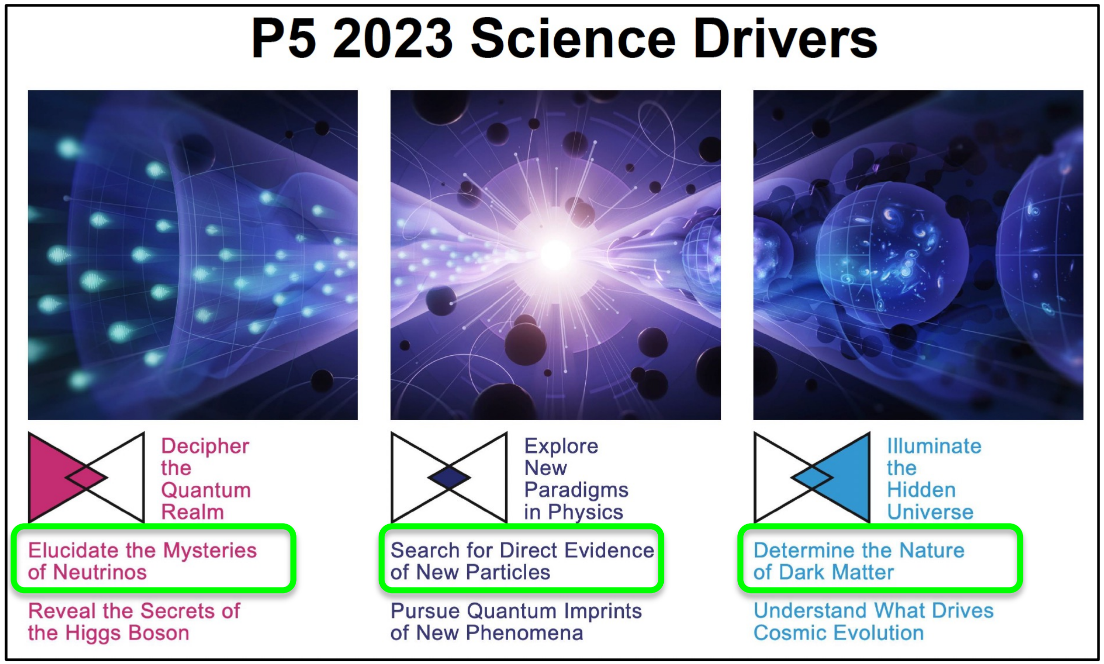
Forward Physics Facility

Joint BSM/FPC Meeting, Physics Beyond Colliders

Jonathan Feng, UC Irvine, 20 November 2024

INTRODUCTION

- In the last few years, there has been a transformation in our understanding of forward physics at colliders.
- Previously: luminosity measurements, pomerons, odderons, …
- Now: we understand that the forward region contains a treasure trove of both SM and BSM physics, addressing many of our most urgent questions.

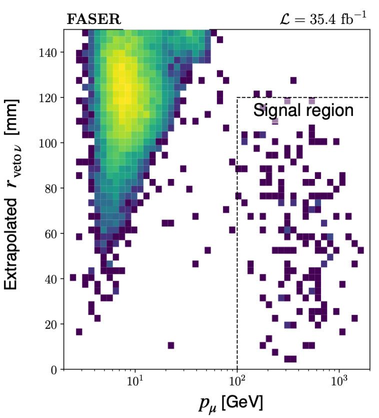


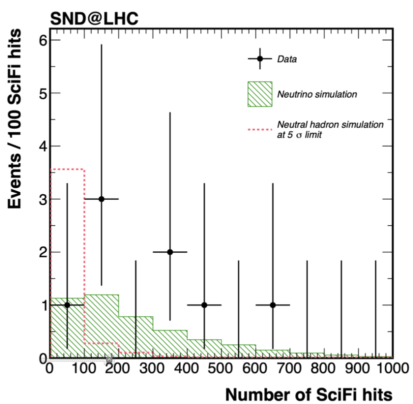
- To fully exploit the physics potential of the LHC, forward detectors are required, just like trackers and calorimeters. The Forward Physics Facility is proposed to house a suite of such detectors at the HL-LHC.

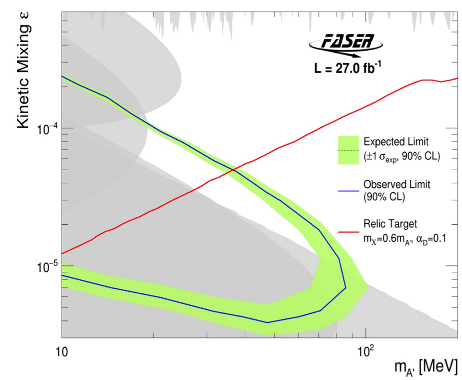
A GOOD YEAR FOR FORWARD PHYSICS

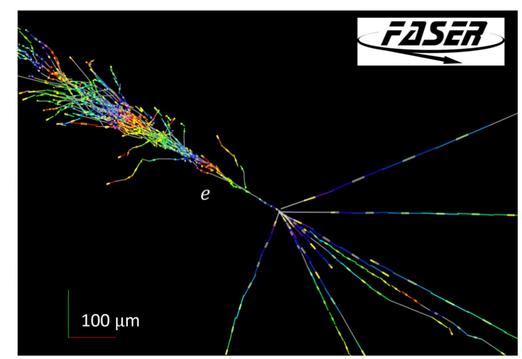
Recent results from FASER, FASERν, SND@LHC:

