Forward Physics Facility:
Proposed Experiments and Prospects

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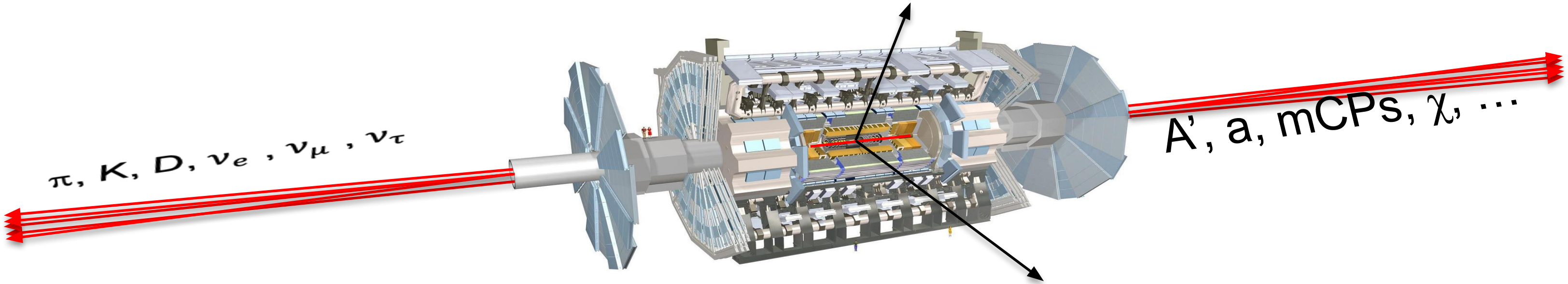
Forward-Looking Physics at the LHC

- The large LHC detectors, while optimized to discover and study heavy particles, are not at all optimally configured to discover and study light particles.

- Heavy particles (W, Z, t, h, …) are produced ~slow, decay ~isotropically.

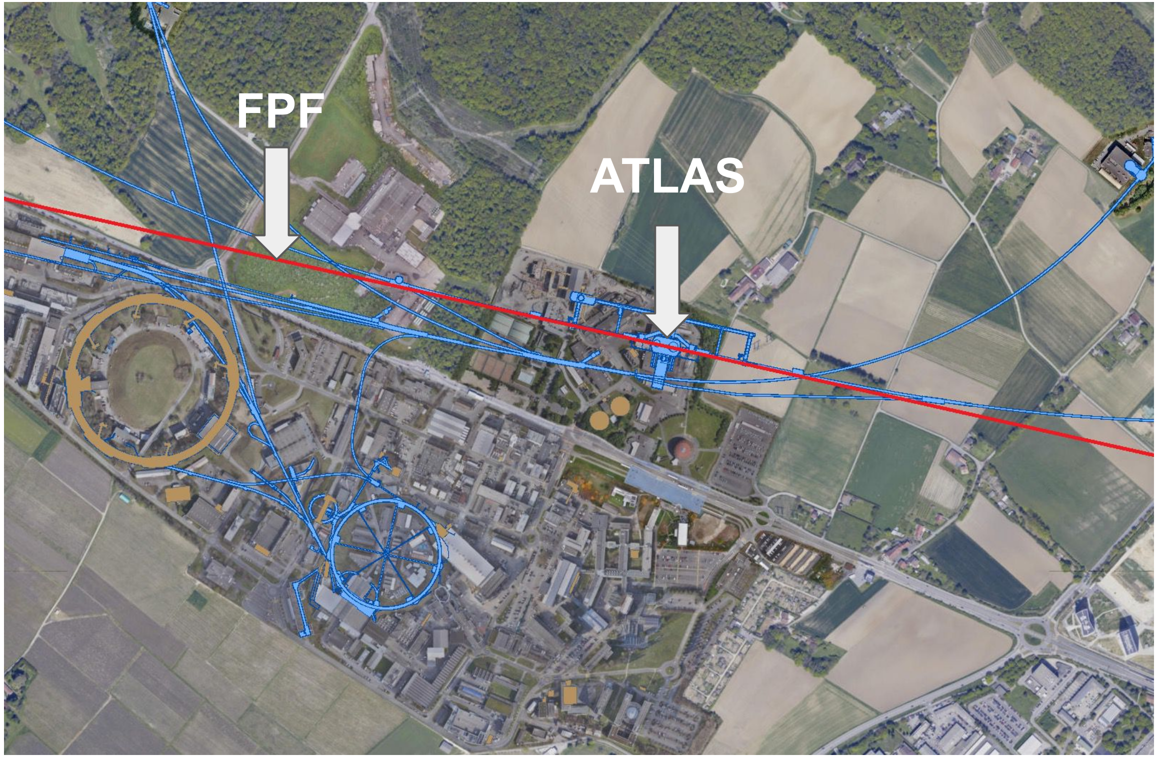


- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles, including neutrinos, which had never been directly detected at a collider before 2023.
  - It is also true for many proposed new particles, especially those motivated by neutrino mass and dark matter.

