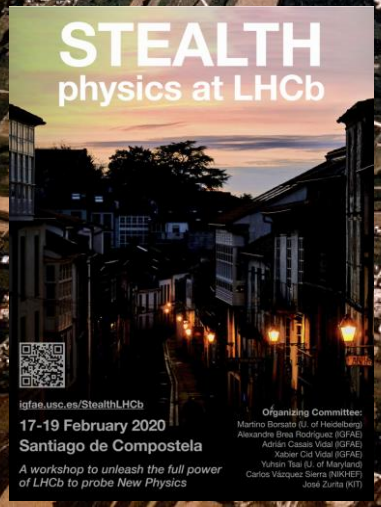
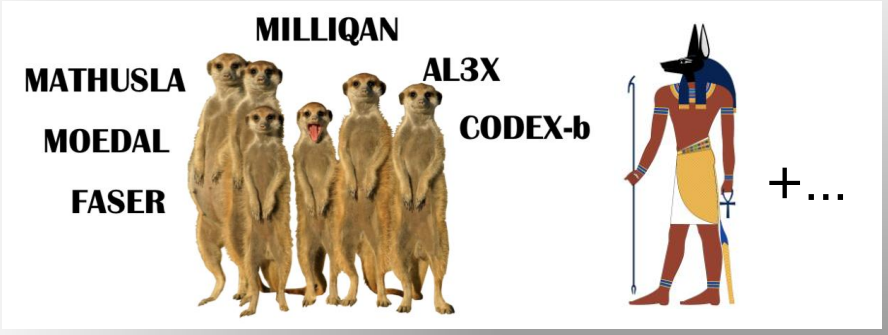
Direct Searches for New Physics
Who are LHCb's Main Rivals?

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

19th February 2020

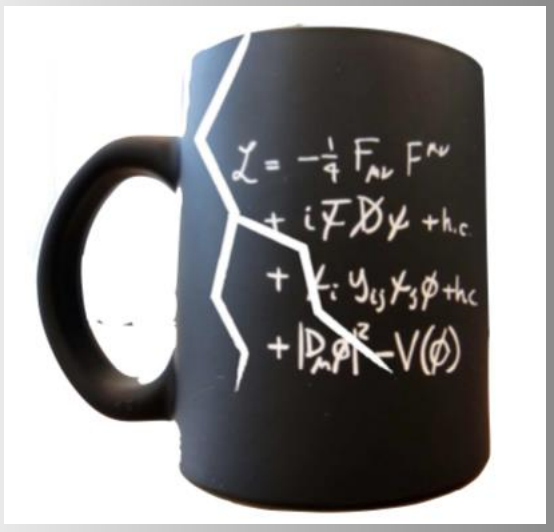


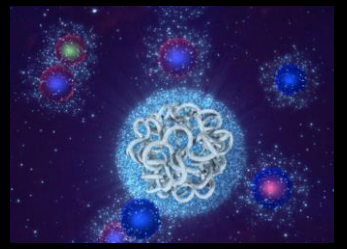


Outline

- Introduction
- Upcoming upgrades of the LHC experiments (ATLAS/CMS)
- Dedicated new experiments @ the LHC!
- Physics beyond collider: fixed target program
- New/current neutrino experiments
- Summary & Outlook

- Personal selection of topics.
- Will mostly consider LLPs.

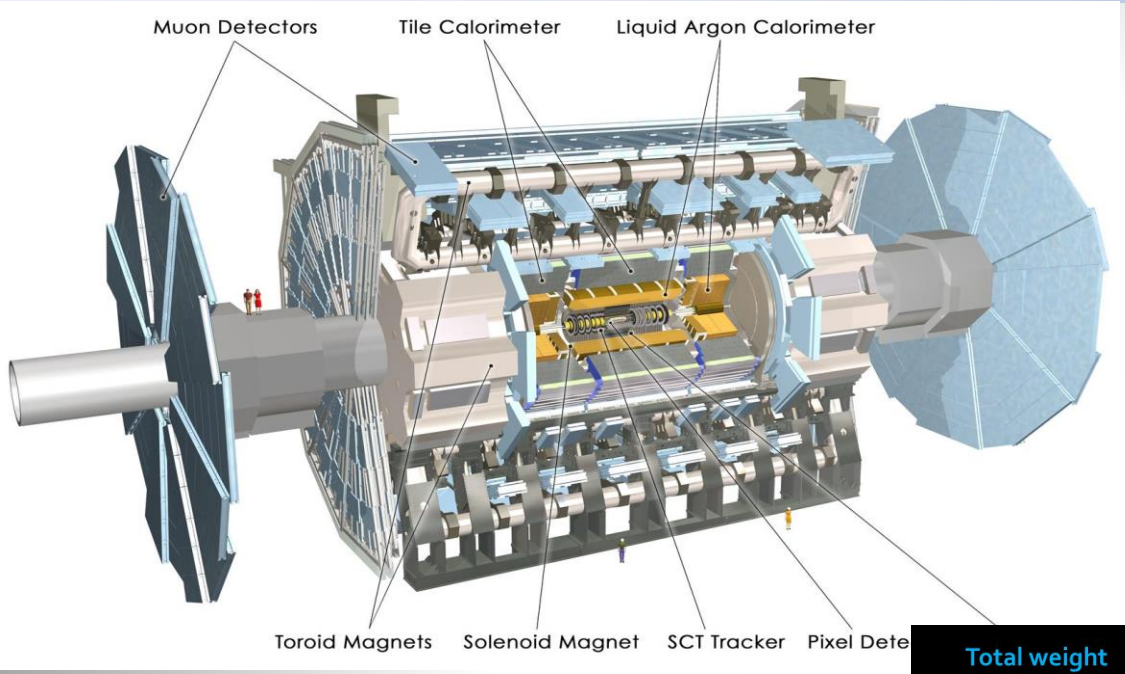




Who are LHCb's Main Rivals?

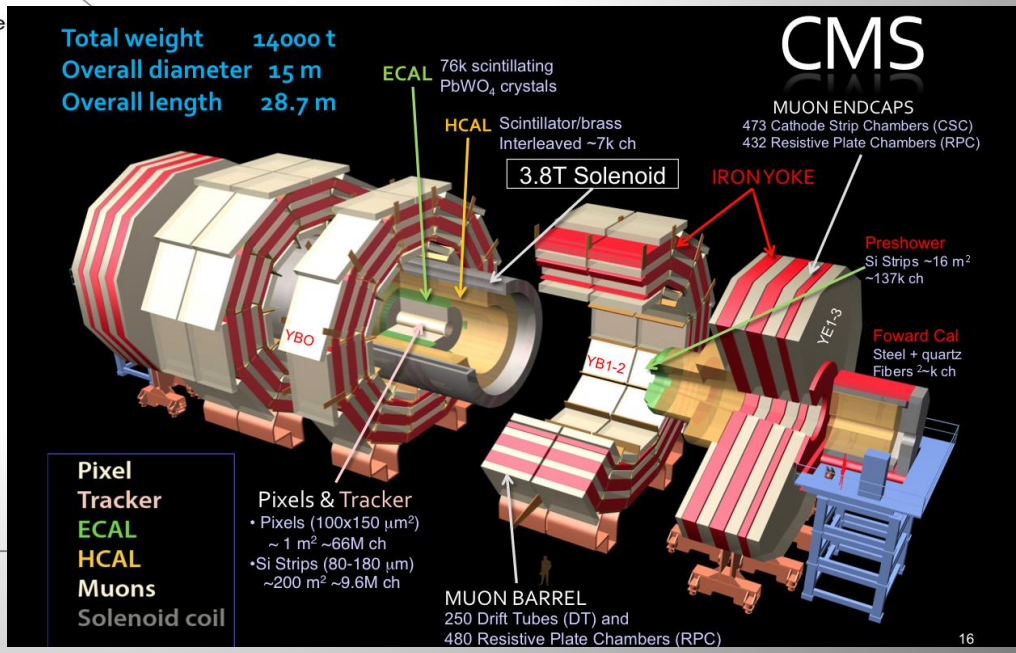
- Present other LHC experiments
  - ATLAS, CMS, MoEDAL(+)
- New proposals/ideas for LHC experiments
  - FASER, MilliQan, MATHUSLA, MAPP, CODEX-b, AL3X, ANIBUS and recently XSEN, FASER-Nu, SND@LHC
- Fixed target/BDF experiments eg at CERN
  - See Physics Beyond Collider-2018 study
- Neutrino experiments present/future
  - SBN, NOVA, T2K, and in future DUNE/T2HK, (ESS-Nu)
- Belle II (50 ab^{-1} in 2027, but not this talk)

