New Experiments at the LHC

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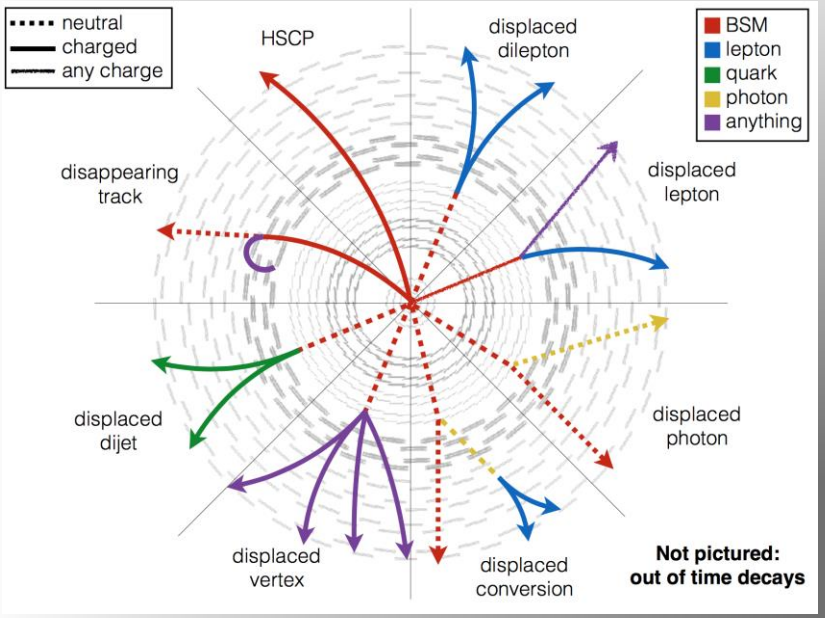
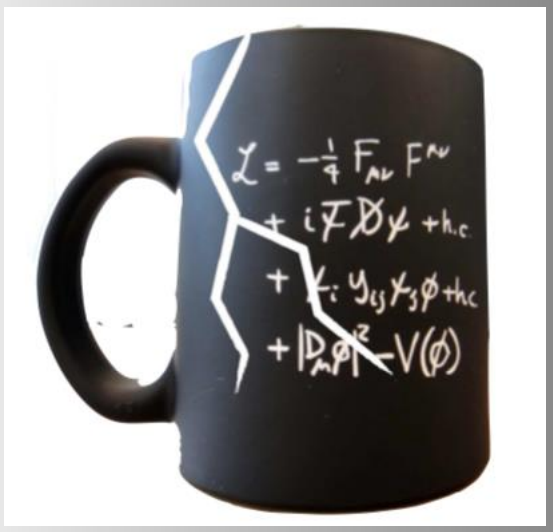
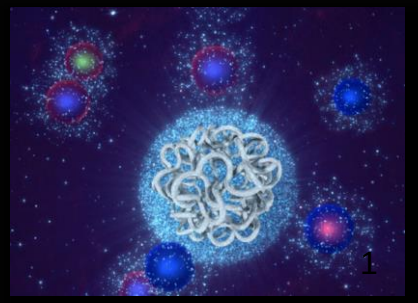


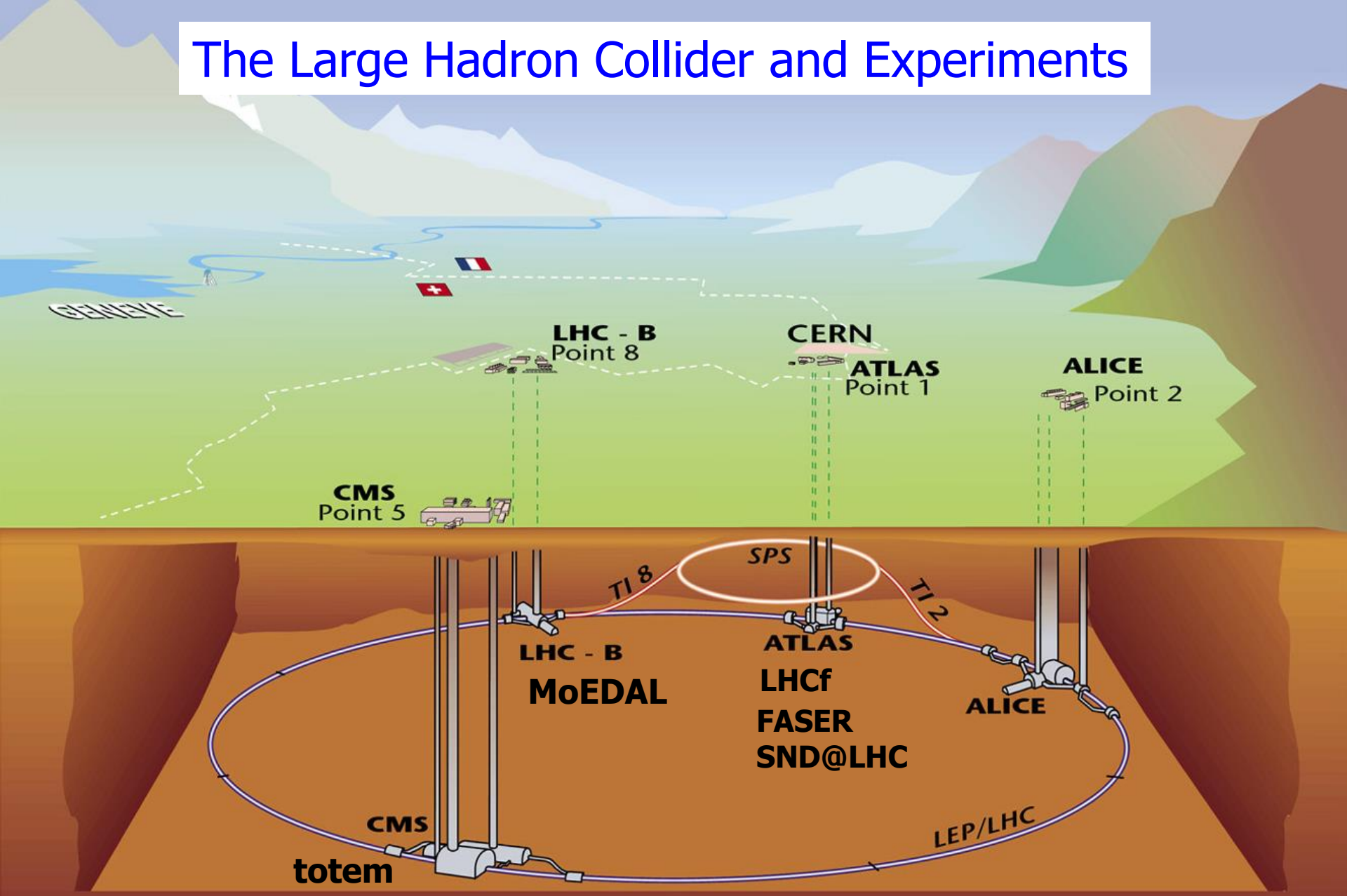
Outline

- Introduction: Why new proposals from new experiments @ LHC ?
- Long Lived Particles
- Forward experiments
- Transverse experiments
- Summary/Outlook





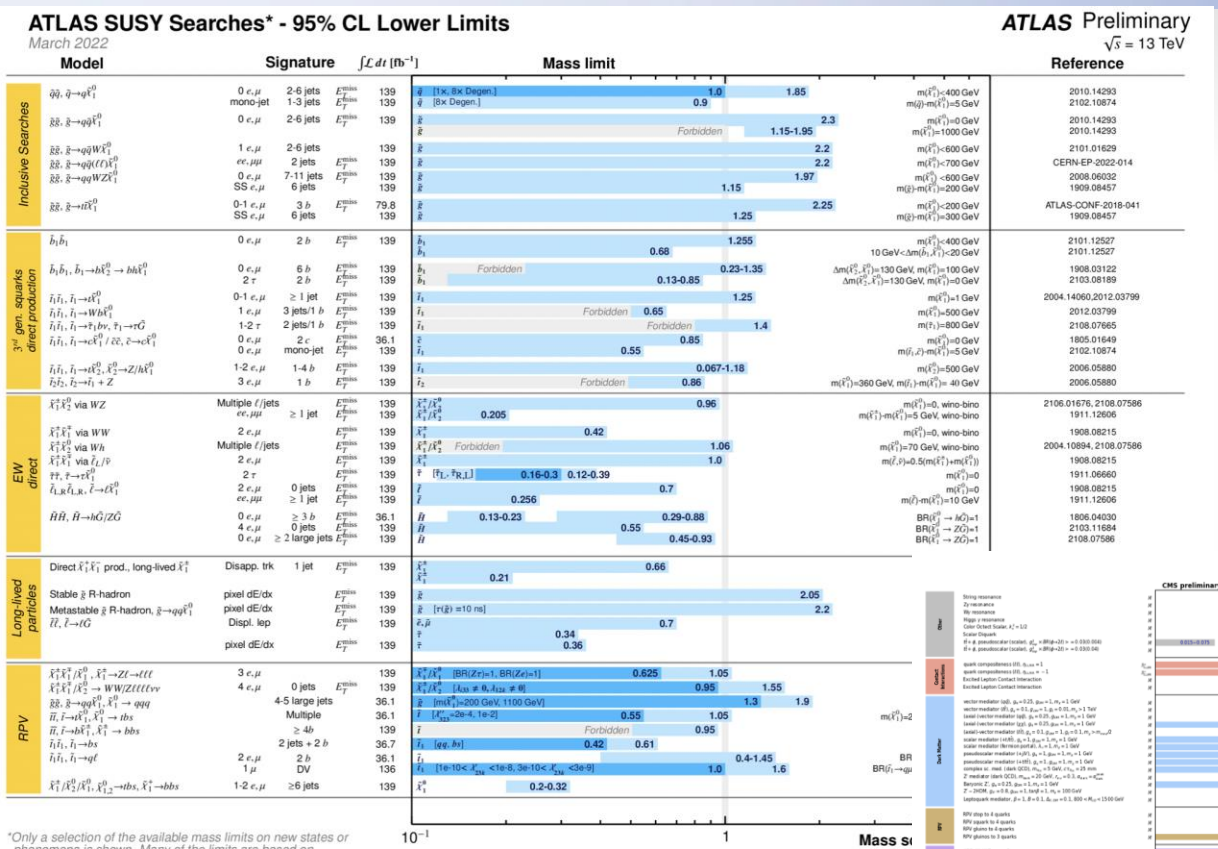
The Large Hadron Collider and Experiments

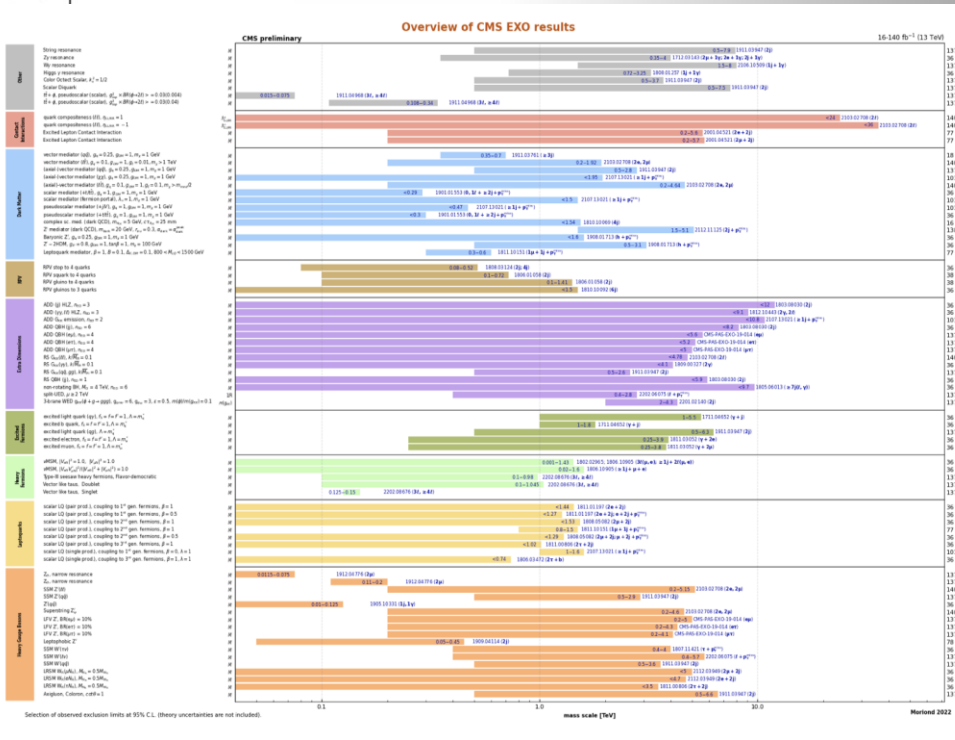


Run-3 started in July after a 3.5 year shutdown

9 experiments are now can take data…

LHC: So far no new physics





Classical Searches
-Supersymmetry
-Exotica
-Flavor Universality
-...

No signal of new physics so far!!

LFU "violation" in LHCb intriguing...

