Current Status and Future Strategy for Long-Lived Particle Searches

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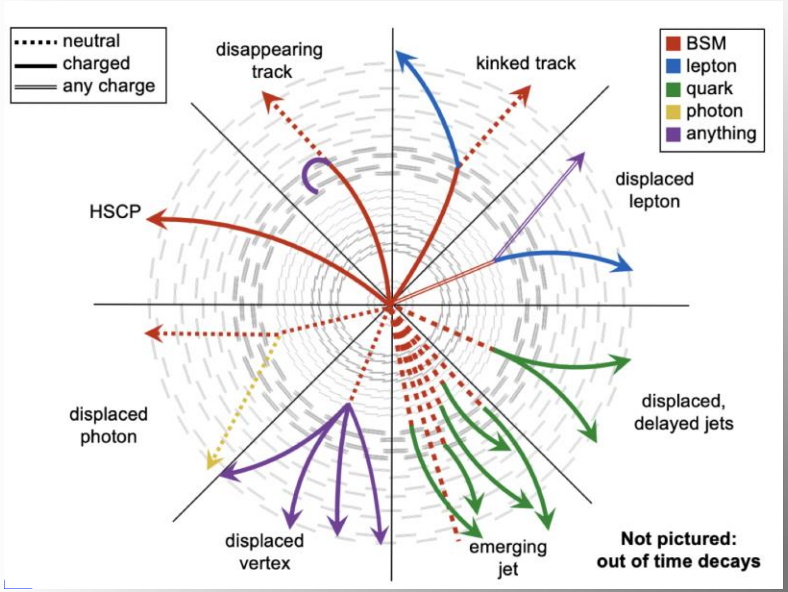
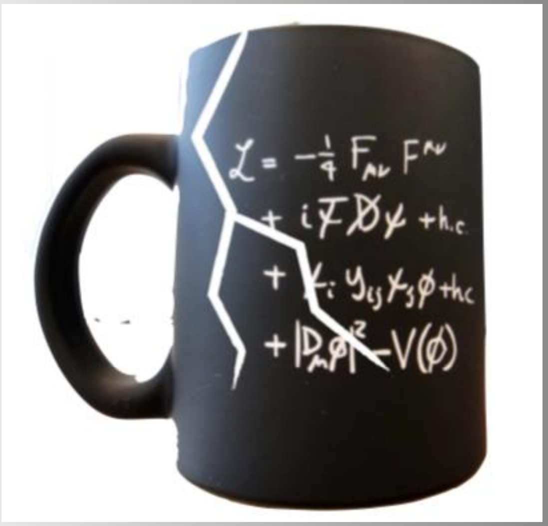
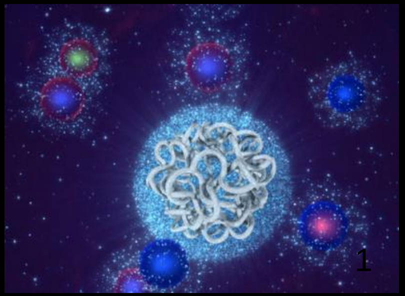


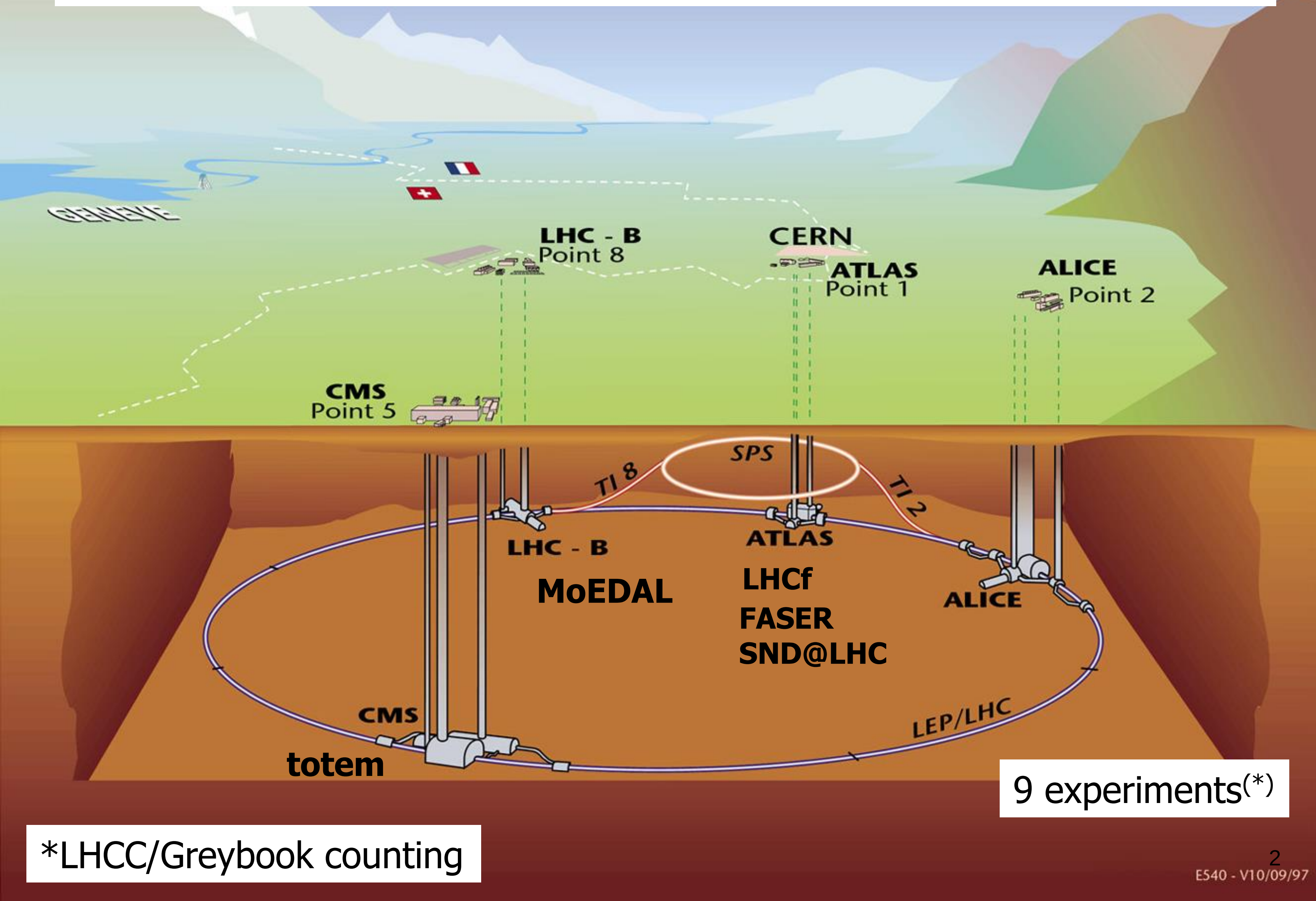
Outline

- Introduction to long lived exotic particles: why do we care?
- Challenges and a few results from the LHC
- New experiments for the LHC
- LLPs at Future Colliders
- Other opportunities for LLPs searches
- Summary/Outlook





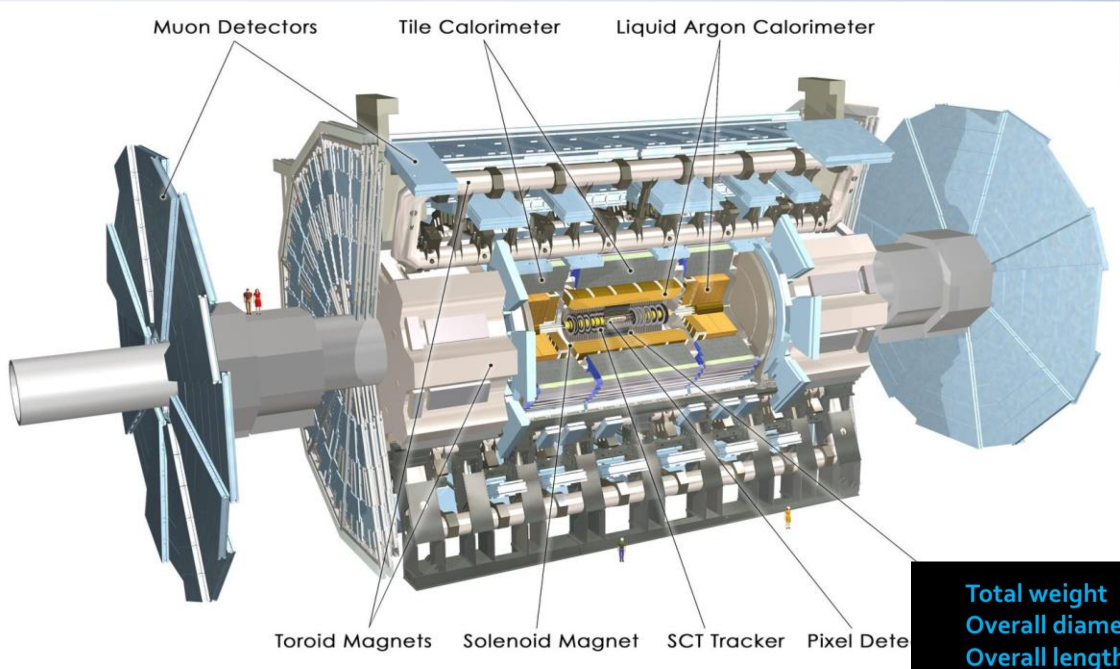
The Flagship Project of CERN: the Large Hadron Collider



9 experiments$^{(*)}$

*LHCC/Greybook counting

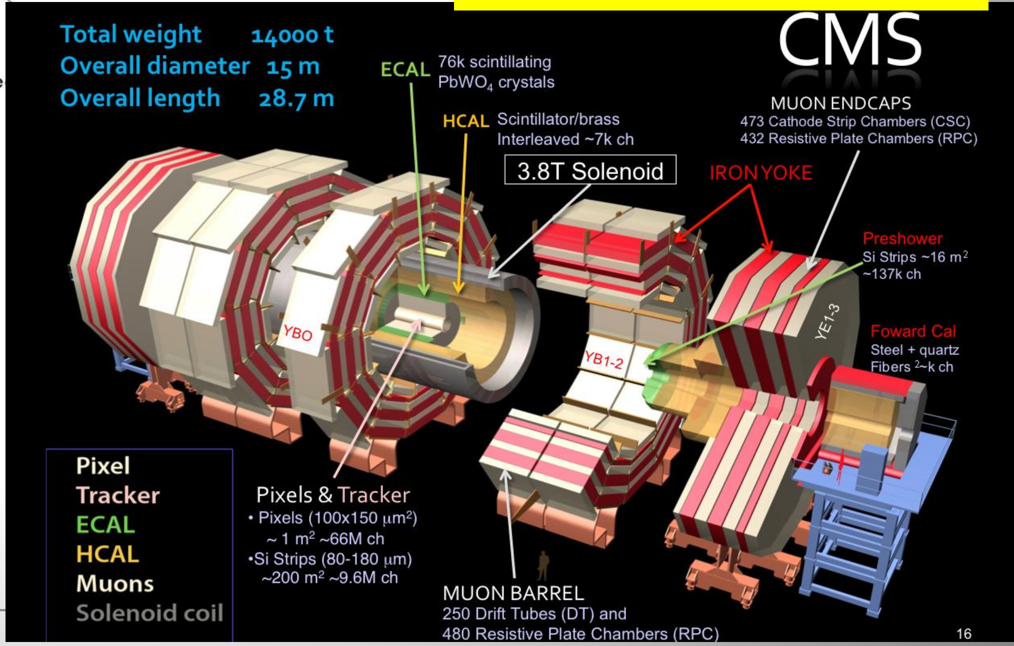
Long-Lived Particle Hunters@ the LHC



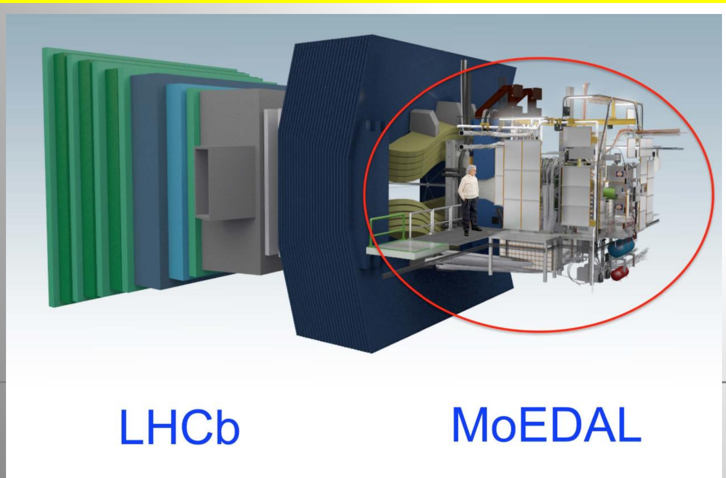
The ATLAS experiment

Up to Run-2…

The CMS experiment

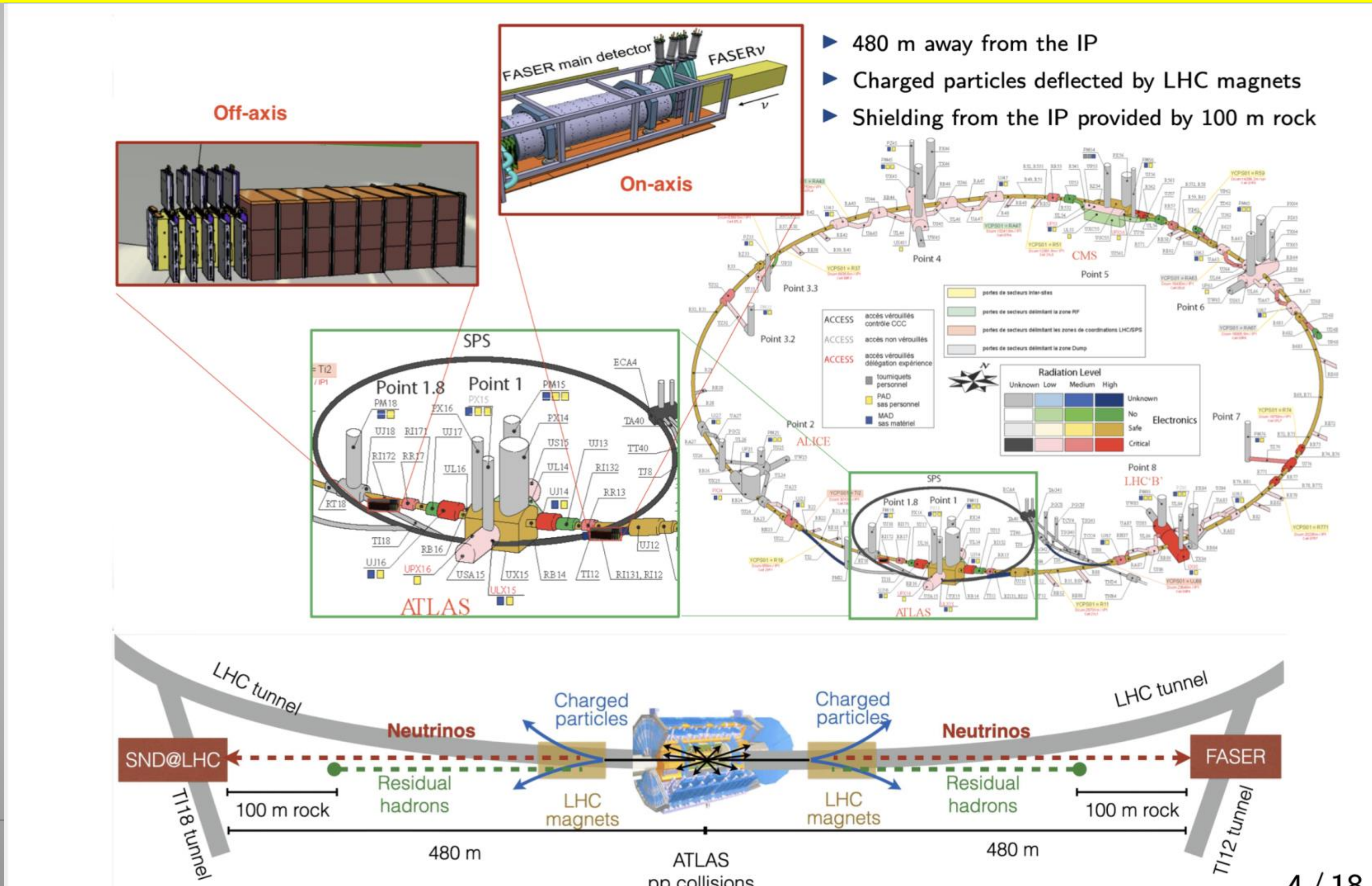


…And also LHCb and MoEDAL



New: SND@LHC and FASER

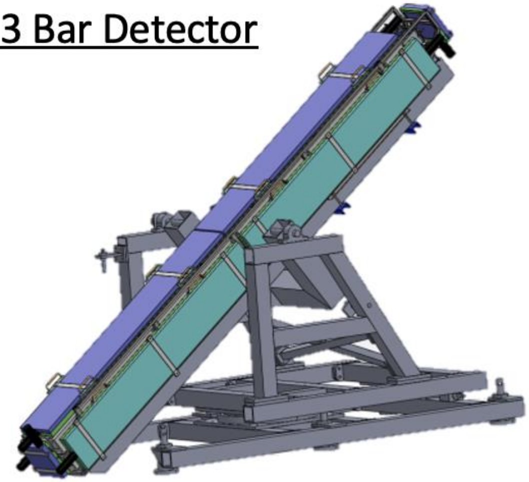
- Two new experiments started in 2022 (Run-3) 480m away from the ATLAS-IP
- Goal: Detection of forward produced neutrinos and search for long lived BSM particles (dark photons, light DM…)



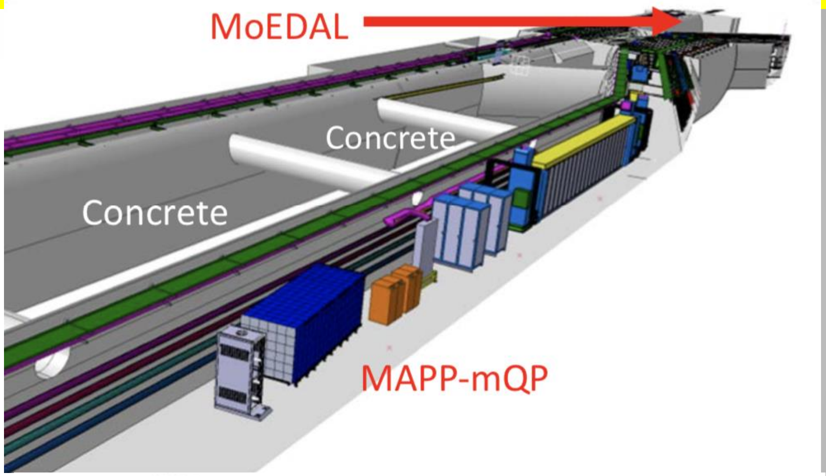
New: MilliQan and MAPP

- Two new detectors being commisioned for Run-3, close to CMS and LHCb
- Search for Millicharges: Particles with very small charges, compared to the electron, expected e.g. in Dark Sector theories.
- Scintillator bar and slab based detectors

Run 3 Bar Detector

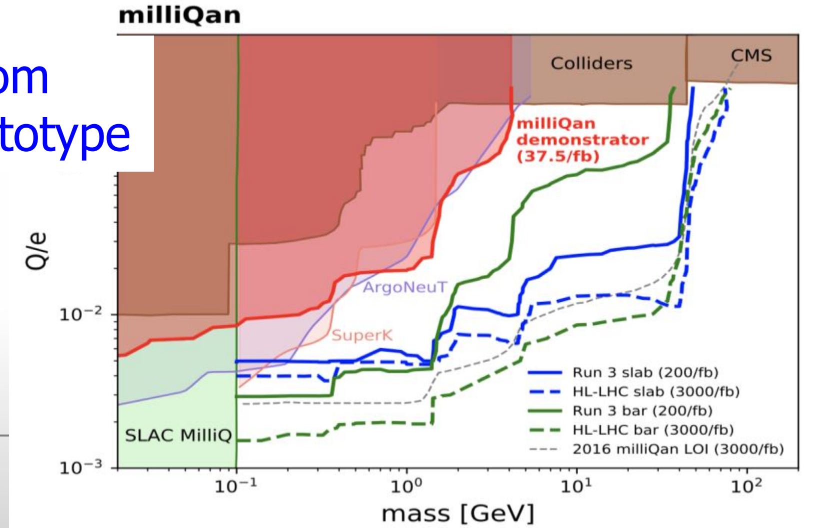


Installed for Run 3



Run 3 Slab Detector

Results from Run-2 prototype



Searching for Long Lived Particles

Long lifetimes arise from a hierarchy of scales or a small coupling

Long lifetimes in the BSM world

Small couplings
e.g. R-parity violating SUSY

Limited phase space
e.g. compressed SUSY scenarios

Decays via heavy particle
e.g. heavy neutrinos

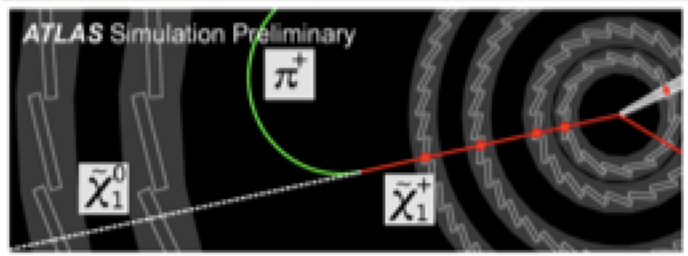
Any model with small couplings, small mass splittings, or decays via off-shell particles can result in long lived particles (LLPs)

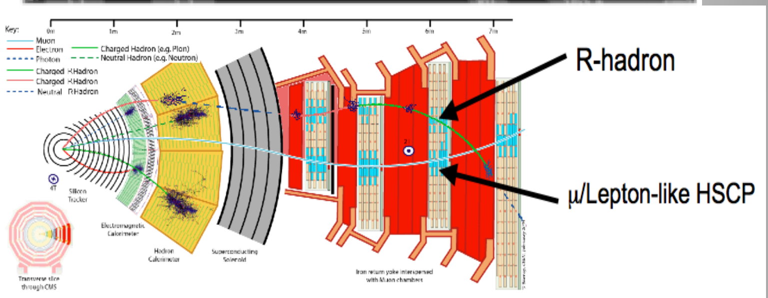
Long Lived Particles

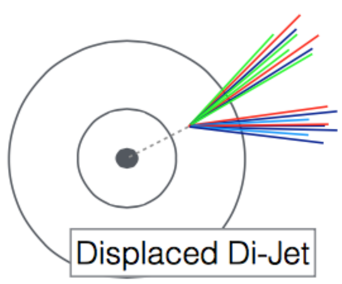
Long lifetimes arise from a hierarchy of scales or a small coupling

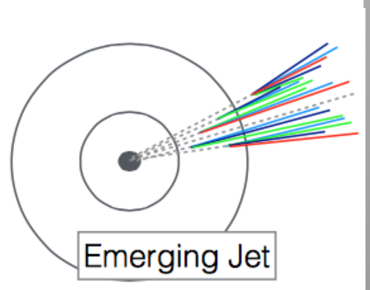
- RP Violating SUSY
- AMSB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ….

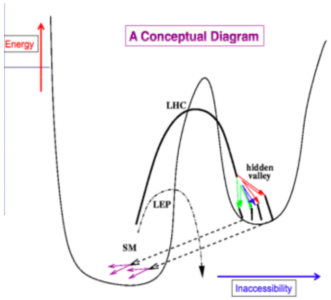
See also Xiao-Ping Wang

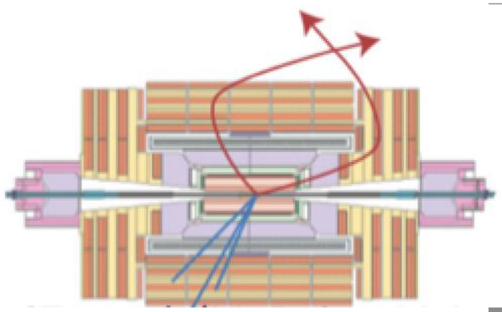






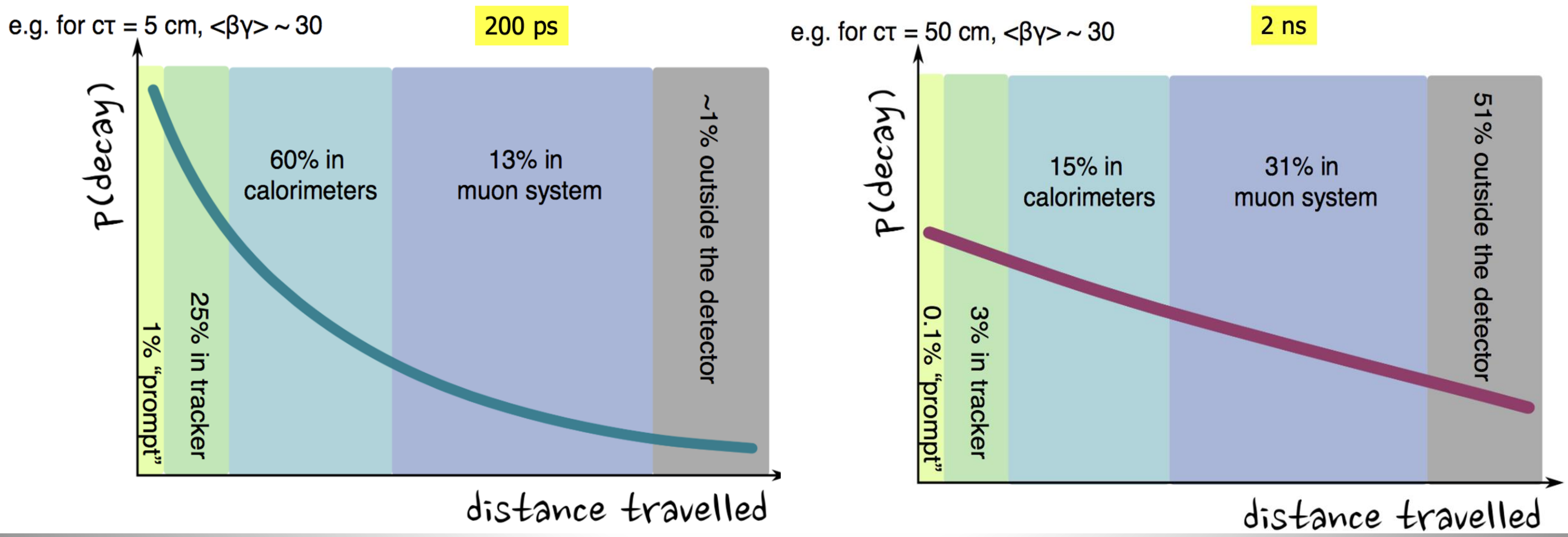






Long Lived Particles @ LHC

Examples of the distance travelled before decay in a central detector (example for ATLAS) depending on lifetime and kinematics



LLP Community Workshops

https://indico.cern.ch/event/1216822/

Searching for long-lived particles at the LHC and beyond: Thirteenth workshop of the LLP Community

Last workshop: 19-23 June 2023
Next workshop: 1-5 July 2024 (Univ. Tokyo)

White paper — chapter statuses and roundtable
[draft here (18 Oct)]

- Simplifed models — First draft done!
- Experimental coverage — First draft essentially done!
- Triggers, upgrades, HL- / HE-LHC opportunities
  — First draft in progress
  —> discussion today [live doc!]
- Re-interpretations / recommendations
  — First draft imminent!
- Backgrounds — First draft imminent!
- Dark showers
  — First draft (summarizing status and advertising for the future) imminent!

