Hidden Sector Experiments

Including Collider Neutrino Measurements

Carl Gwilliam

8th April 2024

IoP Annual Meeting

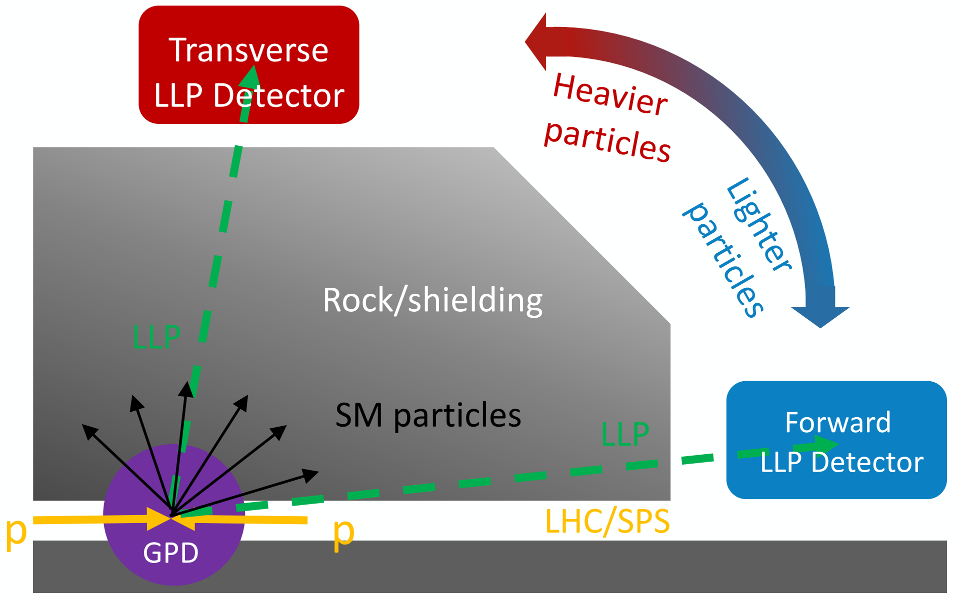
Physics Motivation

- A large variety of BSM theories predict new light, weakly/feebly interacting particles (known as FIPs)
  - Growing interest since can yield DM with correct relic density and may resolve low-E discrepancies (e.g. g-2)
    - Coupled with lack of signs of new physics at the LHC

- Hidden (dark) sector
  - DM may be part of more complex NP sector
  - Interacts with SM through a mediator/portal
    - Vectors e.g dark γ
    - Scalars e.g. dark H
    - Pseudoscalars e.g. ALPs
    - Fermions e.g HNLs

} Weakly interacting → long lived particles (LLPs)

- Many dedicated experiments (existing or proposed) to search for FIPs from LHC/SPS
  - Can be forward or transverse relative to GPD
  - Advantages: shielded from bkg, targeted design, …

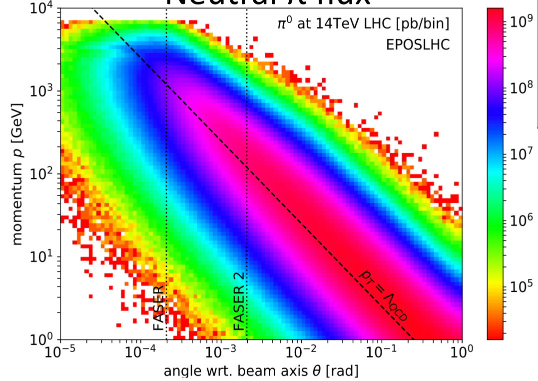


- As well as BSM physics, the light FIPs include SM neutrinos → directly detect/measure collider νs

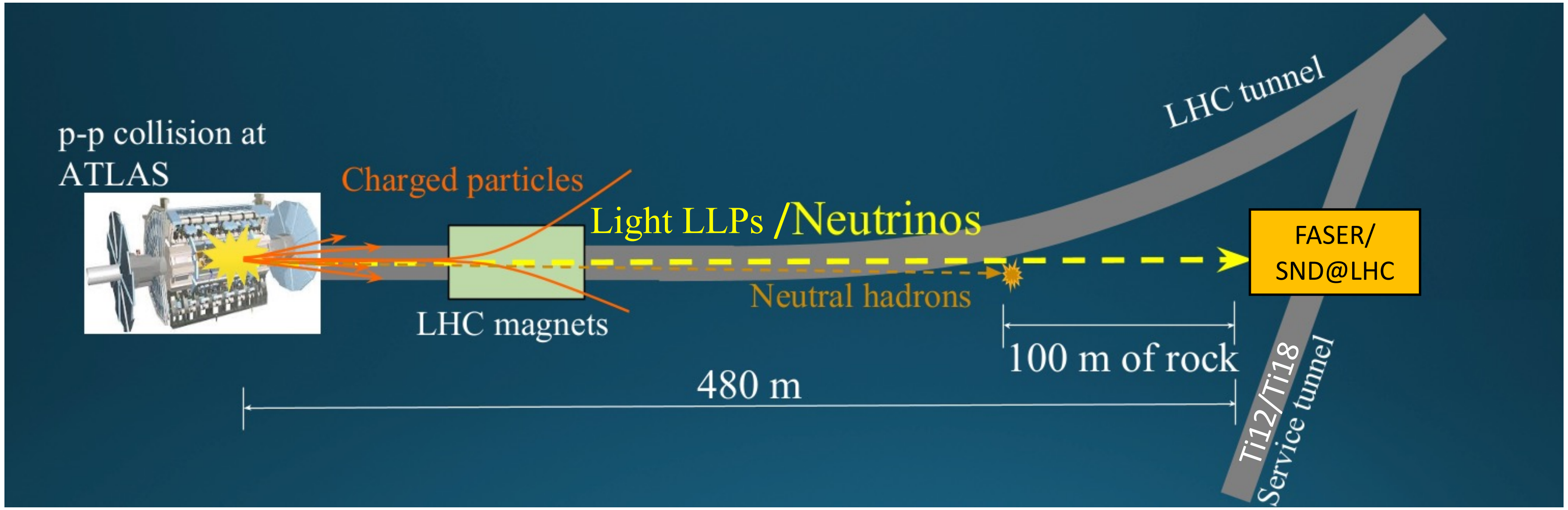
Current Experiments

FASER/SND@LHC

Neutral π flux



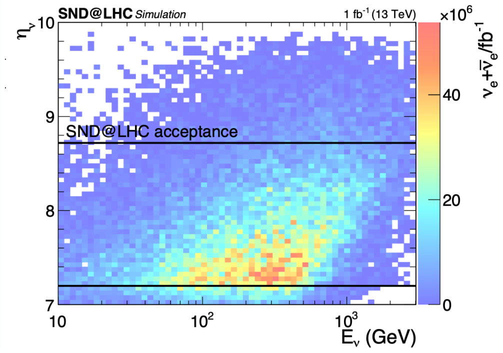
- New run-3 LHC experiments located 480 m downstream of ATLAS
  - High-signal: large LHC collision rate + forward-peaked meson production
  - Low-background: LHC magnets and 100 m of rock shield most background



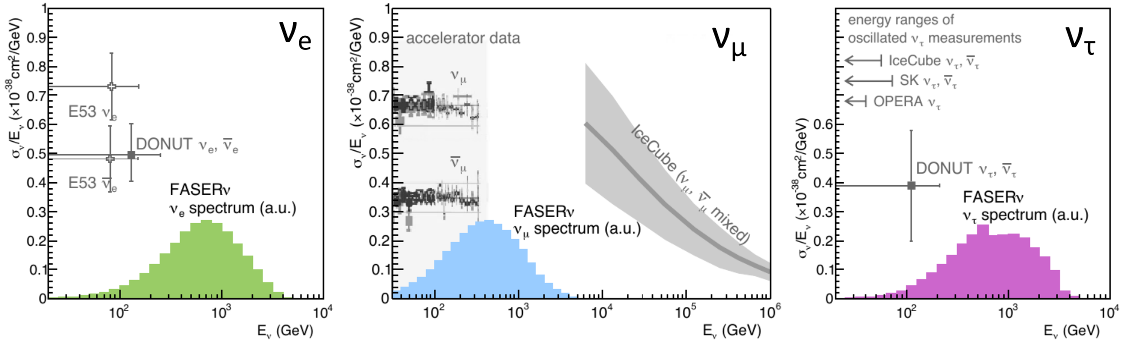
- FASER (Ti12)
  - Spectrometer + dedicated FASERν detector on LOS
  - LIV, MAN, SUSS, RHUL
- SND@LHC (Ti18)
  - Hybrid off-axis neutrino (7.2 < η < 8.4) detector
  - UCL, Imperial

- Meson decays also give rise to large neutrino flux
  - Direct detection of TeV collider neutrinos
  - X-sect measurement in unexplored phase space

Neutrino flux



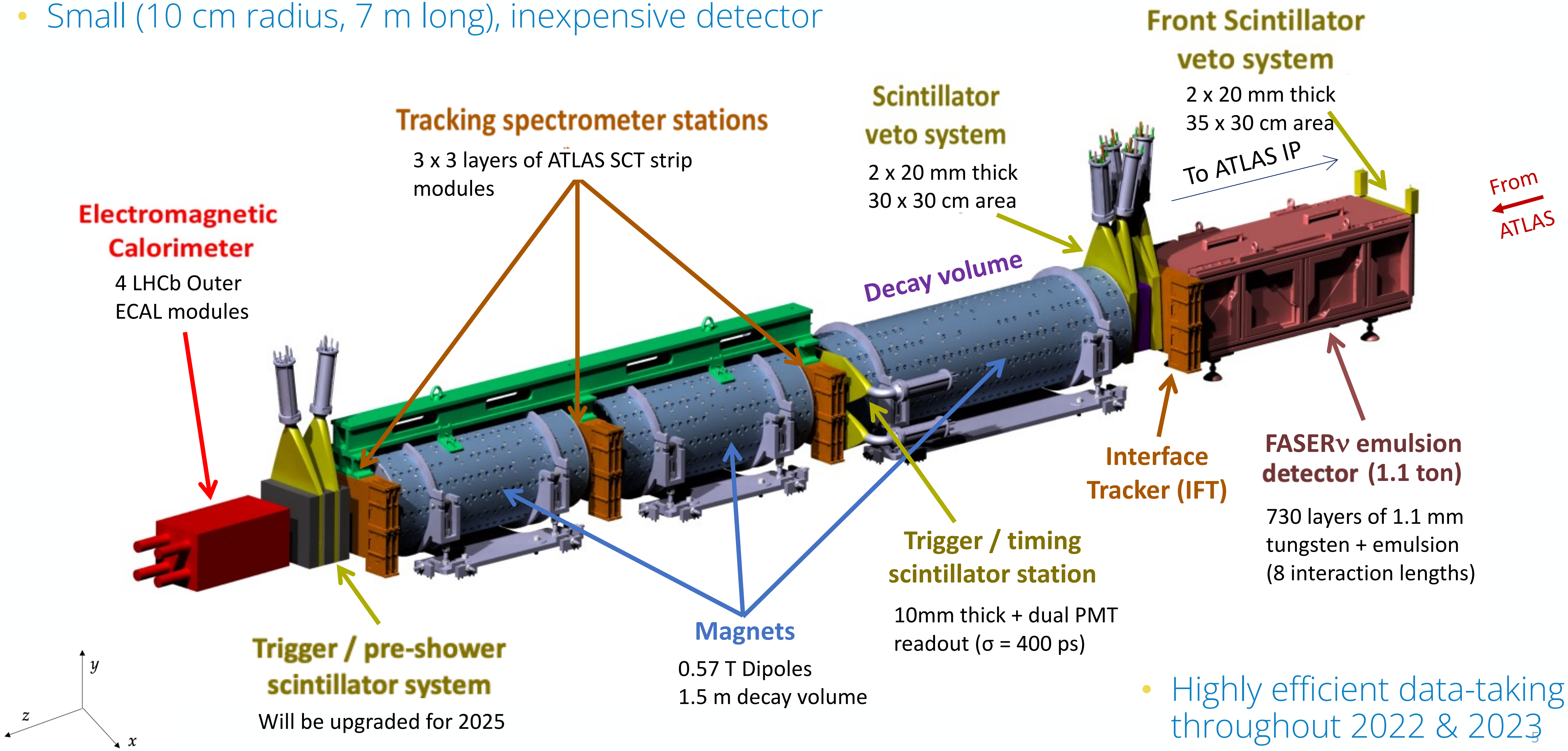
Neutrino cross sections



FASER Detector

Detector paper

- Small (10 cm radius, 7 m long), inexpensive detector

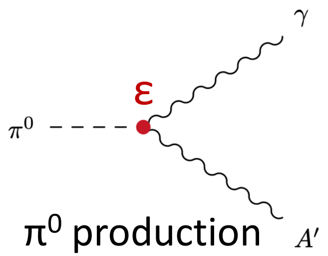


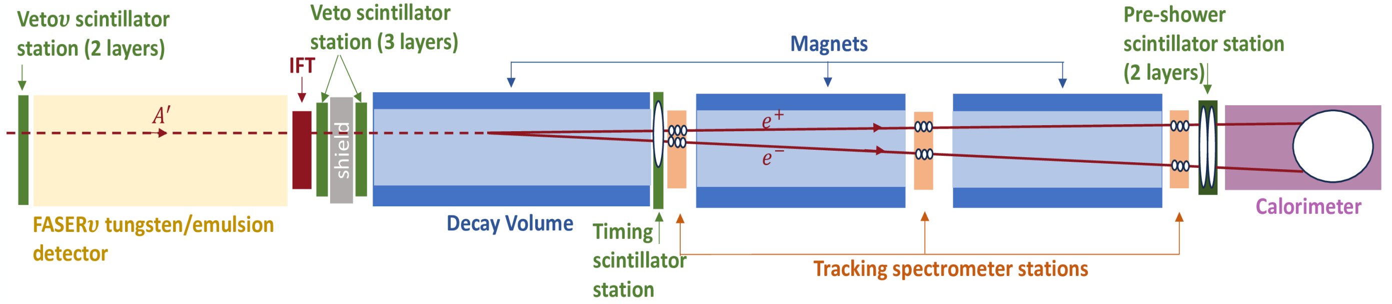
- Highly efficient data-taking throughout 2022 & 2023

FASER: Dark Photons

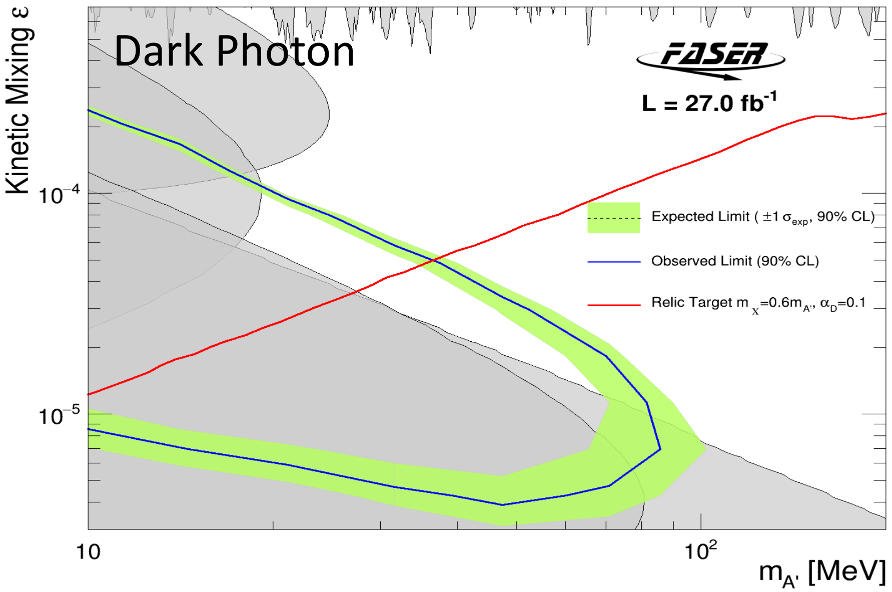
PLB 848 (2024) 138378

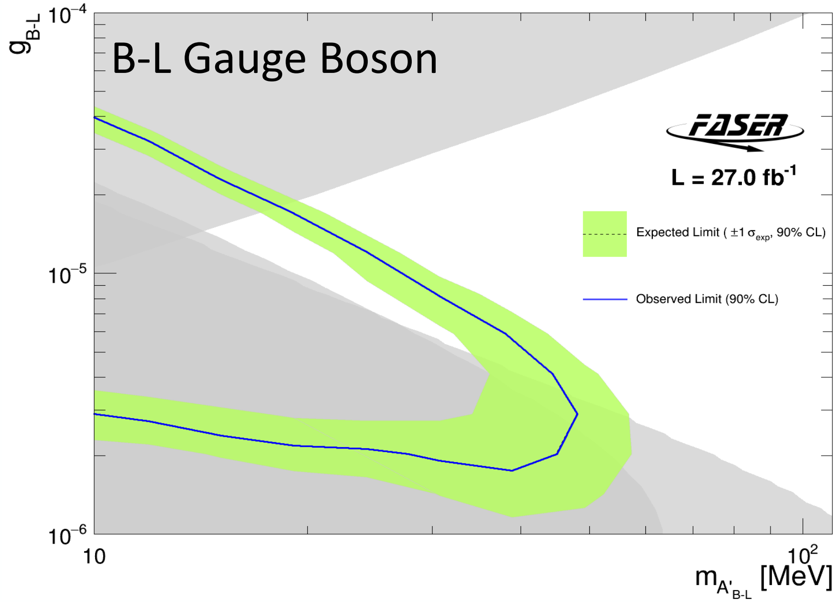
- Search for A′ → e^+e^- using 2022 data (27 fb^{-1})
  - No veto signal, 2 good tracks with timing/preshower signal, Calo E > 500 GeV
  - Small background mainly from neutrino events, modelled with GENIE

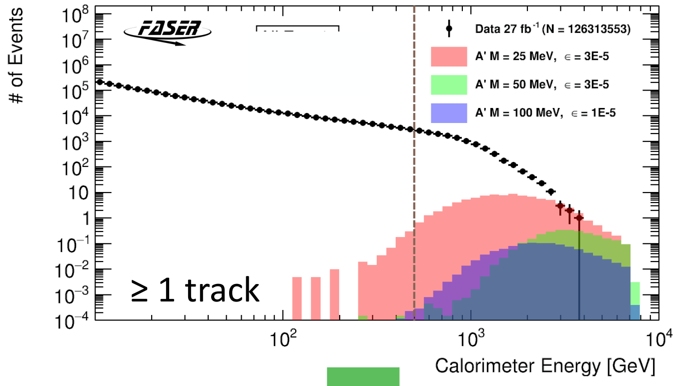


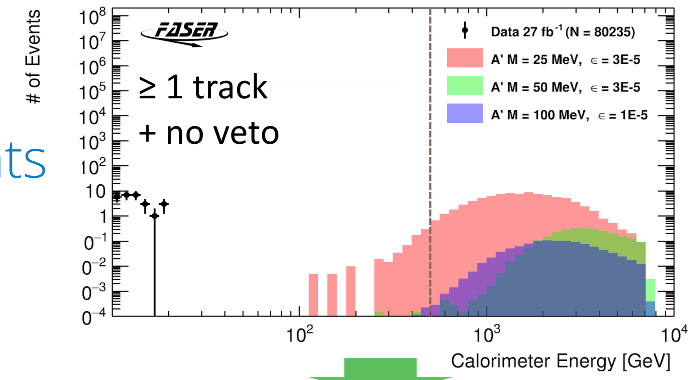


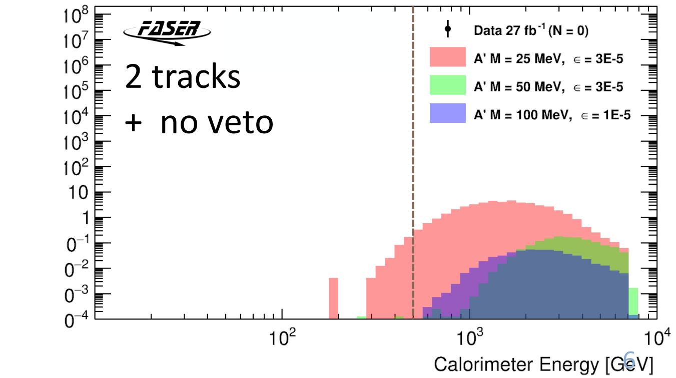
- **Observe 0 events** for background prediction of (2.02 ± 2.4) x 10^{-3} events











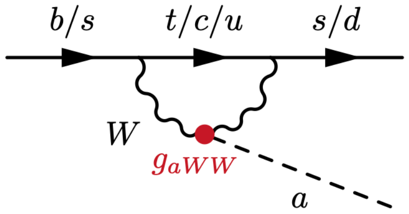
FASER: ALPs

NEW

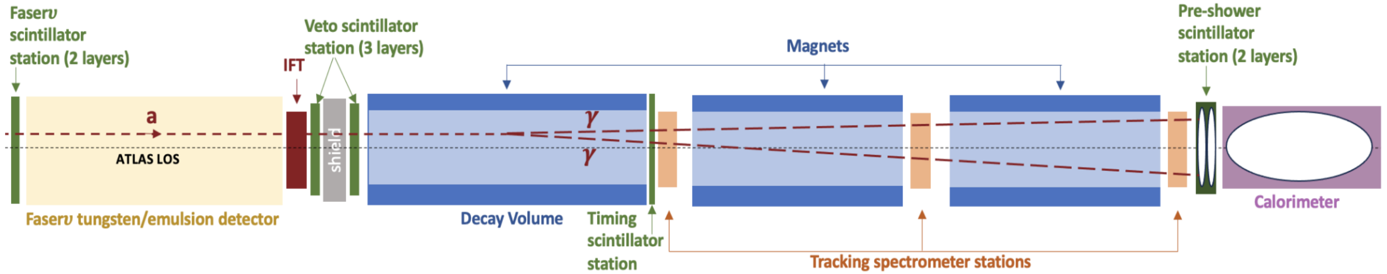
CERN-FASER-CONF-2024-001

See Lottie's parallel talk for more info

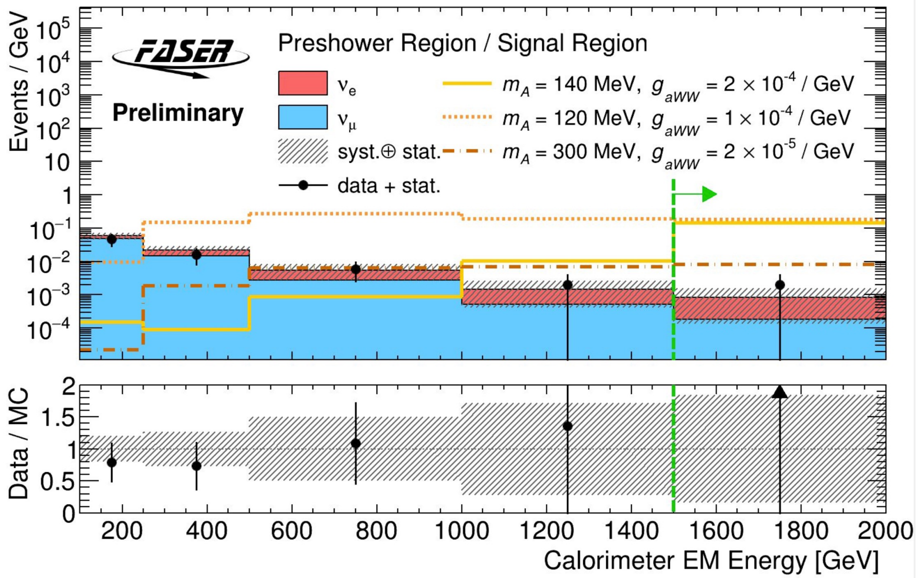
- Search for ALP coupling to $SU(2)_L$ with $a \rightarrow \gamma\gamma$ using 2022+23 data (57.7 fb^{-1})
  - No signal in veto/timing, preshower signal from EM shower, Calo E > 1.5 TeV
  - Main background from CC neutrino interactions near calo: GENIE validated in CRs

