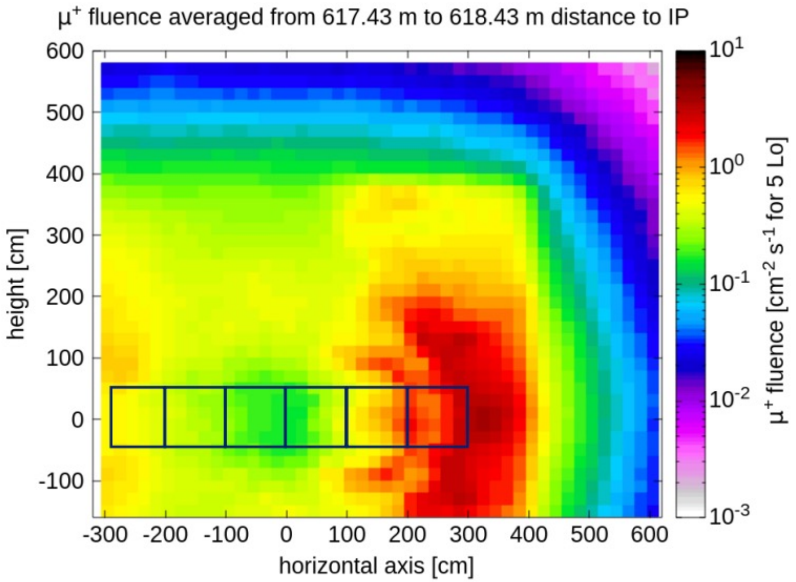
Other studies on the Facility

CERN FLUKA, RP,
beam physics teams

Several results from detailed FLUKA simulations:

- Expected muon flux of 0.6 Hz cm^{-2} close to the LOS, rising >1m away in the horizontal
    - Forms main background for FPF experimens
- Expected neutron and high energy hadron flux less than threshold for silicon damage or radiation effects on electronics
- Radiation levels expected to be low enough that access to cavern possible during beam operations with some restrictions

Study of the effect of excavation works (vibrations/tunnel movements) on beam operations shows positive results.

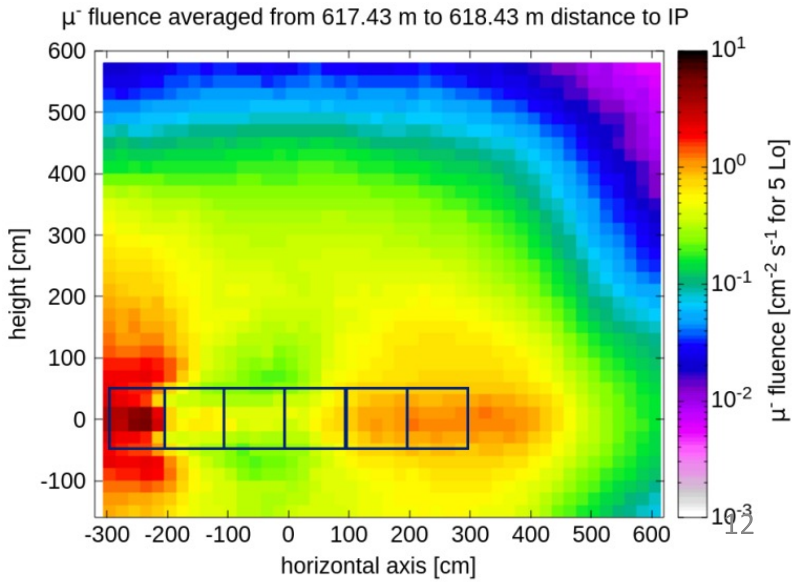


μ^+

Muon rate at (0,0)

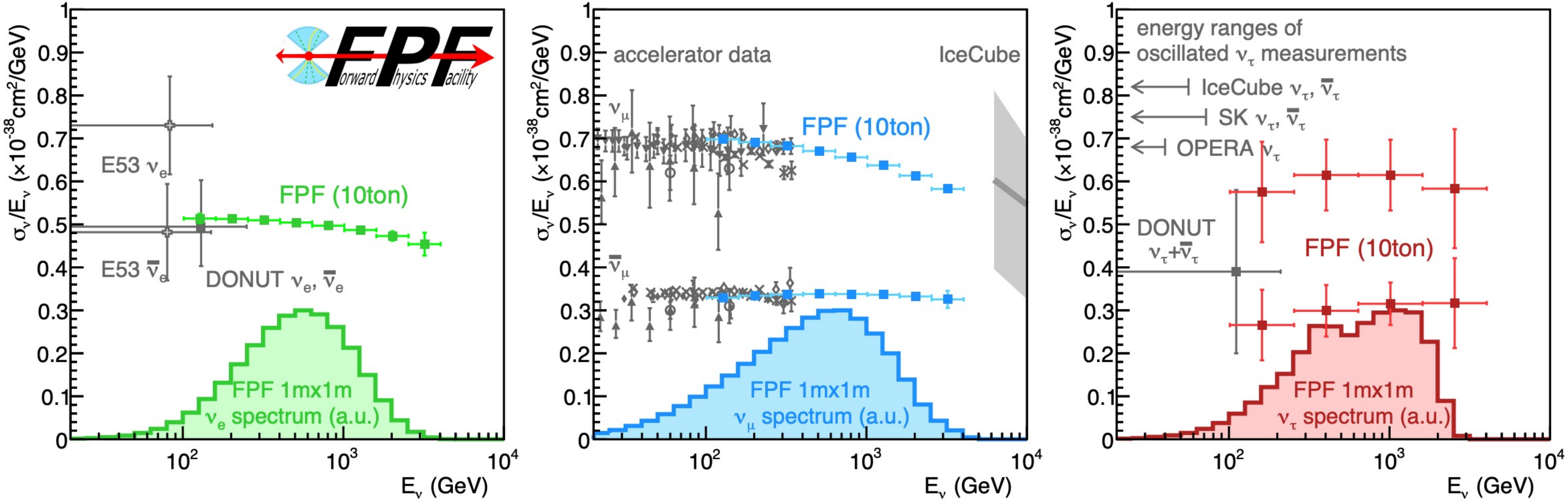
μ^+ : 0.15 cm^{-2} s^{-1}
μ^- : 0.45 cm^{-2} s^{-1}

Total : 0.6 cm^{-2} s^{-1}



μ^-

Physics Studies: Neutrinos



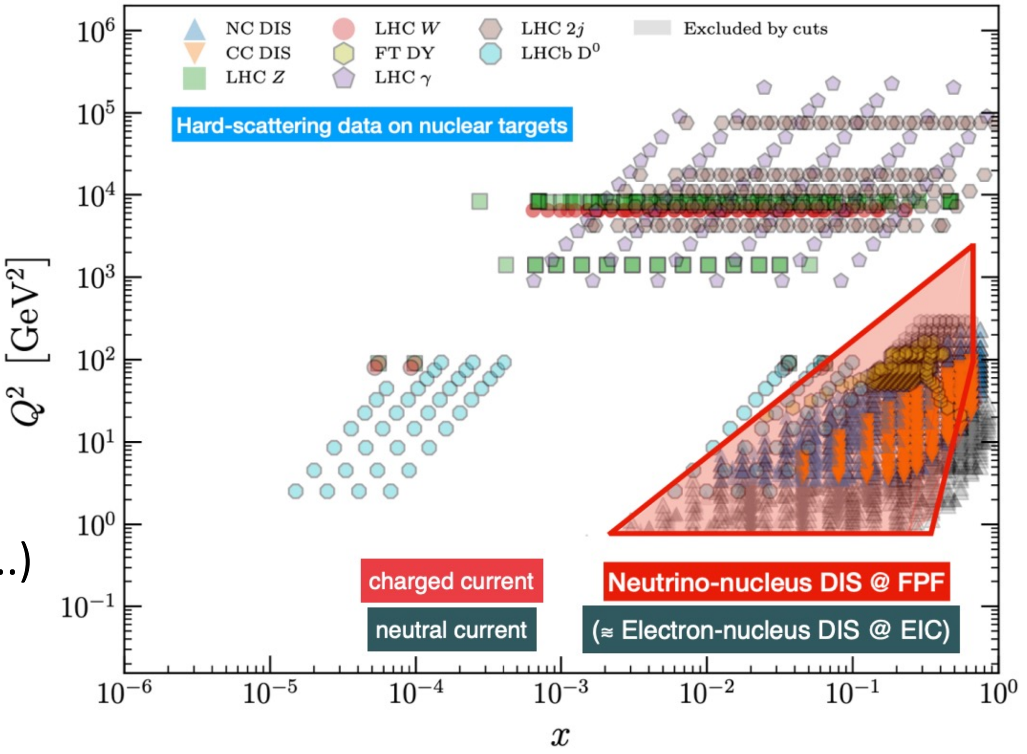
FPF allows to scale up neutrino detector target mass by O(10x) copared to FASERnu/SND@LHC, combined with 10x more luminosity for the HL-LHC.

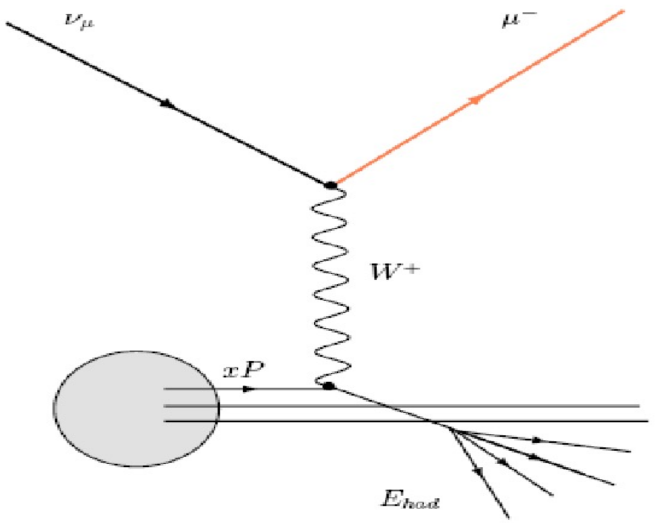
Leads to O(10^5) ν_e, O(10^6) ν_μ, O(10^4) ν_τ

Enabling precise cross section measurements, first obervation of anti- ν_τ, precise studies of ν_τ properties, studies of ν production of heavy flavour and many studies related to QCD (next slides).