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!!

New Experimental Proposals: Searching for Long Lived Particles

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

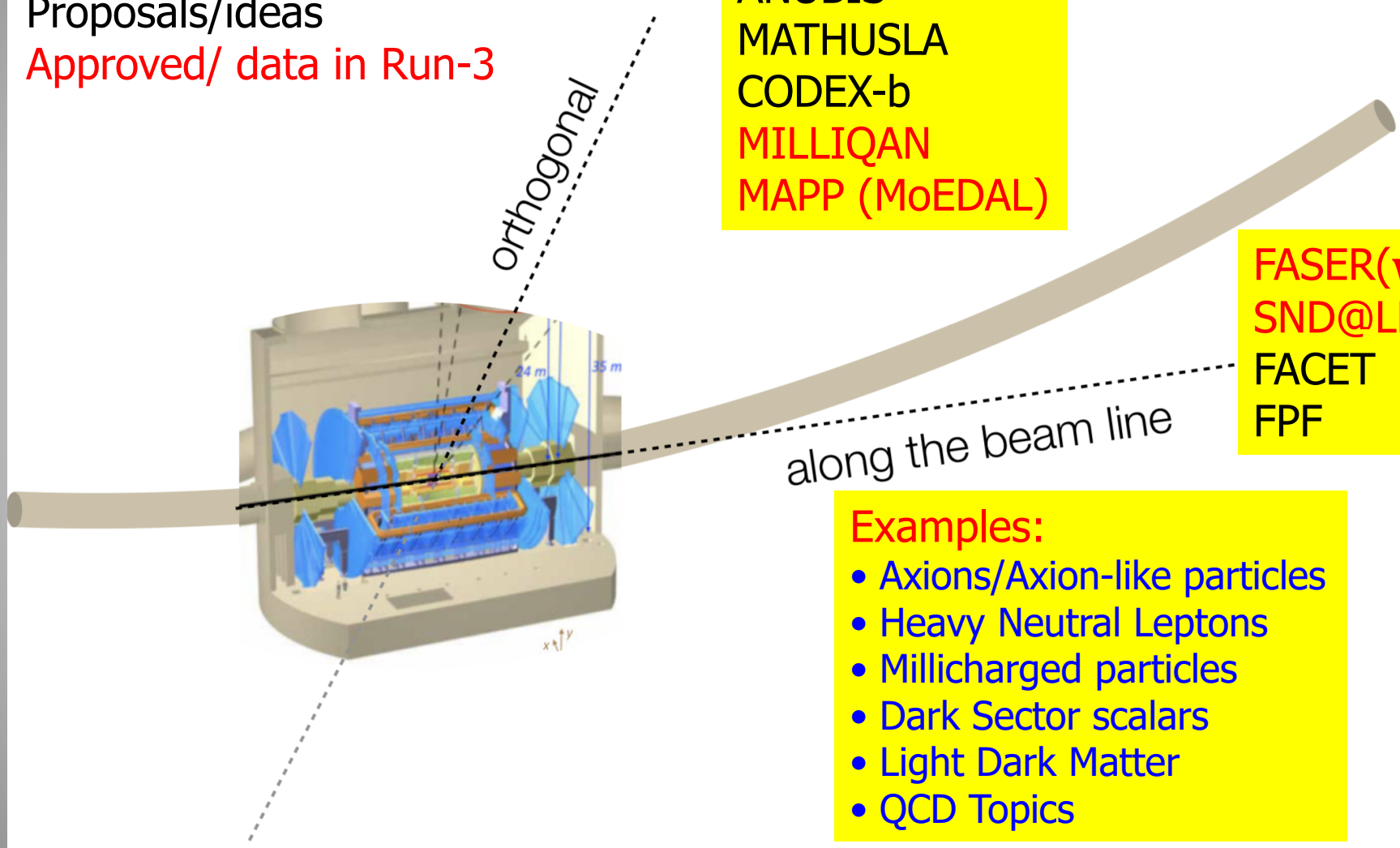
$\Rightarrow$ Opportunities for forward QCD measurements at the LHC and measurements of Cosmic Rays

New Directions/Experiments

Proposals/ideas

Approved/ data in Run-3

ANUBIS
MATHUSLA
CODEX-b
MILLIQAN
MAPP (MoEDAL)



FASER(ν)
SND@LHC
FACET
FPF

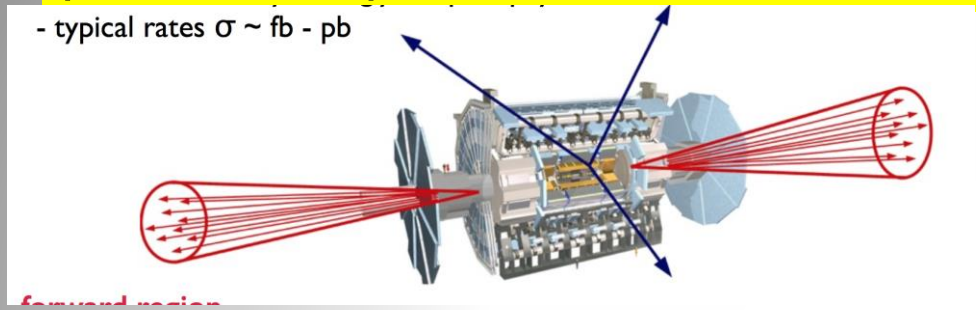
Examples:

- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Light Dark Matter
- QCD Topics

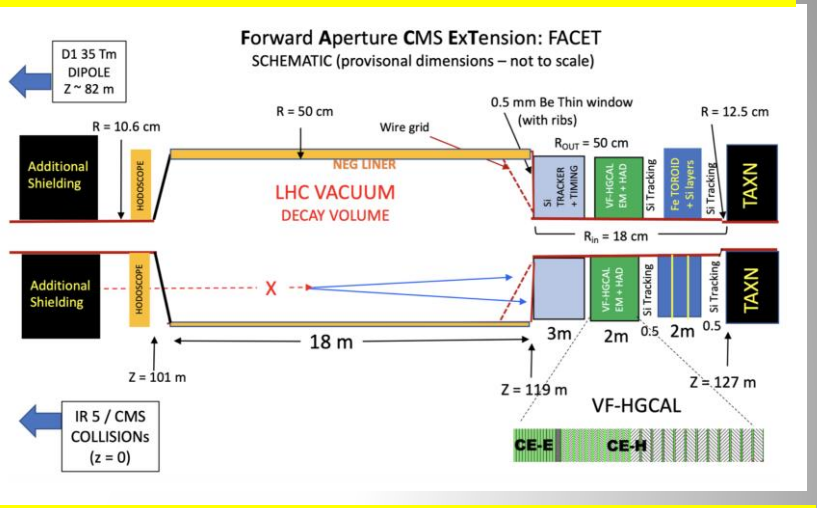
"Transverse Experiments" have minimal to no impact on the LHC machine

New Forward Detector Proposals

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



FACET: Instrumented Beampipe for CMS



SND@LHC: neutrino measurements and long lived particle searches

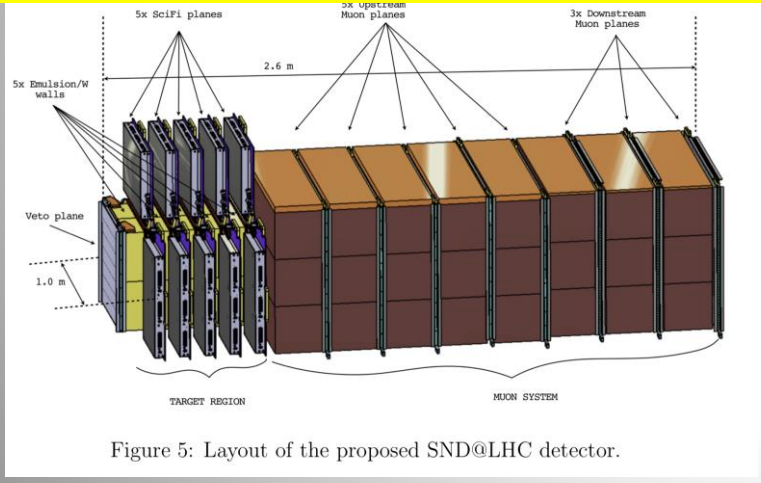
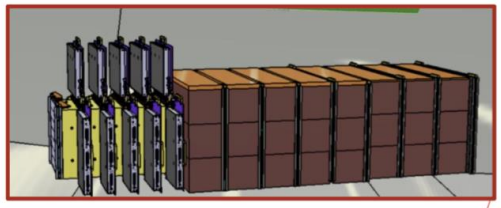


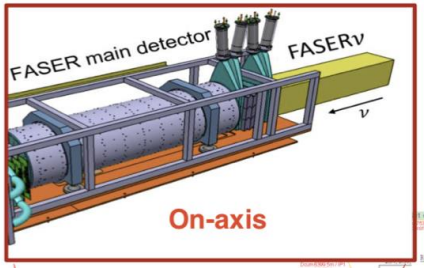
Figure 5: Layout of the proposed SND@LHC detector.

FPF: A Facility for Forward Physics Containing several experiments

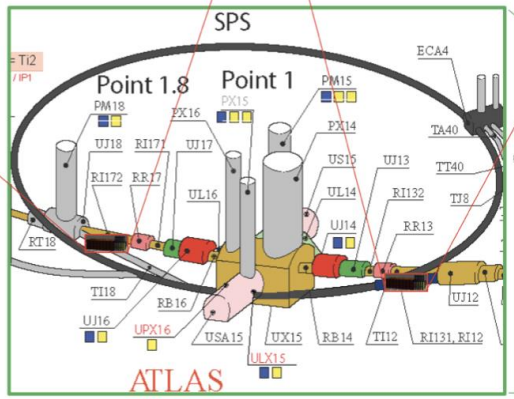
FASER and SND@LHC have been approved in 2019/2020 and were ready in time to take data at the start of Run 3 in 2022; taking data now!

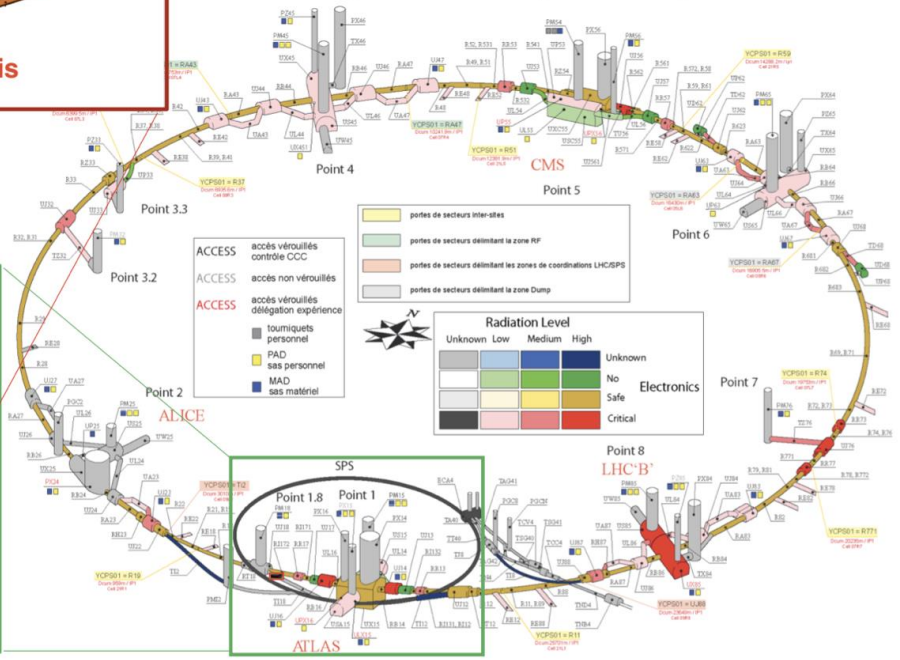
SND@LHC and FASER(Nu)