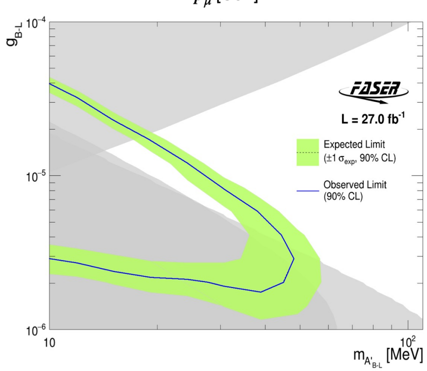
- First Direct Observation of Collider Neutrinos with FASER at the LHC, PRL, 2303.14185
- Observation of Collider Muon Neutrinos with SND@LHC, PRL, 2305.09383
- Search for Dark Photons at FASER, CERN-FASER-CONF-2023-001, PLB, 2308.05587
- Observation of High-Energy Electron Neutrinos with FASERν, CERN-FASER-CONF-2023-002
- Search for $U(1)_{B-L}$ Gauge Bosons at FASER, PLB, 2308.05587
- First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASERν, PRL, 2403.12520

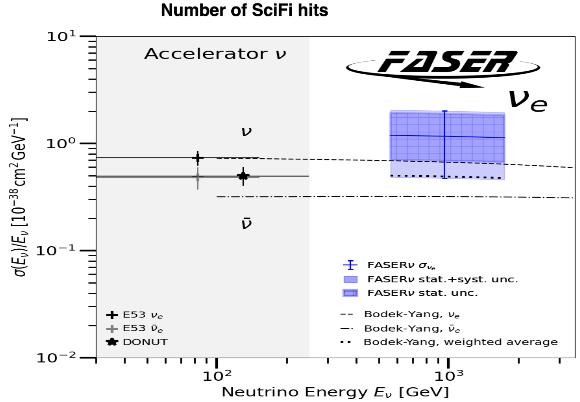


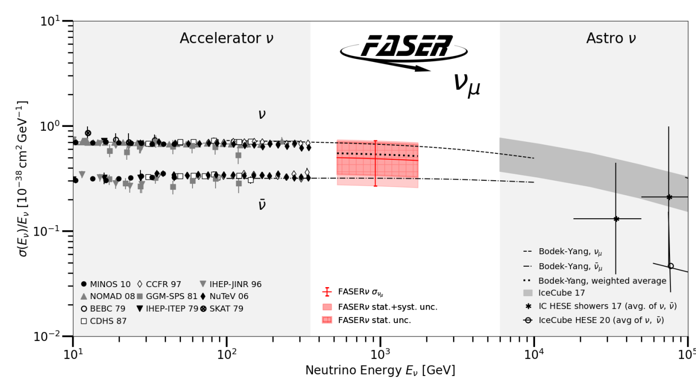






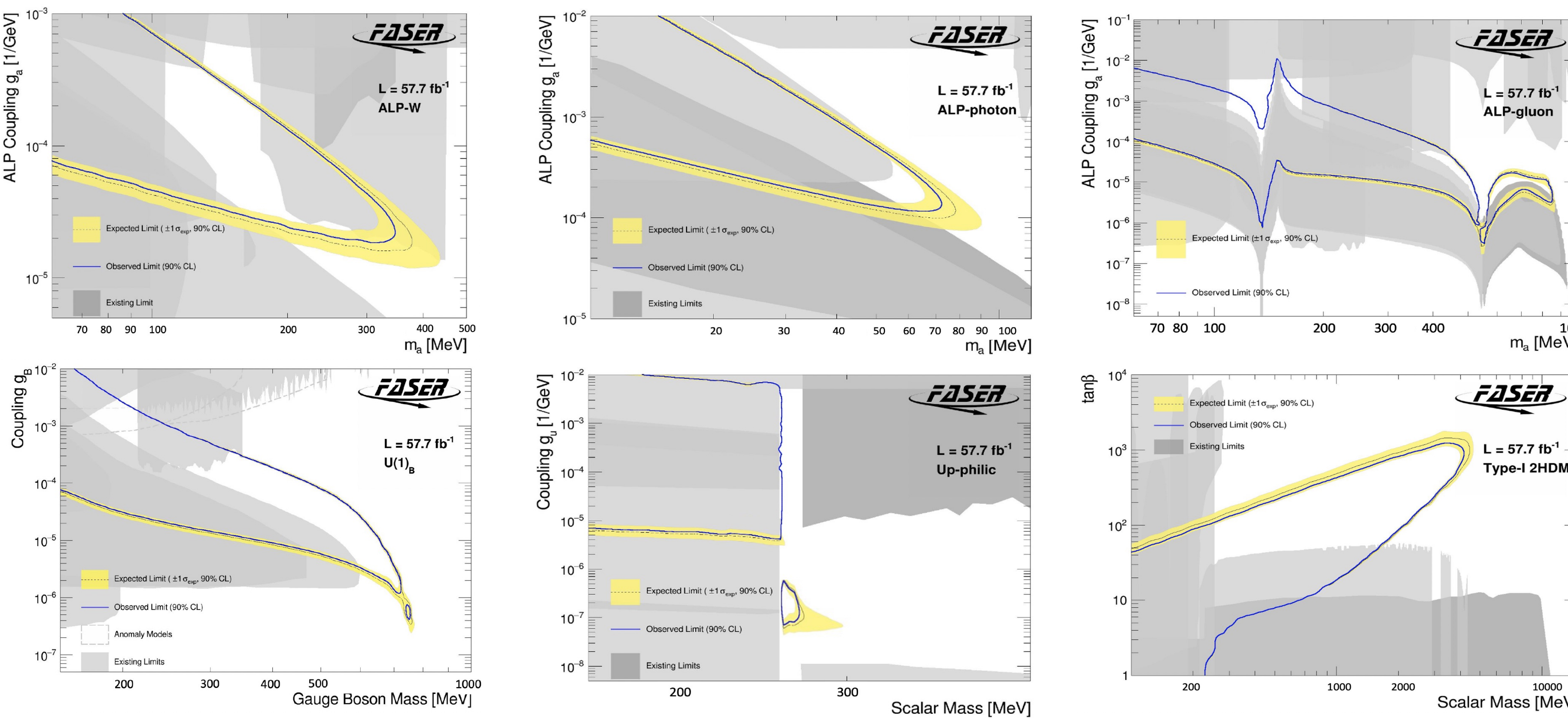






MORE BSM RESULTS

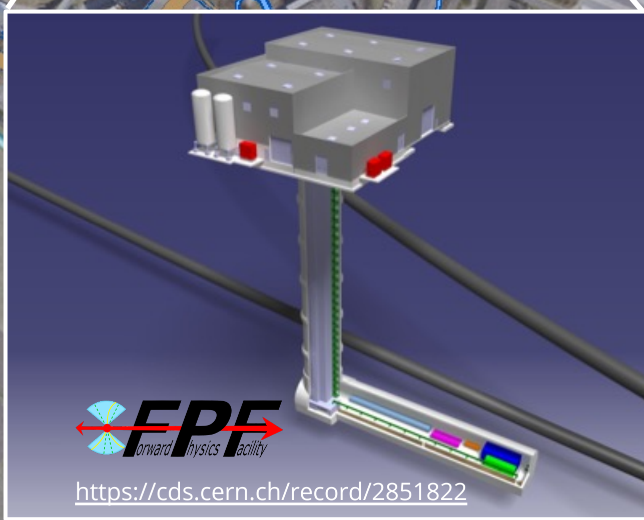
- Also many other search results: axion-like particles with *W*, photon, gluon couplings, U(1)$_B$ gauge bosons, up-philic scalars, two Higgs doublet models.
- Qualitatively different signals: some with charged tracks, some with only photons, some mainly produced in pion decay, some mainly produced in B decay. Shows the characteristic versatility of searches at high-energy colliders.



FASER Collaboration [2410.10363](https://arxiv.org/abs/2410.10363)

FORWARD PHYSICS FACILITY

- Motivated by the results of FASER and SND@LHC, a dedicated Forward Physics Facility has been proposed to house far-forward experiments for the rest of the LHC era from 2030-2040s.



PBC: FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

CERN GIS

FORWARD PHYSICS FACILITY

- The FPF status has been summarized recently in [2411.04175](2411.04175).

SCIENCE AND PROJECT PLANNING FOR THE FORWARD PHYSICS FACILITY IN PREPARATION FOR THE 2024–2026 EUROPEAN PARTICLE PHYSICS STRATEGY UPDATE

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on behalf of the FPF Working Groups