ICTP 2017

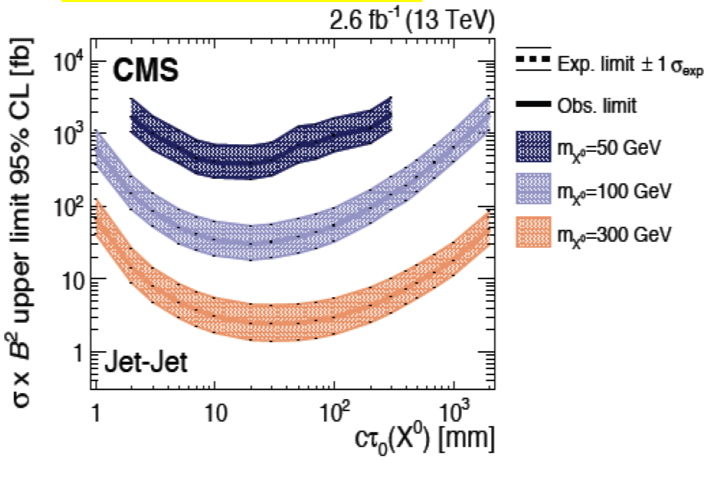
Community White Paper
arXiv:1903.04497

Input from ATLAS, CMS, LHCb, proposed specialized experiments and theory

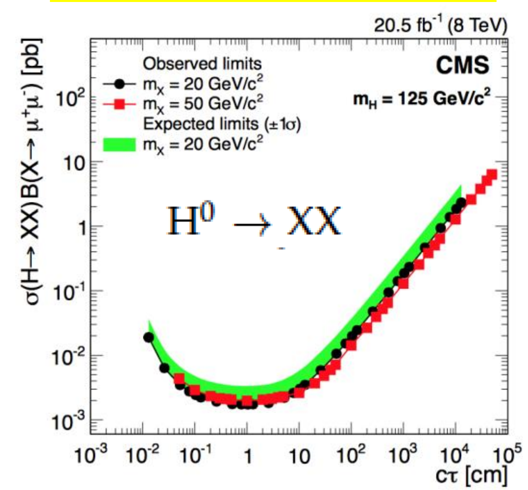
Also meetings with
LHC Dark Matter group
and LHCC working group

Long Lived Searches: Initial Studies

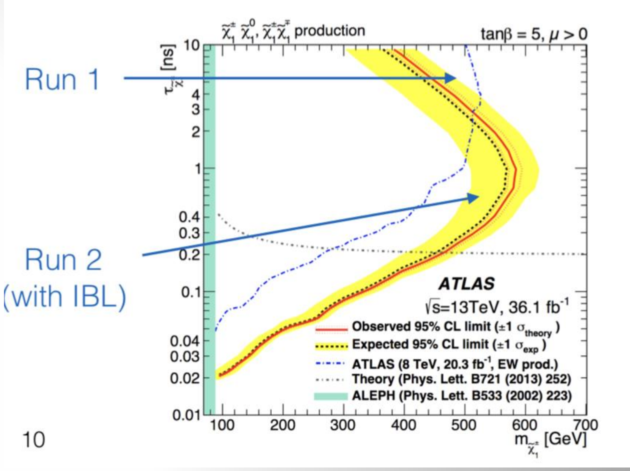
displaced jets



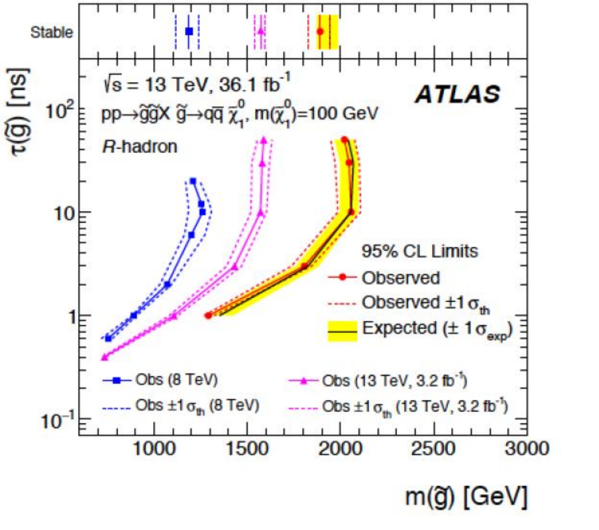
displaced leptons



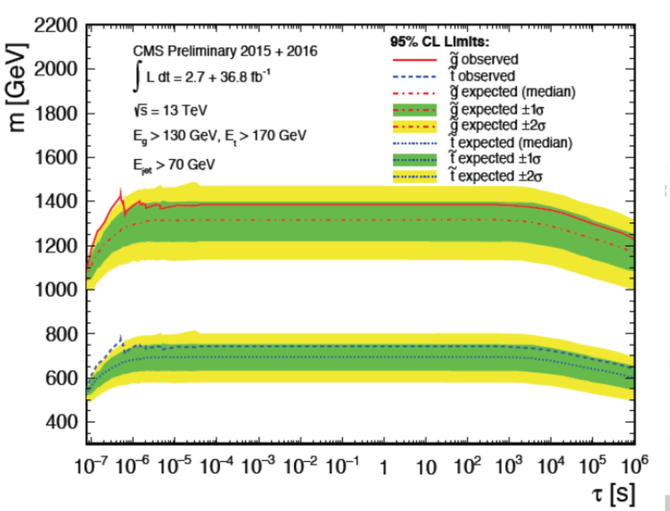
disappearing tracks



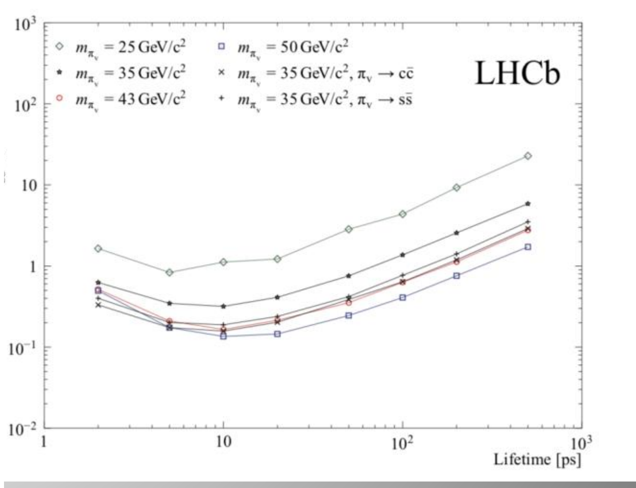
metastable R-hadrons



stopped particles

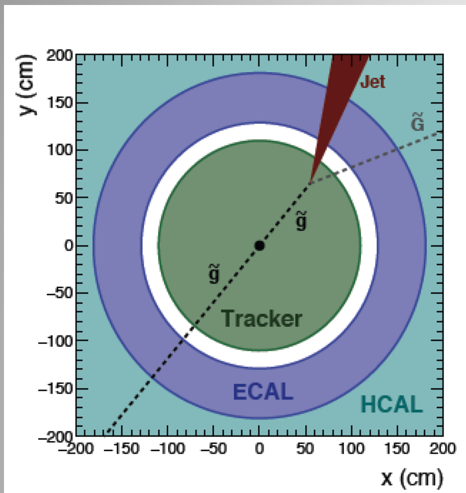


Hidden Valley searches

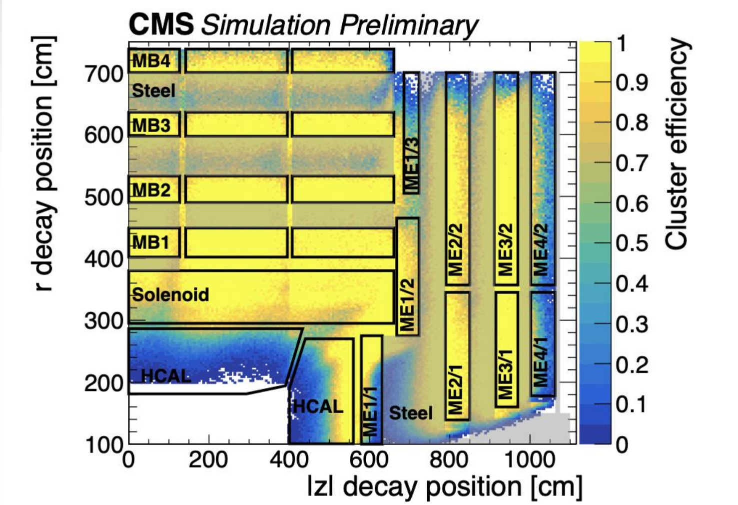


Long Lived Searches: Recent Developments

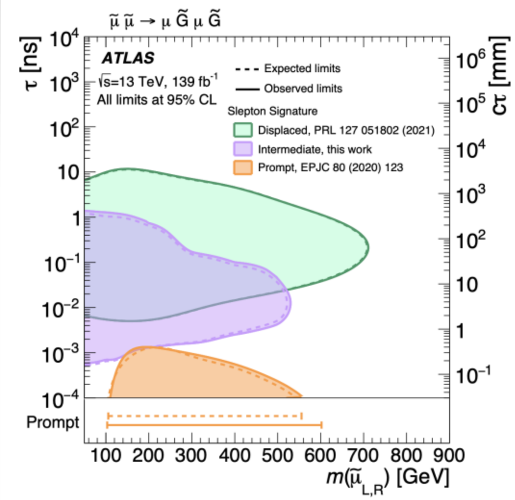
Timing:delayed jets



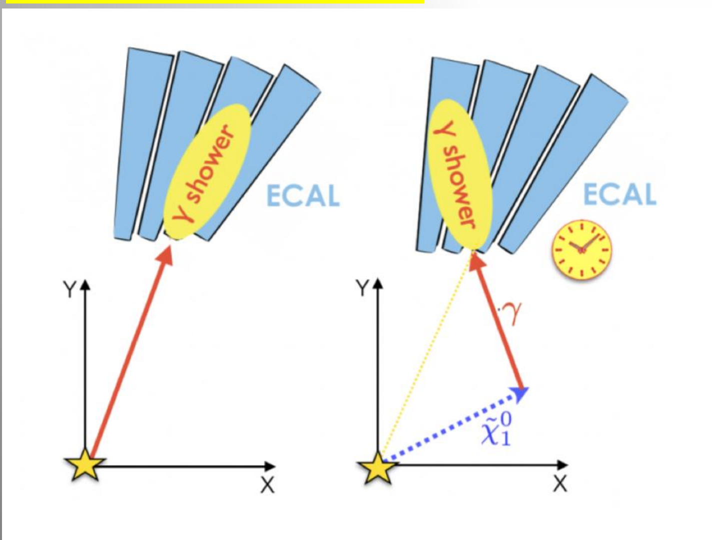
Muon system as a calorimeter



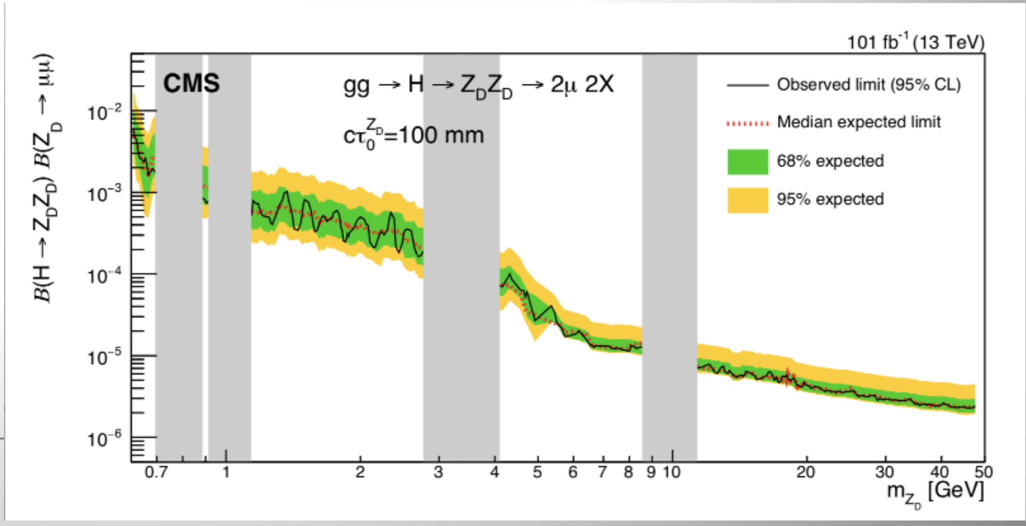
Micro displacements



Timing:delayed



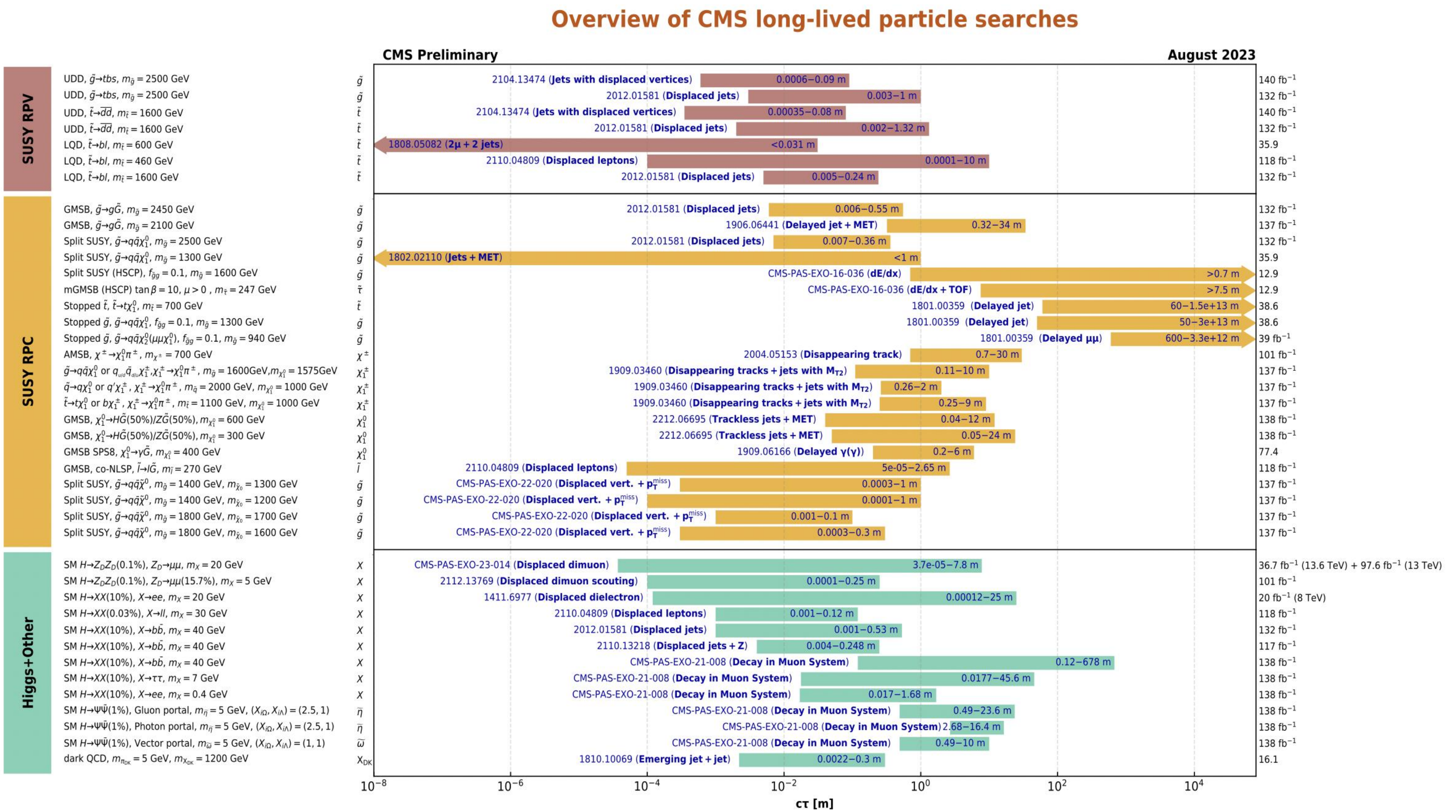
Data scouting to get to low momenta



LHC Developments

- Triggers improvements:
  - Examples LHCb software trigger, displaced objects, timing, … (see eg:2210.14675)
- Data collection improvements
  - Scouting of data & data parking techniques
- Analysis improvements
  - Better use of the detector capabilities, timing, LLP search in all subsystems eg muon system, new reconstruction methods, Machine Learning…
- Detector upgrades for HL-LHC:
  - Extended fast timing (4D reconstruction) and improved triggers (displaced tracks), smart FPGAs in DAQ…
- New/extended experiments @ LHC -> next

Long-Lived Particle Overview



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

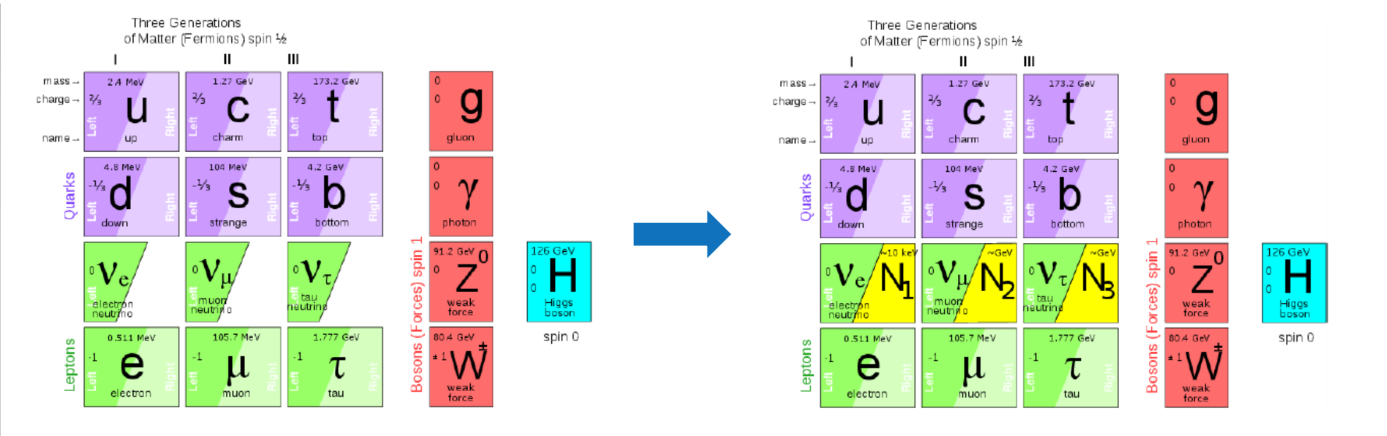
Similar figure for ATLAS in the backup

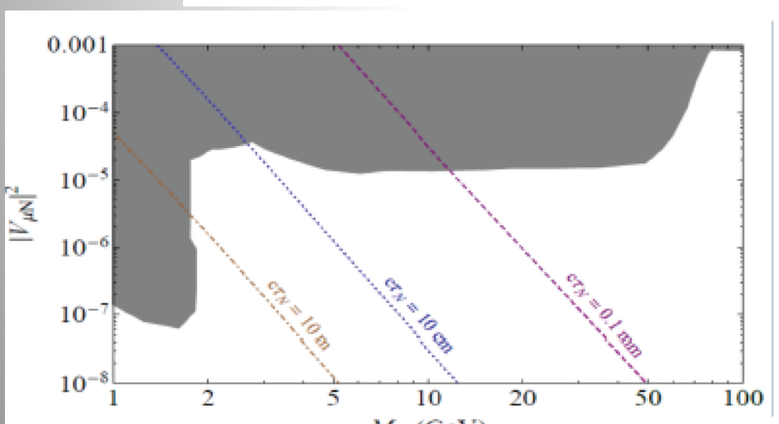
Example: Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3

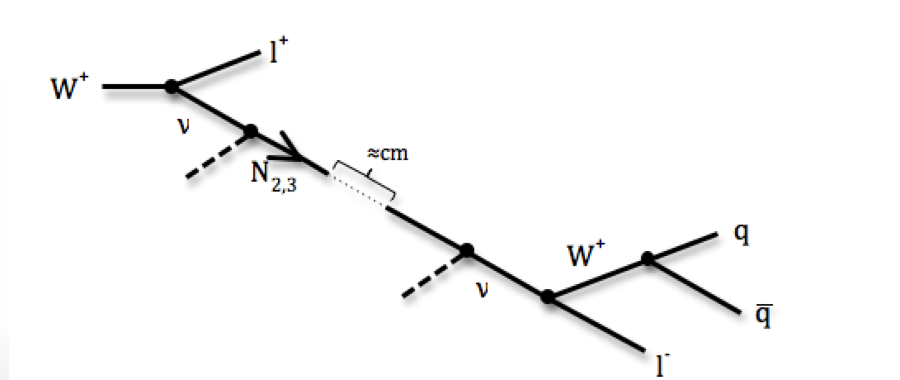
Addresses the masses of neutrinos, baryon asymmetry and dark matter





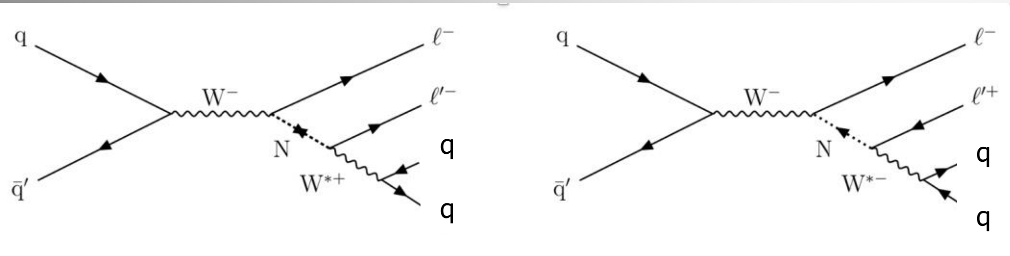
15.11.17

D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015



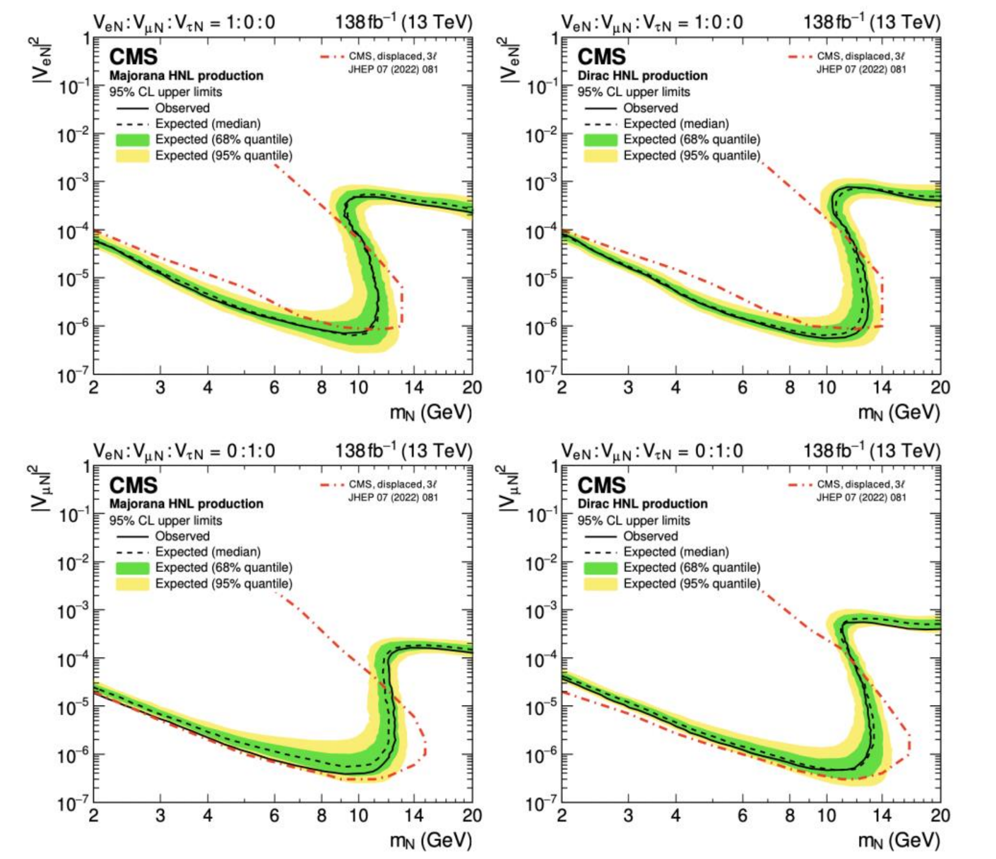
Now we have LHC studies with displaced jets/lepton analyses. L up to ~ 1m

Search for Long Lived Leptons (HNL)



Search for long-lived
heavy neutral leptons (HNLs)

2312.07484



HNLs produced through mixing with SM neutrinos in final state of 2 charged leptons + 2 jets

Low mass HNLs are long lived

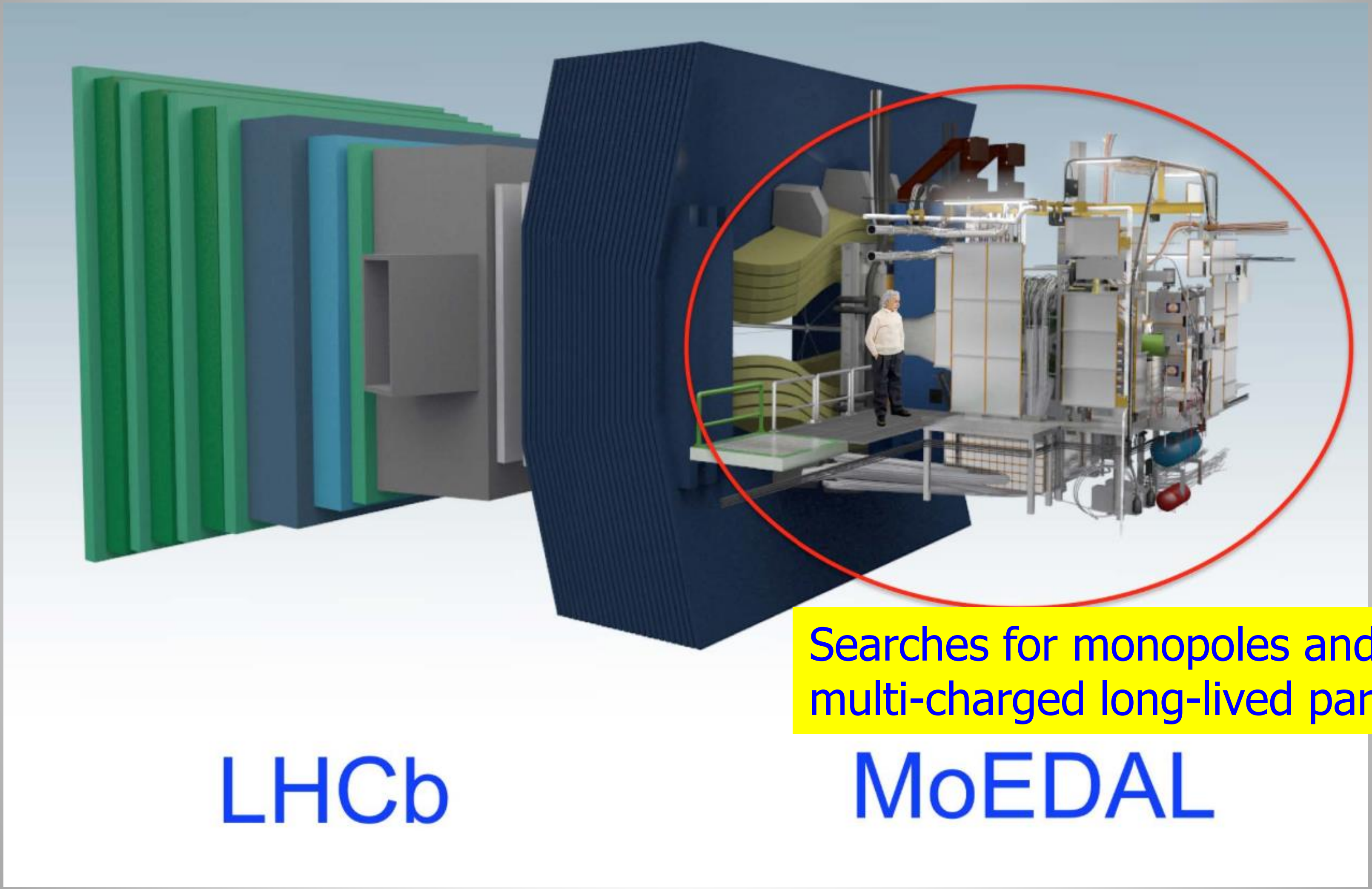
$$\tau_N \propto m_N^{-5} V_{Nl}^{-2}$$

Search for 2 leptons; one forms a displaced vertex with jets

Different sensitivities for Dirac and Majorano neutrinos

…using a displaced jet tagger

The MoEDAL Experiment



Searches for monopoles and multi-charged long-lived particles

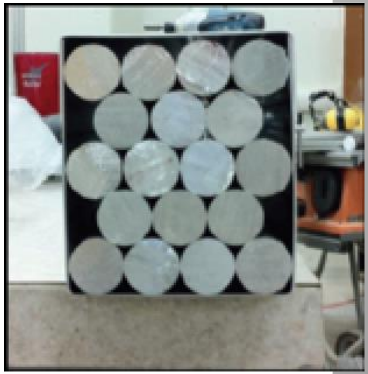
➔ MoEDAL is a passive detector, sensitive to new physics
➔ Example if a dedicated small BSM physics search experiment

