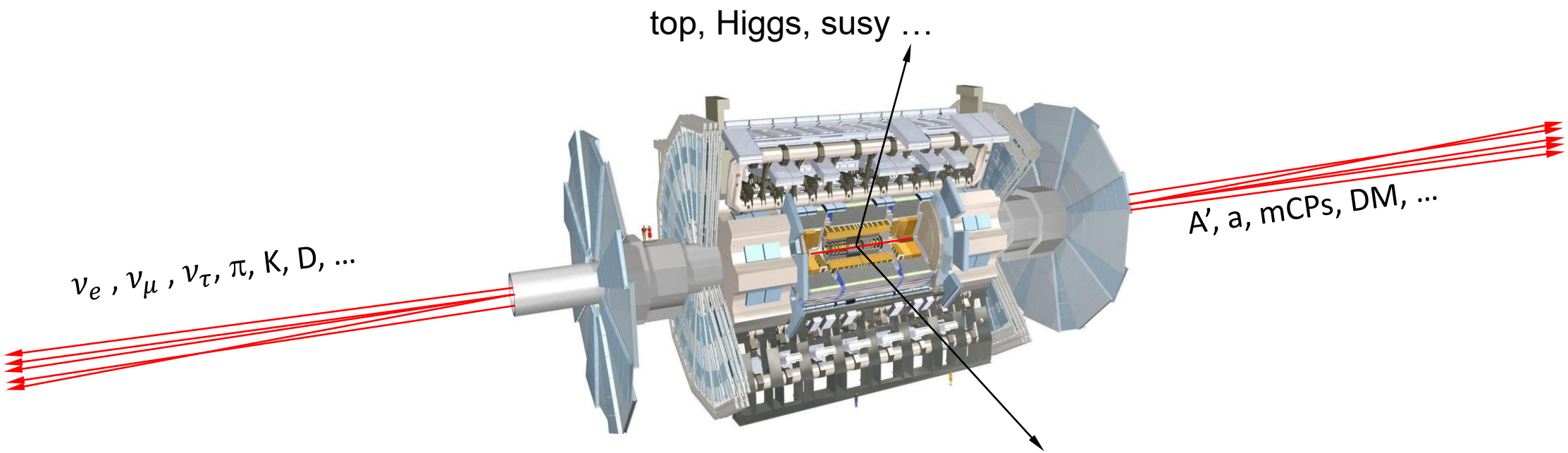
Forward Neutrinos

Using collider neutrino beams for science

Alan Barr

With thanks to colleagues in the FASER, SND and FPF collaborations

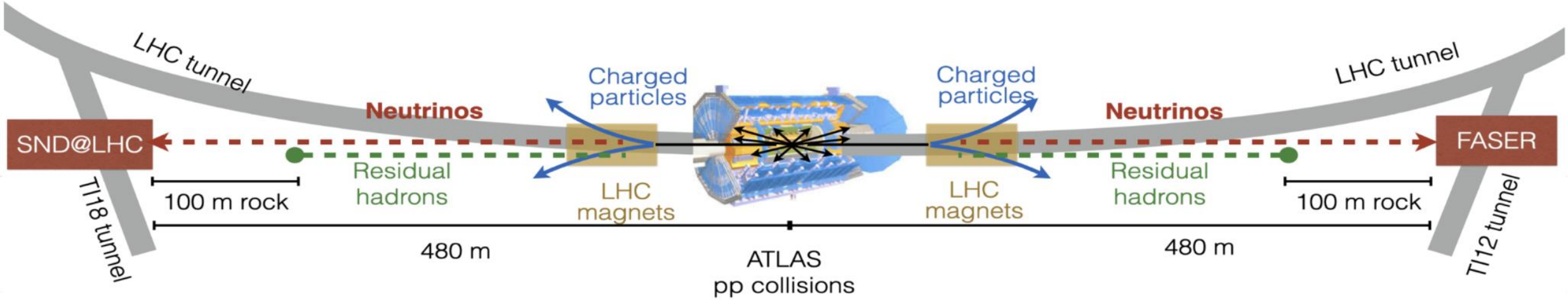
Hadron decays lead **to intense columnated beams** of neutrinos (and BSM particles…?)



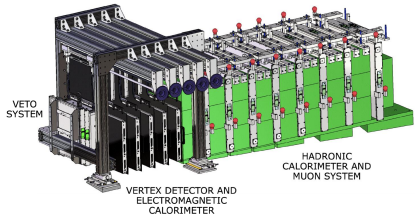
Highest-energy neutrinos produced from laboratory source

1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle (η > 9.2)

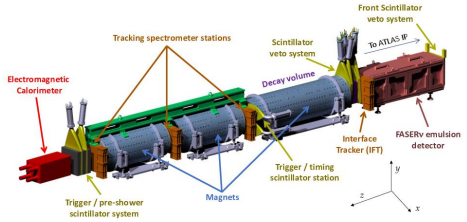
First detectors at the LHC



Scattering and **N**eutrino **D**etector @LHC

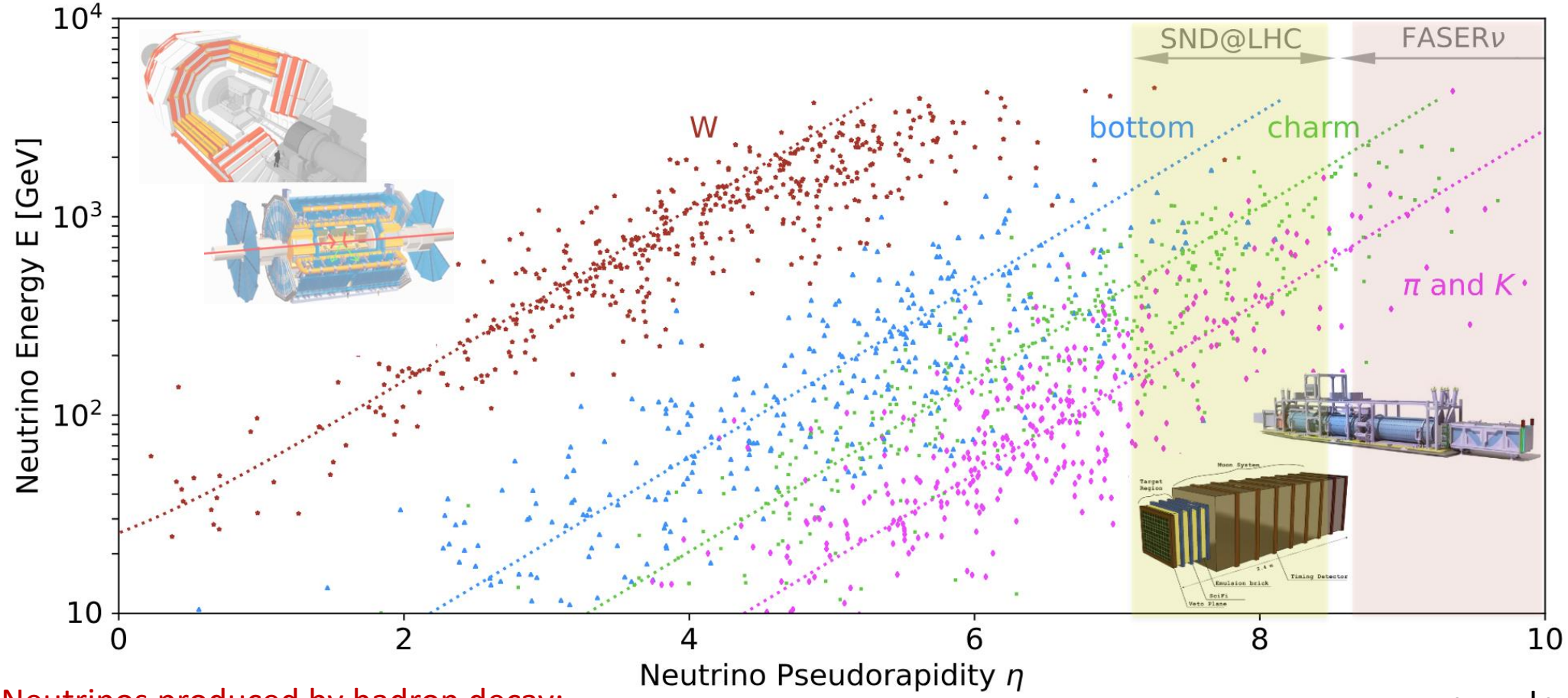


Forw**A**rd **S**earch **E**xpe**R**iment



adapted from
PRD 104 (2021) 113005

Neutrino sources

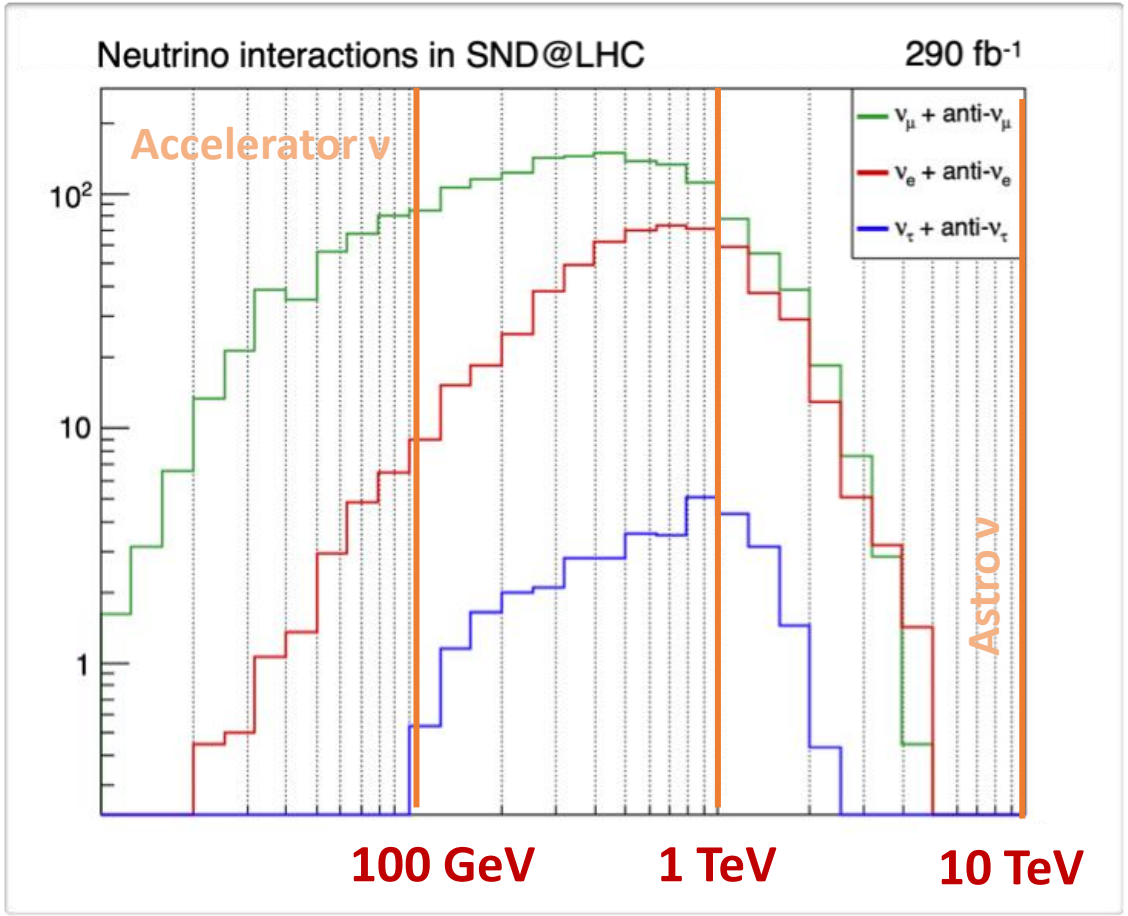


$\eta = -\ln \tan \theta/2$

Neutrinos produced by hadron decay:

- ν_e: mostly from kaon decay and at high energy from charm
- ν_μ: mostly from pion decay, at high energy kaons
- ν_τ: from charm (some B)

Neutrino energies



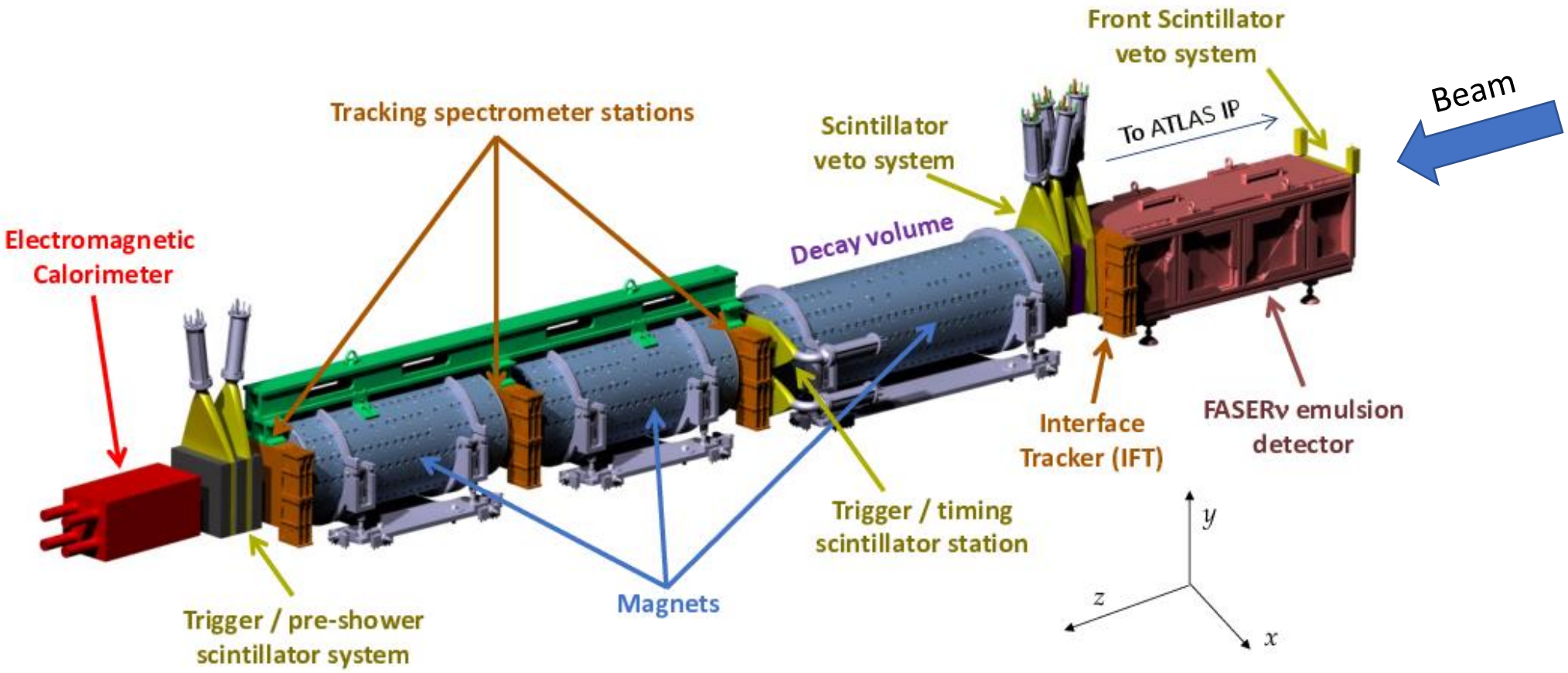
Interactions for different neutrino flavours (SND)

In **LHC Run 3** FASER2 expects:

- **~1700 ν_e** interactions
- **~8500 ν_μ** interactions
- **~30 ν_τ** interactions

FASER Detector

arxiv: 2207.11427



10cm radius of active region of detector (<0.2 mrad, η > 9.2)
1.5m long decay volume
2.5m long tracking spectrometer (0.6T dipole field)

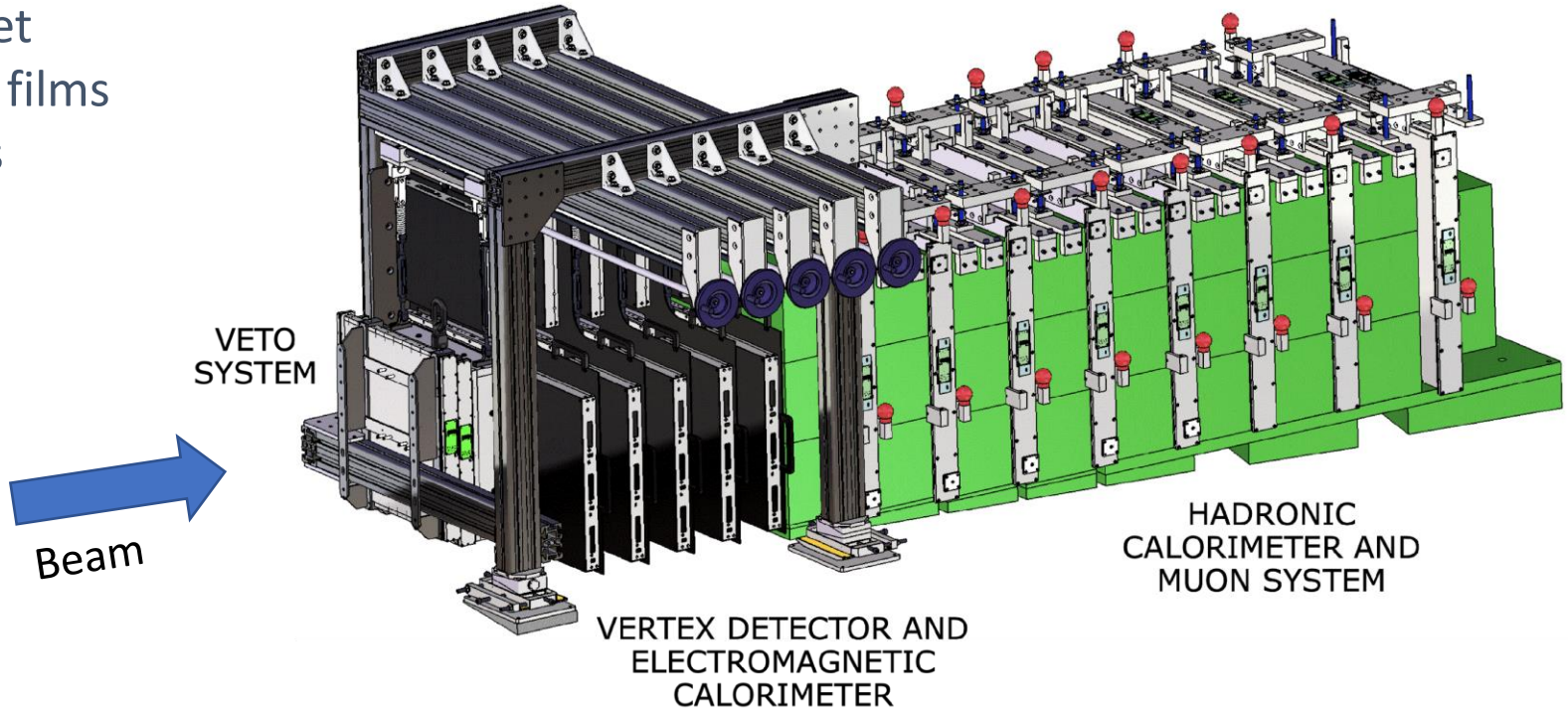
SND@LHC detector

Veto system
2 (2022–2023) / 3 (2024–) scintillator planes

Target, vertex detector and ECAL
830 kg tungsten instrumented target
5 walls x 59 layers = 1200 emulsion films
+ 5 scintillating-fibre (SciFi) stations
84 X_0, 3 λ_{int}