Physics Studies: quark PDFs

- Large rate of high energy neutrino's interacting in FPF detectors
- **Turns the LHC into a neutrino-ion collider**
- Charged current analogue of the Electron Ion Collider, covering similar kinematic range
- High statistics allows differential measurements of neutrino/proton Deep Inelastic Scattering (DIS)
- Impact assessed by PDF fits using xFitter and NNPDF comparing current uncertainties with those including FPF data
    - Significant improvements seen (>2x)
    - Will improve measurements searches at HL-LHC (M_W, high mass DY, ..)





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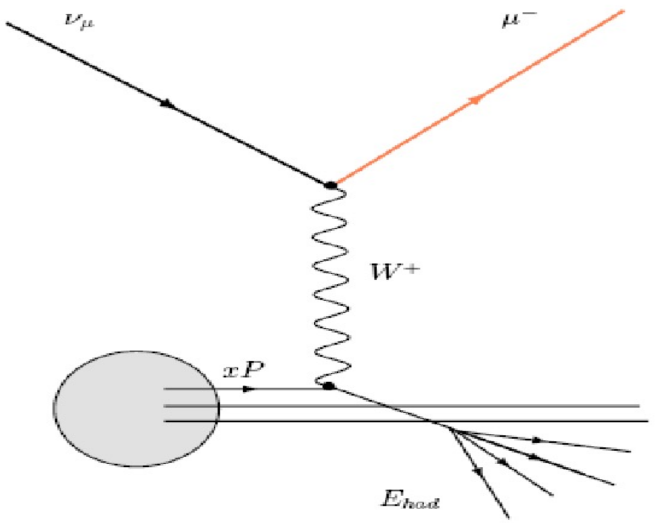
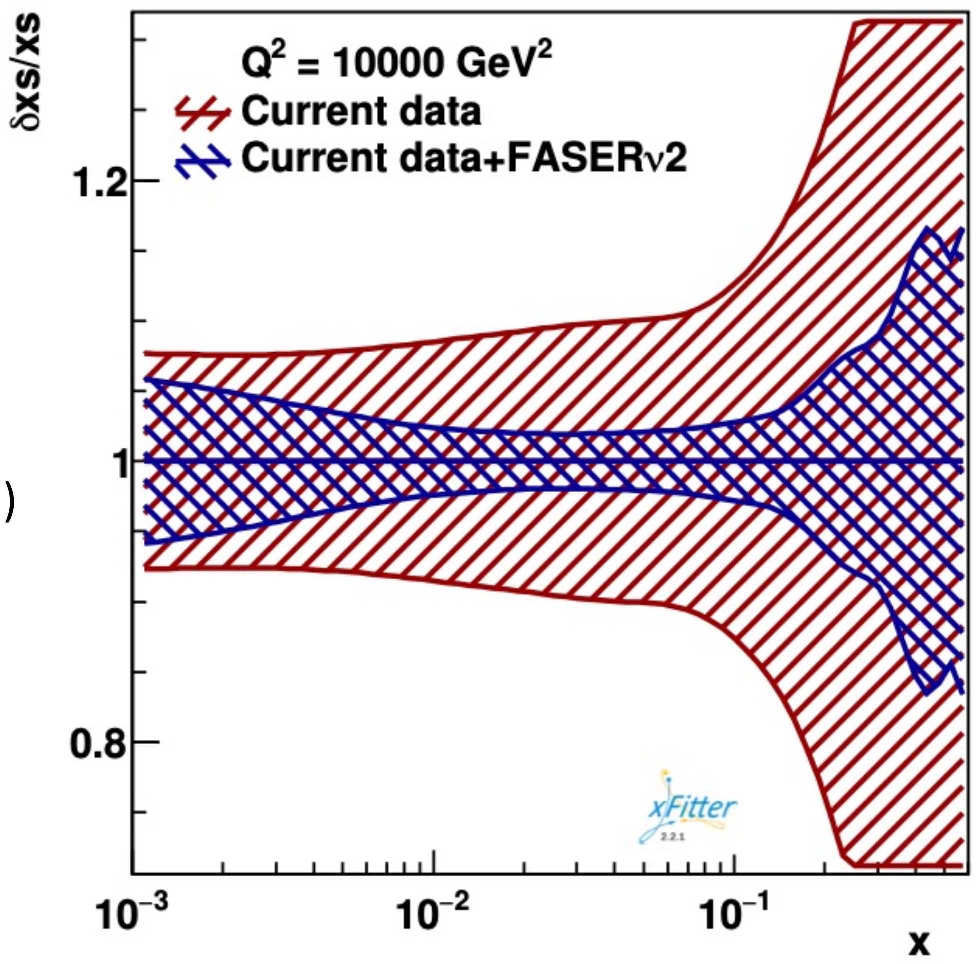
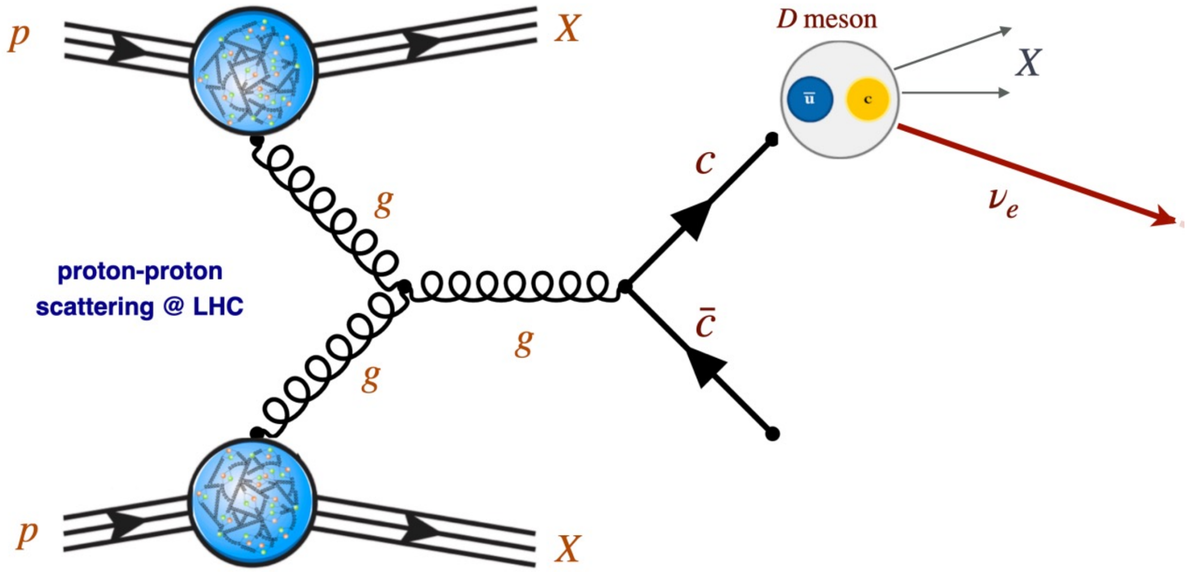
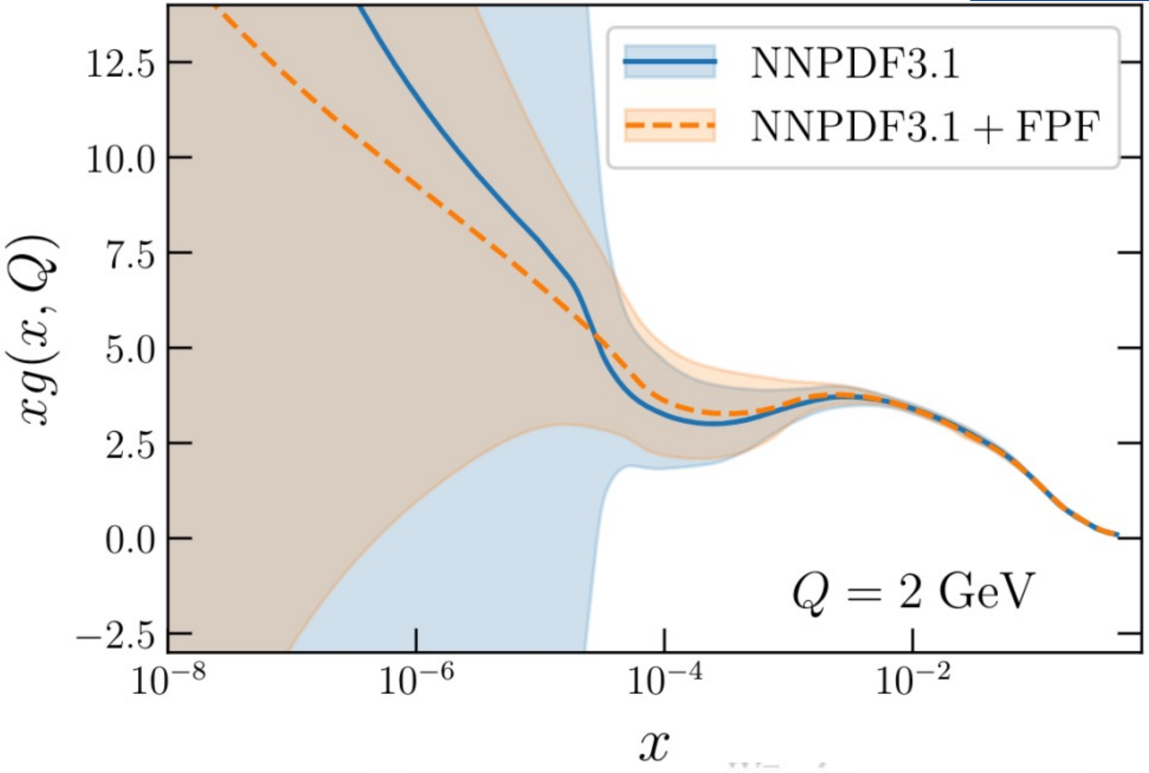


