The Forward Physics Facility at the High-Luminosity LHC

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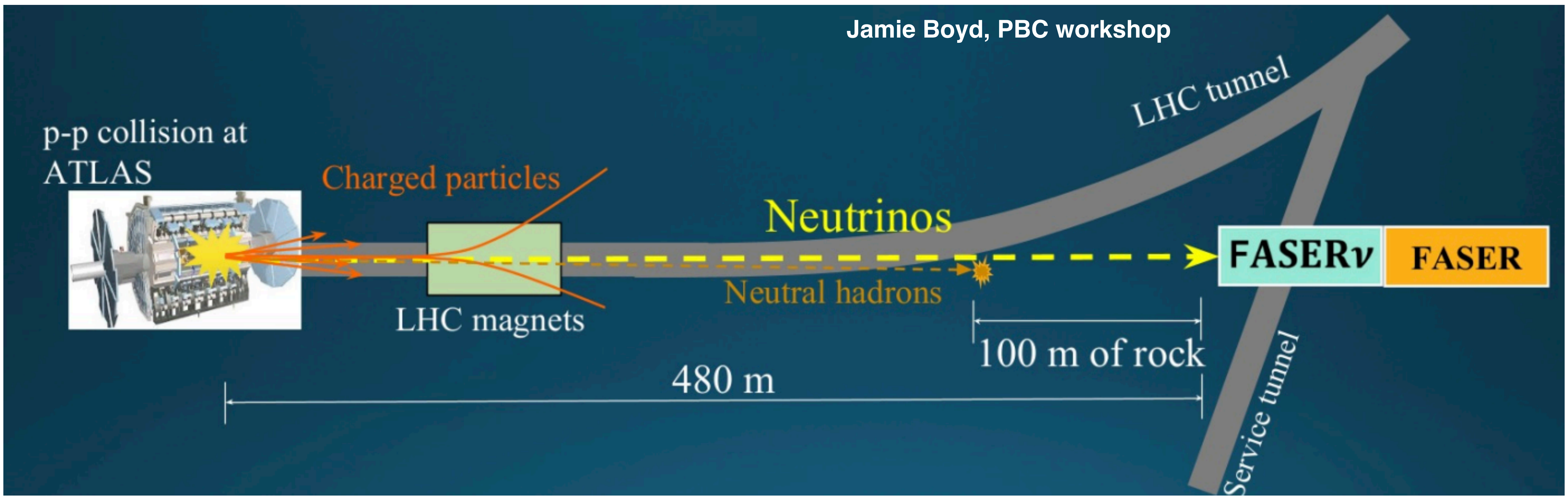
The Forward Physics Facility at the High-Luminosity LHC, Snowmass Whitepaper, arXiv:2203:05090

The Forward Physics Facility

A proposed new facility, located in the **very forward region** of the LHC collision point, suitable to detect **long-lived BSM particles** and **neutrinos** (everything else screened by rock)

Concept demonstrated by **FASER(v)** and **SND@LHC** experiments (Run II + Run III)

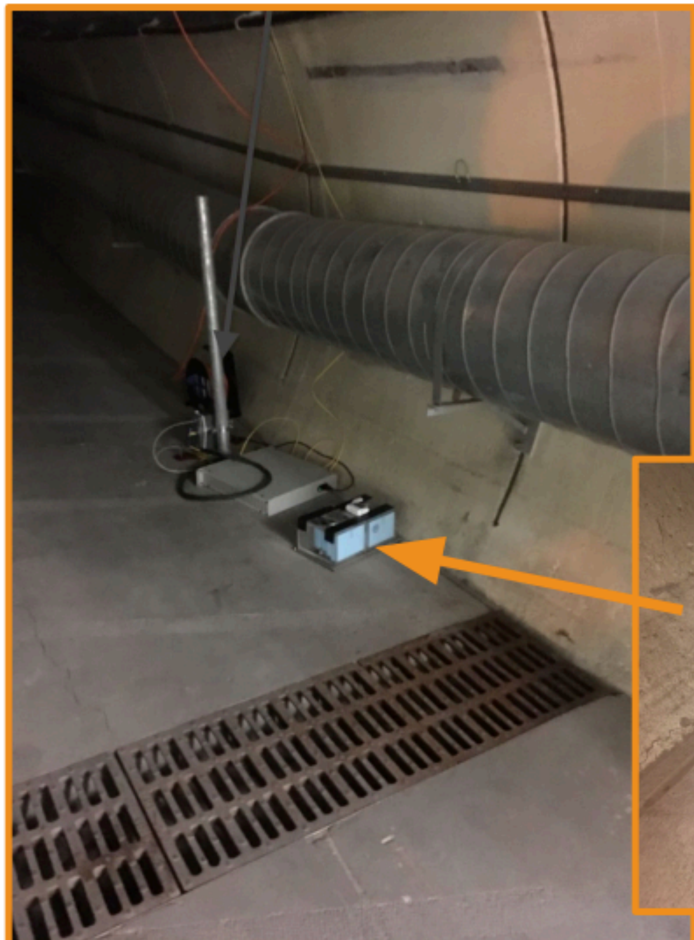


Upscaling this exciting concept for the **HL-LHC era** demands a new suite of experiments (collectively denoted as **FPF**), to be located in a brand new cavern

The Forward Physics Facility

from Felix Kling

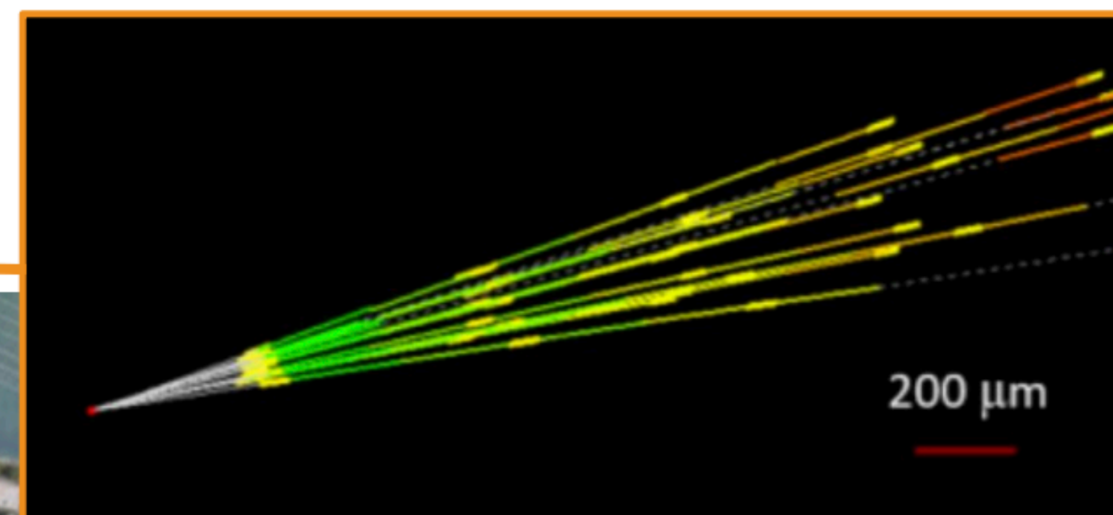
1984 — 2018 — 2022 — 2028

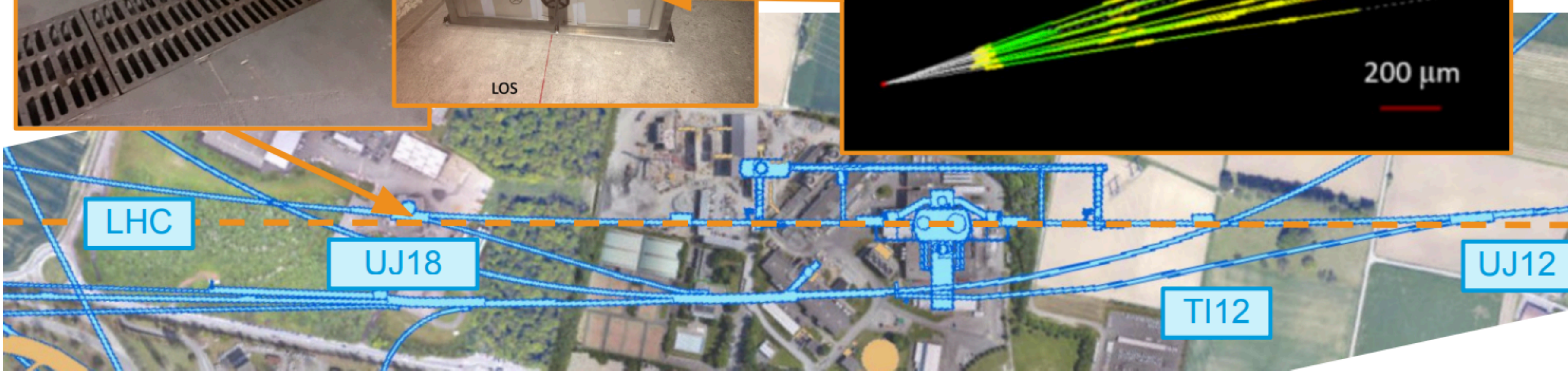


In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks. O(10) neutrino interactions expected

First neutrino interaction candidates were recently reported.