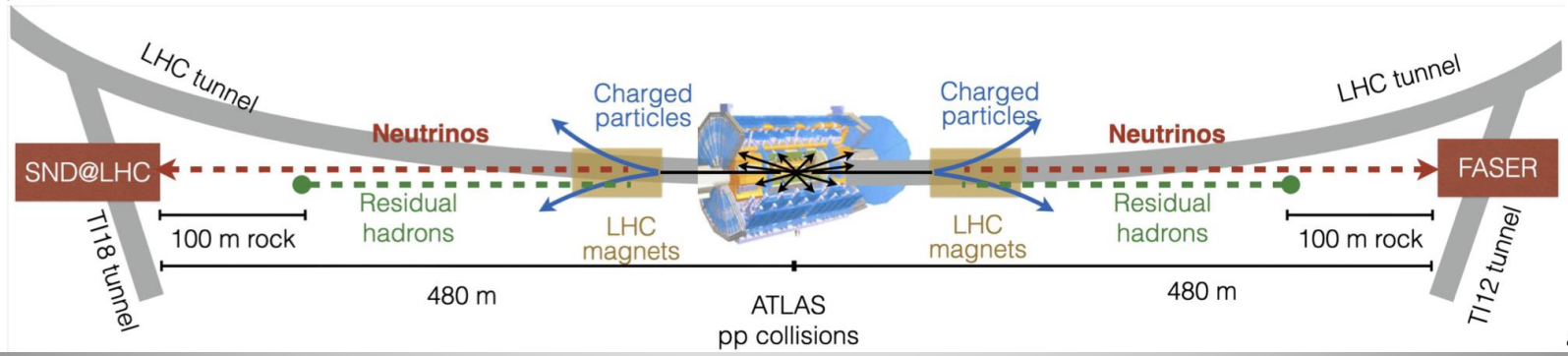




- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock

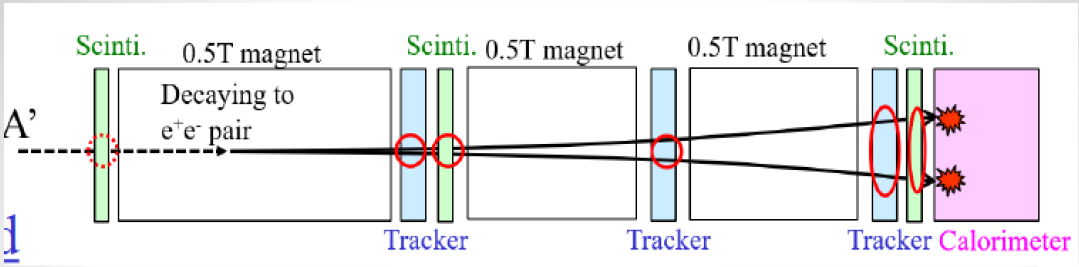






FASER Experiment

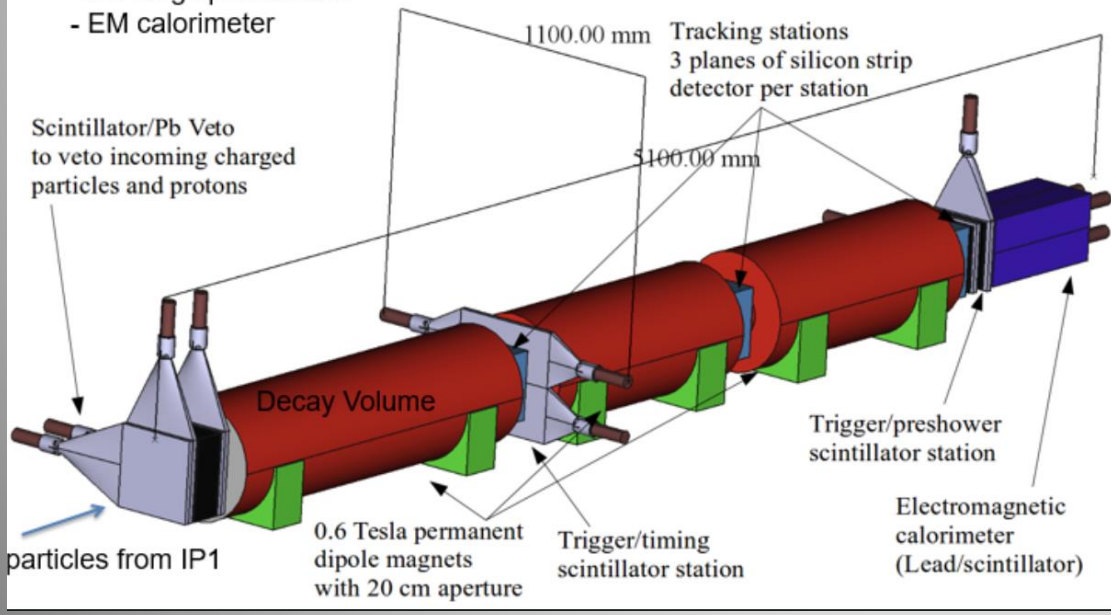
The FASER experiment (phase 1) has been approved March 5th 2019



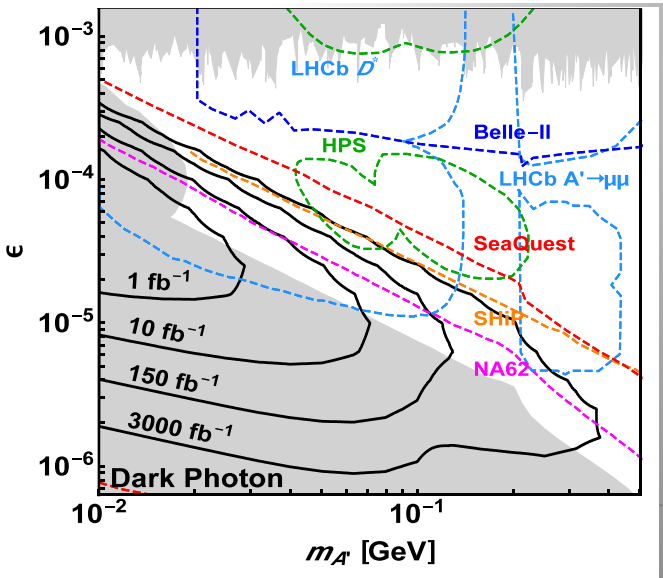
arXiv:1901.04468

THE FASER DETECTOR

The detector consists of:
- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter



Use spare ATLAS SCT silicon tracking modules and LHCb EM calorimeter modules

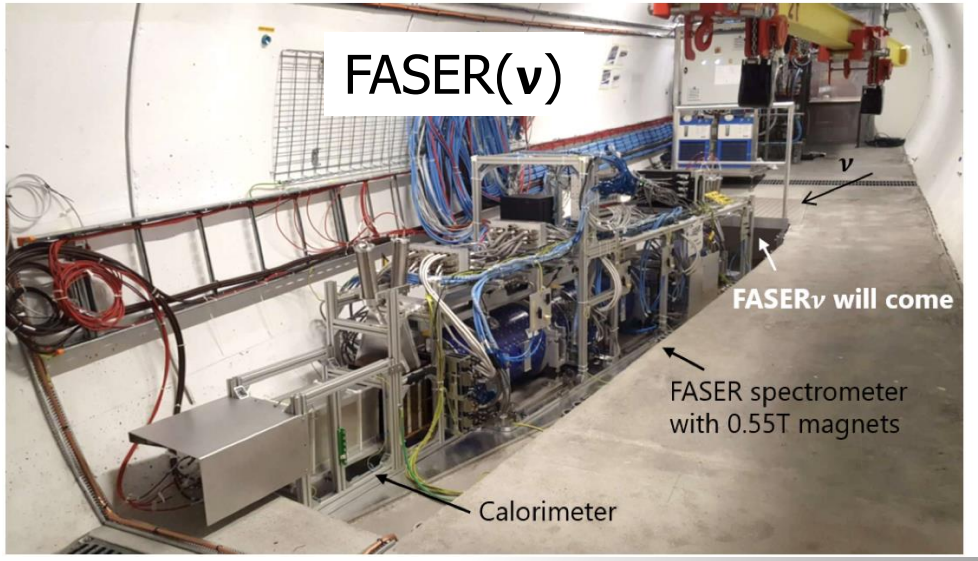


Neutrinos @ the LHC: SND@LHC & FASERν

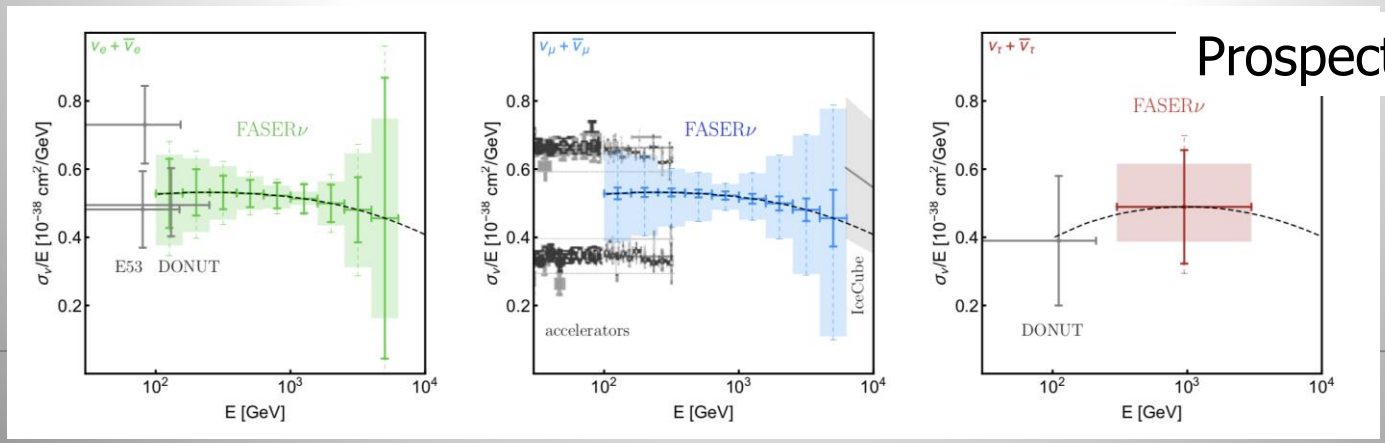
SND@LHC: approved March '21

SND= Scattering and Neutrino Detector

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

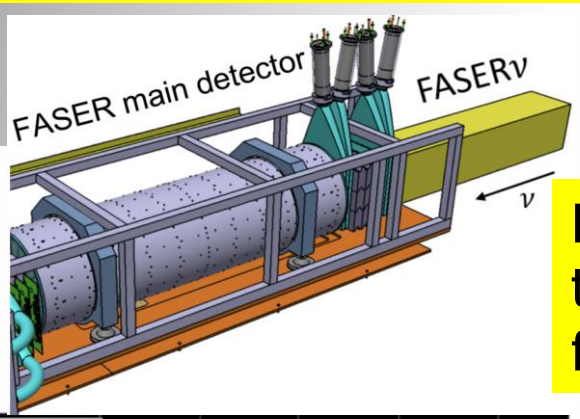


Prospects for Run 3



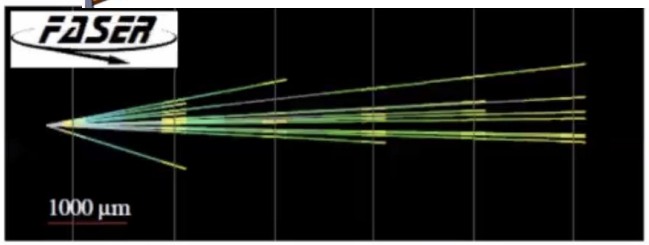
First Observed Neutrinos in FASER-ν

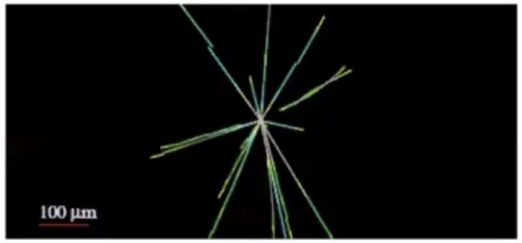
These are the first ever directly observed neutrinos at the LHC!!

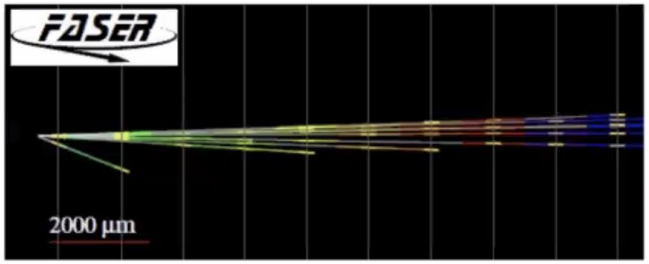


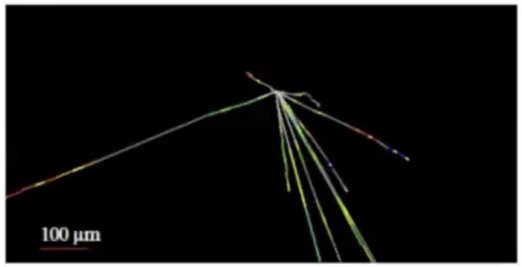
Results from emulsion exposure tests in 2018

