Searches for Long Lived Particles
Present and Future

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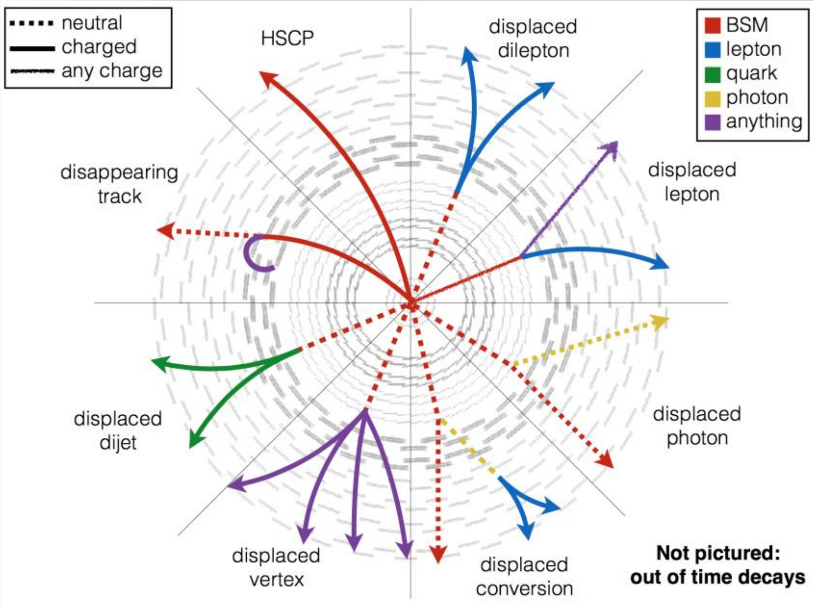
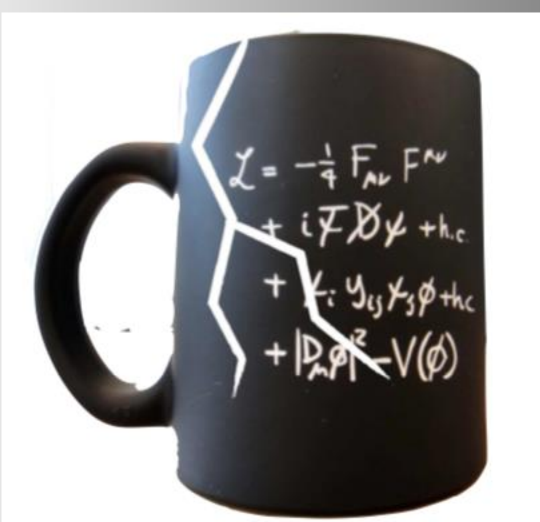
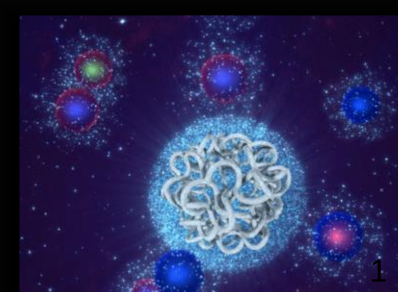
DISCRETE 2024 in Ljubljana
2–6 Dec 2024



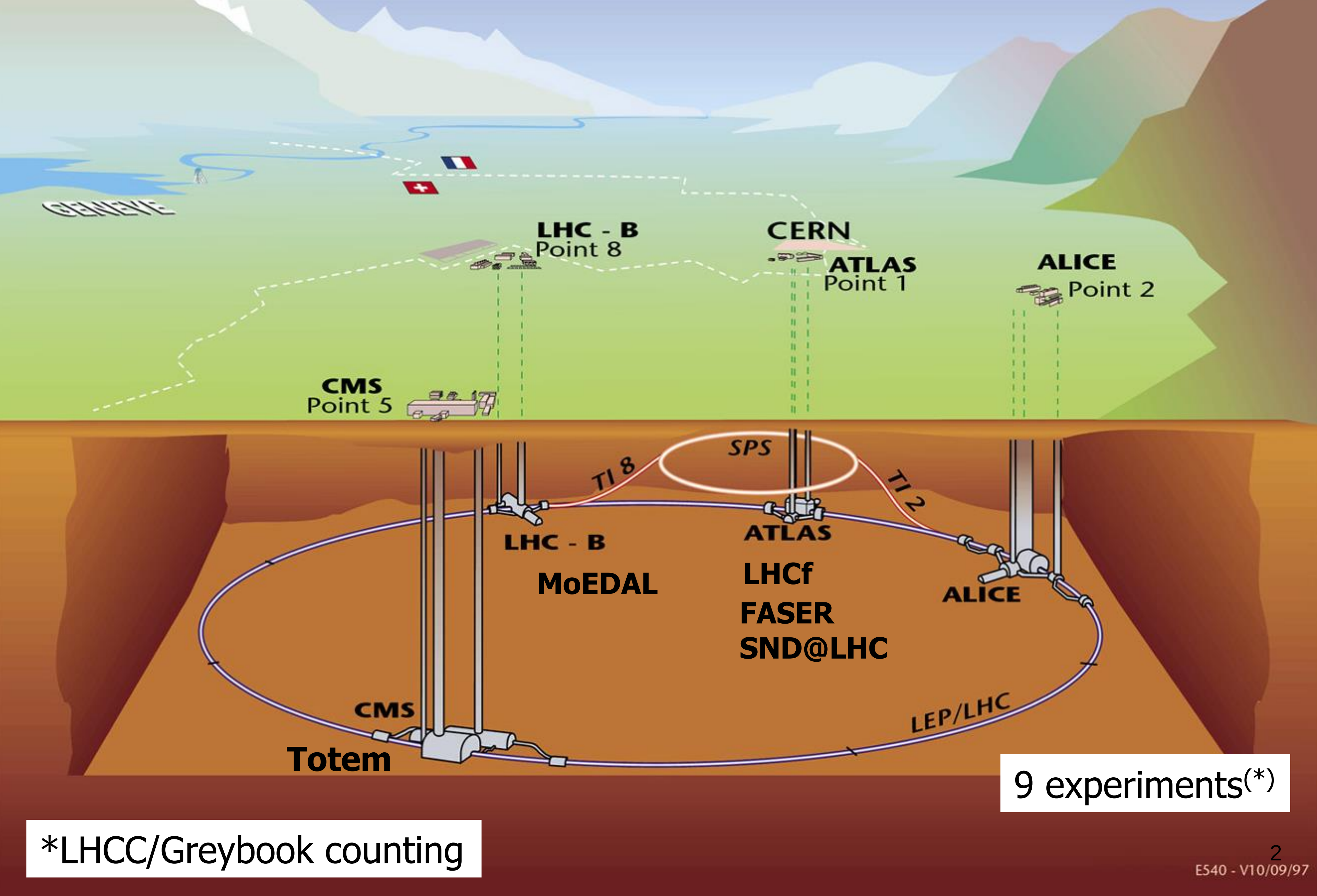
Outline

- Introduction: Long Lived Particles at the LHC
- Proposals for new experiments at the LHC
  - Transverse experiments
  - Forwards experiments
- Non-collider opportunities
- Summary/Outlook





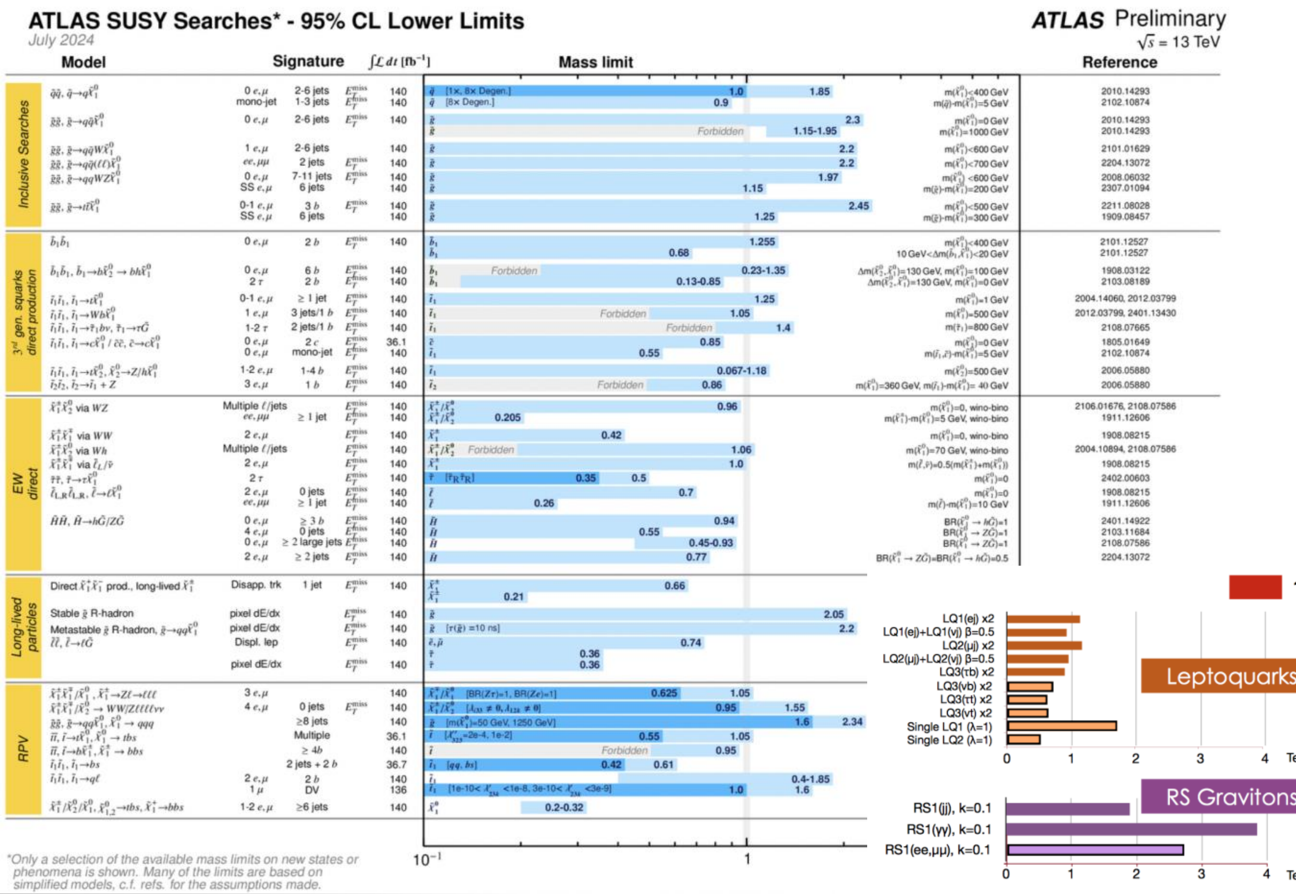
The Large Hadron Collider and Experiments



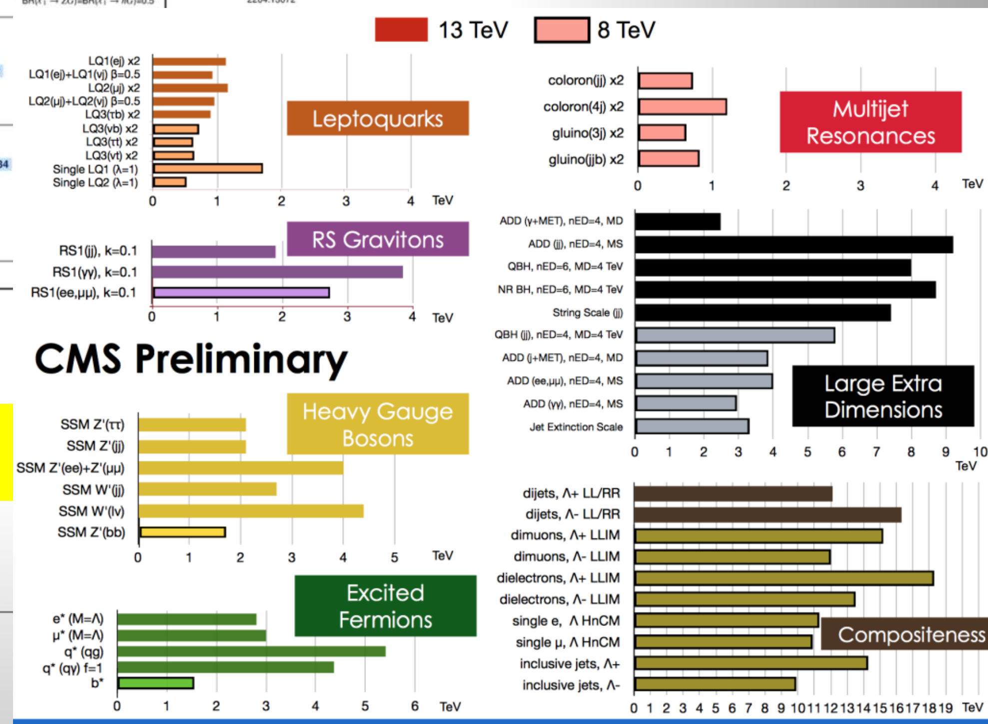
9 experiments(*)

*LHCC/Greybook counting

LHC: So far no New Physics



Classical Searches
- Superymmetry
- Exotica
- Flavor Universality
- ...



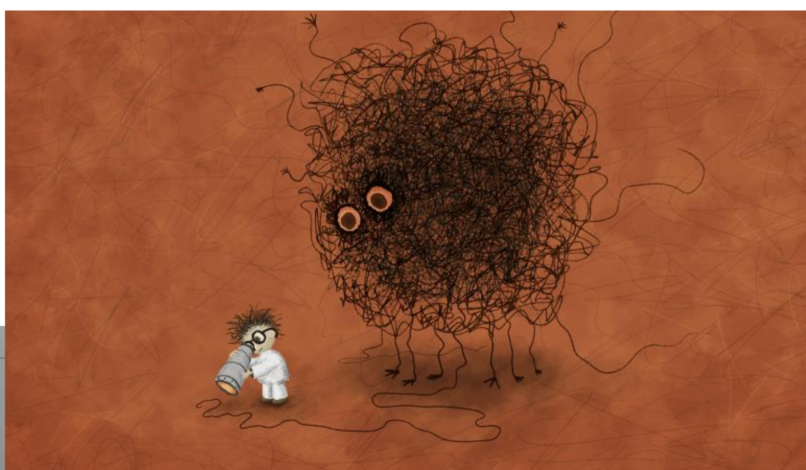
No signal of new physics so far!!

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

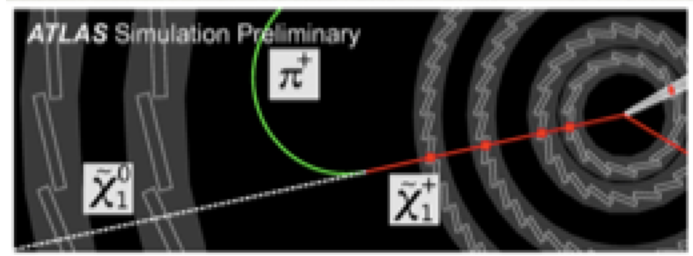
Decays via heavy particle
e.g. heavy neutrinos

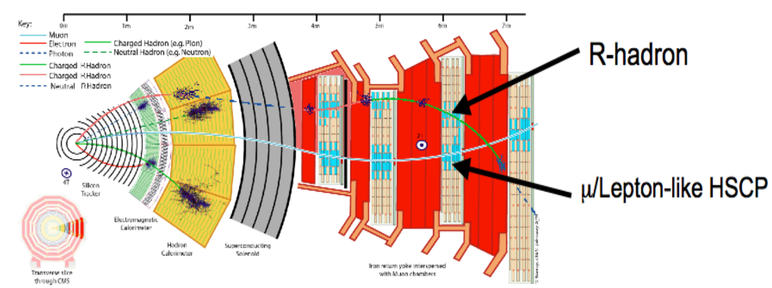
Any model with small couplings, small mass splittings, or decays via off-shell particles can result in long lived particles (LLPs)

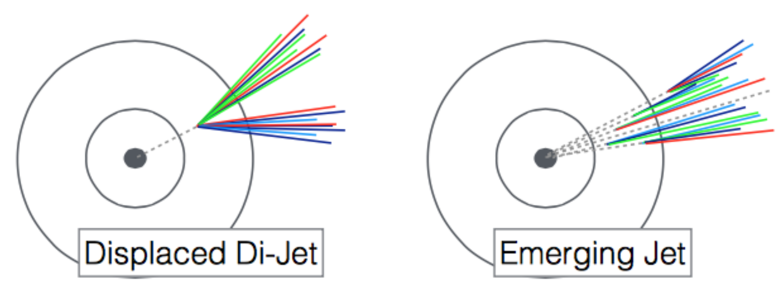
Long Lived Particles

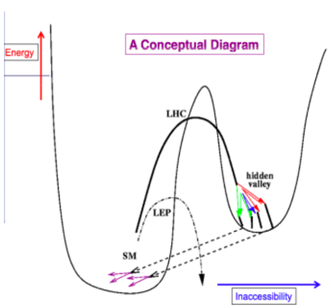
Long lifetimes arise from a hierarchy of scales or a small coupling

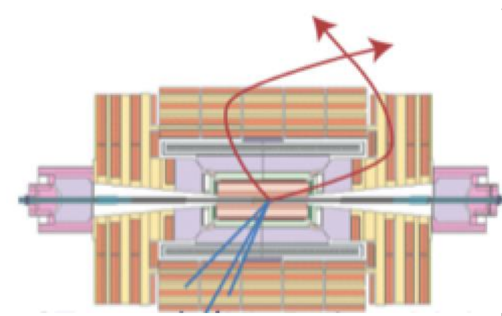
- RP Violating SUSY
- AMSB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Magnetic monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ….