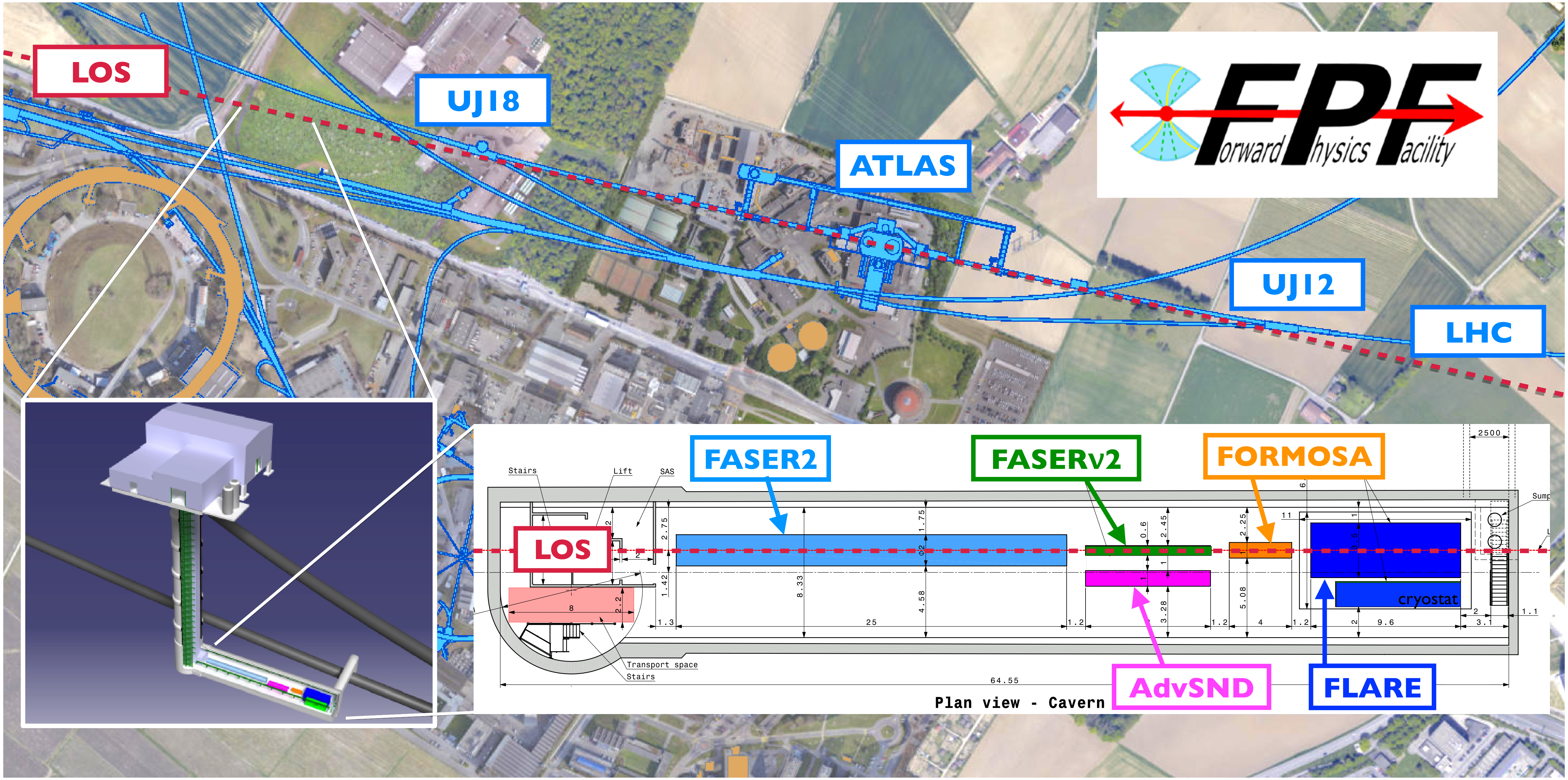
[FASER, 2105.06197]





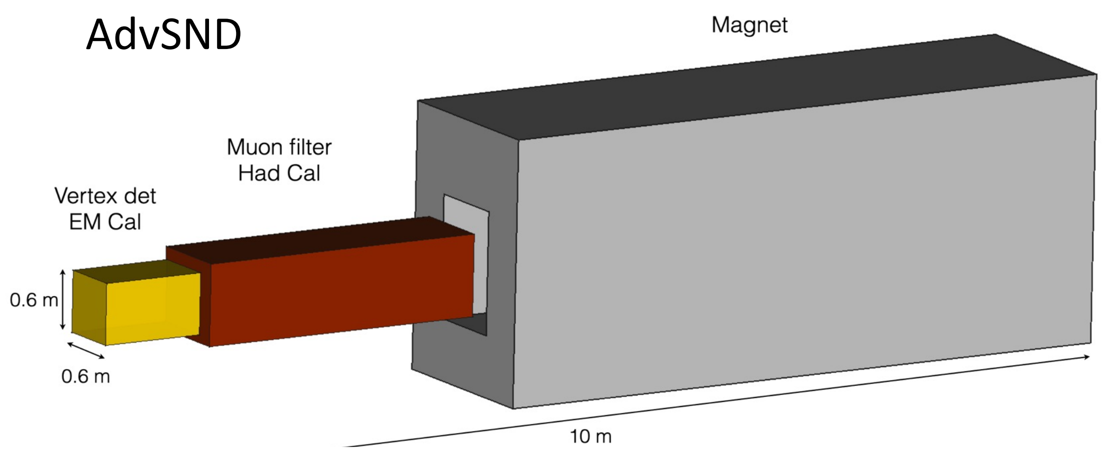
for the first time, **neutrino (candidates)** have been detected at the LHC!

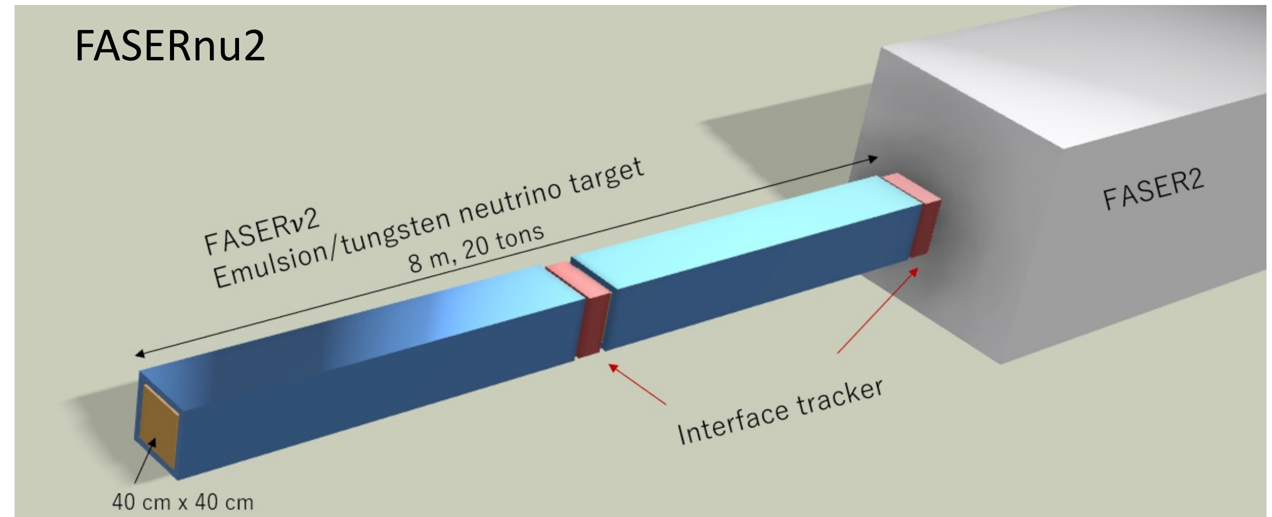
The Forward Physics Facility

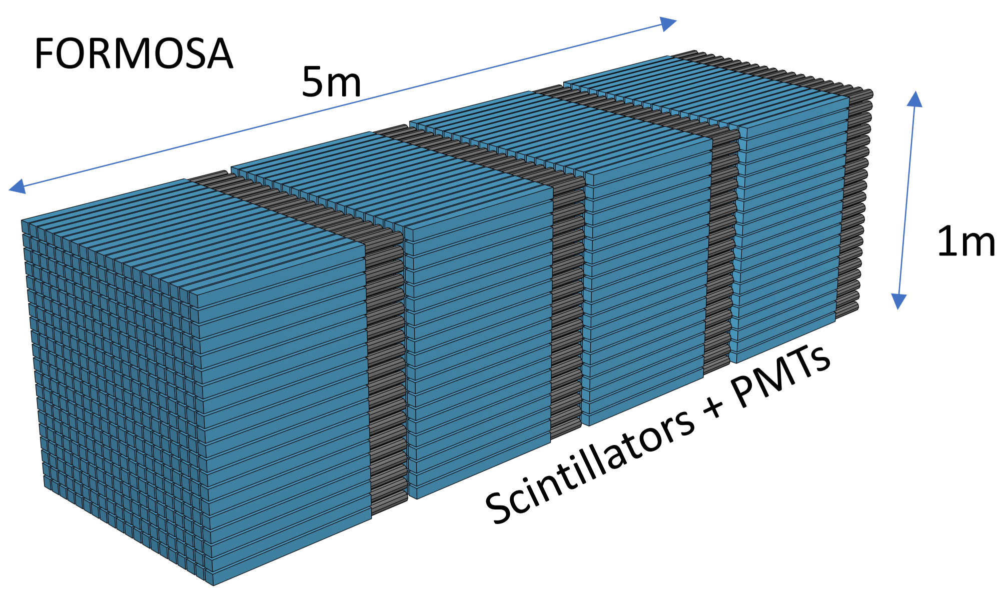


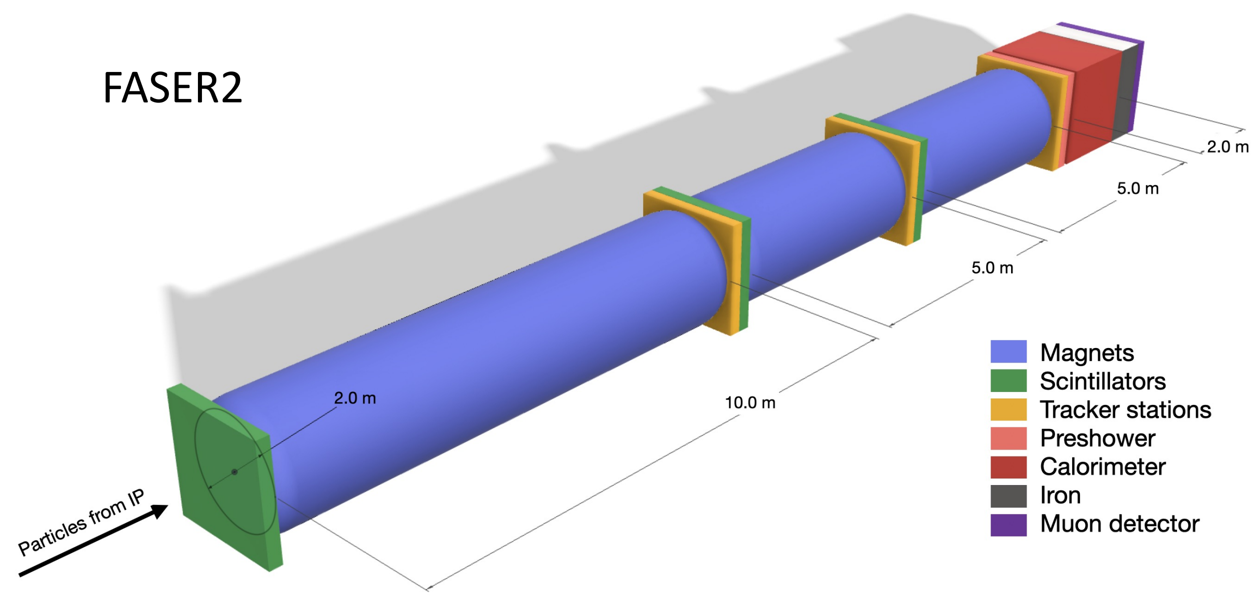
The preferred location for the FPF is a **65 m long and 9 m wide cavern** hosting several detectors, each one with different and complementary physics goals

Experiment sketches









No detailed design for any of these experiments yet

Use 'spare parts' from other LHC experiments such as ATLAS tracker modules and LHCb Calorimeter