Emulsion/Tungsten target of 1.2 tons for Run-3









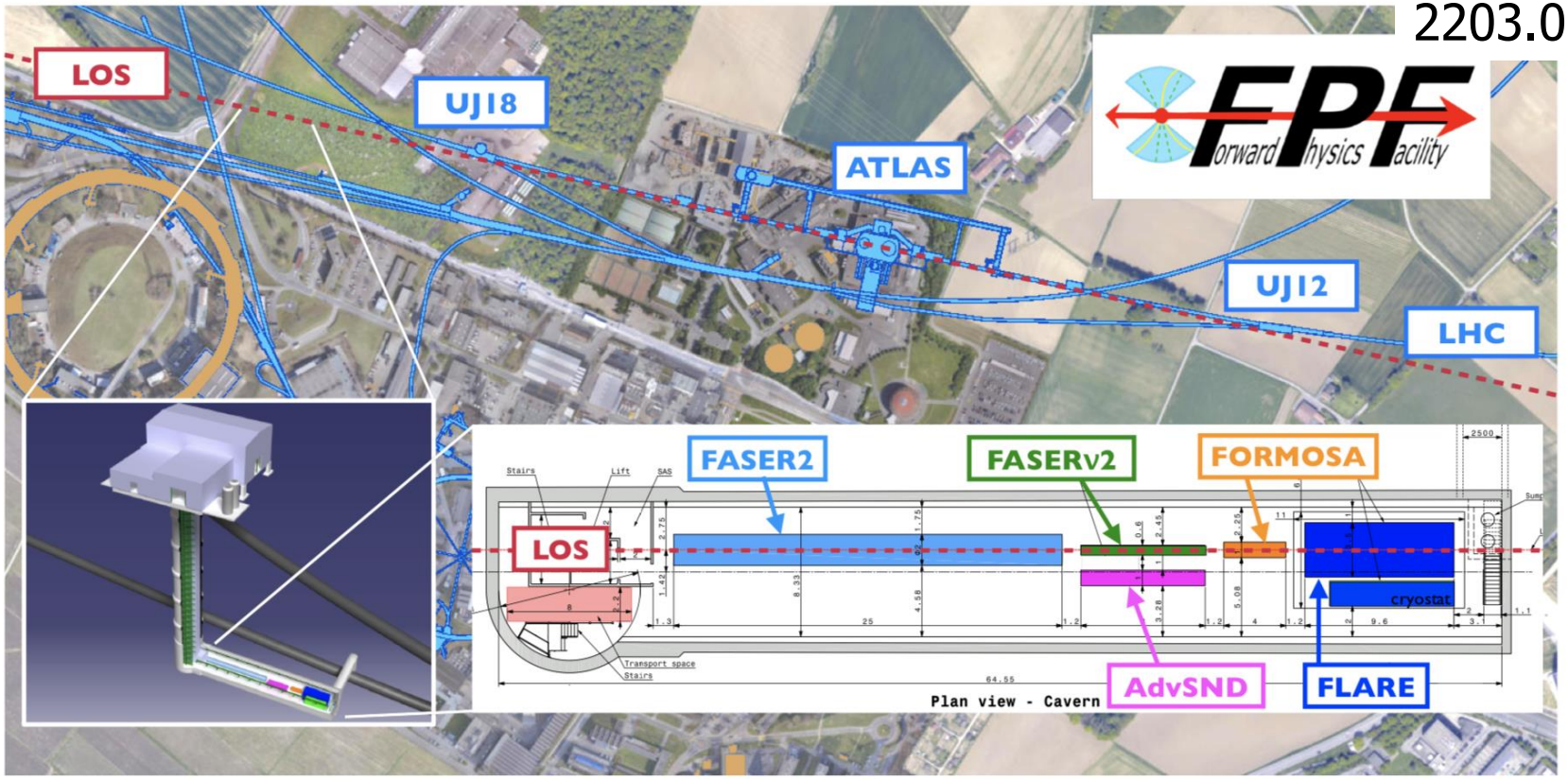
Highlights the potential of the forward LHC location fro neutrino physics!

First neutrino interaction candidates at the LHC, arXiv:2105.06197

NEW: The Forward Physics Facility

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

2203.05090

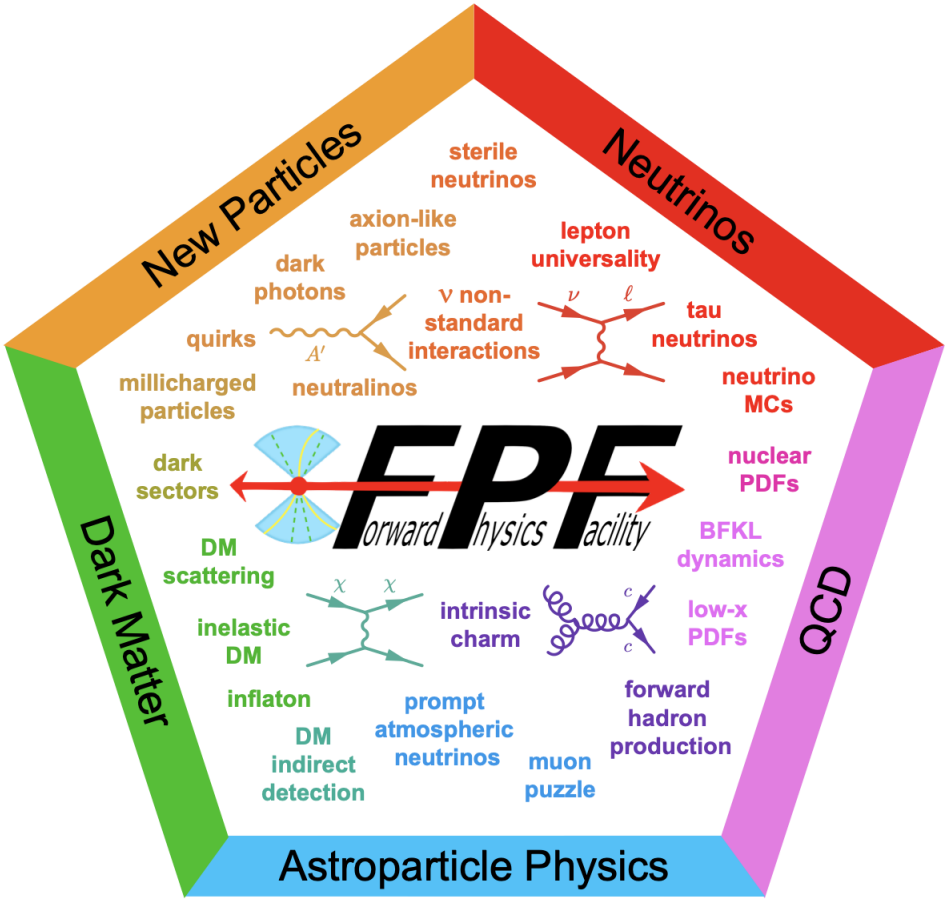


FASER->FASER2, SND@LHC->AdvSND, MilliQan->FORMOSA, FLARE->LAr/LKr TPC

NEW: The Forward Physics Facility

Originally for searches for New Physics
Extended to cover Neutrinos, QCD, Astroparticle Physics, Dark Matter Searches

2203.05090



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…

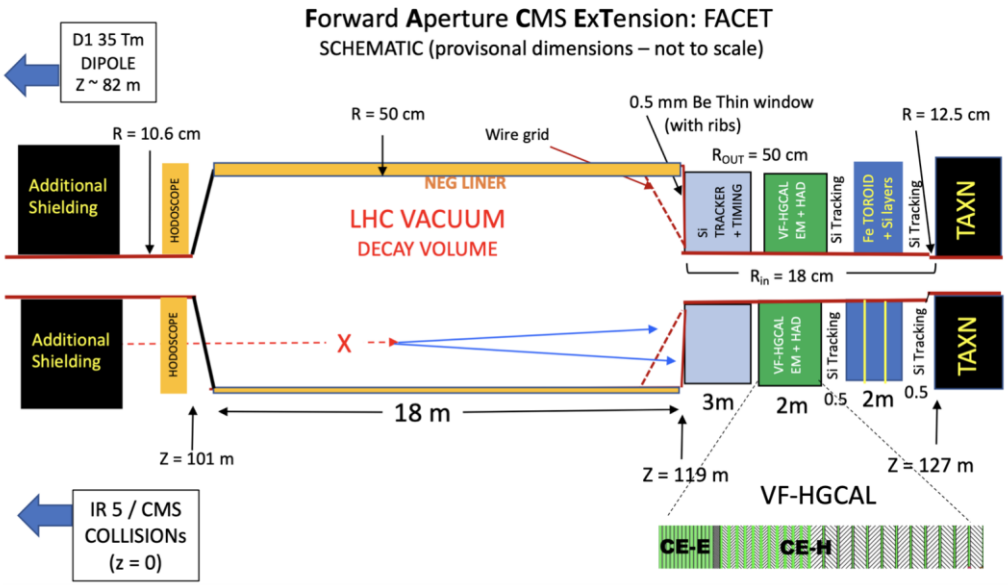
Neutrino: TeV scale neutrinos, about 1000 Tau neutrinos, tau and anti- neutrino separation…

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

FACET

Forward-Aperture CMS ExTension will be sensitive to any particles that can penetrate at least 50 m of magnetized iron and decay in an 18 m long, 1 m diameter vacuum pipe. The decay products will be measured in detectors using identical technology to the planned CMS Phase-2 upgrade.



2201.00019

Instrumented extended radius beampipe from 10 to 50 cm

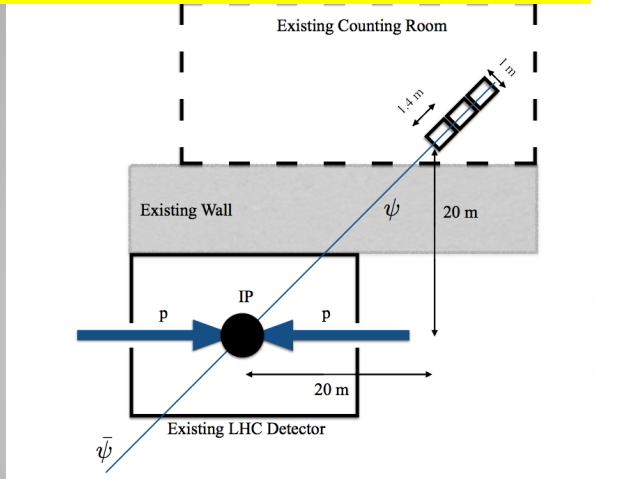
Considered as an extension of the CMS experiment

- Cover the forward region 7.6 > η > 6.2
- The decay volume is at high vacuum (LHC quality: part of the LHC beam pipe) Essentially all the SM backgrounds having direct paths from the IP are eliminated

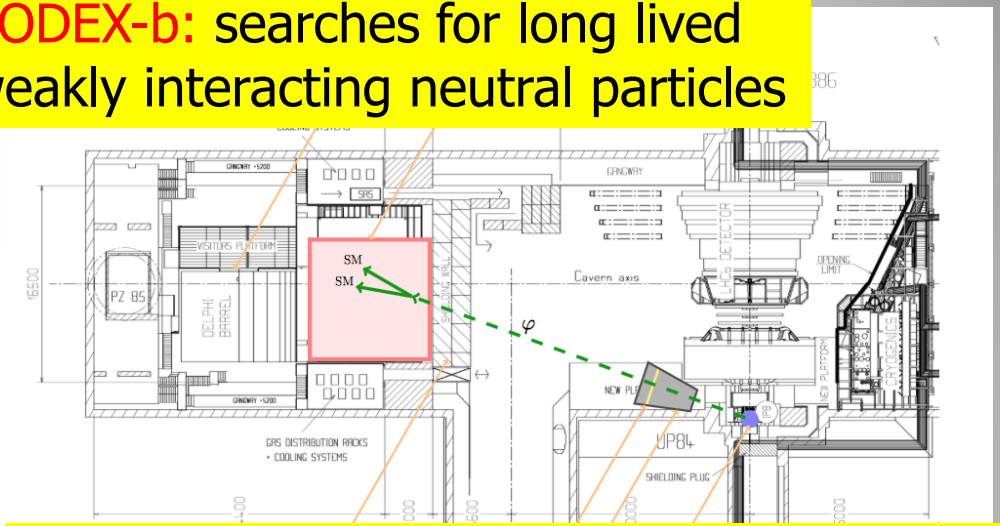
Timeline: a proposal for Run4 starting ~ 2030

New Transverse Experiment Proposals

MilliQan: searches for millicharged particles
MAPP: MoEDAL upgrade

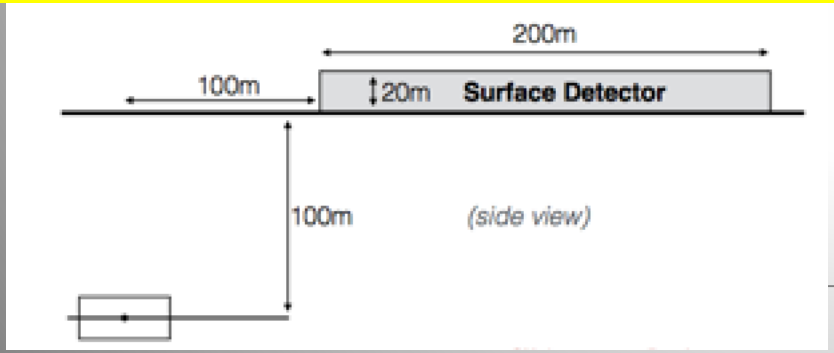


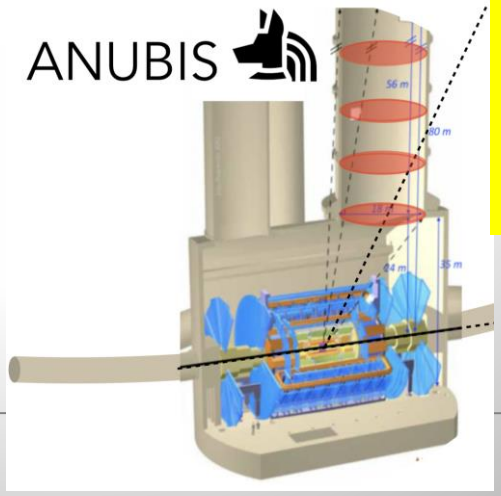
CODEX-b: searches for long lived weakly interacting neutral particles



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

MATHUSLA: searches for long lived weakly interacting neutral particles



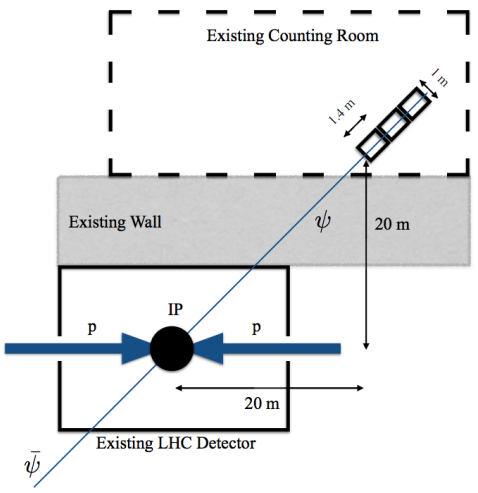


ANUBIS: searches for long lived weakly interacting neutral particles

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

Particles with Milli-Charges?