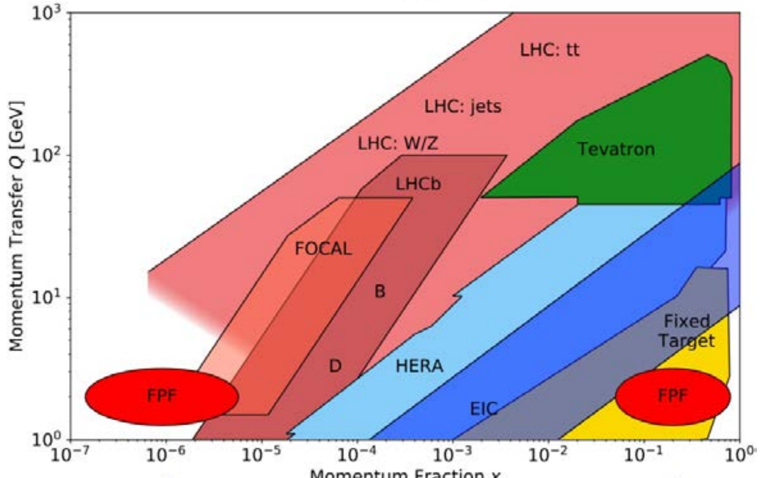


Physics Studies: gluon PDFs

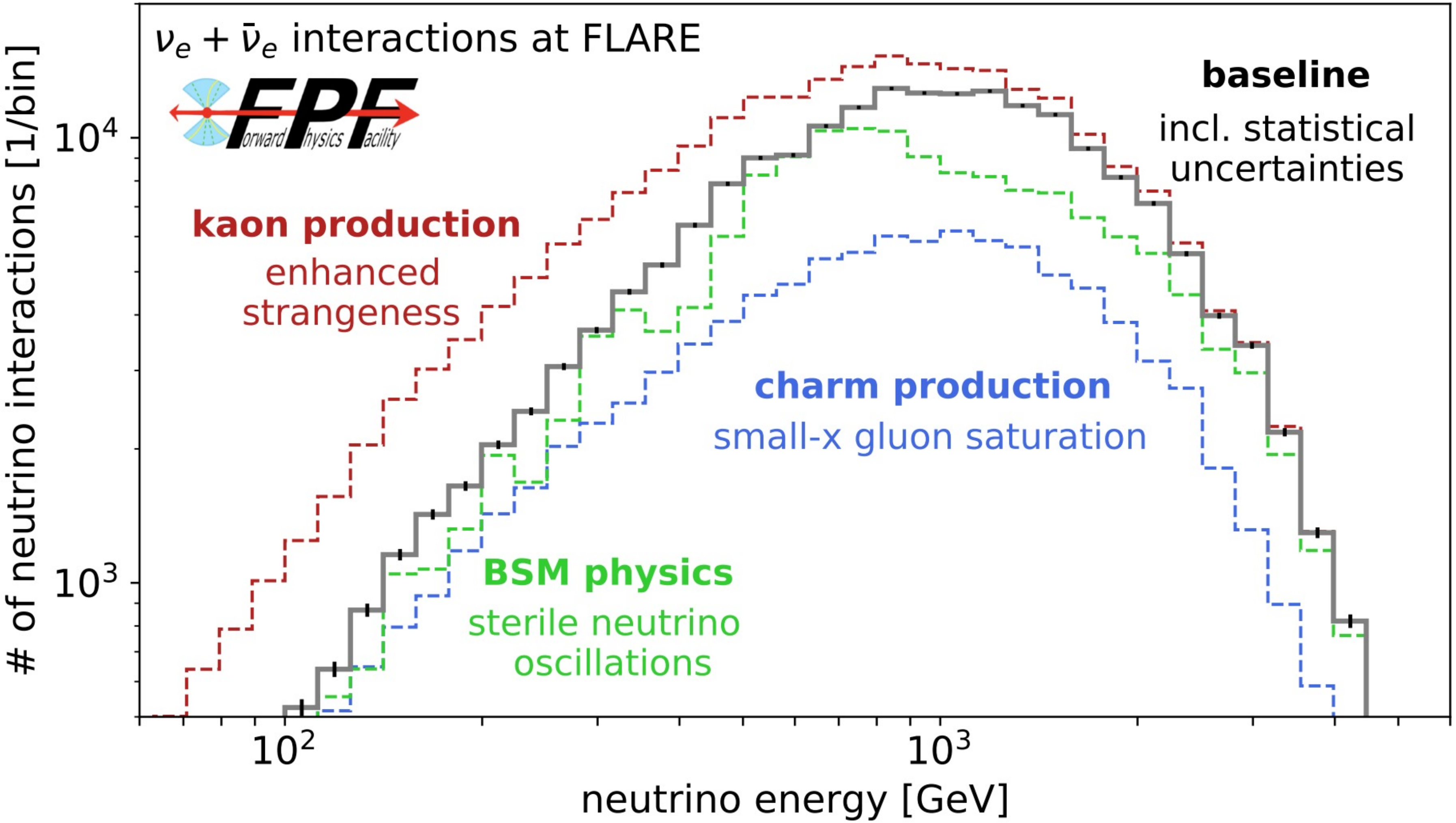




- Charm production from gluon fusion
- Forward charm probes small- and large- x gluons
- High energy electron neutrinos measured in the FPF come from charm
- FPF measurements can constrain low-x gluon PDF in currently unconstrained region
- Relevant for future colliders:
  - e.g. Higgs production at FCC



Physics Studies: Electron Neutrinos



Baseline spectra (with stat errors shown)

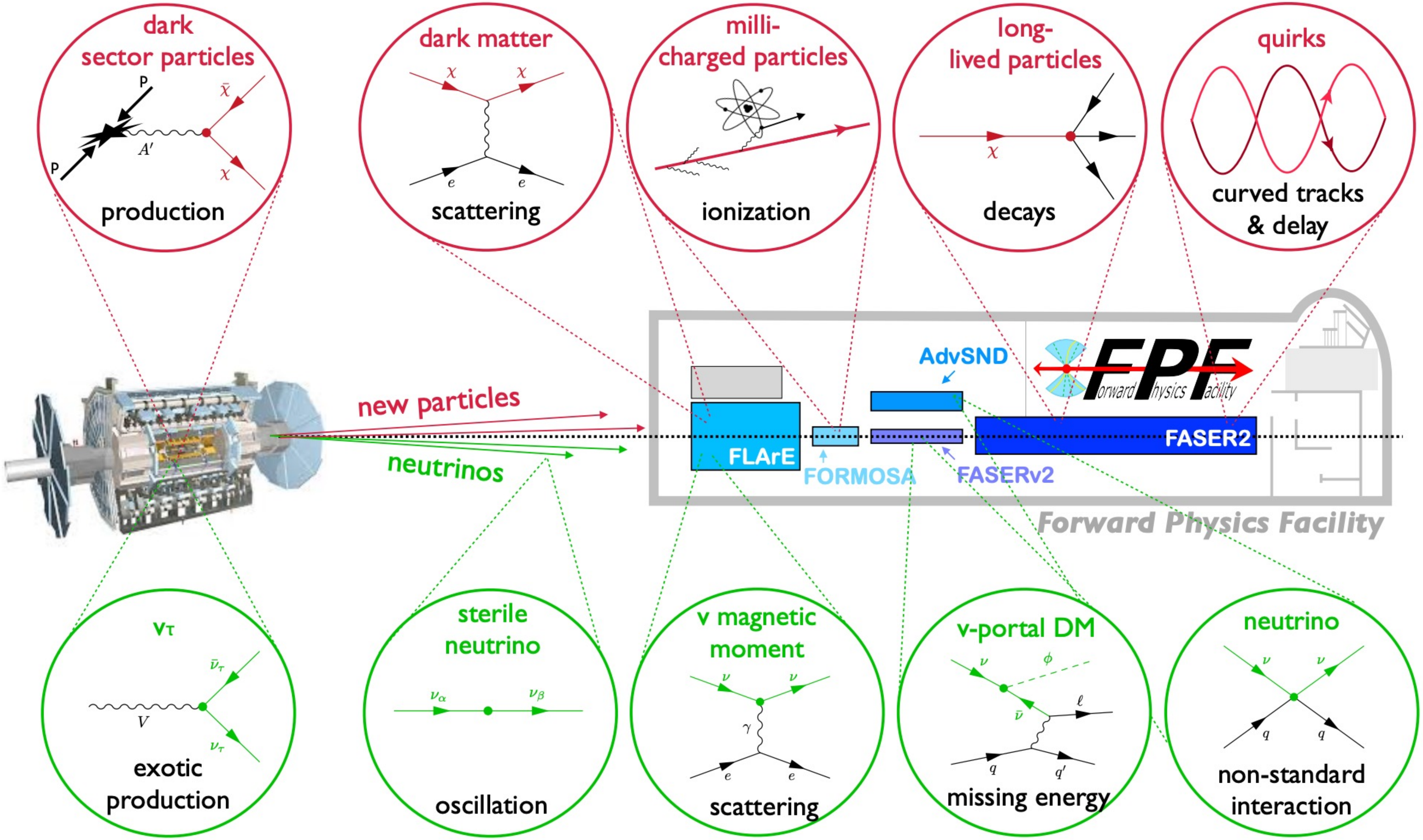
Enhanced strangeness model related to cosmic ray muon puzzle

