FPF — Forward Physics Facility

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on behalf of the FPF Working Groups

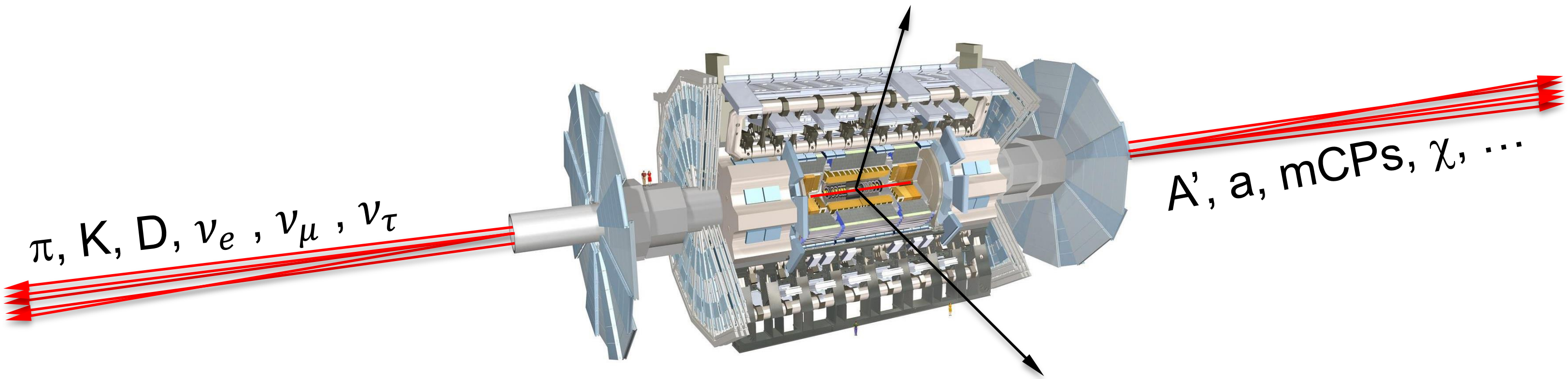
P5 Town Hall Meeting on the Future of High Energy Physics

Brookhaven National Laboratory, 12 April 2023

Captions

THE NEED FOR FORWARD-LOOKING PHYSICS

- Collisions at the LHC produce an enormous number of particles along the beam collision axis line of sight (LOS), which escape existing LHC detectors.



- We now know that, without new detectors, the LHC is blind to a beautiful program of SM and BSM physics in the far-forward direction.

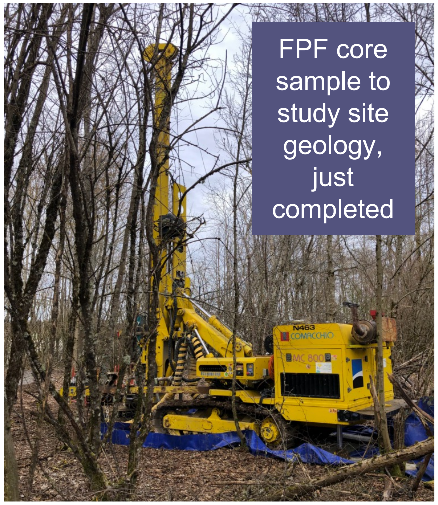
- The Forward Physics Facility is a proposal to build a new underground cavern to host a suite of far-forward experiments to capture this physics and greatly enhance the LHC's potential for groundbreaking discoveries in the HL-LHC era.

Our highest immediate priority accelerator and project is the HL-LHC, …including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades. – 2022 Snowmass Energy Frontier Report

The full physics potential of the LHC and the HL-LHC...should be exploited. — 1st recommendation of the 2020 European Strategy Update

FORWARD PHYSICS FACILITY

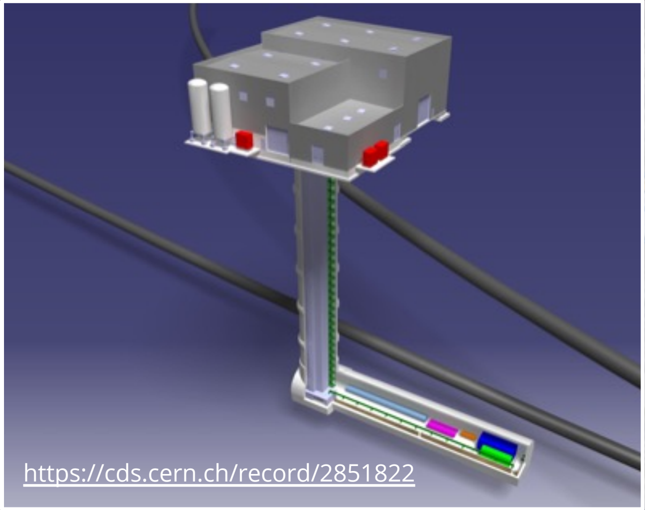
- A comprehensive site selection study by the CERN Civil Engineering group has identified an ideal location ~600 m west of ATLAS.



ATLAS

LHC

LOS



- 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
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

CERN GIS

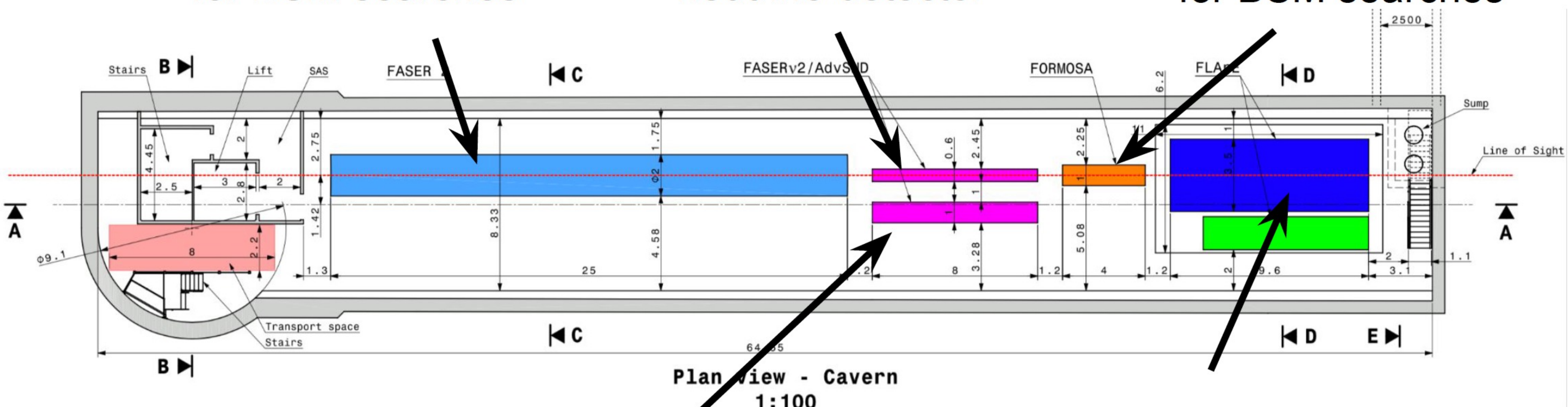
FPF EXPERIMENTS

- At present there are 5 experiments being designed for the FPF.
- Diverse technologies optimized for particular SM and BSM topics.
- FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$.

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

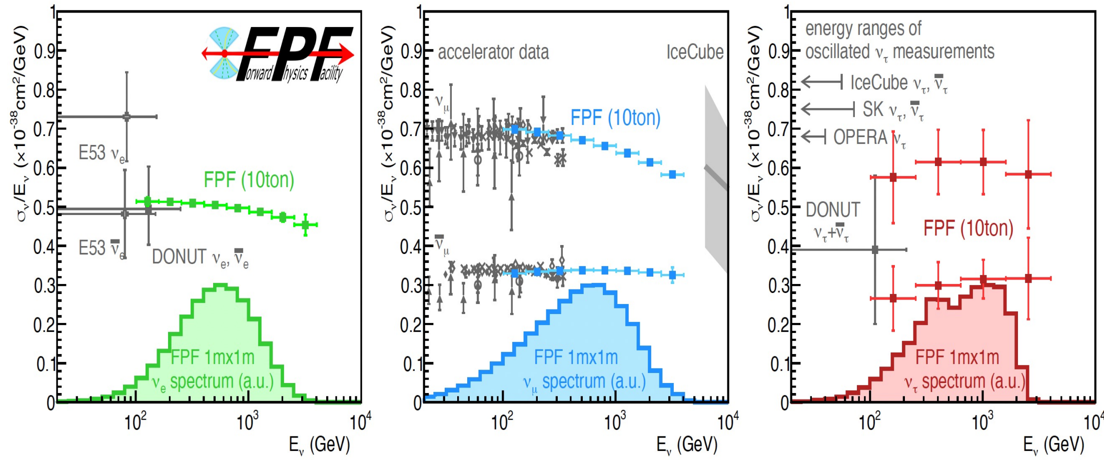
THE FPF NEUTRINO PROGRAM

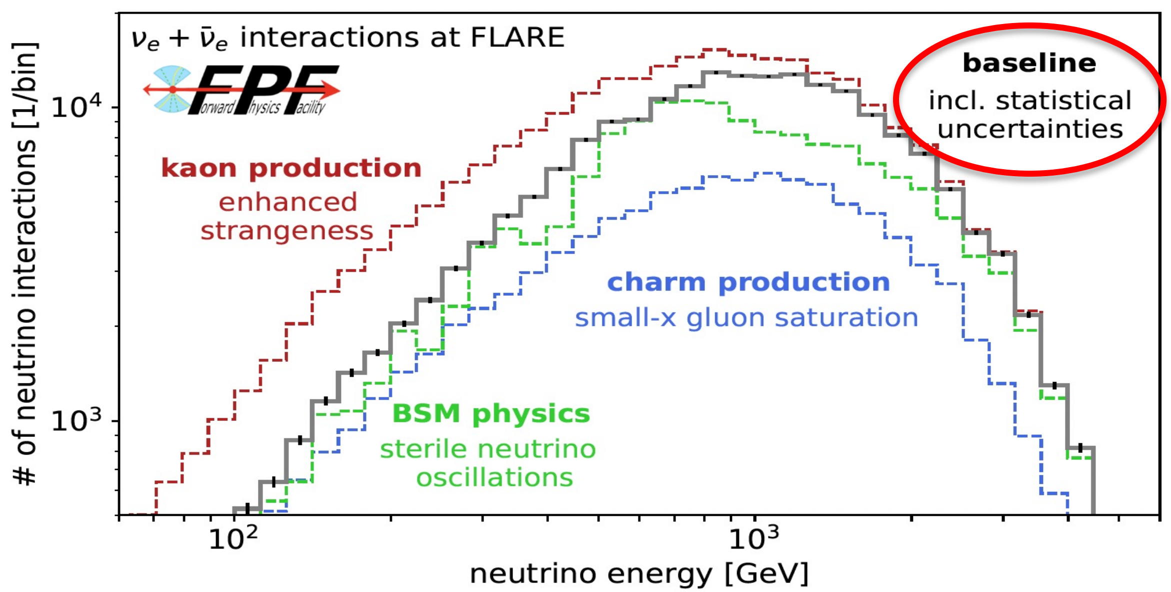
- Pathfinder experiments FASERν and SND@LHC have recently directly observed collider neutrinos for the first time.