New Physics Hunters @ the LHC

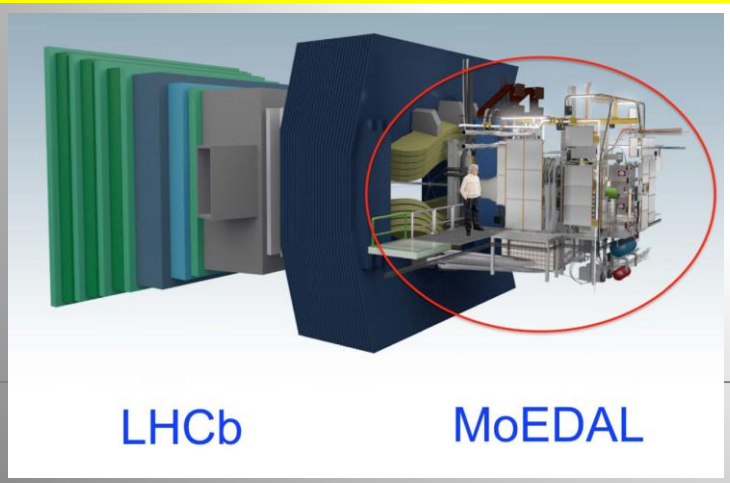


The ATLAS experiment

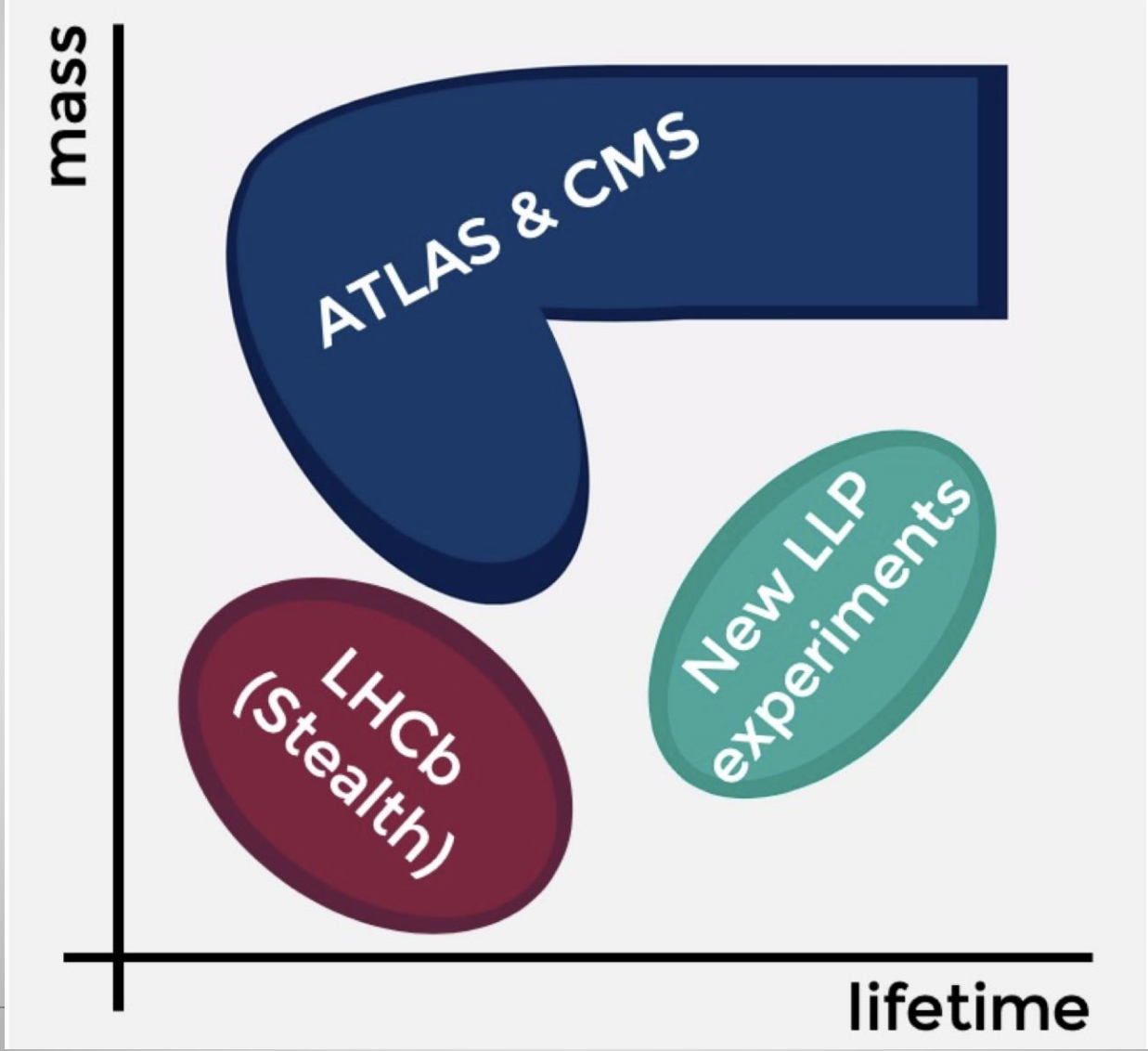
The CMS experiment



...And also LHCb and MoEDAL

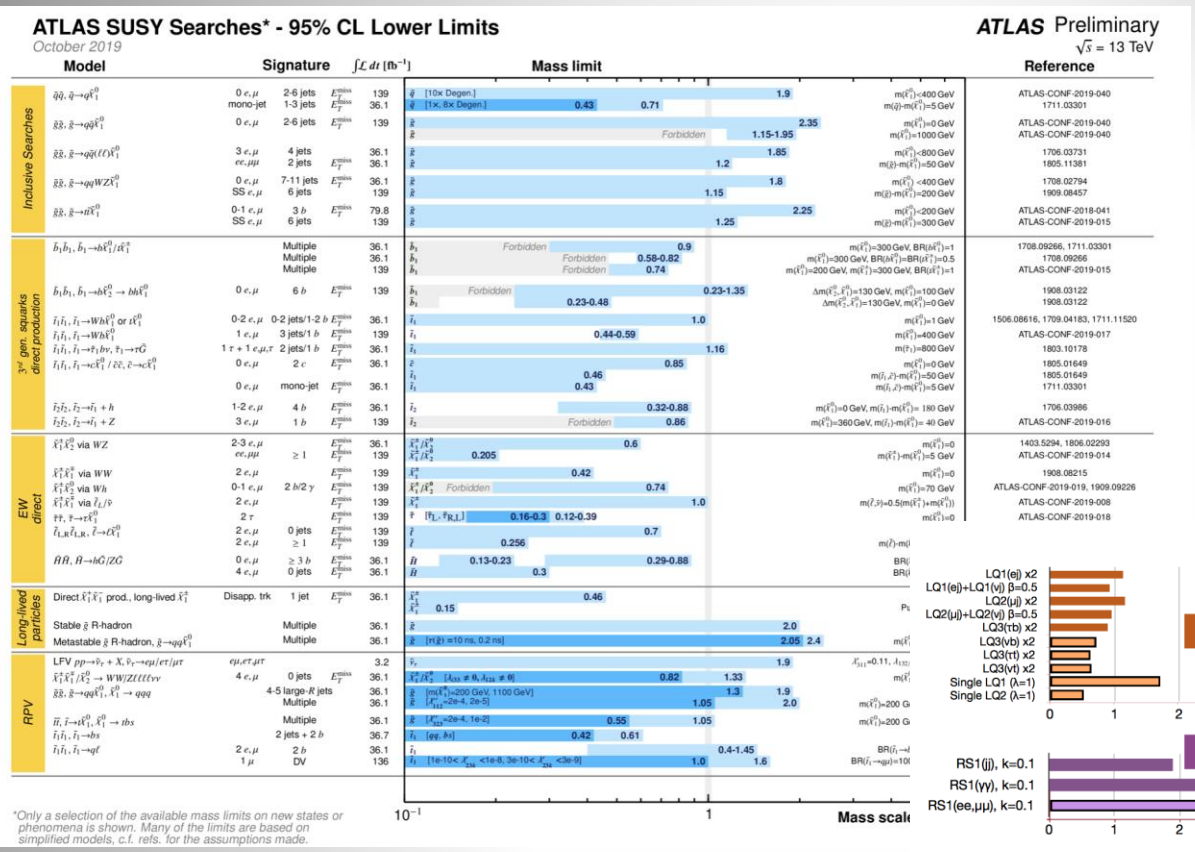


Coverage Sketch

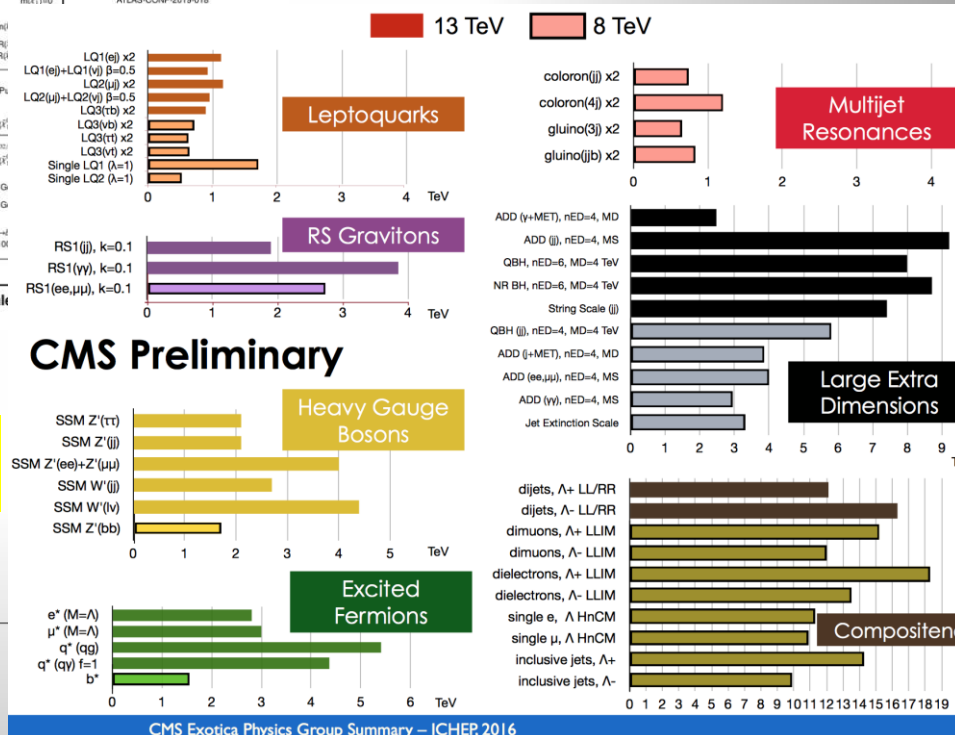


Xabier: first day

LHC: So far no New Physics



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



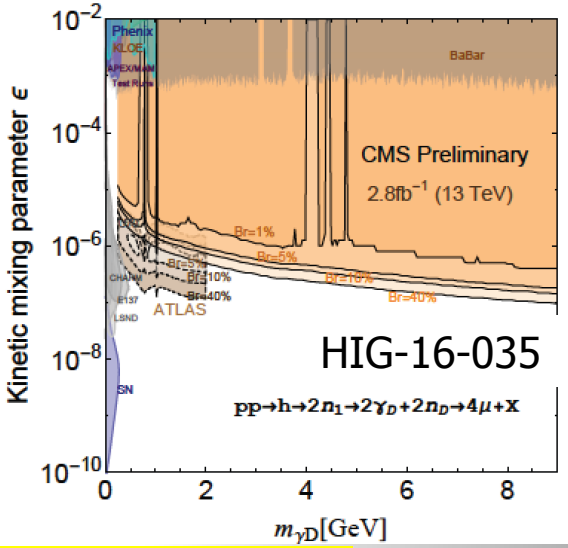
No signal of new physics so far!!

ATLAS/CMS Searches

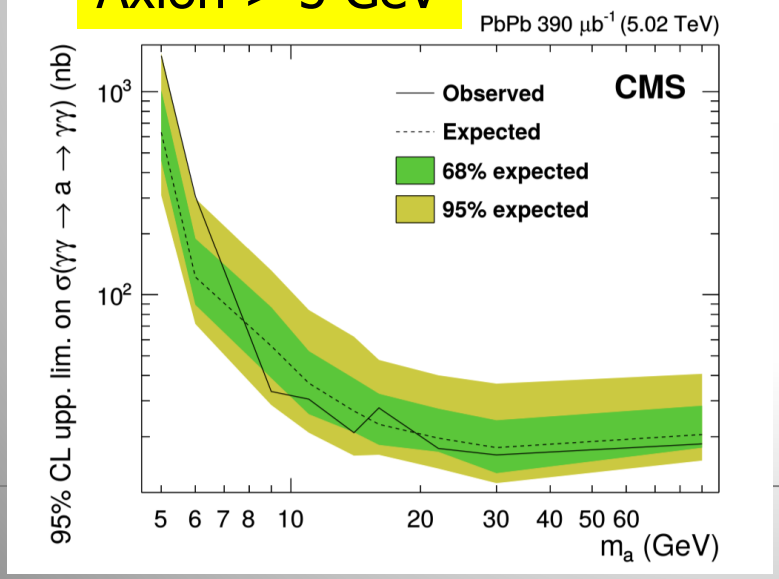
- Generally high mass, high p_T

  An important issue is the trigger
- Cross section (x BR) limits to ~0.01 fb
- A few low mass analyses - often resonance searches but also eg DM searches via mono-object production…
- Examples of searches ->

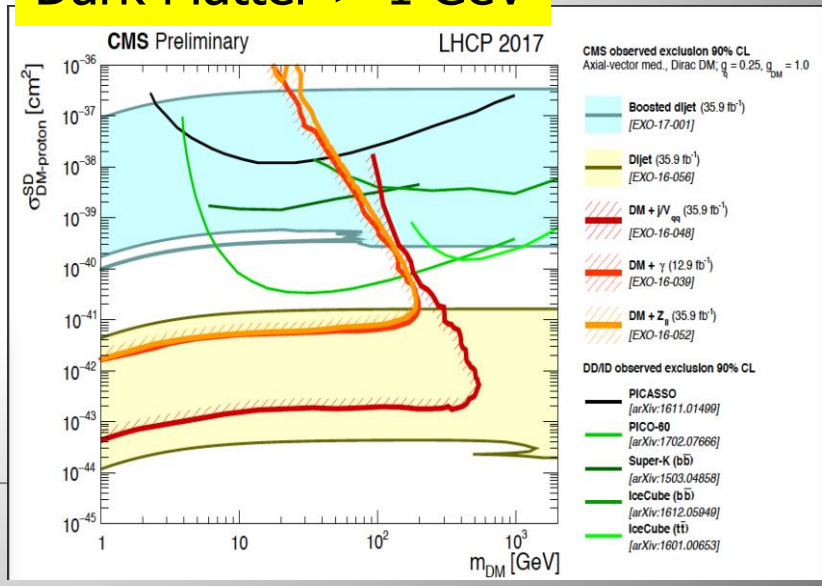
Dark photon > 250 MeV



Axion > 5 GeV

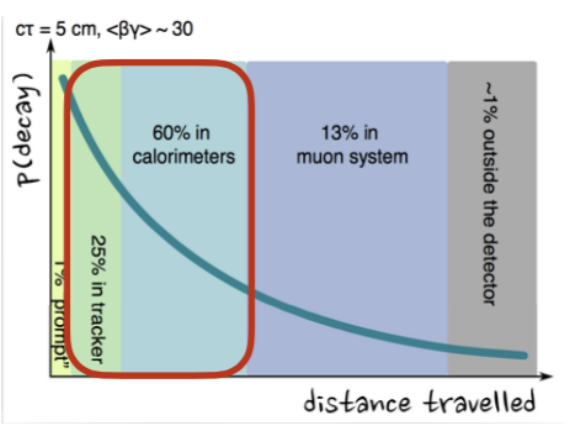


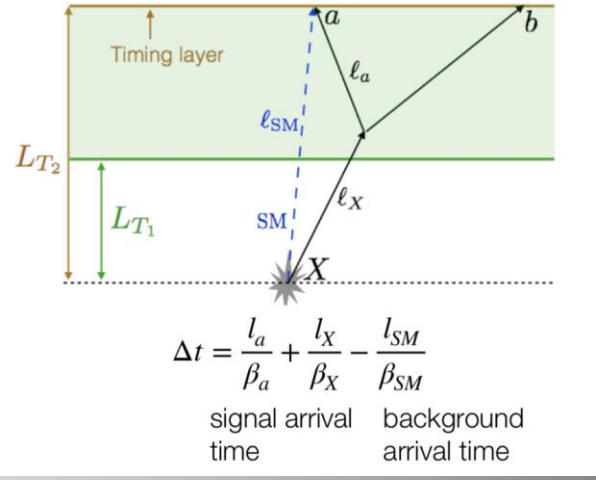
Dark Matter > 1 GeV



Trigger Improvements for Run3/Phase 2

- Trigger upgrades in hardware trigger part for run3 for LLPs
  - HCalorimeters: delayed jets, energy depth and timing lifetimes nanasecods to micro seconds)
  - Muons: less constrained from the vertex
- More tailored software triggers in run3 for LLPs, GPUs?
- LLP trigger updates for the Phase 2
  - Tracking trigger at hardware level
  - Muon trigger improvements for LLPs
  - Good timing in barrel and endcaps (30ps)