Forward Physics Facility: Site

- Comprehensive site selection study performed by the CERN Civil Engineering.
- Ideal location identified ~600 m west of ATLAS.

- The site is on CERN land in France
- The cavern is 75 m long, 10 m wide
- 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



FPF Site Investigations

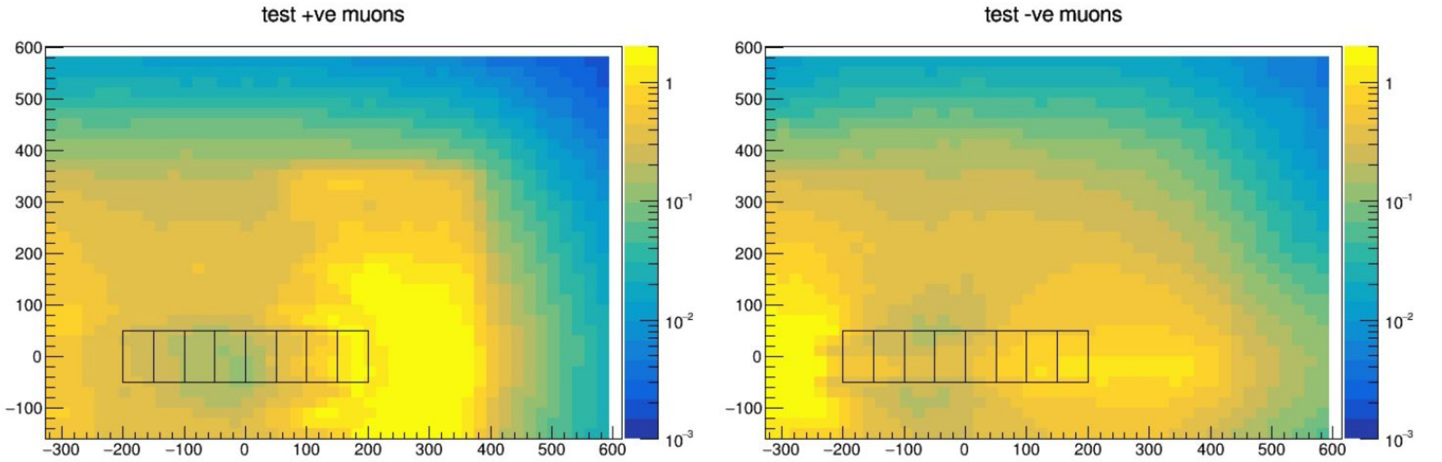
Core sample drilled in 2023.
Analysis shows area looks good for excavation.

- Drilling machine in place

- Works started

- Core samples

Muon Flux



- FLUKA simulation of muon fluxes at the FPF has been performed, including full magnetic maps.

- Flux of about **0.5 hz/cm^2** along LOS.

- This number is promising, but note hot spots off-axis - the muon rate must inform experiment design.

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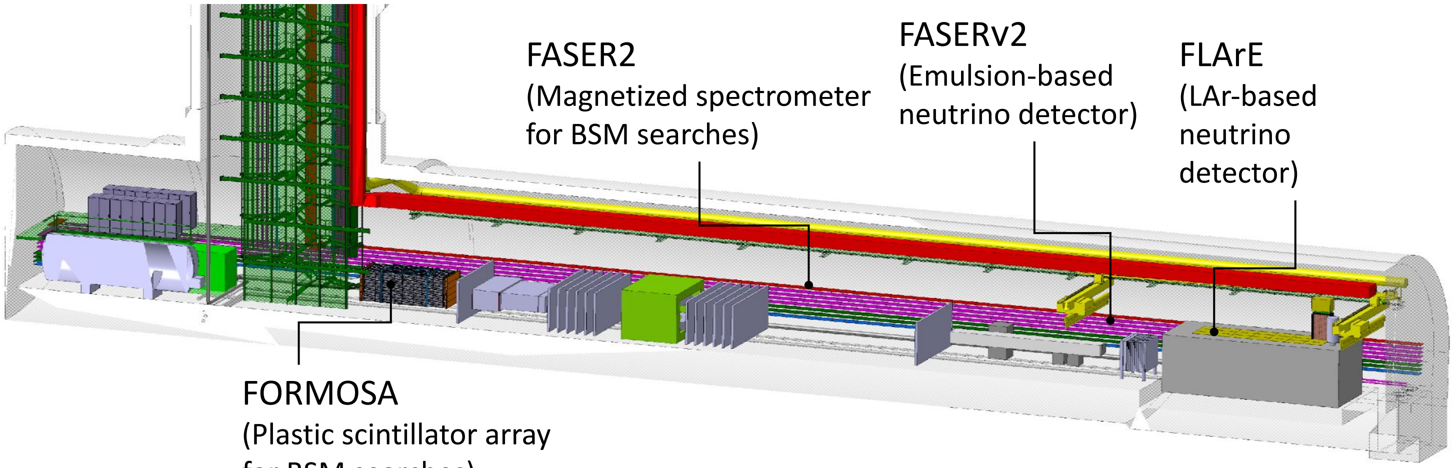
FPF Hall