  Moriond 2023
  2303.14185

- FPF experiments FLArE, FASERν2, and AdvSND will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ interactions at ~TeV energies.

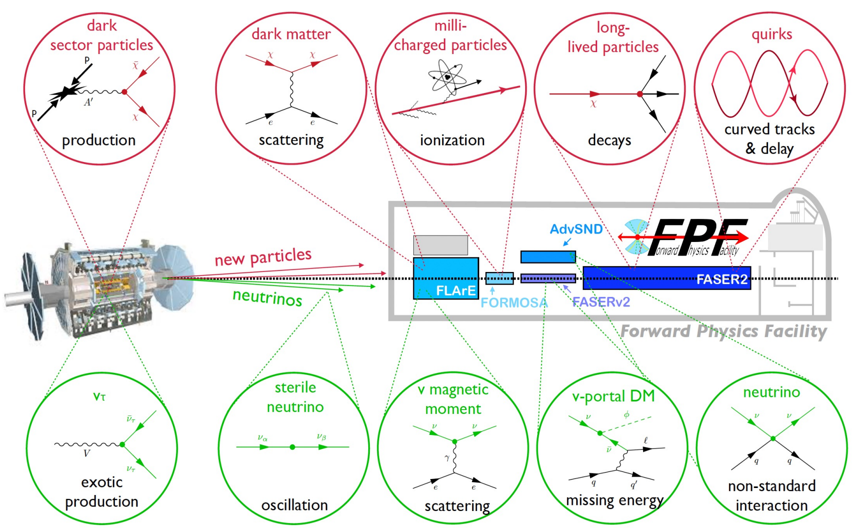
- Implications for
  – neutrino properties
  – QCD ($x \sim 10^{-7} - 0.1$, DIS)
  – astroparticle physics

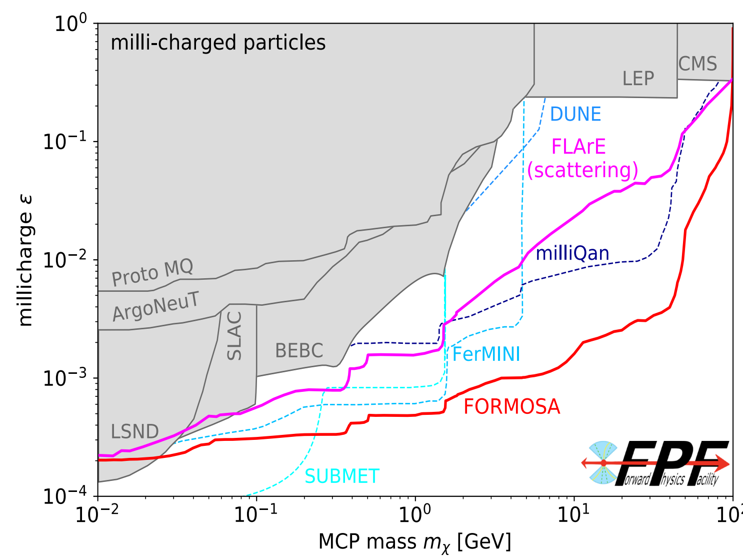




THE FPF BSM PROGRAM

- Wide variety of BSM probes: new physics in neutrino production, propagation, and interaction, FIPs, LLPs, DM scattering, inelastic DM, and dark sectors.
- The FPF detectors each have unique capabilities to probe BSM topics. E.g.:
  - Pathfinder experiment FASER has recently set new limits on dark photons, extended sensitivity in the thermal target region from low coupling for the first time in 3 decades. FPF experiment FASER2 increases sensitivity by ~60,000 for many particles.
  - Pathfinder experiment milliQan has already set stringent bounds on mCPs for m ~ GeV. FPF experiment FORMOSA will extend to leading sensitivity for m ~ 100 MeV–100 GeV.





FPF USER COMMUNITY

- The FPF user community is large, vibrant, and growing.
  - Strong base provided by the collaborations of the current pathfinder detectors (FASER, FASERν, SND@LHC, milliQan) and the FLArE working group, ~300 people, over 60 institutions.
  - FPF White Paper: 429 pages, 392 authors+endorsers, over 200 institutions, J. Phys. G, 2203.05090.
  - 5 dedicated FPF meetings since 2020; exciting exchange of ideas across frontiers; rapid progress; new ideas, new experiments welcome.
  - Fully international.

arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Forward Physics Facility

The Forward Physics Facility
at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

COST

- Very preliminary budget and schedule assembled by CERN groups and experiment proponents. For details, see the FPF Summary document submitted to P5.
  - Facility Costs: civil construction and outfitting costs (electrical service, safety, ventilation, transportation, and lift service) provided by CERN civil engineering and technical infrastructure groups, respectively. Class 4 estimate based on HL-LHC experience.
  - International Experiment Costs: FASERν2, AdvSND, and a share of FASER2.
  - US Experiment Costs: FLArE, FORMOSA, and a share of FASER2. US-style accounting, includes labor, overhead, contingency. Range depends on technical decisions.

Component	Cost Range	Comments
Facility Costs		
FPF civil construction	20-35 MCHF	Construction of shaft and cavern
FPF outfitting costs	7-15 MCHF	Electrical, safety, and other services
Total	**27-50 MCHF**	Total including integration
Int'l Experiment Costs		Labor, overhead, contingency not included
FASER2	17 MCHF	Non-US portion
FASERν2	16 MCHF	
ADV-SND	12 MCHF	
Total	**45 MCHF**	
US Experiment Costs		Labor, overhead, contingency included
FLArE	\$39-65 M	Contingency 40%
FORMOSA	\$7-8 M	Contingency 20%
FASER2	\$6-10.5 M	Contingency 50%, US portion
Total	**\$52-83.5 M**	

SCHEDULE AND BUDGET PROFILE

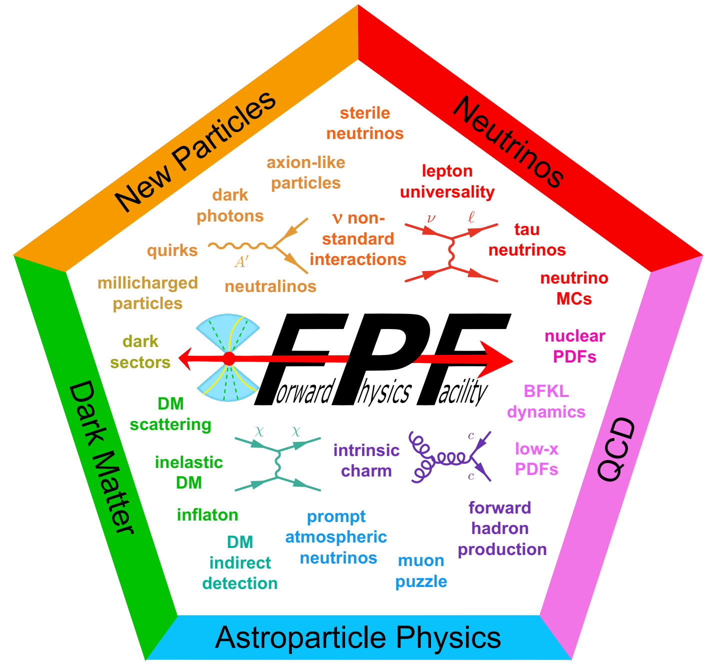
- All of the planned experiments are relatively small and inexpensive, require limited R&D, and can be constructed in a timely way.
- To fully realize the LHC's potential, the FPF and its experiments should be ready for physics in the HL-LHC era as early as possible in Run 4 (2029-32).
- A possible timeline:
  - Build FPF during Long Shutdown 3 from 2026-28.
  - Install support services and experiments starting in 2029.
  - Experiments begin taking data not long after the beginning of Run 4.

Year	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*	*2031*	*2032*	*2033-34*
(HL)-LHC nominal schedule	*Run3*	*Run3*	*Run3*	*Run3*	*LS3*	*LS3*	*LS3*	*Run4*	*Run4*	*Run4*	*Run4*	*LS4*
FPF/FLARE milestones		*Pre-CDR and physics proposal*	*R&D and detetor prototypes*	*CDR- long lead item magnet*	*Start of civil constr. TDR for detectors*	*Detector construction start*	*Long lead items for detector*	*End of civil constr. Install services*	*Detector install*	*Detector Commissioni ng and physics start*	*Physics running with full complement of detectors*	
US-DOE FLARE (kUS$)						*9750*	*19500*	*19500*	*13000*	*3250*		
US-DOE FORMOSA (kUS$)						*800*	*1600*	*4000*	*1600*			
US-DOE-FASER2 (kUS$)			*875*	*1750*	*3500*	*2625*	*1750*					
Total US-DOE (kUS$)			*875*	*1750*	*3500*	*13175*	*22850*	*23500*	*14600*	*3250*		

Budget profile based on the maximum cost estimate.

FPF SUMMARY

- The FPF will greatly expand the HL-LHC's potential for groundbreaking discoveries at the energy frontier.
  - Guaranteed SM progress from the study of $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ at ~TeV energies.
  - Rich program of BSM physics.



- The FPF is built on a large and growing community, including collaborations that have already demonstrated the ability to take ideas from concept to world-leading physics results on budget and on time.

- The FPF is a sustainable program, requiring no modifications to the LHC and no additional energy for the beam beyond the existing LHC program.

- The FPF is a mid-scale project composed of smaller experiments that can be realized on short timescales, with new ideas possible and very welcome. It will provide a multitude of scientific and leadership opportunities for junior researchers, who can make important contributions from construction to data analysis in a single graduate student lifetime.

EXTRAS

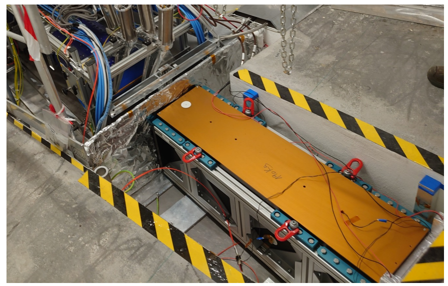
FPF PATHFINDER EXPERIMENTS

De Rujula et al. (1984)

- Four detectors have recently demonstrated the potential to do ground-breaking science in the far-forward region with small, fast, and inexpensive detectors.