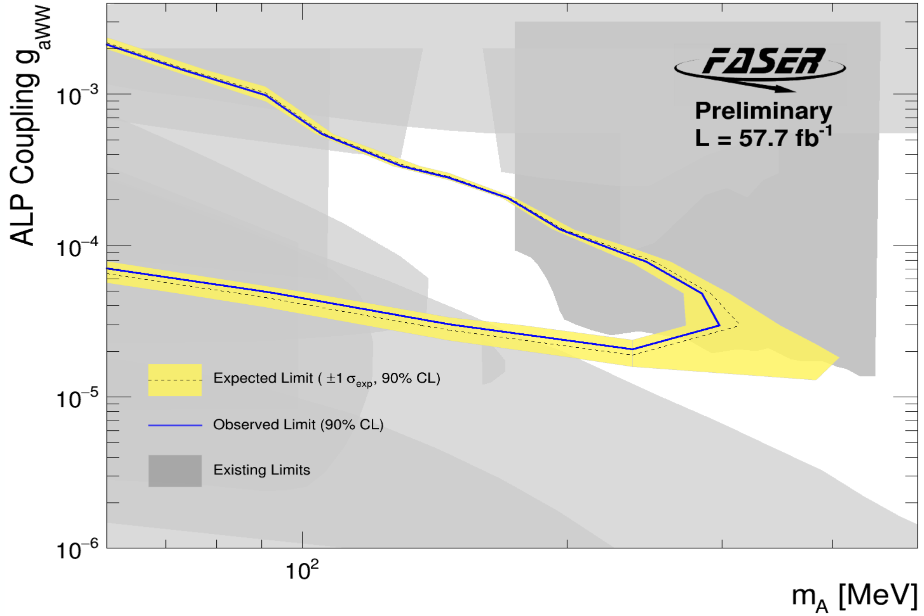


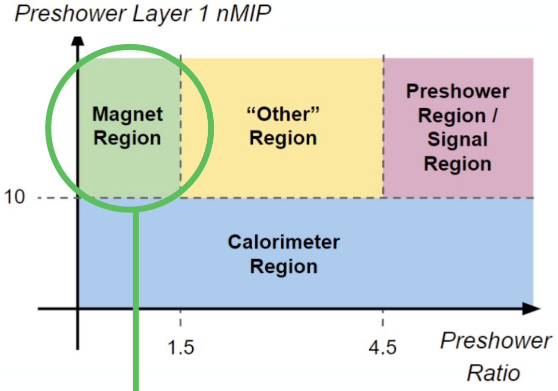
B-meson production

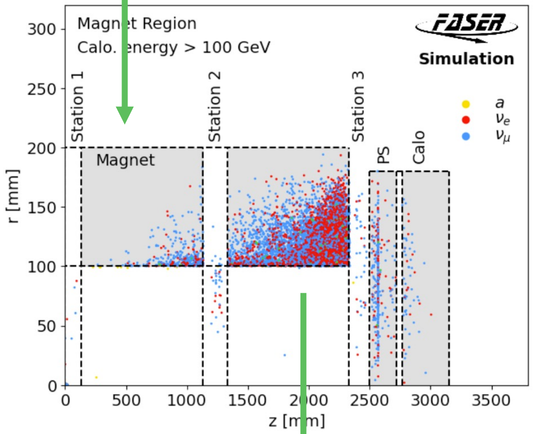


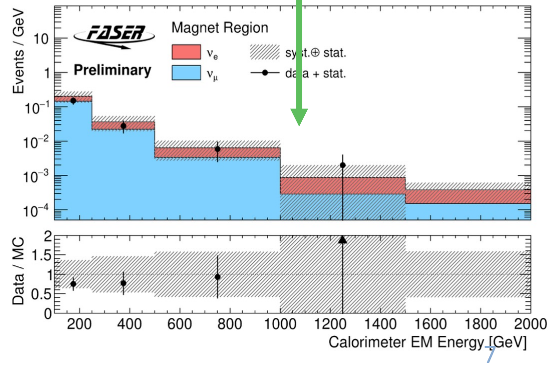
- Preliminary result: **observe 1 event** for exp. background of 0.4 ± 0.4 events







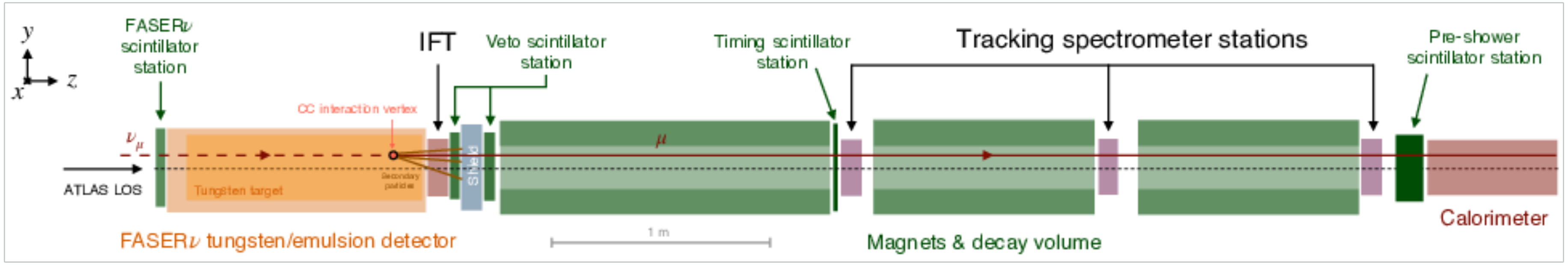




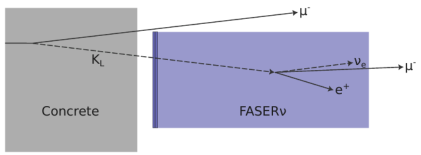
FASER: Muon neutrinos in Electronic Detector

PRL 131 (2023) 031801

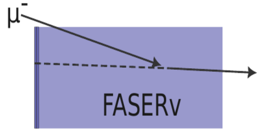
- Muon νs interacting in FASERν tungsten produce a muon that can be detected in spectrometer
  - No signal in front veto but a signal in second veto station + 1 good track with timing/preshower MIP signal
  - Background mainly from neutral hadrons (0.11±0.06 from MC) and large-angle muons (0.08±1.83 from data)



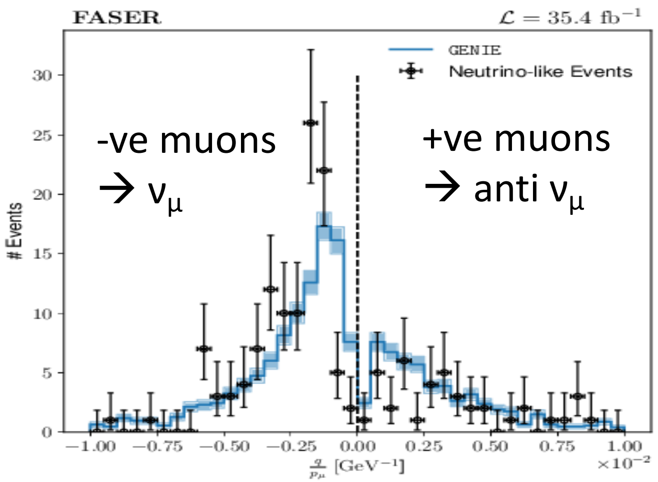
Neutral hadrons



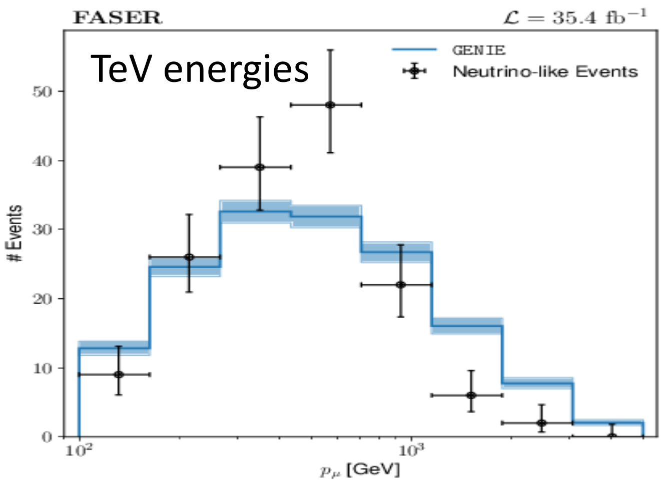
Large-angle μ



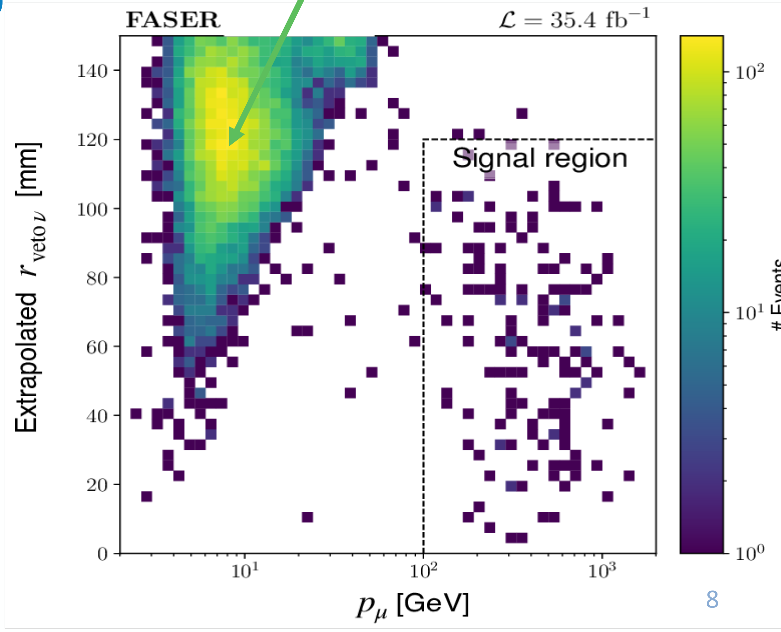
- **Observe 153 + 12 – 13 CC ν_μ interactions** (151 ± 41 exp) in 35.4 fb^{-1}
  - First *direct* observation of collider neutrinos (16σ)!



Muon charge/momentum



Muon momentum

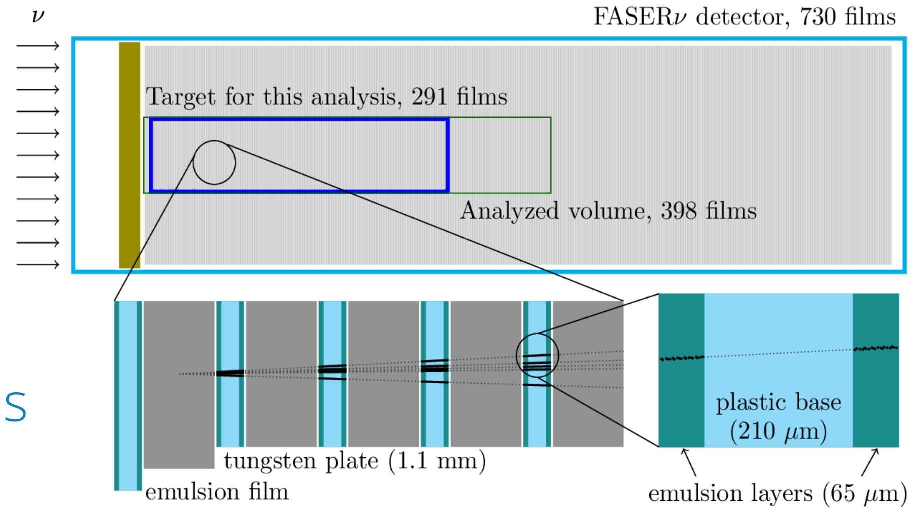


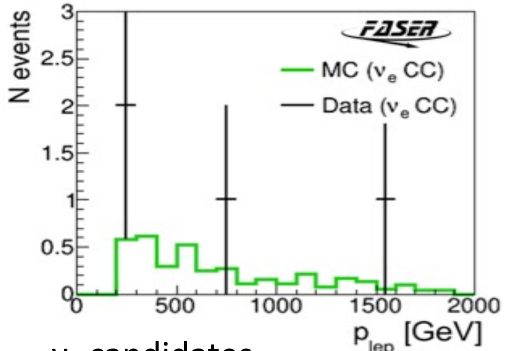
FASER: Neutrinos in Emulsion Detector

NEW

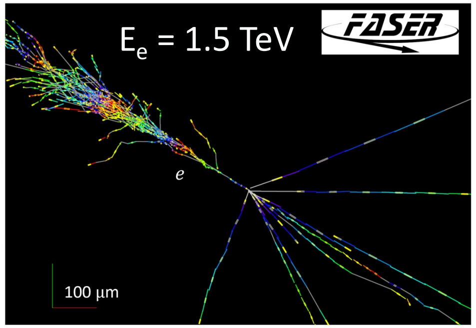
Submitted to PRL

- Analysed fraction of 2022 exposure
- Candidate CC vertices reconstructed & selected by scanning emulsion films
  - Elec energy from shower multiplicity
  - Muon momentum from RMS of MS
- Background mainly from neutral hadrons
  - Produced in muon interactions in rock



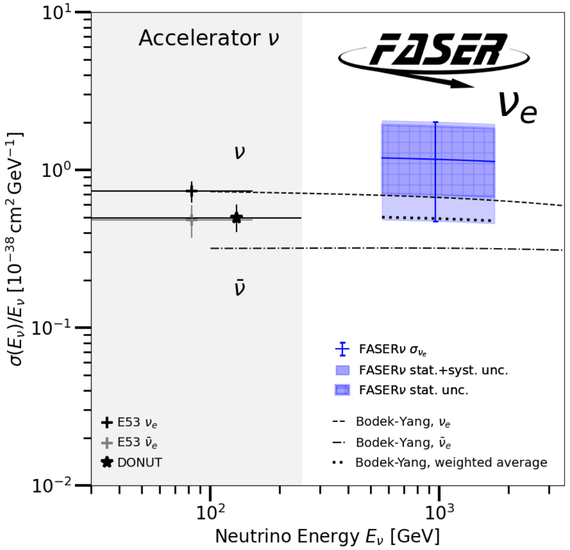


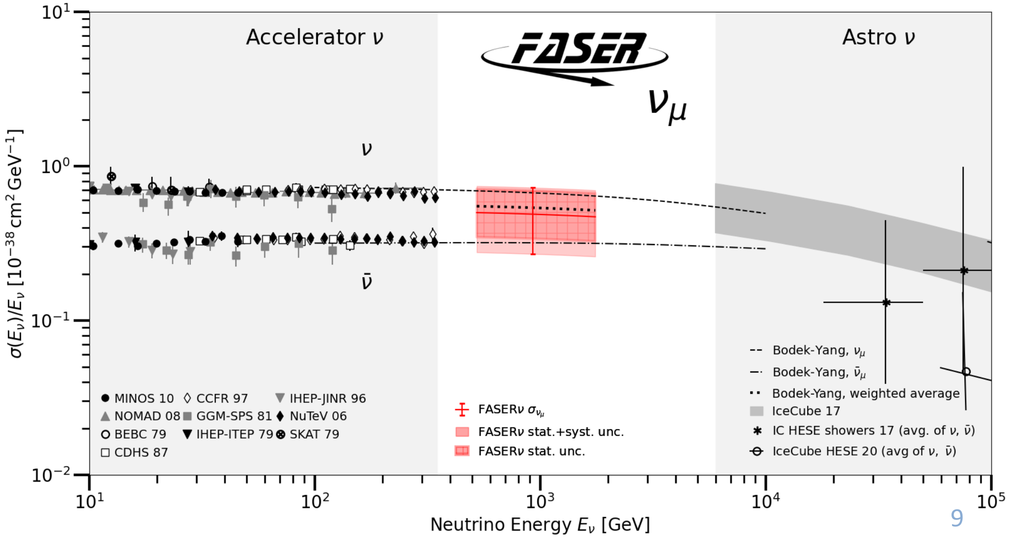
ν_e candidates



- **Measure both ν_e and ν_μ CC cross-section** in unexplored region with 9.5 fb^{-1}
  - Results after vertex selections:

	ν_e	ν_μ
Bkg	0.03 ± 0.01	0.22 ± 0.08
Exp	1.1 – 3.3	6.5 – 12.4
Obs	4	8
Sig	**5.2σ**	**5.7σ**

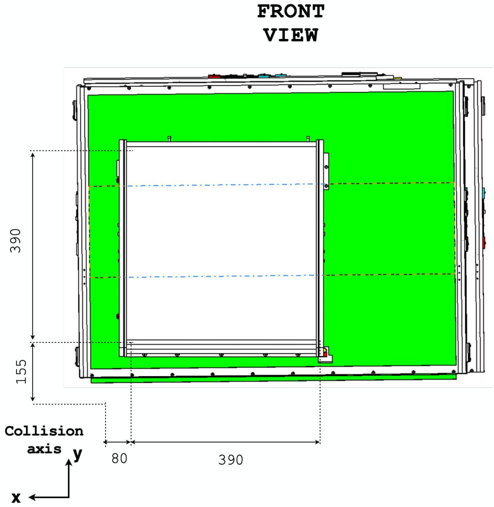




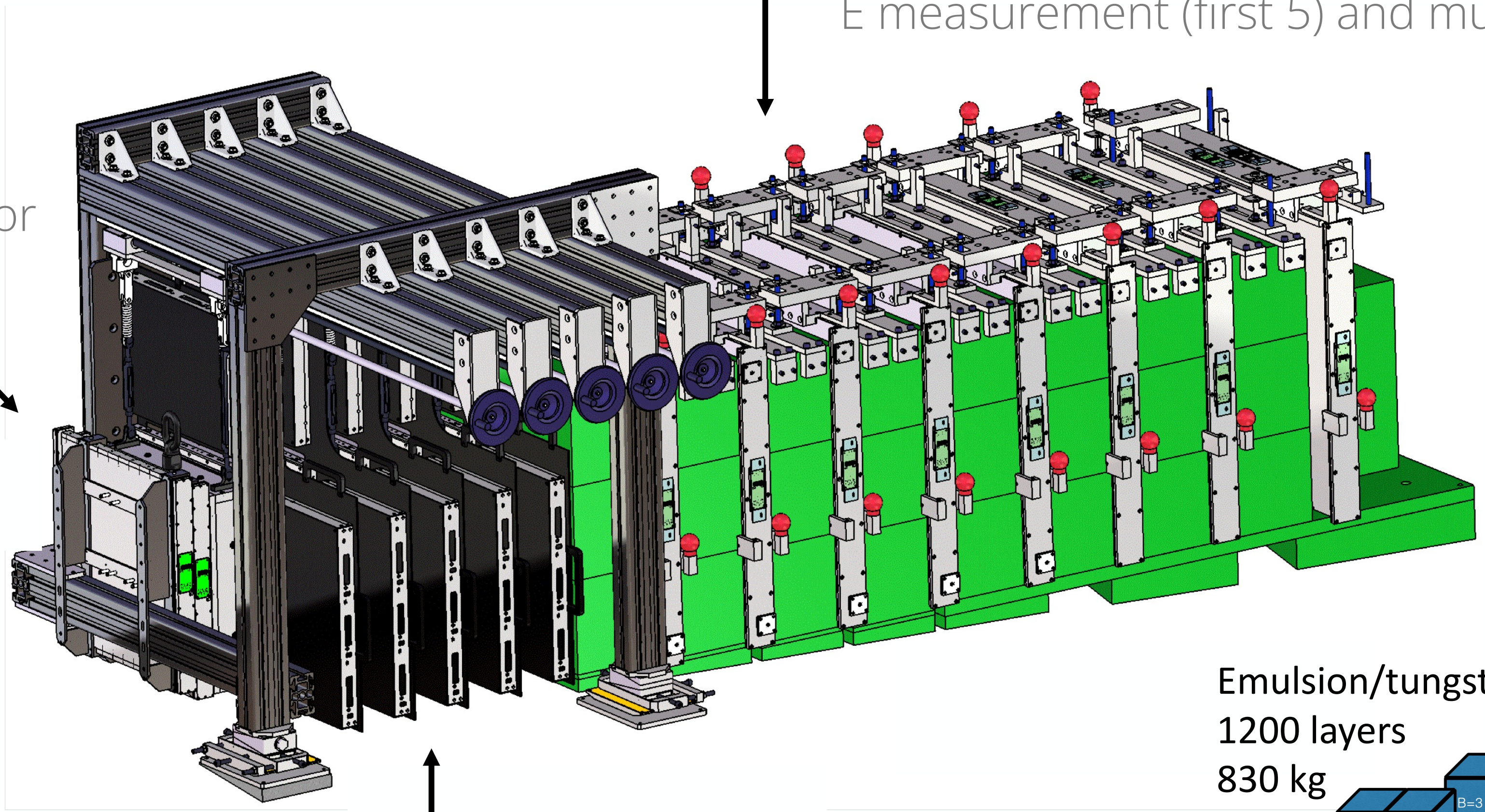
SND@LHC Detector

Detector paper

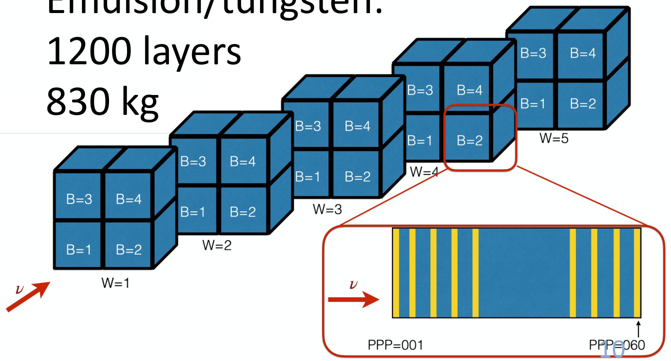
- 1 m x 2.6 m off-axis detector (7.2 < η < 8.4)
- Veto
  - 2+1 (2024) scintillator layers to tag muons



- Hadronic calorimeter and muon system
  - Iron interleaved with plastic scintillator for had. E measurement (first 5) and muon ID (last 3)



Emulsion/tungsten:
1200 layers
830 kg

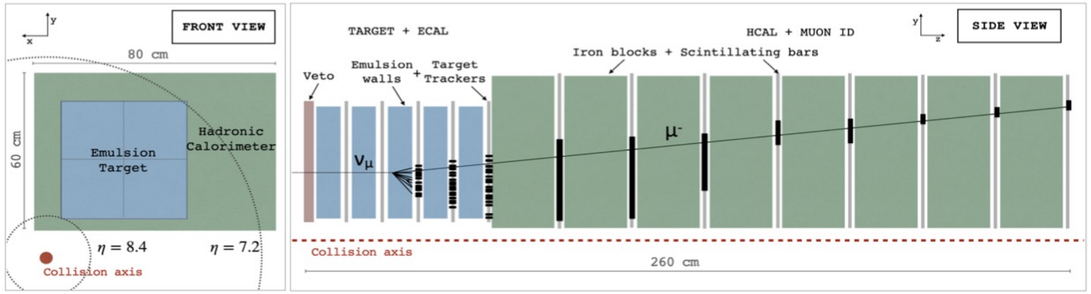


- Vertex detector and EM calorimeter
  - 5 sets of emulsion/tungsten to detect neutrino interactions
  - 5 sets of scintillating fibres for timing and E measurement

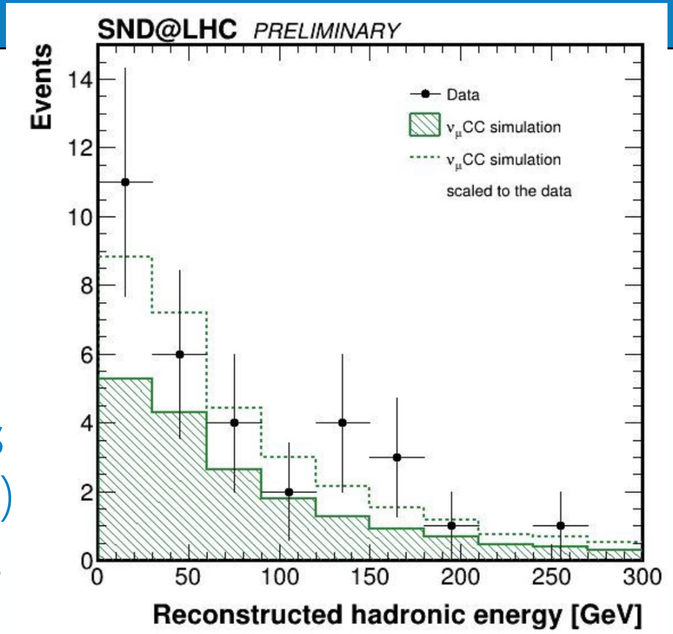
SND@LHC: Neutrinos

PRL 131 (2023) 031802 Moriond QCD Talk

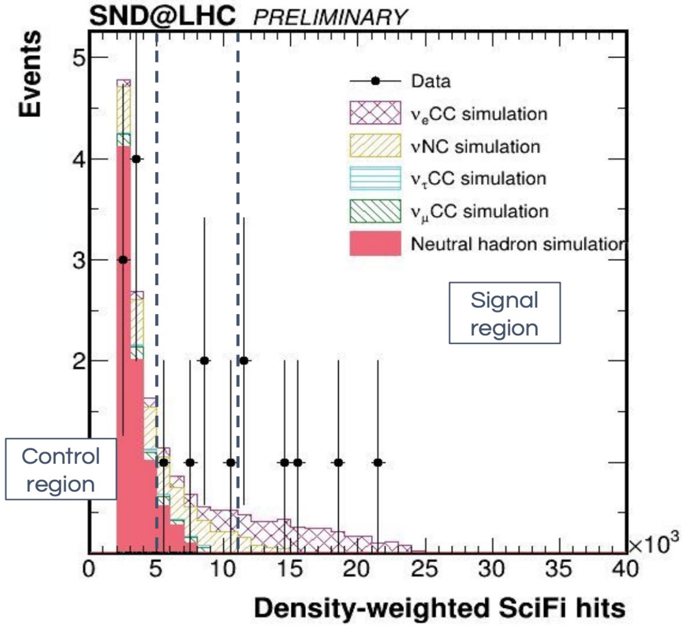
- **CC ν_μ**: updated result with extended fiducial volume + 2023 data
  - Look for event interacting after 1st target wall with no veto signal
  - Large SiFi and HCal activity + 1 muon track associated to vertex
  - Predict 0.25 ± 0.06 background events mainly from neutral hadrons (MC)