There are currently four experiments planned for the FPF.
FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$.



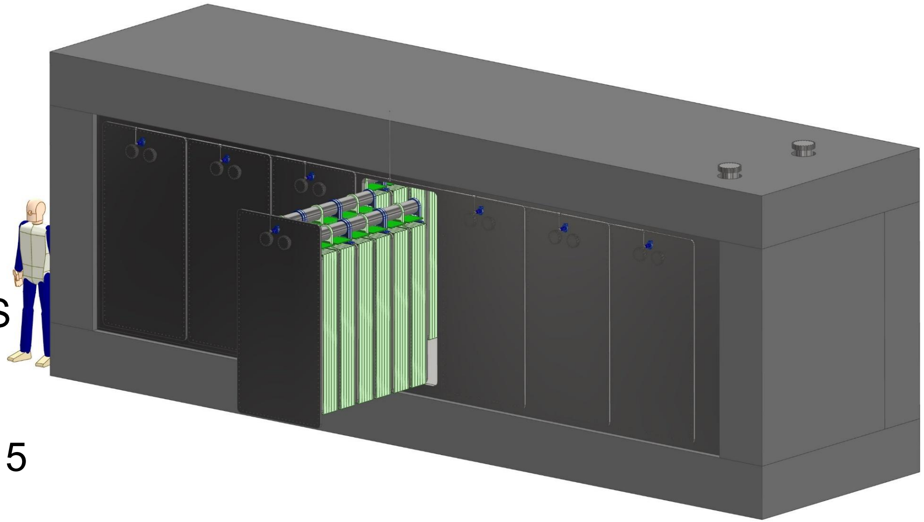
Diverse technologies optimized for SM and BSM physics
Synergies exist between FPF detectors

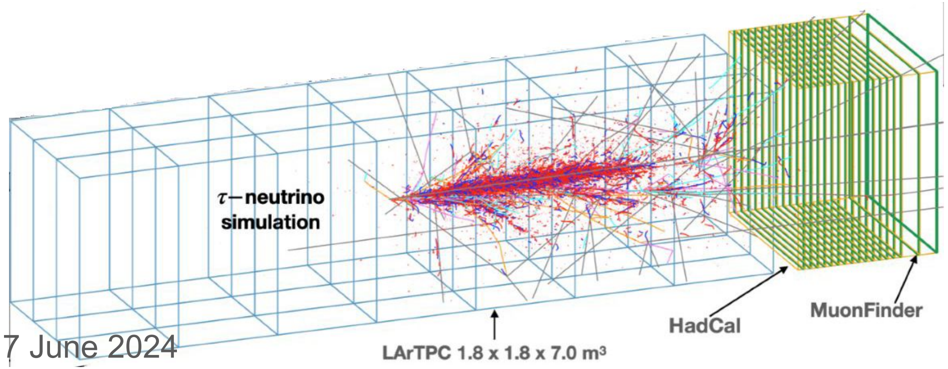
FPF Experiments: FLArE

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

- Considering two options for readout:
  - Pixellized anodes using QPix or similar electronics (single phase), or
  - ARIADNE-like optical readout using TPX3CAMS (dual phase)

- Need for high-resolution readout, pixel size ~1 to 5 mm.





- Conceptual installation design under development.