Small-x gluon saturation

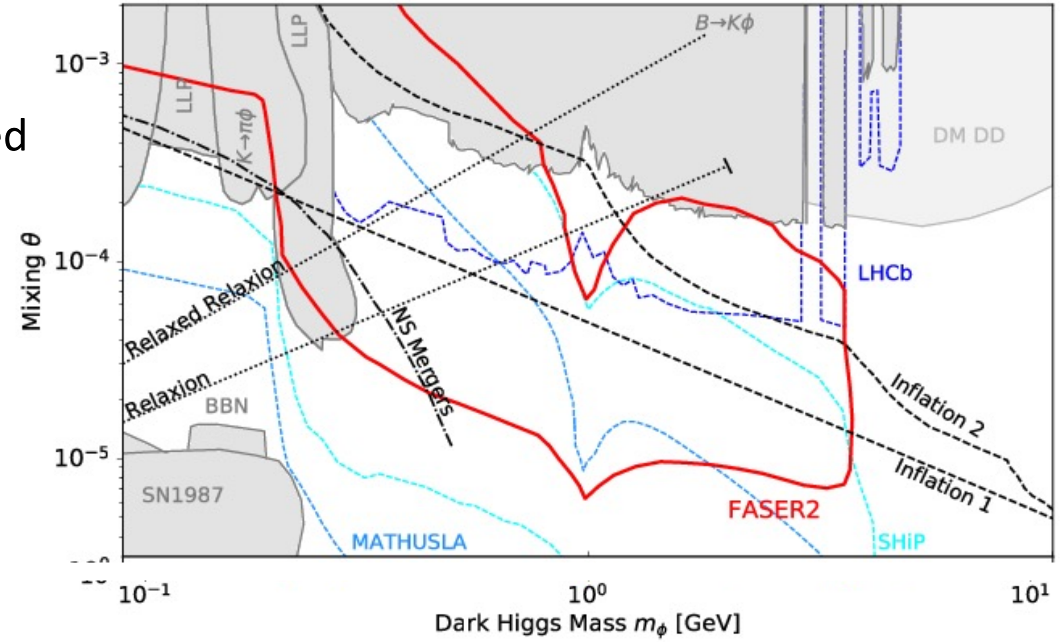
BSM sterile neutrino oscillation

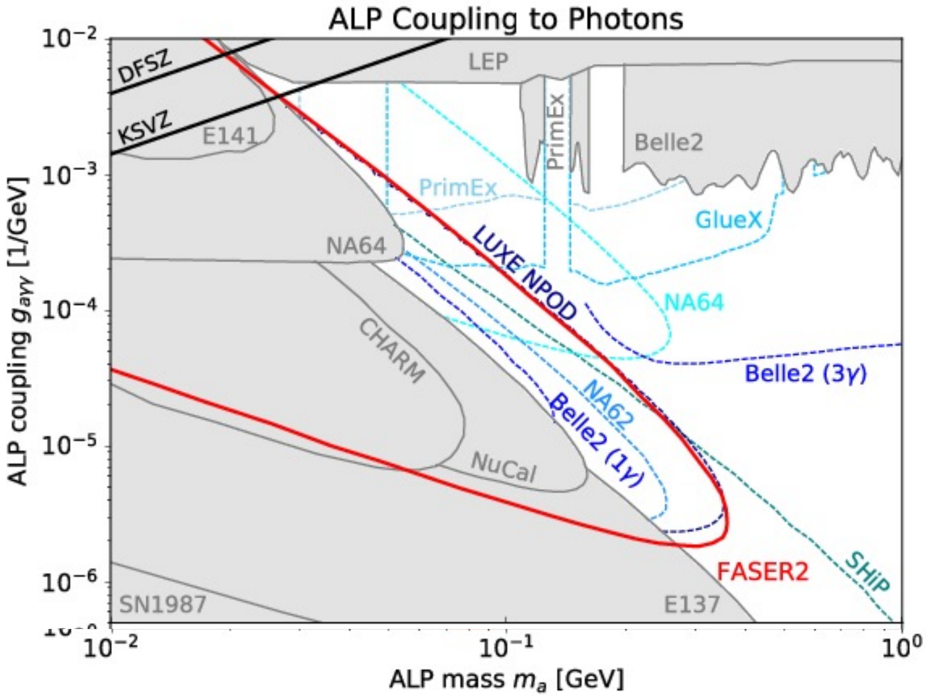
FPF forward charm measurements (via ν_e) very relevant for neutrino telescopes observation of diffuse high energy astrophysical neutrinos, where main background is from charm production in high energy cosmic ray interaction in atmosphere. FPF rapidity probes most relevant energy region.

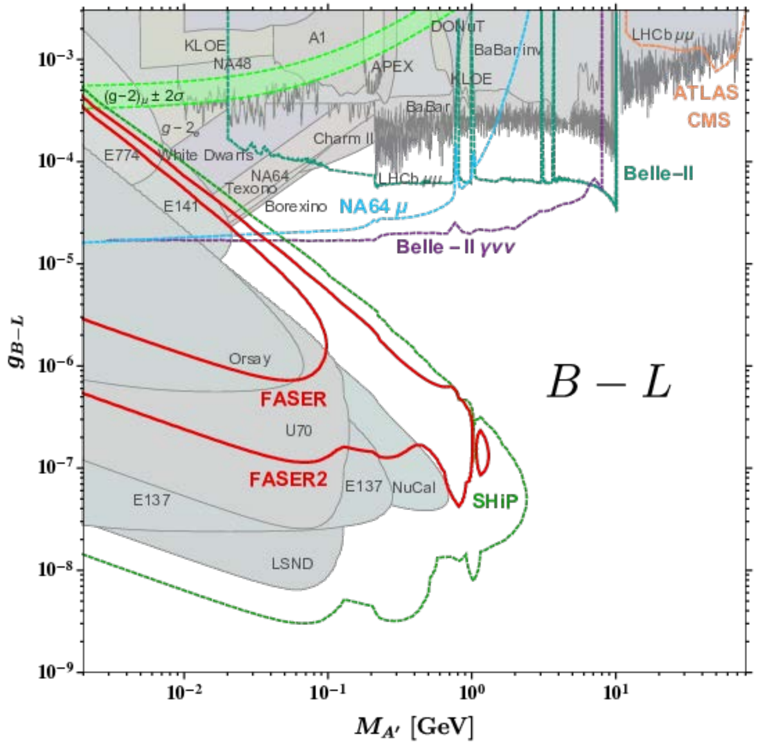
Physics Studies: BSM

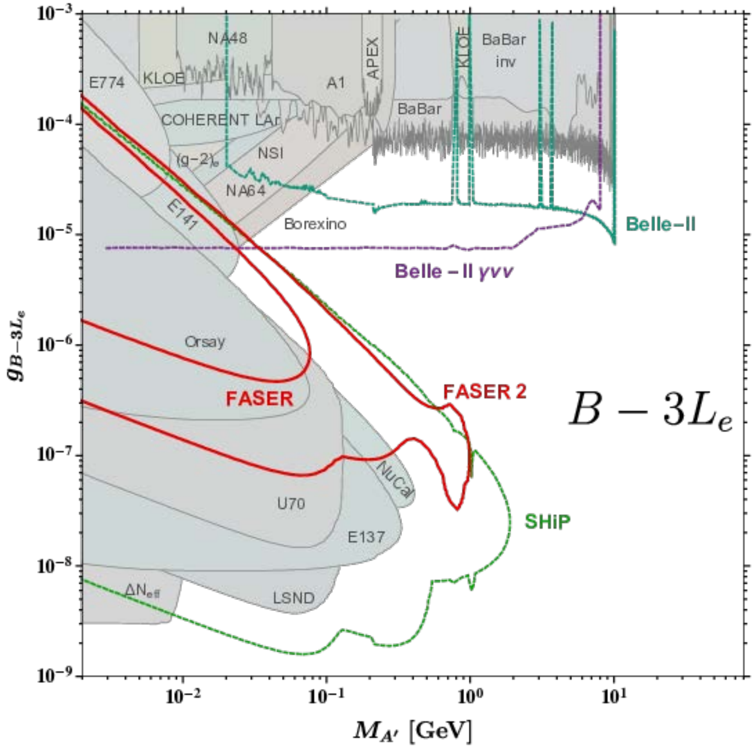


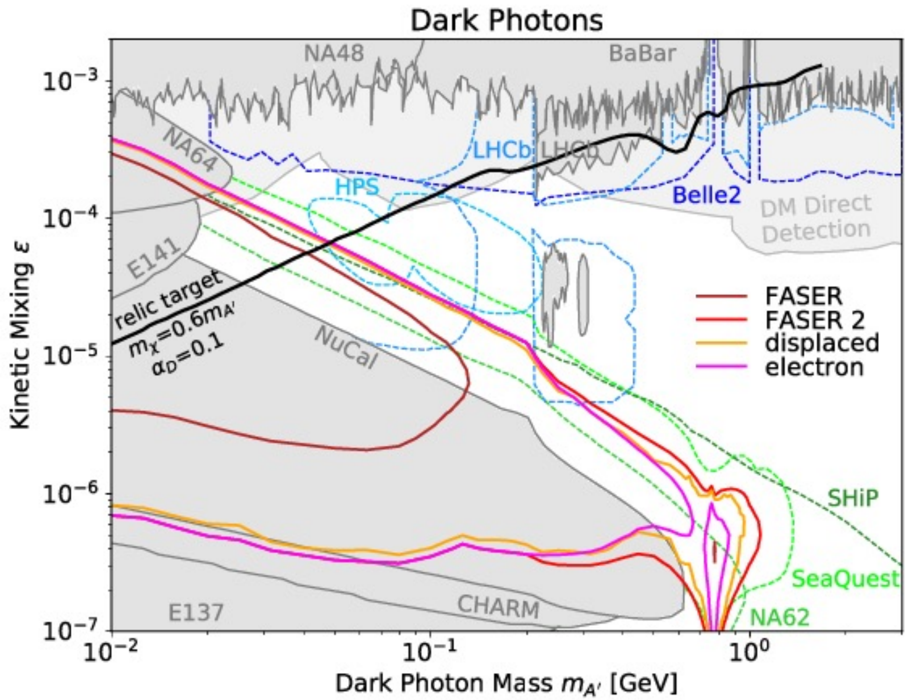
Example FASER2 sensitivity in various models.
Many more models included in the white paper:
J. Phys. G 50 (2023) 030501, 1-410 ([arxiv:2203.05090](https://arxiv.org/abs/2203.05090))