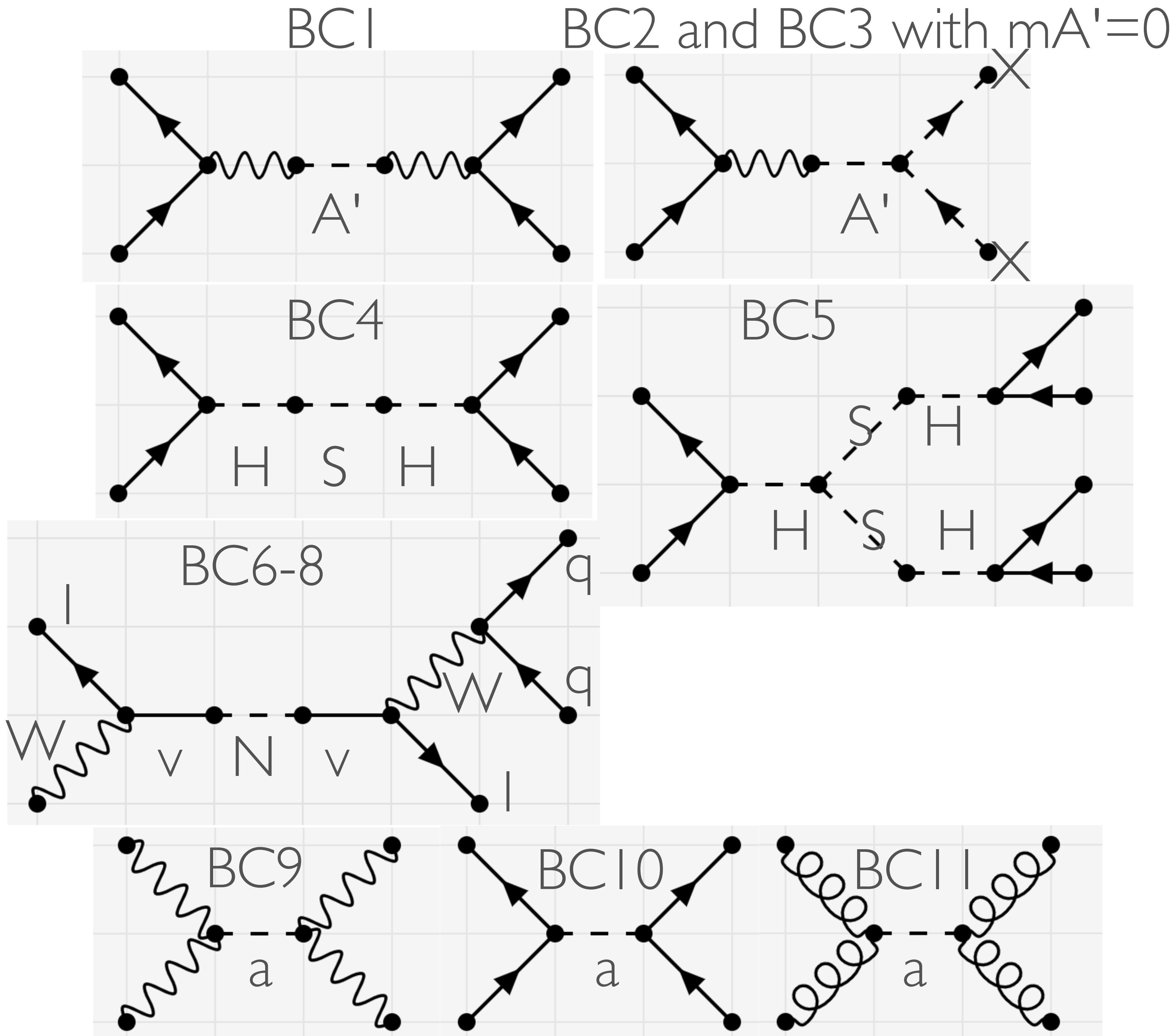
BSM benchmark models

Dark Photons, Dark Matter, Millicharged particles

Dark Scalars

Heavy Neutral Leptons

Axion-Like Particles

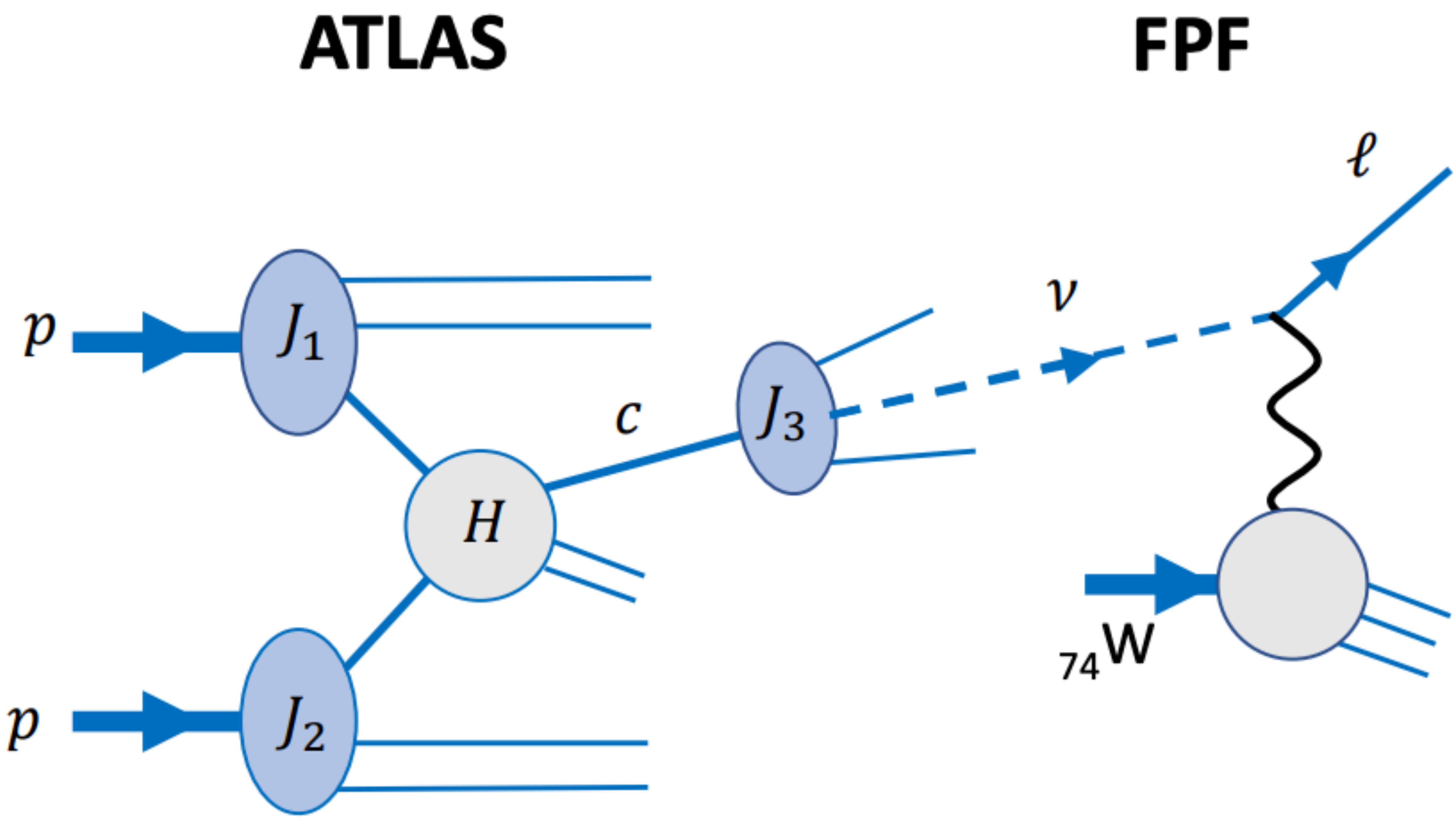


There are 11 models of light, weakly-interacting particles (LLPs, FIPs)

The discovery prospects for FASER and FASER 2 are well-studied by the PBC

Recent studies show the promise of the FPF for exploring all the BCs

Neutrinos at the LHC



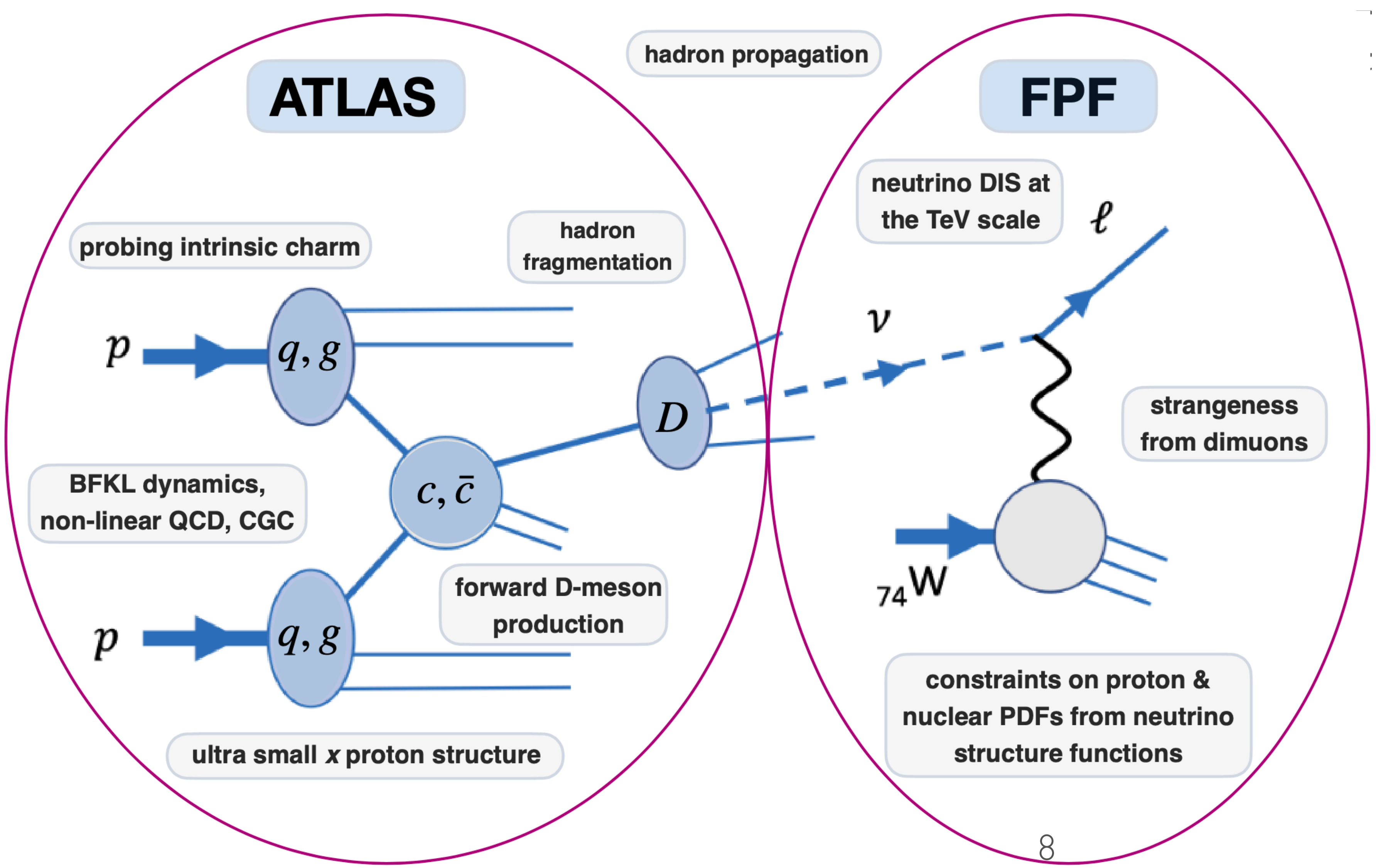
The LHC is a prodigious source of **high-energy neutrinos** from light hadron and charmed meson decays, which currently escape undetected