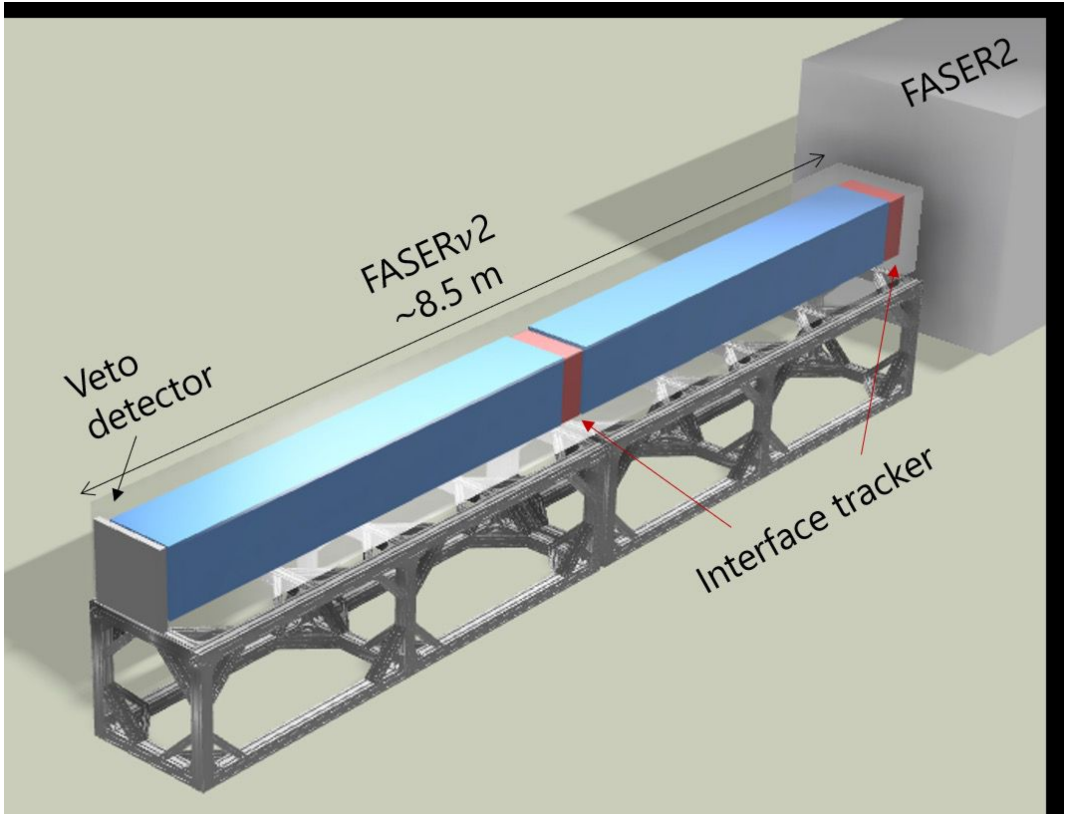
- Simulation studies are ongoing.

FPF Experiments: 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

Can identify heavy flavor particles produced in neutrino interactions, including τ, charm, and beauty.