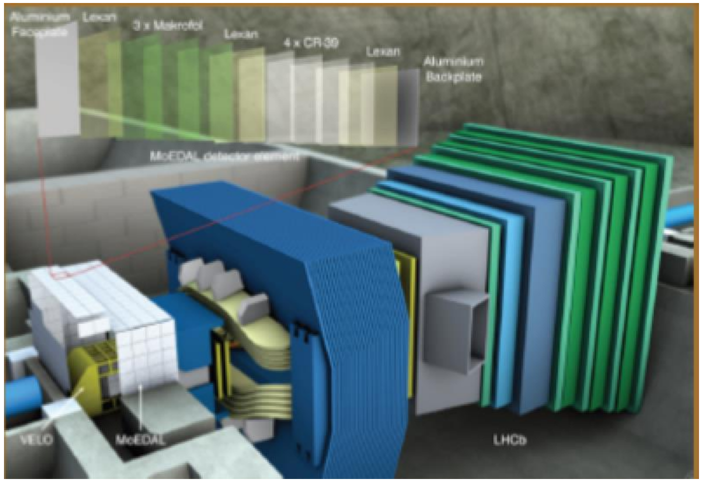
The MoEDAL Experiment

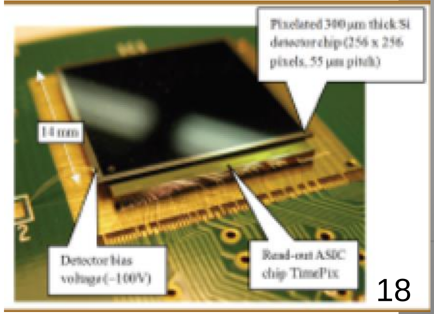
-> Three subdetector systems

- Passive Nuclear Track-Etch Detectors (NTDs)
  - 120m^2 of CR39 and Makrofol (for very high ionization)
  - Detection threshold is “charge/β > 5”
- Passive Trapping Detectors (MMTs)
  - 794 kg of aluminium bars
- MediPix chip based online radiation monitor system

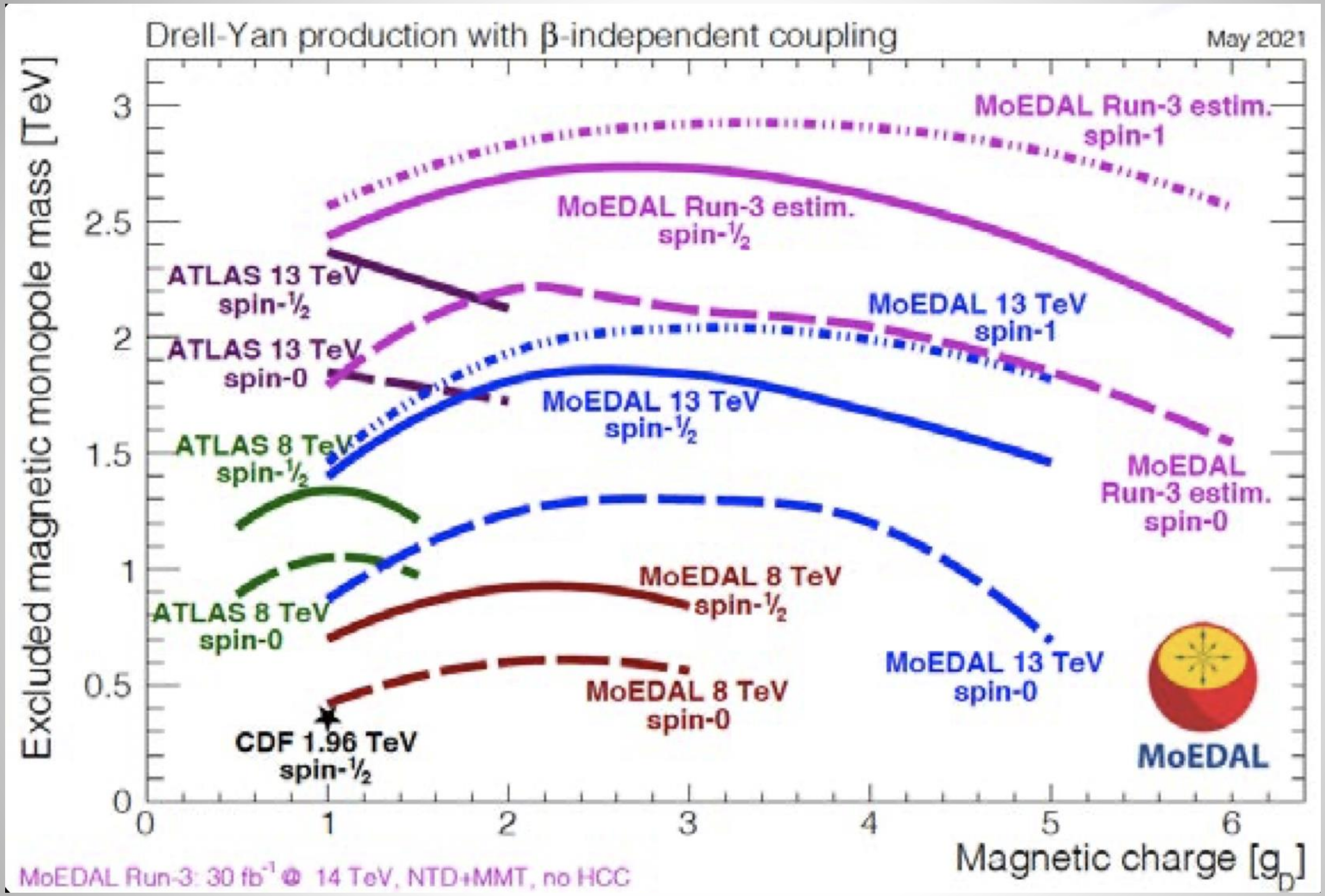
The NTD and MMT detectors are exchanged every year







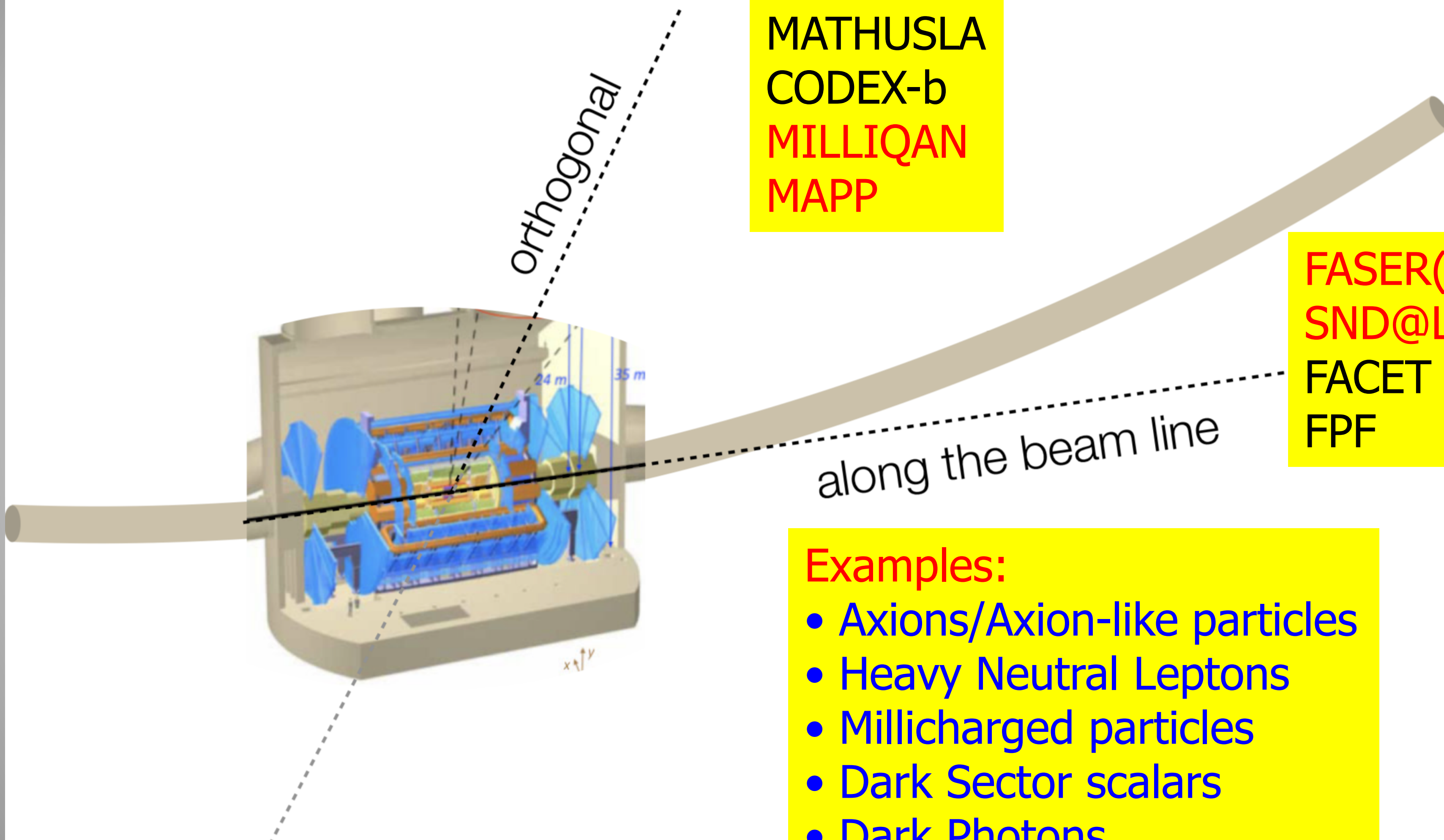
LHC Monopole Searches



Also results on dyons and high electric charge objects

NB: ATLAS results have been updated in 2308.04835

Newly Added/Proposed Experiments



ANUBIS
MATHUSLA
CODEX-b
MILLIQAN
MAPP

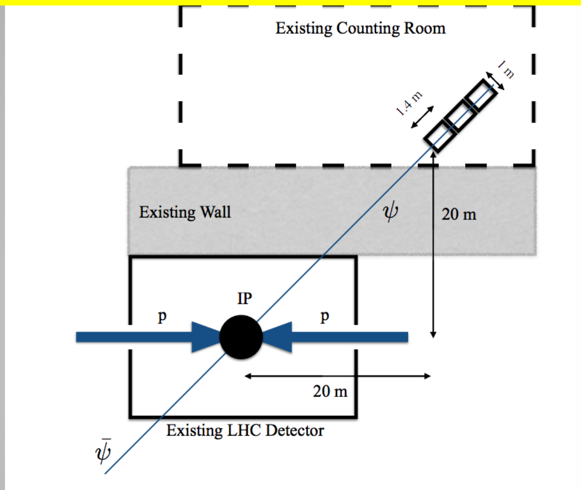
FASER(Nu)
SND@LHC
FACET
FPF

Examples:
- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Dark Photons
- Light Dark Matter …

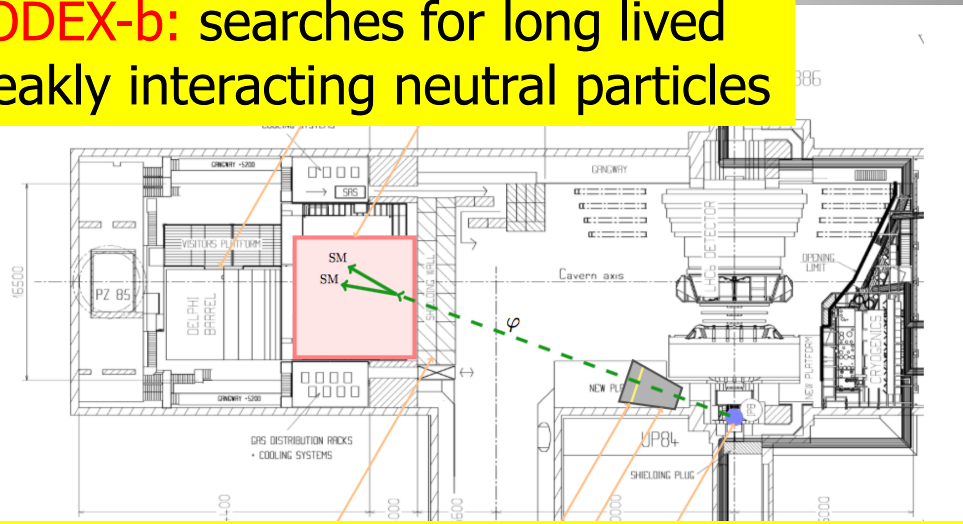
Red: taking data
Black: proposal

New Transverse Experiment Proposals

MilliQan: searches for millicharged particles
MAPP: MoEDAL upgrade

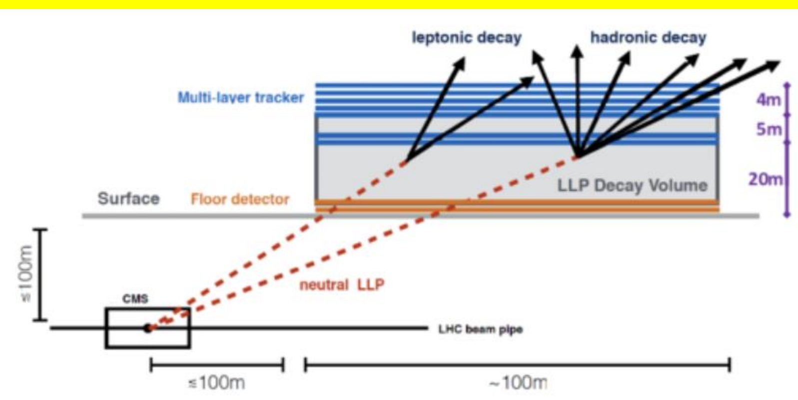


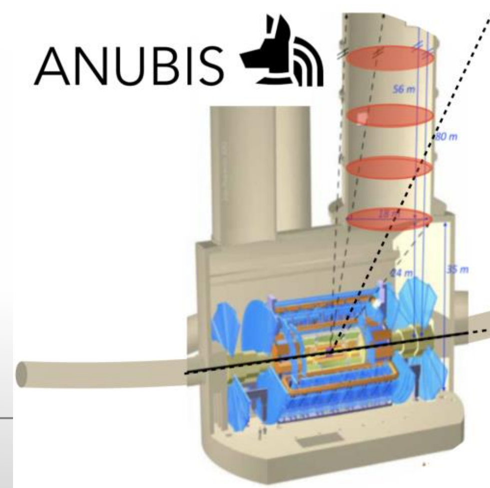
CODEX-b: searches for long lived weakly interacting neutral particles



Also: AL3X ('ALICE' for LLP arXiv.1810.03636)..

MATHUSLA: searches for long lived weakly interacting neutral particles



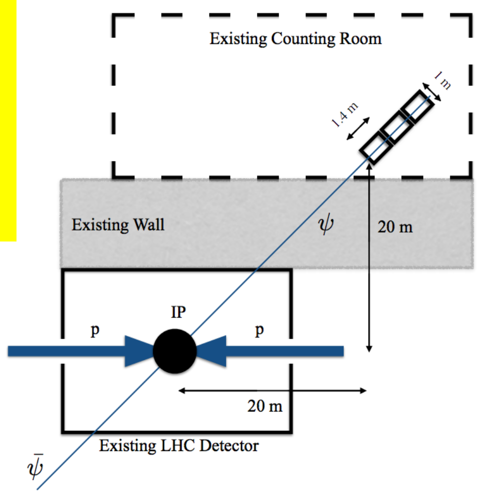


ANUBIS: searches for long lived weakly interacting neutral particles

+Recently (2021): a new detector for CMS cavern..

Particles with Milli-Charges?

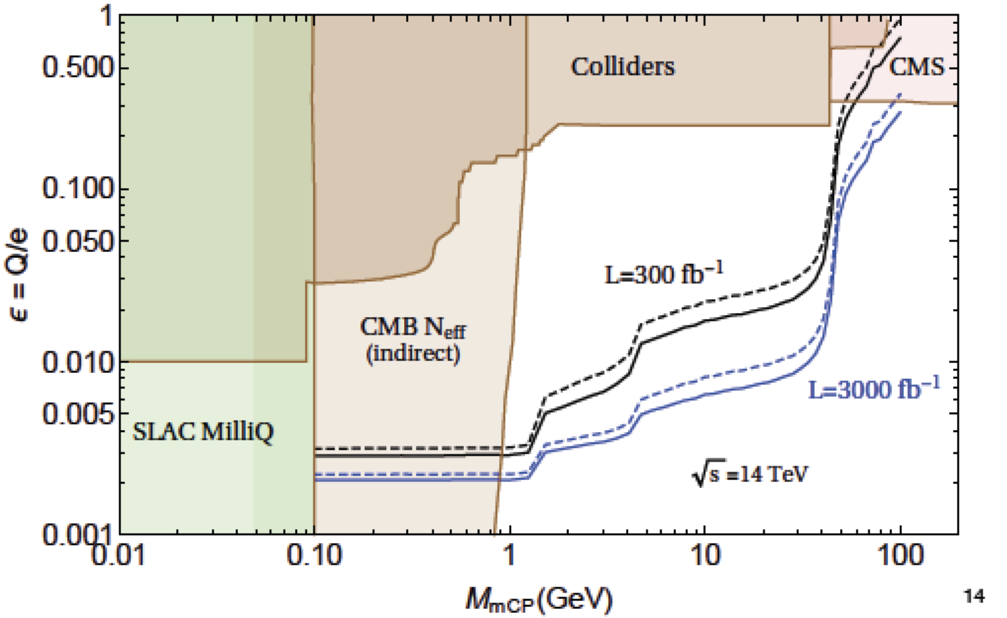
"New" idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017 till 2018



arXiv:1607.04669

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]



MilliQan Experiment

Motivation:
- "Dark QED" ie QED in the dark sector that kinematically mixes with the SM QED.
- The EDGES anomaly…?

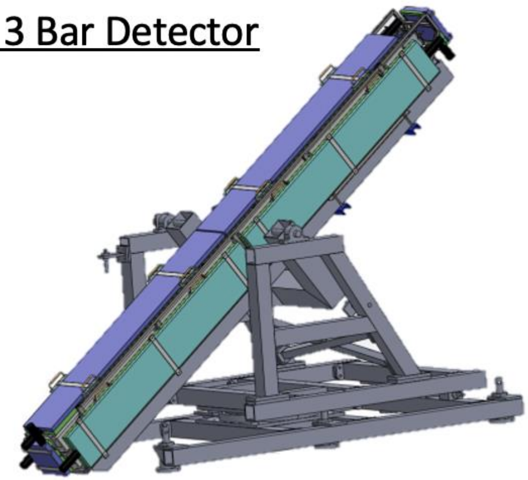
Detection technique:
scintillators-> low light signals

Millicharged Particles

Search for Millicharges: Particles with very small charges, compared to the electron, expected e.g. in Dark Sector theories.

- Scintillator bar and slab based detectors

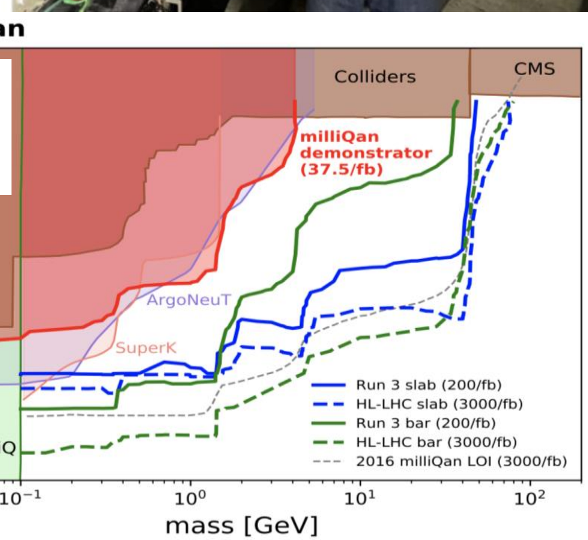
Run 3 Bar Detector



Installed for Run-3 2022/23: being commisioned

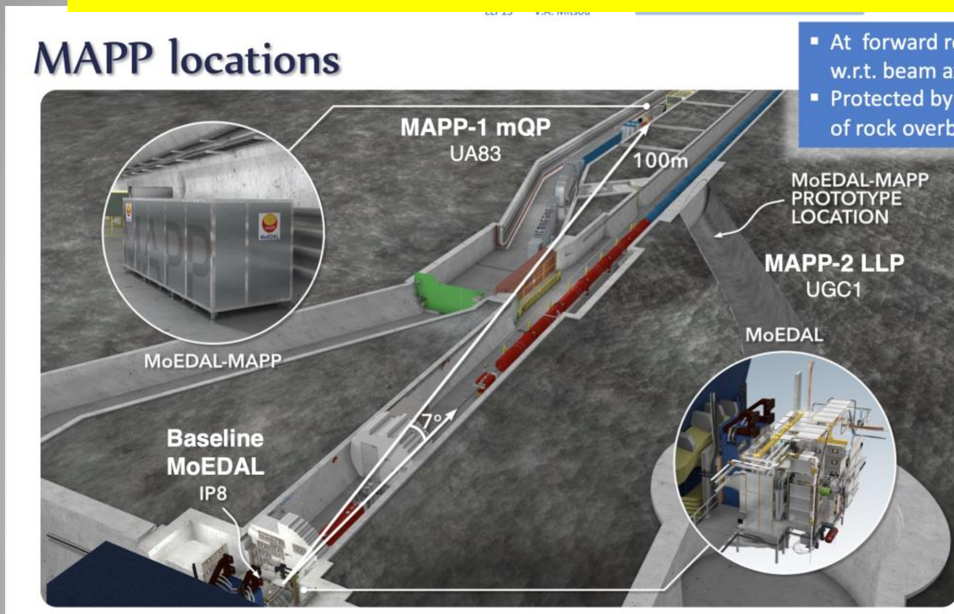
Run 3 Slab Detector

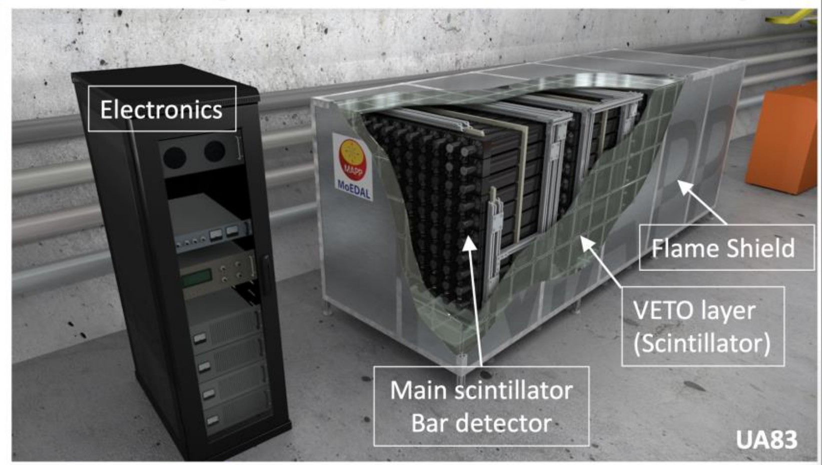
Results from Run-2 prototype



MAPP/MoEDAL

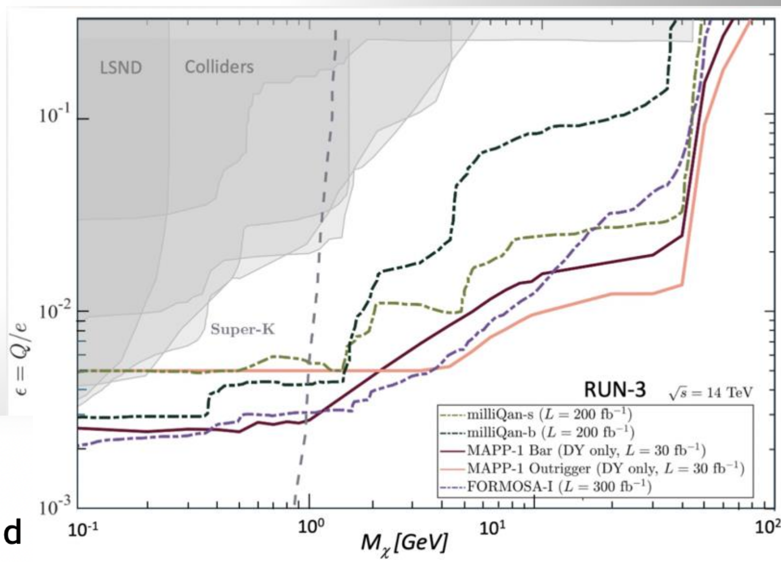
MAPP is a detector for the upgrade of MoEDAL
MAPP is a scintillator detector –like MilliQan– being installed at CERN





- 400 scintillator bars ($10\times10\times75$ cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

2023: MAPP is being commissioned for physics. First results in 2024?