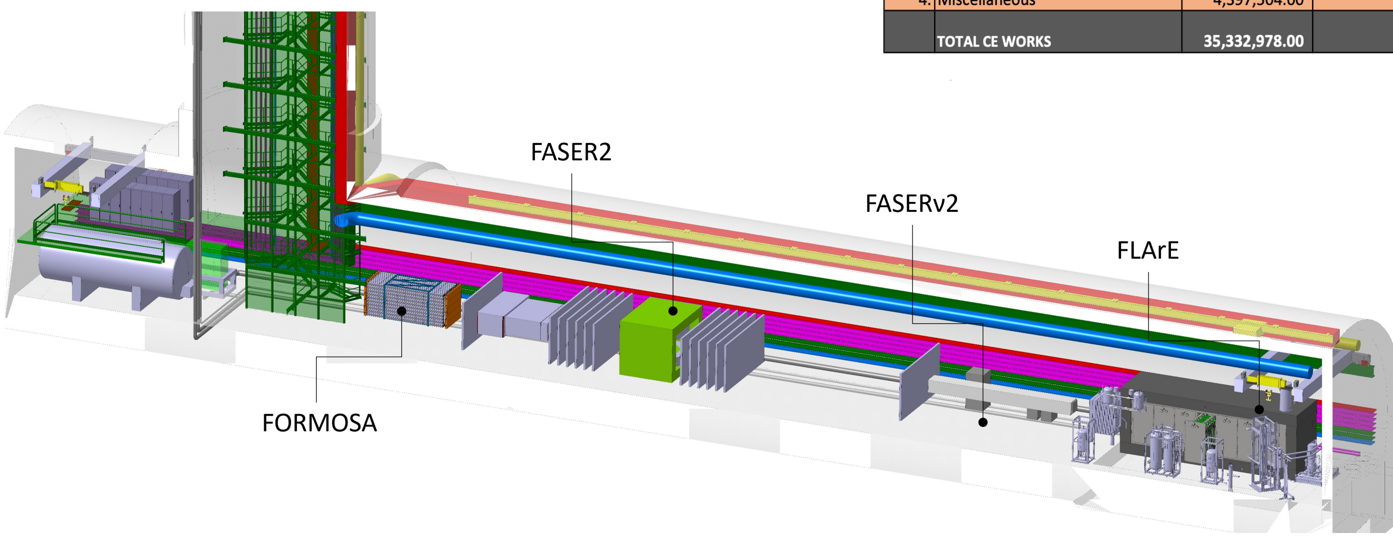
The recent direct detection of neutrinos at the LHC has opened a new window on high-energy particle physics and highlighted the potential of forward physics for groundbreaking discoveries. In the last year, the physics case for forward physics has continued to grow, and there has been extensive work on defining the Forward Physics Facility and its experiments to realize this physics potential in a timely and cost-effective manner. Following a 2-page Executive Summary, we present the status of the FPF, beginning with the FPF's unique potential to shed light on dark matter, new particles, neutrino physics, QCD, and astroparticle physics. We summarize the current designs for the Facility and its experiments, FASER2, FASERν2, FORMOSA, and FLArE, and conclude by discussing international partnerships and organization, and the FPF's schedule, budget, and technical coordination.

THE FPF CAVERN

- Continued excellent work by the PBC to refine the Facility.
- New developments
  - Slightly enlarged to 12 m wide, 75 m long.
  - Includes a service cavern on the other side of the shaft.
  - Moved back slightly to 627 m from ATLAS IP to maintain 10 m from LHC tunnel.
- Estimated (Class 4) cost is 35 MCHF (not including experiments and outfitting).

Civil Engineering Cost Estimate FPF // September 2024

Ref.	Work Package	Cost [CHF]	Percentage of the CE Works
1.	Underground Works	12,392,344.00	35%
1.1	Preliminary activities	1,845,000.00	5.2%
1.2	Access shaft	4,424,143.00	12.5%
1.3	Experimental Cavern	6,123,201.00	17.3%
2.	Surface Works	6,727,231.00	19%
2.1	General items	720,776.00	2.0%
2.2	Topsoil and earthworks	702,227.00	2.0%
2.3	Roads and network	796,122.00	2.3%
2.4	Buildings	4,508,106.00	12.8%
2.4.1	Access building	2,224,786.00	6.3%
2.4.2	Cooling and ventilation building	1,497,350.00	4.2%
2.4.3	Electrical Building	563,689.00	1.6%
2.4.5	External platforms	222,281.00	0.6%
3.	General items	11,815,899.00	33.4%
4.	Miscellaneous	4,397,504.00	12.4%
	TOTAL CE WORKS	35,332,978.00	100.0%