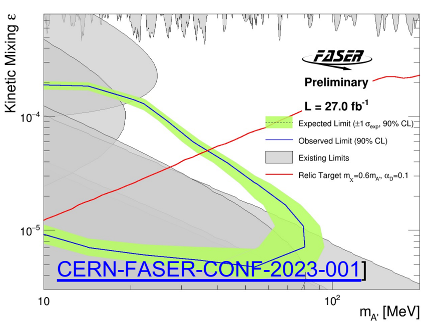
FASER

FASERν

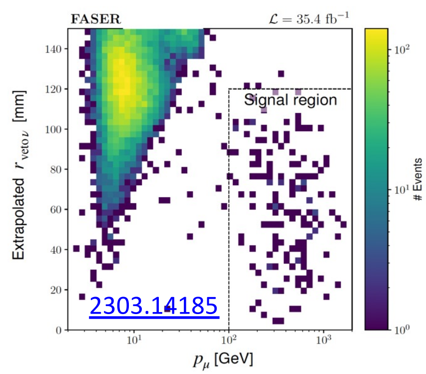


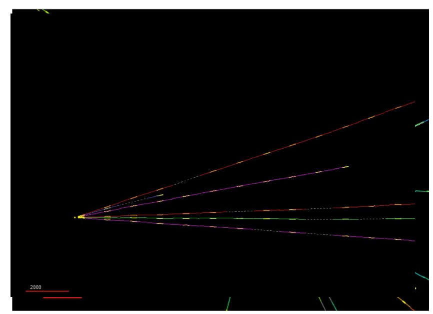
SND@LHC

milliQan

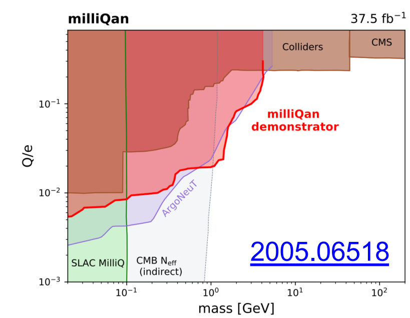


First new probe of dark photon thermal target from low ε in 30 years





First direct observation of collider neutrinos and the highest energy neutrinos from a human source



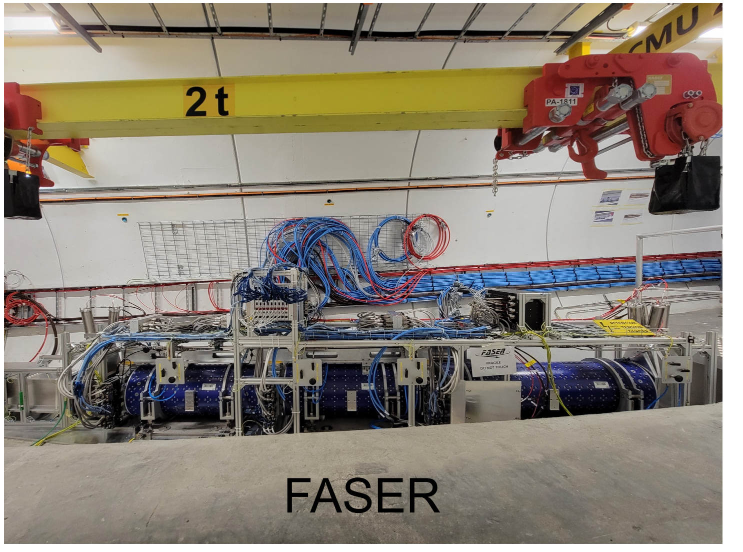
Leading bound on ~GeV milli-charged particles

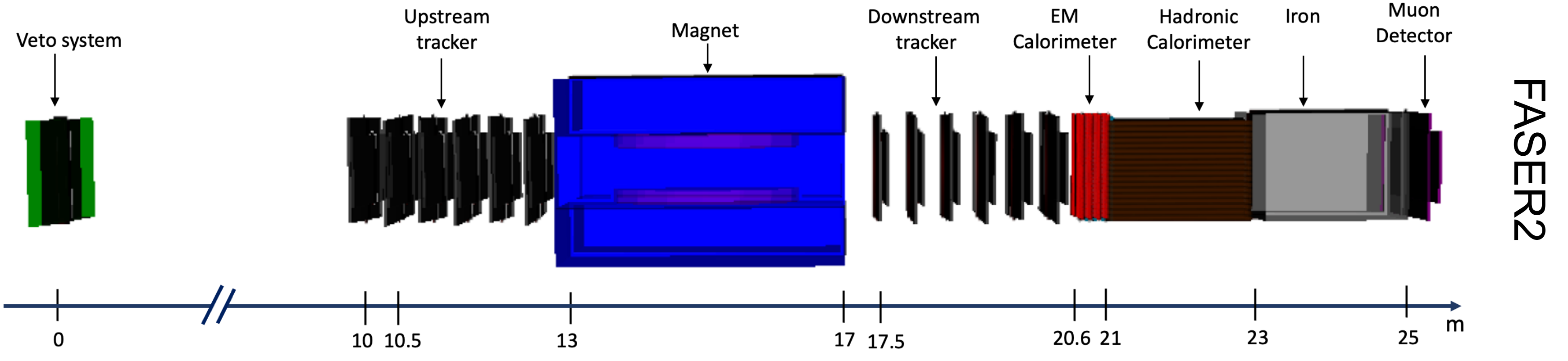
- Exciting results now, demonstrate technical readiness of FPF expts, provide a base for the large and growing FPF user community (~300 people from ~60 institutions).

FASER2

- On-axis magnetic spectrometer
  - Superconducting magnet with 4 Tm bending power
  - Trackers based on LHCb's SciFi detector

- FASER → FASER2
  - R = 10 cm, L = 1.5 m ($V = 0.05\ m^3$) → 3 m x 1 m x 10 m ($V = 30\ m^3$)
  - Luminosity ~ $30\ fb^{-1}$ → $3\ ab^{-1}$
  - Sensitivity increases over current bounds by ~60,000 for many models

