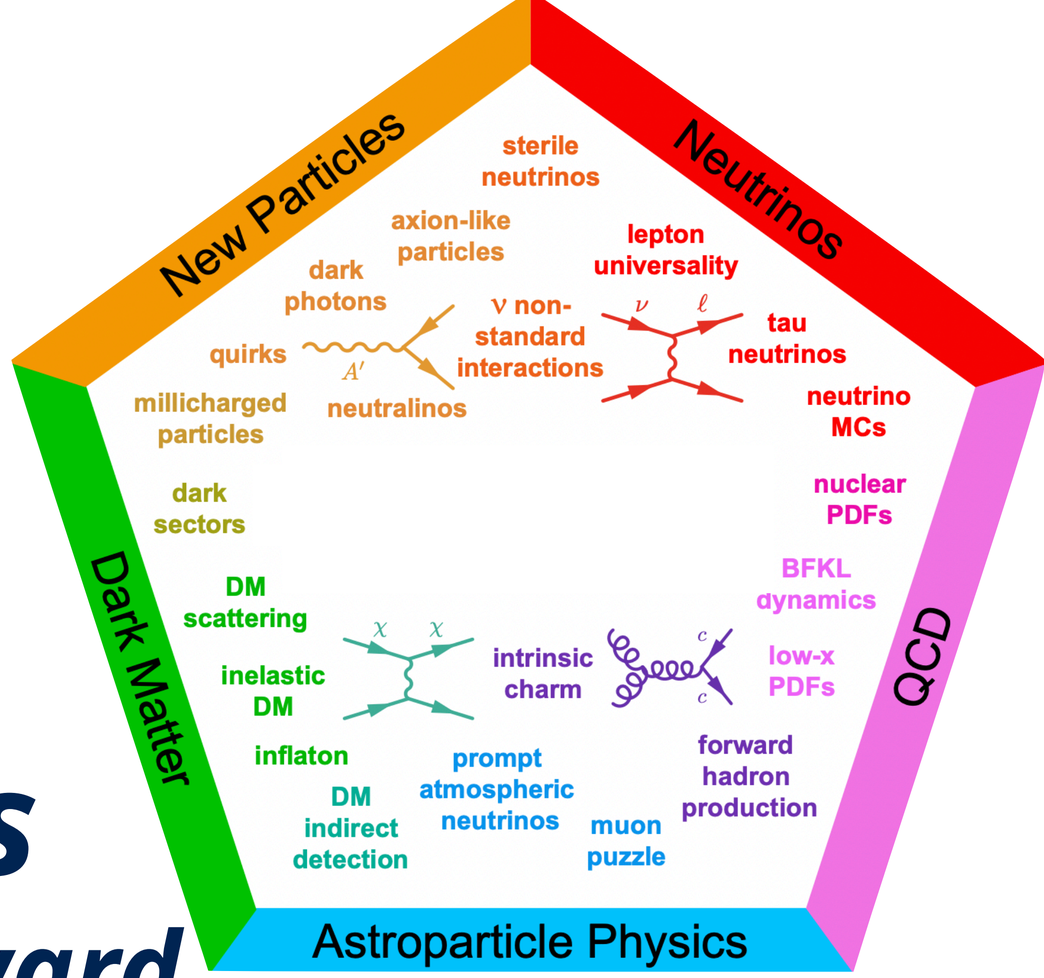
LLPs & Neutrinos in Auxiliary Experiments

Beam Dump/Transverse/Forward



PPAP Meeting

26/6/2024

Josh McFayden (Sussex) [with input from many others!]

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Context for auxiliary detectors/facilities

- Much of what's shown today was not included in the previous roadmap:
  - Many projects mentioned in the following slides have moved quickly in recent years
  - But they are strongly aligned with community goals and should be represented in roadmap

- 2020 European Strategy Update:
  - *"The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics… searches for axions, dark sector candidates and feebly interacting particles.* ***…A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported****"*

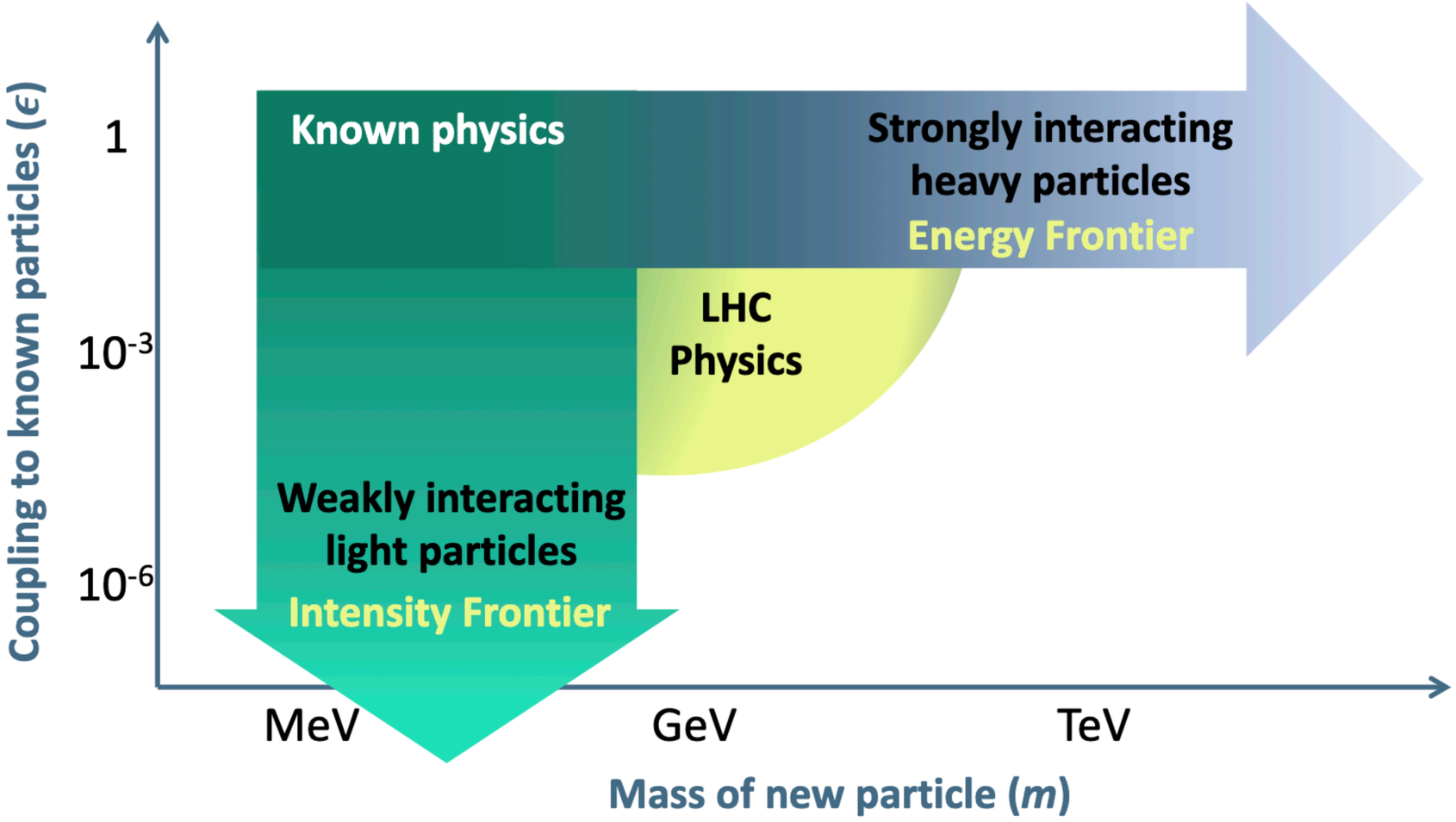
- Snowmass 2021 Energy Frontier Report:
  - *"Our highest immediate priority accelerator and project is the HL-LHC****,…including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades****"*

BSM | Motivation

- The **LHC experiments** are producing incredible results, extending reach to more extreme phase-spaces and performing increasingly precise measurements.

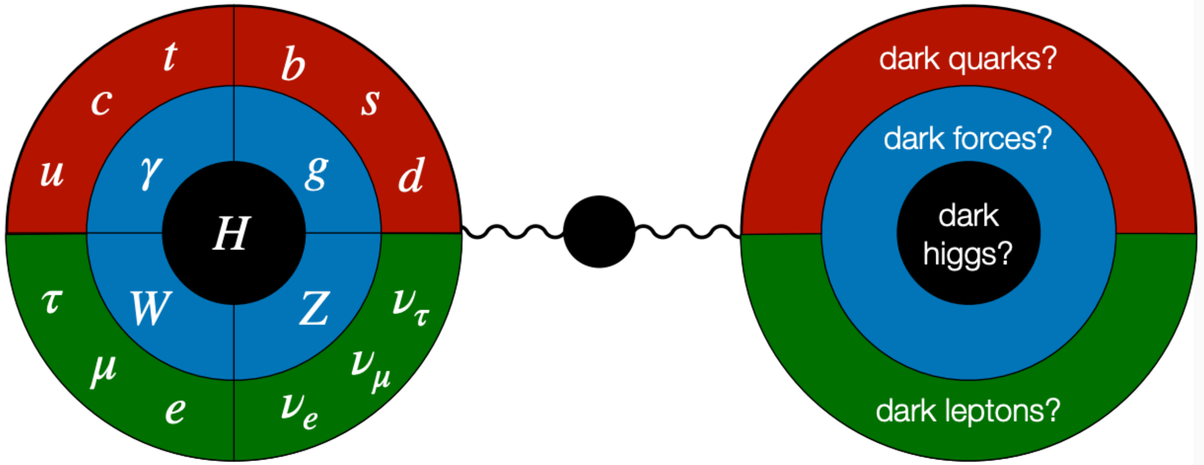
- But the lack of any observation of BSM physics motivates **looking elsewhere** too.

- Weakly interacting long-lived light particles could be the solution!



BSM | Models

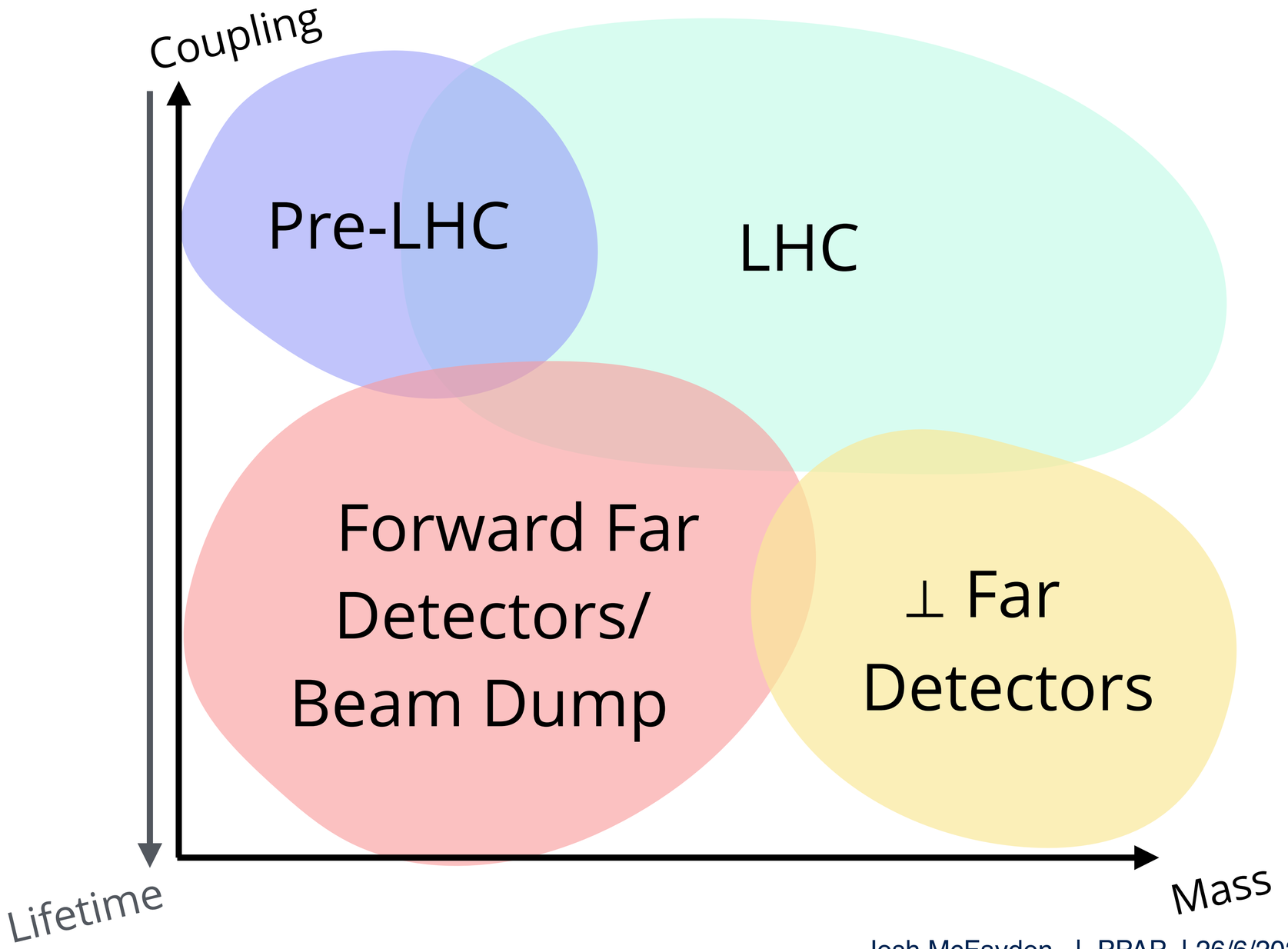
- A range of models can offer these DM candidates (as well as strongly motivated solutions to other issues particle physics)
  - Dark-sector mediators
    - Vector, Axion, Scalar, Neutrino portals
  - Milli-charged particles
  - Light DM scattering



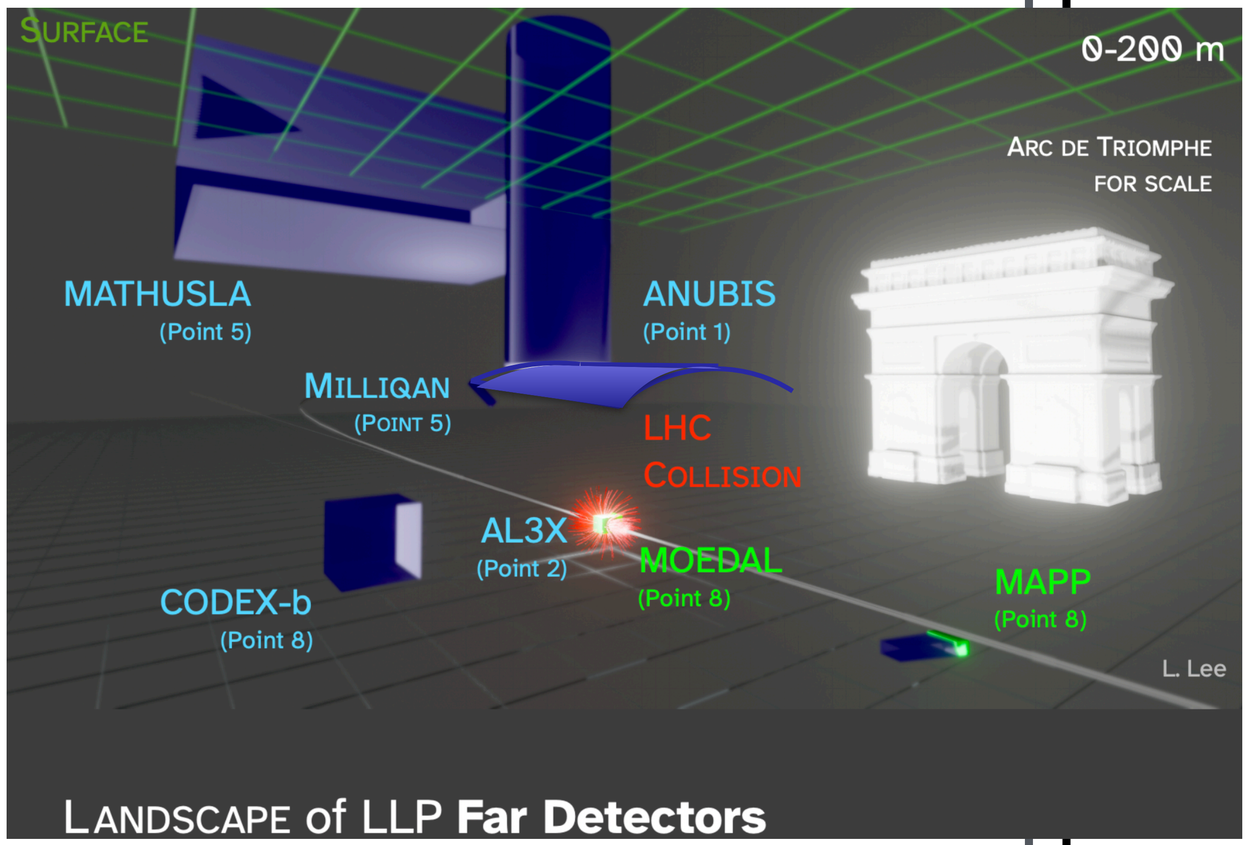
[Snowmass'21, arXiv:2209.04671]

Benchmark Model
BC1: Dark Photon
BC1': $U(1)_{B-L}$ Gauge Boson
BC2: Invisible Dark Photon
BC3: Milli-Charged Particle
BC4: Dark Higgs Boson
BC5: Dark Higgs with hSS
BC6: HNL with e
BC7: HNL with μ
BC8: HNL with τ
BC9: ALP with photon
BC10: ALP with fermion
BC11: ALP with gluon

BSM | Experimental landscape

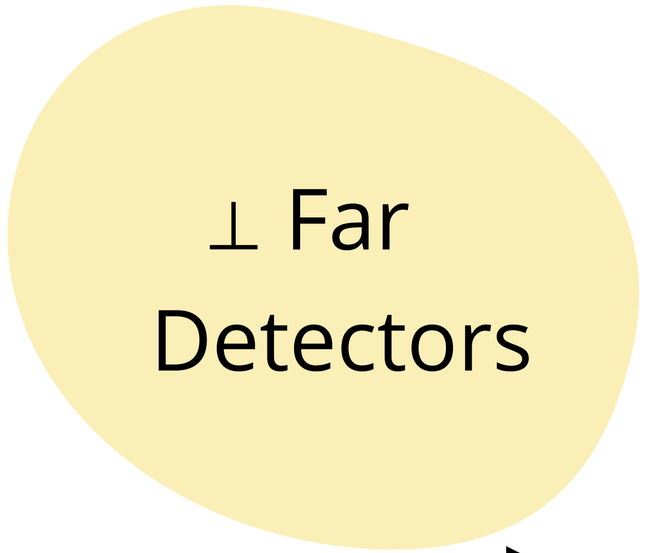


BSM | Experimental landscape



UK involvement:

- ANUBIS
- CODEX-b
- MOEDAL-MAPP



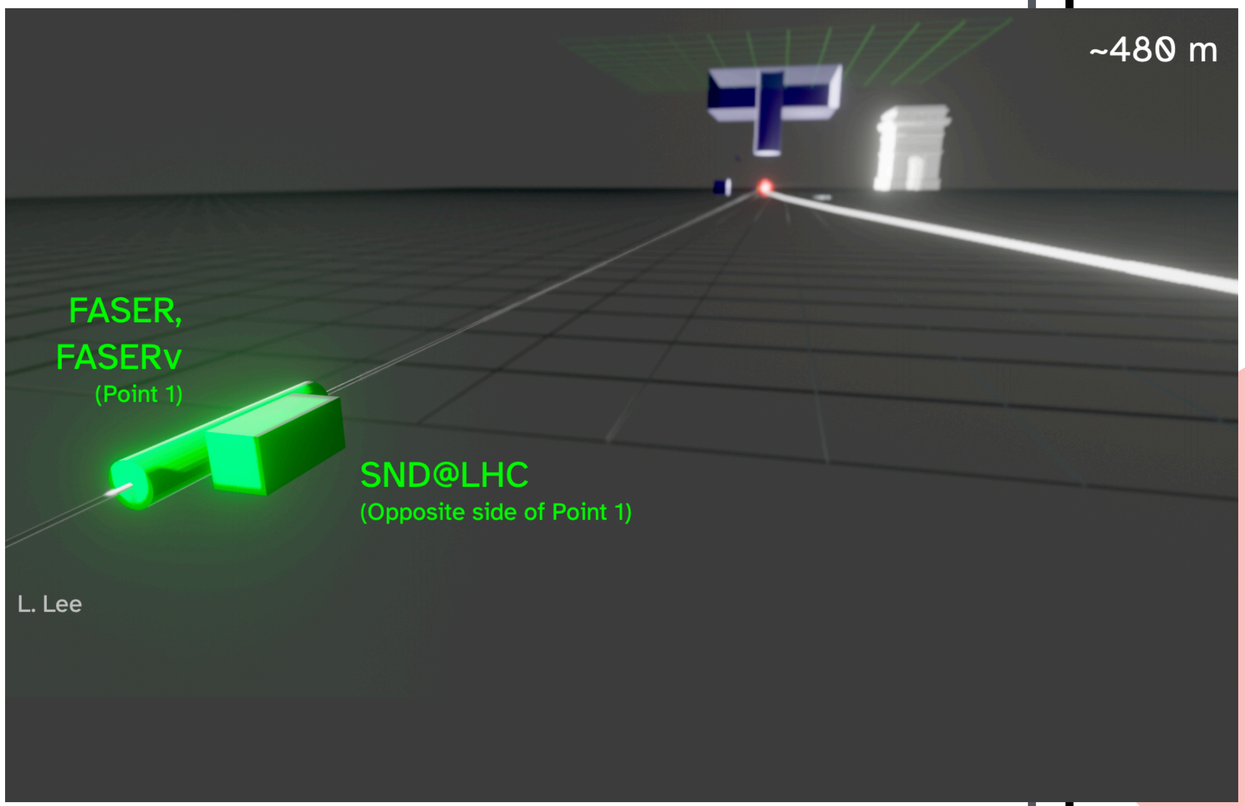
Coupling

Lifetime

Mass

Credit: Larry Lee

BSM | Experimental landscape



Coupling

Lifetime

Mass

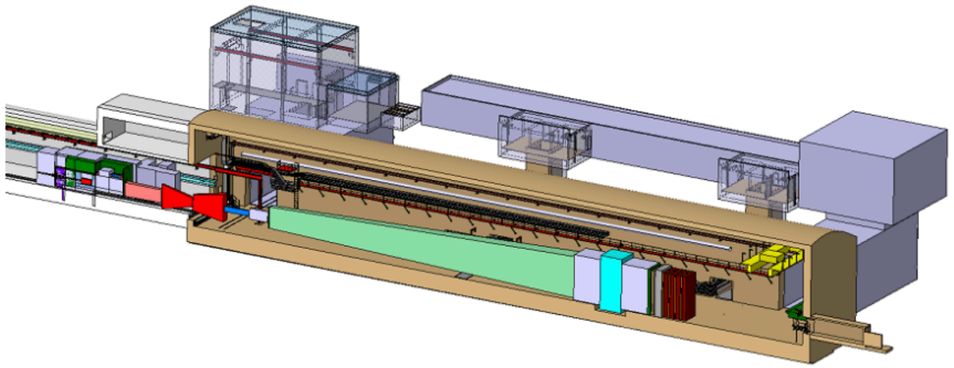
Forward Far Detectors

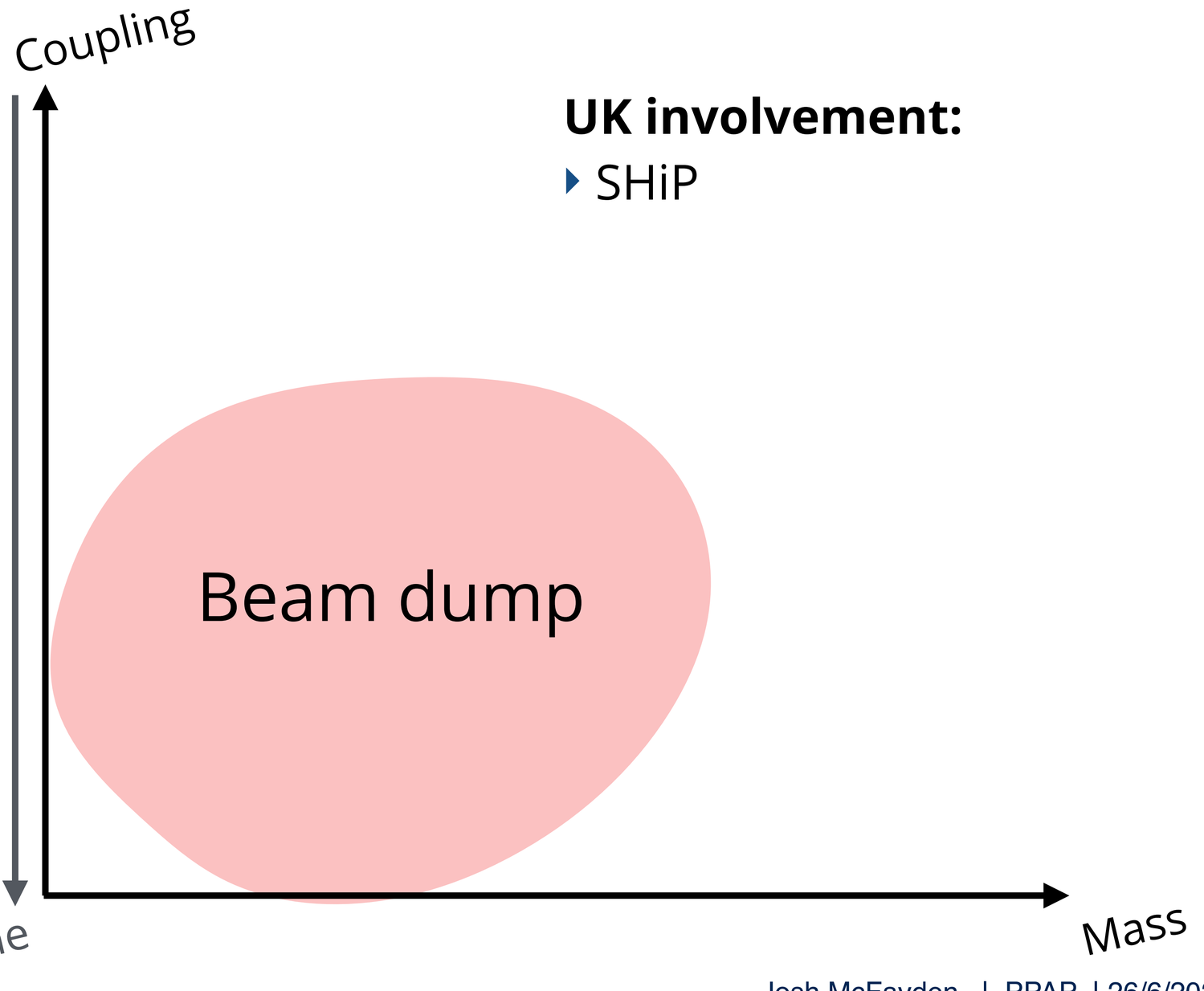
UK involvement:

- FASER
- SND@LHC

Credit: Larry Lee

BSM | Experimental landscape



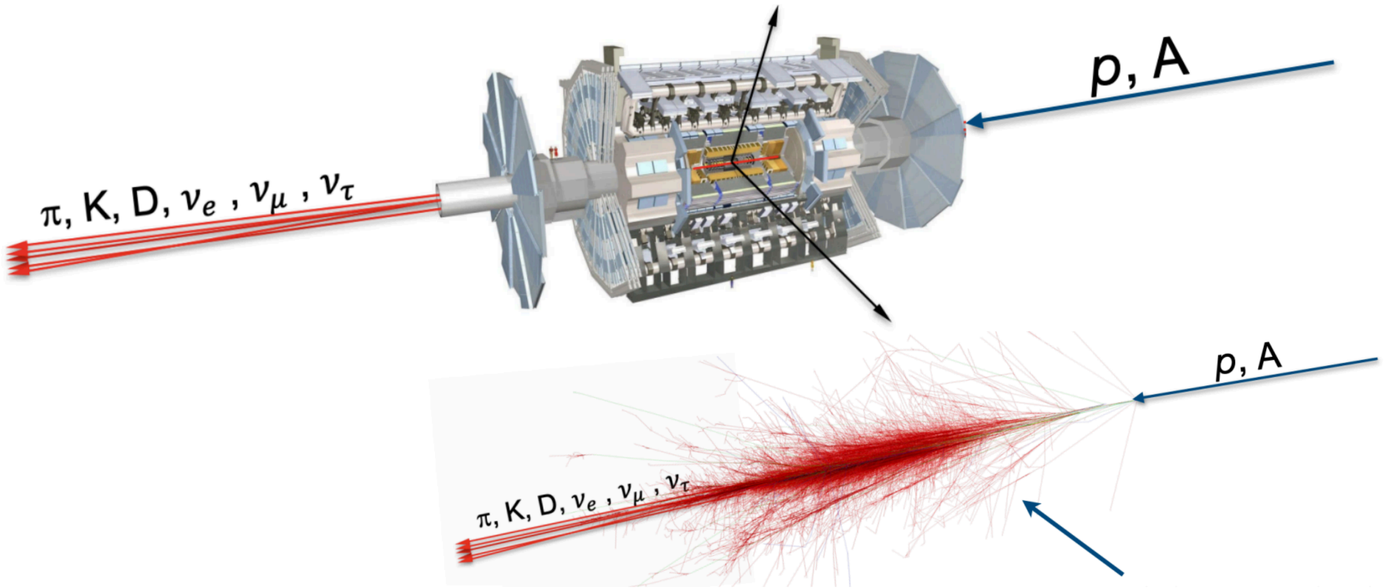


UK involvement:

- SHiP

Neutrinos | Motivation

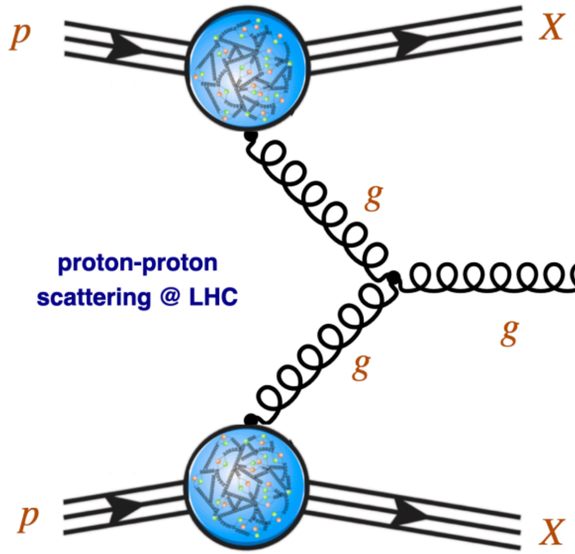
- Currently failing to exploit some the most energetic and high-intensity neutrino beams ever produced in a laboratory
- There are guaranteed physics targets to be reached should we instrument these
  - Both at beam dump facilities and forward regions of the LHC

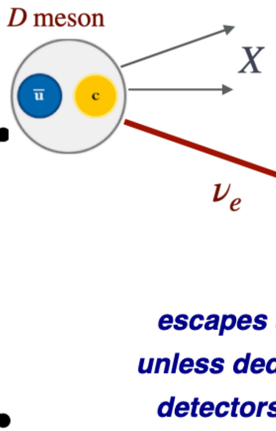


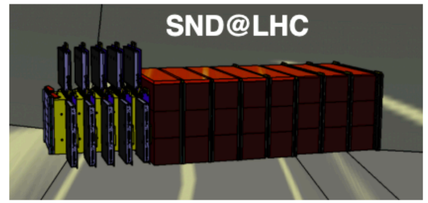
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux

Neutrinos | Motivation

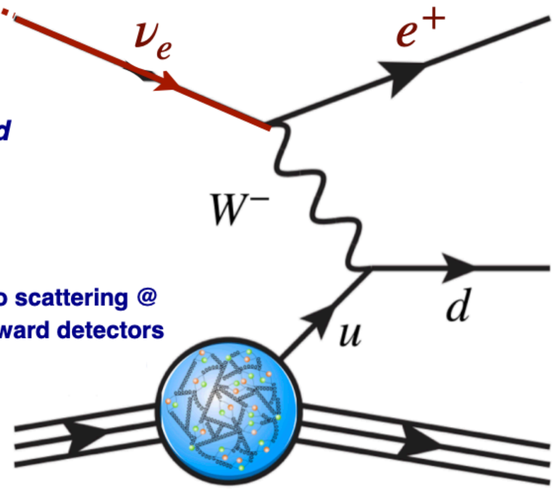
- Unique coverage of TeV energy region
  - High-statistics for all three neutrino flavours
- Anomalous neutrino couplings
- Lepton-flavour universality tests with neutrinos



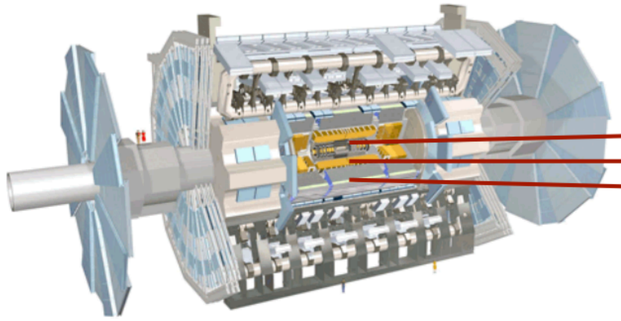


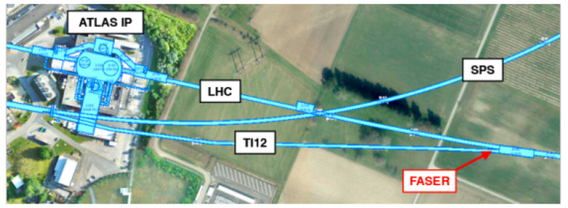


escapes undetected...
unless dedicated forward
detectors are installed



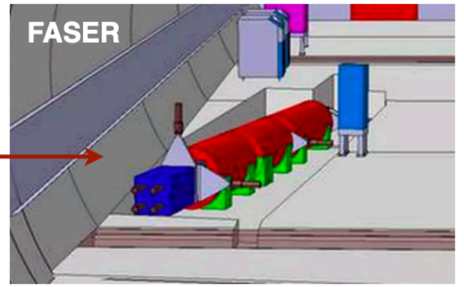
ATLAS@LHC





ν

isolated by 500 m of
rock and concrete



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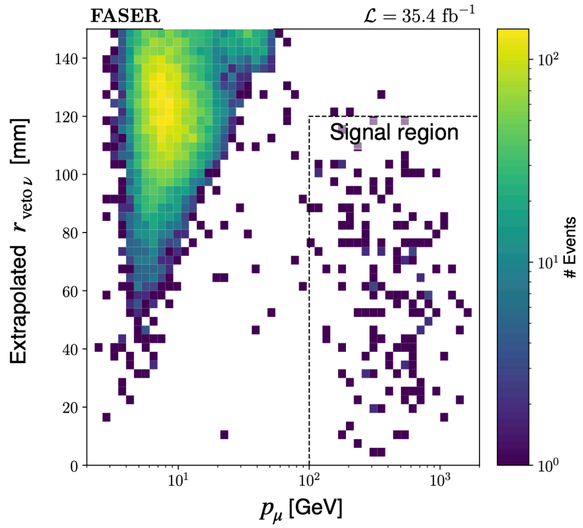
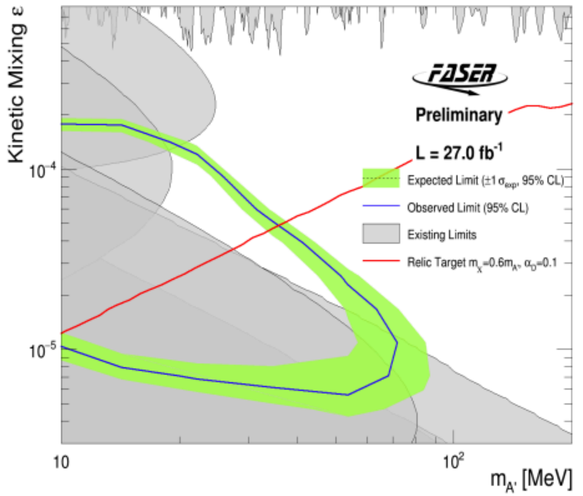
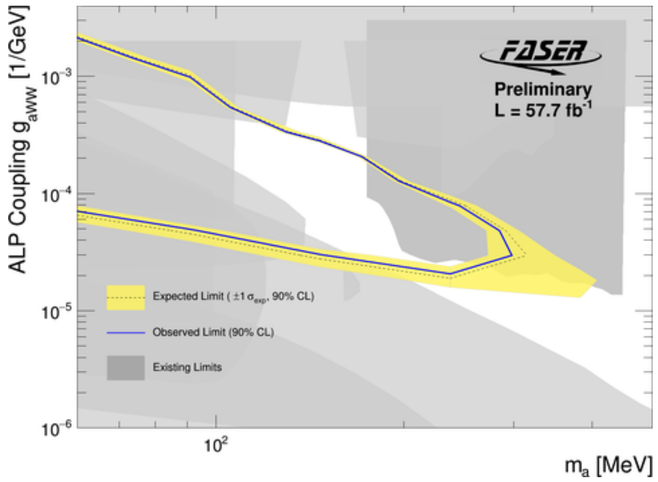
Existing experiments

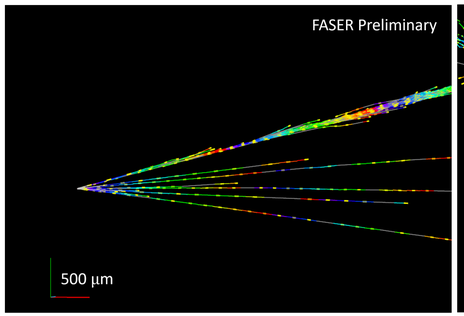
FASER

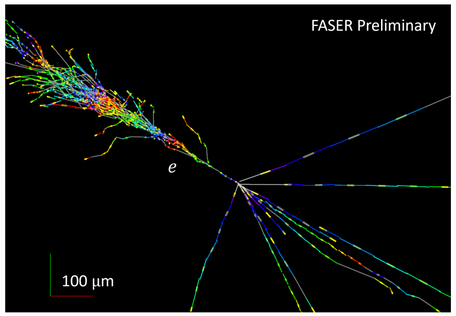
- First direct observation of collider neutrinos
  - Opens a new field: neutrino physics at the LHC
  - Published in PRL [2303.14185]
- First Dark Photon search
  - First limit in thermal relic region from low coupling for 30 yrs
  - Published in PLB [2308.05587]
- High-energy ν_e and ν_μ interactions in emulsion detector
  - [2403.12520]
- ALP search
  - World-leading constraints on ALPs
  - [CERN-FASER-CONF-2024-001]
- Approved to continue in Run 4