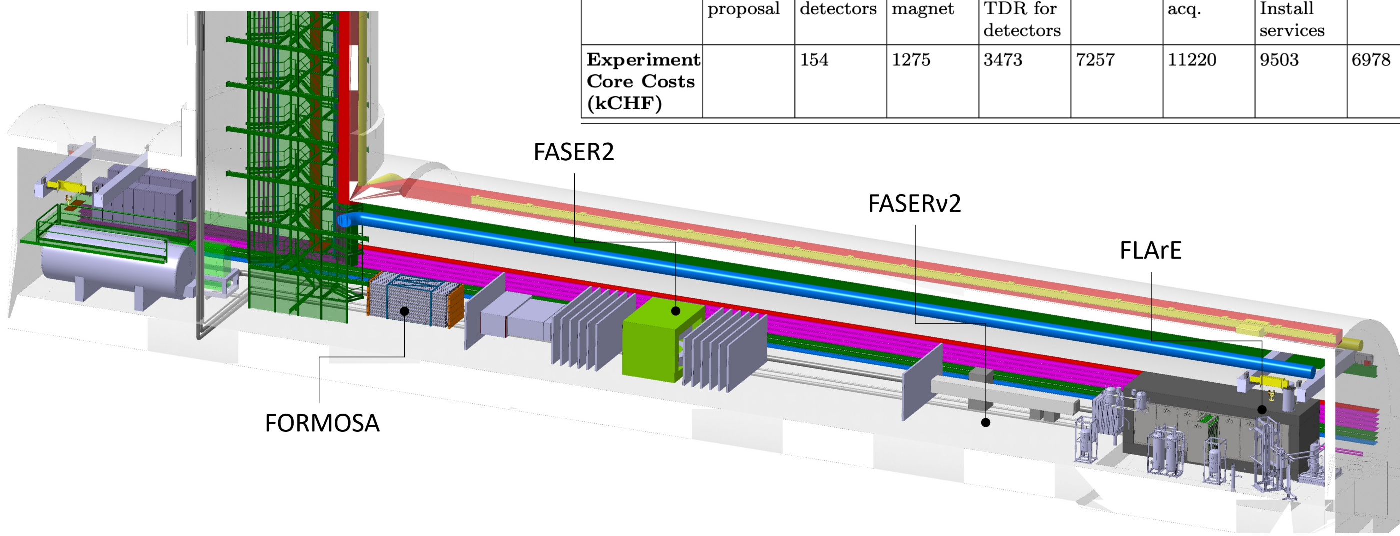
FPF EXPERIMENTS

- There are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)

- Core costs of the experiments vary from 2 to 15 MCHF, total is 41 MCHF.

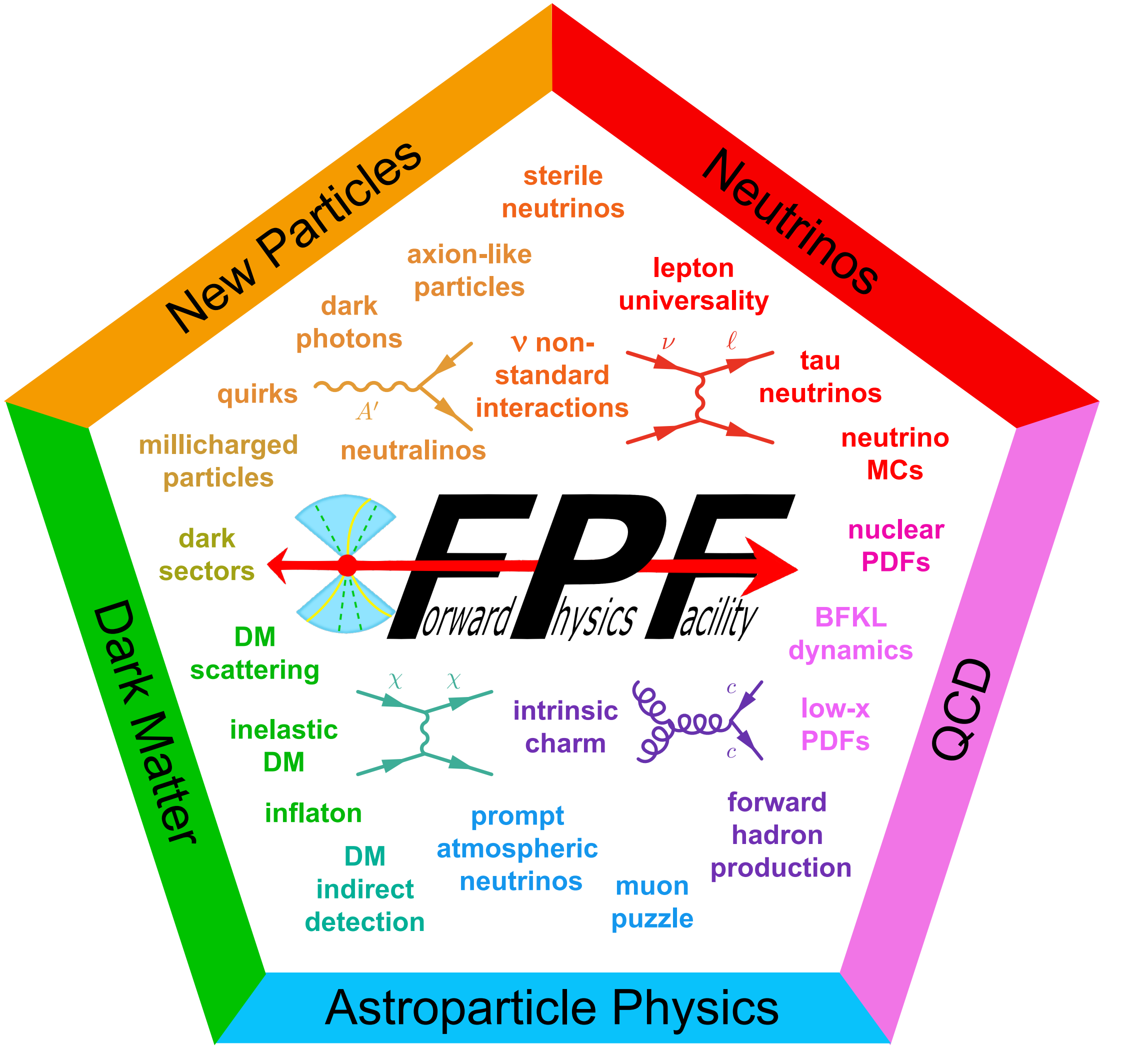
- Timeline: Physics in Run 4

Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
(HL-)LHC Nominal Schedule	Run 3	Run 3	Run 3 / LS 3	LS 3	LS 3	LS 3	LS 3 / Run 4	Run 4	Run 4	Run 4
FPF Milestones	Pre-CDR and physics proposal	R&D and prototype detectors	CDR, long lead items, magnet	Start of civil construction, TDR for detectors	Detector construction start	Major equipment acq.	End of civil construction, Install services	Detector install	Detector commissioning, physics start	Physics running all detectors
Experiment Core Costs (kCHF)		154	1275	3473	7257	11220	9503	6978	741	