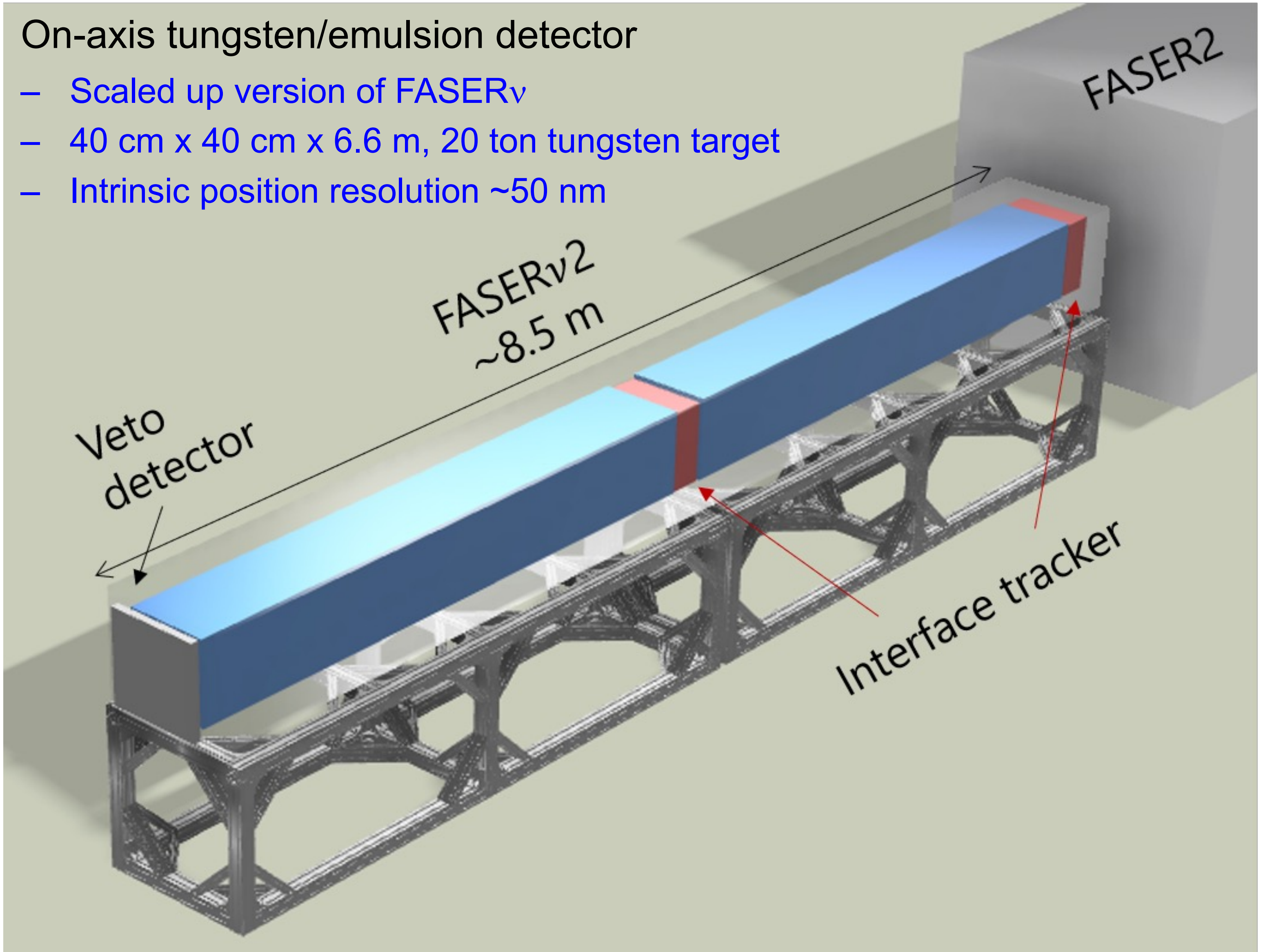




FASERν2

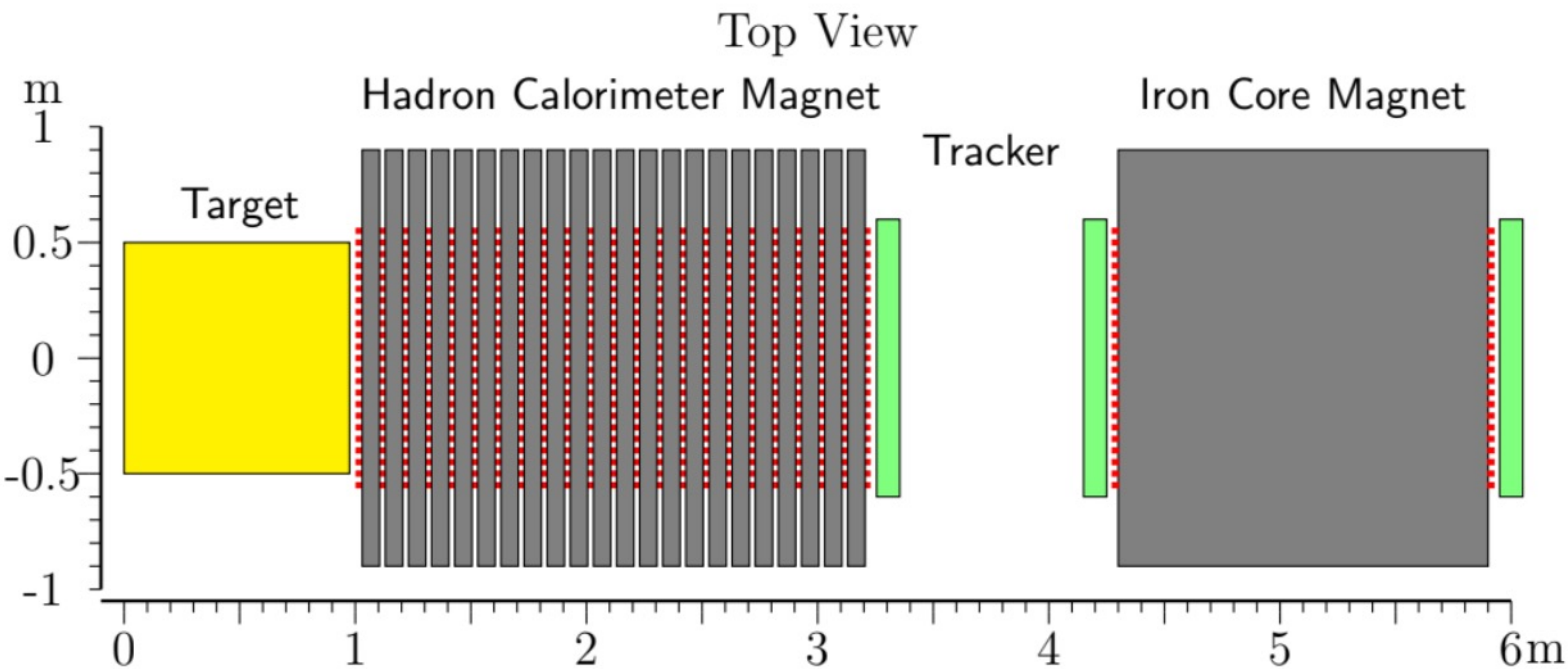
On-axis tungsten/emulsion detector

- Scaled up version of FASERν
- 40 cm x 40 cm x 6.6 m, 20 ton tungsten target
- Intrinsic position resolution ~50 nm



ADVANCED SND

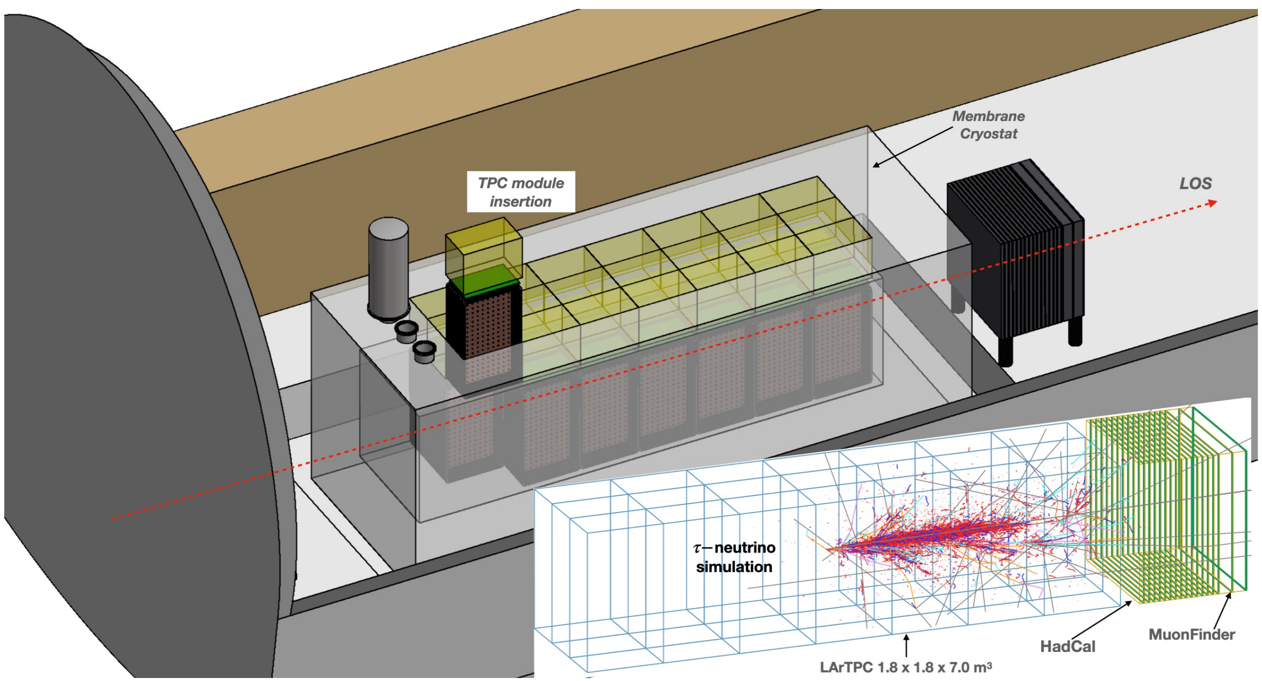
- Off-axis electronic neutrino detector
- Magnet to identify lepton charge, distinguish muon and tau neutrinos from anti-neutrinos



FLARE

- On-axis LArTPC neutrino and light DM detector
- 1.8 m x 1.8 m x 7 m, ~10 ton LAr mass

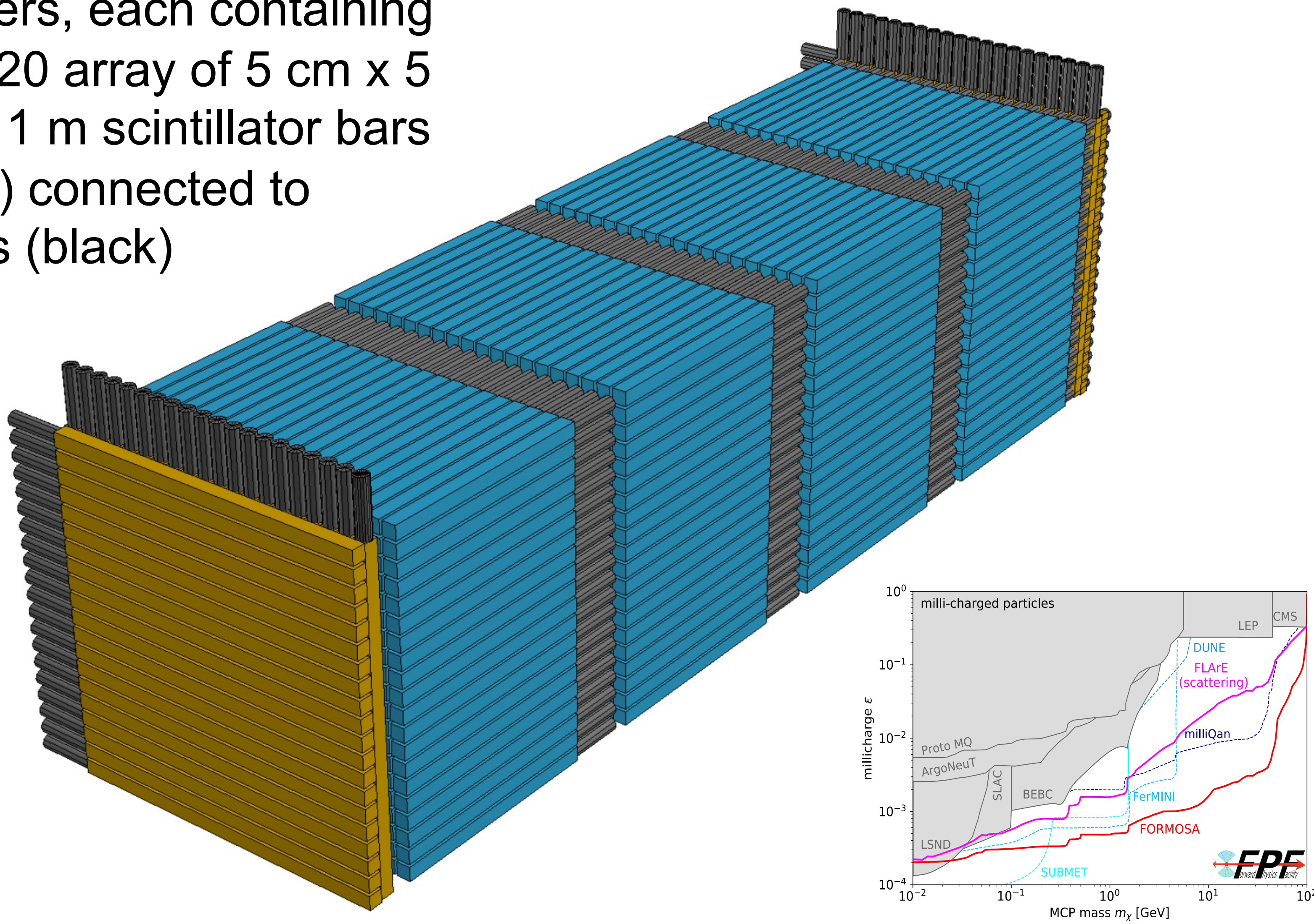
	Value	Remarks
LAr detector fiducial mass	>10 tons	
Active dimensions	1.8 m $\times$ 1.8 m $\times$ 7 m	not including cryostat
Cryostat dimensions	3.5 m $\times$ 3.5 m $\times$ 9.6 m	membrane type
TPC modules/drift length	3 $\times$ 7 (gap: $\sim$30 cm)	short gap TPC
TPC height	1.8 m	
Spatial resolution	<1 mm	in drift and tranverse dimension
Charge readout	pixels	pixel/wire hybrid approach possible
Trigger and light readout	SiPMs/WLS-plates	needed for neutrino trigger and time
Background muon rate	$\sim 1/\mathrm{cm}^2/\mathrm{s}$	at luminosity $5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
Neutrino event rate	$\sim 50/\mathrm{ton}/\mathrm{fb}^{-1}$	for all flavors of neutrinos
Hadronic calorimeter (hadmu)	$\sim 6-10\lambda$	interactions lengths
Dimensions	1.8 m $\times$ 1.8 m $\times$ 1.05 m (depth)	Fe/scint sandwich
Muon tagger and momentum	1 Tesla magnetized Fe/scint	same as the hadmu



FLArE with simulated 500 GeV tau neutrino

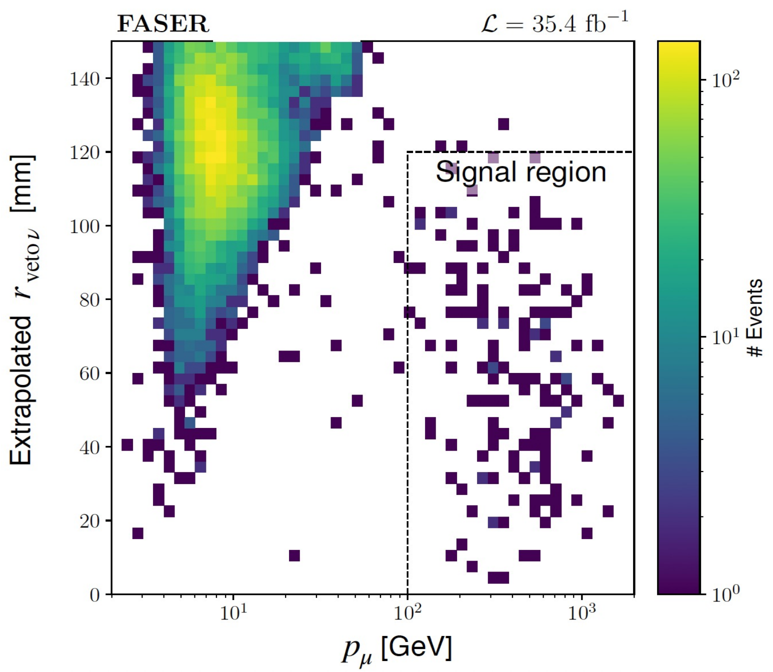
FORMOSA

- 4 layers, each containing 20 x 20 array of 5 cm x 5 cm x 1 m scintillator bars (blue) connected to PMTs (black)