- **Observe 32 ν_μ CC events** in 68.6 fb^{-1} (19.1 ± 4.1 exp)
  - Rate high but kinematics agree with prediction



- **NC + CC ν_e**: shower-like events with no muons in 2022 + 23 data
  - No veto signal, large SiFi & HCal activity, no hits in last 2 muon layers,
  - Predict 0.20 ± 0.11 background events mainly from ν_μ and ν_τ (MC)



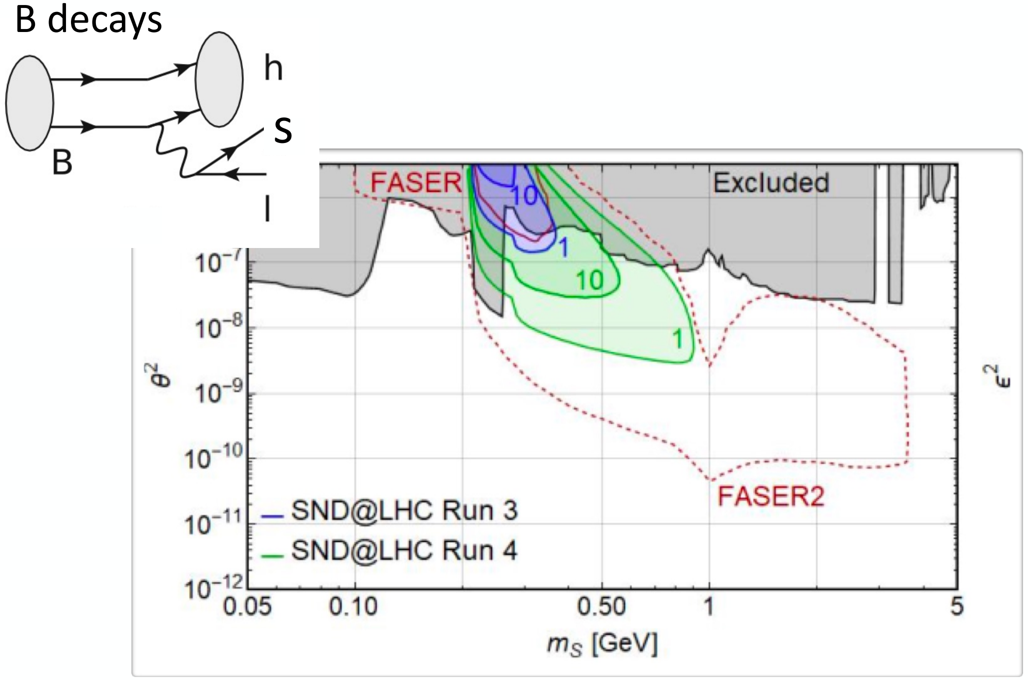
- **Observe 6 events** in 68.6 fb^{-1}, compared to 4.66 expected signal
  - 4.7σ observation of NC + CC ν_e
  - Paper in preparation

SND@LHC: Hidden Sector Projections

JHEP 03 (2022) 006

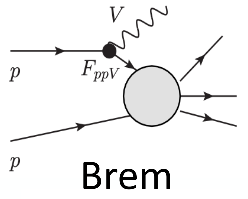
- Beyond its primary neutrino goal, SND@LHC also has predicted sensitivity to hidden-sector particles

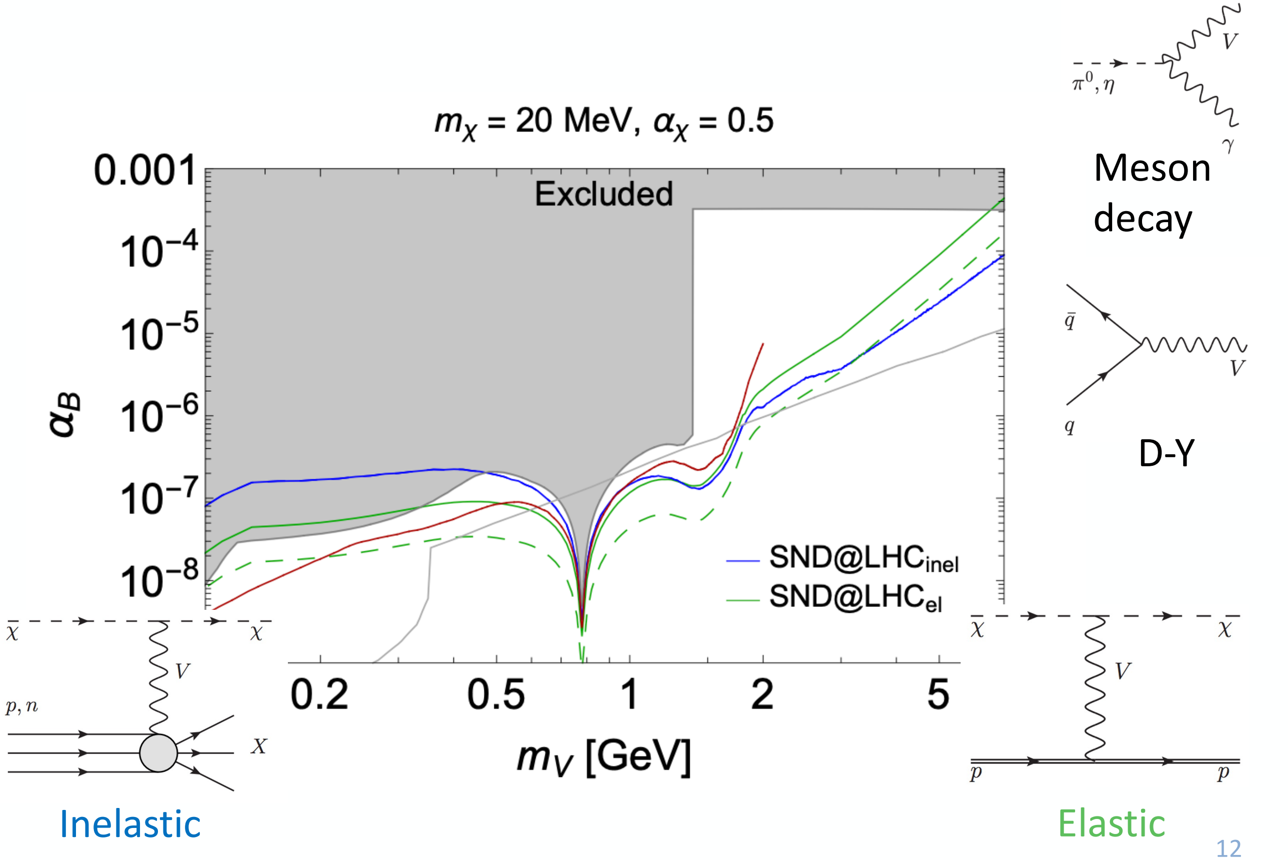
- Decay signature
  - **Dark scalars (s)**, dark photons, HNLs
  - Decaying into pair of charged tracks



- Stay tuned for first BSM search results

- Scattering signature
  - E.g. **Leptophobic DM (χ)** interacting with nucleus via vector portal (V)



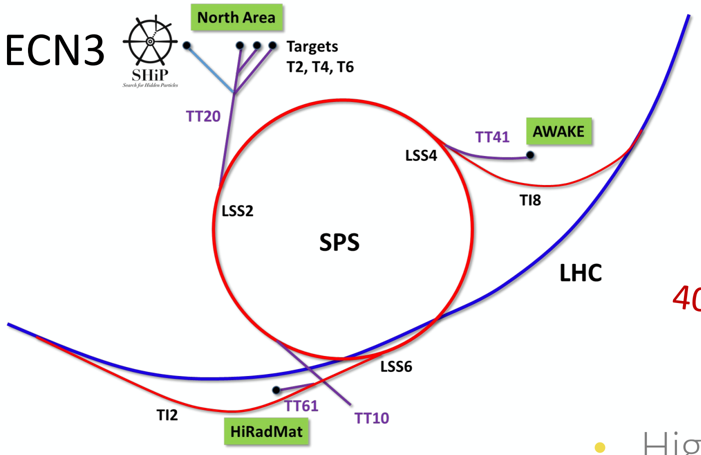


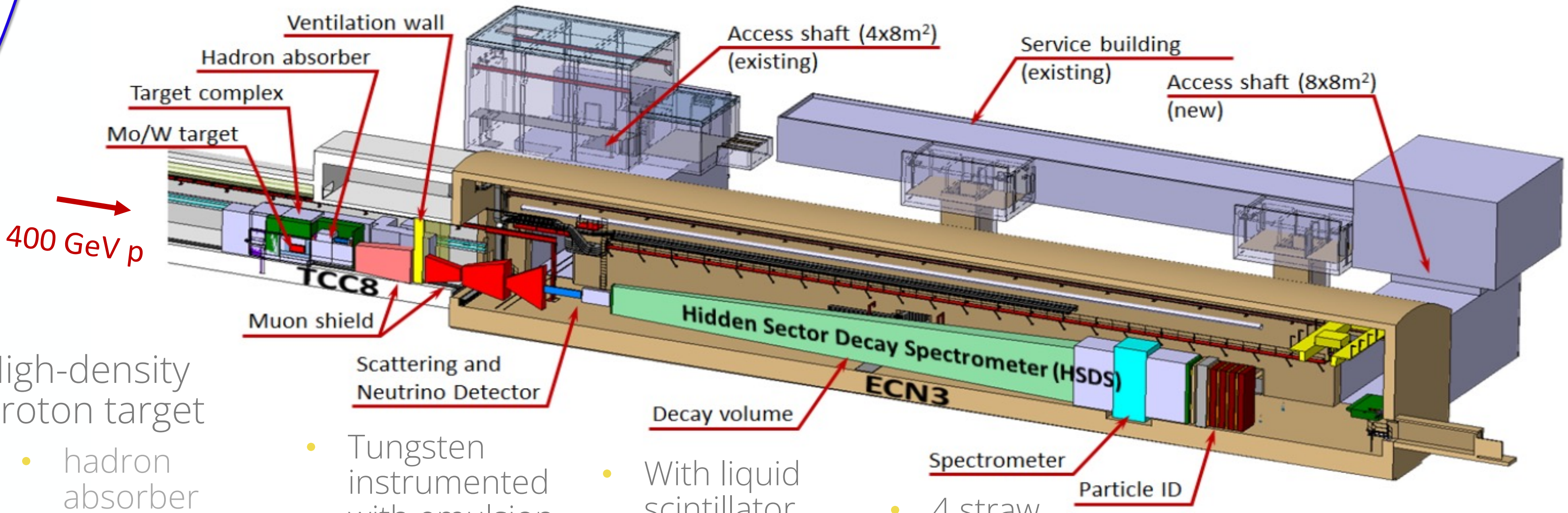
Future Experiments

SHiP Experiment

Letter of Intent

- New dedicated beam-dump experiment recently approved for ENC3 cavern at CERN's SPS NA
  - Aiming for TDR in 2026, followed by PRR and installation in 2028/9
  - Start data-taking in latter half of run 4, aiming to collect 6 x 10^{20} POT over 15 years





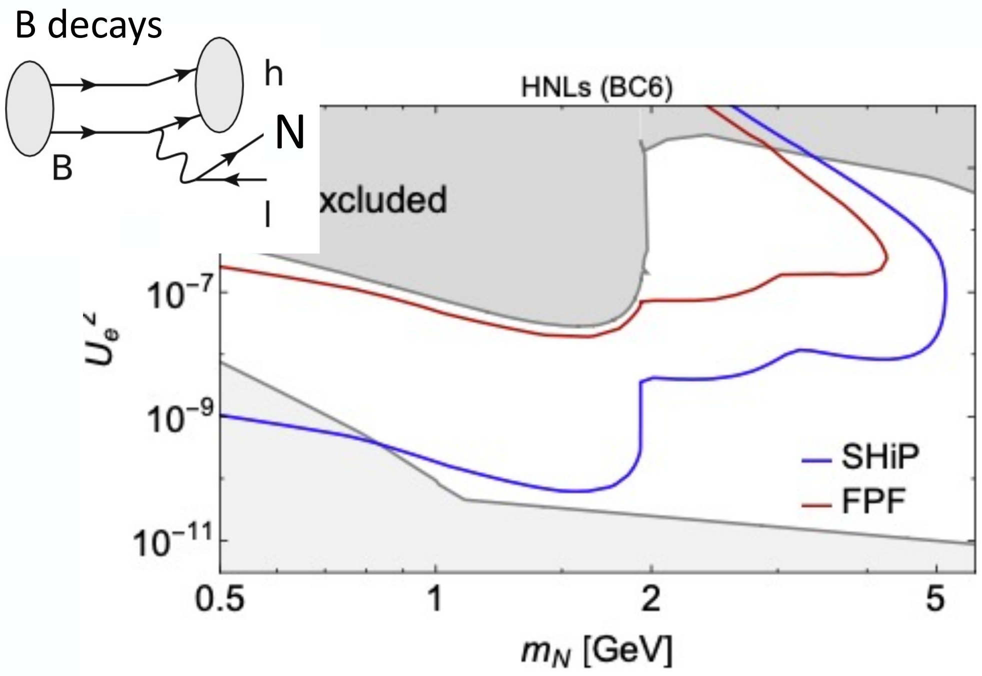
- High-density proton target
  - hadron absorber
  - muon shield
- Tungsten instrumented with emulsion
- With liquid scintillator bkg tagger
- 4 straw trackers in B=1 T
- EM Calorimeter
- 3 muon layers

- Currently 4 UK institutes: Bristol, Imperial (spokesperson), UCL, Warwick
  - But several more interested in joining now formally approved

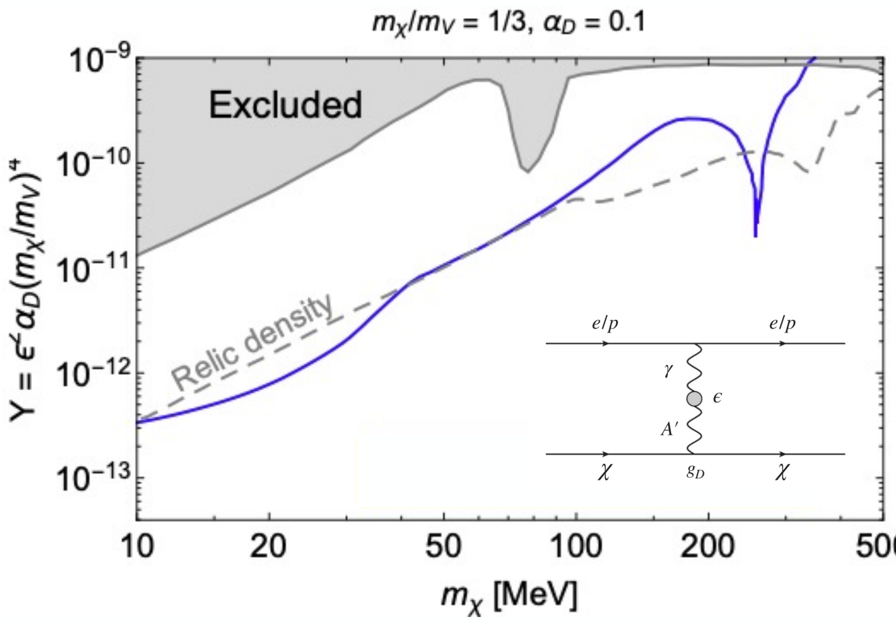
SHiP Physics Reach

- World-leading sensitivity to a wide range of Hidden sector models, probing uncovered phase space

- Decay signature:
  - Dark scalars, dark photons, **HNLs (N)**, ALPs



- Scattering signature:
  - E.g. **Light dark matter** interacting with e or p via vector portal (V)



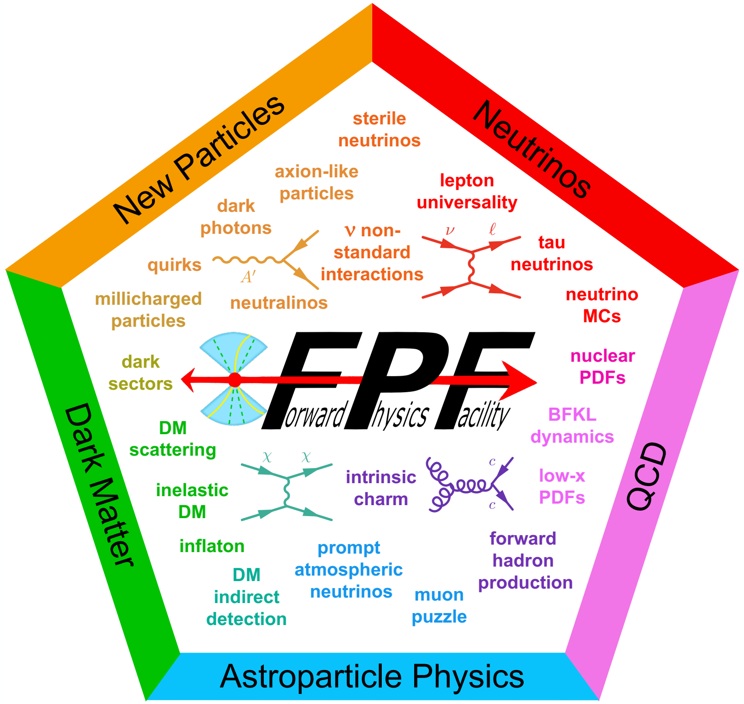
- In addition, large sample of neutrinos up to ~100 GeV
  - Especially ν_τ from $D_s \rightarrow \tau\nu$
  - Measure cross-sections for neutrino oscillation expts.

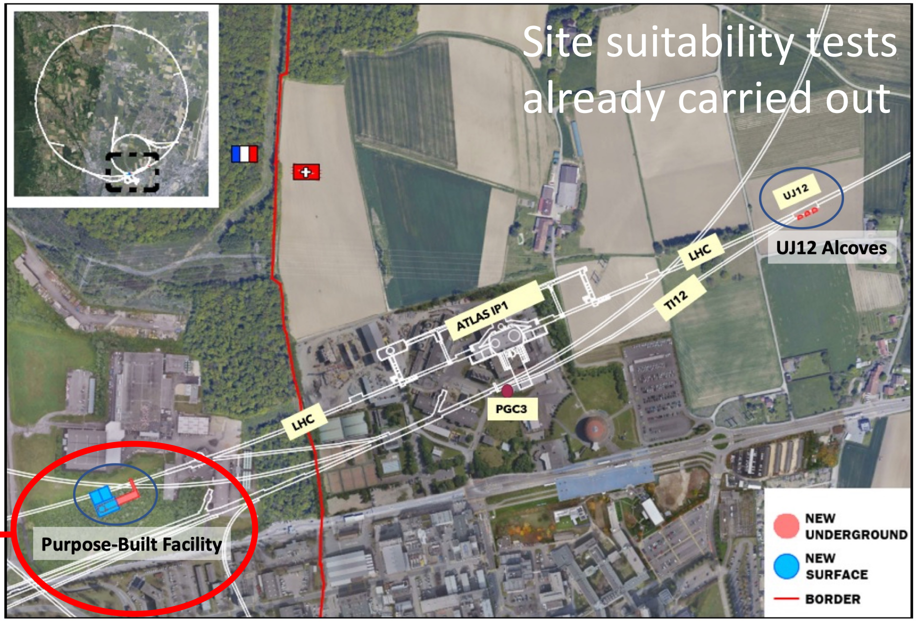
	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^{6}
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^{6}
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^{4}
$N_{\bar{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^{5}
$N_{\bar{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^{6}
$N_{\bar{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^{4}

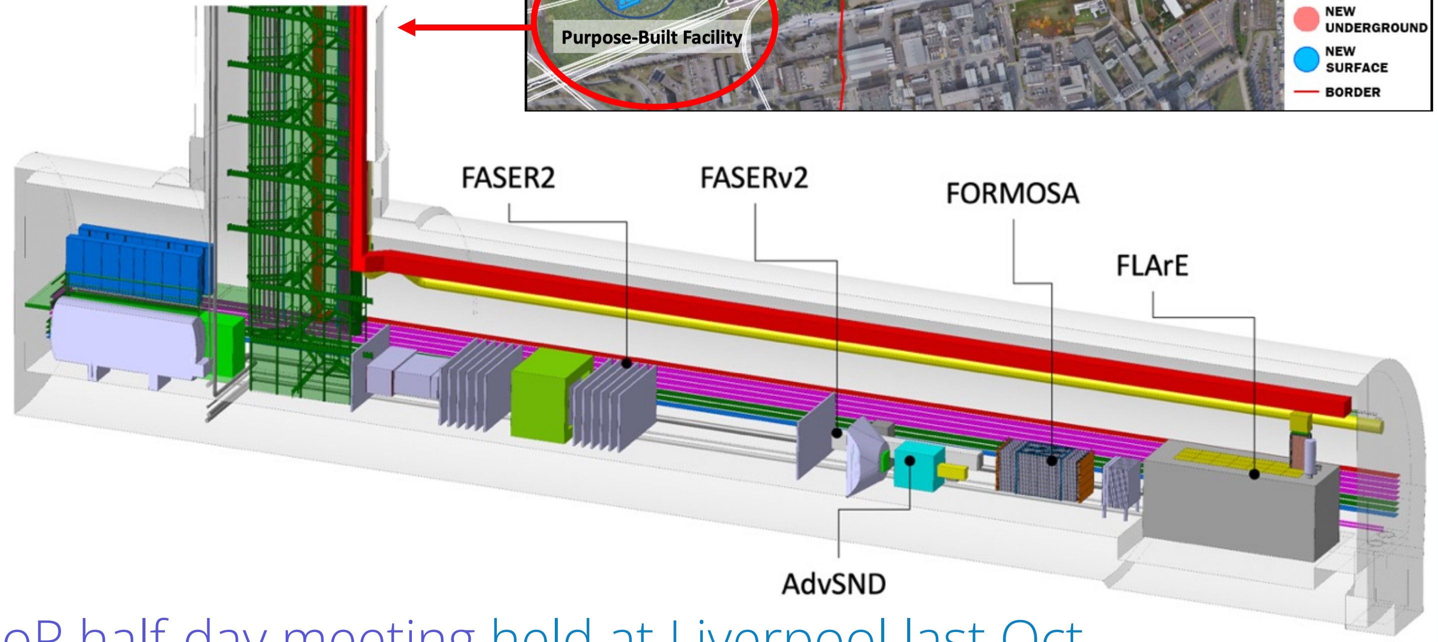
Forward Physics Facility (FPF)

White paper

- Proposed dedicated forward-physics facility at the HL-LHC
  - New ~65m long cavern, 620 m from ATLAS
- 5 dedicated experiments with very broad physics program
  - New particles, DM, neutrinos, QCD, astroparticle physics
- Conceptual design ongoing, aiming for LoI in early 2025
  - Could take data in late run-4 (FASER approved for run 4)