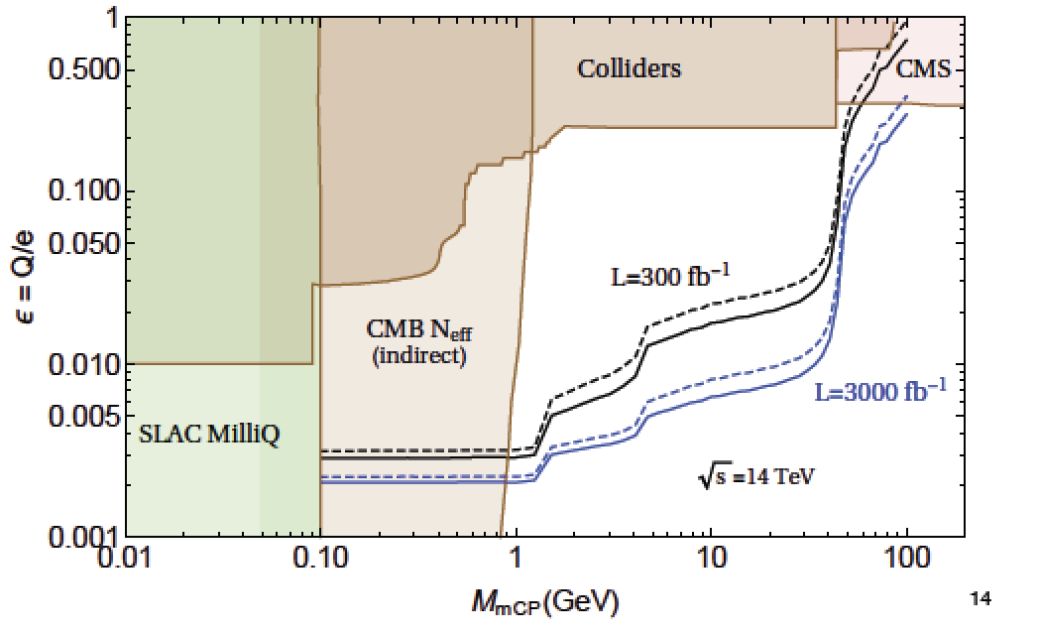
Idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) took data from mid-2017 to end 2018



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…?

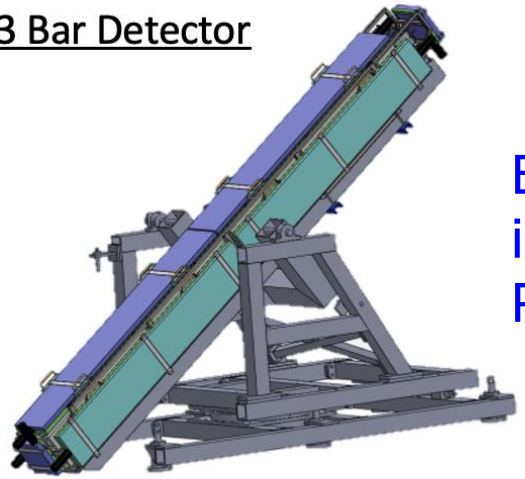
Detection technique:
scintillators-> low photon signals

Millicharged Particles

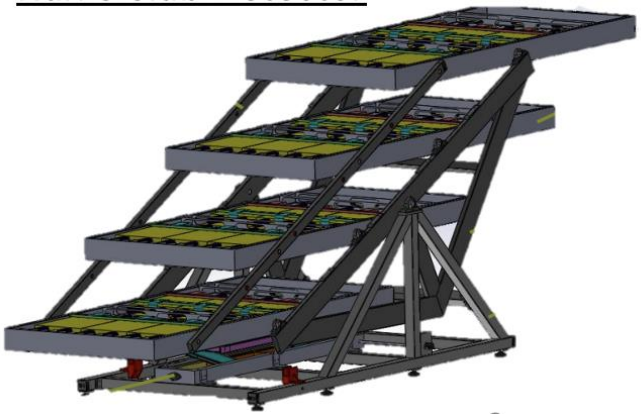
Search for Millicharges: Particles with very small charges, compared to the electron, expected e.g. in Dark Sector theories.

- MilliQan and MAPP now LHCC endorsed/approved projects, and being installed
- Scintillator bar and slab based detectors

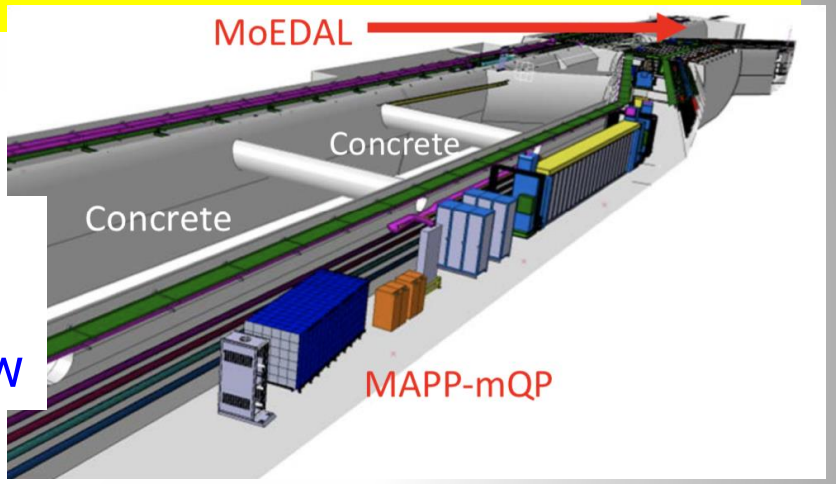
Run 3 Bar Detector

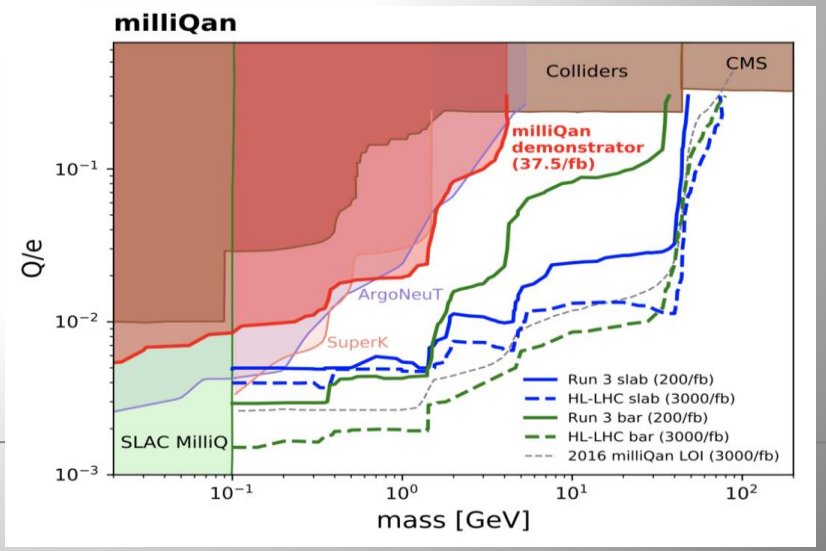


Run 3 Slab Detector



Both are being installed for Run 3 right now



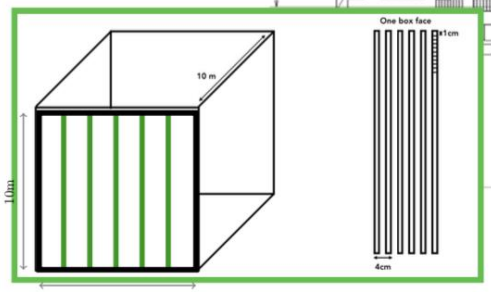


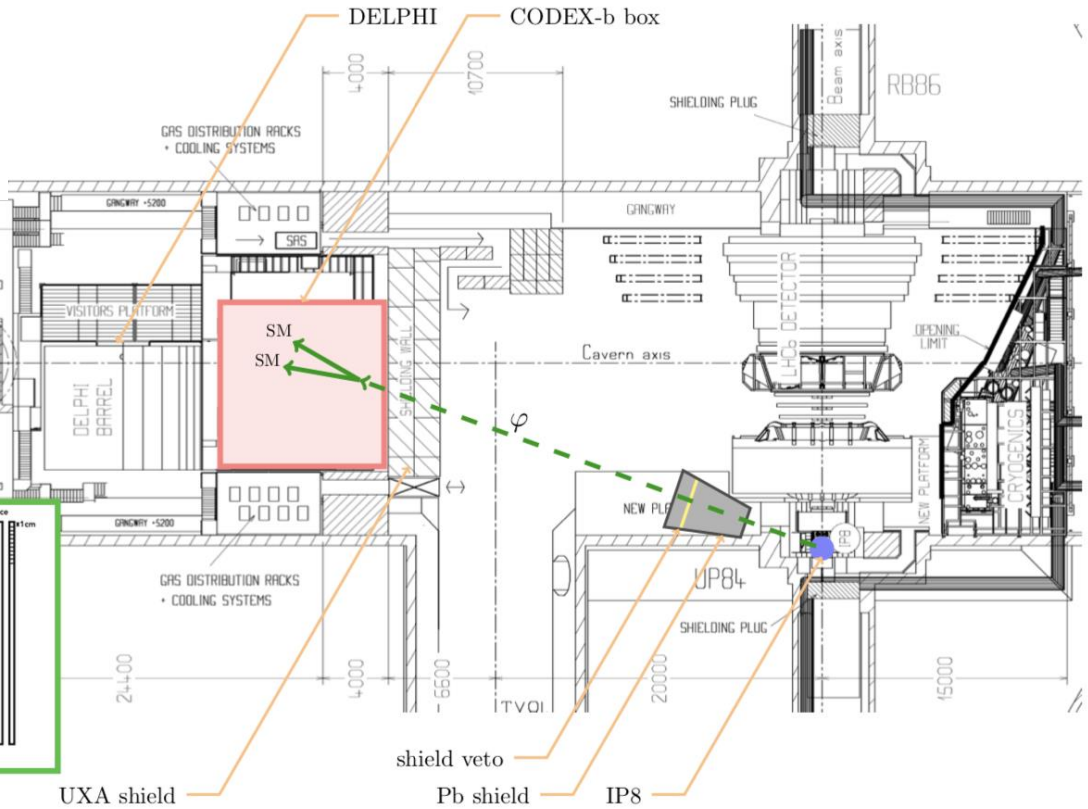
CODEX-b

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
- Demonstrator in preparation: 2x2x2m volume test- set up with RPCs

