Searches for Long Lived Particles Present and Future

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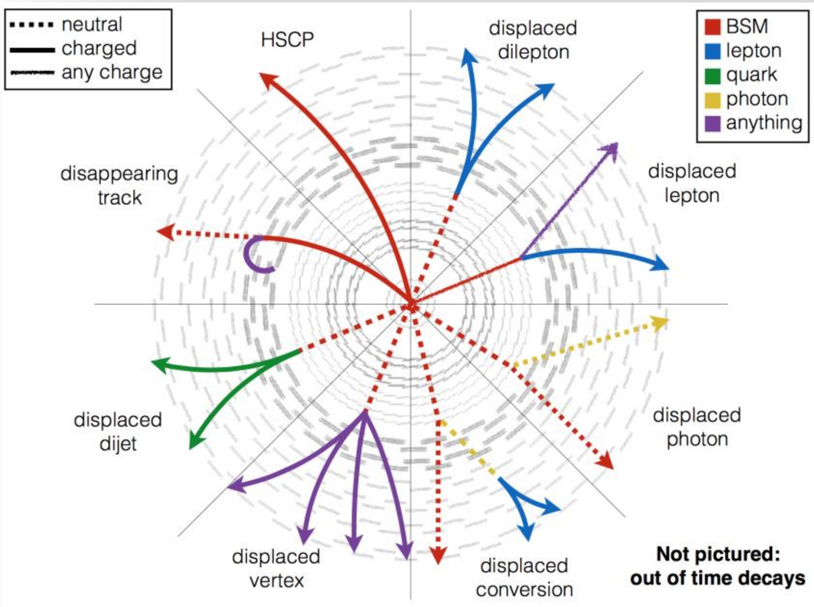
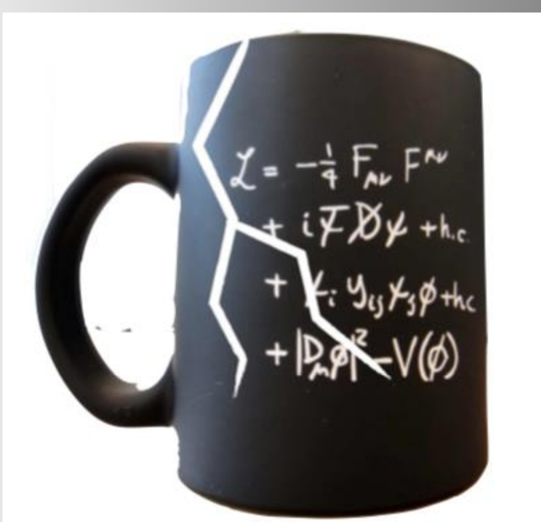
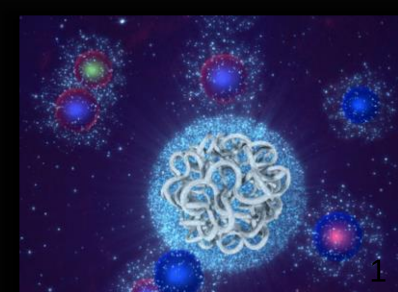


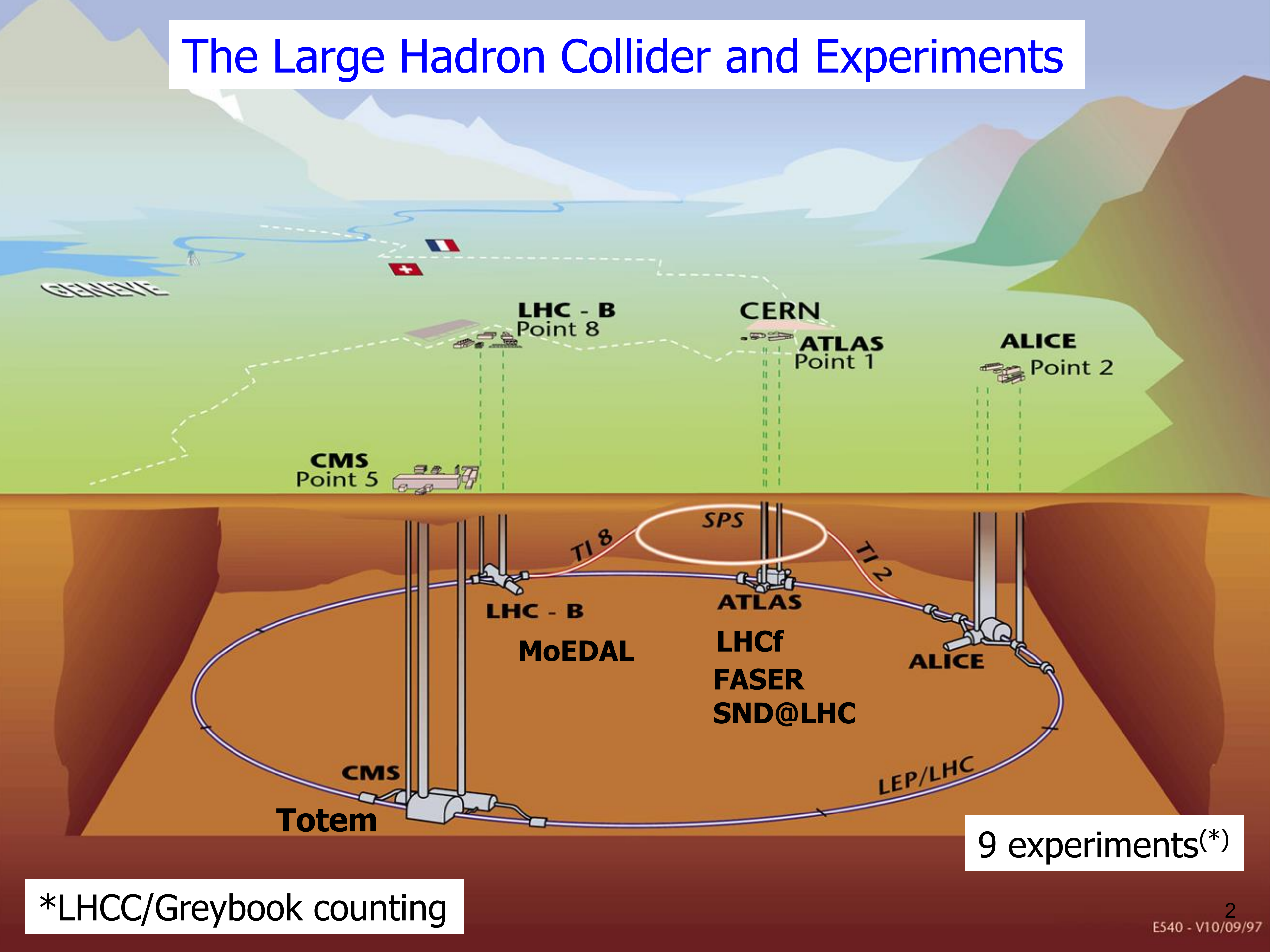


Outline

- Introduction: Long Lived Particles
- Long Lived Particle searches at the LHC
- Proposals for new experiments at the LHC
    - Transverse experiments
    - Forwards experiments
- Non-collider opportunities
- (Future Colliders)
- Summary/Outlook



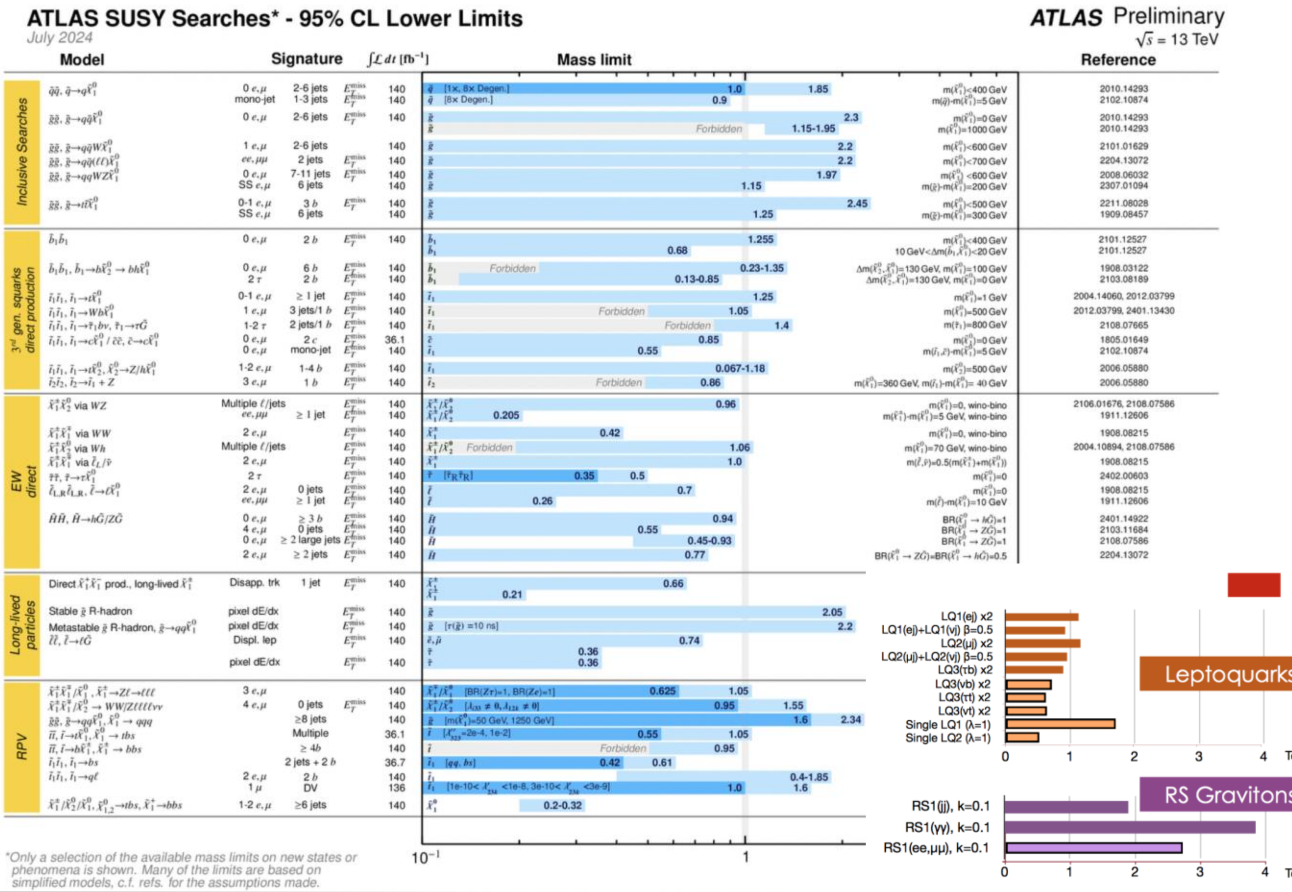
The Large Hadron Collider and Experiments



9 experiments(*)

*LHCC/Greybook counting

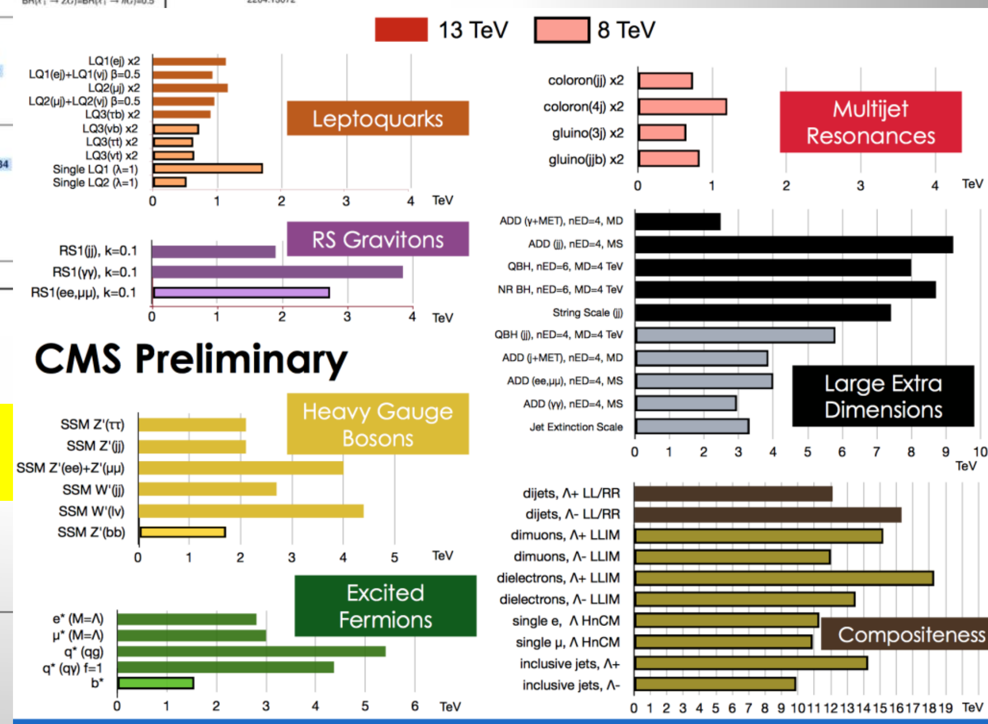
LHC: So far no New Physics



Classical Searches
-Superymmetry
-Exotica
-Flavor Universality
-…

No signal of new physics so far!!

LFU "violation" $R_{K(*)}$ went away ☹



Are we leaving no stones unturned?

- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
- But are we looking at the right place and do we leave not stones unturned? -> Recent focus on long lived particles
- Time for more effort in thinking of complementary searches: -> What could the LHC miss with the present detectors?

Are we looking at the right place?

Leave no stone unturned!!

Long lifetimes in the BSM world

Small couplings
e.g. R-parity violating SUSY

Limited phase space
e.g. compressed SUSY scenarios

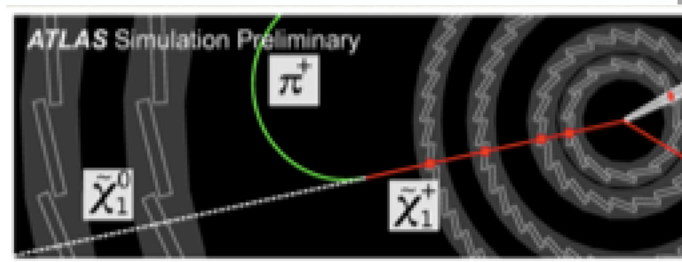
Decays via heavy particle
e.g. heavy neutrinos

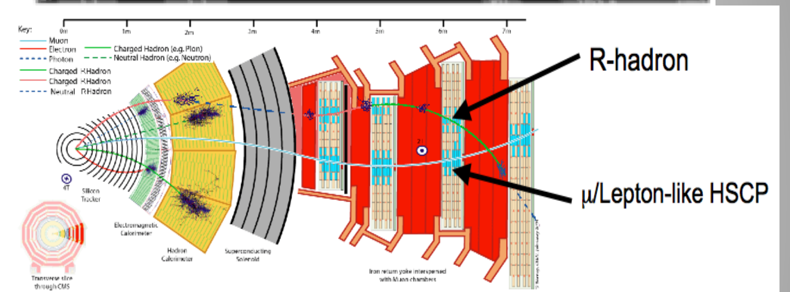
Any model with small couplings, small mass splittings, or decays via off-shell particles can result in long lived particles (LLPs)

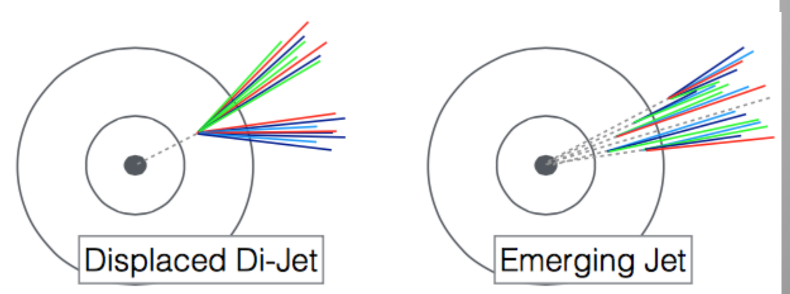
Long Lived Particles

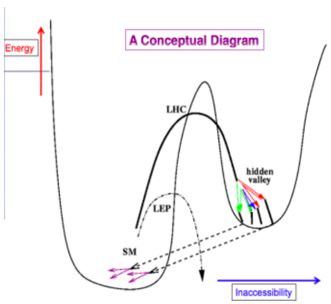
Long lifetimes arise from a hierarchy of scales or a small coupling

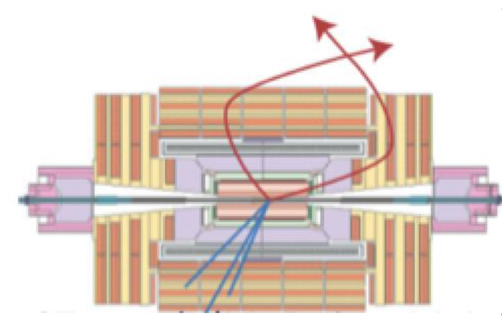
- RP Violating SUSY
- AMSB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Magnetic monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ….



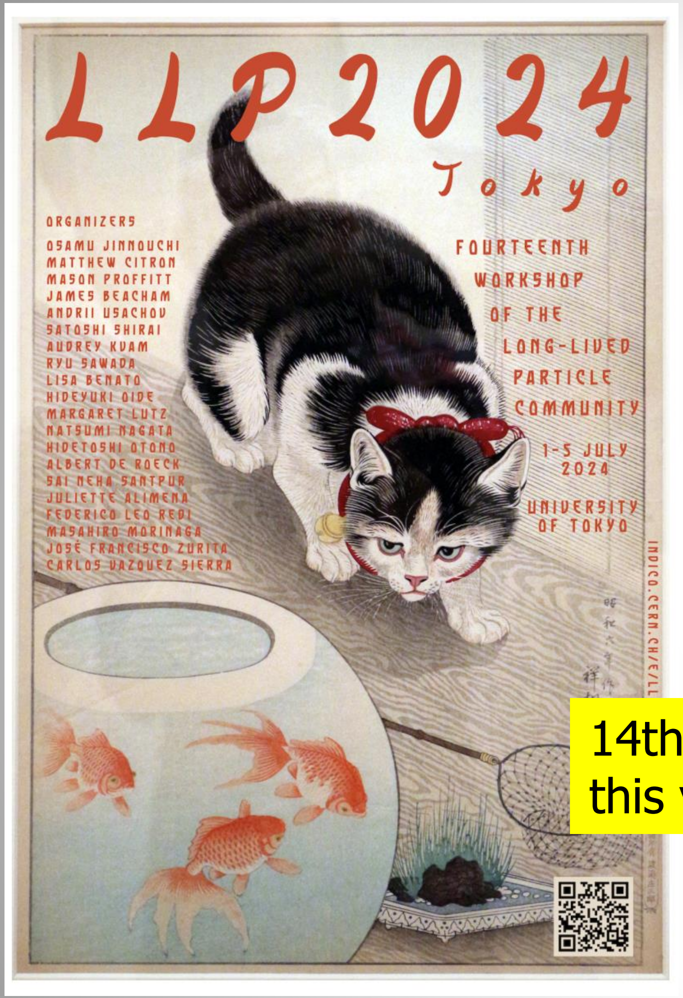








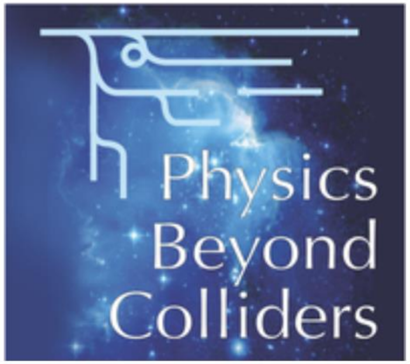
LLP Community Workshops



14th workshop this year

https://indico.cern.ch/event/1381368/

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



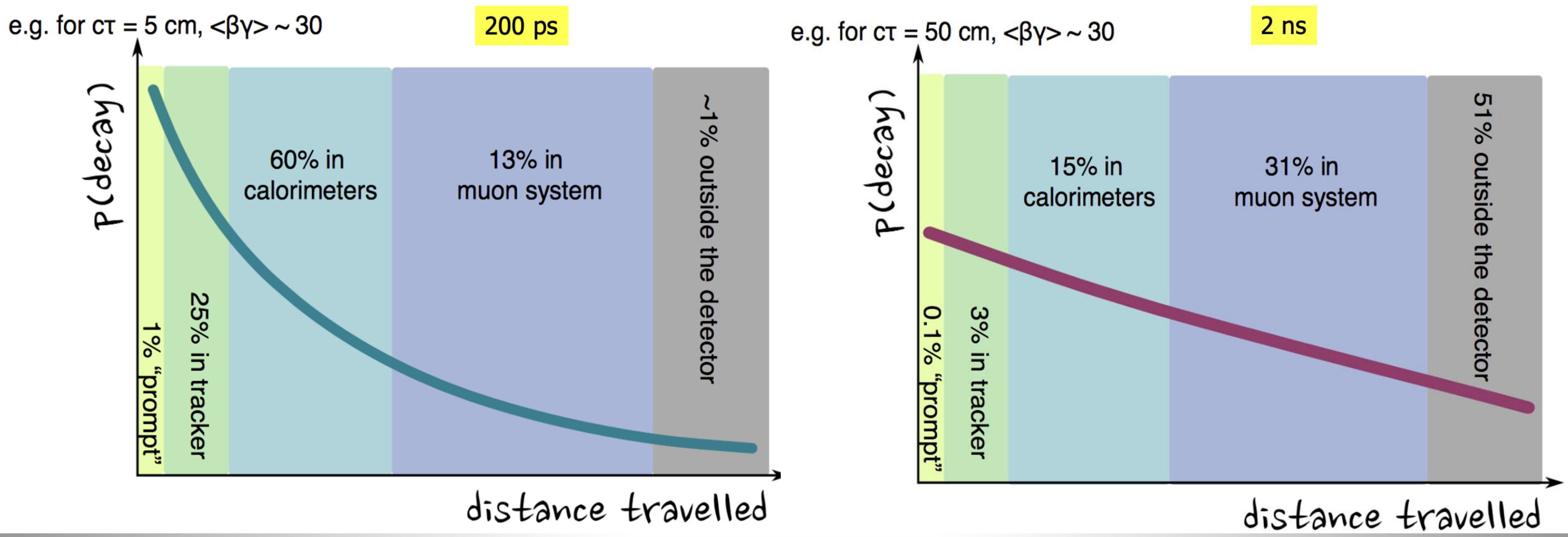
Physics Beyond Colliders Study Group

e.g. https://indico.cern.ch/event/1369776/

LLP Community White Paper: arXiv:1903.04497

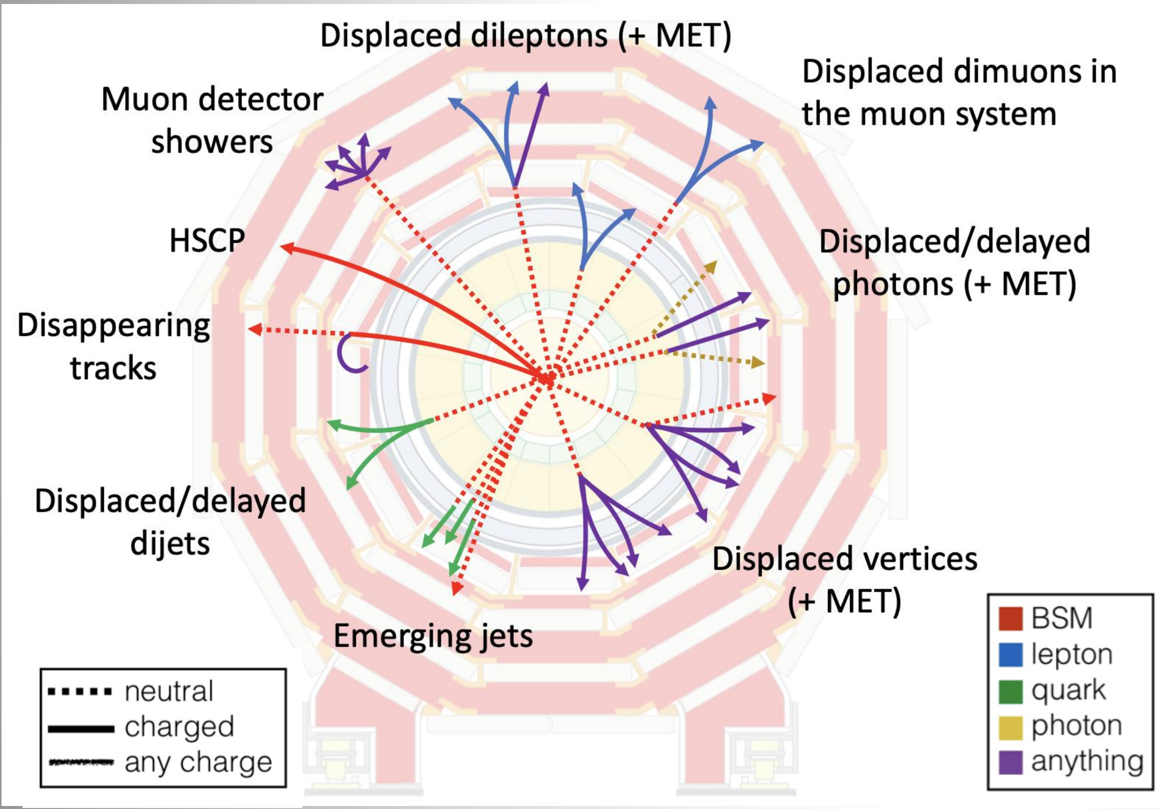
Long Lived Particles @ LHC

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



Long Lived Particles @LHC

Signatures



Some of the Challenges

Triggers: Tracking detectors are powerful but difficult to use in trigger

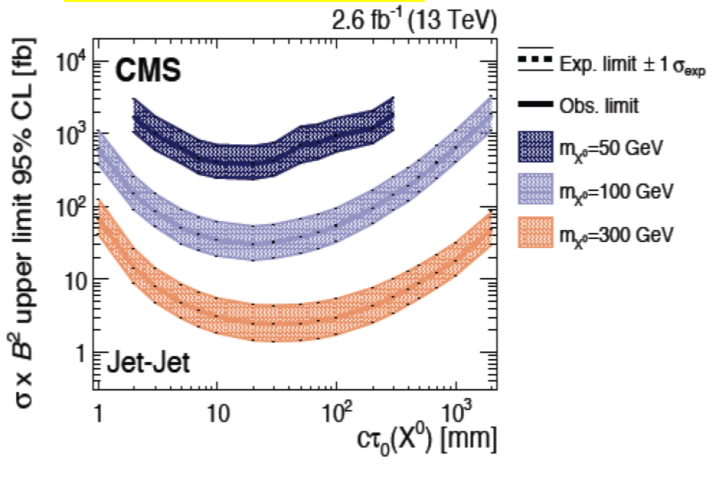
SM backgrounds often low. But need special studies (punch through, secondary interactions, tails, cosmics…)

Special reconstruction is often needed

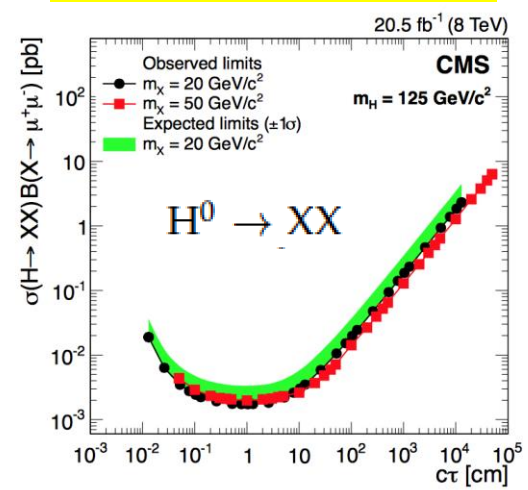
Some detector upgrades for High-Luminosity LHC (>2029) address these issues.