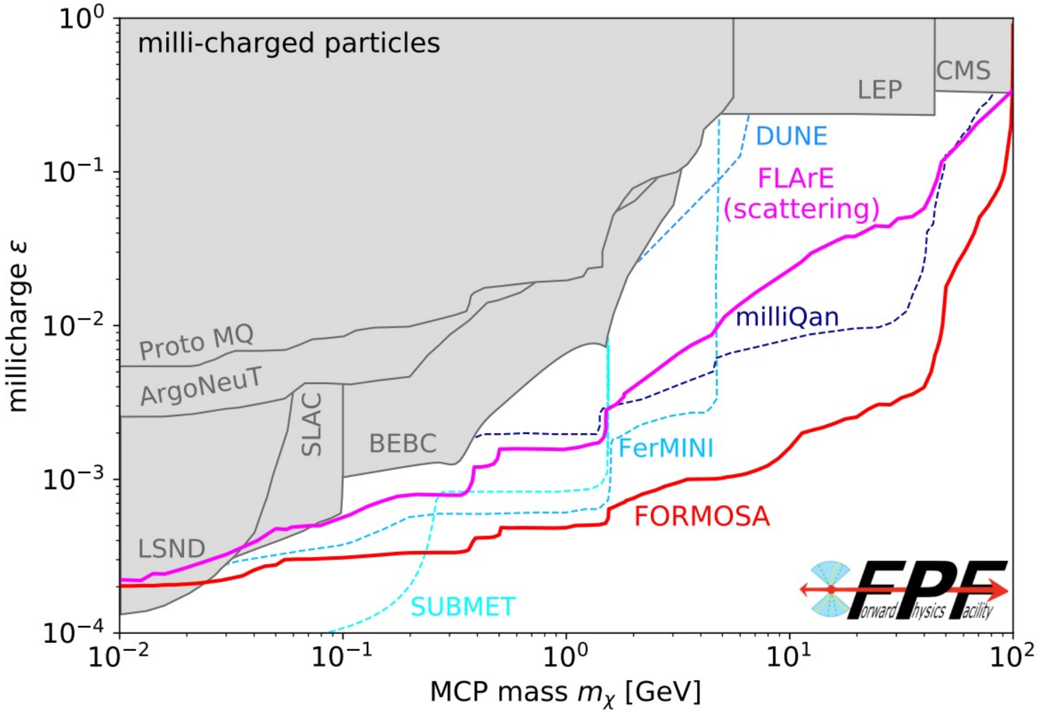


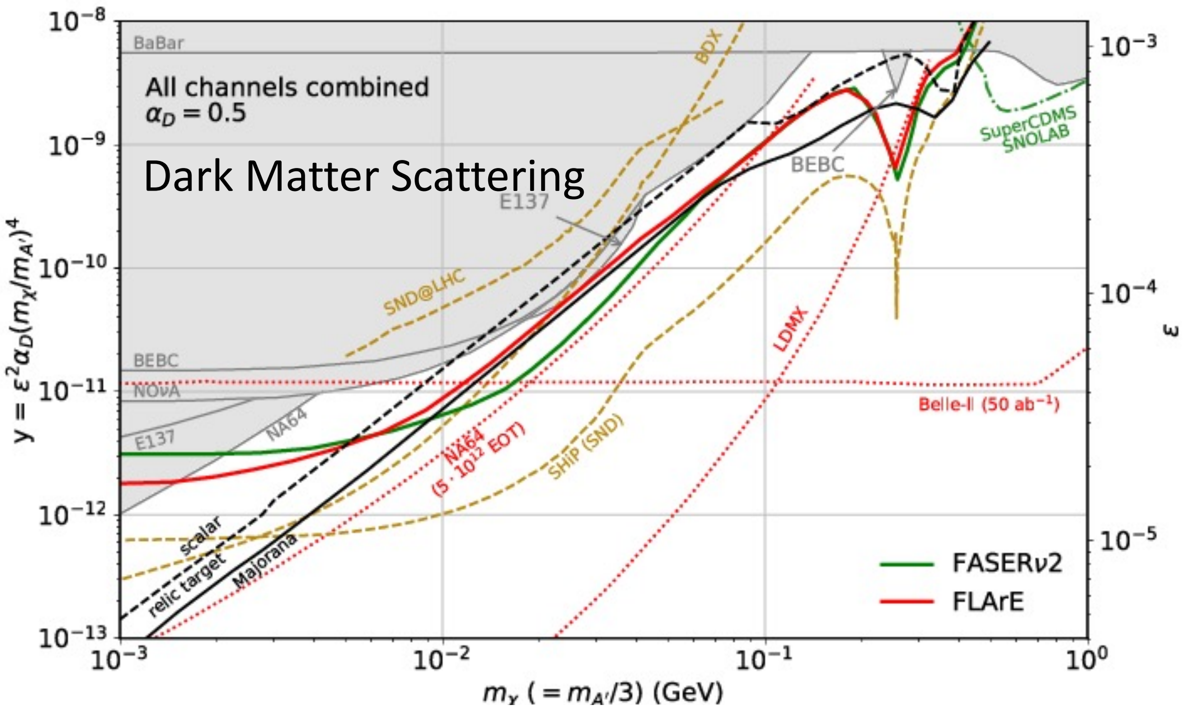




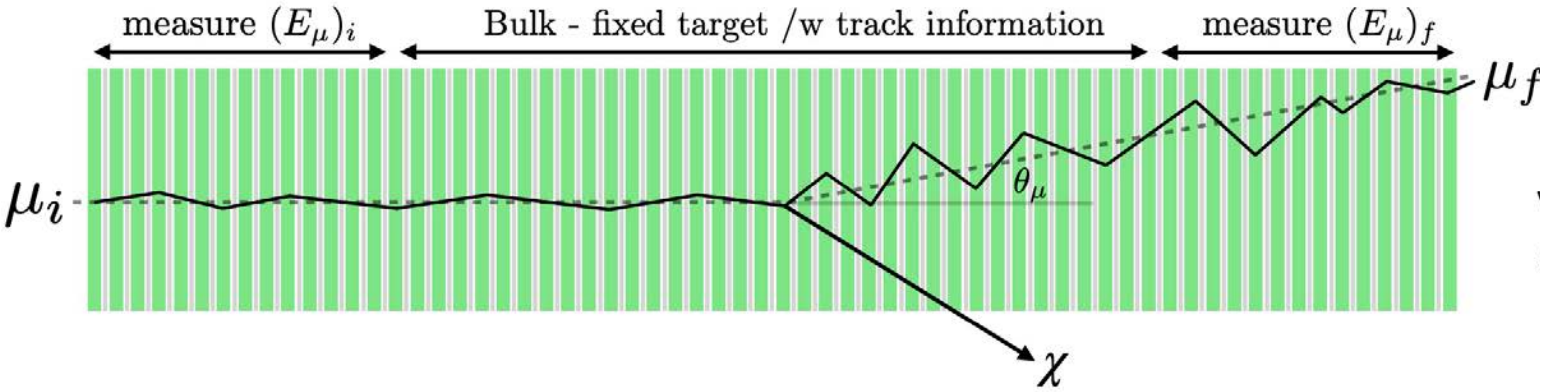


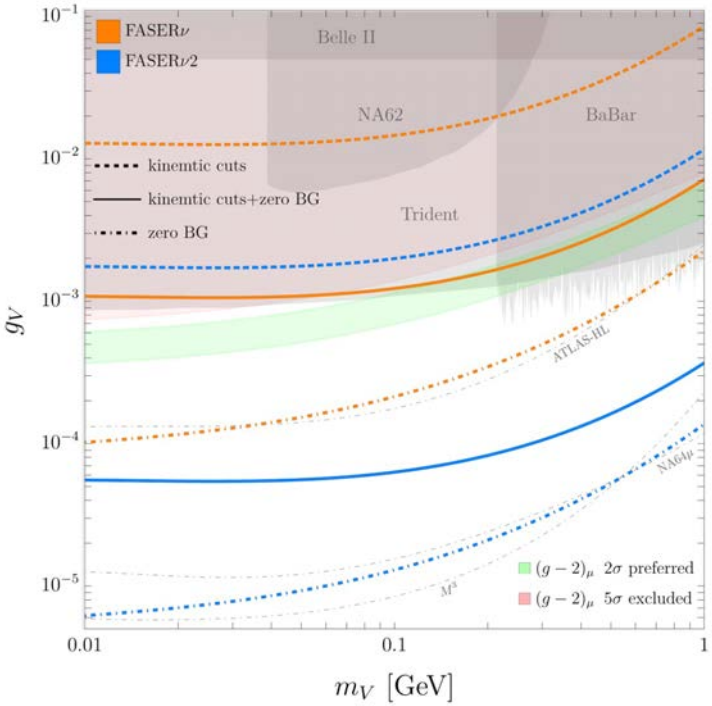
Examples of non-FASER2 FPF BSM sensitivity