HCAL and muon system
Eight 20 cm Fe blocks
+ scintillator planes
Last 3 planes have finer granularity to track muons
9.5 λ_{int}

Off-axis location: 7.2 < η < 8.4
enhances ν flux from **charm**



arXiv:2210.02784

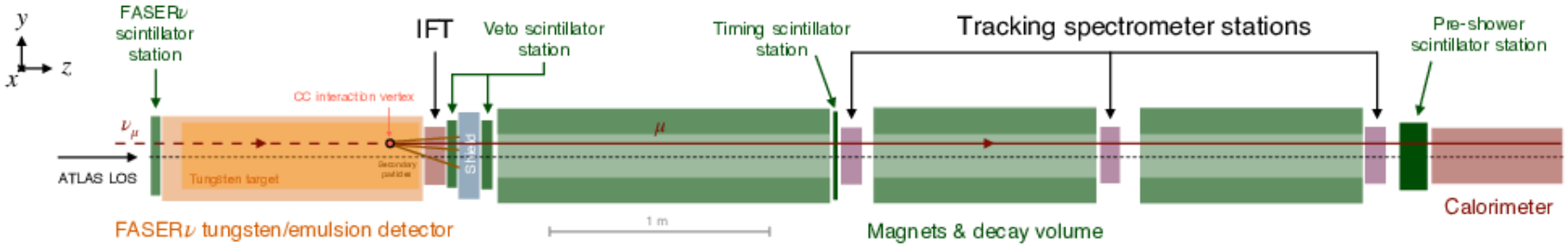
SND@LHC

FASER

Observations of Collider Neutrinos

Phys. Rev. Lett. 131 no. 3, (2023) 031801
2303.14185

First observation of collider Neutrinos



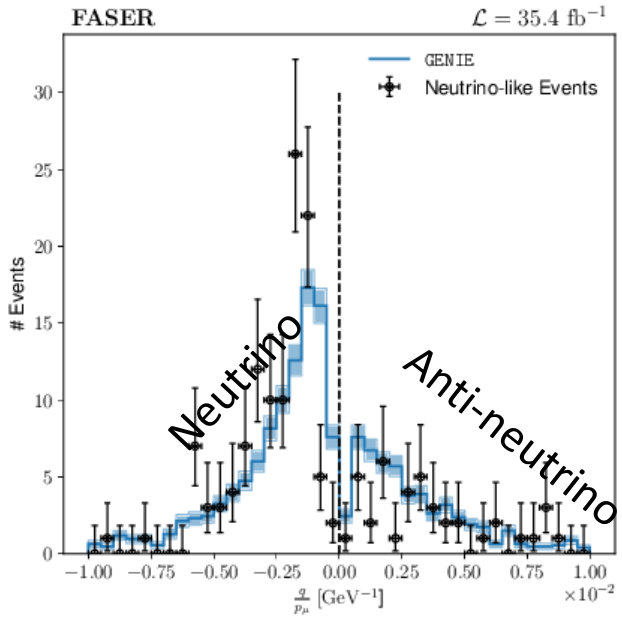
Using **2022** dataset (35/fb). Only for **ν_μ CC**.

Simple/robust event selection:

- No signal in front veto scintillators
- Reconstructed charged particle track
  - **P > 100GeV**
  - Within central region of scintillators when extrapolated to the veto

Backgrounds considered:

- Scintillator inefficiency
- Large angle muons that miss the veto
- Neutral hadrons produced by upstream muon interactions in rock
- Basically background free

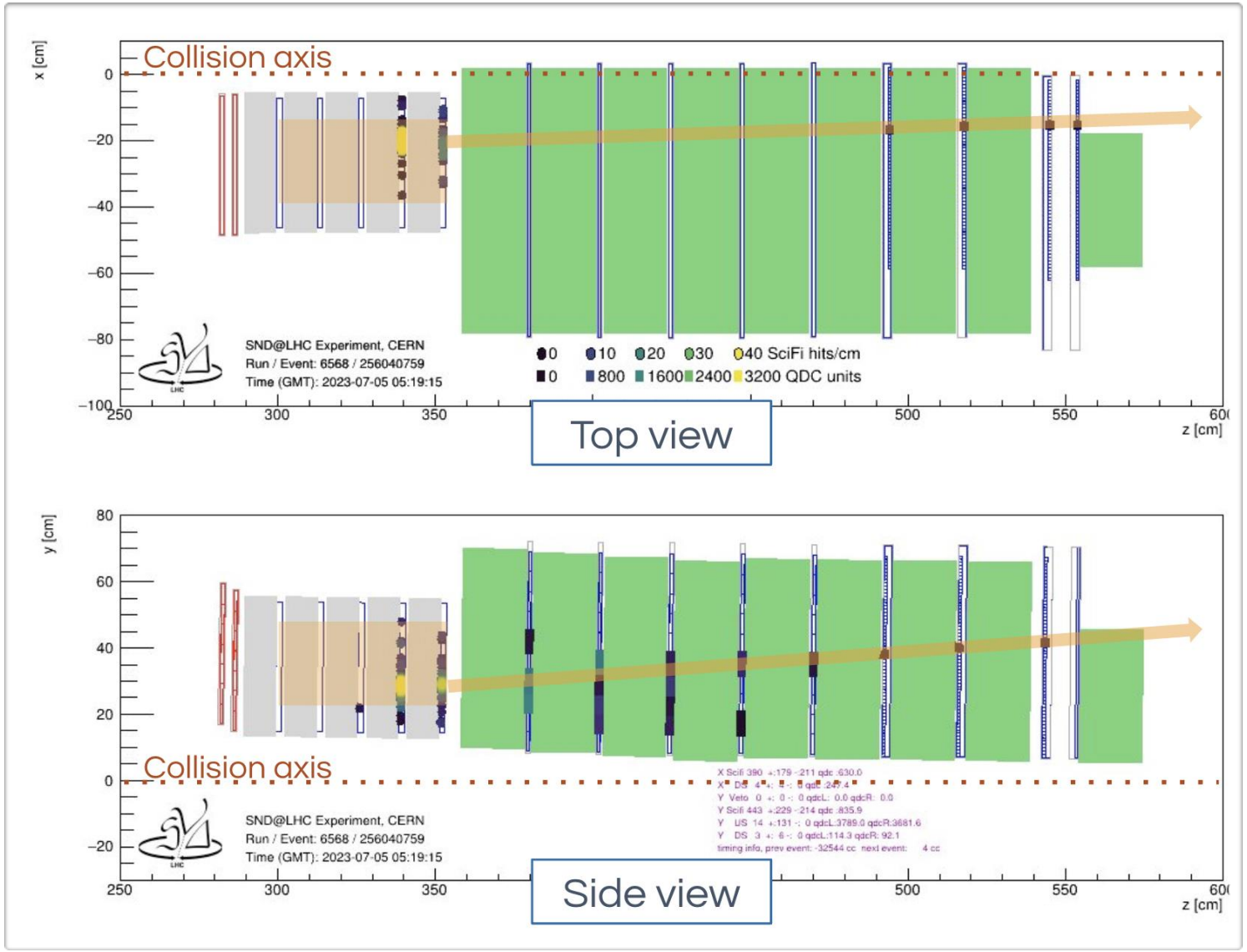


Observe 150 events

(expected neutrino signal 151+/-41)

PRL 131 (2023) 031802

Display of a ν_μ CC candidate event at SND@LHC



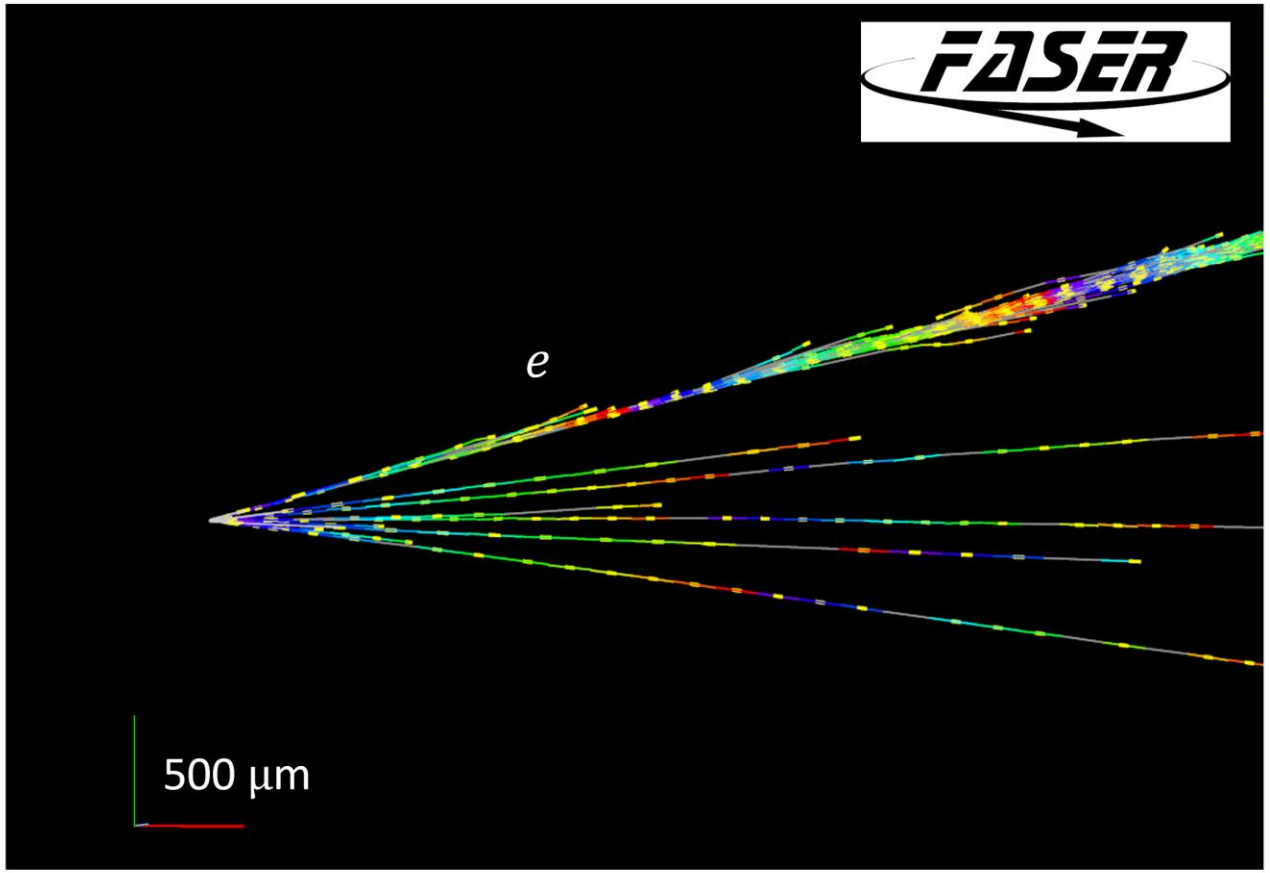
Uses data from the electronic detectors

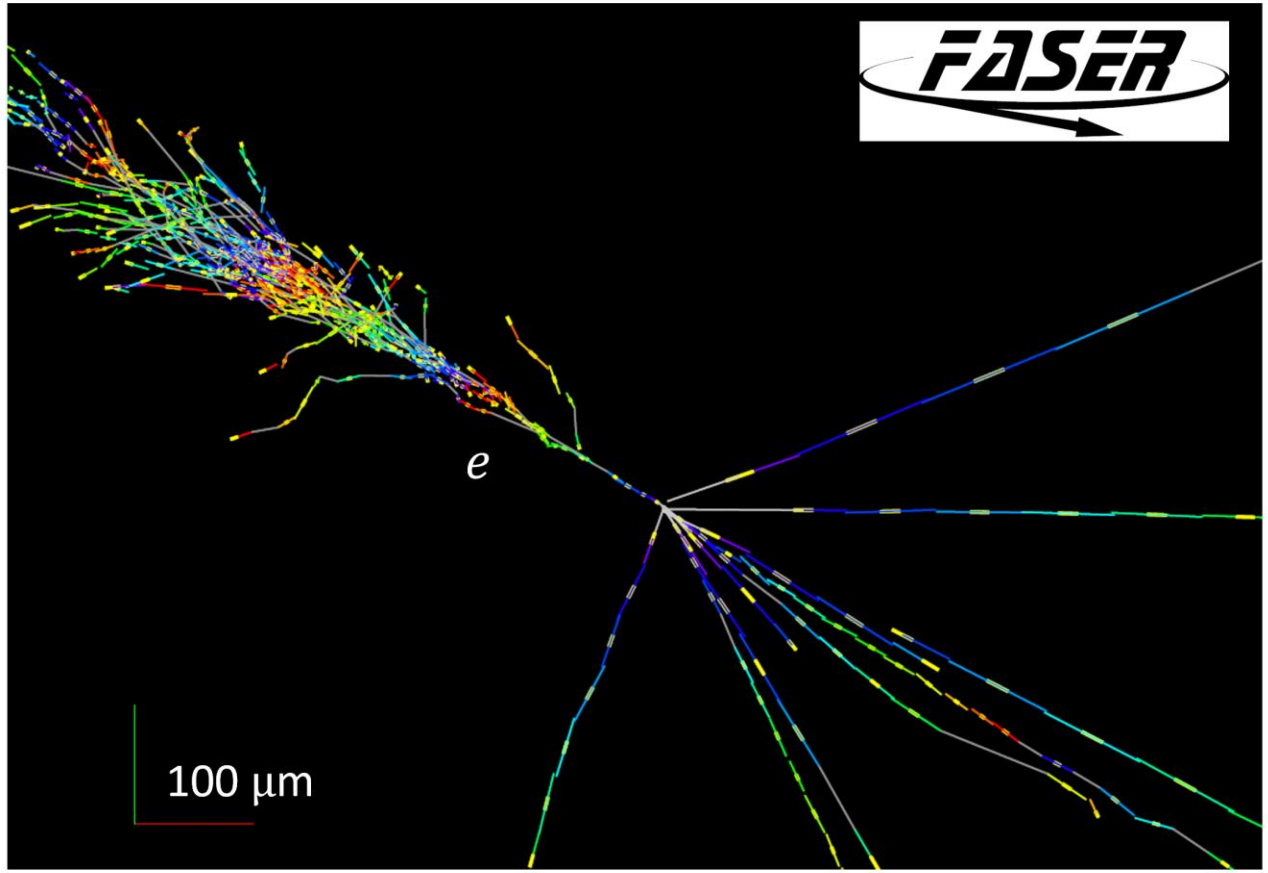
8 ν_μ interaction candidate events
Background: 0.086 events,
Significance of about 7σ

First FASERν measurements

Phys. Rev. Lett. **133**, 021802
arxiv: 2403.12520

Electron neutrino candidate (electron energy estimated at 1.5 TeV)





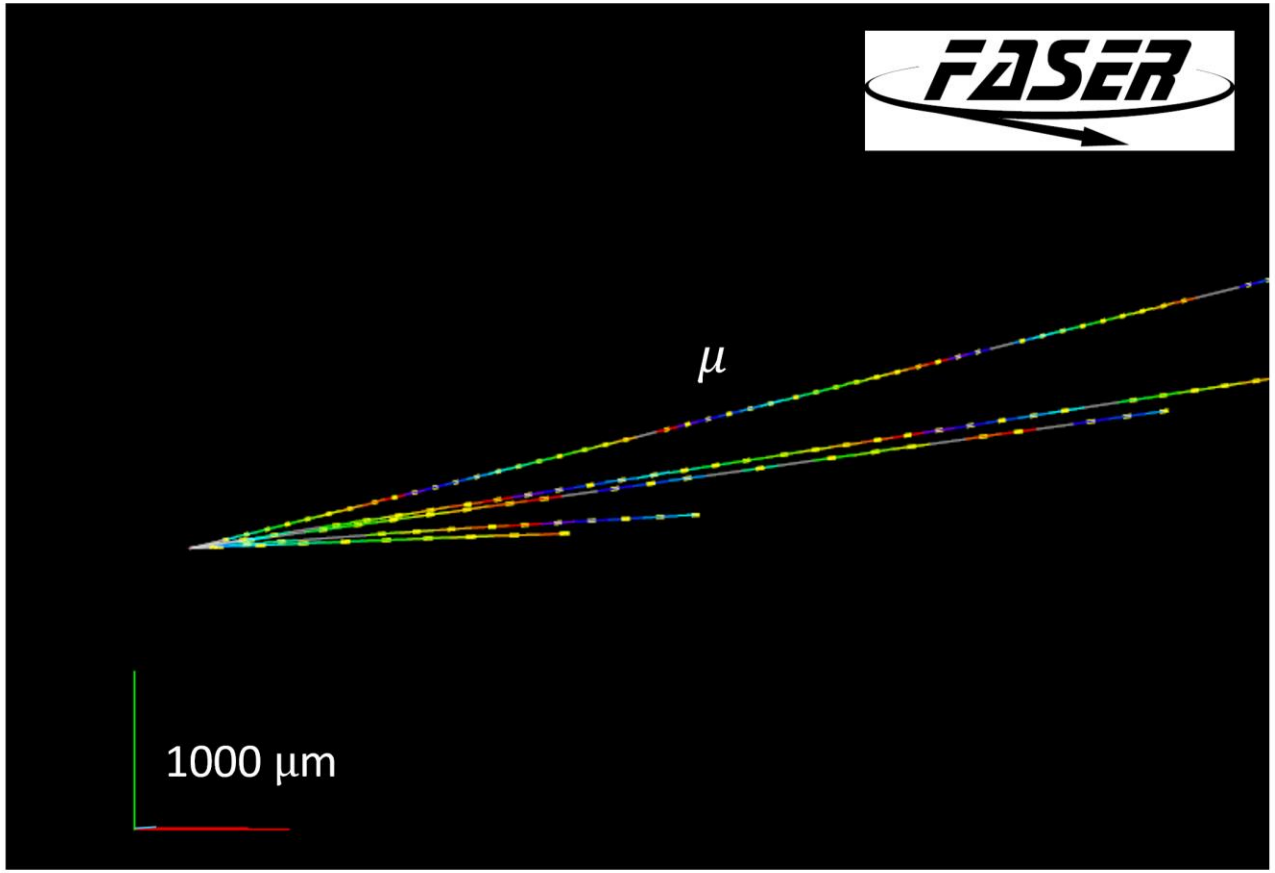
	Background	Expected	Observed	Significance
$\nu_e CC$	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	4	5.2σ