Long Lived Searches: Examples

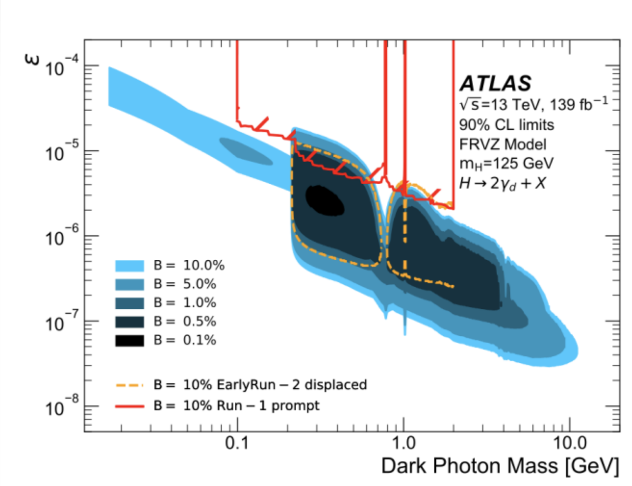
displaced jets



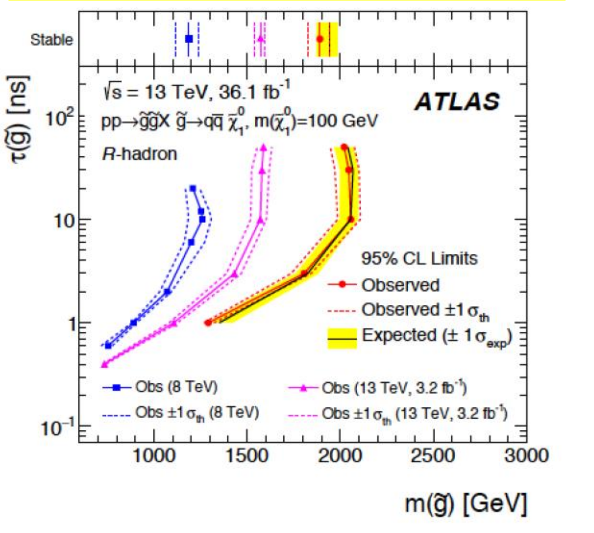
displaced leptons



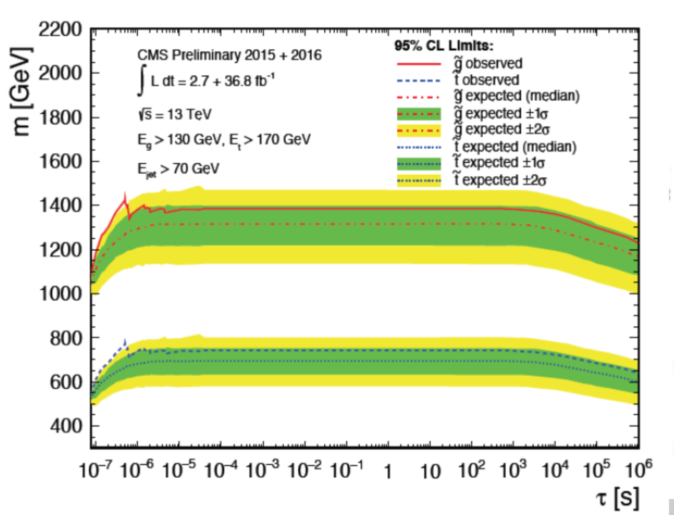
dark photons



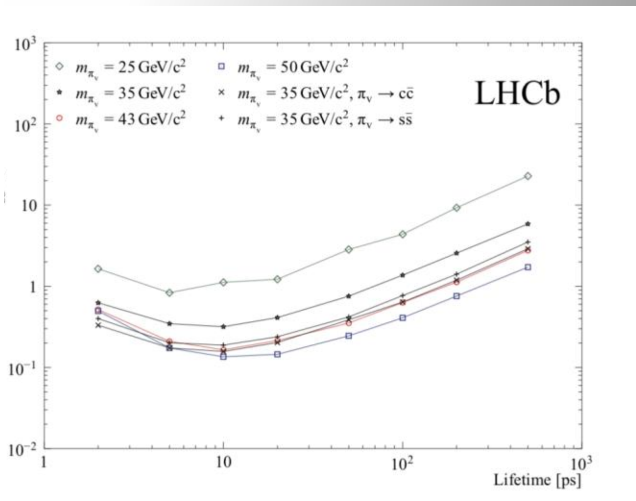
metastable R-hadrons



stopped particles

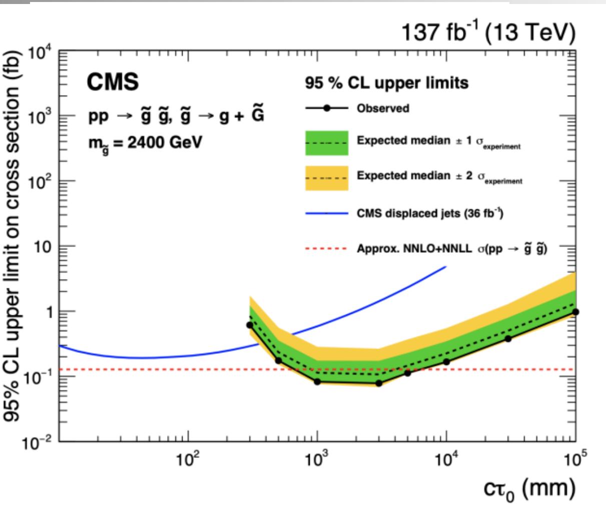


Hidden Valley searches

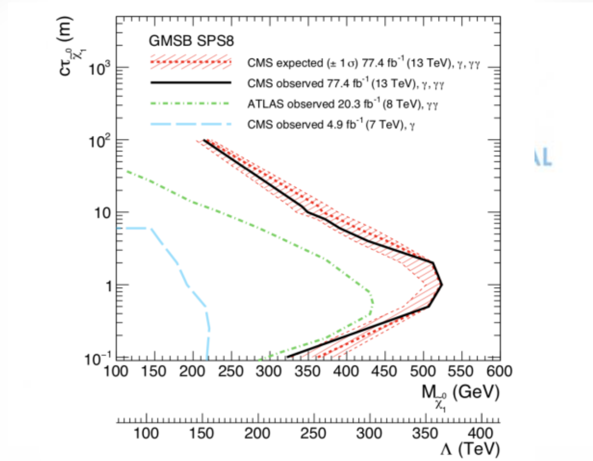


Long Lived Searches: Examples

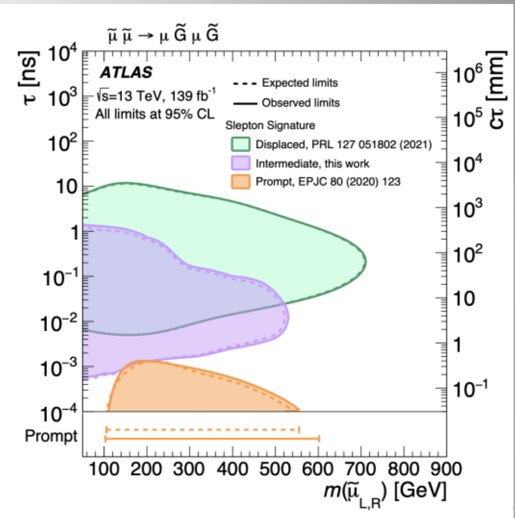
delayed jets



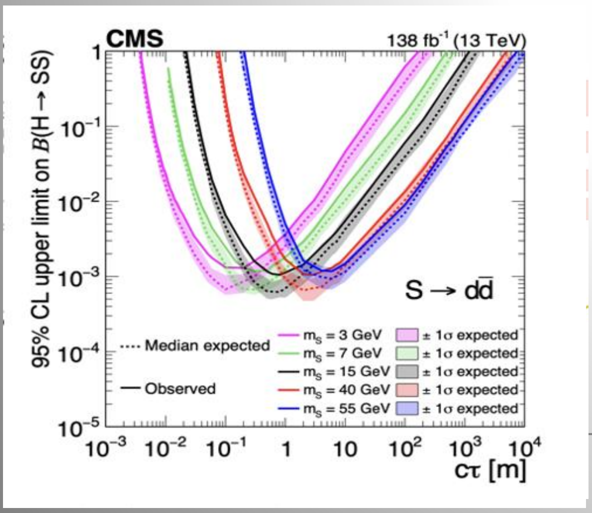
displaced photons



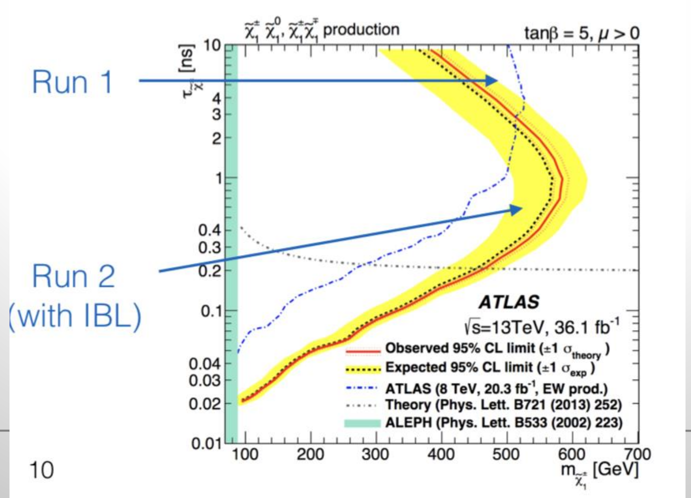
Small displacements



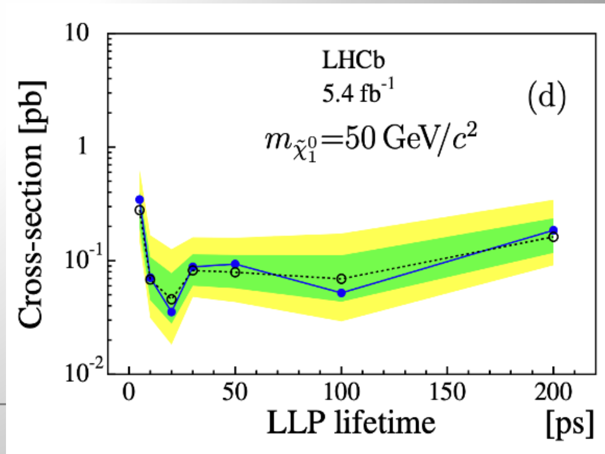
LLPs in muon system



Disappearing tracks



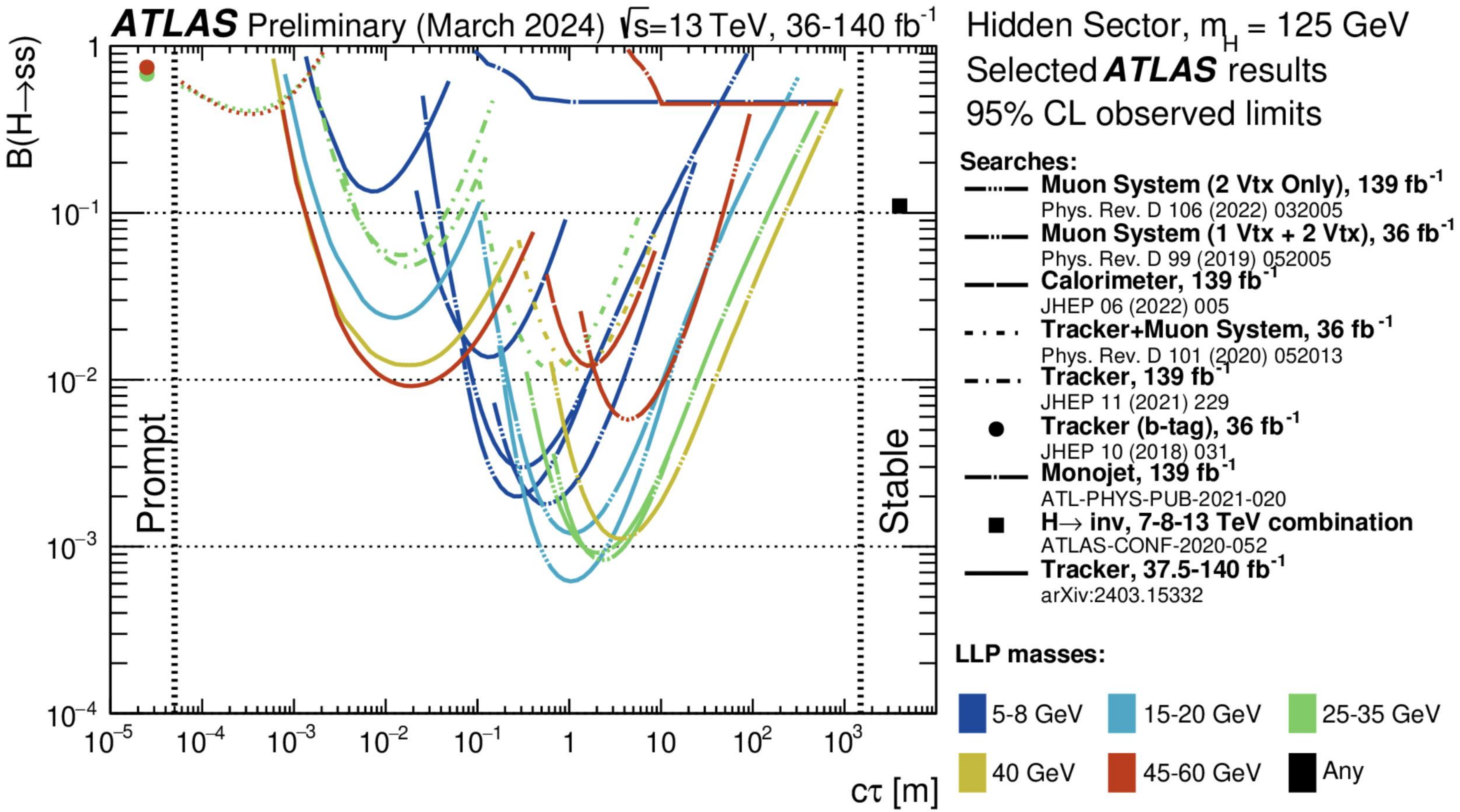
RPV searches



Developments @ LHC Analyses

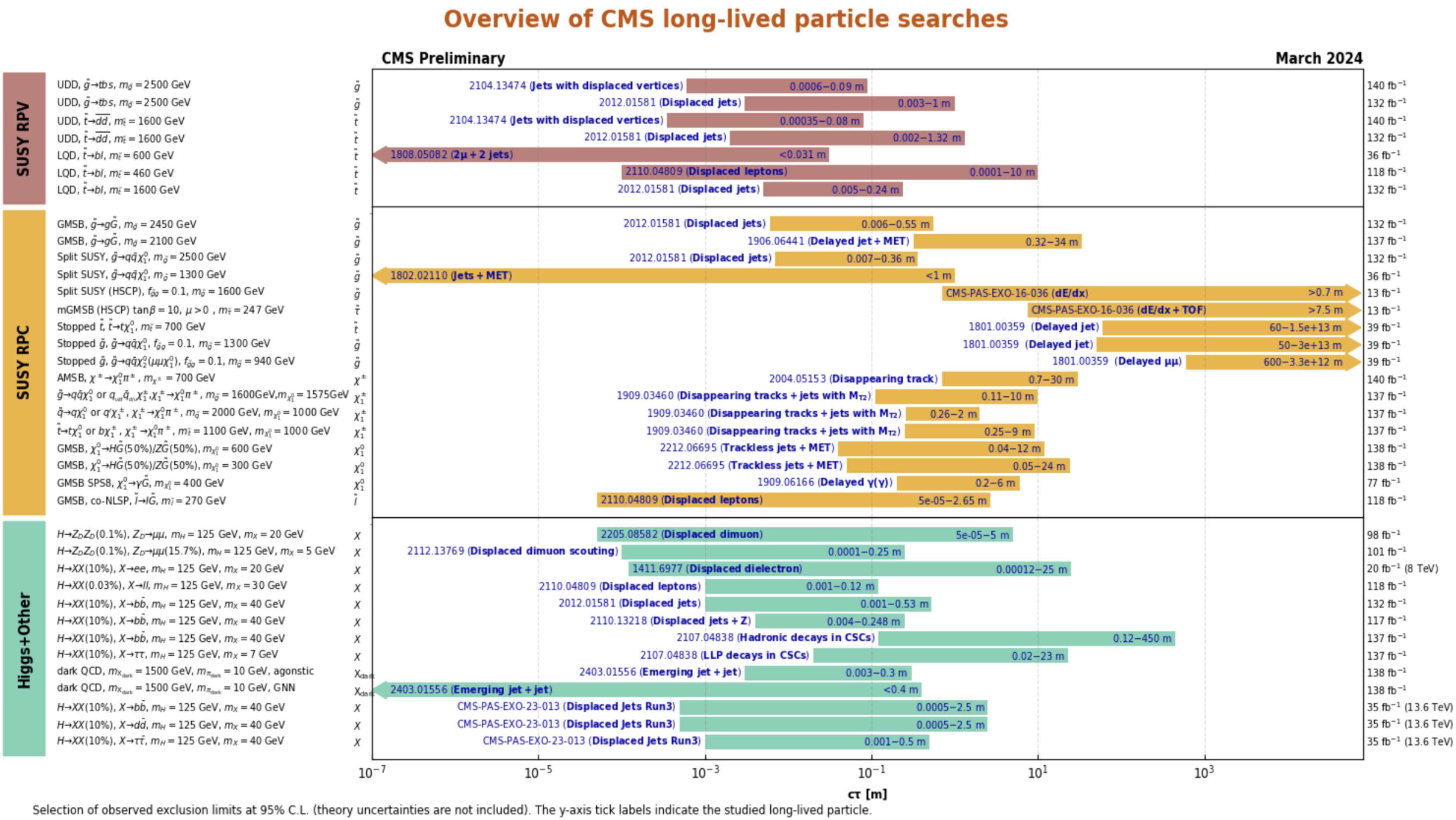
- Triggers improvements:
  - Examples LHCb software trigger, displaced objects, timing, … (see eg:2210.14675)
- Data collection improvements
  - Scouting of data & data parking techniques
- Analysis improvements
  - Better use of the detector capabilities, timing, LLP search in all subsystems eg muon 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

LLP Summary Plot for Hidden Sector Models



95% CL exclusion limits on Higgs branching to a pair of spin-0 LLPs

Long-Lived Particle Overview



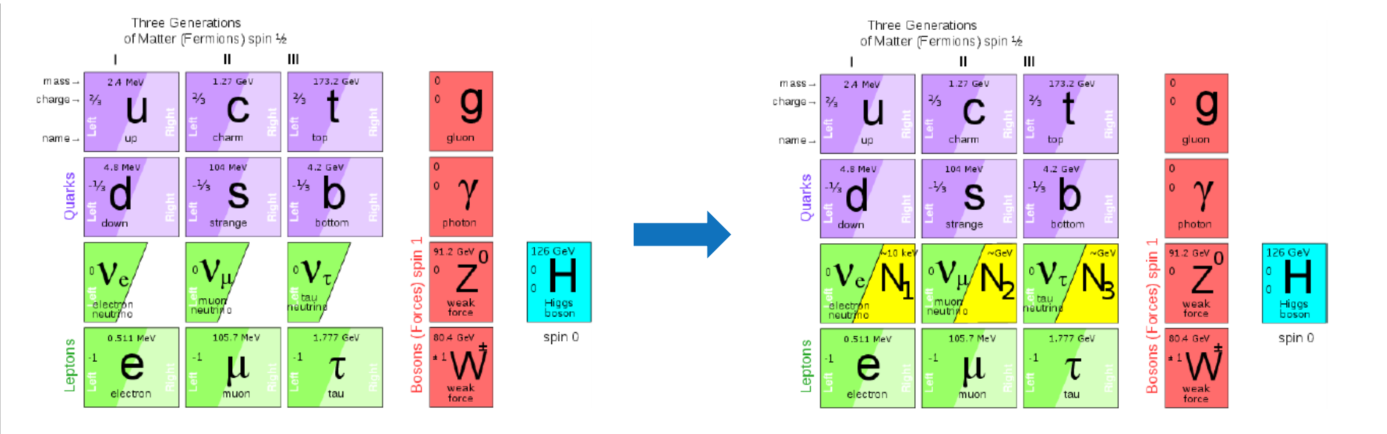
Some recent results wil be covered in talks by G. Landsberg, Alex Oh., Andrea Perrotta…

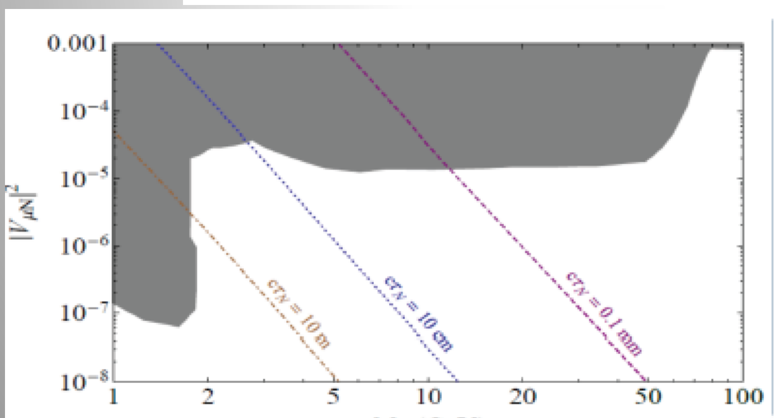
Example: Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

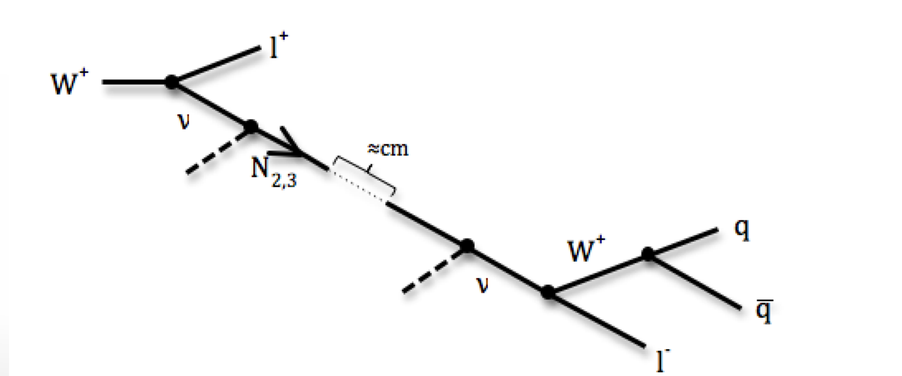
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3

Addresses the masses of neutrinos, baryon asymmetry and dark matter



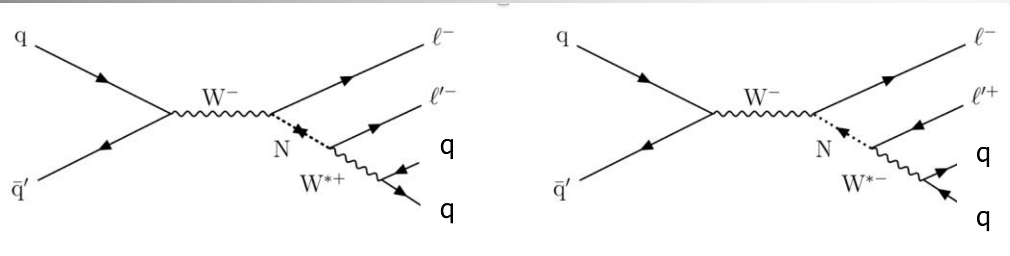


D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015



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

Search for Long Lived Leptons (HNL)



Search for long-lived heavy neutral leptons (HNLs)

arXiv.2312.07484

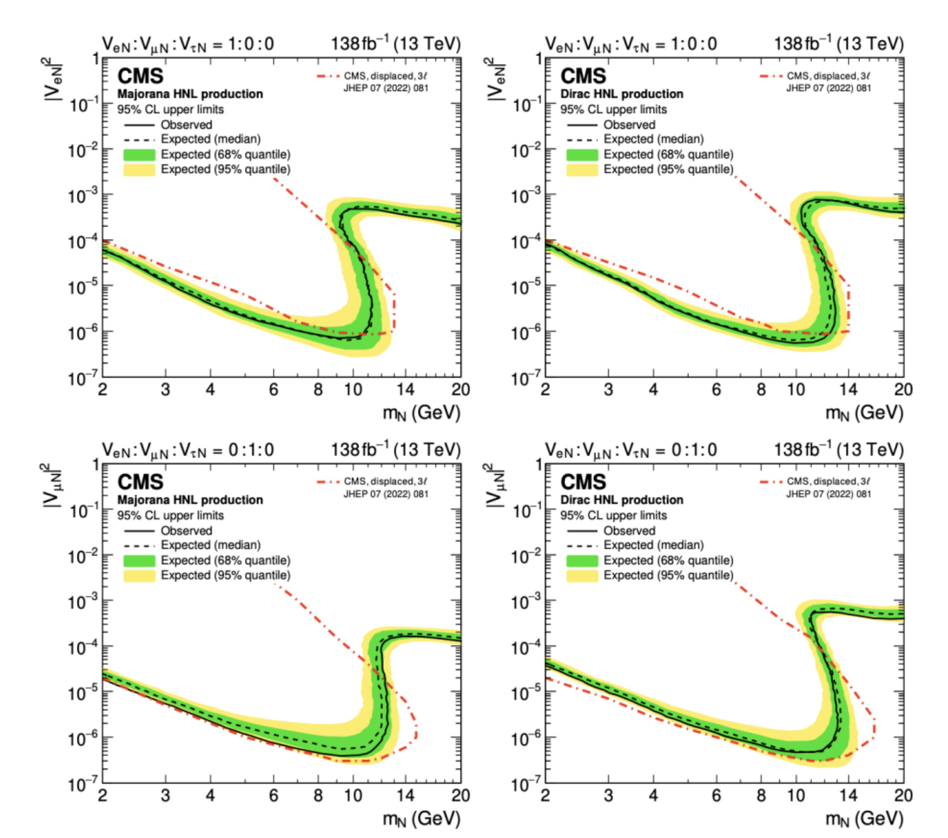
HNLs produced through mixing with SM neutrinos in final state of 2 charged leptons + 2 jets

Low mass HNLs are long lived

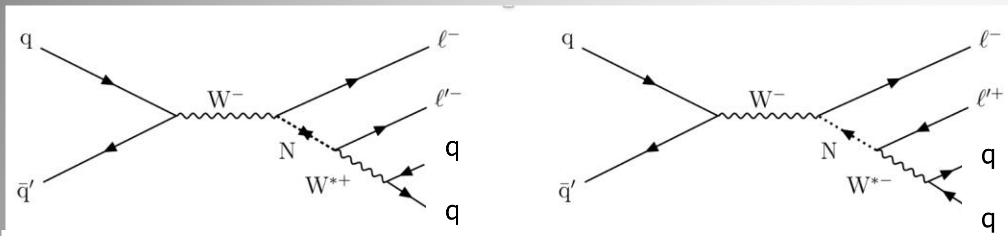
$$\tau_N \propto m_N^{-5} V_{Nl}^{-2}$$

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

Different sensitivities for Dirac and Majorano neutrinos

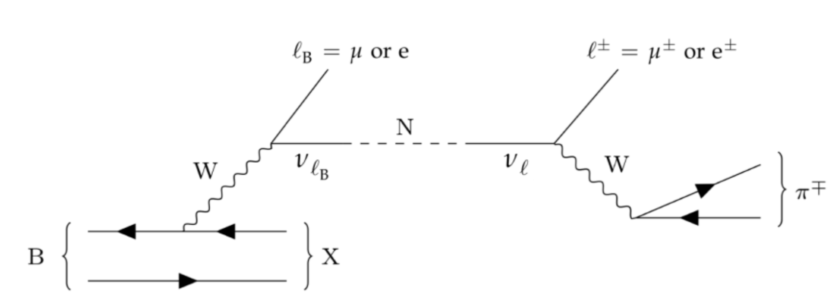


Search for Long Lived Leptons (HNL)

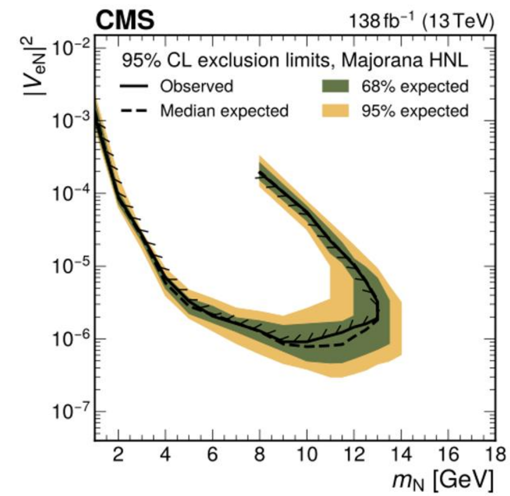


Search for long-lived heavy neutral leptons (HNLs)

Jets+lepton displaced vertex

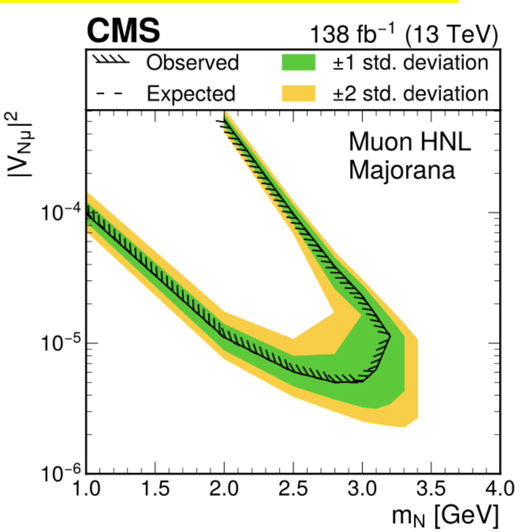


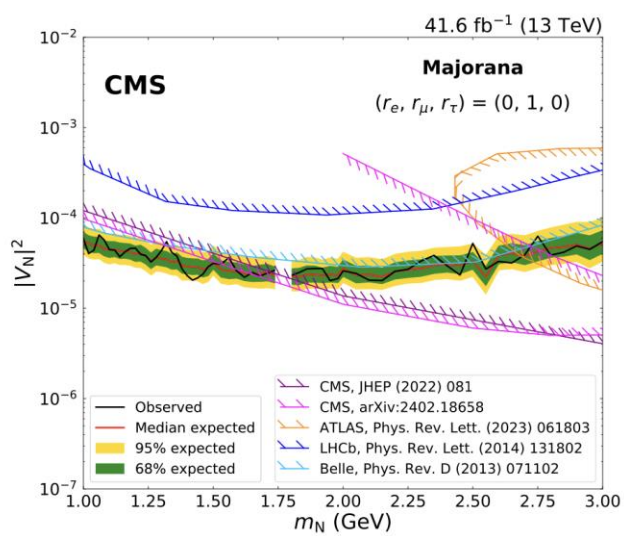
arXiv.2407.10717
arXiv.2402.18658
arXiv.2403.04584

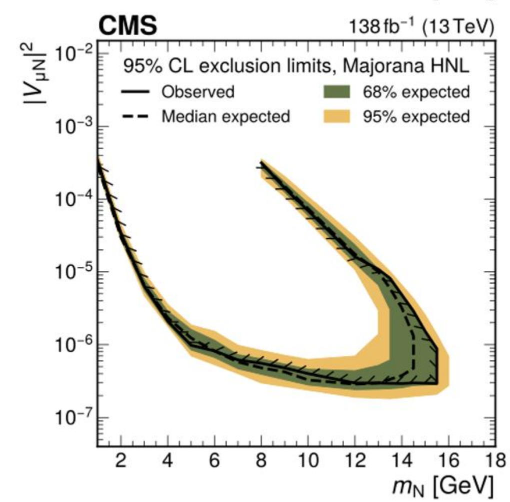


HNLs decaying in Muon system

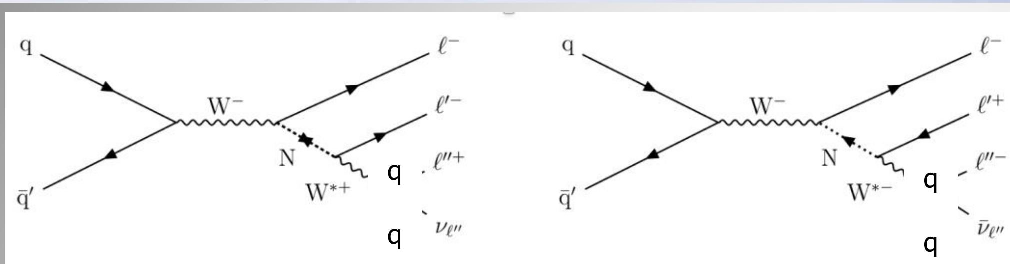
HNLs from b-quark decays

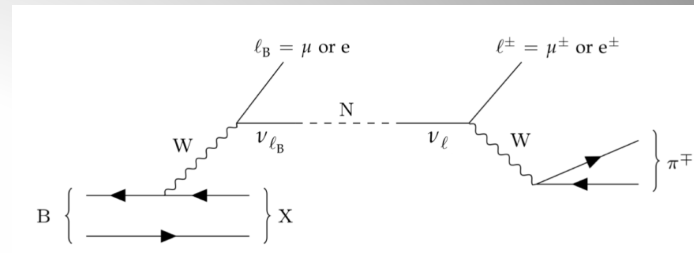






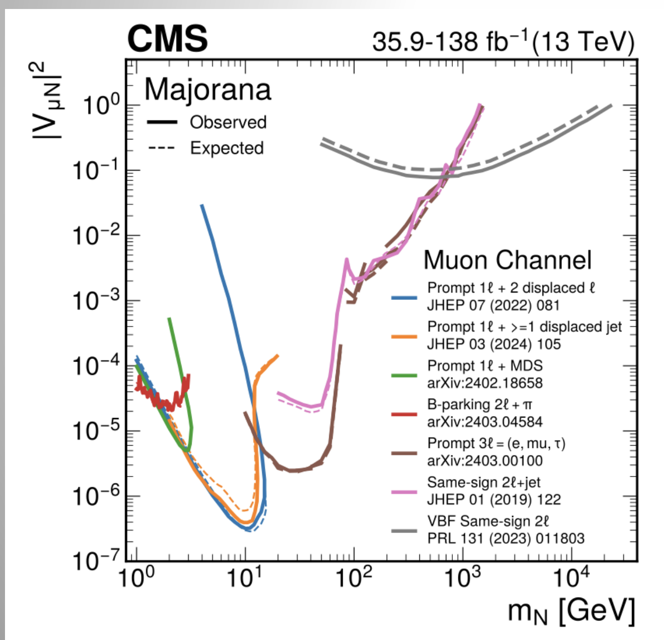
Search for Long Lived Leptons (HNL)





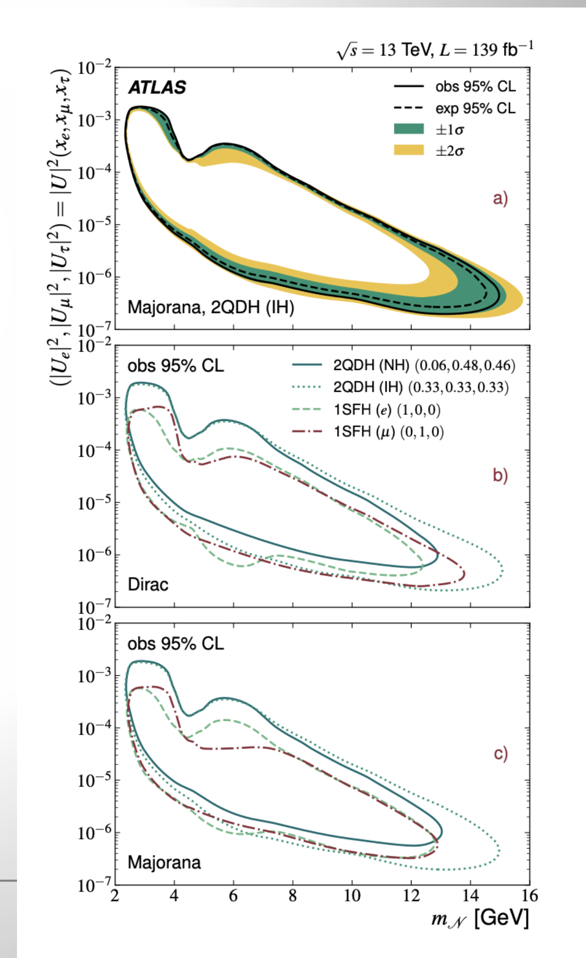
Summary of HNL results

2204.11988



2405.17605

HNL
Type I seesaw
model



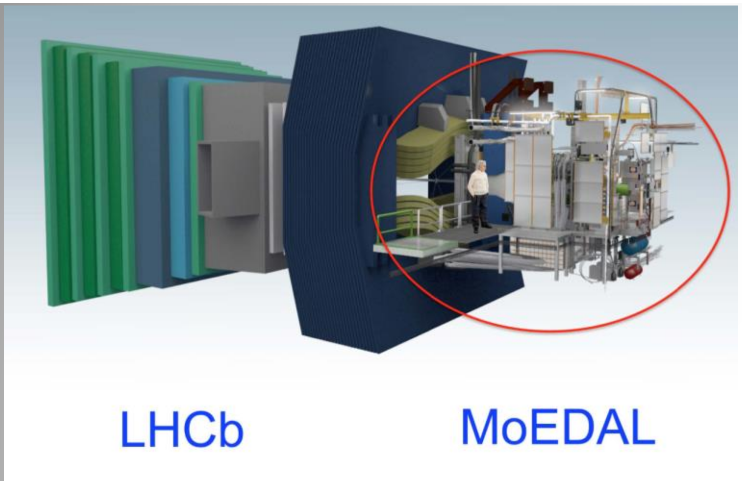
- Displaced decays
- Neutrinos from B and W decays

Dedicated LHC Experiments for Searches for Long Lived Particles

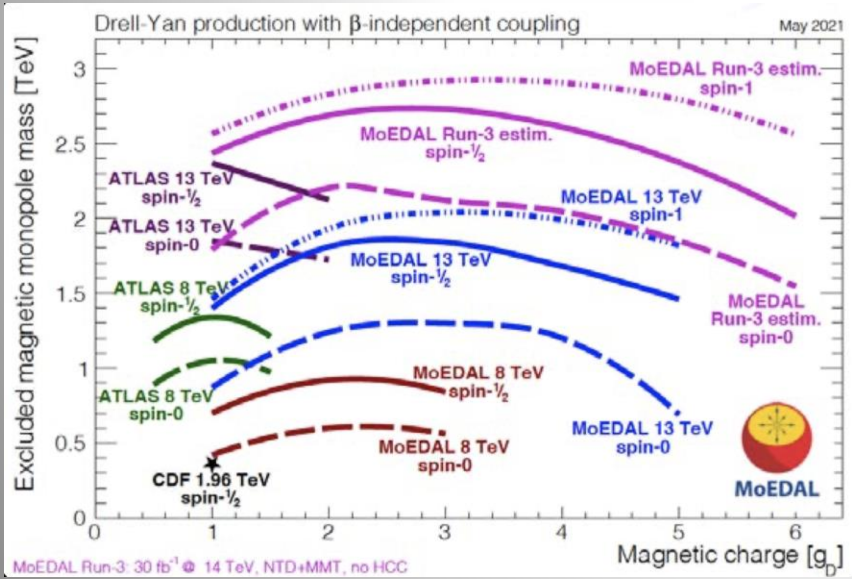
The MoEDAL Experiment

…A search for Magnetic Monopoles and more…

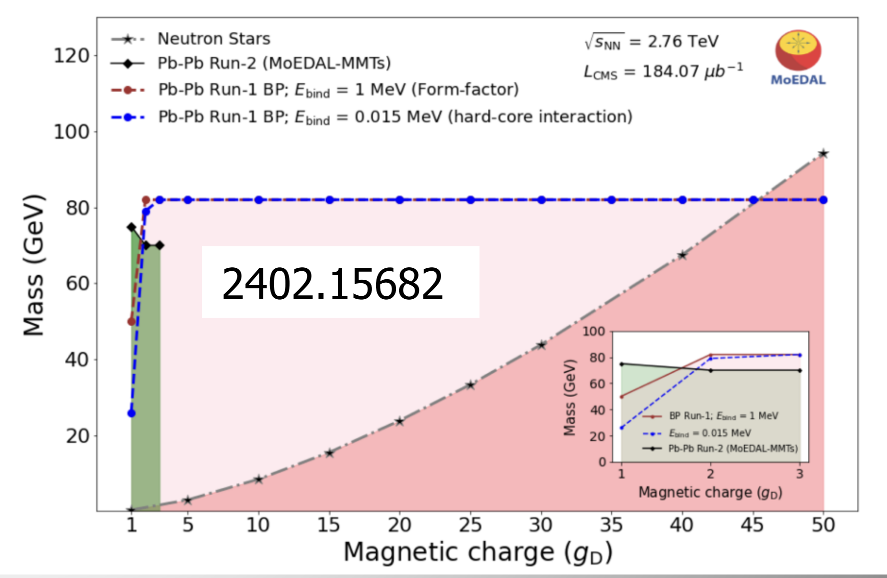
See talk J. Pinfold



MoEDAL = ~ 75 physicists from 22 institutes and 11 countries
-> MoEDAL is a passive detector, sensitive to new physics



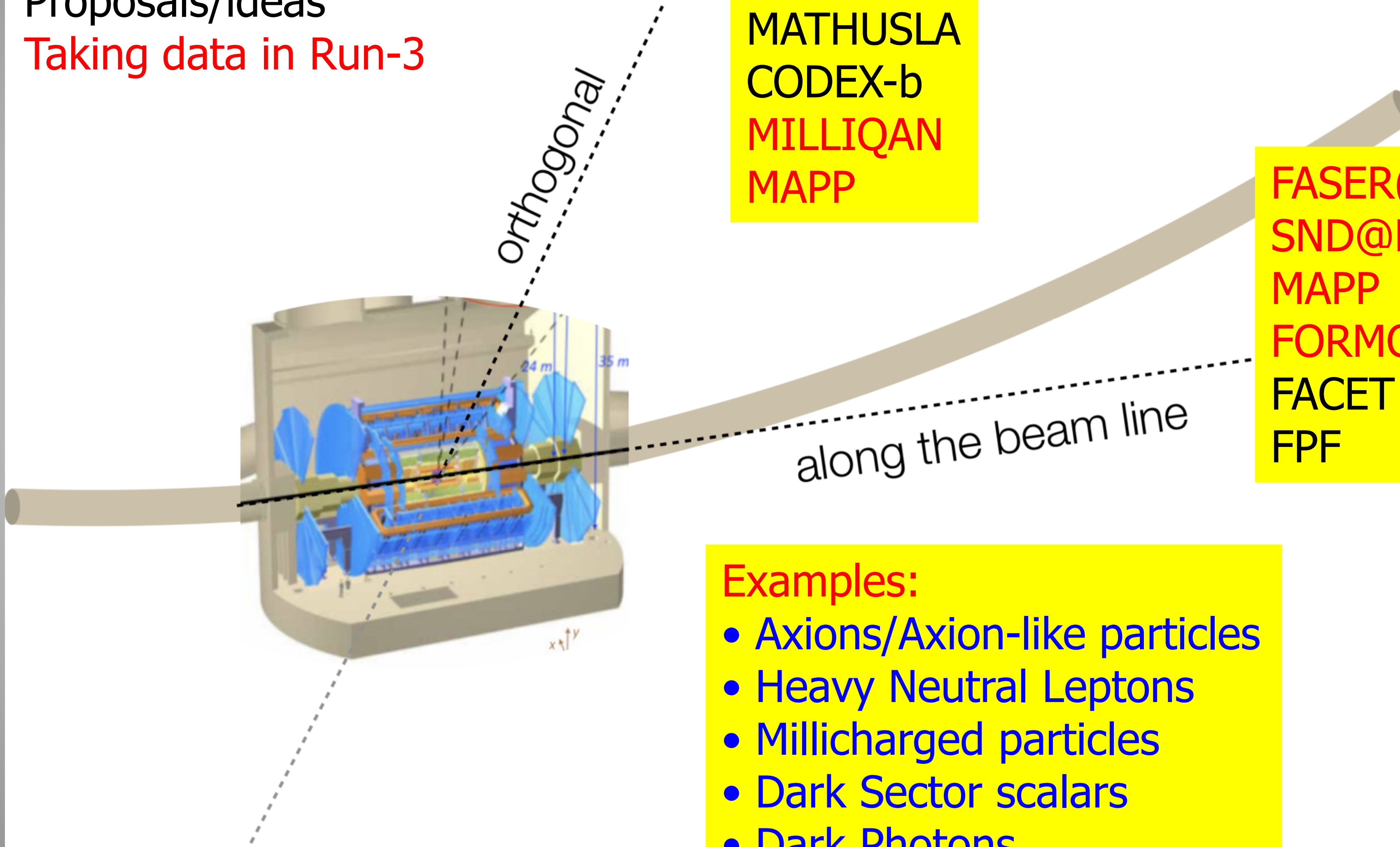
Monopole search in heavy ion data using Schwinger model



MoEDAL is THE prototype of a small dedicated BSM experiment @LHC

New Directions for Experiments

Proposals/ideas
Taking data in Run-3



ANUBIS
MATHUSLA
CODEX-b
MILLIQAN
MAPP

FASER(Nu)
SND@LHC
MAPP
FORMOSA
FACET
FPF

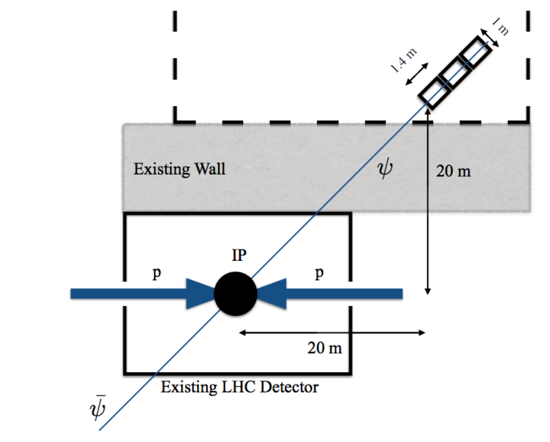
Examples:
- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Dark Photons
- Light Dark Matter …

Proposals for Transverse Detectors

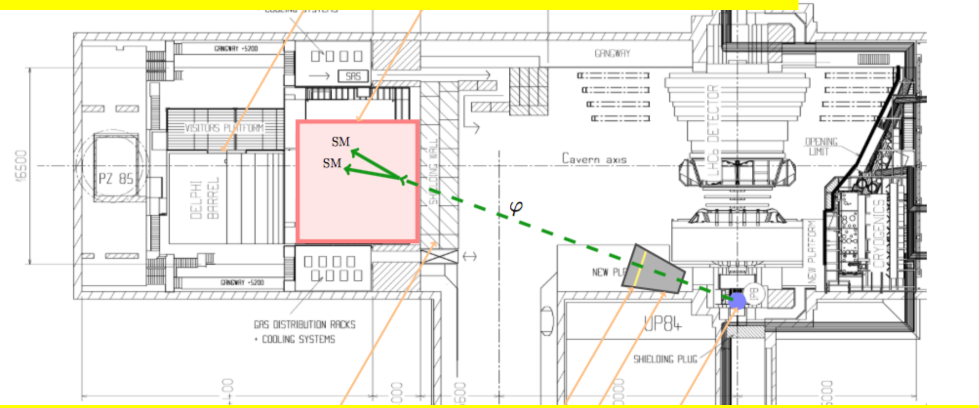
New Transverse Experiment Proposals

~2020

MilliQan: searches for millicharged particles
MAPP: MoEDAL upgrade
FORMOSA: demonstrator

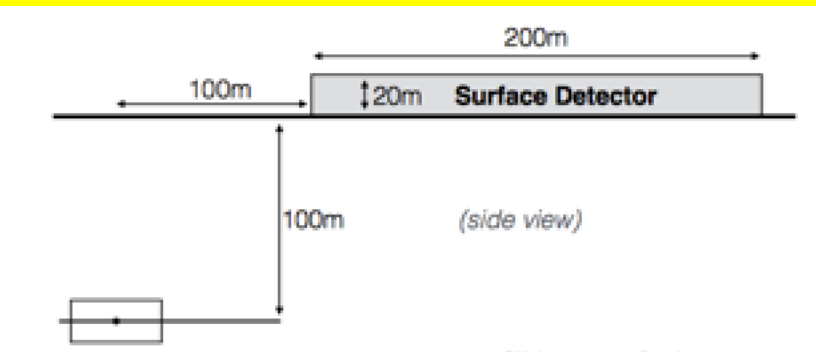


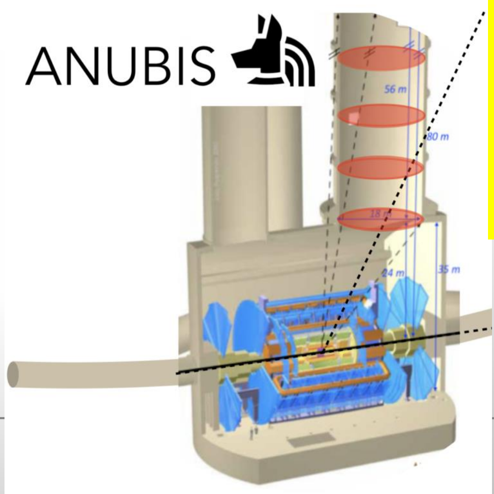
CODEX-b: searches for long lived weakly interacting neutral particles



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

MATHUSLA: searches for long lived weakly interacting neutral particles



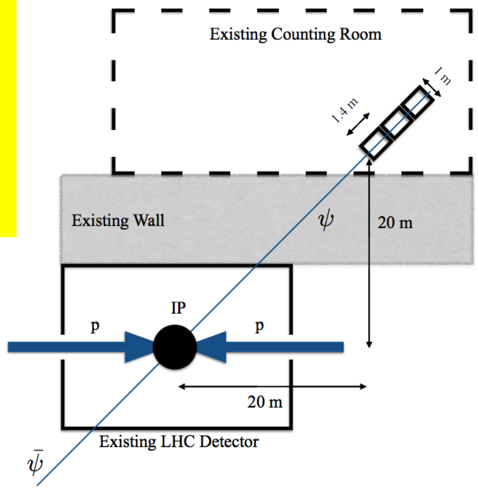


ANUBIS: searches for long lived weakly interacting neutral particles

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

Particles with Milli-Charges?