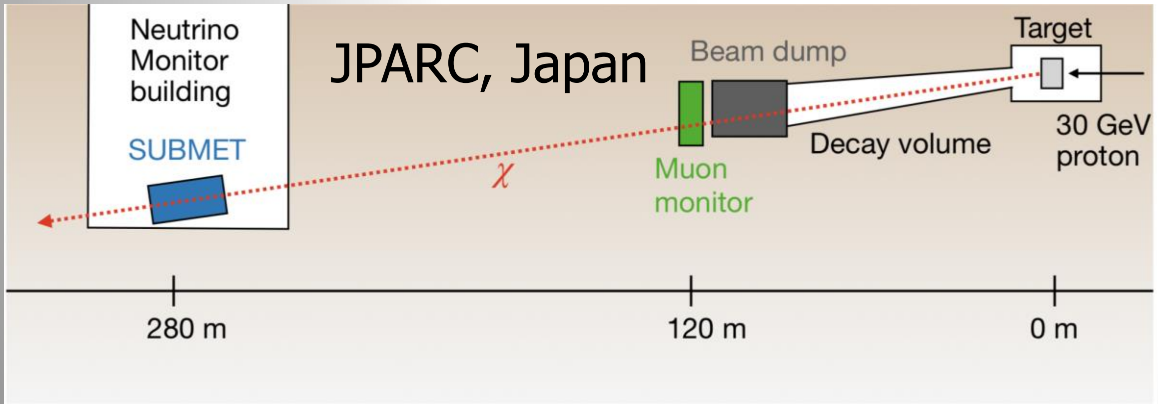


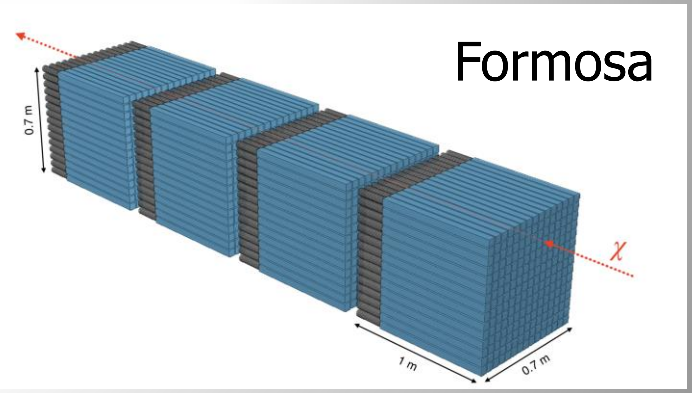
MAPP-1: DY only, 100% eff., no background
milliQan: DY+meson decays, bkg.+detector eff. included
FORMOSA-1: DY+meson decays, 100% eff., no background

MilliQan: a new type of new physics hunter

- The idea of detector and the success of the demonstrator in 2018-2020 has led to new proposals for MilliQan-like experiments..
  - SUBMET: T2K 'neutrino' beam (mass< @ GeV). Proposal submitted last month. Most funding available. arXiv:2007.06329 (Japan)
  - FerMINI: FNAL fixed target experiment arXiv:1812.03998 (USA)
  - MoEDAL/MAPP: @LHCb IP arXiv:1909.05216 (CERN)
  - FORMOSA: @FPF Cavern of the HL-LHC arXiv:2203.05090 (CERN)

Example: the SUBMET proposal (funded and approved in June '23)





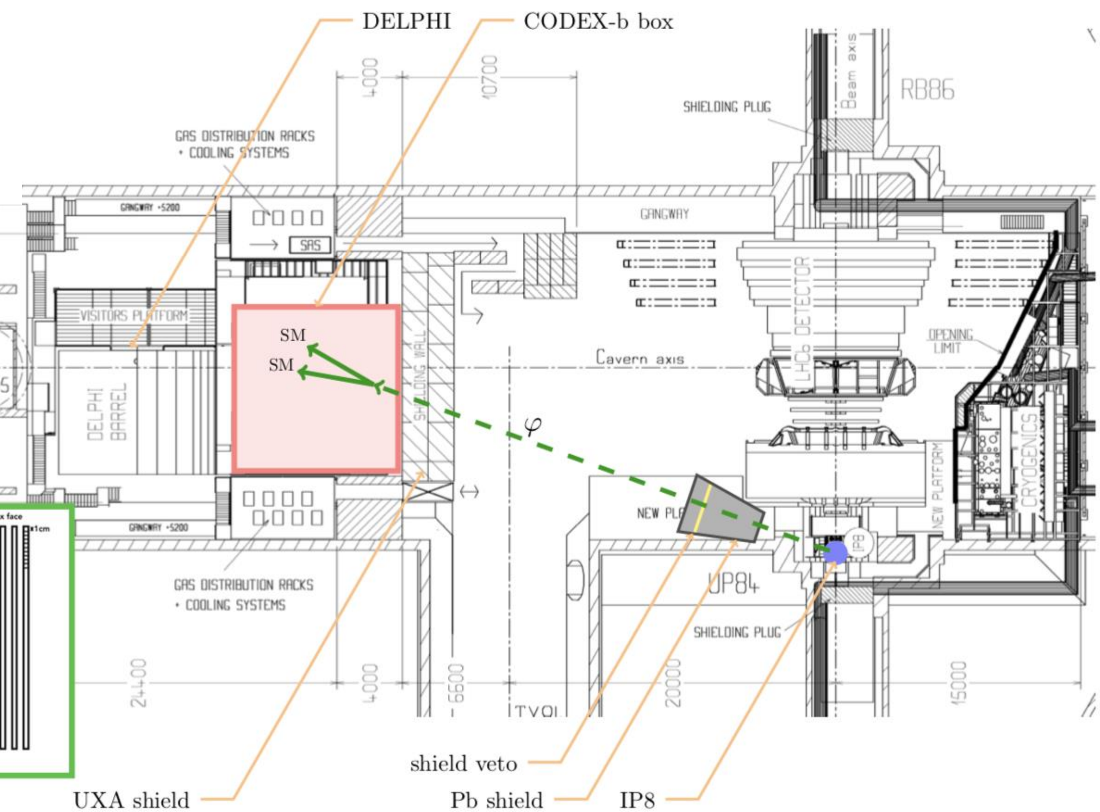
Other technologies: SENSEI (FNAL) uses skipper-CCD for electron scattering
Liquid Argon TPCs (neutrino experiments)

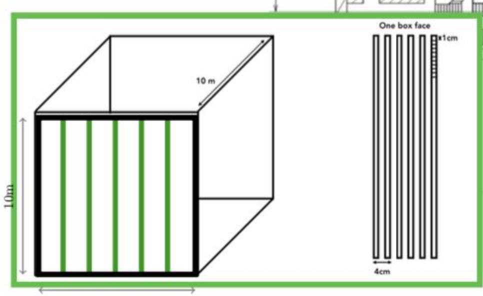
CODEX-b

COmpact Detector for EXotics at LHCb: a dedicated LLP detector@ IP8

First ideas: 1708.09395
EOI: 1911.00481
Backg. studies: 1912.03846

Search for weakly interacting neutral Long-Lived Particles





10 × 10 × 10 m

- Nominal design: $10 \times 10 \times 10\,m^3$ tracking volume 25 m away from the IP, preceeded by an active shield of $(25+5)\lambda$ Pb + 7λ concrete -> 1% angular acceptance
- RPC tracking detectors (ATLAS Phase 1 upgrade), integrated in LHCb triggerless readout -> Good vertexing and timing
- Modifications to the volume possible if DELPHI detector will be relocated

CODEX-β

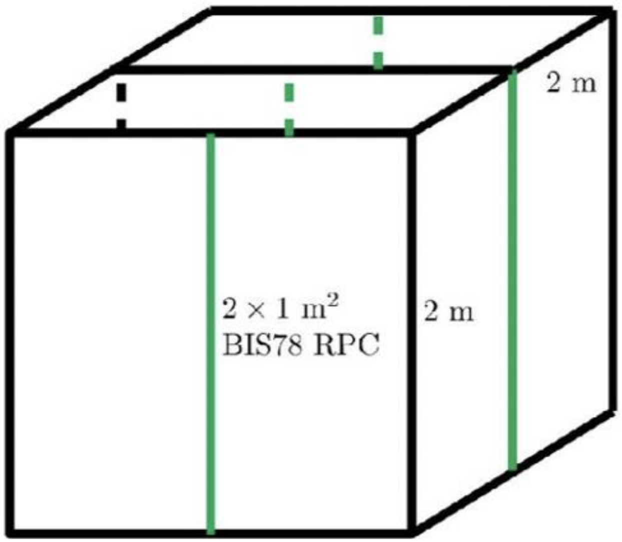
Demonstrator to test technologies planned for CODEX-b

Integration with LHCb DAQ, measure backgrounds, develop & test reconstruction algorithms & simulation, + physics performance (but no shield)

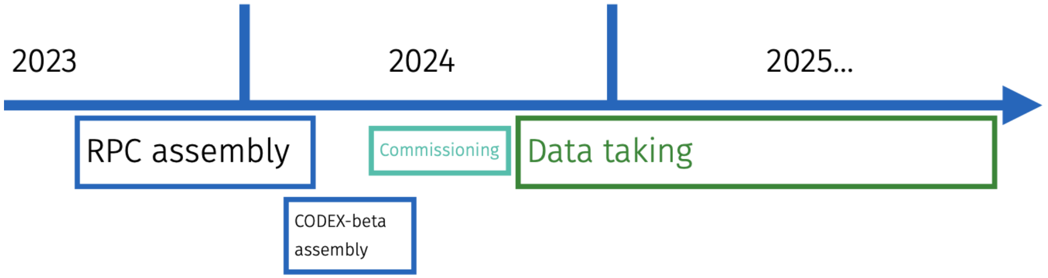
- $2x2x2m^3$ cube in LHCb HLT D1 server room in Run 3
- 14 triplets of RPC designed for ATLAS Phase I upgrade of muon spectrometer. Cost O(200 kCHF)

Expect 10^7 K_L to decay in the demonstrator volume.

Some reach for a search of multi-tracks (4+) LLP decays (appear eg in Hidden Valley models)



- CODEX-beta for Run 3 progressing steadily
  - Ramping up hardware production and software activities
  - RPC assembly to begin next month
  - Investigating first toy data analyses
- Collaboration is growing



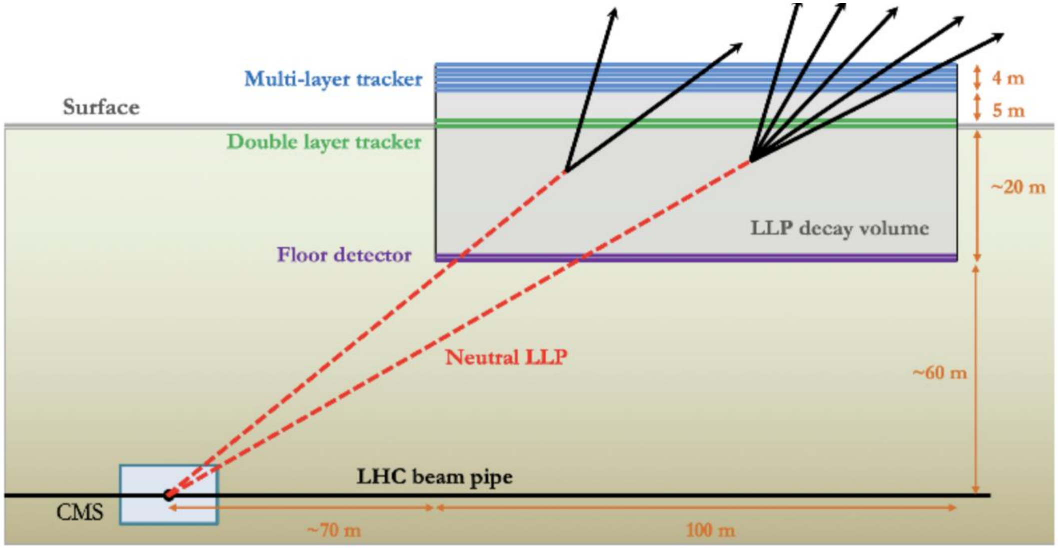
MATHUSLA

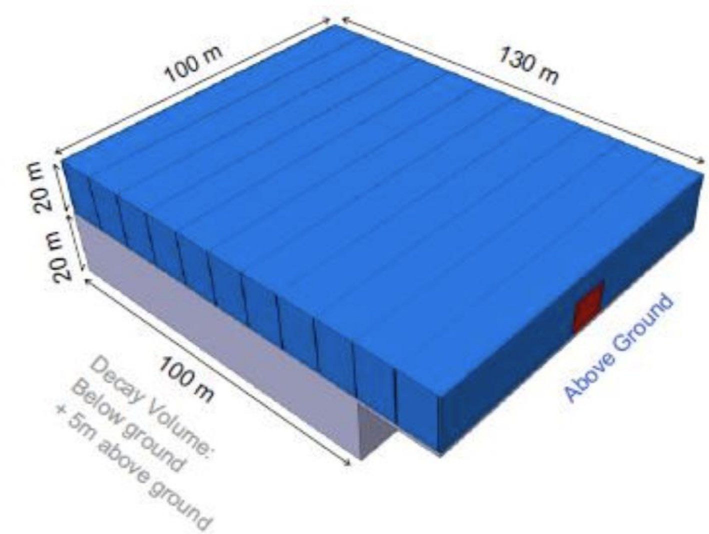
MATHUSLA: MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

Dedicated detector sensitive to neutral long-lived particles with lifetime up to the Big Bang Nucleosynthesis limit ($10^7 - 10^8$ m) for the HL-LHC

Proposed large area surface detector located above CMS with robust tracking and background rejection

- Large volume ~100x100x30m^3
- 4D tracking with ~ns time resolution
- Can run standalone or "combined" to CMS



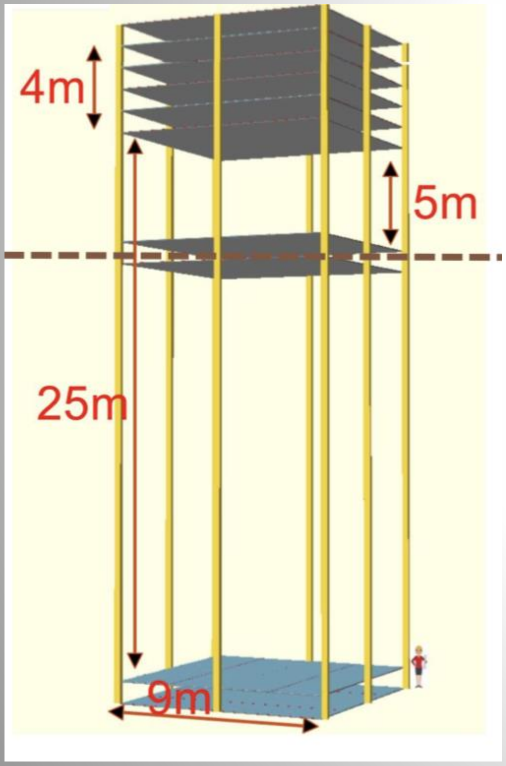


MATHUSLA

MATHUSLA will be build up from 9x9x30m^3 modules

- 6-layer tracking/timing detectors at the top
- Additional double tracking/timing layer at ground level
- Double tracking/timing layer at the floor level

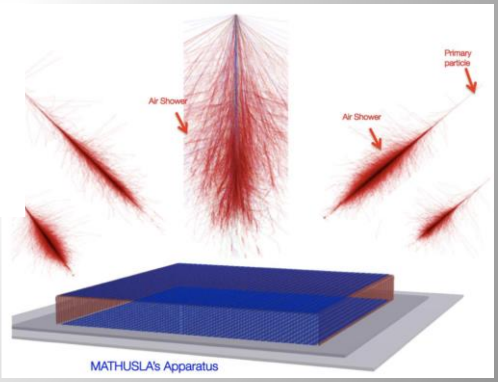
- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025



Baseline technology: extruded scintillator bars with wavelength shifting fibers (WLSF) connected to SiPMs.

->2018 RPC test-stand feasibility study (2005.02018)

Measurements of cosmic ray showers provide a guaranteed physics return!!



CDR (being) completed. Prototype module construction ongoing.
Next plan towards a detector for HL-LHC (installation in stages)

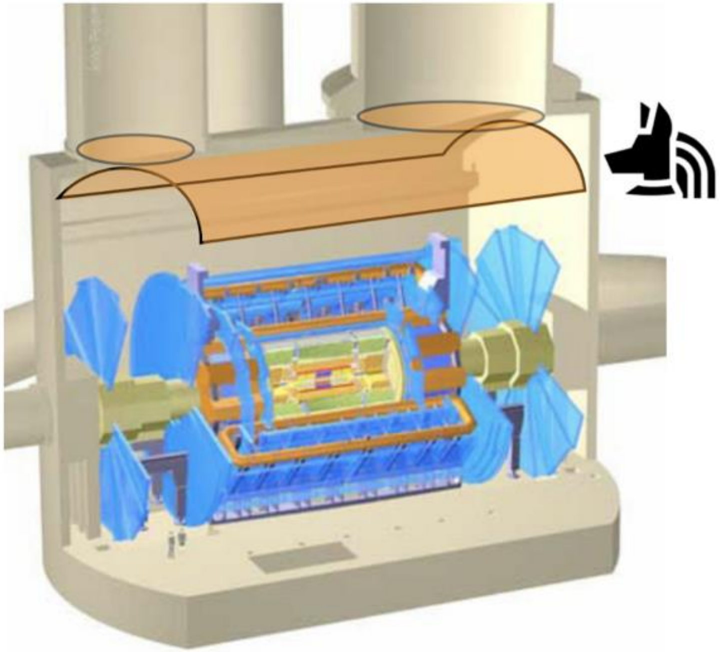
ANUBIS

ANUBIS: searches for long lived weakly interacting neutral particles

Originally proposal to use the ATLAS access shaft

1909.13022

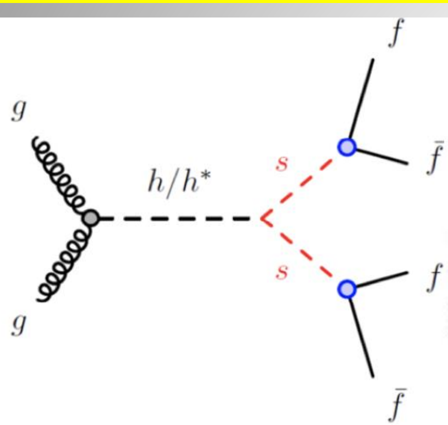
- **AN U**nderground **B**elayed **I**n-**S**haft detector
- No longer propose to instrument entire ATLAS access shaft, but instead only shaft bottom + cavern ceiling
- Avoids serious difficulties in removal of detector for access
- Shorter distance to IP more than compensated by larger solid angle
  -> better sensitivity
- Detector ~25m from IP: use cavern volume for decays
- Use ATLAS itself as active veto.
- Incorporated as an official sub-project of ATLAS



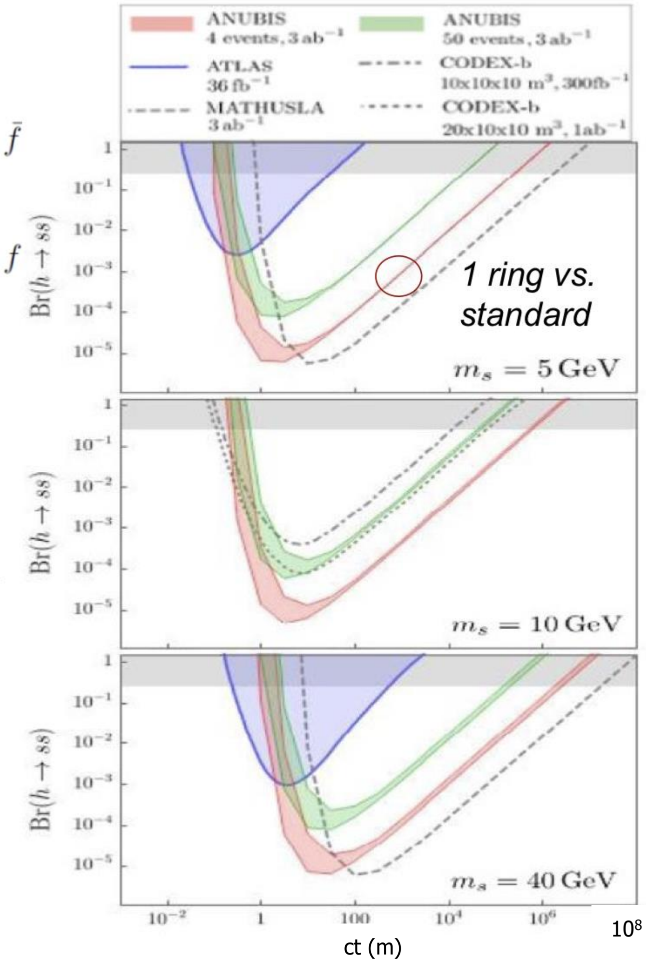
ANUBIS demonstrator being tested in the ATLAS cavern

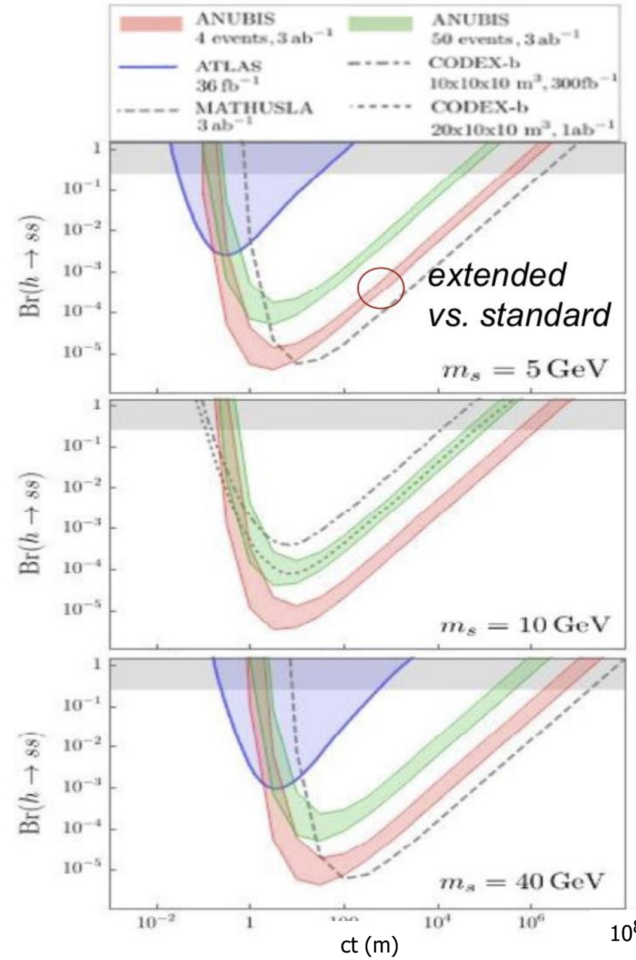
Example Process

Higgs as a portal to the Dark Sector, with a long lived scalar states s



- For a given decay volume length
  - More solid angle if closer to the IP
  - Number of decays higher if closer to the IP (for shorter decay lengths)



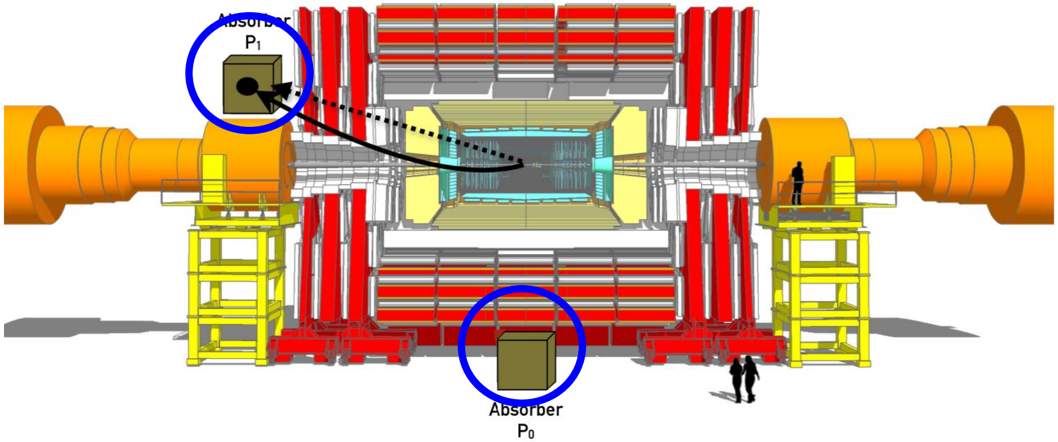


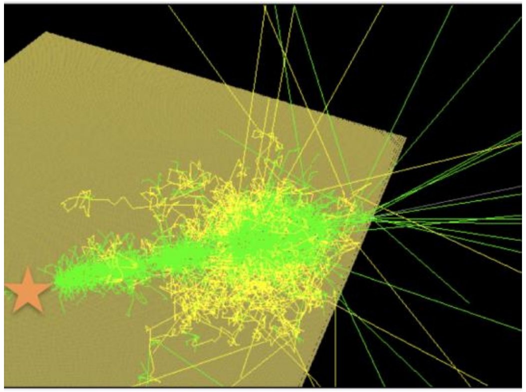
The different proposals have different strengths and levels of complementarity
Studies regularly reported in PBC, FIP, and LLP meetings

Developing Idea: Trapping Particles

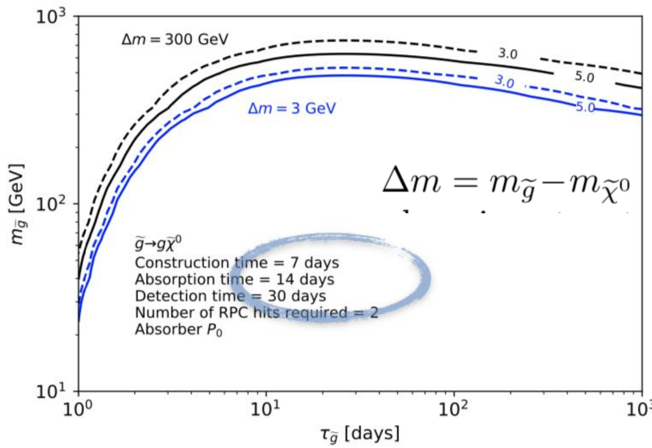
arXiv:2110.13837

- Proposal for detecting LLPs trapped in detector material:
  -> $2x2x2m^3$ dense target (rods), turned into a LAr calorimeter
- Sensitivity studied for e.g. R-hadrons





- Take the absorber apart (brass rods, 1cm x 1cm)
- Submerge into LAr, leave 1cm space between rods
- Apply voltage to each rod and attach readout electronics
  - LAr calorimeter!



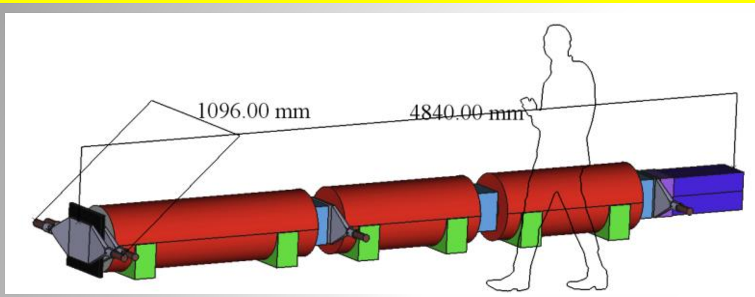
Trap the particles and wait for its decay

Reach longer lifetimes: > weeks, months!

Proposals for Forward Detectors

New Forward Detector Proposals

FASER: searches for long lived dark photons-like particles, neutrinos



SND@LHC: neutrino measurements and long-lived particle searches

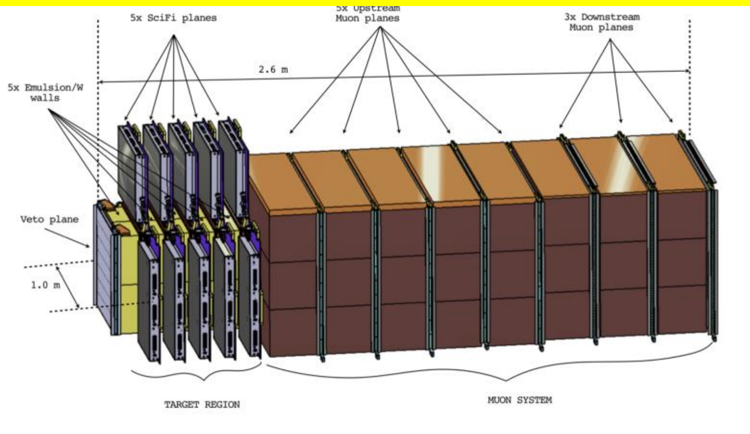
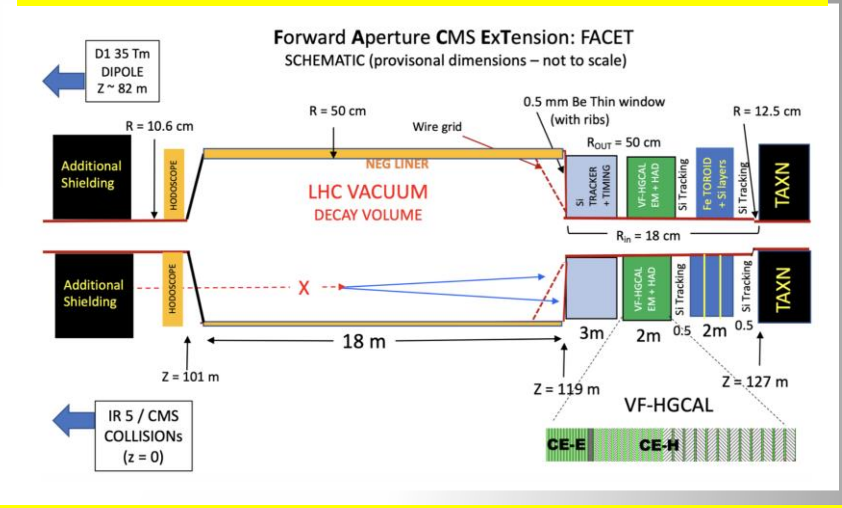


Figure 5: Layout of the proposed SND@LHC detector.