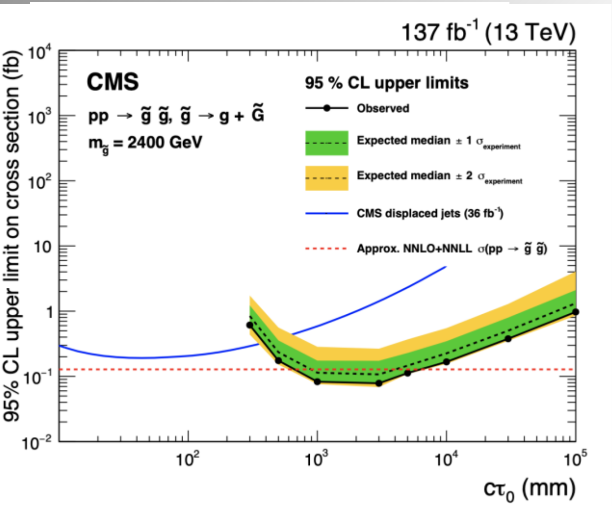




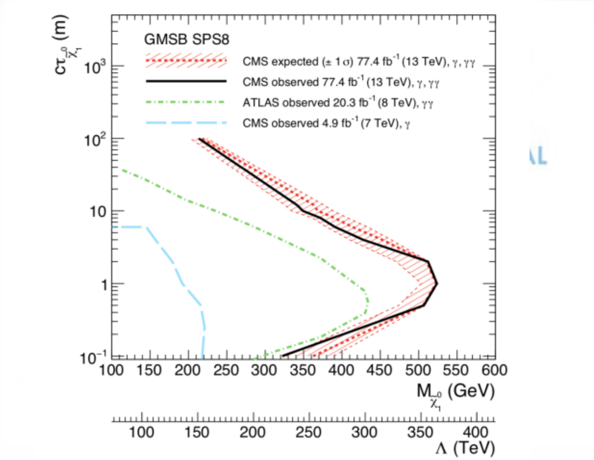


Long Lived Searches: Examples

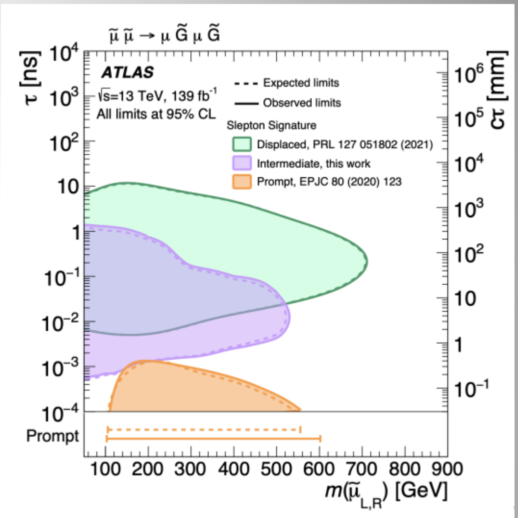
delayed jets



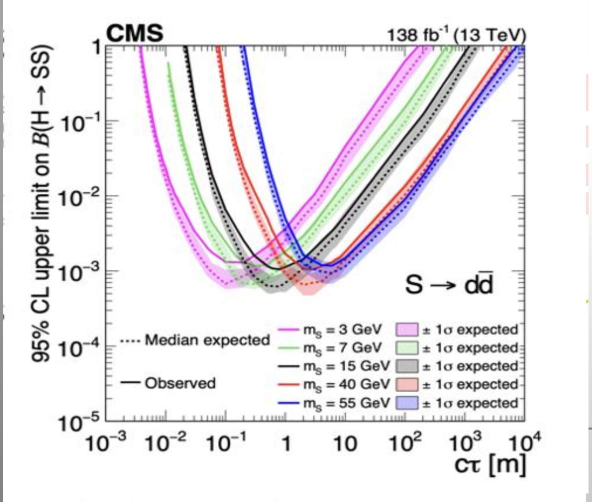
displaced photons



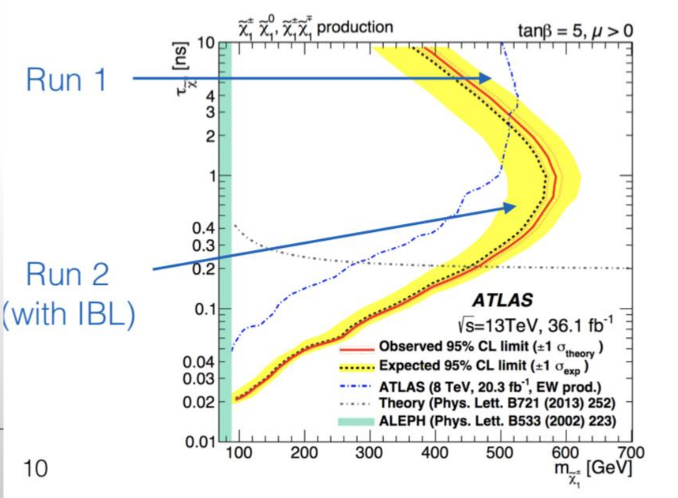
Small displacements



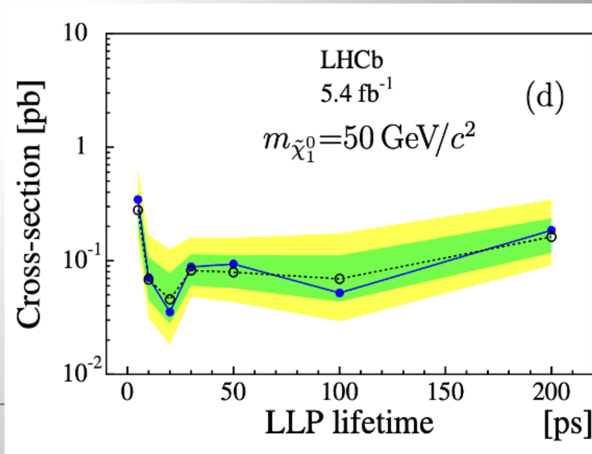
LLPs in muon system



Disappearing tracks



RPV searches



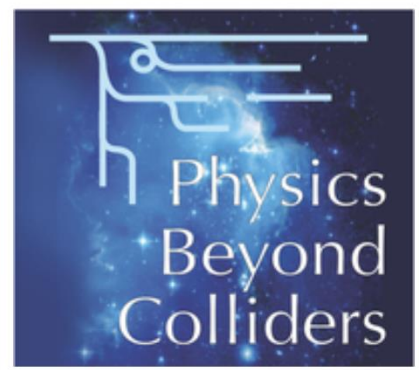
LLP Community Workshops

14th workshop
this year

15th workshop
2-6 June 2025
València, Spain

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

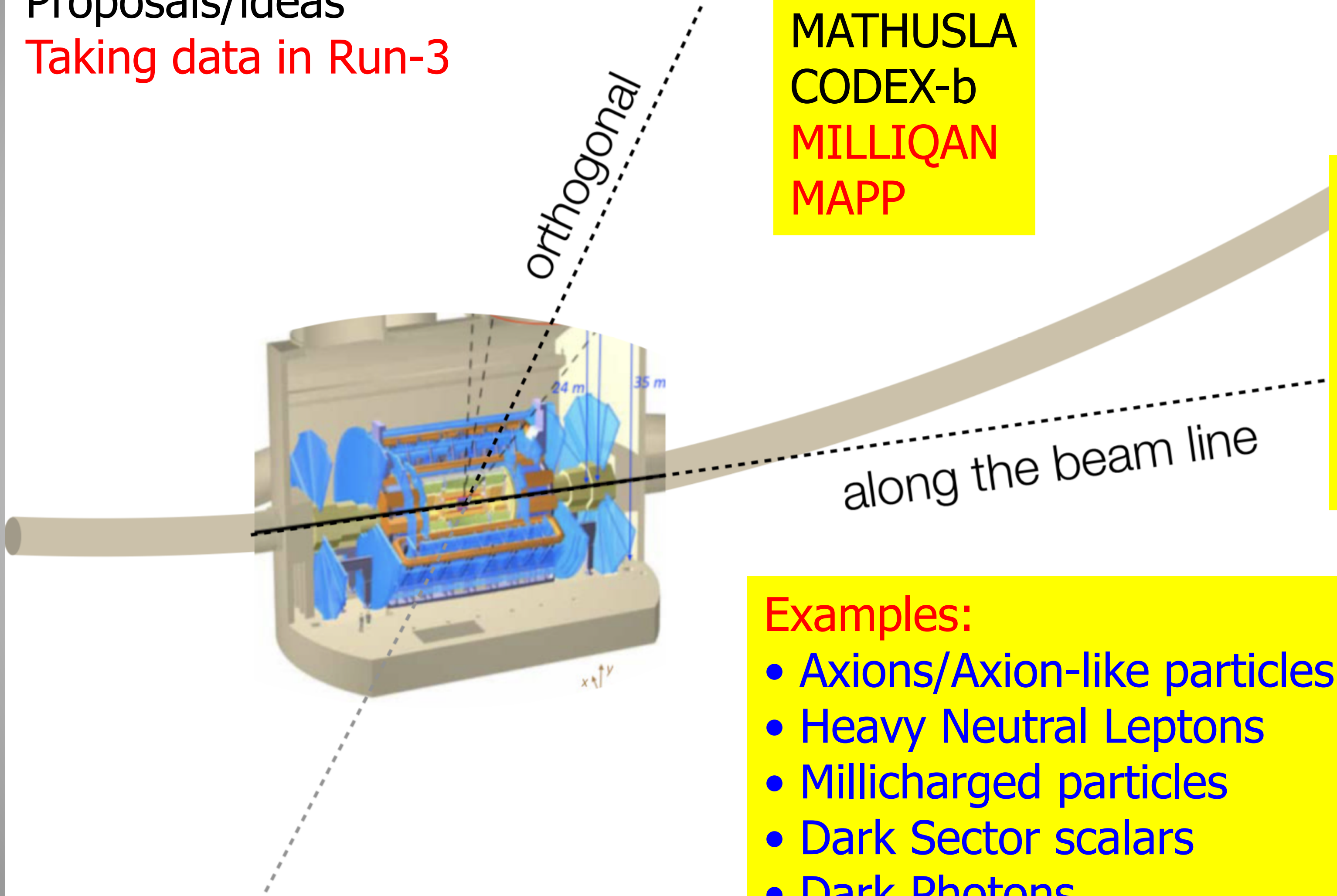
New Experimental Proposals: Searching for Long Lived Particles

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

⇒ Opportunities for forward QCD measurements at the LHC and measurements of Cosmic Rays

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

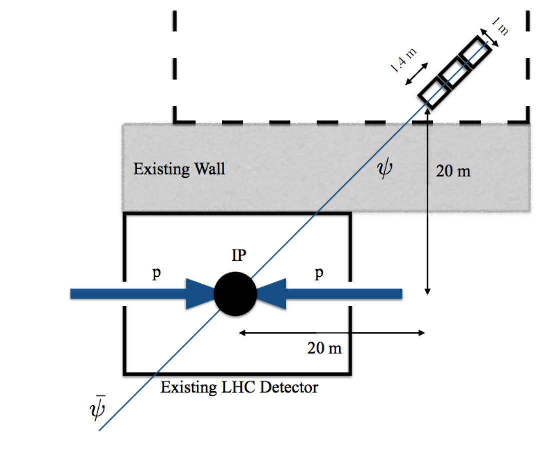
Examples:
- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Dark Photons
- Light Dark Matter …

Proposals for Transverse Detectors

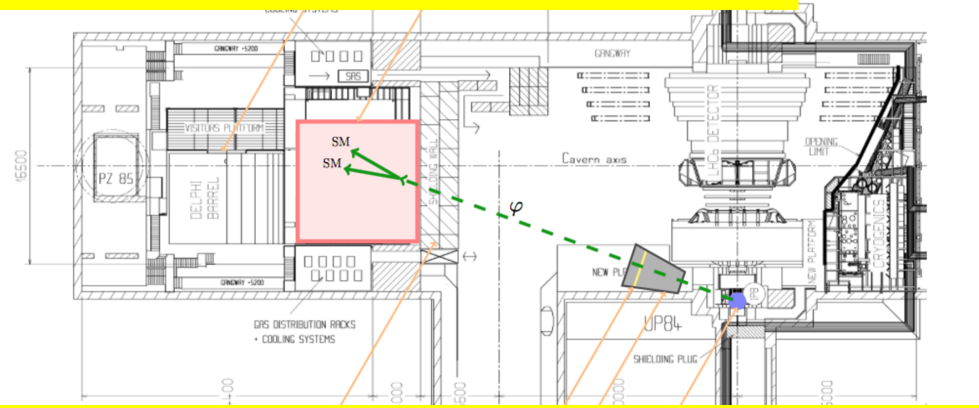
New Transverse Experiment Proposals

~2020

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

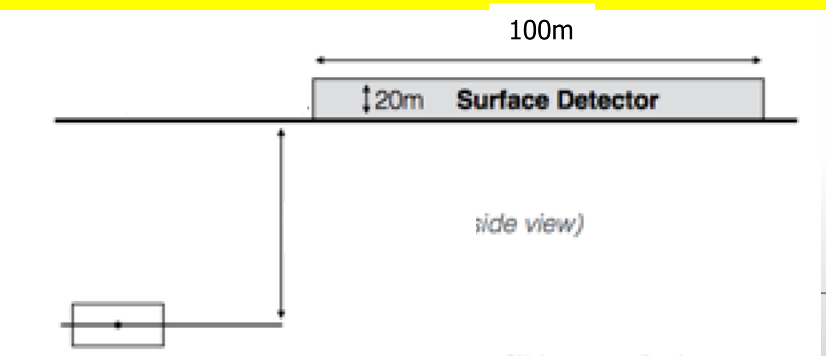


CODEX-b: searches for long lived weakly interacting neutral particles

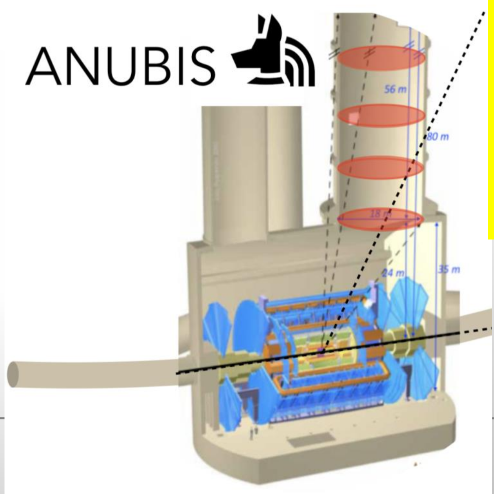


Also: AL3X ('ALICE' for LLP arXiv.1810.03636)..

MATHUSLA: searches for long lived weakly interacting neutral particles



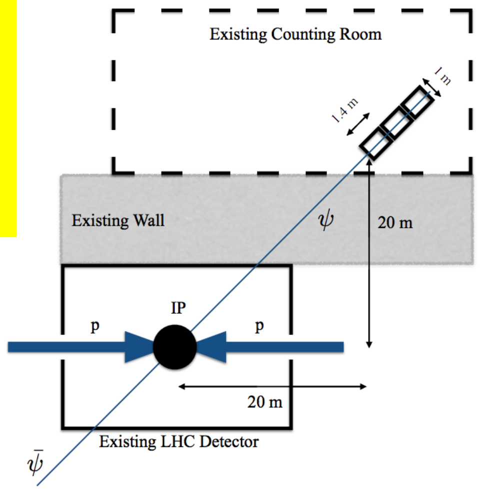
ANUBIS: searches for long lived weakly interacting neutral particles



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

Particles with Milli-Charges?

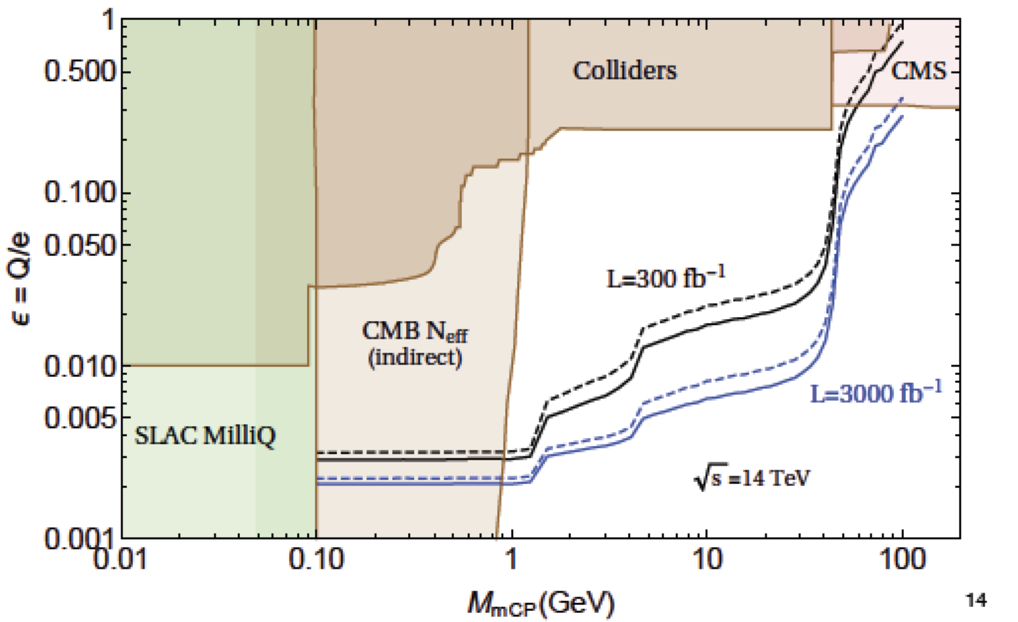
"New" idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017 till 2018



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…?

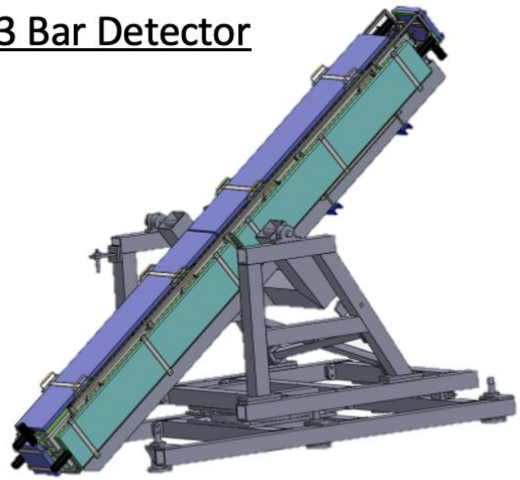
Detection technique:
scintillators-> low light signals

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 +PMTs

Run 3 Bar Detector

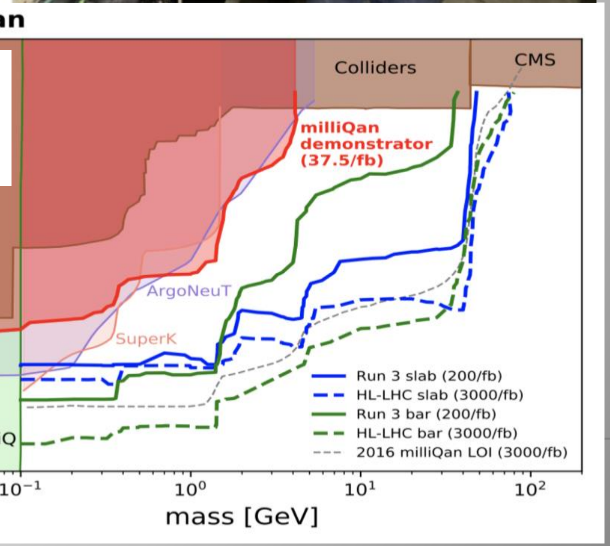


Installed for Run-3

2024: taking data

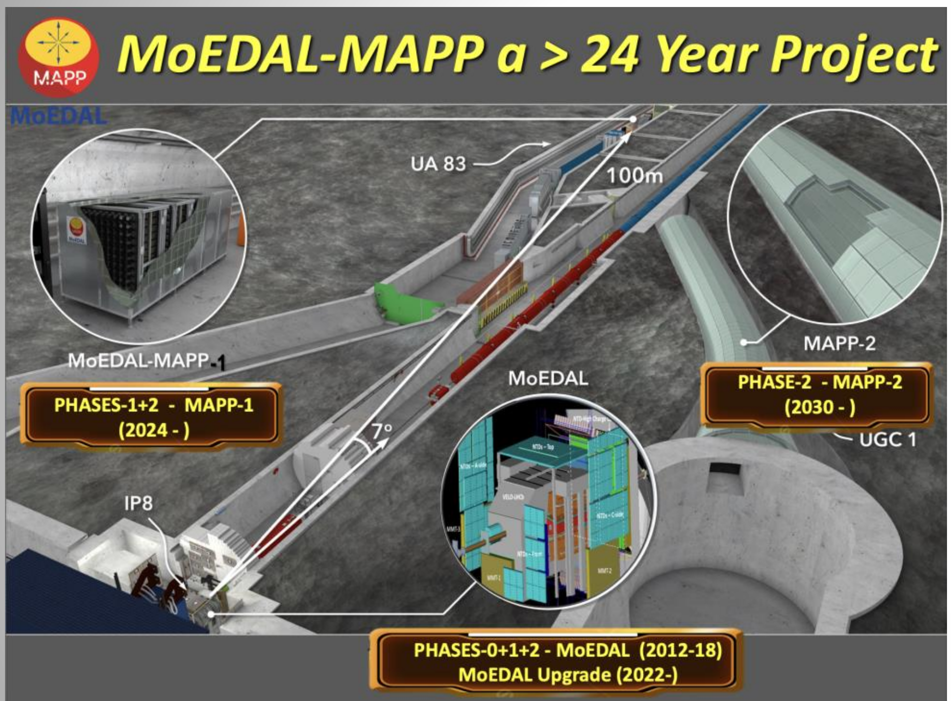
Run 3 Slab Detector

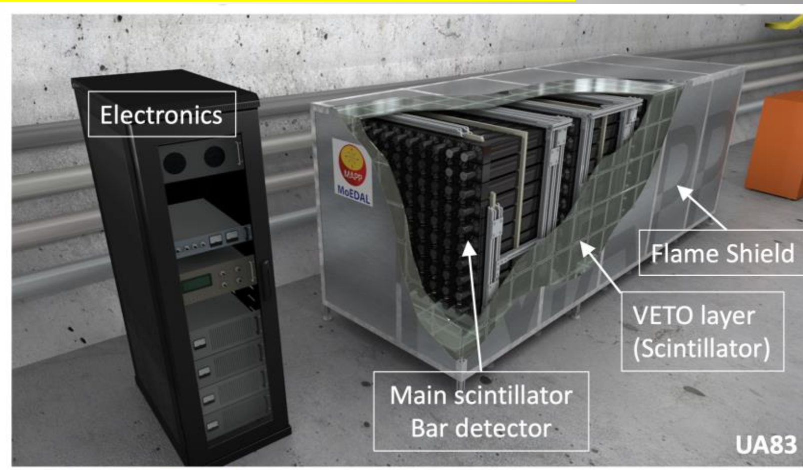
Results from the Run-2 prototype



MAPP/MoEDAL

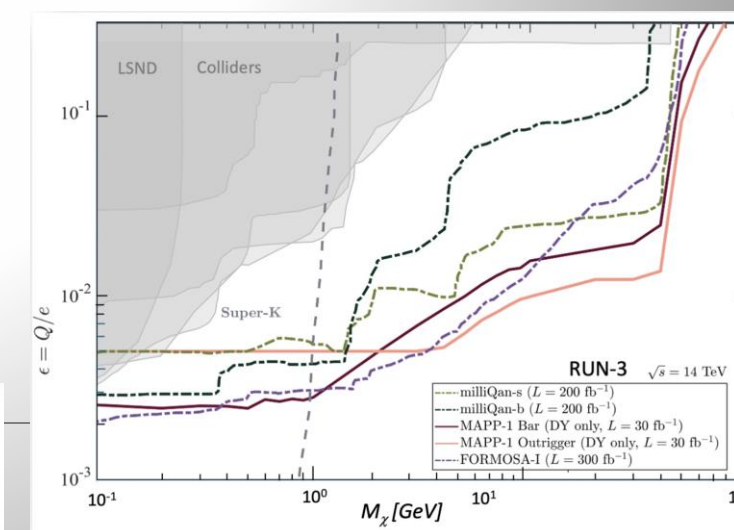
MAPP is a detector for the upgrade of MoEDAL
MAPP is a scintillator detector –like MilliQan– installed at CERN





- 400 scintillator bars (10×10×75 cm³) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

MAPP is being commissioned for physics.

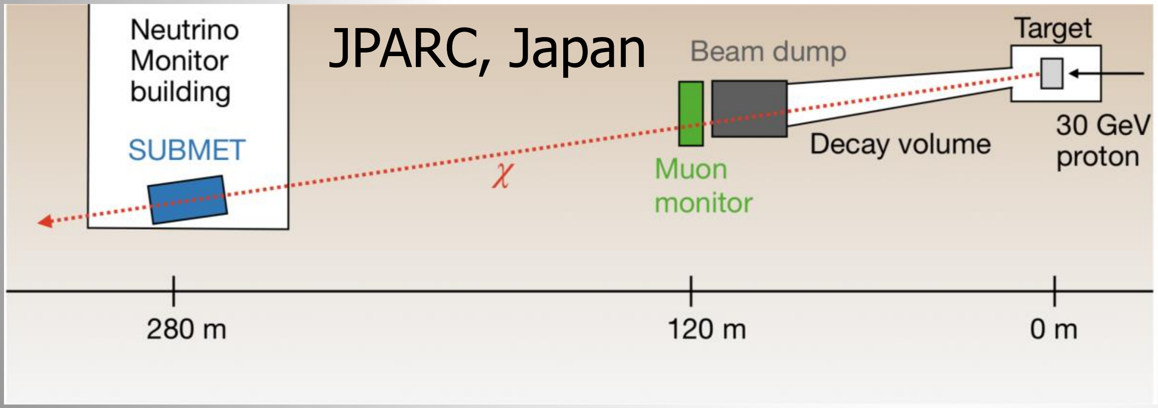


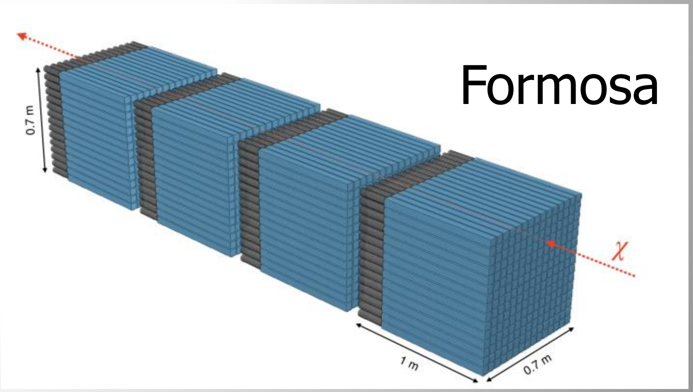
MAPP-1: DY only, 100% eff., no background
milliQan: DY+meson decays, bkg.+detector eff. included
FORMOSA-1: DY+meson decays, 100% eff., no background

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)





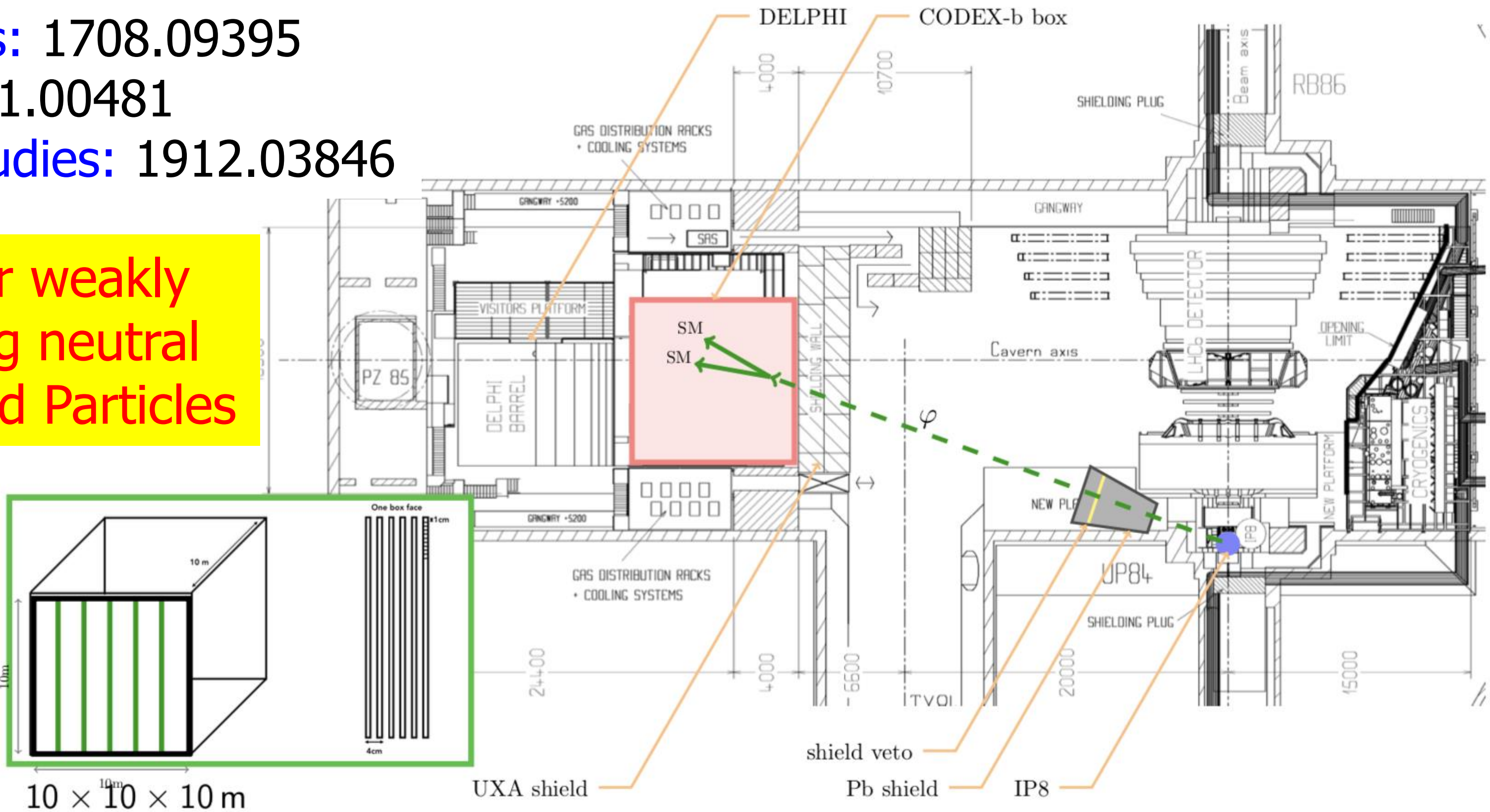
MilliQan collaboration is involved in SUBMET, FerMINI & FORMOSA Detectors
=>This is a science program for up to 2040 and beyond!!