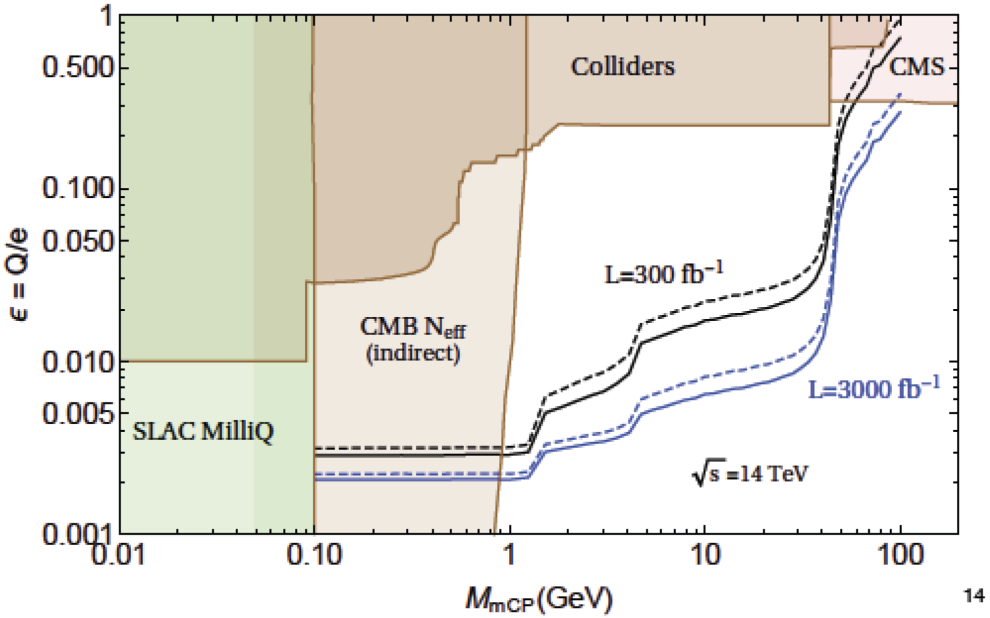
"New" idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017 till 2018



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

arXiv:1607.04669

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

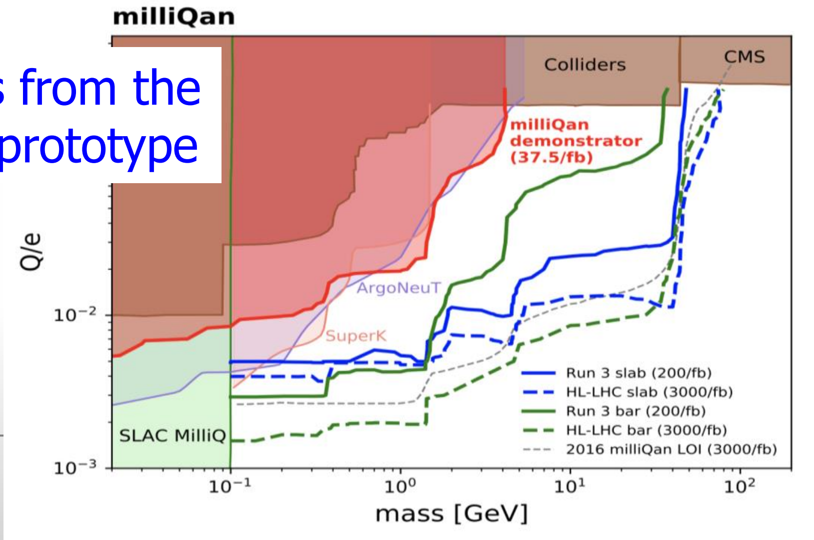
Millicharged Particles

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 +PMTs

Installed for Run-3 2022/23: being commisioned

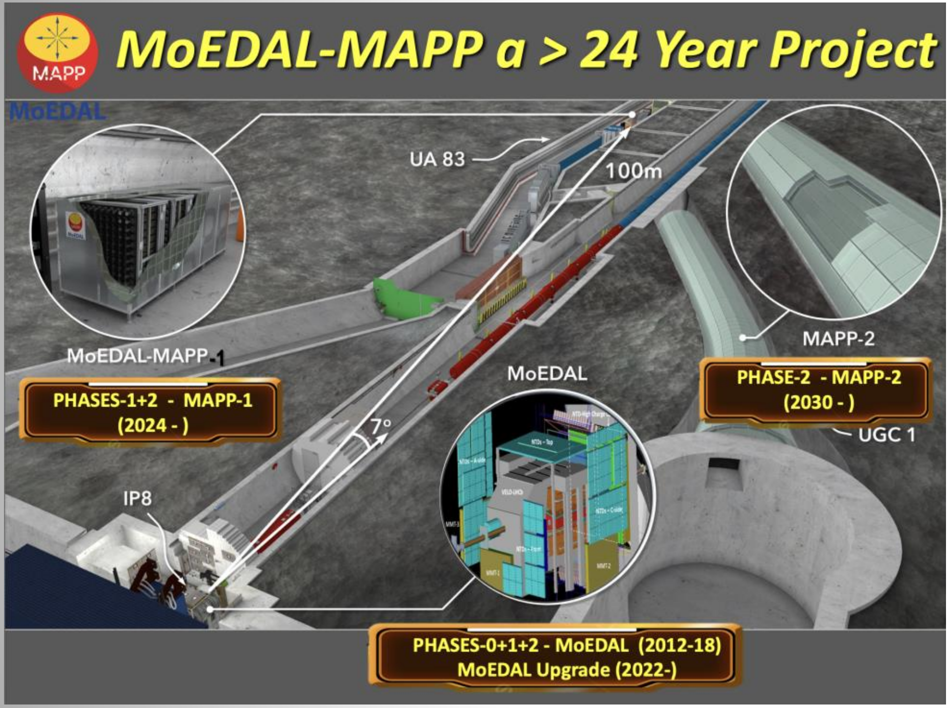
Results from the Run-2 prototype

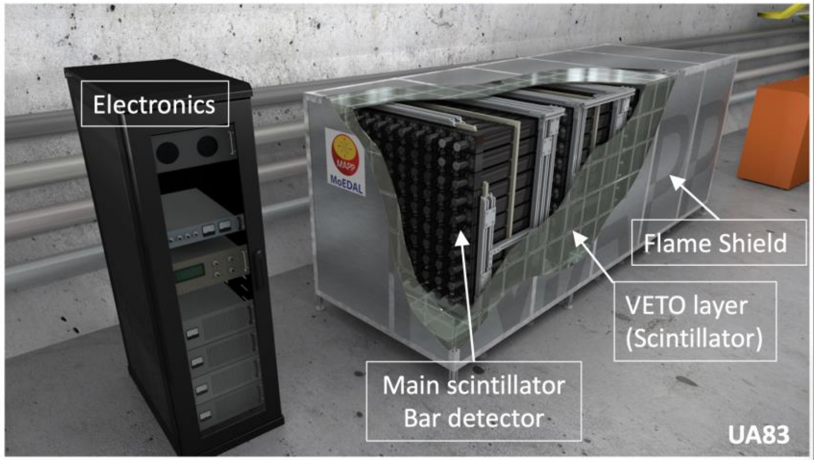


MAPP/MoEDAL

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

See talk J. Pinfold

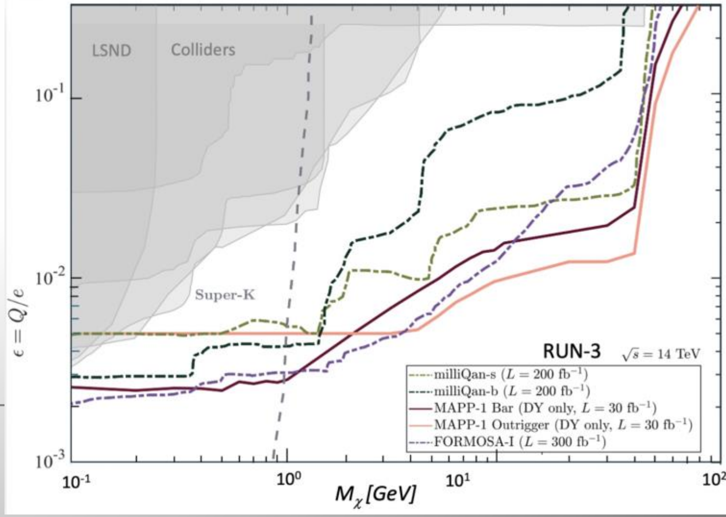




- 400 scintillator bars ($10\times10\times75$ cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

MAPP is being commissioned for physics.

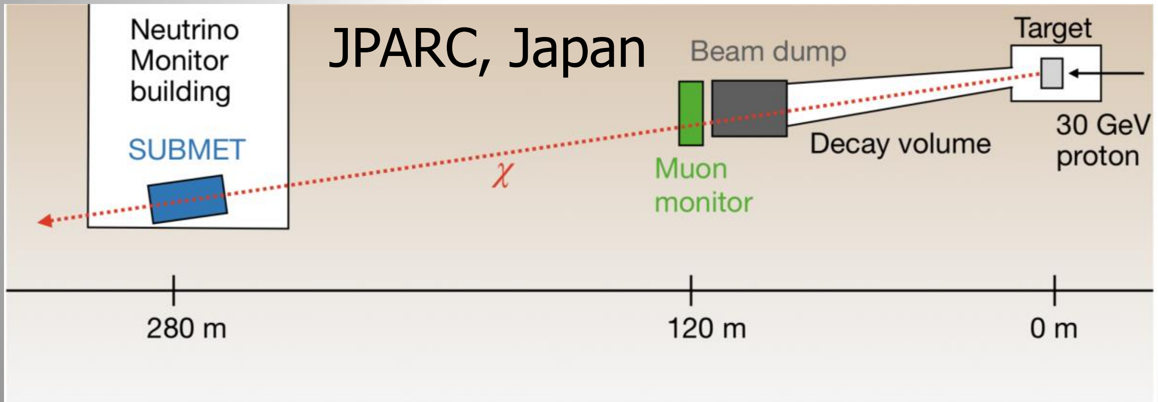
MAPP-1: DY only, 100% eff., no background
milliQan: DY+meson decays, bkg.+detector eff. included
FORMOSA-1: DY+meson decays, 100% eff., no background

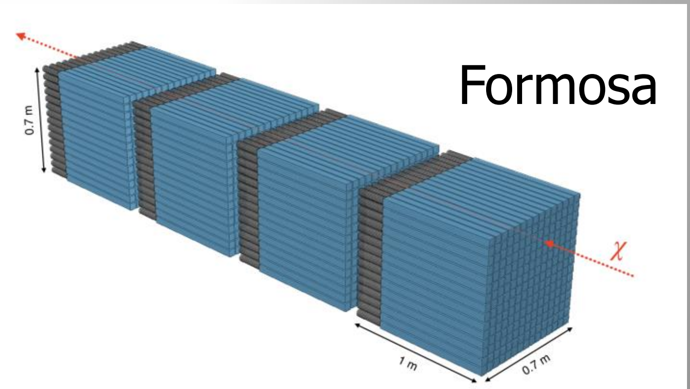


MilliQan: a new type of new physics hunter

- 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< 2 GeV). Experiment installed and being comissioned right now. arXiv:2007.06329 (Japan)
  - MoEDAL/MAPP: @LHCb IP arXiv:1909.05216 (CERN)
  - FORMOSA: @FPF Cavern of the HL-LHC arXiv:2203.05090 (CERN)
  - FerMINI: FNAL fixed target experiment arXiv:1812.03998 (USA)

E.G the SUBMET proposal (funded and approved in June '23; Installed '24)

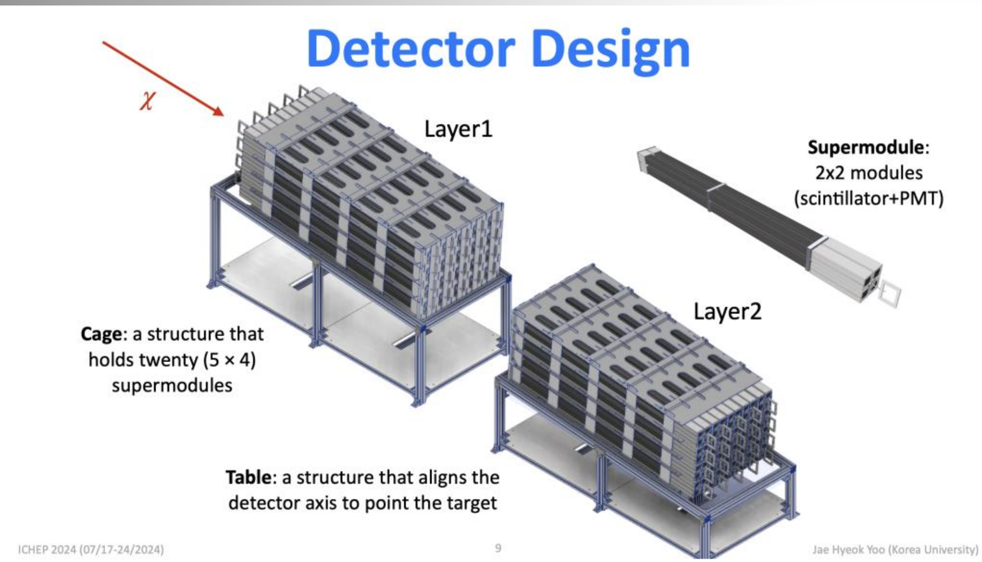


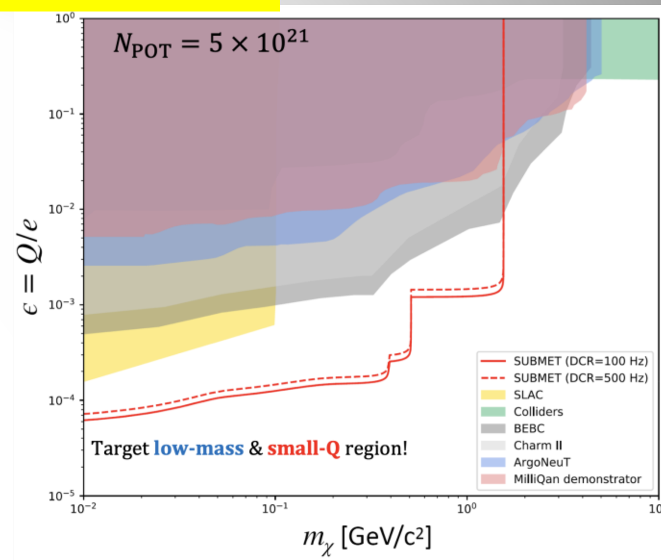


MilliQan collaboration is involved in SUBMET, FerMINI & FORMOSA Detectors
=>This is a science program for up to 2040 and beyond!!

SUBMET Experiment at J-PARC

SUB-Millicharge ExperimenT





At the 30 GeV proton beam of J-PARC (next to the T2K near detector)

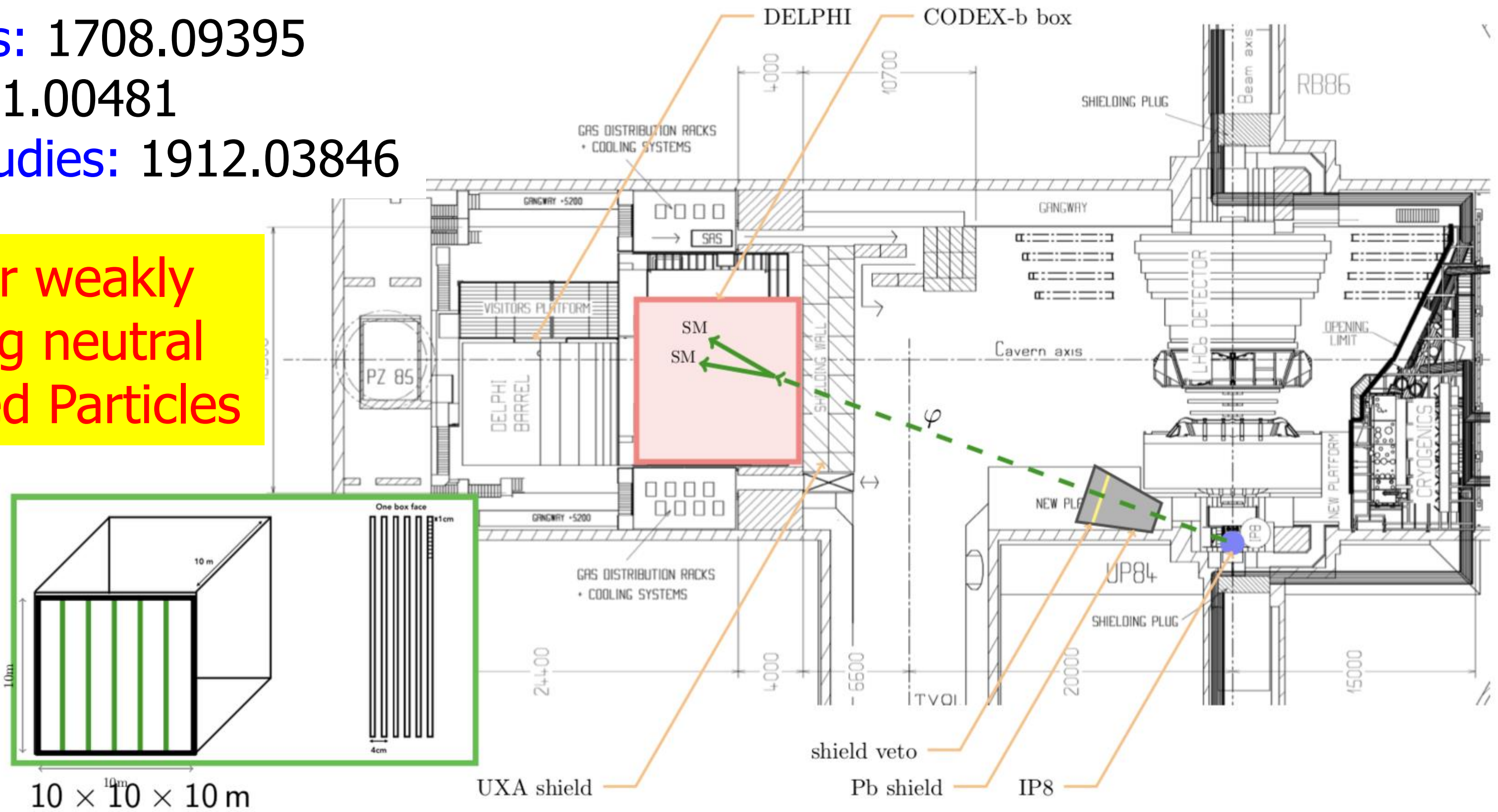
- Detector installed spring/summer 2024
- Comissionong run with beam July 2024
- First Physics run this fall !

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



- Nominal design: 10x10x10m^3 tracking volume 25 m away from the IP, preceeded by an active shield of (25+5)λ 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

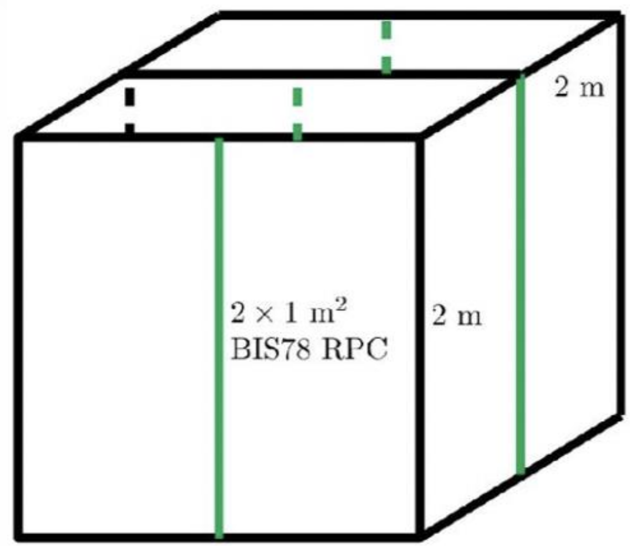
Demonstrator to test technologies planned for CODEX-b

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

- $2 \times 2 \times 2 m^3$ 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)

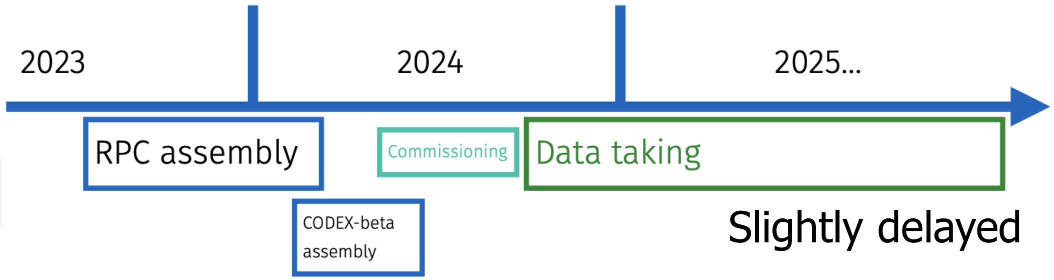
Expect 10^7 K_L to decay in the demonstrator volume.

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

Detector being prepared to be installed this winter shutdown



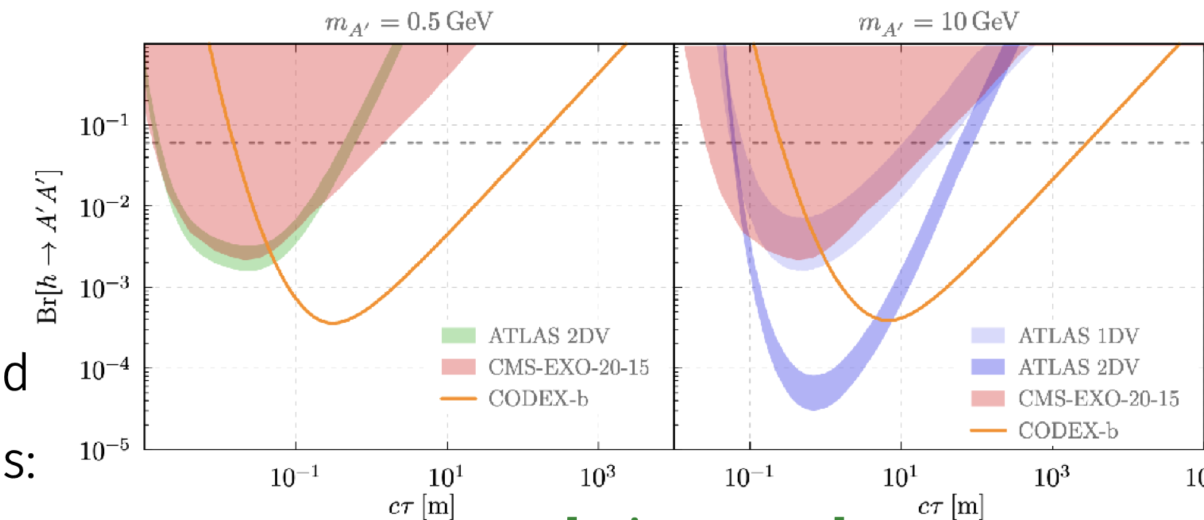
More collaborators welcome!

Slightly delayed

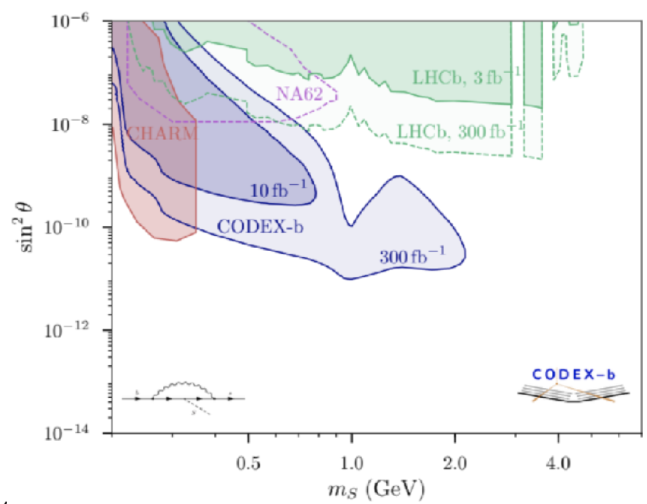
CODEX-b: Physics

Physics reach

- Many UV complete and minimal benchmarks studied
- Two representative examples:
  - $h \to A'A' \to 2e2e$
  - $b \to sS \to s\ell\ell$
- Unique reach from CODEX-b wrt existing experiments
- Find many more scenarios in the EoI **[arXiv:1911.00481]**



[arXiv:2203.07316]



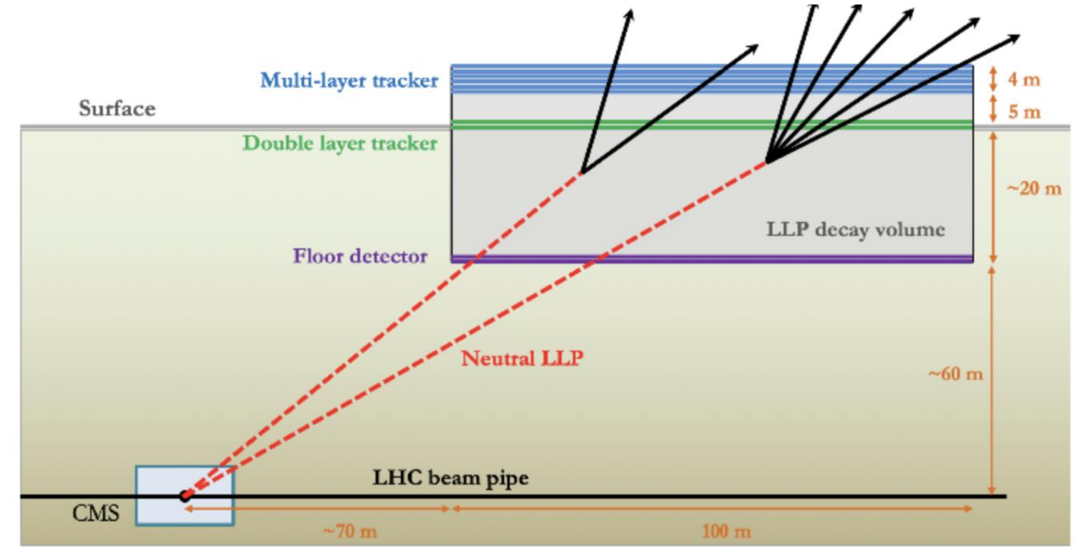
MATHUSLA

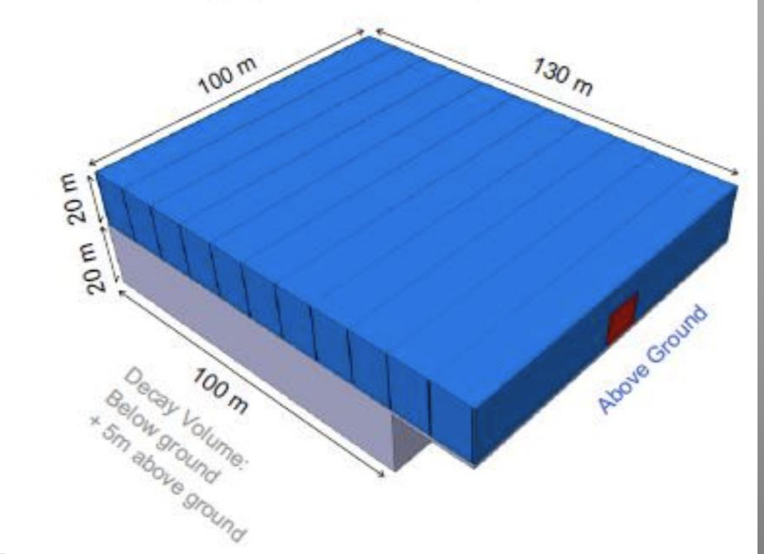
MATHUSLA: MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

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

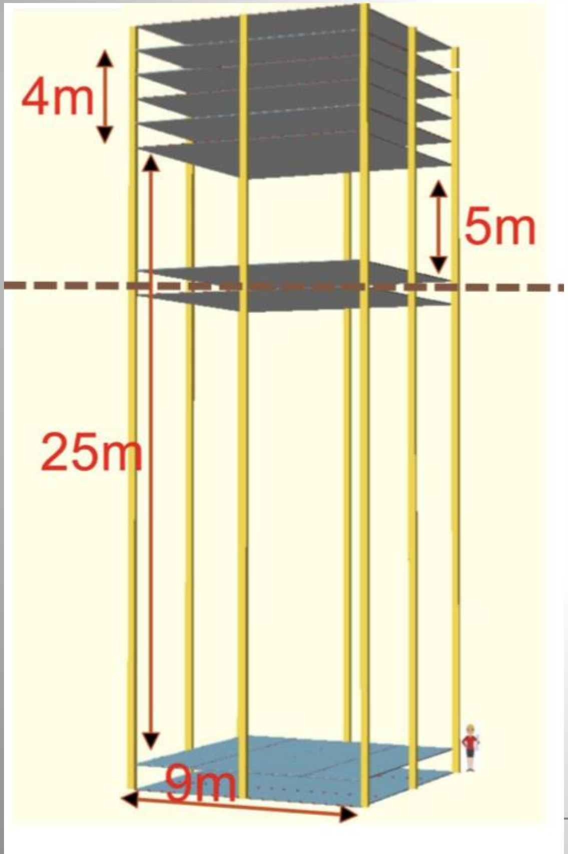




MATHUSLA

MATHUSLA to 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. Possibly with RPCs or cosmic ray data.
->2018 RPC test-stand feasibility study (2005.02018)

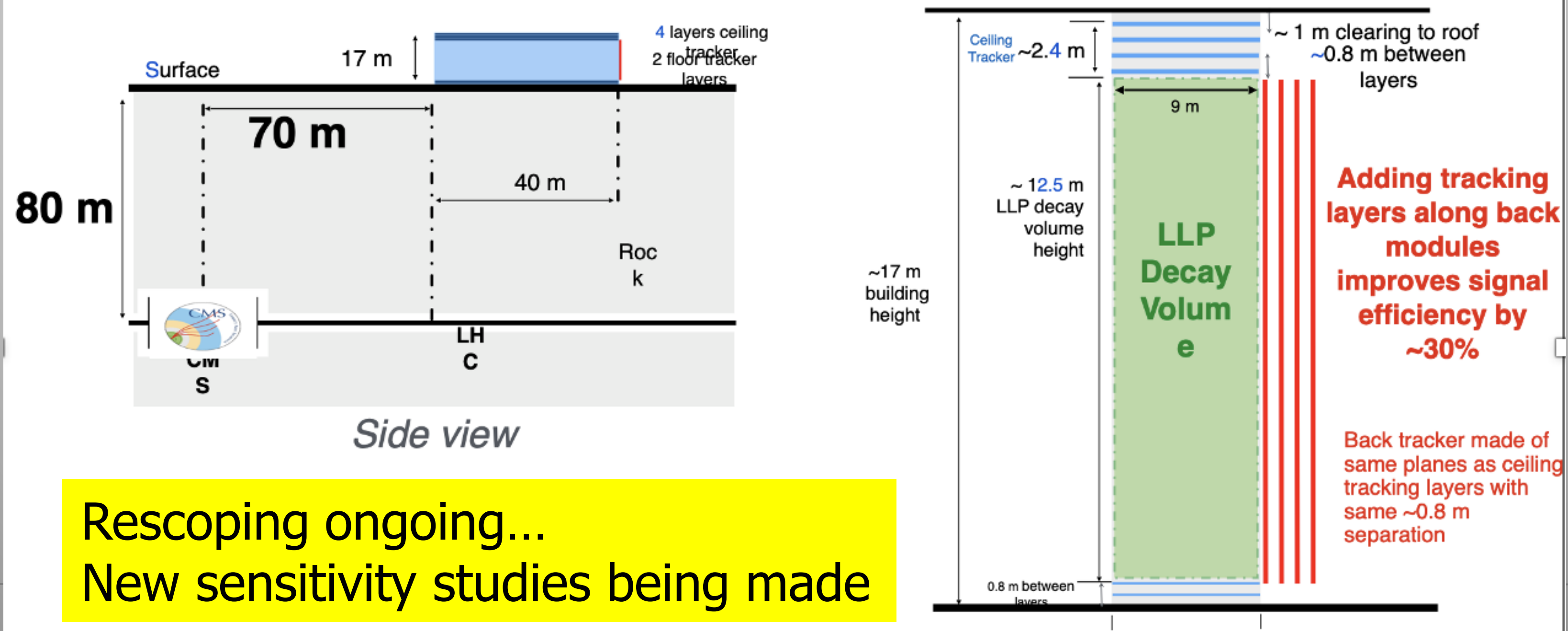
To reconstruct hit position along scintillator bar: use difference in arrival time between separate measurements at two ends
Lab tests: Target timing resolution ~1 ns

MATHUSLA

Recent devopments: rescoping MATHUSLA

- P5 confirmed that **"auxiliary experiments like CODEX-b and MATHUSLA can extend the sensitivity to BSM particle lifetime in Higgs decays by several orders of magnitude"**. However, it did not recommend DOE to fund MATHUSLA in its full 100 m x 100 m scale and proposed it will compete in the portfolio for the smaller scale Agile projects

40 m x 40 m x 17 m



Rescoping ongoing…
New sensitivity studies being made

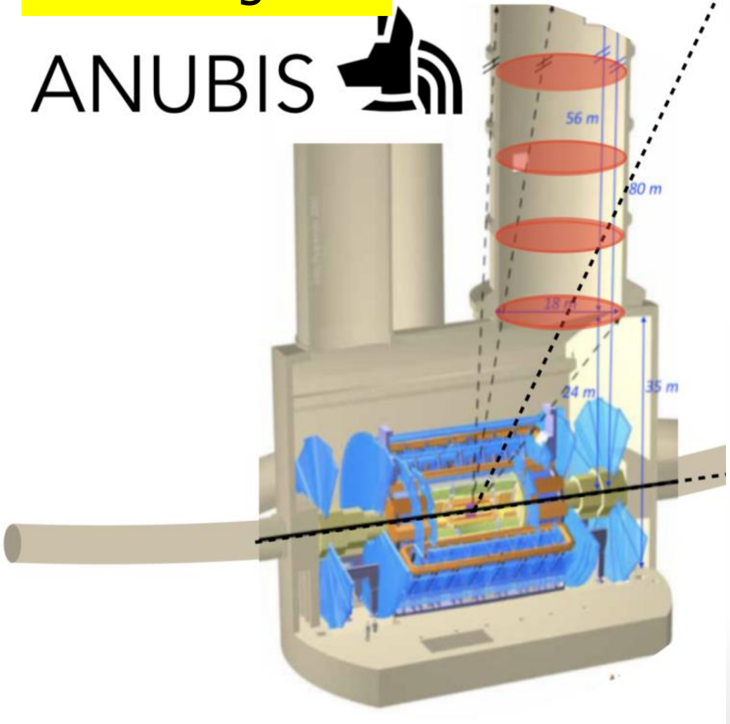
ANUBIS

ANUBIS: searches for long lived weakly interacting neutral particles

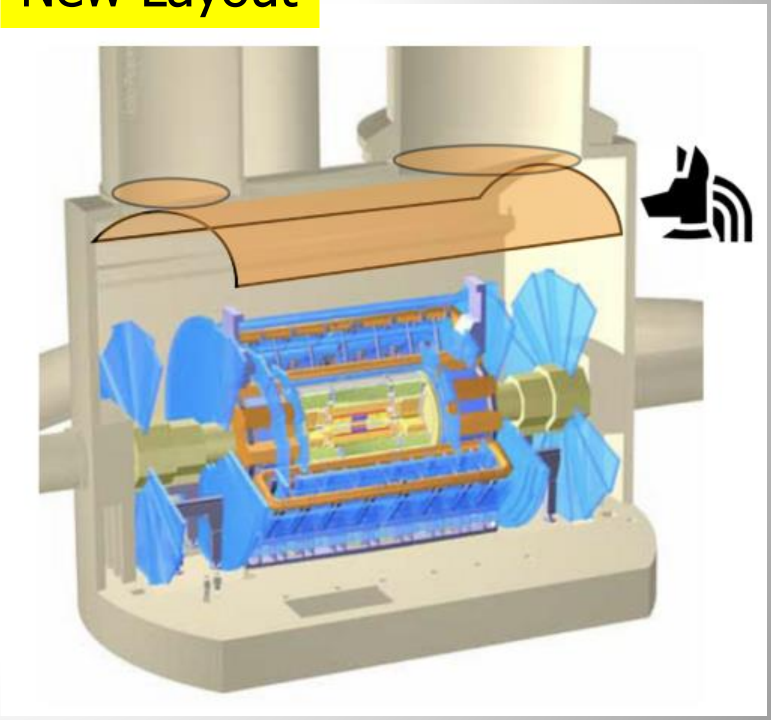
AN **U**nderground **B**elayed **I**n-**S**haft detector

arXiv:1909.1302

The "Original"



New Layout

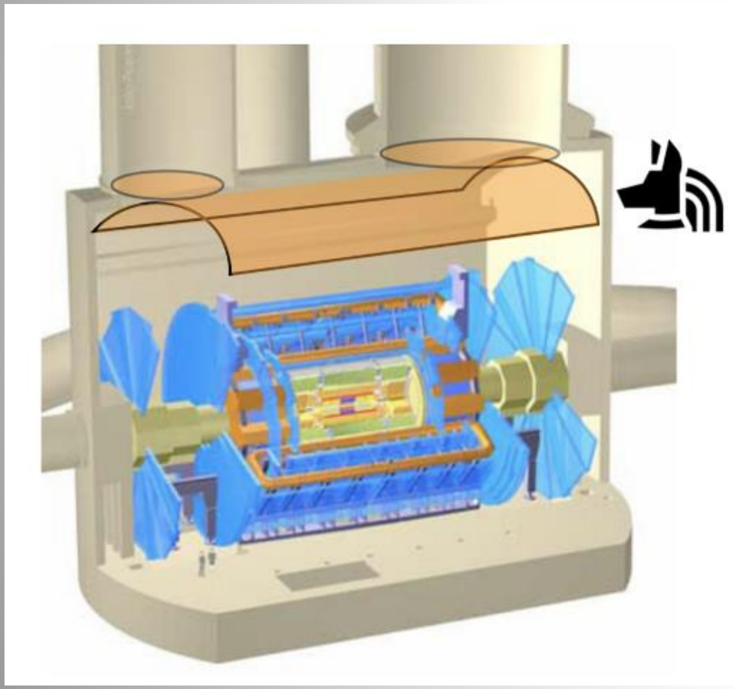


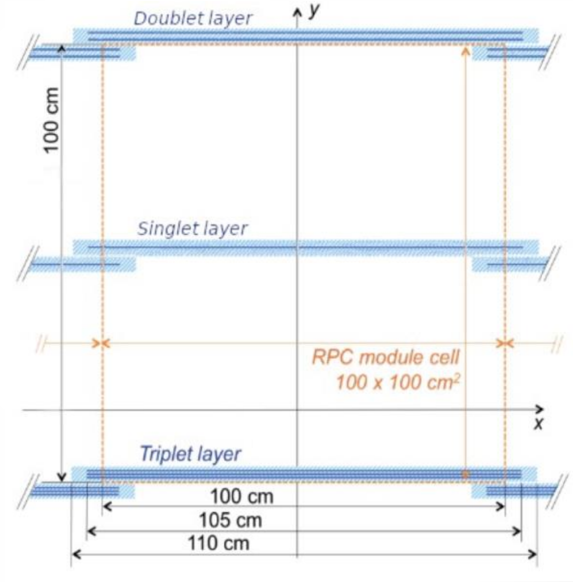
ANUBIS changed from 'in shaft' to 'in cavern'