FACET: Instrumented Beampipe for CMS



FPS: A Facility for Forward Physics Containing several experiments

FASER and SND@LHC have been approved in 2019/2020 and take data since the start of Run-3

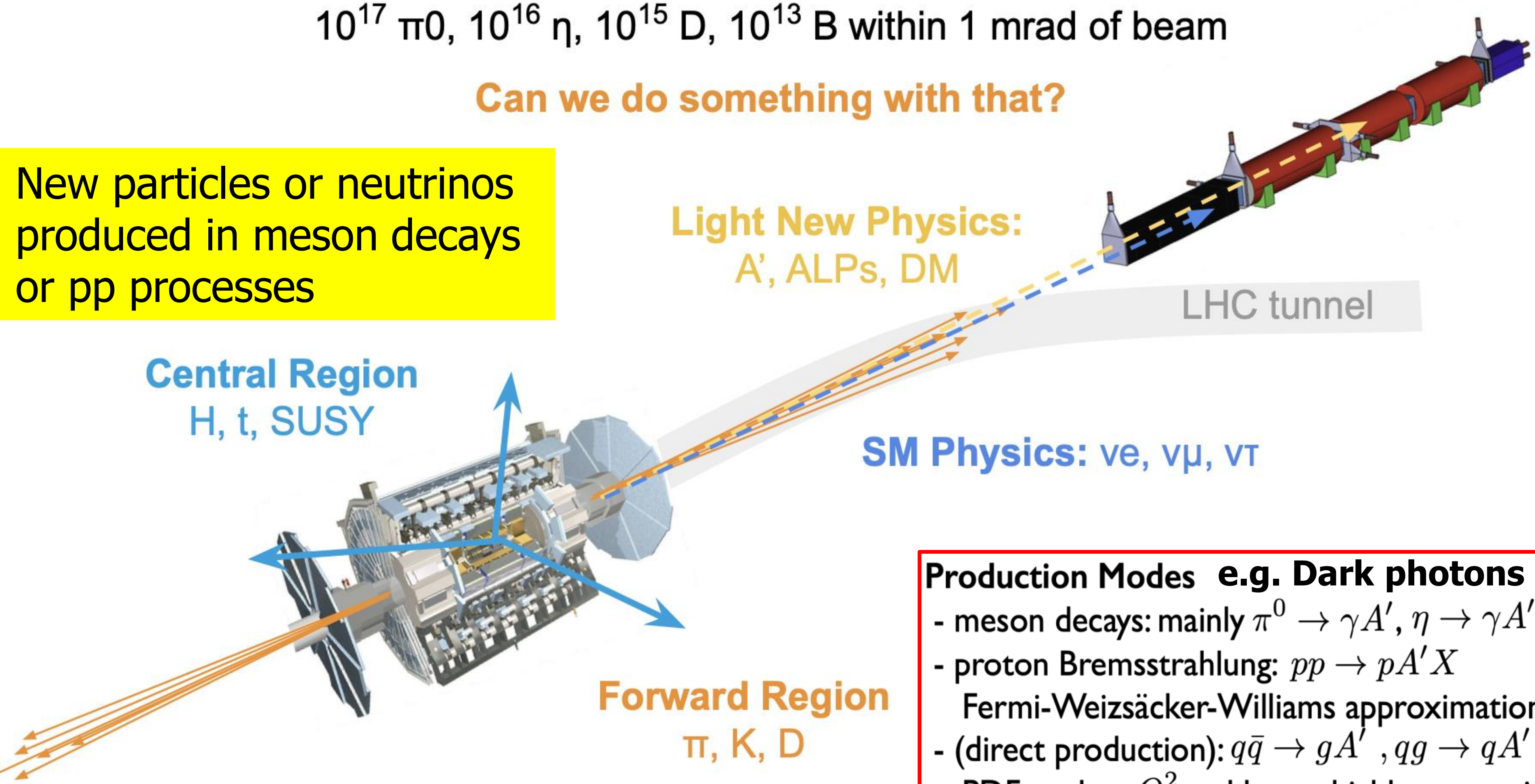
Forward Particle Production

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

Can we do something with that?

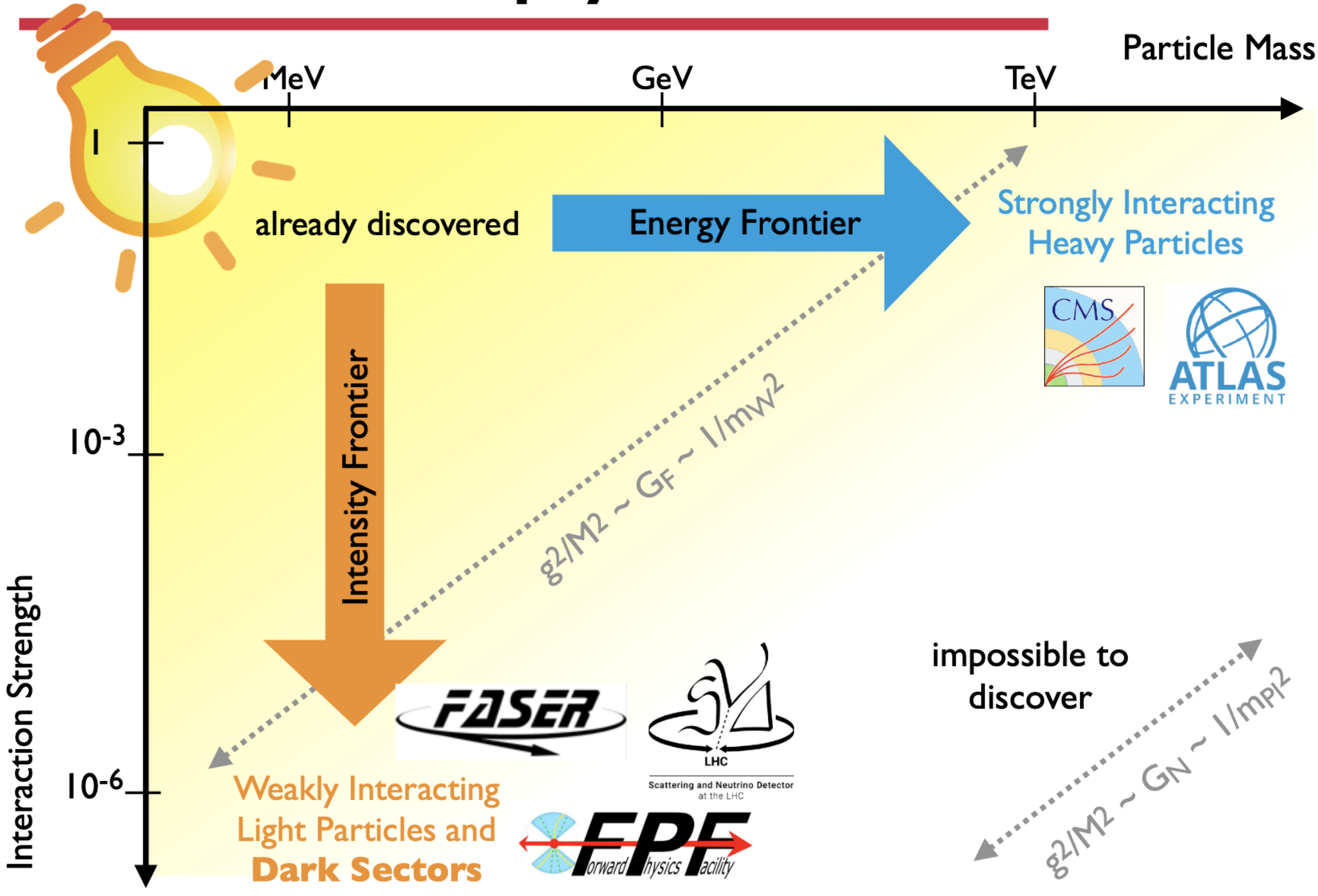
New particles or neutrinos produced in meson decays or pp processes



Production Modes **e.g. Dark photons**

- meson decays: mainly $\pi^0 \to \gamma A'$, $\eta \to \gamma A'$
- proton Bremsstrahlung: $pp \to pA'X$
  Fermi-Weizsäcker-Williams approximation
- (direct production): $q\bar{q} \to gA'$, $qg \to qA'$
  PDFs at low Q^2 and low x highly uncertain

Where could new physics be:

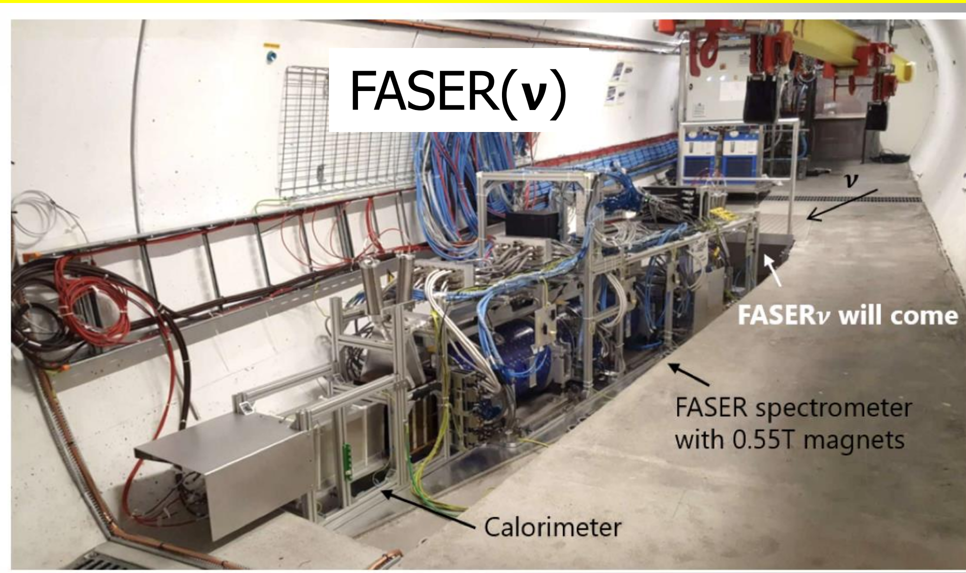


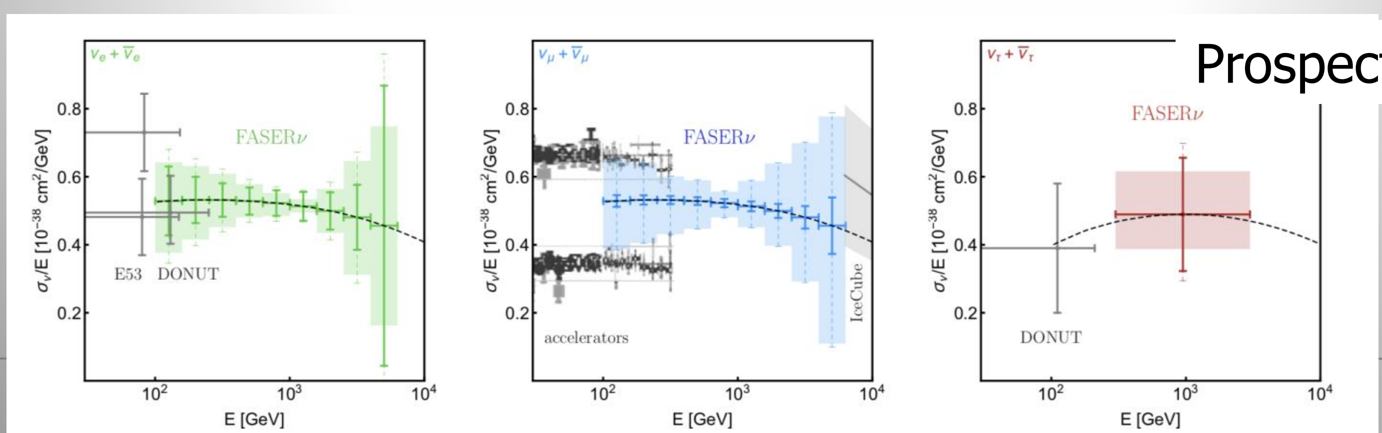
Neutrinos @ the LHC: SND@LHC & FASERν

SND@LHC: approved March '21

SND= Scattering and Neutrino Detector

SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors





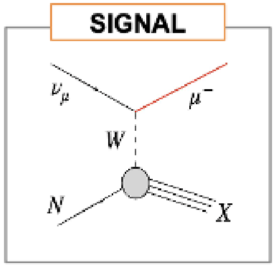
Prospects for Run-3

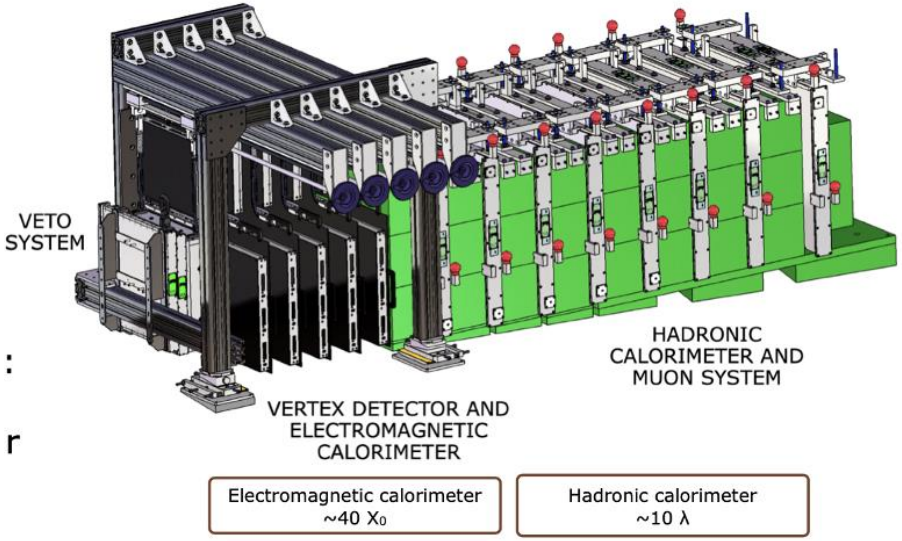
Neutrinos from the LHC

Direct Neutrino observation by SND@LHC and FASER

Neutrino observation with electronic detectors

- Analysis strategy:
  - Full Run 3 **2022 dataset**, 39 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach
  - ~10^9 muon events: apply **cuts with a strong rejection power** to reach a negligible background level





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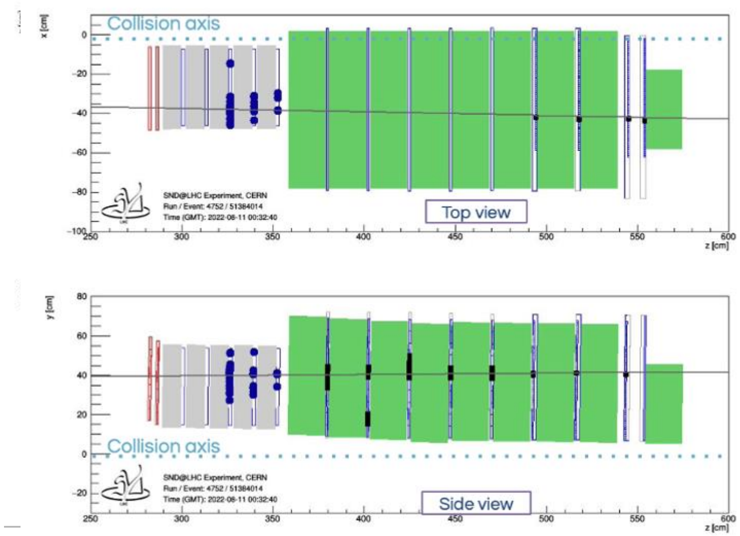
SND@LHC: 2305.09383
FASER: 2303.14185

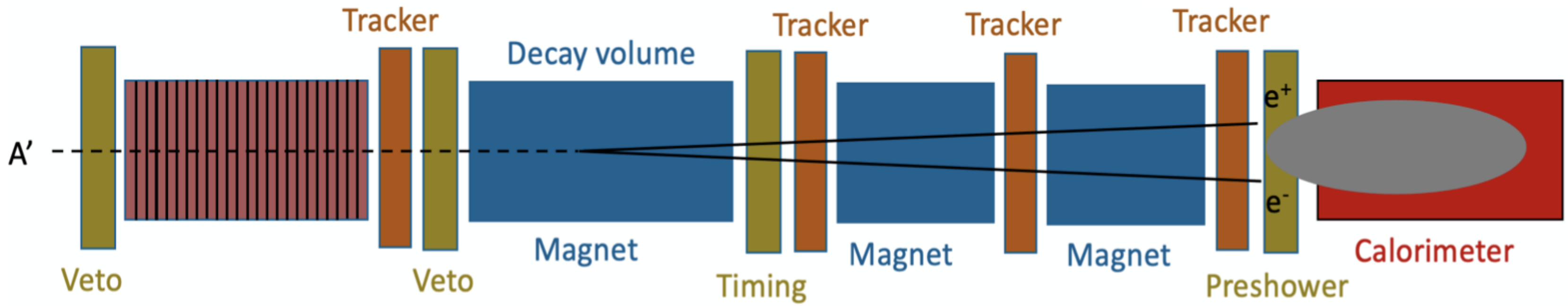
Aug 11th 2022



- **Observed ν_μ candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

FASER: New Limits on Dark Photons

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

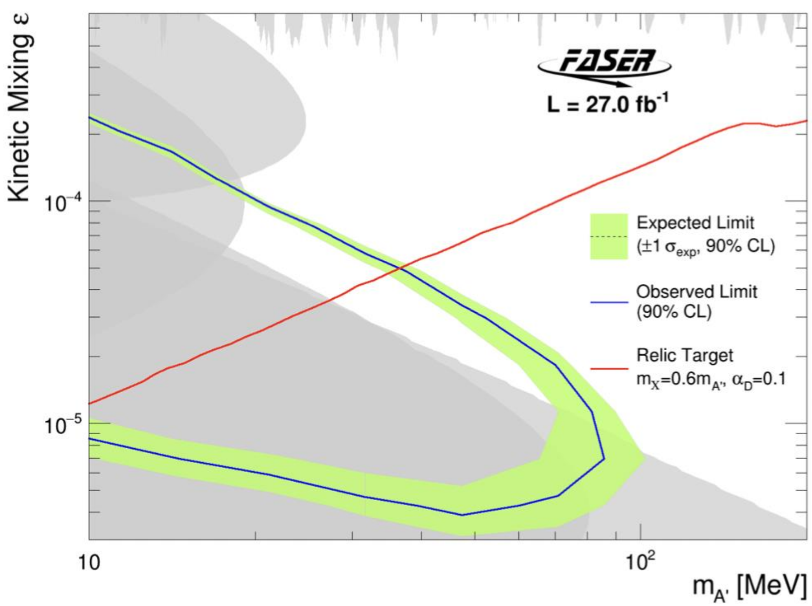


arXiv:2308.05587

- After unblinding, no events seen in signal region. Background ~ 10^{-3} events, FASER sets limits on previously unexplored parameter space.

- First incursion (with NA62) into the thermal target from low coupling since the 1990's.

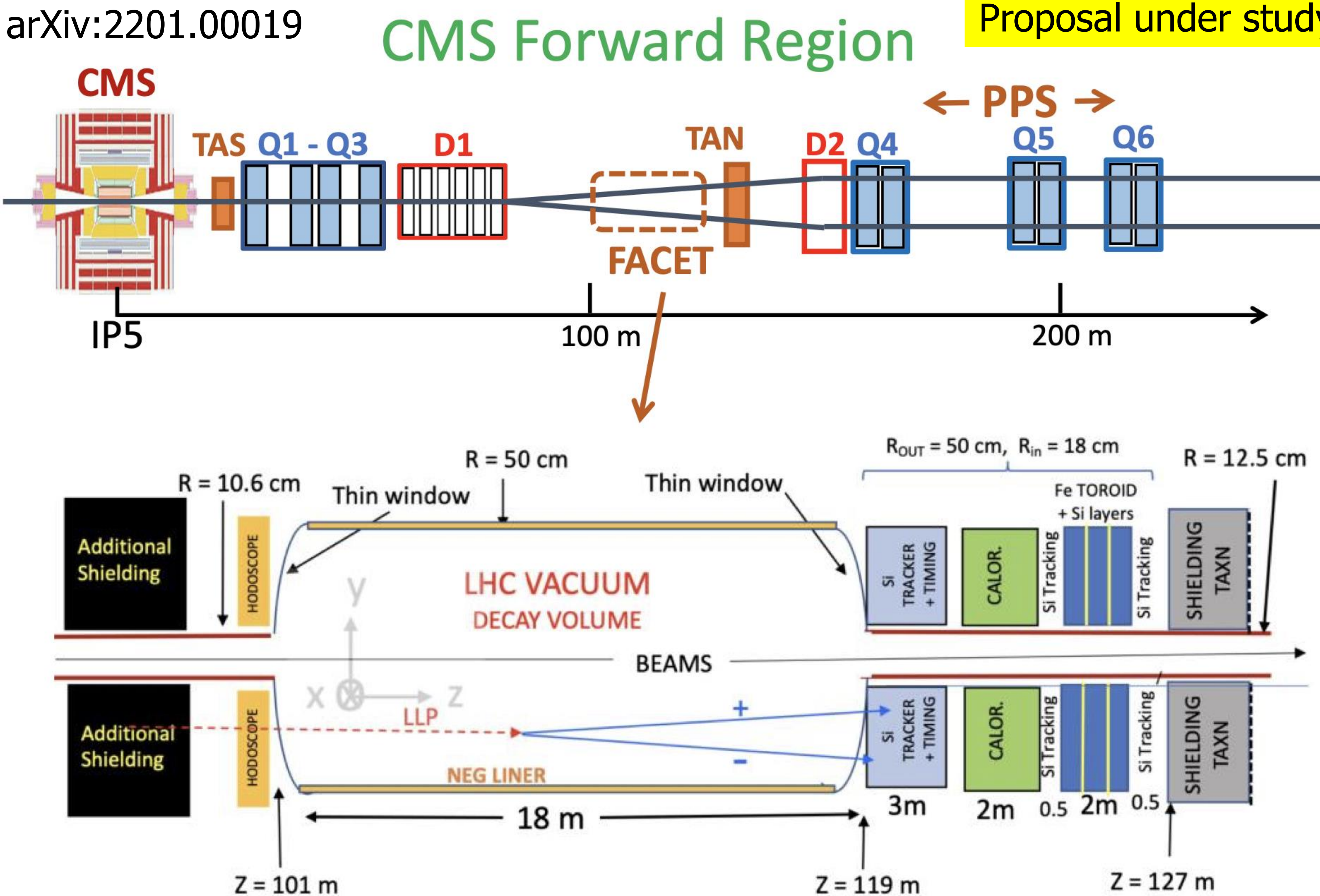
- Background-free bodes well for the future: FASER2 has ~60,000 better sensitivity.



FACET

arXiv:2201.00019

Proposal under study

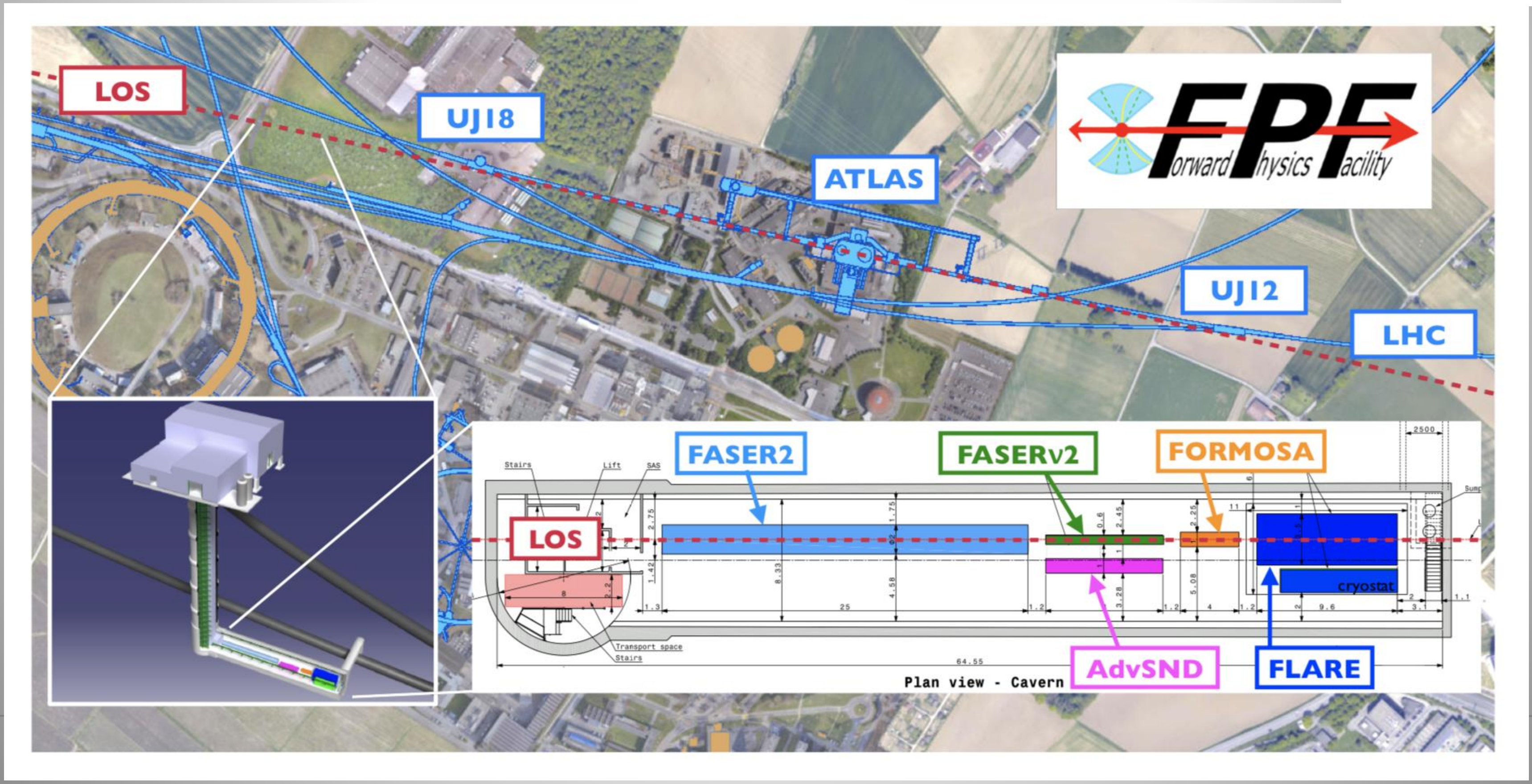


An Option for the FUTURE:
The Forward Physics Facility

FUTURE: The Forward Physics Facility?