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: $10\text{x}10\text{x}10\text{m}^3$ 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

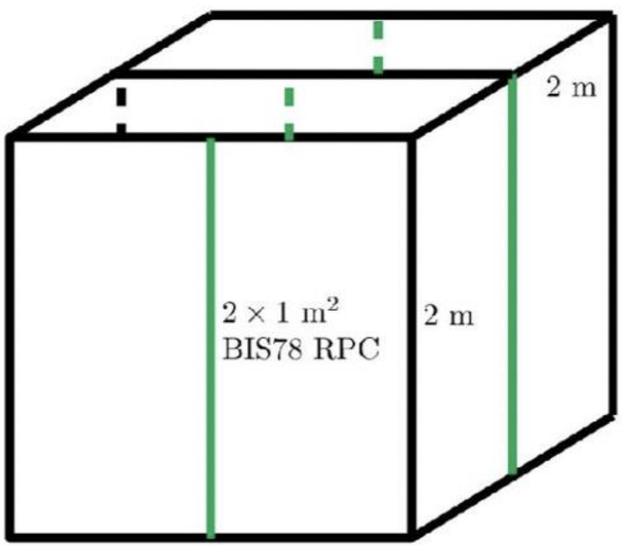
Demonstrator to test technologies planned for CODEX-b

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

- $2x2x2m^3$ 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)

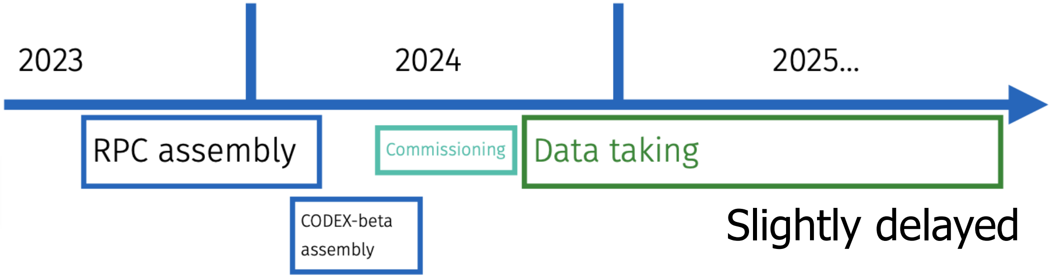
Expect 10^7 K_L to decay in the demonstrator volume.

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

Detector being prepared to be installed this winter shutdown



Slightly delayed

More collaborators welcome!

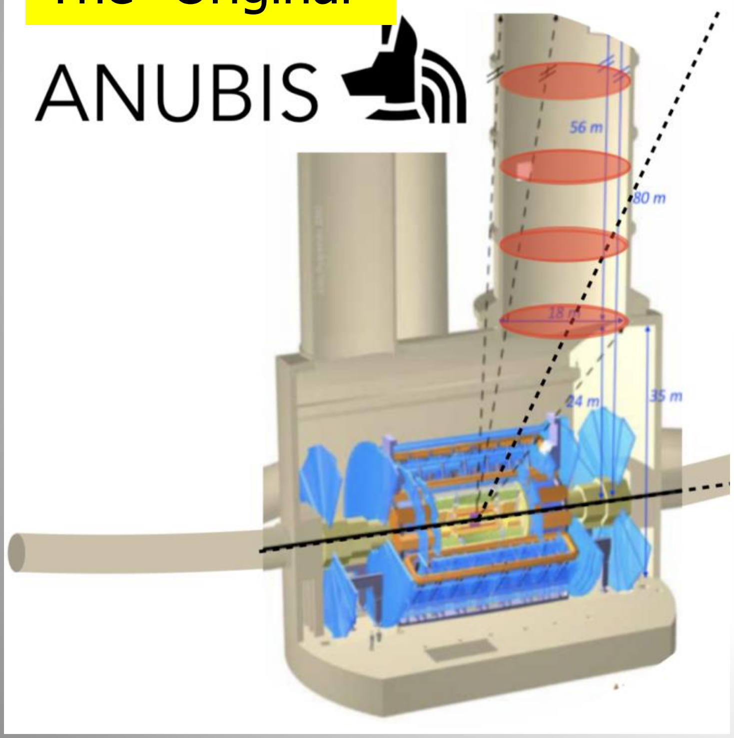
ANUBIS

ANUBIS: searches for long lived weakly interacting neutral particles

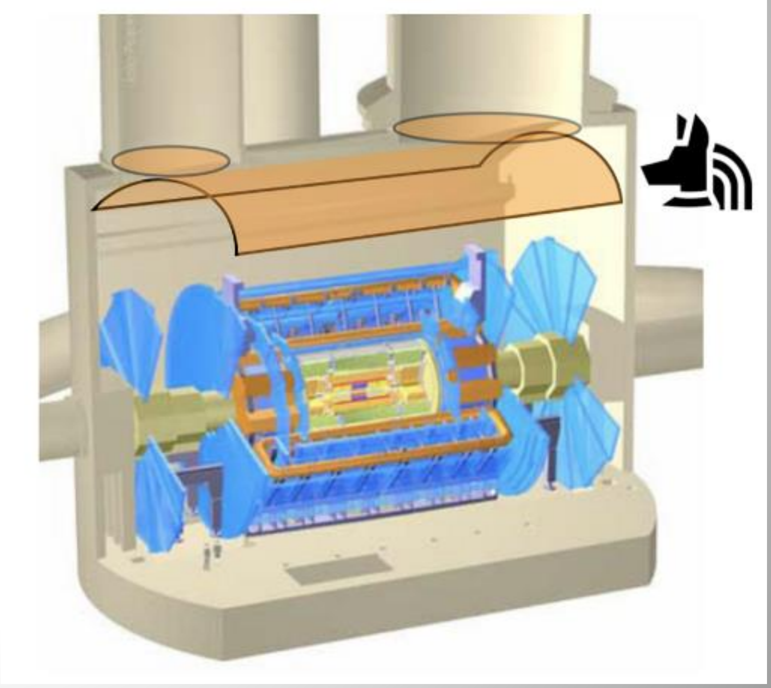
AN Underground **B**elayed **I**n-**S**haft detector

arXiv:1909.1302

The "Original"



New Layout

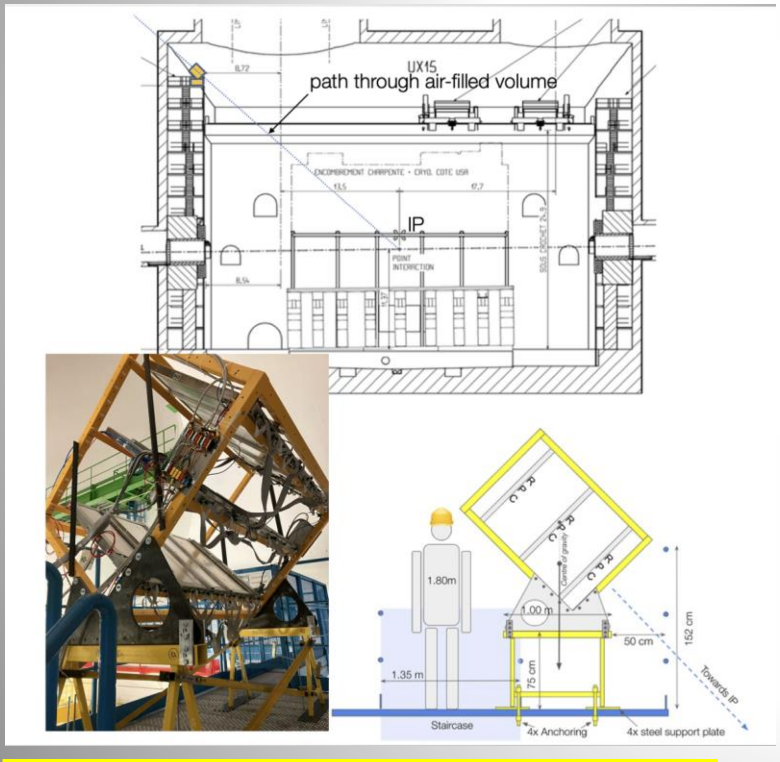


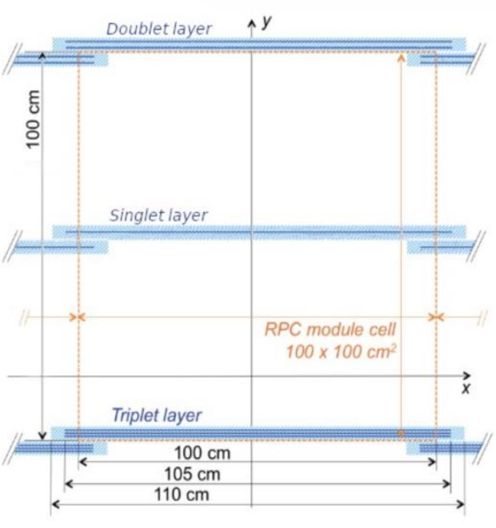
ANUBIS changed from 'in shaft' to 'in cavern'

ANUBIS

ANUBIS: searches for long lived weakly interacting neutral particles

AN Underground **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+

proANUBIS: A protoype in ANUBIS in the ATLAS cavern

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	$\varepsilon \gtrsim 98\%$

MATHUSLA Rescoping

MATHUSLA: MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

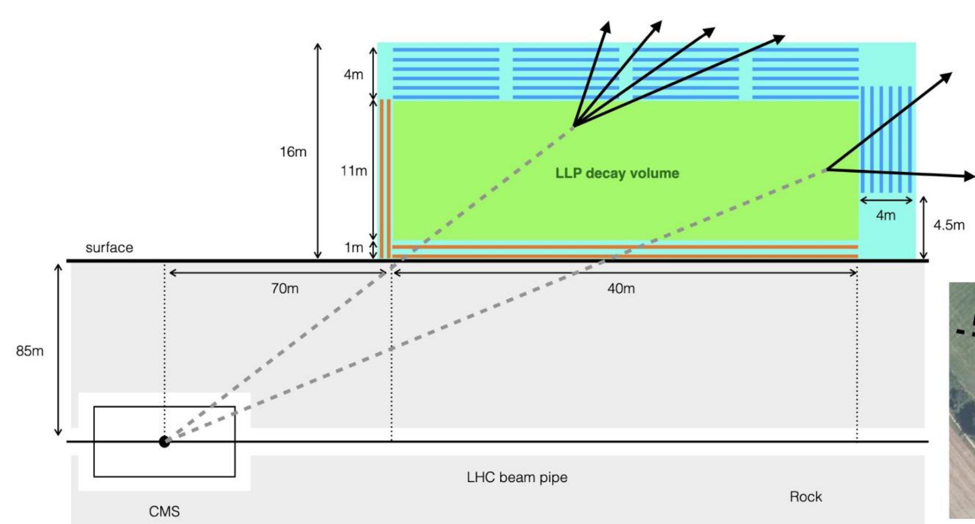
Dedicated detector sensitive to neutral long-lived particles with lifetime up to the Big Bang Nucleosynthesis limit ($10^7 - 10^8$ m) for the HL-LHC

1806.07396

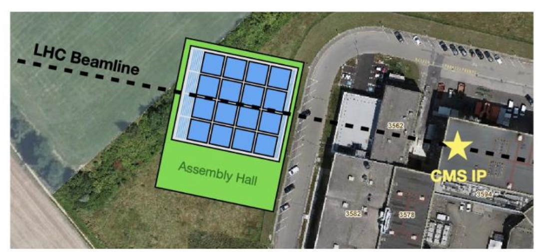
Proposed large area surface detector located above CMS with robust tracking and background rejection

- Large volume 40x40x16m^3
- 4D tracking with ~ns time resolution
- Can run standalone or “combined” to CMS

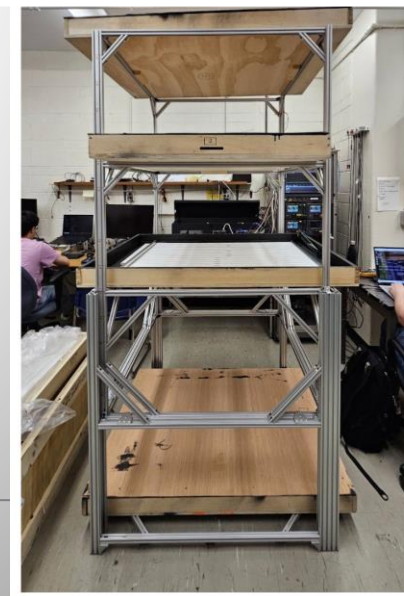
Aim to complete and submit CDR in 2025
New sensitivy studies being made



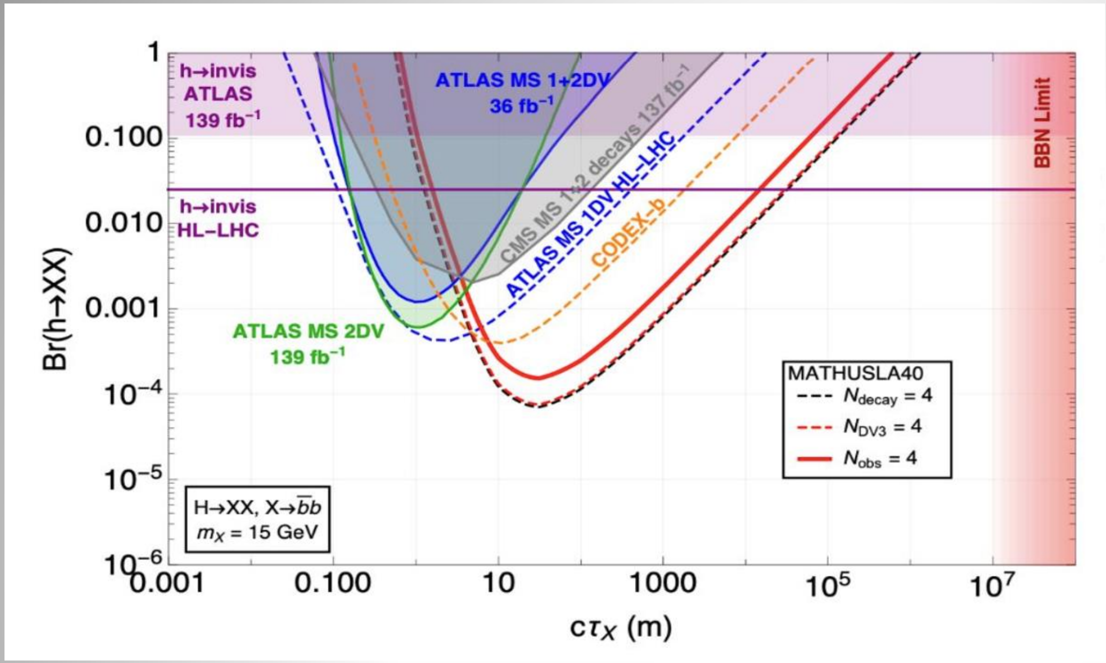
Reduced from 100x100x30 m^3

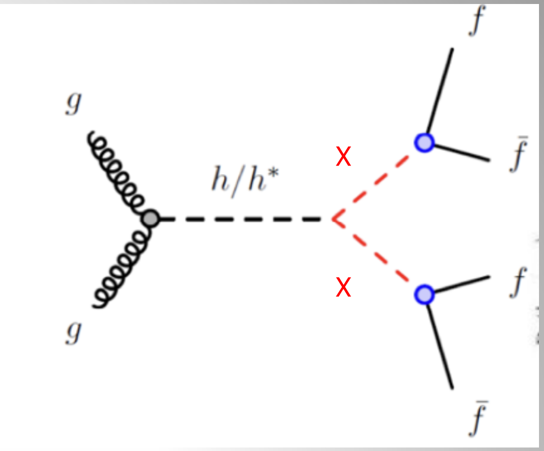


MATHUSLA test stand

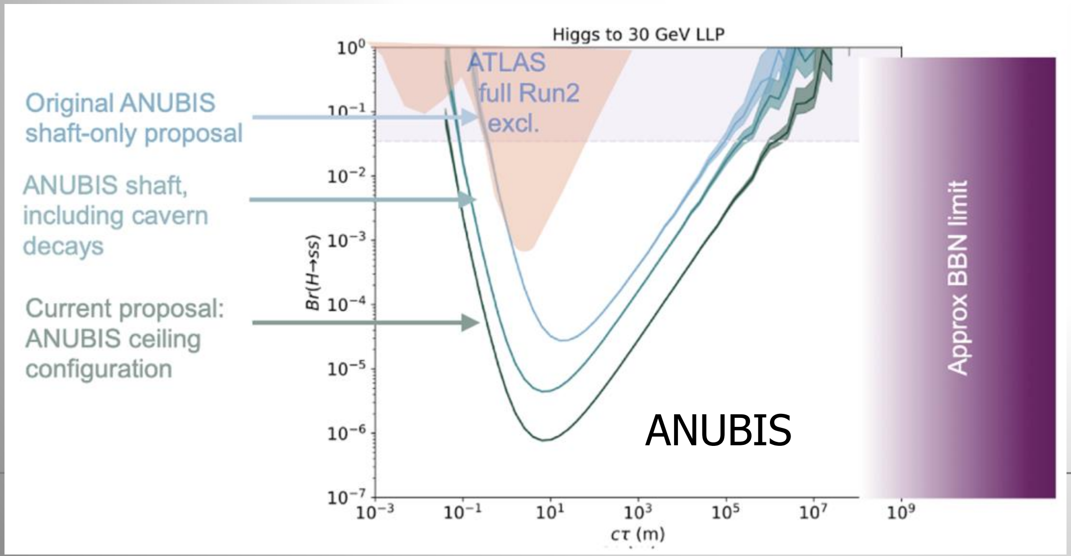


Comparisons in Reach





Reach for H-> XX and X-> bb



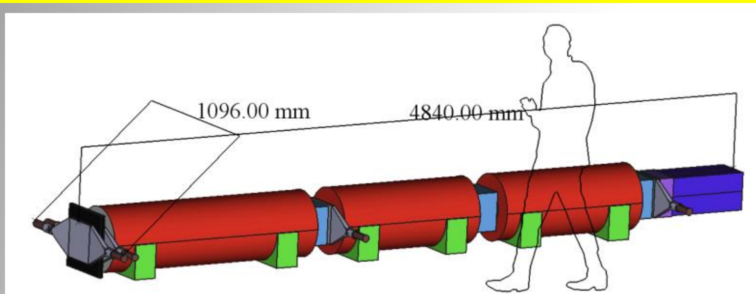
Comparisons for MATHUSLA, CODEX-b and ANUBIS

More benchmarks comparisons expected for European Strategy input..

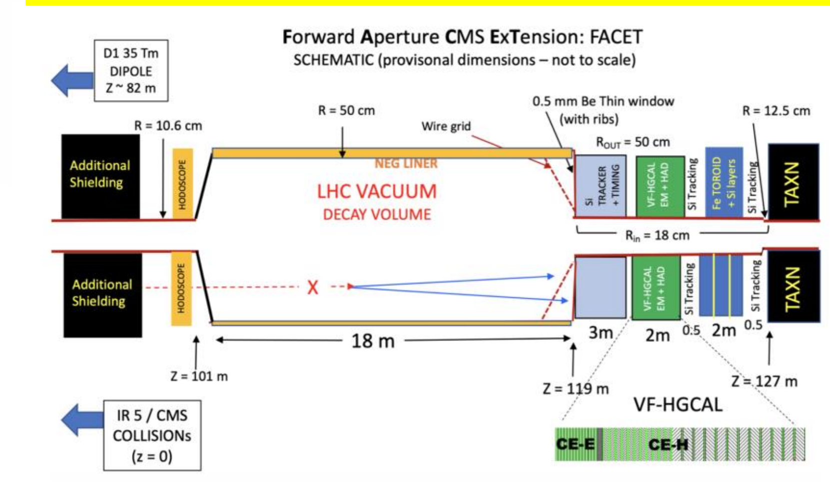
Proposals for Forward Detectors

New Forward Detector Proposals

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



FACET: Instrumented Beampipe for CMS



SND@LHC: neutrino measurements and long lived particle searches

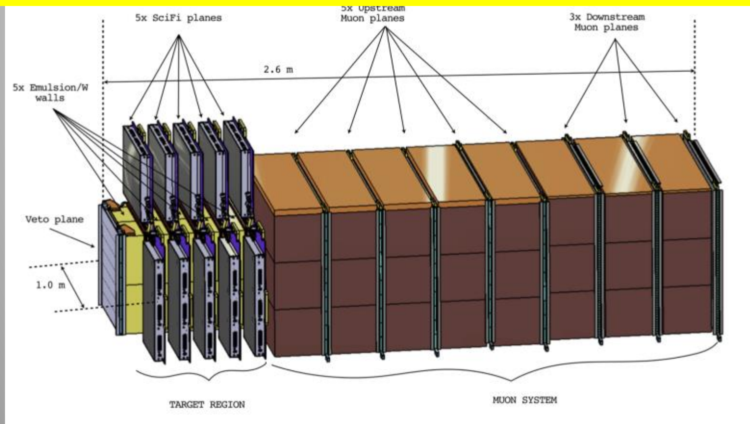


Figure 5: Layout of the proposed SND@LHC detector.