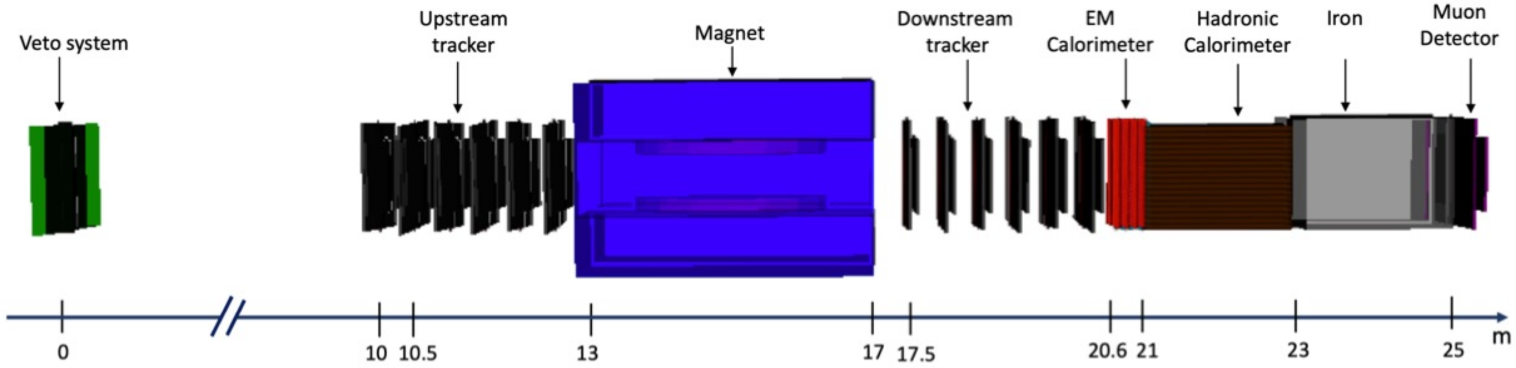




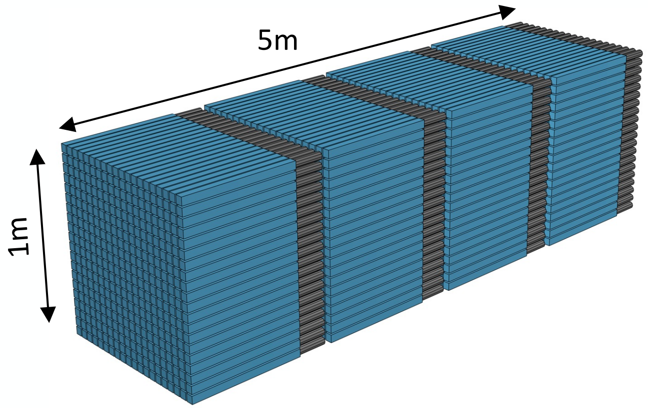
- IoP half-day meeting held at Liverpool last Oct
  - Significant UK interest across several institutes

FPF Experiments

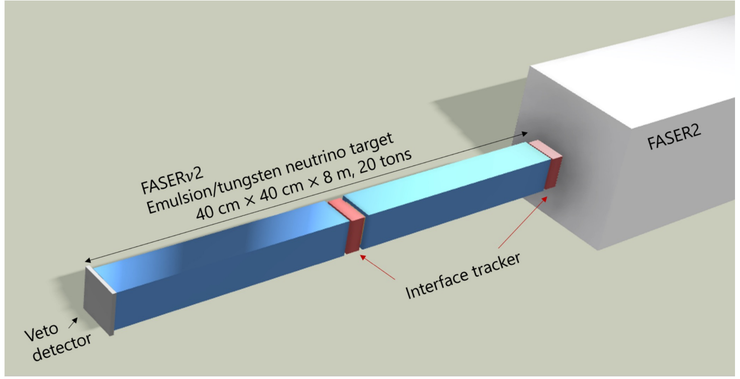
- FASER 2: 3 m^2 aperture spectrometer in B = 2-4 T field
  - 1000x decay volume for LLP searches

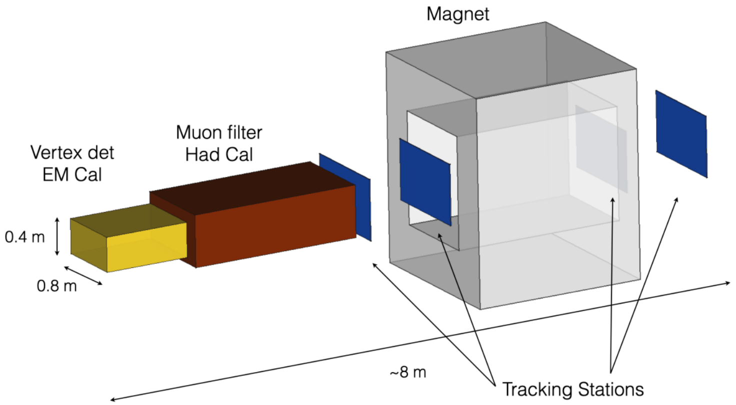


- FORMOSA: W + plastic scintillator
  - For milli-charged particles



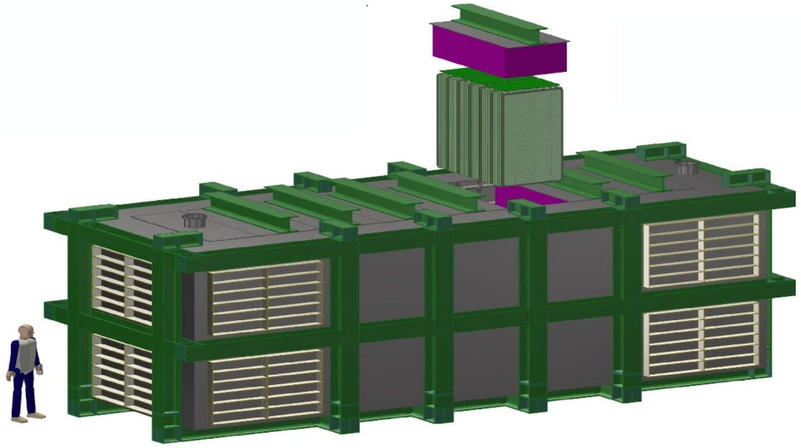
- On- and off-axis neutrino detectors with 10x target mass
  - FASERν 2: 20T W + emulsion
  - AdvSND: electronic detector





(Also investigating Ti18 upgrade)

- FLArE: 10T LAr TPC
  - For neutrinos and DM

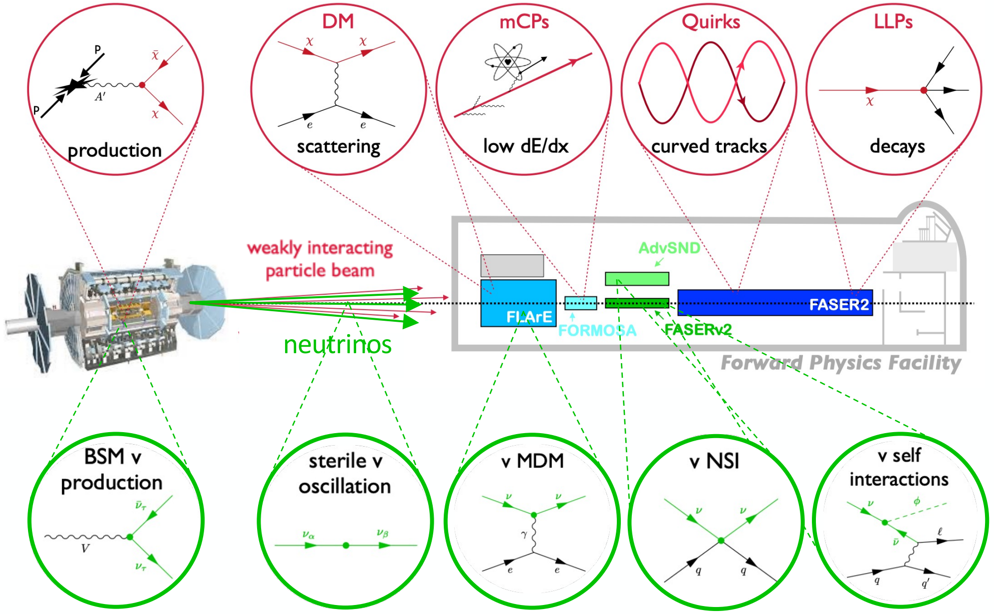


FPF Physics Potential

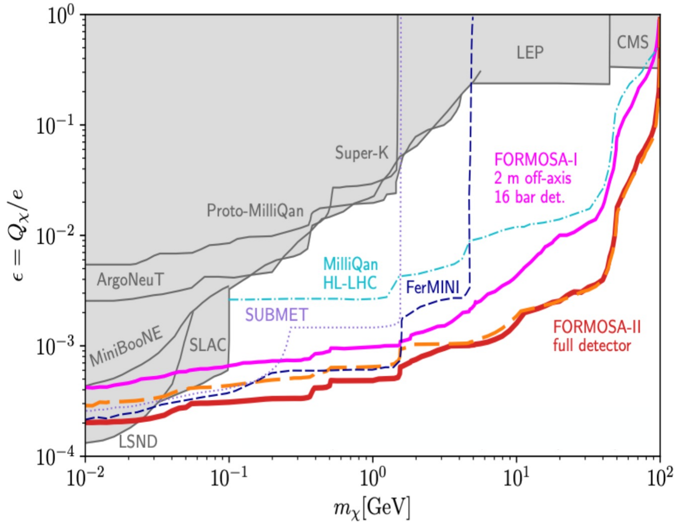
White paper
PRD 104 (2021) 035014
PRD 99 (2019) 095011

- Hidden sectors

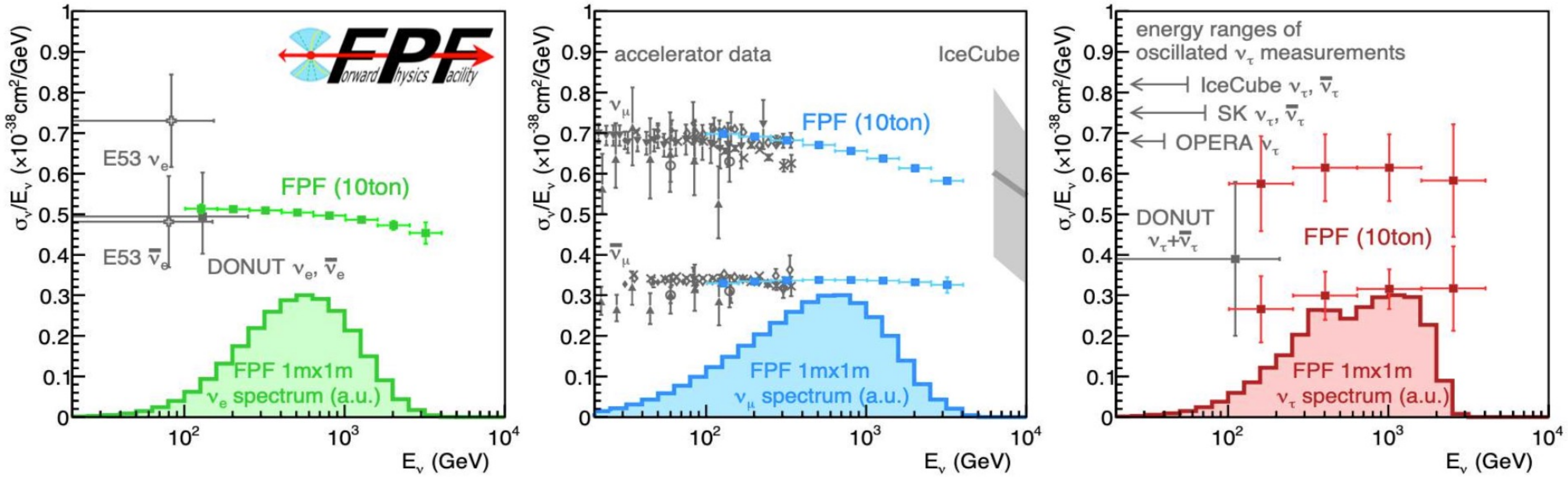
Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√



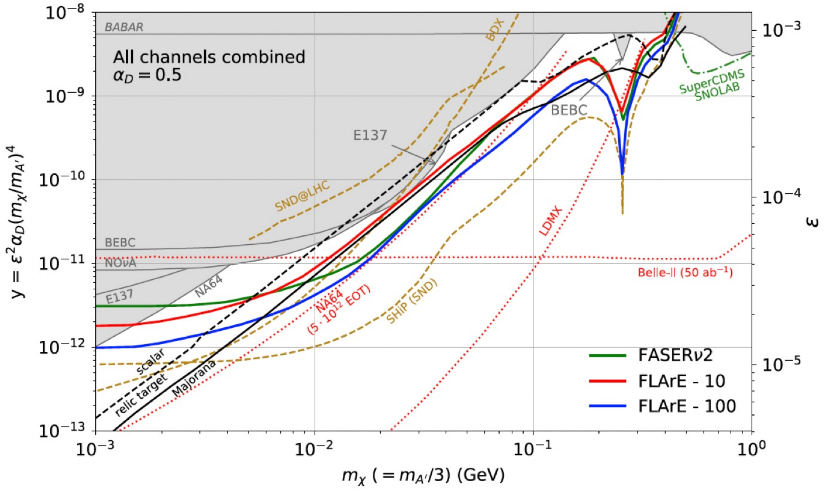
- Millicharged particles



- Differential ν flux measurements for all flavours at TeV



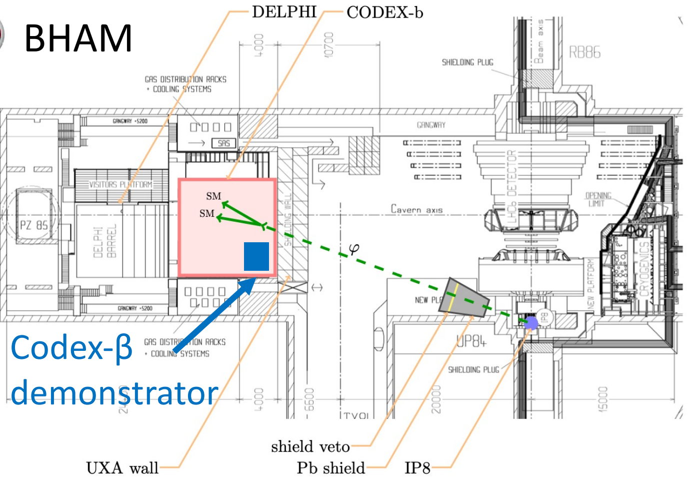
- Light DM scattering



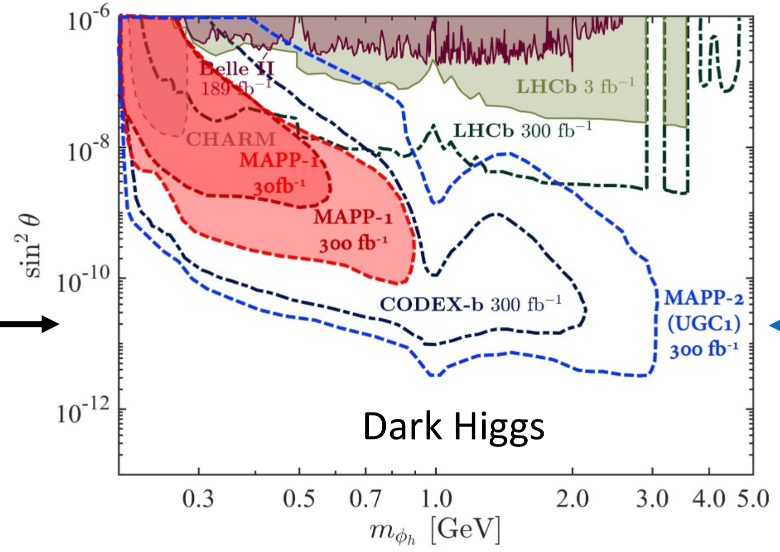
Other Proposals with UK involvement

- **CODEXb**: 25m away (transverse)
  - RPC for Run 4 (β prototype now)

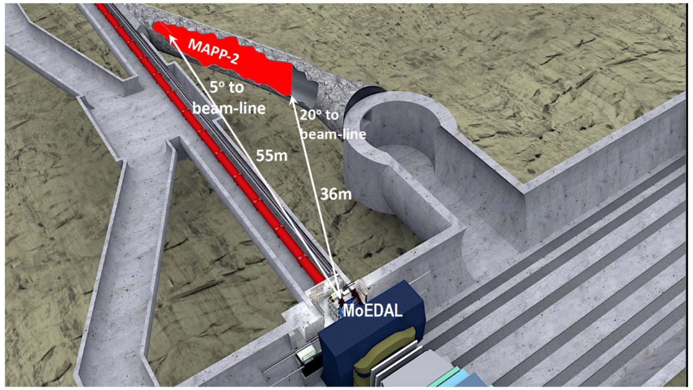
BHAM



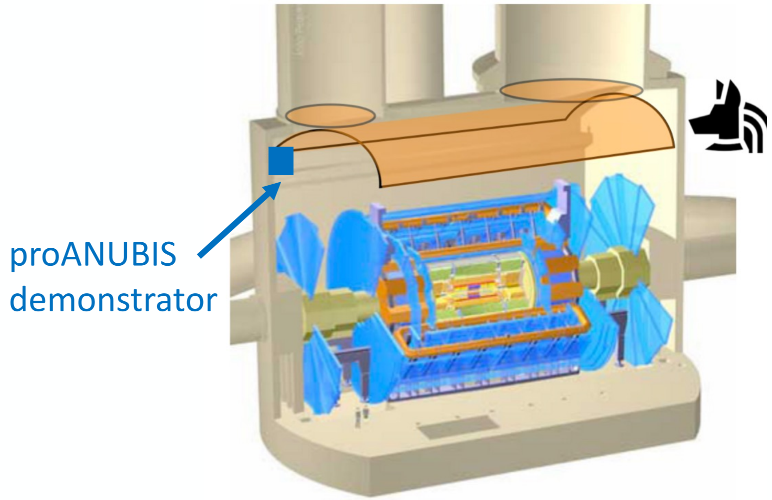
LHCb (IP8)



- **MoEDAL-MAPP**: 55m away (forwards)
  - Scintillator + PMT for HL-LHC

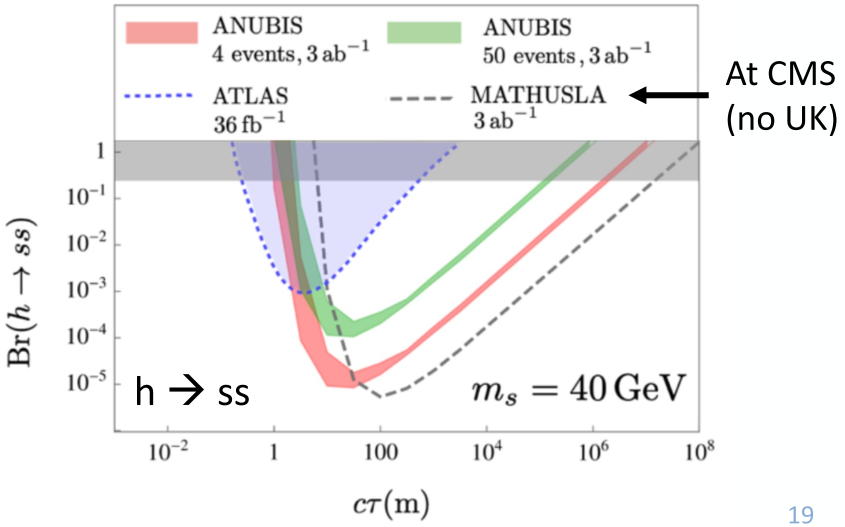


Bristol, Imperial, KCL, QMUL



- **ANUBIS**: 25m from ATLAS (transverse)
  - RPC for HL-LHC
  - proAnubis demo.

CAM, Durham



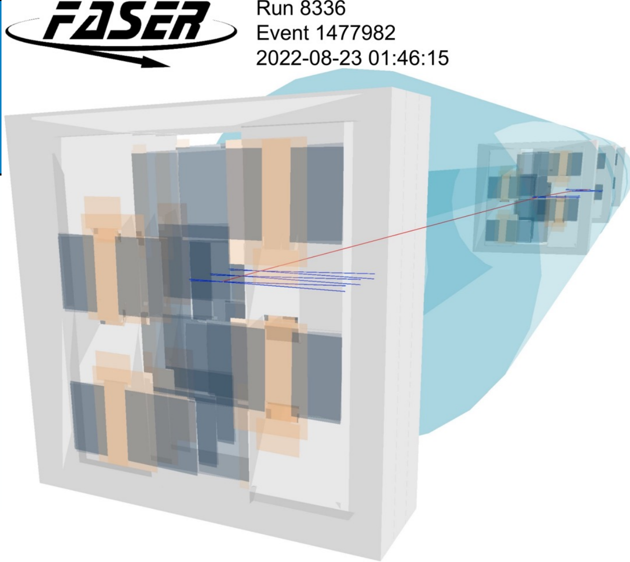
Conclusions

- Growing interest in searches for long-lived weakly interacting particles
  - With several experiments taking data and many more planned / proposed
- Current experiments showcase the power of small, inexpensive detectors
  - Providing a wealth of complementary physics results in previously unexplored areas
- In addition to FIPs, they provided first direct observation of TeV-scale neutrinos from colliders
  - Opening up a new frontier in neutrino measurements and a new window for discovery
- Proposed programs are highly complementary
  - Different models, lifetimes and masses probed
- UK well placed to exploit these

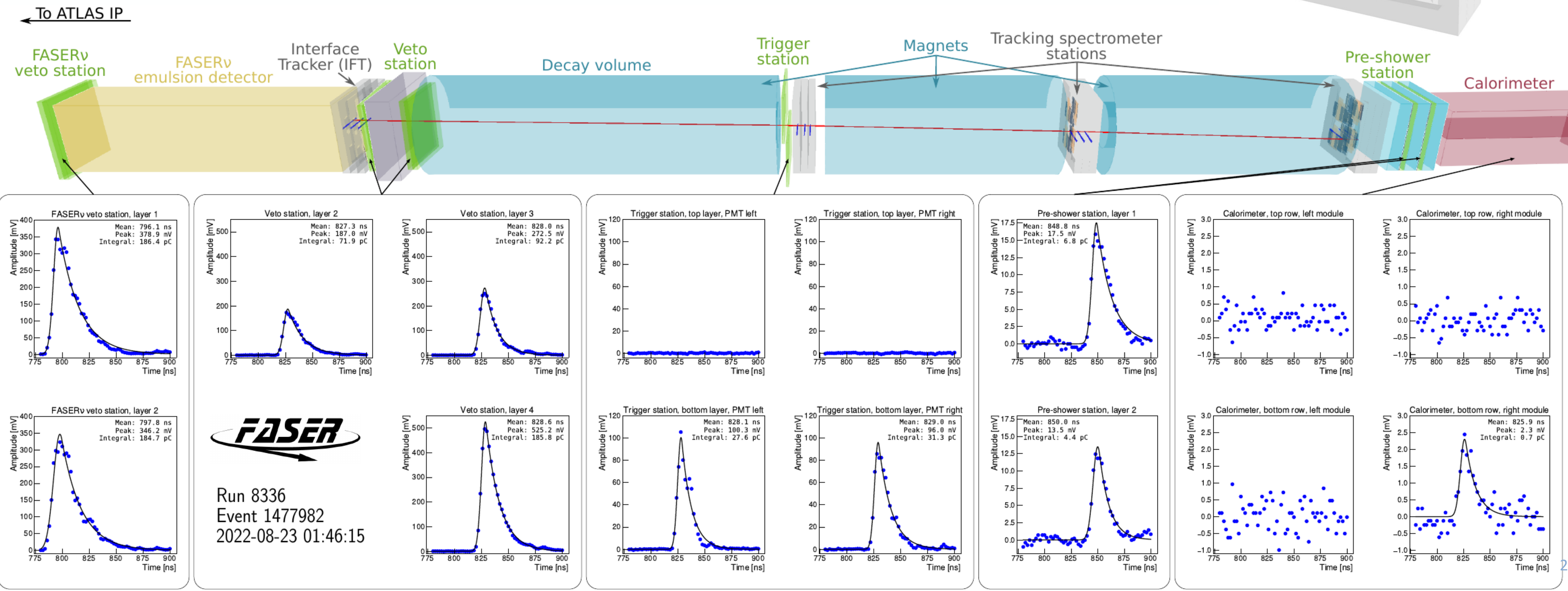
Backup

Successfully Installed in Ti12

FASER Operations

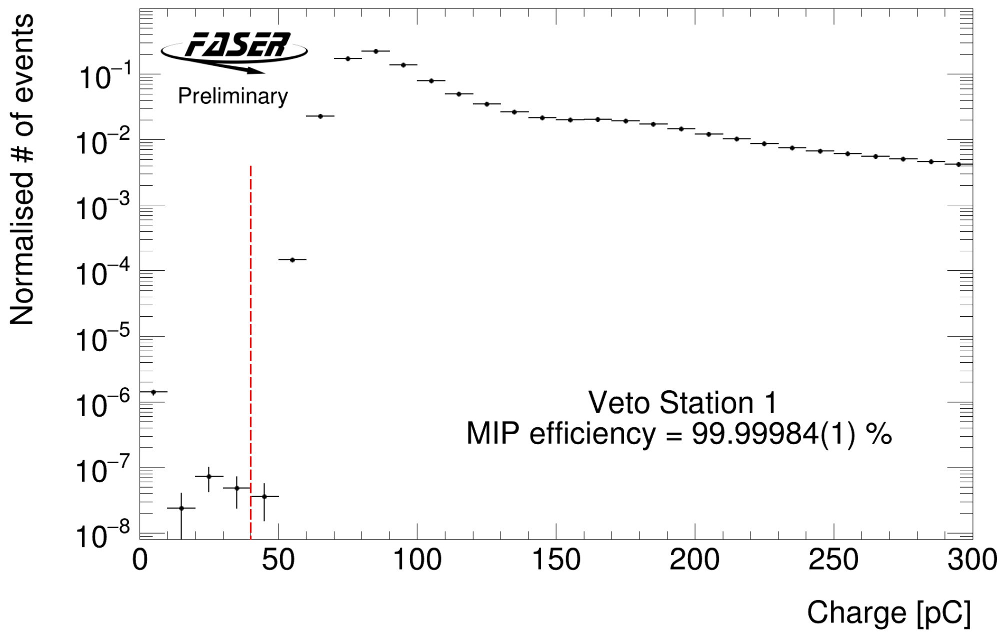


- All detector components performing excellently
- More than 350M single-muon events recorded
  - Example: muon leaving track passing through full detector + scintillator/calorimeter deposits consistent with MIP