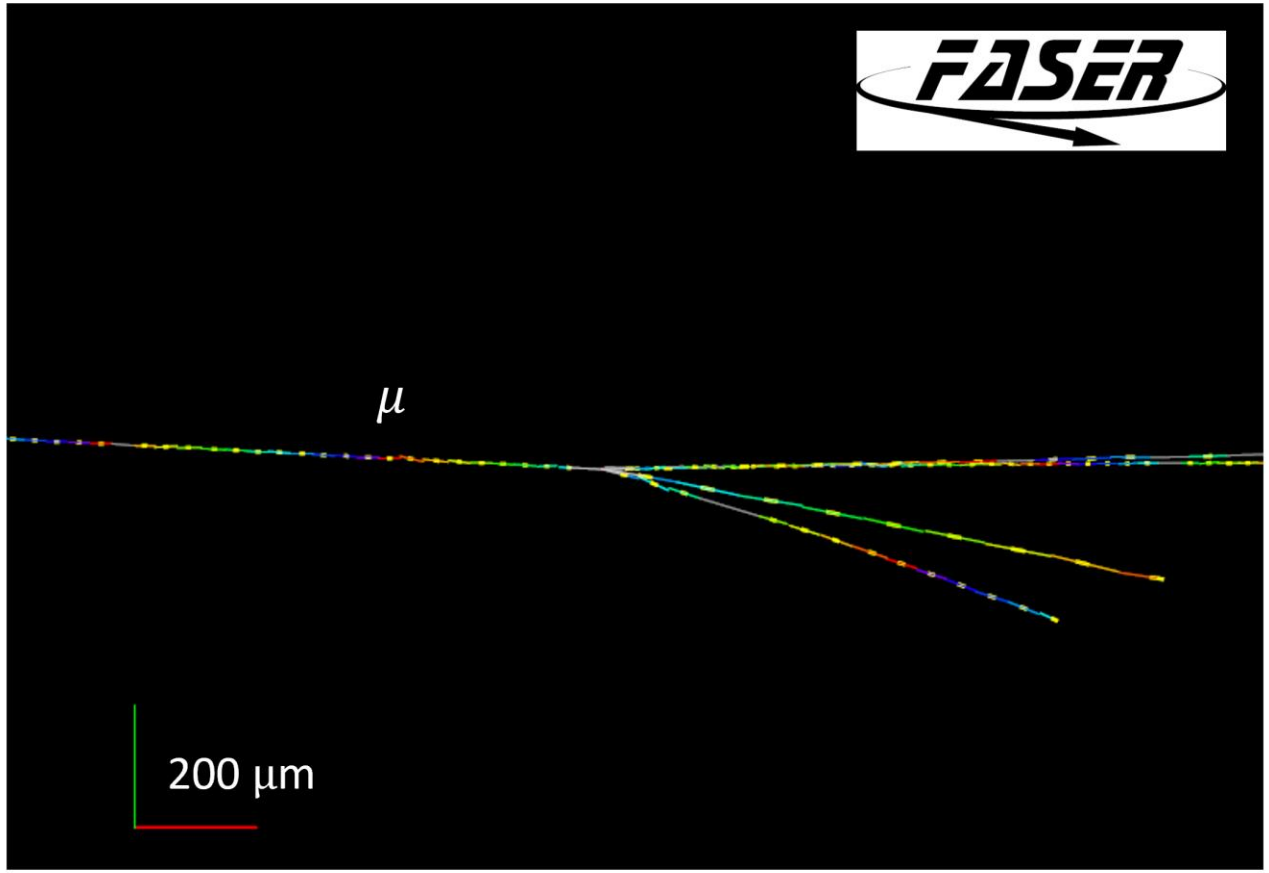
First observation of electron neutrinos produced at a collider

First FASERν measurements

Phys. Rev. Lett. **133**, 021802
arxiv: 2403.12520

Muon neutrino candidate (muon energy estimated at 860 GeV)

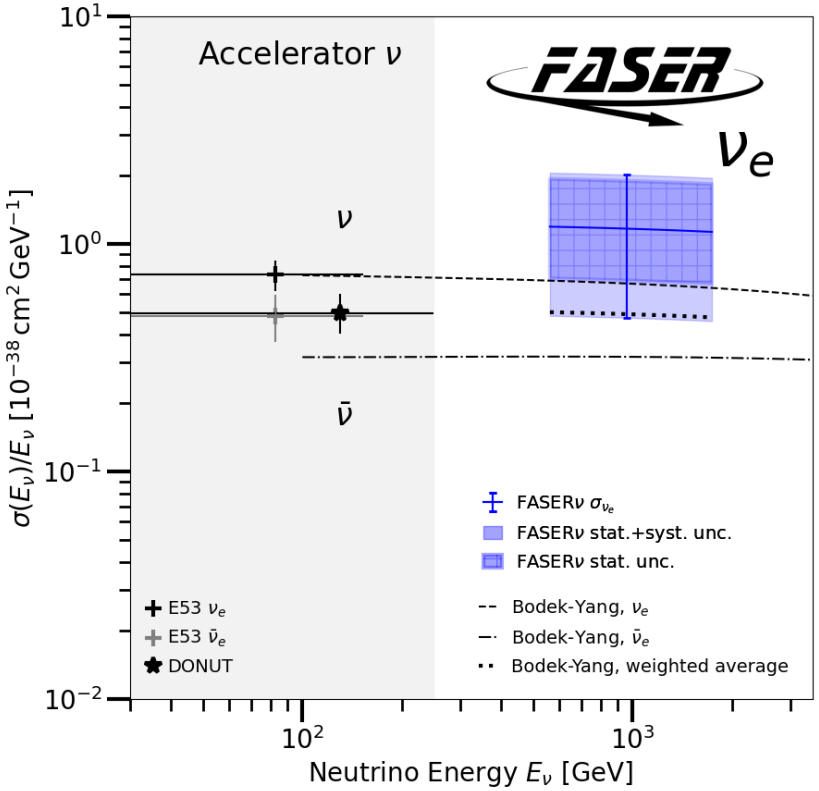


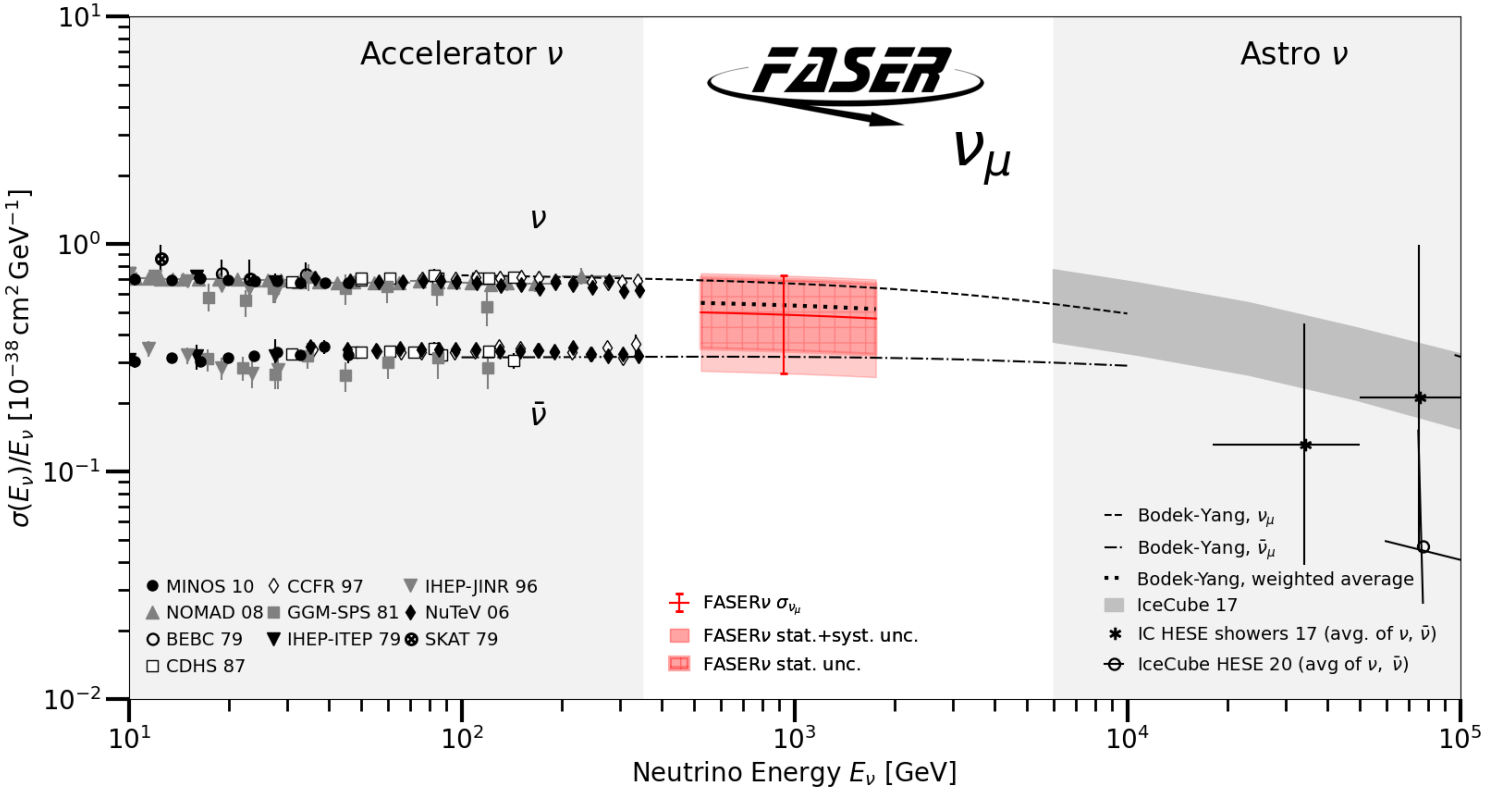


	Background	Expected	Observed	Significance
$\nu_\mu CC$	$0.22^{+0.09}_{-0.07}$	$6.5 - 12.4$	8	5.7σ

First FASERν measurements

Phys. Rev. Lett. **133**, 021802
arxiv: 2403.12520





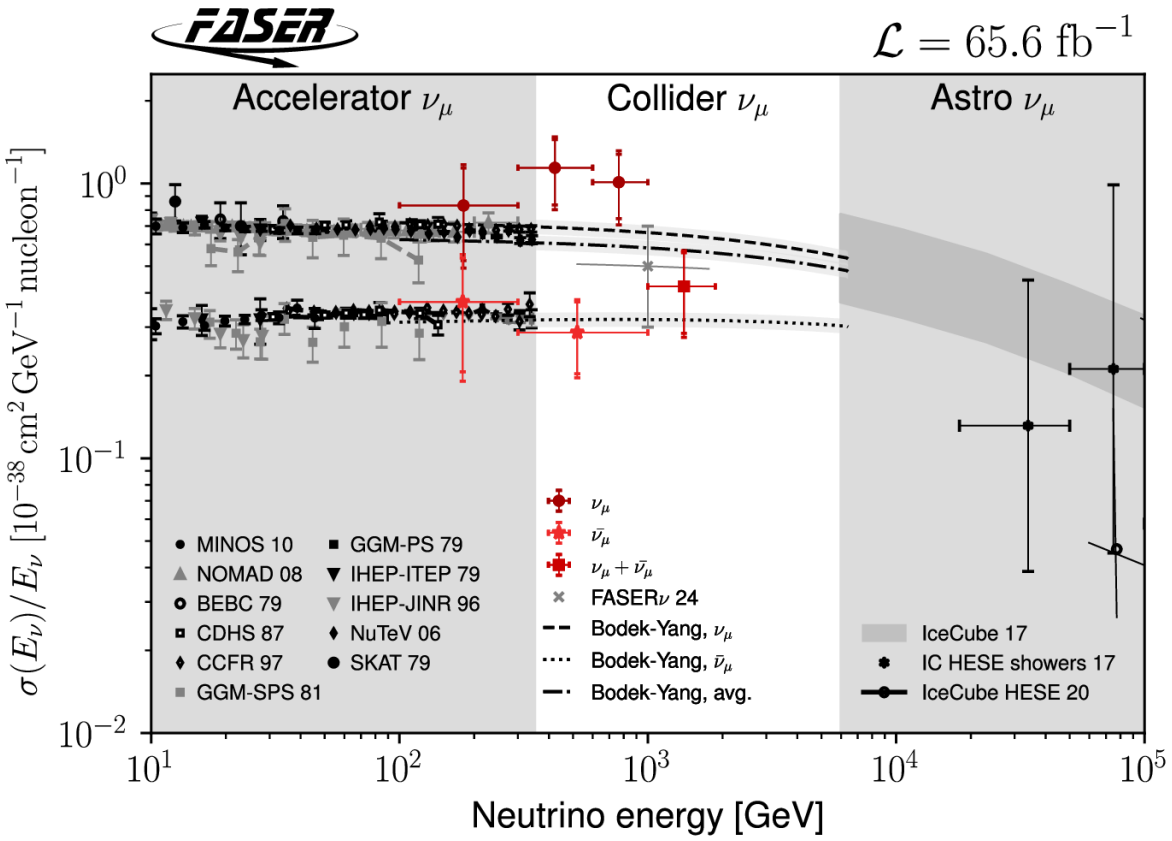
First neutrino interaction cross section measurements in this energy regime
Relative measurement with respect to theoretical curve (from GENIE)
Using only 2% of FASERν data already collected

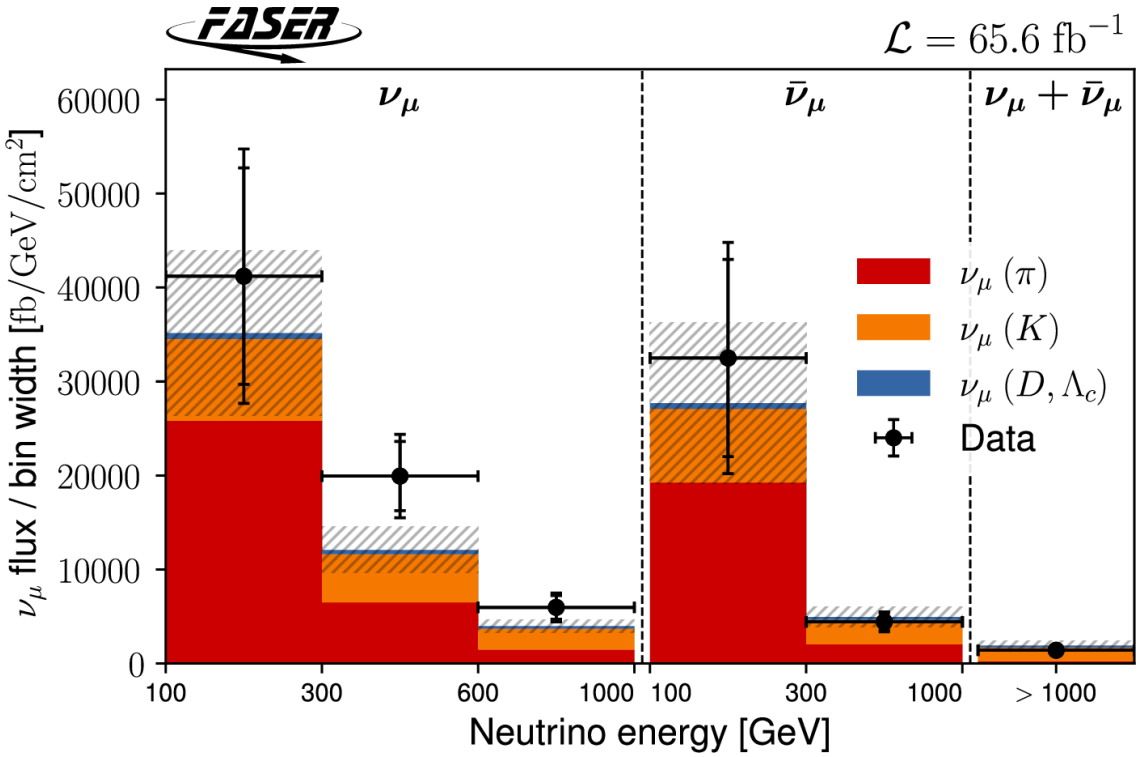
arXiv:2412.03186

First differential measurements

Result interpreted in 2 ways:

- Assume neutrino flux, and measure cross section
- Assume theoretical cross section and measure the neutrino flux