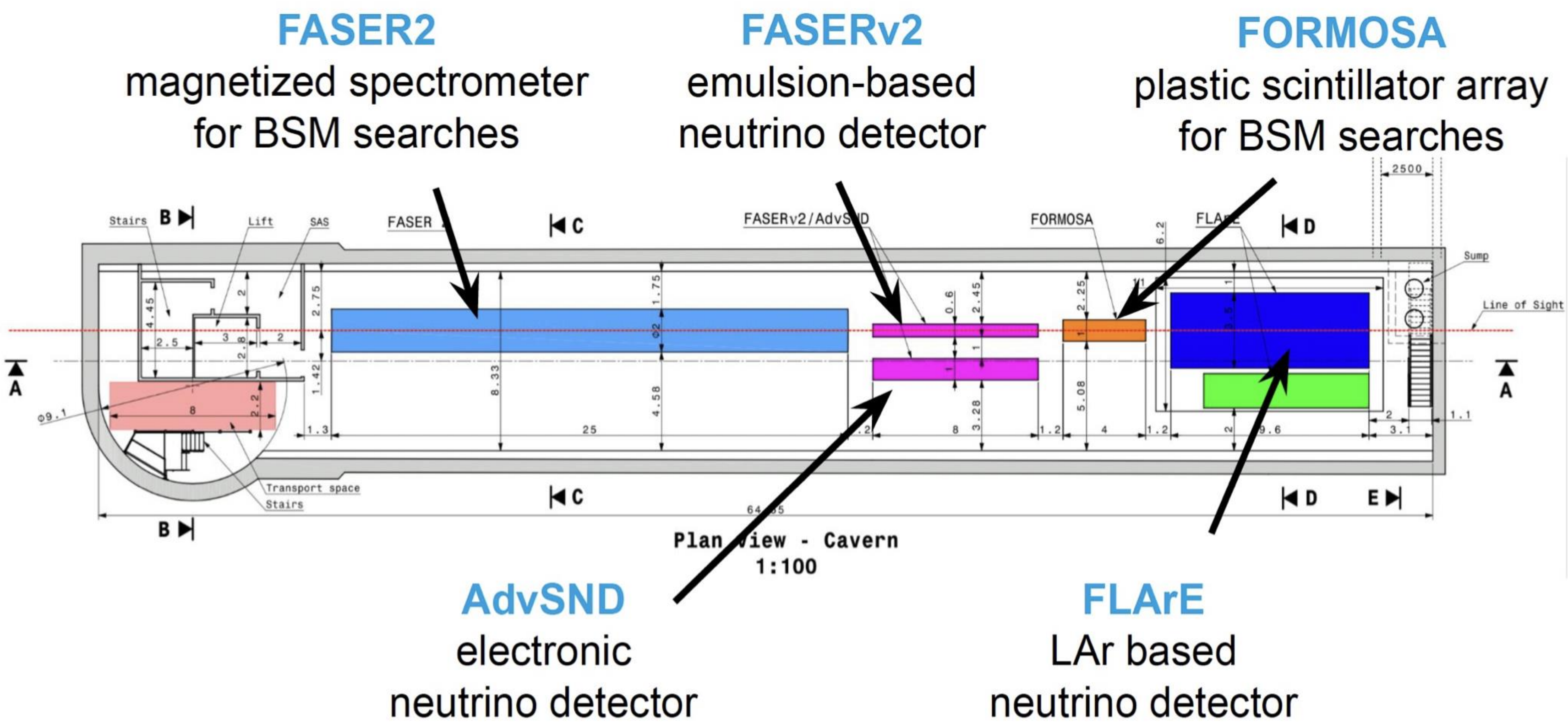
Origine :Letter of intent contributed to the Snowmass21 process.
Based on the FASER experience and studies: propose to have a Forward Physics Facility (FPF) experimental hall with room to include forward detectors for new physics searches (and QCD/neutrinos): FASER2, others …

2203.05090



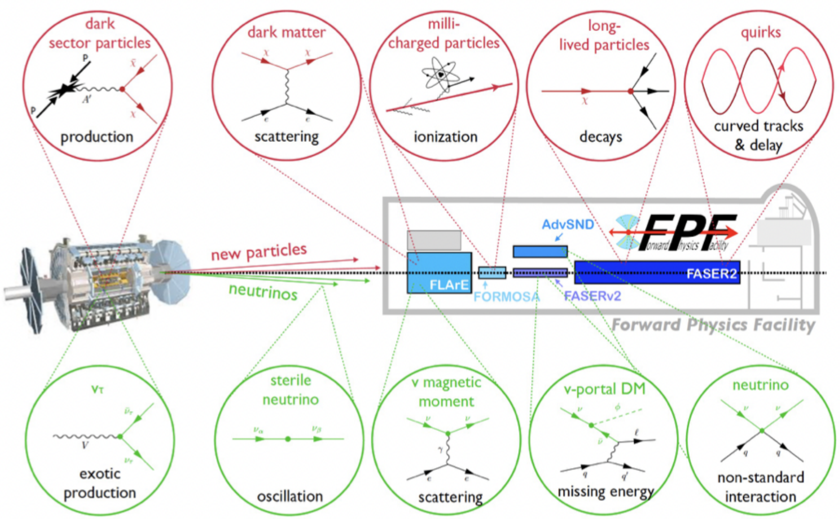
FPF Detectors

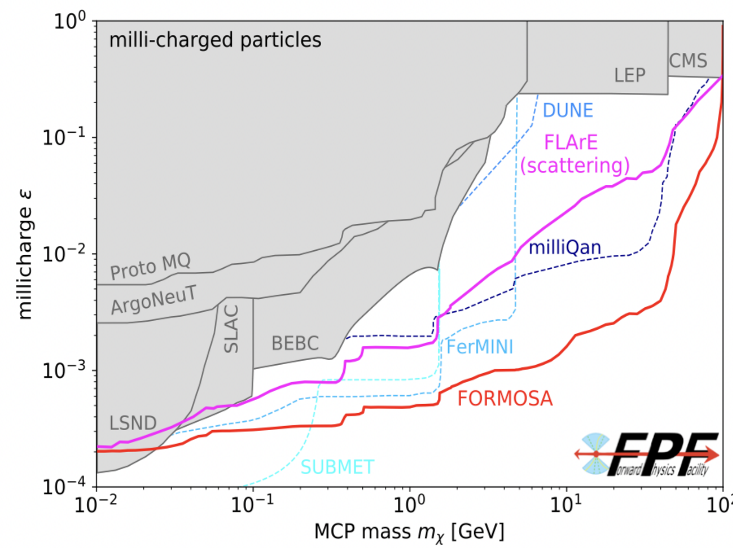
- At present there are 5 experiments being designed to explore the breadth of physics topics.
  - Millions of TeV-energy neutrinos will provide new probes of neutrino properties, QCD, and astroparticle physics.
  - $O(10^4)$ times greater sensitivity for new particle searches.



FPF Physics Program

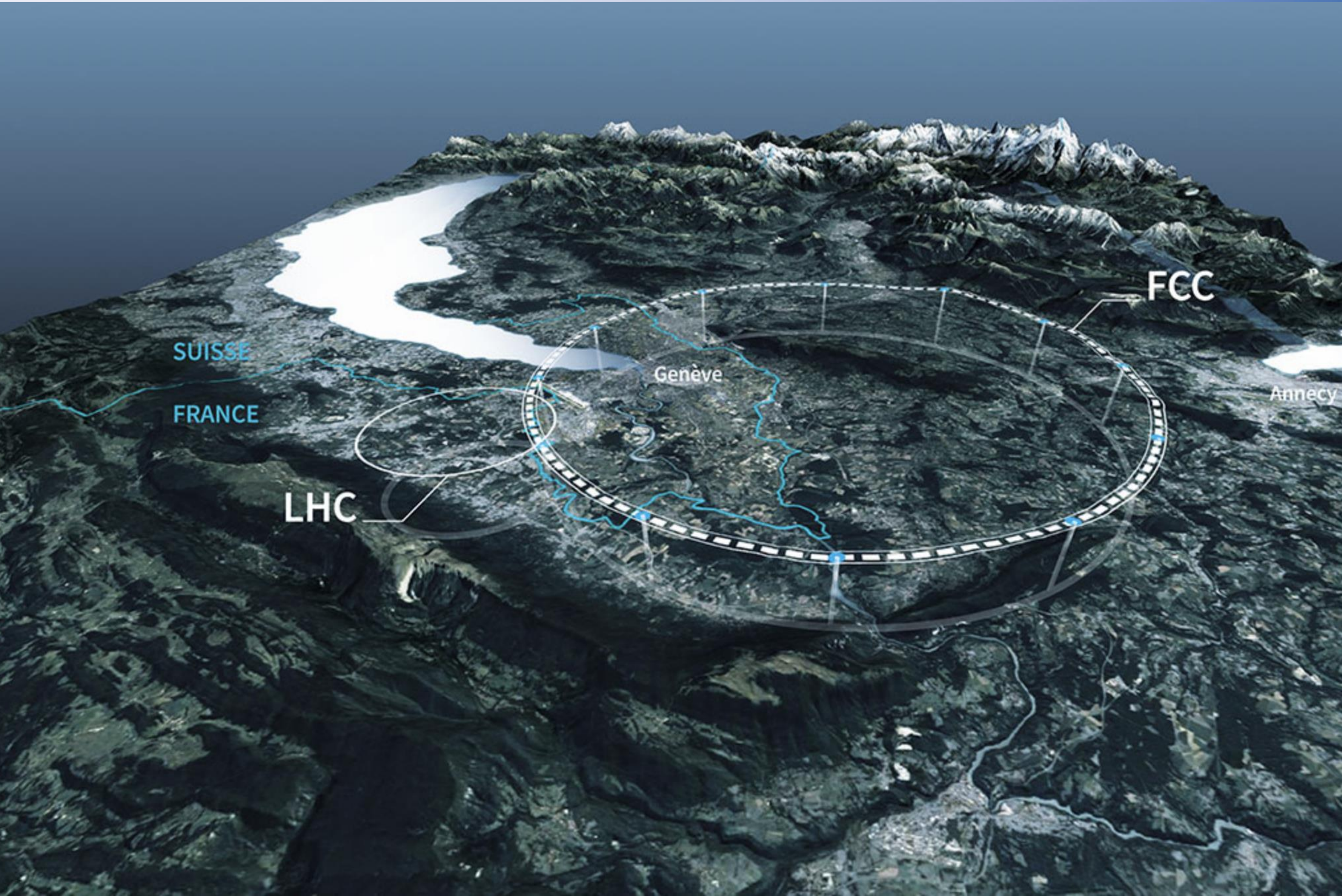
- Wide variety of BSM probes: new physics in neutrino production, propagation, and interaction, FIPs, LLPs, DM scattering, inelastic DM, and dark sectors.
- The FPF detectors each have unique capabilities to probe BSM topics. E.g.:
  - Pathfinder experiment FASER has recently set new limits on dark photons,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





+ neutrino physics, QCD …

Future Colliders

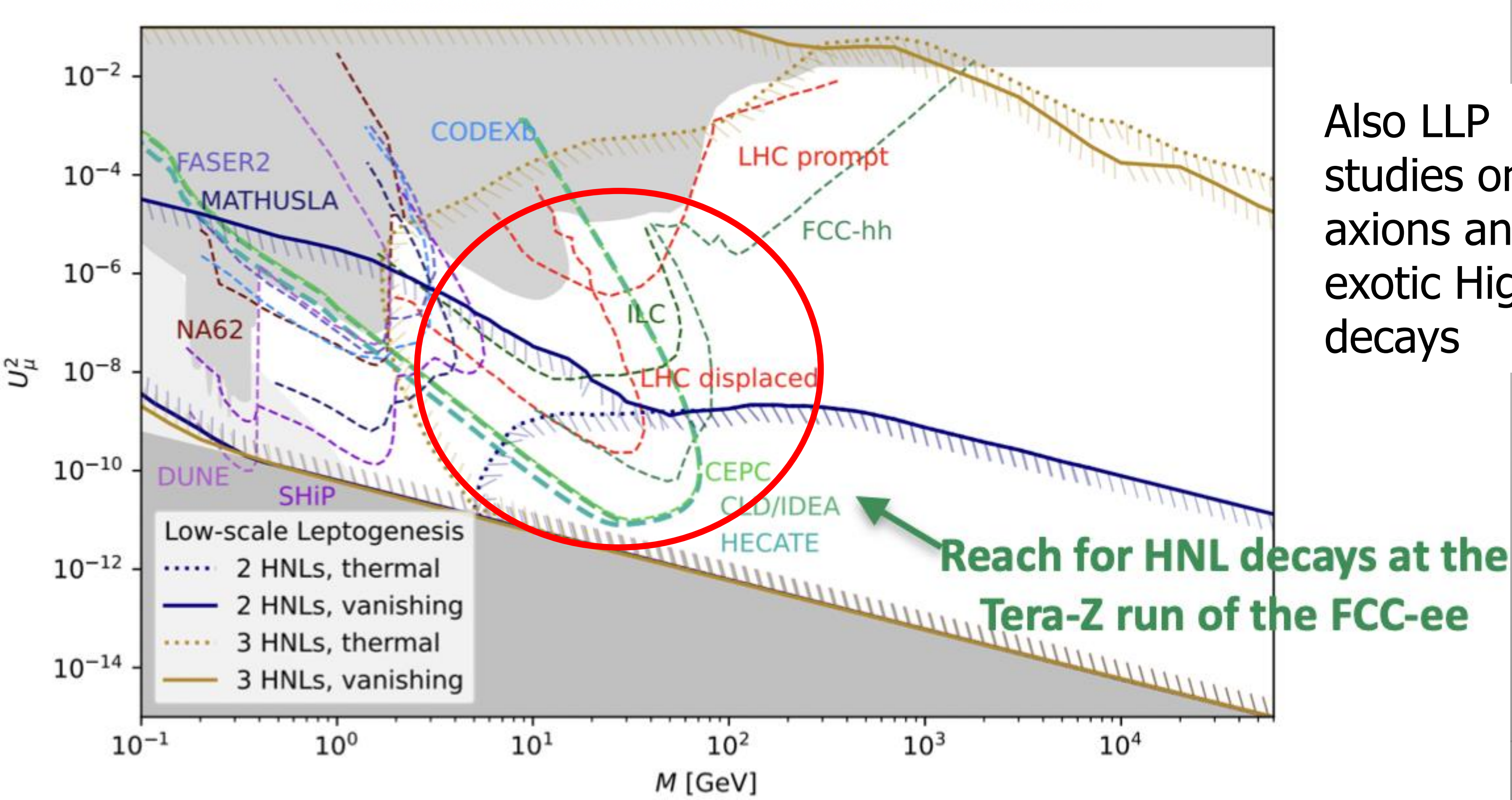


FCC-ee Studies

FCC_ee reach for HNLs, for 5×10^{12} Z boson decays and a central detector (IDEA or CLD type)

$$e^+e^- \to Z \to \nu N \qquad N \to \ell W^* \to \ell jj$$

2203.05502



Also LLP studies on axions and exotic Higgs decays

Ideas for LLP Detectors Future Facilities

Important: take LLP requirements into account from the start! (Snowmass2021)

Dedicated LLP Detectors at Future Facilities?

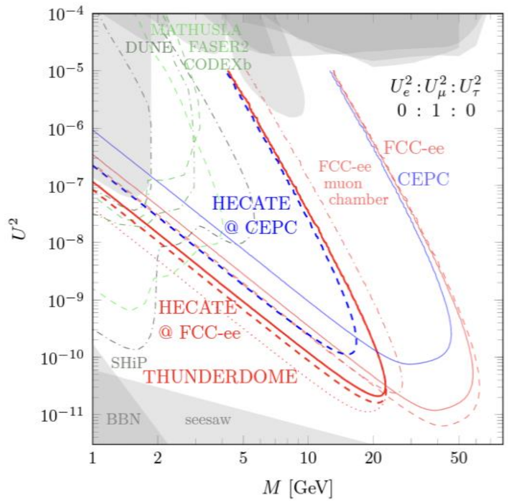
- FCC-ee baseline is consistent with having 2 or 4 detectors
- Opportunities for new, creative designs!

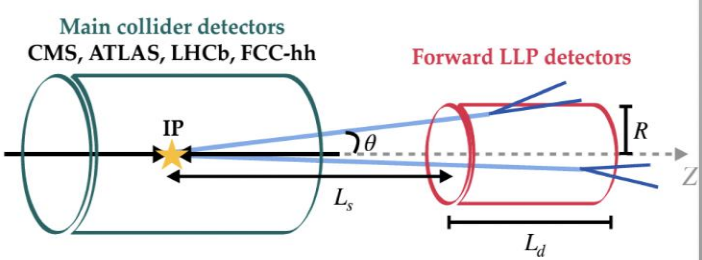
Lepton collider ideas:

- **HECATE** (EPJC 81 (2021) 546 / arXiv:2011.01005)
  - Instrument cavern walls with scintillators or RPCs
- **Study at ILC** (PRD 107 (2023) 076022 / arXiv:2202.11714)
  - Conclude that ILD still does better for LL ALPs

Hadron collider ideas:

- **DELIGHT** (PRD 106 (2022) 095018 / arXiv:2111.02437)
  - Transverse detector
- **FORESEE** (PRD 104 (2021) 035012 / arXiv:2105.07077)
  - Numerical package to simulate sensitivity of far-forward detectors
- **FOREHUNT** (arXiv:2306.11803)
  - Forward detector





From J. Alimena

- CEPC studies: FAR detector 1911.06576

Ideas for LLP Detectors Future Facilities

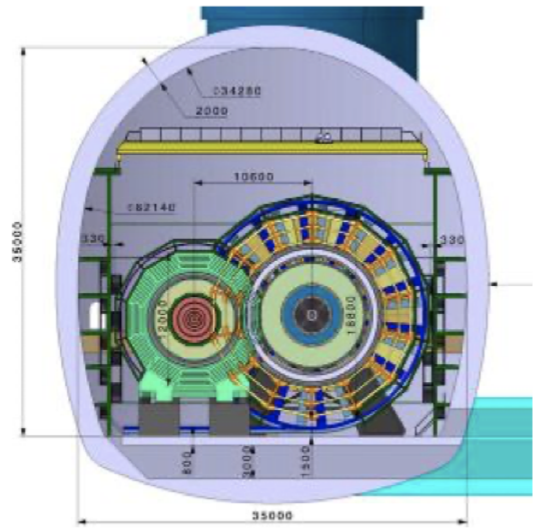
HECATE: Instrument the cavern walls! Cover DLs up to 15 meters

LLPs @ FCC-hh, FCC-ee

Proposal: 2011.01005

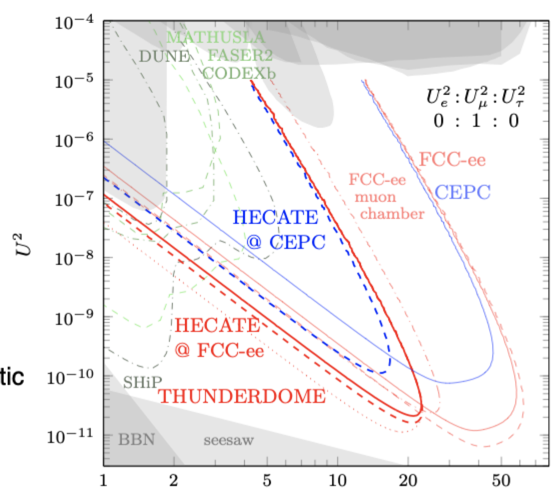
HECATE: HErmetic CAvern TrackER. A long-lived particle detector concept for FCC-ee or CEPC

- For FCC-hh / FCC-ee, main detector will be relatively smaller than the cavern
- Cover detector cavern walls with scintillator plates or RPCs
  - >= 2 layers of 1 m² separated by a sizeable distance — timing
  - >= 4 layers for good tracking
  - 4π coverage LLP detector
- FCC main detector as active veto
- Sensitive to a unique area of phase space



- Cavern size: r~15 m and z~50 m
- Main detector size =(10m)

- Example: HNLs
- THUNDERDOME: Totally Hyper-UNrealistic DEtectoR in a huge DOME (maximum distance from IP=100m for comparison)

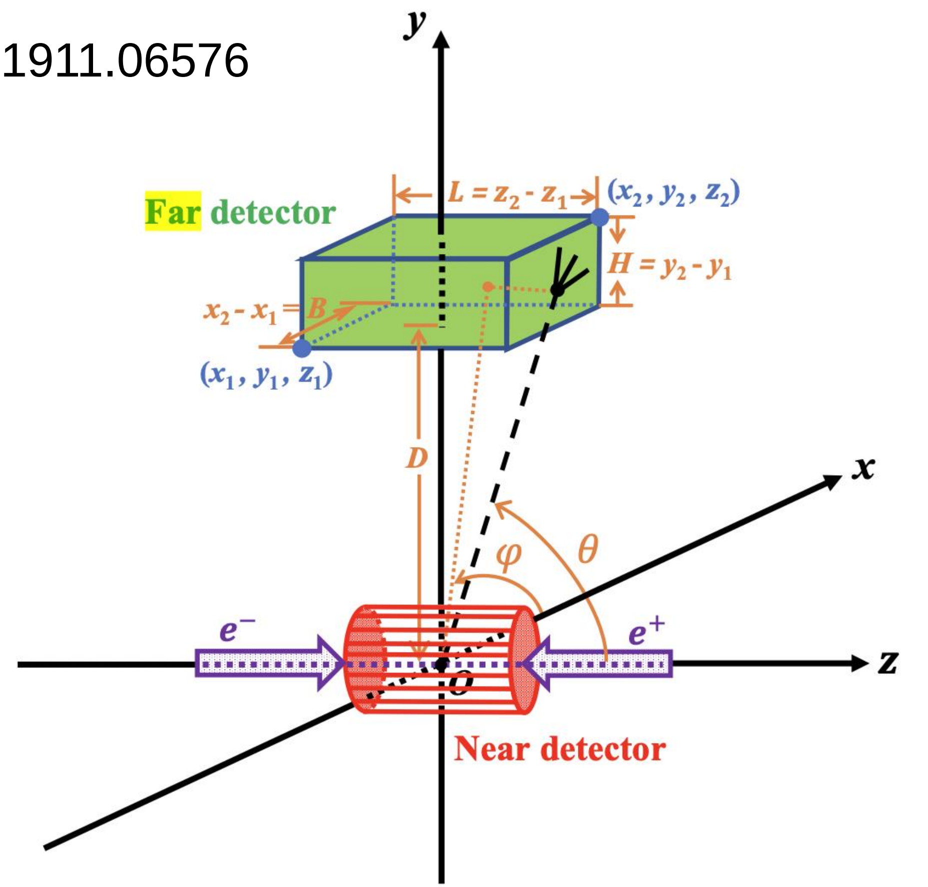


Ideas for LLP Detectors Future Facilities

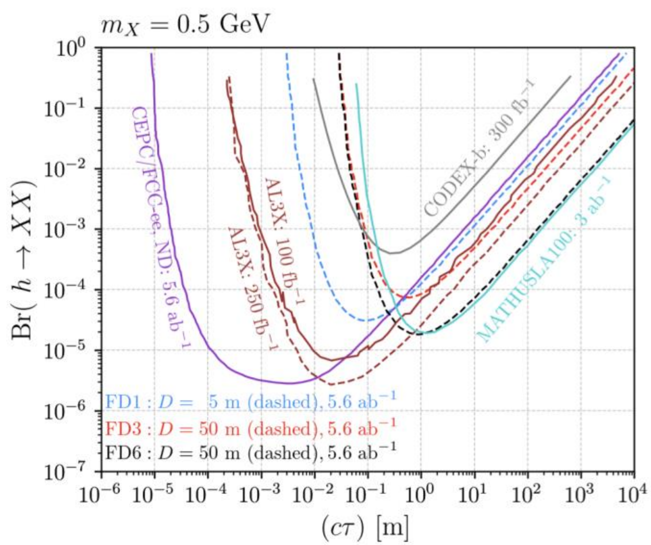
CEPC Studies: the Far Detector

16 options studied for
D = 5-100m
L,B = 50-2000m
H = 10-80m

1911.06576



Light Scalars from Exotic H Decays



See also Xuai Zhuang

The FD will extend and complement the sensitivity to the LLPs compared with the (central) Near Detector

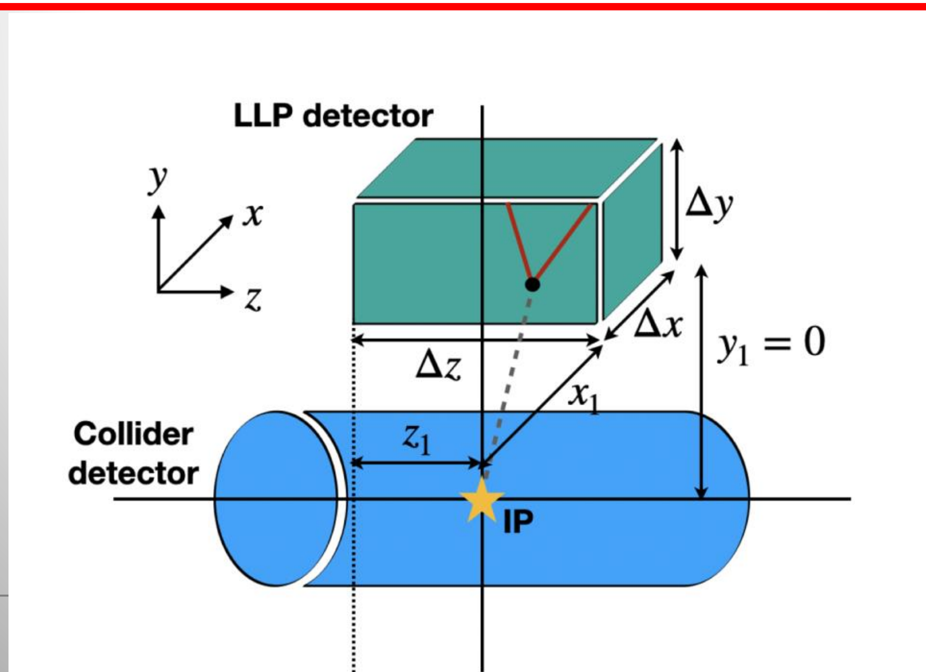
Ideas for LLP Detectors Future Facilities

DELIGHT: A MATHUSLA or CODEX-b type of detector for the FCC-hh integrated from the start!