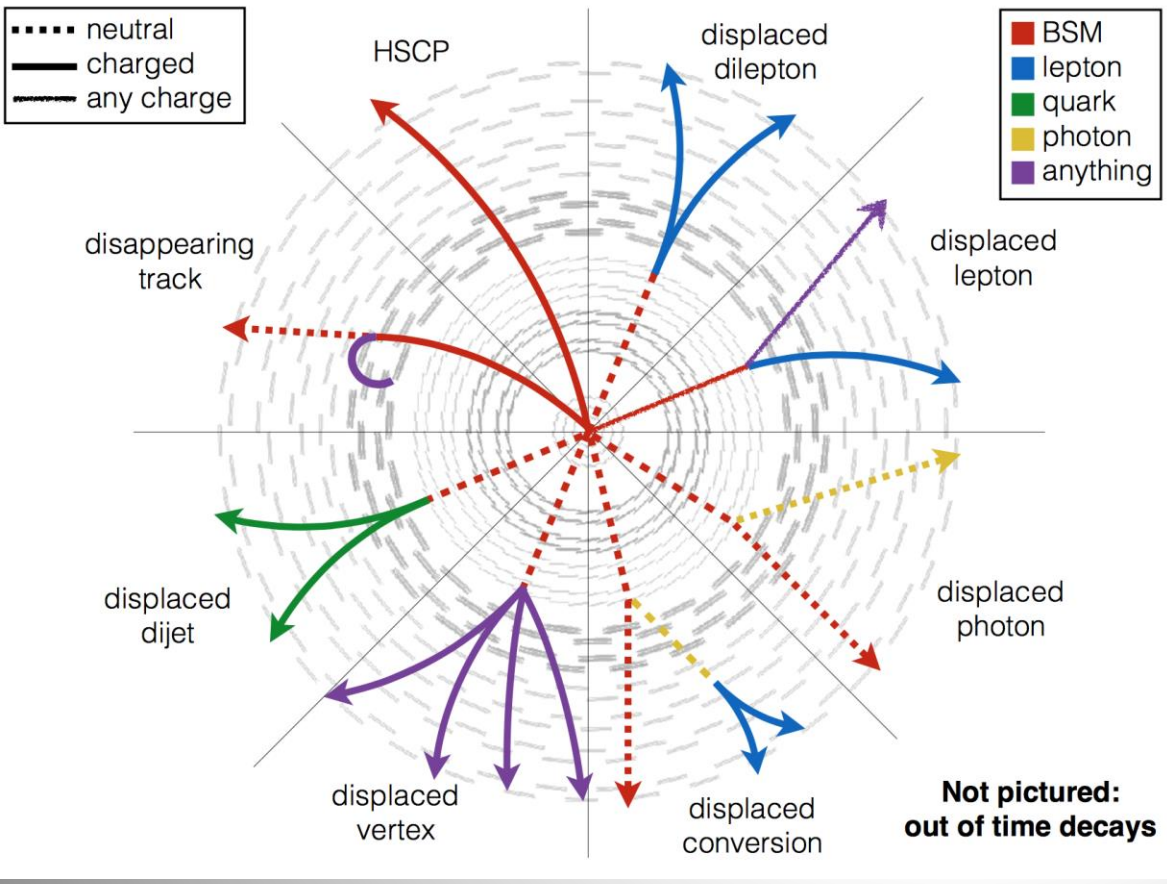


Data Set Collection Improvements

- Normally the data taking rate is ~1 kHz, for events of about 1.5 Mb in size. This is mostly limited by the data handling off-line (prompt ReCo). Special data taking:
- Scouting data: reduce event information by a factor ~100, and collect much higher rate (eg jets evts with low treshold)
- Parked data: collected another 1-2 kHz of data but just store them. Processing of these data at quiet times (eg shutdowns). Eg unbiased b-sample -> 10^{10} events in 2018!
- Minimum bias data: All triggers have the hard scatter event + 20-30 minimum bias events. Exploring how we can use these events for -> potential to access low masses and couplings for new particles (HNLs, A0, LDM…)
- Special runs: (especially in 2021) with lower rates

Long Lived Particles @LHC

Signatures of LLPs



Some of the Challenges

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

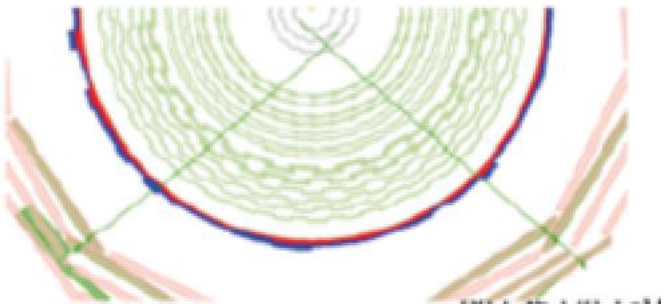
SM backgrounds often low. But need special studies (punch through, secondary interactions, tails, cosmics…)

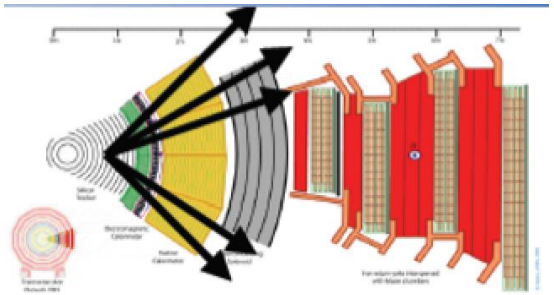
Special reconstruction is often needed

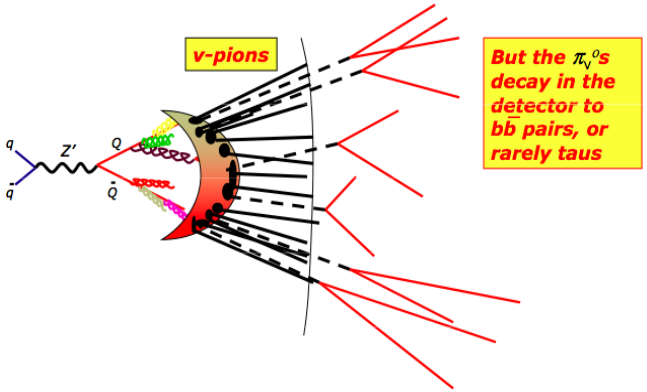
Some detector upgrades for High-Luminosity LHC (>2026) address these issues.

ATLAS/CMS LLP Searches

- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced leptons & lepton jets
- Displaced photons
- Dark photon decays
- Heavy Stable Charged Particles
- Stopped particles
- Emerging jets/dark showers
- Monopoles
- Heavy Neutral Lepton searches
- Strongly Interaction Massive Particles
- ….