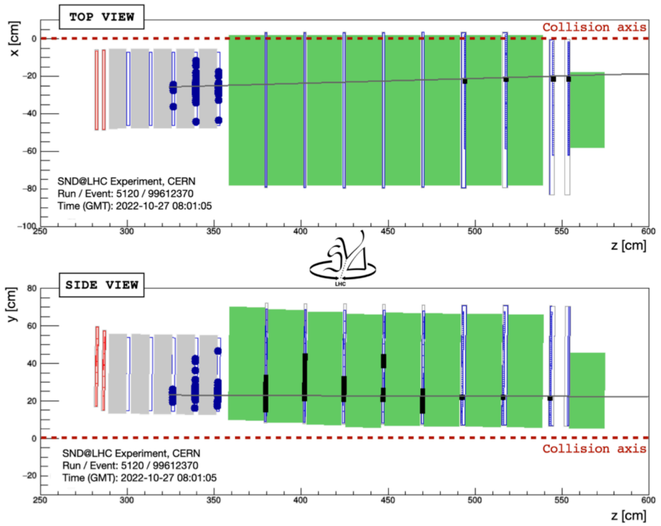


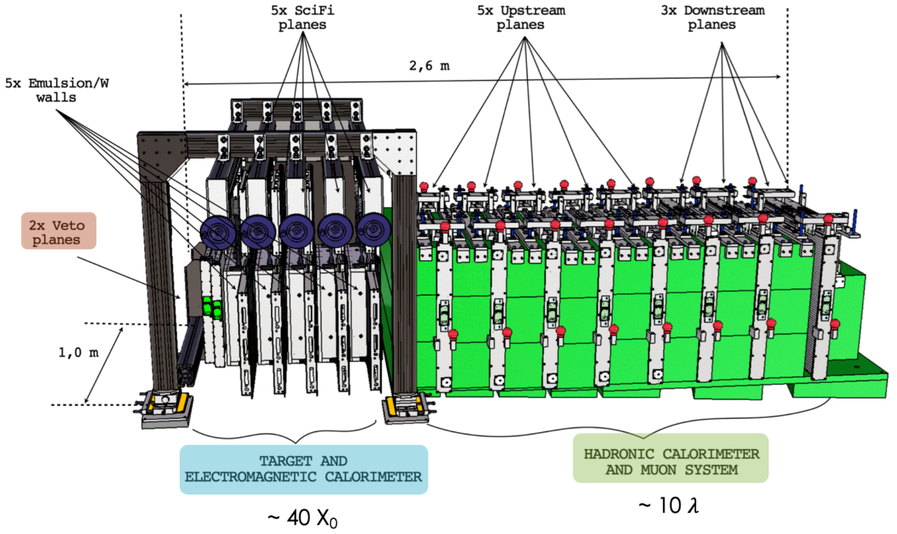


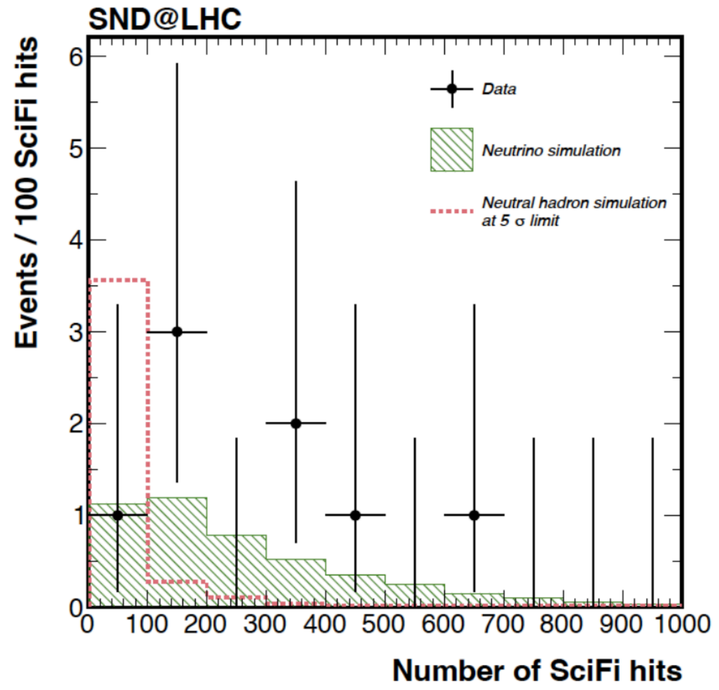


SND@LHC

- Very similar philosophy experiment to FASER(ν)
  - Opposite side of ATLAS P1
- Also recently made observation of ν_μ
  - Published in PRL [2305.09383]
- Measurement of the muon flux
  - Published in EPJC [2310.05536]
- UK involvement
  - UCL and Imperial College



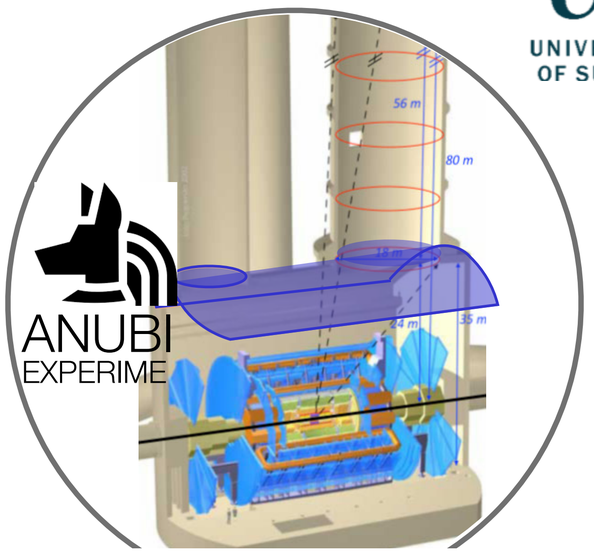


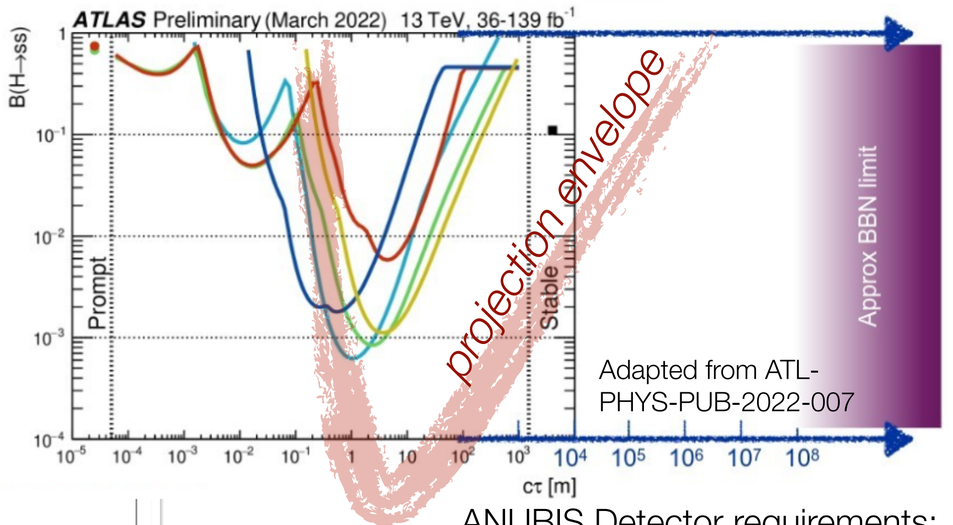


[arXiv:2305.09383]

ANUBIS

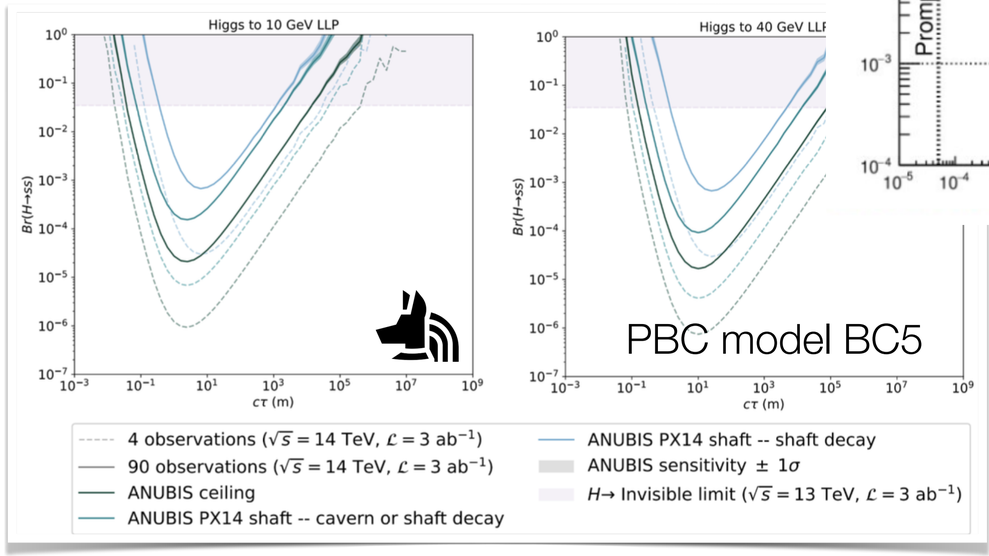
- Proposal: Extend fiducial volume → harvest sensitivity!
- Timeline: Bulk installation in LS4
- Ongoing work
  - RPC work at Cambridge: Adapt & exploit ATLAS Phase II tech
    - Eco-gases, QA for gas leaks, mech. stability
    - Within DRD1 context
  - Sensitivity projections:
    - e.g. PBC benchmarks

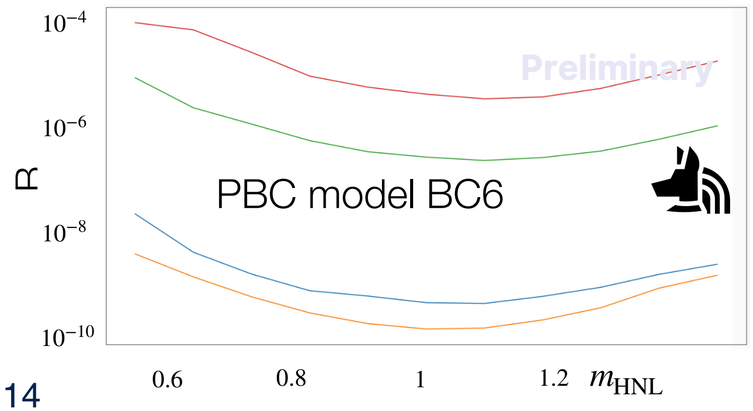




Adapted from ATL-PHYS-PUB-2022-007

CERN-THESIS-2022-169





ANUBIS Detector requirements:

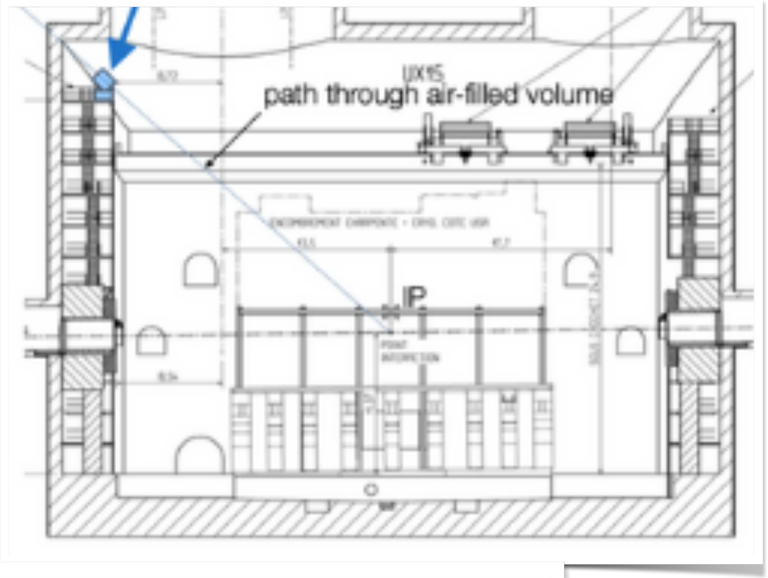
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

ANUBIS

- proANUBIS demonstrator
  - 24.5 fb-1 collected, data analysis ongoing
  - Validate technology
  - Measure K_L in punch-through
  - Hadronic interaction rates in air

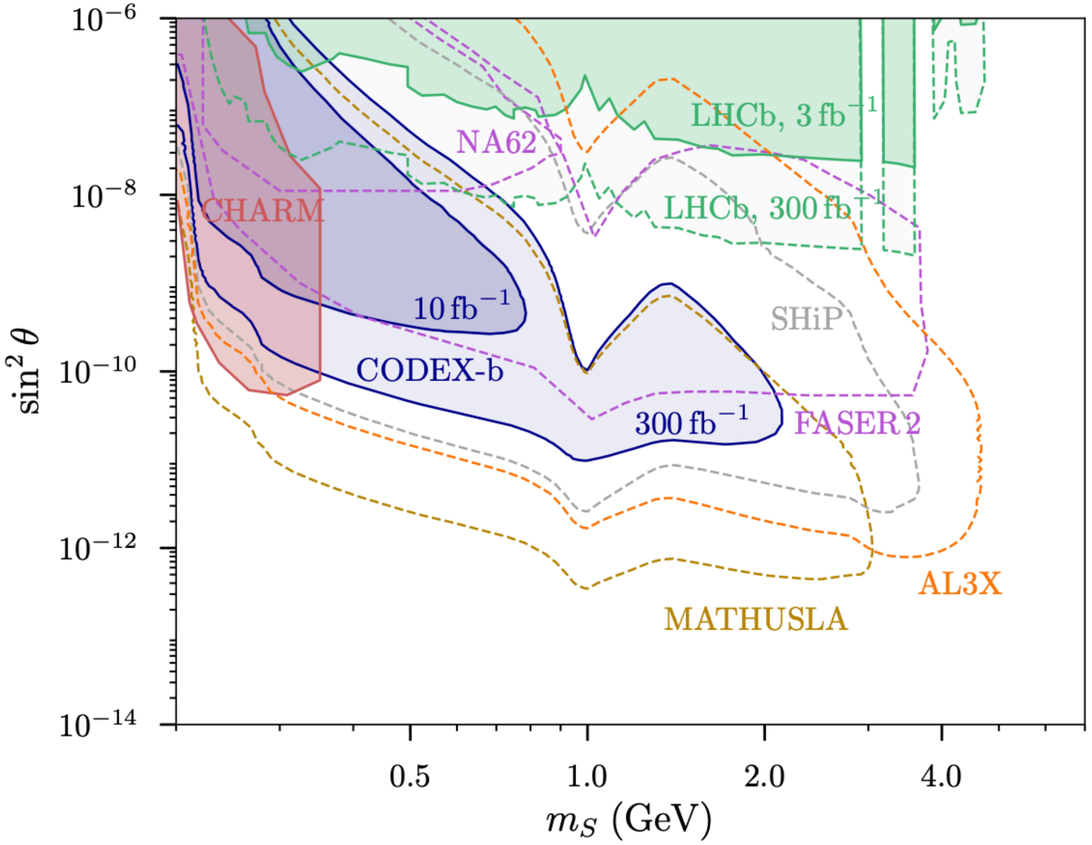
- ANUBIS collaboration UK-led:
  - Ideal starting point for UK leadership in the future!
    - Unique discovery potential (until FCC).
    - Interesting hardware with non-trivial electronics after Phase II.
    - Strong UK position for FCC detector R&D

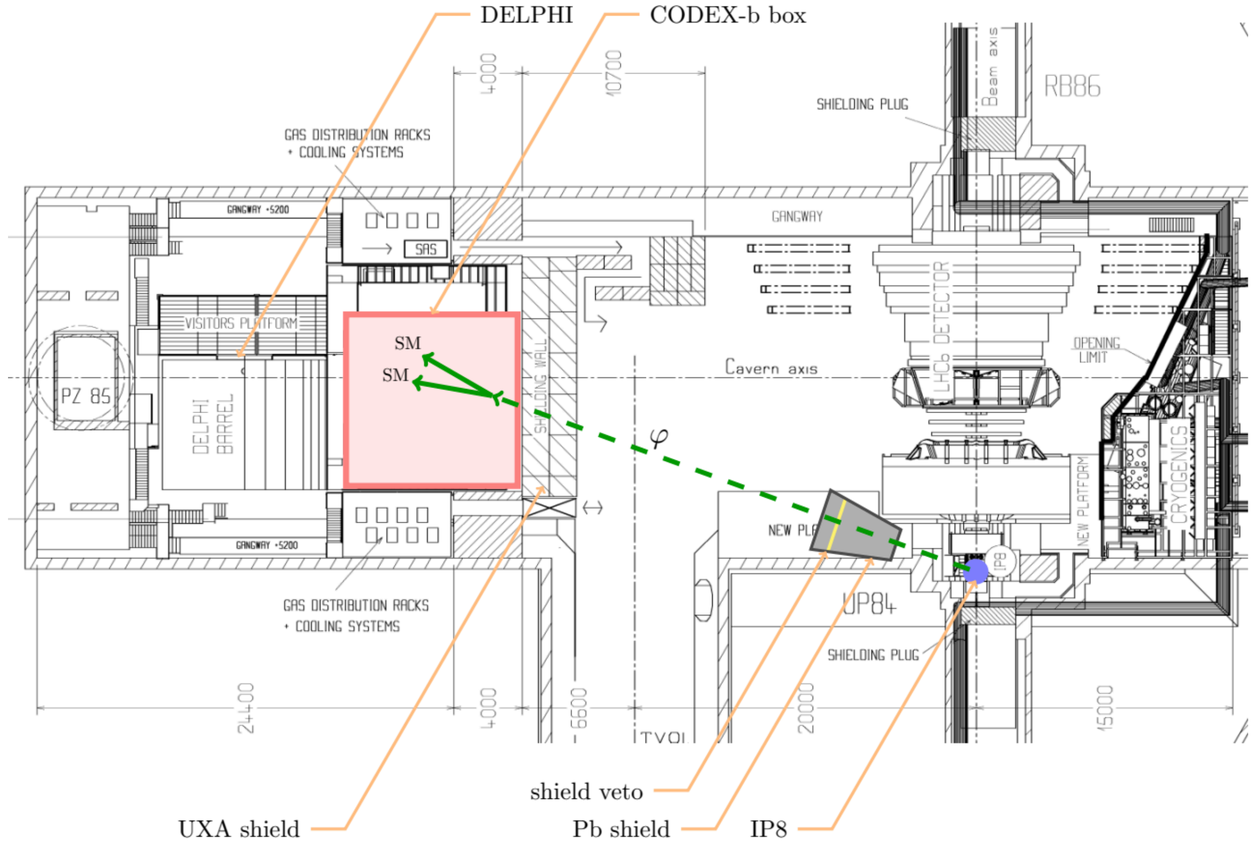
PROANUBIS DEMONSTRATOR



CODEX-b

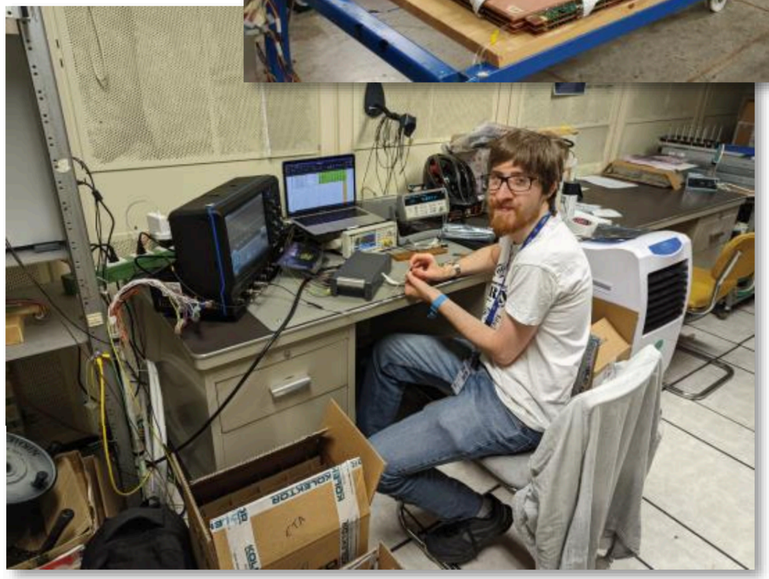
- CODEX-b is another transverse LLP experiment proposed for LHCb cavern
- Sensitivity primarily to heavier LLPs
  - Reach studies:

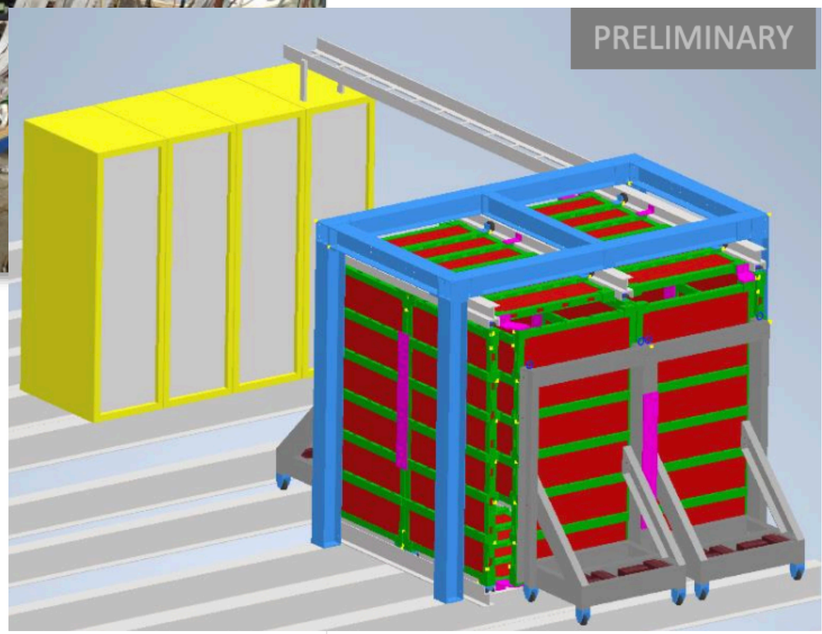




CODEX-b

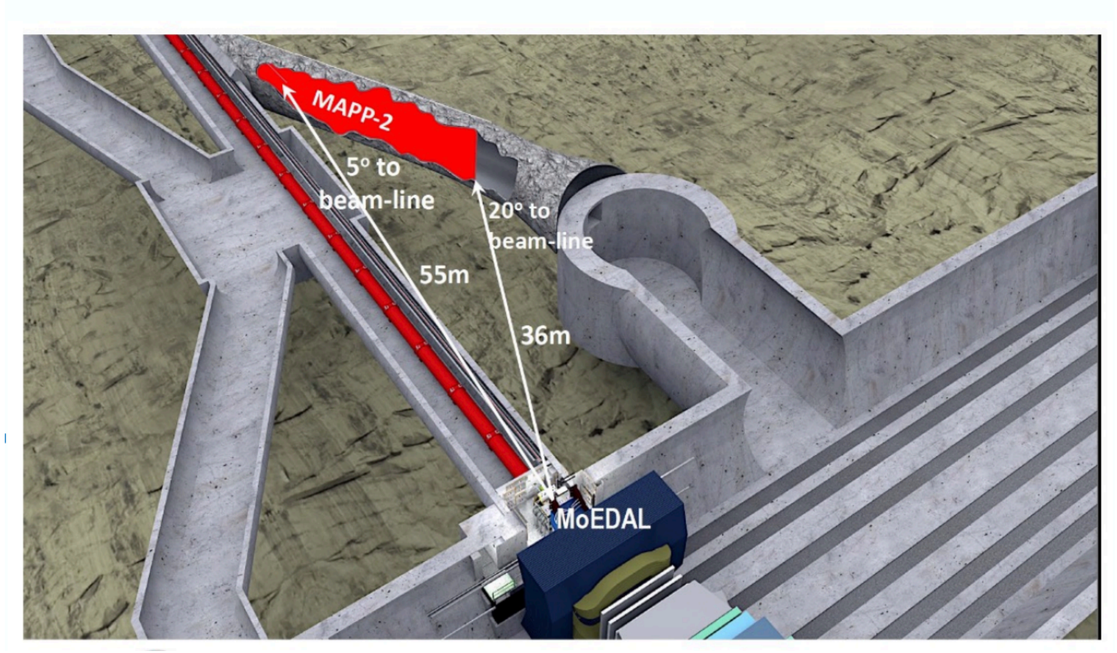
- CODEX-b is another transverse LLP experiment proposed for LHCb cavern
- Sensitivity primarily to heavier LLPs
- CODEX-β demonstrator project recently approved as LHCb R&D project.
  - UK involvement from Birmingham
  - Ops foreseen from 2025 to end of run
- TDR: [2406.12880]
- Towards installation
  - Verify bkg level estimates
  - Test integration with LHCb DAQ
  - Provide operational expertise of RPC-based tracking detector.

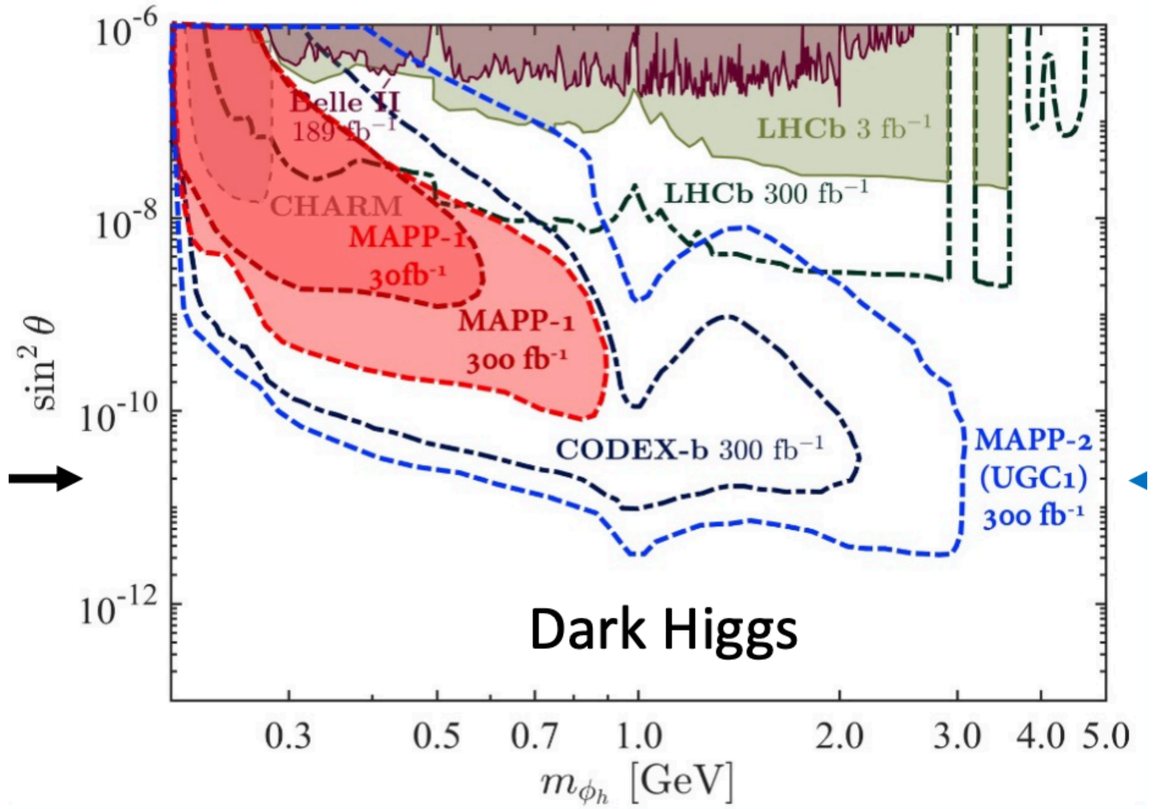




MoEDAL-MAPP

- Similar motivation to ANUBIS and CODEX-b
- For Run 3 MoEDAL detector upgraded to MoEDAL-MAPP.
  - Additional detector, MAPP (MoEDAL Apparatus for Penetrating Particles) to extend physics, providing sensitivity to milli-charged particles and long-lived exotic particles





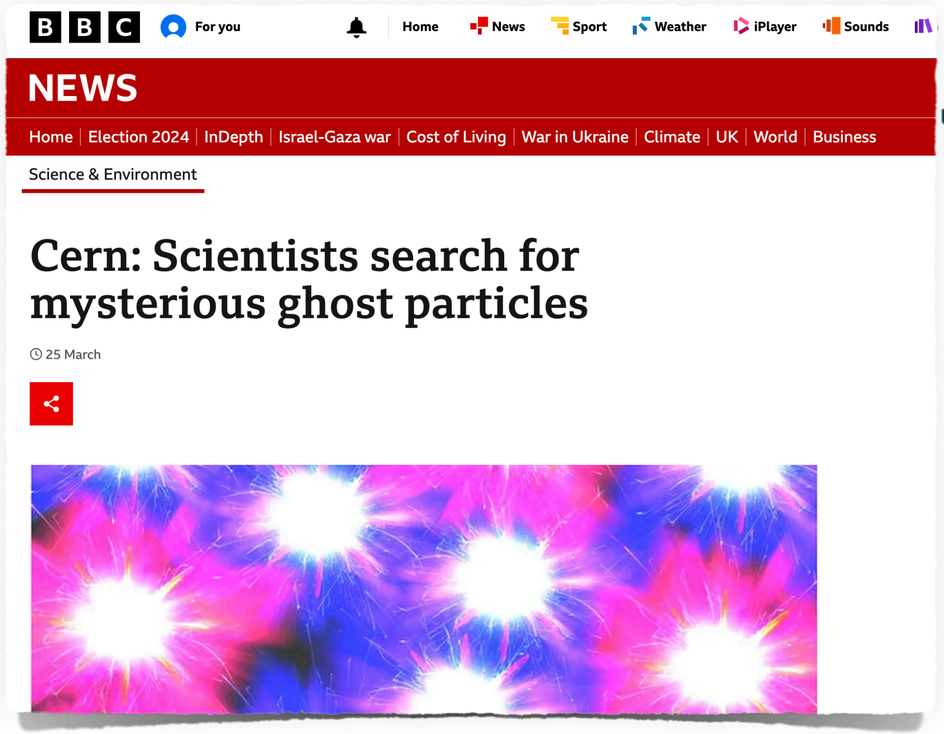
Future facilities

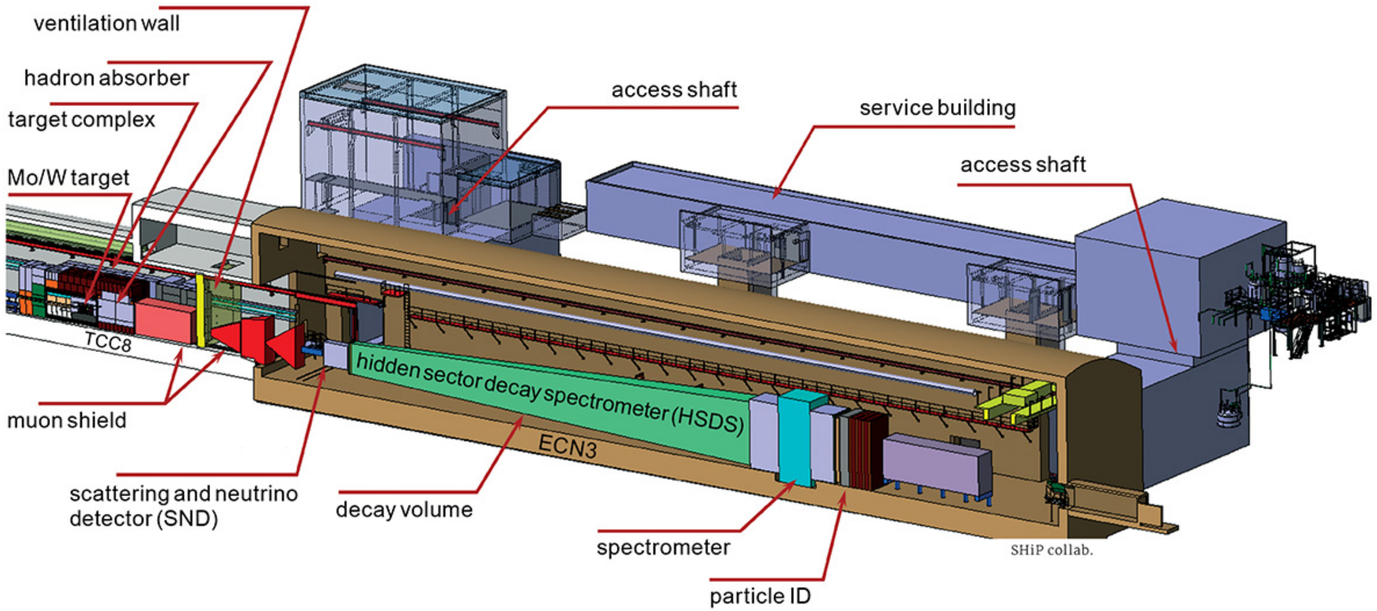
BDF/SHiP | Overview

- Unique discovery potential for feebly interacting BSM particles as well as unique tau neutrino program.

- CERN has approved construction of 69MCHF facility, sole user of which is SHiP
  - Proton delivery foreseen to extend beyond lifetime of HL-LHC

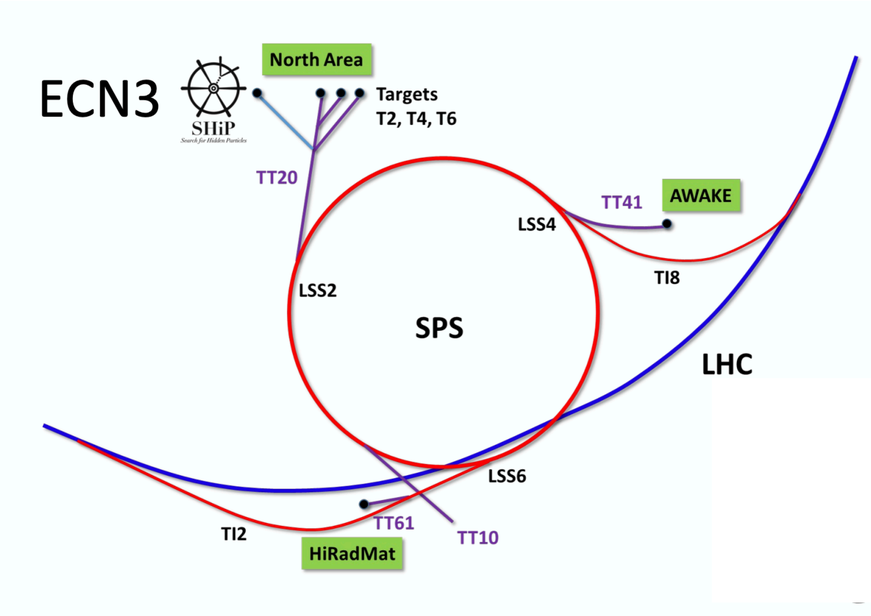
- The BDF/SHiP project has been initiated and led by UK physicists
  - Imperial, RAL, Bristol and UCL
  - A unique opportunity for the UK.
  - Should be included in the PPAN roadmap as a high priority project.





BDF/SHiP | Timeline

- ~3 years for detector TDRs
  - Active discussion on how UK might seek to contribute
- Key milestone is to start data taking >1 year before LS4
- Operation through to late 2040s
  - Several upgrades/extensions of the BDF/SHiP in consideration over the operational life



Accelerator schedule	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC	Run 3				LS3			Run 4				LS4
SPS (North Area)												
BDF / SHiP	Study		Design and prototyping			Production / Construction / Installation				Operation		
Milestones BDF		TDR studies			PRR				GwB			
Milestones SHiP			TDR studies			PRR			GwB			

Approval for TDR

Submission of TDRs

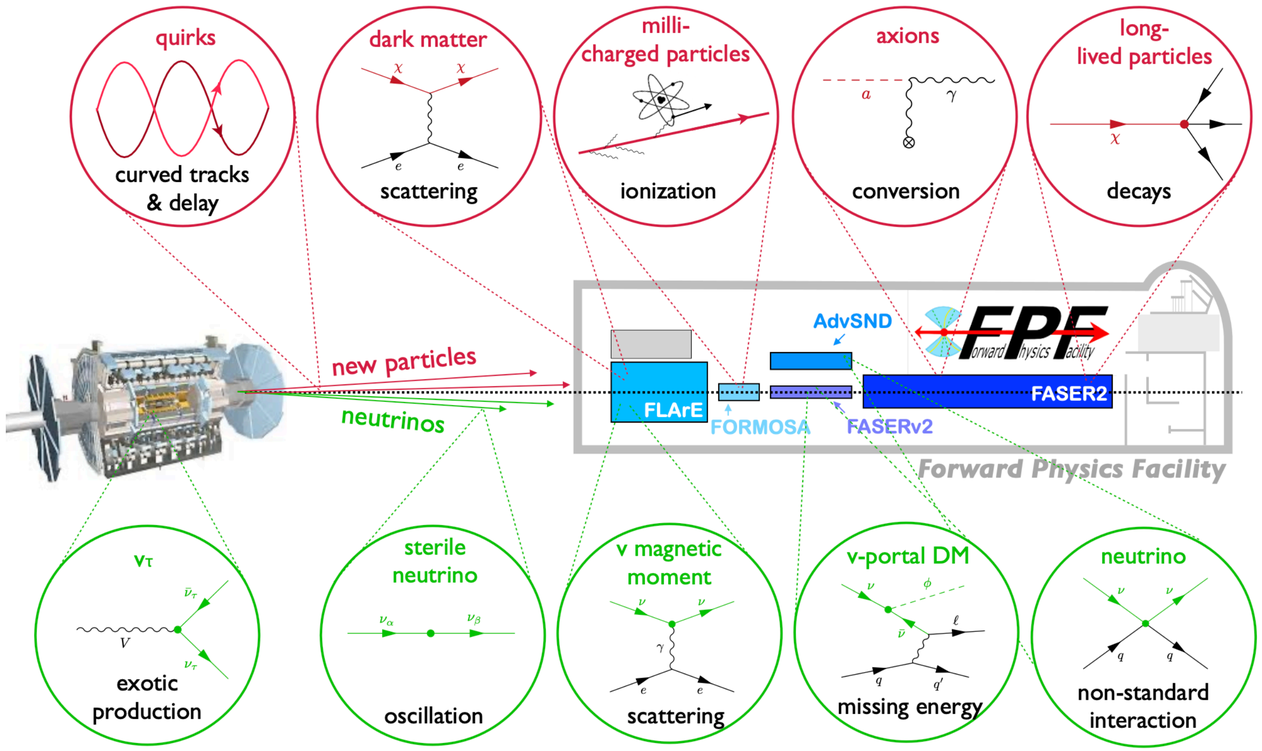
Facility commissioning

Forward Physics Facility | Overview

- FASER and other proposed detectors currently **constrained by tunnels and infrastructure** that was never designed to support experiments.
  - Clear that there is a **rich physics program in the far-forward region**
  - Strongly **motivates to create a dedicated facility** to house far-forward experiments