DELIGHT (A):	The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.
DELIGHT (B):	Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.
DELIGHT (C):	Twice the same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

$x_1 = 25$ m
$y_1 = 0$ m
$z_1 = -\Delta z/2$

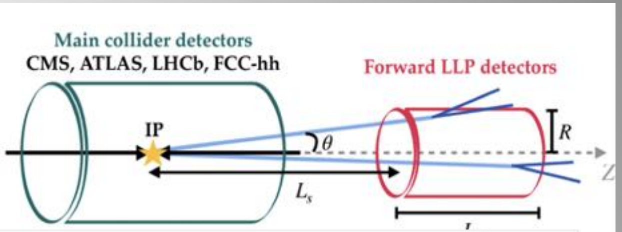
2111.02437
2306.11803



DELIGHT
Detector for long-lived particles at high energy of 100 TeV

Ideas for LLP Detectors Future Facilities

FOREHUNT: a Forward Detector for FCC-hh like FASER



arXiv:2306.11803

2306.11803

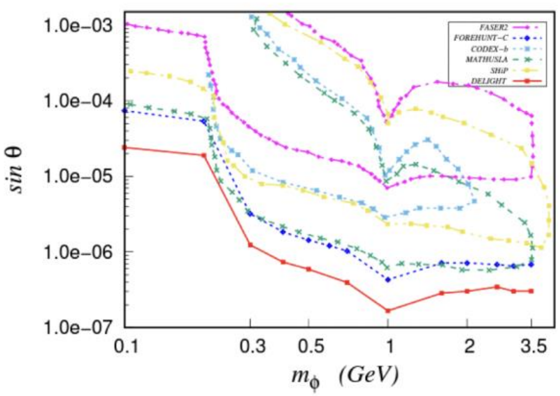
FOREHUNT

- Brand new proposal (June 20, 2023)
- Place **dedicated LLP detector** in the **forward region** at the **FCC-hh**
- **Target LLPs from B-meson decays**

- Assume main FCC-hh detector at $z \in$ [-25, 25] m and sufficient shielding
- **Put FOREHUNT at at least 50 m in z**
- Option: put FOREHUNT-C slightly off z-axis
  - 1 m off z-axis: acceptance drops by factor of 2
  - 5 m off z-axis: acceptance falls drastically

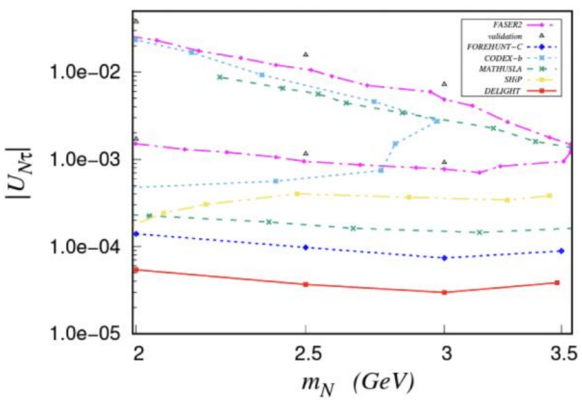
Dark Higgs scalar:

$$B^{\pm} \to K^{\pm}\phi$$



HNLs:

$$B^0 \to D^{\pm}\tau^{\mp}N_\tau\,,$$
$$B^{\pm} \to D^0\tau^{\pm}N_\tau\,,$$
$$B^{\pm} \to \tau^{\pm}N_\tau\,.$$



Detector Configuration @100 TeV	Radius (R)	Length (L_d)	Position (Z)
FOREHUNT-A	1 m	10 m	50 m
FOREHUNT-B	2 m	20 m	50 m
FOREHUNT-C	5 m	50 m	50 m
FOREHUNT-D	2 m	20 m	75 m
FOREHUNT-E	5 m	50 m	75 m
FOREHUNT-F	5 m	50 m	100 m

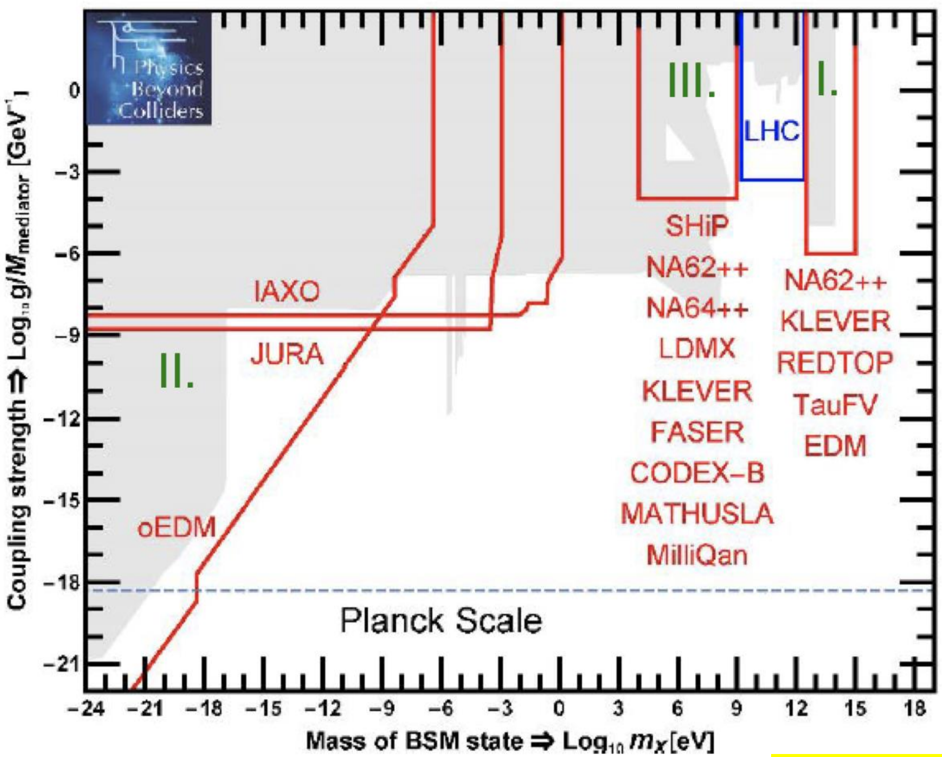
Non-Collider Experiments

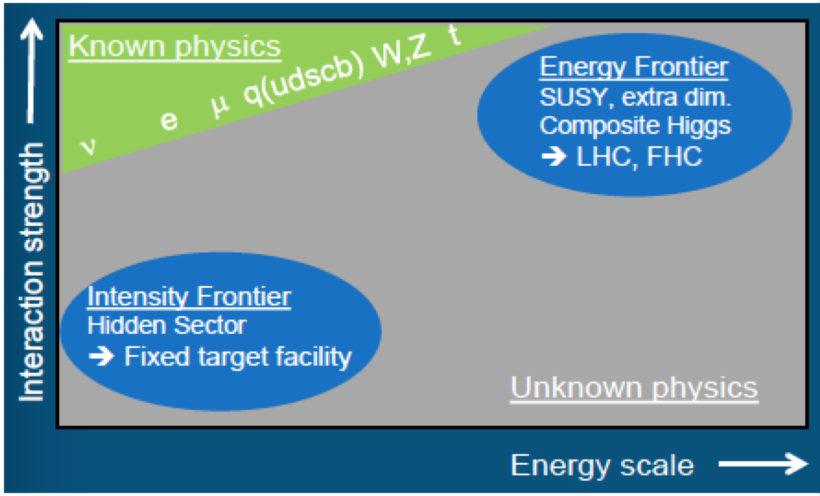
- Neutrino Experiments
- Beam Dump Experiments
- High Intensitiy Experiments

…

Physics Beyond Colliders

- Physics Beyond Colliders was a response at CERN to increasing interest in complementary methods to high energy frontier colliders to explore searches for BSM physics.
- It was a discussion forum for input to the 2019 European Strategy Update.
- It is continuing its activities..



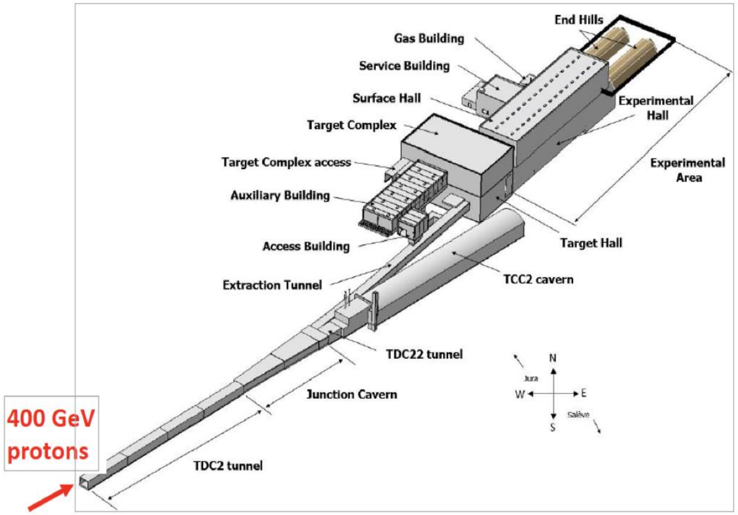


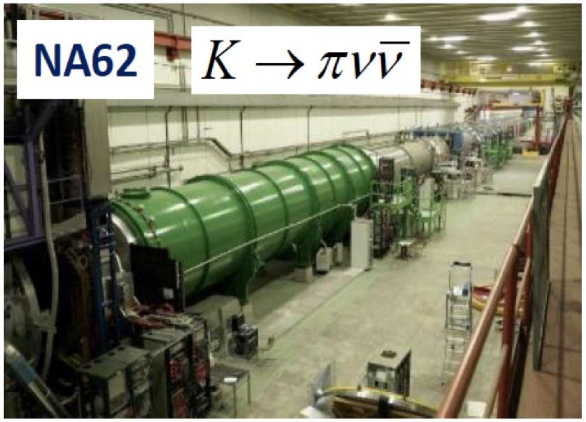
Next meeting 25-27 March 2024 @ CERN

Physics Beyond Collider

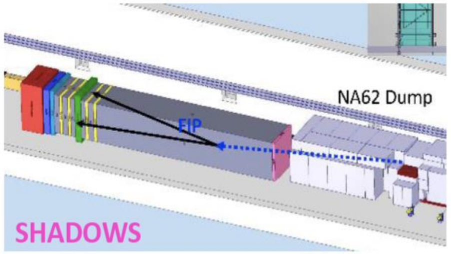
CERN Proton Beam Dump Facility

- Comprehensive Design Study of a new SPS facility done within PBC
- Promising option (lower cost) identified in existing ECN3 underground hall in CERN North Area (currently used by NA62)
- Under evaluation with respect to alternative NA62 extension + SHADOWS option (new idea to search off-axis for feebly interacting particles)

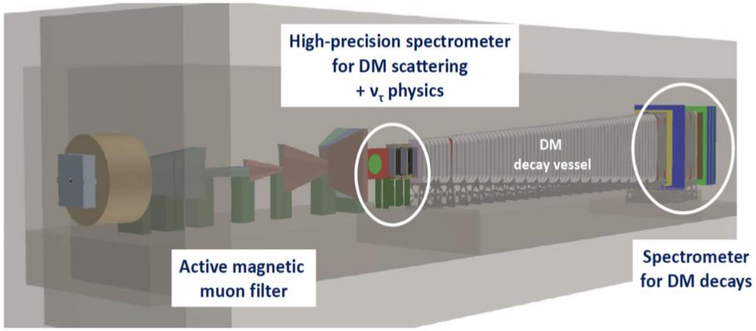




Instrumentation of NA62 decay vessel well adapted to searches in visible decay mode



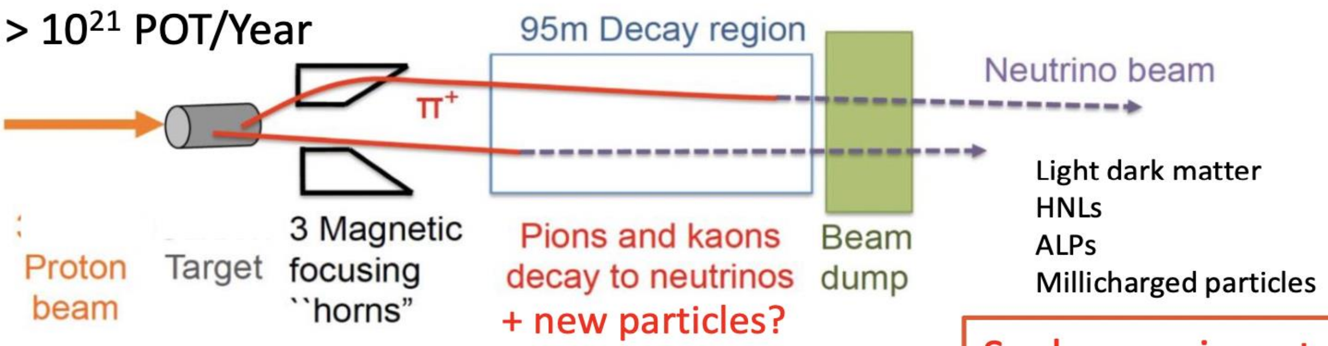
SHiP on the Beam Dump Facility



Decision on the CERN Beam Dump Facility & Experiments in 2024

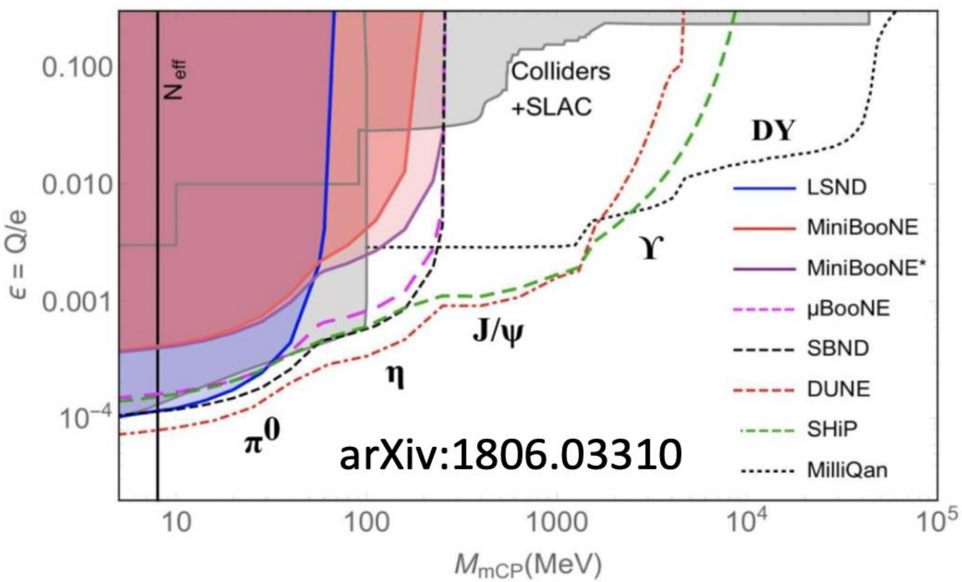
Neutrino Experiments Near Detectors

High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



Near Detectors are ~475 m away from target

Such experiments can perform searches for low mass New Physics particles
Example: Searches for millicharged particles
- Particles with a charge << electron charge
- Eg from "dark QED" through kinetic mixing with SM QED
- detect in LArTPC via electron scattering
<- Initial sensitivity study



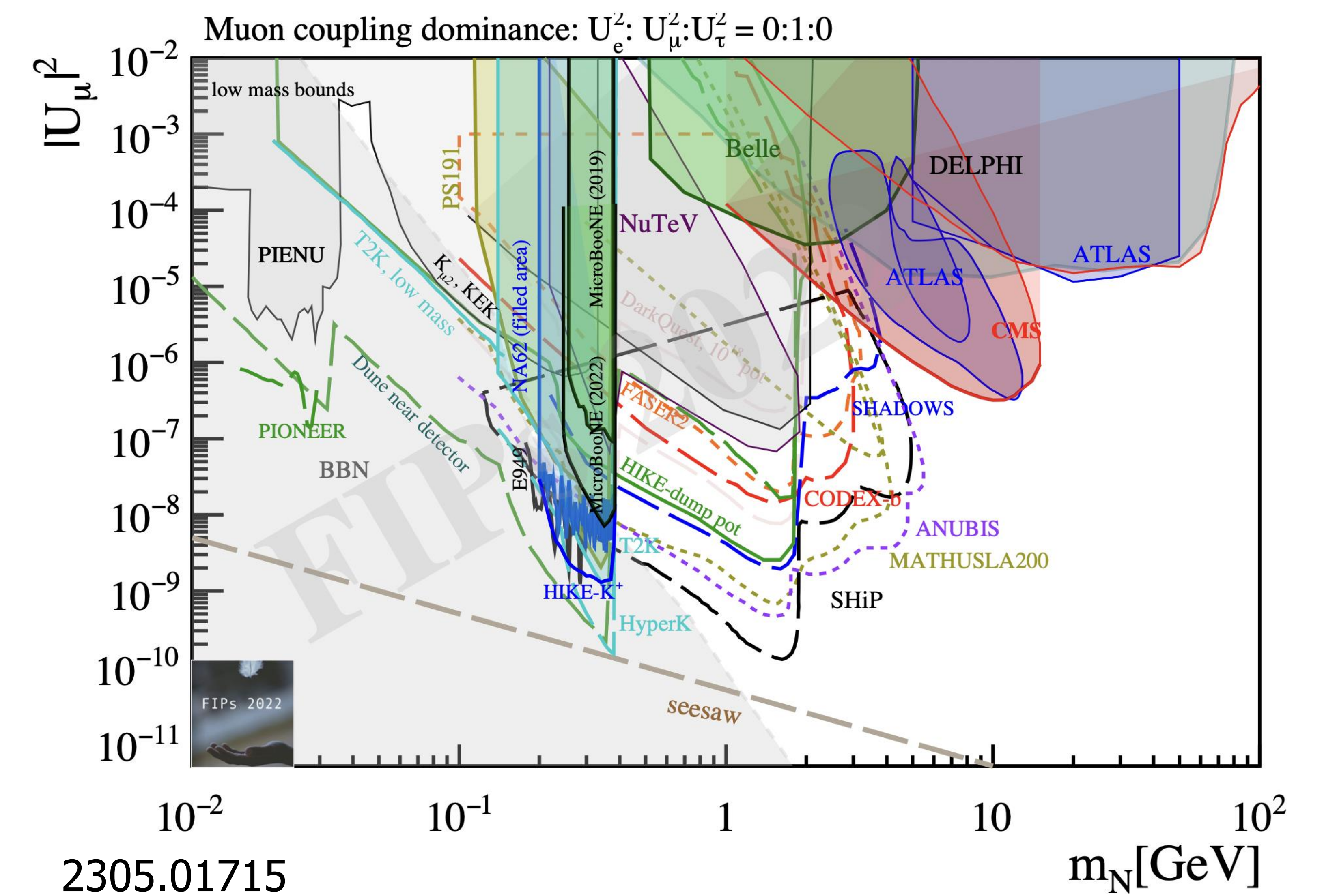
White Paper on New Opportunities at the Next-Generation Neutrino Experiments
(Part 1: BSM Neutrino Physics and Dark Matter)

C.A. Argüelles[1], A.J. Aurisano[2], B. Batell[3], J. Berger[3], M. Bishai[4], T. Boschi[5], N. Byrnes[6], A. Chatterjee[6], A. Chodos[6], T. Coan[7], Y. Cui[8], A. de Gouvêa[* 9], P.B. Denton[4], A. De Roeck[* 10], W. Flanagan[11], D.V. Forero[12], R.P. Gandrajula[13], A. Hatzikoutelis[14], M. Hostert[15], B. Jones[6], B.J. Kayser[16], K.J. Kelly[16], D. Kim[17], J. Kopp[10,18], A. Kubik[19], K. Lang[20], I. Lepetic[21], P. Machado[16], C.A. Moura[22], F. Olness[6], J.C. Park[23], S. Pascoli[15], S. Prakash[13], L. Rogers[6], I. Safa[24], A. Schneider[24], K. Scholberg[25], S. Shin[26,27], I.M. Shoemaker[28], G. Sinev[25], B. Smithers[6], A. Sousa[* 2], Y. Sui[29], V. Takhistov[30], J. Thomas[31], J. Todd[2], Y.-D. Tsai[15], Y.-T. Tsai[32], J. Yu[* 6], and C. Zhang[4]

arXiv:1907.08311

Physics Beyond Colliders

Example: Heavy Neutral Leptons



2305.01715

Summary

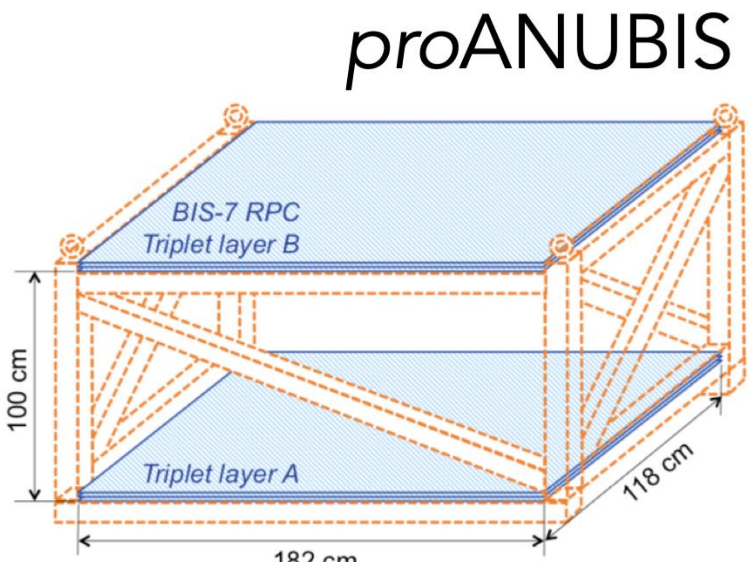
- Clearly and increased interest in low mass/coupling and LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. No signal observed yet; only top of the iceberg covered so far.
- New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, MAPP, MATHUSLA, CODEX-b, AL3X, ANUBIS, FACET, FPF…. LLPs also focus in the "Physics Beyond Collider" studies.
- New: FASER & SND@LHC: Ready and are taking data
- MilliQan: demonstrator works ->now several other proposals
- Several proposals for facilities at the high intensity frontier, and first studies for facilities at future colliders
- If we would observe one significant anomaly …

Backup

Possible backgrounds & Demonstrator

Laboratoire de Physique de Clermont

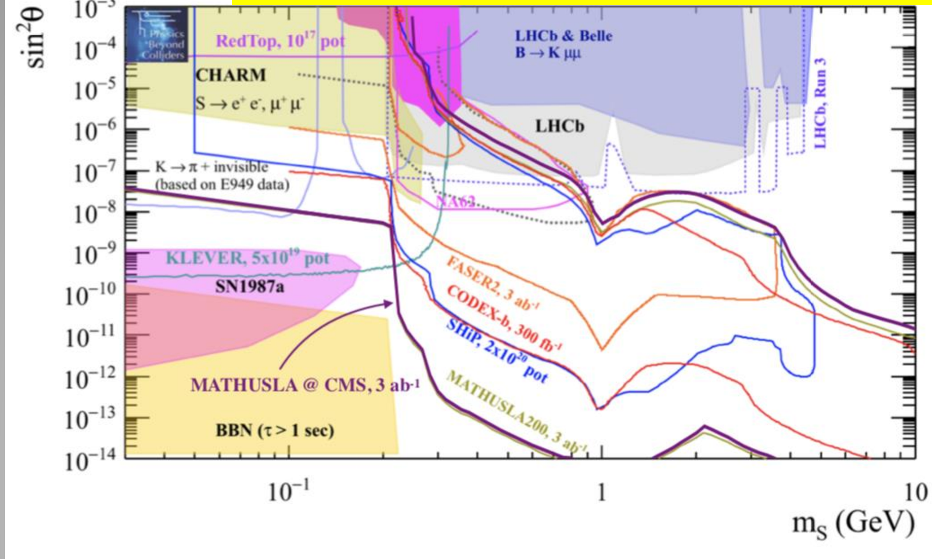
- Neutron-air interactions, kaon decays and interactions: sources of background Likely controllable from collimated pairs of charged tracks. But need to validate background model in-situ... Calls for a prototype!



- Most exciting: proANUBIS prototype is current IN THE CAVERN and being commissioned! Watch this space for exciting results and validation of ANUBIS proof of concept!

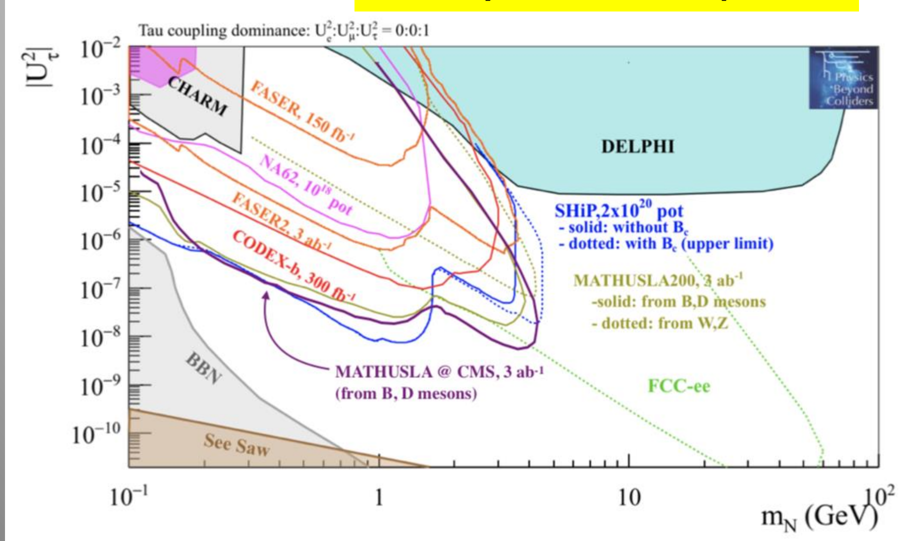
More Example Processes

Singlet Scalar mixing with Higgs

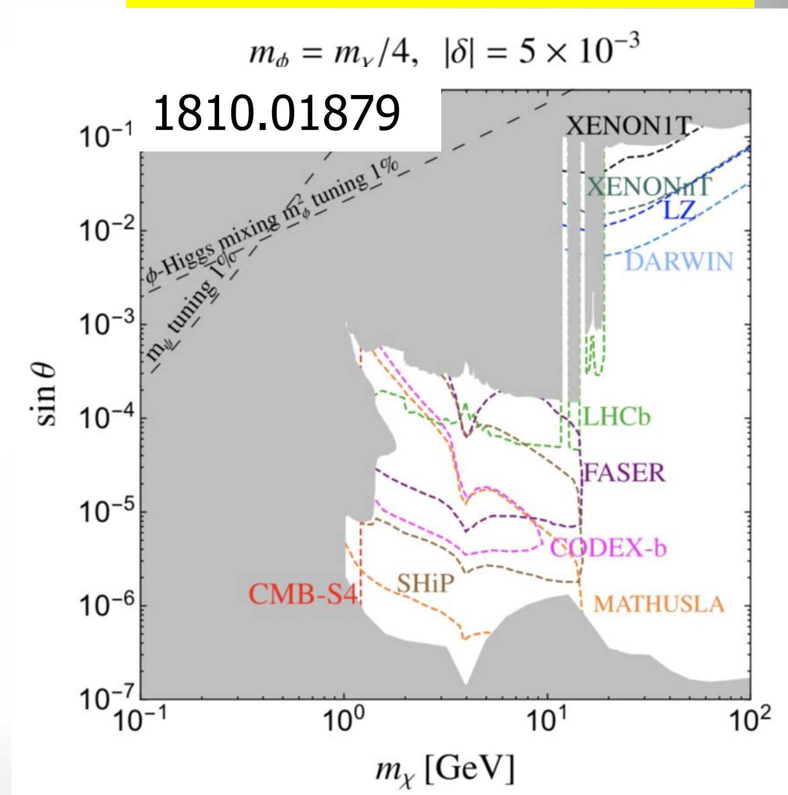


2009.01693

Heavy neutral leptons



Inelastic Dark Matter Model



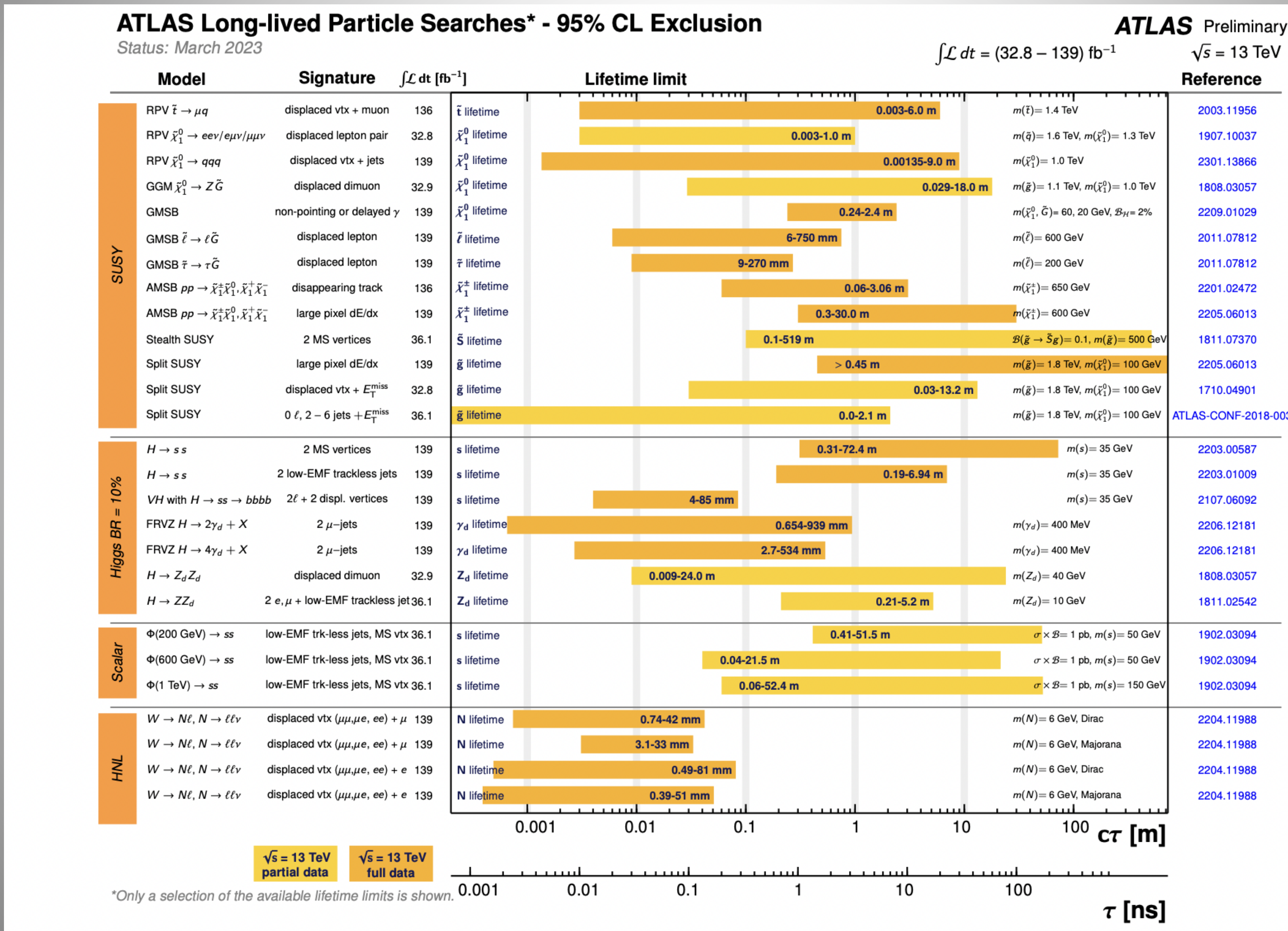
Long-Lived Particles

New physics vs. Long-Lived Particle causes

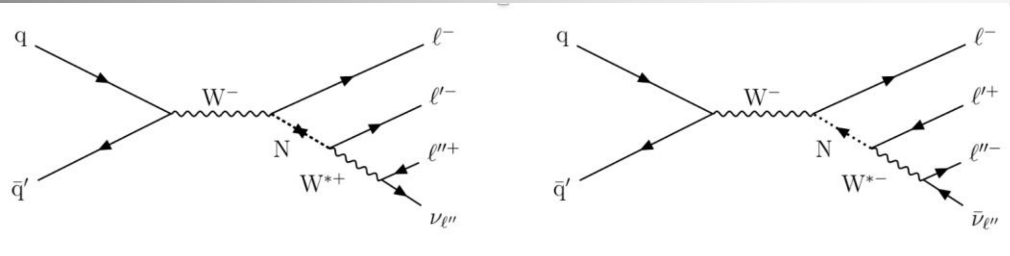
1810.12602

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

Long-Lived Particle Overview



Search for Long Lived Leptons (HNL)