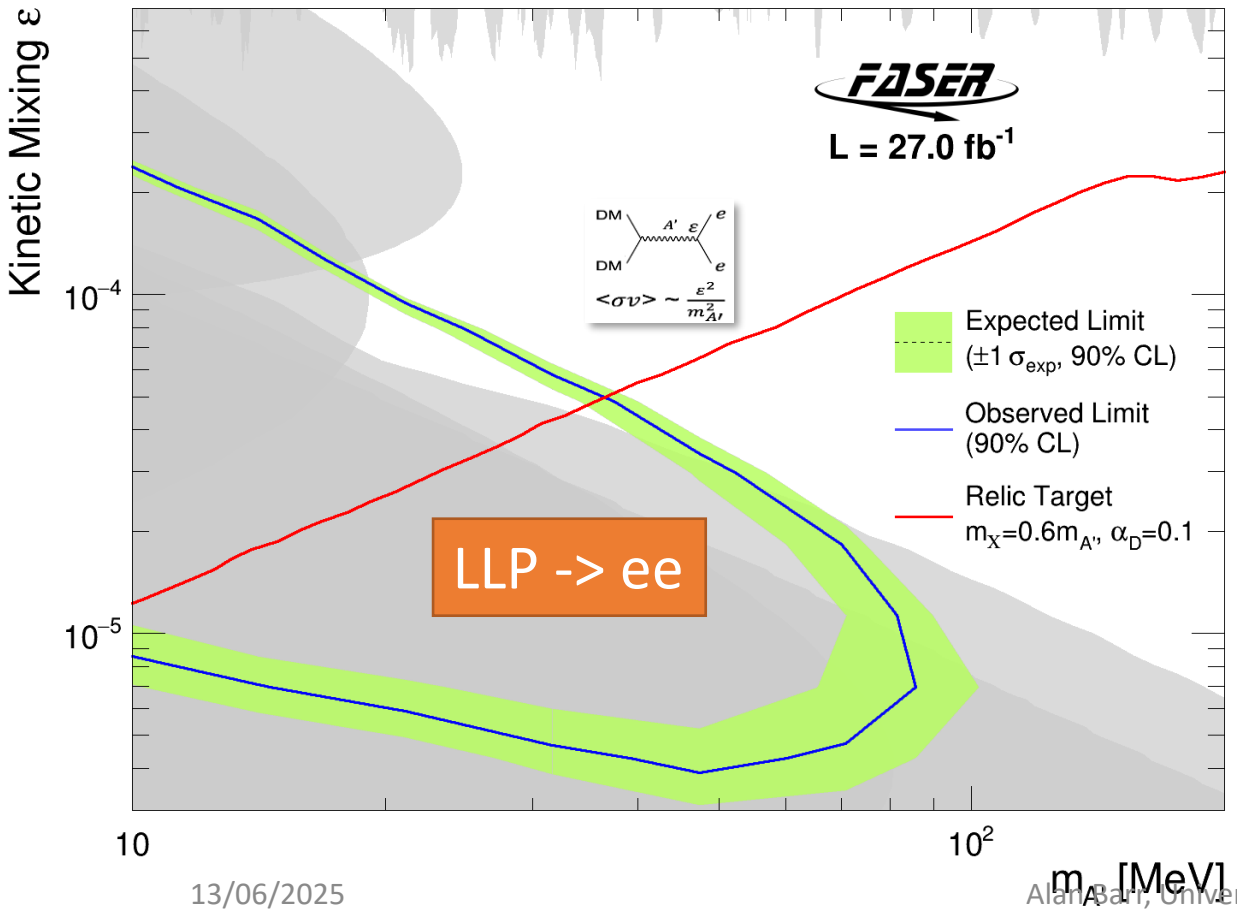




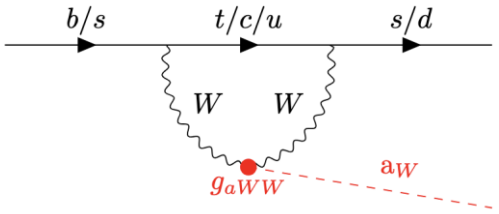
Strong BSM search programme

arxiv:2308.05587
PLB, 848, 138378, 2024

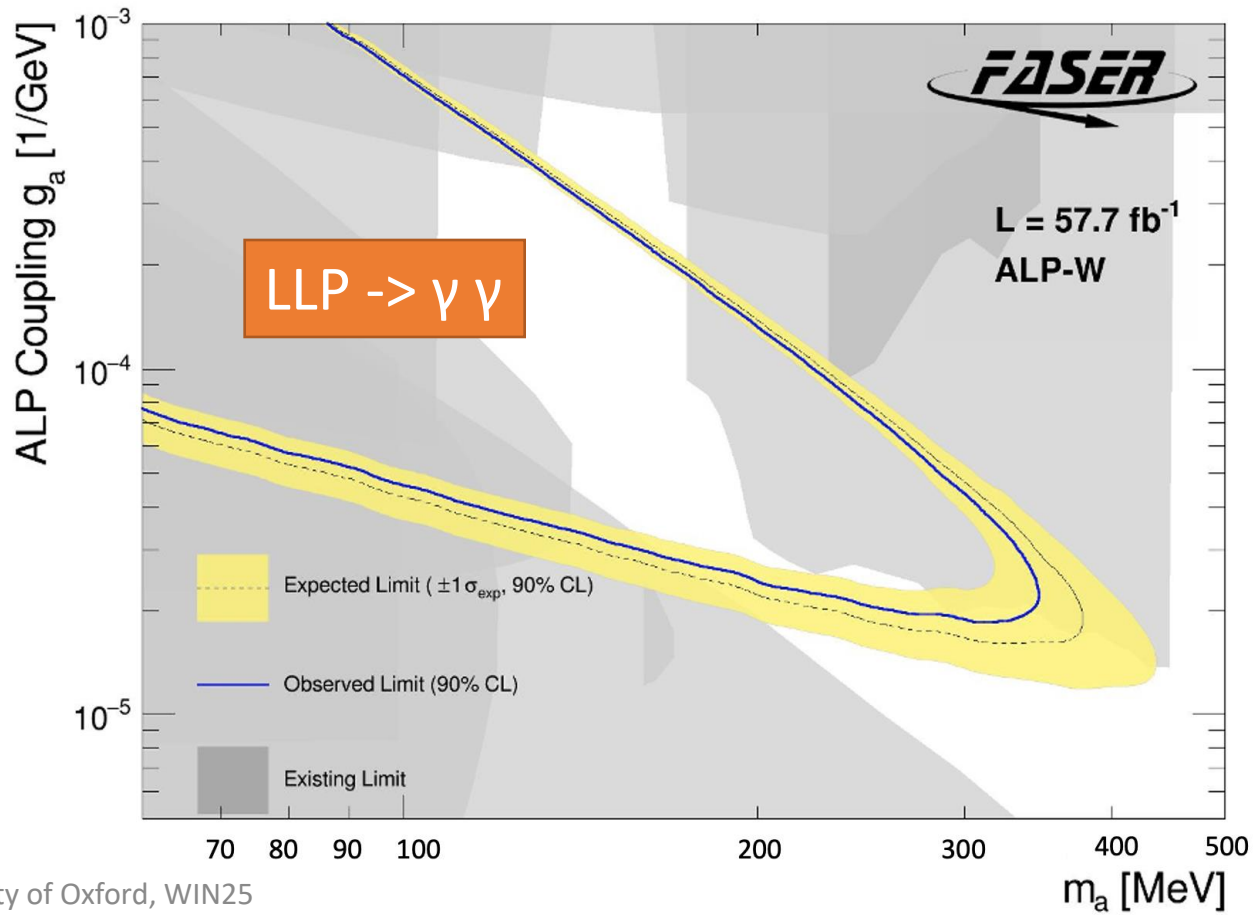
Dark Photons

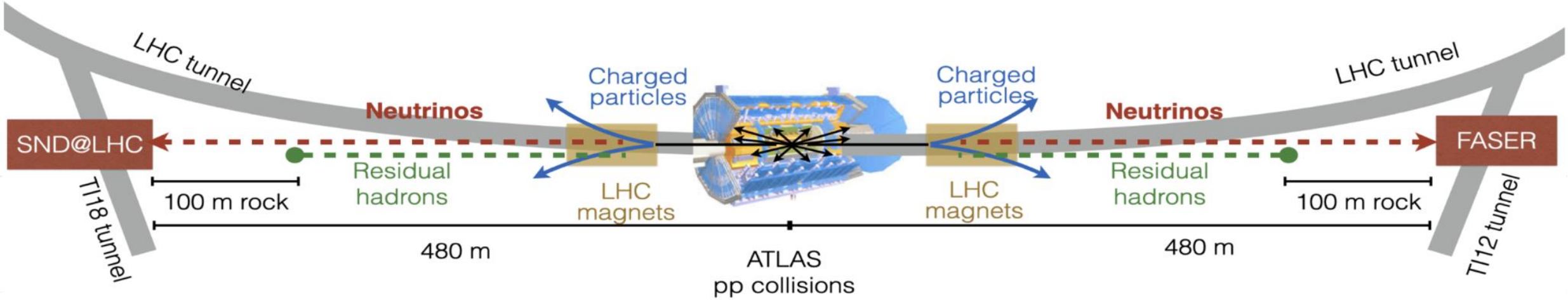


arXiv:2410.10363
JHEP, 2025, 199 (2025)



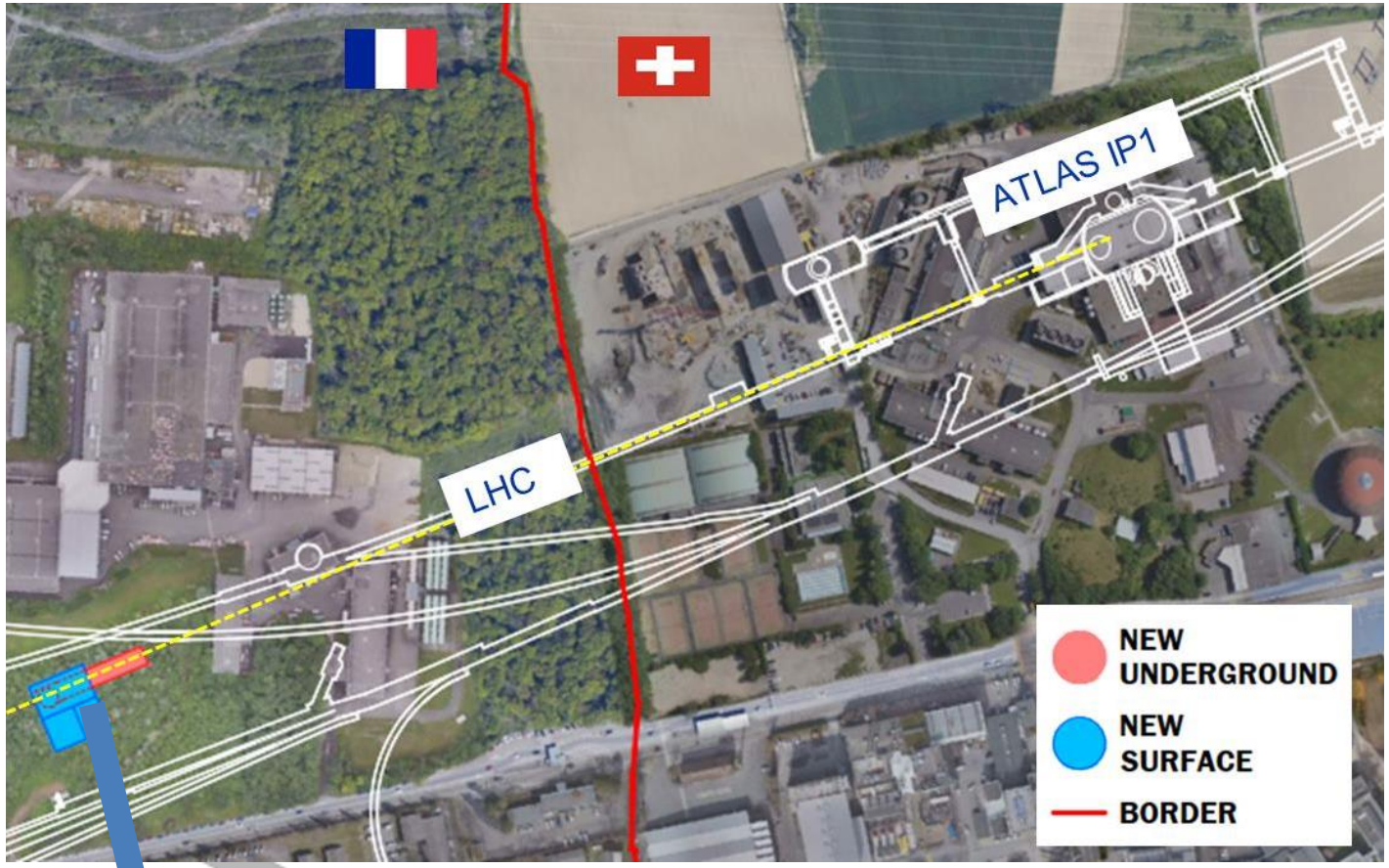
Axion-Like-Particles




LHC tunnel
Neutrinos
Charged particles
Charged particles
Neutrinos
LHC tunnel
SND@LHC
FASER
Residual hadrons
Residual hadrons
100 m rock
100 m rock
LHC magnets
LHC magnets
TI18 tunnel
TI12 tunnel
480 m
480 m
ATLAS
pp collisions

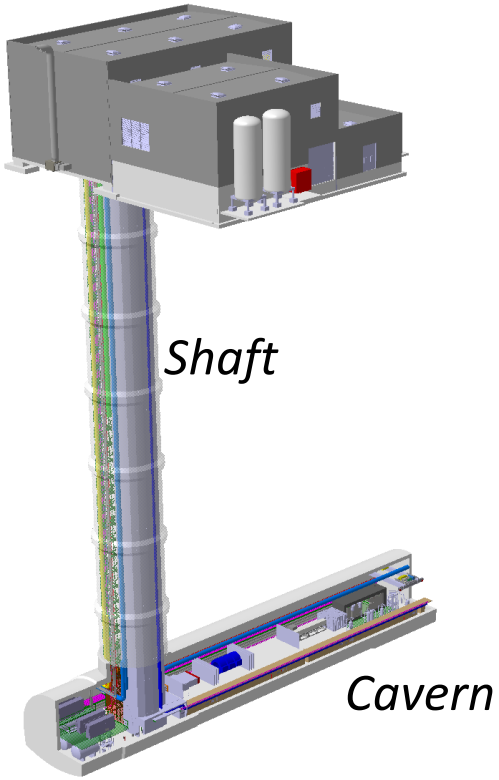
The Forward Physics Facility

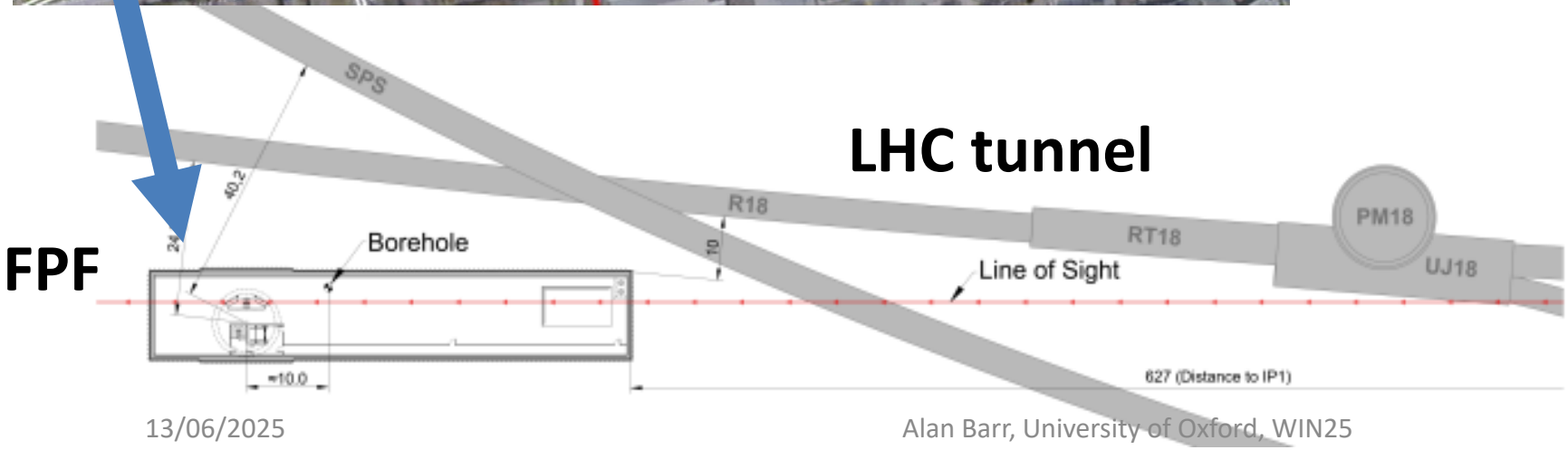
FPF working group under CERN/PBC



Site selection:
627m from ATLAS IP1
90m deep; 75m long; 21m wide
10m away from LHC tunnel
Shielding > 200m rock/concrete

Surface buildings

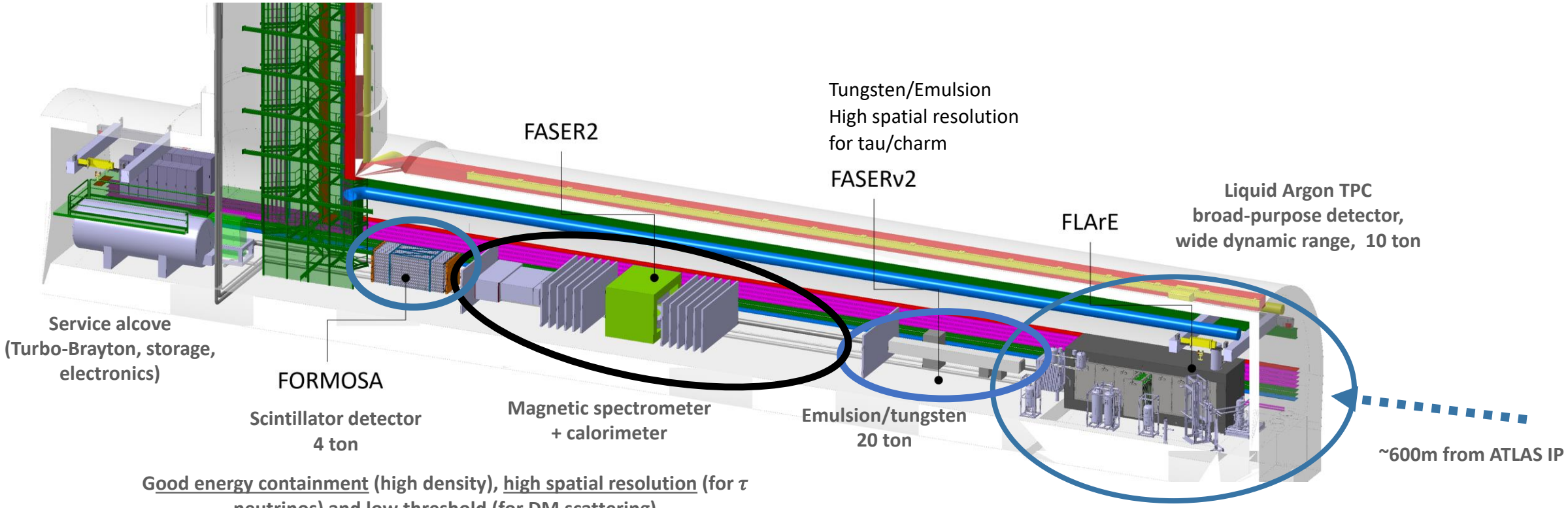




FPF: Complementary technologies

Baseline design

Complementary technologies & capabilities maximise scientific reach



Good energy containment (high density), high spatial resolution (for τ neutrinos) and low threshold (for DM scattering)

FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$

Scientific case

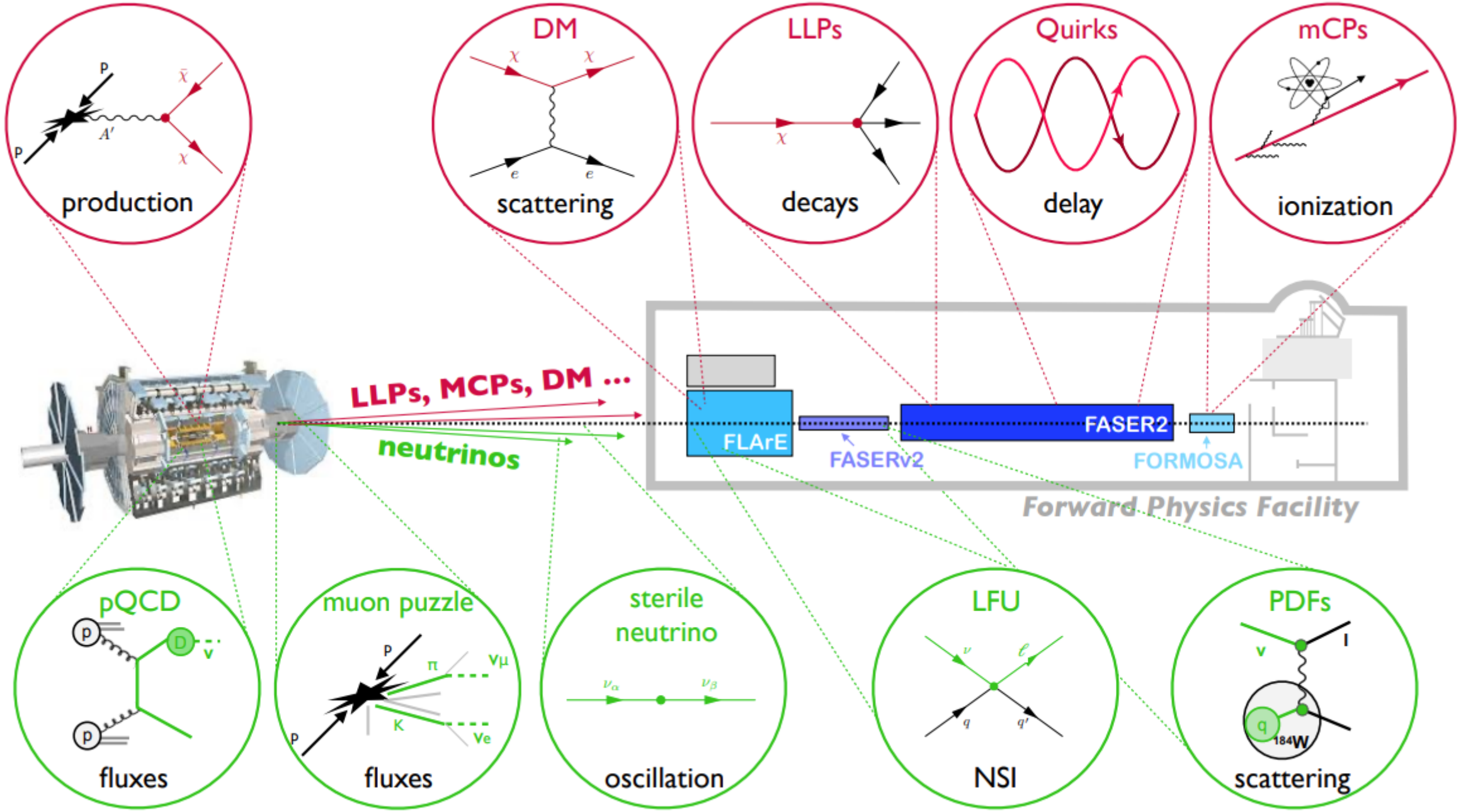
Expected data set ~10^6 ν_μ~ 10^5 ν_e and ~10^4 ν_τ interactions from HL-LHC