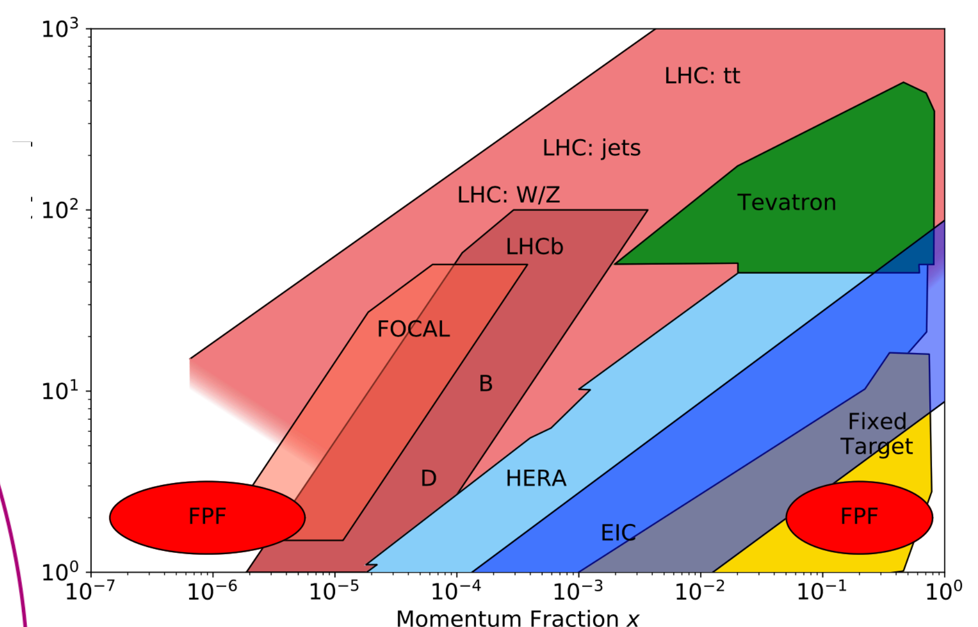
The FPF would detect these neutrinos by means of the **deep-inelastic scattering** processes on a nuclear target

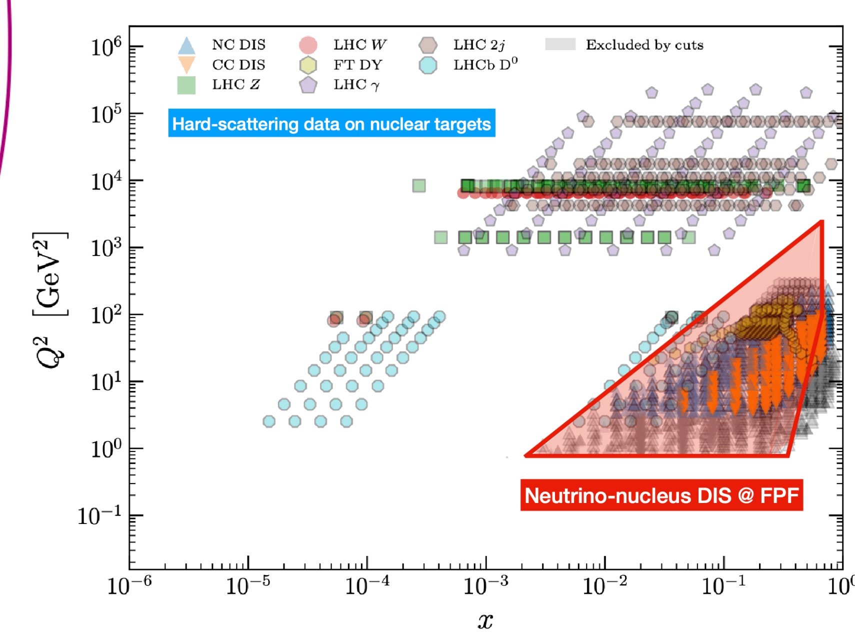
QCD studies at the FPF

Broad and rich program on **QCD**, **hadron structure**, and **astroparticle physics**

- **BFKL dynamics** in LHC collisions, modelling charm & hadron production in forward region
- Proton structure **down to *x*=10^{-7}**, input for **(U)HE neutrino & cosmic ray** experiments
- **Neutrino cross section** measurements complementing and extending available data
- Neutrino deep-inelastic scattering in the TeV region to constrain **proton and nuclear structure**







FPF physics potential

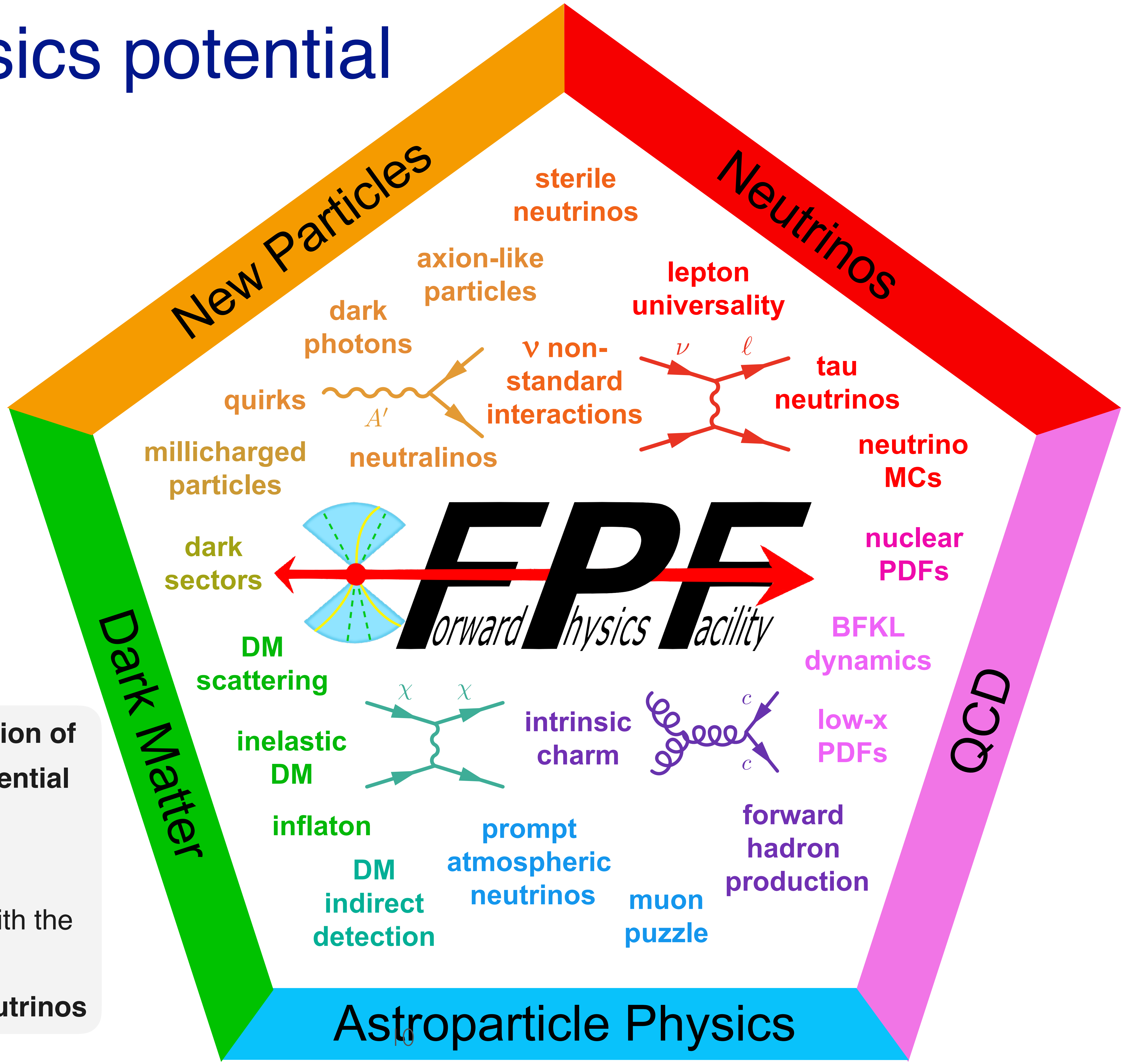
Remarkably **broad** and **far-reaching potential** of the FPF experiments:

- BSM searches
  - **Light BSM particles** produced in the very forward direction
  - Decaying **dark sector long-lived particles** (dark photons, dark Higgs, heavy neutral leptons…)
  - Milli-charged particles, dark matter scattering, …

- Neutrino physics
  - **Tau neutrino** studies (3k tau neutrino interactions, current world sample <20)
  - Separation of tau neutrino / anti-neutrino, constrain tau neutrino EDM
  - Tau neutrino decays into heavy flavour (connection with **LHCb LFV anomalies**)
  - **EFT constraints** on neutrino interactions

- QCD, hadron structure, and astroparticle physics
  - **Neutrino cross section** measurements (energy region not covered by any other experiment)
  - Neutrino DIS to constrain **proton and nuclear structure**
  - Testing **BFKL dynamics** in LHC collisions, modelling charm, hadron production in forward region
  - Key input for neutrino (IceCube, KM3NET) and cosmic ray **astroparticle experiments**

FPF physics potential



Very significant **extension of HL-LHC scientific potential** for moderate price tag!