Emulsion will need to be replaced ~1/year



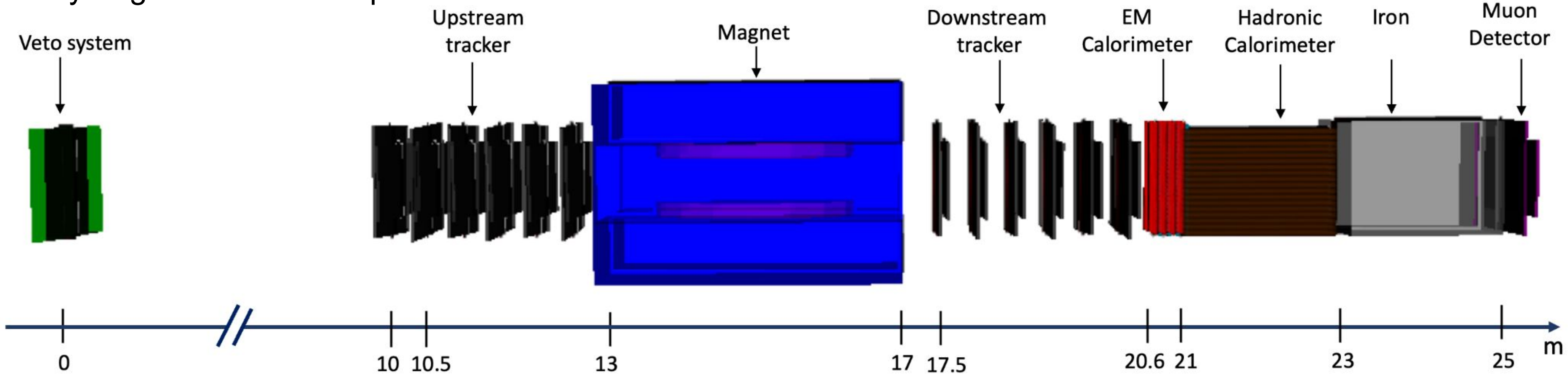
FPF Experiments: FASER2

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

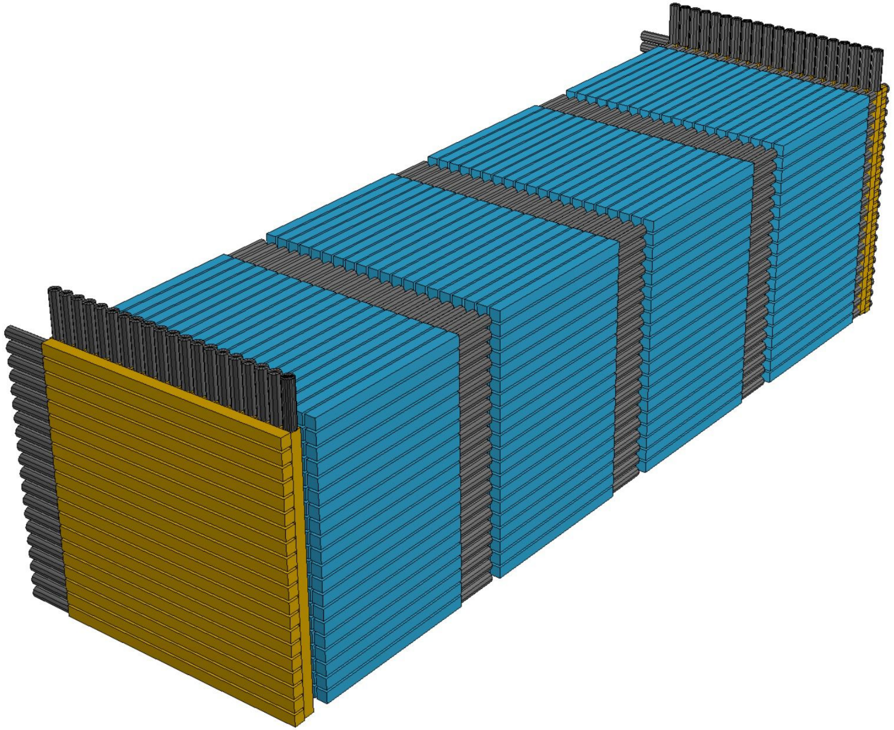
Builds on successful operation of smaller FASER detector in LHC transfer tunnel, which recently detected collider neutrinos for the first time.

Two options for magnet: SAMURAI-like magnet or off-the-shelf crystal puller magnet.

Synergies: Serves as spectrometer for FASERν2 and FLArE.



FPF Experiments: FORMOSA



Search for feebly-interacting millicharged particles that arise naturally in many dark sector models.

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

Segmented beam-muon veto panels on front and back.

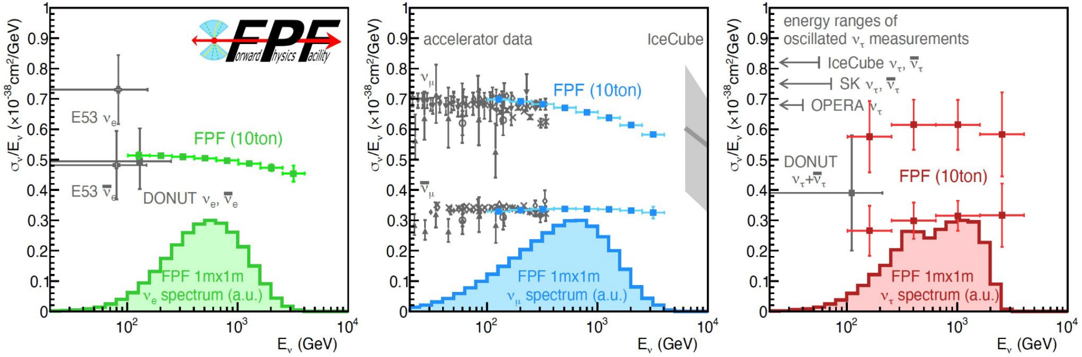
Design informed by successful operation of milliQan.