ANUBIS

ANUBIS: searches for long lived weakly interacting neutral particles

AN **U**nderground **B**elayed **I**n-**S**haft detector



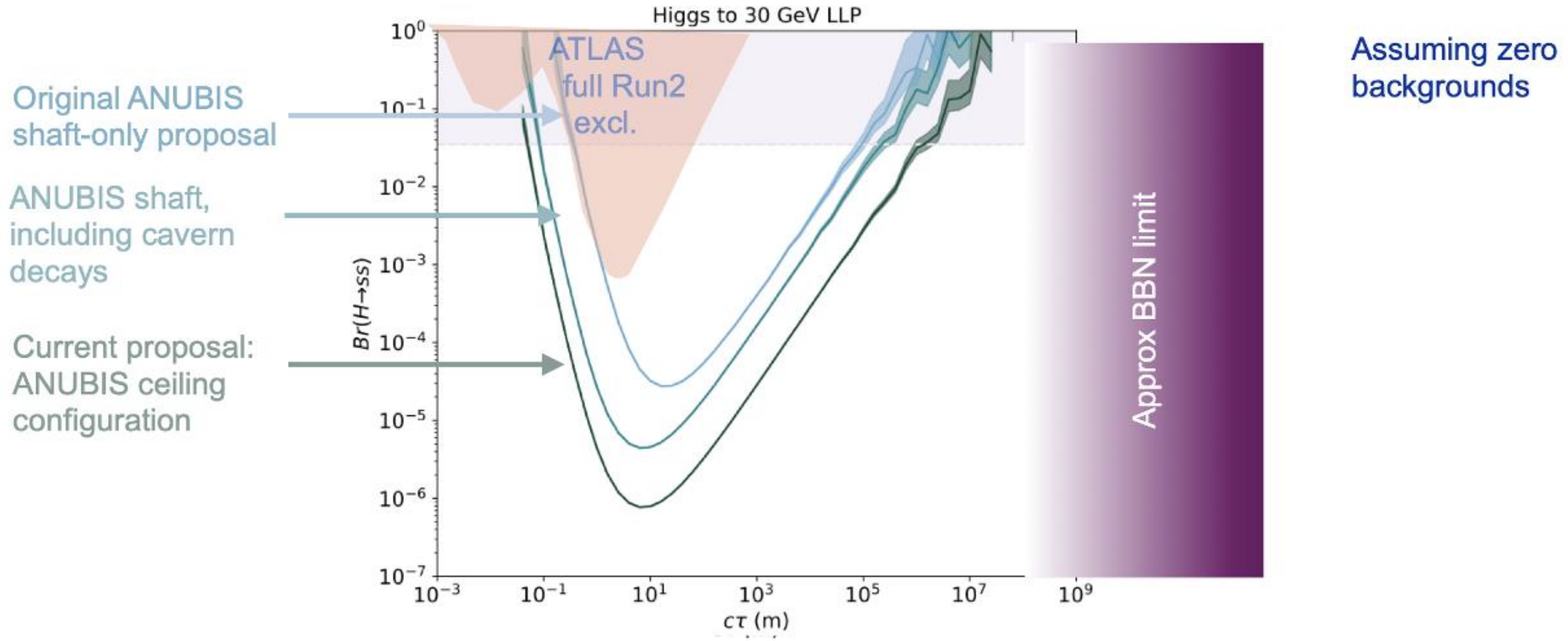


- 3 layers of tracking stations of ATLAS phase-2 upgrade RPCs
- 2x1x1m^3 test set-up deployed
- partial detector in 2028+, full detector in 2033+

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

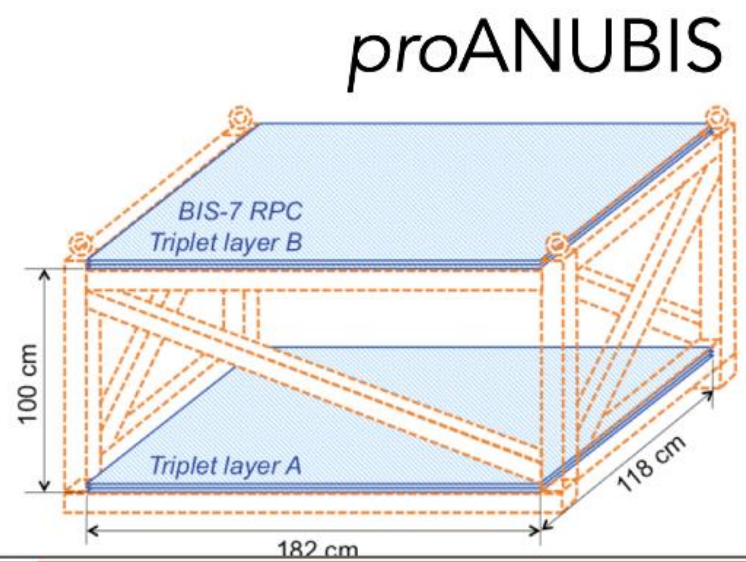
How close can ANUBIS get to the BBN limit?



ANUBIS

proANUBIS: A protoype for ANUBIS in the ATLAS cavern

- 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!

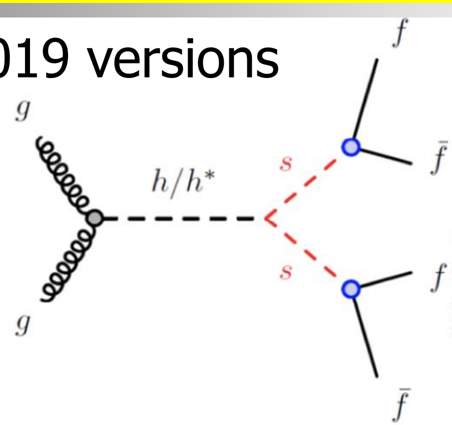


The proANUBIS prototype is currently installed (again) in the cavern for the 2024 run and being commisioned. Proof of concept for ANUBIS!

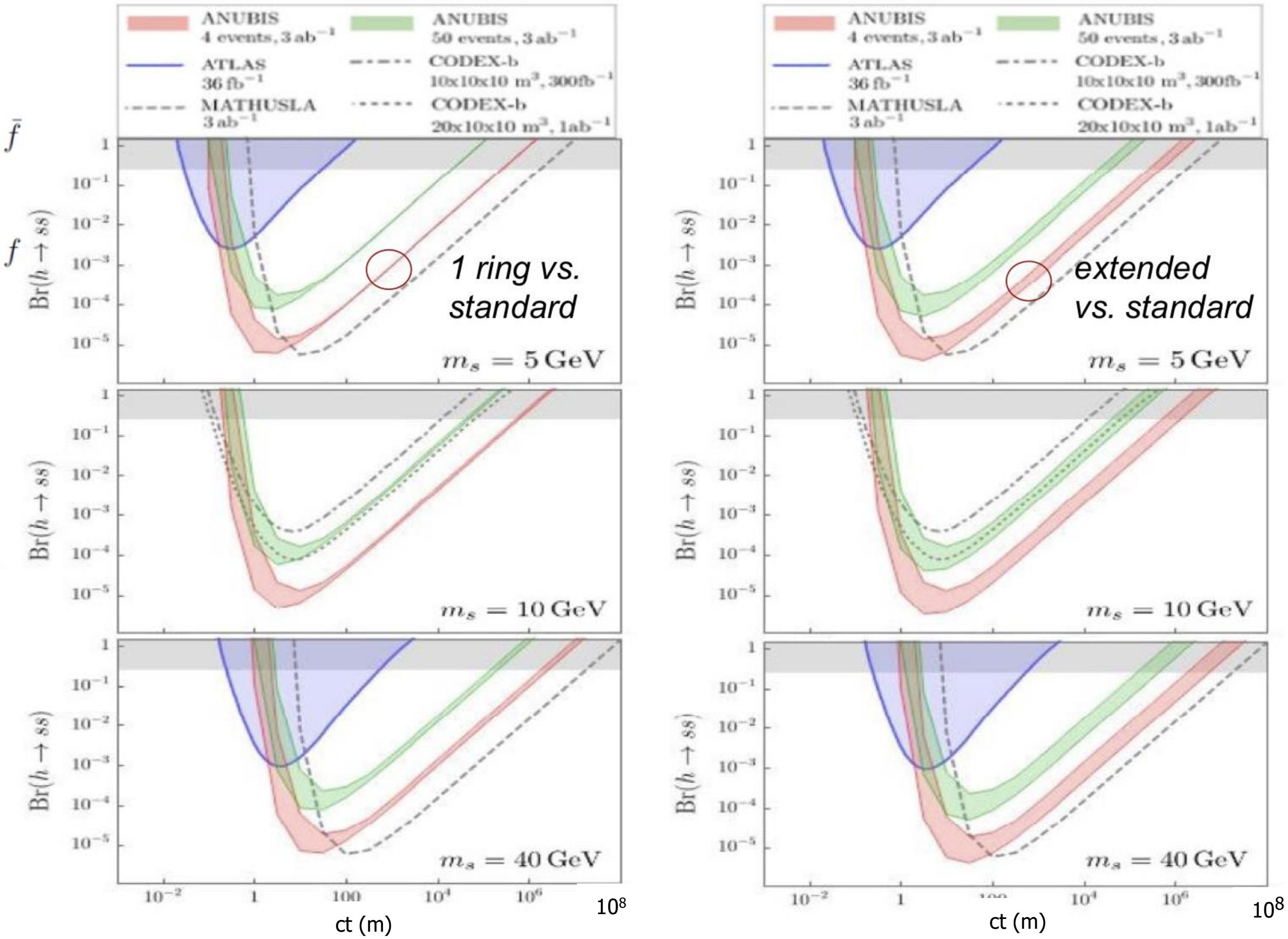
Sensitivities for an Example Process

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

2019 versions



- 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)

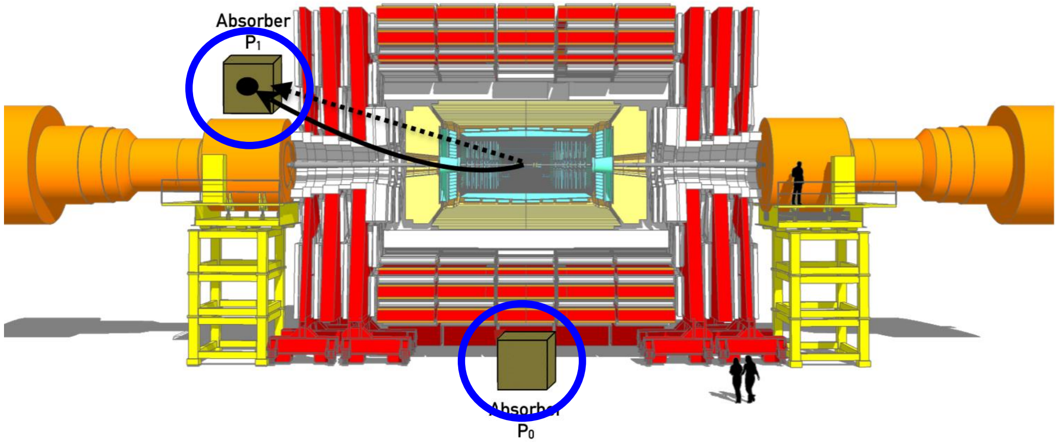


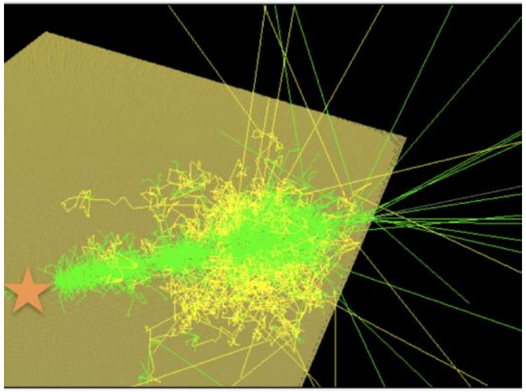
The different proposals have different strengths and levels of complementarity
Studies regularly reported in PBC, FIP, and LLP meetings

Trapping Particles

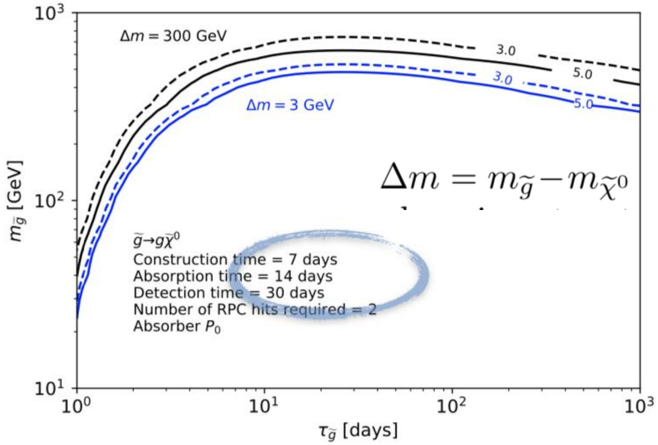
arXiv:2110.13837

- 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

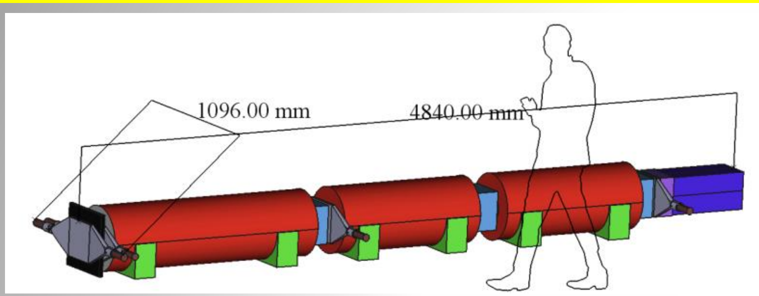
Reach longer lifetimes: > weeks, months!

Not been followed up recently… ☹

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

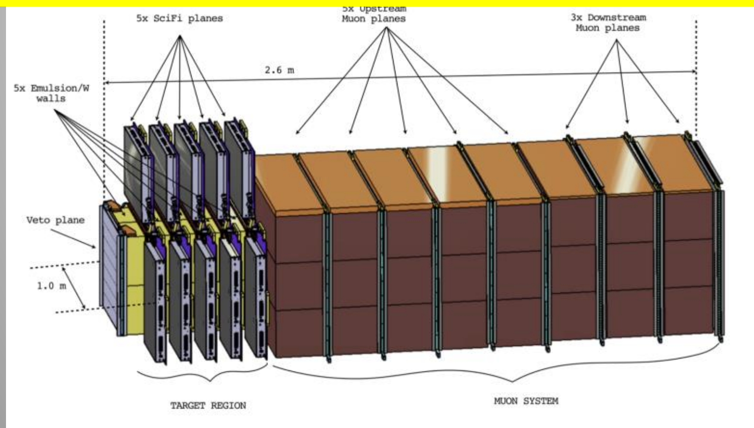
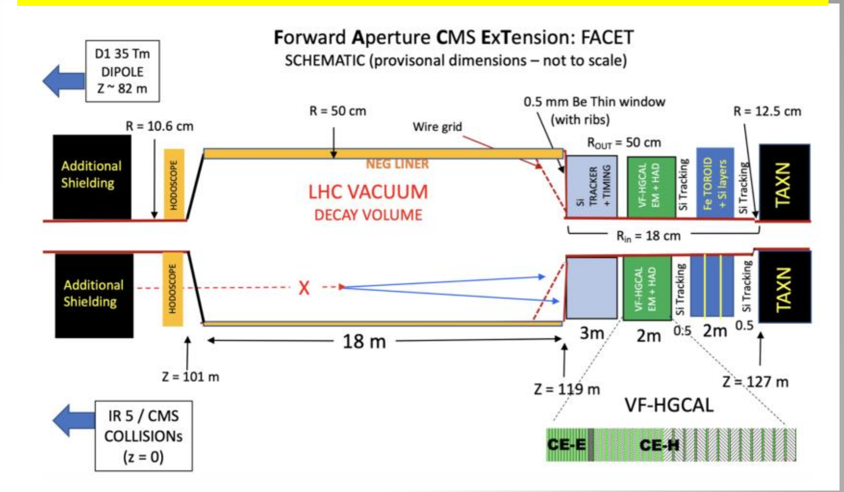


Figure 5: Layout of the proposed SND@LHC detector.

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 are taking data during Run 3

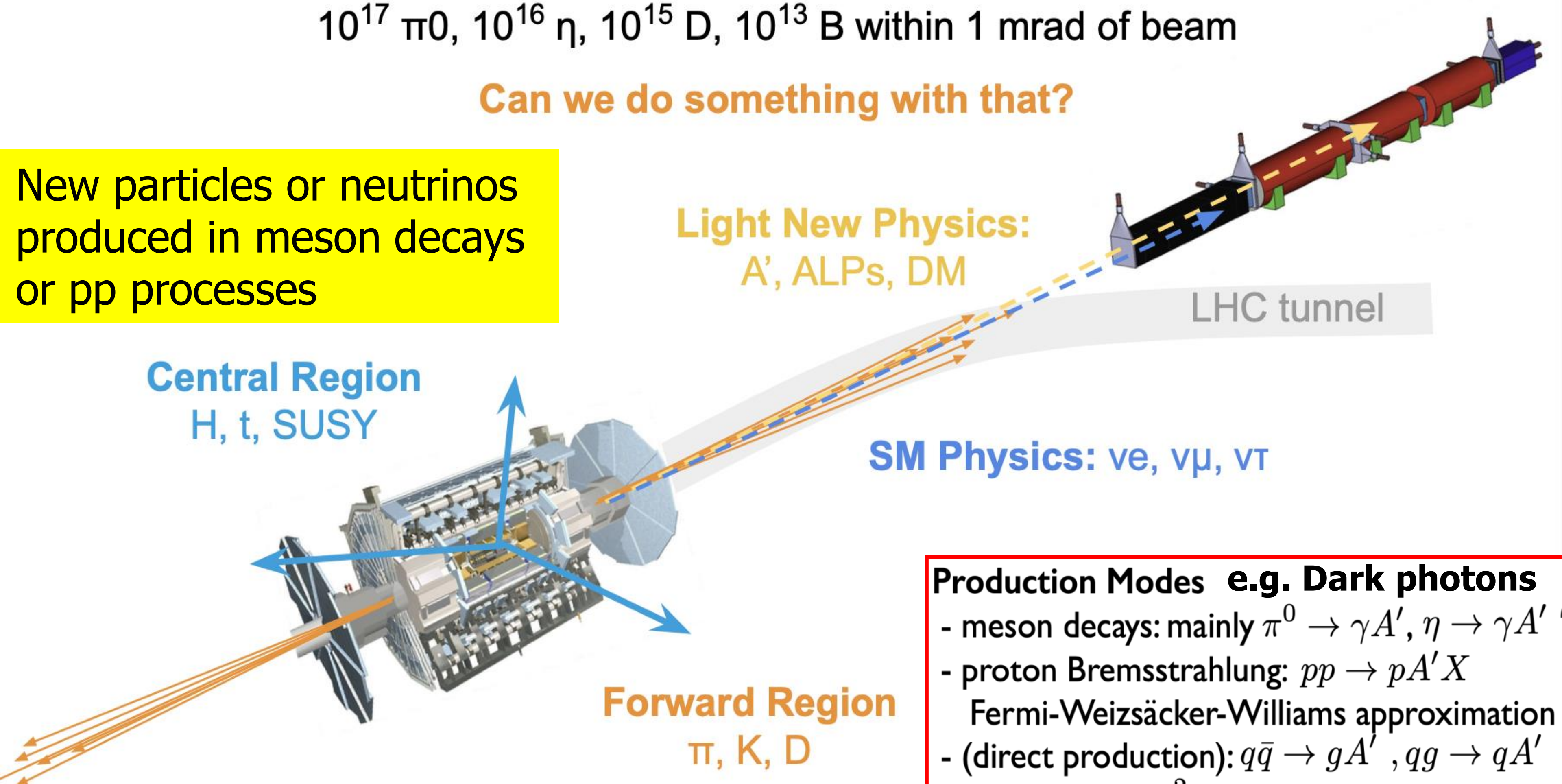
Forward Particle Production

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?

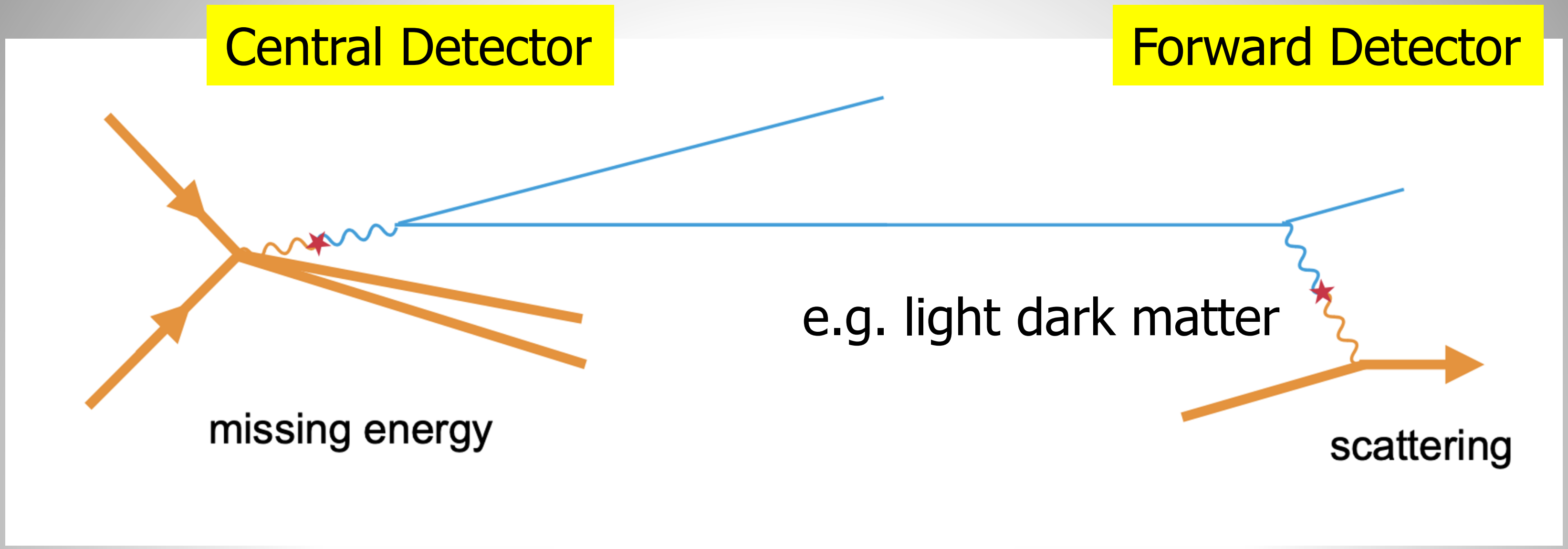
New particles or neutrinos produced in meson decays or pp processes

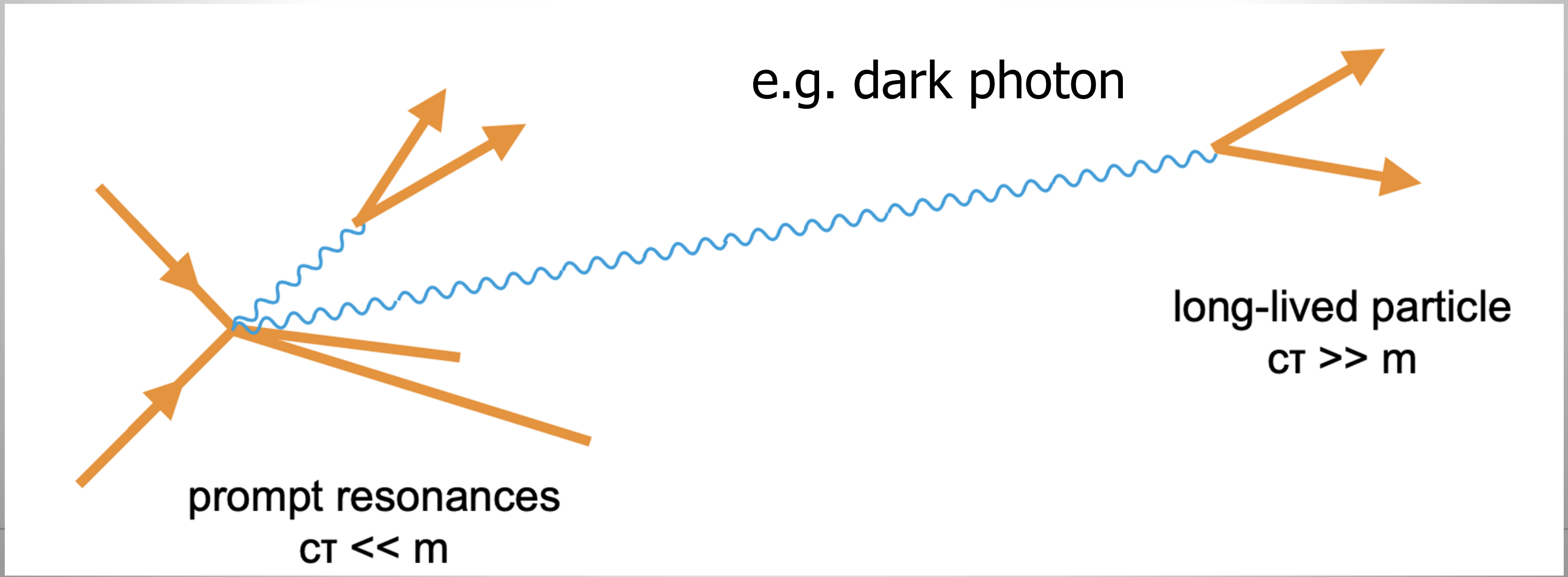


Production Modes **e.g. Dark photons**

- 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

Experimental Technqiues

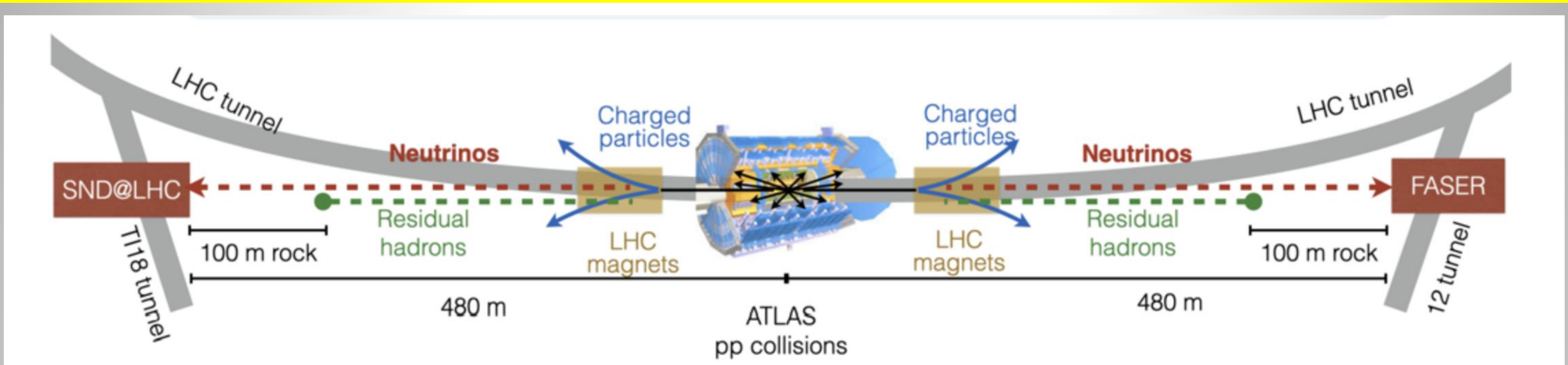




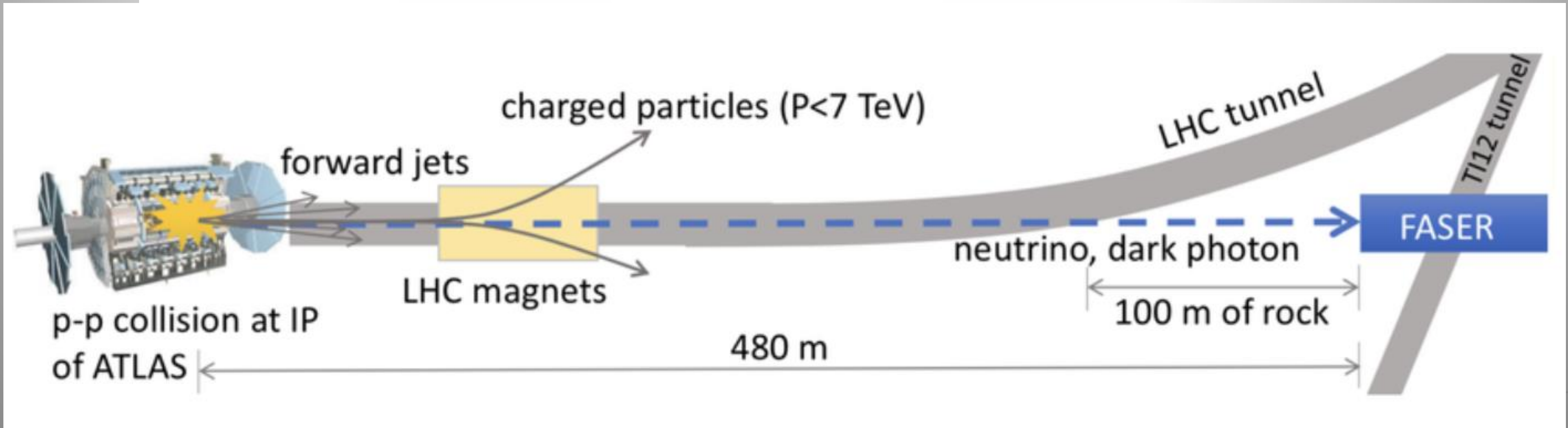
Two New Detectors at the LHC
FASER and SND@LHC

FASER and SND@LHC

Experiments to search for forward produced LLP (ALPs, Dark Photons, DM…) and neutrinos



E.G. FASER



History of FASER and SND@LHC

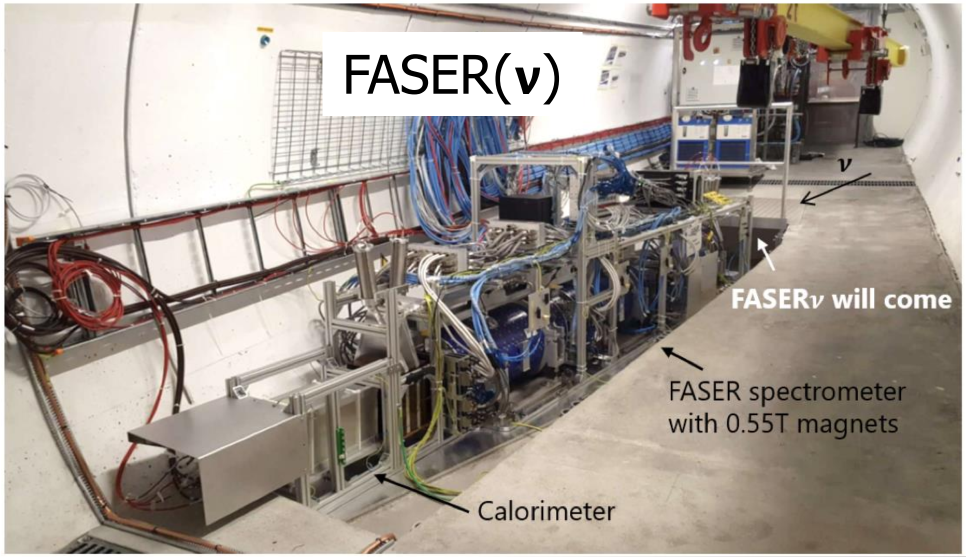
- FASER: proposed in 2018
  - Approved in 2019
  - Partially using spare parts from ATLAS and LHCb
  - Partially “private” sponsored (Simons Foundation)
  - Passive Neutrino added in 2019 (FASERnu)
  - Construction started 2020/finished 2021
- SND@LHC: proposed in 2020
  - SND detector technology partialy based on SHIP proposal
  - TDR end of 2020. Approved March 2021
  - Construction started 2021/finished 2021!!

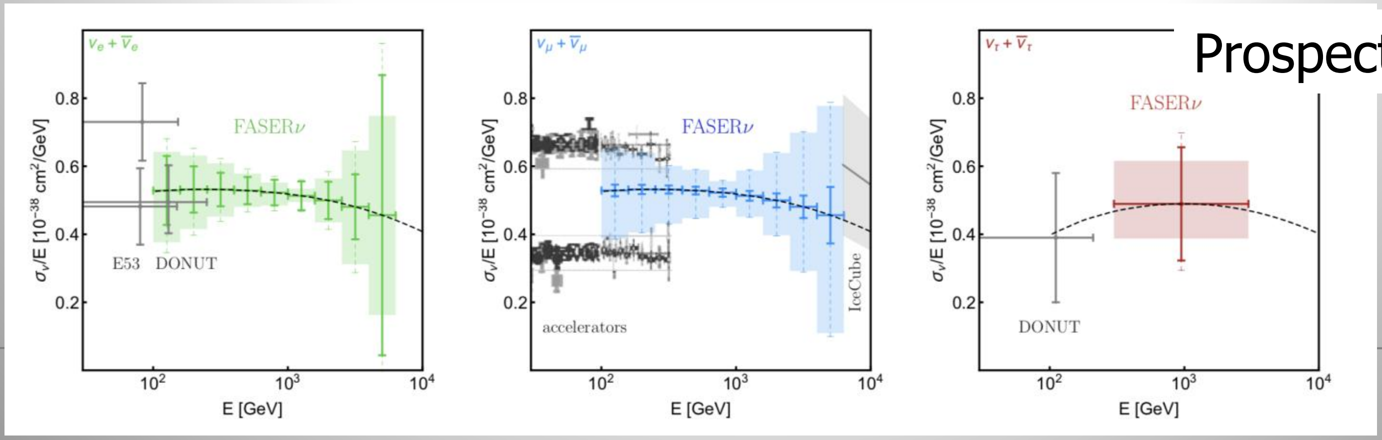
Both experiments were ready to take data in Run 3 in May 2022!