BSM PHYSICS AT THE FPF

- The FPF at the HL-LHC will have many unique capabilities:
  - 10,000 times greater (decay volume * luminosity) for BSM searches (10x greater in every spacetime dimension).
  - Will detect millions of TeV neutrinos, including ~10,000 tau neutrinos, ~1000 neutrinos of all flavors/day.
- The new document presents unique opportunities beyond the PBC benchmarks, complementarity with SHiP and other experiments. Some examples are given here.



COMPRESSED SPECTRA / INELASTIC DARK MATTER

- Very generically: LLPs can result from
  - small couplings (many studies)
  - compressed spectra (few studies)

- Prominent example of the 2nd possibility: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings to the SM.

- Viable scenarios with m ~ tens of GeV. Only probed at LHC (FASER, MATHUSLA,…).

- Viable scenarios with very soft decay products, which can be seen only if highly boosted. E.g., require E_γ > 300 MeV.

m_1

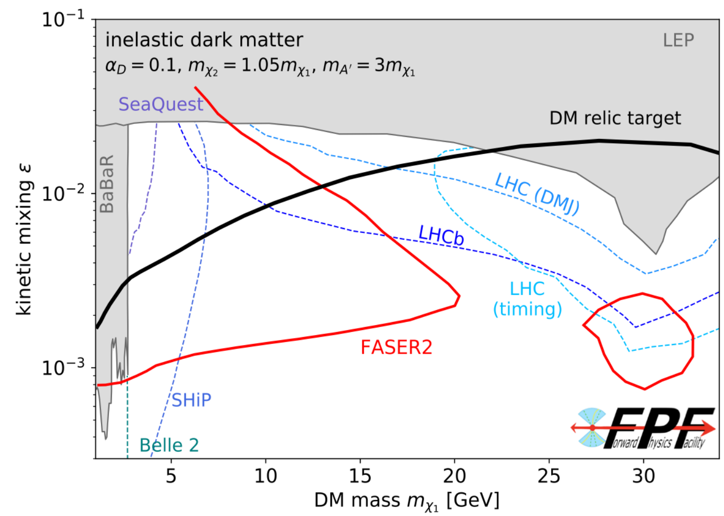
m_0

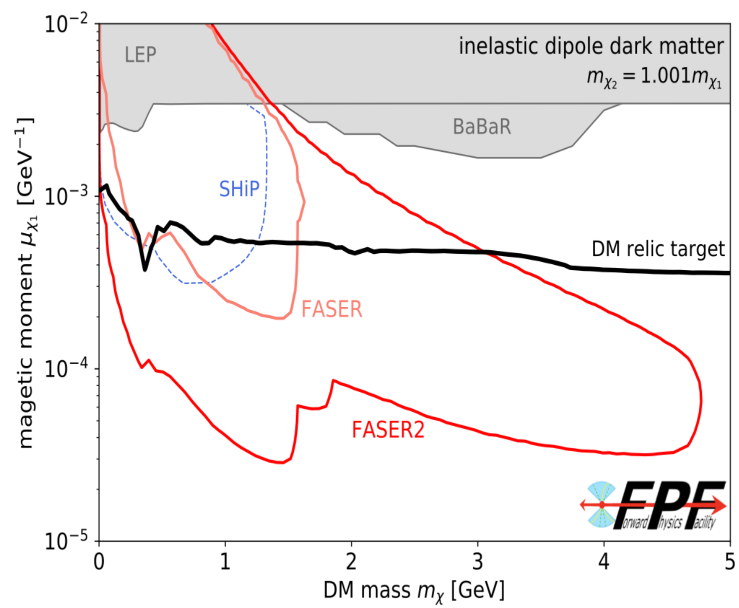
$$\chi_1 \to \chi_0 \gamma$$

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

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

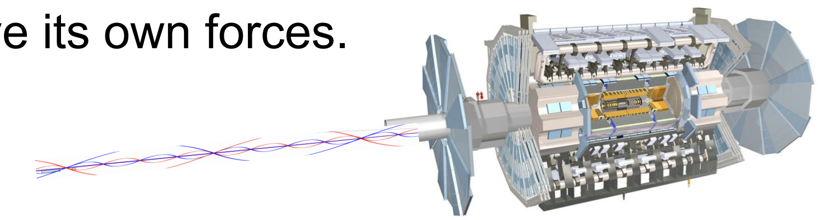
0





QUIRKS

- Very generically: hidden sector may have its own forces.
  - Abelian symmetry (many studies)
  - Non-Abelian symmetry (few studies)