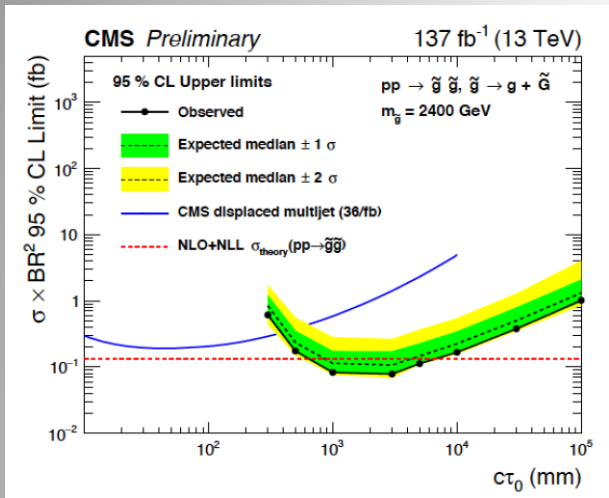




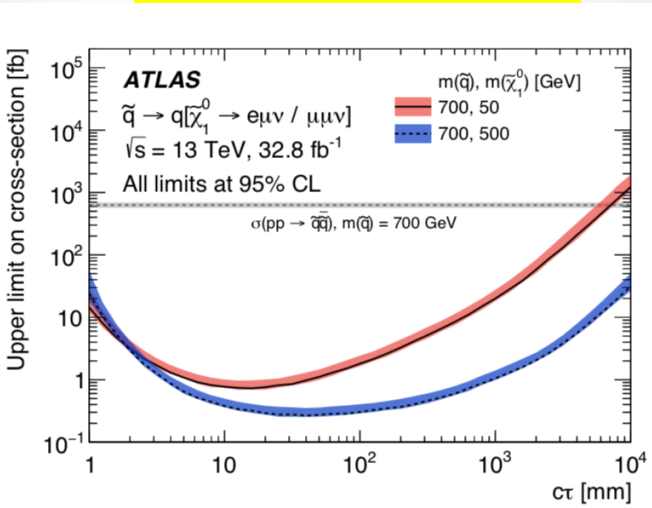


Long Lived Searches: Examples

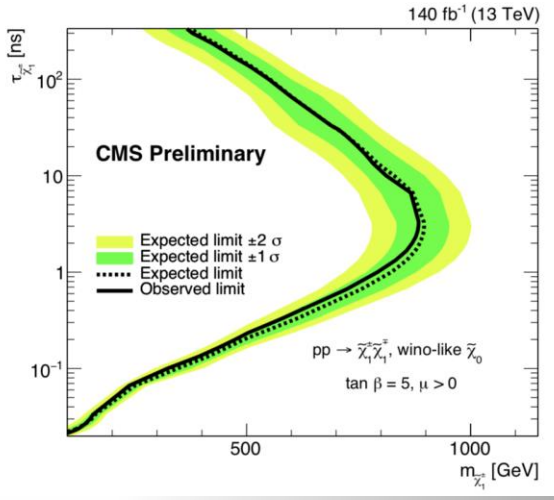
delayed jets



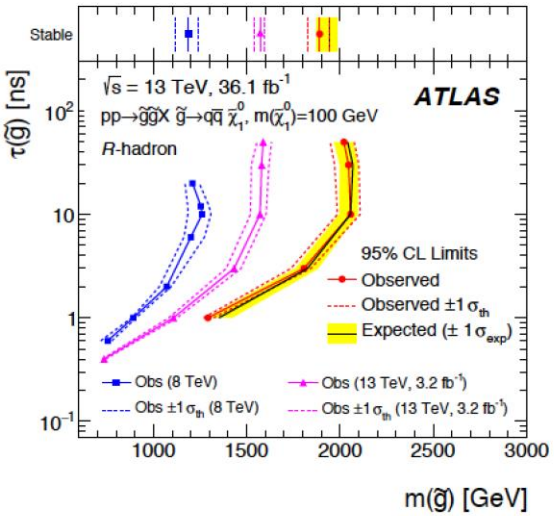
displaced leptons



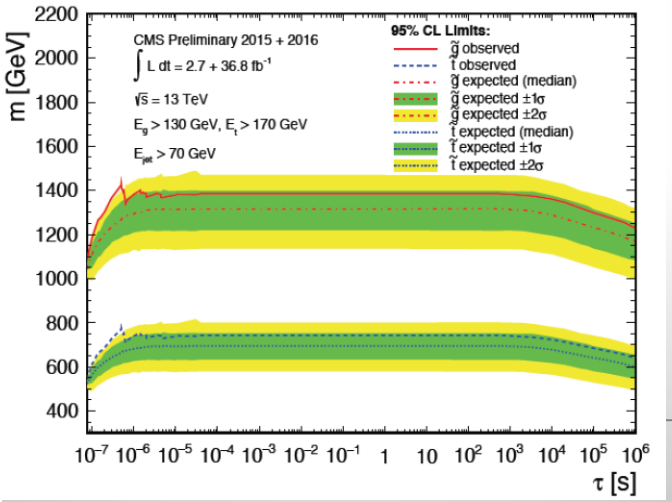
disappearing tracks



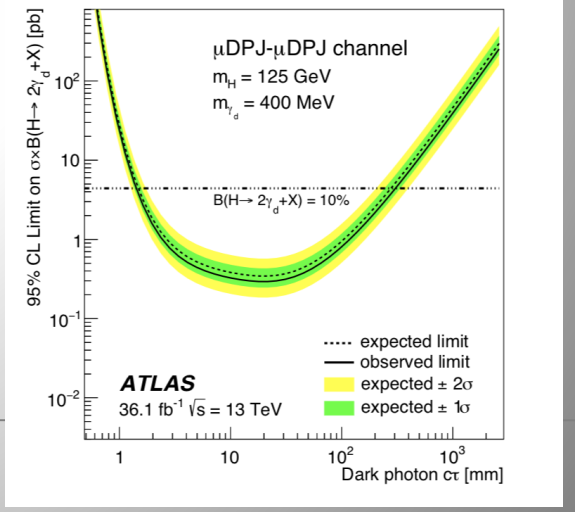
metastable R-hadrons



stopped particles

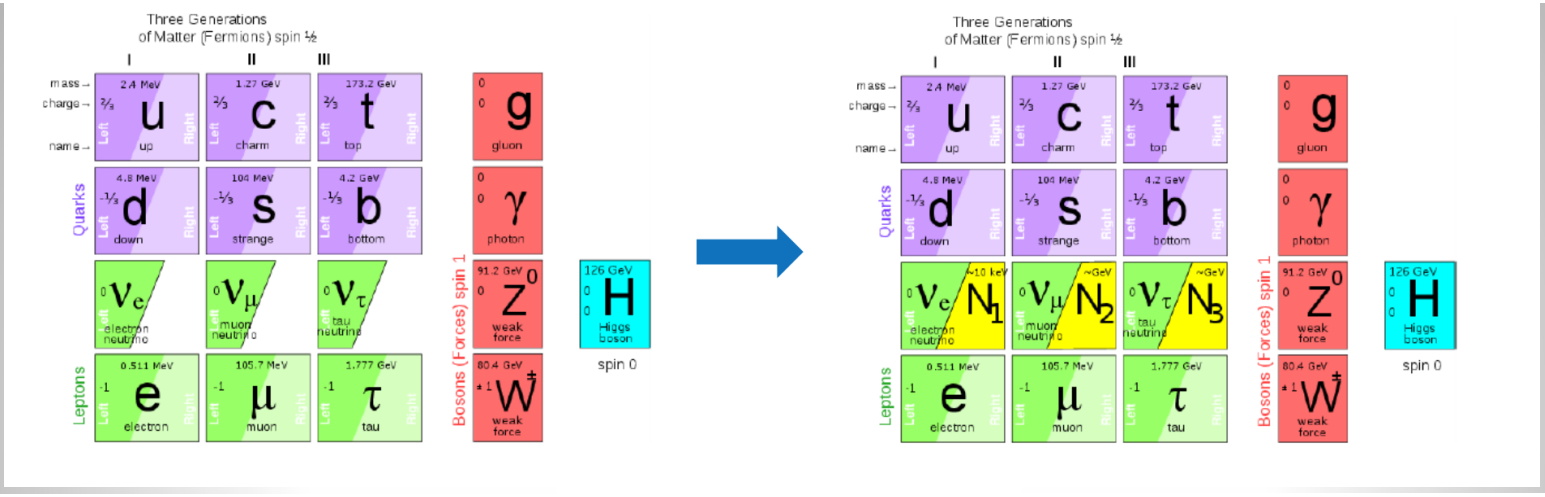


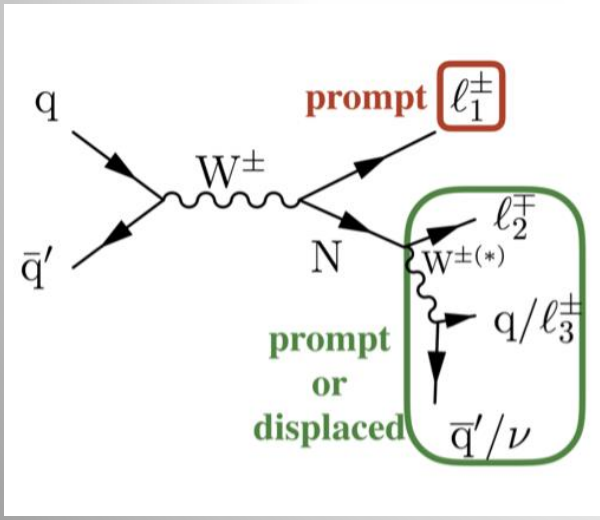
Low mass dark photons

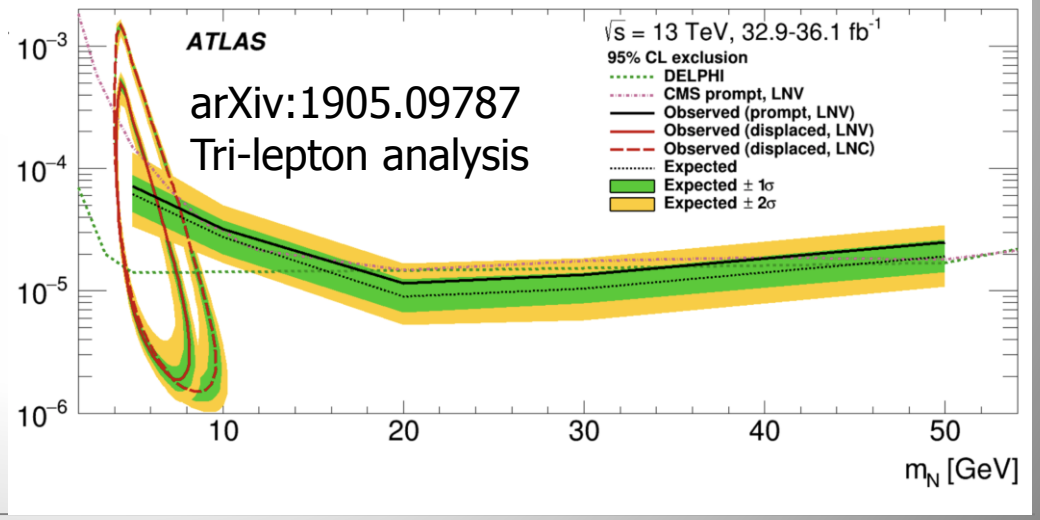


Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.



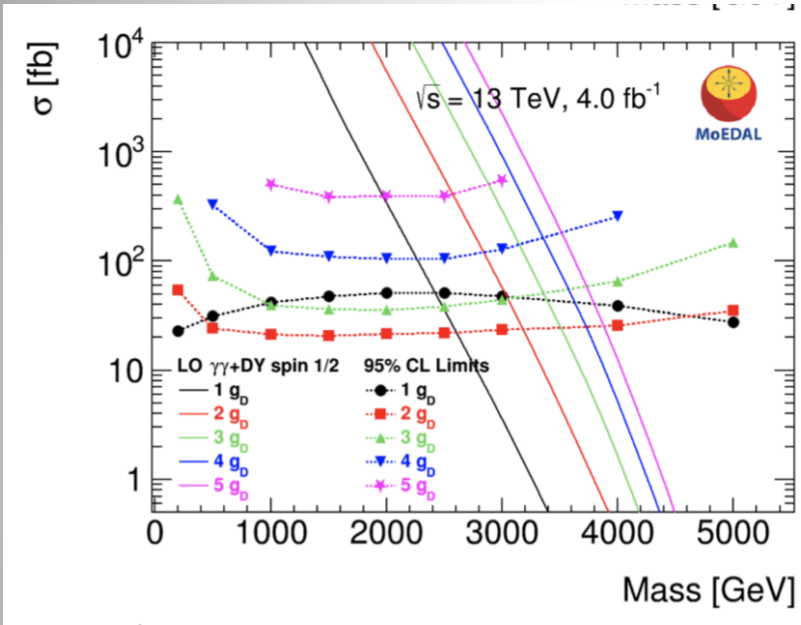


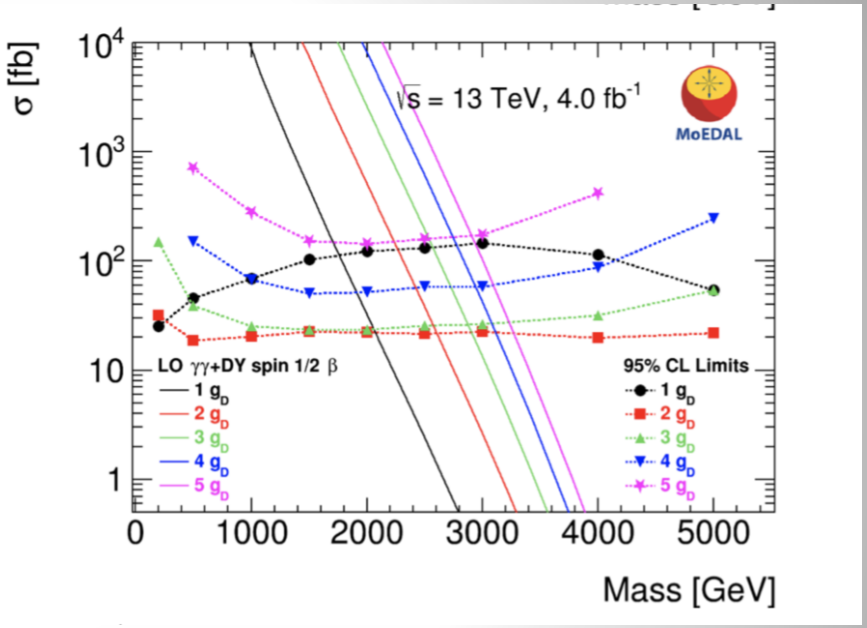


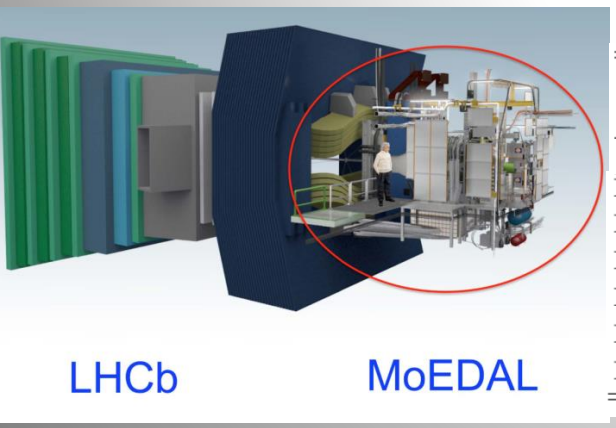
-> HNL hunting also focus of the SHIP experiment proposal

Monopole Searches: MoEDAL @ 13TeV

Run-2 data analysis base on 794 kg Aluminium to "stop" the monopoles and search for them with a SQUID precision magnet (4.0fb^{-1}) arXiv:1903.08491







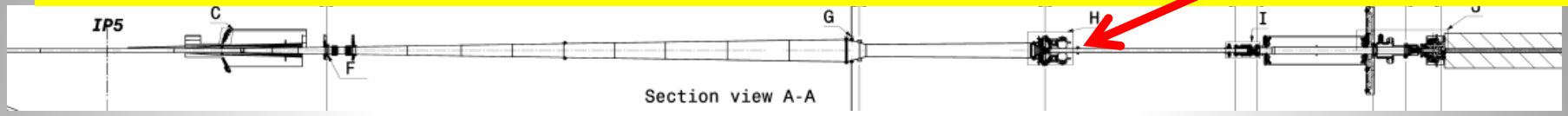
Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY+γγ	0	2190	2930	3120	3090	–
DY+γγ	1/2	2420	3180	3360	3340	–
DY+γγ	1	2920	3620	3750	3740	–
DY+γγ β-dep.	0	1500	2300	2590	2640	–
DY+γγ β-dep.	1/2	1760	2610	2870	2940	2900
DY+γγ β-dep.	1	2120	3010	3270	3300	3270

- Limits for different monopole charges
- First monopole search result @LHC at 13 TeV No signal yet.

Monopoles Stopped in the Beampipe

ADR et al., Eur. Phys .J. C72 (2012) 2212

Test performed with pieces of material from the LHC from 18 m away from the interaction region in 2012: set up SQUID procedure



CERN Courier 18/2/2019!!

MONOPOLES

CMS beam pipe to be mined for monopoles

On 18 February the CMS and MoEDAL collaborations at CERN signed an agreement that will see a 6 m-long section of the CMS beam pipe cut into pieces and fed into a SQUID in the name of fundamental research. The 4 cm diameter beryllium tube – which was in place (right) from 2008 until its replacement by a new beampipe for LHC Run 2 in 2013 – is now

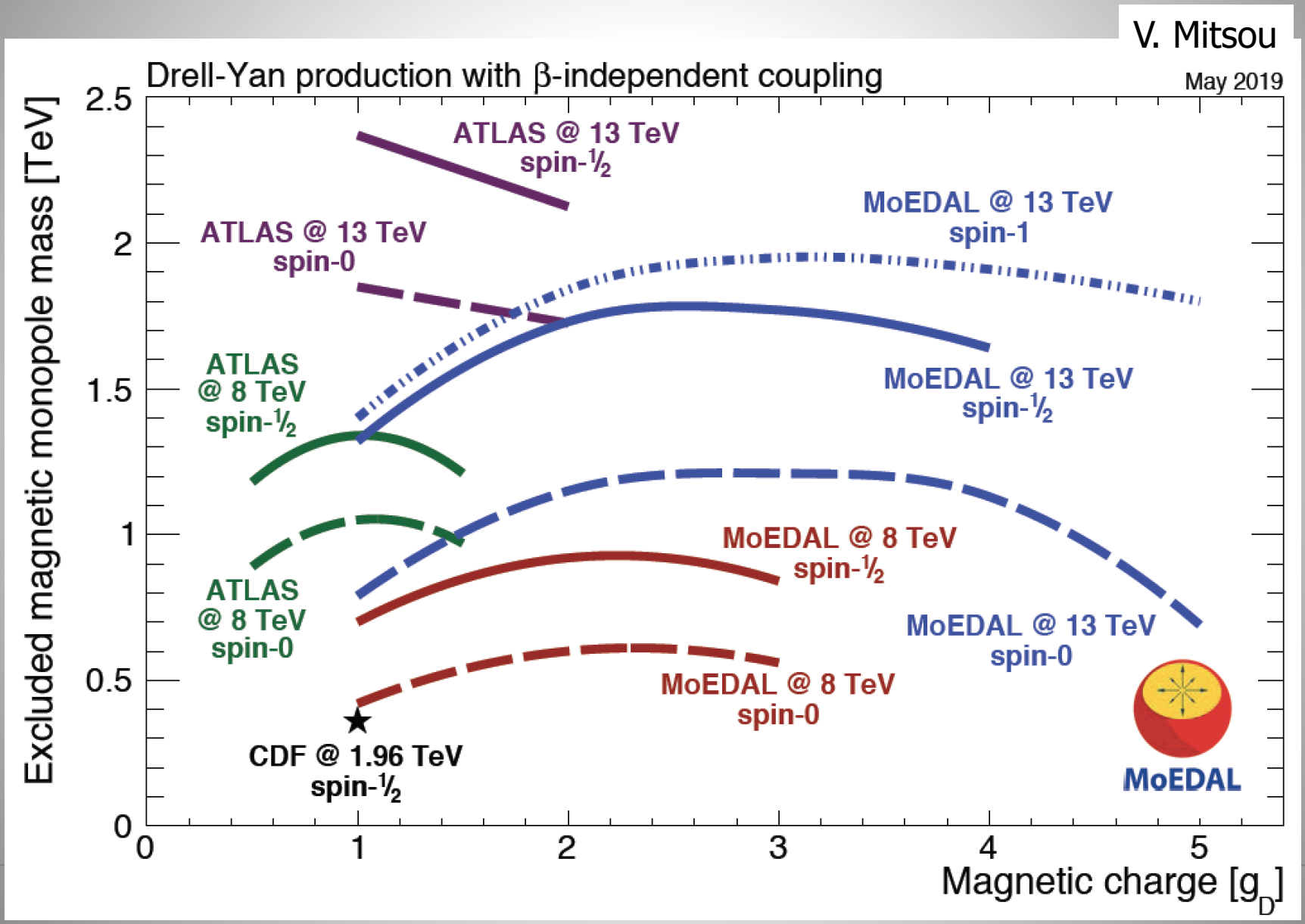
$|g| \geq 4g_D$

A beampipe analysis effort has been put into place in MoEDAL

-> CMS beampipe being prepared for the ETH SQUID in Alberta right now

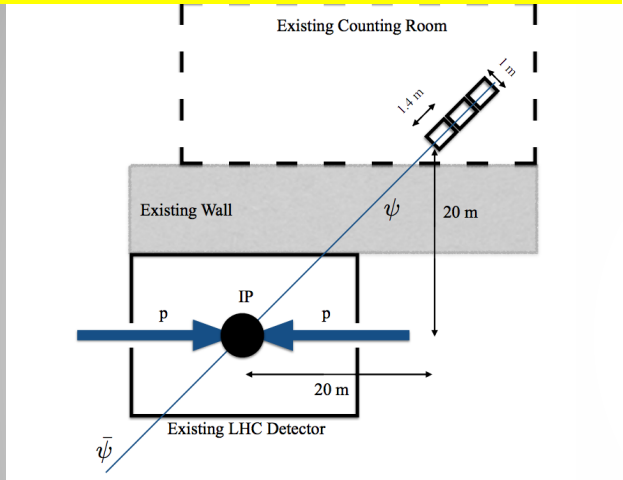
Other beampipes under discussion (RHIC, BaBar…)