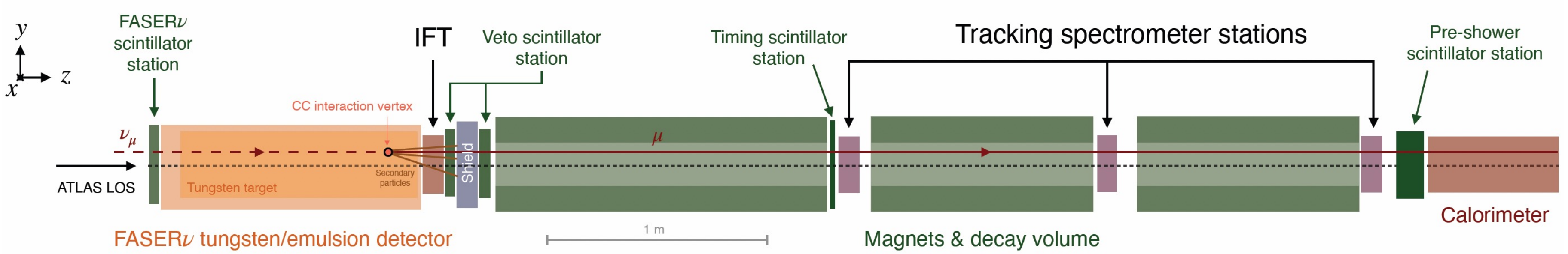


FIRST OBSERVATION OF COLLIDER NEUTRINOS

- Signal: ~TeV neutrinos produced in meson decays, interact in FASERν. Focus on CC interactions $\nu_\mu N \rightarrow \mu X$, producing a high-energy muon.
- After unblinding, find 153 signal events with ~0 background (+ 8 from SND@LHC)
- 1st direct observation of collider neutrinos
  - Signal significance of ~16σ
  - Muon charge → both ν and $\bar{\nu}$
  - Almost certainly the highest energy ν and $\bar{\nu}$ from a human source

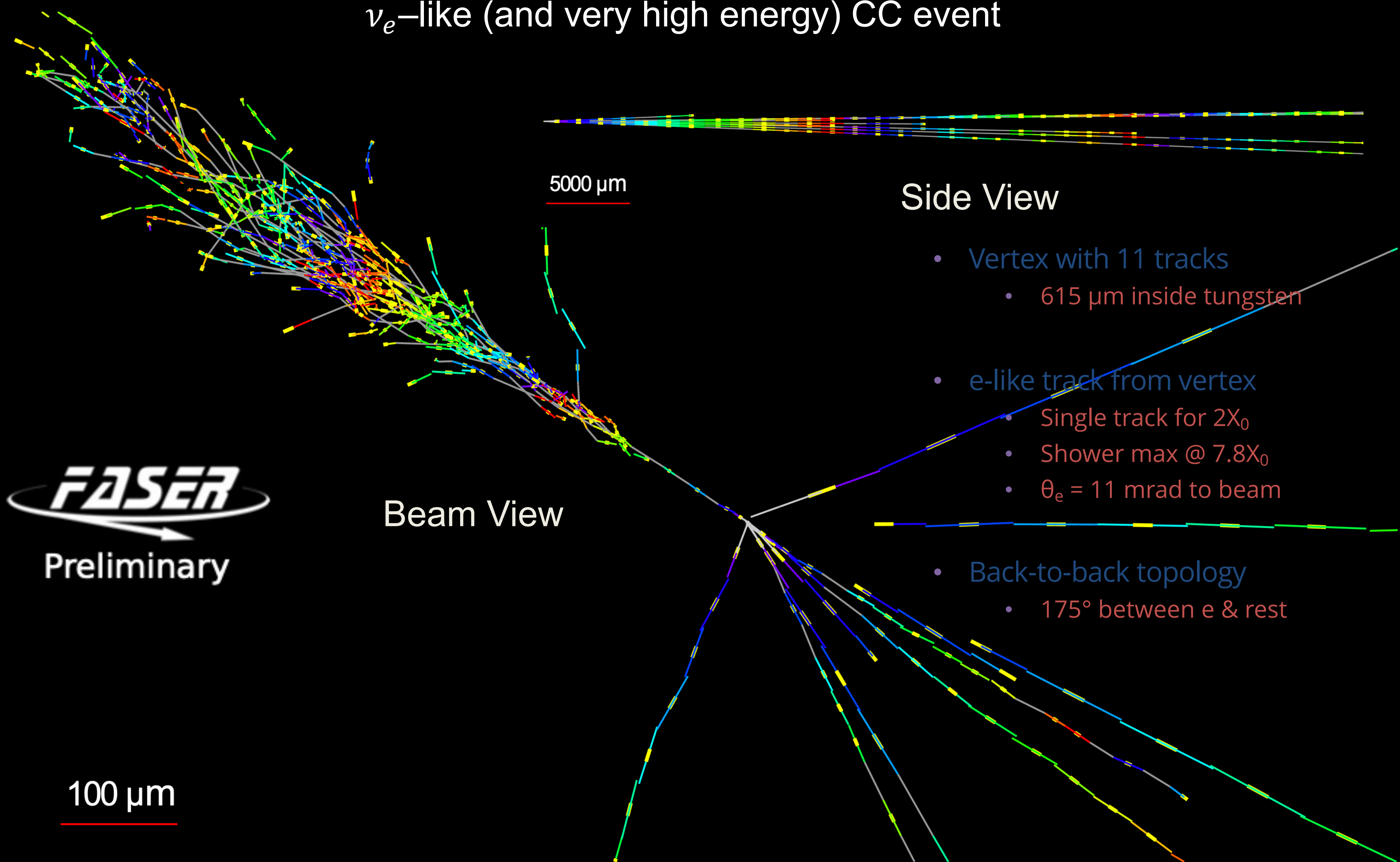


FASER Collaboration (2303.14185)



NEUTRINOS FROM EMULSION IN FASERν

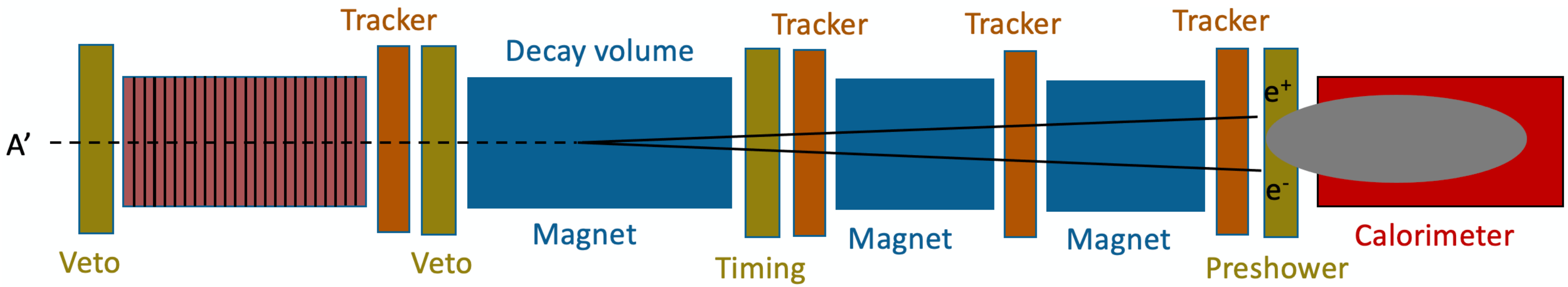
Much more to come: 1st direct observation does not even use the emulsion data! Analysis underway, but already many neutrino candidates, including this highly ν_e–like (and very high energy) CC event



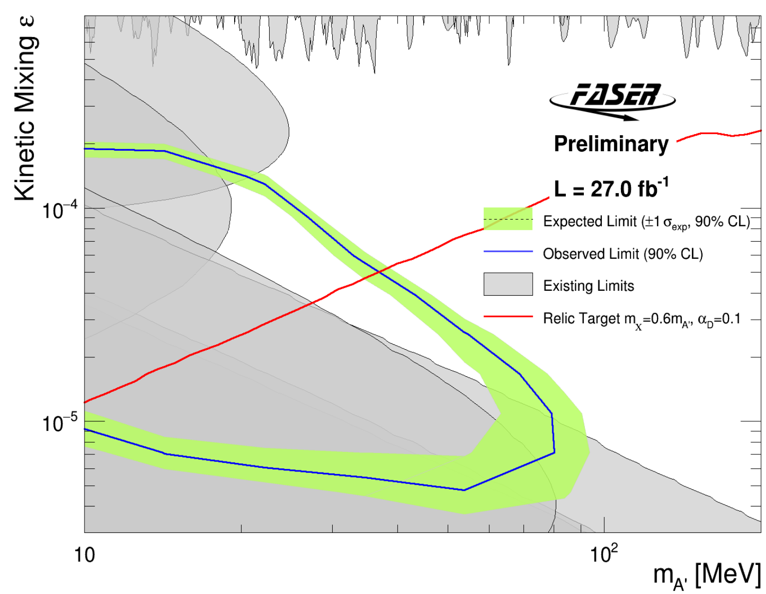
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

NEW DARK PHOTON RESULTS

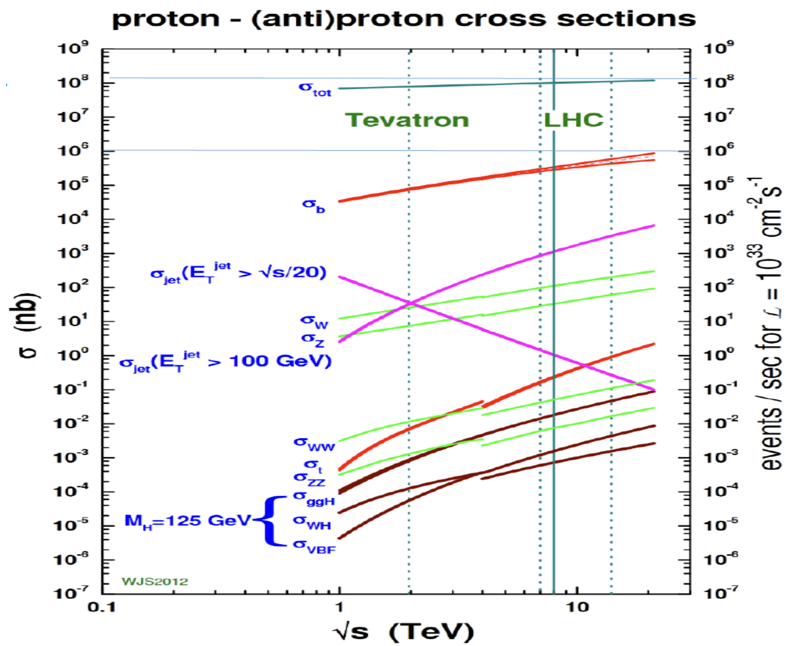
- Signal: $\pi/\eta \rightarrow A'\gamma$ or $pp \rightarrow ppA'$, A' travels 476 m through rock/concrete, then decays $A' \rightarrow e^+e^-$. Probes thermal target: m ~ $10 - 100$ MeV, $\varepsilon \sim 10^{-5} - 10^{-4}$.