Deep synergies also with the **Electron Ion Collider, cosmic rays, UHE neutrinos**

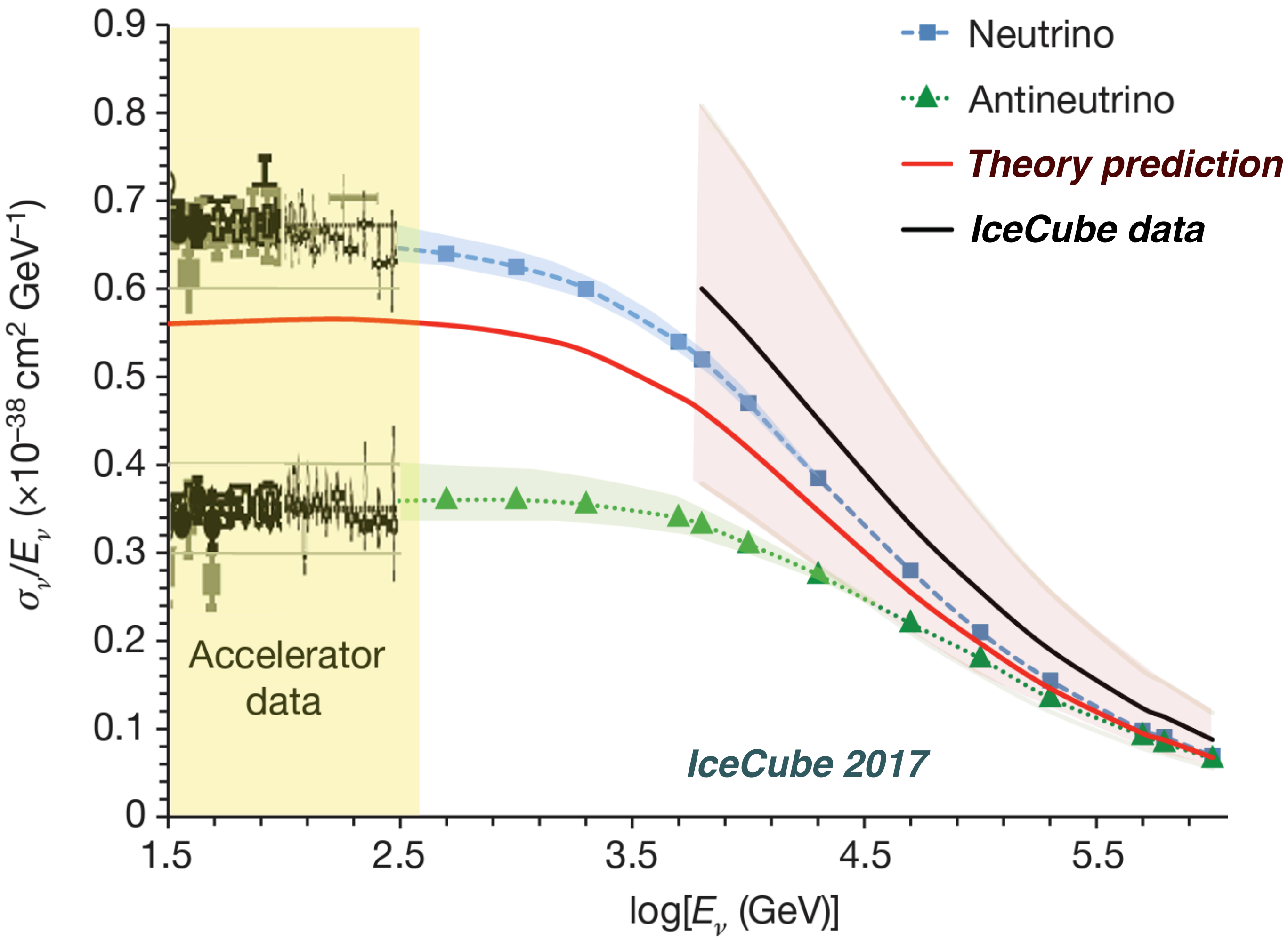
Timeline and cost

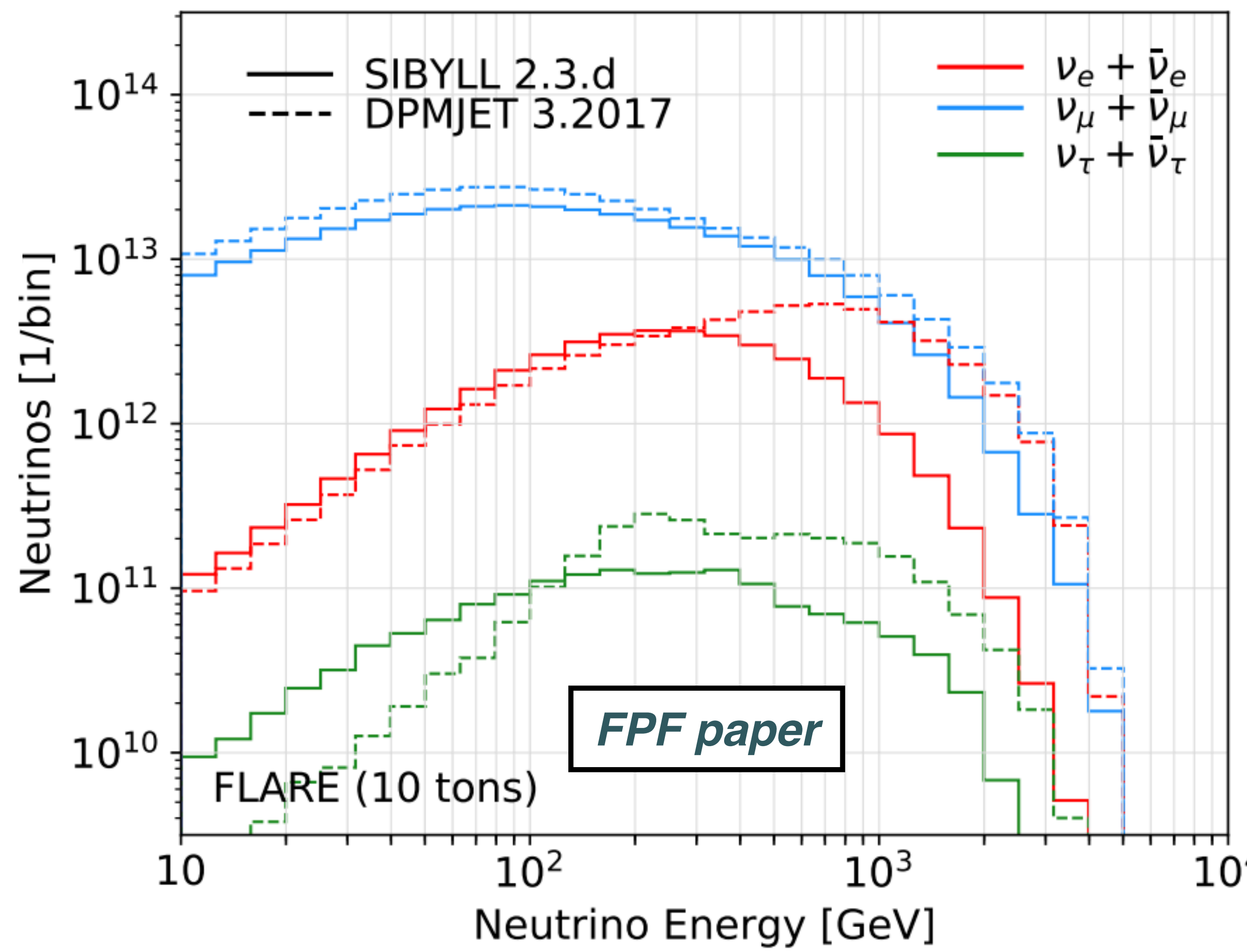
Timeline and Cost The FPF is well aligned with the 2020 European Strategy Update's first recommendation that "the full physics potential of the LHC and the HL-LHC...should be exploited." To fully exploit the far-forward physics opportunities, many of which will disappear for several decades if not explored at the FPF, the FPF should be available for as much of the HL-LHC era as possible. The FPF requires no modifications to the LHC, and all of the planned experiments are relatively small, inexpensive, and fast to construct. A very preliminary costing for the FPF has yielded estimates of 25 MCHF for the construction of the new shaft and cavern and 15 MCHF for all necessary services. To this must be added the cost of the individual experiments. A possible timeline is for the FPF to be built during Long Shutdown 3 from 2026-28, the support services and experiments to be installed starting in 2029, and the experiments to begin taking data not long after the beginning of Run 4. Such a timeline is guaranteed to produce exciting physics results through studies of very high energy neutrinos, QCD, and other SM topics, and will additionally enhance the LHC's potential for groundbreaking discoveries that will clarify the path forward for decades to come.

- Key selling points of the FPF
  - **Aligned with ESPPU**: maximal exploitation of HL-LHC potential (unique chance!)
  - **Reasonably affordable** (in the scale of CERN experiments)
  - Connects particle physics with hadronic, nuclear, neutrino, and astroparticle physics

Neutrino-nucleus interactions

Neutrino cross-sections extensively studied for **energies up to 300 GeV** with accelerator neutrinos





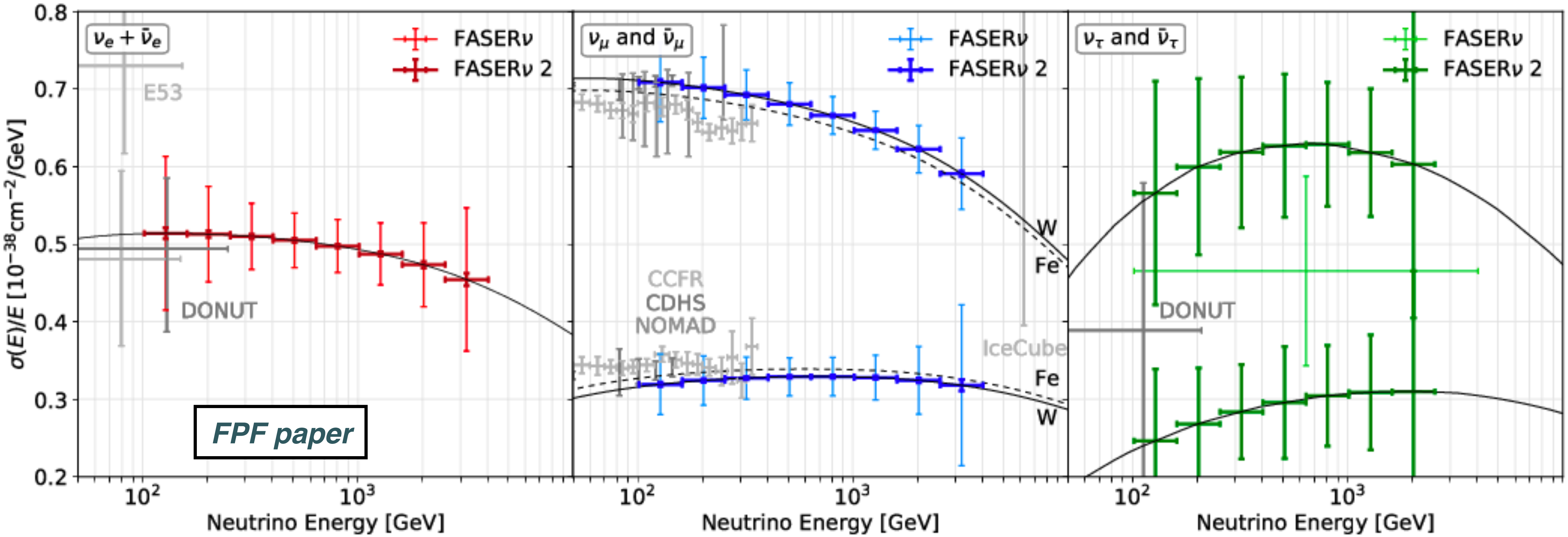
At higher energies, **IceCube** has measured cross-sections between 5 TeV and 10^4 TeV

but with large uncertainties

Neutrinos arriving at the Forward Physics Facility have **energy distributions** peaking between **100 GeV and 10 TeV**. Unique opportunity to test neutrino interactions