LHC Monopole Searches

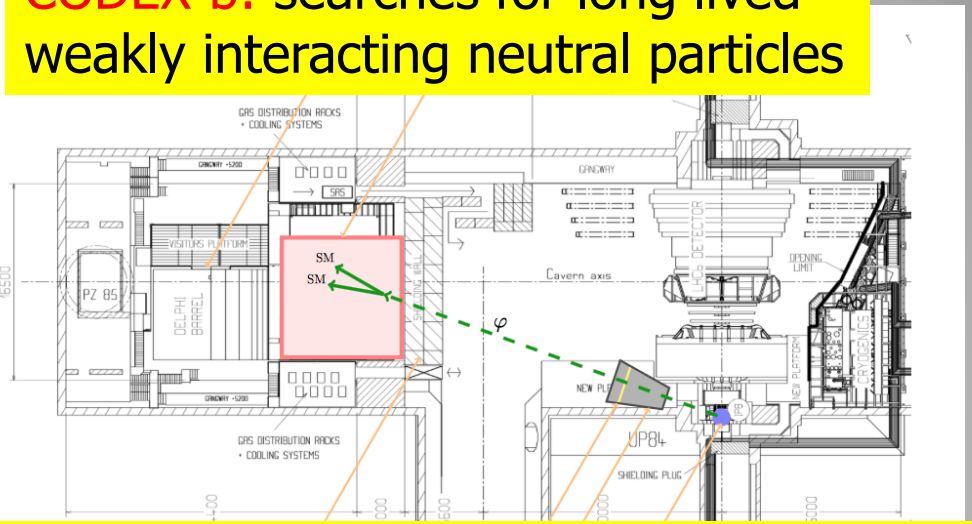


Proposals for New Experiments @LHC

MilliQan: searches for millicharged particles
MAPP: Similar to MoEDAL

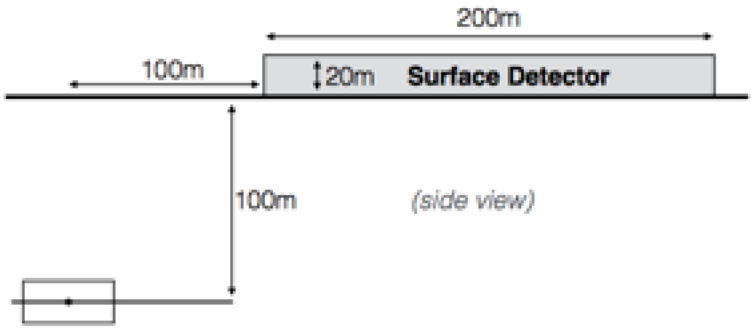


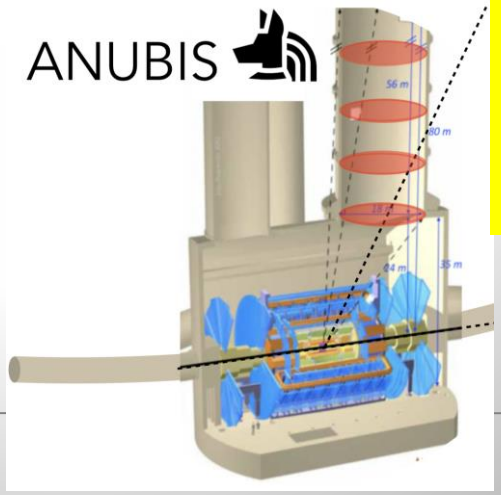
CODEX-b: searches for long lived weakly interacting neutral particles



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

MATHUSLA: searches for long lived weakly interacting neutral particles

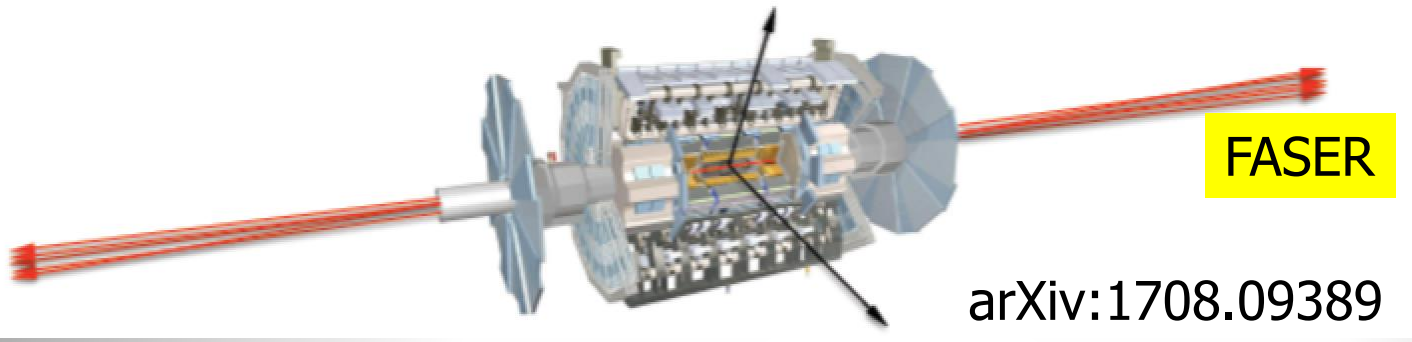


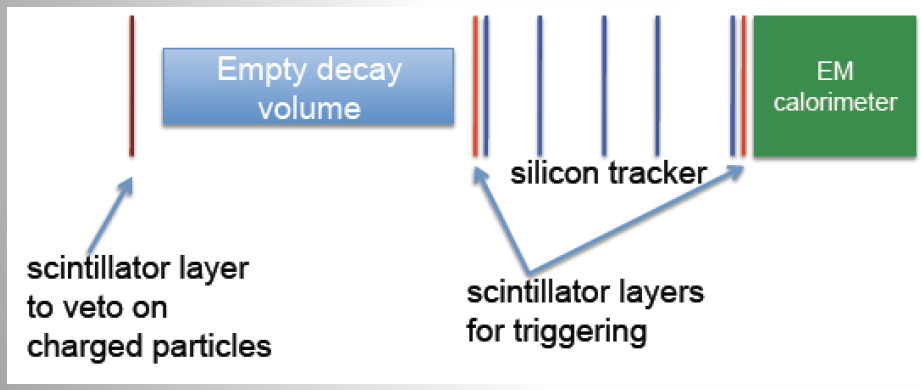


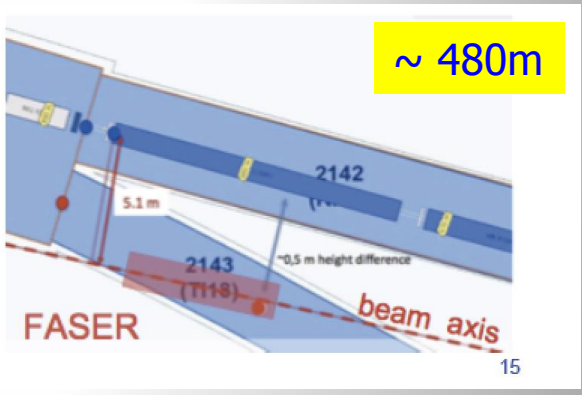
ANUBIS: searches for long lived weakly interacting neutral particles

+ Experiment Proposals for TeV neutrinos

FASER Experiment



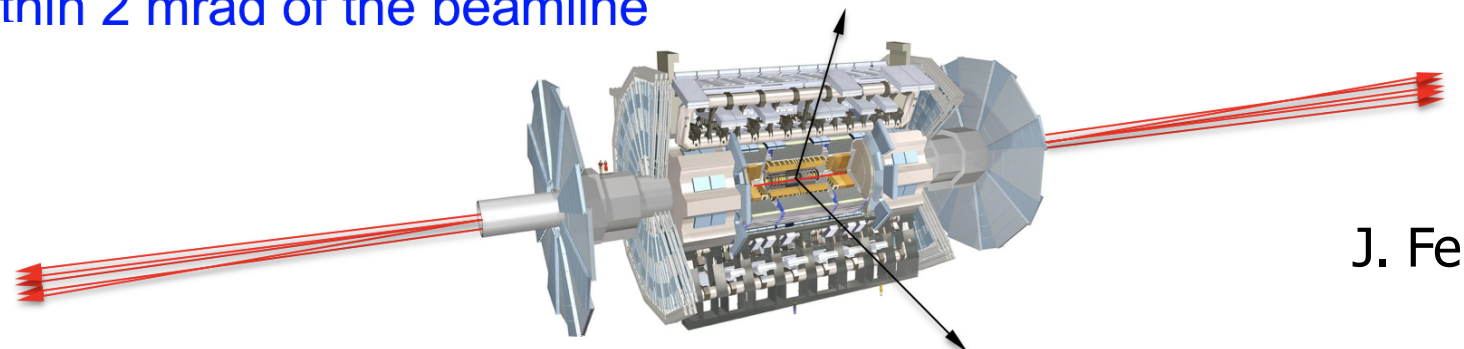




- FASER has significant discovery potential for dark photons dark Higgs bosons, heavy neutral leptons (sterile neutrinos), ALPs, other gauge bosons, and many other new particles.

FASER: The Idea

- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles
  - σ ~ fb to pb → N_{events} ~ 10^3 – 10^6, produced ~isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided
  - Light → we can produce them in π, K, D, B decays
  - Weakly-interacting → need extremely large SM event rate to see them
- Conclusion: we should go where the pions are: at low p_T along the beamline
  - σ_{inel} ~ 100 mb → N_{events} ~ 10^{17}, and 10% of the pions are produced within 2 mrad of the beamline



J. Feng

FASER Approval

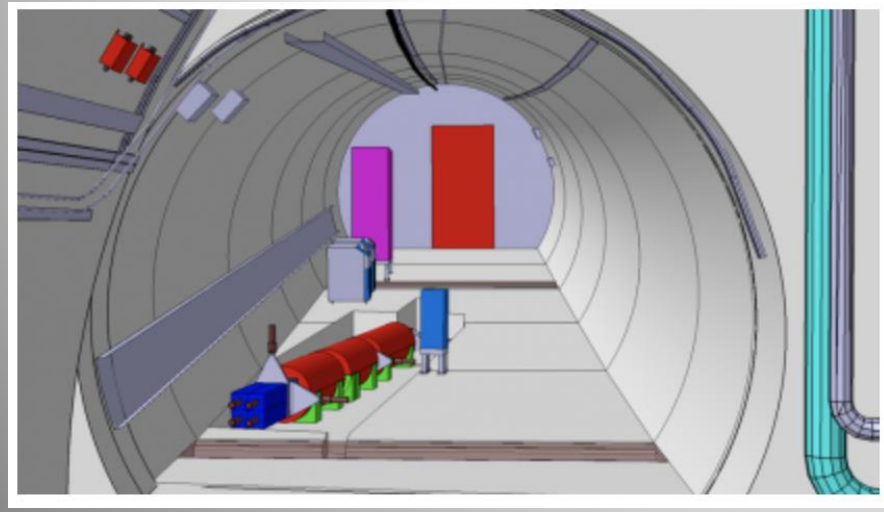
The FASER experiment (phase-I) has been approved March 5th