FPS: A Facility for Forward Physics Containing several experiments

Forward Physics Facility

FASER and SND@LHC have been approved in 2019/2020 and are taking data during Run 3

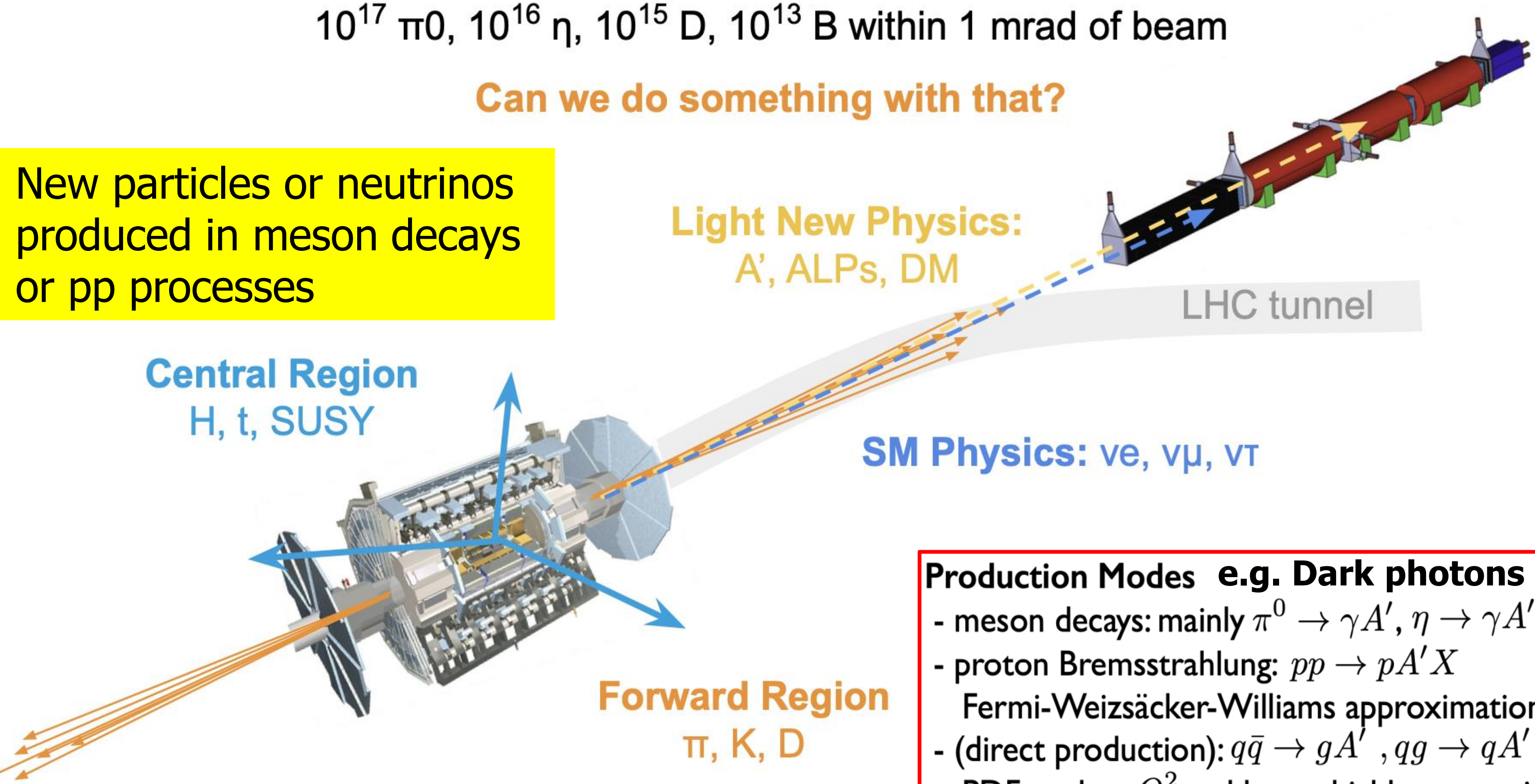
Forward Particle Production

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**

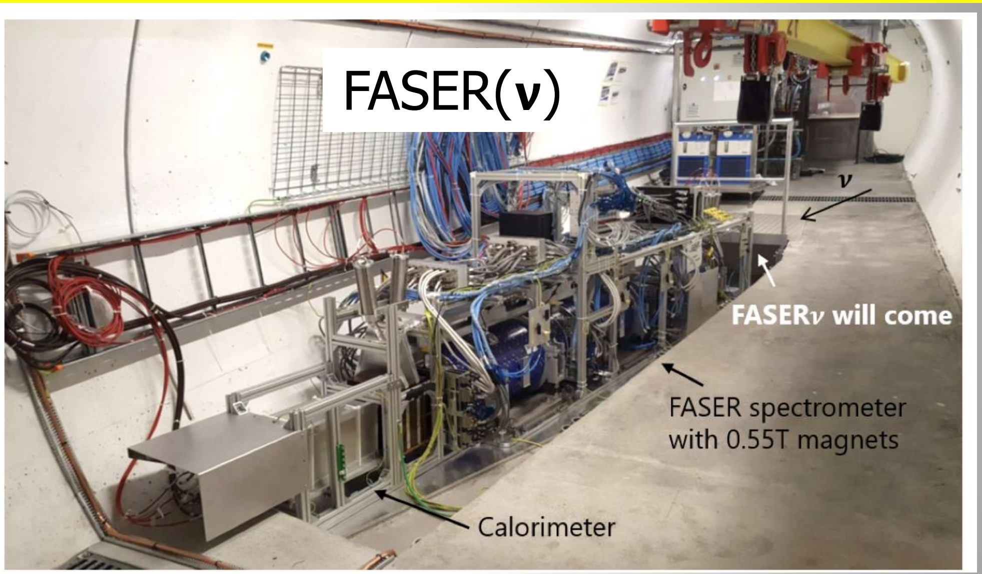
- meson decays: mainly $\pi^0 \to \gamma A'$, $\eta \to \gamma A'$
- proton Bremsstrahlung: $pp \to pA'X$
  Fermi-Weizsäcker-Williams approximation
- (direct production): $q\bar{q} \to gA'$, $qg \to qA'$
  PDFs at low Q^2 and low x highly uncertain

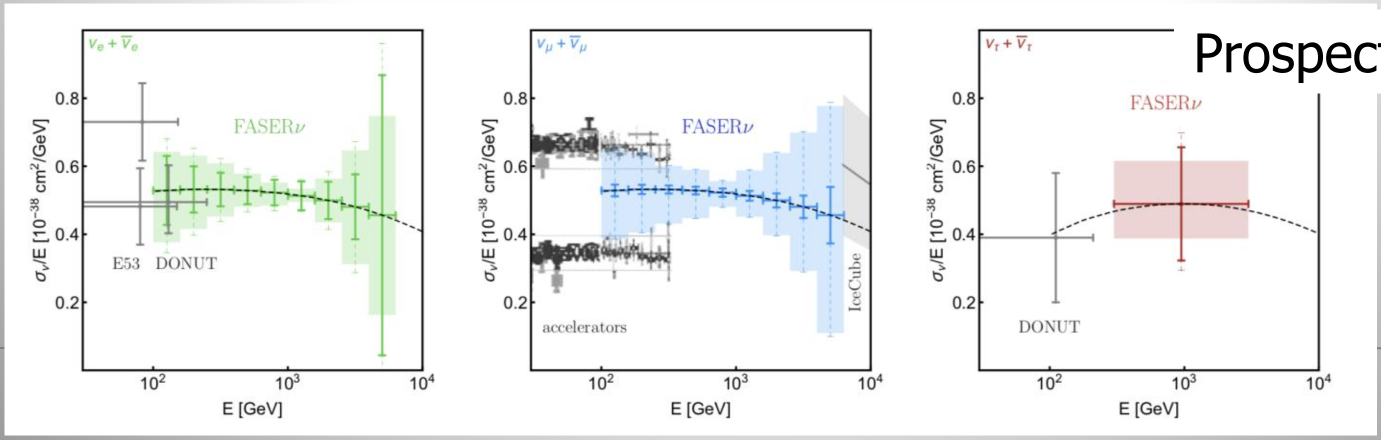
Two New Detectors at the LHC
FASER and SND@LHC

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

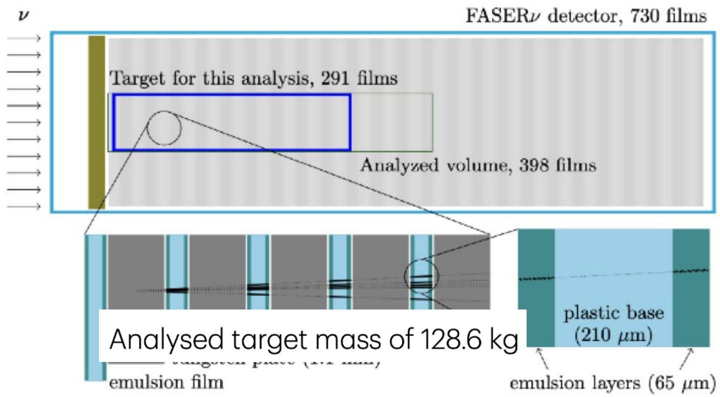




ν_e and ν_μ Interaction Cross Sections

First results in 2023: Direct observation of ν_μ neutrinos at the LHC!

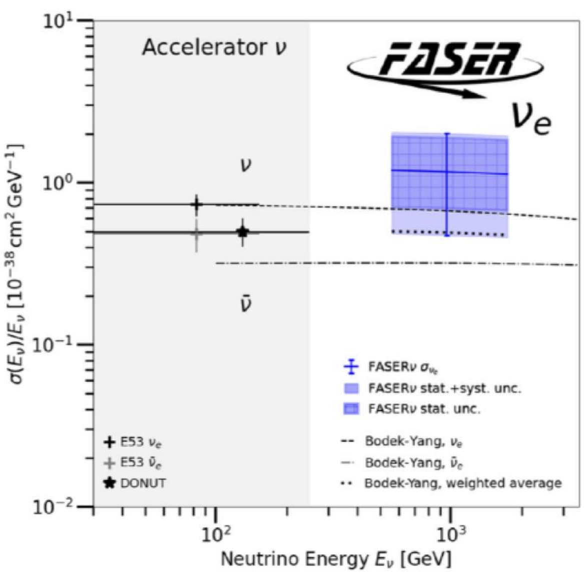
2303.14185, 2305.09383

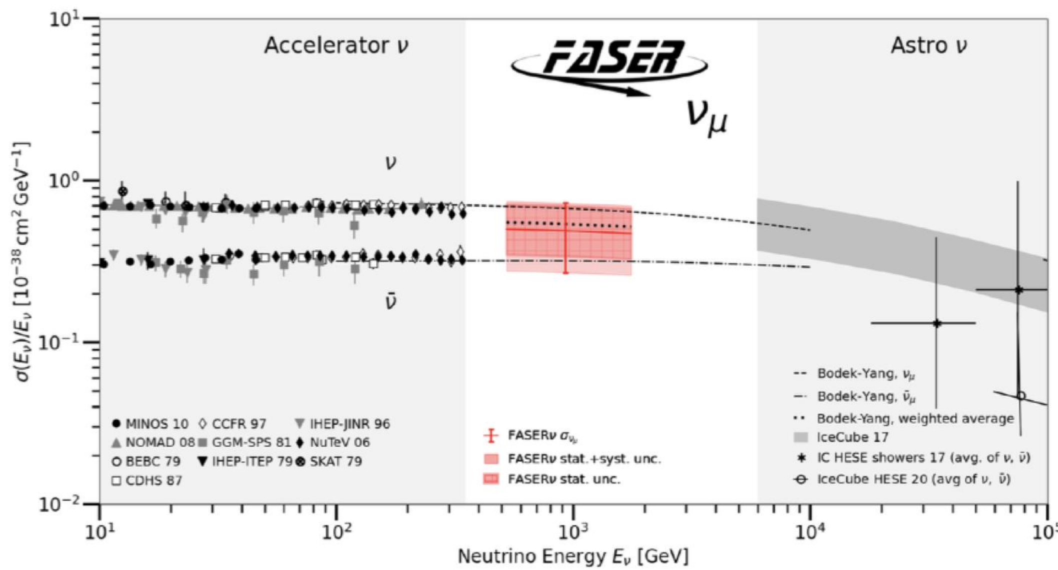


- Only small fraction of 2022 analyzed so far
- Candidate vertices reconstructed in emulsion films
  - Energy measurement (e) from shower multiplicity
  - Momentum measurement (μ) from track RMS (via Multiplescattering)

2403.12520

- Electron neutrino events observed: 4 (5.2σ)
- Muon neutrino events observed: 8 (5.7σ)

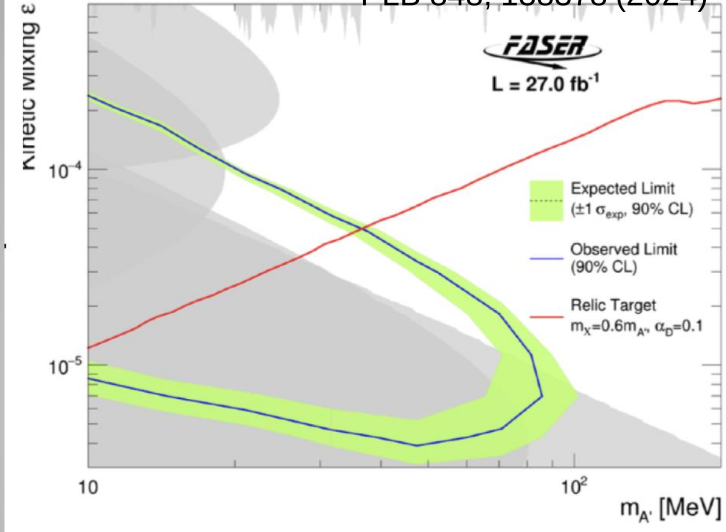




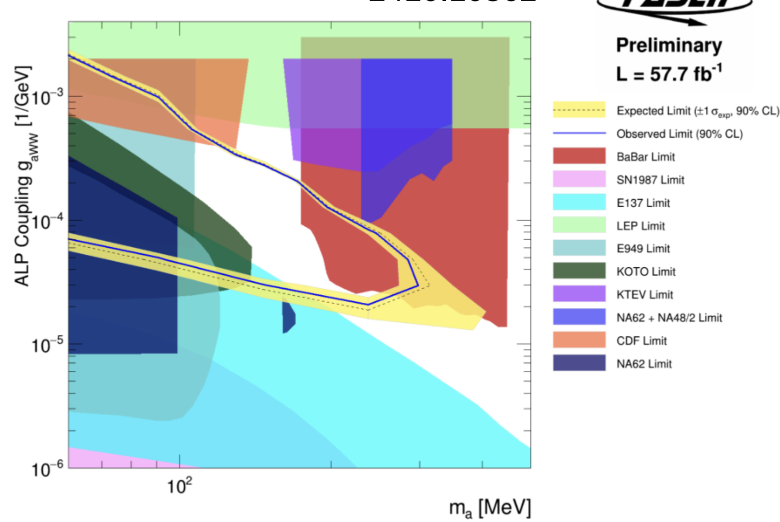
BSM Searches

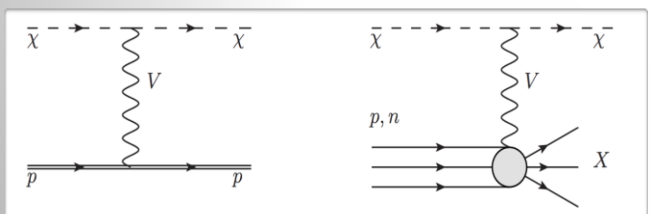
- FASER: Results on searches for ALPs and dark photons (decays)
- SND@LHC: Sensitivity for light dark matter (scasttering)

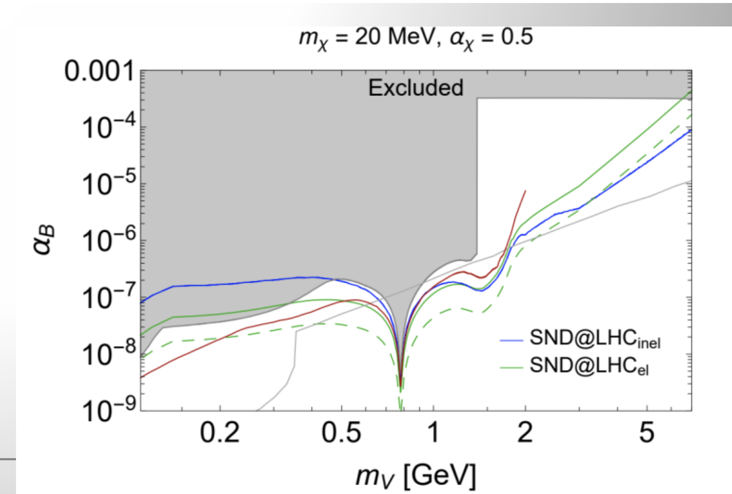
PLB 848, 138378 (2024)



2410.10362







JHEP 03 (2022) 006

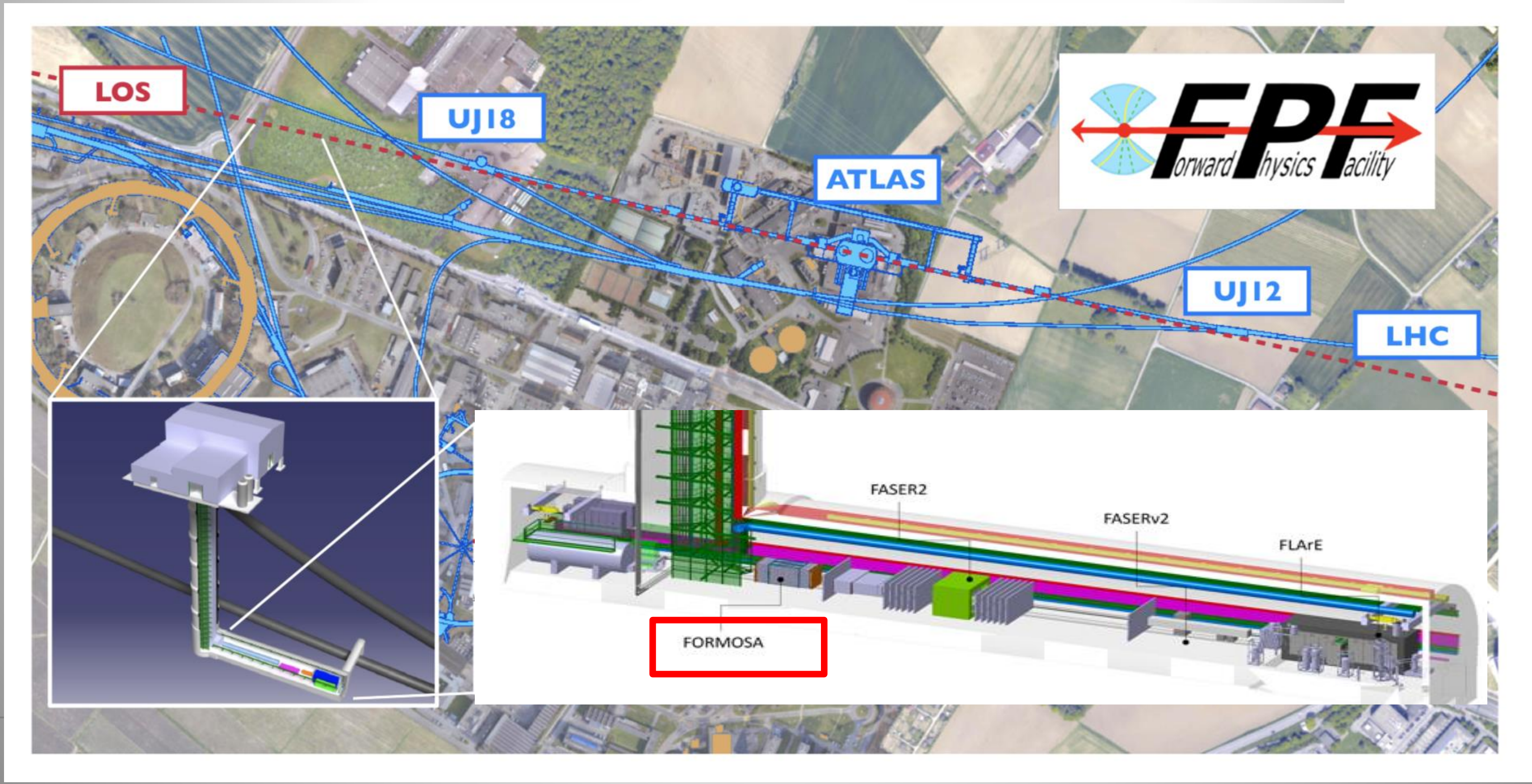
- More channels to explore:
  Higgs-like scalars, Heavy Neutral Leptons, final state radiation effects, Quirks, LFV with tau excess, exotic interactions…

An Option for the FUTURE:
The Forward Physics Facility

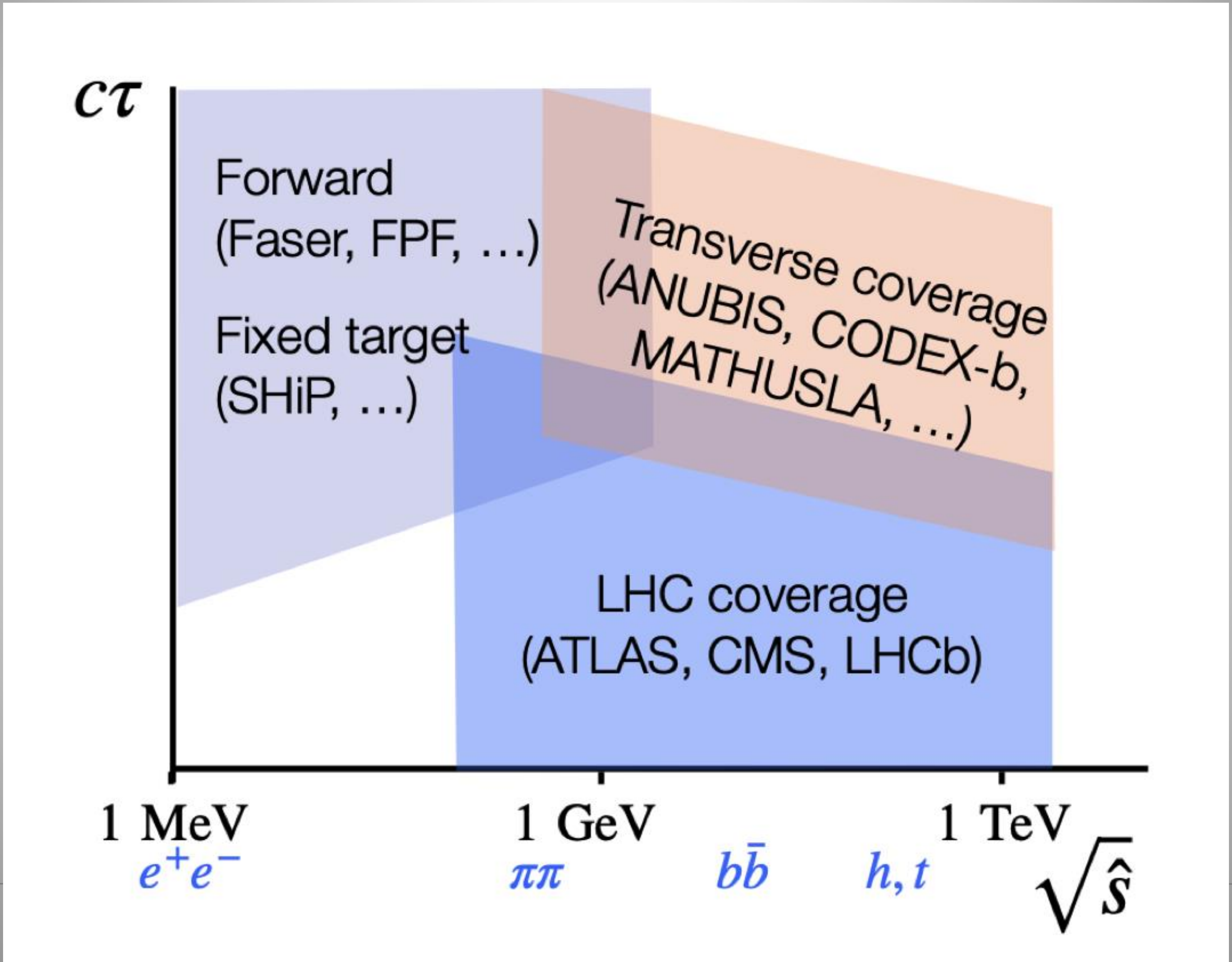
NEW: The Forward Physics Facility

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



Phase Space Overview

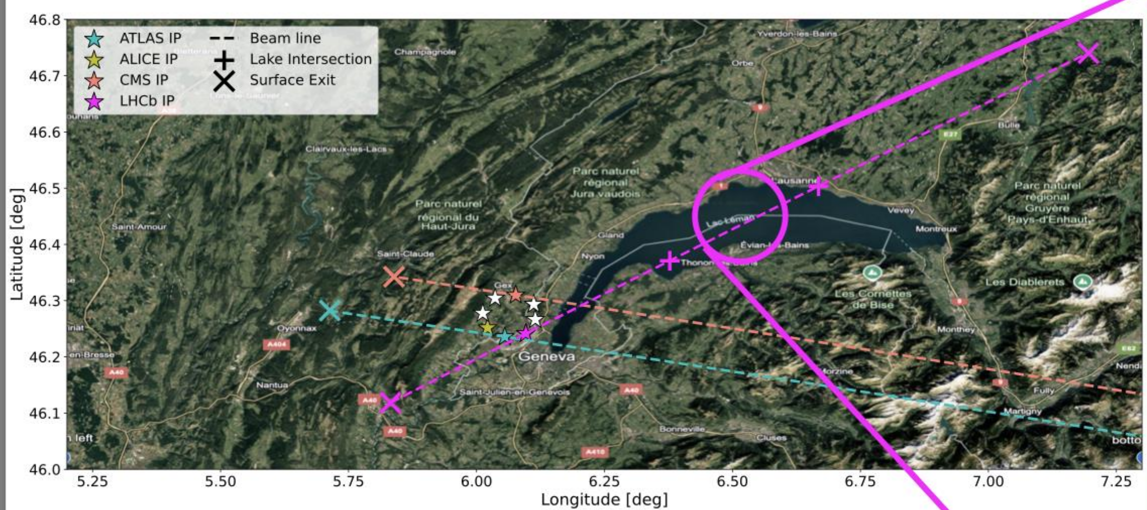


More Neutrinos Experiments?