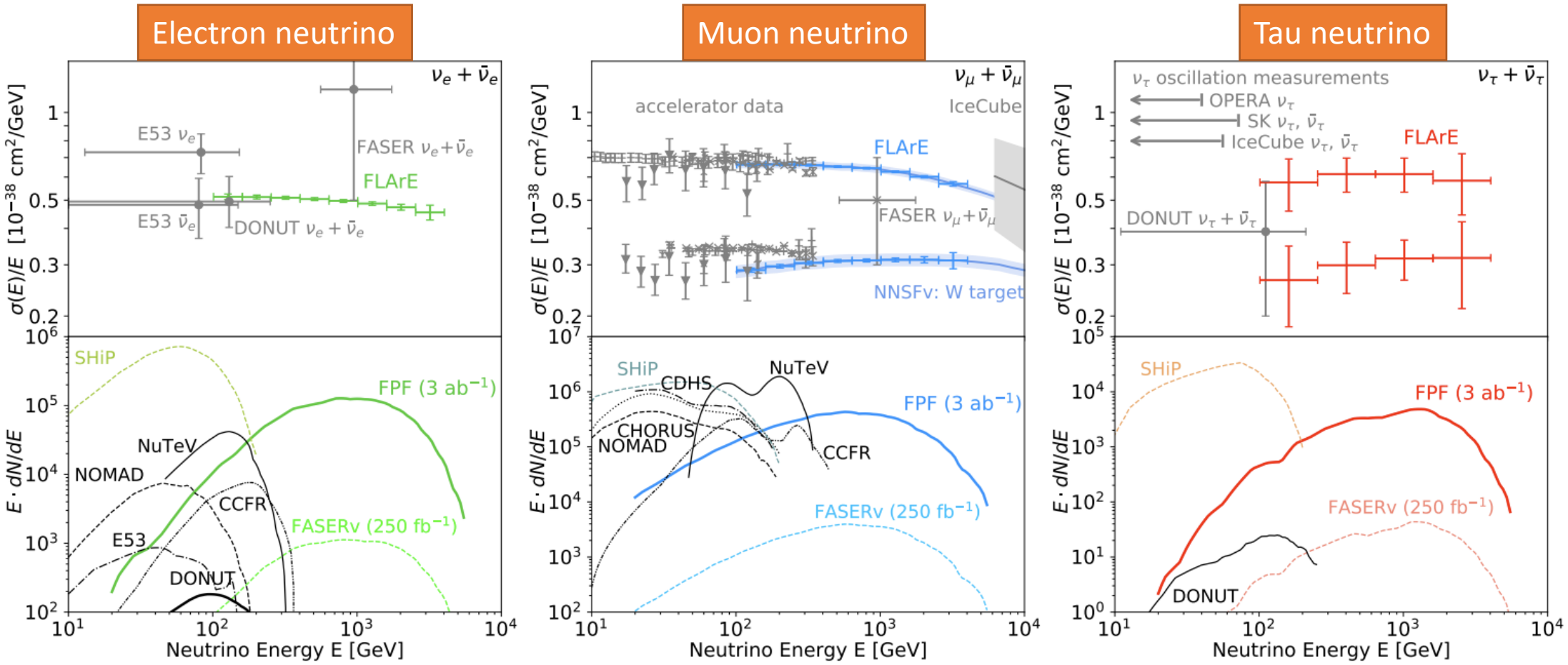
- **x 100** compared to estimates for the current program with FASER/FASERnu and SND@LHC

Unique impact on **HL-LHC discovery potential**, **QCD**, **astrophysics**, and **neutrino physics**

Broad program for **discovery science or BSM physics**, and rare phenomena

- Search **for dark sector** decays to SM particles: dark photons, dark higgs, heavy neutral leptons, axion-like particles
- **Unique sensitivity** to inelastic dark matter. Decays of dark matter into lighter DM and SM particles
- DM **scattering** with electrons or nuclei
- **Millicharged particles**


production
DM
scattering
LLPs
decays
Quirks
delay
mCPs
ionization
LLPs, MCPs, DM ...
neutrinos
FLArE
FASERν2
FASER2
FORMOSA
Forward Physics Facility
pQCD
fluxes
muon puzzle
fluxes
sterile neutrino
oscillation
LFU
NSI
PDFs
scattering

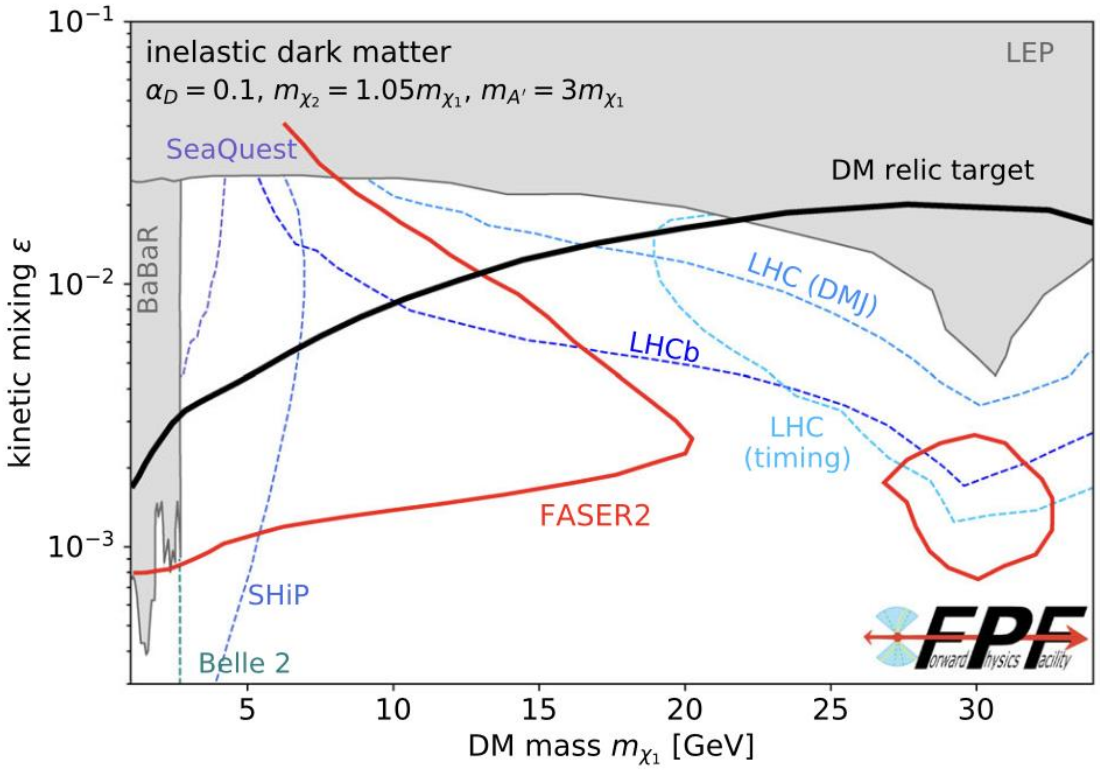


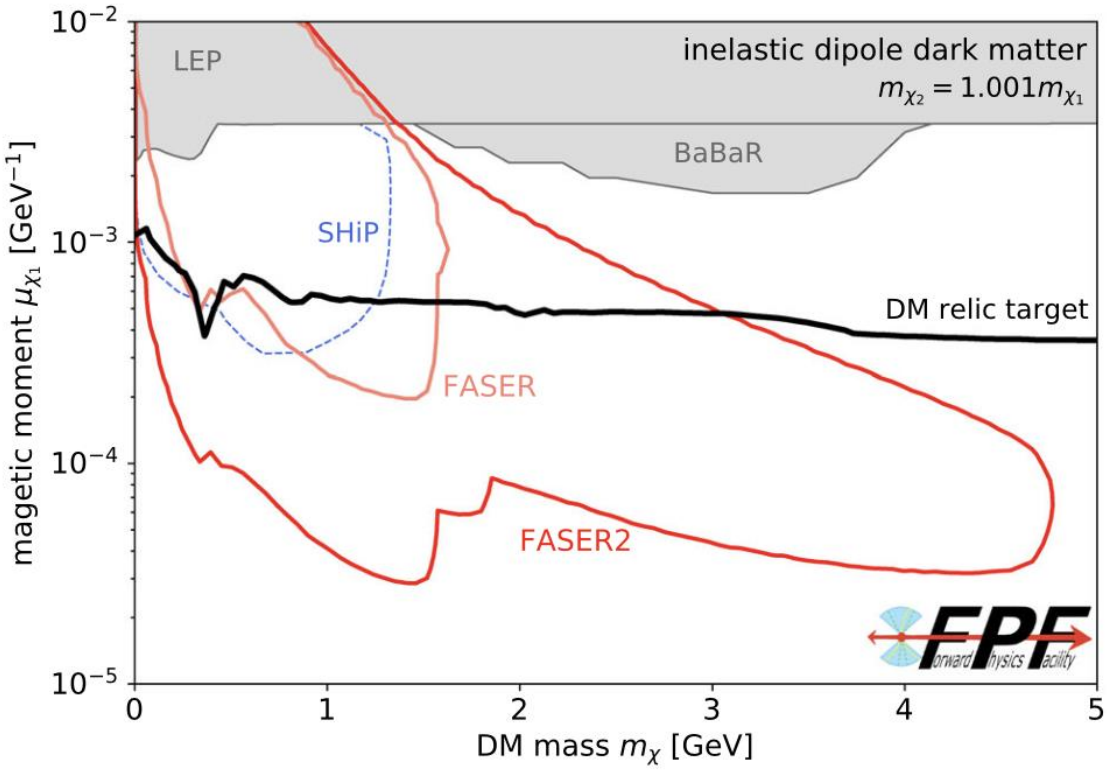
FPF experiments have potential to detect:
O(**10^6**) muon neutrinos, O(**10^5**) electron neutrinos, O(**10^4**) tau neutrinos

➔ Flavour universality, non-standard interactions, neutrino tridents, sterile neutrinos, …

Dark sector searches

Unique FPF sensitivity



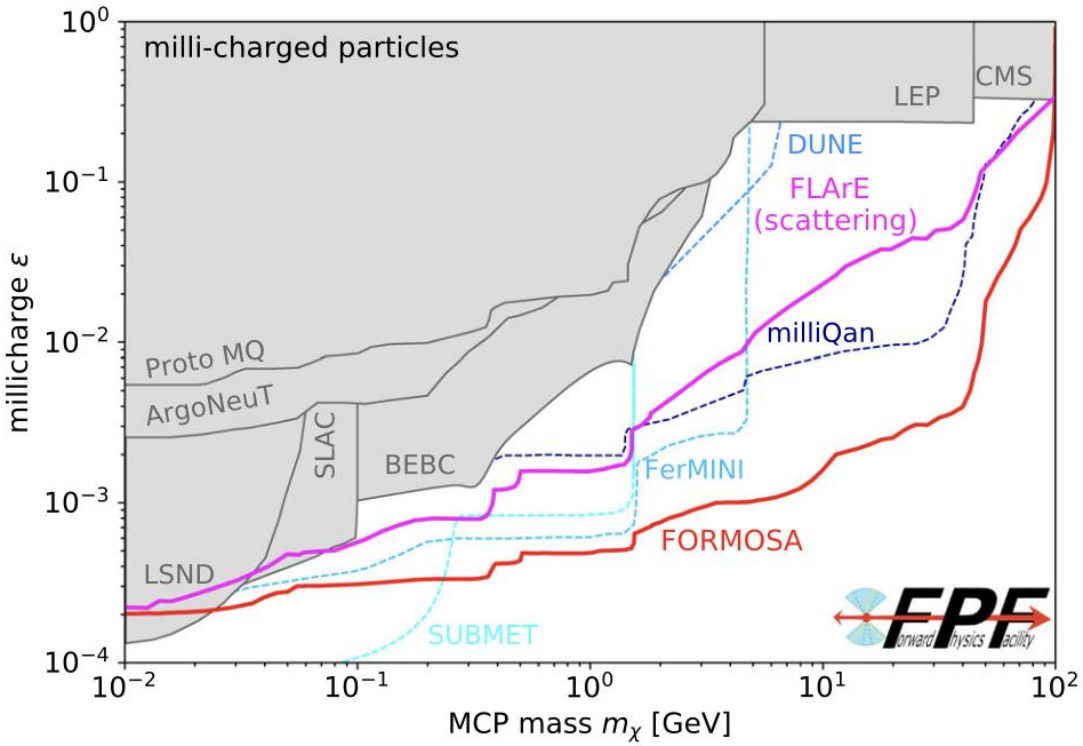


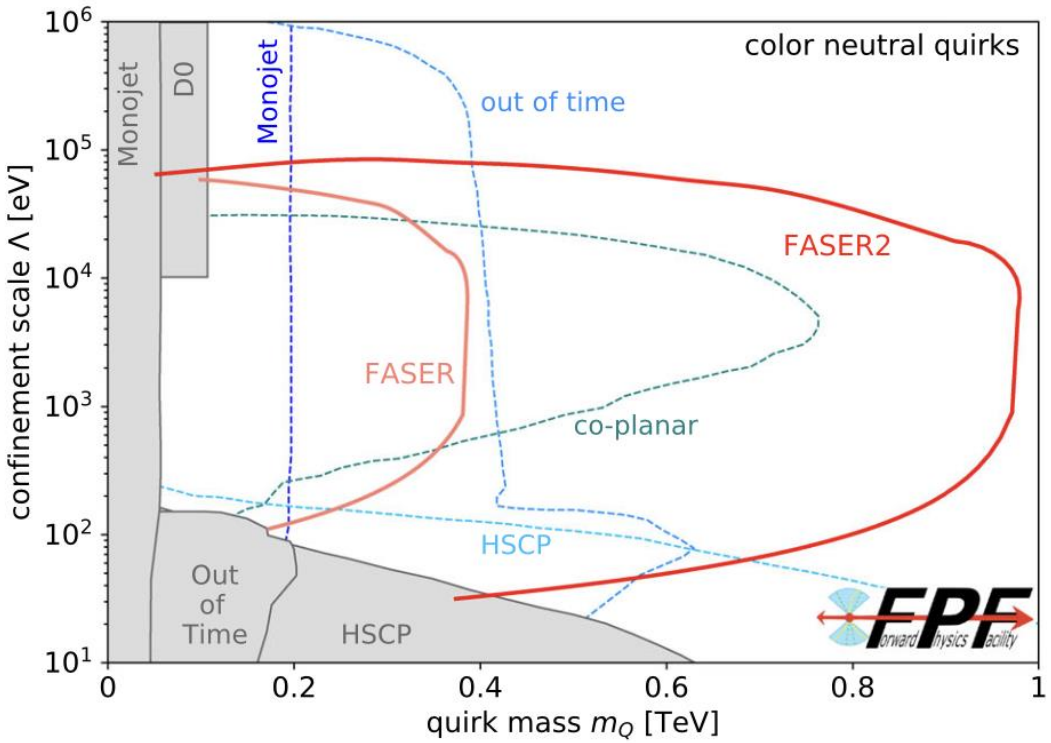
Heavy inelastic dark matter
Inelastic to be above threshold to produce

Light inelastic DM → need energy/boost to observe

*The FPF can discover a wide variety of new particles that **cannot** be discovered at fixed target facilities or other LHC experiments.*

Milli-charged particles and quirks



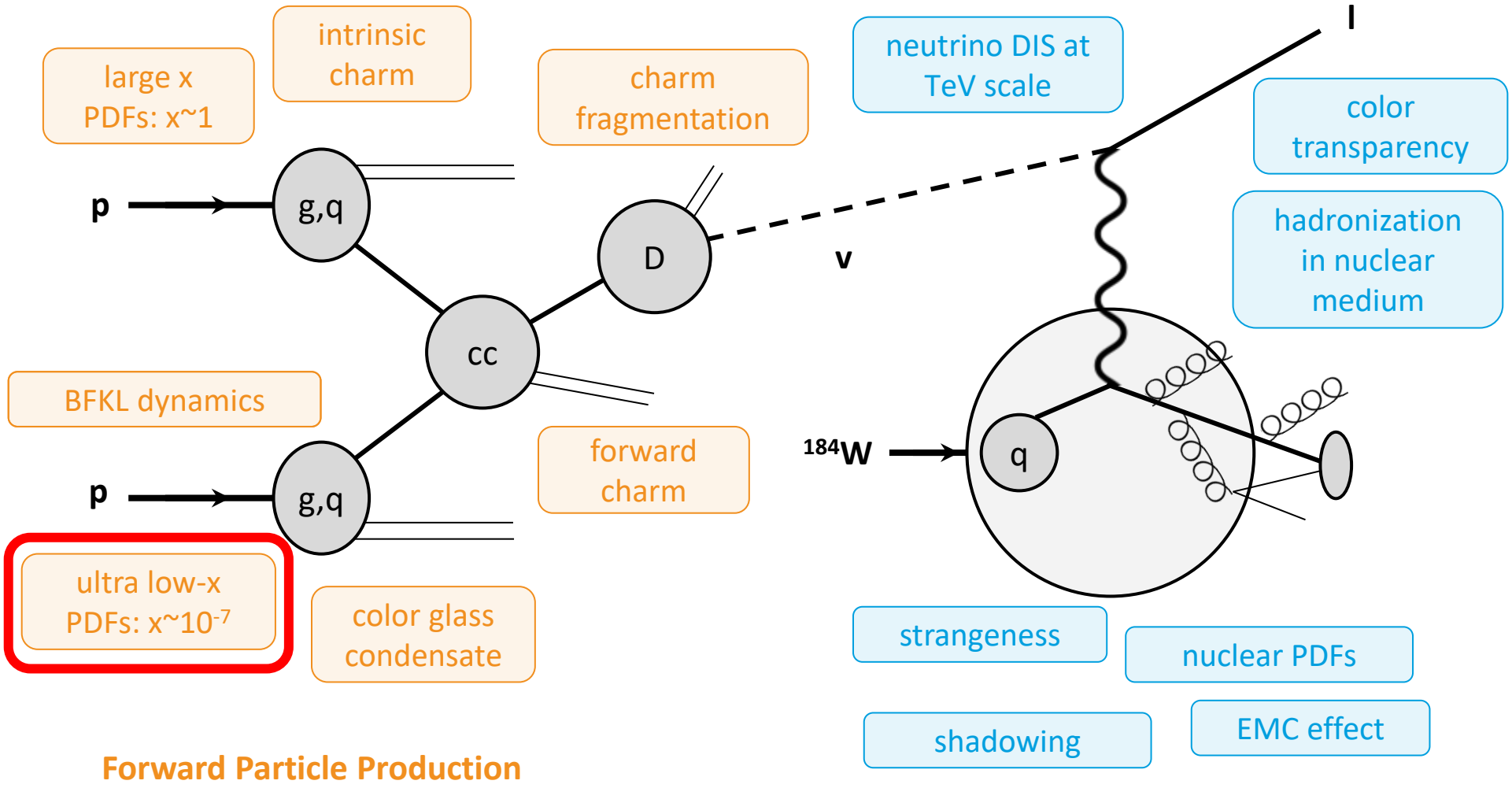


FORMOSA will have leading sensitivity to milli-charged particles

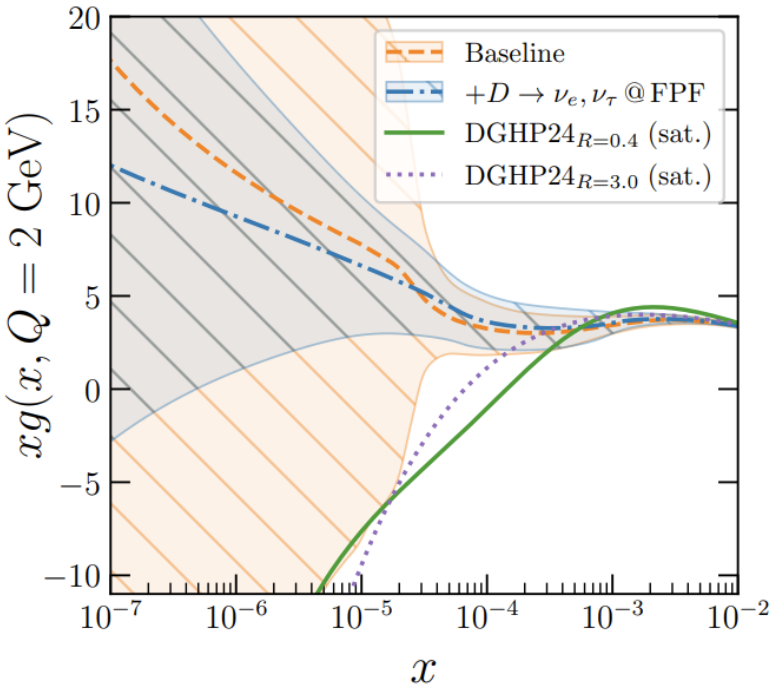
Unique sensitivity to Quirks coloured under non-SM gauge group