INTERACTIONS.ORG
PARTICLE PHYSICS NEWS AND RESOURCES

FASER: CERN approves new experiment to look for long-lived, exotic particles

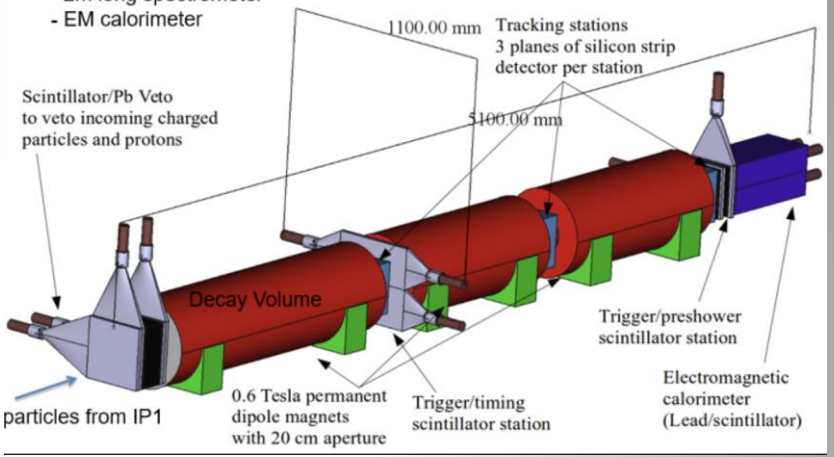
Date Issued
March 5th, 2019

FASER is the 8th LHC experiment



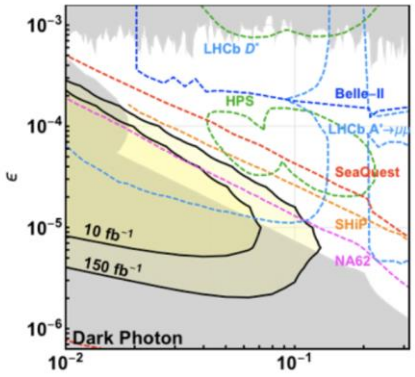
THE FASER DETECTOR

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



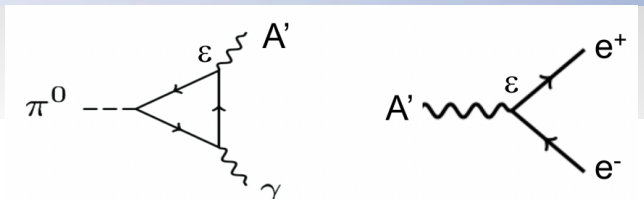
EXPECTED SENSITIVITY

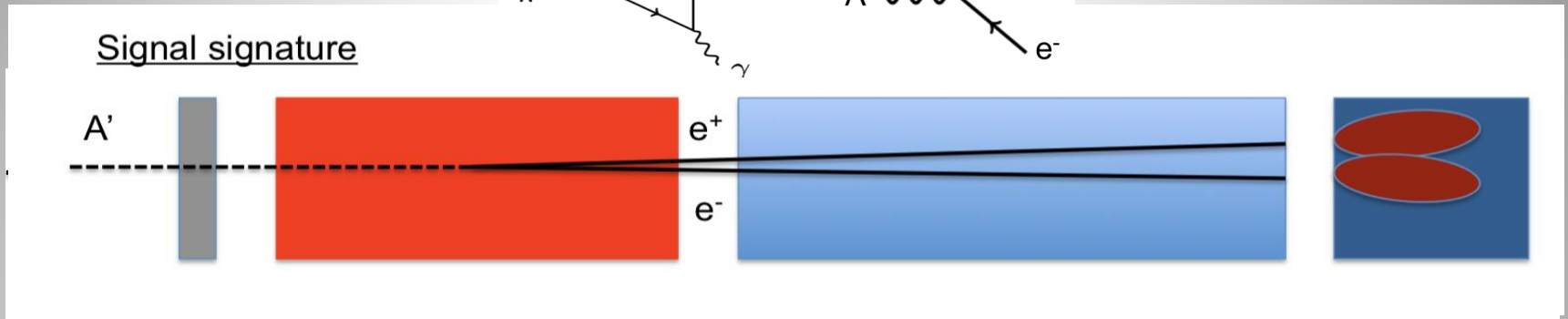
- Sensitivity for dark photons
  - Assuming no background and 100% signal efficiency
  - Curves only slightly effected by O(1) changes in efficiency



Even with 10/fb (to be collected by end of 2021?) have sensitivity to uncharted territory.
With full Run 3 dataset (150/fb) significant discovery potential.

Dark Photon Detection





- The signal is spectacular: 2 ~TeV-energy, oppositely-charged tracks originating in the decay volume and pointing back to IP
- Initial scintillators: veto entering tracks
- Tracker: detect charged tracks
- Magnets: separate the 2 charged tracks sufficiently to resolve them in the tracker

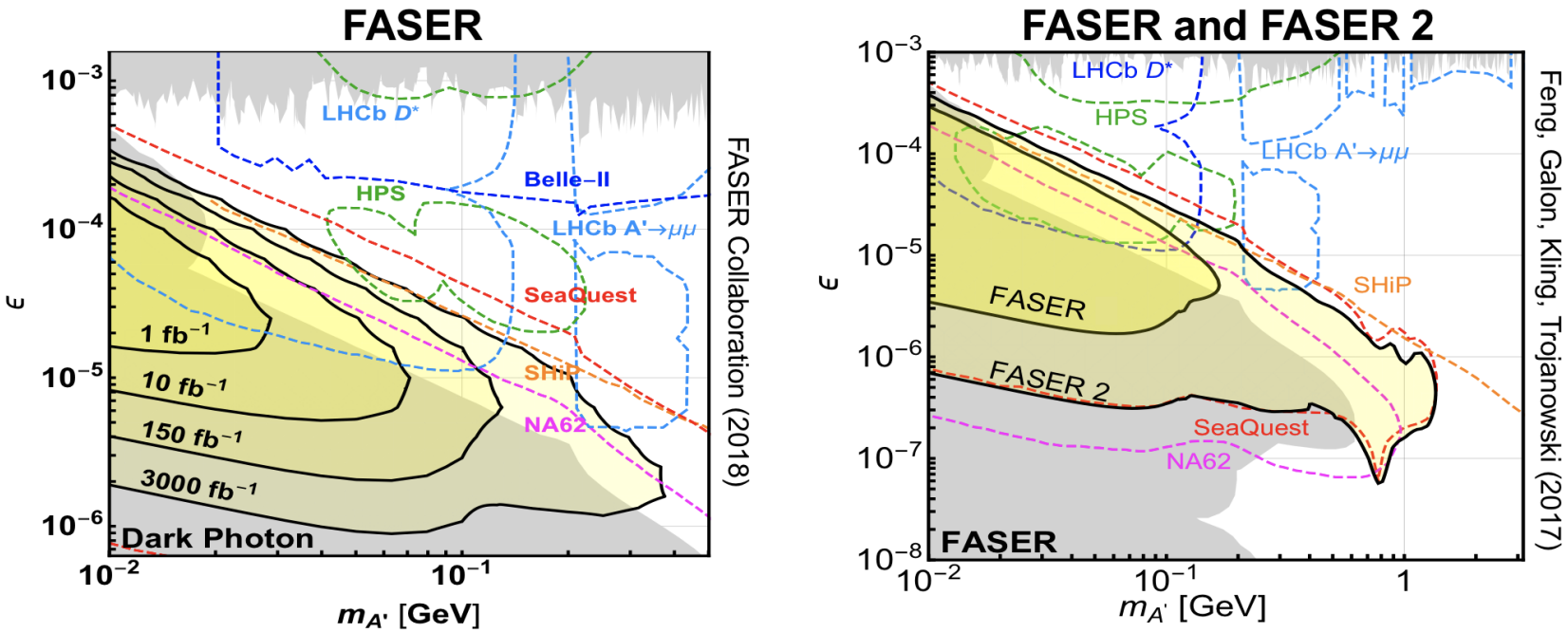
$$h_B \approx \frac{ec\ell^2}{E}B = 2\ \text{mm}\ \left[\frac{1\ \text{TeV}}{E}\right]\left[\frac{\ell}{3\ \text{m}}\right]^2\left[\frac{B}{0.6\ \text{T}}\right]$$

- Calorimeter: differentiate e from μ, detect γ, measure energy

Dark Photon Sensitivity Reach

FASER should be completed before run-3 starts
FASER 2 still needs approval

- FASER: R=10cm, L=1.5m, Run 3; FASER 2: R=1m, L=5m, HL-LHC

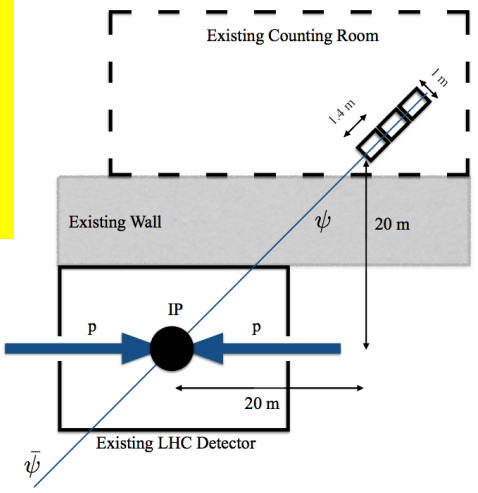


- FASER probes new parameter space with just 1 fb^{-1} starting in 2021

- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by ~10^6

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

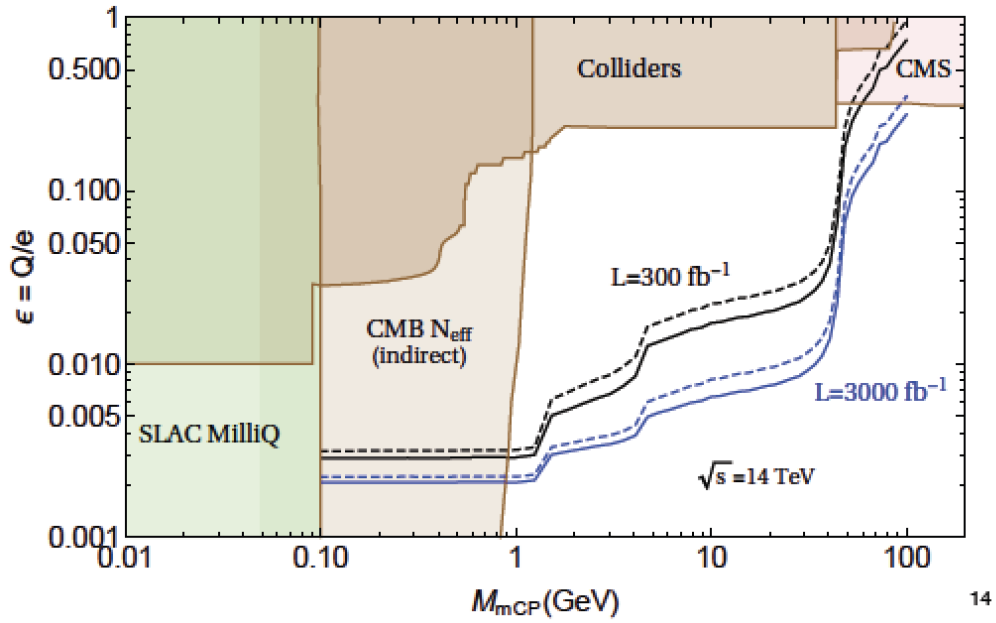


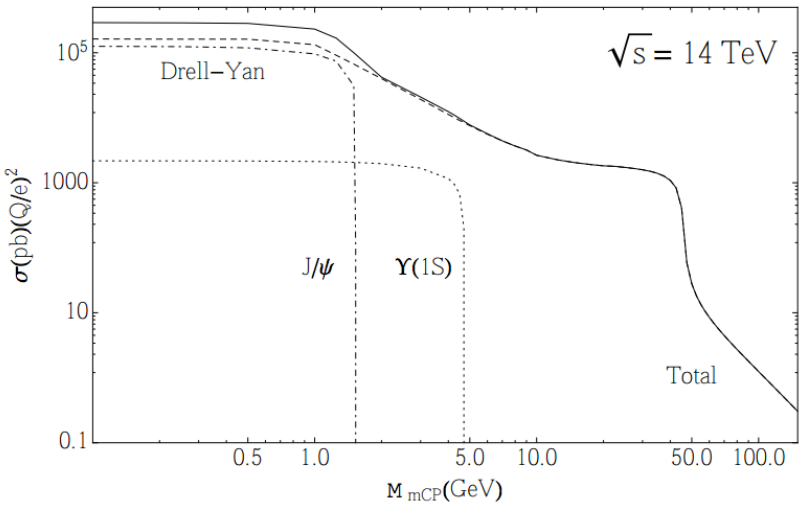
A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