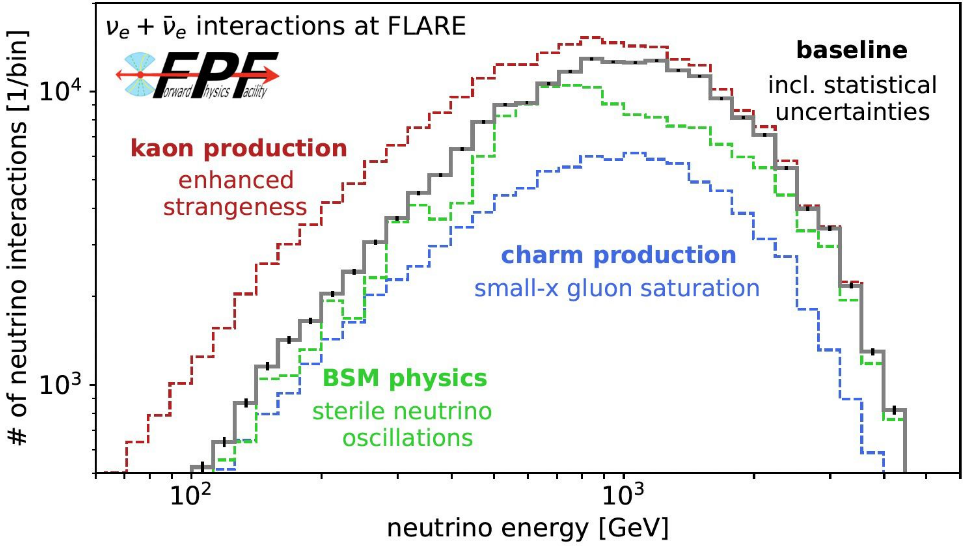
Physics Program: Neutrinos

- Collider neutrinos have recently been detected for the first time by pathfinder experiments FASERν and SND.

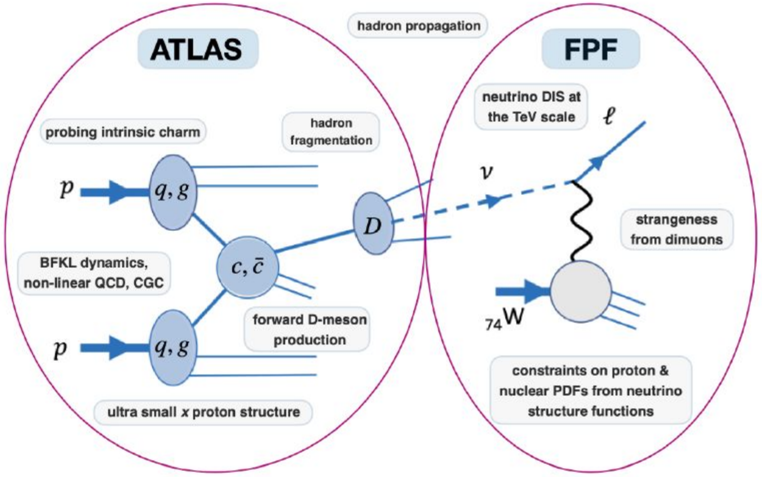
- FPF experiments FLArE and FASERν2 will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at ~TeV energies.

- The current data from accelerators ends around 300 GeV. FPF would provide data that fills in the gap between accelerators and atmospheric neutrinos.





Physics Program: QCD

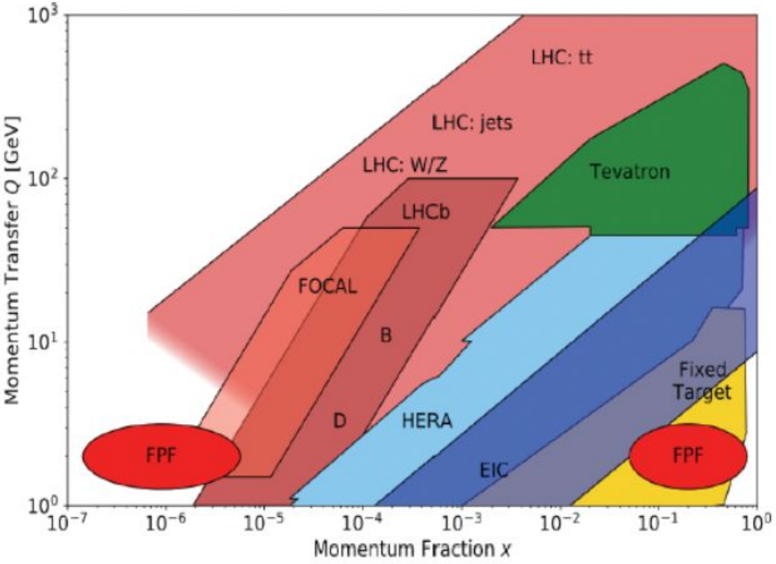


Can study:

- At low x: small-x proton structure, BFKL dynamics
- At high x: intrinsic charm
- Via DIS: nuclear structure functions

- QCD physics accessed both by production in forward direction and by DIS at FPF.