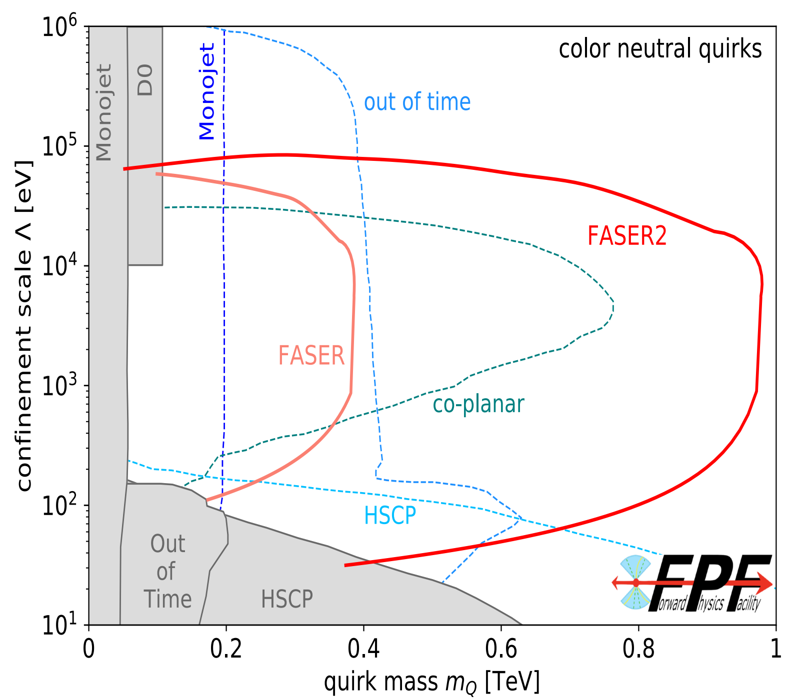


- If non-Abelian, can have quirks, particles charged under both the SM and another strong force, with $m \gg \Lambda$.

- Quirks can be pair-produced at the LHC, but then are bound by a color string, oscillate about their center-of-mass and travel down the beamline.

- By looking for 2 coincident slow or delayed tracks, FPF experiments can discover quirks with masses up to ~TeV, as motivated by neutral naturalness.

- Unique discovery potential at the FPF: very challenging at ATLAS/CMS, not possible at fixed target experiments.



NEUTRINO STUDIES

- FPF will constrain neutrino properties at TeV energies, where there is currently little or no data.