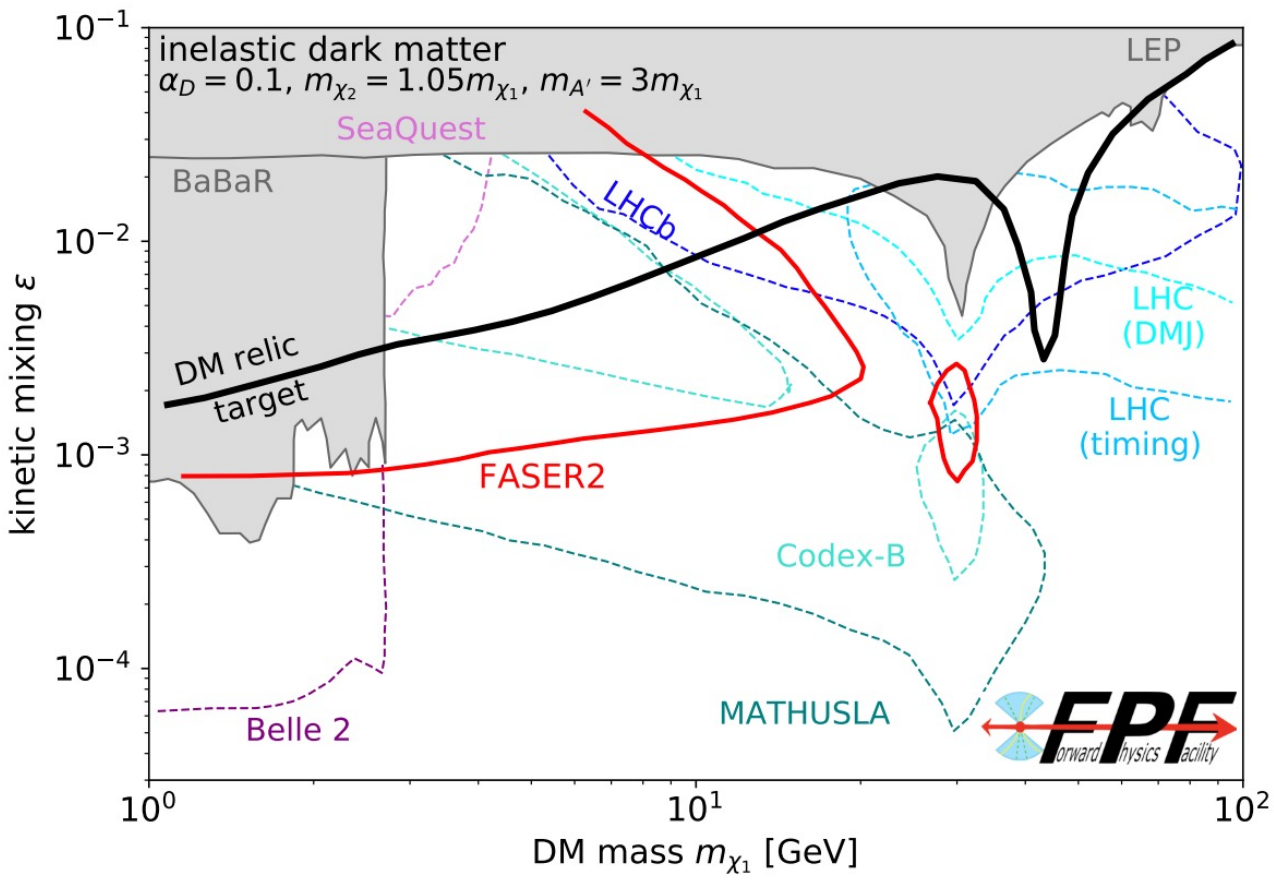


Searching for muonic forces (motivated by g-2) with FASERν2
([arxiv:2305.03102](https://arxiv.org/abs/2305.03102))





Physics Studies: BSM



FPF experiments have strong sensitivity in the usual dark sector benchmark scenarios:
Dark photons, Dark Higgs, ALPs etc…

Recent studies looking at models where high energy of LHC beam brings sensitivity (e.g. compared to beam dump experiments).

- Idea: inelastic dark matter, two states χ_1 (DM), χ_2,
  + assume dark photon mediator

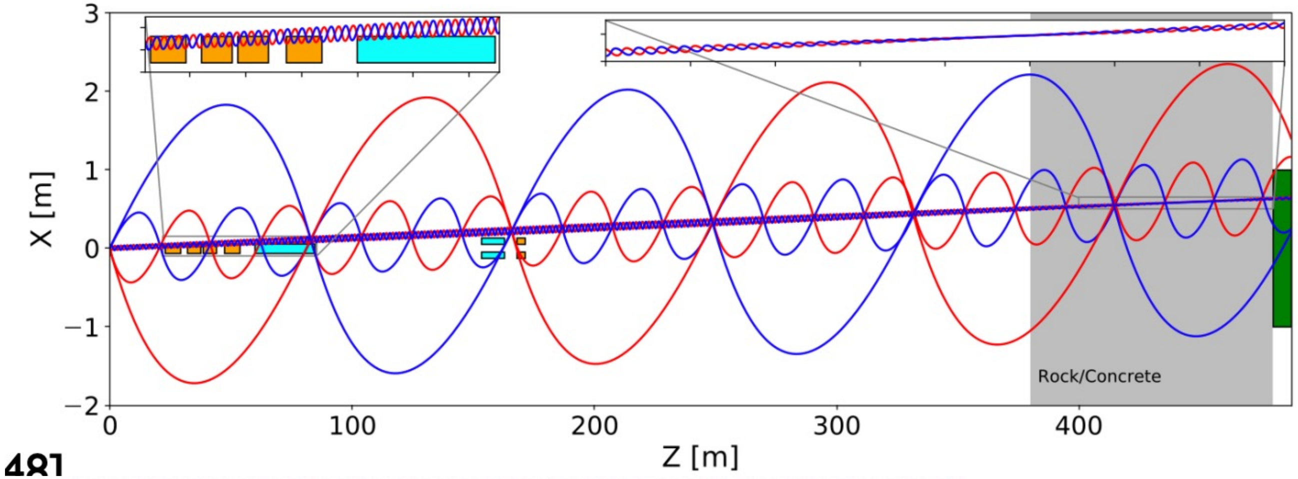
Small mass splitting: $\Delta = (m\chi_2 - m\chi_1) / m\chi_1$

Heavier state decays semi-visibly: $\chi_2 \rightarrow \chi_1 + (e^+e^-$ or $\mu^+\mu^-, \ldots)$

For $\Delta \ll 1$, only a small fraction of energy goes into visible particles

1810.01879 – A.Berlin, F.Kling
2301.05252 – K.Diennes, J.L.Feng, M.Fieg, F.Huang, S.J.Lee, B.Thomas
2305.16781 – K. Jodlowski

Physics Studies: BSM



FPF experiments have strong sensitivity in the usual dark sector benchmark scenarios:
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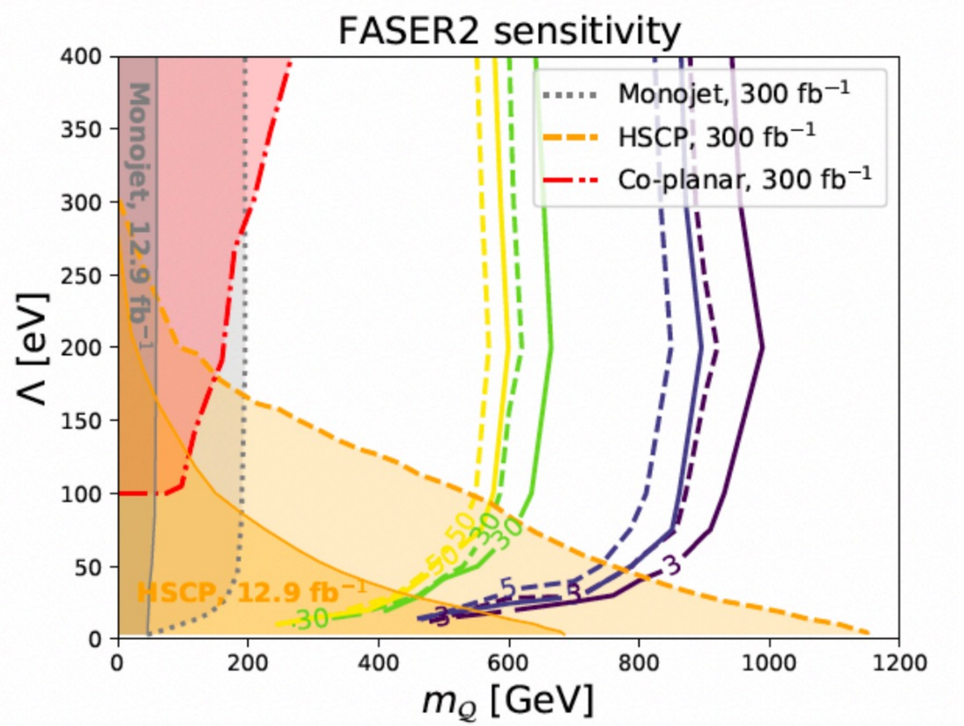
Recent studies looking at models where high energy of LHC beam brings sensitivity (compared to traditional LLP experiments such as beam dumps).



- **Quirks**: exotic particles that carry SM charges and form bound states of macroscopic size due to a darknon-Abelian force
- Produced in pairs, with very low intrinsic pT of the system
- In this case very forward FPF detectors sensitive to heavy particles (masses up to TeV)

J. Li, J. Pei, L. Ran, W. Zhang, 2108.06748

Summary

Excellent progress in all aspects of the Forward Physics Facility in last year

Technical:
- Site investigation study ongoing, first results look encouraging
- Many other positive studies related to the facility (background rates, radiation, excavations etc…)
- Design of the experiments advancing well

Physics case (covering neutrinos, QCD, BSM and with strong connections to astroparticle):
- Strong first results from FASER/SND@LHC highlight strong physics potential
- First quantitative studies of Standard Model physics case very encouraging
- Investigating sensitivity in BSM models not within reach of typical LLP experiments

Next steps:
- Updated costing of facility
- Work on integration of experiments into facility including infrastructure/services requirements
- Collaboration building and securing funding

Aim to submit LOI to LHCC in early 2025

Many thanks to the CERN PBC for invaluable support!

Final Words….