Neutrinos @ the LHC: SND@LHC & FASERν

SND= Scattering and Neutrino Detector

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

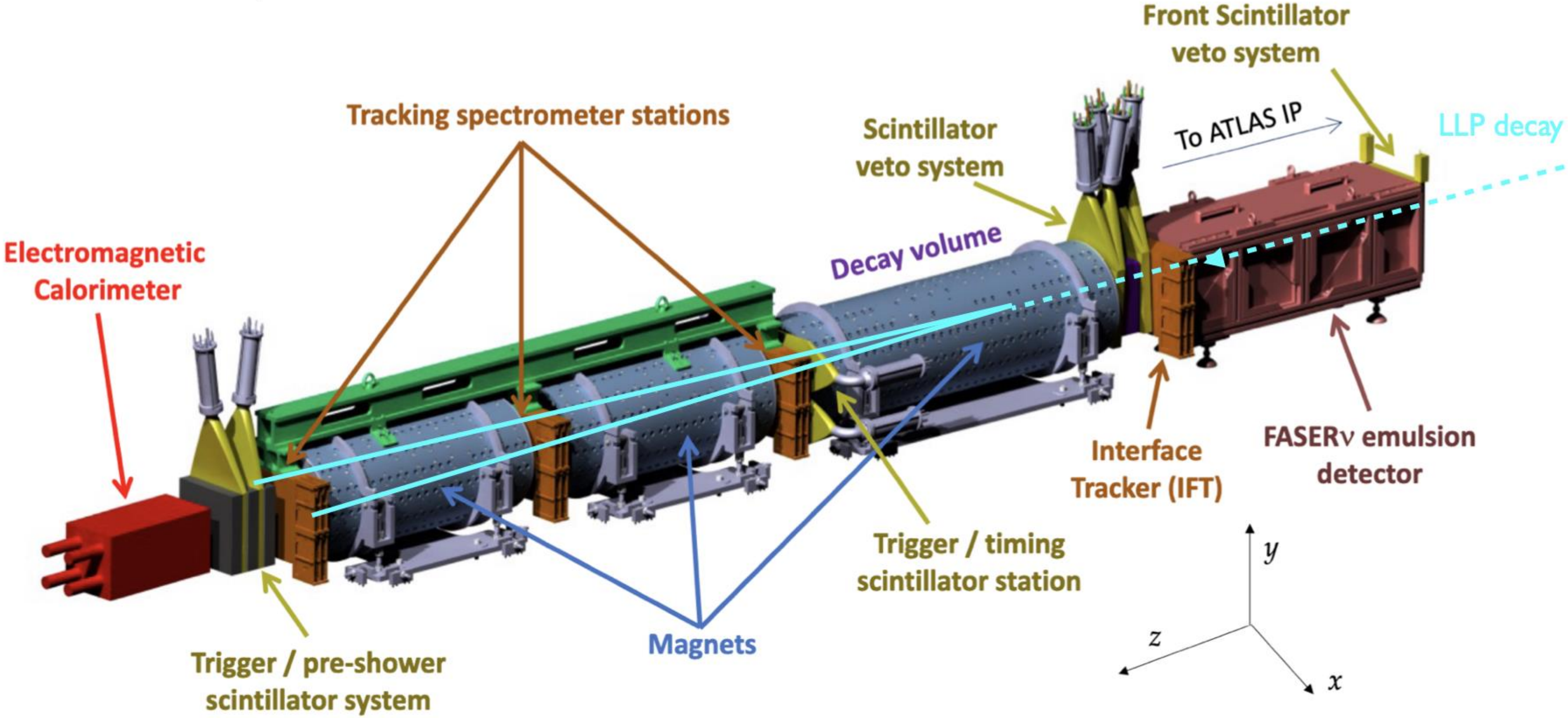




The FASER & FASERν Detectors

FASER: ForwArd Search ExpeRiment at the LHC

Documentation:
LOI: 1811.10243
TP: 1812.09139
Detector Paper: 2207.11427

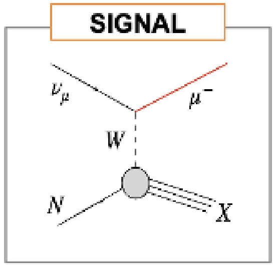


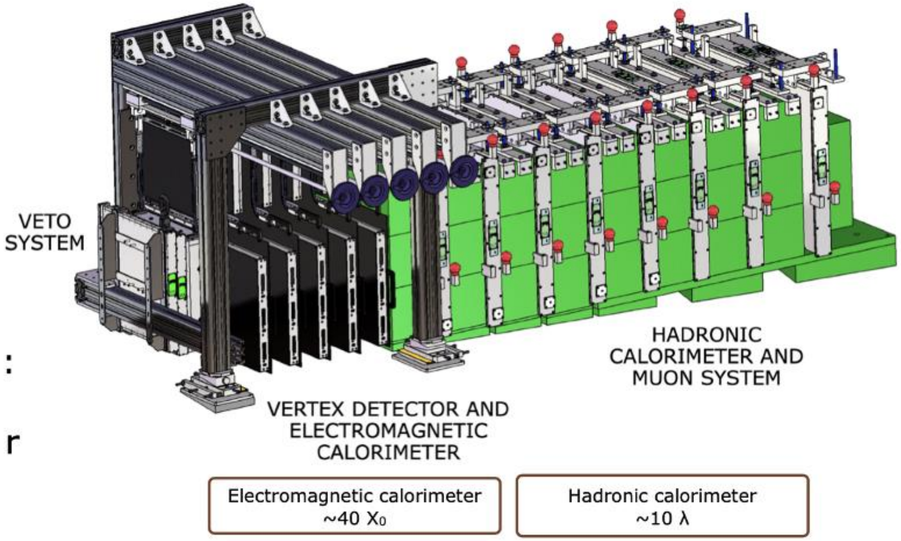
Neutrinos from the LHC

Direct Neutrino observation by SND@LHC and FASER

Neutrino observation with electronic detectors

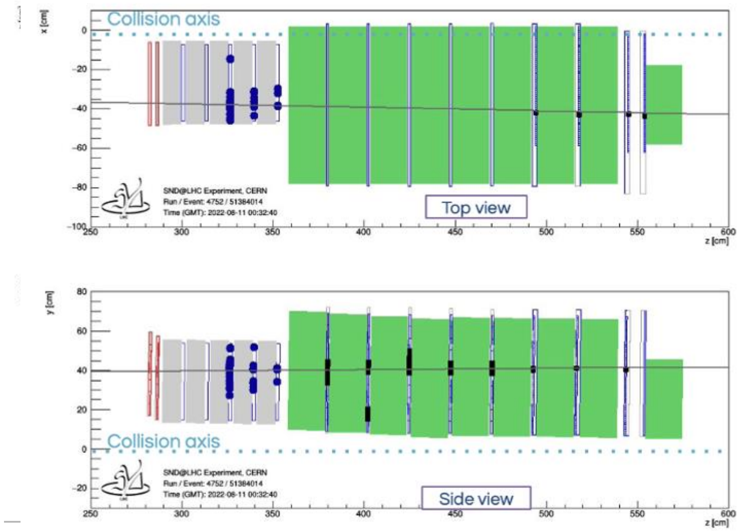
- Analysis strategy:
  - Full Run 3 **2022 dataset**, 39 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach
  - ~10^9 muon events: apply **cuts with a strong rejection power** to reach a negligible background level





SND@LHC: 2305.09383
FASER: 2303.14185

Aug 11th 2022

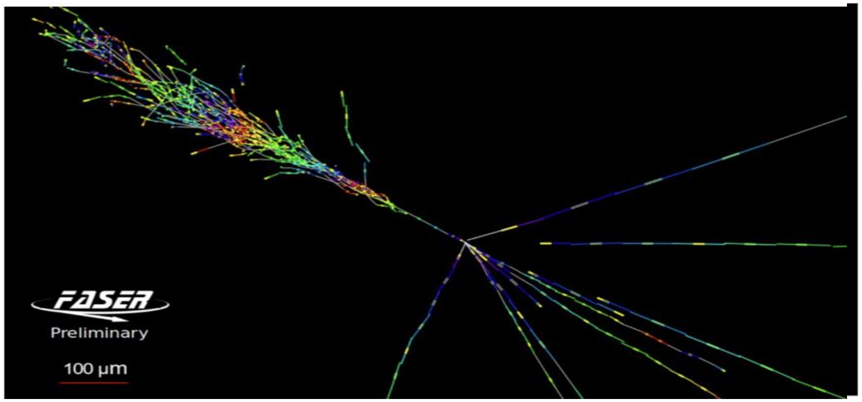


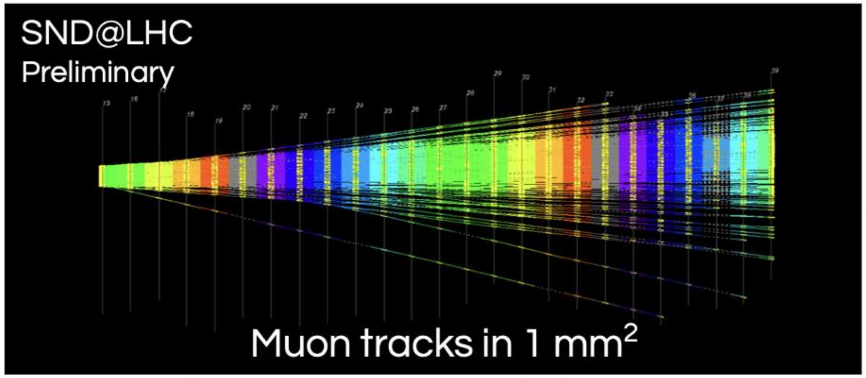
- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

SND@LHC & FASER

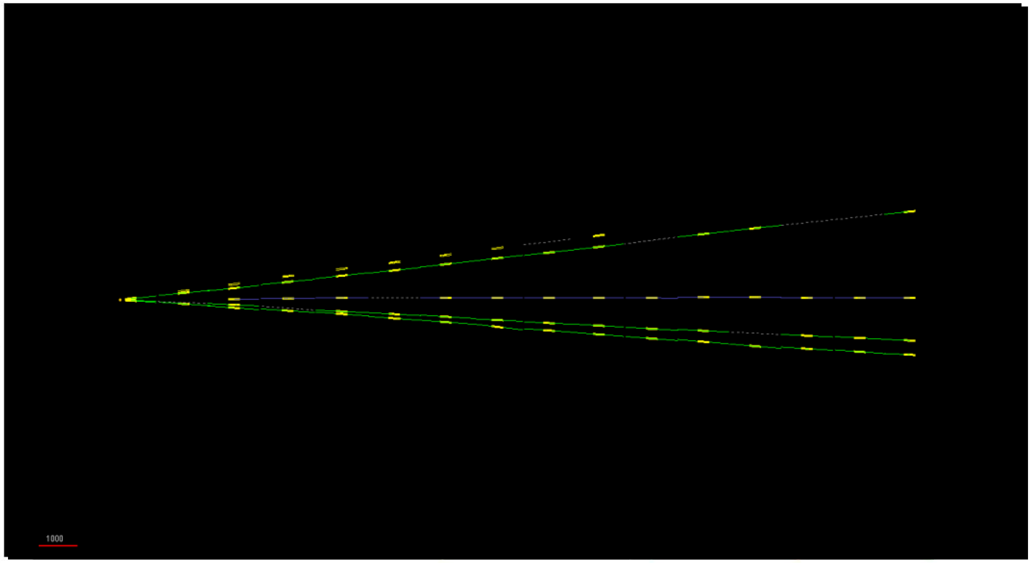
Emulsion detector analyses

Analysis of emulsion detector data is ongoing



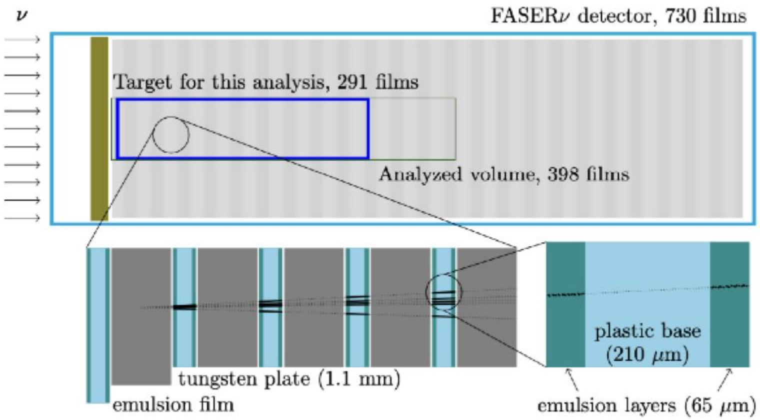


10^5 tracks/cm^2 in 10 fb^{-1} exposure



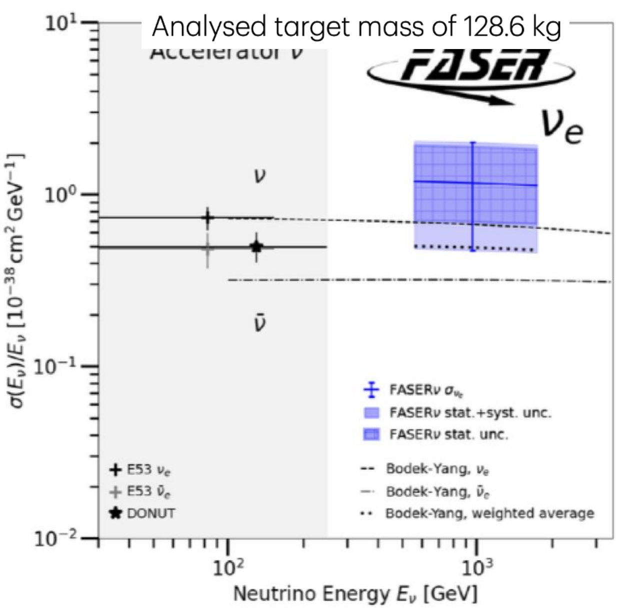
- Significant parts from 2022 data have been already scanned. 2023 data to start
- Examples of vertices found based on predictions from electron detectors

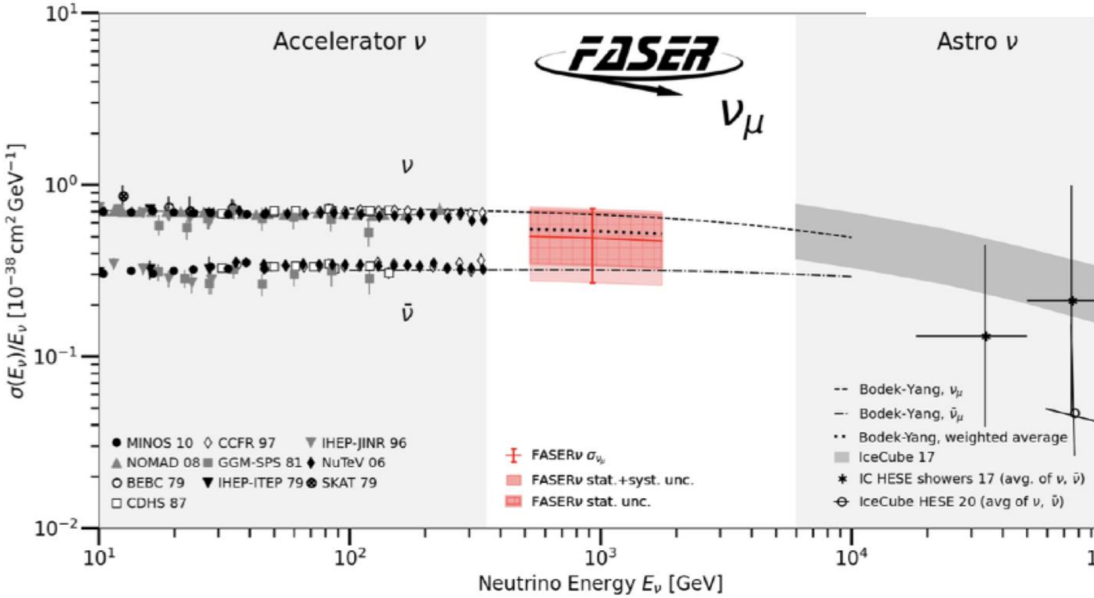
ν_e and ν_μ Interaction Cross Sections



- Only small fraction of 2022 analyzed so far
- Candidate vertices reconstructed in emulsion films
  - Energy measurement (e) from shower multiplicity
  - Momentum measurement (μ) from track RMS (via Multiplescattering)
- Electron neutrino events observed: 4 (5.2σ)
- Muon neutrino events observed: 8 (5.7σ)

2403.12520





Light Long Lived Particles

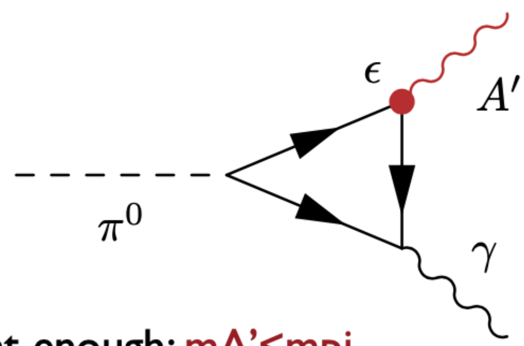
There are light long-lived particles in the SM: muon, pion, kaon, neutron …

many BSM scenarios also include (light) long-lived particles

Example: dark photon

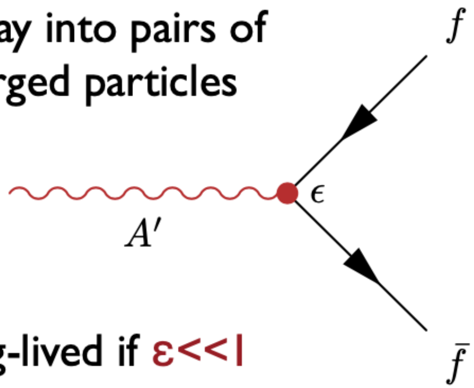
similar to the SM photon but with mass mA’ and couplings to SM particles suppressed by ε

$$\mathcal{L} = \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu + \sum \bar{f}(i\,\partial\!\!\!/ - \epsilon e q_f A\!\!\!/') f$$



if light enough: mA’<mpi
produced via meson decays

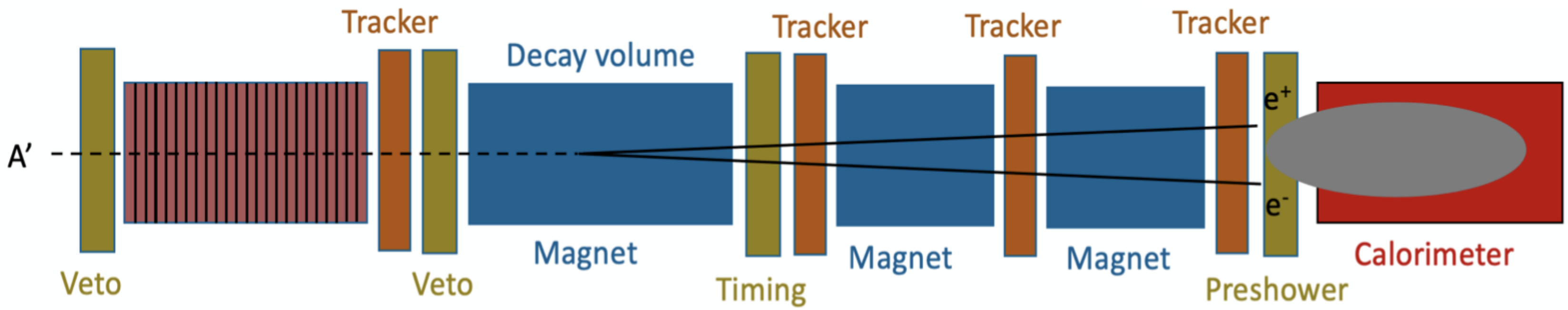
- decay into pairs of charged particles



- long-lived if ε<<1 lifetime

FASER: Dark Photon Search

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



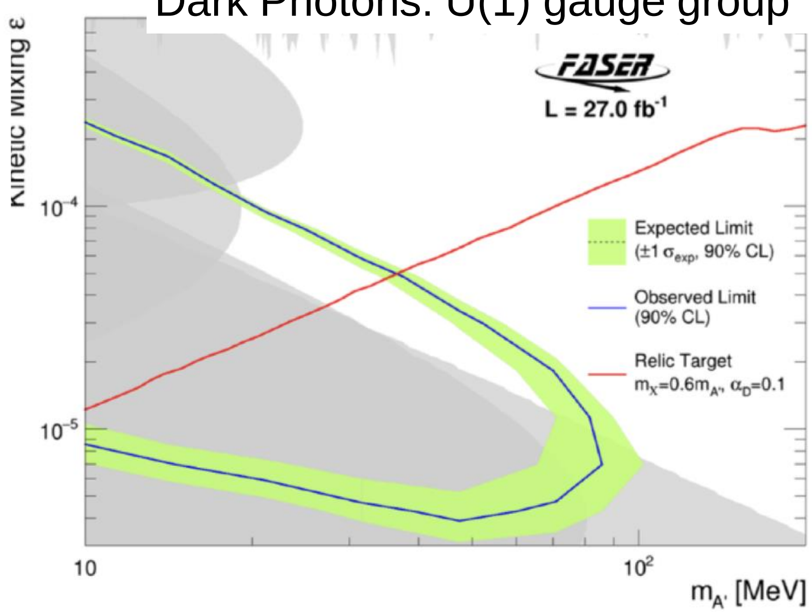
PLB 848, 138378 (2024)

- 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.

Dark Photons: U(1) gauge group



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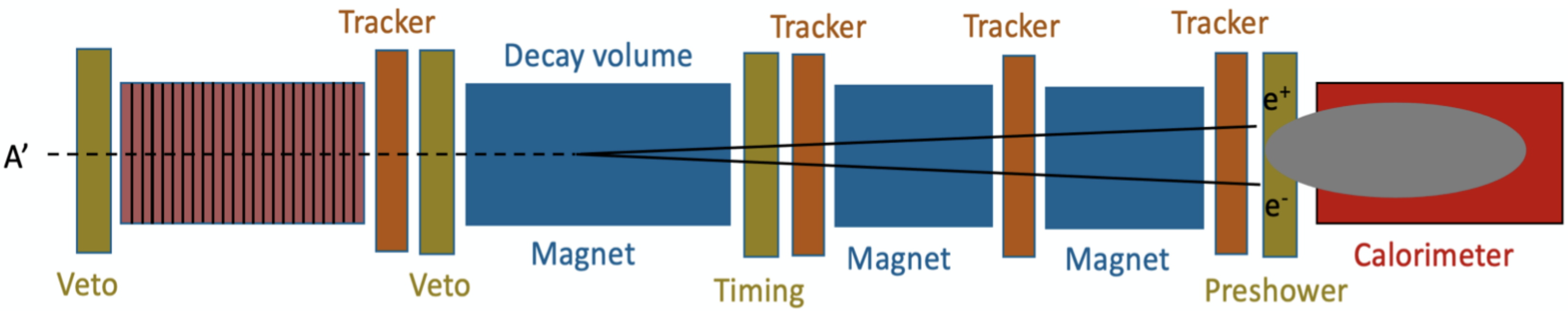

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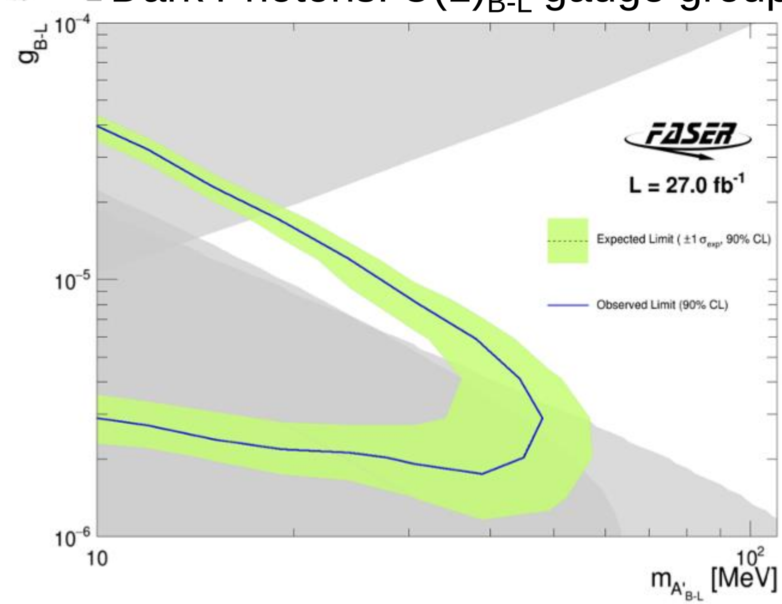
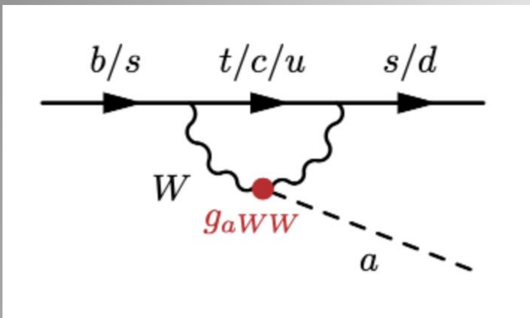
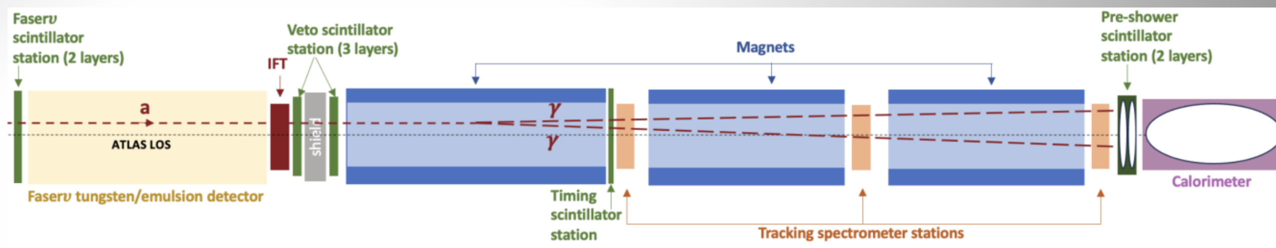
Dark Photons: $U(1)_{B-L}$ gauge group



FASER: Axion-Like Particle Search



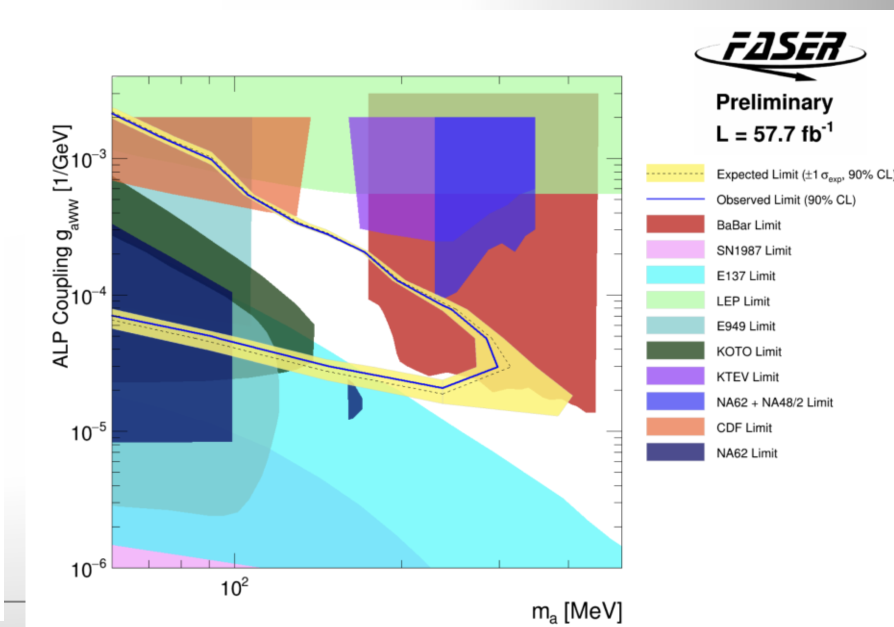


Mainly from
B decays

CERN-FASER-CONF-2024-001

- Currently sensitive to axion-like particles (ALPs) coupling to $SU(2)_L$ gauge bosons
- Signature:
  - decay a-> $\gamma\gamma$ with >1 TeV in calorimeter
  - No signal in veto counters
  - In time with LHC collision
  - Background dominated by neutrinos interacting in the detector material!

1 event observed / 0.4 +/- 0.4 expected

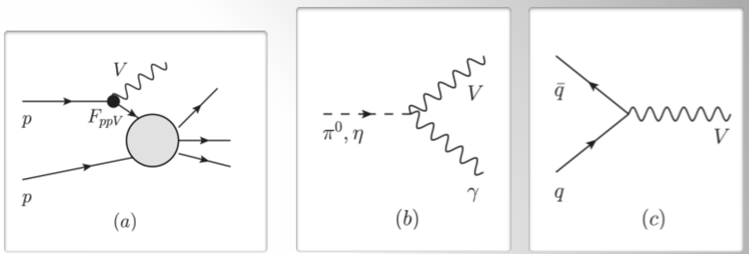


More BSM Searches to Come

▸Eg. SND@LHC sensitivity for light dark matter

Production: consider a scalar χ particle coupled to the Standard Model via a leptophobic portal,

$$\mathcal{L}_{\rm leptophob} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$

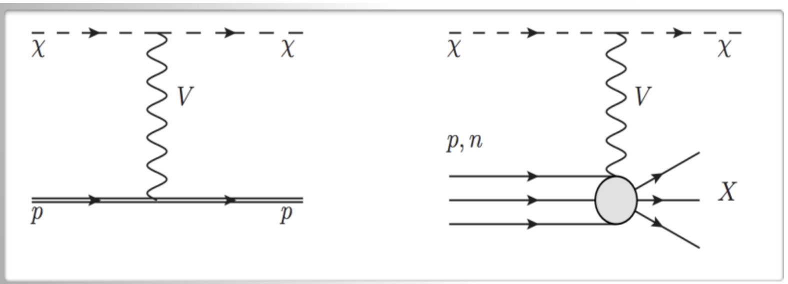


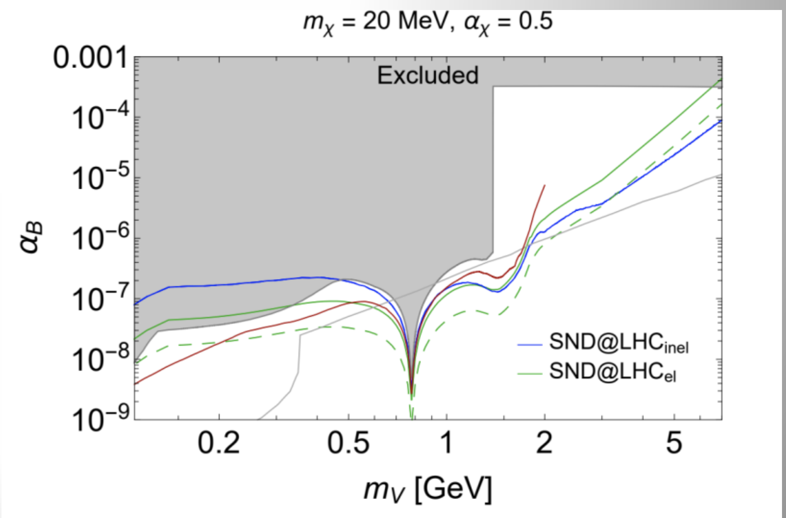
Proton bremsstrahlung

Meson decay

Drell-Yan process

Detection: χ elastic/inelastic scattering off nucleons of the target



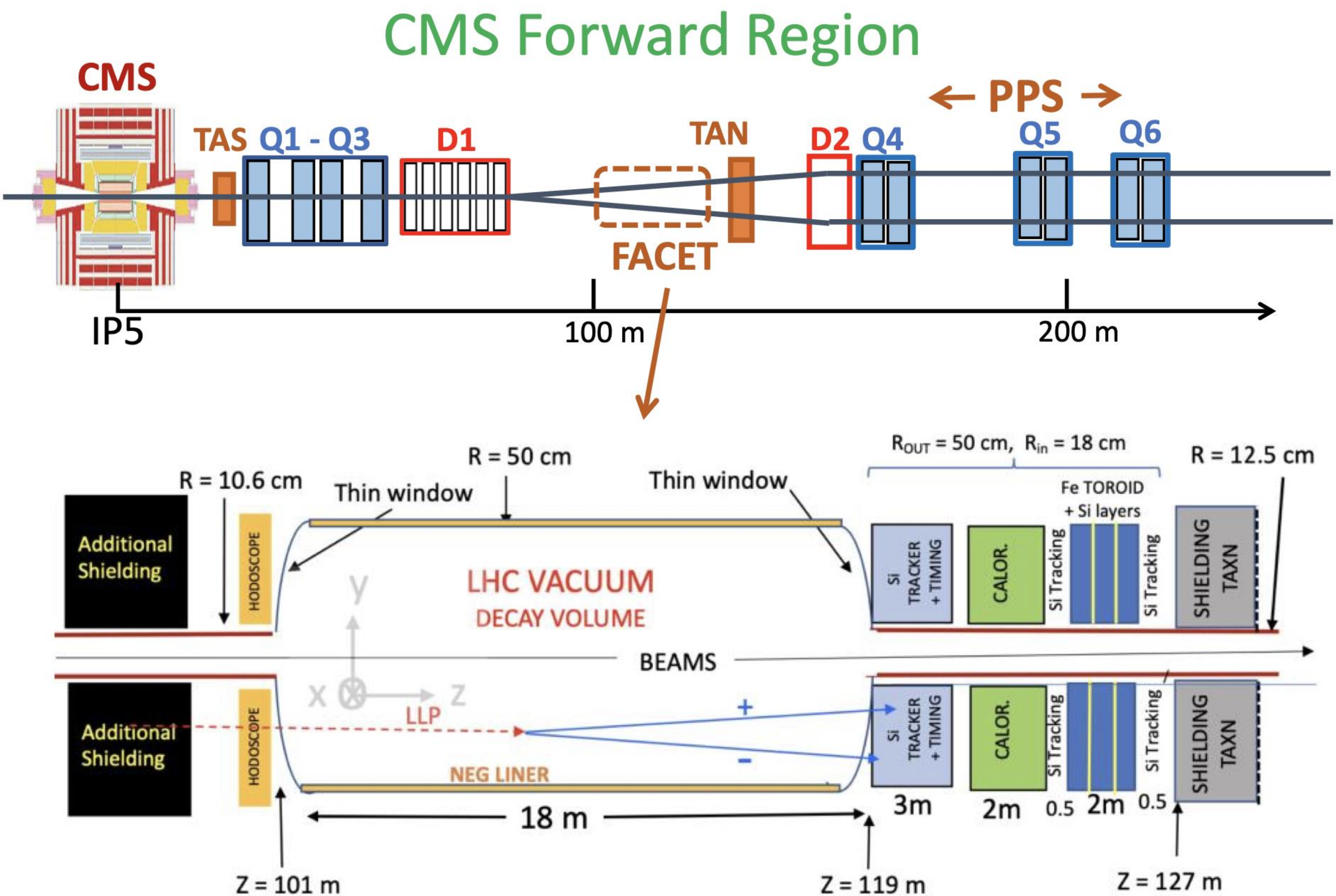


- More channels to explore by SND@LHC and FASER

➔ Higgs-like scalars, Heavy Neutral Leptons, final state radiation effects, Quirks, LFV with tau excess, exotic interactions…

JHEP 03 (2022) 006

FACET



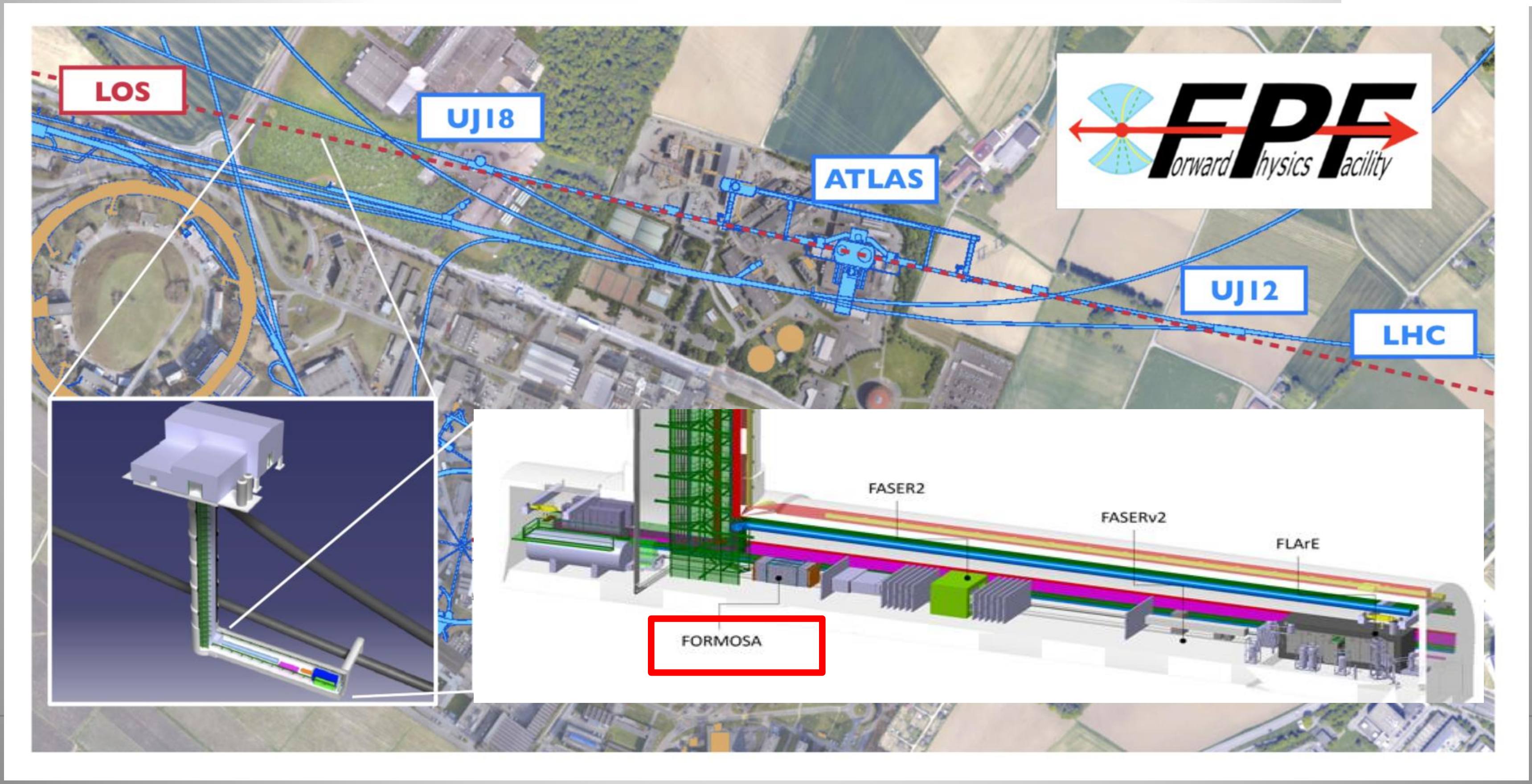
CMS Forward Region
CMS
TAS
Q1 - Q3
D1
TAN
D2
Q4
← PPS →
Q5
Q6
FACET
IP5
100 m
200 m
R = 10.6 cm
Thin window
R = 50 cm
Thin window
R_OUT = 50 cm, R_in = 18 cm
R = 12.5 cm
Additional Shielding
HODOSCOPE
LHC VACUUM
DECAY VOLUME
y
x
z
LLP
+
-
NEG LINER
BEAMS
Si TRACKER + TIMING
CALOR.
Si Tracking
Fe TOROID + Si layers
Si Tracking
SHIELDING TAXN
Additional Shielding
HODOSCOPE
Si TRACKER + TIMING
CALOR.
Si Tracking
Si Tracking
SHIELDING TAXN
18 m
3m
2m
0.5
2m
0.5
Z = 101 m
Z = 119 m
Z = 127 m

An Option for the FUTURE:
The Forward Physics Facility

NEW: The Forward Physics Facility

Origin: 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): FASER2, others

2203.05090



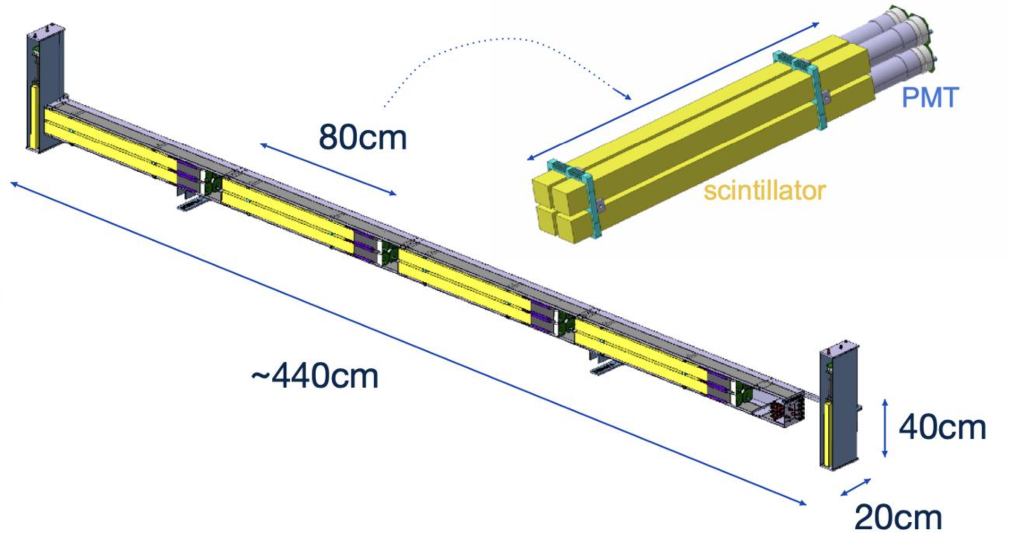
FORMOSA Demonstrator

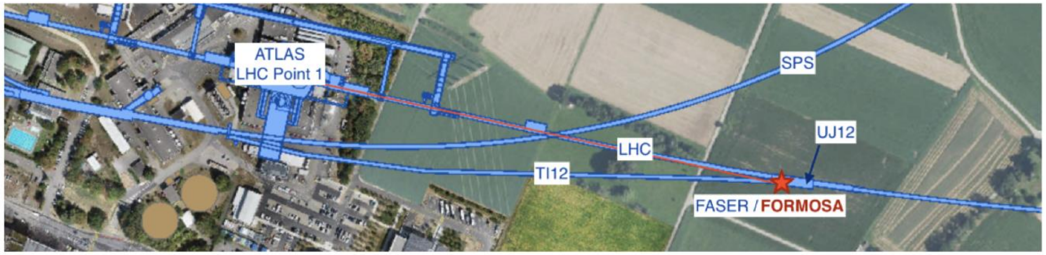
A small-scale version of the full FORMOSA was installed during YETS 2023