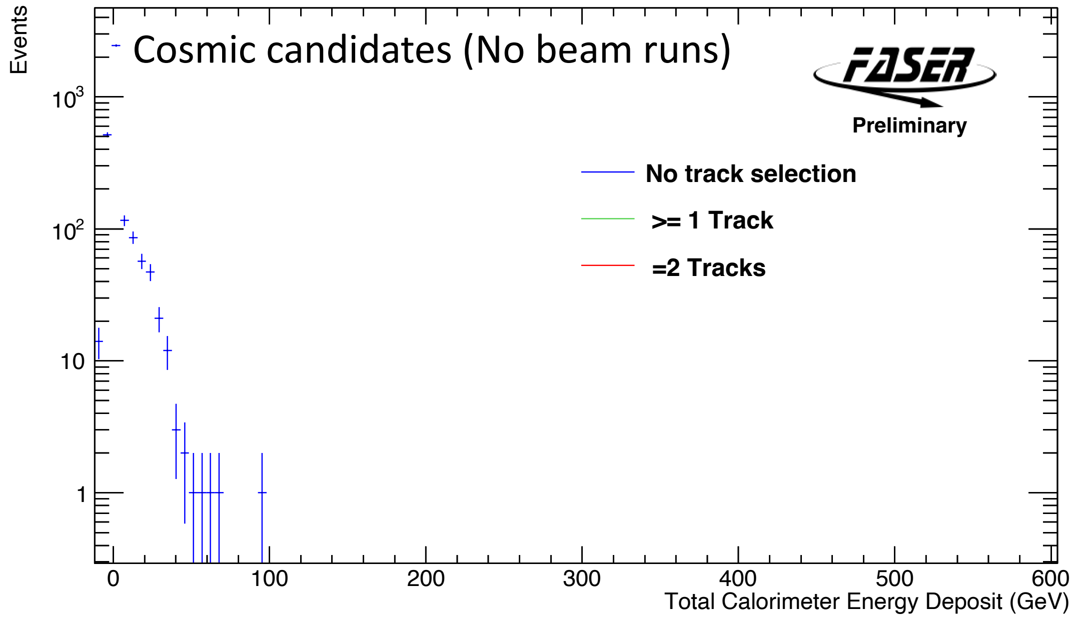


FASER: Dark Photon Backgrounds

- Veto inefficiency
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. 10^8 muons to negligible level (even before cuts)



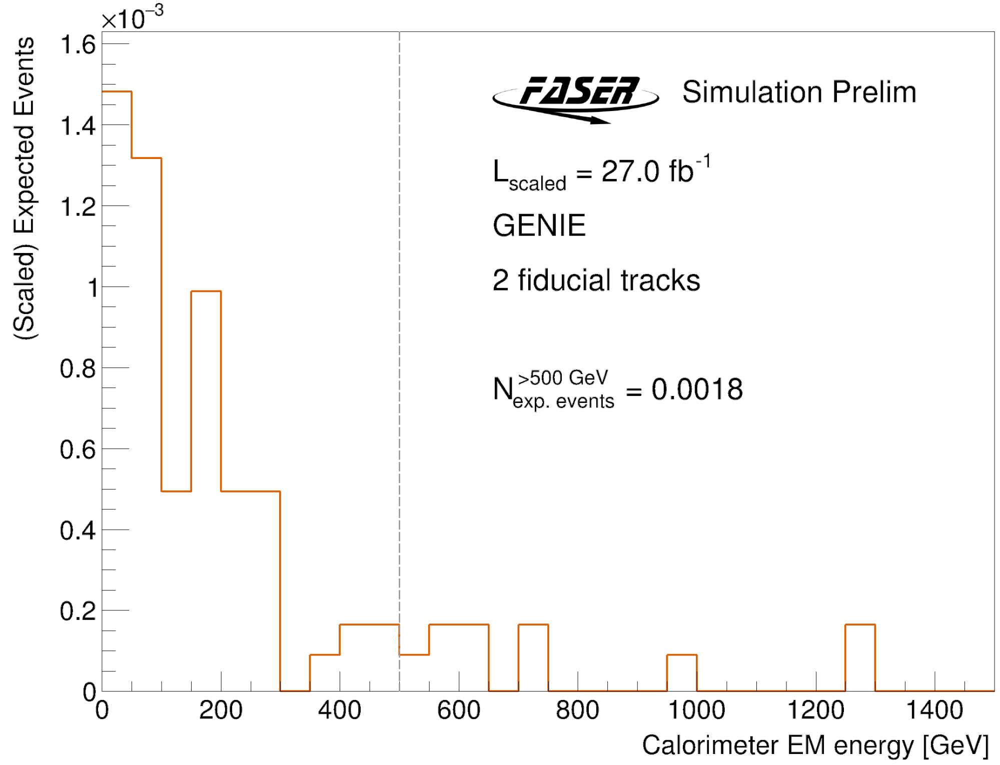
- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually



FASER: Dark Photon Backgrounds (2)

- Main background is from neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab^{-1})
    - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

$$N = (1.8 \pm 2.4) \times 10^{-3}$$



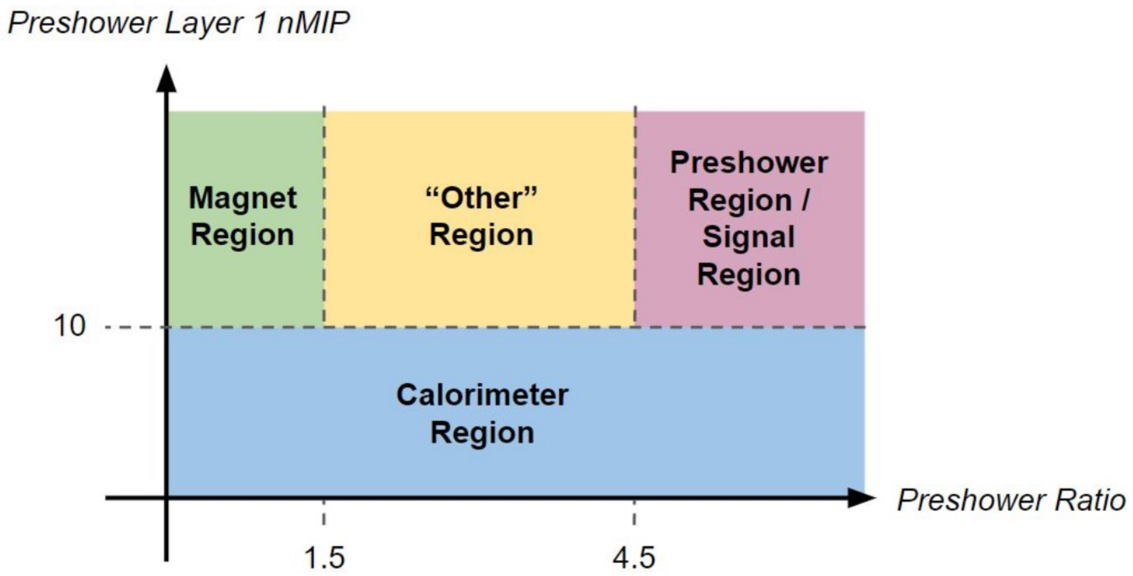
- Neutral hadrons (e.g. K_S) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed since:
    - Muon nearly always continues after interaction
    - Has to pass through 8 interaction lengths (FASERν)
    - Decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

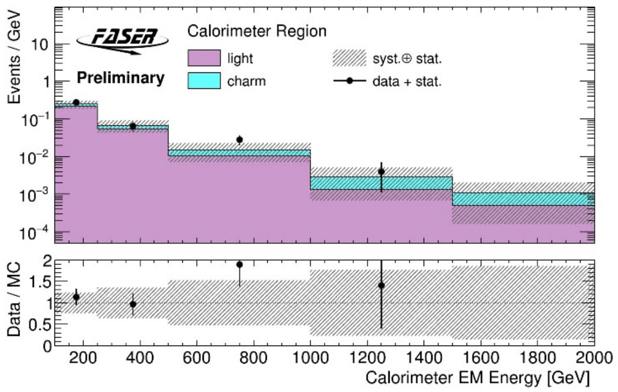
$$N = (2.2 \pm 3.1) \times 10^{-4}$$

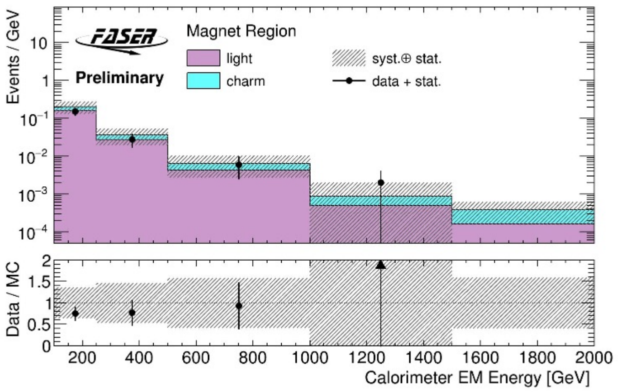
- Total background prediction

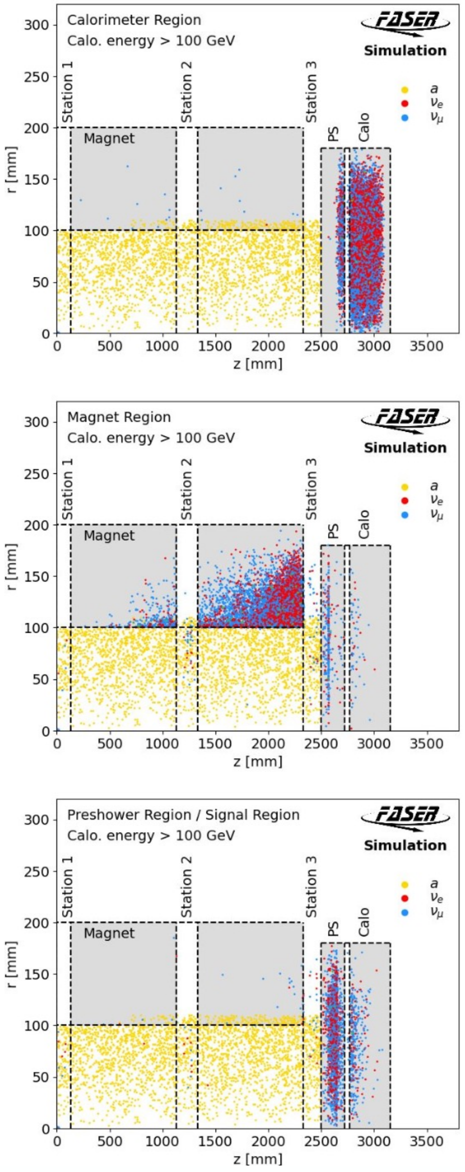
$$N = (2.02 \pm 2.4) \times 10^{-3}$$

FASER: ALPs backgrounds







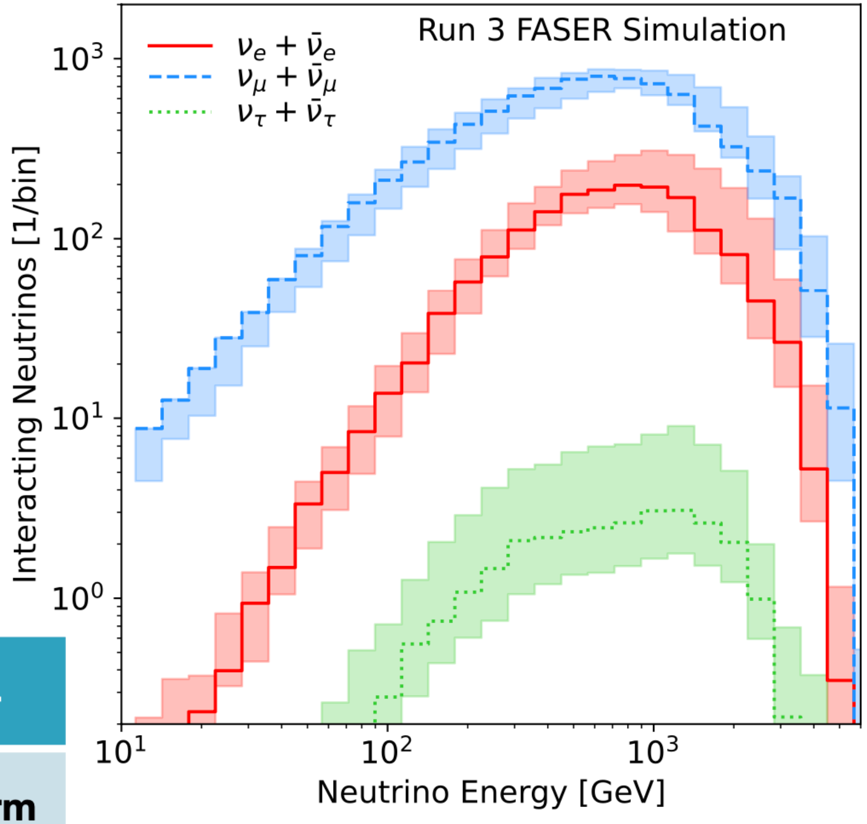


LHC Neutrinos

- Copious production of neutrinos in forward region
- All species produced at ~TeV energy range
- Allows first direct observation of ν from collider

R3: 250 fb^{-1}	ν_μ	ν_e	ν_τ
Primary Source	Pions	Kaons/ Charm	Charm
Traversing FASER	~10^{12}	~10^{11}	~10^{9}
Interacting in FASERnu	8,500	1,700	30