Search for long-lived
heavy neutral leptons (HNLs)

arXiv:2201.05578

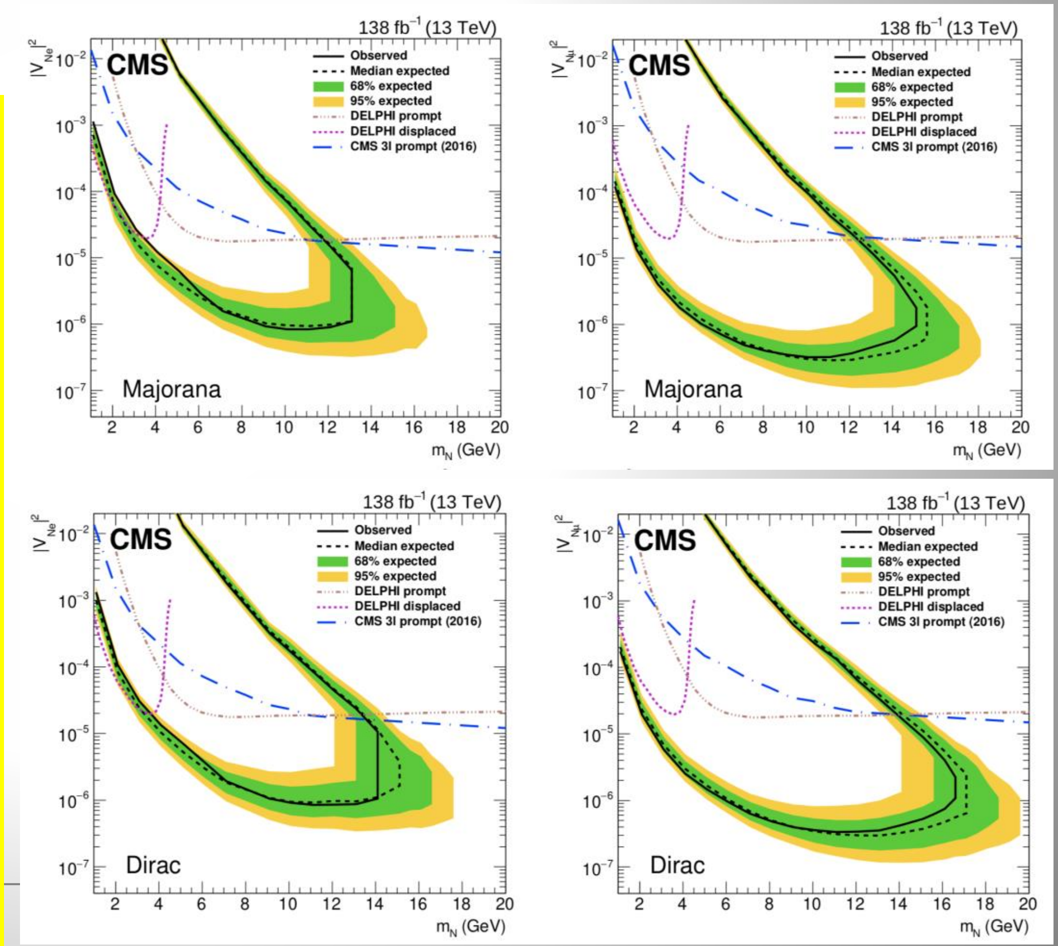
HNLs produced through mixing with SM neutrinos in final state of 3 charged leptons + a neutrino

Low mass HNLs are long lived

$$\tau_N \propto m_N^{-5} V_{Nl}^{-2}$$

Search for 3 leptons; two form a displaced vertex

Different sensitivities for Dirac and Majorano neutrinos



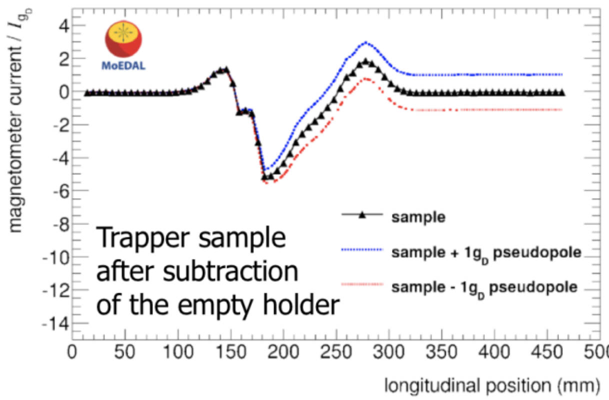
Magnetometer Measurements

Laboratory of Natural Magnetism, ETH Zurich

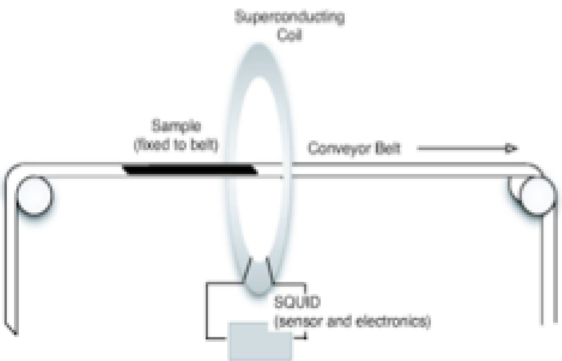
Magnetically shielded room

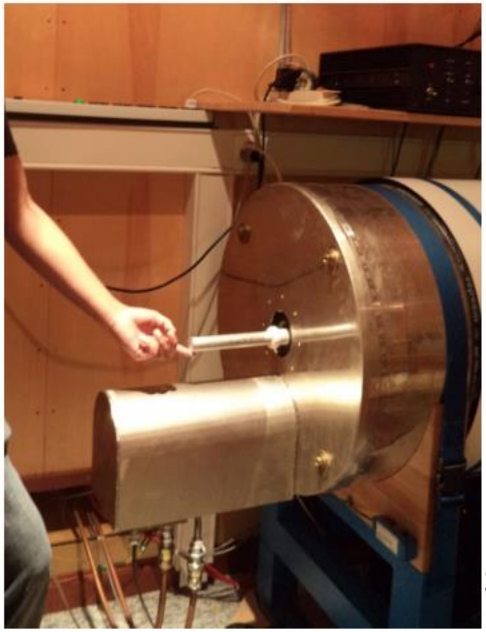
DC-SQUID magnetometer

->Detection Method: Measure a persistent current induced in the superconducting coil of a sensitive SQUID magnetometer



A DC-SQUID rock magnetometer (2G Enterprises model 755)

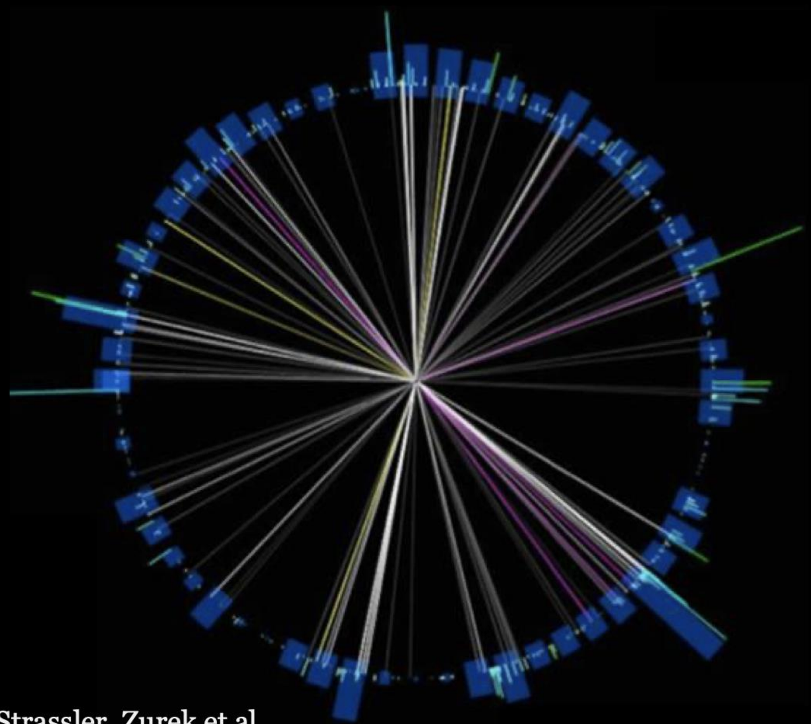


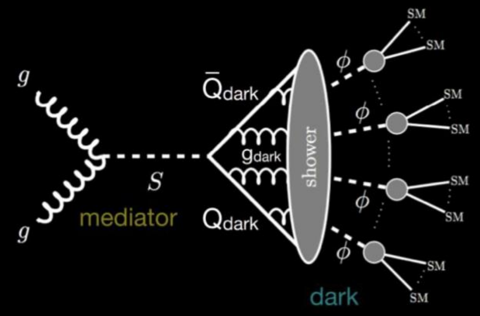


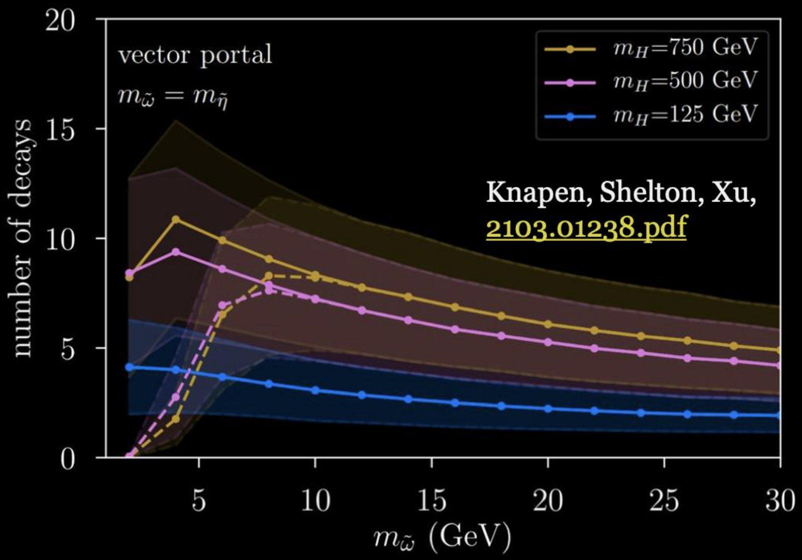
Still lot's of channels/ideas to be explored

E.g. Searches for dark Showers

More generally, dark showers in various forms







Knapen, Shelton, Xu, 2103.01238.pdf

e.g., Strassler, Zurek et al,
Knapen, Pagan Griso, Papucci, Robinson, 1612.00850
Pierce, Shakya, Tsai, Zhao, 1708.05389
Recent development could help catching certain dark showers
Cesarotti, Thaler, 2004.06125, Cesarotti, Reece, Strassler, 2009.08981

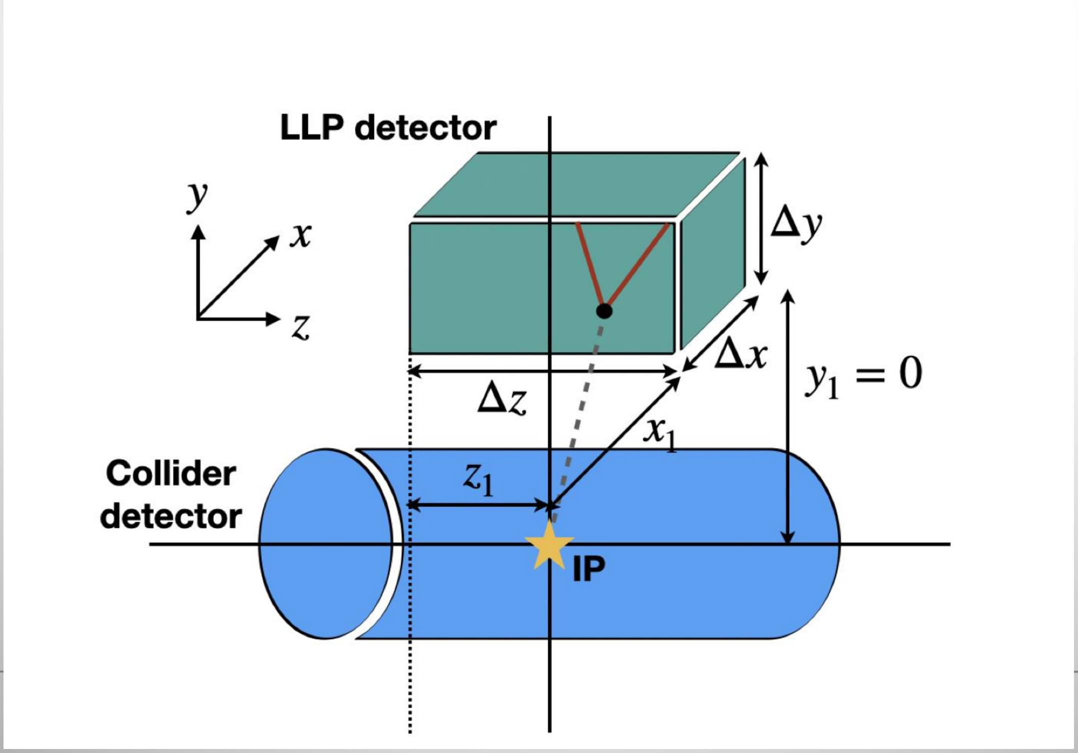
Search for: Emerging jets, semi-visible jets, soft unclustered energy patterns…

DELIGHT: Several Options

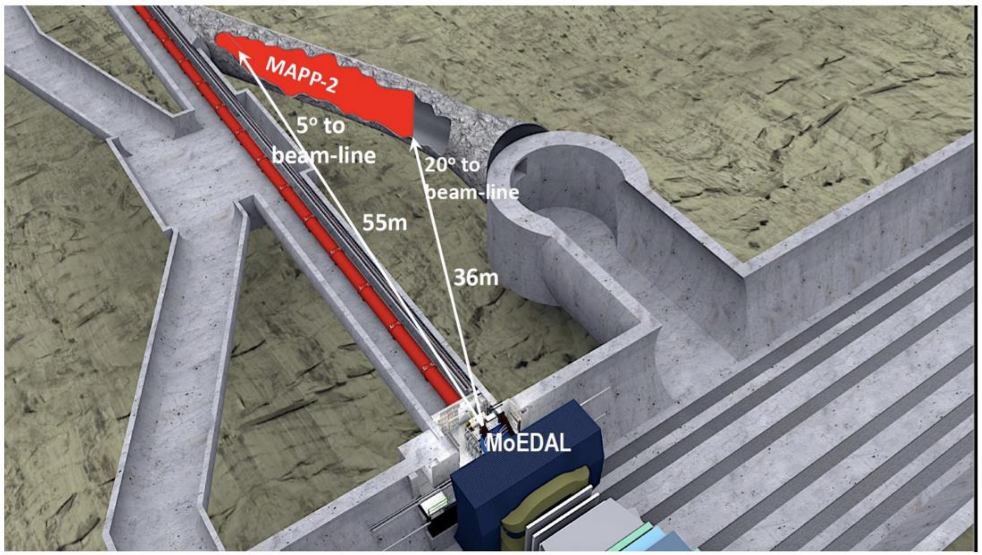
DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

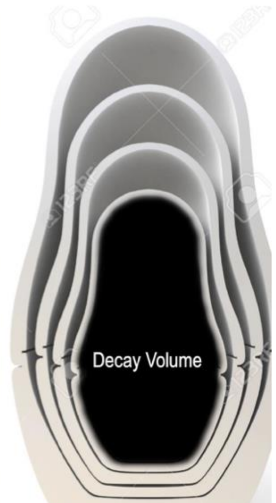
DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (C): Twice the same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

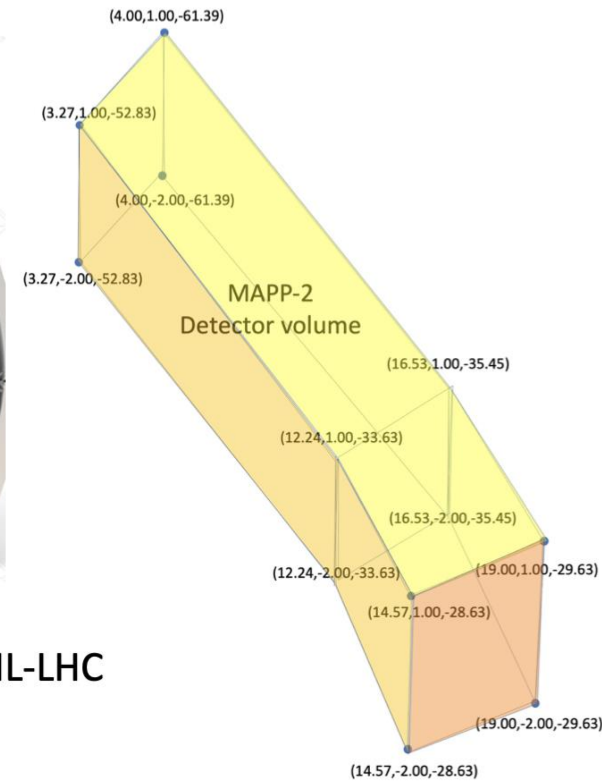


Phase-2: MAPP-2 upgrade for HL-LHC





"Russian doll" configuration
of scintillator walled boxes

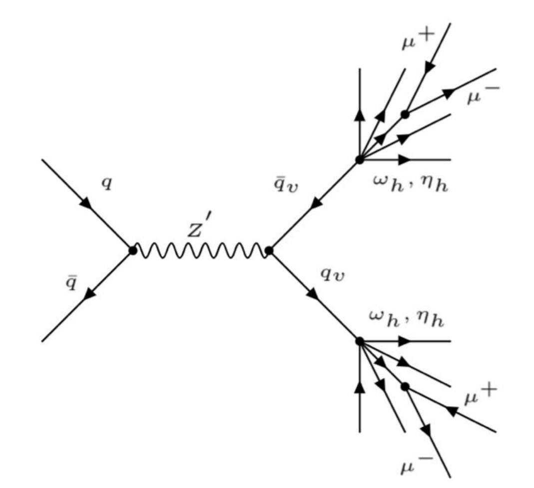


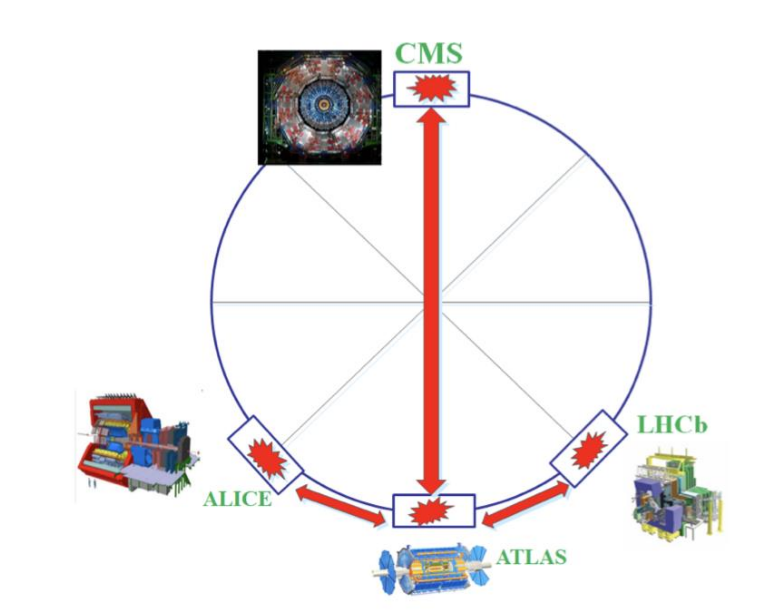
- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery
- Detector technology: large scintillator tiles with optical-fibre readout
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining UGC1 walls

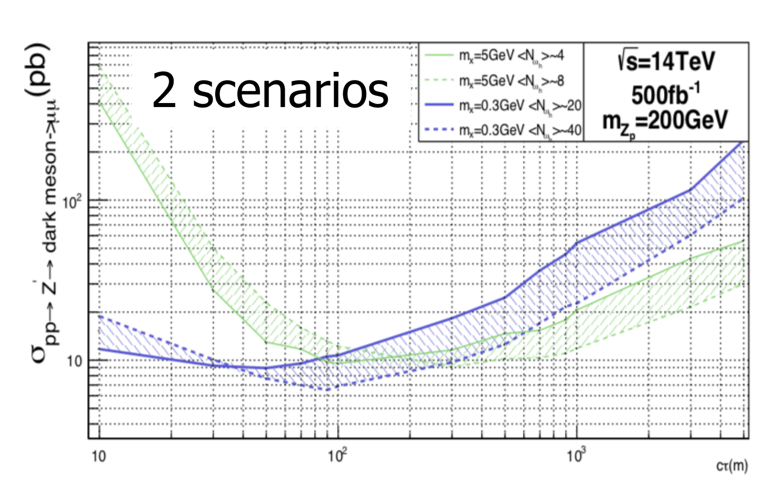
A Wild Idea?

2004.08820

- LLPs can escape the detector at the collision point and accidentally decay in the vicinity of detectors far away. Spooky?
- Estimates using ATLAS and ALICE for (favourable) Hidden Valley scenario, detecting the muons..





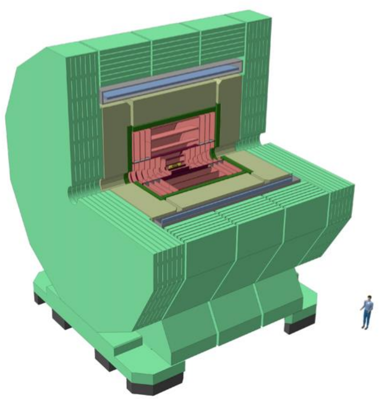


Detectors at the FCC-ee

A few detector concepts being used for integration, performance, and cost estimates:

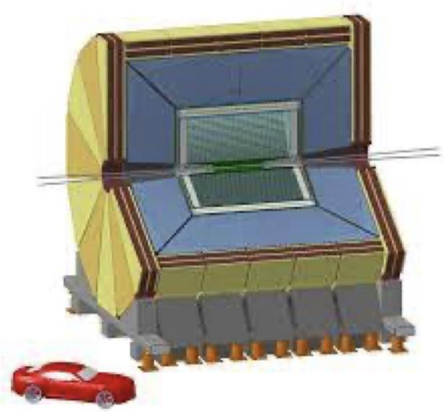
CLIC-like Detector (CLD)

- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter



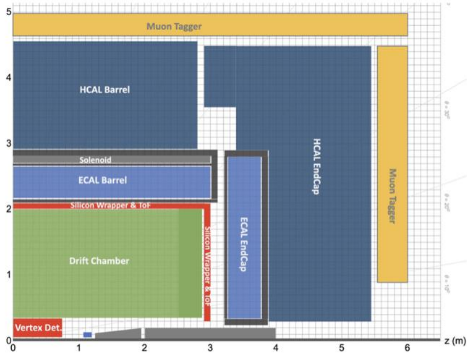
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



Noble Liquid

- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal



Have the opportunity to design general-purpose detectors with LLPs in mind!

- Can prioritize e.g. displaced tracking and precision timing information
- Can also prioritize LLPs in the online filtering and offline reconstruction

HNL production sources

- FCC-ee: Z-mediated production, no advantage to go to b decays
- FCC-hh:
  - $\times 30$ b (1.5×10^{17}) and $\times 120$ W compared to HL-LHC
  - plenty of time to think how to best exploit these sources
  - estimates:
    - use distributions and predictions from PYTHIA8 and FONLL for heavy flavor and W bosons production
    - take 100% signal efficiency in visible decay channels
    - compute only signal rate (no background estimate)

Feebly Interacting Particles FIPs

…Spin-off of the PBC forum…

https://indico.cern.ch/event/1119695/

This year the Workshop will be organized along three main directions:

1. MeV-GeV Dark Matter and its searches at accelerator, direct and indirect detection experiments;
2. Heavy neutral leptons and their connection to active neutrino physics;
3. Ultra-light (< 1 eV) FIPs in particle physics, astroparticle, and cosmology.

Forward Production

Physics Program

- Searches for new physics: light weakly interaction new partices, detected through decay or scattering
- Neutrinos produced in LHC collisions: the highest neutrino energies in the lab!
- QCD: low-x proton structure