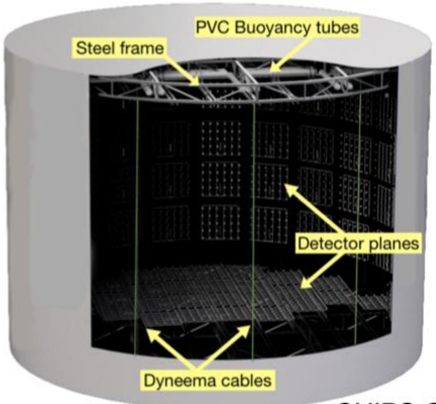
Instead of digging a new underground area.. Let the LHC neutrinos surface!
….And catch them with a detector, eg in Lake Geneva…

N. Kamp et al., CERN PBC Meeting Nov. 24

UNDINE: UNDerwater Integrated Neutrino Experiment



- A suite of CHIPS-style water Cherenkov detectors deployed in a modular fashion
- Benchmark lake detector: 5 CHIPS modules (~30 kT)



CHIPS Collab. 2024

Non-Collider Experiments

- Neutrino Experiments
- Beam Dump Experiments
- High Intensitiy Experiments

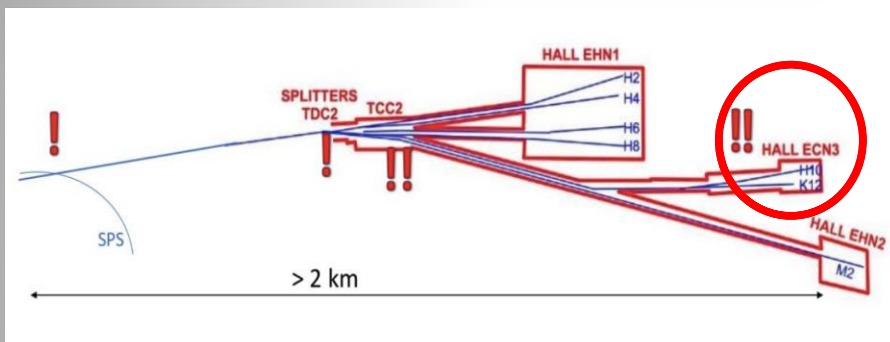
…

Ongoing and planned projects:
Belle-II, BES-III,NA62, NA64, MicroBooNE, T2K, DAMSA, Shiness, BaBar, LUXE, SUBMET, DarkQuest, LHCb-U1…

See also C. Hearly

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

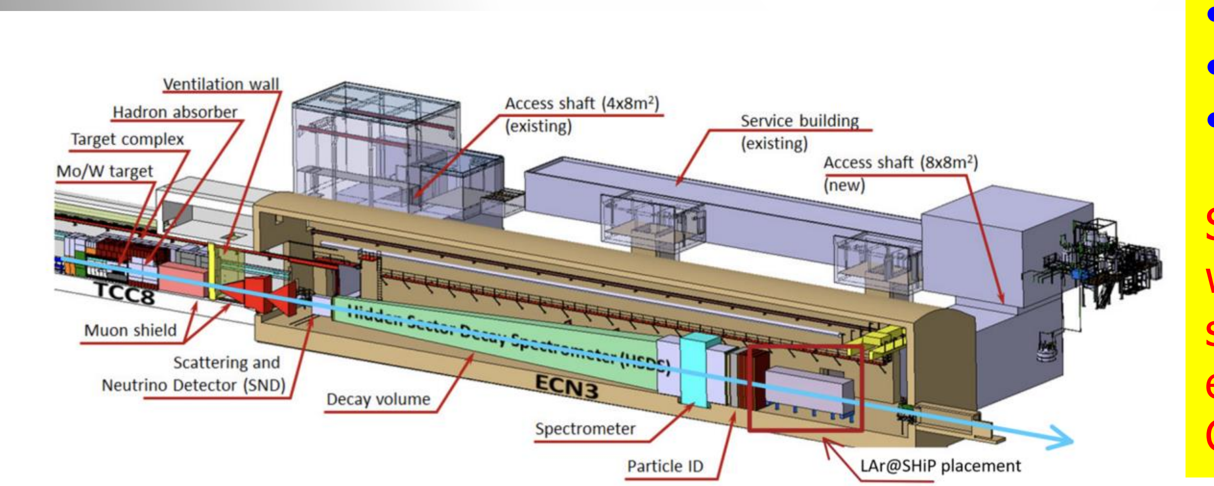


CERN-SPSC-2023-033

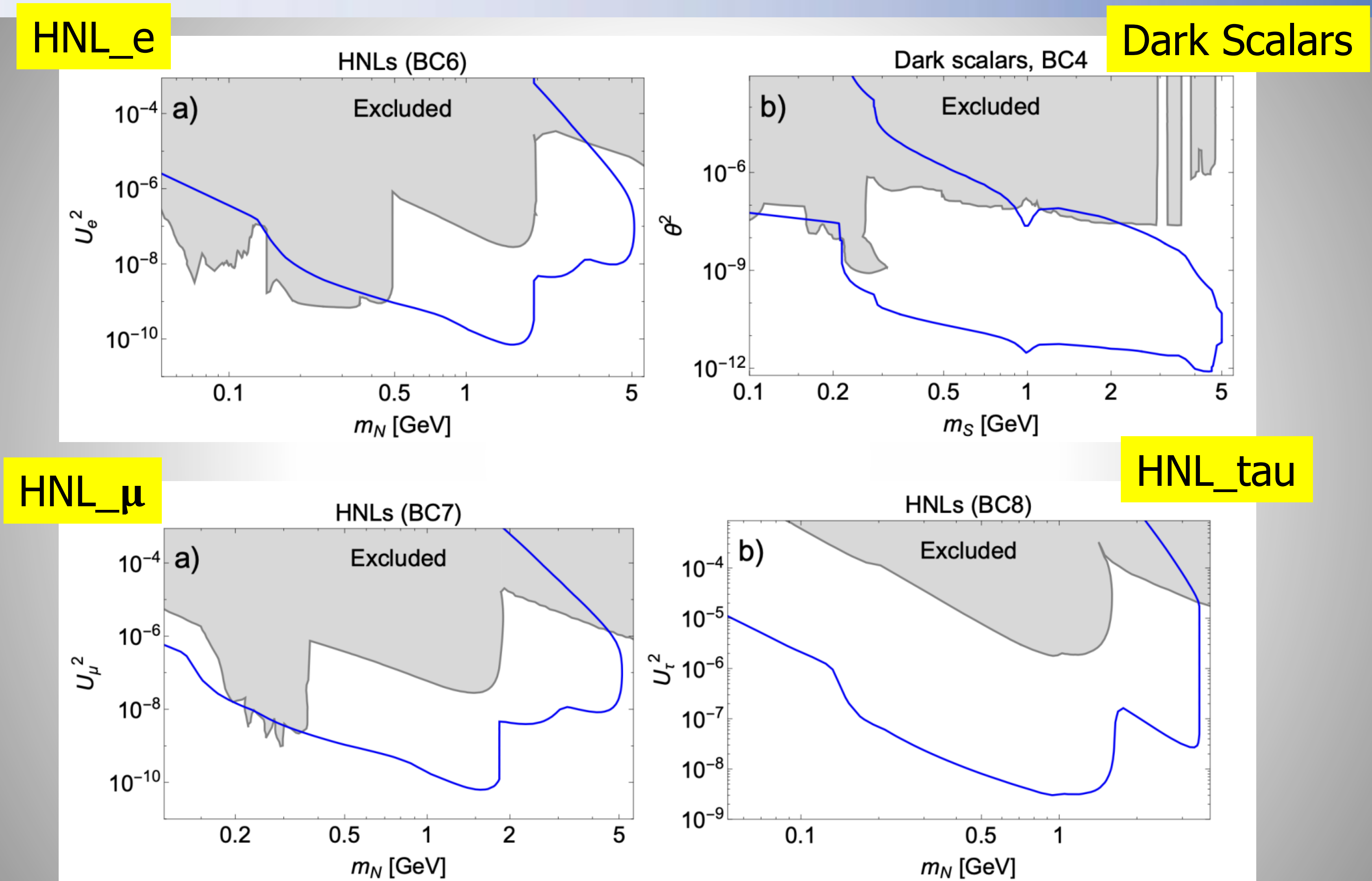
SHiP is an optimized detector for searches for Feebly Interacting Particles (FIPS) such as:

- 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



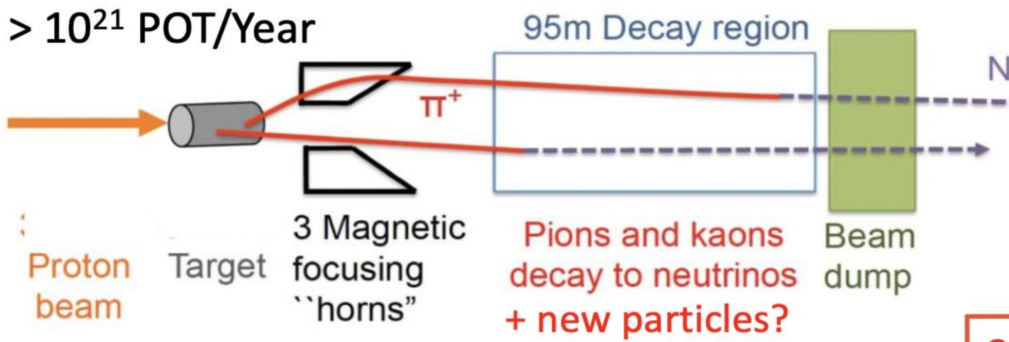
SHiP Physics Prospects



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



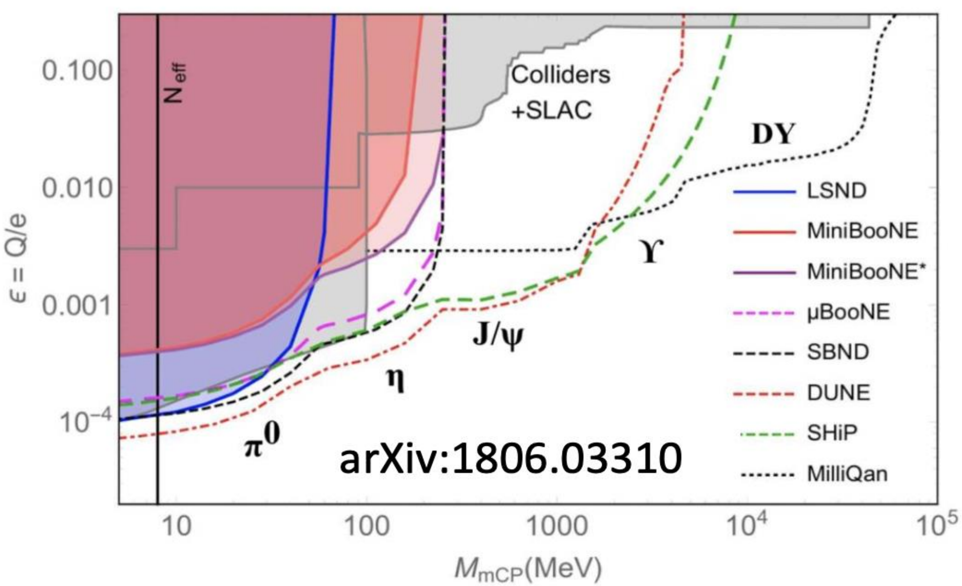
Light dark matter
HNLs
ALPs
Millicharged particles

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



arXiv:1806.03310

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

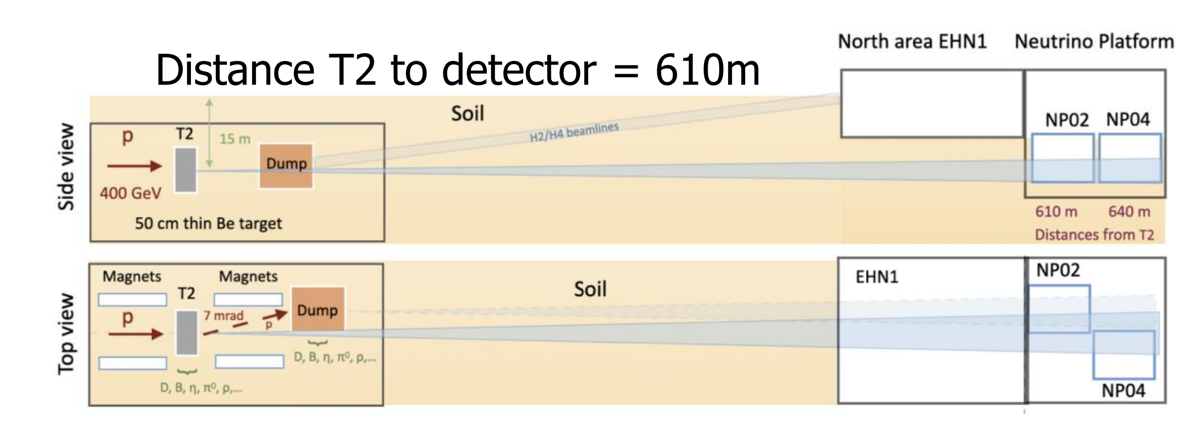
ProtoDUNEs for BSM Searches?

arXiv:2304.06765

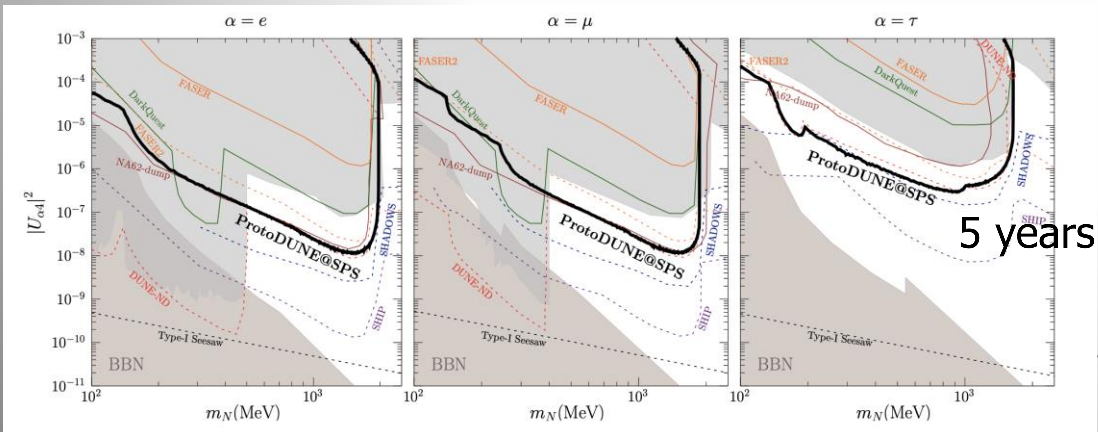
New Physics searches using ProtoDUNE and the CERN SPS accelerator

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

Use the ProtoDUNE detectors (700t LArTPCs) 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

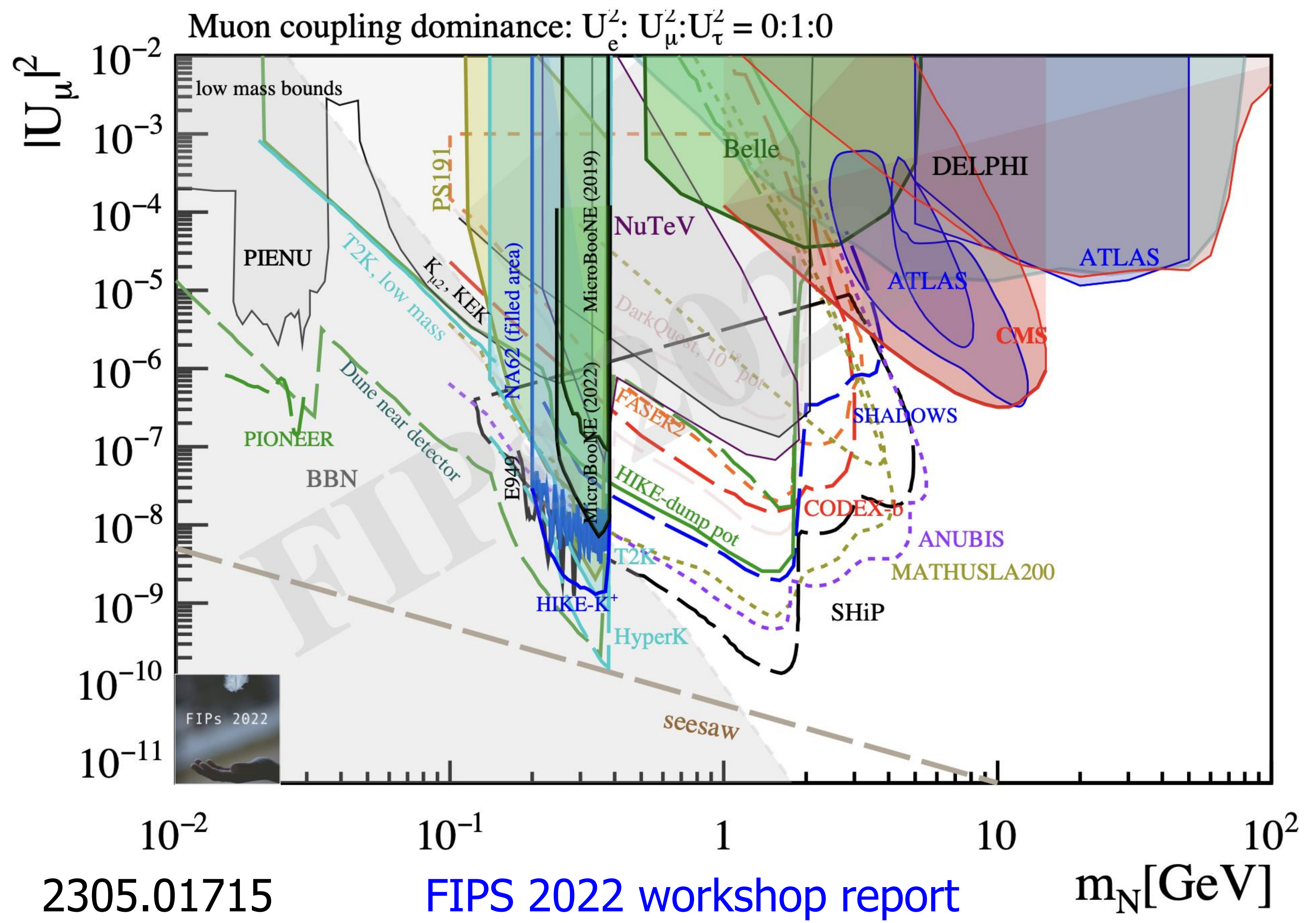


HNL Sensitivity: Competitive for masses above the Kaon threshold

Experimental feasibility study ongoing…

Physics Beyond Colliders

Example: Heavy Neutral Leptons



2305.01715 FIPS 2022 workshop report

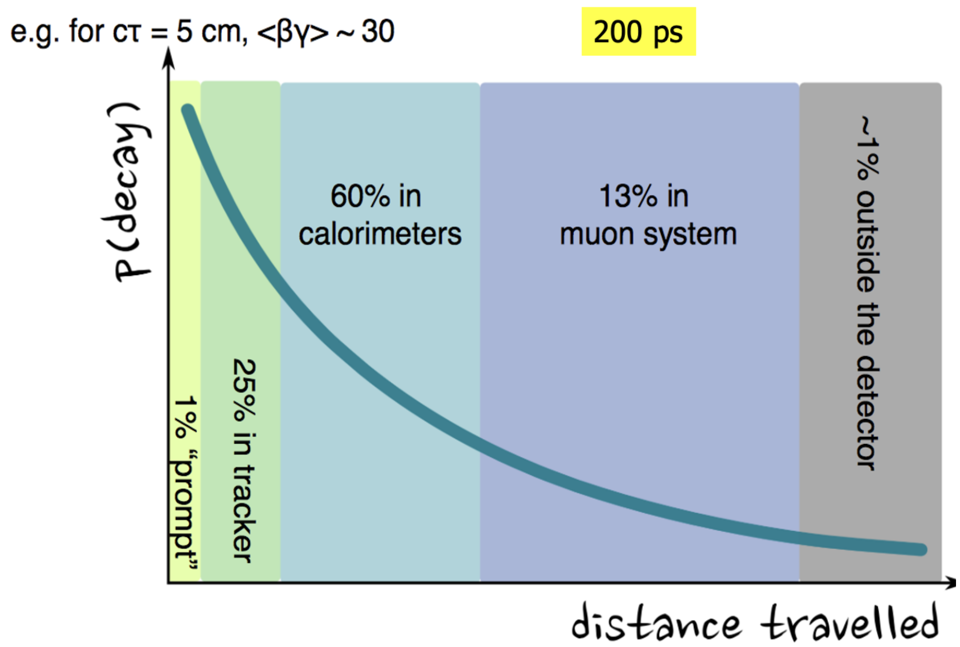
Summary

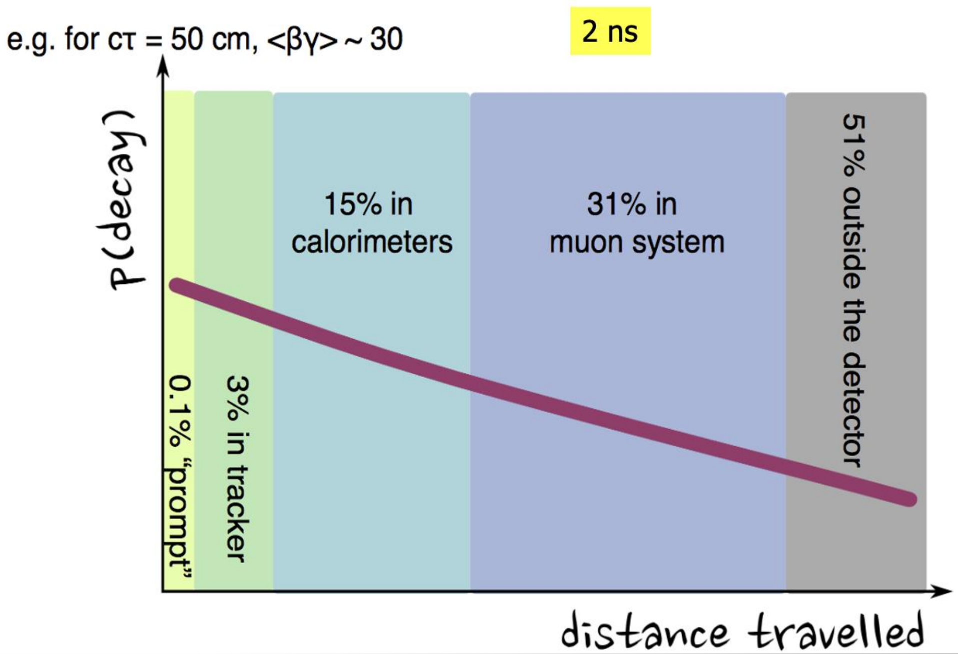
- Clearly and increased interest in low mass/coupling and LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. Many analyses done or in are progress. No signal observed yet, but only top of the iceberg covered so far.
- New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, 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 other proposals!
- European Strategy Updata for Particle Physics 2025/2026 will play a significant role in selecting/prioritizing
- If we would observe one significant anomaly …

Backup

Long Lived Particles @ LHC

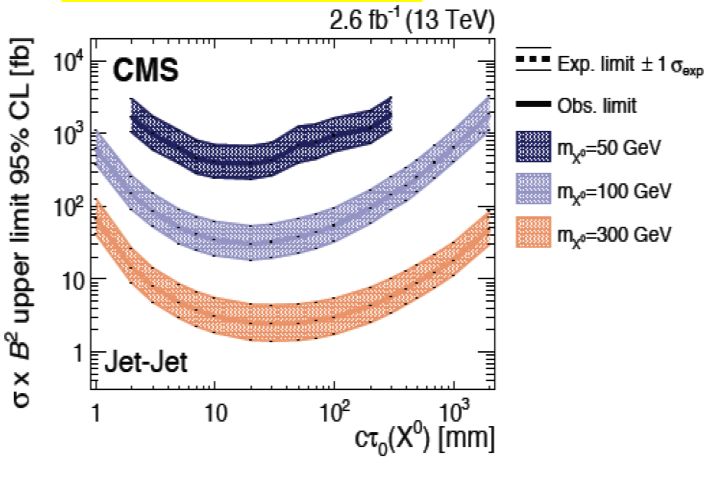
Examples of the distance travelled before decay in a central detector (example for ATLAS) depending on lifetime and kinematics