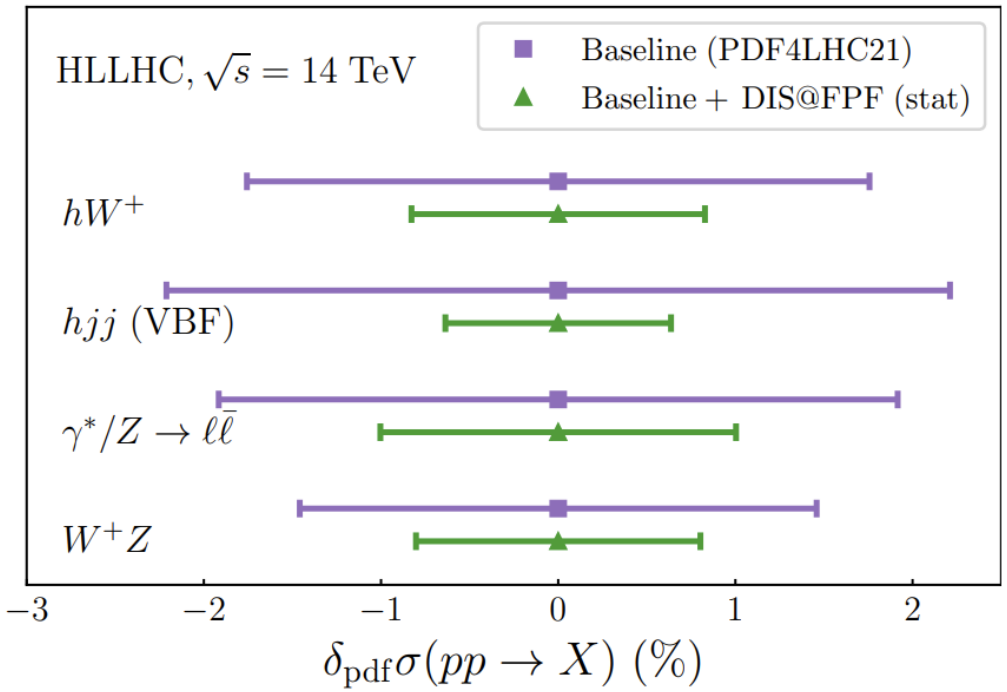
Just some examples from very broad BSM programme

Neutrinos as a probe



Enhancing HL-LHC discovery potential



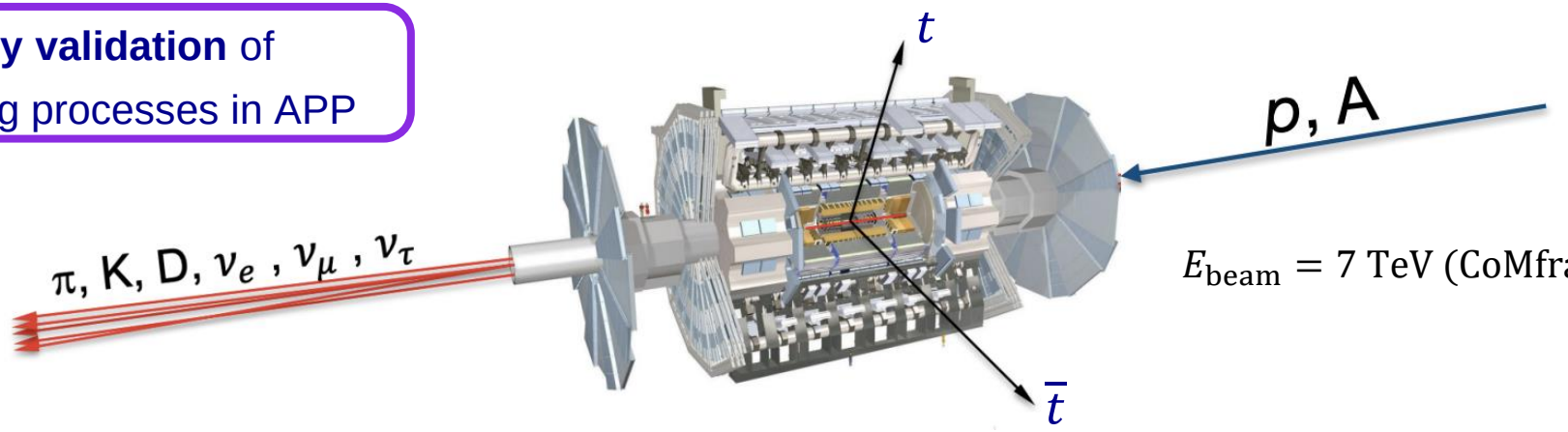


FPF measures the **gluon probability (PDF)** at low momentum fractions

Improves predictions of **Higgs-** and **weak gauge-boson** cross sections at the HL-LHC

Improving astroparticle physics

Unique **laboratory validation** of extreme scattering processes in APP



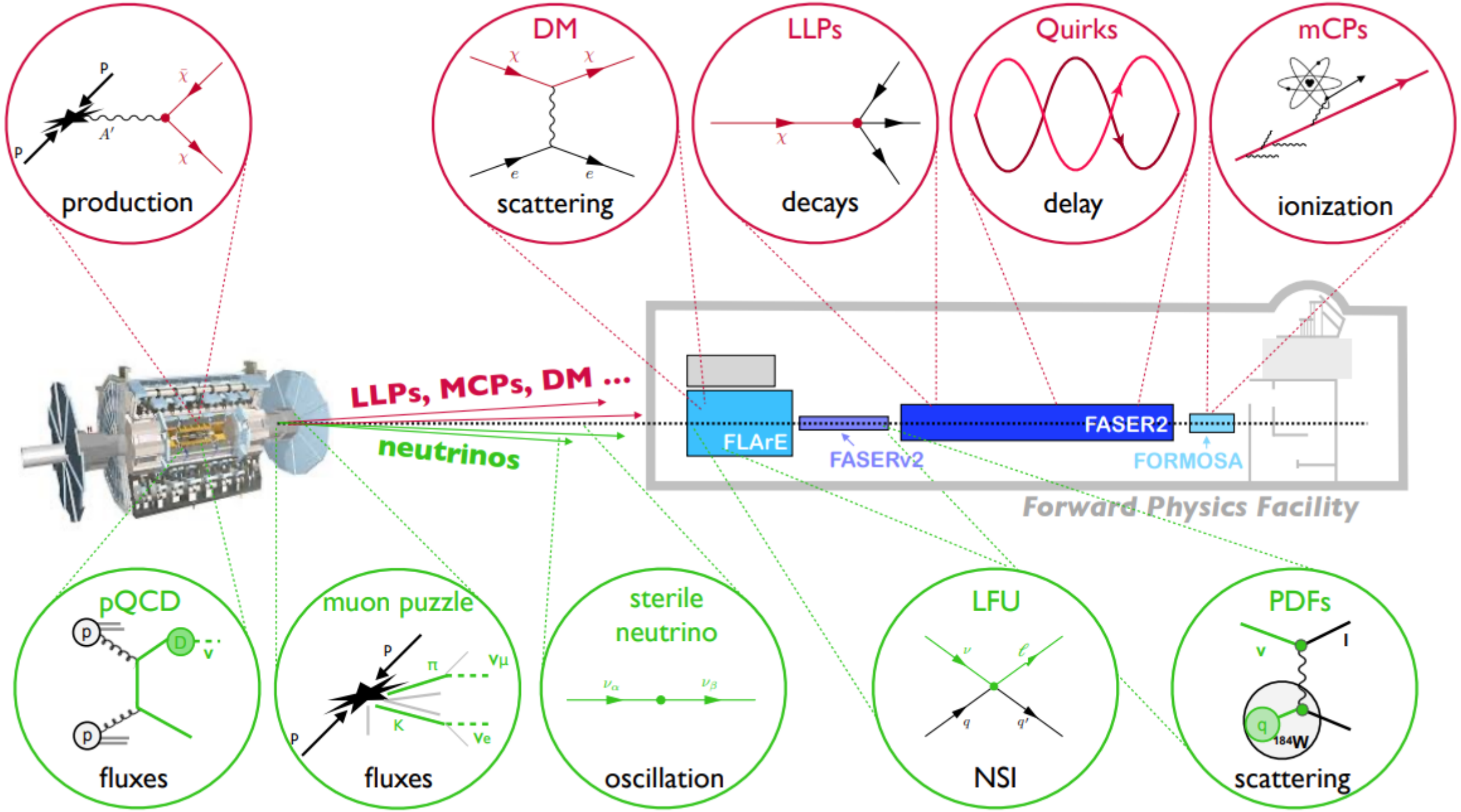
$E_{\text{beam}} = 7$ TeV (CoMframe)

Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux

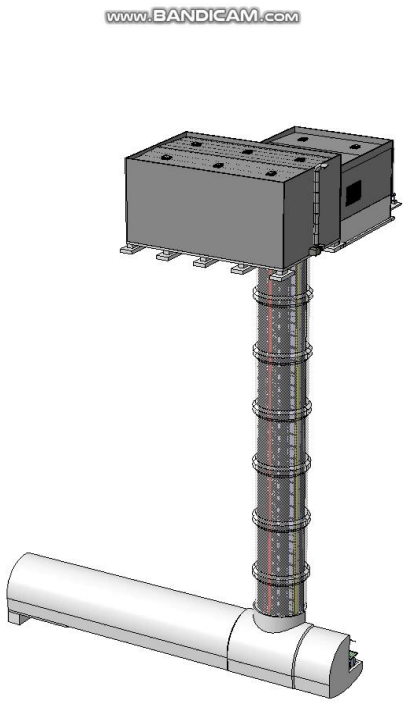
$E_{\text{beam}} \sim 10^5$ TeV (fixed target frame)

Auger, IceCube, KM3NET, GRAND, …

→ Cosmic ray muon anomaly


production
DM
scattering
LLPs
decays
Quirks
delay
mCPs
ionization
LLPs, MCPs, DM ...
neutrinos
FLArE
FASERν2
FASER2
FORMOSA
Forward Physics Facility
pQCD
fluxes
muon puzzle
fluxes
sterile neutrino
oscillation
LFU
NSI
PDFs
scattering

Status of Technical Studies and Integration



ENGINEERING DEPARTMENT

CERN beam physics group: Vibration/tunnel movement are not expected to be an issue either during construction or operation.

CERN radioprotection group: Can access cavern for trained personnel during beam operations.

Muon backgrounds: CERN fluke team, muon flux will be < 1 Hz/cm^2 in a region 1 meter around LOS. Generally acceptable for experiments.

CERN site investigation: Geological conditions appear good for proposed excavation.

CERN safety: Addition of over-pressure safety corridor allows a single access point (no physical connection to LHC).

The cryo system to be separated underground; has an industrial cooler(Turbo Brayton), LAr and LN2 storage ; all sized to be installed thru shaft.

Conceptual installation plan for all services and detectors developed at FPF8

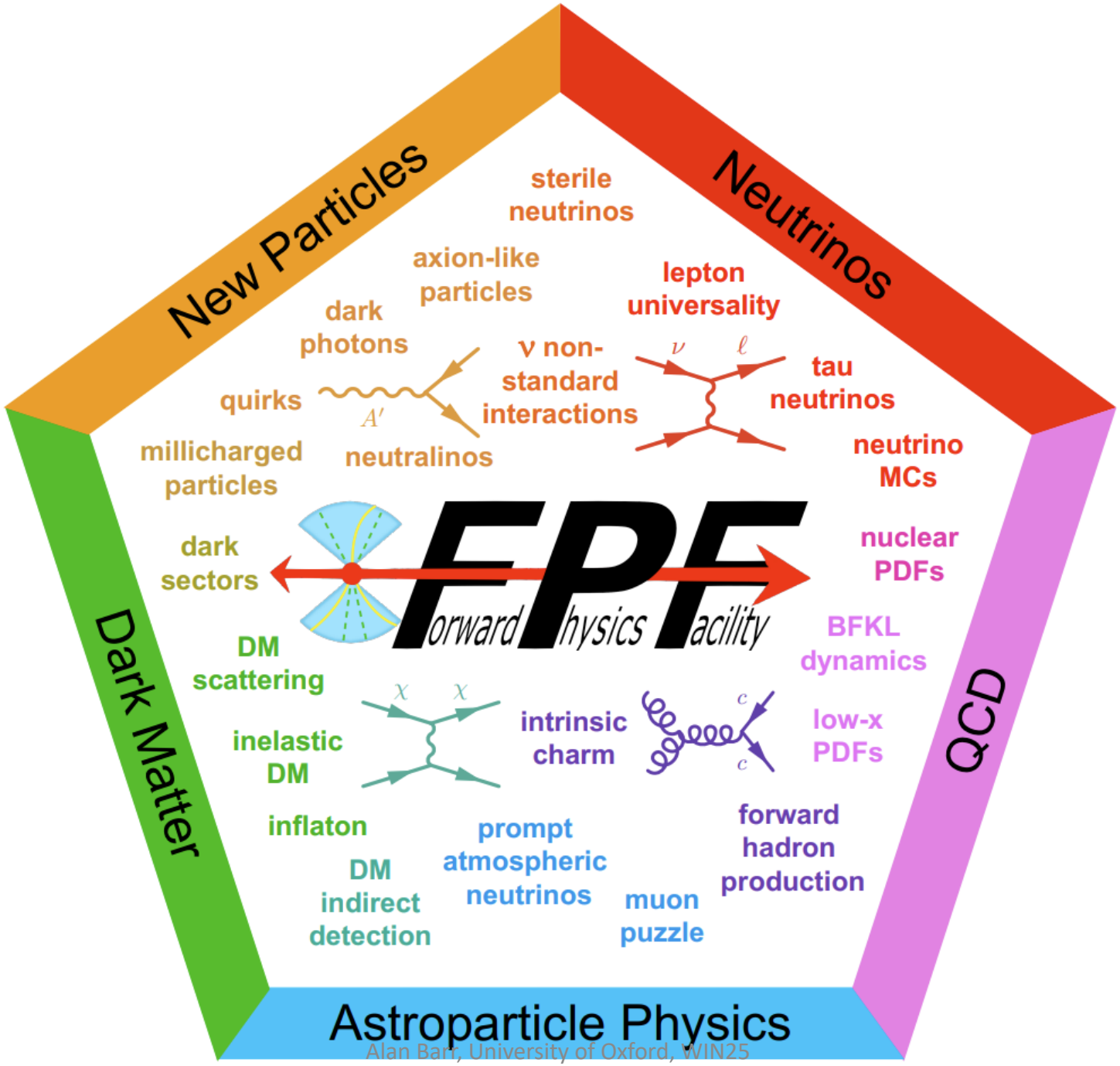
- **Achievability & practicality:**
  - Makes use of the existing HL-LHC beams
  - The detectors deliverable with existing detector technologies
    - Allowance for future technologies and upgrades
  - Can be constructed and operated in parallel with the operation of the LHC
- **Timescale:**
  - The FPF needs to operate within the HL-LHC running window
    - Collect as much of the HL-LHC luminosity as possible
    - Constraints from scheduling and approval requirements can be accommodated
  - Step-change in the capability of the FPF
    - factors of order 100 larger active volumes beyond the pathfinder experiments
    - that the sensitivity will world-leading almost as soon as the experiments are operational

In **all** scenarios it should be the scientific goal to fully exploit the physics potential of the **HL-LHC**, including the **collider neutrino** and **forward dark sector** programmes - which can be added at modest marginal cost.