The FPF is fully aligned with the recommendations of the European Strategy for Particle Physics and the the US Snowmass process.
It represents a sustainable project to maximise the physics from the HL-LHC with a very broad physics programme.
If you are interested in getting involved please contact me: **Jamie.Boyd@cern.ch**

2020 EPPSU 1st Recommendation

The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

2022 Snowmass Energy Frontier Summary

Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

Resource needs and plan for the 5-year period starting 2025:

1. Prioritize HL-LHC physics program, including auxiliary experiments.

FPF Organization

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

WG0 Facility: Jamie Boyd

Physics WGs

WG1 Neutrino Interactions: Juan Rojo

WG2 Charm Production: Hallsie Reno, 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

WG8 AdvSND: Giovanni De Lellis

WG9 FORMOSA: Matthew Citron, Chris Hill

WG Liaisons	WG5 FASER2	WG6 FASERnu2	WG7 FLArE	WG8 AdvSND	WG9 FORMOSA
WG1	Josh McFayden	Aki Ariga, Tomoko Ariga	Steve Linden, Wenjie Wu	Antonia Di Crescenzo	Matthew Citron
WG2	Josh McFayden	Aki Ariga, Tomoko Ariga	Steve Linden, Wenjie Wu	Antonia Di Crescenzo	Matthew Citron
WG3	Josh McFayden	Aki Ariga, Tomoko Ariga	Steve Linden, Wenjie Wu	Antonia Di Crescenzo	Matthew Citron
WG4	Josh McFayden	Aki Ariga, Tomoko Ariga	Steve Linden, Wenjie Wu	Cristovao Vilela	Matthew Citron

Site Investigation works: First Results

- At depths of 67.3, 76.20 and 82.0 m, 40 to 70 cm thick levels of very soft, crushed marl soil like (hard clay and silt with concretions of marls and sandstone) were found
- Should be taken into consideration for the design of the shaft and experimental cavern
- Signs of hydrocarbons were found in the soft sandstone at depths between 84m and 90m
- The excavated material needs to be disposed in a biocentre or in a non-hazardous waste storage facility
- Foundations of the surface buildings will sit within the moraine.
- Additional shallow boreholes are recommended to check the variations in the thickness of the backfill over the entire area
- No water table has been identified. Overall the ground is not very permeable, only low-flow infiltration has been identified in a slightly more permeable zone of the moraine.

Report on detailed analysis of site investigation in preparation.
Will feed into updated costing of facility.

Vibrations etc…

https://www.ipac23.org/preproc/pdf/THPA039.pdf
CERN Beam Physics and Mechanical engineering groups

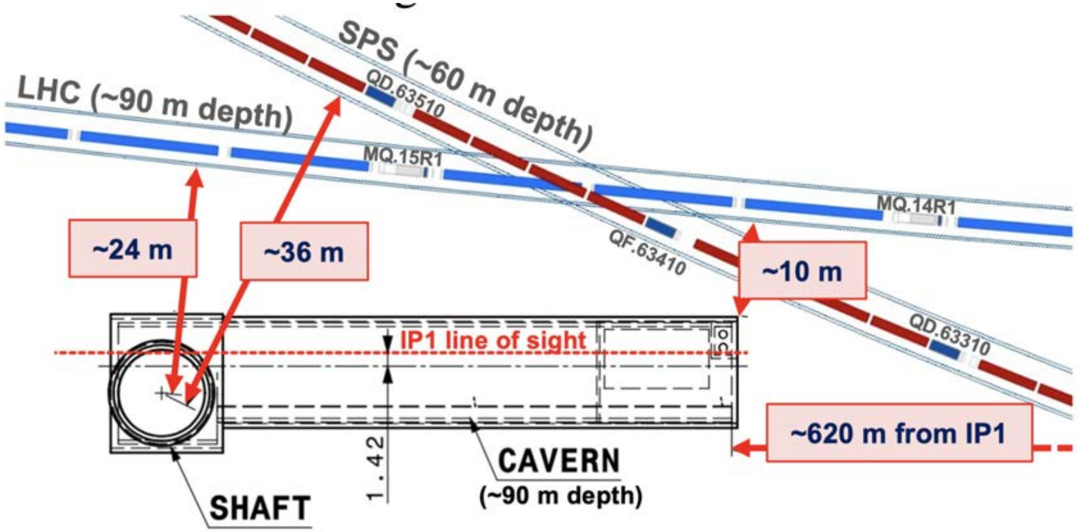
Study on effect of excavation work on HL-LHC (& SPS) operations in terms of vibrations and possible tunnel movements, based on similar studies for HL-LHC civil engineering works close to ATLAS/CMS.

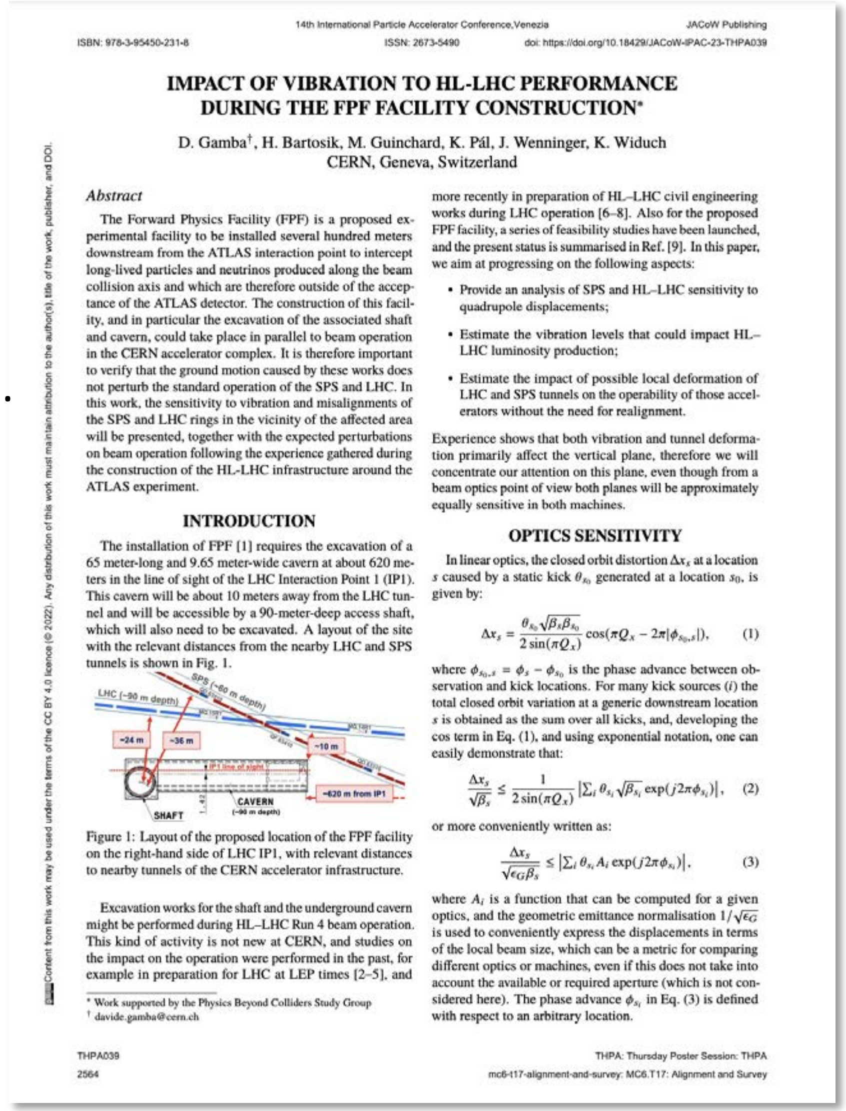
Preliminary results presented at IPAC conference in May and public document available.

Results seem positive that FPF excavations could happen during beam operations.

Last line of the conclusions:

"The general conclusion is that no major disruption of the HL-LHC and SPS performance is expected during the FPF excavation works."





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IMPACT OF VIBRATION TO HL-LHC PERFORMANCE DURING THE FPF FACILITY CONSTRUCTION*

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Abstract

The Forward Physics Facility (FPF) is a proposed experimental facility to be installed several hundred meters downstream from the ATLAS interaction point to intercept long-lived particles and neutrinos produced along the beam collision axis and which are therefore outside of the acceptance of the ATLAS detector. The construction of this facility, and in particular the excavation of the associated shaft and cavern, could take place in parallel to beam operation in the CERN accelerator complex. It is therefore important to verify that the ground motion caused by these works does not perturb the standard operation of the SPS and LHC. In this work, the sensitivity to vibration and misalignments of the SPS and LHC rings in the vicinity of the affected area will be presented, together with the expected perturbations on beam operation following the experience gathered during the construction of the HL-LHC infrastructure around the ATLAS experiment.

INTRODUCTION

The installation of FPF [1] requires the excavation of a 65 meter-long and 9.65 meter-wide cavern at about 620 meters in the line of sight of the LHC Interaction Point 1 (IP1). This cavern will be about 10 meters away from the LHC tunnel and will be accessible by a 90-meter-deep access shaft, which will also need to be excavated. A layout of the site with the relevant distances from the nearby LHC and SPS tunnels is shown in Fig. 1.

Figure 1: Layout of the proposed location of the FPF facility on the right-hand side of LHC IP1, with relevant distances to nearby tunnels of the CERN accelerator infrastructure.

Excavation works for the shaft and the underground cavern might be performed during HL–LHC Run 4 beam operation. This kind of activity is not new at CERN, and studies on the impact on the operation were performed in the past, for example in preparation for LHC at LEP times [2–5], and more recently in preparation of HL–LHC civil engineering works during LHC operation [6–8]. Also for the proposed FPF facility, a series of feasibility studies have been launched, and the present status is summarised in Ref. [9]. In this paper, we aim at progressing on the following aspects:

- Provide an analysis of SPS and HL–LHC sensitivity to quadrupole displacements;
- Estimate the vibration levels that could impact HL–LHC luminosity production;
- Estimate the impact of possible local deformation of LHC and SPS tunnels on the operability of those accelerators without the need for realignment.

Experience shows that both vibration and tunnel deformation primarily affect the vertical plane, therefore we will concentrate our attention on this plane, even though from a beam optics point of view both planes will be approximately equally sensitive in both machines.