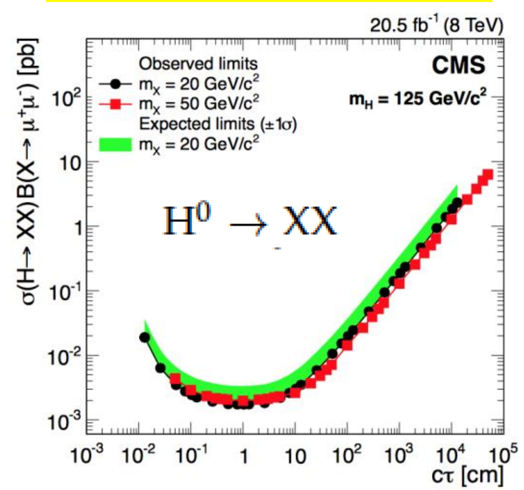


Long Lived Searches: Examples

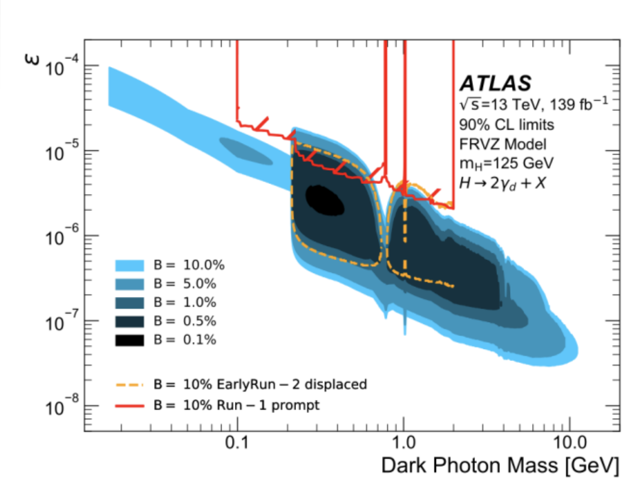
displaced jets



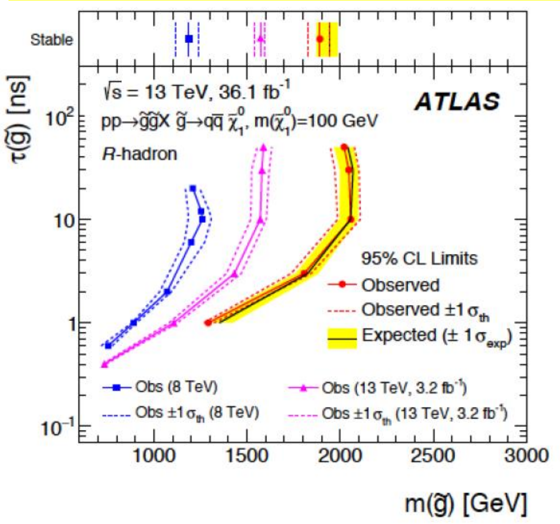
displaced leptons



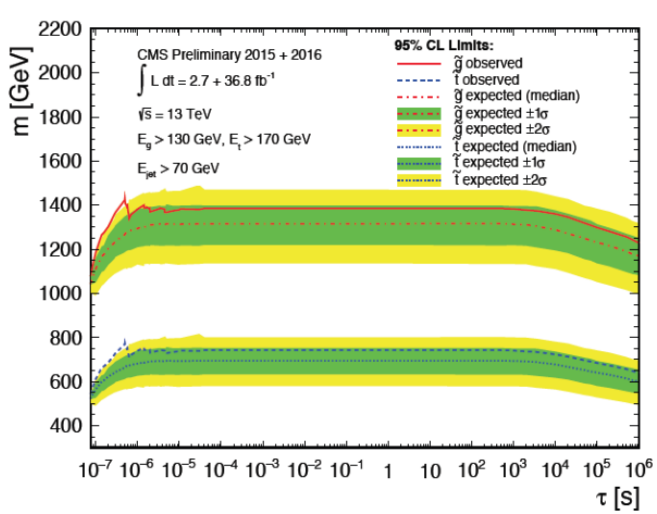
dark photons



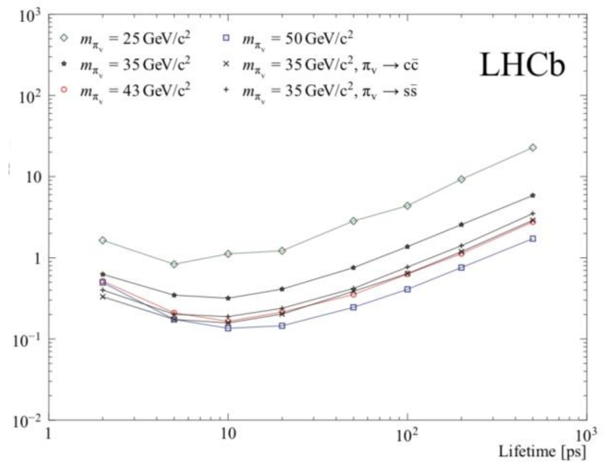
metastable R-hadrons



stopped particles

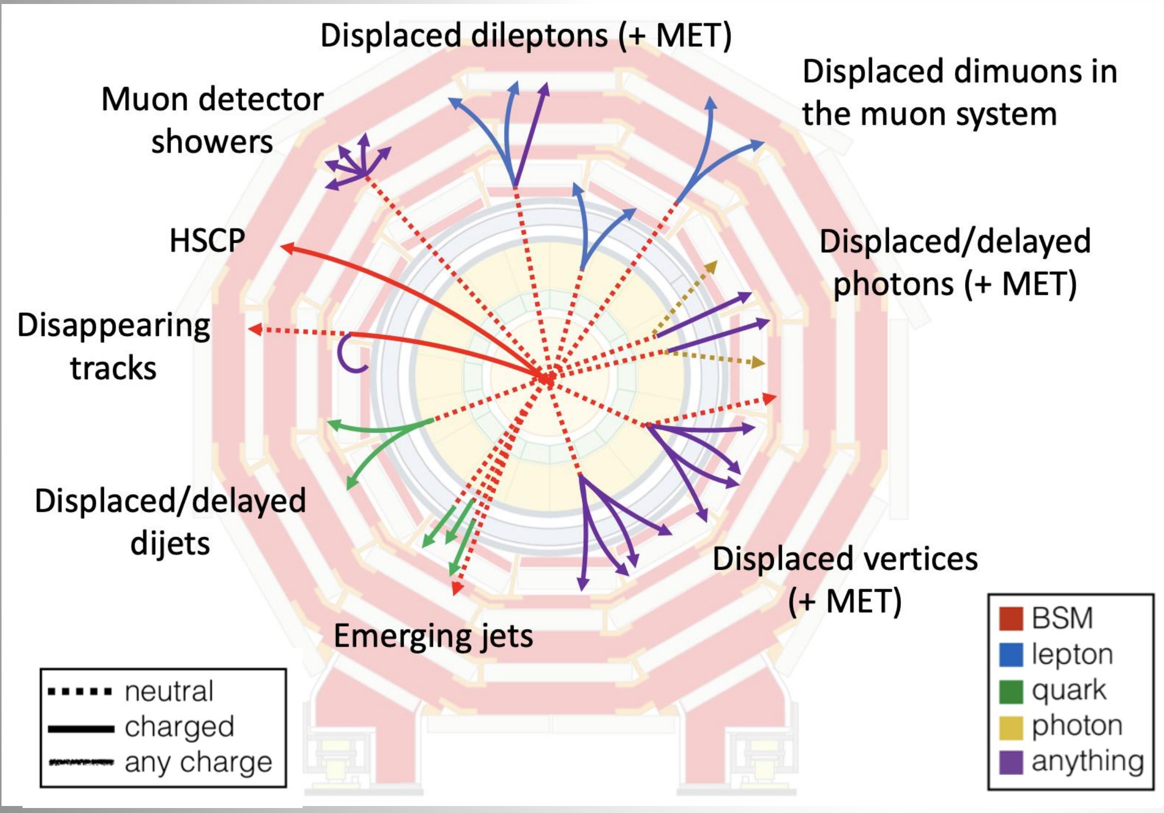


Hidden Valley searches



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.

Developments @ LHC Analyses

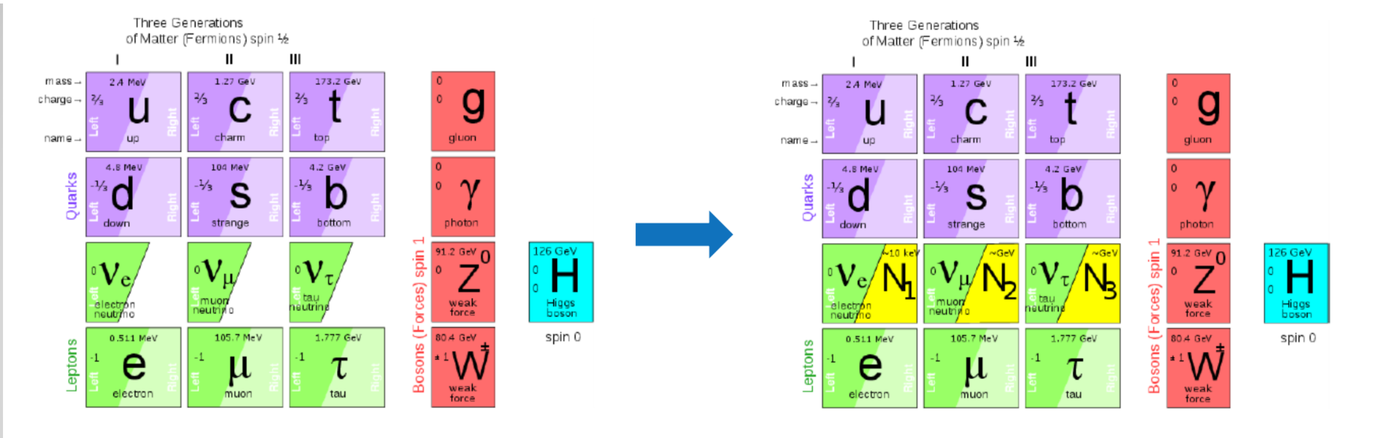
- Triggers improvements:
  - Examples LHCb software trigger, displaced objects, timing, … (see eg:2210.14675)
- Data collection improvements
  - Scouting of data & data parking techniques
- Analysis improvements
  - Better use of the detector capabilities, timing, LLP search in all subsystems eg muon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

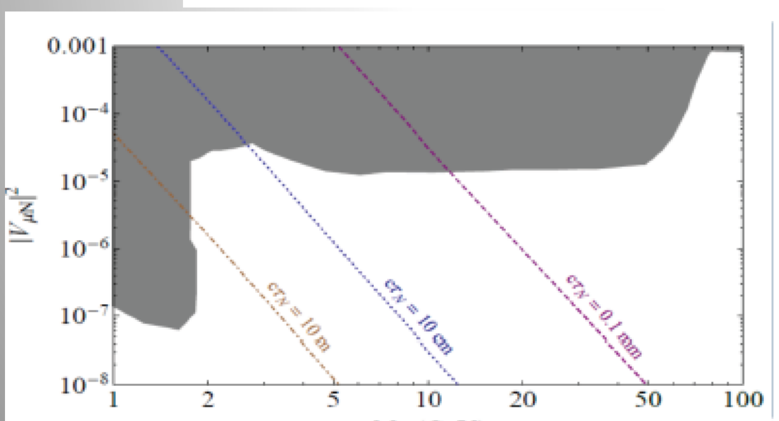
Example: Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

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

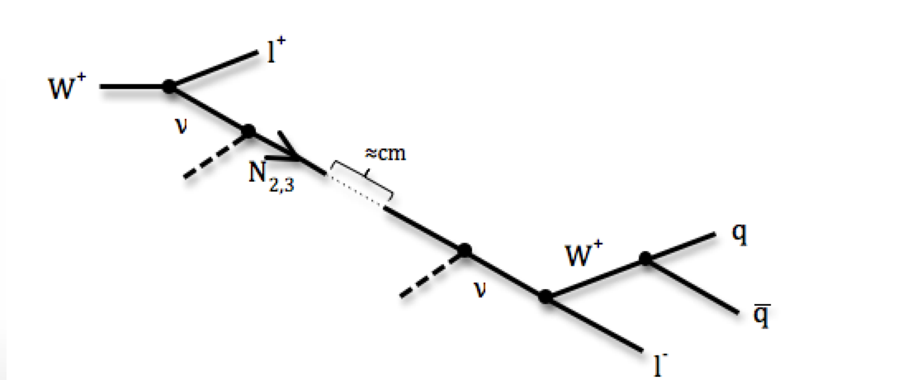
Addresses the masses of neutrinos, baryon asymmetry and dark matter





15.11.17

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



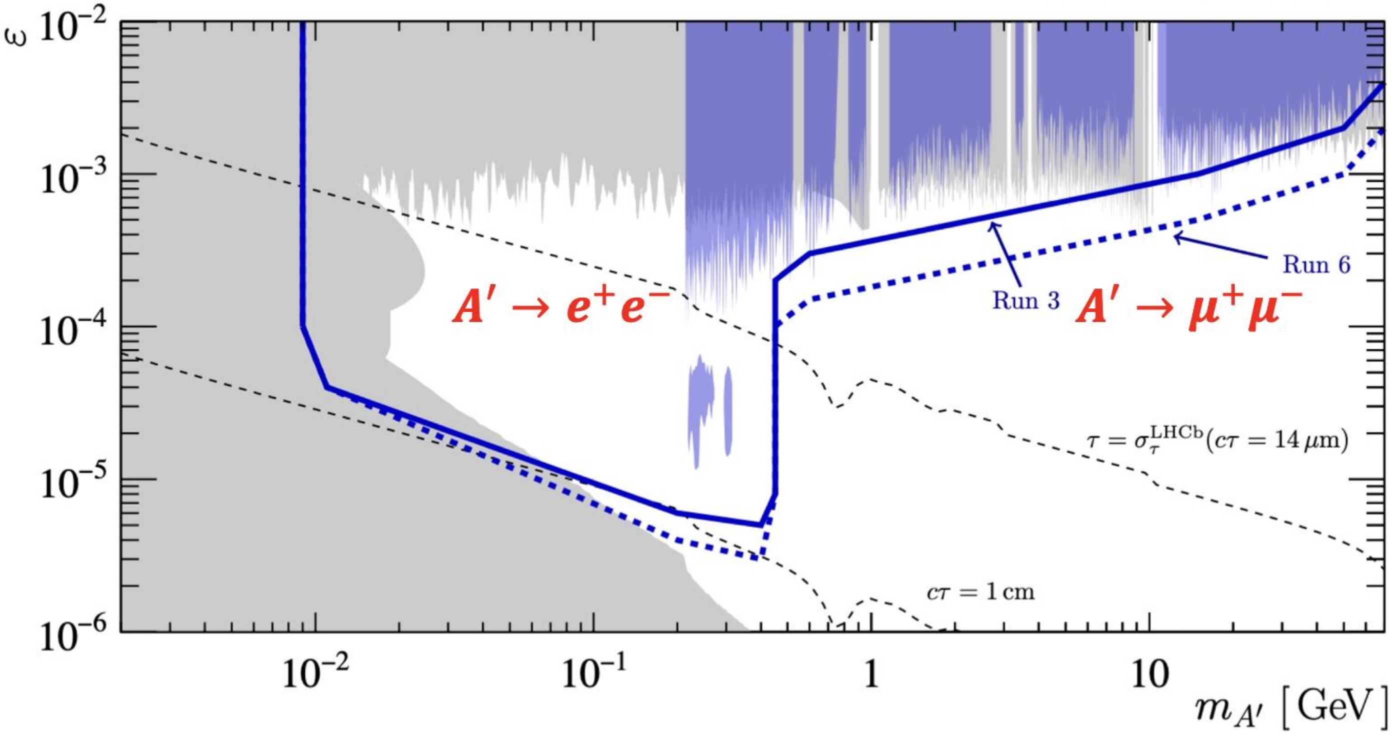
Now we have LHC studies with displaced jets/lepton analyses with L~ 1m

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**

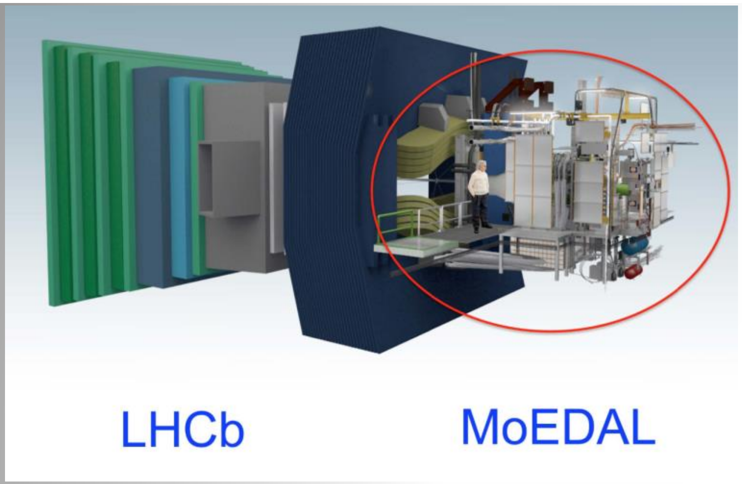
arXiv:2203.07048



The MoEDAL Experiment

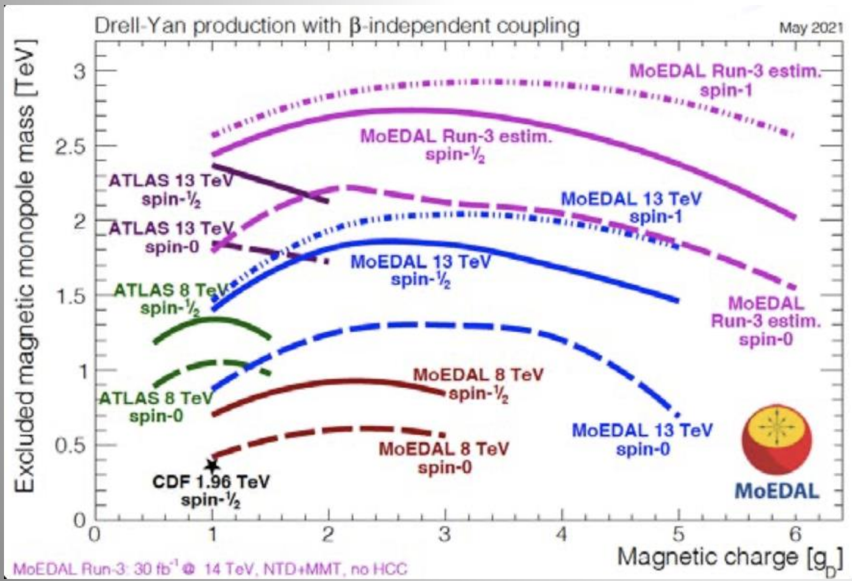
…A search for Magnetic Monopoles and more…

See talk J. Pinfold

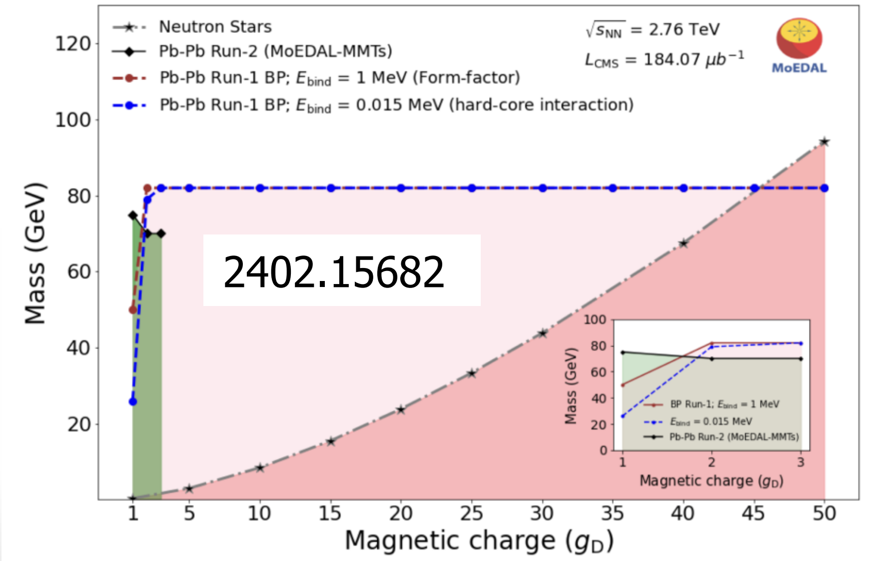


MoEDAL = ~ 75 physicists from 22 institutes and 11 countries

-> MoEDAL is a passive detector, sensitive to new physics



Monopole search in heavy ion data using Schwinger model

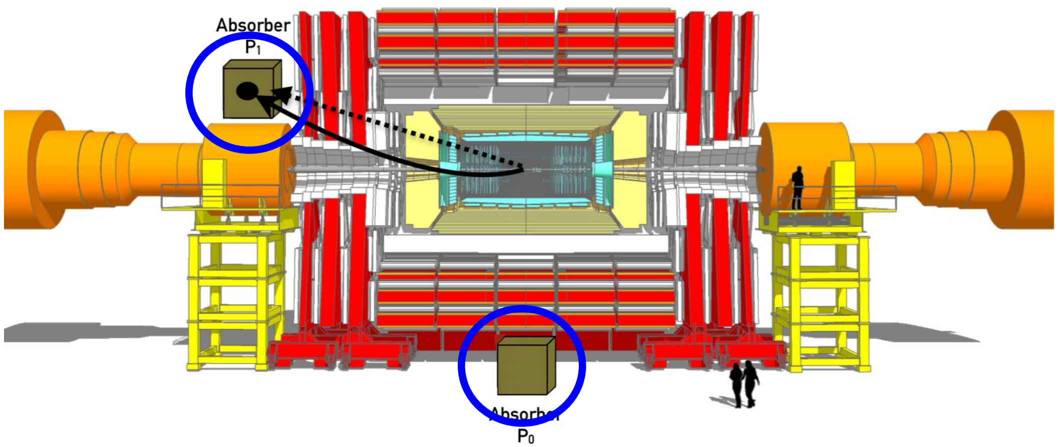


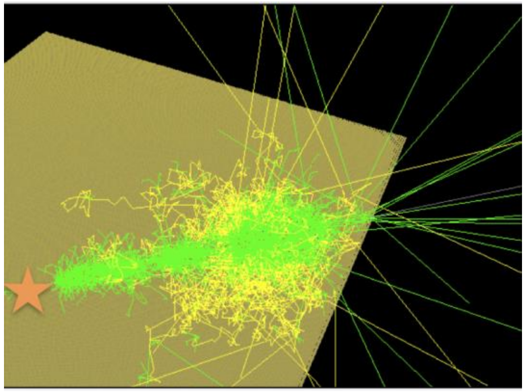
MoEDAL is THE prototype of a small dedicated BSM experiment @LHC

Trapping Particles

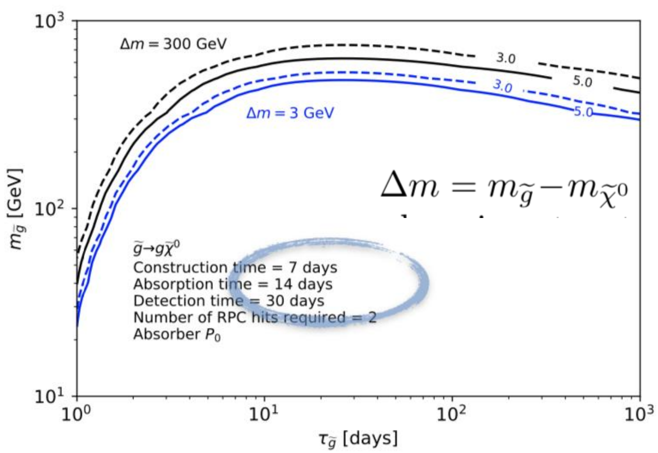
arXiv:2110.13837

- 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!