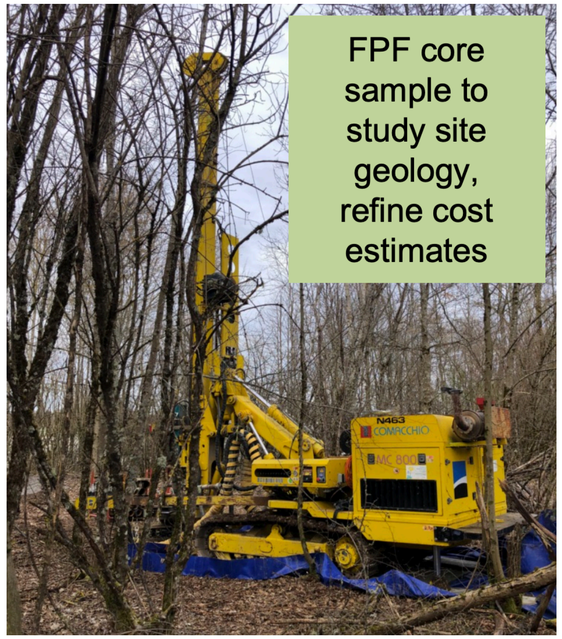
- FPF Papers:
  - "Short" Paper: Phys. Rept. 968, 1 (2022)
  - White Paper: J. Phys. G (2022)

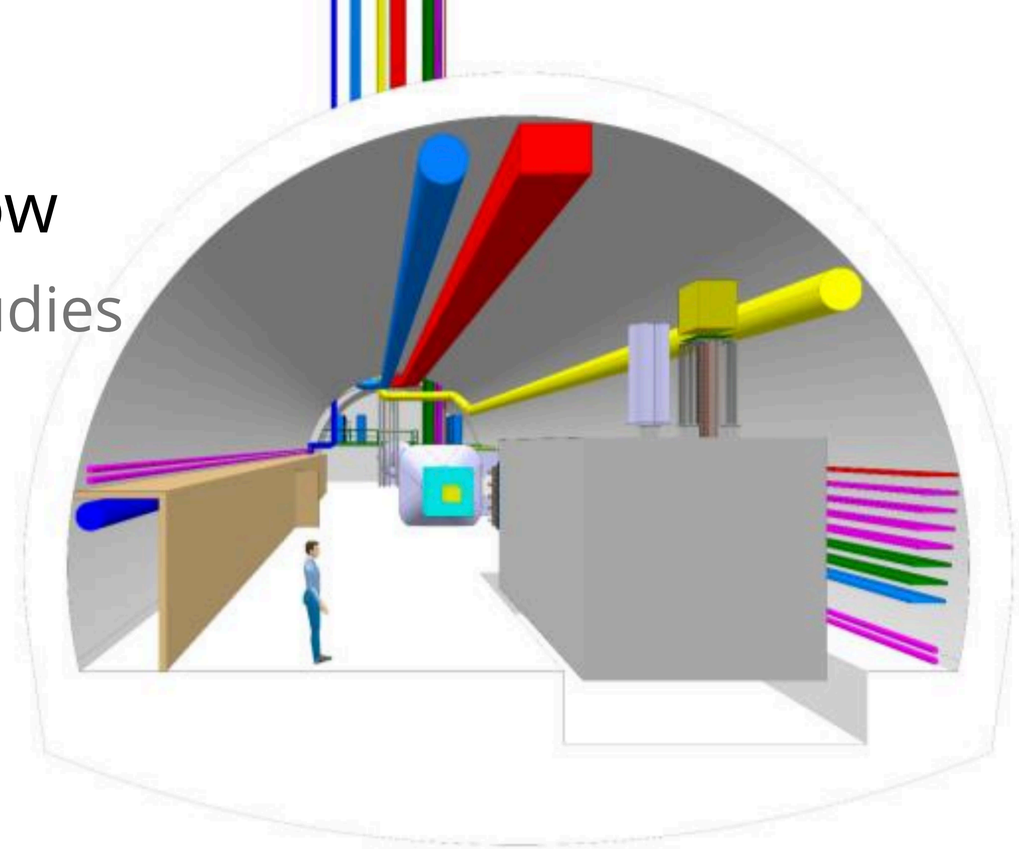
- Significant UK involvement
  - FPF UK meeting in October

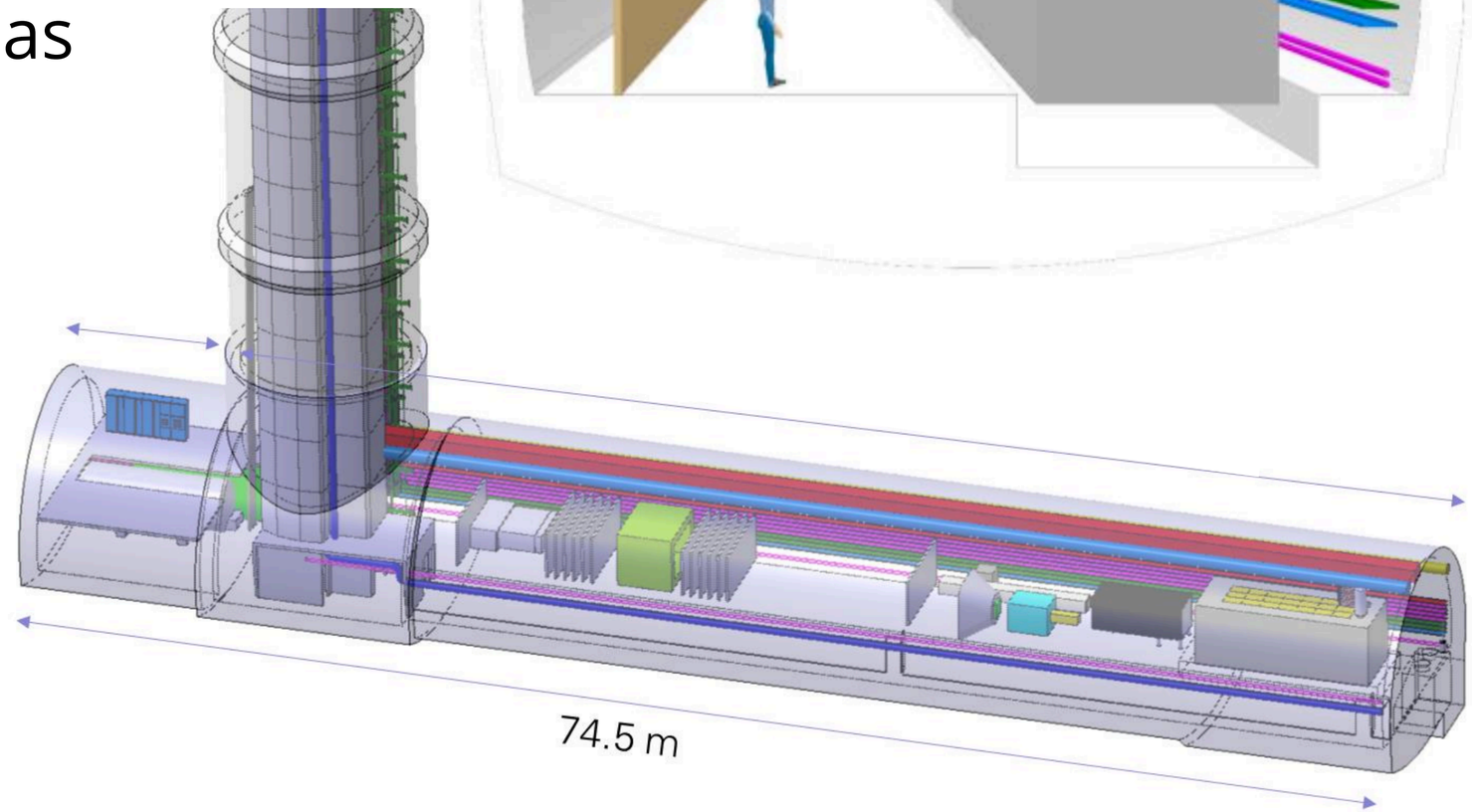


FPF | Milestones

- PBC report on facility and infrastructure ~ now
  - Positive outcome of ongoing site investigation studies (geological drill down to the cavern depth)
- ESU input early 2025, LoI to CERN after.
- Start civil engineering as close as possible to LS3
- Data-taking as early as possible in Run 4.

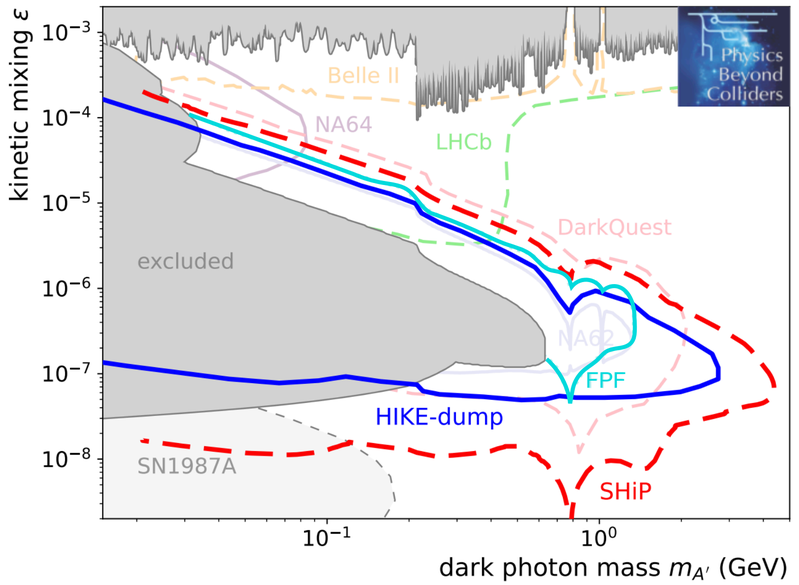


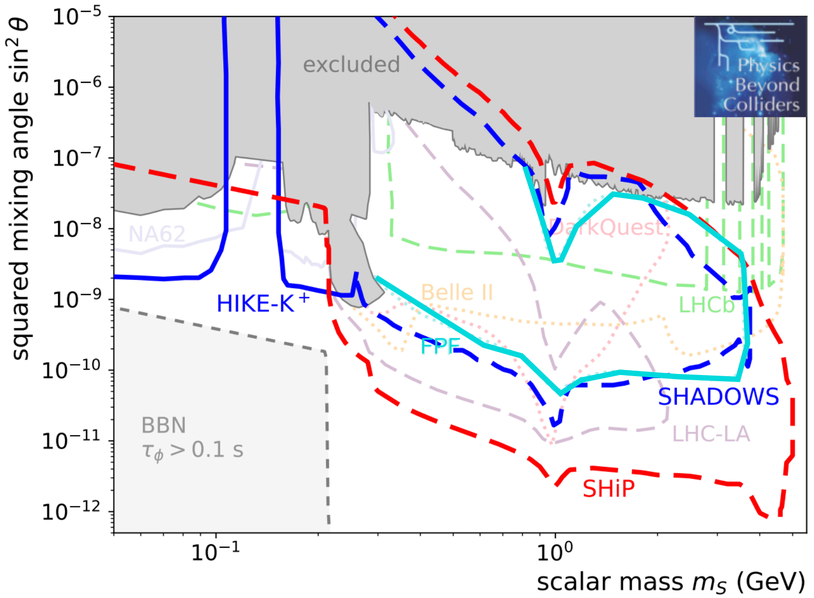


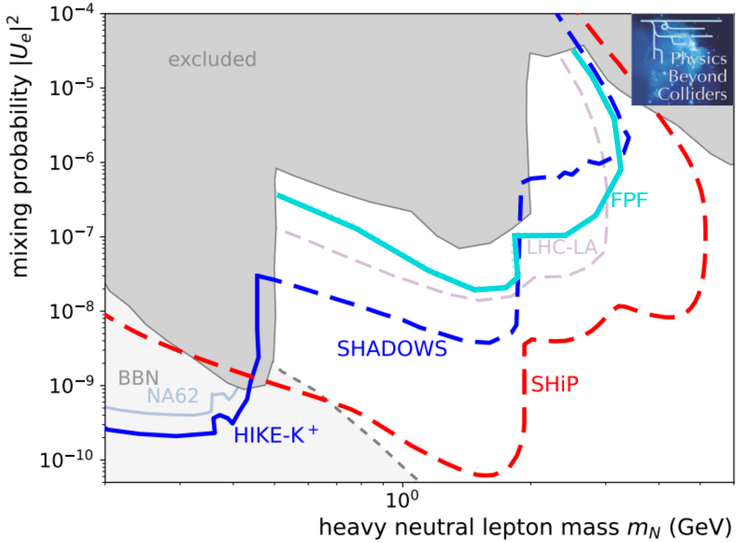


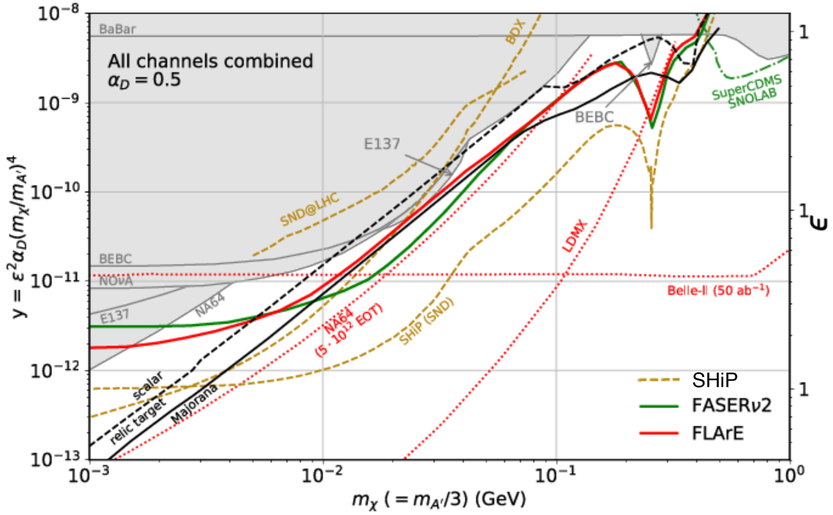
Future prospects | BSM

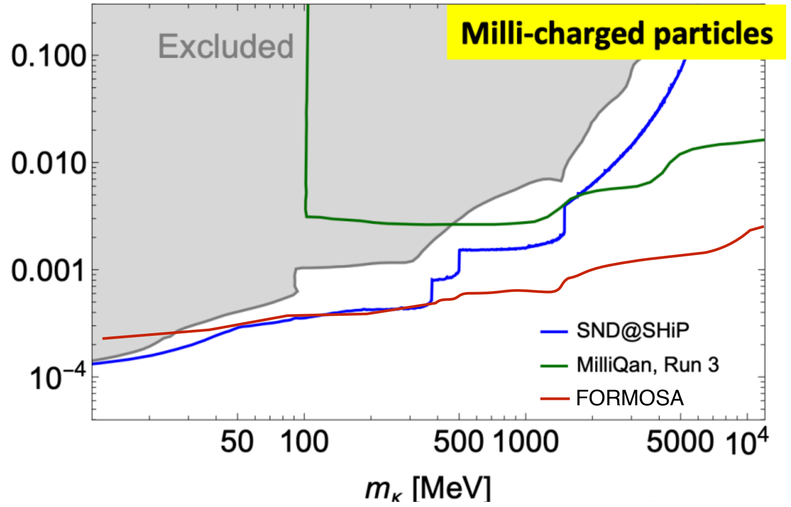
- SHiP BSM reach projections show world-beating sensitivity in a number of scenarios
  - FPF stronger in scenarios where higher energy is important





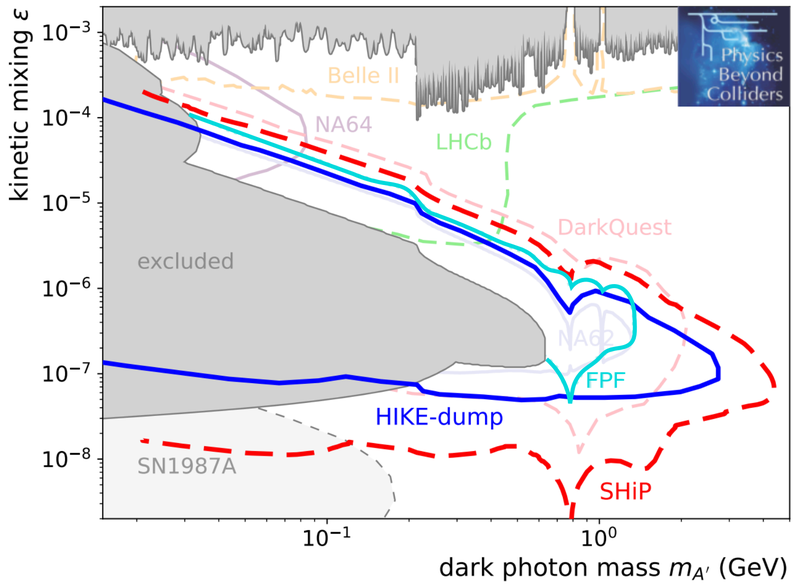


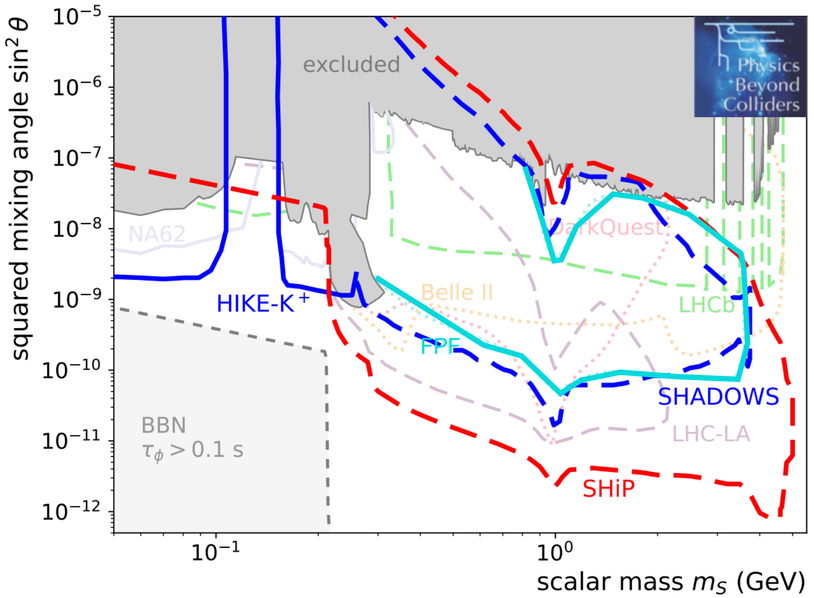


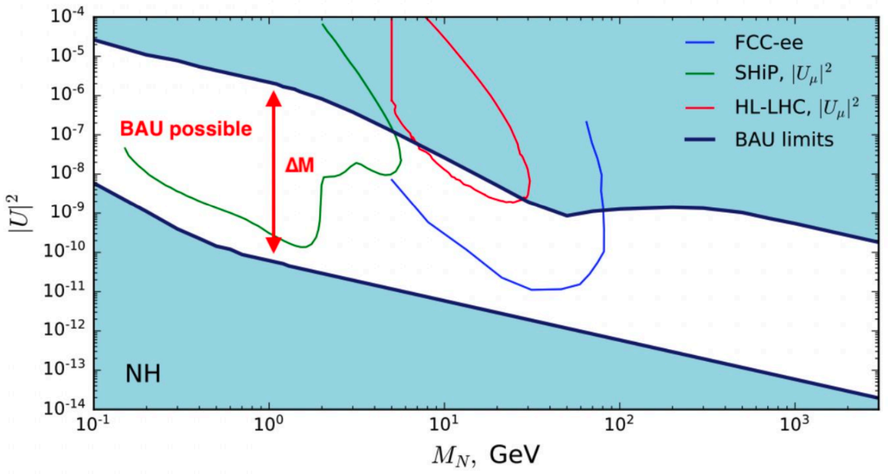


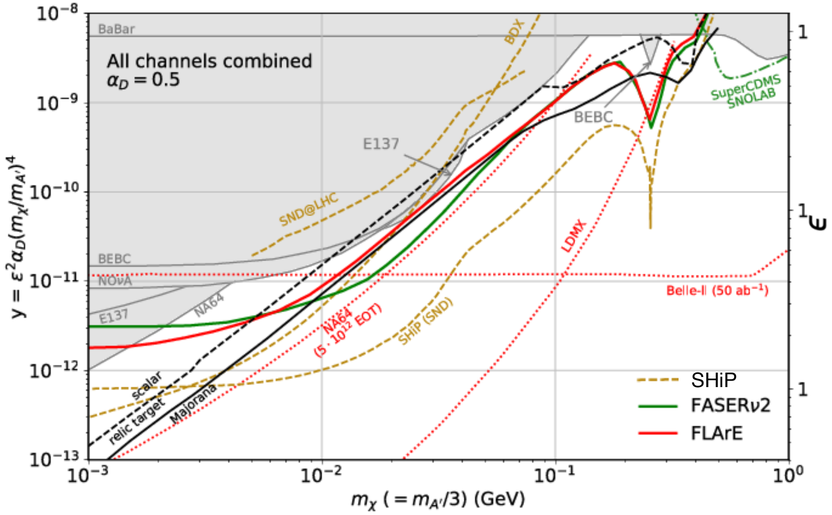
Future prospects | BSM

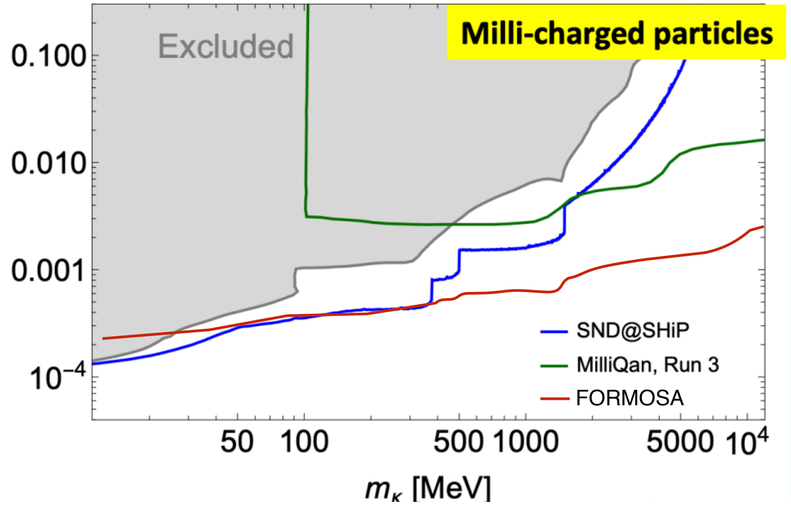
- SHiP BSM reach projections show world-beating sensitivity in a number of scenarios
  - FPF stronger in scenarios where higher energy is important