- Access to unexplored kinematic regions at low Q, high x and low Q, low x

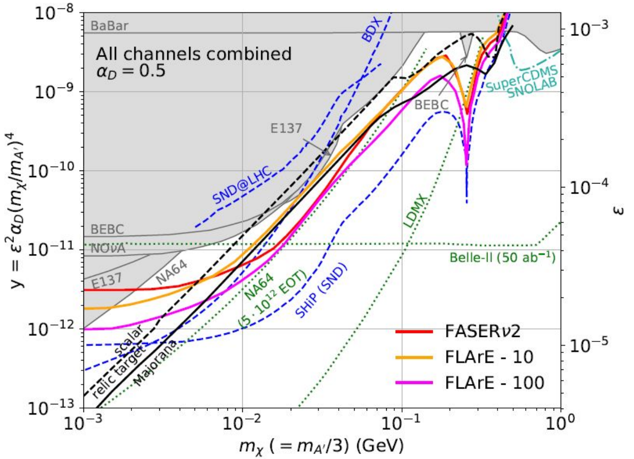


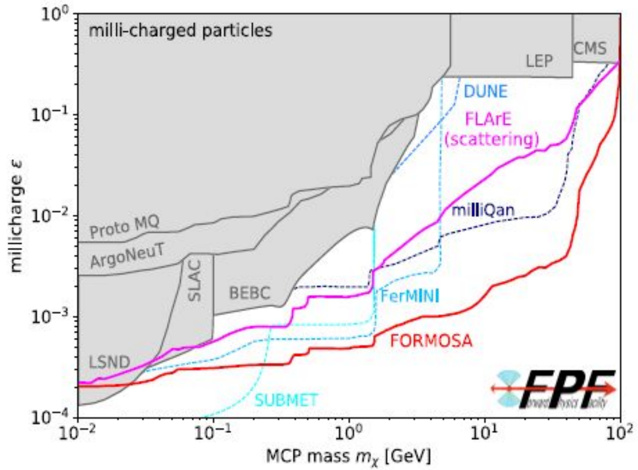
Physics Program: BSM

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. 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.
– FLArE and FASERν2 will extend sensitivity to light dark matter to target sensitivity indicated by relic background for many masses





FPF Community

FPF white paper: 392 authors & endorsers, over 200 institutions (J. Phys. G, 2203.05090)

Seventh FPF workshop held at CERN Feb 29 – Mar 1:

- https://indico.cern.ch/event/1358966/timetable/?view=standard
- 135 people registered, ~50 in person at CERN

Growing community - if you're interested in becoming involved, please talk to us!

FPF Outlook

- Conceptual design work on experiments ongoing.

- Report to Physics Beyond Colliders group (primarily on facility) in progress, will be submitted June 2024.

- LOI planned for early 2025.

- Technically limited timeline:

– Build FPF during Long Shutdown 3 from 2026-28.
– Install support services and experiments starting in 2029.
– Experiments begin taking data during Run 4.

Summary

- The forward region, previously largely neglected, is in fact a treasure trove of interesting physics.

    - Collider neutrinos at TeV energies, QCD, astroparticle physics, and high p_T physics.

    - World-leading searches for light (and also heavy) BSM particles, including many motivated by dark matter.

- The multi-messenger era in collider physics: FASER and SND@LHC have shown that this can be exploited by small, fast, and cheap detectors, producing world-leading, background-free results.

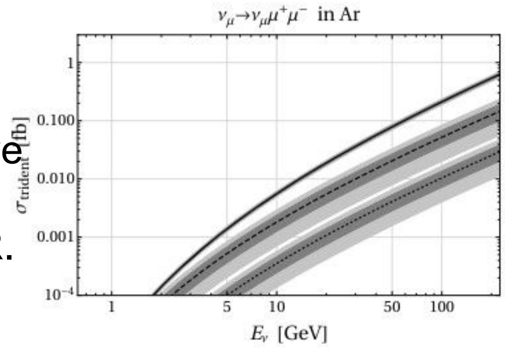
- The Forward Physics Facility is now being considered to fully exploit this new capability for the HL-LHC era from 2028-2042.

- Without the FPF, the LHC will remain blind to this physics.