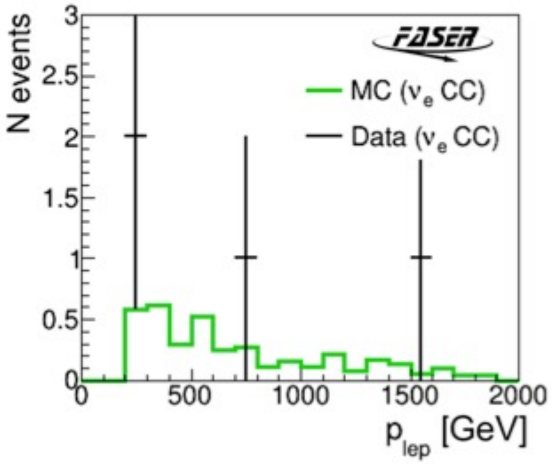
Spectrum of interacting ν



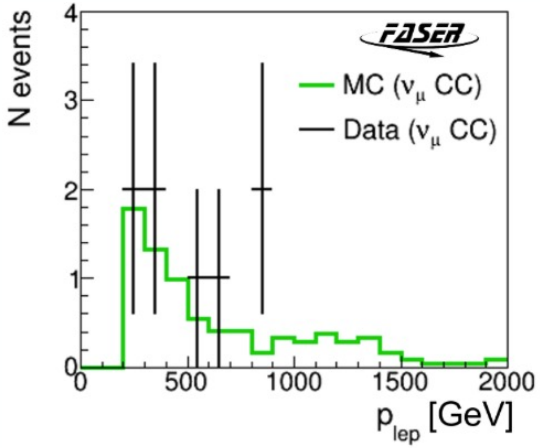
Rate Paper: arXiv: 2402.13318

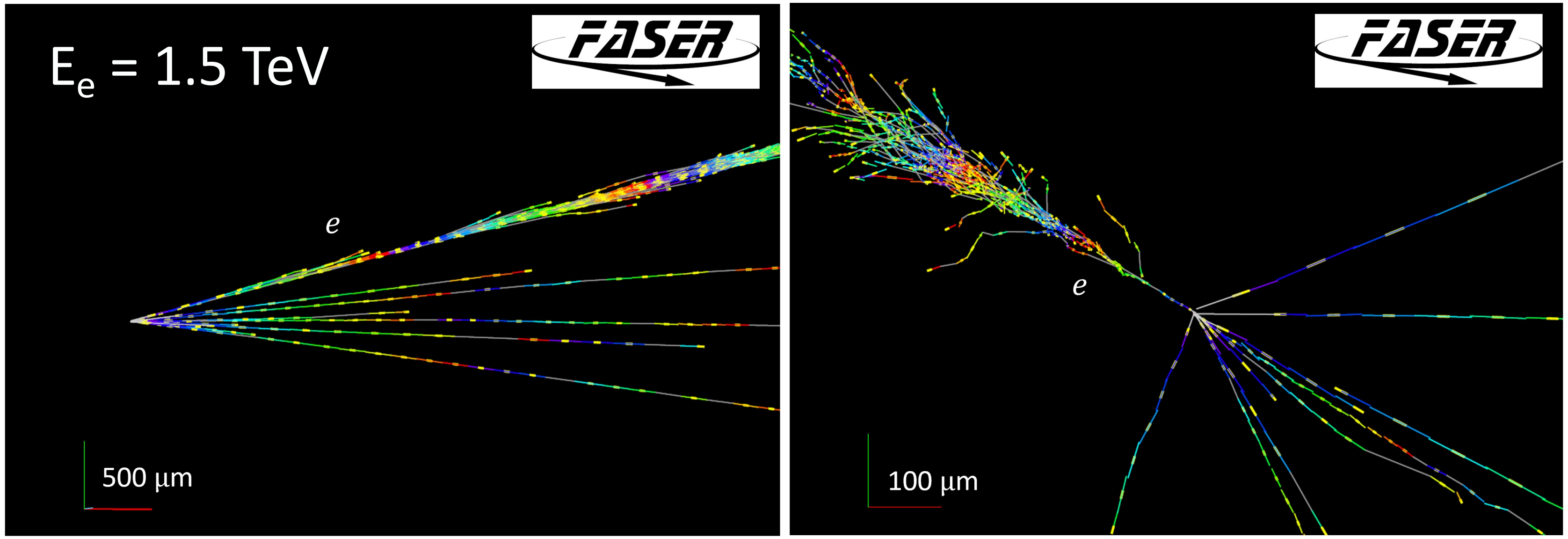
FASER: Neutrinos in Emulsion Detector

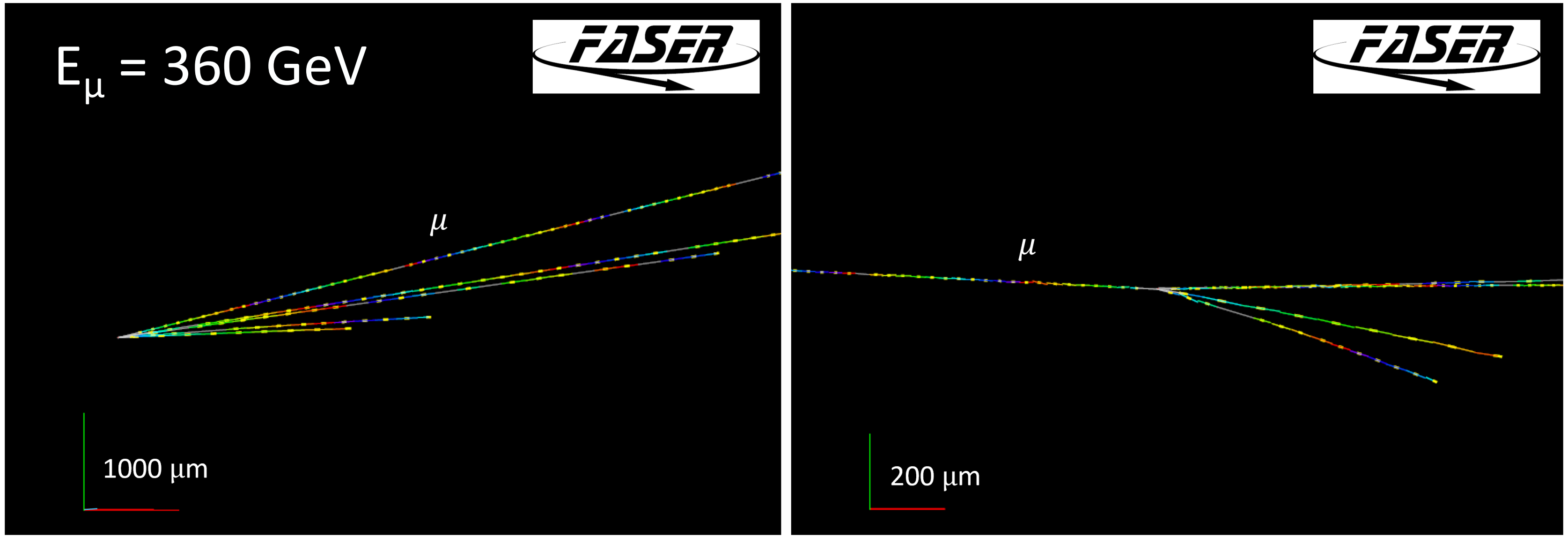
- Electron neutrinos



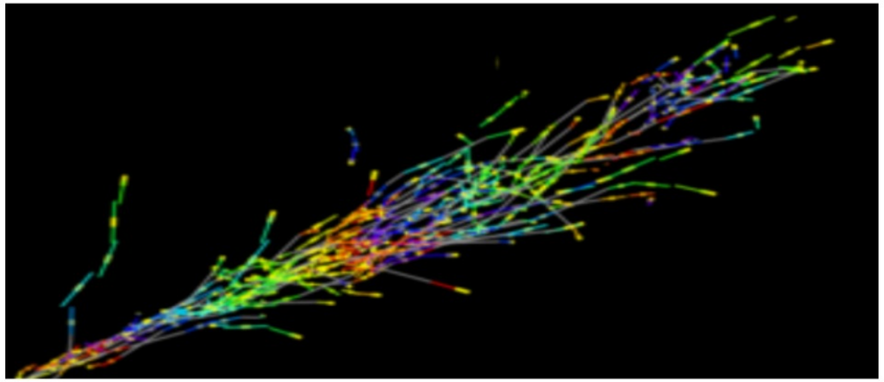
- Muon neutrinos

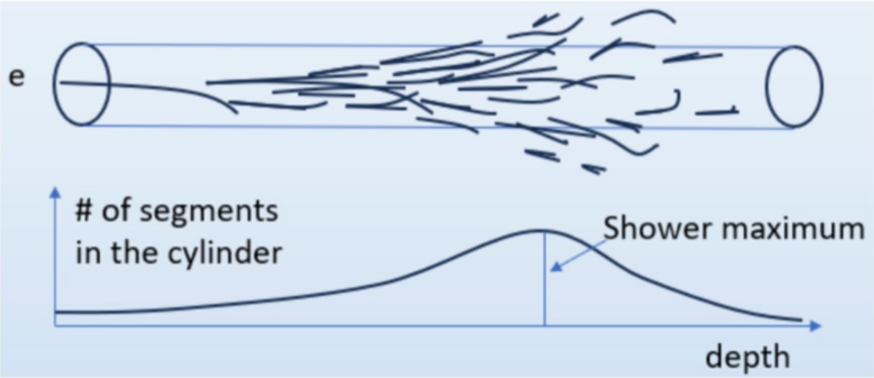


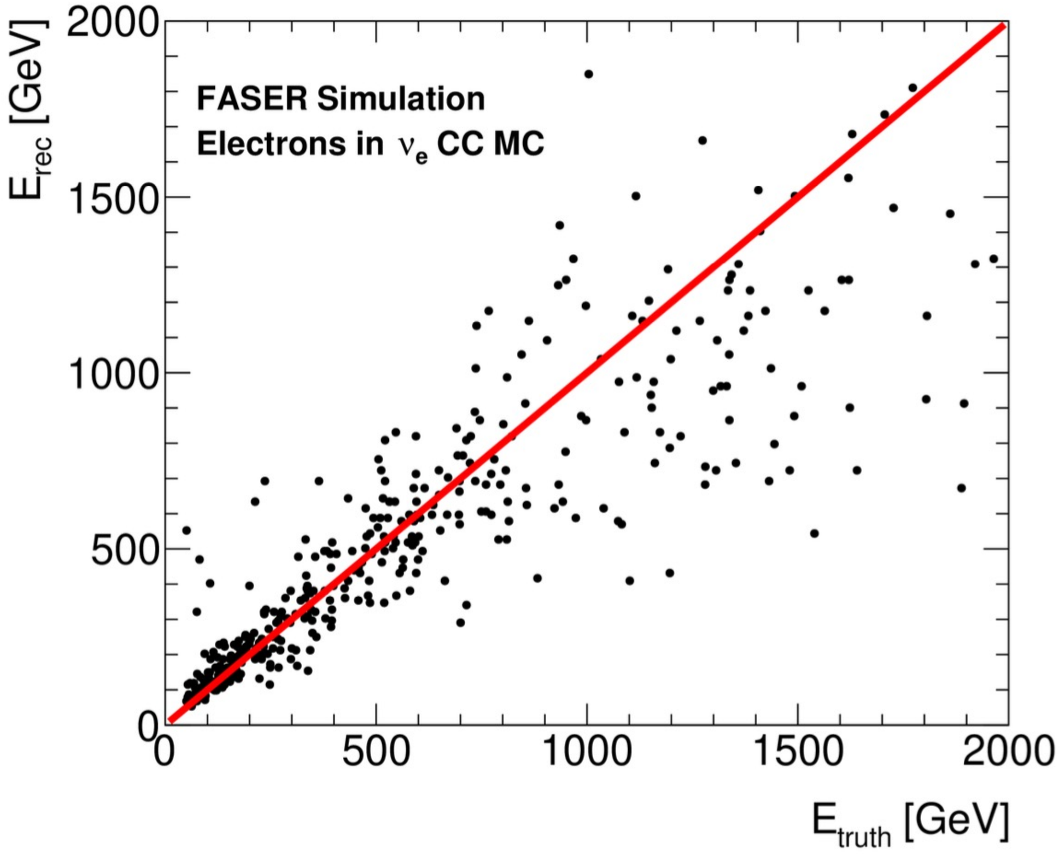




Neutrino Energy

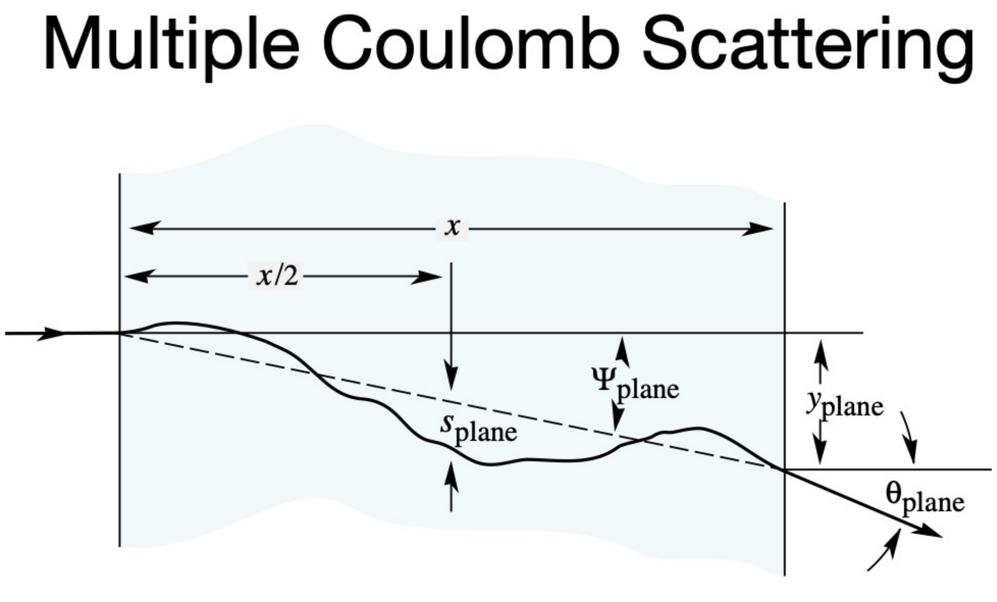


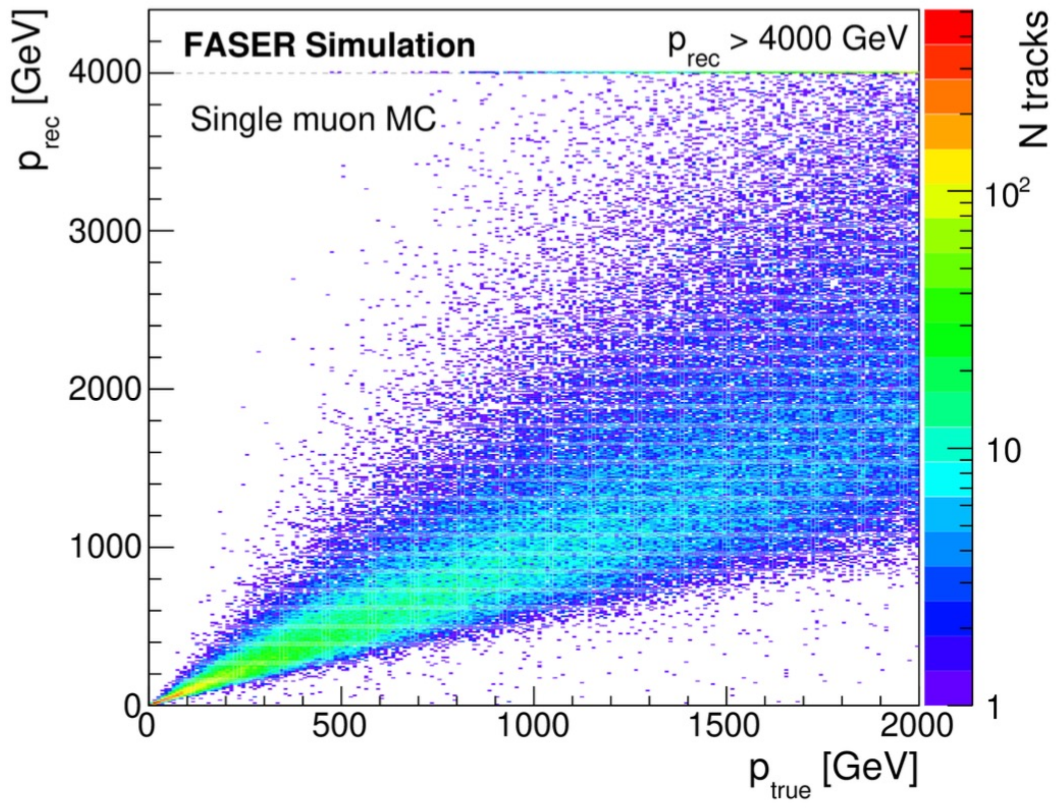




dE/E ~ 25% at 200 GeV, up to 40% at higher E

Neutrino Momentum





dE/E ~ 30% at 200 GeV, up to 50% at higher p

Successfully Installed in Ti18

SND: Muon Neutrinos

- Last year at Moriond, we reported the observation of 8 muon neutrino candidates in the 2022 data, with a significance of 6.8 σ. Phys. Rev. Lett. 131, 031802

New this year
Updated analysis with 2023 data and extended fiducial volume.

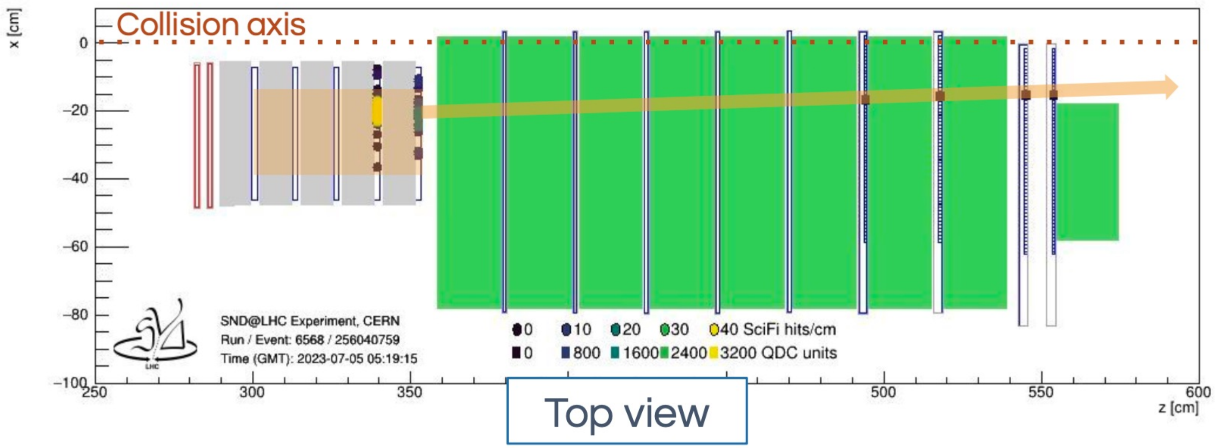
Event selection

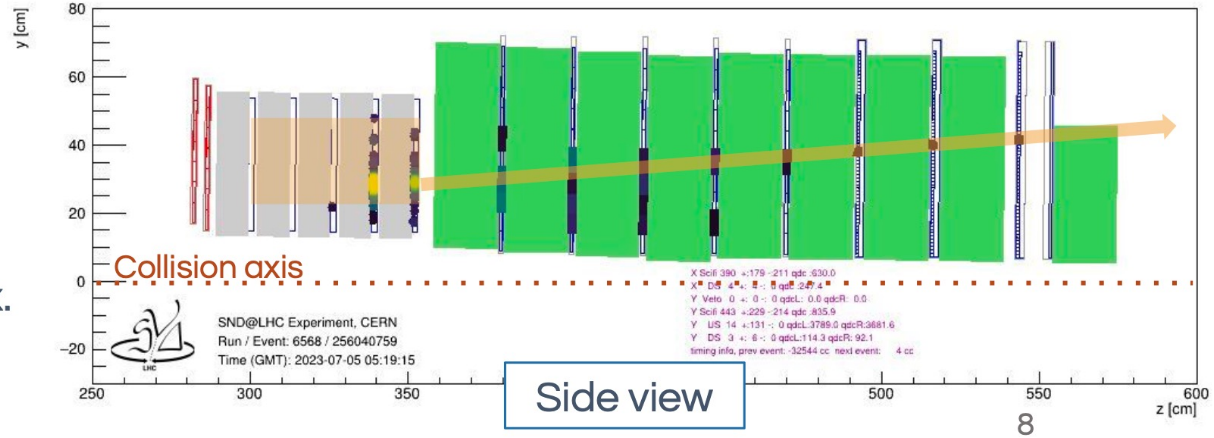
Fiducial volume

- Reject events in first wall.
  - Previously used only walls 3 and 4.
- Reject side-entering backgrounds.
- Signal acceptance: 18%
  - Up from 7.5%.

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 35%



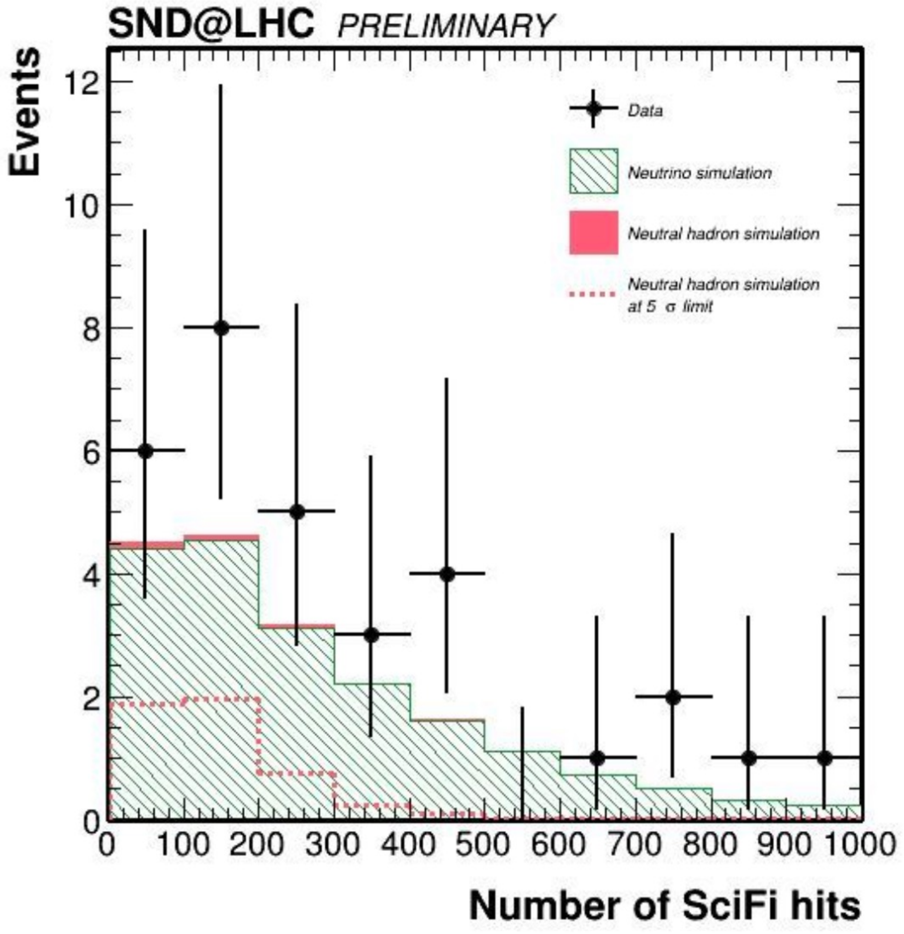


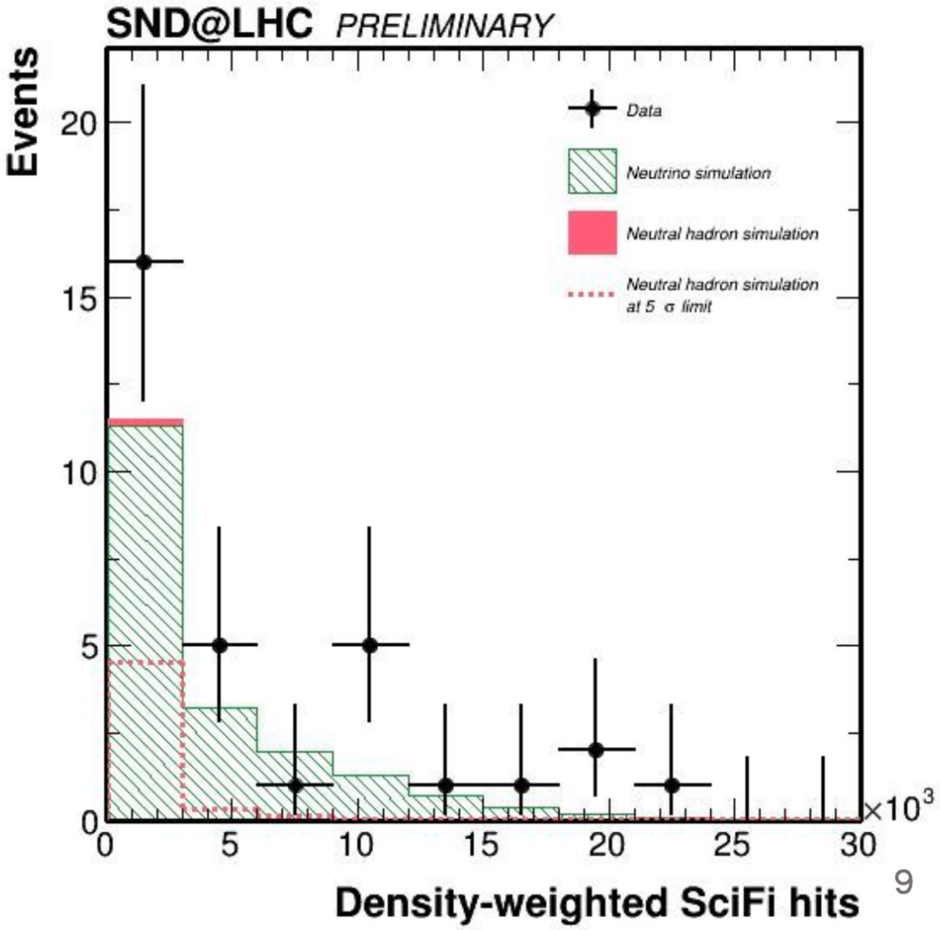
SND: Muon Neutrinos (2)

Number of events expected in 68.6 fb^{-1}

- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

Number of events observed: 32





9

SND: Shower-like 0-muon Neutrino Events

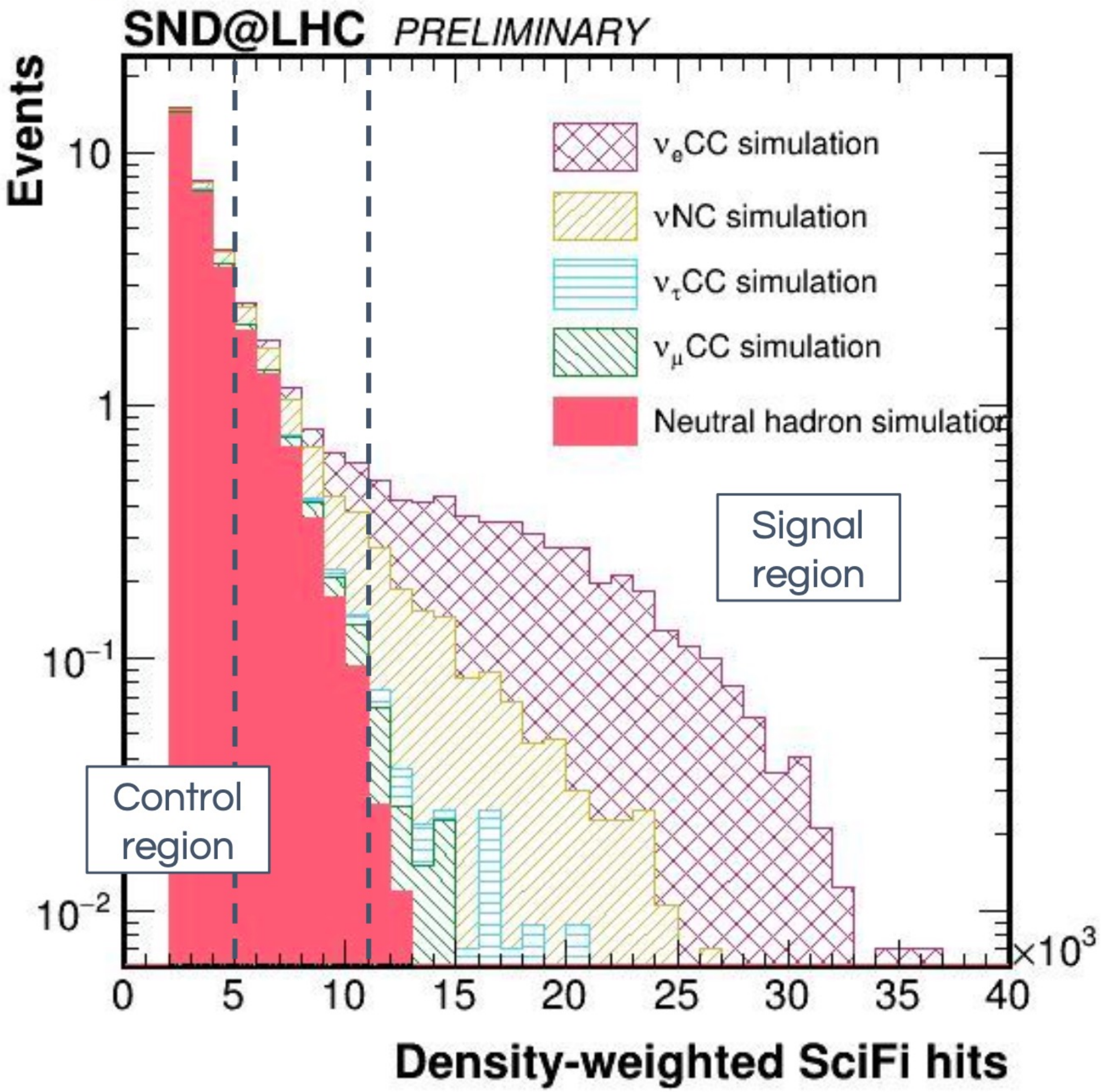
Signal: ν_eCC and NC interactions

Fiducial volume

- No hits in the veto detector.
- Reject side-entering backgrounds.
- Signal acceptance: 12%

0μ neutrino event identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- No hits in last two muon system planes.
  - No reconstructable muon.
- Density-weighted number of hits in most active station > 11×10^3.
  - Optimized for maximum expected significance
- Signal selection efficiency: 42%



SND: Shower-like 0-muon Neutrino Events (2)

Neutral hadron background

- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
  - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region: 0.01**

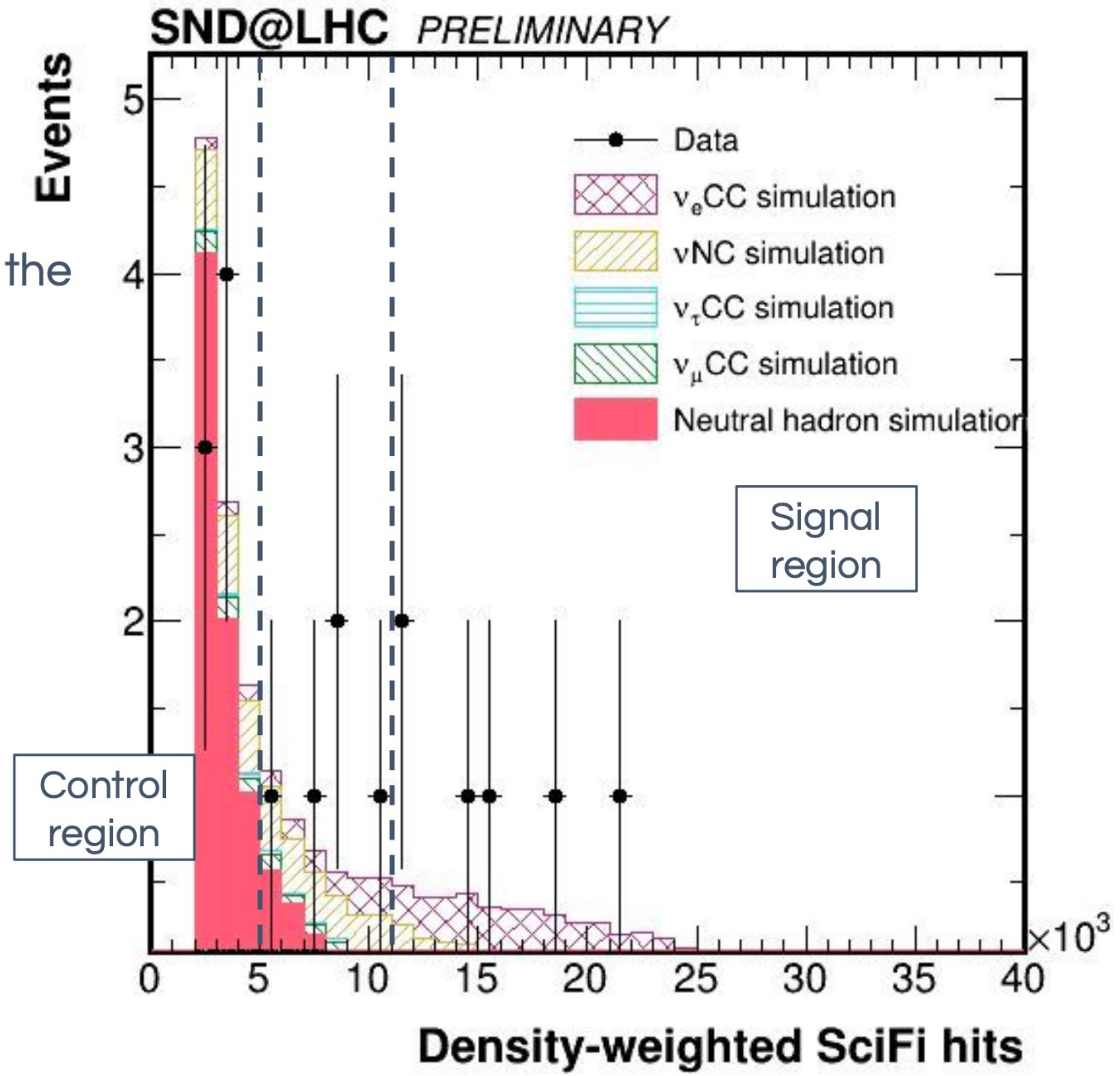
Neutrino background

- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC interactions expected: **0.07**