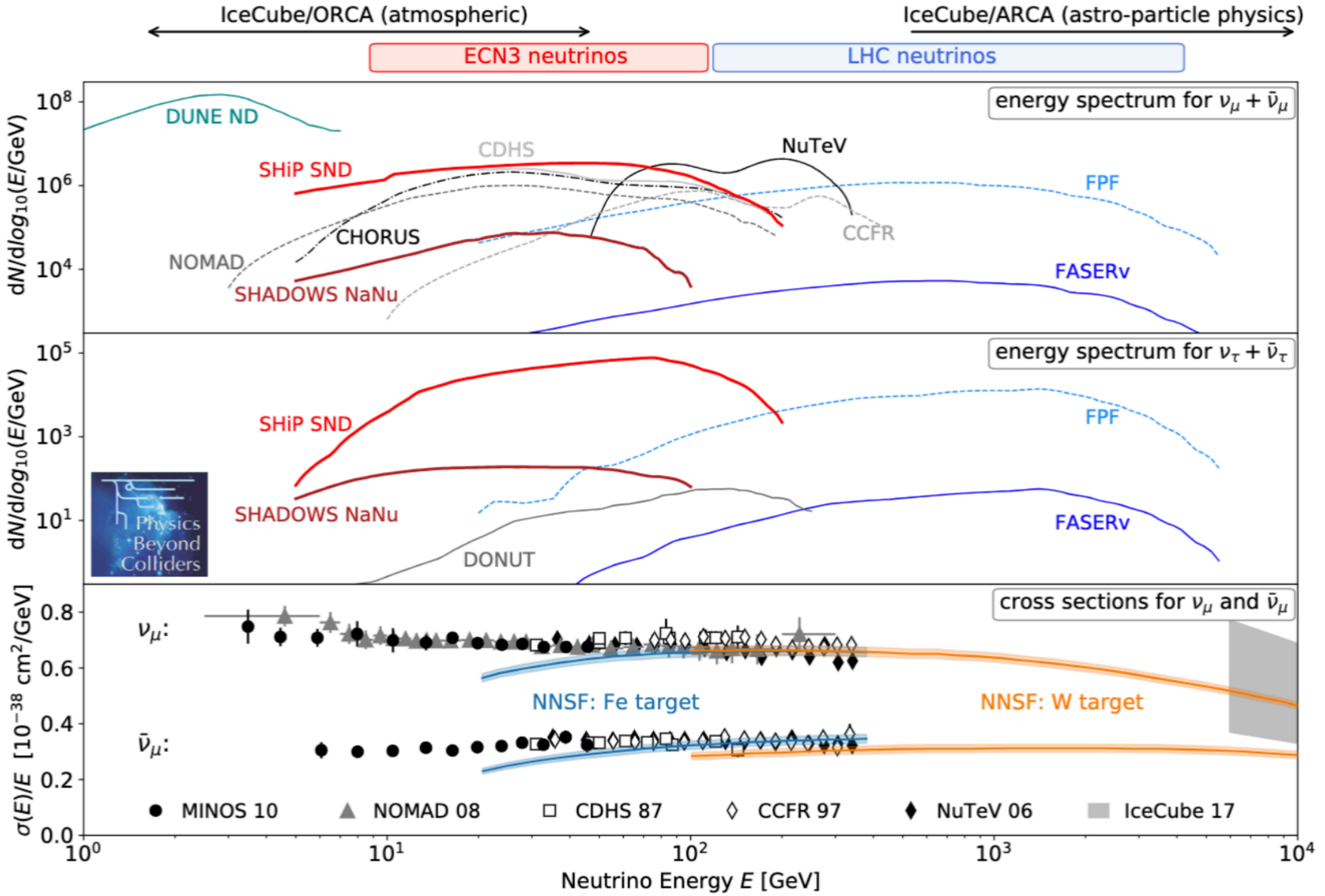






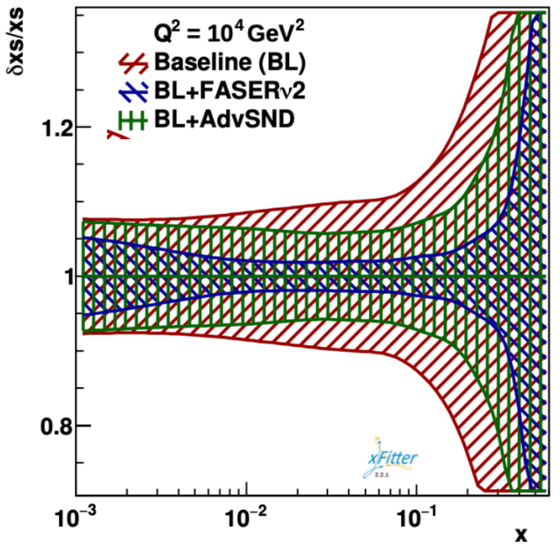
Future prospects | Neutrinos

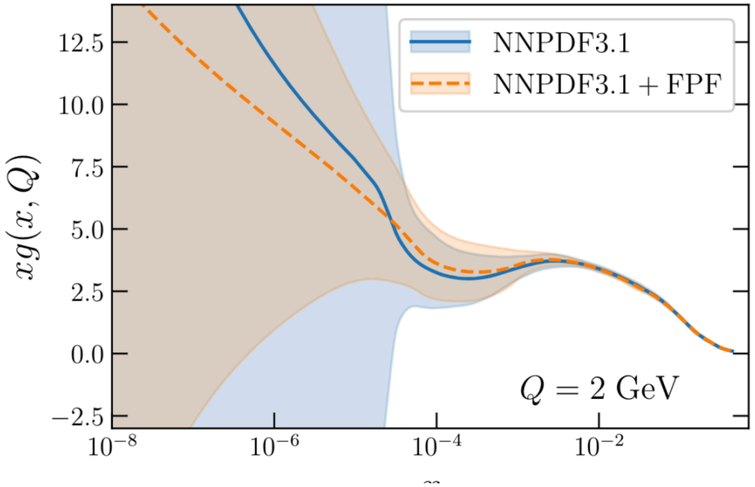
- Complementarity between ECN3 and FPF neutrinos programs
  - Different energy ranges
- Energy range probed by FPF currently unconstrained

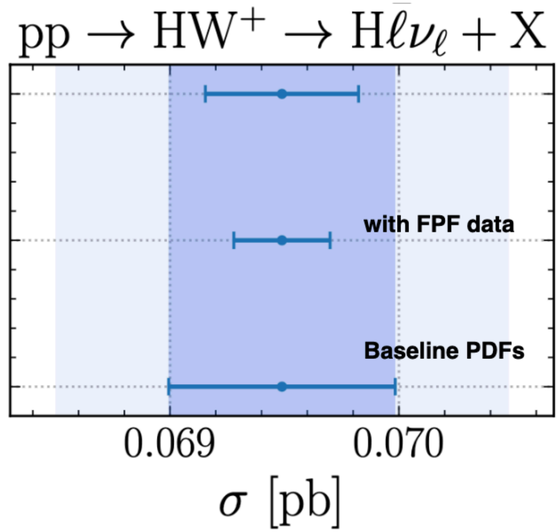


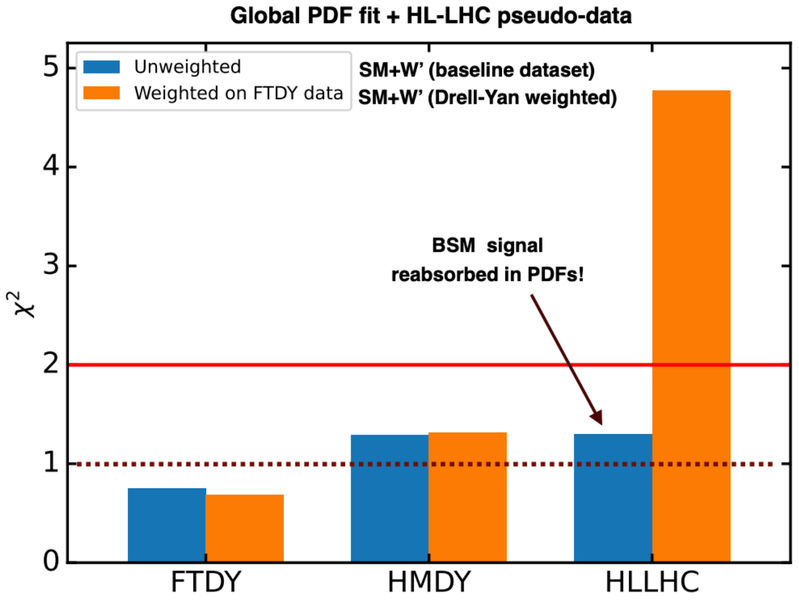
Future prospects | Neutrinos

- Better PDF constraints can impact HL-LHC!
  - Improvements for Higgs measurements
  - More accurate low-energy measurements needed to constrain large-x PDFs and disentangle QCD from BSM effects
    - FPF neutrino DIS measurements can break this PDF/BSM degeneracy!
- Essential input to realise the full potential of the HL-LHC



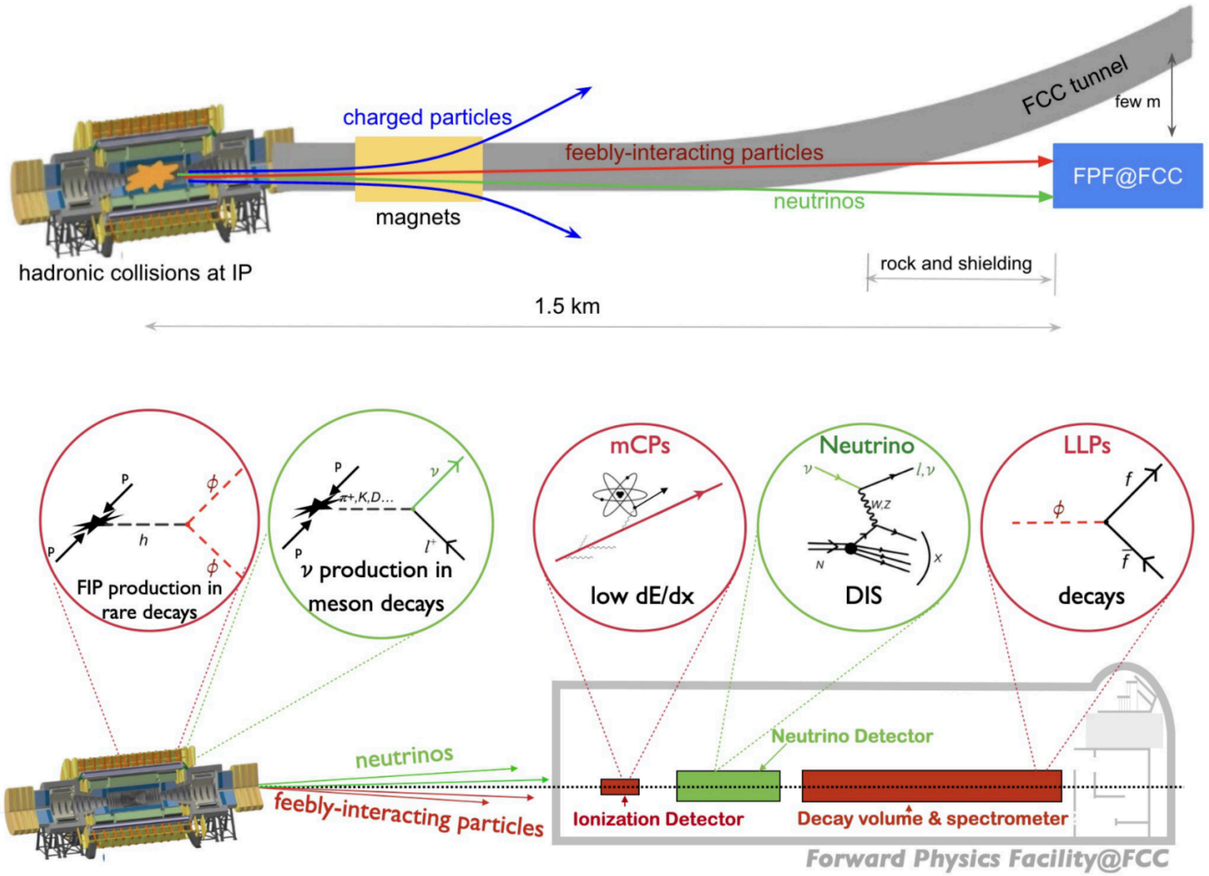


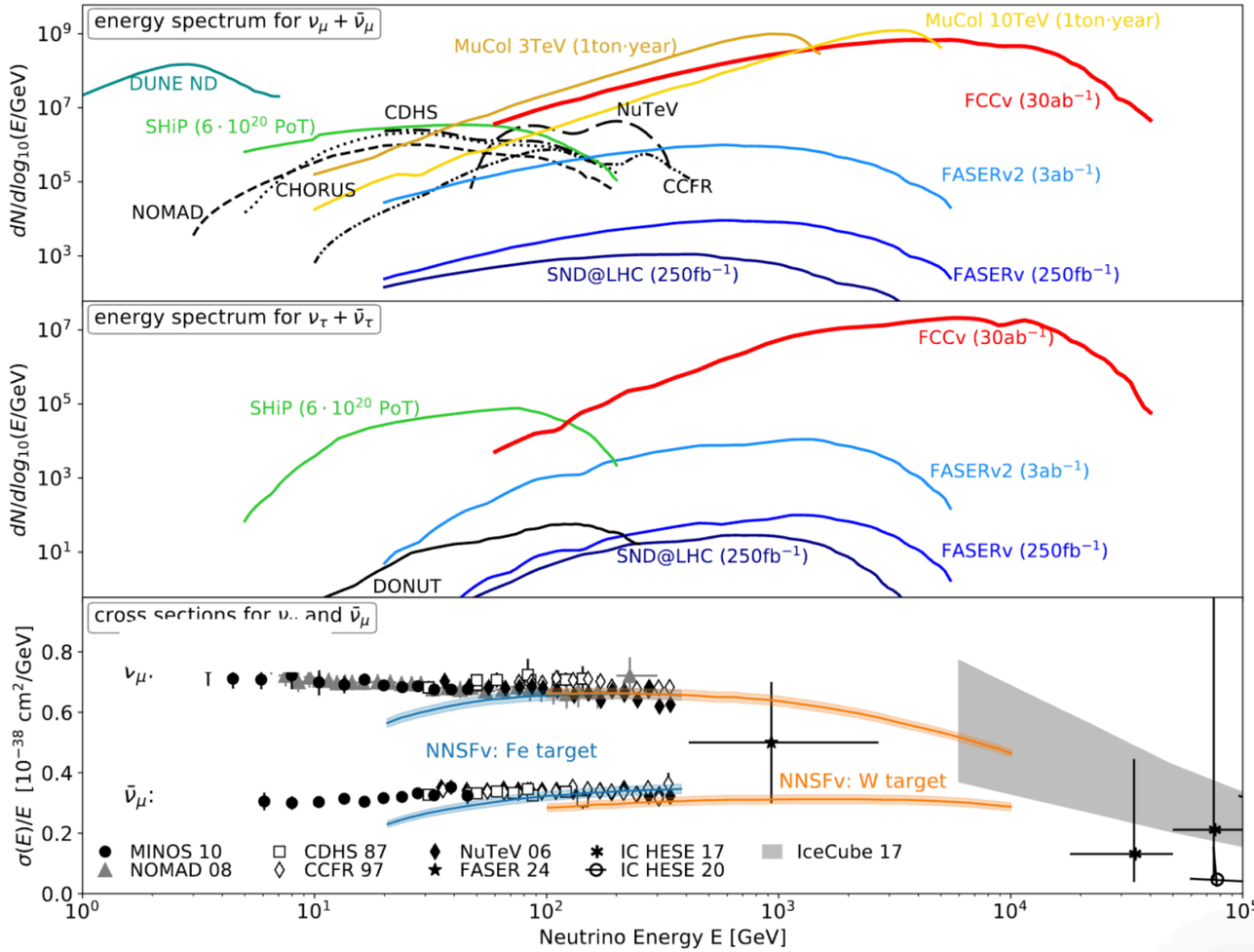




FPF@FCC?