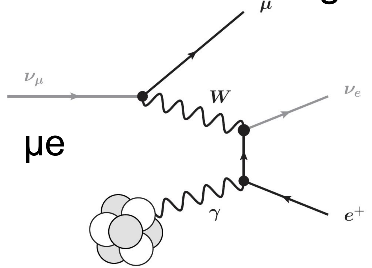
Backup

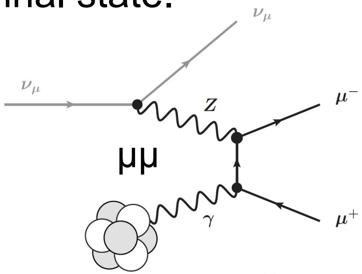
Physics Program – Neutrino Tridents

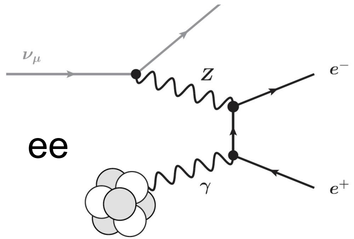
- Neutrino induced production of charged lepton pairs in the presence of a nucleus.
- Mediated by electroweak interactions at tree level and sensitive to new physics.
- Rare process. μ+μ- has evidence from (CHARM-II) and CCFR.
- Various interaction modes possible: the cleanest could be **coherent** scattering to μ+μ- final state.

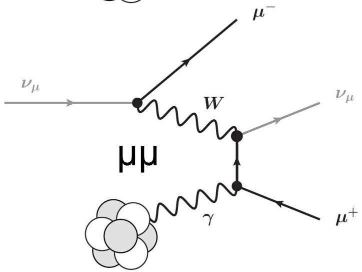


W. Altmannshofer, 1902.06765



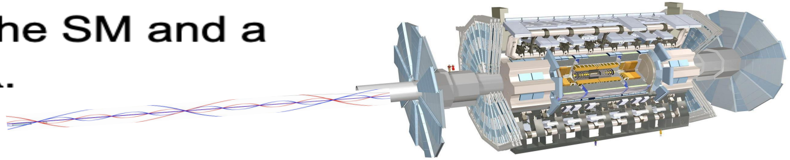




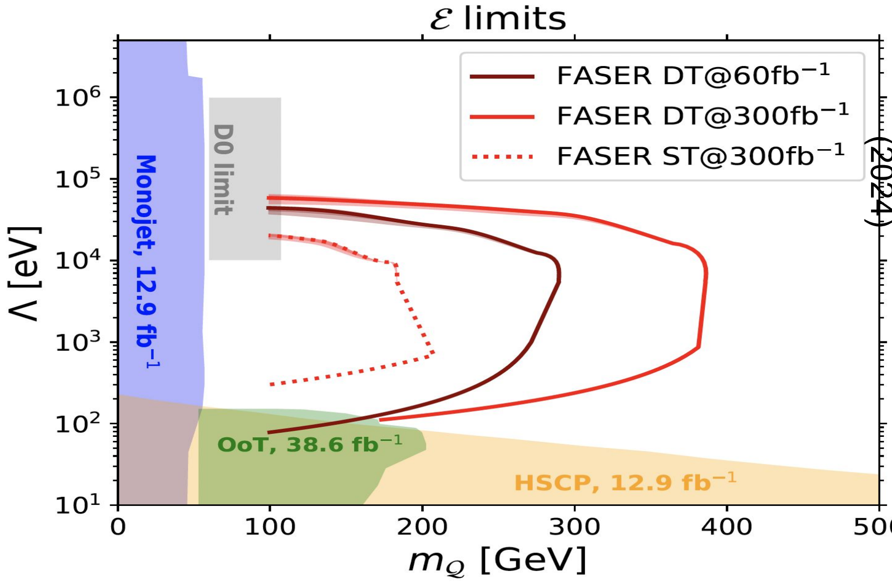


- **Challenge**: small opening angle between the muons
→ likely crucial to go below 100mrad resolution
- If 30 mrad resolution could be achieved, up to ~20-25 events could be detected.
- Neutrino-induced backgrounds:
– CCRES single-pion production (could be rejected based on too soft pions/muons)
– CCDIS associated with charm (could be rejected based on non-purely leptonic nature)

QUIRKS: STRONGLY-INTERACTING DARK SECTORS



- Quirks are particles charged under both the SM and a strong-interacting dark force, with $m \gg \Lambda$.
- Quirks can be pair-produced at the LHC, but the quirk-anti-quirk pair is bound together and has $p_T \approx 0$. They therefore preferentially travel down the beampipe, and may pass through FPF detectors.
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FASER and FASER2 can discover quirks with masses up to ~ hundreds of GeV to TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.



Feng, Li, Liao, Ni, Pei (2024)