OPTICS SENSITIVITY

In linear optics, the closed orbit distortion Δx_s at a location s caused by a static kick θ_{s_0} generated at a location s_0, is given by:

$$\Delta x_s = \frac{\theta_{s_0}\sqrt{\beta_s \beta_{s_0}}}{2\sin(\pi Q_x)} \cos(\pi Q_x - 2\pi|\phi_{s_0,s}|), \quad (1)$$

where $\phi_{s_0,s} = \phi_s - \phi_{s_0}$ is the phase advance between observation and kick locations. For many kick sources (i) the total closed orbit variation at a generic downstream location s is obtained as the sum over all kicks, and, developing the cos term in Eq. (1), and using exponential notation, one can easily demonstrate that:

$$\frac{\Delta x_s}{\sqrt{\beta_s}} \leq \frac{1}{2\sin(\pi Q_x)} \left|\sum_i \theta_{s_i} \sqrt{\beta_{s_i}} \exp(j2\pi\phi_{s_i})\right|, \quad (2)$$

or more conveniently written as:

$$\frac{\Delta x_s}{\sqrt{\epsilon_G \beta_s}} \leq \left|\sum_i \theta_{s_i} A_i \exp(j2\pi\phi_{s_i})\right|, \quad (3)$$

where A_i is a function that can be computed for a given optics, and the geometric emittance normalisation $1/\sqrt{\epsilon_G}$ is used to conveniently express the displacements in terms of the local beam size, which can be a metric for comparing different optics or machines, even if this does not take into account the available or required aperture (which is not considered here). The phase advance ϕ_{s_i} in Eq. (3) is defined with respect to an arbitrary location.

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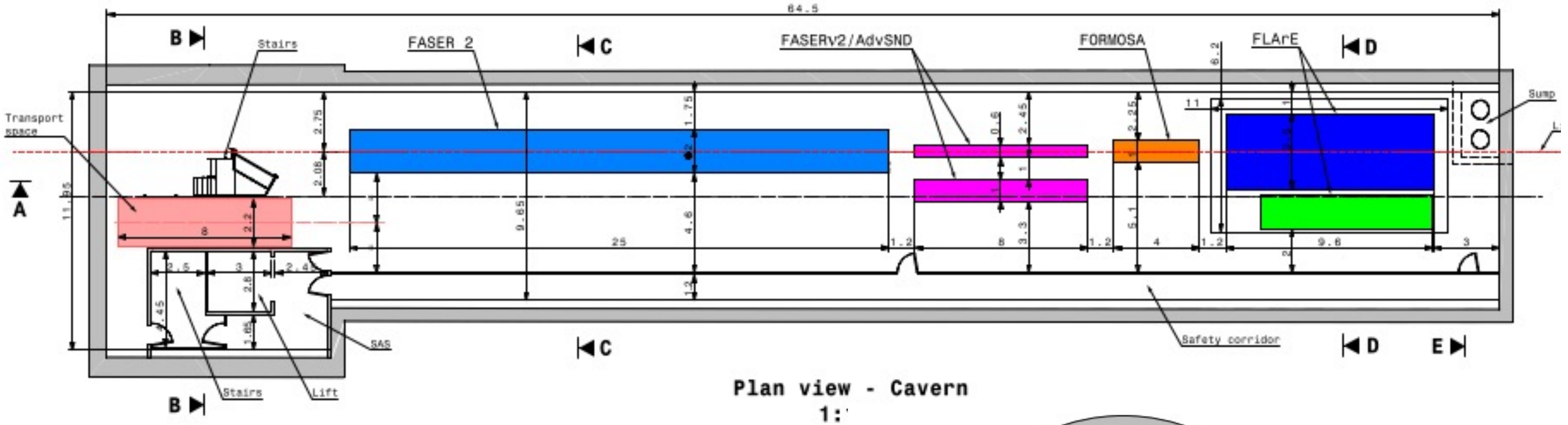
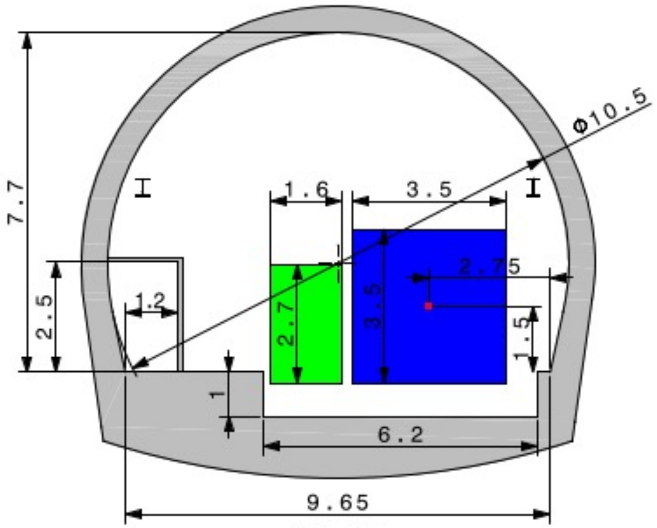
The Facility Design

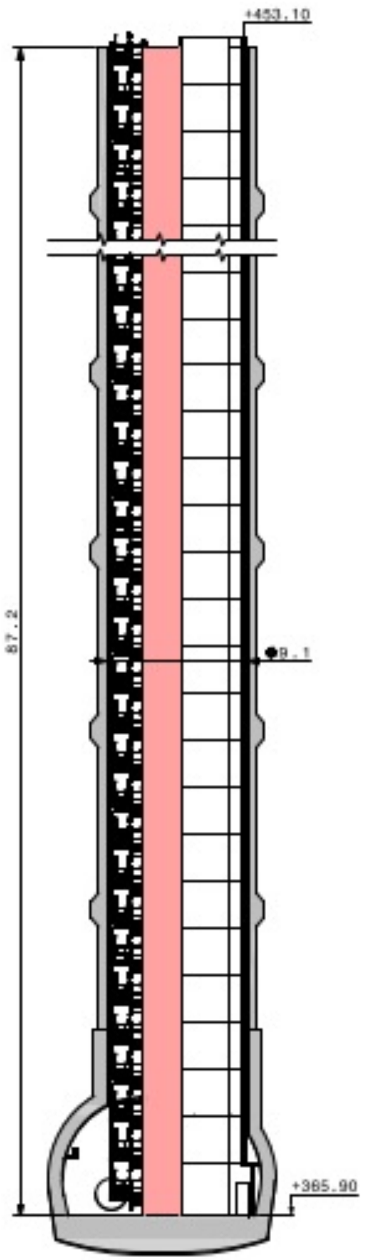


Plan view - Cavern

1:



D-D



Results: proton PDFs

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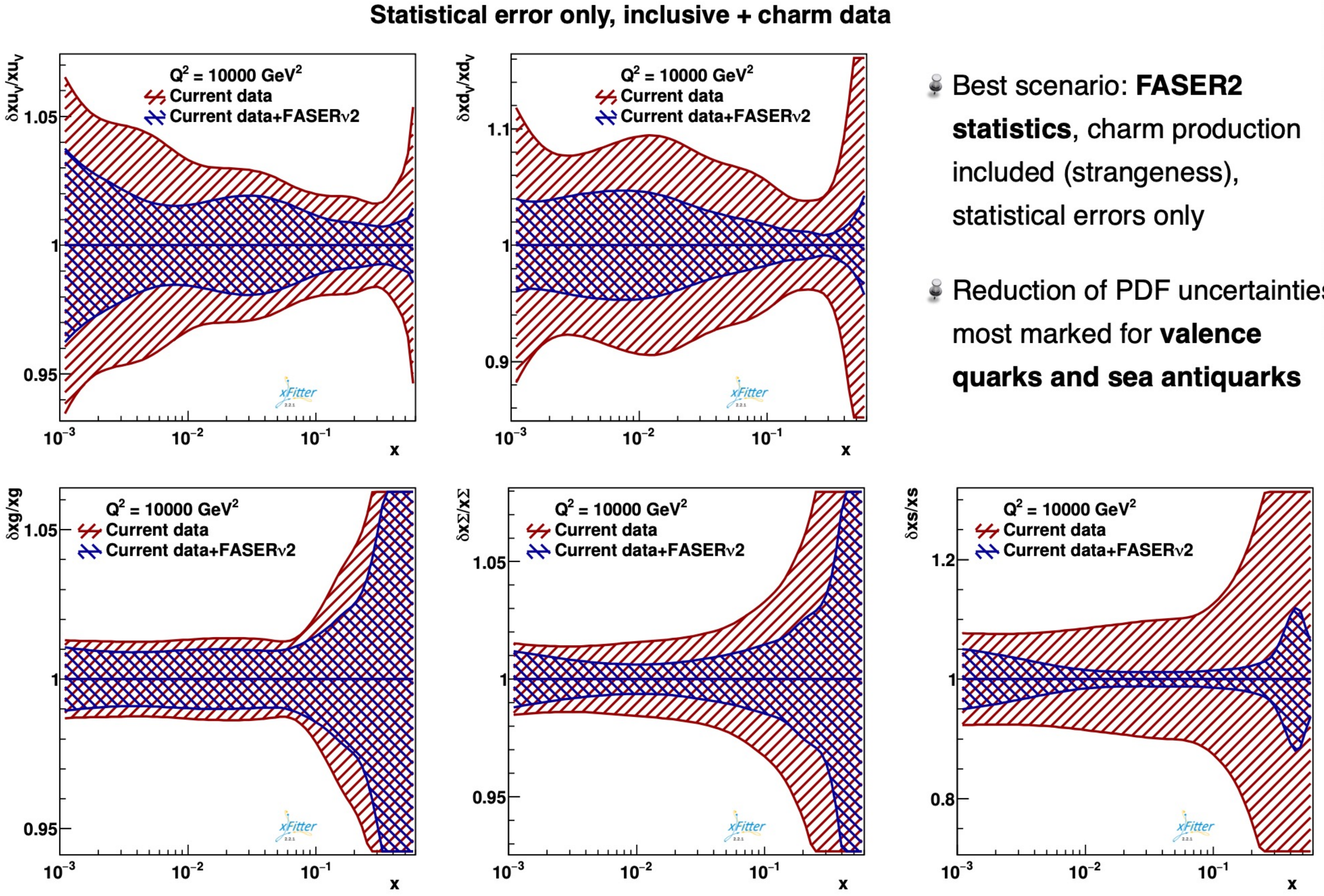

- Best scenario: **FASER2 statistics**, charm production included (strangeness), statistical errors only
- Reduction of PDF uncertainties most marked for **valence quarks and sea antiquarks**