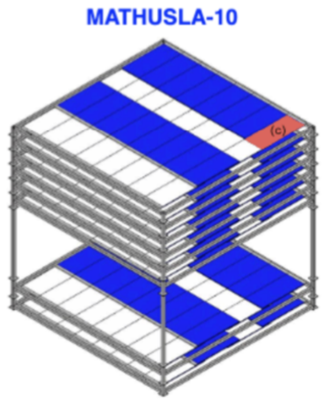
Trap the particles and wait for its decay

Reach longer lifetimes: > weeks, months!

Not been followed up recently… ☹

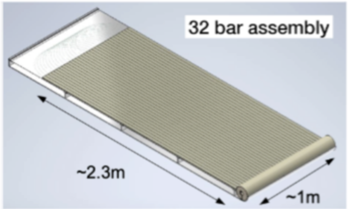
MATHUSLA

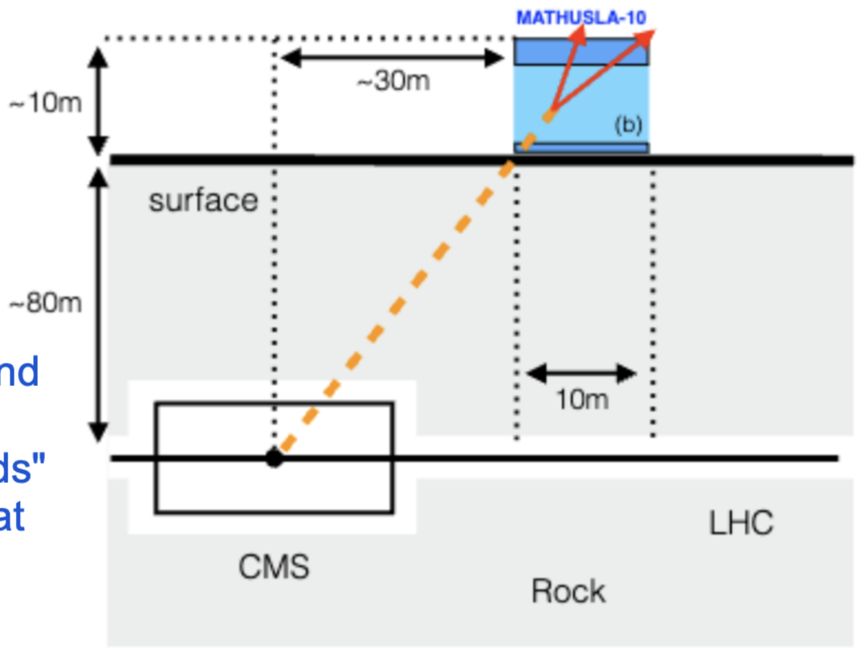
Module 0



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

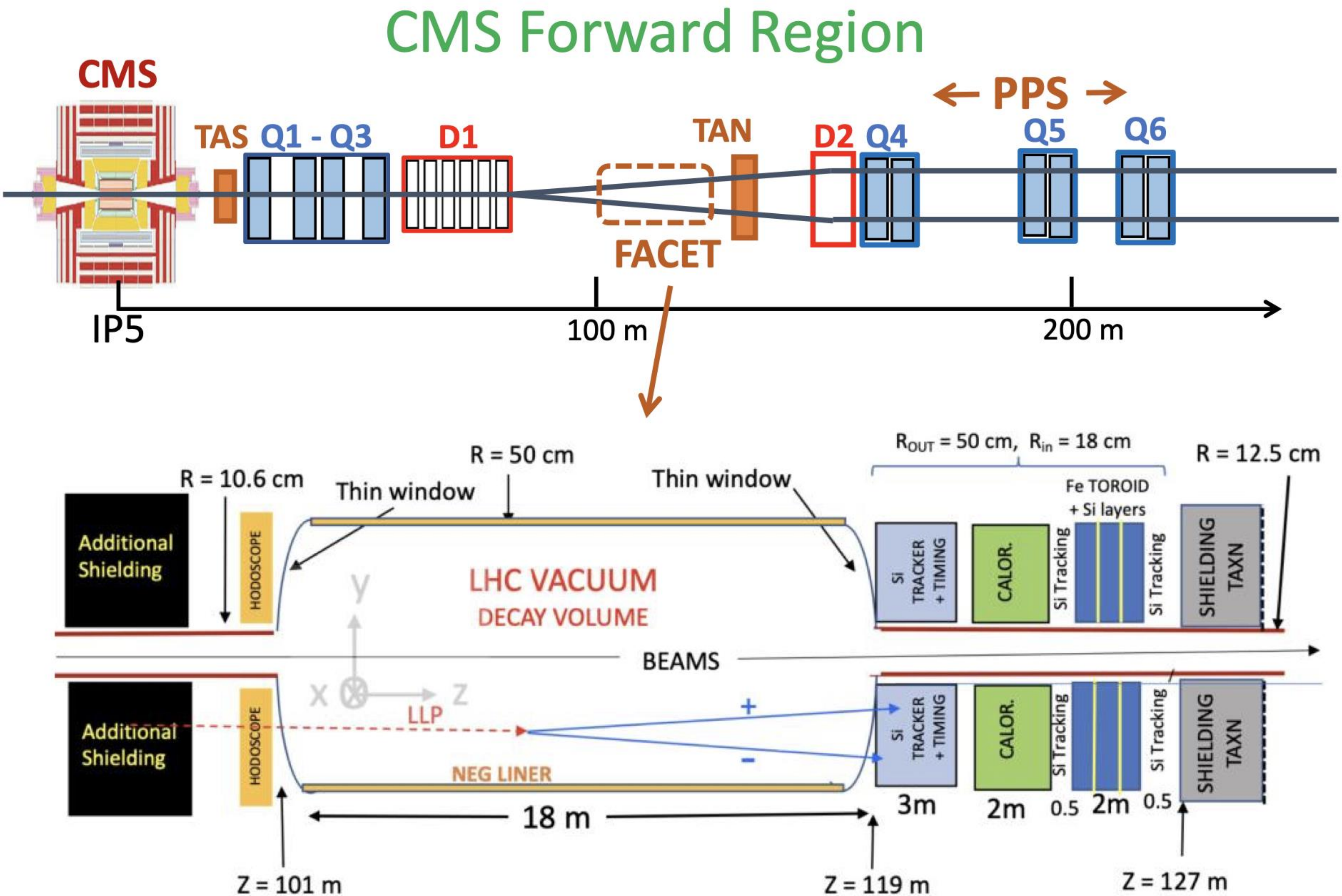
- Dimensions **~10 x 10 m², H~flexible**
- Prototype for the detector technology
- To be placed above CMS, and even as a stand-alone module can extend the LHC reach for LLP





- 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.

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
R = 50 cm
Thin window
Thin window
ROUT = 50 cm, Rin = 18 cm
R = 12.5 cm
Additional Shielding
HODOSCOPE
LHC VACUUM
DECAY VOLUME
Si TRACKER + TIMING
CALOR.
Fe TOROID + Si layers
Si Tracking
Si Tracking
SHIELDING TAXN
BEAMS
y
x
z
LLP
+
-
NEG LINER
Additional Shielding
HODOSCOPE
18 m
3m
2m
0.5
2m
0.5
Z = 101 m
Z = 119 m
Z = 127 m

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!!

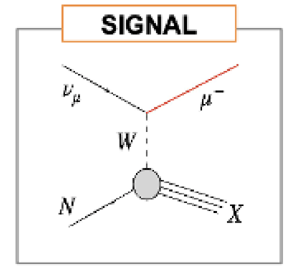
Both experiments were ready to take data in Run 3 in May 2022!

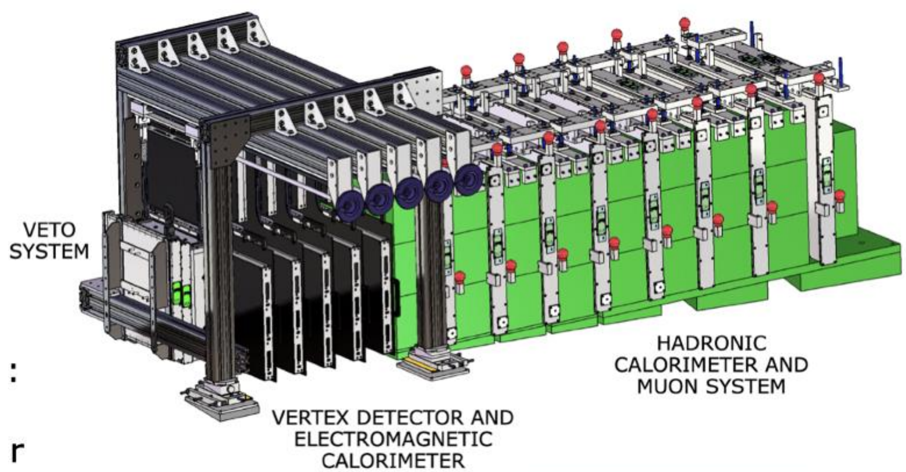
Neutrinos from the LHC

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

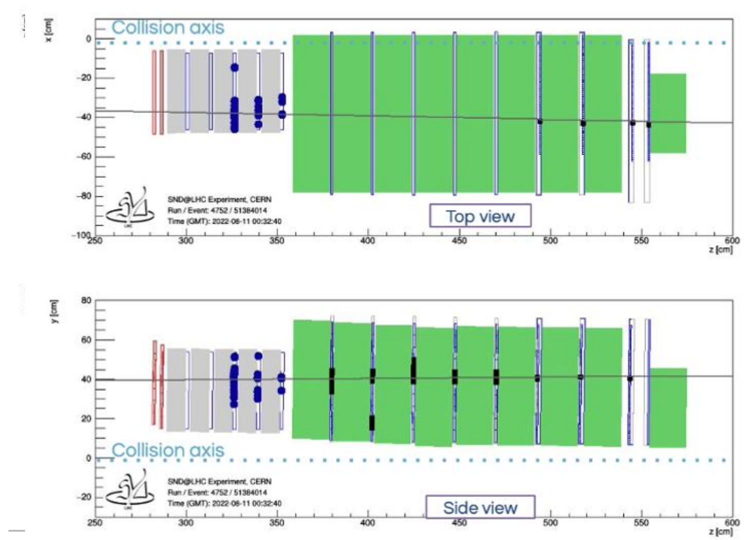




Electromagnetic calorimeter ~40 X_0	Hadronic calorimeter ~10 λ

SND@LHC: 2305.09383
FASER: 2303.14185

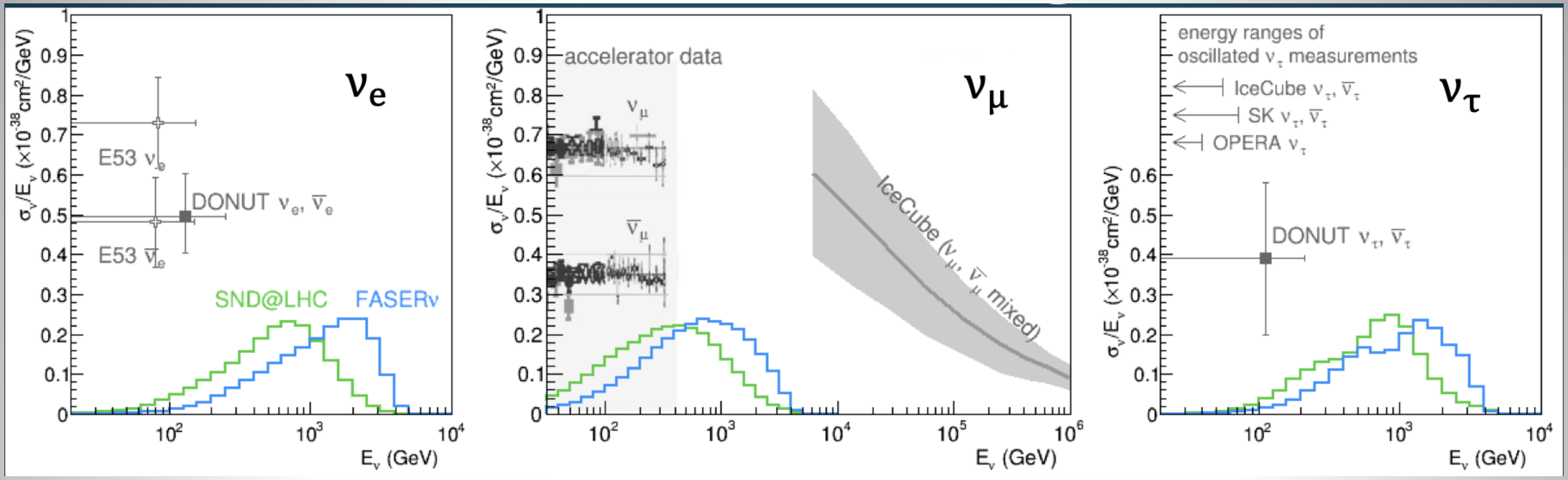
Aug 11th 2022



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

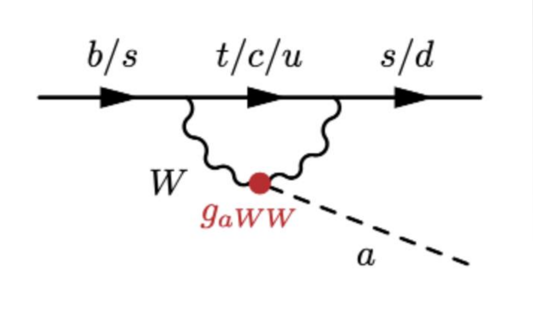
Neutrinos at the LHC

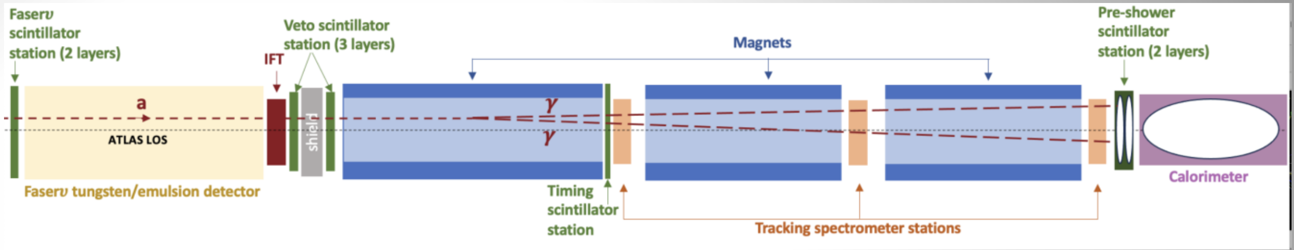
Cross section/neutrino energy



- 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?

FASER: Axion-Like Particle Search



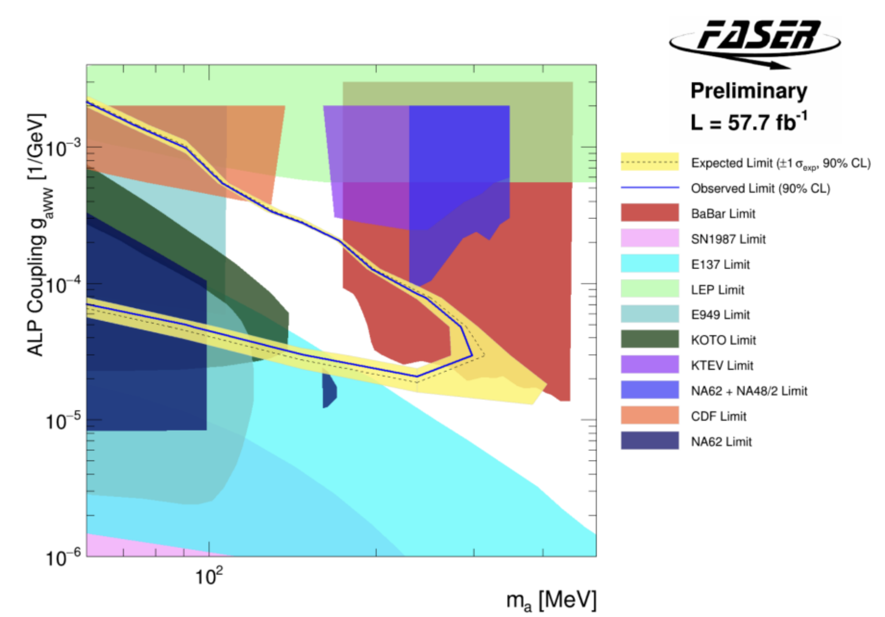


Mainly from
B decays

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!