→ 2rows x 2columns x 4 layers

Located in the UJ12 cavern (behind FASER), in the opposite side of the to-be FPF

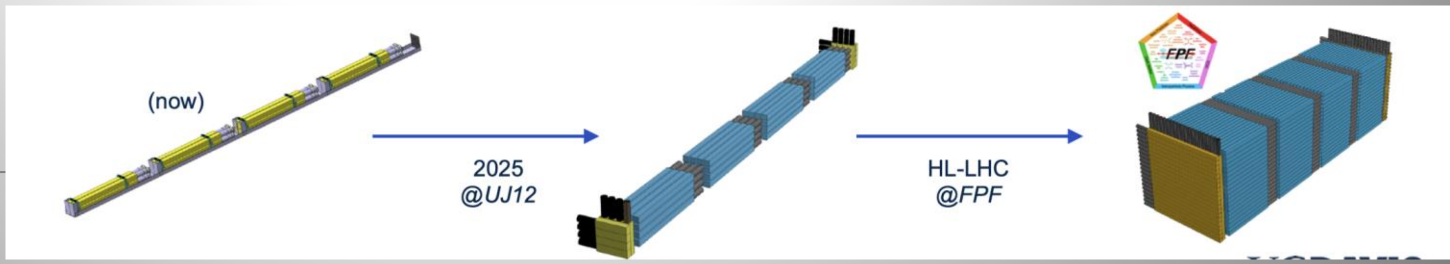
The demonstrator allows to **prove concept** and **target new phase space**





UCDAVIS

Expected evolution over the next few years



Non-Collider Experiments

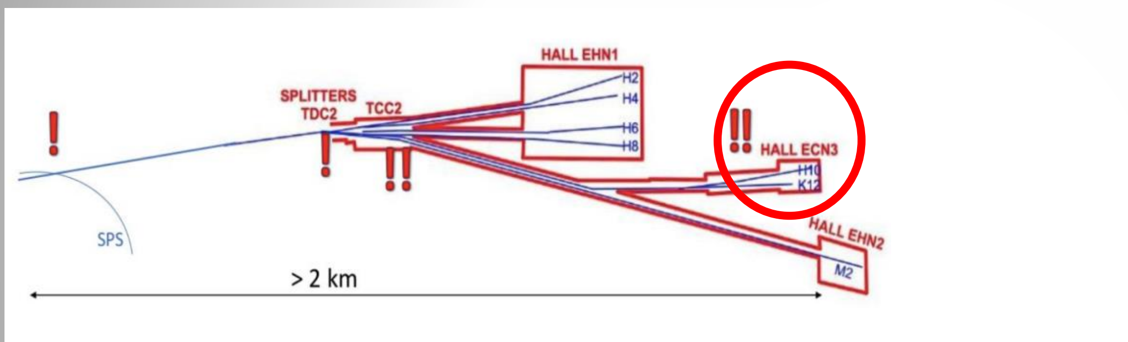
- Neutrino Experiments
- Beam Dump Experiments
- High Intensitiy Experiments

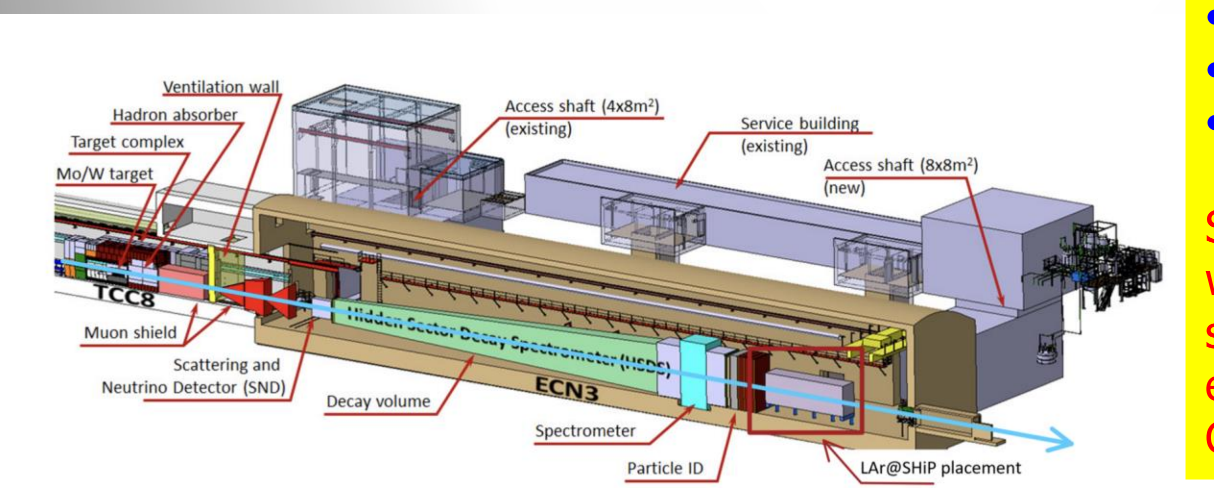
…

Ongoing and planned projects:
Belle-II, BES-III,NA62, NA64, MixroBooNE, T2K, DAMSA, Shiness, LUXE, SUBMET,…

New: The SHiP Experiment

NEWS: March 24 CERN management selected SHiP as the experiment for the new beam dump facility for the CERN fixed target North Hall. SHiP foreseen to take data as of ~2030 for 15 years





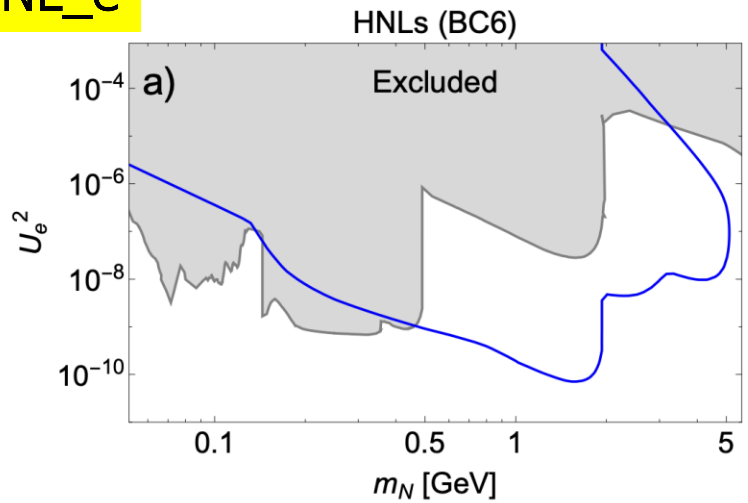
SHiP is an optimized detector for searches for Feebly Interacting Particles (FIPS) such as:

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

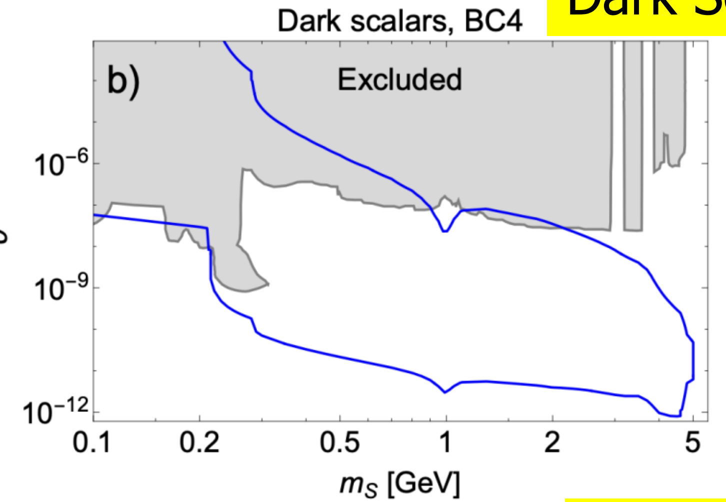
SHiP will be a 15+ year program with a ~2 orders improved sensitivity compared to present experiments in the region of a few GeV

SHiP Physics Prospects

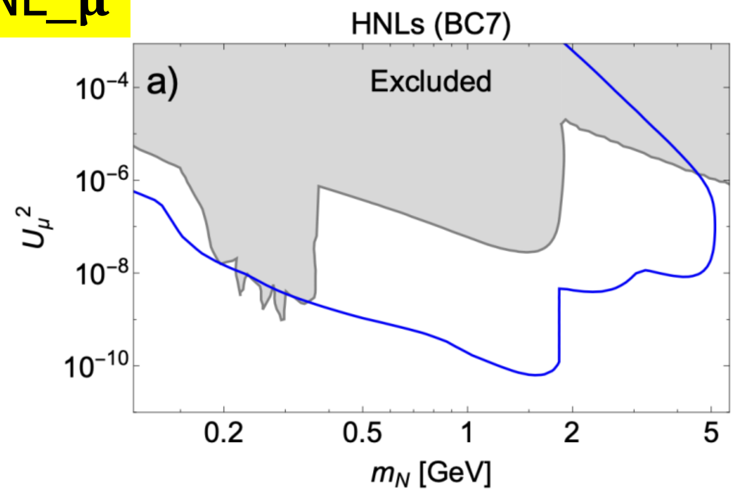
HNL_e



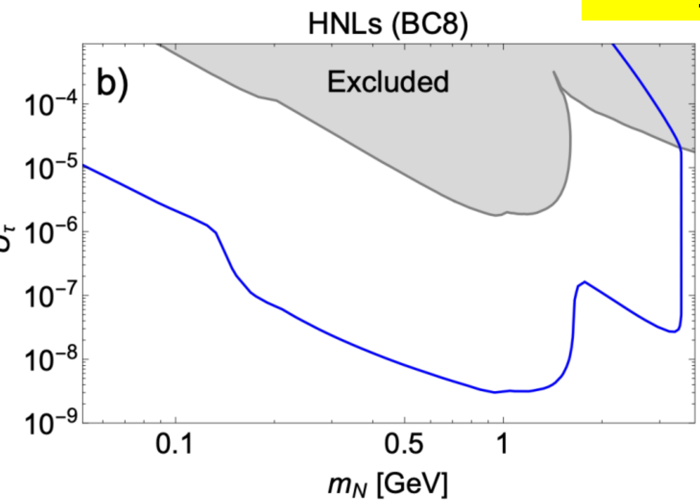
Dark Scalars



HNL_μ



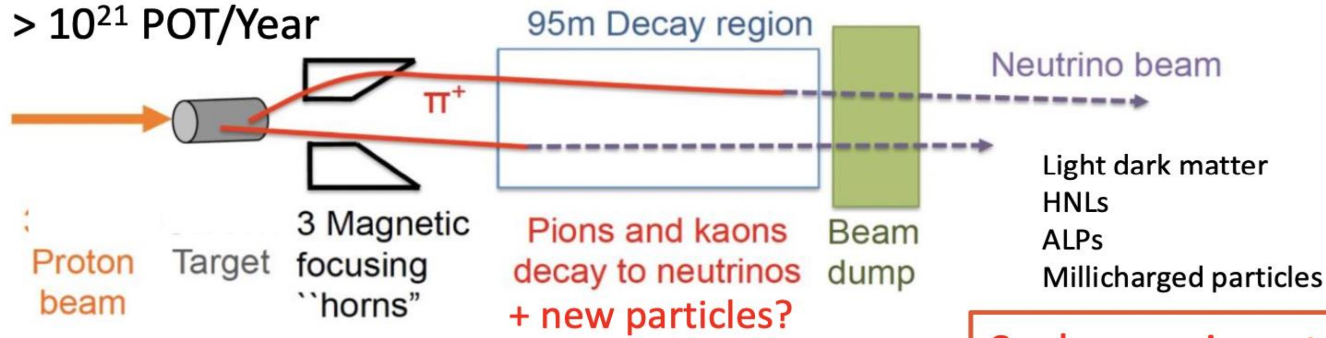
HNL_tau



All plots are based on 6×10^{20} PoT, and limits correspond to 90% CL, translating to 2.3 events in the absence of background

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



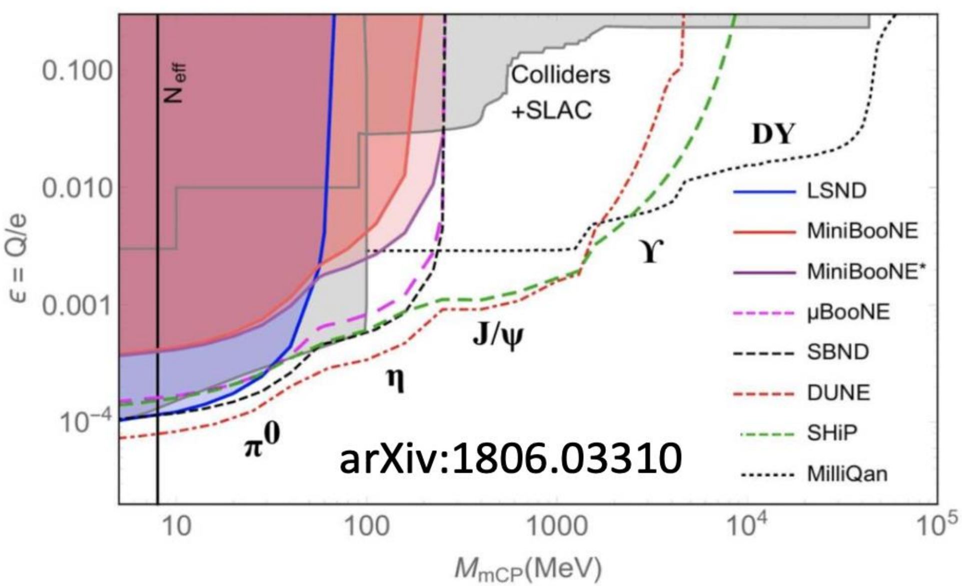
Near Detectors are ~475 m away from target

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], .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

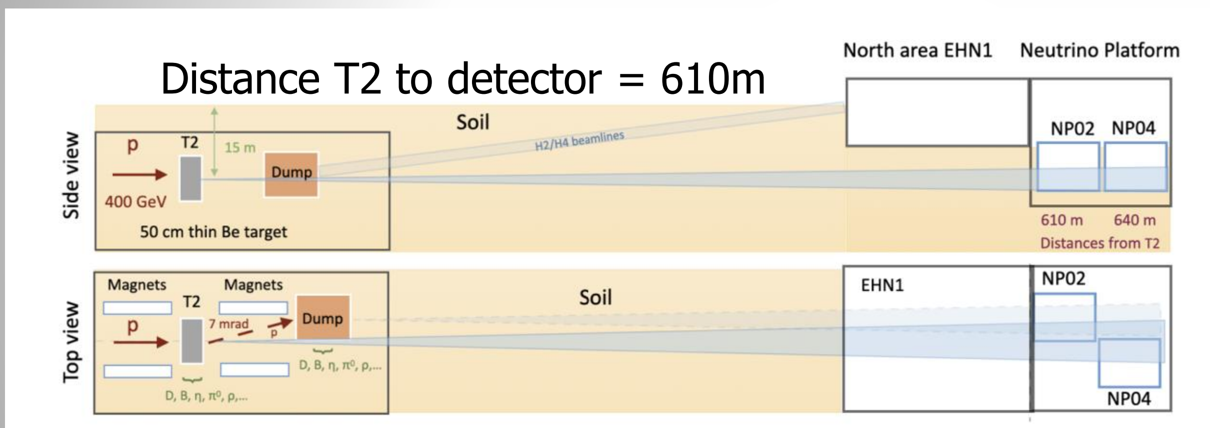
ProtoDUNEs for BSM Searches?

arXiv:2304.06765

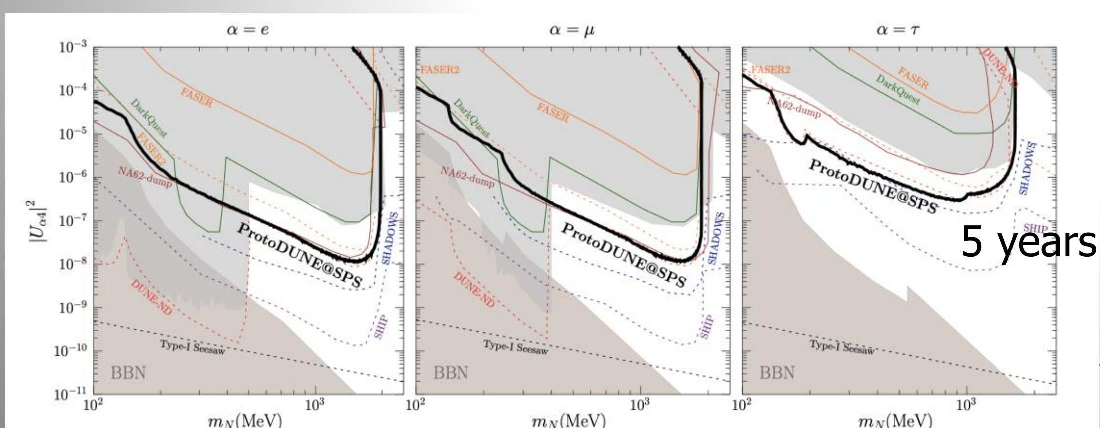
New Physics searches using ProtoDUNE and the CERN SPS accelerator

Pilar Coloma,[1,*] Jacobo López-Pavón,[2,†] Laura Molina-Bueno,[2,‡] and Salvador Urrea[2,§]

Use the ProtoDUNE detectors to hunt for weakly interaction LLPs or light dark matter scattering? The 'beam' comes for free!!



The T2 target in the North Hall "acts" like a beam dump for the 400 GeV SPS beam, and can deliver 3.5×10^{18} POTs/year

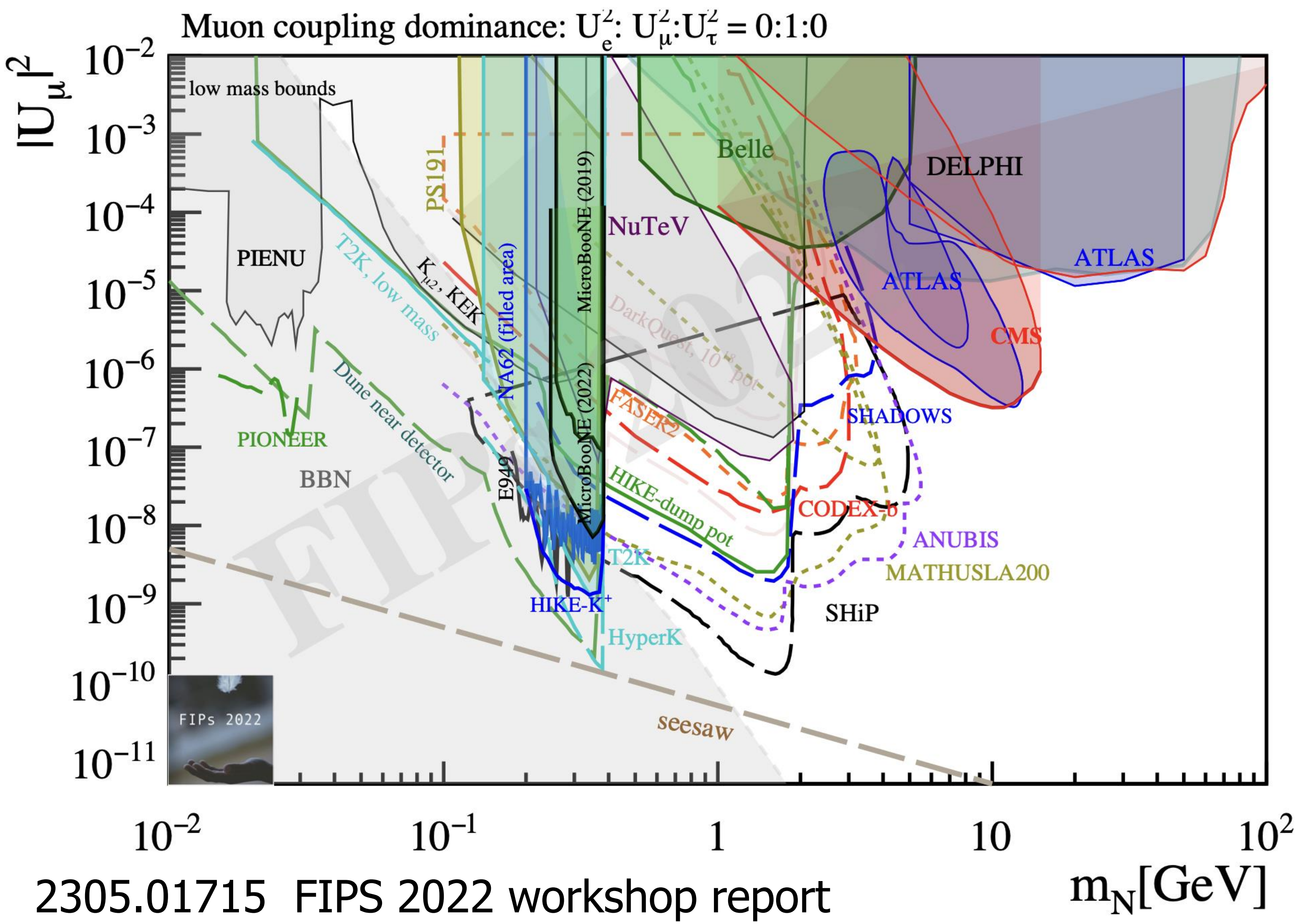


HNL Sensitivity: Competitive for masses above the Kaon threshold

Experimental feasibility study ongoing…

Physics Beyond Colliders

Example: Heavy Neutral Leptons



2305.01715 FIPS 2022 workshop report

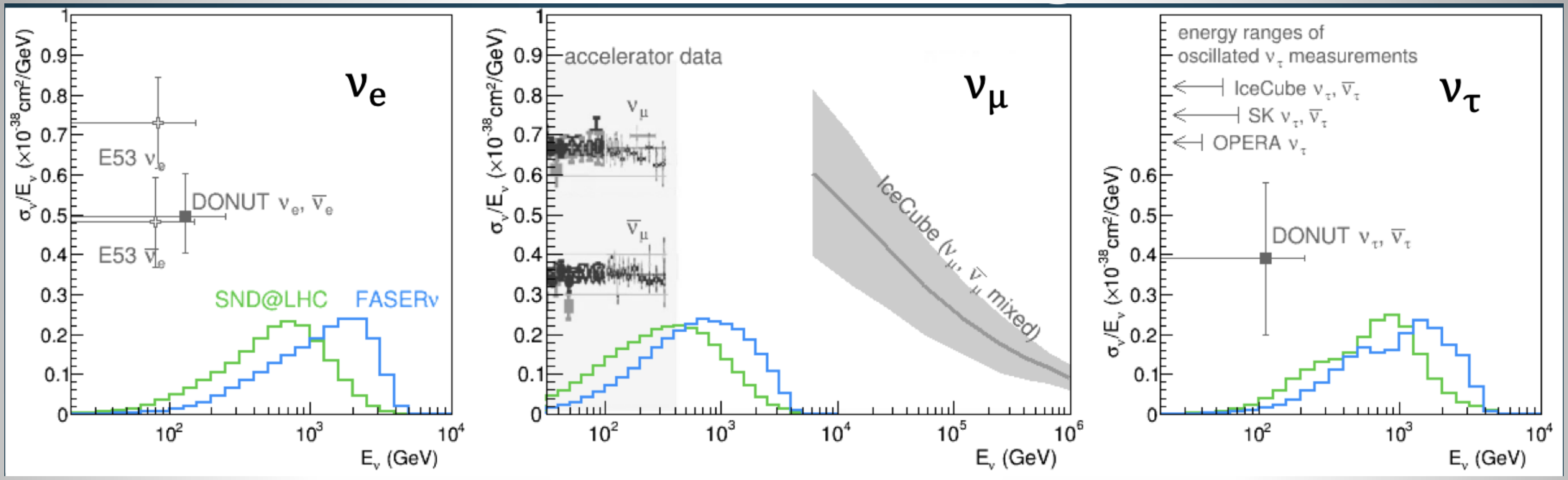
Summary

- Clearly and increased interest in low mass/coupling and LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. Many analyses done or in are progress. No signal observed yet, but 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…. LLPs also focus in the "Physics Beyond Collider" studies @ SPS (SHiP…. ProtoDUNEs?)
- New: FASER & SND@LHC Ready and take run 3 data
- Milliqan: Technology works: ->now several c
- Snowmass21 process: . Several new ideas experiments at the LHC proposed recently: t
- If we would observe one significant anomaly

Backup

Neutrinos at the LHC

Cross section/neutrino energy

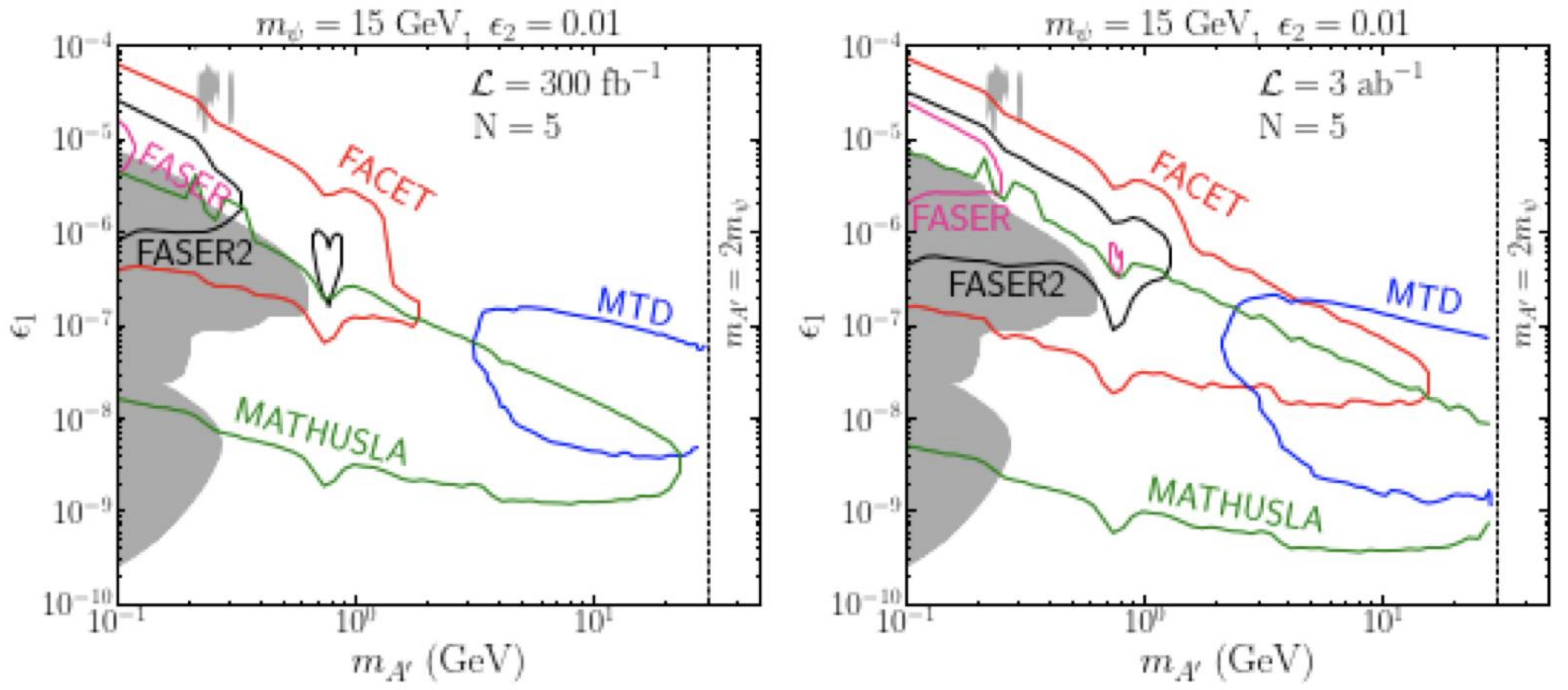


- Highest neutrino energy made by man-kind
- Behavior of neutrinos at TeV energies?
- Lepton Universality in neutrino scattering?
  - ν_τ and heavy quarks → Flavor anomaly e.g. R_D
- Any new physics effects at high energy?

FACET

Dark Photons

Mingxuan Du, Rundong Fang, Zuowei Liu and Van Que Tran, Enhanced long-lived dark photon signals at lifetime frontier detectors, arXiv:2111.15503v1 [hep-ph] 30 Nov 2021

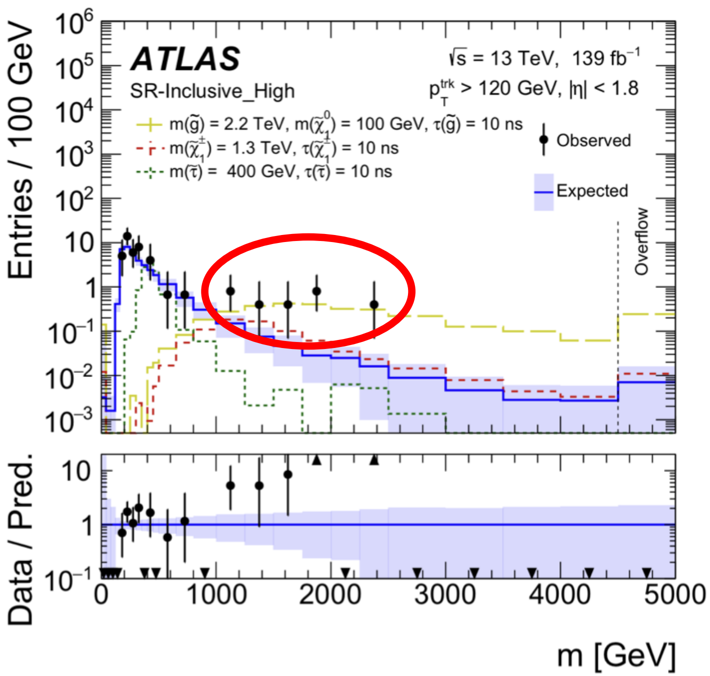


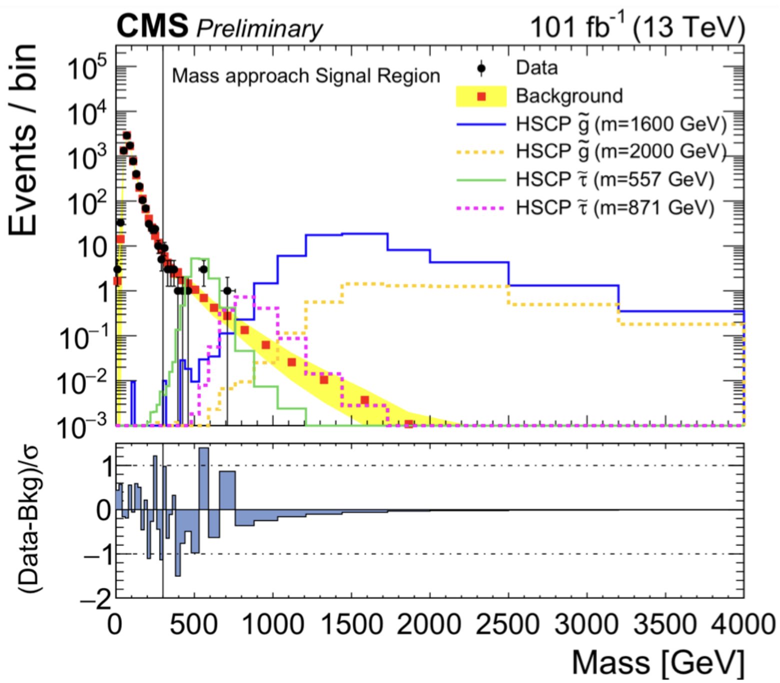
Heavy Stable Charged Particles

- ATLAS saw an intruiging excess in high de/dx particles in 2022 2205.0613
- CMS released a similar analysis to ATLAS but no excess observed

- ATLAS found a 3.3σ global excess in their Run 2 analysis
- But CMS **does not** see any excesses in the same region

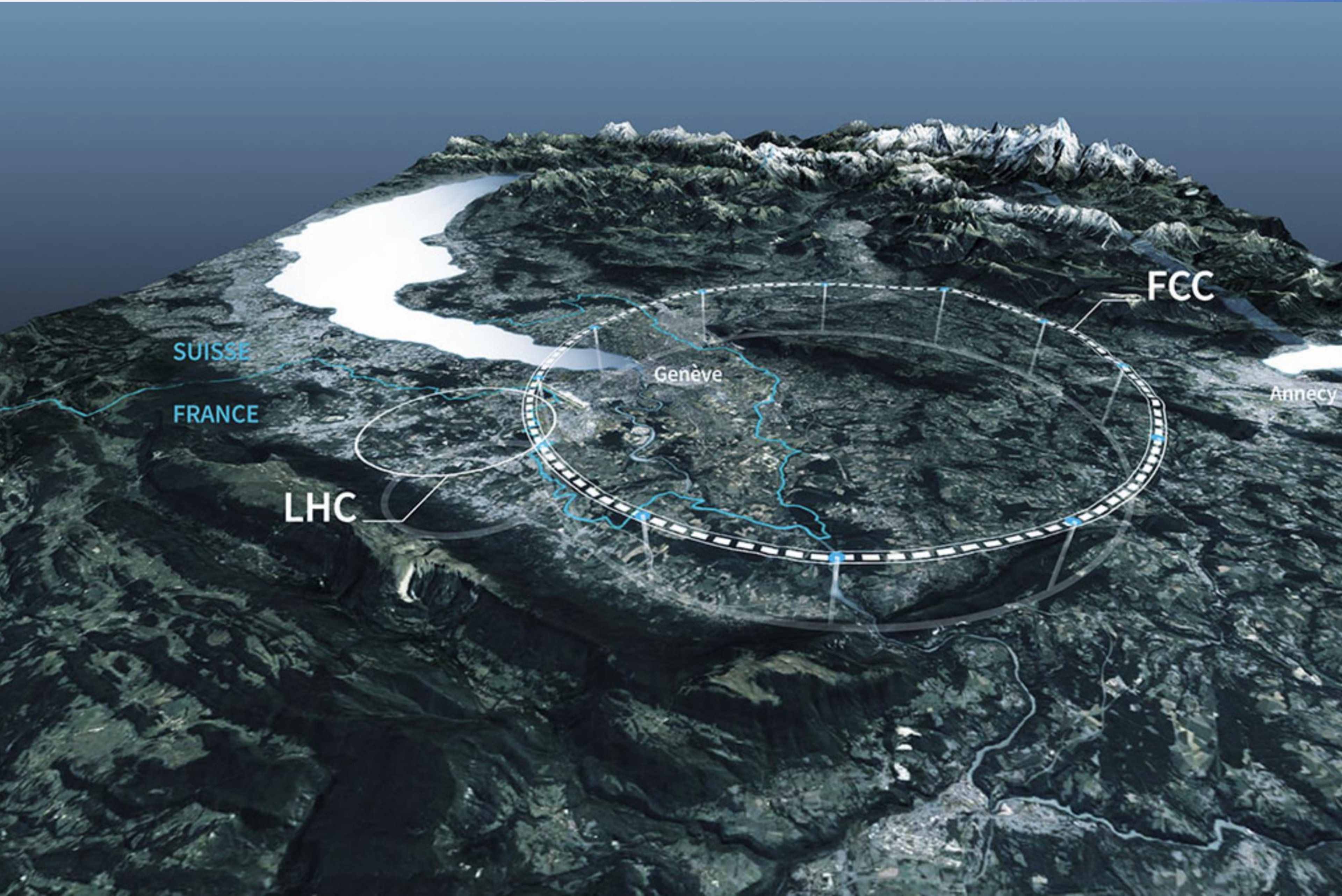
CMS-EXO-18-002





Also no significant excess in different ATLAS de/dx analysis

Future Colliders

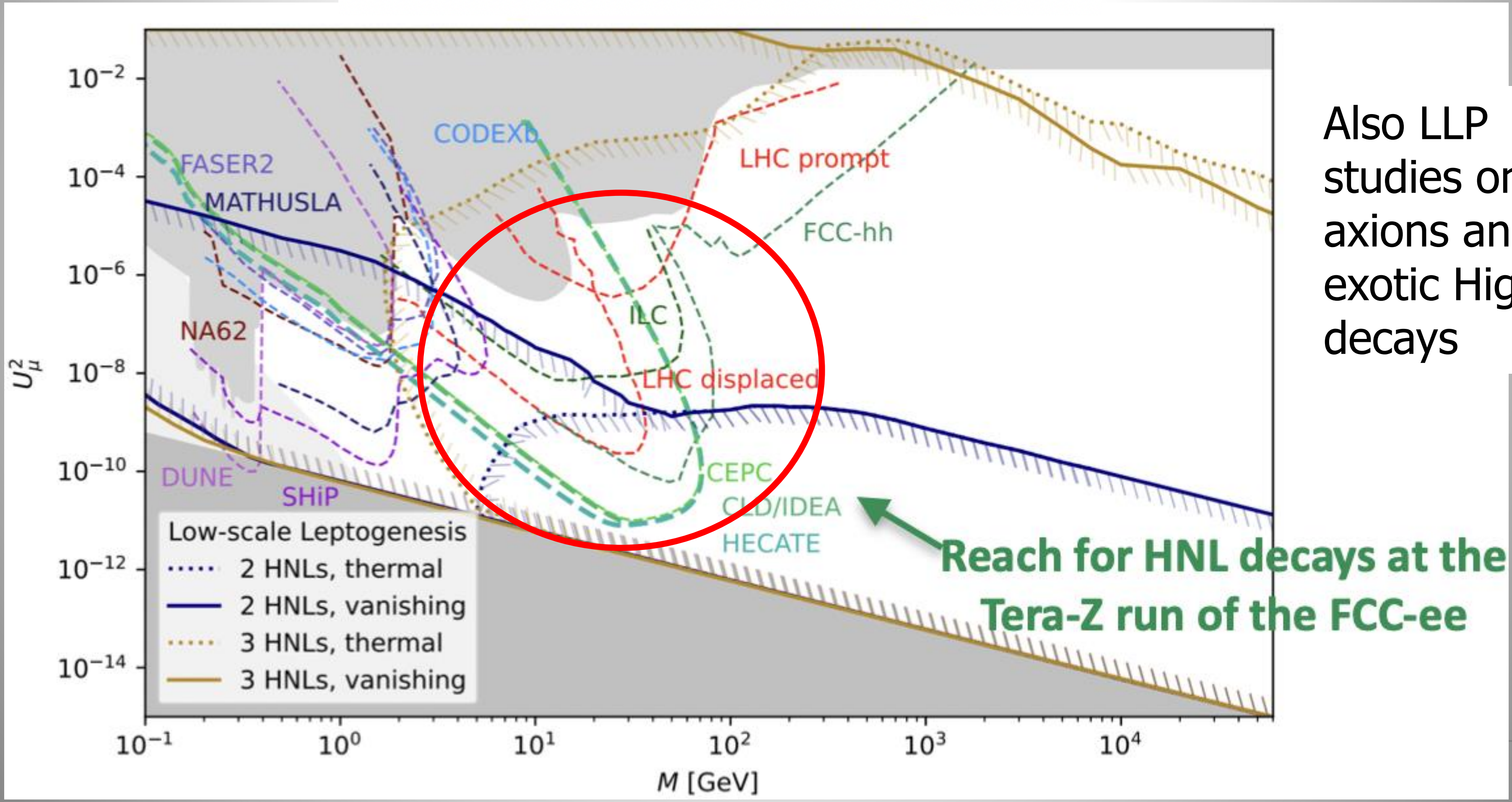


FCC-ee Studies

FCC_ee reach for HNLs, for $5x10^{12}$ 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



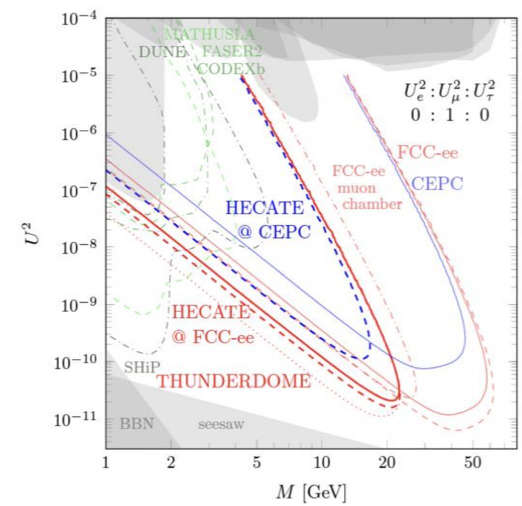
Also LLP studies on axions and exotic Higgs decays

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!