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

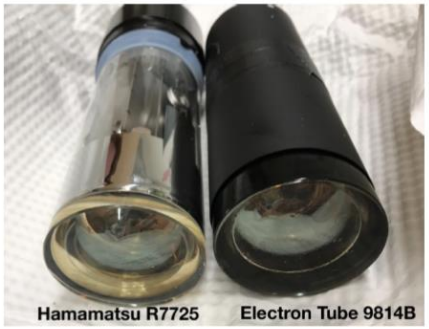


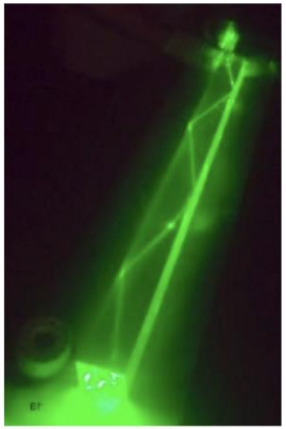


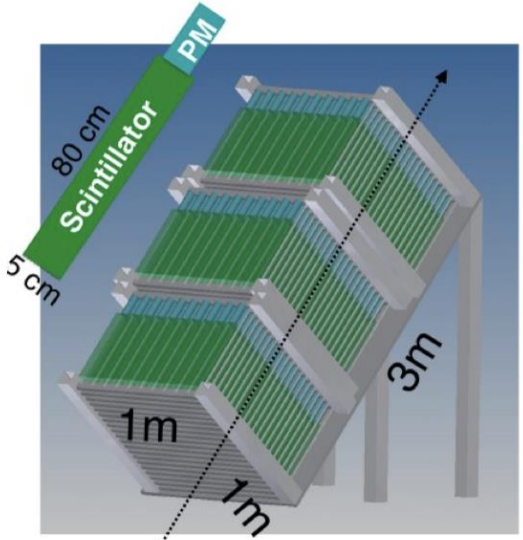
MilliQan Experiment

milliQan detector principle

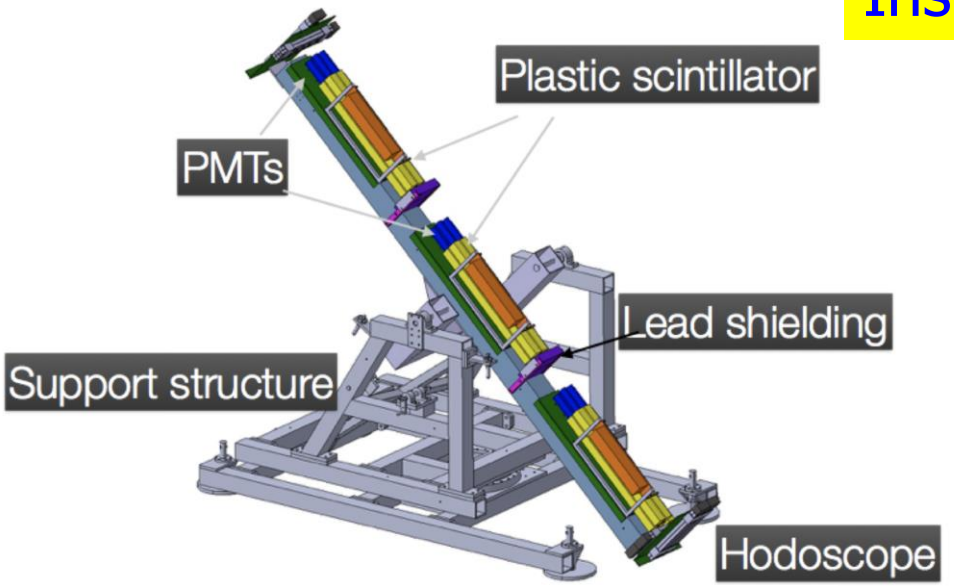
- concept: arXiv:1410.6816; LOI: arXiv:1607.04669
- basic element is 5x5x80 cm^3 plastic scintillator
- attached to photomultiplier tube
- 1x1x3 m^3 in 3 length-layers
- search coincidence of few photons in consecutive scintillators pointing to IP





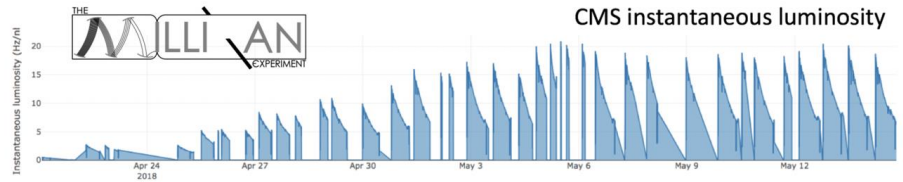


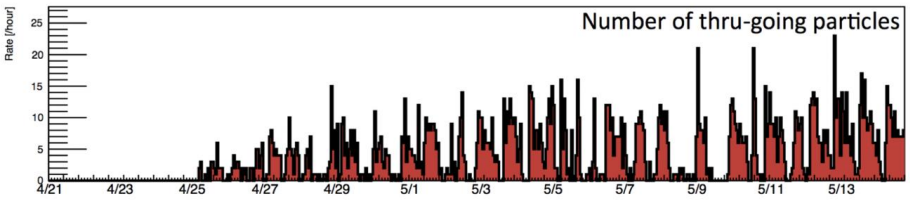
MilliQan Experiment



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT

Installed demonstrator in 2017





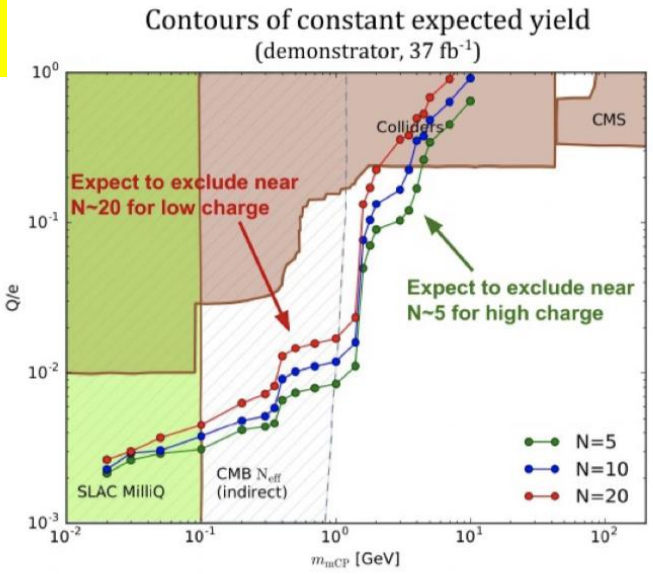
- Took data since September 2017
  → ~37 fb^{-1} of data on tape
- Data well understood!
- First physics paper in preparation

MilliQan Experiment

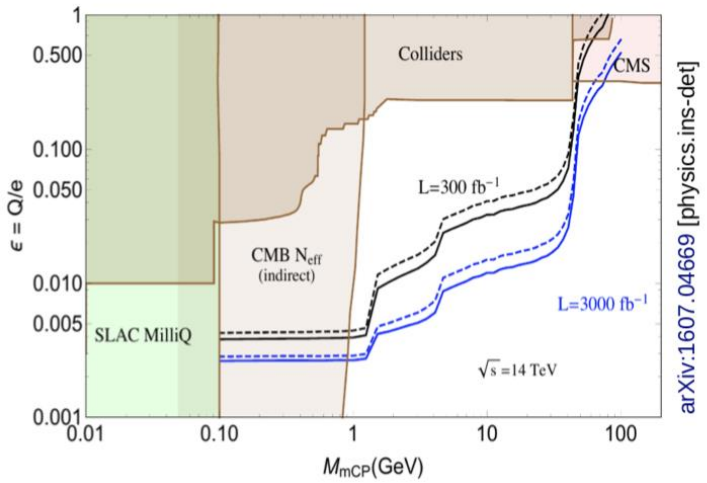
Sensitivity

Projections using the 1% demonstrator and the full detector

- demonstrator analysis coming along
- preview:
  expected limits versus number of B
  - expect to exclude along red line for low charge
  - expect to exclude along green line for high charge
- expect new sensitivity already with demonstrator data



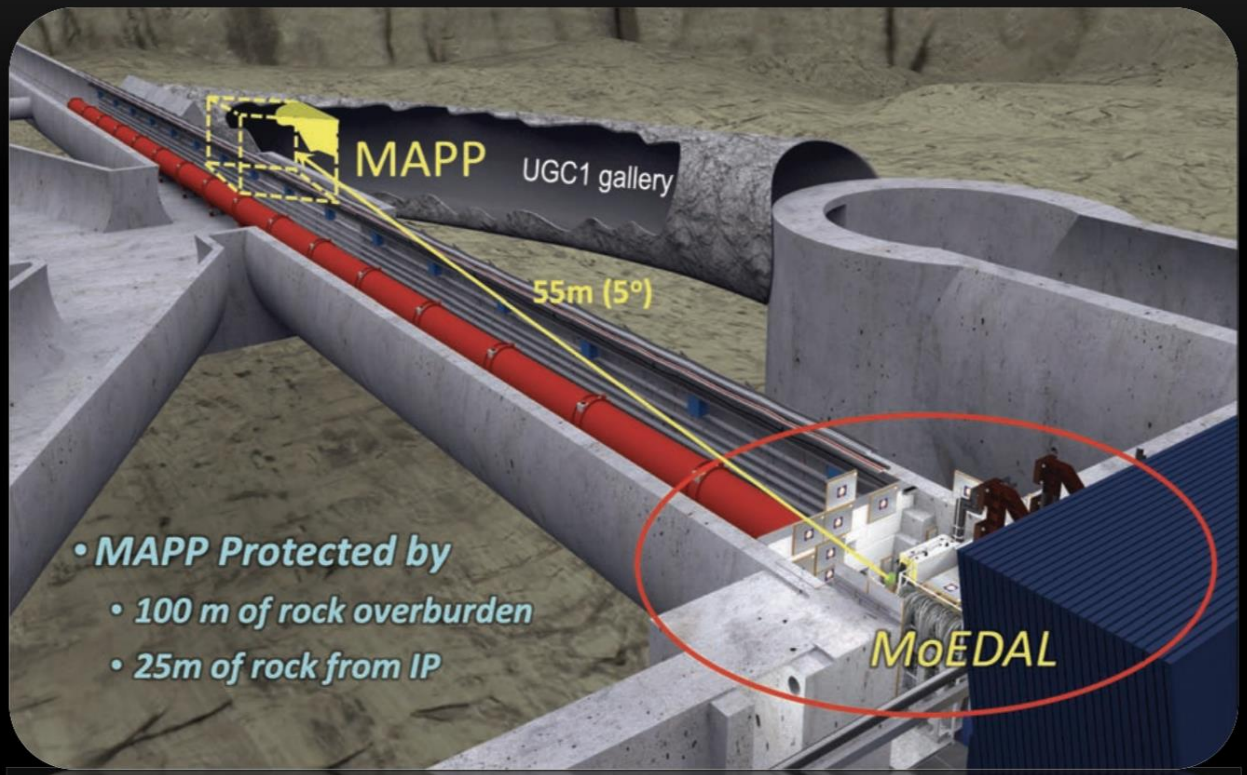
- old background estimate in LoI:
  - 165 events in Run-3 (300/fb)
  - 330 events during HL-LHC (3000/fb)
- update soon

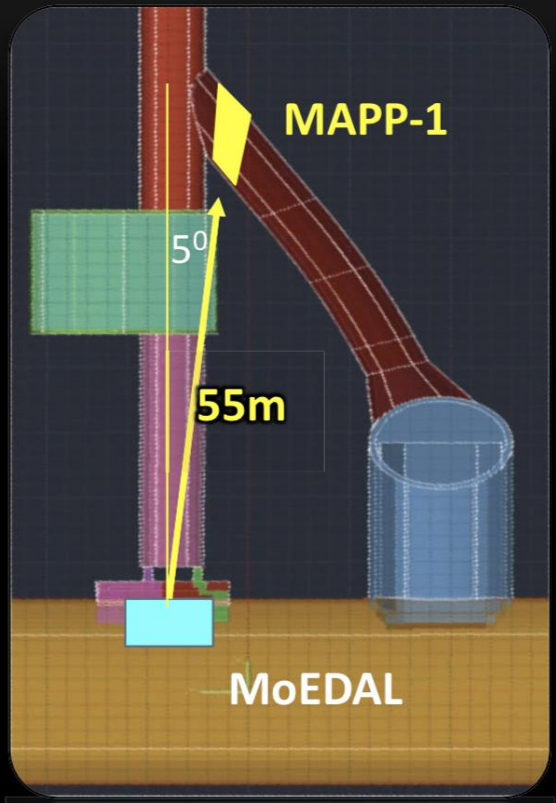


Demonstrator results paper in preparation

MAPP-1 – MoEDAL Upgrade for RUN-3

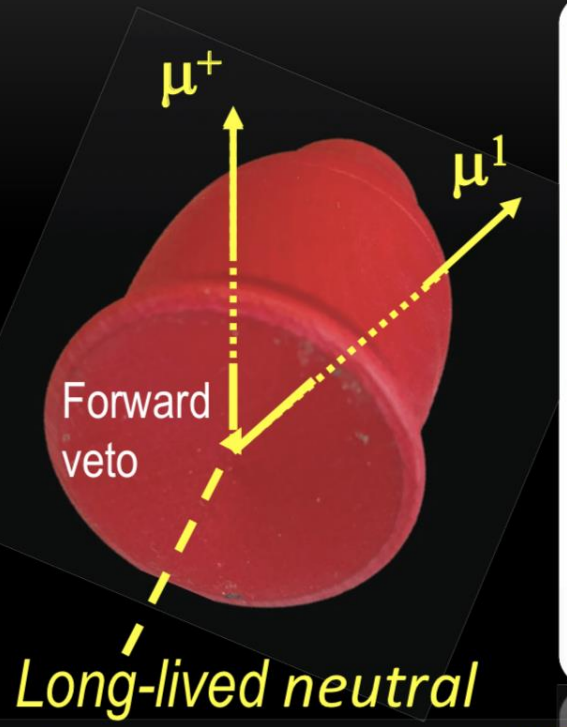
(MoEDAL Apparatus for Penetrating Particles)



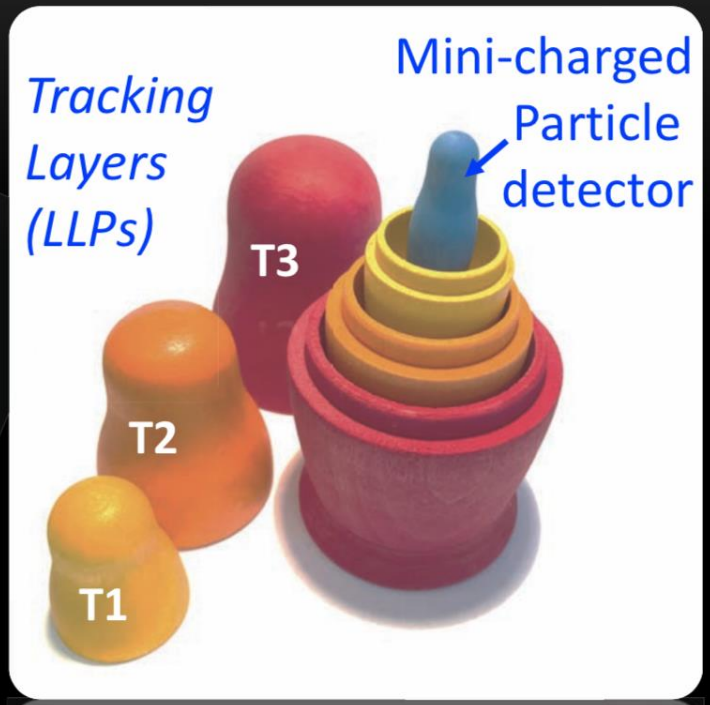


- *MAPP (to be installed for Run-3 of the LHC) has 2 motivations*
  - *To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge around e ≥ 1/3)*
  - *To search for new weakly interacting neutrals with long lifetime*