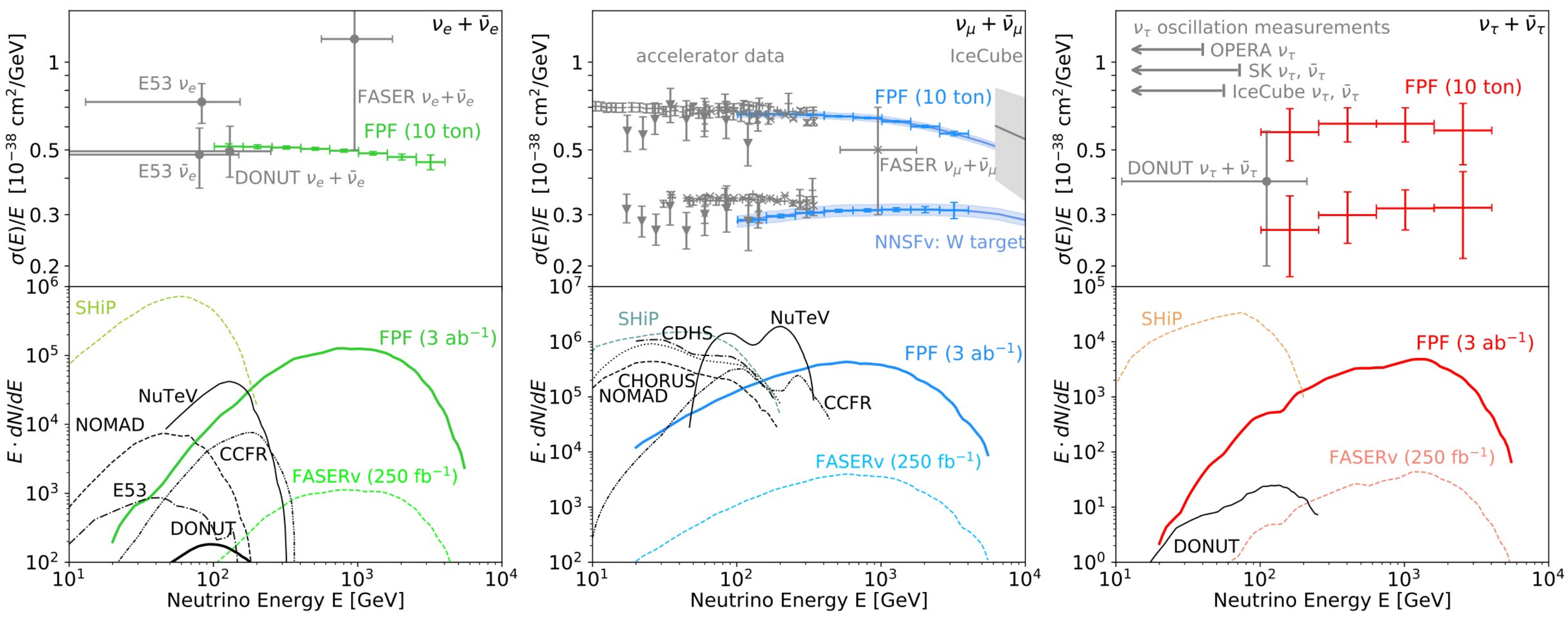


FIG. 6. **Neutrino yields and cross sections at the FPF.** The expected precision of FPF measurements of neutrino interaction cross sections (top, statistical errors only) and the spectrum of neutrinos interacting in the FPF experiments (bottom) as a function of energy for electron (left), muon (middle), and tau (right) neutrinos. Existing data from accelerator experiments [28], IceCube [29], and the recent FASERν result [30] are also shown, together with the prospects for SHiP.

COMPLEMENTARITY WITH HIGH P$_T$ PHYSICS

- FPF neutrino studies will constrain pdfs, which will sharpen predictions for ATLAS and CMS.
- For example, W, Z, and Higgs boson cross sections.
- Will also remove degeneracies between pdfs and new physics (“fitting away new physics”), enhancing the reach for new particle searches.

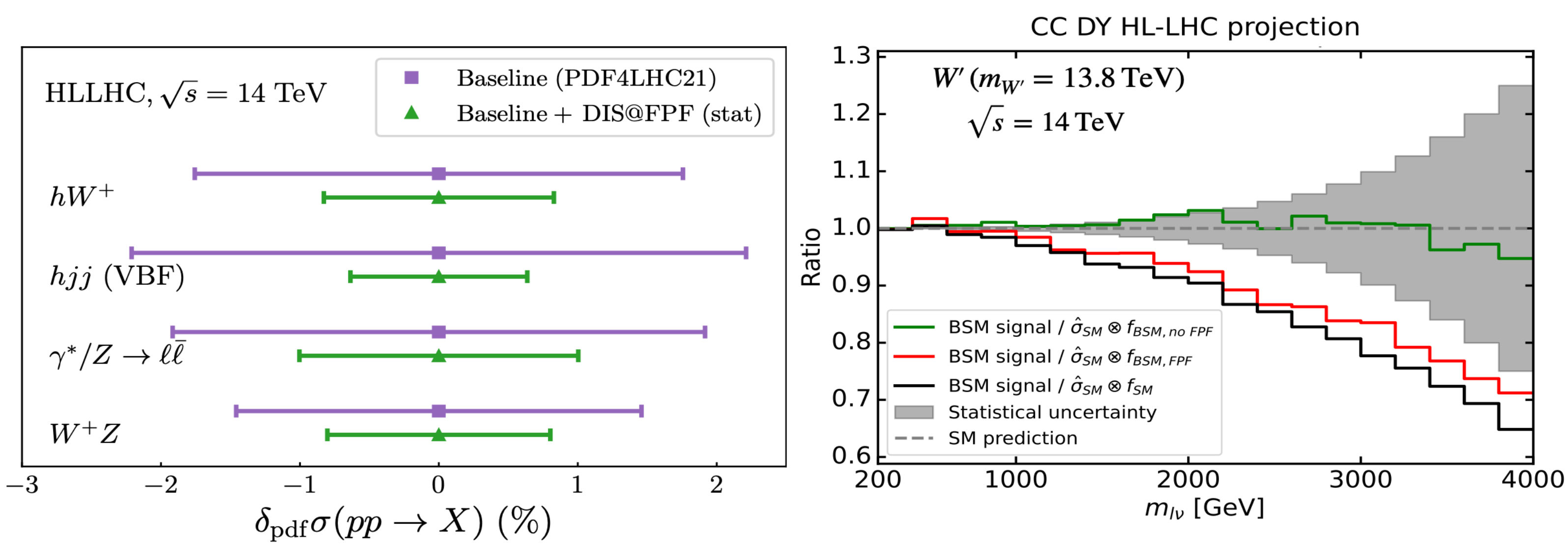


FIG. 9. **Impact of FPF neutrino measurements on traditional BSM Searches at the HL-LHC.** Left: Reduction of uncertainties on Higgs- and weak gauge-boson cross sections at the HL-LHC, enabled by neutrino DIS measurements at the FPF. Right: Evidence for a new heavy W' boson with $m_{W'} = 13.8$ TeV would be reabsorbed in a PDF fit including Drell-Yan data from the HL-LHC ($f_{\rm BSM,noFPF}$), unless the PDFs are constrained by “low energy” FPF neutrino data ($f_{\rm BSM,FPF}$).

SUGGESTIONS FOR BSM/FPC COORDINATED ACTIVITIES

- Adopt new PBC benchmarks. Simple models that illustrate something generic, but is not represented by existing benchmarks
  - Compressed spectra: LLPs from reduced phase space.
  - Quirks: Non-Abelian forces in the hidden sector.

- Adopt a uniform neutrino flux model to compare prospects across different experiments. FASER has presented a prescription in 2402.13318, which can be an input to this effort.