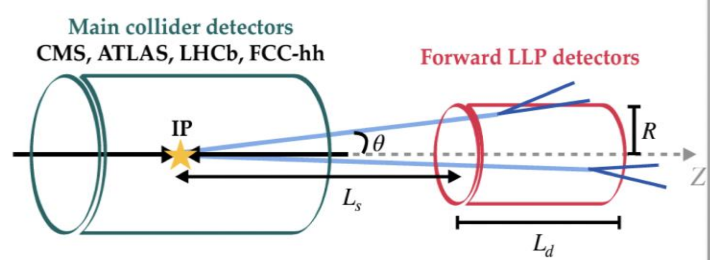


Lepton collider ideas:

- **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

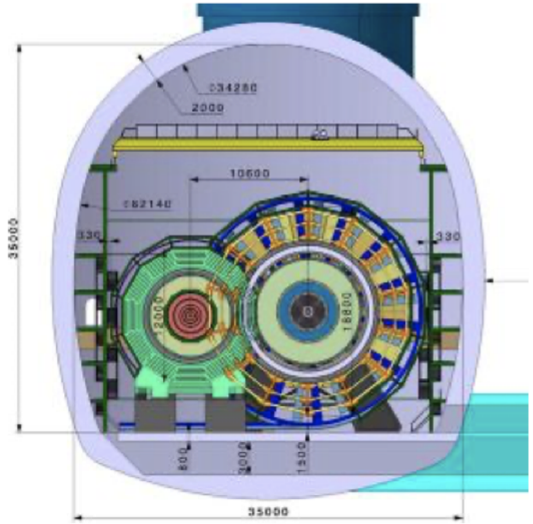
HECATE: Instrument the cavern walls! Cover DLs up to 15 meters

LLPs @ FCC-hh, FCC-ee

Proposal: 2011.01005

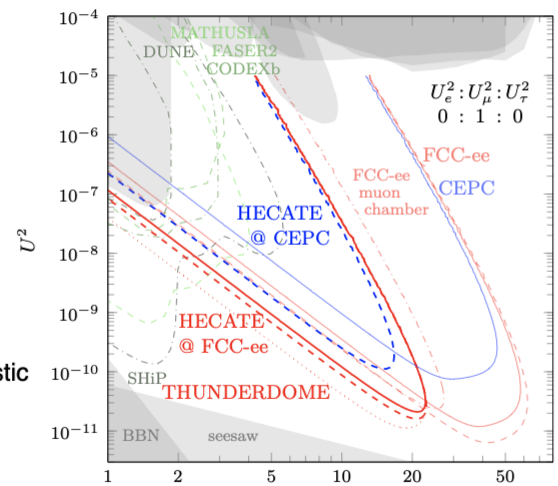
HECATE: HErmetic CAvern TrackER. A long-lived particle detector concept for FCC-ee or CEPC

- 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 m^2 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)

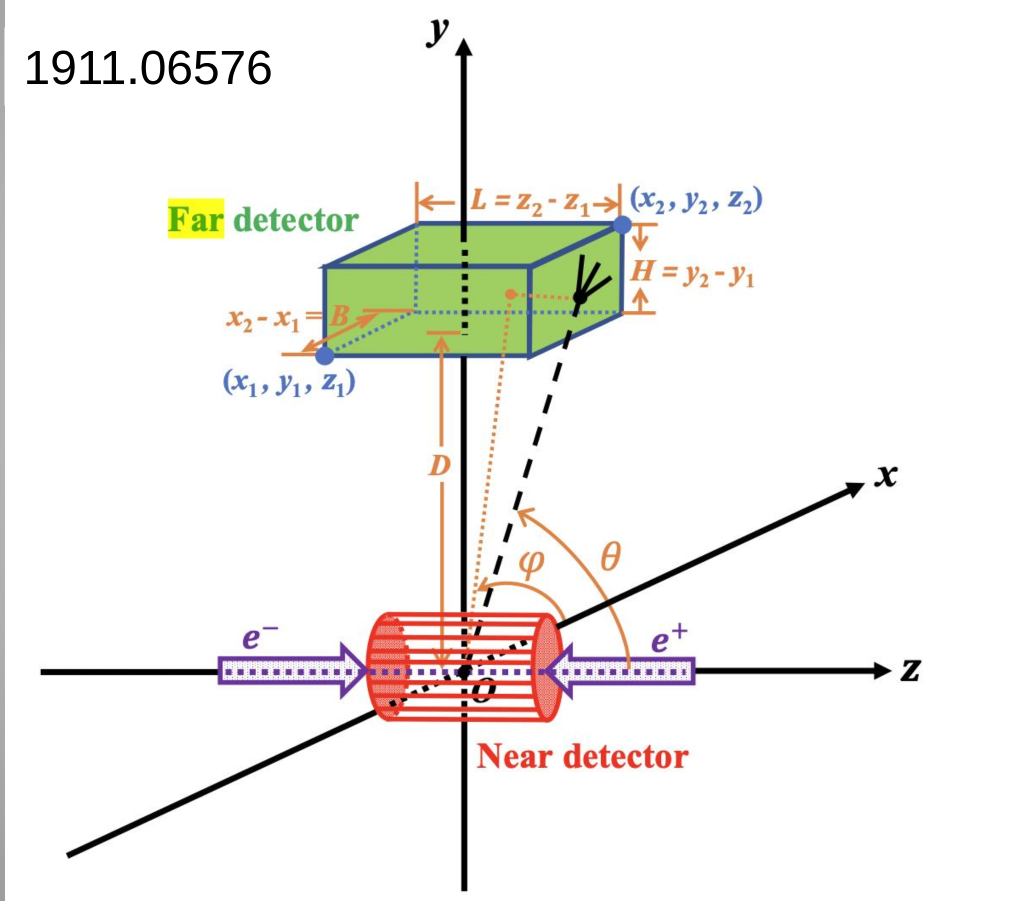
- Example: HNLs
- THUNDERDOME: Totally Hyper-UNrealistic DEtectoR in a huge DOME (maximum distance from IP=100m for comparison)



Ideas for LLP Detectors Future Facilities

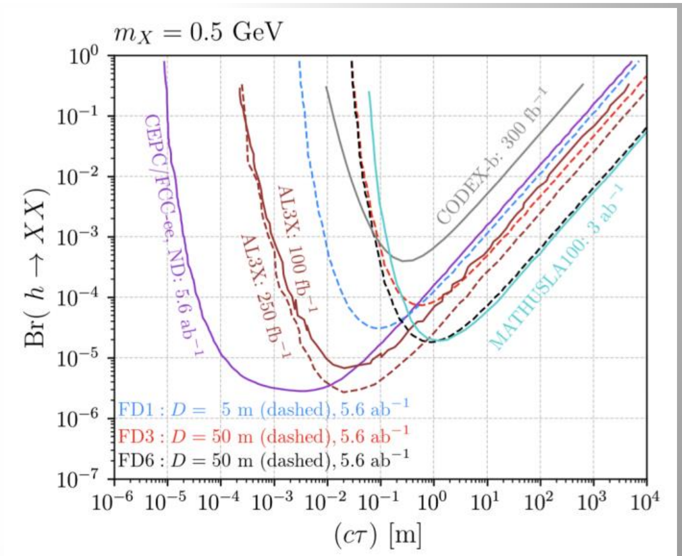
CEPC Studies: the Far Detector

1911.06576



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

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!

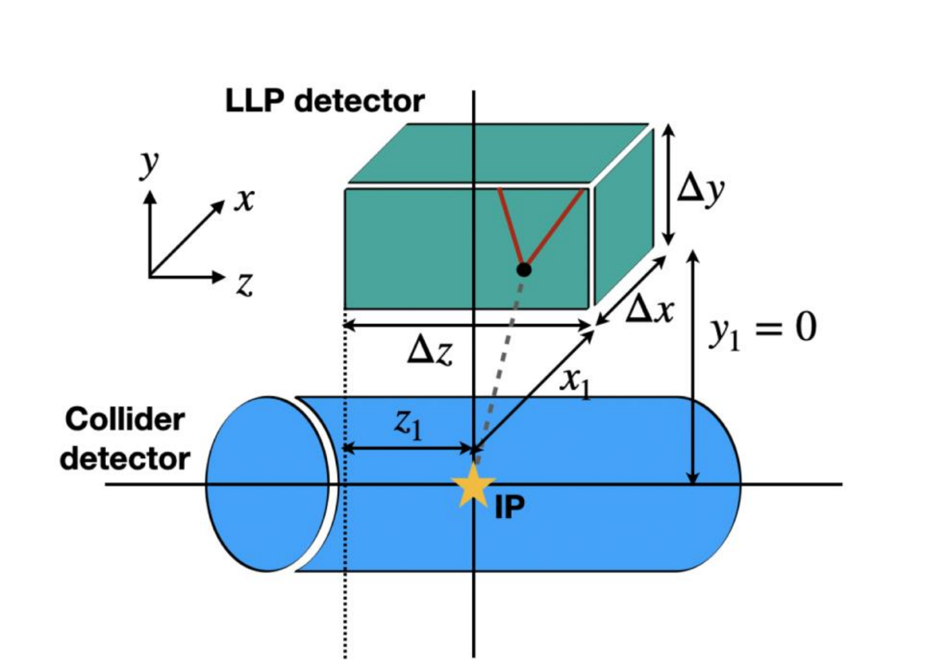
DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

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
$z_1 = -\Delta z/2$

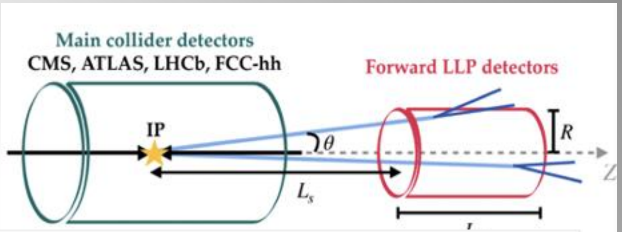
2111.02437
2306.11803



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

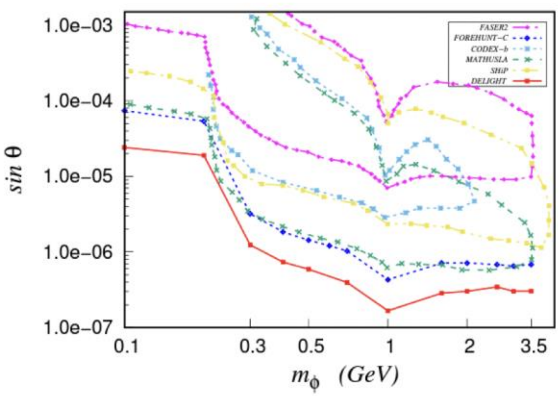
FOREHUNT

- 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

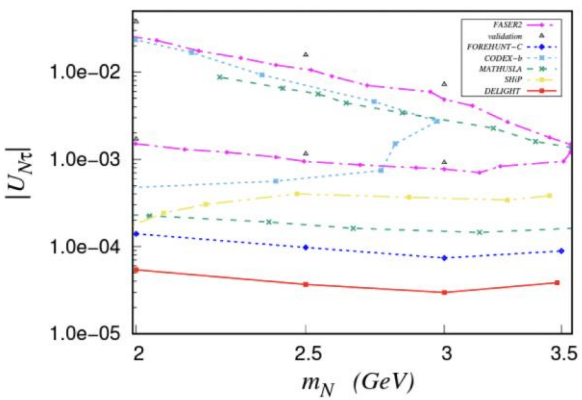
Dark Higgs scalar:

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



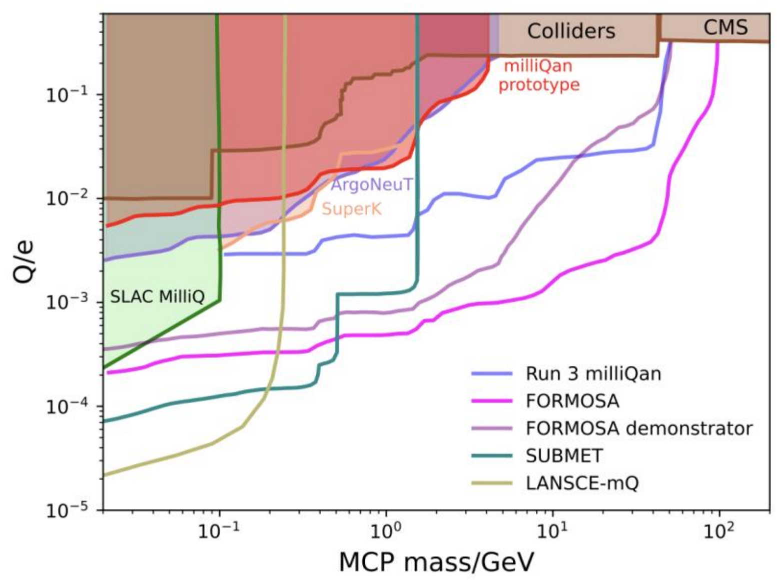
HNLs:

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



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

FORMOSA



Positive outcomes from P5

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 like FASER2 and FORMOSA at the proposed Forward Physics Facility at CERN 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).

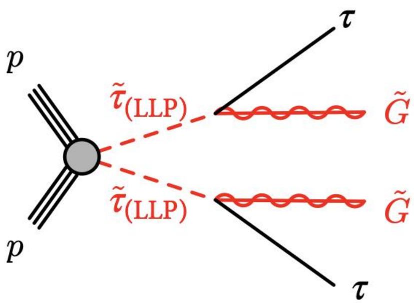
FORMOSA mentioned explicitly as good example of “Agile” project for dark sector sensitivity

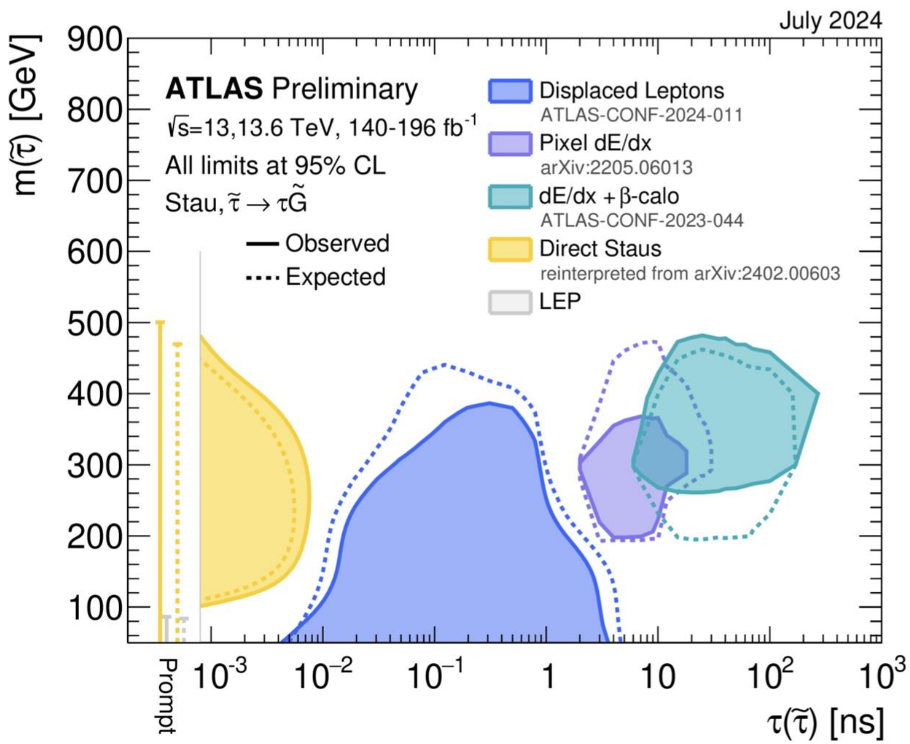
FORMOSA: An experiment to search for millicharged particles in the LHC collisions. It builds on the experience of the MilliQan experiment and is proposed to be housed at the FPF.

Displaced Leptons

New for ICHEP

Displaced Leptons: Big Picture



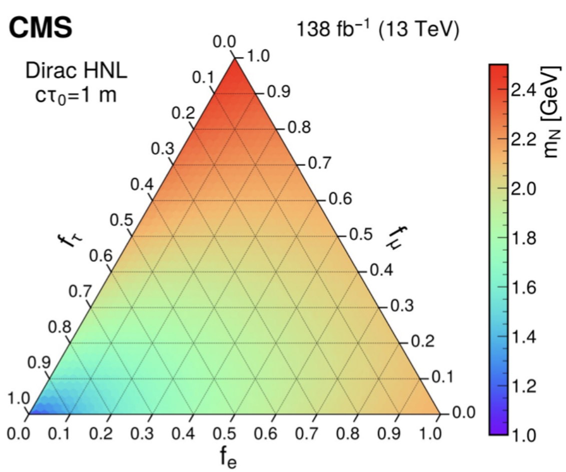


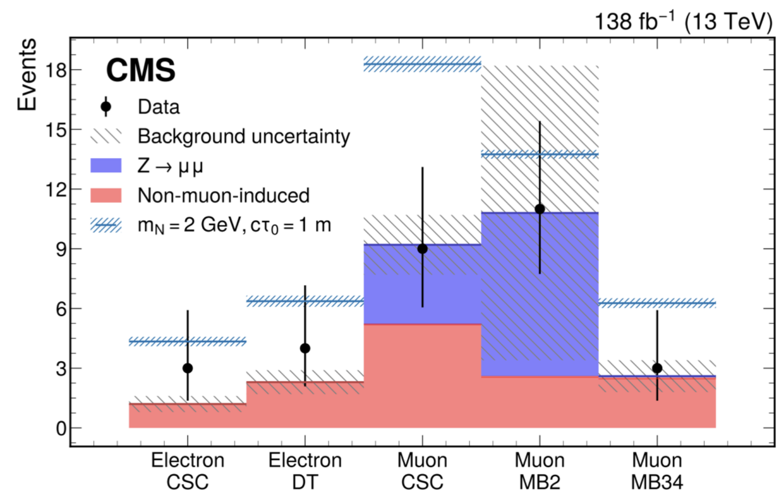
- New results from re-interpretation of **prompt direct staus** [ATL-PHYS-PUB-2024-007] + **Displaced Leptons** offer new sensitivity to staus **(but gaps still remain!)**

HNLs in the muon system

- Now we have published the first search for HNLs using MDS!
- The very large displacement acceptance translates to exquisite sensitivity to small V_{Nl} values in the mass range 1--3 GeV
- See talk by Martin Kwok for more details!

2402.18658
CMS-EXO-22-017



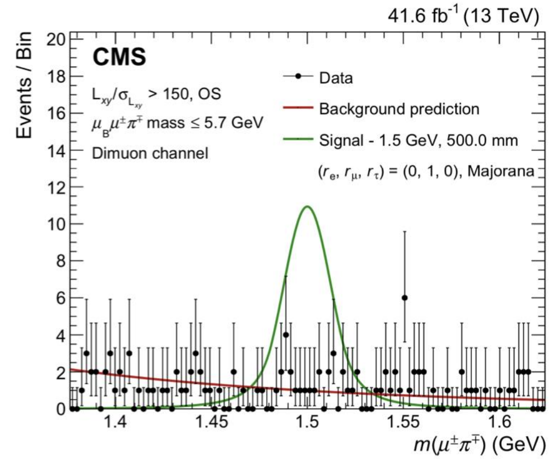


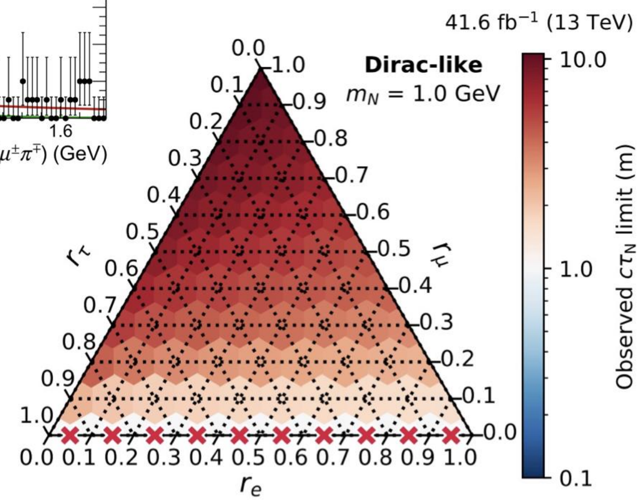
HNLs

HNLs in the B-parking dataset

[2403.04584](https://arxiv.org/abs/2403.04584)
CMS-EXO-22-019

- We present a search for LL HNLs in our Run 2 B-parking dataset
- Look for HNLs produced in B meson decays: $B \to l_B N X$, $N \to l\pi$
- Provides excellent sensitivity in intermediate m_N ranges, ~3-6 GeV
- First EXO search using parking dataset! Anne-Mazarine Lyon's talk will cover this result



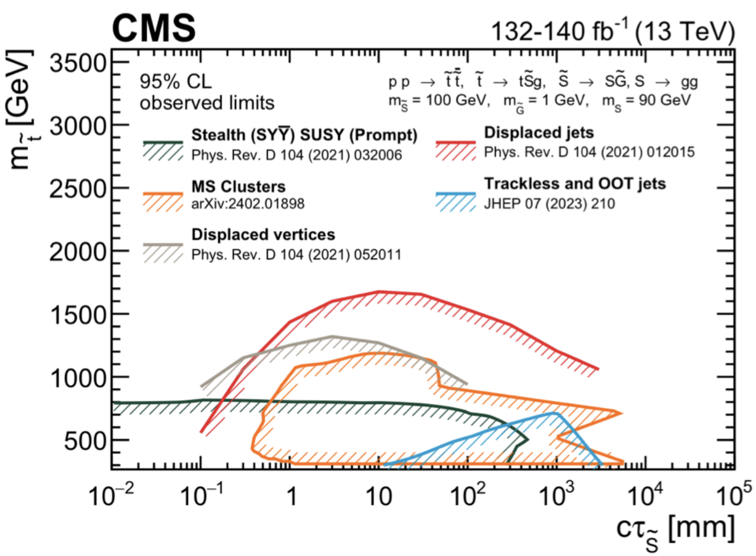


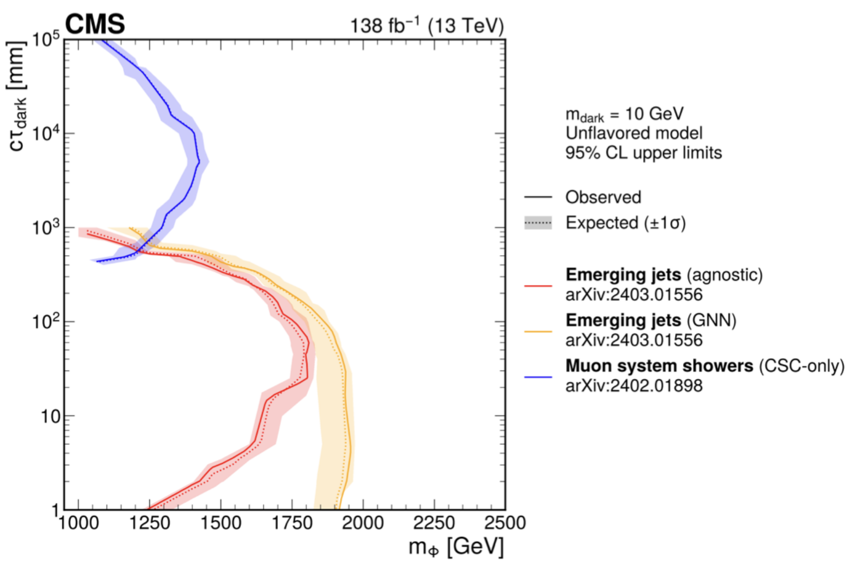
Summary Plots

CMS and dark sectors

- New summary plots of parameter space coverage
- Several LLP searches included in the combinations

[2405.13778](#)
[CMS-EXO-23-005](#)





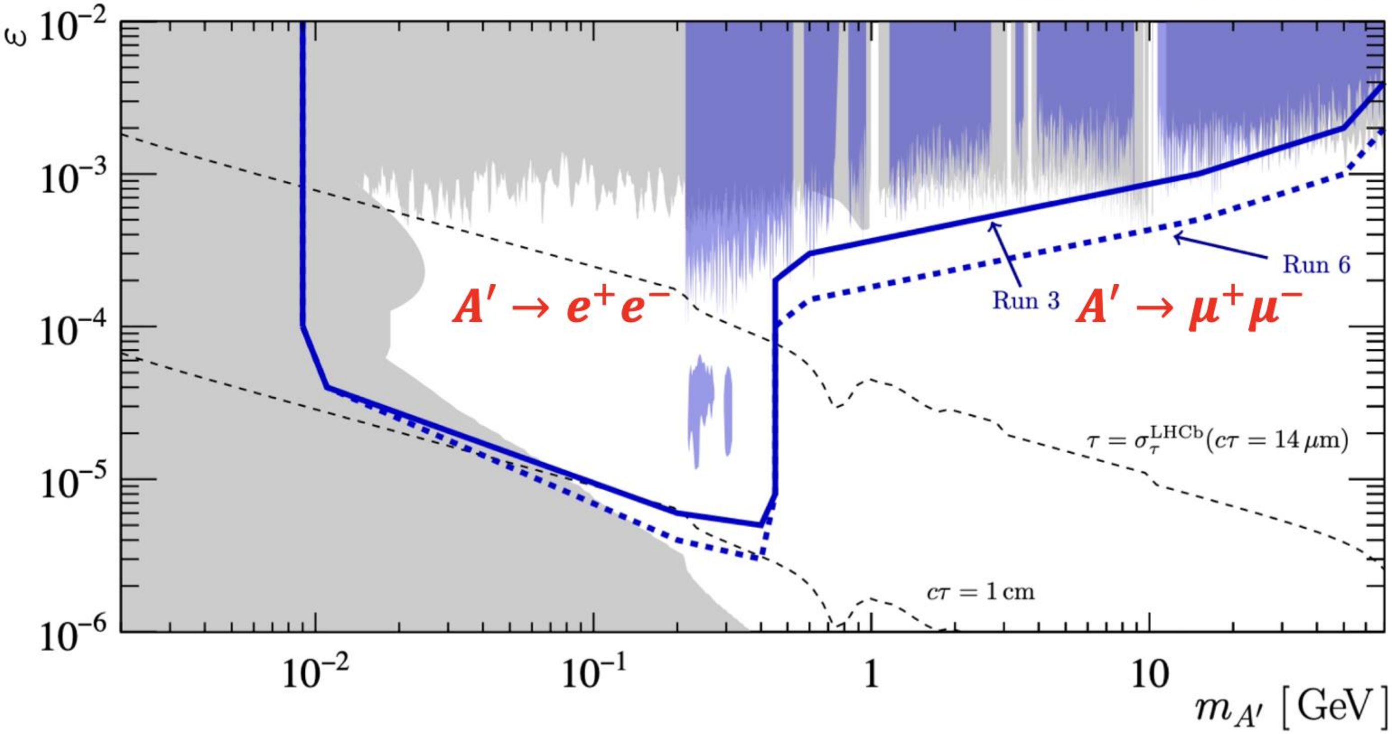
Future LHCb Sensitivity

Dark photons: new muon and electron ID

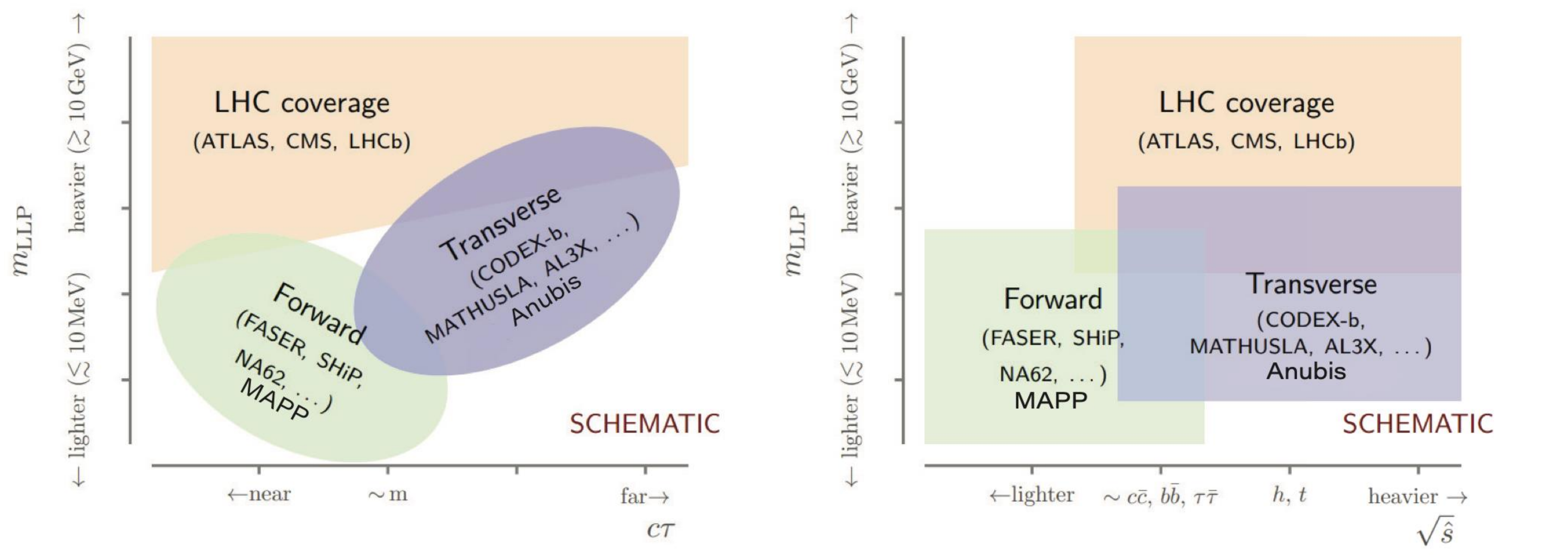
- Better tracking-based **muon ID** - massive improvement at low momentum

  - can be / going to be further improved with NNs
- Monotonic and fast Lipsitz NN for **electron ID**

arXiv:2203.07048



CODEX-b Expresion of interest

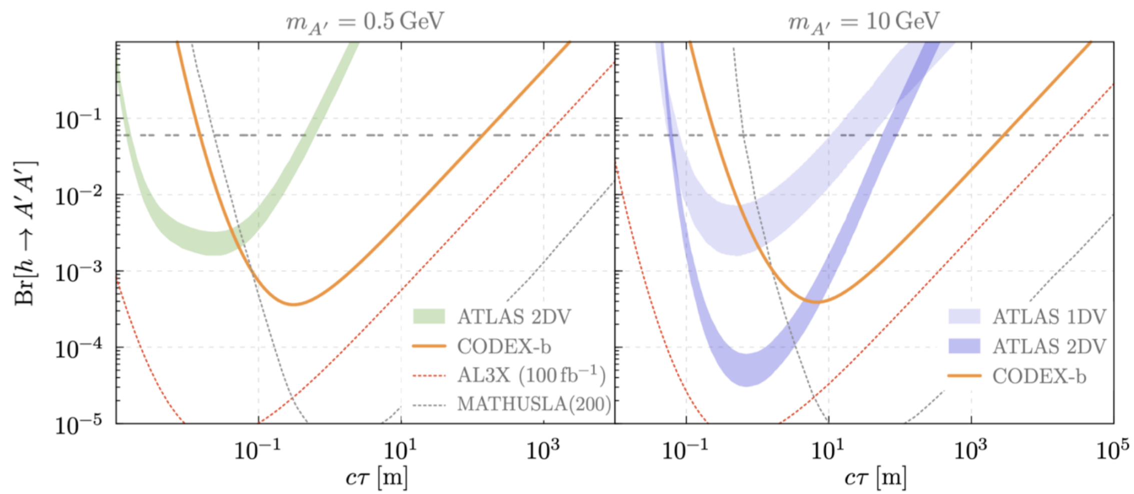


arXiv:1911.00481

CODEX-b

CODEX-b offers a competitive sensitivity to a number of BSM models at a relatively low cost $\mathcal{O}(\$10\,\mathrm{M})$:

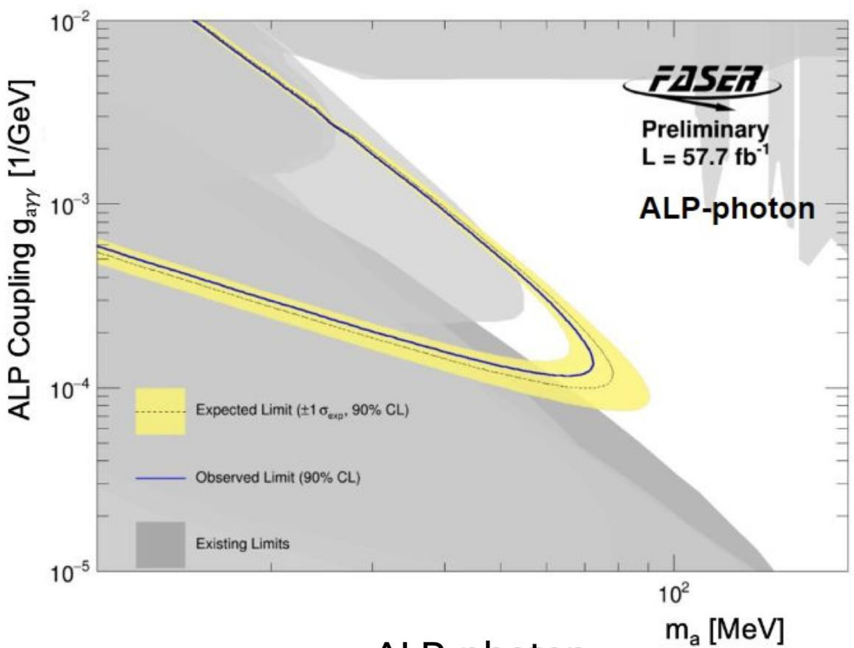
- Abelian hidden sector
- Dark Higgs
- Axion-like particles
- Heavy neutral leptons
- R-parity violating supersymmetry
- Relaxation models
- Neutral naturalness
- Inelastic dark matter
- Dark matter coscattering
- Dark matter from sterile coannihilation
- Asymmetric dark matter
- Baryogenesis
- Hidden valleys
- And many more!



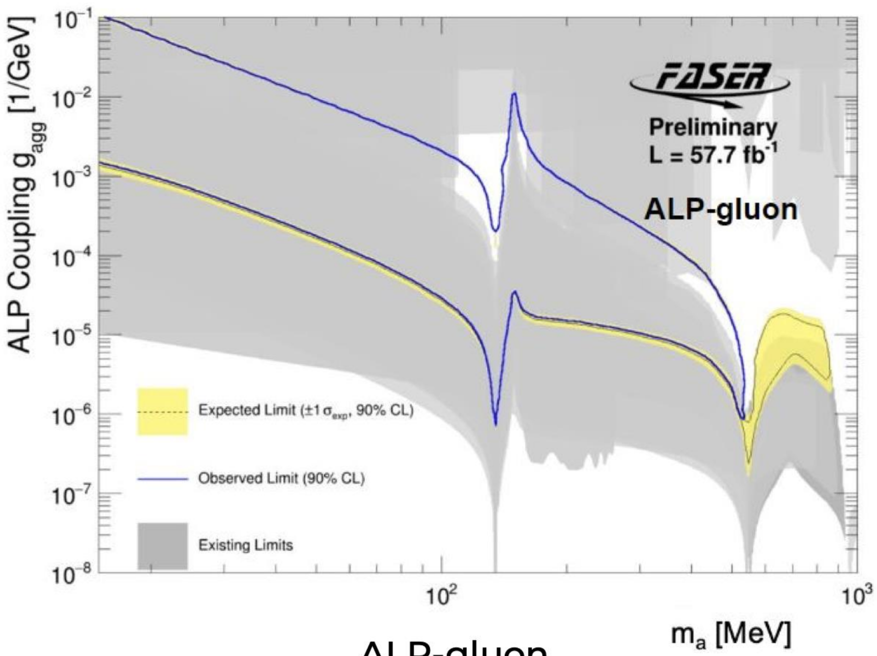
Lower limit on the branching ratio of Higgs decay to two dark photons, where the dark photons decay to leptons.