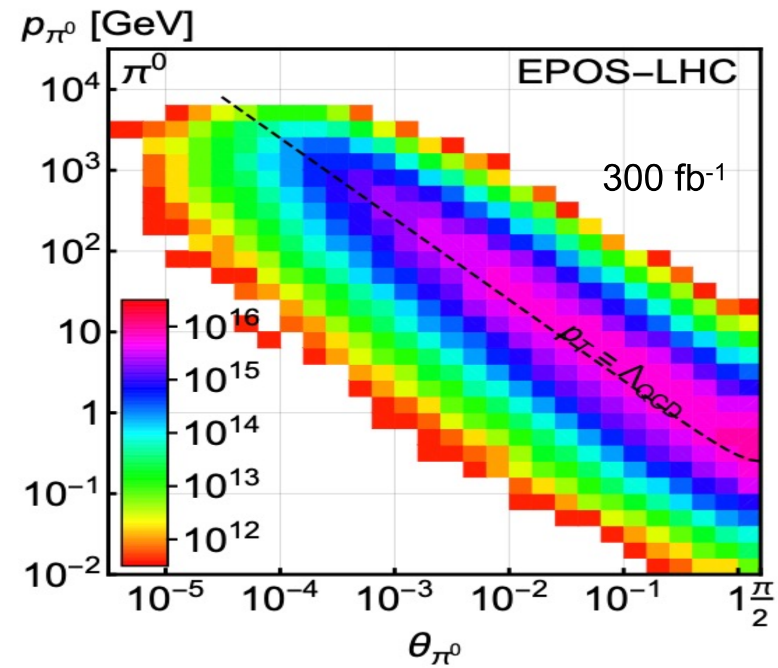


- After unblinding, no events seen in signal region. Background ~ 10^{-3} events, FASER sets limits on previously unexplored parameter space.
- First incursion (with NA62) into the thermal target from low coupling since the 1990's.
- Background-free, bodes well for the future: FASER2 has ~60,000 better sensitivity.



LIGHT, WEAKLY INTERACTING PARTICLES





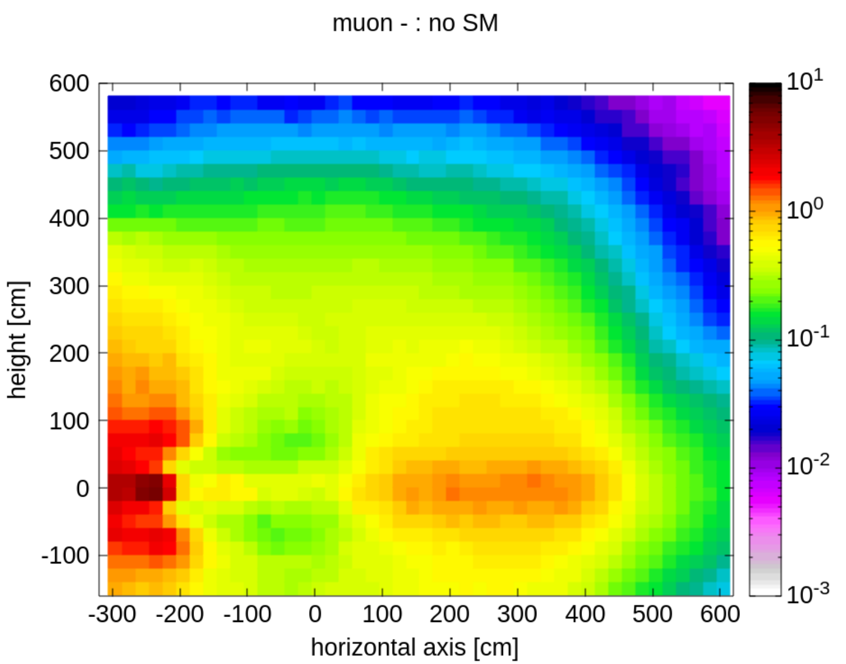
Feng, Galon, Kling, Trojanowski (2017)

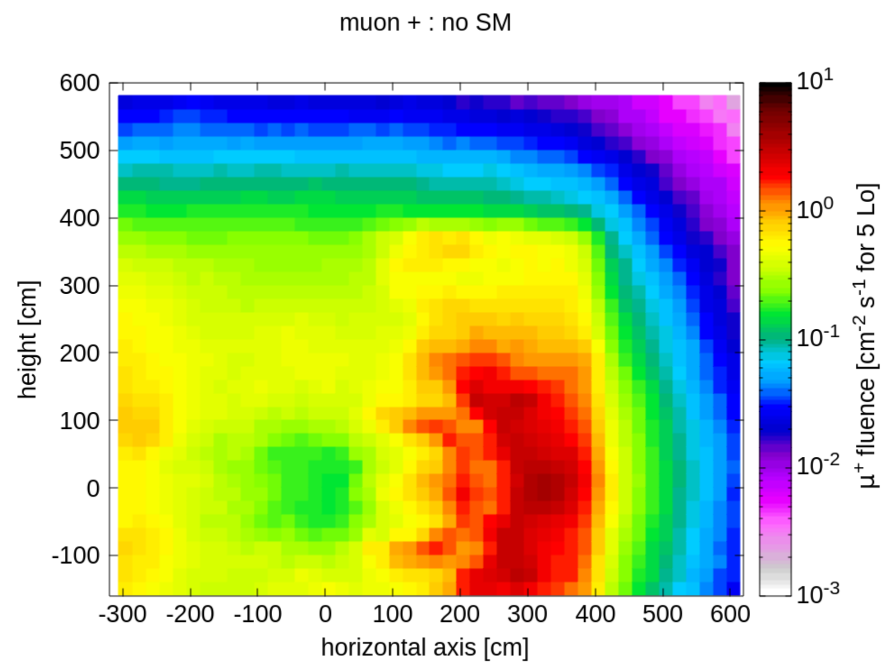
- Most BSM searches focus on σ ~ fb, pb.
- But if the new particles are
  - light → can be produced in decays of light SM particles.
  - weakly-interacting → need large numbers of SM particles to see rare processes.

- These considerations strongly motivate considering σ_{tot} ~100 mb, the typically "wasted" cross section for BSM searches.
- Typically low p_T, but possibly high p.
- The most energetic particles are very far forward. E.g., for pions, enormous rates with p ~ TeV with $\theta \lesssim$ 1 mrad ($\eta \gtrsim$ 7.6).

MUON FLUX AT THE FPF

- Muons from ATLAS IP are the main background for most FPF signals.
- FLUKA results for the LHC have been validated to ~30% in Run 3 by FASER and SND@LHC.
- FLUKA results for the HL-LHC are 0.6 Hz/cm^2 at LOS, much larger at some locations ~1 m from the LOS; easy to veto for most FPF signals.

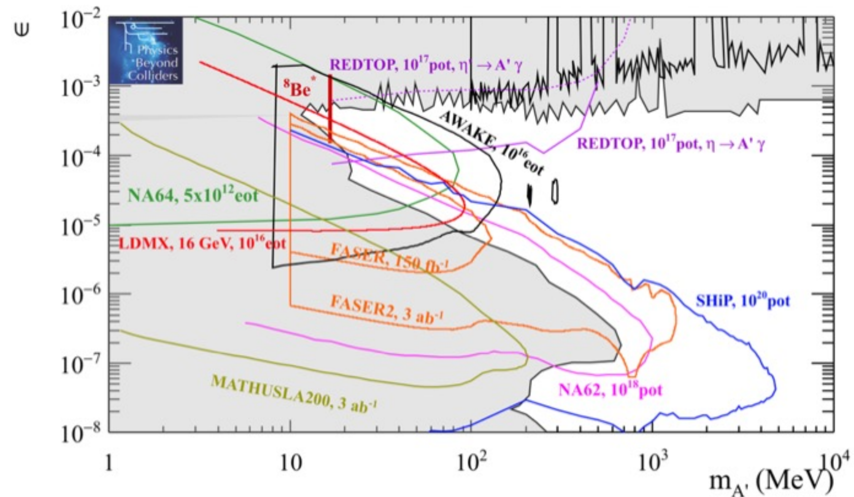




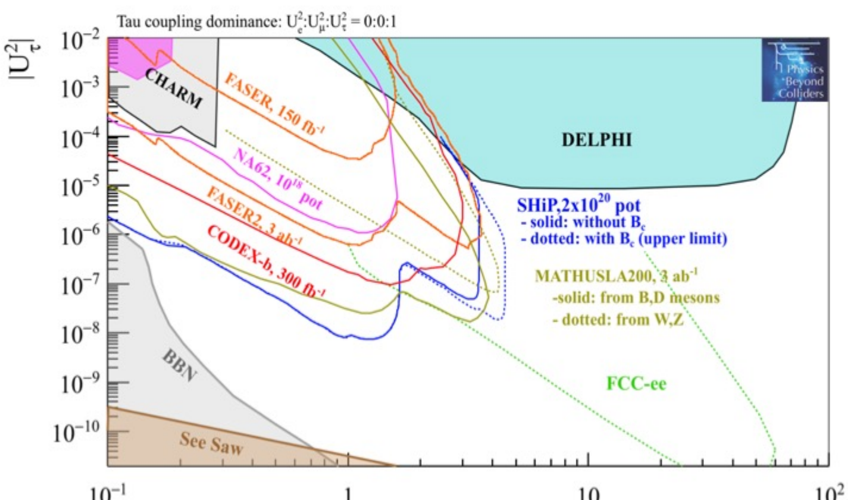
DARK SECTOR SEARCHES

- FPF detectors have significant discovery potential for a wide variety of BSM/LLP models: dark photons; B-L and related gauge bosons; dark Higgs bosons; HNLs with couplings to e, mu, tau; ALPs with photon, gluon, fermion couplings; light neutralinos, inflatons, relaxions, and many others.