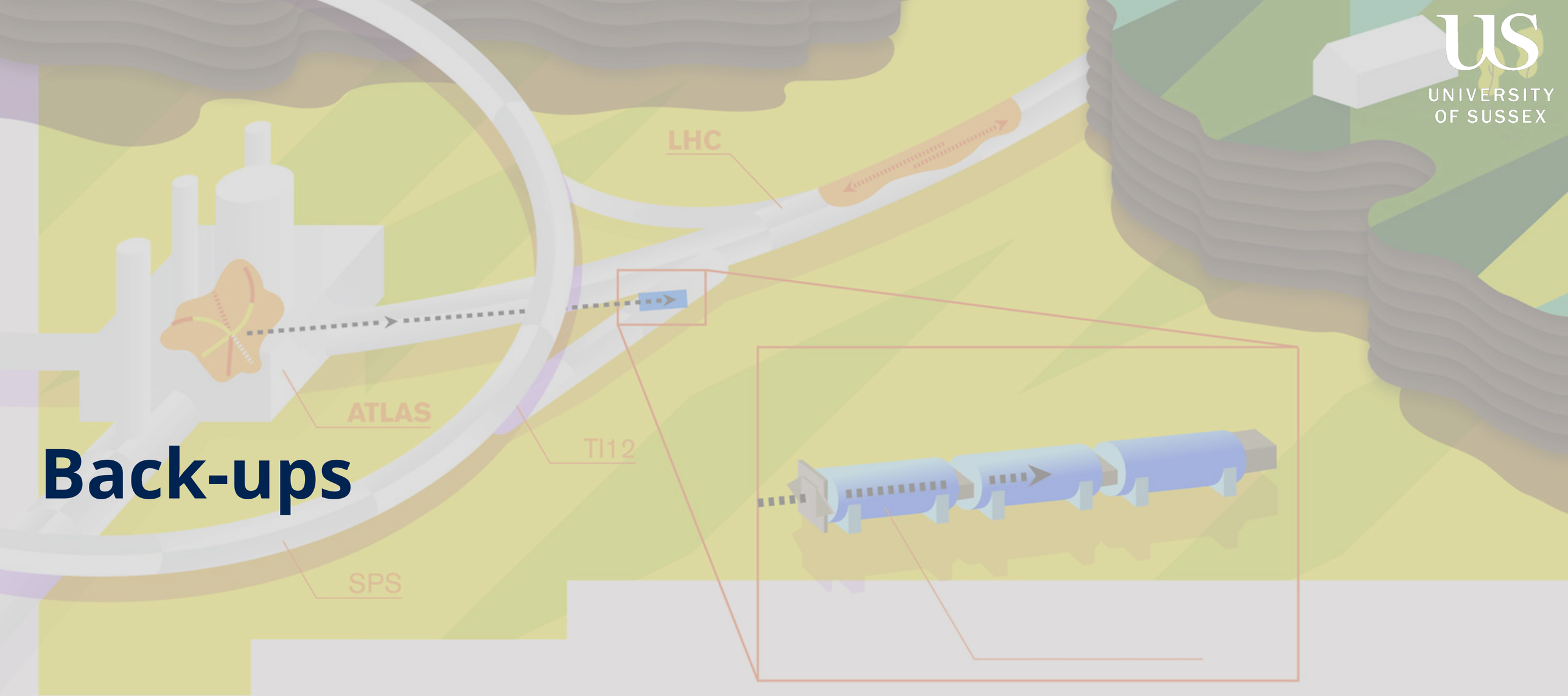
- At the LHC the forward physics program has been a bit of an afterthought
  - A future collider should consider it from the beginning!





Summary

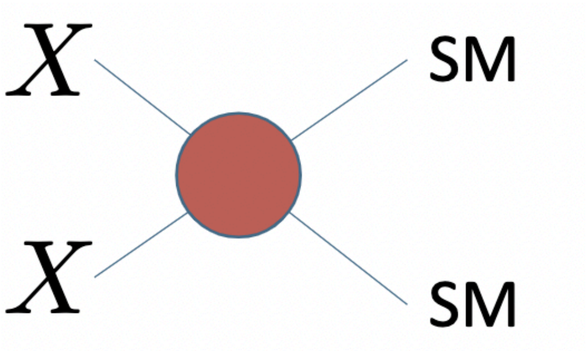
- Several “auxiliary” experiments with significant UK involvement have emerged since the last roadmap exercise
  - Physics programs a focussed on long-lived BSM searches and neutrino measurements
  - Several proof-of-principle experiments and prototypes running successfully
- These projects offer important complementary and diversity to LHC/CERN program
  - Timescale matches well the 10 year roadmap and next European Strategy Update
- The approval of BDF/SHiP is a major project with UK leadership
  - Other possibilities such as the FPF should also be pursued
- Future large projects will require UK culture of construction large infrastructure
  - Particularly those with an opportunity to involve industry, e.g. construction of large magnetic systems.
  - Auxiliary experiments offer opportunity to be test-beds for future collider technologies
- World-leading science opportunities and unique opportunities for the UK.
  - Should be included in the roadmap (some as high priority projects).

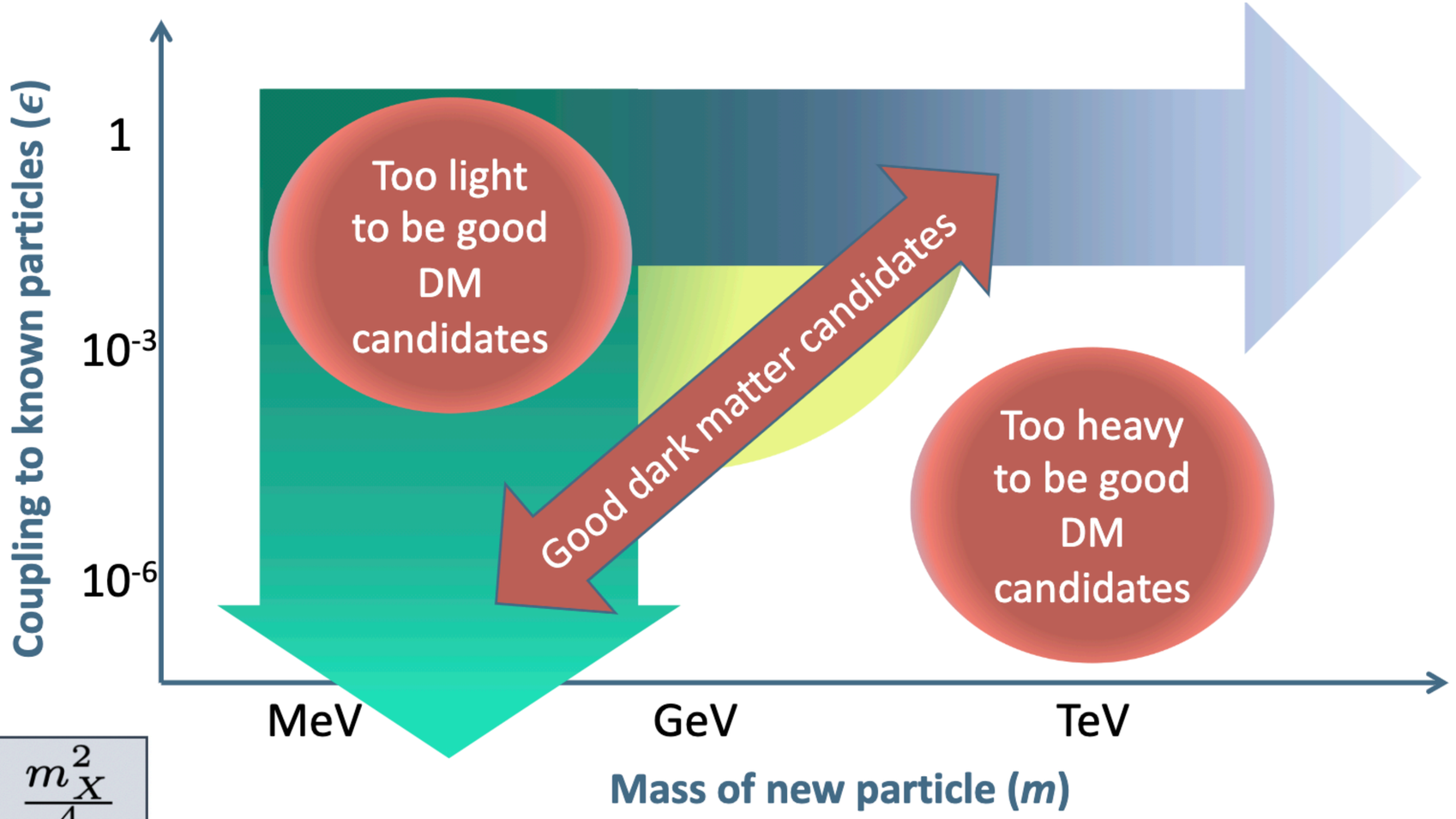


Back-ups

LDM | Light Weak DM Motivation

- Main region of interest is for new particles that satisfy DM relic density requirements.





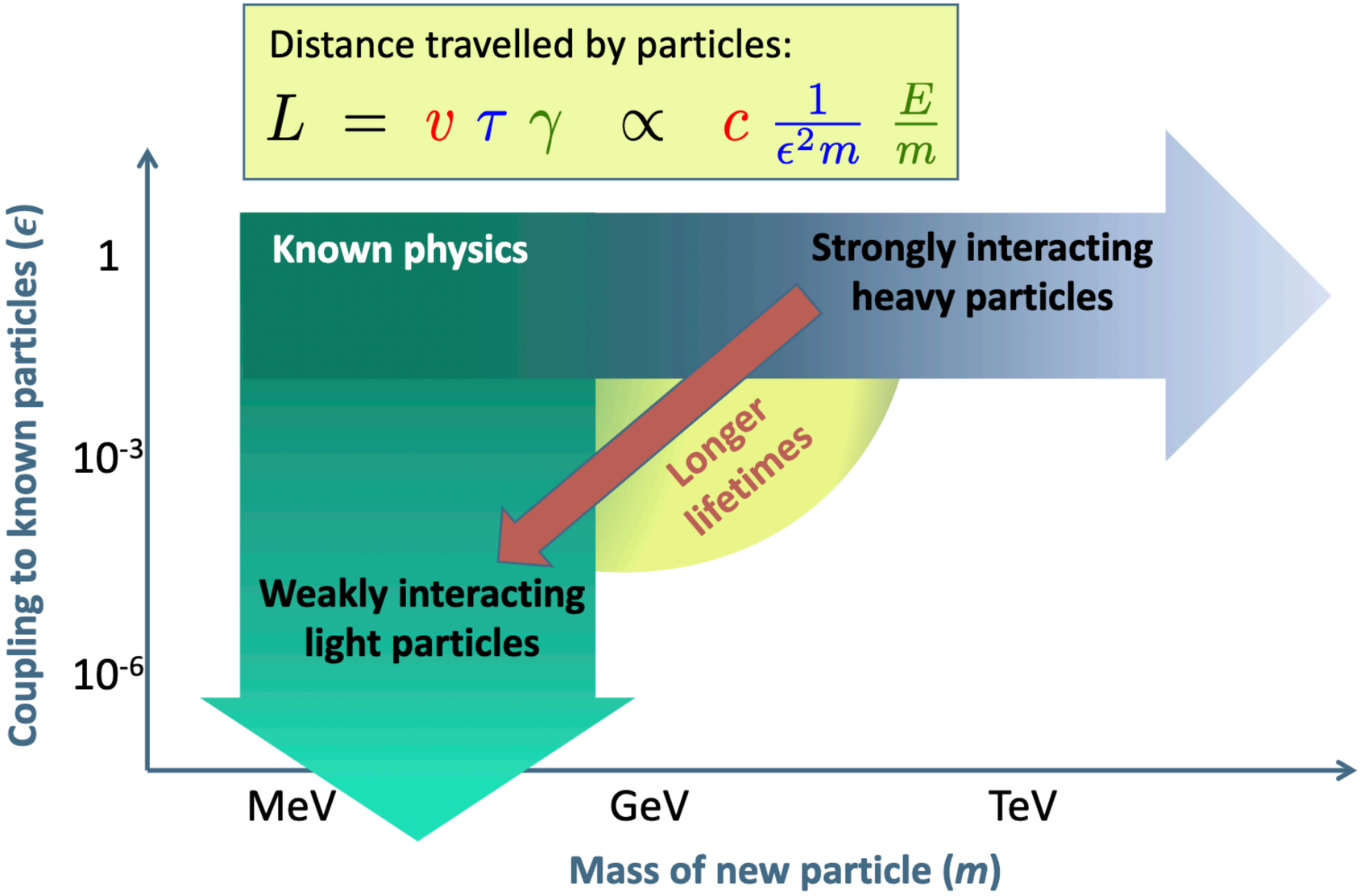
Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

LDM | Light Weak DM Motivation

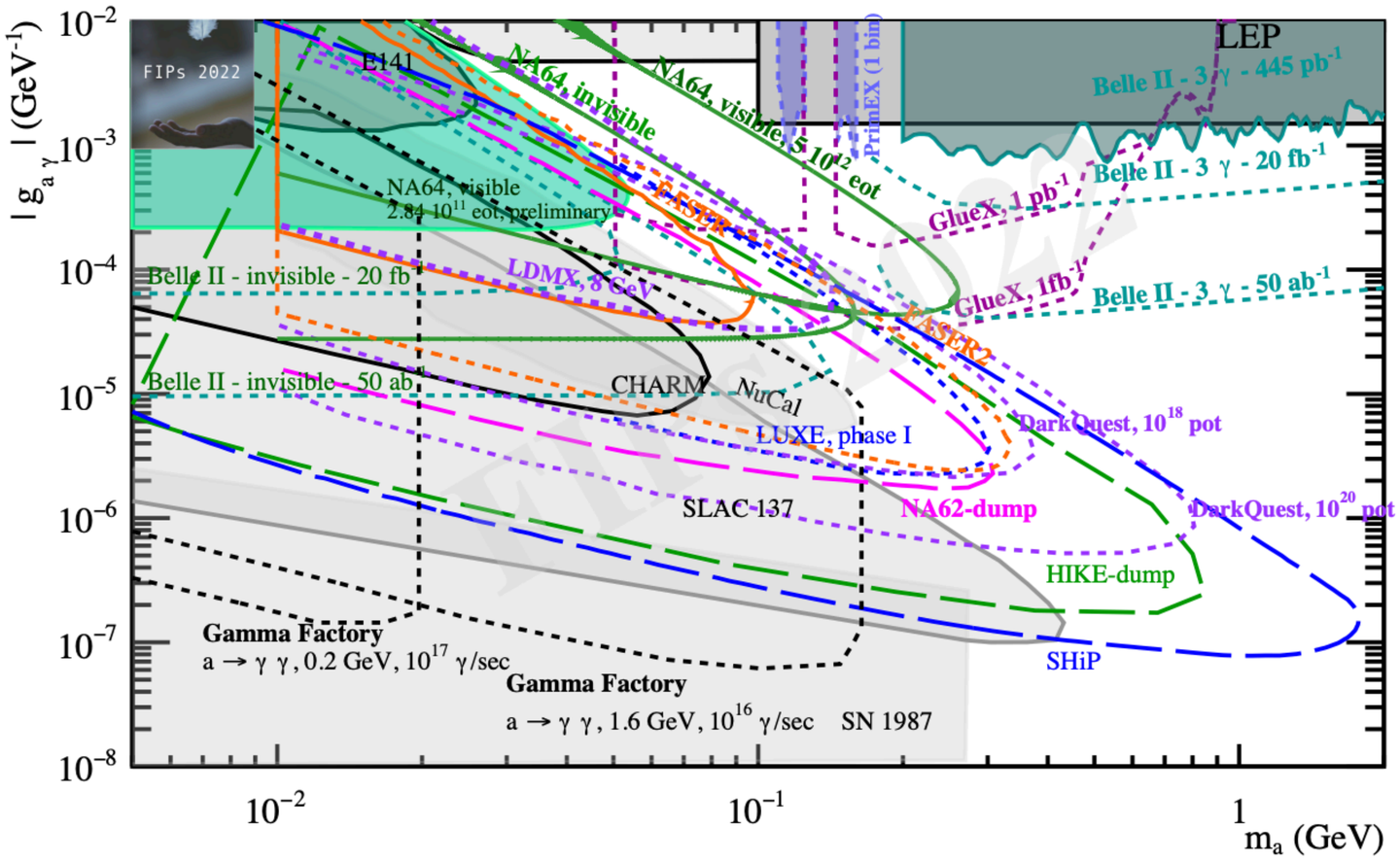
- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.

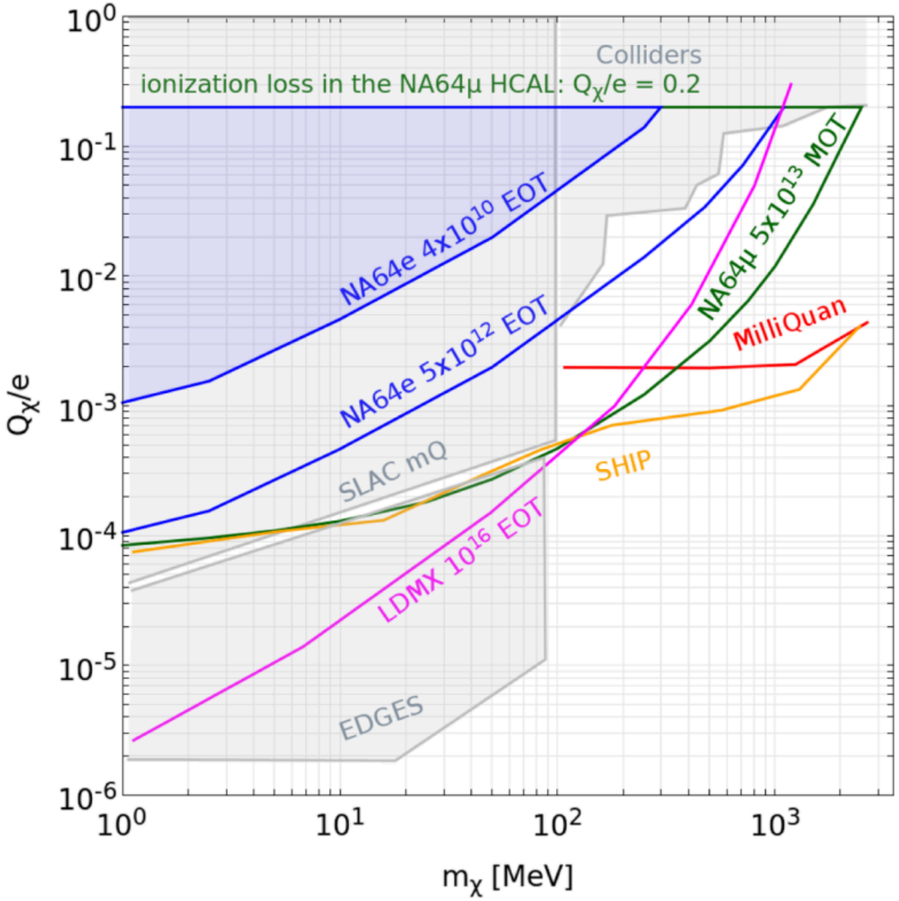
- Distinct signatures

- Opportunity for exploration!