Unblinded results - II

- **Analysis also sensitive to other multi-photon signatures**
  - Exclude new parameter space for ALP-photon, ALP-gluon, $U(1)_B$ and up-philic scalar



ALP-photon



ALP-gluon

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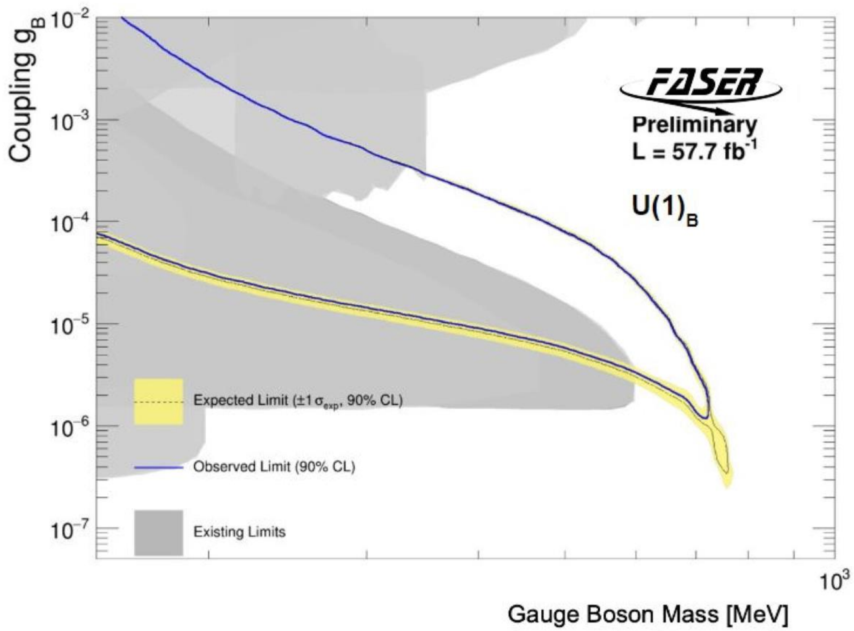
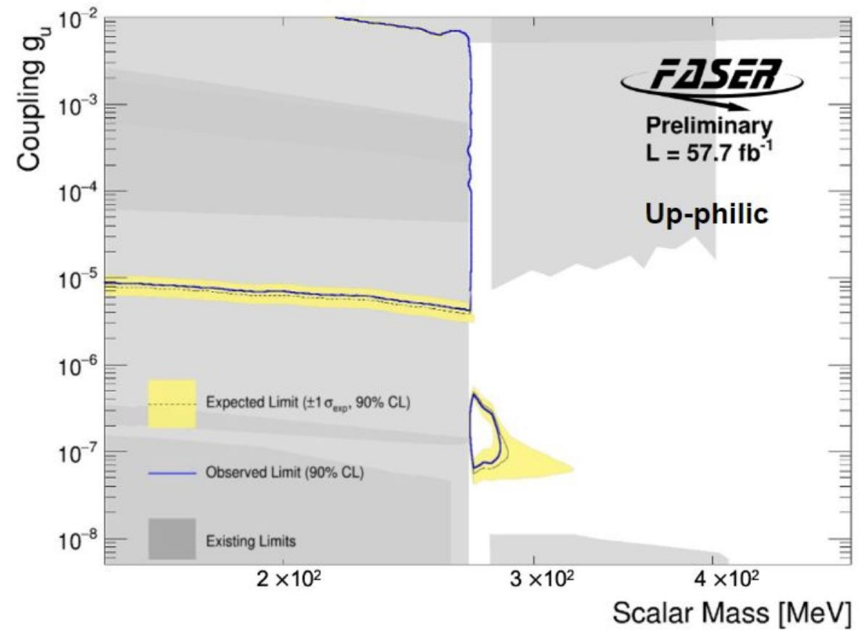
Unblinded results - III

➔ **Analysis also sensitive to other multi-photon signatures**
- Exclude new parameter space for ALP-photon, ALP-gluon, $U(1)_B$ and up-philic scalar



$U(1)_B$



Up-philic scalar

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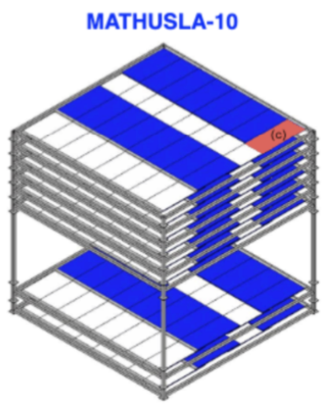
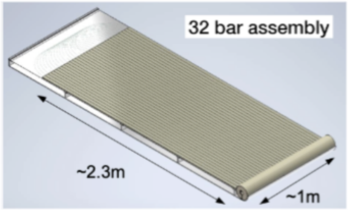
MATHUSLA

Module 0

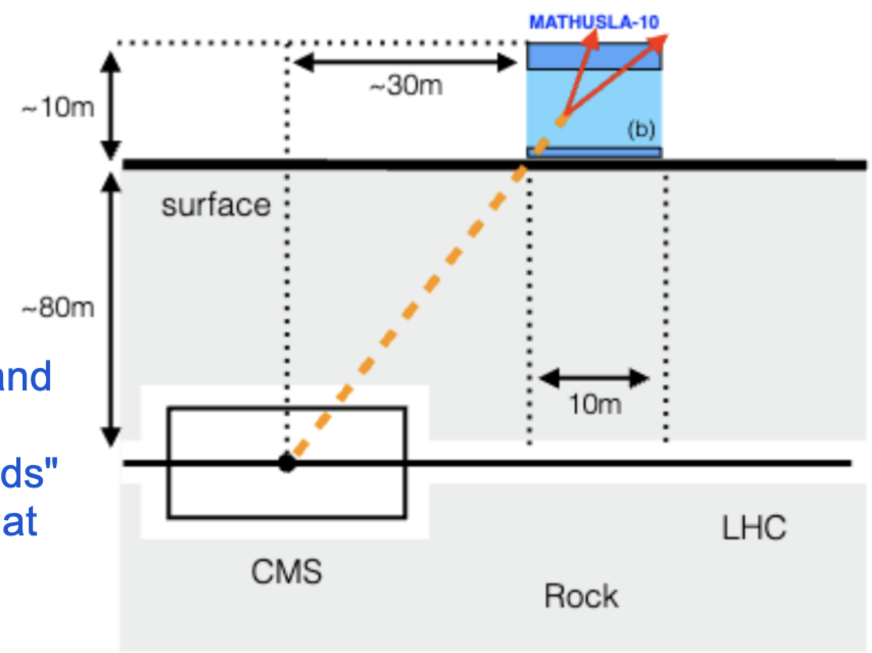


Proposal for **MATHUSLA-10** (Canada)

- Dimensions **~10 x 10 m², H~flexible**
- Prototype for the detector technology
- To be placed above CMS, and even as a stand-alone module can extend the LHC reach for LLP



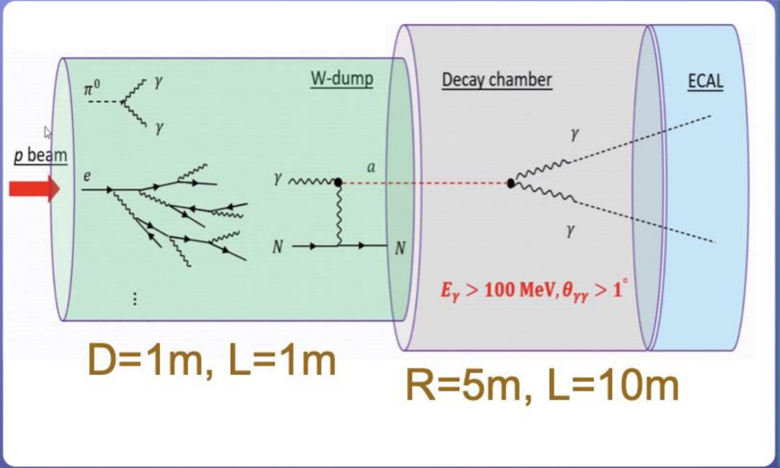
- Manufacturing and operating the building blocks of the large scale detector.
- Exercise on real data: tracking, efficiency and timing resolution using CR, at UofT.
- Characterize "beam-associated backgrounds" (rare SM particles in HL-LHC by operating at CERN P5 during LHC runs.



DAMSA

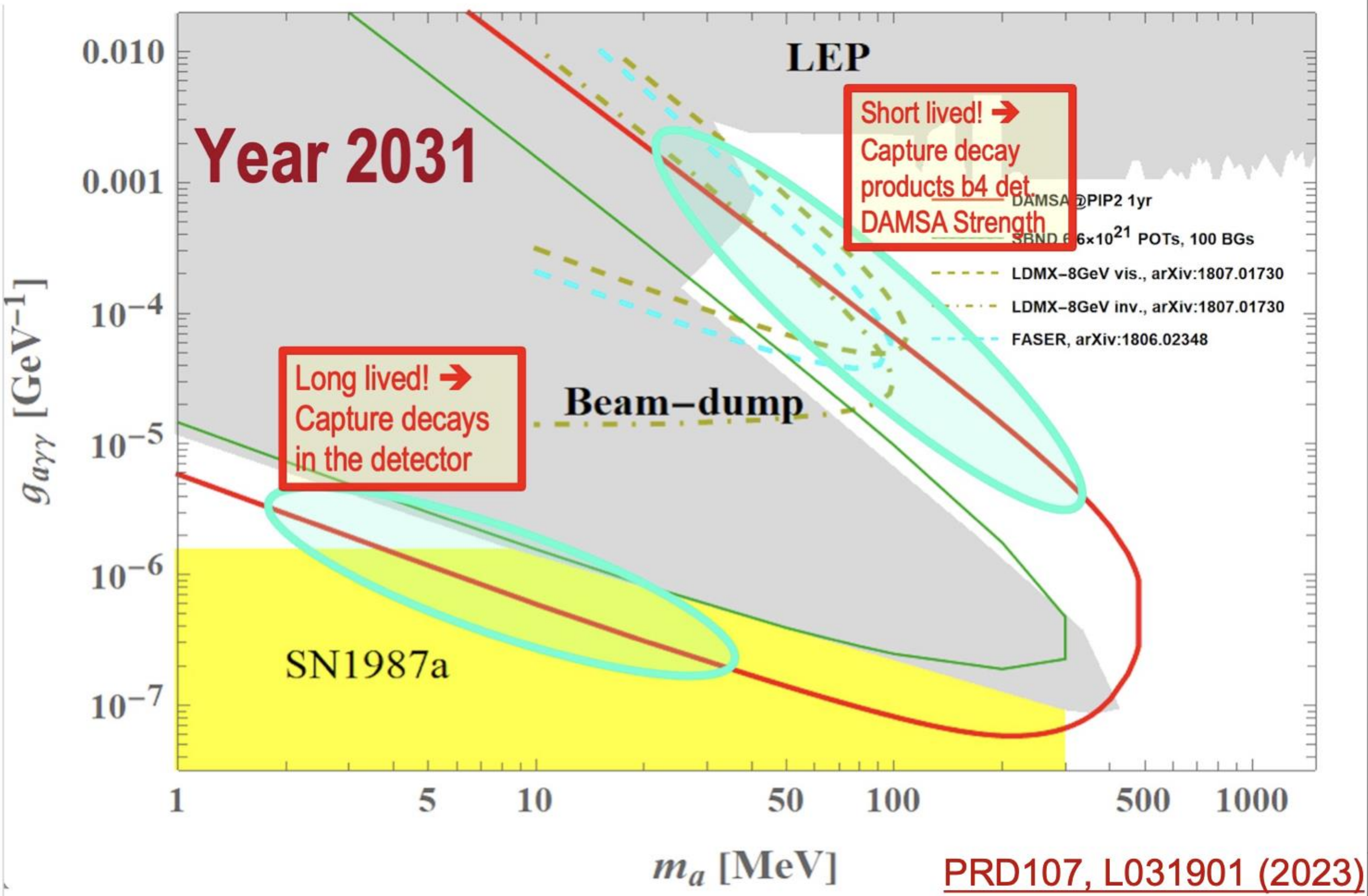
Conceptional Design

- Inject and absorb as many protons and produce as large number of γ in the dump as possible
- Allow higher coupling ALP's to decay in the vacuum w/ as small number of neutrons escaping the dump as possible
- Place the detector as close to the dump as possible on axis to expand the mass reach to higher mass region
- Search for ALP to two photons, dark photons to e^-e^+



- Good vertex pointing resolution for $\gamma\gamma$ and e^+e^-
- Sub-ns timing difference resolution (0.1ns)
- Low E threshold identification of e^+e^-
- Good mass resolution

DAMSA



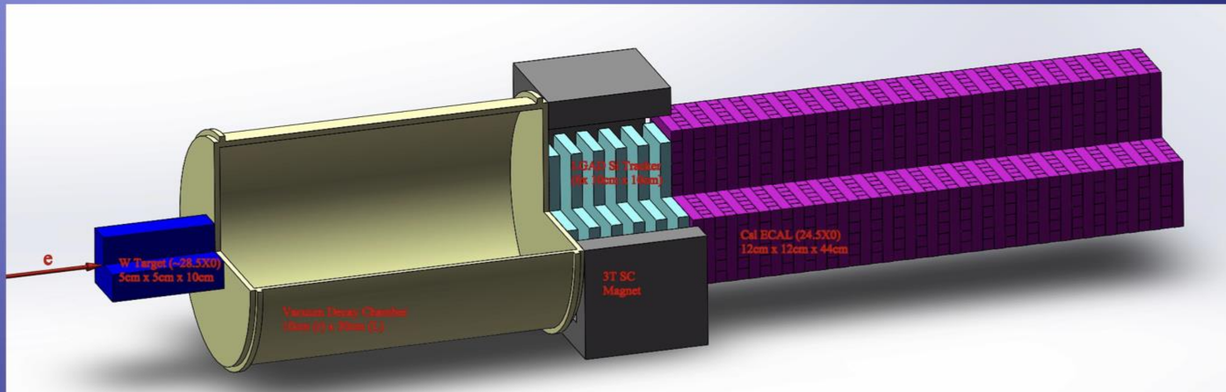
PRD107, L031901 (2023)

DAMSA

DAMSA Pilot experiment

- **Goal: do a physics demonstrator in the next 2 yrs**
- **Beam: 300 MeV e-beams at Fermilab FAST**

  ➔ greatly reduced neutron bkgds, compared to proton beam
- **Target: 5cm x 5cm x 10cm W target (~28.5X_0)**
- **Vacuum decay chamber : 10cm (R) x 30cm (L)**
- **Detector: 6 layers of 10cm x 10cm Si tracker (LGAD) under magnetic field + CsI ECal total absorption (24X_0)**

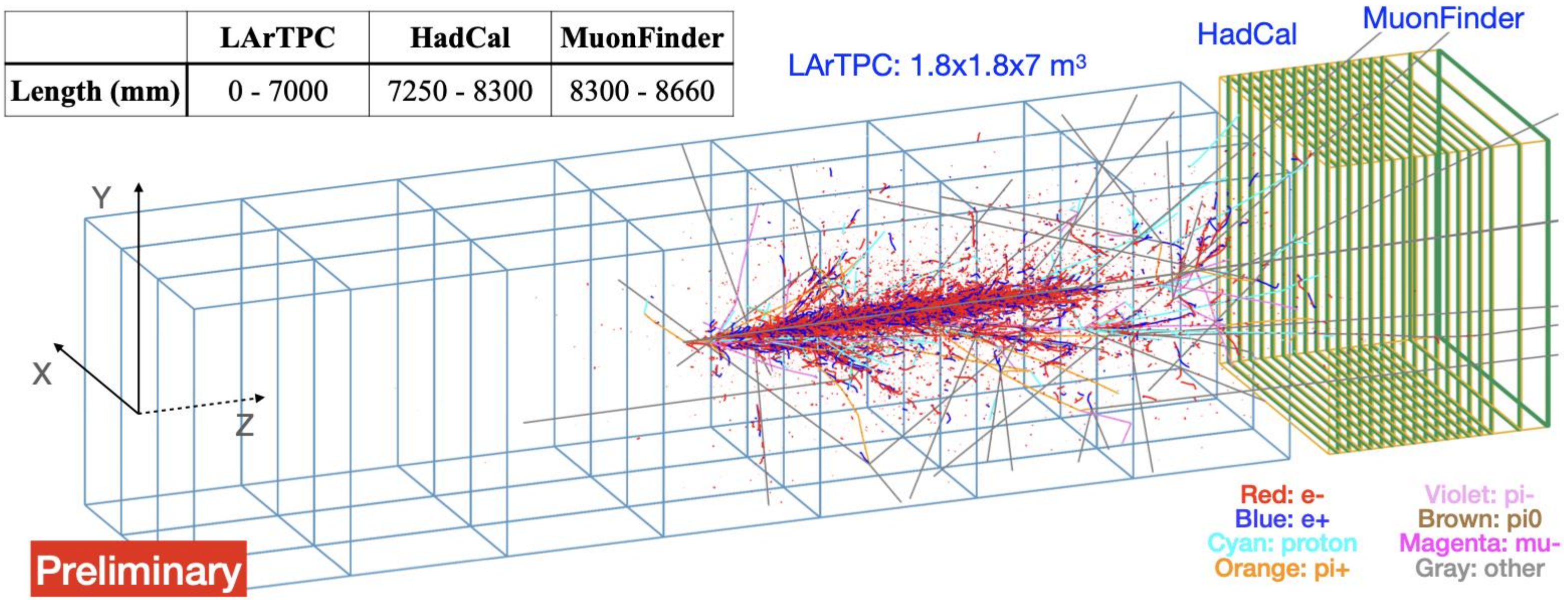


FLArE

Forward Liquid Argon Experiment (FLArE)

- FLArE: a liquid argon time projection chamber (LArTPC) detector in FPF to detect neutrinos and dark matter from LHC
  - Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter
  - Detector needs to have good energy containment and resolution for neutrino physics
  - Muon and electron ID. Very good spatial resolution (~1 mm) for tau neutrino detection

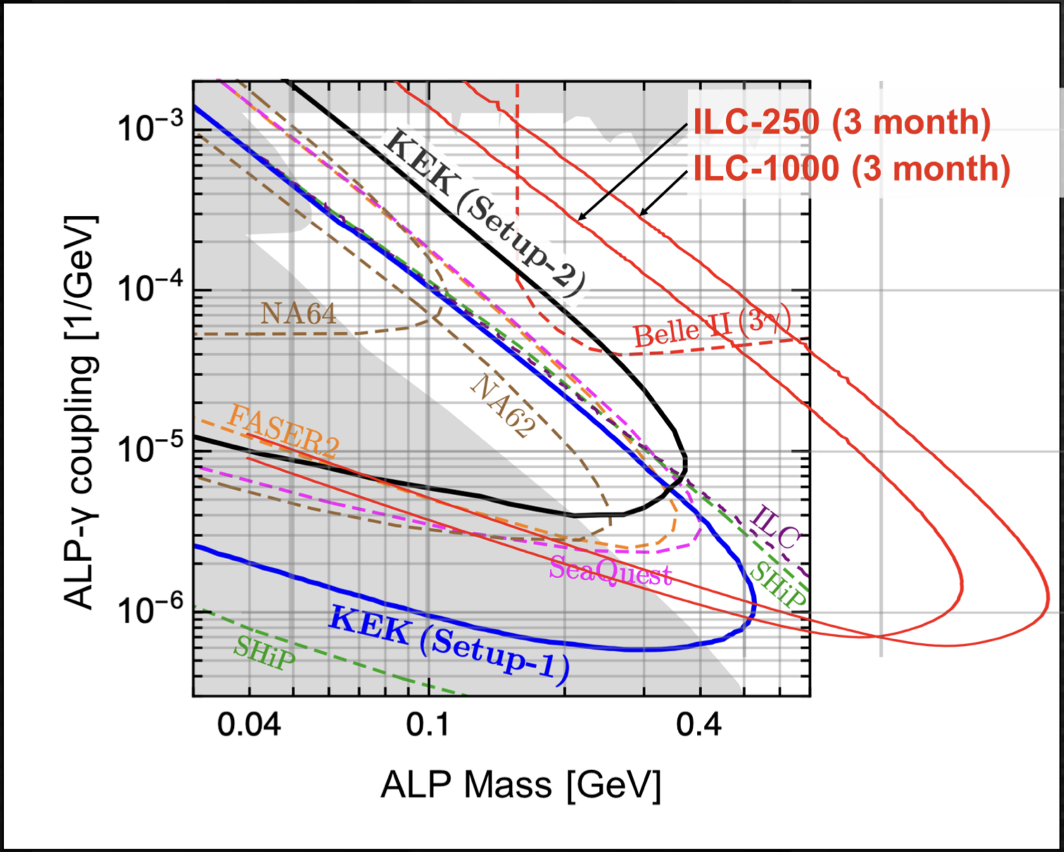
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660



EBES

We will try to do a physics run during 2024-2025 (depending on availability of the beam)

- With 50-100 cm L_{dec} depending on background
- SiW-ECAL introduced again (need to optimize mechanics and readout software)



Will proceed to Setup-2 if magnet is available

- Having prospects of magnet

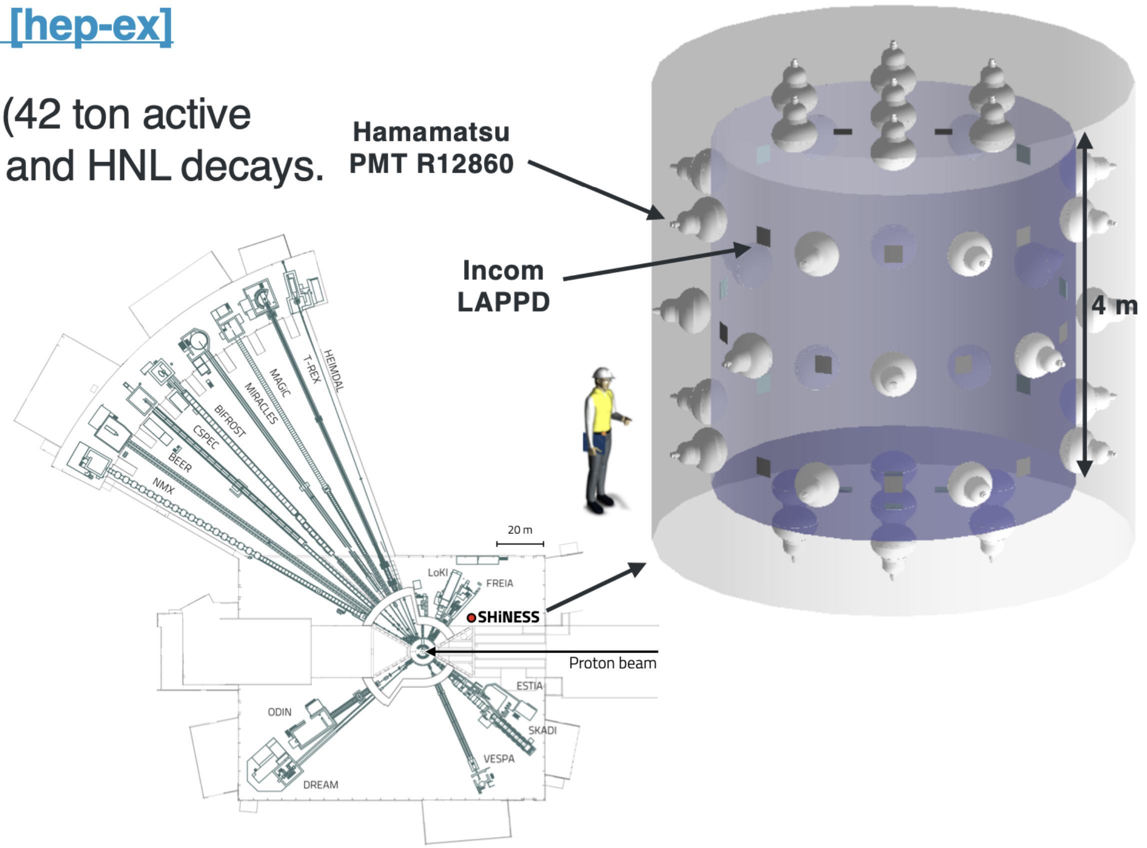
Far future: (I)LC beam dump experiment

SHiNESS proposal

SHiNESS

JHEP 03 (2024) 148 arXiv:2311.18509 [hep-ex]

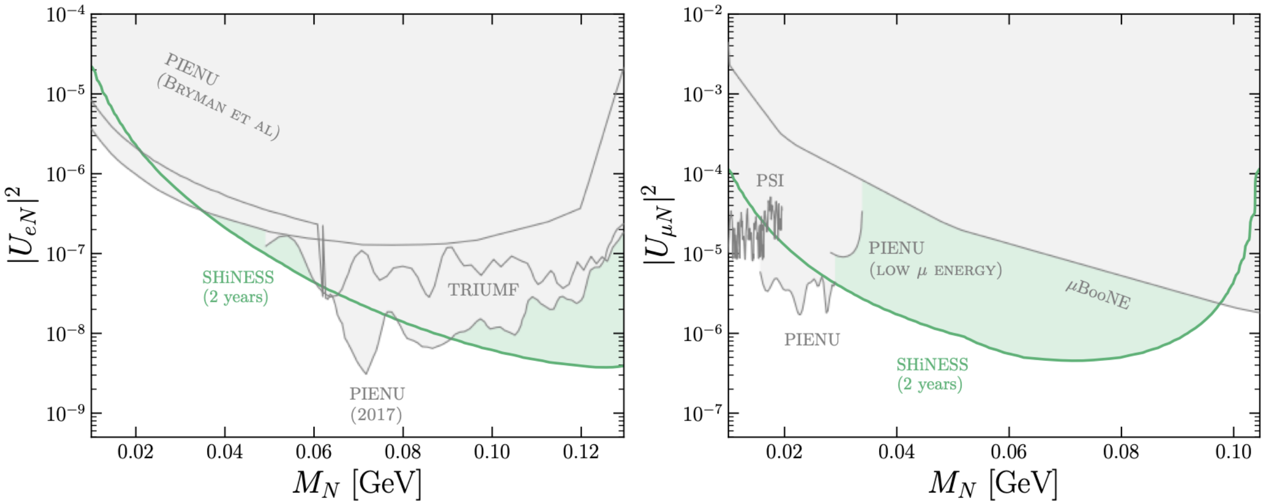
- We propose a **liquid scintillator tank** (42 ton active volume) to detect neutrino interactions and HNL decays.
- Detector is placed **25 m far from the beam target** off-axis in the backward direction (to suppress backgrounds).
- Light is detected by **large-area PMTs** and **Incom LAPPDs**, which allow to distinguish between Cherenkov and scintillation, **enabling directionality**.



HNL sensitivity

SHiNESS

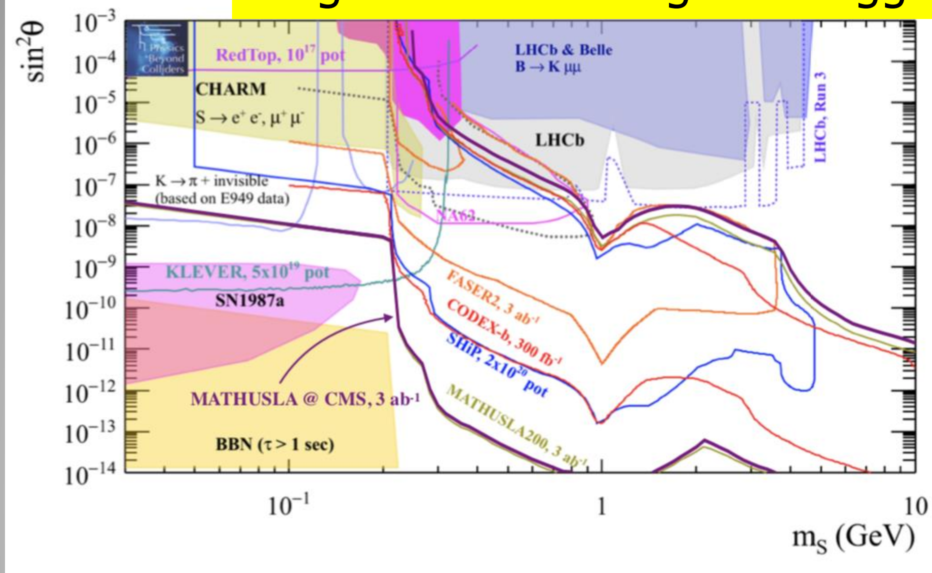
- The e^+e^- can be detected in the liquid scintillator tank by looking for compatible **energy depositions** and **Cherenkov cones**.
- Analogous studies have been conducted for other π^+DAR experiments (e.g. LSND, JSNS²), but the **directionality capabilities of SHiNESS**, enabled by the LAPPDs, allow to reach **world-leading sensitivities** in the 10-100 MeV mass range.



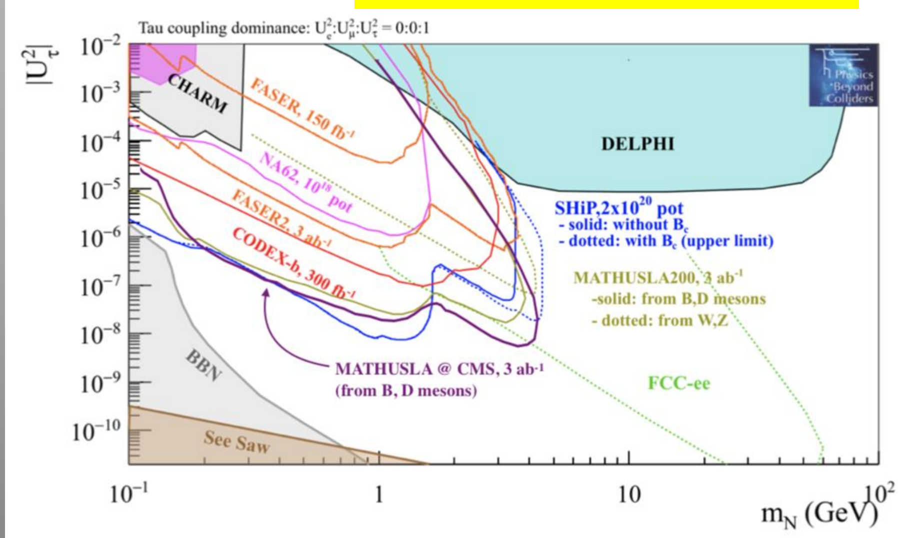
More Example Processes

2009.01693

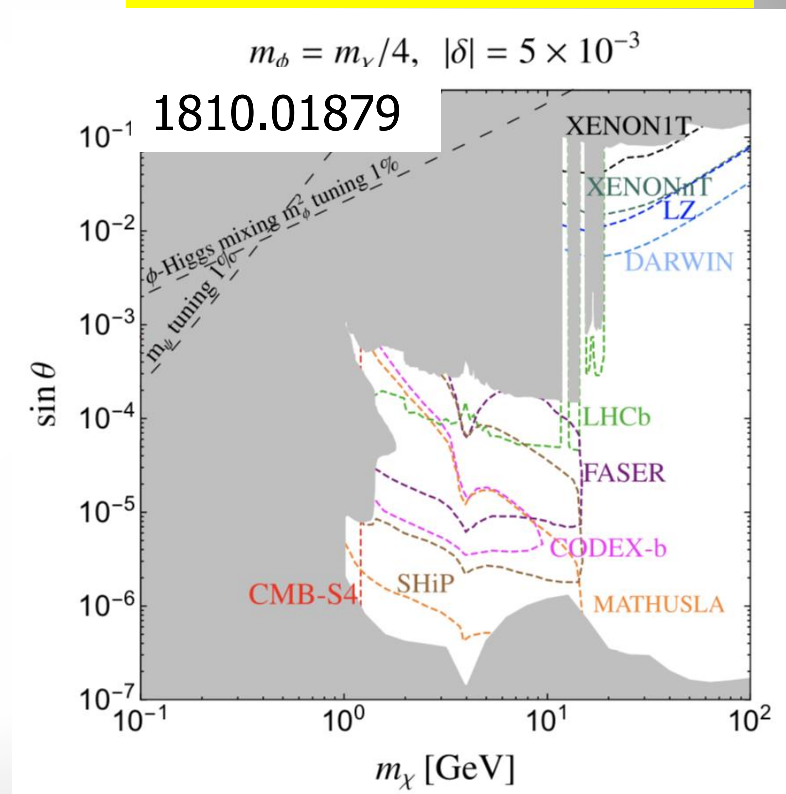
Singlet Scalar mixing with Higgs



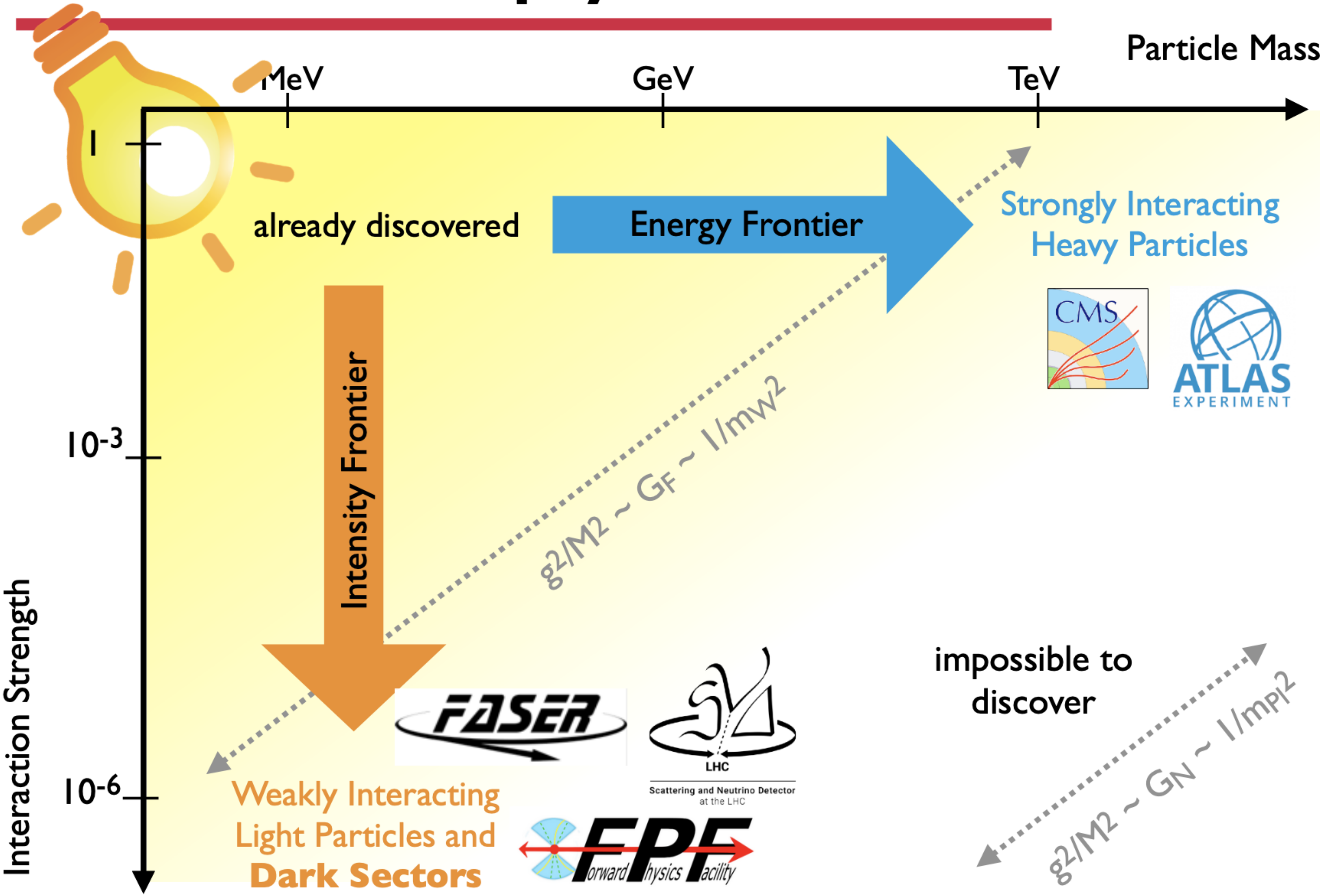
Heavy neutral leptons



Inelastic Dark Matter Model



Where could new physics be:

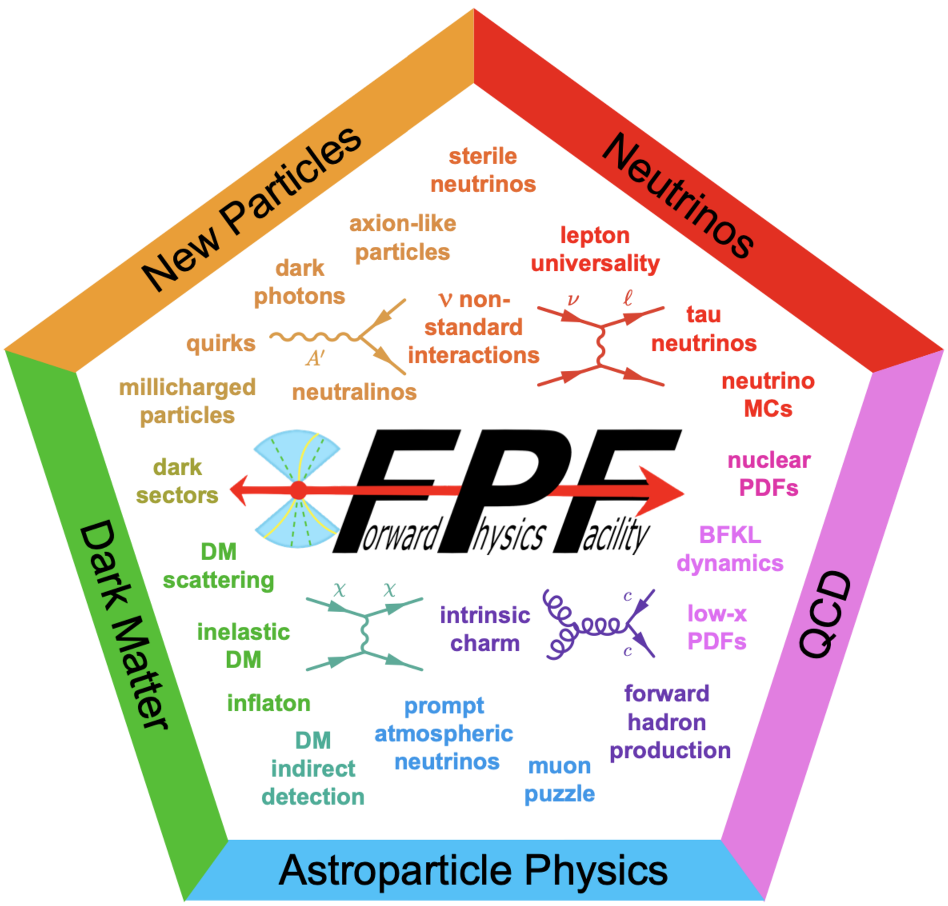


NEW: The Forward Physics Facility

Originally for searches for New Physics

2203.05090

Extended to cover Neutrinos, QCD, Astroparticle Physics, Dark Matter Searches



QCD: PDFs, very forward production of light and charmed mesons, very low-x (10^{-7}) and very high-x regions eg intrinsic charm, **ν**-DIS…

Neutrino: TeV scale neutrinos, about 1000 Tau neutrinos, tau and anti- neutrino separation…

Astroparticle physics: improve the modelling of high-energy hadronic interactions in the atmosphere. Help to understand the atmospheric neutrino flux

Timeline: a proposal for Run4 starting ~ 2030