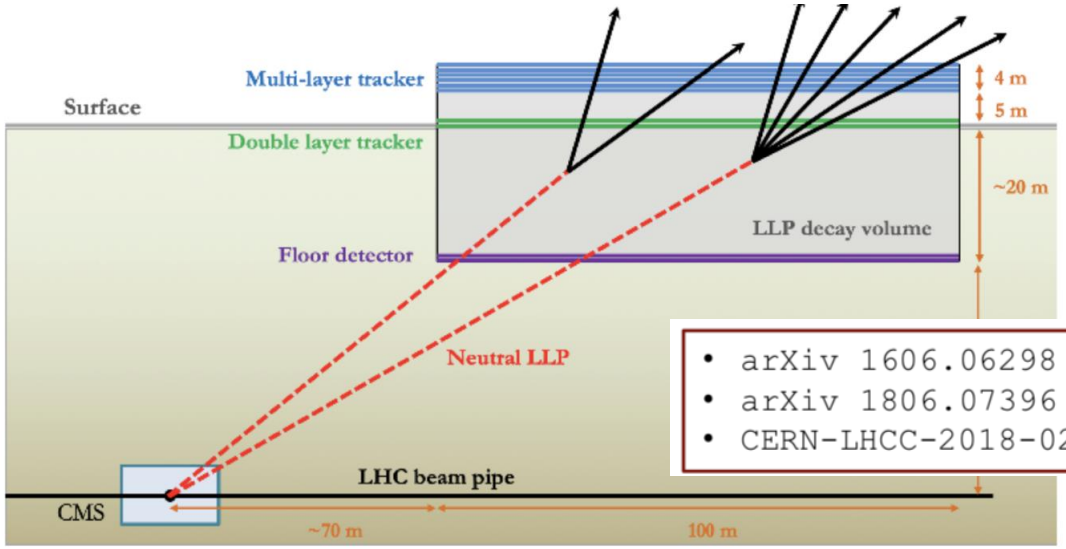
MATHUSLA

MATHUSLA: MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

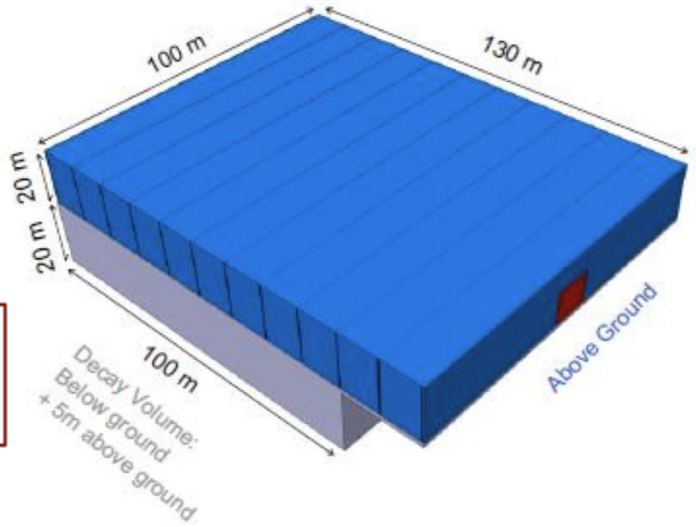
Dedicated detector sensitive to neutral long-lived particles with lifetime up to the Big Bang Nucleosynthesis limit (10^7 – 10^8 m) for the HL-LHC

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

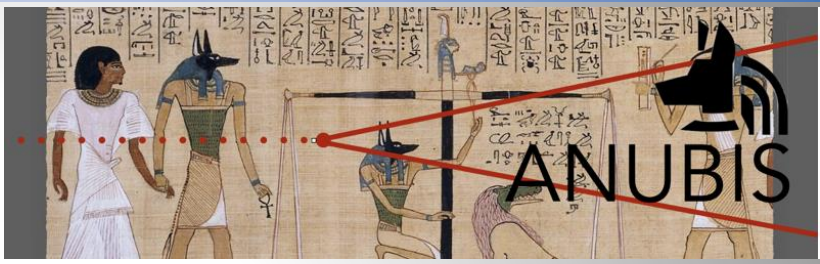


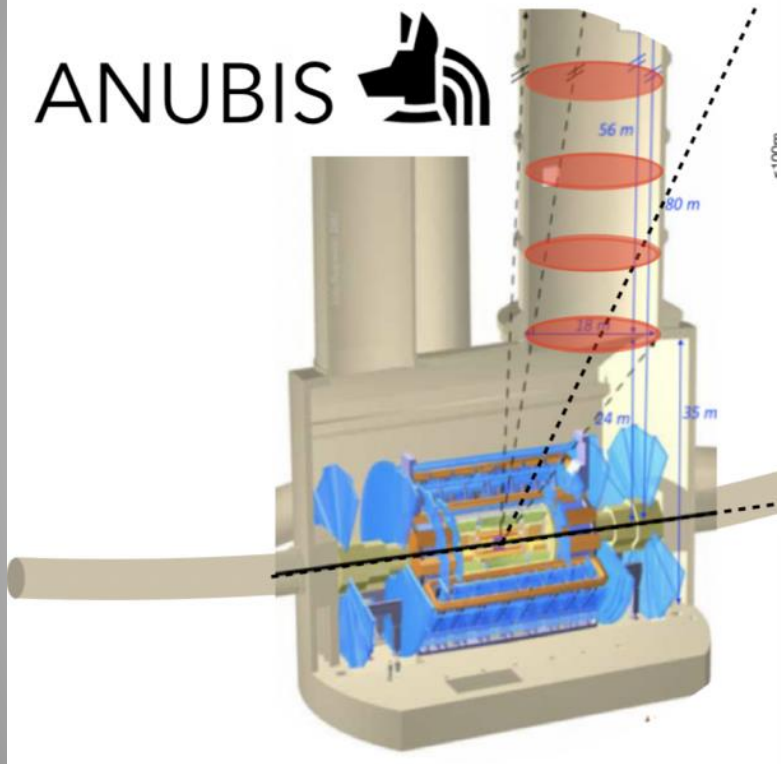
- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025



ANUBIS

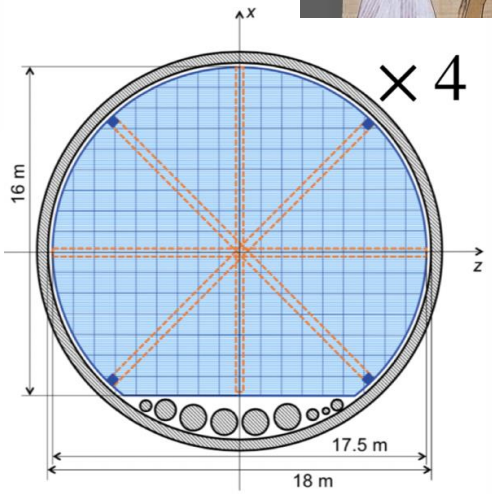
ANUBIS: searches for long lived weakly interacting neutral particles

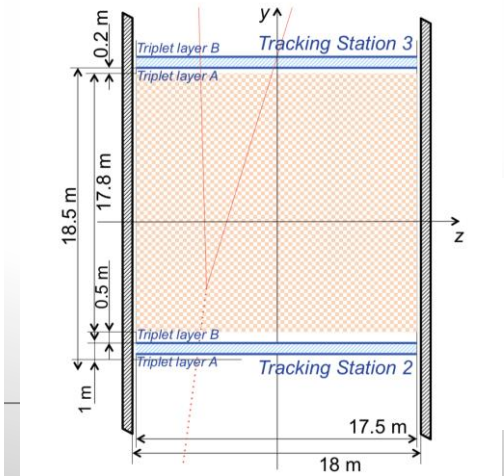




We propose to instrument the ATLAS service shaft

arXiv:1909.13022



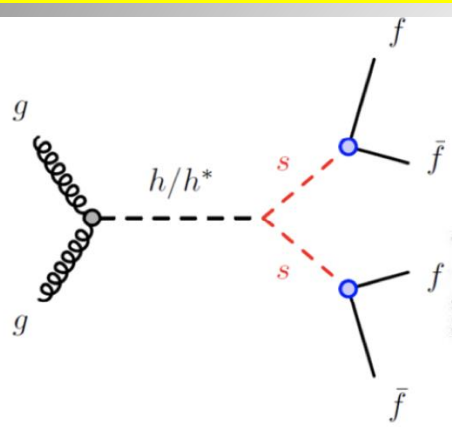


- 4 tracking stations of ATLAS phase-2 upgrade RPCs
- Total about 2300 m^2 of instrumented area
- Each tracking station weighs 30 tons
- Propose to have $2x1x1m^3$ test set-up

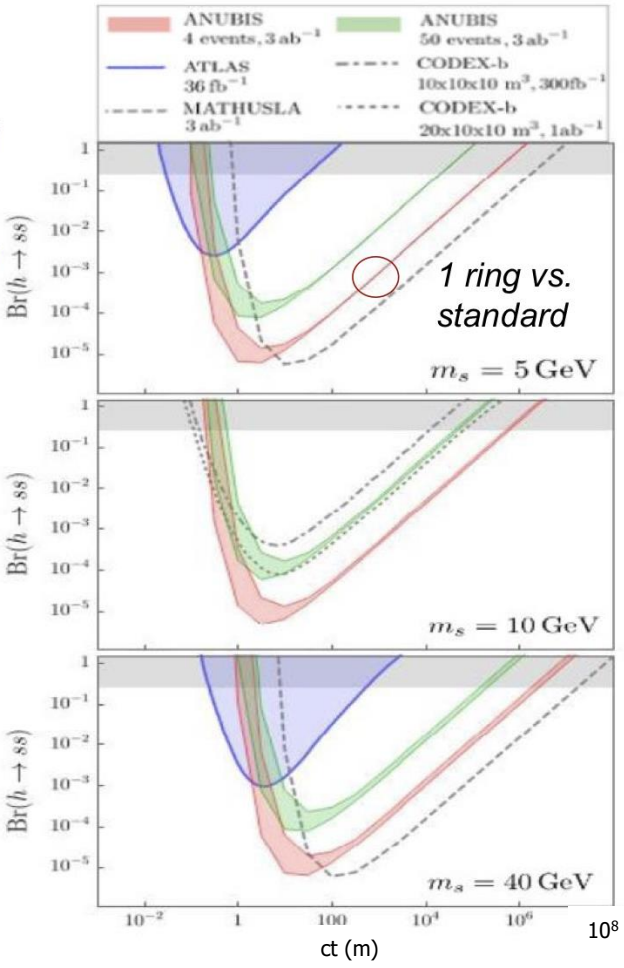
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

Example Process

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



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



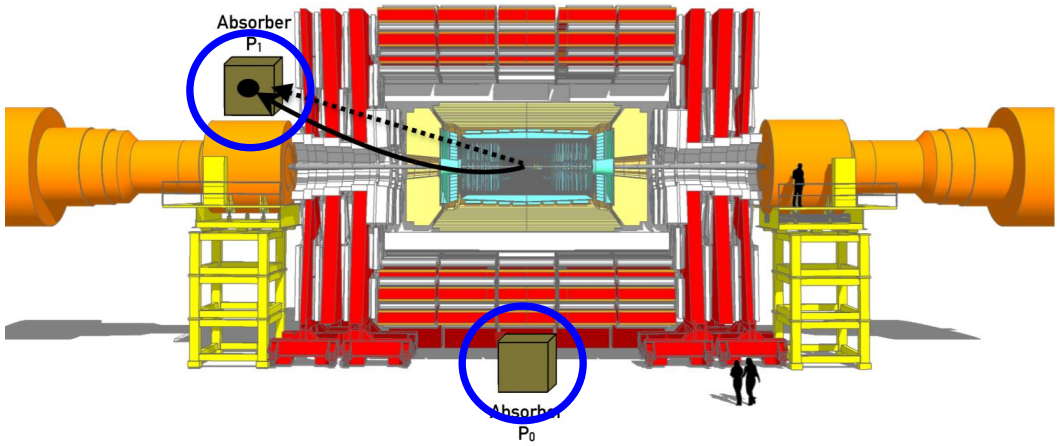
The different proposals have different strengths and levels of complementarity

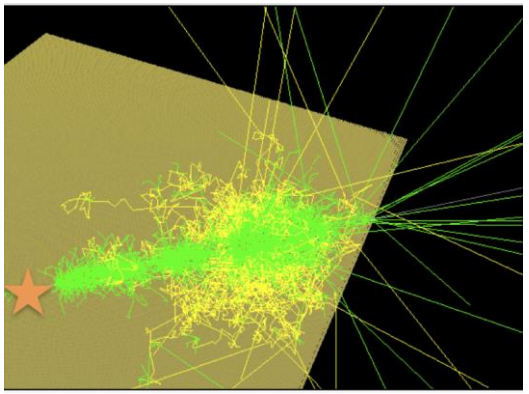
Studies regularly reported in PBC, FIP, and LLP meetings

New: Trapping Particles

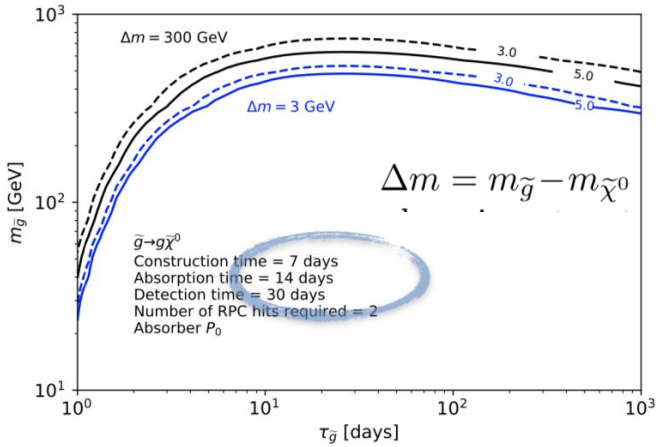
arXiv:2110.13837

- 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!