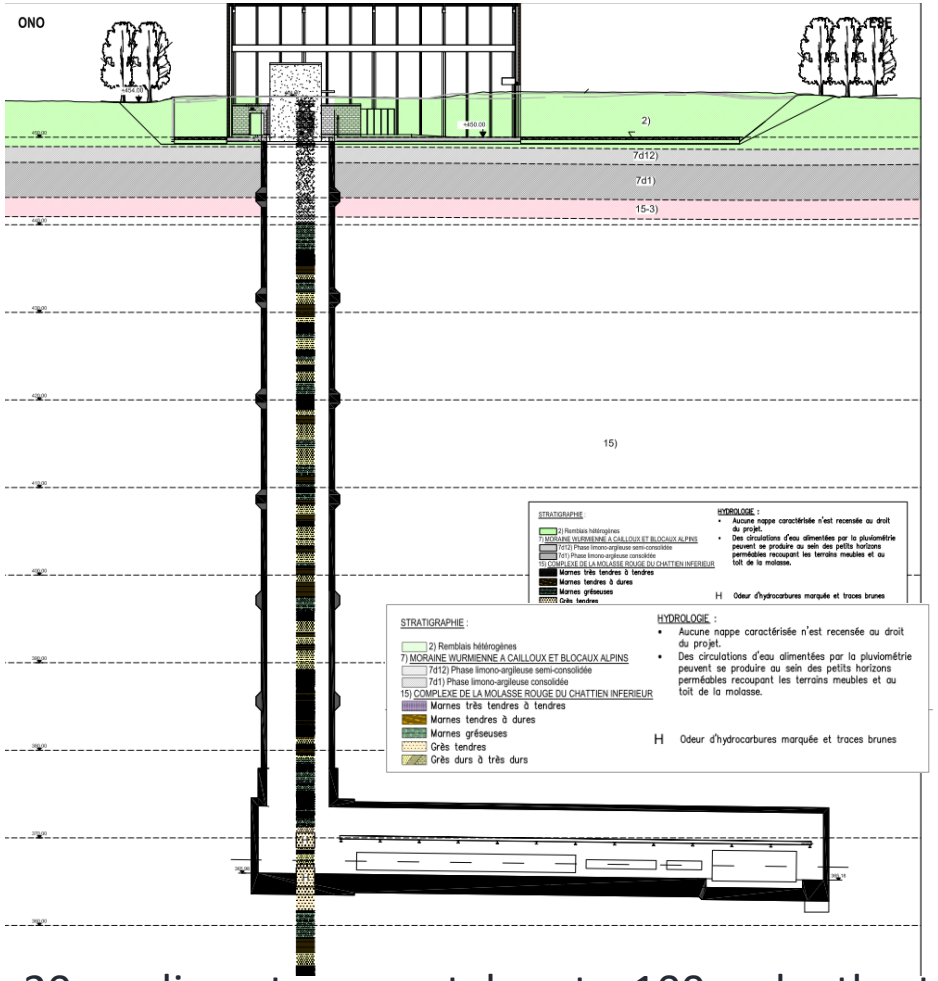
EXTRAS

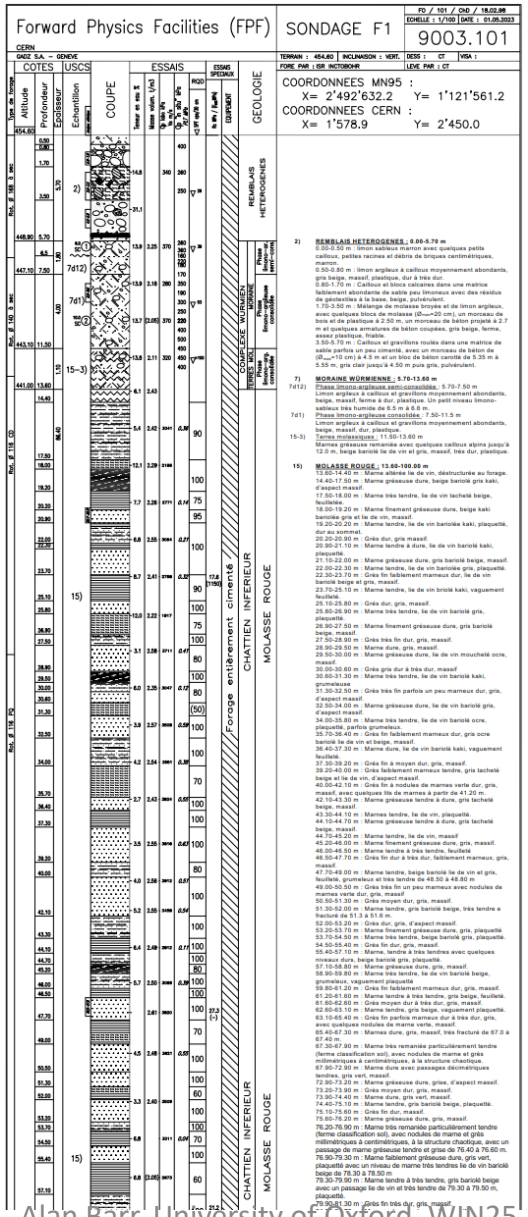
FPF Information Sheet

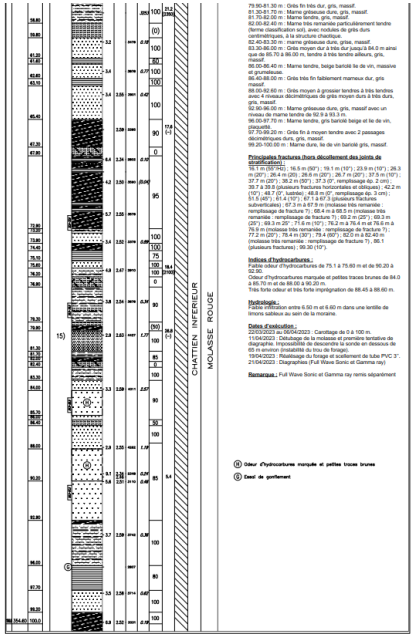
- Effort Name: Forward Physics Facility and Experiments at the High Luminosity LHC.
- Short Abstract: The **Forward Physics Facility (FPF)** is a proposed new underground cavern at the Large Hadron Collider (LHC) that will host a suite of new experiments during the High-Luminosity LHC (HL-LHC) era. The existing large LHC detectors have un-instrumented regions along the beam line, and so miss the rich physics opportunities provided by the enormous flux of particles produced in the far-forward direction. A diverse set of experiments are planned to detect millions of neutrinos and a wide range of new physics possibilities.
- Contact: https://fpf.web.cern.ch/
- Useful Link: https://pbc.web.cern.ch/ , https://pbc.web.cern.ch/fpf-resources
- White papers: https://arxiv.org/abs/2411.04175


New Particles
Neutrinos
QCD
Astroparticle Physics
Dark Matter
sterile neutrinos
axion-like particles
dark photons
quirks
millicharged particles
neutralinos
ν non-standard interactions
lepton universality
tau neutrinos
neutrino MCs
nuclear PDFs
BFKL dynamics
low-x PDFs
forward hadron production
muon puzzle
prompt atmospheric neutrinos
DM indirect detection
inflaton
inelastic DM
DM scattering
dark sectors
intrinsic charm
FPF
Forward Physics Facility

FPF CE Site Investigation Works







- 20cm diameter core taken to 100m depth at proposed FPF location
- Detailed geological study of core carried out
  - No showstoppers identified
  - Area looks **good for excavation**

FPF Detector parameters and physics (summary)

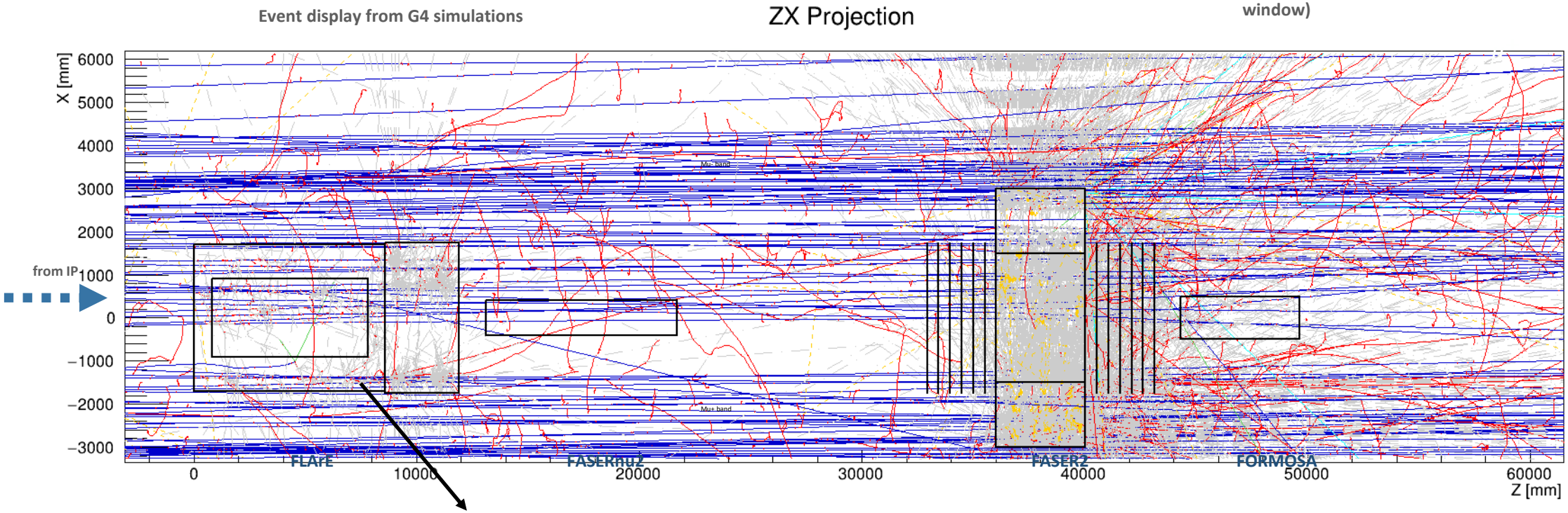
Detector	Design/Parameter	Standard Model Physics	Discovery and Rare Phenomena Physics
FLArE	Liquid argon TPC/10 ton active target/~ns timing/Fe-Scin hadronic calorimeter(40 ton)	High eff. Muon/Electron neutrino spectrum. wider eta coverage, Low purity Tau neutrinos spectrum	LLP interactions with low threshold. Inelastic DM, DM scattering, mCP interactions. Neutrino Tridents
FASERnu2	Tungsten/emulsion/20 ton/high spatial resolution <1micron.	High eff Tau neutrino detection. Charm detection. Muon/electron neutrino spectra at high eta	DM scattering, Neutrino Tridents
FASER2	Magnetic Spectrometer/SciFi/~4 T-meter/aperture ~ 3mx1m; dp/p ~ 5% @ TeV	High acceptance Muon spectrometer for FLArE and FASERnu2	Dark sector decays of neutral LLPs, Inelastic DM, Quirks
FORMOSA	Plastic Scintillator Array/high resolution dE/dx (4 layers, 4 tons)	—	Millicharged particles with sensitivity $q \sim 10^{-3}$ Quirks

Each detector is designed to have unique scientific reach. System of detectors enhance the scientific case for the facility. Simulations are in progress to evaluate acceptances and resolutions.

Full simulation of muon backgrounds shows that detector background rates on LOS are manageable

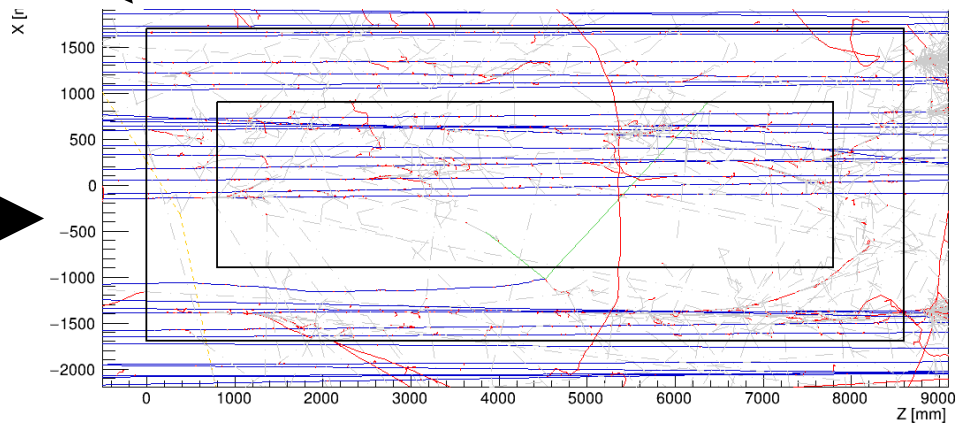
Event display from G4 simulations

Overlayed background events in **187.5 us** (FLArE acquisition window)



Zoom on FLArE volume

The muon rates (0.5 Hz/cm^2) and space charge effects are manageable around the line of sight.



$\mu^{\pm}$: blue

p : black

$e^{\pm}$: red

π^{0} : magenta

n : orange

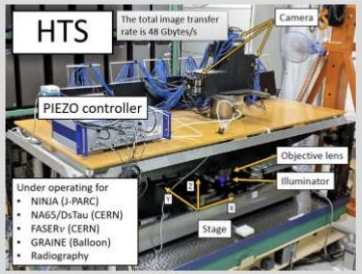
$\pi^{\pm}$: cyan

other: green

γ : gray

FASERν

Workflow



In Japan

Emulsion film production →

At CERN

Detector assembling → **Exposure** → **Disassembling** → **Development** →

In Japan

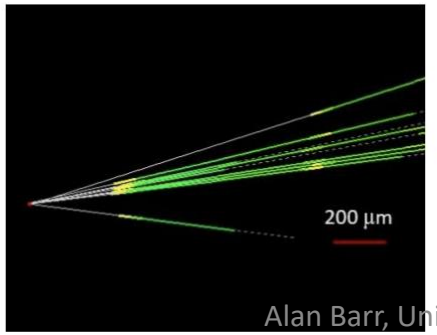
Full area readout →

Off-line analysis

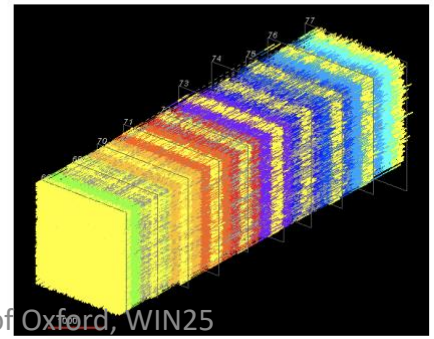
Alignment → **Track reconstruction** → **Vertex reconstruction** → **μ / e ID** → **Search for tau/charm decays** → **Kinematical analysis**

Interface tracker data

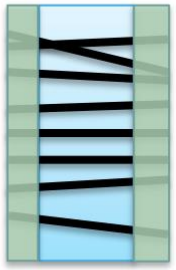
Spectrometer data

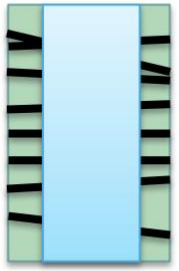


500-1000 TB/Run3



~500 TB/Run3





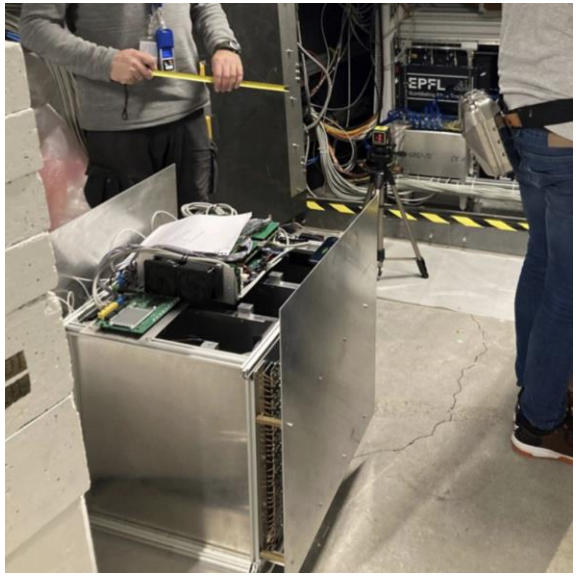
SND Detector upgrades (Run3)

Veto detector upgrade (2024)

- Third veto plane installed
- Additional redundancy to improve detector acceptance and efficiency
- ~10cm floor excavation to lower the whole Veto system
- Significant increase of the fiducial volume used in neutrino analyses

New muon telescope (2024)

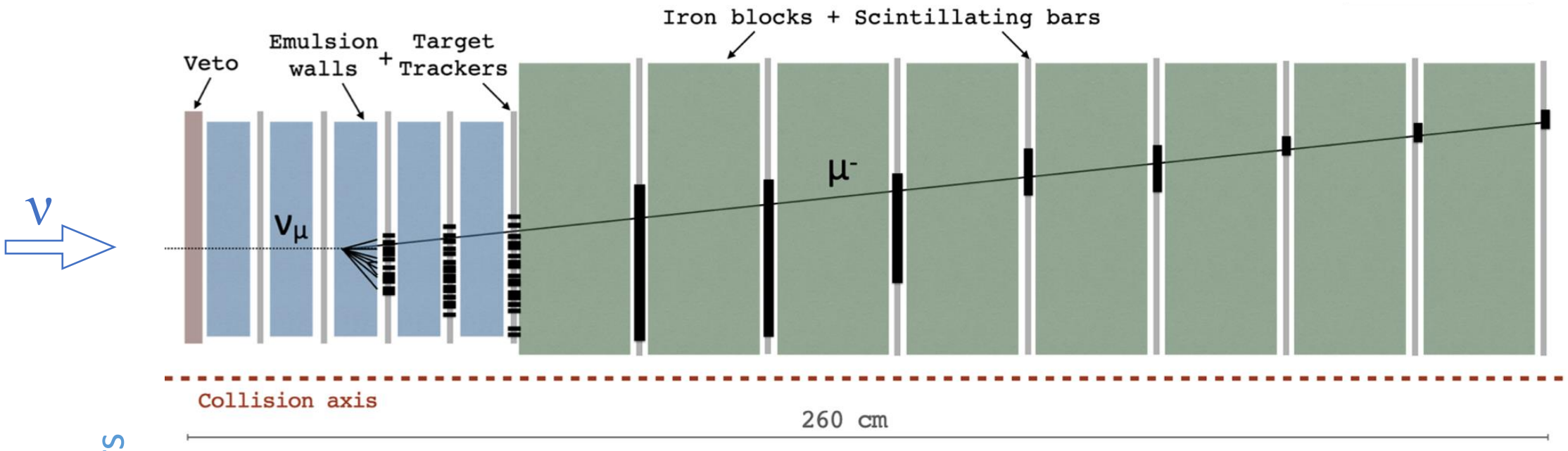
- Technology demonstrator: *sealed* resistive-plate chambers
- Measurement of the muon flux beyond nominal SND@LHC acceptance
- Further validation of the background model



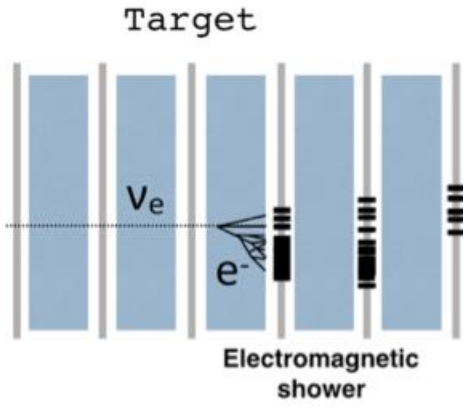
Muon system upgrade (2025)

- Two Drift Tube chambers installed
- Improve muon tracking
- Improve track extrapolation to the vertex
- Resolution: cm ⤻ 0.1mm