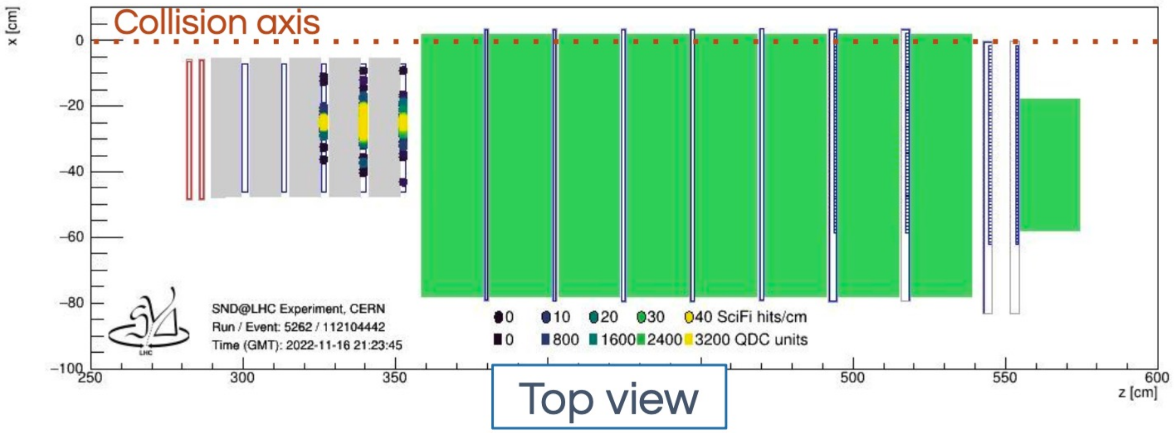
0μ observation significance

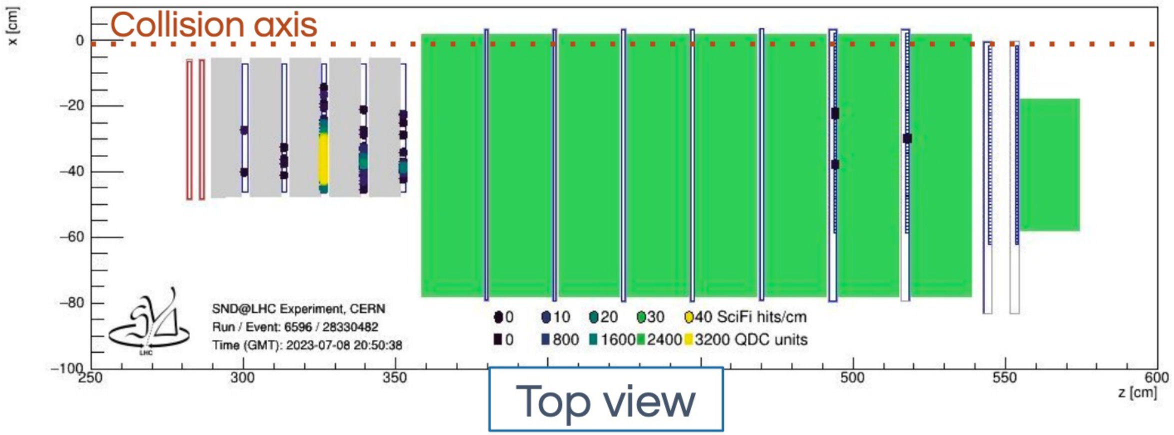
- **Total expected background: 0.20 ± 0.11 events**
- **Expected signal: 4.66 events**
- **Expected significance: 4.0 σ**

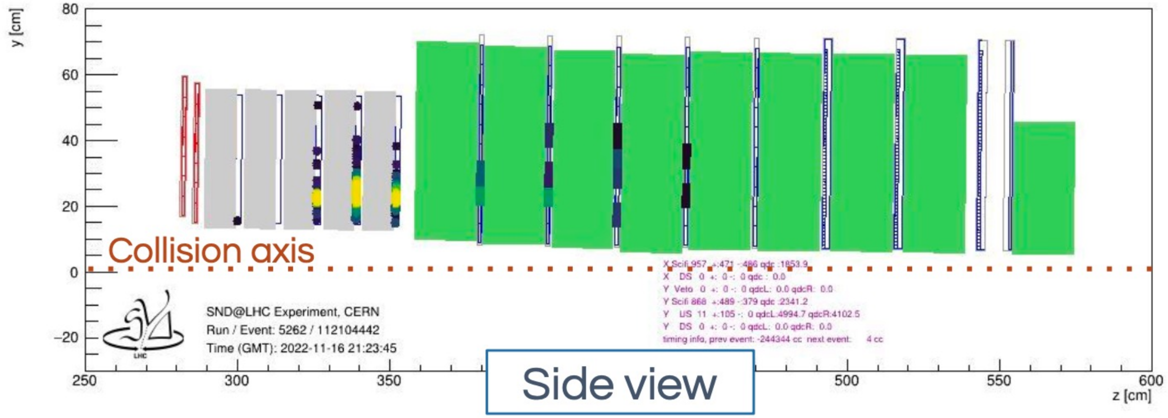
Number of events observed: 6
Observation significance: 4.7 σ

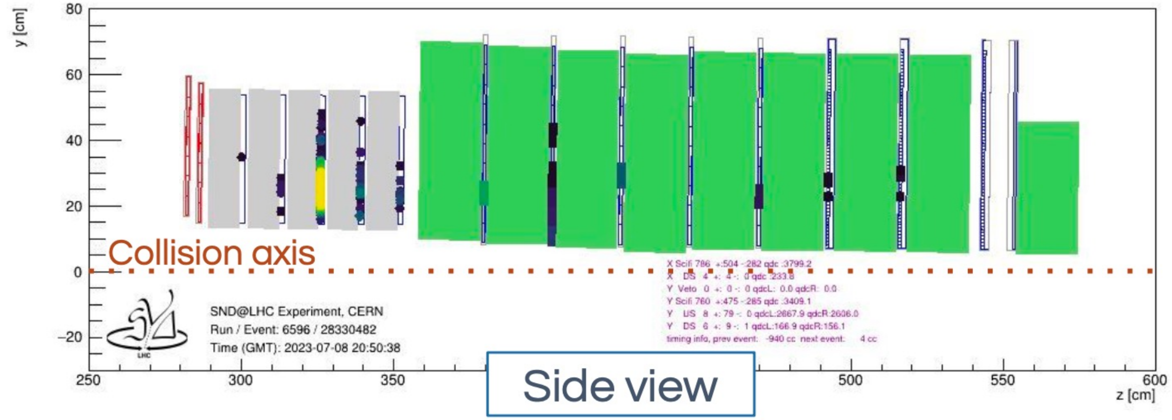


SND: Shower-like 0-muon Neutrino Events (3)









SND: Electron Neutrinos in Emulsion

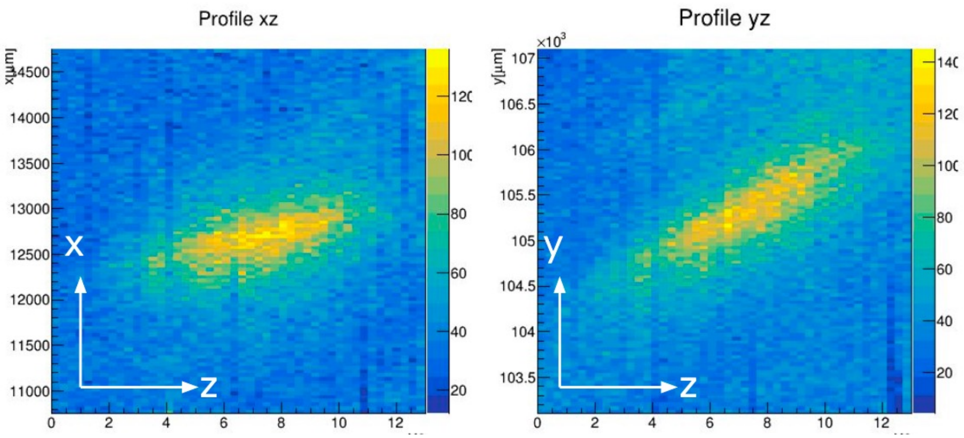
e

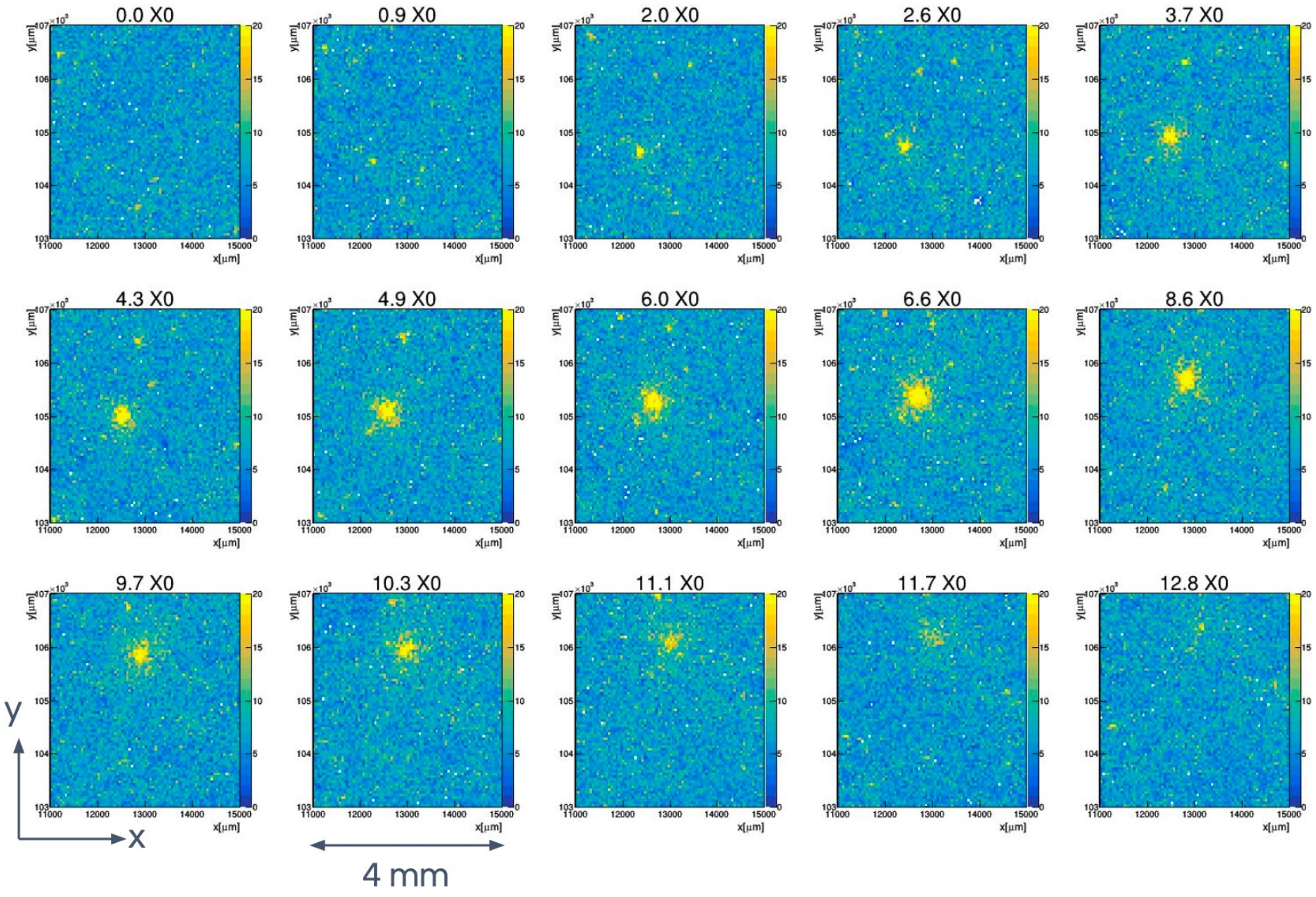
Strategy

- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

Status

- Electromagnetic shower patterns identified.
- Vertex association ongoing.

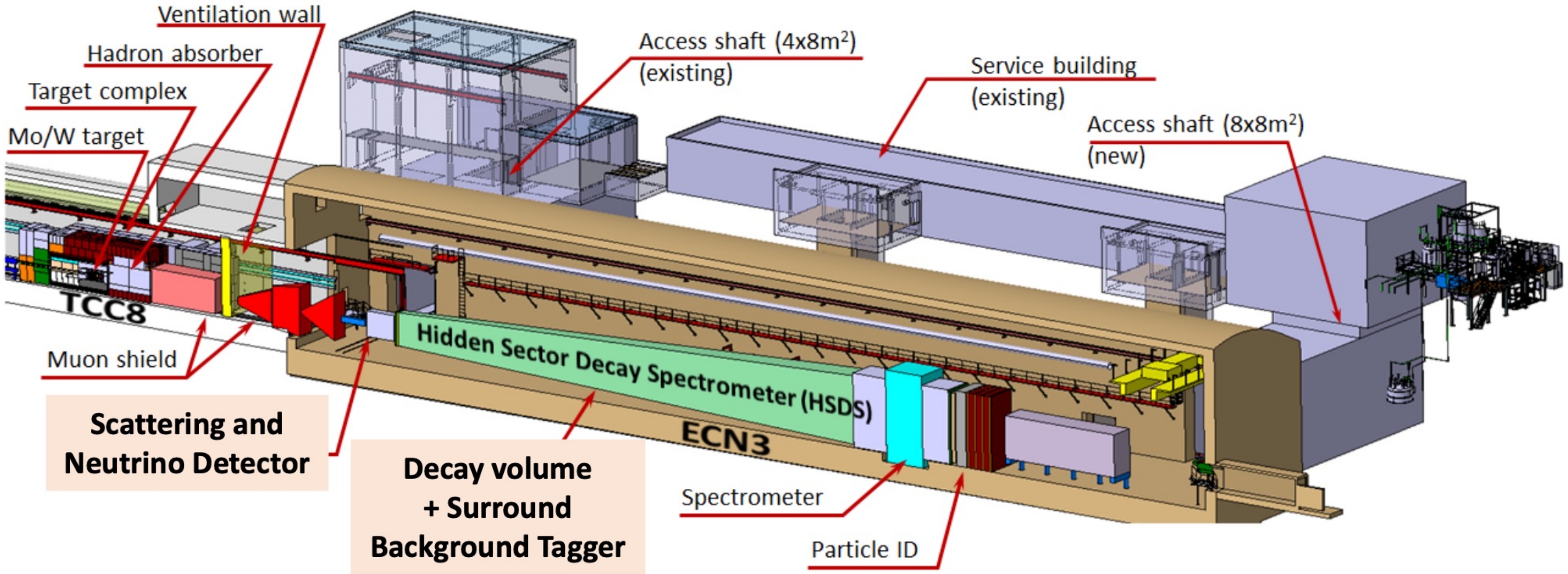




14

Modified SHiP Geometry

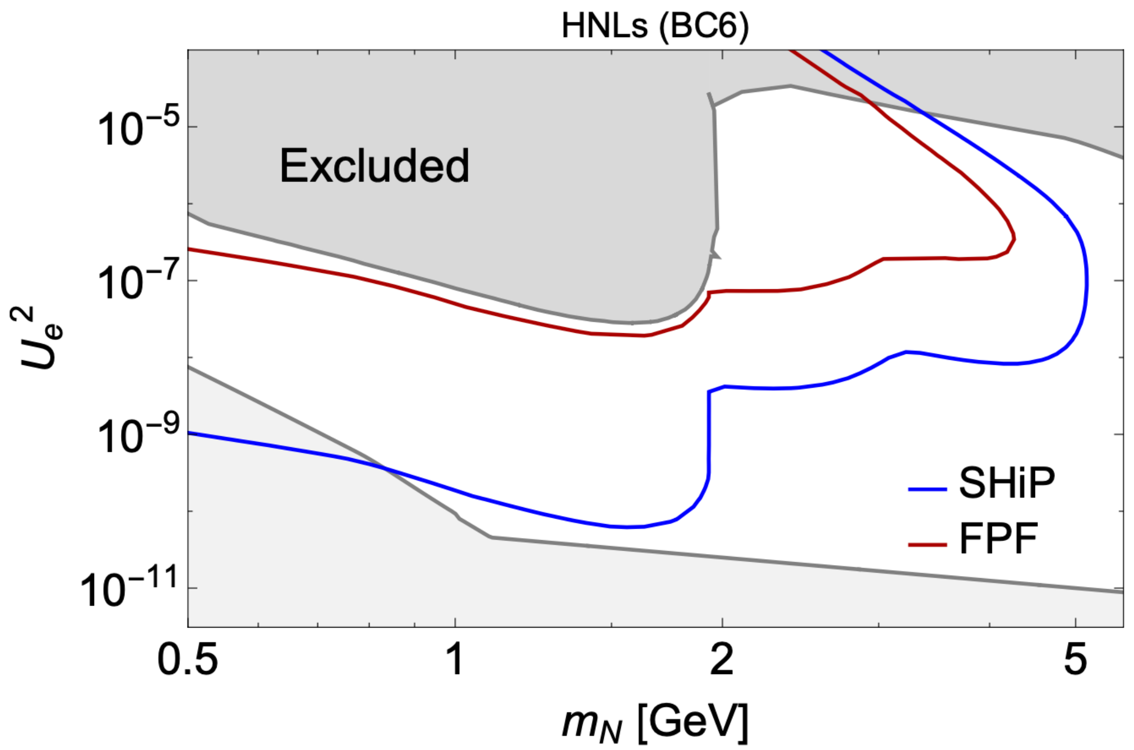
- ✓ ***Hybrid muon shield***
- ✓ ***New layout of SND***
  SND is at closer distance and sees higher flux of neutrinos → more compact detector ($145\ m^2$ of emulsion, just three times more than at SND@LHC)
- ✓ ***SBT with reduced thickness of Liquid Scintillator (20cm)***
  Good spatial and time resolution demonstrated with prototypes
- ✓ ***Single PID system**, merging ECAL and Muon detectors*

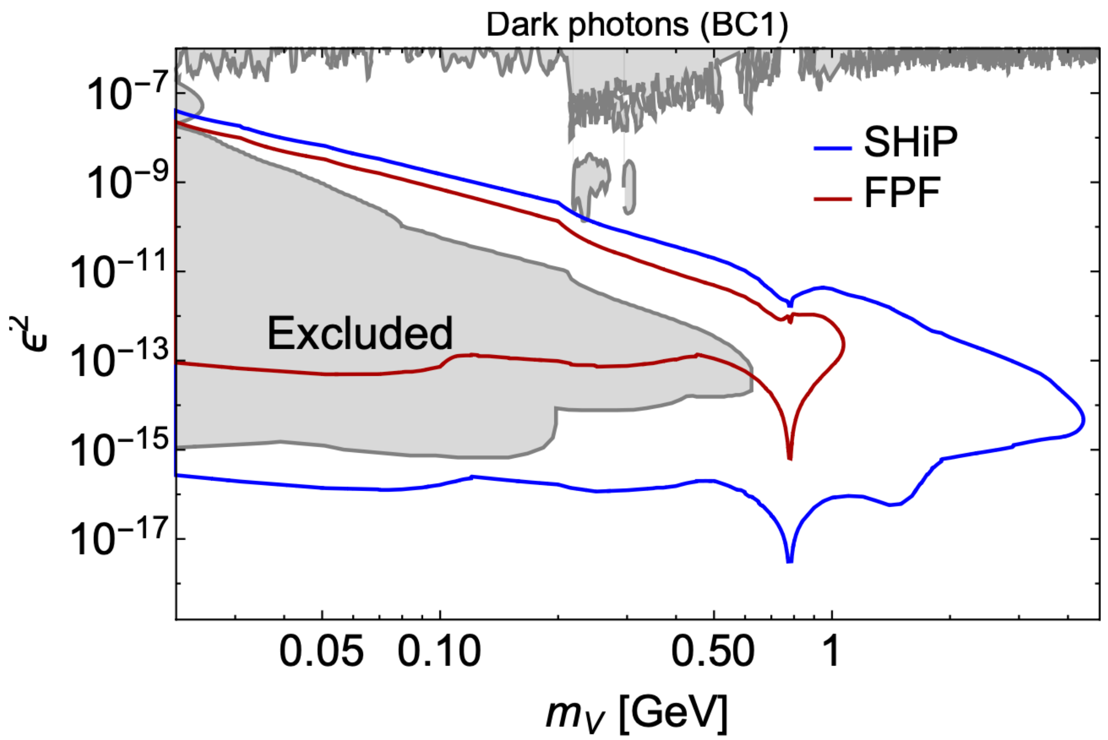


Modified SHiP configuration implemented in FairShip as an alternative to the LoI configuration

SHiP: FIPs via Decay

Similar to the CDS sensitivities for the same Npot. But significant increase comes from assuming data taking for 15 years. SHiP sensitivity is not limited by backgrounds. Specialized infrastructure, required to collect 6×10^{20} or more, has been studied and is not a limiting factor



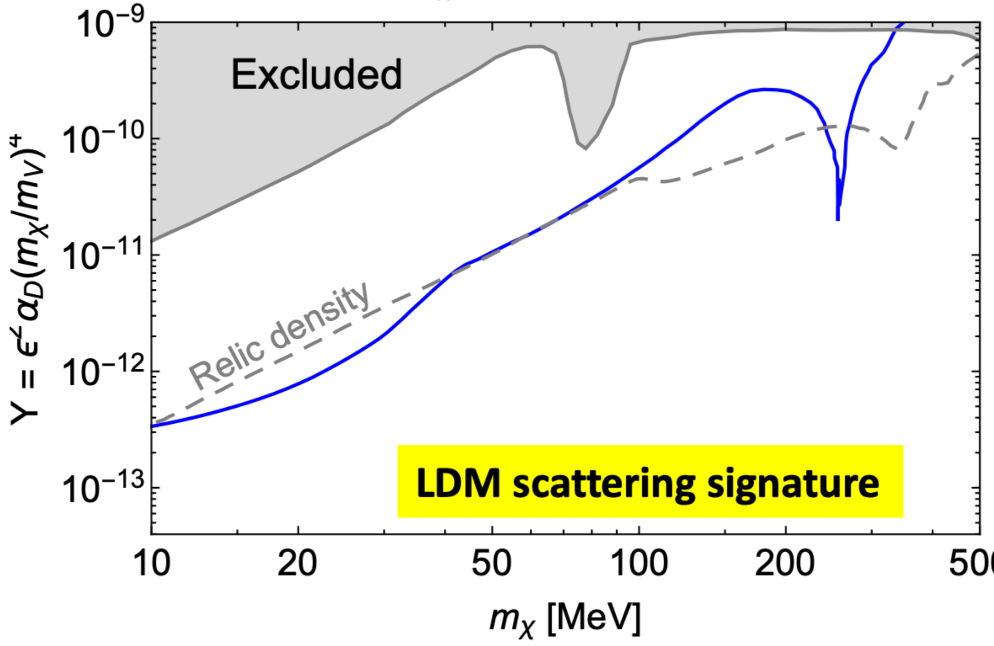


SHiP sensitivities to FIPs are orders of magnitude better than the ones for competing projects, including FPF