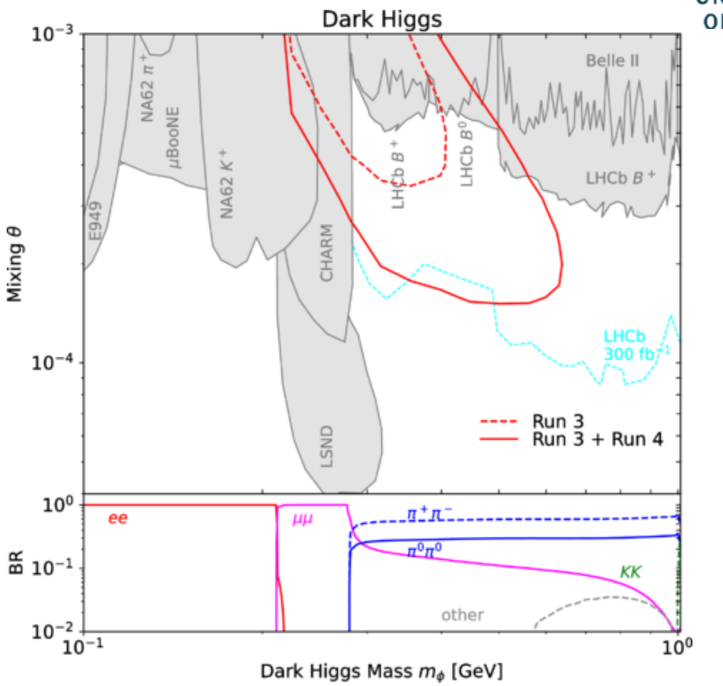


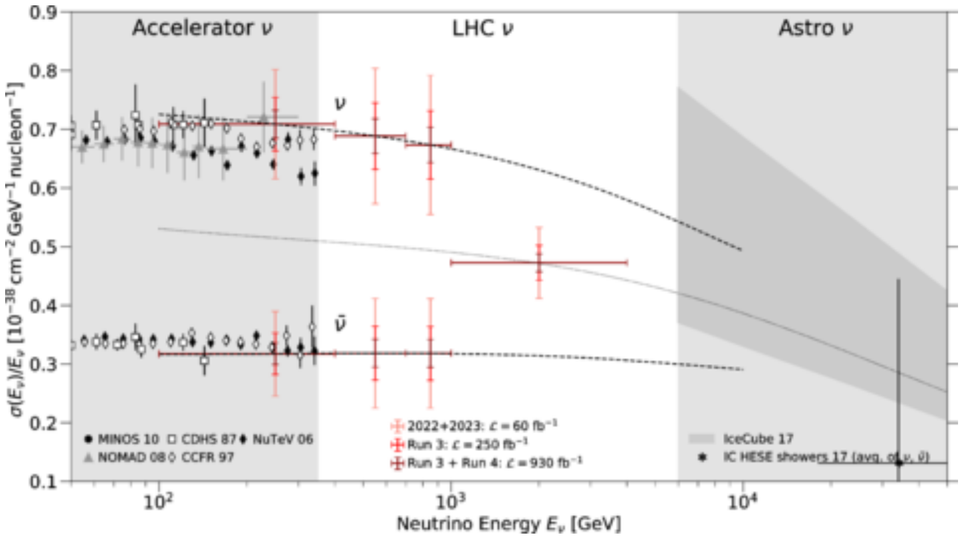
NA64

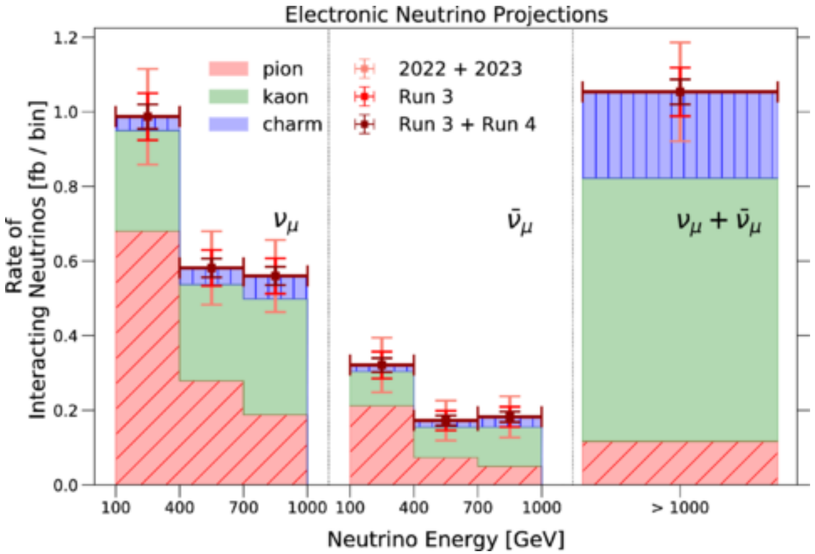

FIPs 2022
E141
NA64, visible
2.84 10^11 eot, preliminary
NA64, invisible
NA64, visible, 5 10^12 eot
PrimEX (1 bin)
LEP
Belle II - 3 γ - 445 pb^-1
Belle II - 3 γ - 20 fb^-1
GlueX, 1 pb^-1
FASER
LDMX, 8 GeV
GlueX, 1fb^-1
Belle II - 3 γ - 50 ab^-1
Belle II - invisible - 20 fb
Belle II - invisible - 50 ab
CHARM
NuCal
FASER2
LUXE, phase I
DarkQuest, 10^18 pot
SLAC 137
NA62-dump
DarkQuest, 10^20 pot
HIKE-dump
SHiP
Gamma Factory
a → γ γ, 0.2 GeV, 10^17 γ/sec
Gamma Factory
a → γ γ, 1.6 GeV, 10^16 γ/sec SN 1987
| g_aγ | (GeV^-1)
m_a (GeV)


Colliders
ionization loss in the NA64μ HCAL: Q_χ/e = 0.2
NA64e 4x10^10 EOT
NA64e 5x10^12 EOT
NA64μ 5x10^13 MOT
MilliQuan
SLAC mQ
SHIP
LDMX 10^16 EOT
EDGES
Q_χ/e
m_χ [MeV]

FASER Run 4


Dark Higgs
Mixing θ
BR
Dark Higgs Mass m_ϕ [GeV]
Belle II
LHCb B^+
LHCb B^0
NA62 π^+
μBooNE
NA62 K^+
E949
CHARM
LSND
LHCb 300 fb⁻¹
Run 3
Run 3 + Run 4
ee
μμ
$\pi^+\pi^-$
$\pi^0\pi^0$
KK
other


Accelerator ν
LHC ν
Astro ν
$\sigma(E_\nu)/E_\nu$ [10^{-38} cm^{-2} GeV^{-1} nucleon^{-1}]
Neutrino Energy E_ν [GeV]
MINOS 10 CDHS 87 NuTeV 06
NOMAD 08 CCFR 97
2022+2023: $\mathcal{L}$ = 60 fb^{-1}
Run 3: $\mathcal{L}$ = 250 fb^{-1}
Run 3 + Run 4: $\mathcal{L}$ = 930 fb^{-1}
IceCube 17
IC HESE showers 17 (avg. of ν, ν̄)

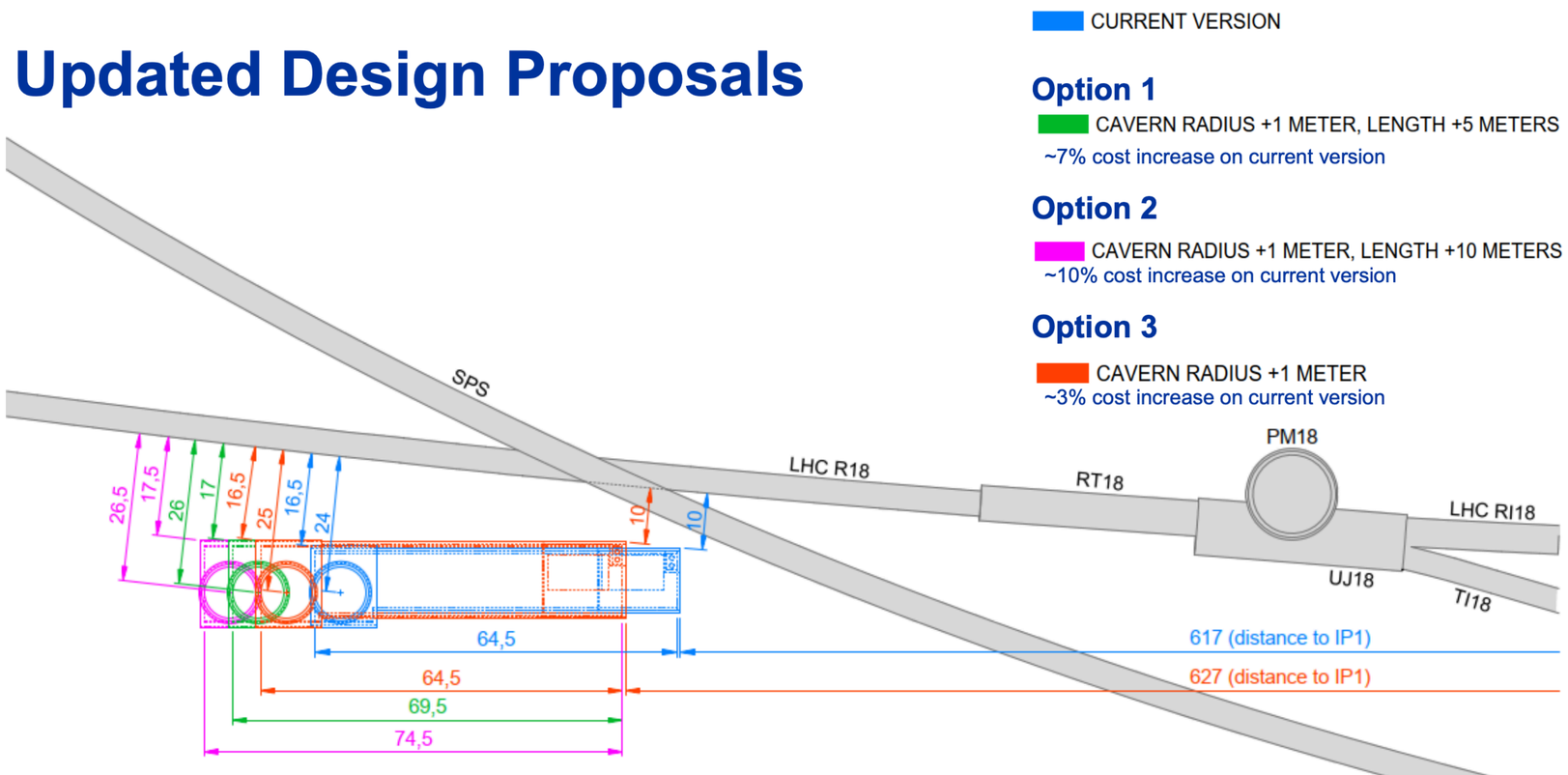

Electronic Neutrino Projections
Rate of Interacting Neutrinos [fb / bin]
Neutrino Energy [GeV]
pion
kaon
charm
2022 + 2023
Run 3
Run 3 + Run 4
ν_μ
$\bar{\nu}_\mu$
$\nu_\mu + \bar{\nu}_\mu$

FPF | Civil Engineering

- Updated costing taking into account more accurate estimates, core sample information and inflation.
  - Slightly higher estimate than before, but not too much
- Costings for different design options
  - Longer cavern and increased radius are O(1MCHF) extra

Ref.	Work Package	Cost [CHF]
1.	Underground Works	10,000,000.00
1.1	Preliminary activities	1,600,000.00
1.2	Access shaft	3,900,000.00
1.3	Experimental Cavern	4,500,000.00
2.	Surface Works	6,120,000.00
2.1	General items	640,000.00
2.2	Topsoil and earthworks	660,000.00
2.3	Roads and network	730,000.00
2.4	Buildings	4,090,000.00
2.4.1	Access building	2,000,000.00
2.4.2	Cooling and ventilation building	1,400,000.00
2.4.3	Electrical Building	490,000.00
2.4.5	External platforms	200,000.00
3.	General items	10,000,000.00
4.	Miscellaneous	4,000,000.00
	TOTAL CE WORKS	30,120,000.00

Updated Design Proposals



	Additional cost
5m longer cavern	700,000 CHF- 1,000,000.00 CHF
10m longer cavern	1,400,000 CHF - 2,000,000.00 CHF
Increase of the radius of the cavern by 1m	700,000 CHF- 1,000,000.00 CHF

FPF7 | Civil Engineering

- Very rough timeline:

NB Very early stage estimate for schedule

Design must be frozen before technical design can begin

Timeline

- In June, at FPF6 and in coordination with PBC (Gianluigi Arduini), LHCC (Frank Simon), and CERN management (Fabiola Gianotti), we agreed on a timeline for CERN review of the FPF.
- July 2023
  - Define a revised organizational structure, including a coordination panel to make decisions that concern and impact the facility and all experiments. DONE
- August 2023 – Early 2024
  - Core study results. DONE
  - A document summarizing the core study results, additional facilities updates, revised estimate for CERN host lab costs. WG0
  - A unified plan for size and placement of experiments in the cavern. WGs 5-9
  - Completion of “flagship” physics studies that emphasize core strengths and also complementarity with the rest of the world-wide program. WGs 1-4
- Early 2024: PBC reviews maturity of the FPF based on these deliverables.
- Early 2025: LOI submitted to LHCC. Successful review → TDR, ..., approval.
- Other relevant milestones
  - P5 presented to DOE/NSF in Oct 2023, final report released 7 Dec 2023.
  - ECN3 decision on SHiP, HIKE, SHADOWS expected by end of 2023.

FPF UK | Existing involvement

- FASER and SND@LHC running successfully with UK involvement and leadership.
  - Providing proof-of-principle for FPF

- Significant input from UK institutes in FPF R&D
  - FASER2: Physics exploitation, detector construction in the area of colorimeter, tracking and infrastructure
  - FLArE: Interest in optical readout from Liverpool (as shown in slides by Steven yesterday)
  - Beam simulation: BDSIM, neutrino fluxes
  - Theory: Astro-particle, Generators, BSM

- Next step is to formalise, and ideally increase, UK participation
  - Led to UK FPF meeting…

P5 report | Report

- Specific comment about the FPF:
  - “It has a broad physics program utilizing the beam of HL-LHC by placing detectors at the forward direction from the collision point. The facility does require commitment from CERN for civil engineering, which is yet to be decided. Individual experiments in the facility can be candidates in the agile-experiment portfolio.”

8.2

Hard Choices for Baseline Budget Scenario

The overall cost of the projects proposed during the Snowmass community study exceeded the budget scenario by many times. As a result, we had to make tough choices based on the principles stated above. We carefully selected projects that have the biggest scientific impact while maintaining the balance among science areas as well as satisfying the budgetary constraints resulting in an exciting program for the next ten years. The baseline budget scenario assumes an initial bump in the budget thanks to the CHIPS & Science Act, and an annual 3% increase to keep pace with inflation.

The following project list reflects the sacrifices made in P5’s prioritization process, starting with the largest and moving down to the funding level of approximately $100M.

...

Forward Physics Facility. It has a broad physics program utilizing the beam of HL-LHC by placing detectors at the forward direction from the collision point. The facility does require commitment from CERN for civil engineering, which is yet to be decided. Individual experiments in the facility can be candidates in the agile-experiment portfolio.

...

Some of the tough choices on which projects to include were based on the need to rebalance the portfolio to allow for research in underfunded areas of theory, instrumentation, computing, GARD, a new program for agile experiments, as well as virtually non-existent targeted collider R&D program.

P5 report

- *"The adaptability and deployment flexibility of agile experiments, whether near beams or reactors, offer promise for synergistic explorations of hidden sector particles and other phenomena in the evolving BSM field."*

- *"The ASTAE portfolio for neutrinos should encompass precise measurements of neutrino interactions, comprehensive neutrino flux assessments, and searches for neutrino BSM physics, coupled with development of cutting-edge technologies for future detectors (Recommendation 3a)."*

3.1

Elucidate the Mysteries of Neutrinos

...

3.1.6 – New Initiative: A Portfolio of Agile Projects for Neutrinos

A healthy portfolio of agile experiments focused on neutrino physics and capable of delivering transformative insights and technological advancements is essential to the future of the field. To advance the understanding of neutrinos, a multifaceted approach must support a versatile and dynamic portfolio of ASTAE experiments, as described in section 6.2.

Key breakthroughs in neutrino physics have been achieved through experiments shedding light on hidden facets of neutrino interactions and resolving outstanding neutrino anomalies. These experiments highlight the potential for discovery science in agile neutrino projects. Accurate measurements are also important for a deeper understanding of neutrinos, their interactions, energy spectra, flux and their roles in astrophysical phenomena and long-baseline neutrino oscillation experiments. The adaptability and deployment flexibility of agile experiments, whether near beams or reactors, offer promise for synergistic explorations of hidden sector particles and other phenomena in the evolving BSM field. Technology development, such as innovative materials and unique sensors, is critical to shaping the future of neutrino experiments.

The ASTAE portfolio for neutrinos should encompass precise measurements of neutrino interactions, comprehensive neutrino flux assessments, and searches for neutrino BSM physics, coupled with development of cutting-edge technologies for future detectors (Recommendation 3a).

P5 report

- *"In pursuit of understanding dark matter, a diverse and agile portfolio of ASTAE experiments, as described in Section 6.2, offers the potential for significant discoveries and technological advancements."*
- *"Small but sensitive detectors are ideal for studying low mass dark matter since the needed size of the detectors scales roughly with the dark matter mass."*
- *"This multi-faceted approach maximizes the potential for seminal discoveries and pushes the boundaries of what is measurable in the realm of dark matter."*
- *"These initiatives are integral components of the broader portfolio of ASTAE experiments (Recommendation 3a; Section 6.2)."*

4.1

Determine the Nature of Dark Matter

…

4.1.3 – New Initiative: A Portfolio of Agile Projects for Dark Matter

In pursuit of understanding dark matter, a diverse and agile portfolio of ASTAE experiments, as described in Section 6.2, offers the potential for significant discoveries and technological advancements. Small but sensitive detectors are ideal for studying low mass dark matter since the needed size of the detectors scales roughly with the dark matter mass. This strategic approach focuses on two promising areas: hidden sector models and QCD axions, both of which boast high-priority benchmark models that can best be addressed by this scale of experiment.

Accelerator-based searches for the production of hidden sector particles leverage beam dumps at existing beamlines and have sensitivity to thermal benchmark models in the MeV-GeV mass ranges. The direct searches for these hidden sector particles utilize innovative materials and ultra-low noise detectors with the ability to detect down to sub-eV energy depositions to reach the benchmarks. This synergistic combination of approaches is necessary to understand and unlock the secrets of hidden sector dark matter.

The search for axions and ALPs is also well-suited for this agile portfolio. Specific QCD axion models provide definitive benchmarks, and through a series of carefully designed experiments, the parameter space spanning masses from 40 neV to 1 eV can be thoroughly explored. Additionally, these endeavors lay a foundation for even more ambitious projects that target the lightest masses falling within the range of 1 peV to 40 neV.

This multi-faceted approach maximizes the potential for seminal discoveries and pushes the boundaries of what is measurable in the realm of dark matter. Notably, this portfolio has already been set in motion by the Dark Matter New Initiatives (DMNI) experiments, which have completed their design phases and now await construction funding. These initiatives are integral components of the broader portfolio of ASTAE experiments (Recommendation 3a; Section 6.2).

P5 report

- *"Another strategy to look for long-lived particles at colliders is to construct auxiliary experiments that are placed far away from the primary collision points."*
- *"Experiments at the proposed Forward Physics Facility at CERN like FASER2 and FORMOSA would be sensitive to the hidden sectors through the Vector and Heavy Neutral Lepton portals."*
- *"By the end of this 20-year period we will have ultimate LHC results from the general purpose experiments and a constellation of agile auxiliary experiments."*

5.1

Search for Direct Evidence of New Particles

5.1.3 – New Initiative: A Portfolio of Agile Projects to Search for Direct Evidence of New Particles

Another strategy to look for long-lived particles at colliders is to construct auxiliary experiments that are placed far away from the primary collision points. Proposed auxiliary experiments like CODEX-b and MATHUSLA can extend the sensitivity to BSM particle lifetimes in Higgs decays by several orders of magnitude. Experiments at the proposed Forward Physics Facility at CERN like FASER2 and FORMOSA would be sensitive to the hidden sectors through the Vector and Heavy Neutral Lepton portals. At Fermilab, PIP-II is expected to make many more protons than needed for DUNE, and we anticipate proposals for experiments using the excess protons. These experiments should compete in the portfolio for agile projects (see Recommendation 3a and Section 6.2).

5.1.5 – 20-Year Vision & Future Opportunities

The program described in this section consists of a combination of large and small projects and holds great promise for discovery. By the end of this 20-year period we will have ultimate LHC results from the general purpose experiments and a constellation of agile auxiliary experiments. We will also be in the final stages of construction of a Higgs