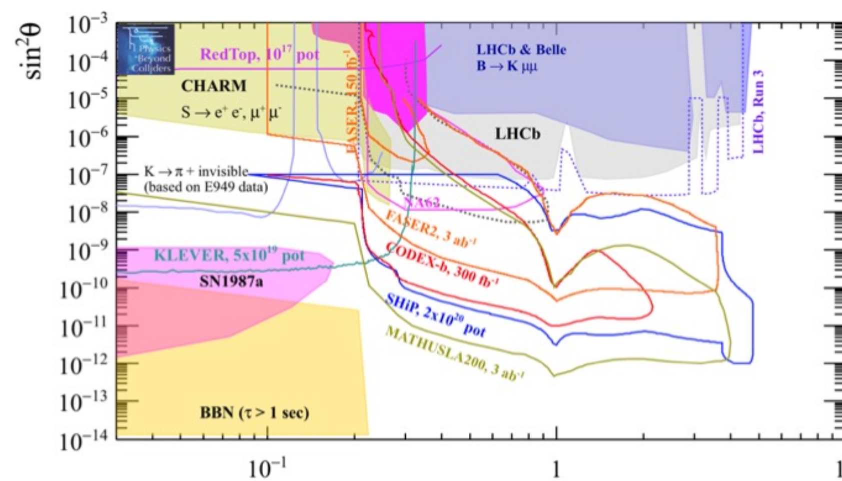
FPF White Paper (2022)



Dark Photon



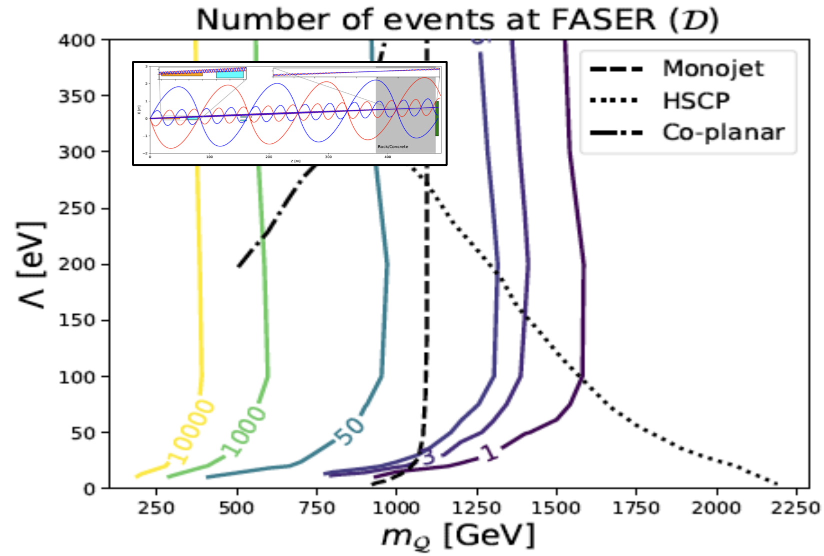
Dark Fermion



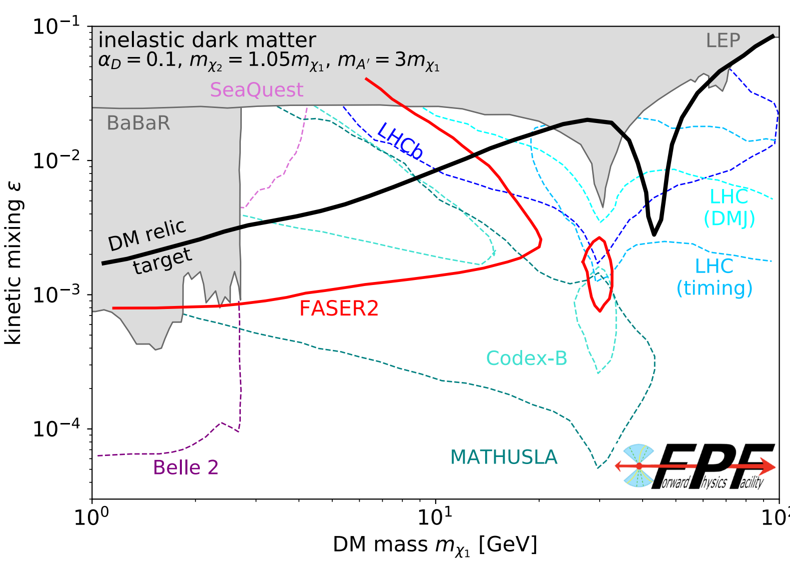
Dark Scalar

FPF BSM SEARCHES

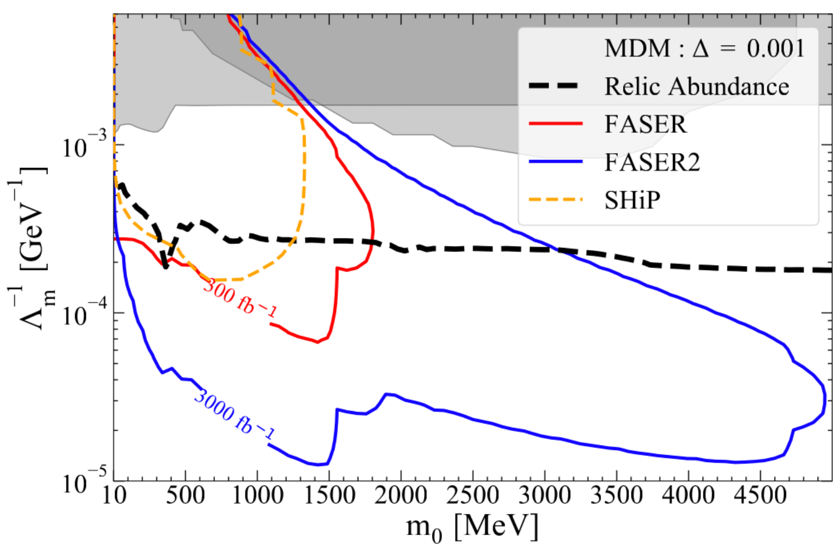
- Complementarity of high energy and fixed target experiments. High energy experiments probe
  - High mass states (e.g., quirks)
  - High mass mediators
  - Compressed spectra by boosting soft decay products to high energy



Li, Pei, Ran, Zhang, 2108.06748



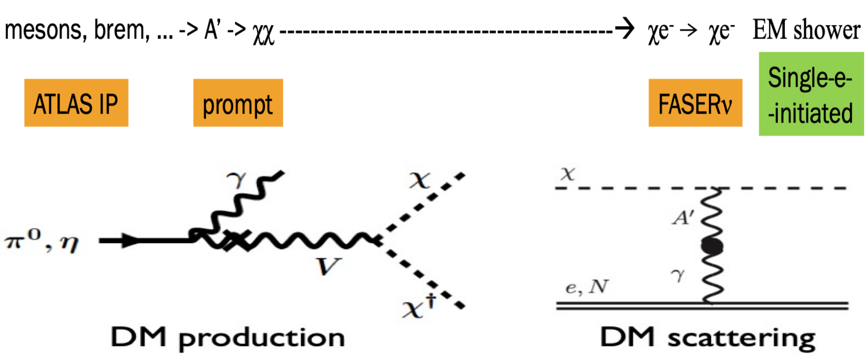
Berlin, Kling, 1810.01879



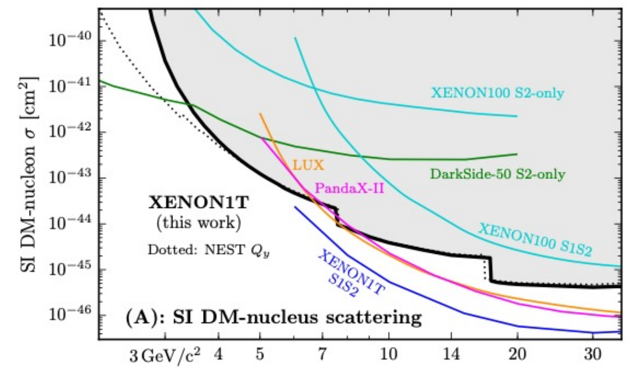
Dienes et al., 2301.05252

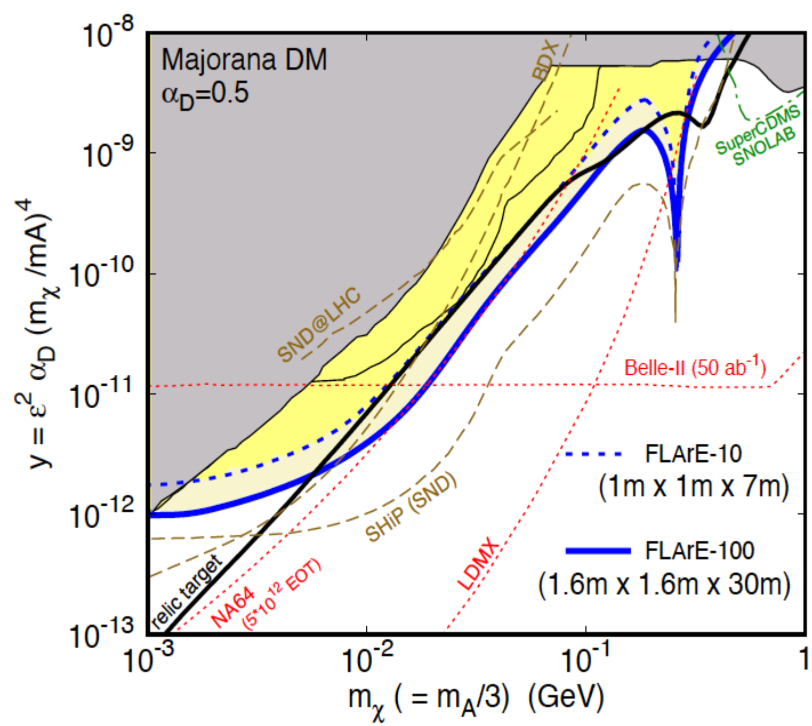
DARK MATTER DIRECT DETECTION

- Light DM with masses at the GeV scale and below is famously hard to detect.
  - Galactic halo velocity ~ 10^{-3} c, so kinetic energy ~ keV or below.
- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.



- FLArE is powerful in the region favored/allowed by thermal freezeout.