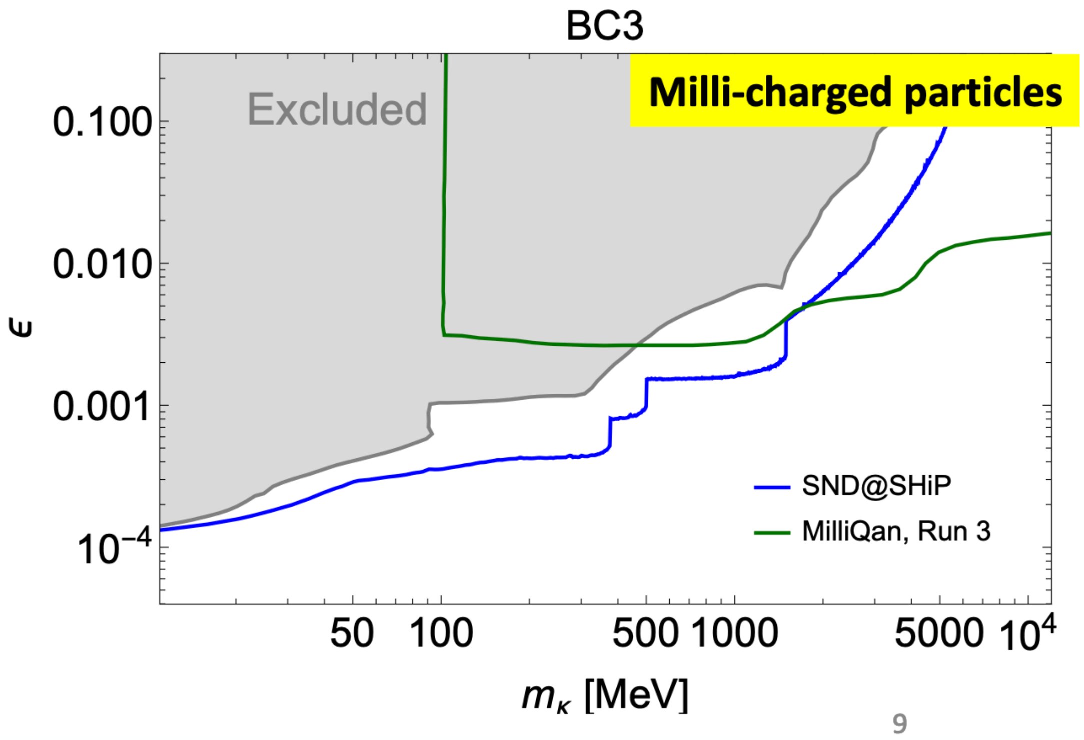
SHiP: FIPS via Scattering

- ✓ *Evaluation of backgrounds is now completed for the new configuration of the SND detector*
- ✓ *Background is dominated by neutrino elastic and quasi-elastic scattering, and is slightly smaller than in CDS (230 events) for the same Npot*

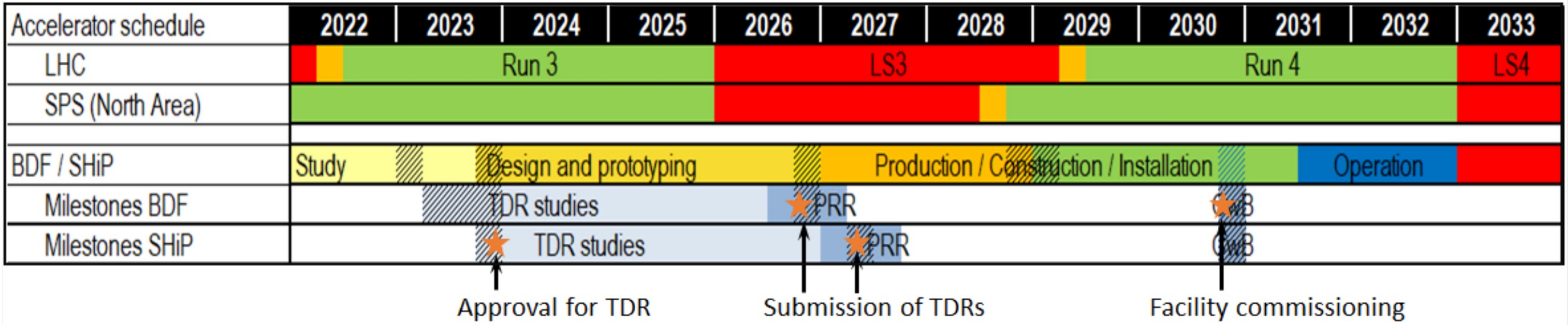
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	52	27	64	42	185
Quasi - elastic scattering	-	9			9
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	52	36	64	42	194



Expectation from relic density is in reach

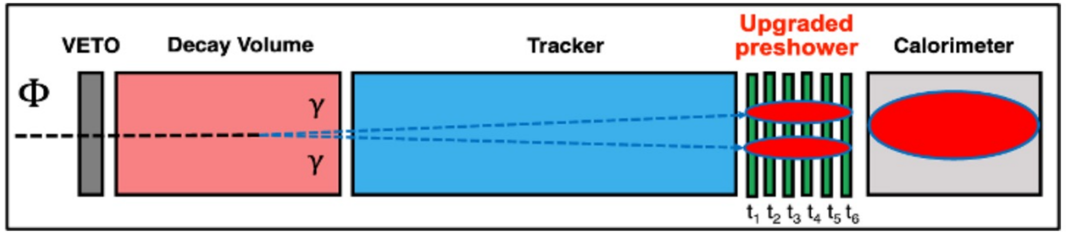


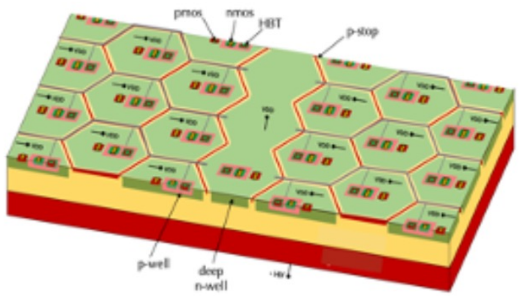
SHiP: Roadmap



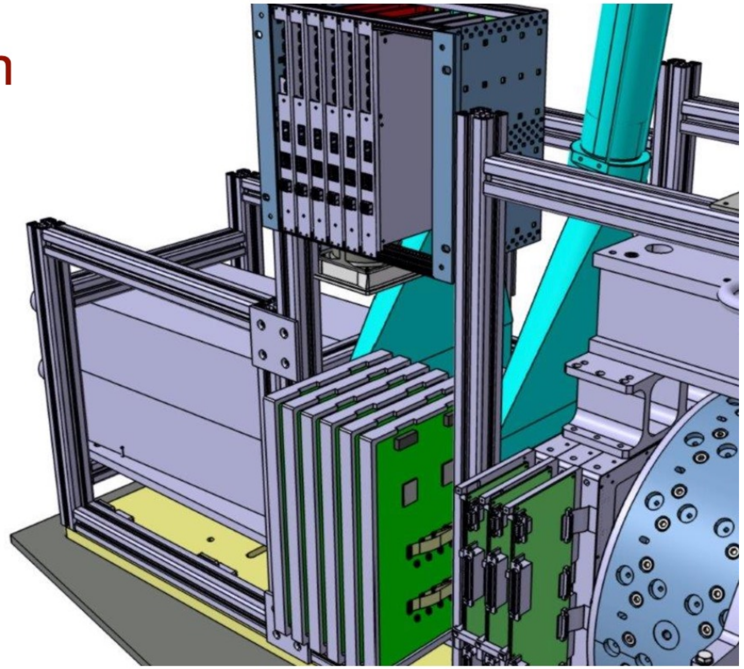
- ✓ ***~3 years for detector TDRs (approval in 2023 is critical to ensure timely funding)***
- ✓ *Construction / installation of facility and detector is decoupled from NA operation*
- ✓ *Availability of test beams challenging*
- ✓ ***Important to start data taking >1 year before LS4***

FASER: Preshower Upgrade



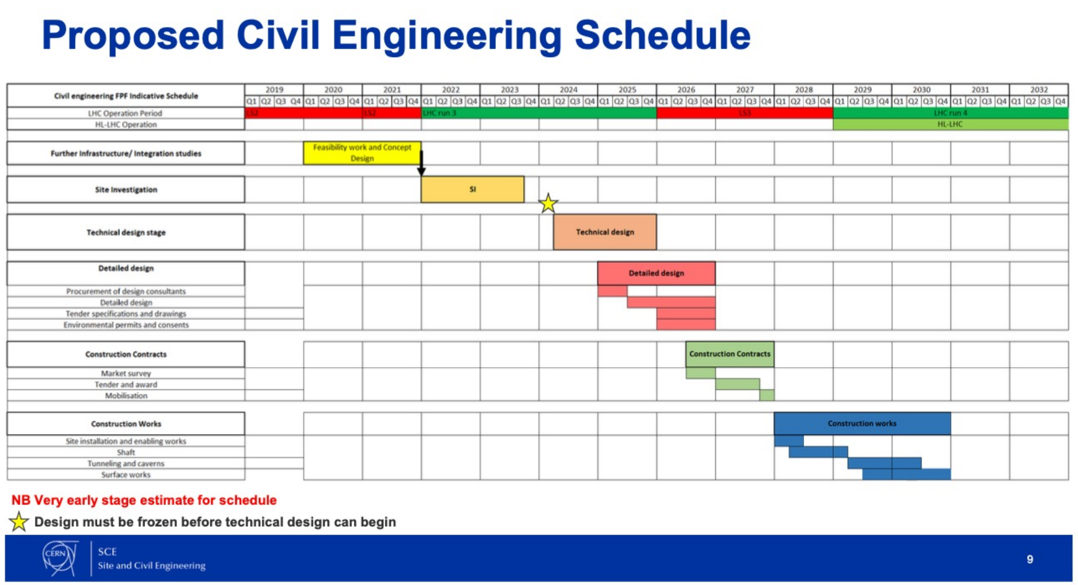


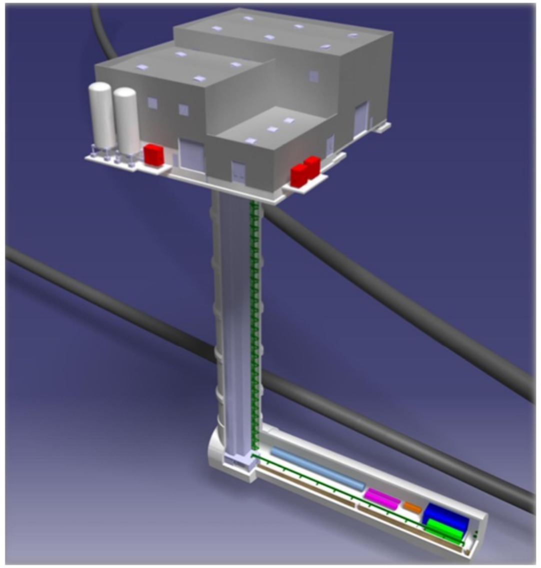
- FASER Preshower upgrade
  - 6 layers of high-granularity Si pixels with W absorber
  - Separate photons at ~200 μm
  - Installed before 2025 (Run3)
- Improve ability to identify 2γ, reject ν backgrounds
- FASER approved for Run4
  - Will record large dataset with upgraded FASER at HL-LHC



 Preshower: CERN-LHCC-2022-006 Run4: CERN-LHCC-2023-009

FPF Design Study





- CERN is very serious about FPF
  - Conceptual design ongoing
- Construction doesn’t interfere with HL-LHC operations
- Cavern could be ready for experiments by 2031 (mid-Run4)

➢ Core samples

FPF & P5

- FPF Snowmass report: [arXiv:2203.05090]
  - ~200 authors, > 400 pages, 18 working groups
- P5 report did not recommend FPF per-se, but…

  # Can be considered as part of ASTAE (small expt program) with reduced scope
- Most expensive detector is FLArE
  - Investigating cheaper options, could be built by non-U.S.
- We believe small experiments are important
  - Need discussion with US agencies, ASTAE does not exist yet

Exploring the Quantum Universe

P5 Report

Figure 2 – Construction in Various Budget Scenarios

Draft

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
Can be considered as part of ASTAE with reduced scope

US Construction Cost >$3B				Science Drivers						
Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
on-shore Higgs factory	N	N	N		P	S		P	P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

FPF Physics

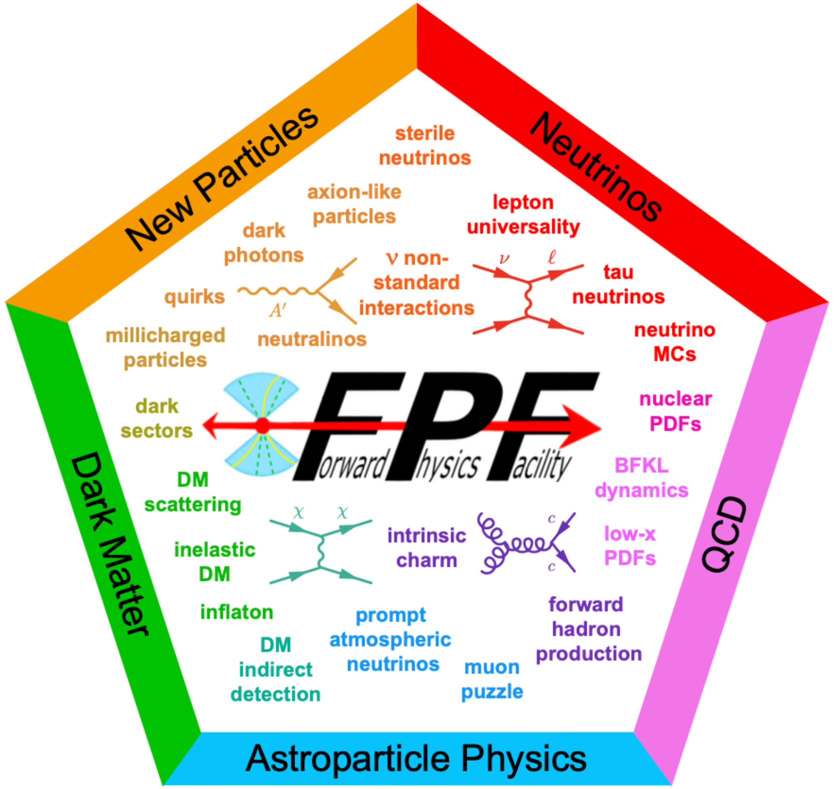
- The FPF physics program is extremely broad, impacting almost every area of particle and astroparticle physics.

- FPF experiments have discovery potential in every one of the PBC benchmark scenarios. These have been useful in comparing different experiments.

- But they do not span the full range of BSM possibilities, and they do not come close to capturing the breadth of the FPF physics program (cf. mSUGRA in SUSY).

- Below are a few generic examples (one PBC benchmark, two not) of the FPF physics potential that make essential use of LHC energies and demonstrate the complementarity to the rest of the worldwide program (e.g., fixed target experiments like SHiP).

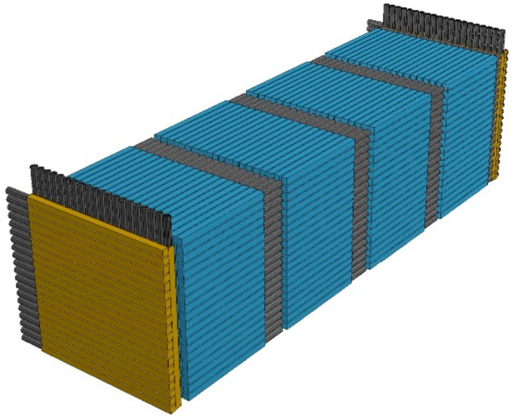
- For more, see J. Rojo's talk, and also the FPF White Paper.



FPF: mCP

- The FPF accommodates a suite of experiments that can be optimized for various physics cases. This diversity is essential in probing a broad range of BSM physics possibilities.

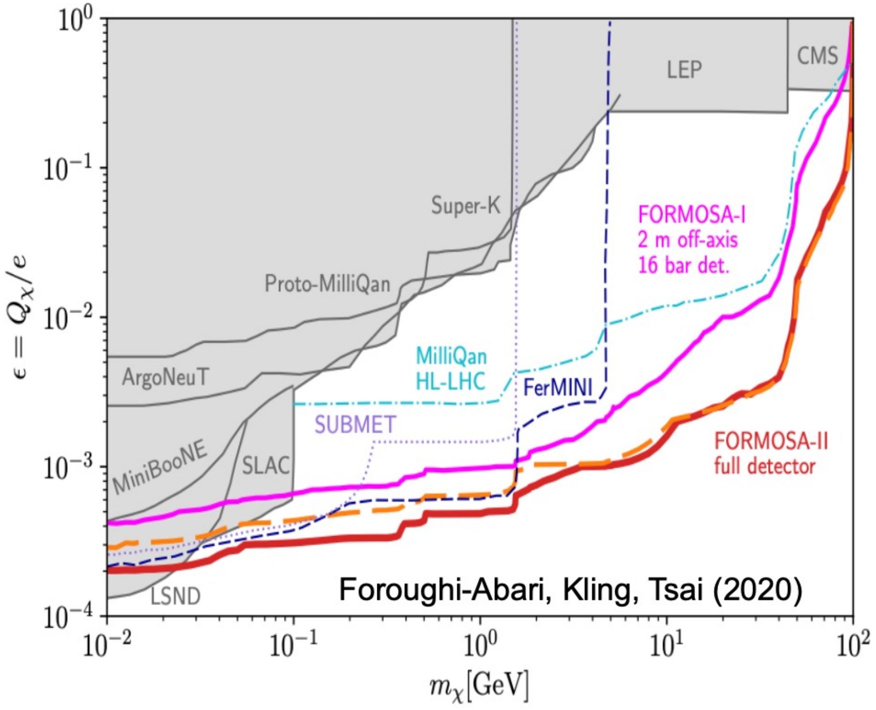
- For example: FORMOSA, targeting milli-charged particles.



- Motivated by dark sectors with massless dark photons, but also new particles with magnetic or electric dipole moments, …

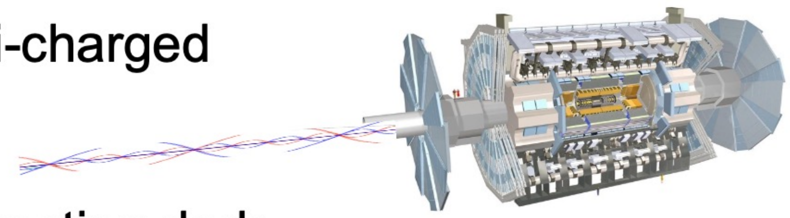
- World-leading sensitivity for masses from ~100 MeV to 100 GeV.

- Will not be probed by SHiP (and no fixed target experiment can produce particles with mass > 10-20 GeV).



FPF: Strongly Interacting Dark Sectors

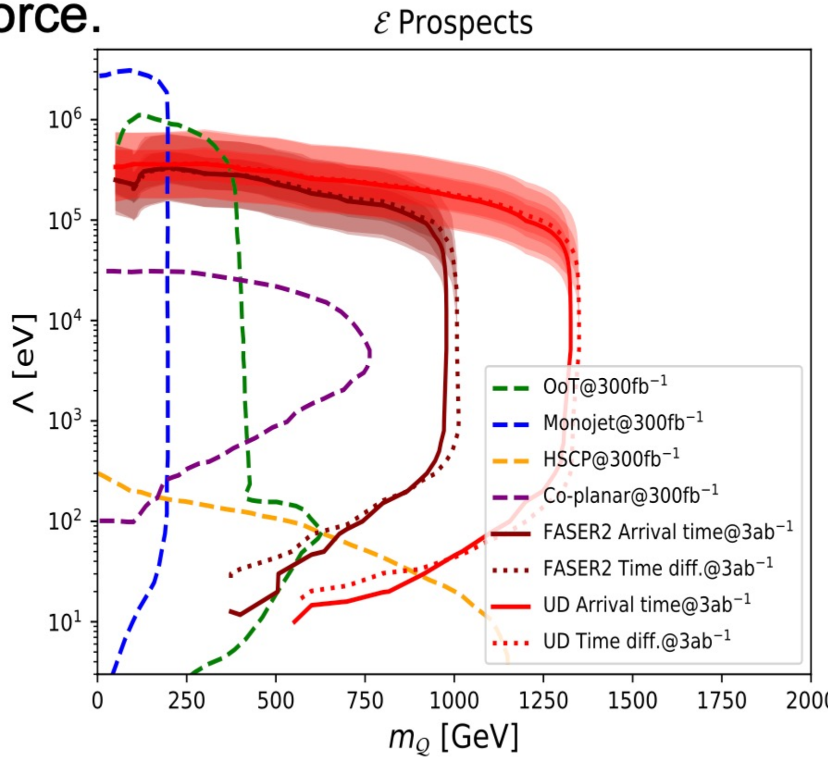
- U(1) dark force → dark photons, milli-charged particles.



- Any other dark force → strongly-interacting dark sector. Dark particles (“quirks”) can be pair-produced at the LHC, but then oscillate down the beampipe, bound together by the dark color force.

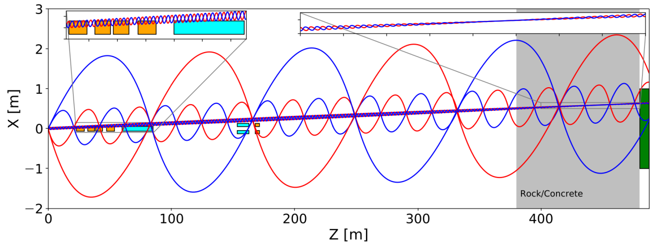
- FASER2 can discover quirks with masses up to ~TeV, as motivated by the gauge hierarchy problem (neutral naturalness).

- Requires LHC energies to produce new TeV particles, impossible to see at fixed target experiments.



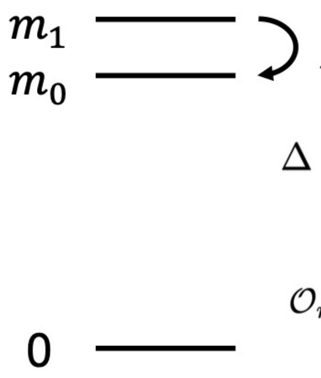
Li, Pei, Ran, Zhang (2021); Li et al. (in progress)

- Quirks
  - Long-lived exotic particles charged under both SM and new confining gauge group
  - Gives rise to oscillatory behaviour



FPF: LLPs from Compressed Spectra

- LLPs can result from weak couplings.
- But they can also arise generically from compressed spectra (e.g., inelastic DM), where decays are phase-space suppressed by degeneracies.

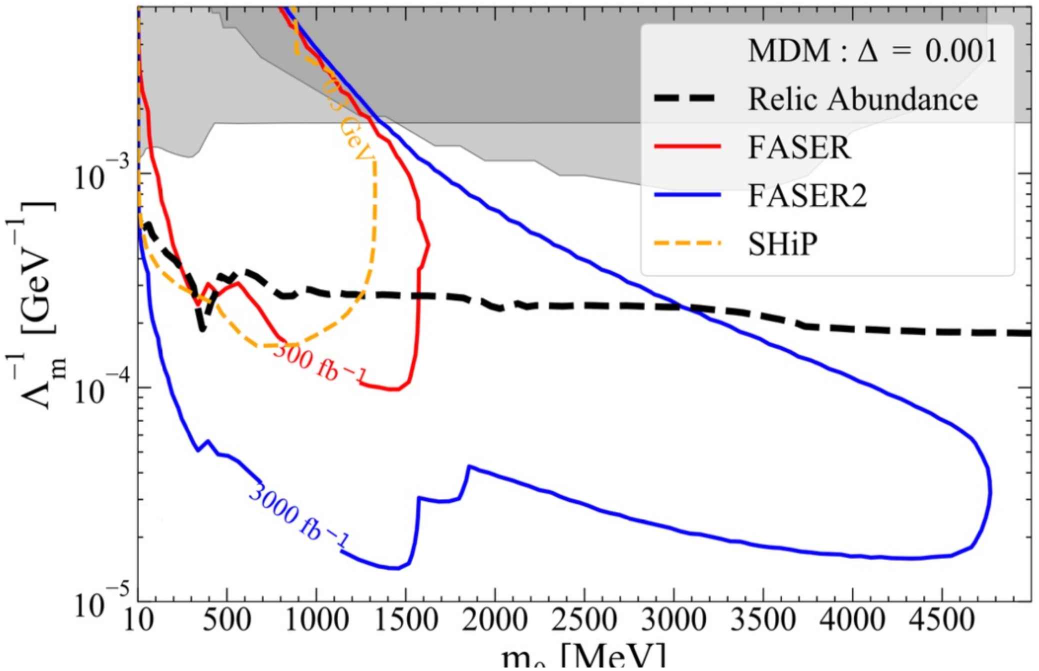


$\chi_1 \rightarrow \chi_0 \gamma$

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

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

- In this case, decays $\chi_1 \rightarrow \chi_0 \gamma$ lead to very soft photons that can be difficult to detect.
- But these are boosted at the LHC by $\gamma \sim 1000$, FASER2 can detect GeV particles with even ~MeV mass splittings, thermal relic target.
- Difficult at SHiP (sensitivity contour assumes E_γ threshold of 300 MeV, 2 10^{20} POT).



Dienes et al. (2023)