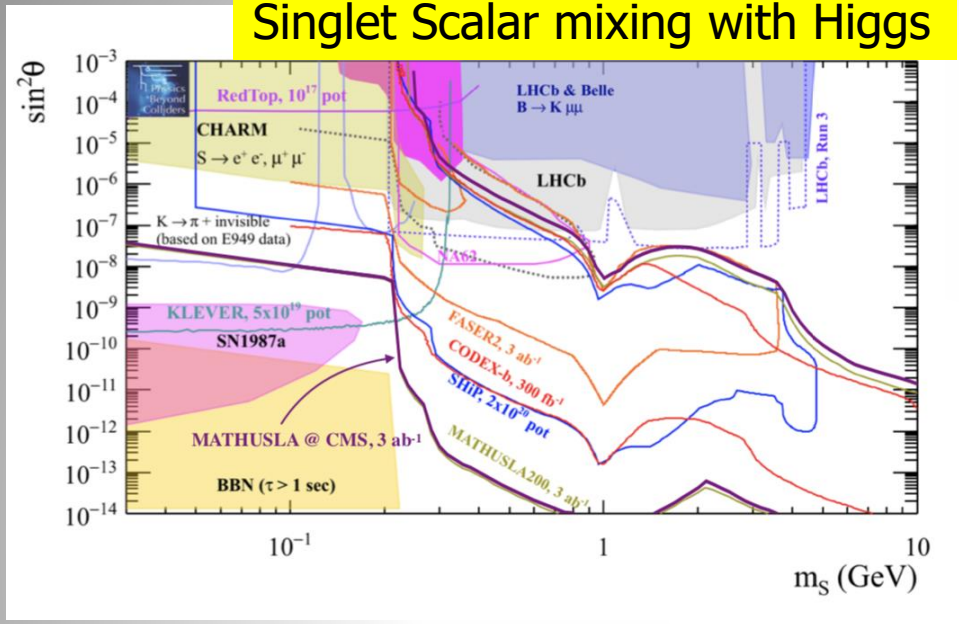
Summary

- LHC so far had seven operational experiments ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL & TOTEM
- For Run-3 there will be two new experiments FASER(**ν**) and SND@LHC and two extensions/upgrades MilliQan and MAPP
- New ideas for additional small experiments at the LHC to increase the coverage: MATHUSLA, CODEX-b, AL3X, ANUBIS, and Forward Physics Facility and FACET. Several have test set-ups for Run-3 and will move to proposals/TDRs
- Mostly for Long-Lived Particle/New Physics Searches but some coverage of QCD, astroparticle physics
- Snowmass21 process: . Several new ideas for experiments at the LHC: FPF, FACET..
- If we would observe one significant anomaly …

Backup

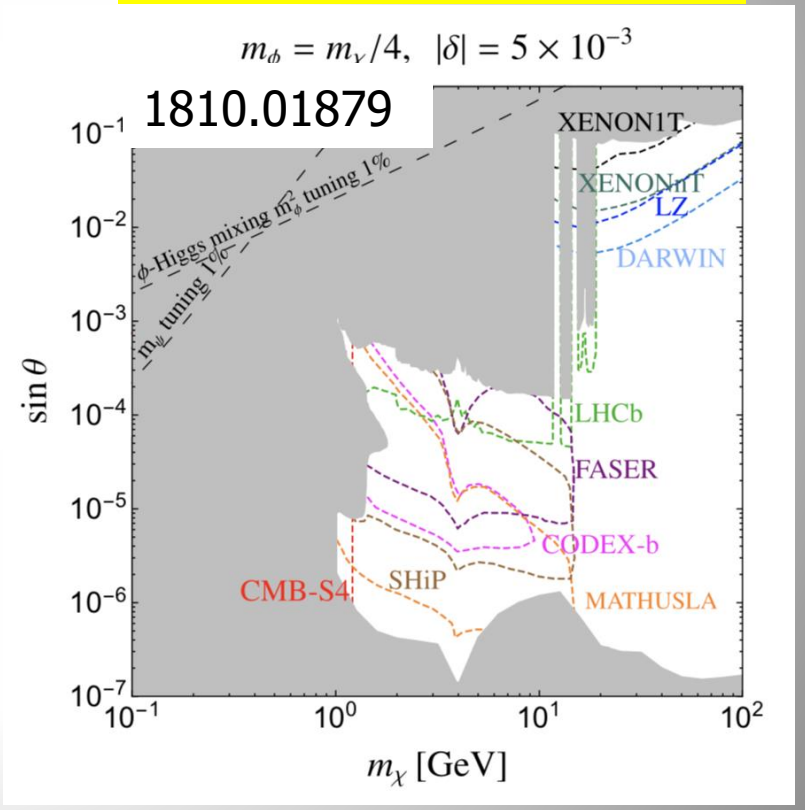
More Example Processes

Singlet Scalar mixing with Higgs

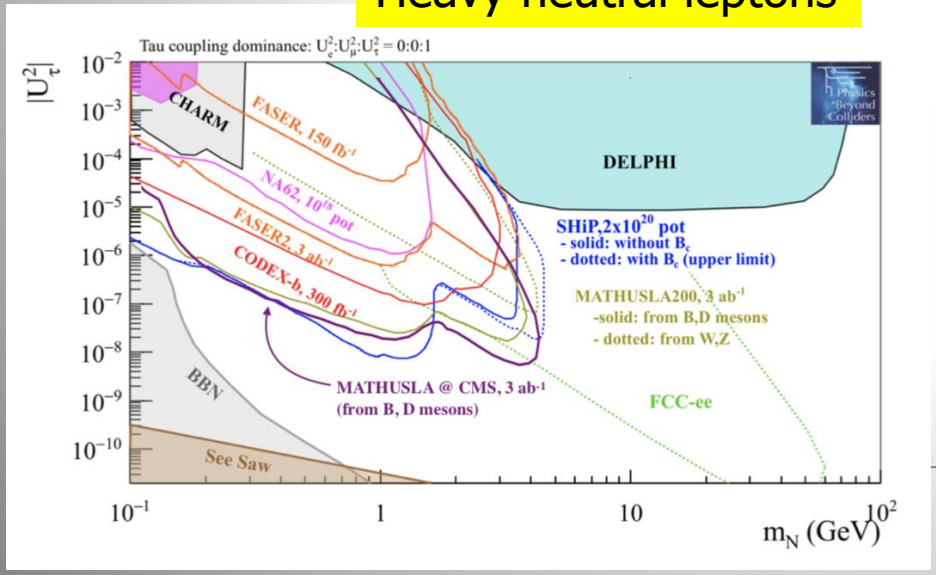


2009.01693

Inelastic Dark Matter Model



Heavy neutral leptons



CODEX-β

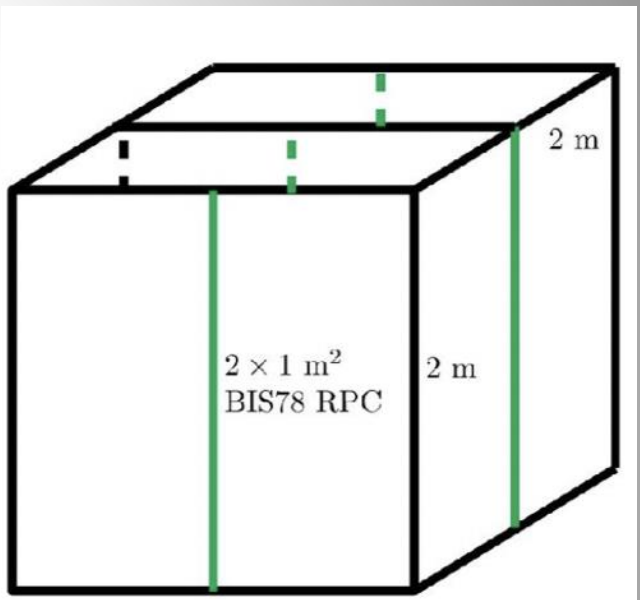
Demonstrator to test technologies planned for CODEX-b

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)

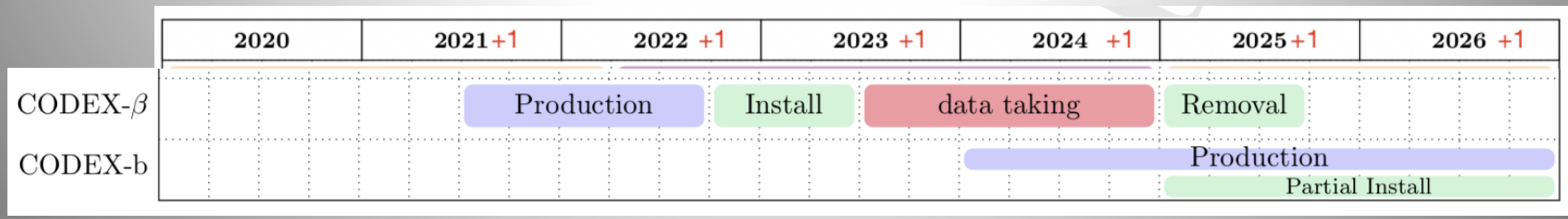
Expect 10^7 K_L to decay in the demonstrator volume.

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



TDR-like installation plan document for CODEX-β being written and will be reviewed by the LHCb technical board.

->Overall timeline shifted by 1 year w.r.t. EOI timeline



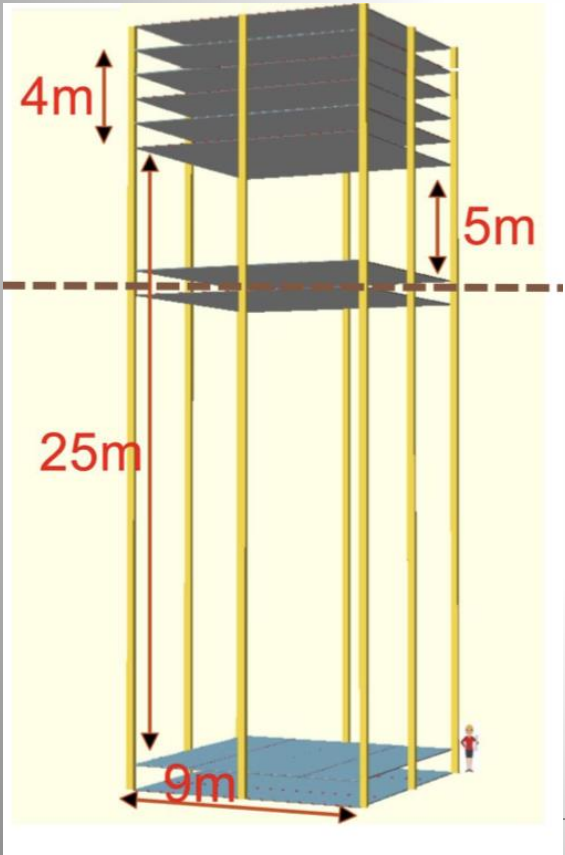
CODEX-b Progress

- Progress on CODEX-β
  - Design support structures, gas services, technical drawings…
  - RPC readout integration with LHCb DAQ boards
  - Materials for RPC manufacturing being purchased
  - TDR / detailed installation plan being completed
- Progress on CODEX-b
  - Fast simulation framework based on reweighing for fast scanning over detector geometries and tracker configurations
  - Reconstruction algorithms & fast simulation development
  - Integration of detector & detector components in Geant4 full simulation
- Plan to complete an LOI for the LHCC in 2022

MATHUSLA

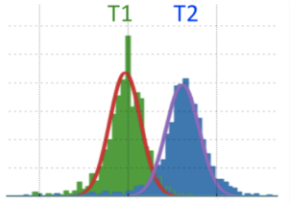
MATHUSLA will be build up from 9x9x30m^3 modules
- 6-layer tracking/timing detectors at the top
- Additional double tracking/timing layer at ground level
- Double tracking/timing layer at the floor level

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

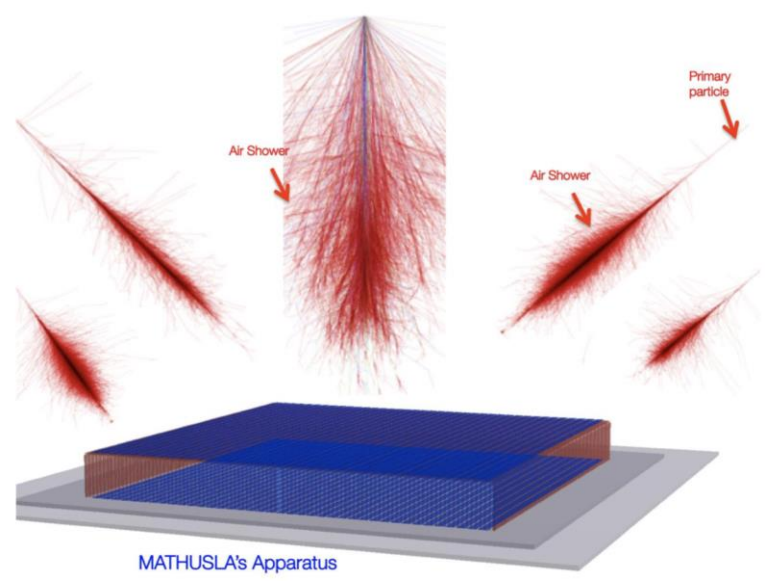


Baseline technology: extruded scintillator bars with wavelength shifting fibers (WLSF) connected to SiPMs. Geometry optimization ongoing
->2018 RPC test-stand feasibility study (2005.02018)