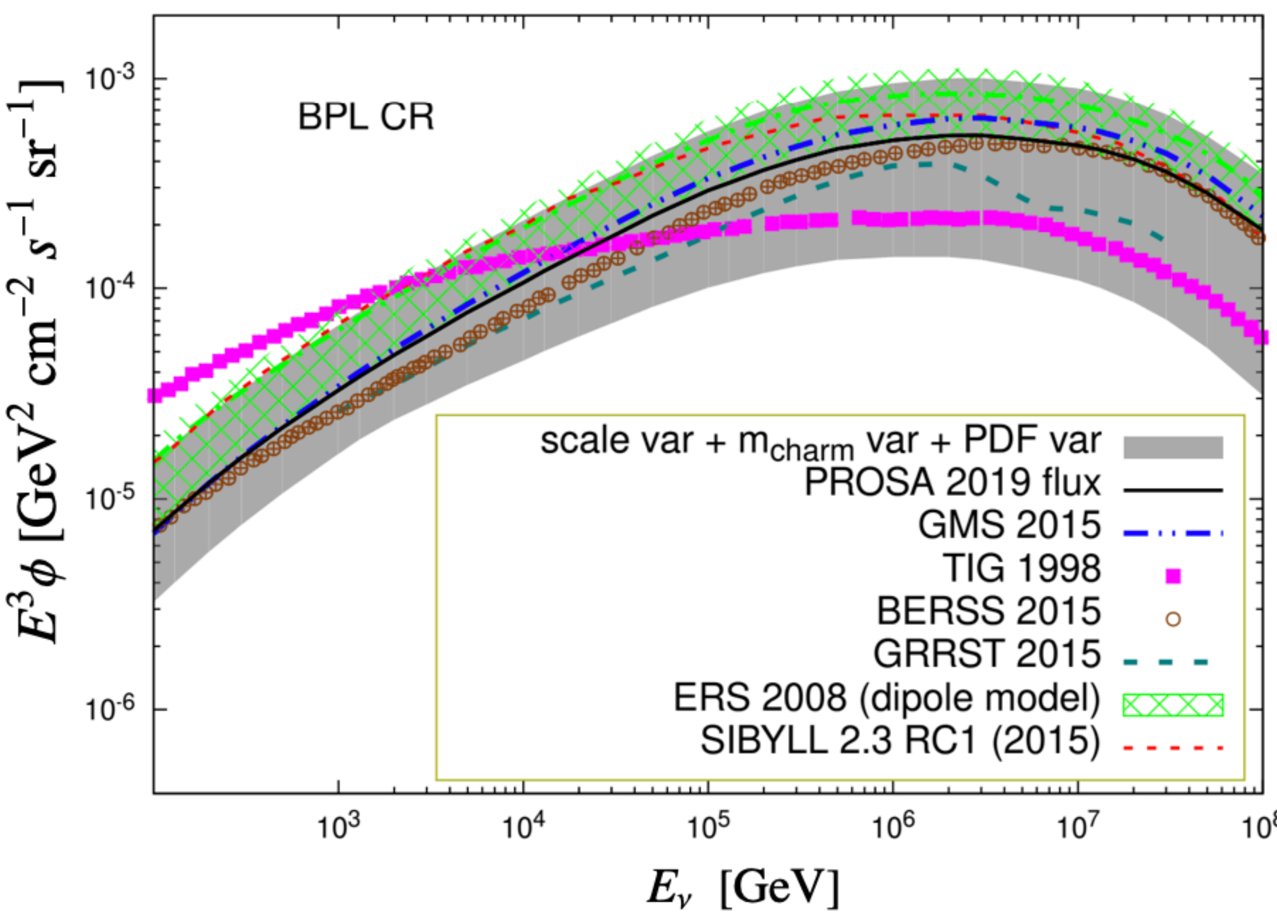
The FPF is effectively a Neutrino-Ion Collider with E_{CM} = 90 GeV!

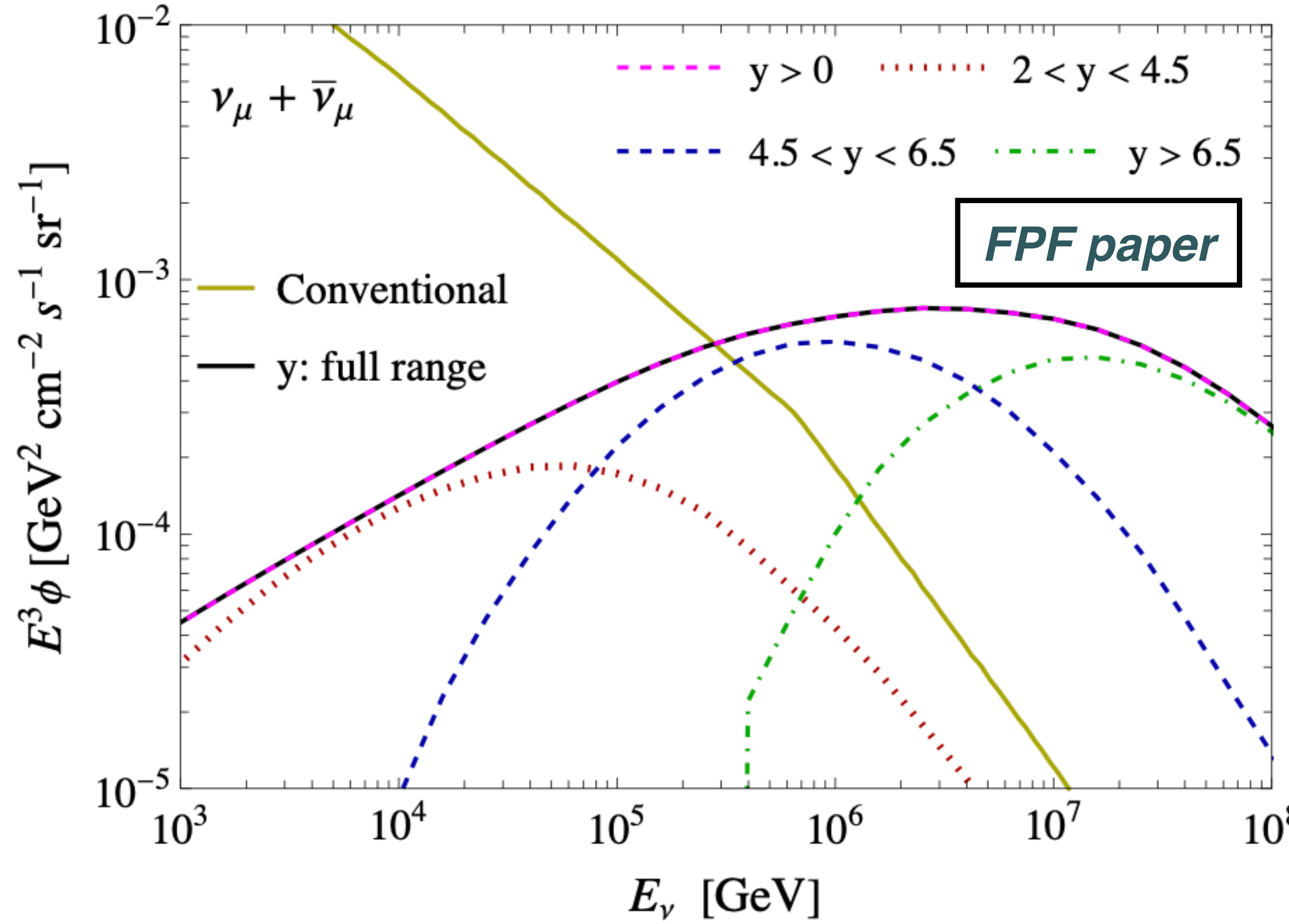
Neutrino DIS @ LHC



- Neutrino cross-sections and structure functions can be measured with **O(few %) statistical precision,** improving on available measurements
- Neutrino DIS provides access to the **quark flavour decomposition** in nucleons and nuclei: sea quark asymmetry, strangeness, charm
- Natural continuation of the extremely succesful **CERN programs on neutrino DIS**

Charm production in forward region





- Most existing calculations of prompt neutrino fluxes already account for information from **LHCb D-meson** cross-sections
- The very forward region **outside the LHCb acceptance (*y > 4.5*)** is particularly important in the evaluation of the prompt neutrino fluxes
- Unique opportunity to test production models and **QCD in the high-energy regime**

Current status

- FASER and FASERnu are currently running
  - No new cavern needed
  - Partially uses 'left-over' detector parts
  - First neutrino candidates measured in test setup
- Snowmass whitepaper has been submitted; arXiv:2203:05090
- Considering submitting a LoI to JENAA; http://www.nupecc.org/jenaa/

FPF Synergies @ Nikhef

- **ATLAS**
  - BSM searches (DM, long-lived particles, exotic models)
  - Improved (n)PDF determinations
  - Hardware expertise
- **ALICE**
  - Cold nuclear matter studies
  - Departures from linear DGLAP in QCD processes
- **LHCb**
  - Flavour studies
  - Hardware expertise

- **Cosmic rays**
  - Tuning of Monte Carlo models for UHE forward particle production
- **Neutrino platform**
  - Neutrino cross section measurements (energy region not covered by any other experiment)
  - Improved predictions for UHE neutrino interactions
  - SM tests in the neutrino sector, studies of tau neutrinos, neutrino EFTs

- **Detector R&D**
- **Dark Matter**

Summary and outlook

- The Forward Physics Facility would realise an exciting program in a broad range of topics from **BSM and long-lived particles** to **neutrinos, QCD, and hadron structure**, with deep connections to astroparticle physics

- **High-energy neutrino DIS** would open a new probe to proton and nuclear structure, complementing existing and future experiments (e.g. CC DIS is challenging at the EIC)

- Charm meson and light hadron production in the forward region represent a **testbed for QCD calculations**: higher-orders, BFKL, fragmentation, non-linear effects, small-x PDFs, …