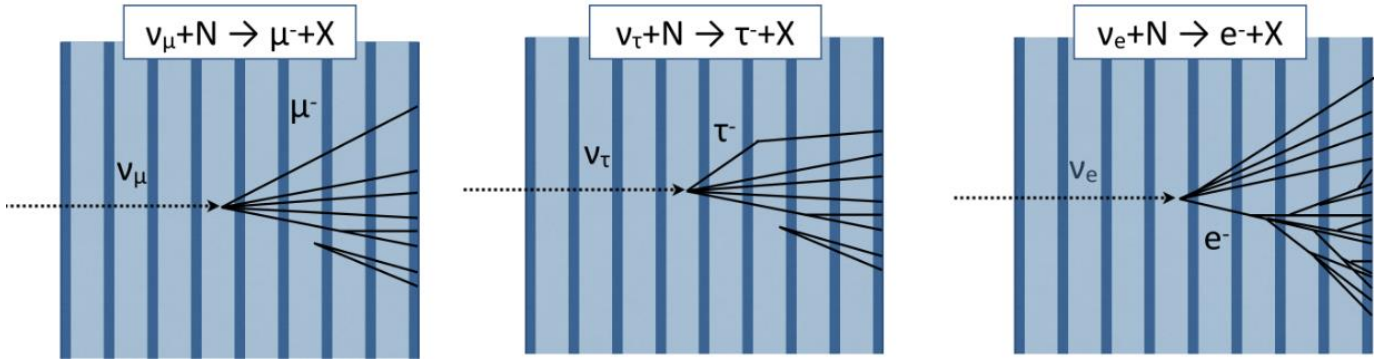
Neutrino identification at SND



phase 1: electronic detectors



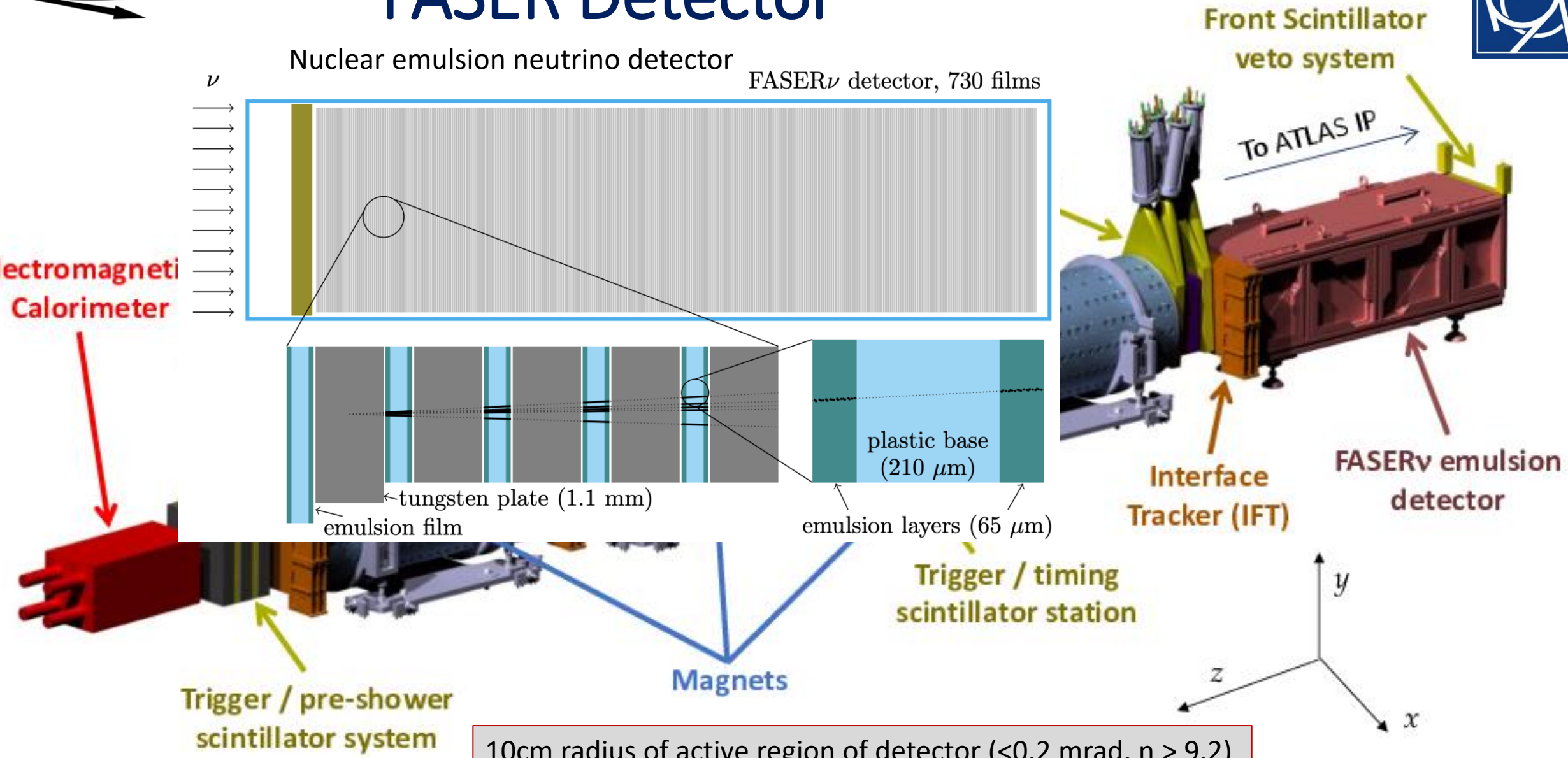
phase 2: emulsions



FASER Detector

arxiv: 2207.11427

Nuclear emulsion neutrino detector

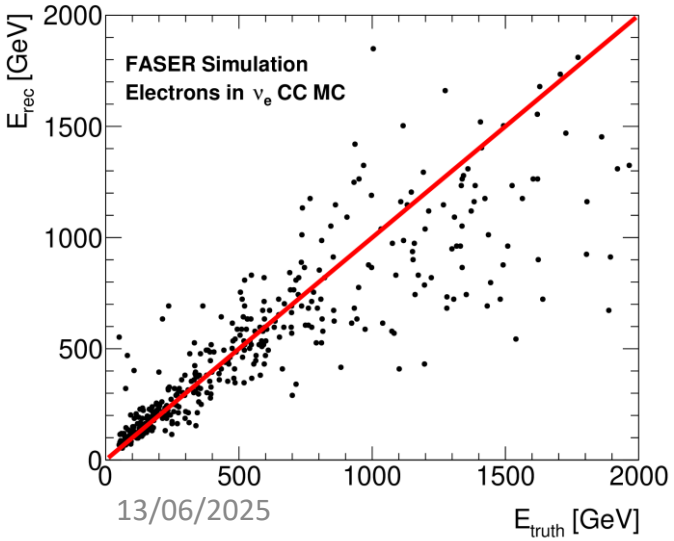


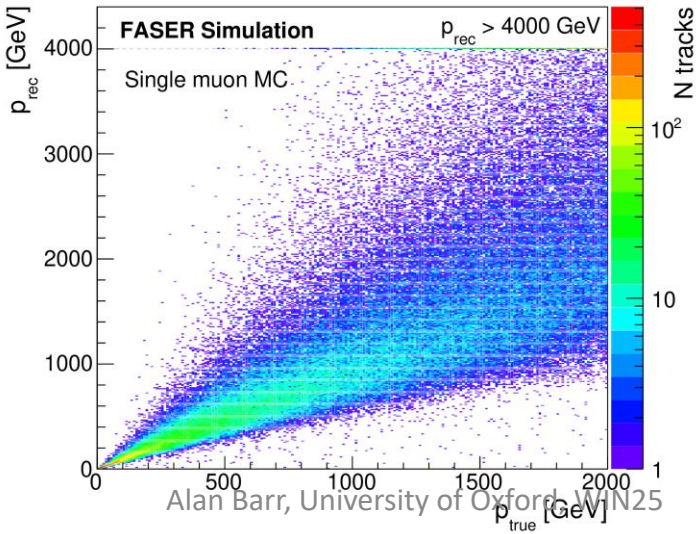
10cm radius of active region of detector (<0.2 mrad, η > 9.2)
1.5m long decay volume
2.5m long tracking spectrometer (0.6T dipole field)

First FASERν measurement

Phys. Rev. Lett. **133**, 021802
arxiv: 2403.12520

- Search for electron and muon neutrino CC interactions in 129 kg subsection of FASERν, exposed to 9.5/fb of pp collisions in 2022
- Require reconstructed high-energy neutral vertex with associated high-energy (E>200GeV) lepton(e,μ) candidate
  - e-candidate: EM shower, with E measured from number of segments at shower max
    - ~25% energy resolution – validated in testbeam
  - μ –candidate: Long track with p measured from multiple columb scattering
    - ~30% resolution – validated in testbeam
- Background from neutral-hadron (e,μ) or neutral-current neutrino interactions (μ-only)
  - From simulation, validated comparing low-energy vertices (which are dominated by neutral-hadrons) between data and simulation

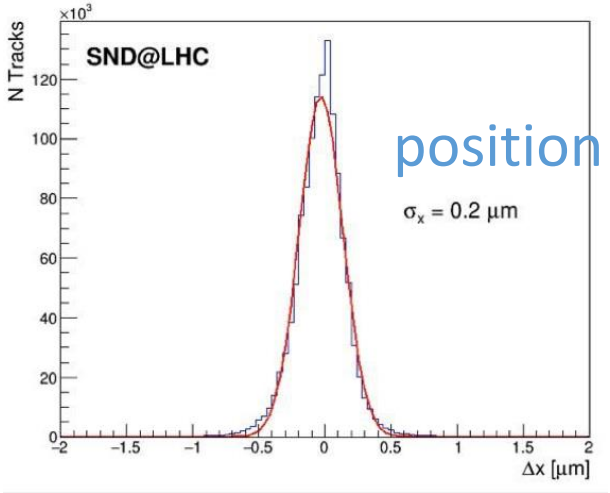


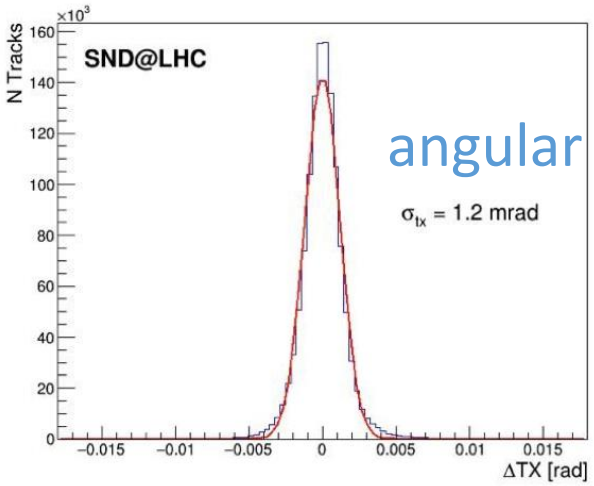


	Background	Expected
$\nu_e CC$	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3
$\nu_\mu CC$	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4

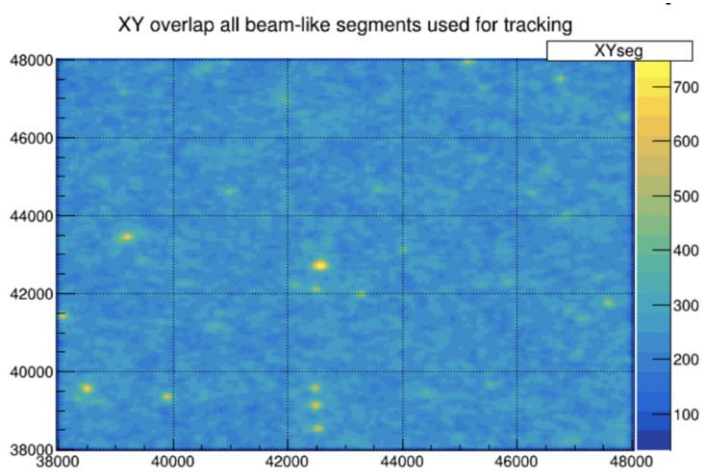
SND@LHC Emulsion data analysis

- excellent tracking **resolution** achieved

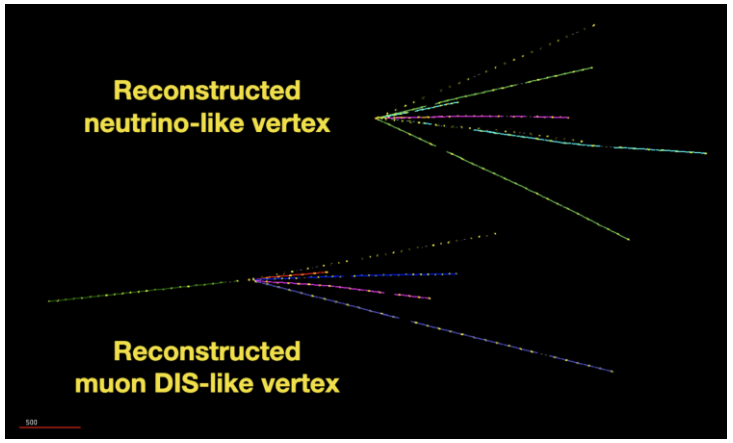




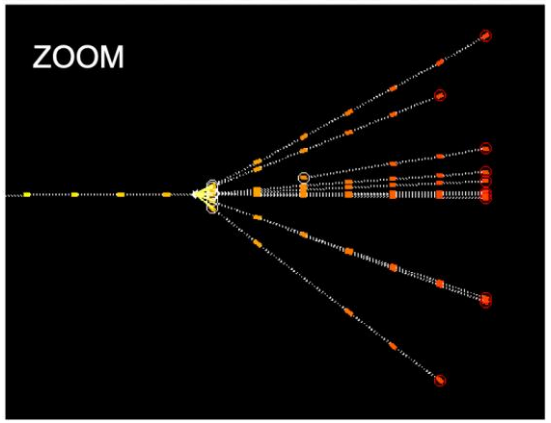
- μ **flux** in agreement with electronic detectors



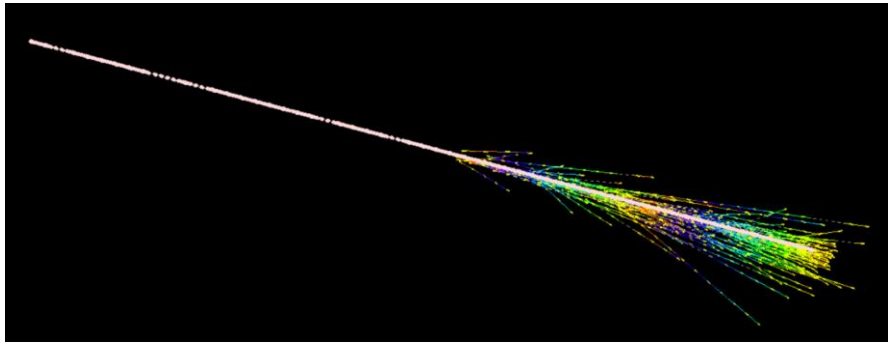
- charged/neutral **vertex** reconstruction



- **muon DIS** event

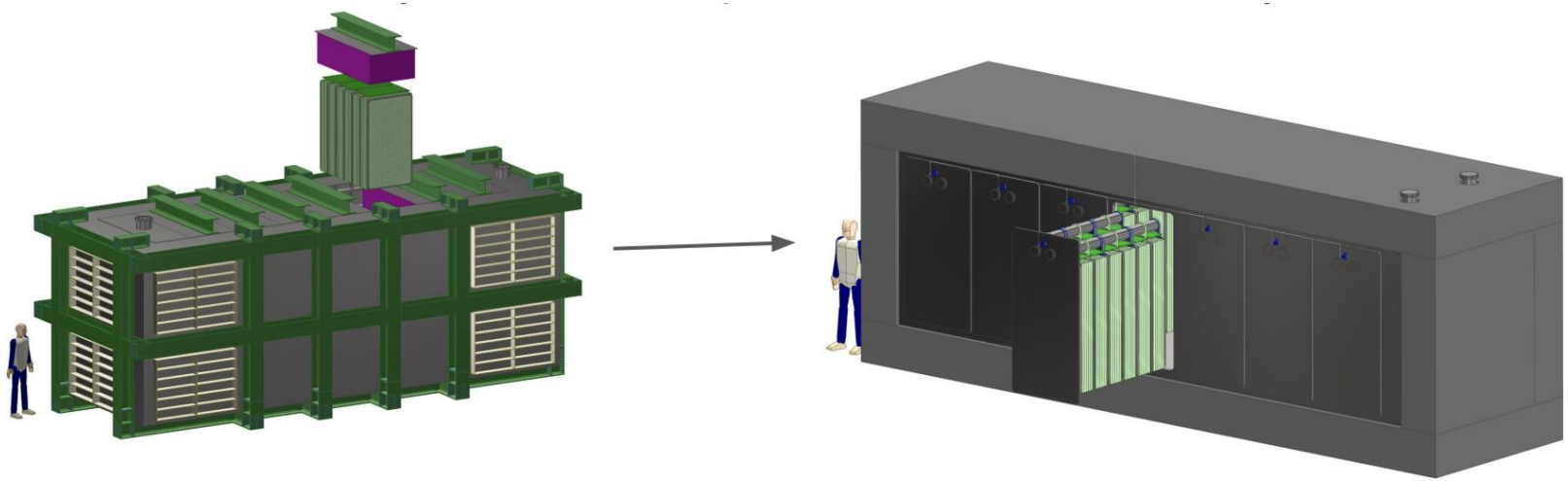


- **EM shower** search, based on detection of high-density spots

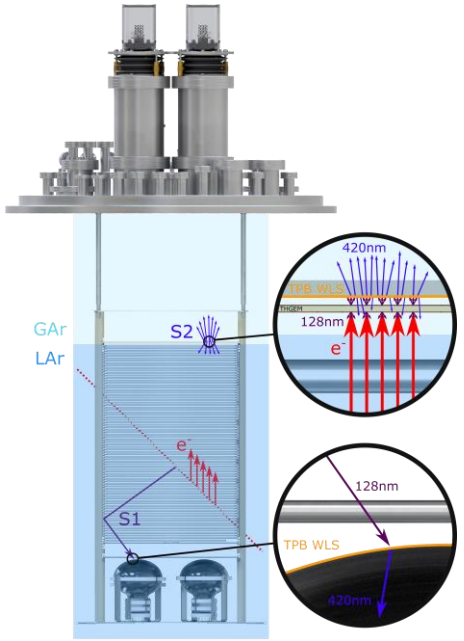


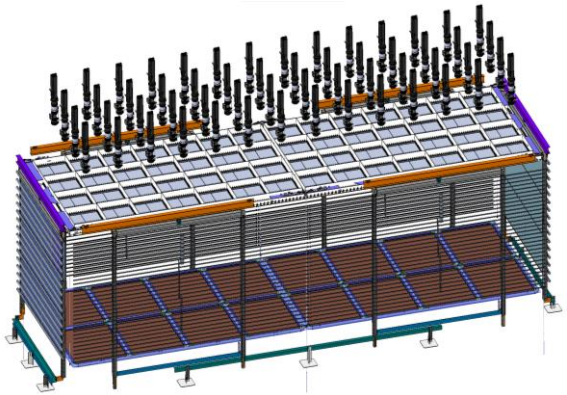
FLArE

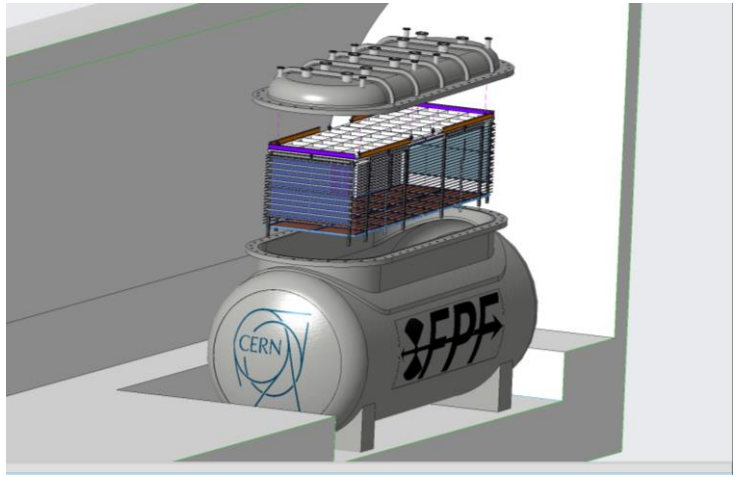
Design evolving considering physics, installation and operation constraints!



- Design changed from TPCs being top-loaded to side-installed “filling cabinet” design







Considering an alternative design using an ARIADNE-style (ARgon ImAging DetectioN chambEr) optical readout

Component	Approximate Cost	Comments
Facility Costs		
FPF civil construction	35.3 MCHF	Construction of shaft and cavern
FPF outfitting costs	10.0 MCHF	Electrical, safety, and integration
Cryogenic infrastructure	3.8 MCHF	Cryogen storage and cooling systems
Total	**49.1 MCHF**	Includes integration for infrastructure
Experiment Costs		Core costs only
FASER2	11.6 MCHF	3+3 tracker layers, SAMURAI-style magnet, dual-readout calorimeter
FASERν2	15.9 MCHF	Tungsten target, scanning system, emulsion films (10 replacements), interface detector
FLArE	10.8 MCHF	Cryostat, proximity cryogenics, detectors
FORMOSA	2.3 MCHF	Plastic scintillator, PMTs, readout
Total	**40.6 MCHF**	Core cost experimental program

TABLE I. Cost for components of the FPF and the experimental program. Costs of the infrastructure at CERN are Class 4 estimates according to international standards; they have a range from −30% to +50%. The costs for experimental components are estimated as core costs, which consist of direct costs of materials and contracts only. Each core cost was computed with conservative technical choices; as new ideas and designs are considered, the costs are expected to change.

https://arxiv.org/abs/2411.04175

Physics motivation for studying LHC neutrinos

Neutrino physics:

- Measure **neutrino** interaction **cross section** in unexplored energy region
- Test Lepton **Flavour conservation** in the neutrino sector
- Study **charm production** in neutrino interactions
- Search for **non-standard** interactions

QCD:

- **Deep inelastic scattering** of high energy neutrinos in target (constrain PDFs)
- Measure forward **hadron production** (light hadrons and charm)
- Constrain gluon PDF at **very low-x** from forward charm (high energy ν_e)

Astroparticle:

- Provide insight into the **cosmic-ray muon puzzle** by studying forward strange production (ν_e / ν_μ ratio)
- Constrain dominant prompt **neutrino-background** for astrophysical neutrino studies by ICECUBE (high energy ν_e)

There is also an extensive LLP & BSM programme

LHC provides a collimated beam of TeV energy neutrinos in the far forward direction

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

... Forty years later, this vision is being realized