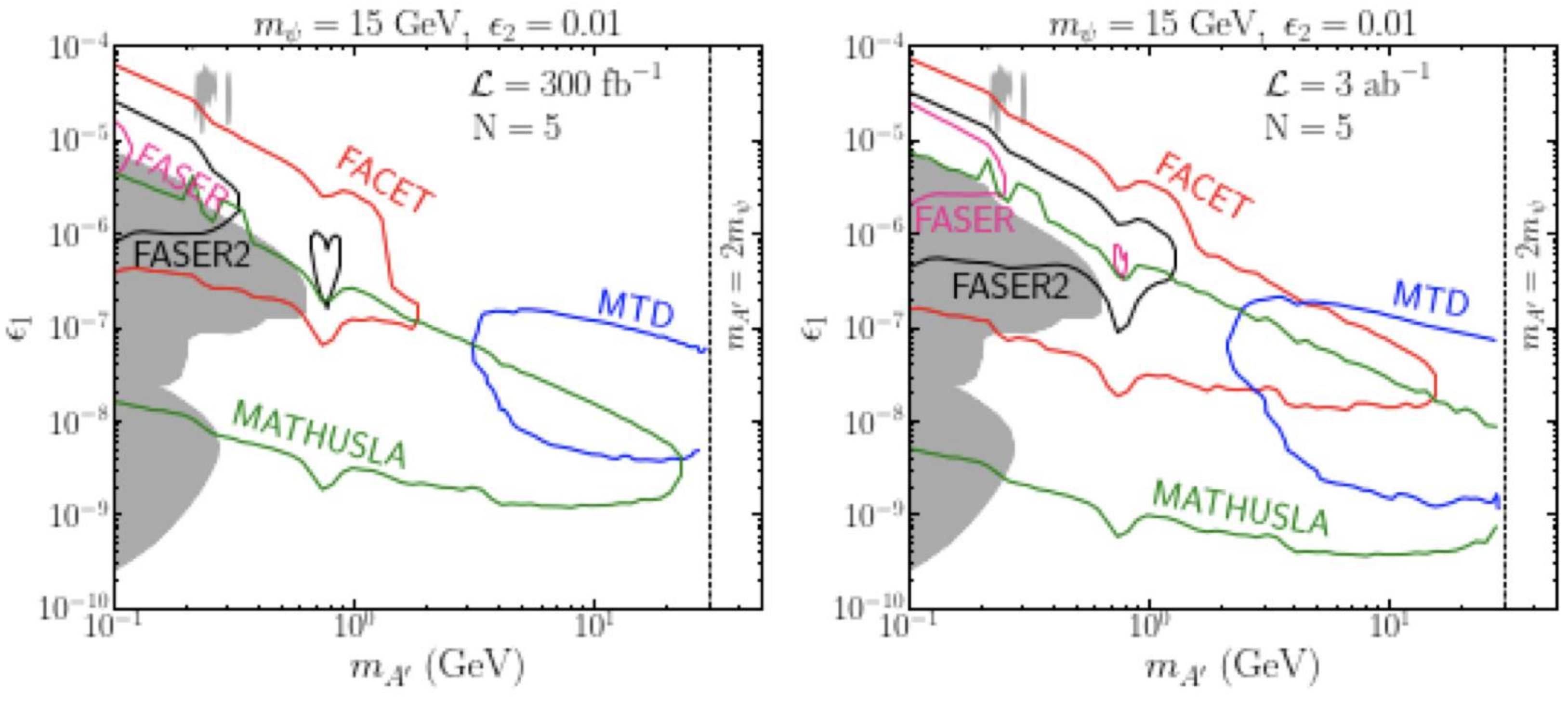
1 event observed / 0.4 +/- 0.4 expected



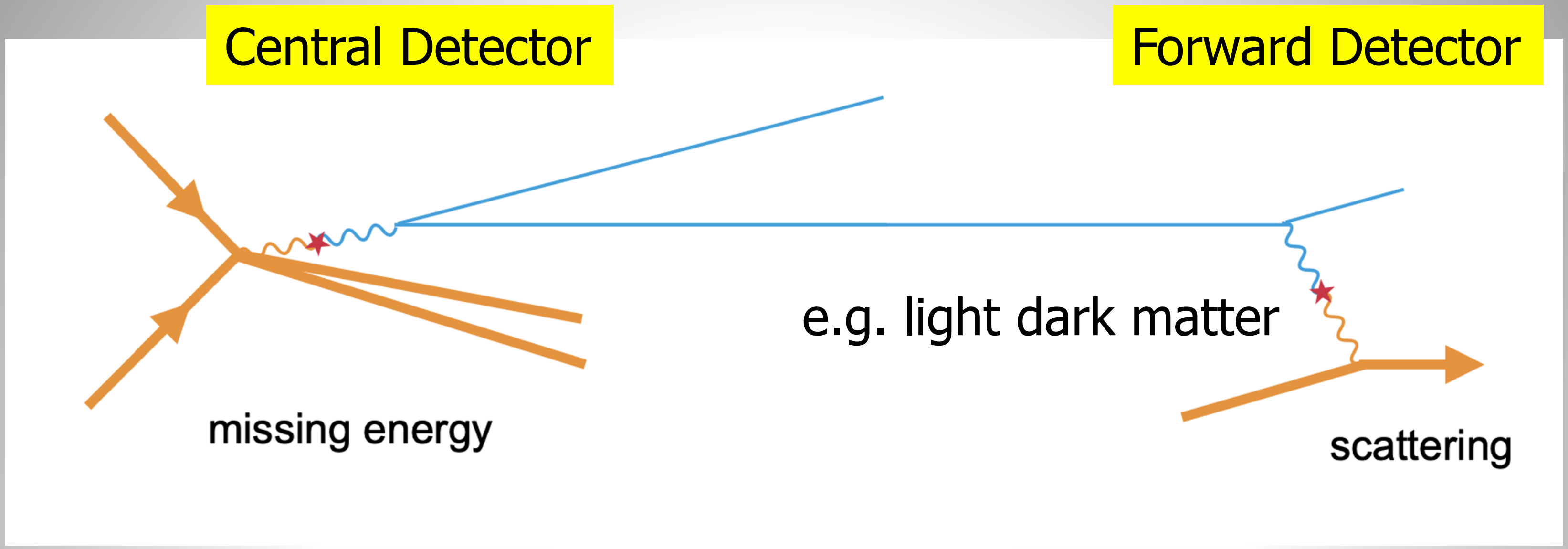
FACET

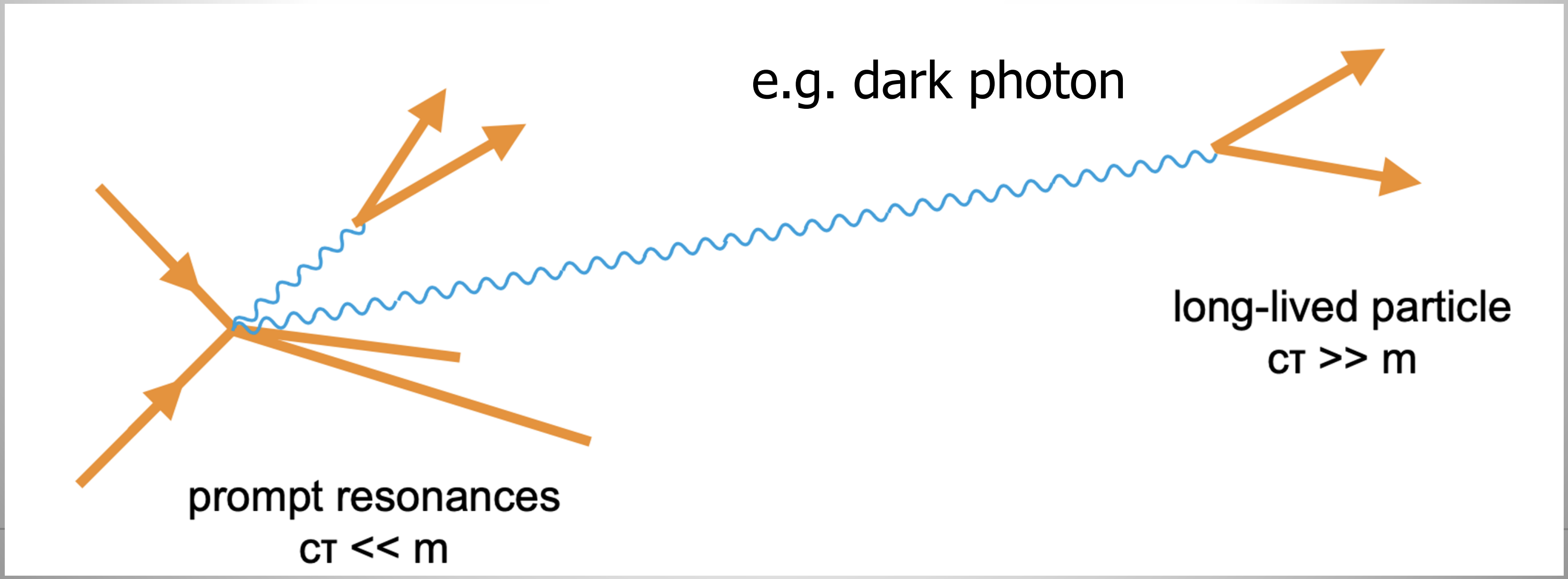
Dark Photons

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



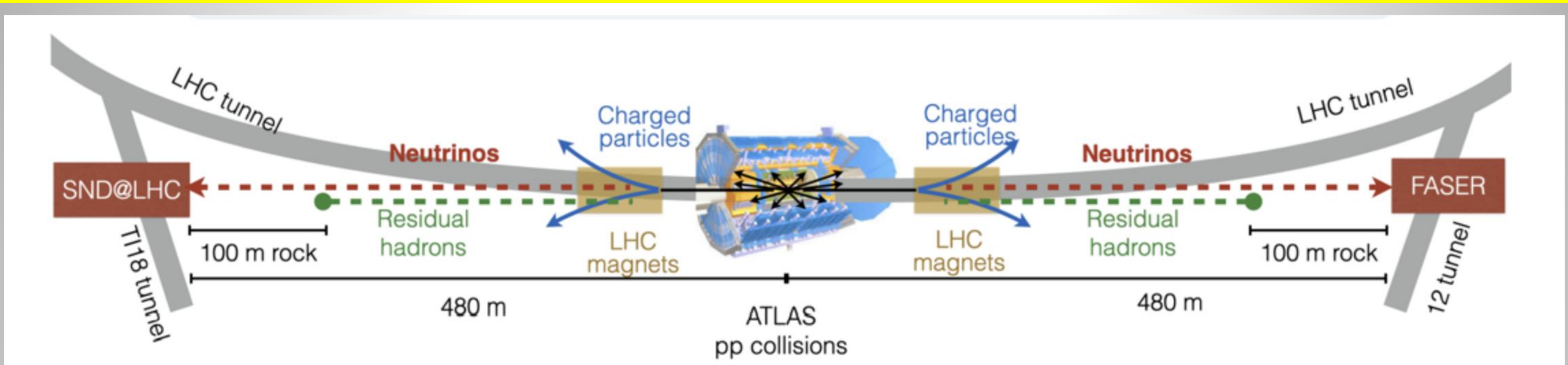
Experimental Technqiues



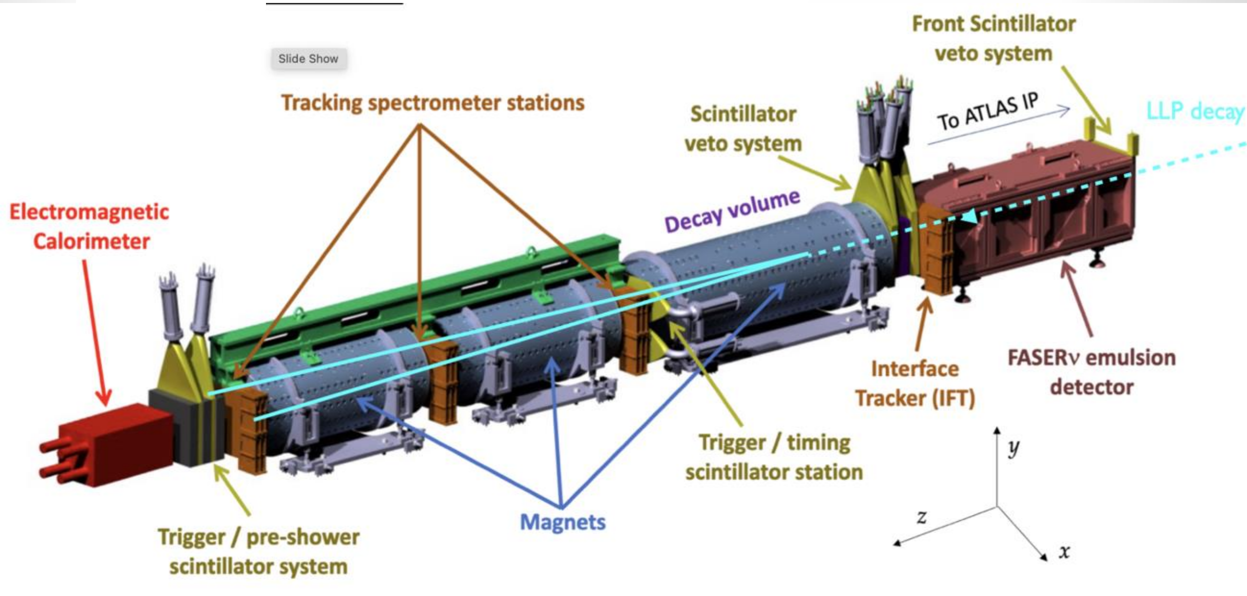


FASER and SND@LHC

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



FASER



Light Long Lived Particles

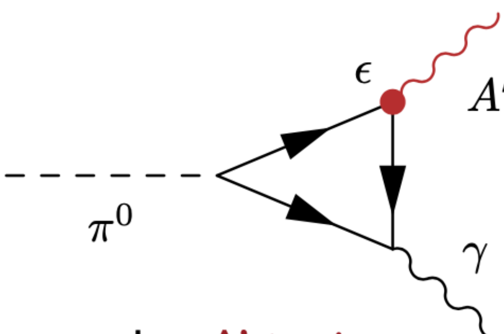
There are light long-lived particles in the SM: muon, pion, kaon, neutron …

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

Example: dark photon

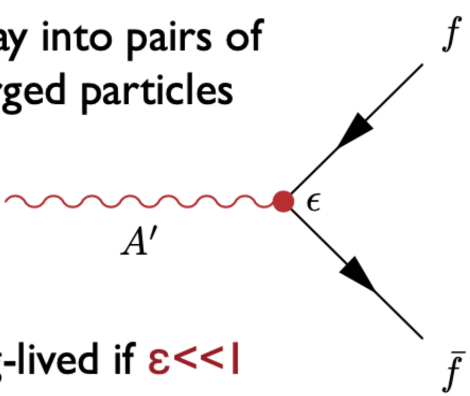
similar to the SM photon but with mass mA' and couplings to SM particles suppressed by ε

$$\mathcal{L} = \frac{1}{2} {m_{A'}}^2 A'_\mu A'^\mu + \sum \bar{f}(i \not\partial - \epsilon e q_f \not{A}')f$$



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

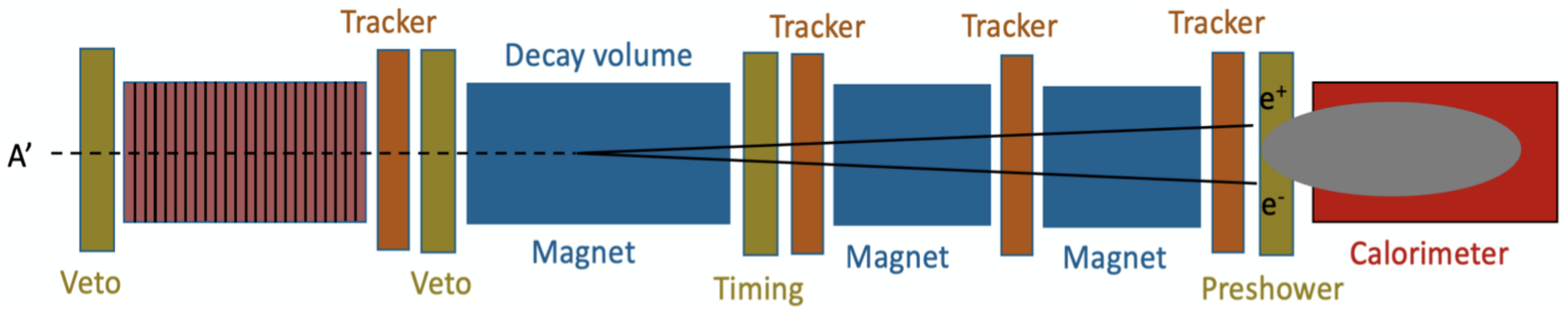
- decay into pairs of charged particles



- 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, $\varepsilon \sim 10^{-5} - 10^{-4}$.



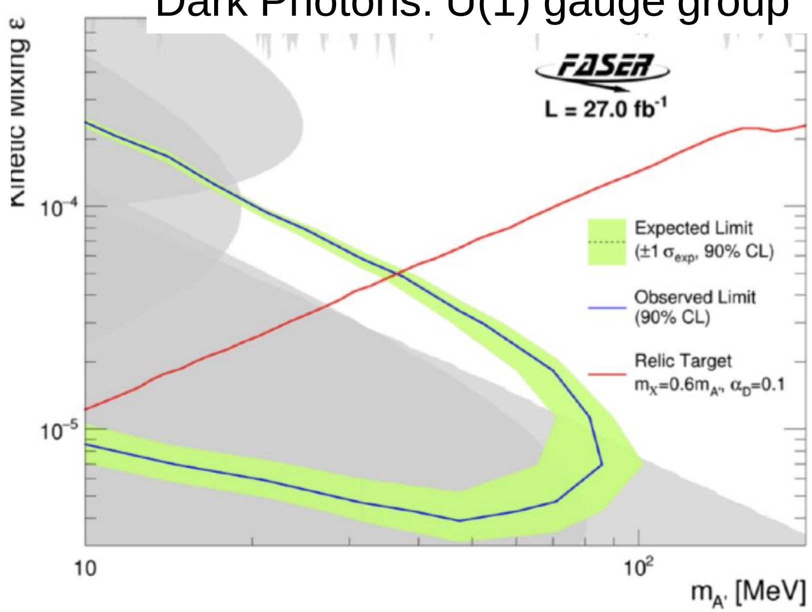
PLB 848, 138378 (2024)

- 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

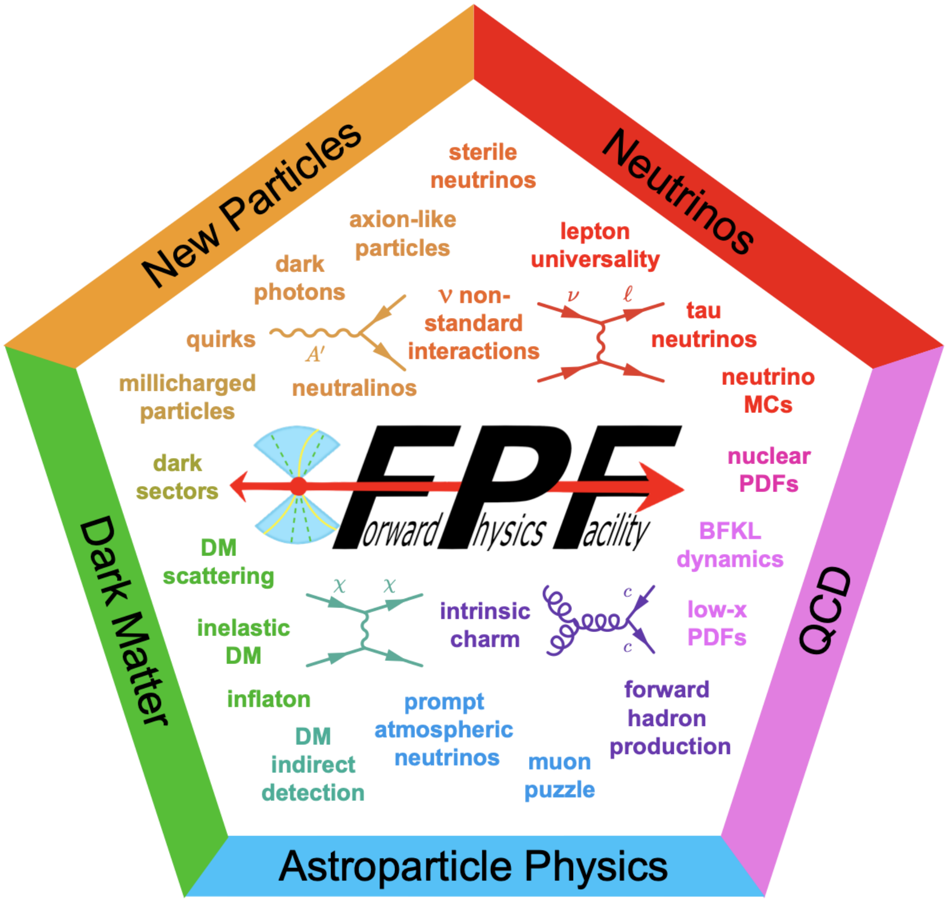


NEW: The Forward Physics Facility

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…

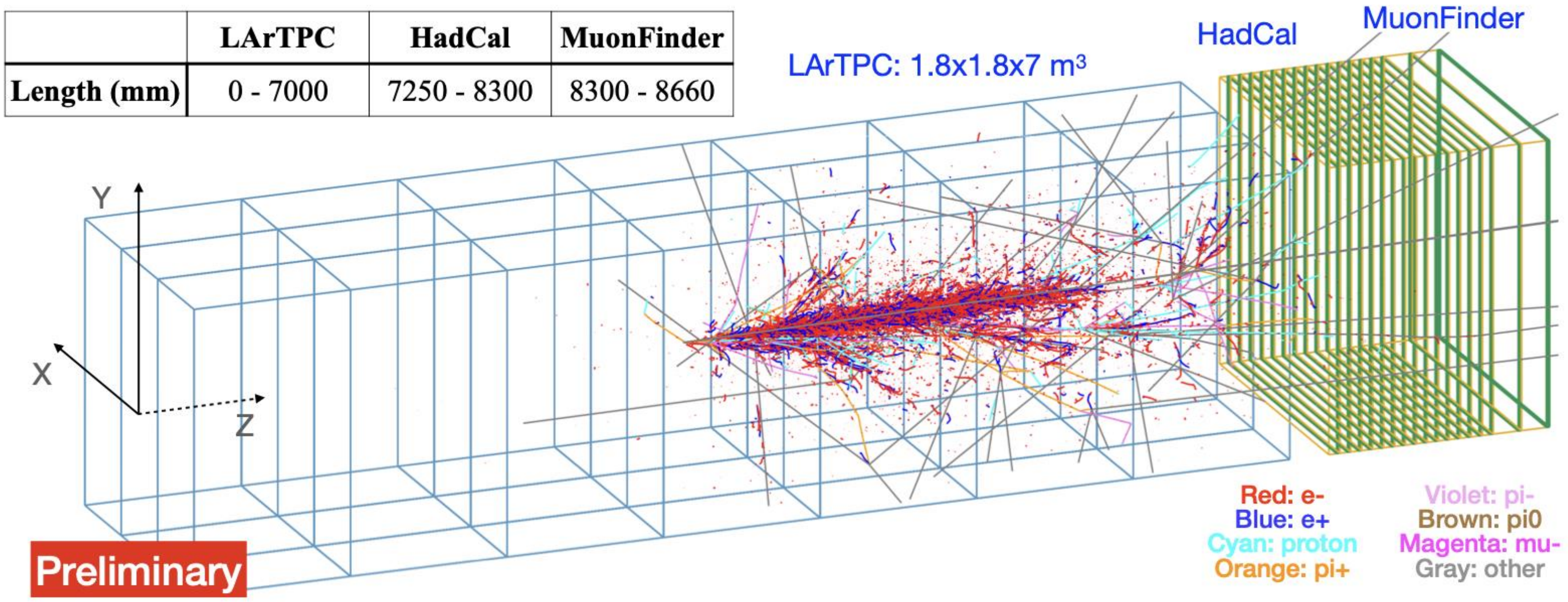
Astroparticle physics: improve the modelling of high-energy hadronic interactions in the atmosphere. Help to understand the atmospheric neutrino flux

Timeline: a proposal for Run4 starting ~ 2030

Forward Liquid Argon Experiment (FLArE)

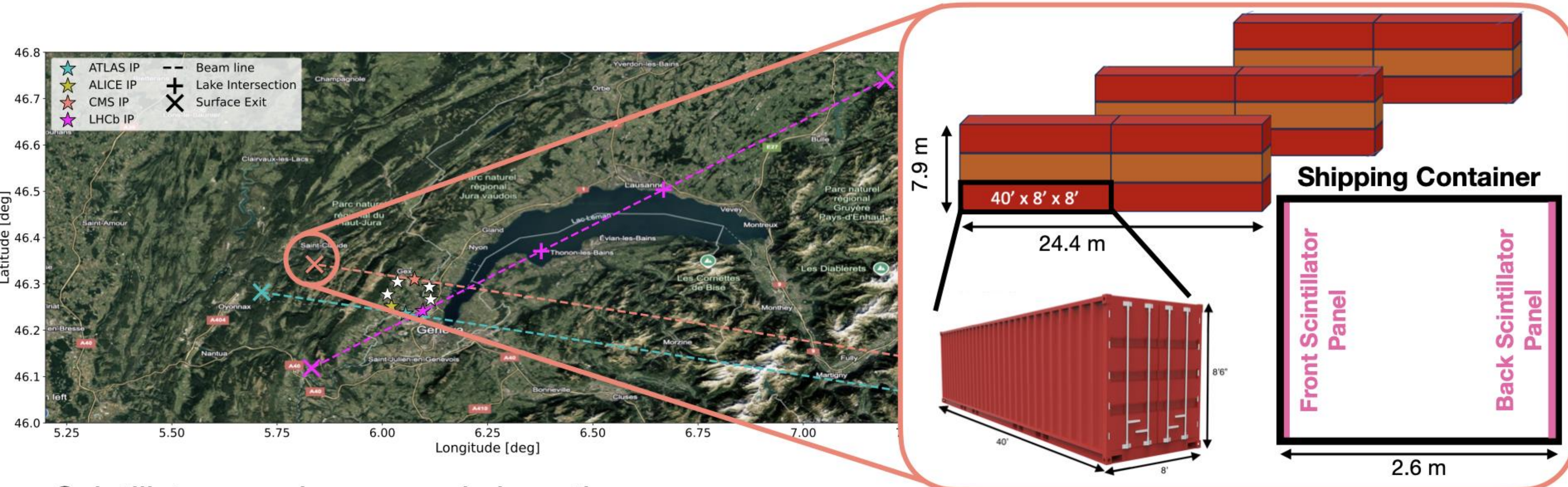
- FLArE: a liquid argon time projection chamber (LArTPC) detector in FPF to detect neutrinos and dark matter from LHC
  - Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter
  - Detector needs to have good energy containment and resolution for neutrino physics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

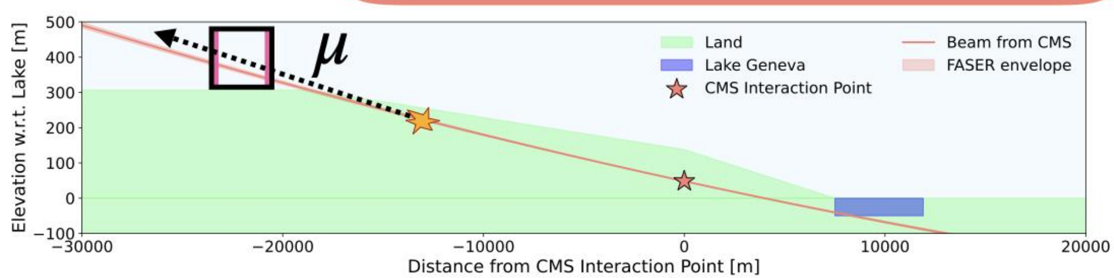


Neutrinos from the LHC

SINE: Surface-based Integrated Neutrino Experiment



- Scintillator panels arranged along the front and back of shipping crates
- Arranged in three sets of 3x2 crates
- **Signal definition:** up-going muons from neutrino interactions in bedrock

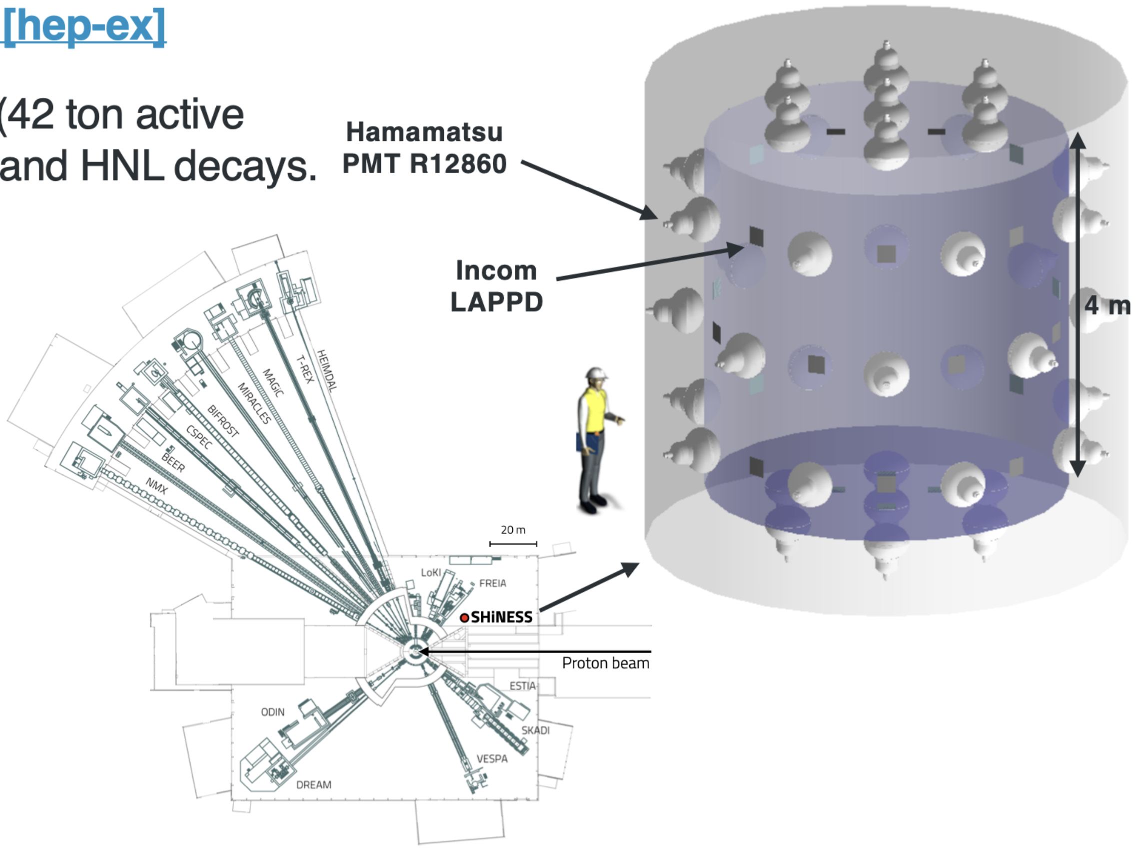


SHiNESS

SHiNESS proposal

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**.



Experiment proposal for ESS