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



MATHUSLA



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

Physics case being made for adding a layer of RPC detector to current scintillator layers for CR studies

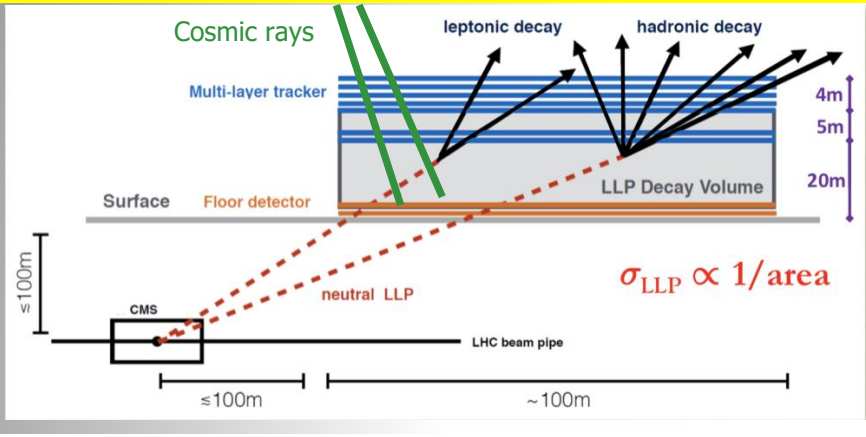
Significant progress is being achieved on multiple fronts in MATHUSLA

- DAQ design
- Detector plane layout
- Scintillator/fiber/ SiPM characterization
- Simulations of rare backgrounds
- Track & vertex reconstruction software
- Cosmic ray studies,

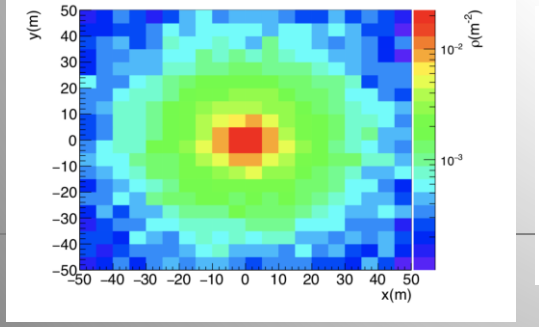
Plan to finish TDR by end 2022, followed by prototype module construction and tests; next plan towards a full detector for HL-LHC

Cosmic Rays & TeV Neutrinos

MATHUSLA and ANUBIS 'on surface' Cosmic Ray measurements possible



Observatory Observatory	Full coverage	Spatial resolution	Angular resolution	Energy precision	CR composition capabilities
MATHUSLA-100	100%	Very good	Very good	Good	Limited by statistics
ARGO-YBJ [204]	93%	Very good	Good	Good	Good
KASCADE [146]	$< 2\%$	Good	Good	Good	Very good
HAWC-Outrigger [86]	$0.8 - 62\%$	Good	Good	Good	In investigation
IceTop [88]	0.044%	Good	Good	Good	In investigation
TALE (TA) [89]	$O(1\%)$	Good	Good	Very good	In investigation



particle density in 10^{15} eV airshower

Topics under study in MATHUSLA – like KASCADE but with full coverage

- Add RPC Layer for CR studies?
- Vertical Detector layers?
- Tailored electronics for CR studies…

Possible Physics Study Topics

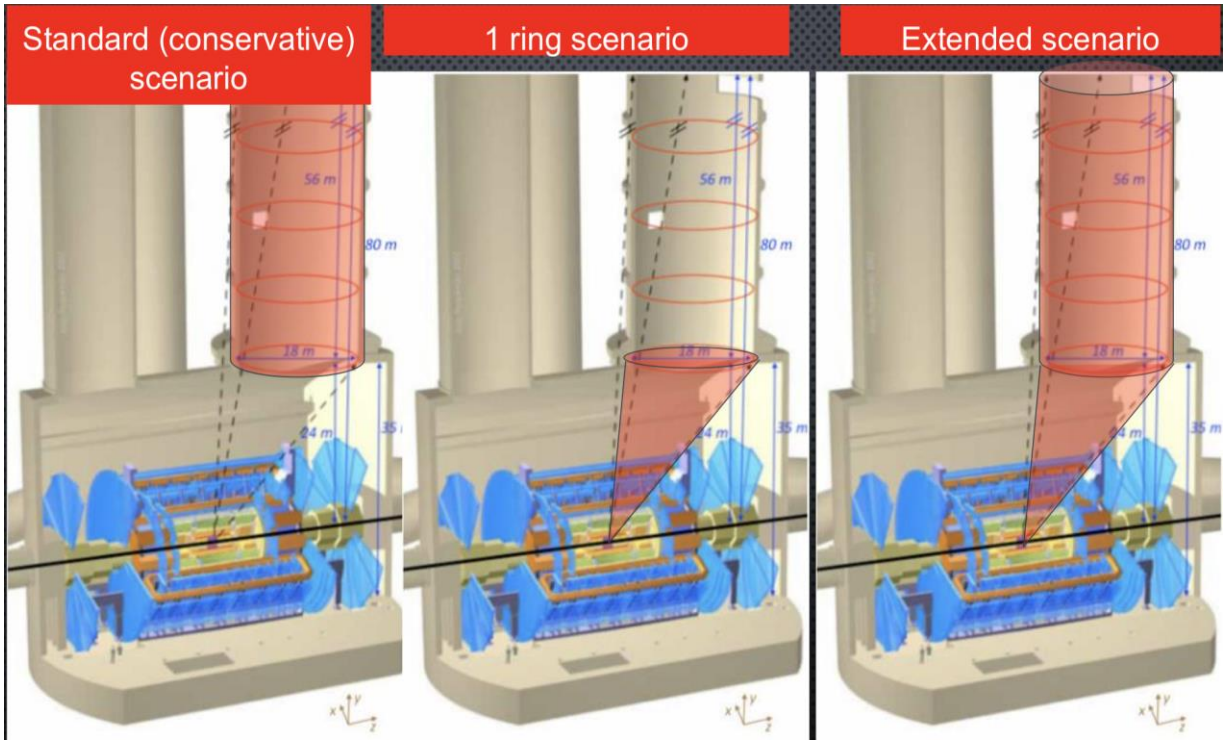
- Primary CR spectra and composition
- Cosmic Ray Anisotropies/point sources
- Highly inclined showers
- Studies of EAS/hadronic int. models
- High Multiplicity Muon Bundels
- Combine with CMS experiment
- …

MATHUSLA: Detailed report on CR studies in preparation

ANUBIS: To be looked into ..

ANUBIS

- The ANUBIS (AN Underground Belayed In-Shaft) search experiment will probe neutral LLPs with decay lenghts > 1m and masses > 1 GeV
- Sensitivity to large decay lengths is established by instrumenting a large decay volume (e.g. the ATLAS cavern + service shaft)



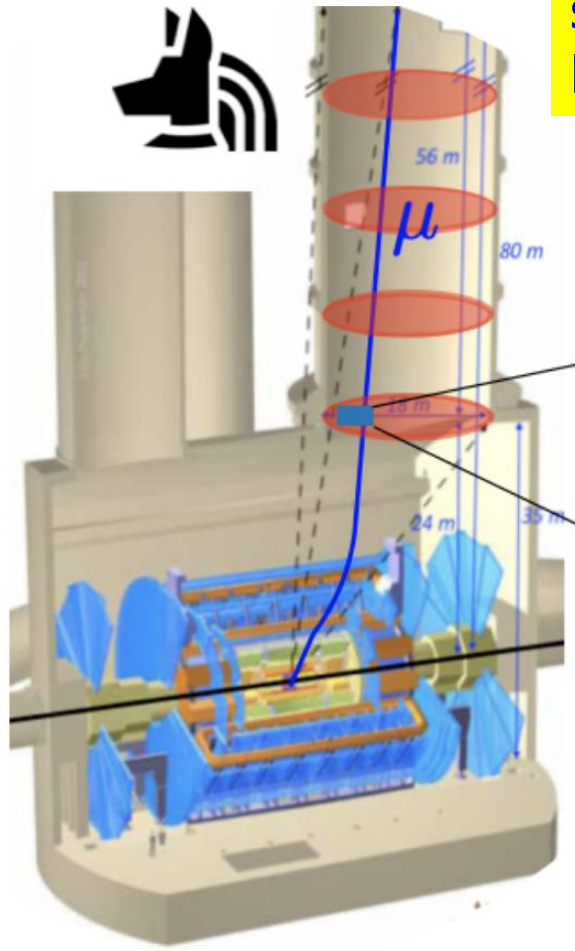
Optimization and G4 based simulation studies ongoing

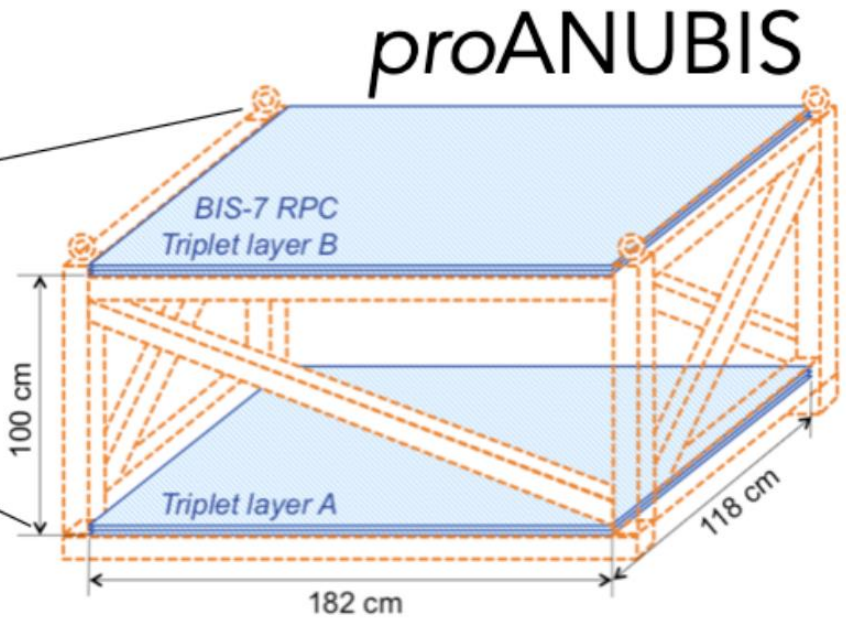
Plan:

- proANUBIS for background study
- EOI to LHCC in due time

ANUBIS

ProANUBIS, a 2x1x1 m^3 prototype of one tracking station unit module for ANUBIS based on BIS-7/8 RPC technology or a Phase 2 upgrade technology



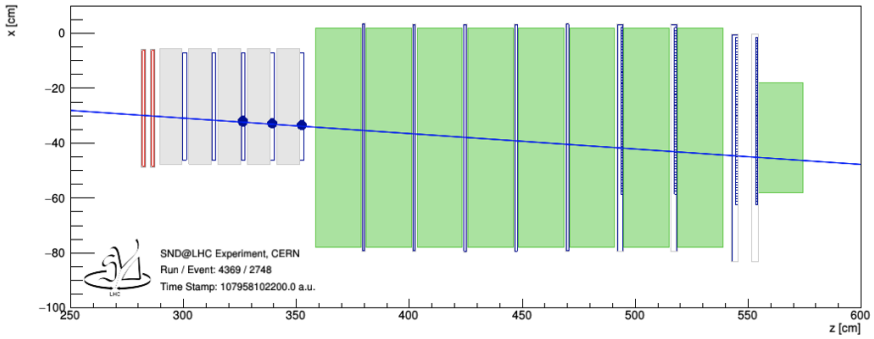


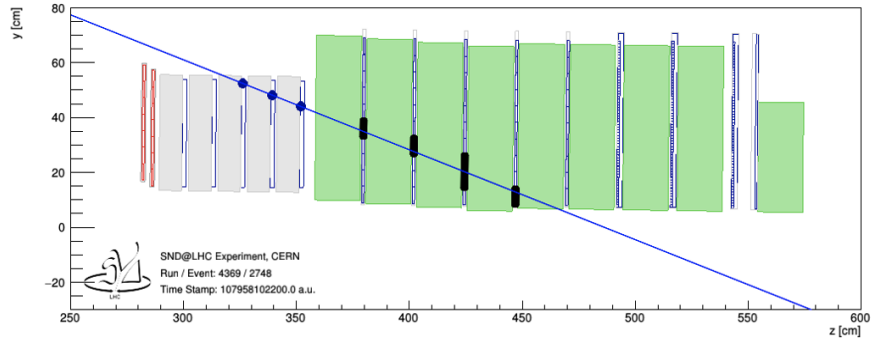
Goal to install proANUBIS during Run 3 as demonstrator; study backgrounds

More information on
https://twiki.cern.ch/twiki/bin/view/ANUBIS/WebHome#Current_efforts

Data taking in TI18

Cosmic ray
(March 5th 2022)





Muon from pp collisions @13.6 TeV
(July 6th 2022)