- Production (ATLAS) and interaction (FPF) processes **intertwined**: *e.g.* intrinsic charm enhances D-meson production which in turn leads to a larger neutrino flux

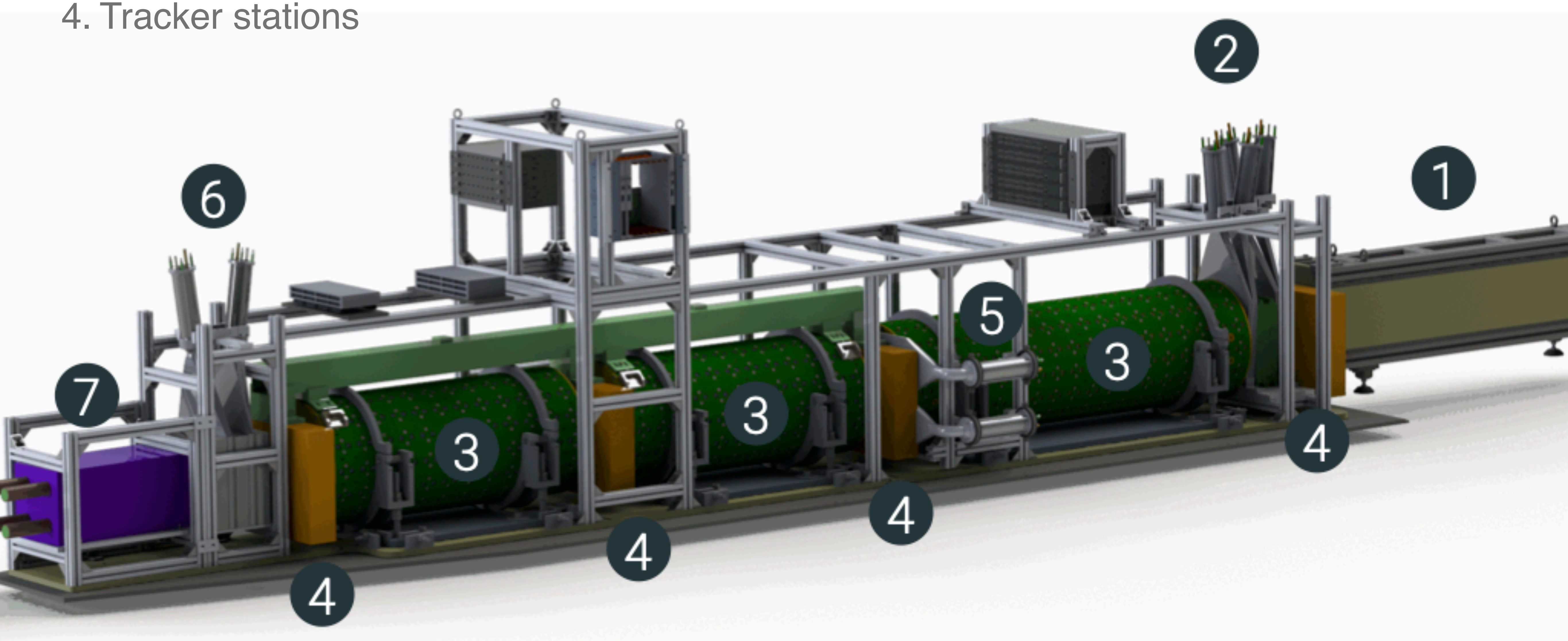
- Ideas and contributions to **further strengthen the FPF potential** more than welcome!

FPF
Forward Physics Facility

Backup

Backup

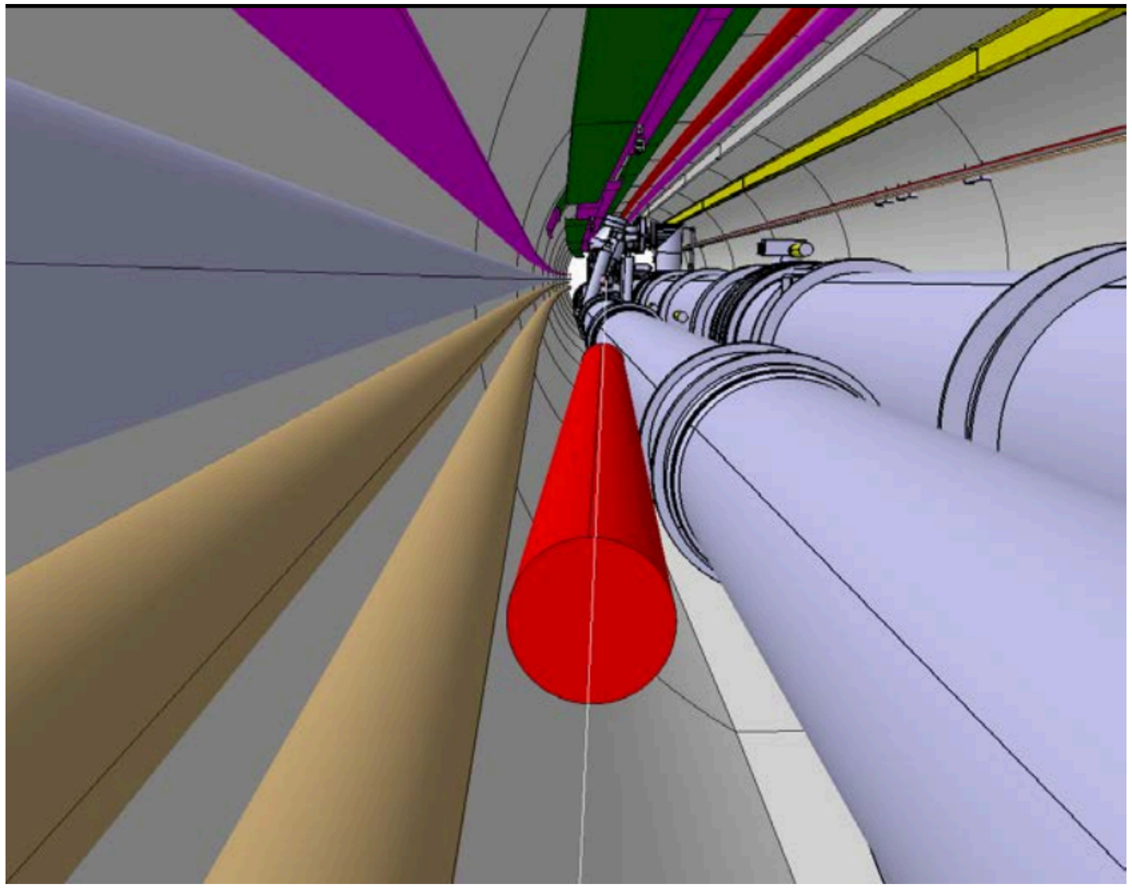
1. FASERν neutrino detector
2. Veto scintillators
3. Dipole magnet (0.6 T)
4. Tracker stations
5. Scintillator (precise timing)
6. Scintillator based preshower
7. Calorimeter



Sweeper magnet

- For the FPF, a **magnet** can sweep away muons, greatly reducing backgrounds.

- A 7-m-long, 20-cm-diameter magnet along the LOS can fit in the LHC tunnel after muons leave the LHC beampipe.