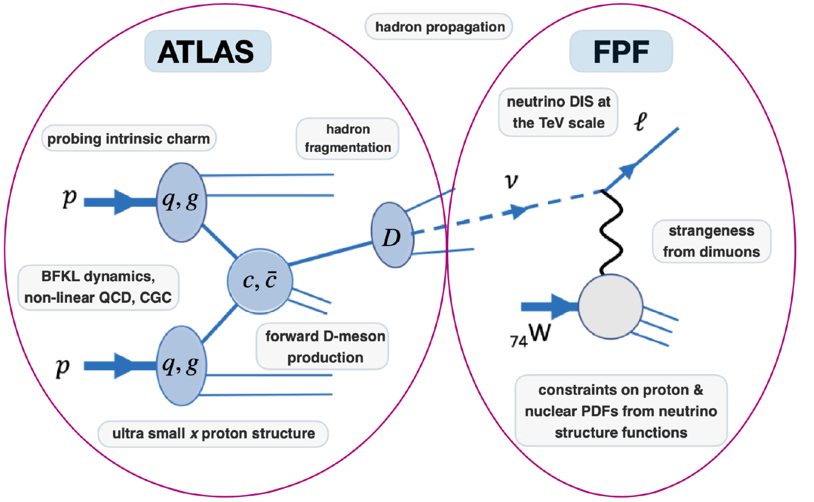




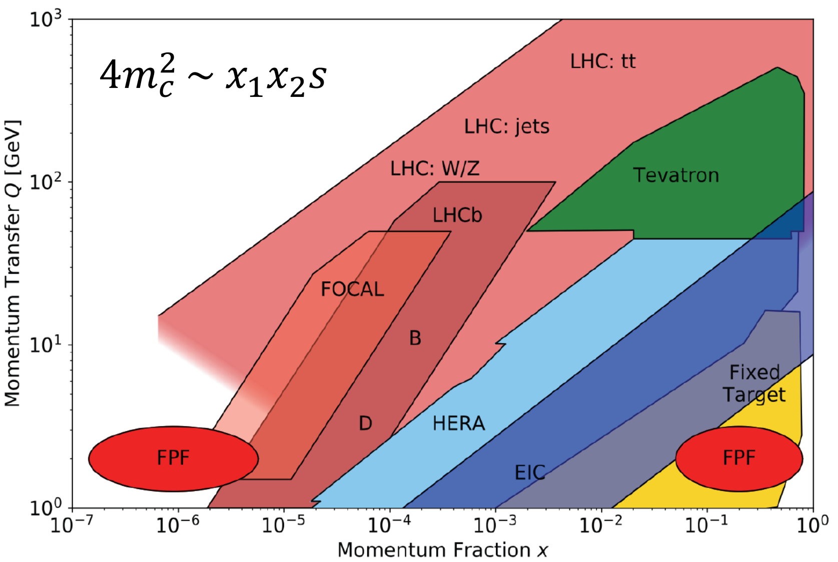
Batell, Feng, Trojanowski (2021)

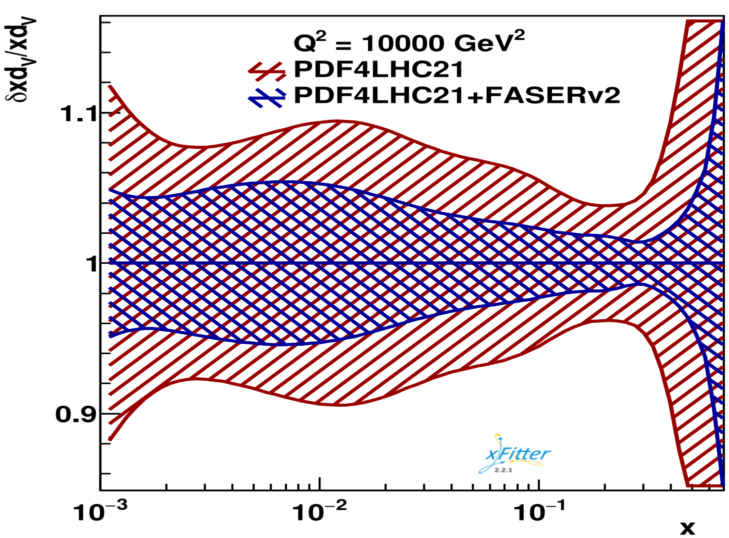
QCD

- The FPF will also support a rich program of QCD and hadron structure studies.
- Forward neutrino production is a probe of forward hadron production, BFKL dynamics, intrinsic charm, and proton structure at ultra small x ~ 10^{-7} to 10^{-6}.
- Fully differential DIS cross sections will improve PDF constraints by factor of ~2.



FASER White Paper (2022)

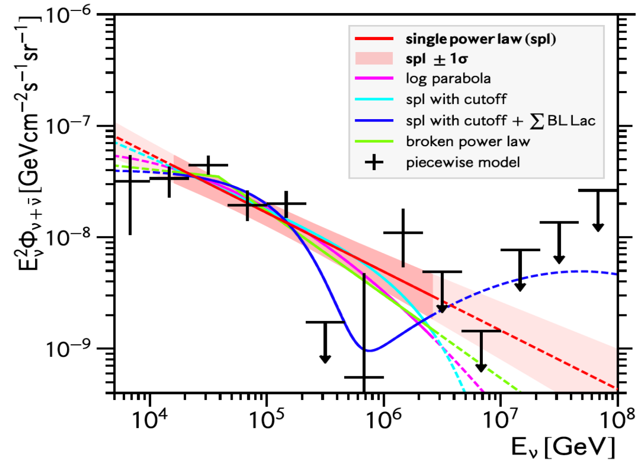




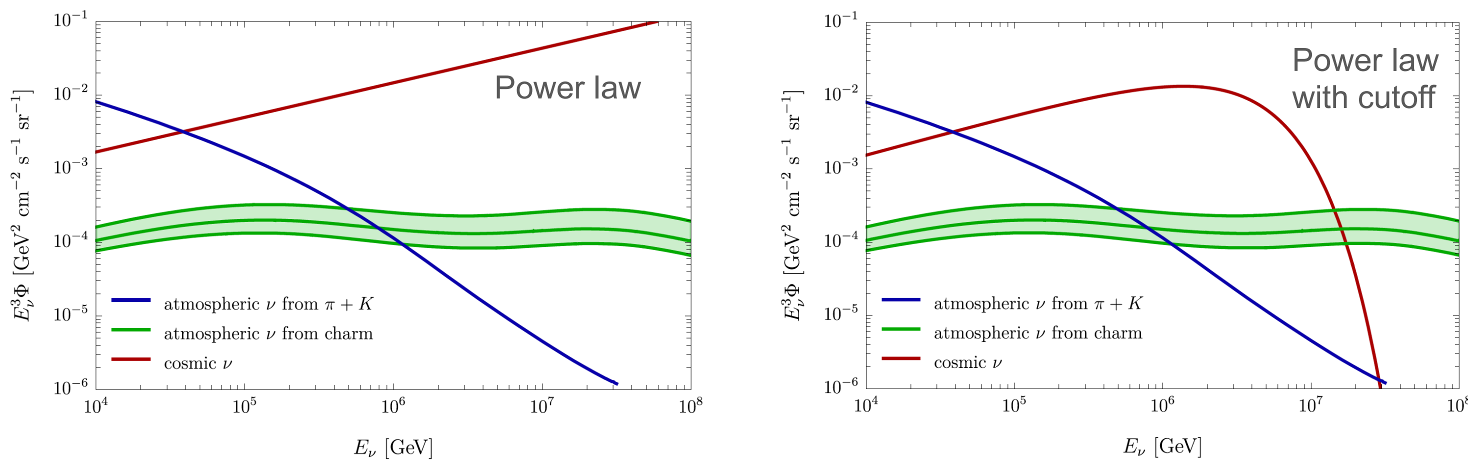
Rojo et al. (2023)

ASTROPARTICLE PHYSICS: COSMIC NEUTRINOS

- The current IceCube cosmic nu flux can be fit by a power law, a power law with cutoff, ...
- More data may be able to distinguish these, but only if the atmospheric neutrino background from charm is better determined.



IceCube 2001.09520



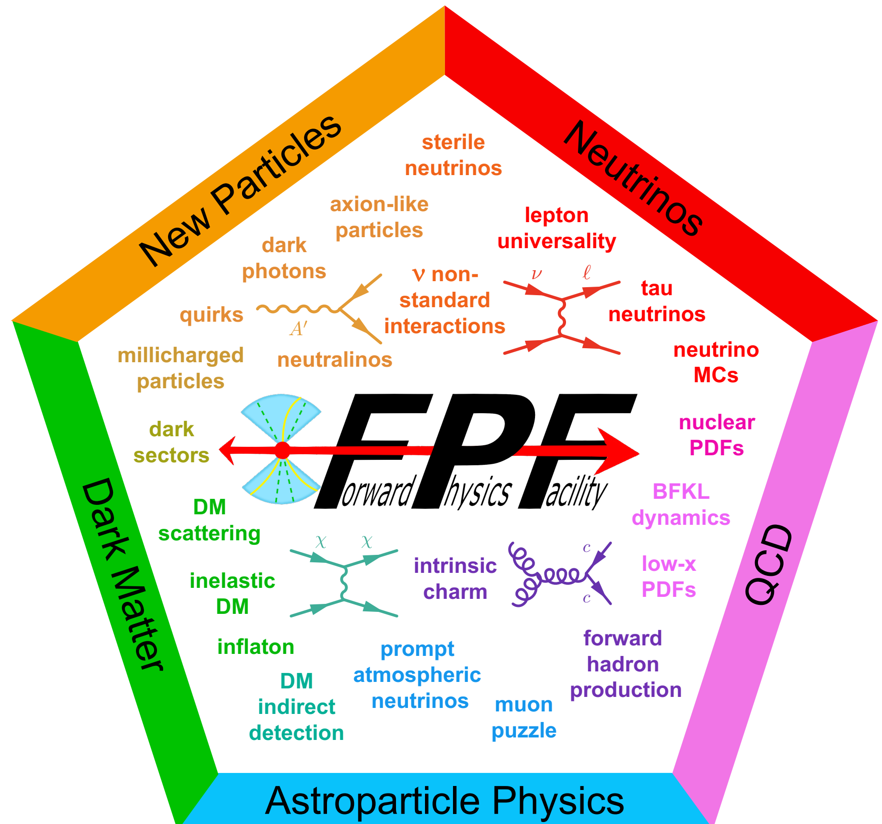
Bhattacharya et al. (1502.01076)

- This can be measured in the controlled environment of a particle collider if
  - $\sqrt{s} \sim \sqrt{2E_\nu m_p} \sim 10$ TeV for $E_\nu \sim 10^7$ GeV: Requires the energy of the LHC
  - $x_{1,2} \sim \frac{m_c}{\sqrt{s}}\, e^{\pm\eta} \;\Rightarrow\; \eta \sim 7$ to 9: Requires the far forward angular coverage of the FPF

Anchordoqui (2022)

FPF MEETINGS AND PAPERS

- The physics program in the far-forward region has been developed in a series of meetings and papers.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan-1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
  - FPF6 Meeting, 8-9 June 2023



- FPF Papers
  - FPF "Short" Paper: 75 pages, 80 authors, Phys. Rept. 968, 1 (2022), 2109.10905.
  - FPF White Paper: 429 pages, 392 authors+endorsers representing over 200 institutions, J. Phys. G (2023), 2203.05090.
- Snowmass 2022: "Our highest immediate priority accelerator and project is the HL-LHC, …including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades."

ORGANIZATIONAL INFRASTRUCTURE

- FPF Working Group structure established to organize the work and provide contact names for new people interested in the FPF.

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

WG3 Light Hadron Prod: Luis Anchordoqui, Dennis Soldin

WG4 BSM: Brian Batell, Sebastian Trojanowski

Detector WGs

WG5 FASER2: Alan Barr, Josh McFayden

WG6 FASERnu2: Aki Ariga, Tomoko Ariga

WG7 FLArE: Jianming Bian, Milind Diwan

WG8 AdvSND: Giovanni De Lellis

WG9 FORMOSA: Matthew Citron, Chris Hill

Exp/Th 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