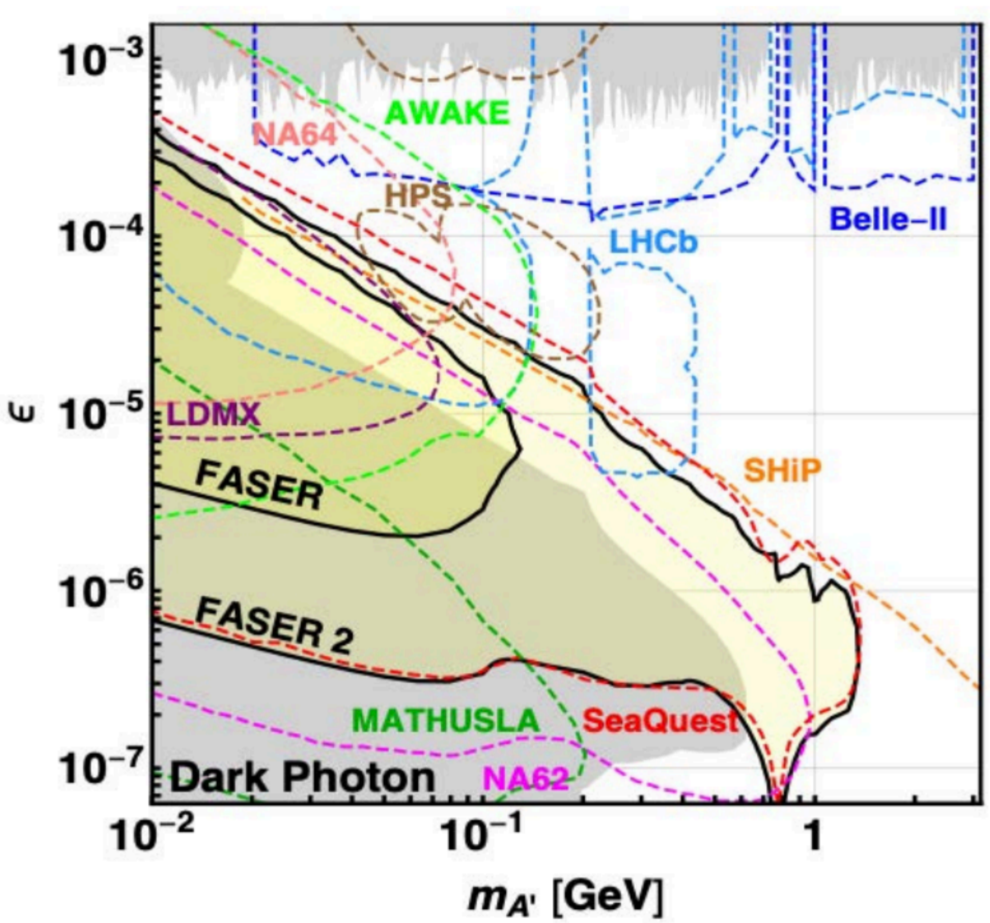
FPF discovery prospects

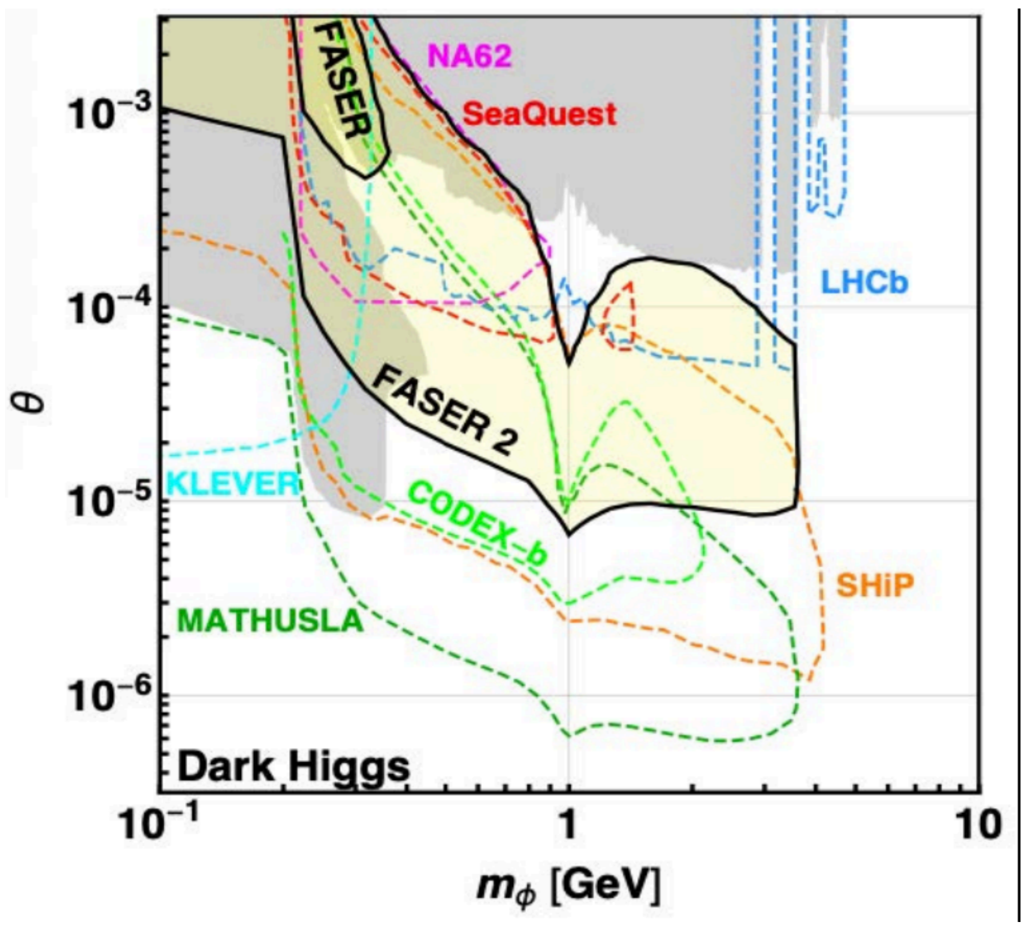
Benchmark Model	Underway	FPF	References
BC1: Dark Photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Dark Matter	–	FLArE	Batell, Feng, Trojanowski, 2101.10338
BC3: Milli-Charged Particle	–	FORMOSA	Foroughi-Bari, Kling, Tsai, 2010.07941
BC4: Dark Higgs Boson	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	FASER	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	FASER	FASER 2	FASER Collaboration, 1811.12522
BC11: ALP with gluon	FASER	FASER 2	FASER Collaboration, 1811.12522

FASER (2) potential

- BC1,4-11

- FASER 2 either extending sensitivity greatly (e.g., dark photon), or providing new discovery prospects (e.g., dark Higgs) complementary to other experiments.

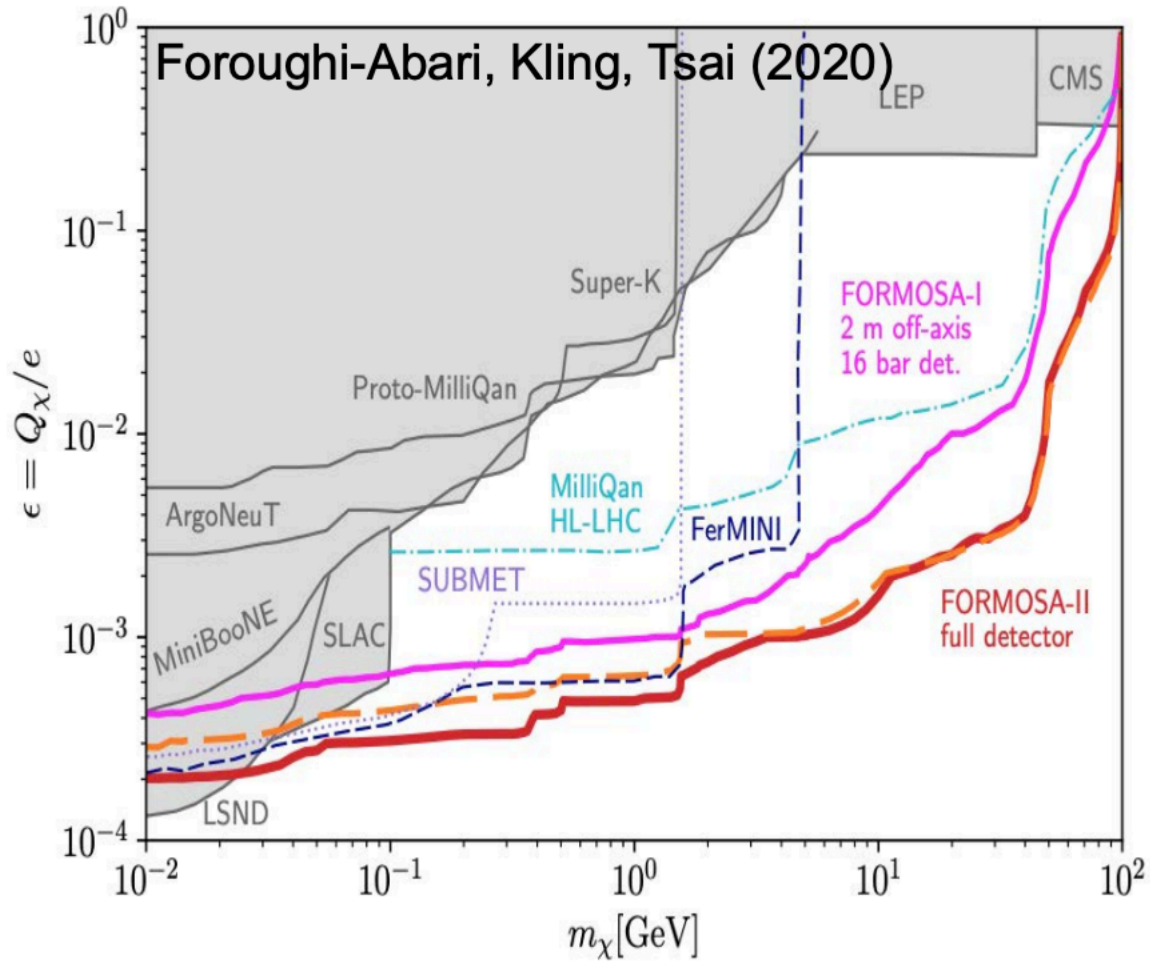




FORMOSA potential

- BC2

- Currently the target of the MilliQan experiment near the CMS IP.

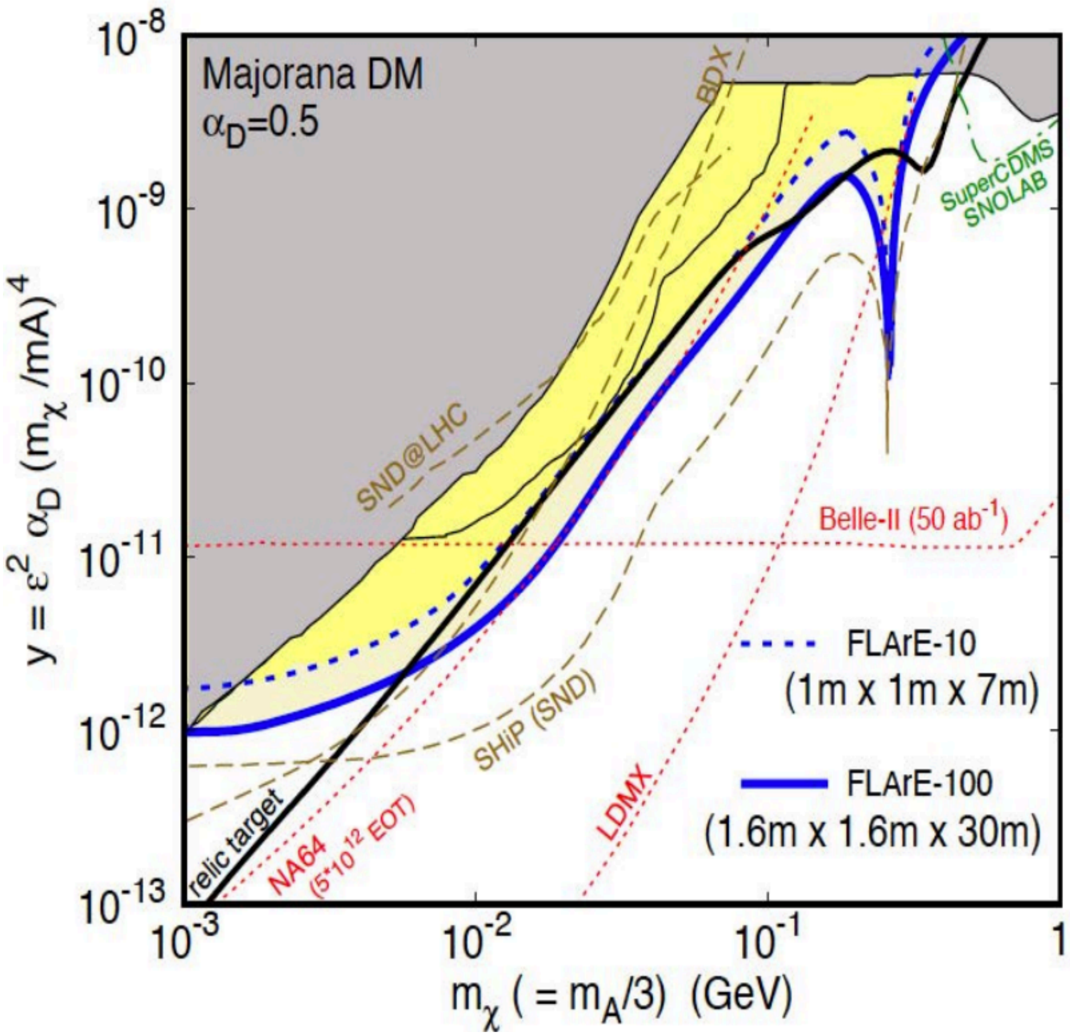


FLARE potential

- BC3

- Can look for the resulting DM to scatter off electrons

- Probes most of the favoured/ allowed relic target region.



Batell, Feng, Trojanowski (2021)

FASERnu potential

- FASERnu will record ~1000 ne , ~10,000 nμ , and ~10 nt interactions at TeV energies.

- FASERnu2 will record ~105 ne , ~106 nμ , and ~103 nt interactions at TeV energies.