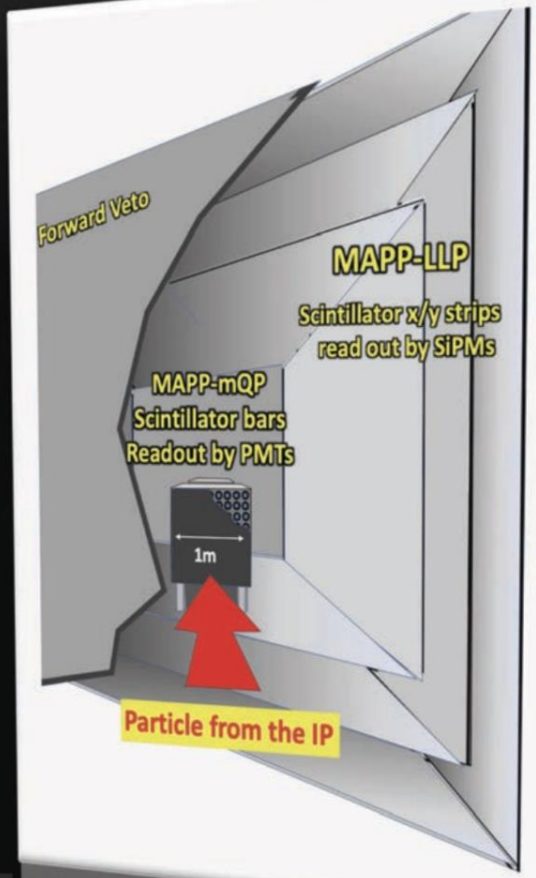
The MAPP Detector Concept



Long-lived neutral decay in MAPP



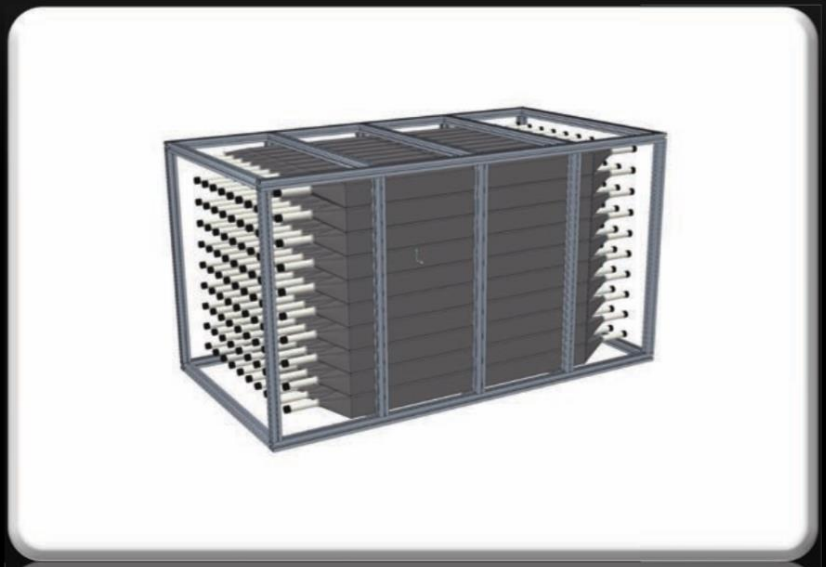
"Russian Doll" configuration

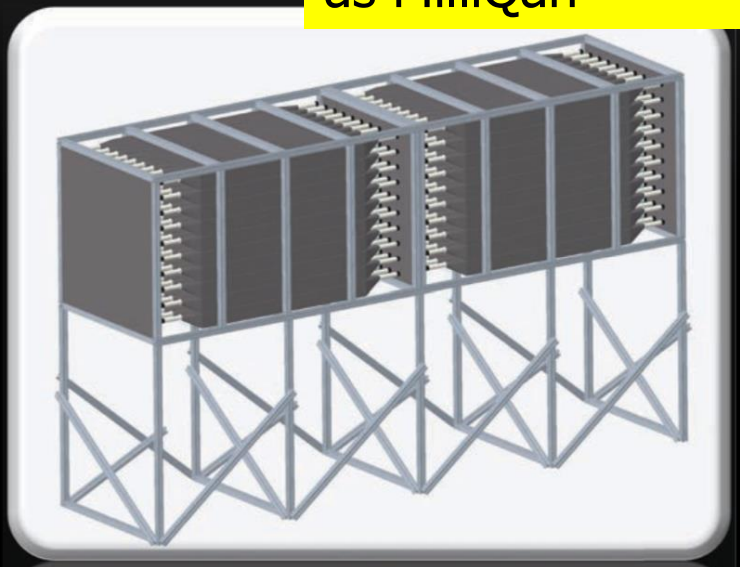


- The MAPP detector is comprised of two parts:
  - The Long-lived particle (MMP-LLP detector) that consists of three X/Y scintillator hodoscope layers in a nested "Russian Doll" configuration (tracking eff. ~ 80%/trk)
  - A central mini-charged particle detector (MMP-mCP)

The MAPP Mini-charged Particle Detector (MAPP-mCP)

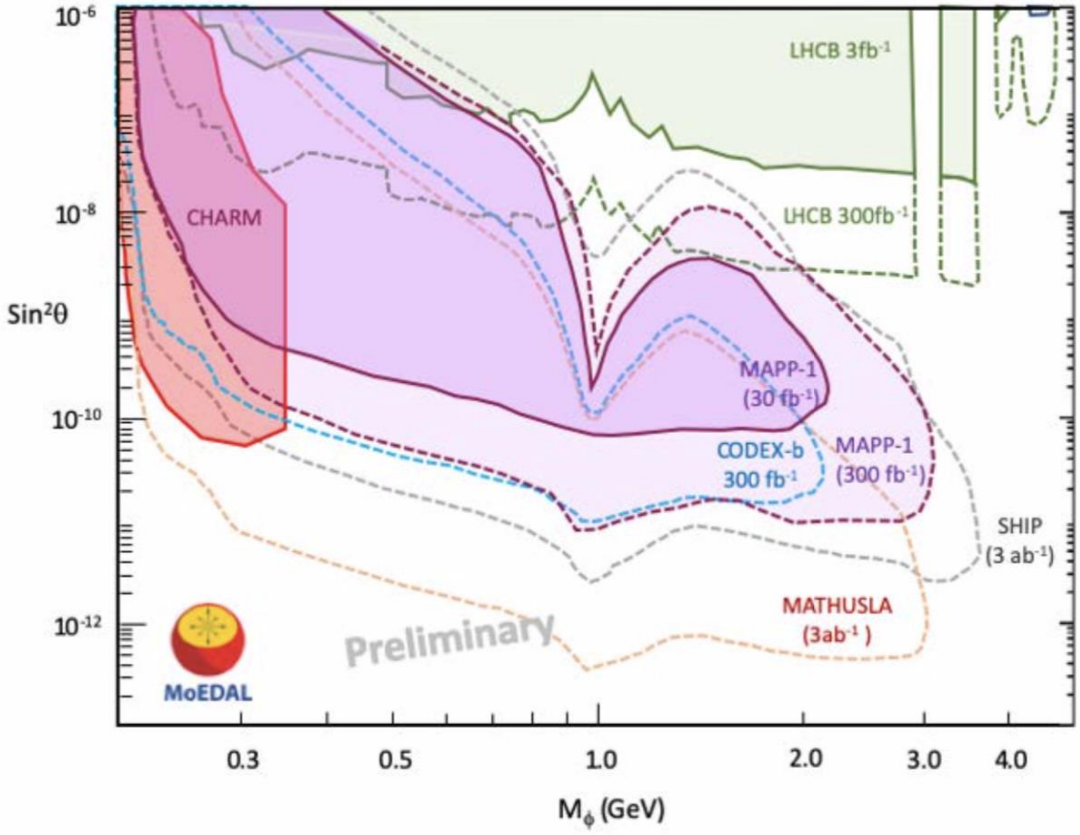
Similar acceptance as MilliQan





- Central Milli-Charged (mQP) Detection Sections:
  - 100 x (10cm x 10cm x 75cm) scintillator bars in 4 lengths, 2 lengths/section readout by 4 low noise 3.1" PMTs, in coincidence
  - No background from dark counts and radiogenic backgrounds
  - Protected from cosmics by 100m of rock overburden + surrounding active veto system (not shown)
  - Protected by 25-26m of rock/concrete (~65 Nuclear Interaction Lengths) from SM particles from the Intercation Point)

Example of MAPP Sensitivity for LLPs



The figures shows MAPP's reach for 30 fb^{-1} and 300 fb^{-1} for the scenario where a Higgs mixing portal admits exotic inclusive $B \rightarrow Xs\phi$ decays, in which φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$

No documentation avaialble yet.

- *We envisage the full MAPP detector will operate in RUN-3 (2021-24)*
  - *Our max. fid. eff. for $B \rightarrow X_s\phi$ is ~ 5 x 10^{-4}*
  - *For comparison 100% tracking efficiency is assumed with no background.*

MATHUSLA

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

arXiv:1811-00927

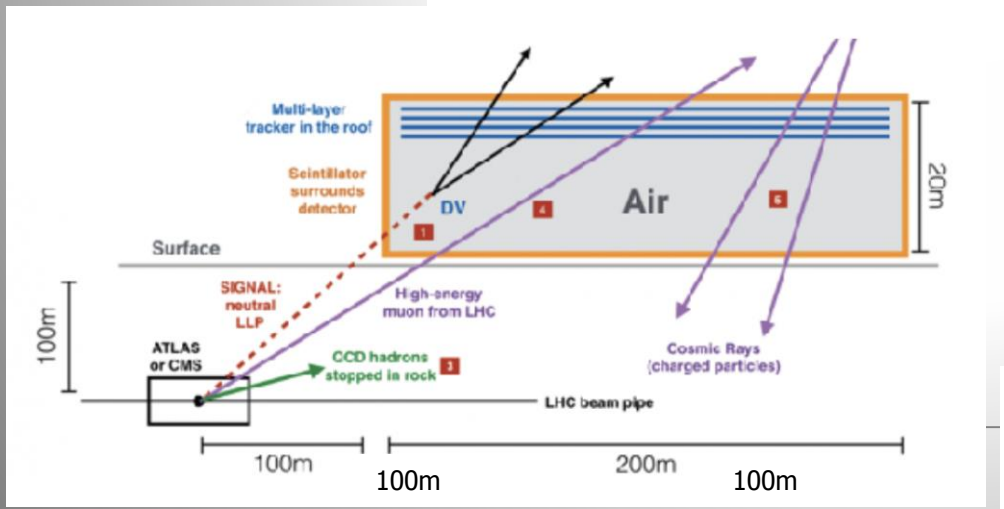
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

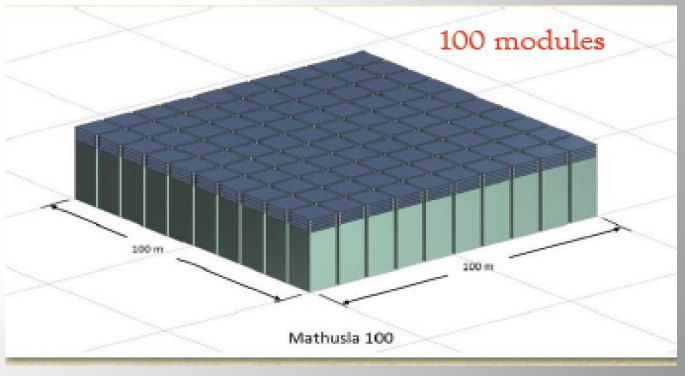
Aim to cover the range

$$c\tau \lesssim 10^7 - 10^8 \text{ m},$$

~ BBN constrained inspired

Physic case arXiv:1806.07396



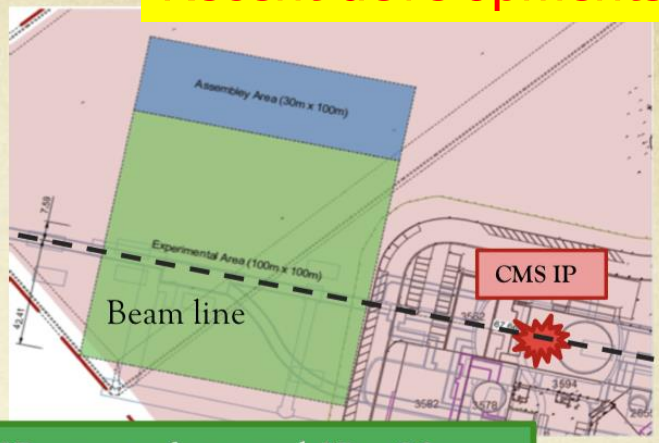


Detector surface array eg above ATLAS or CMS: ~ $(200\text{m})^2$

MATHUSLA @ P5

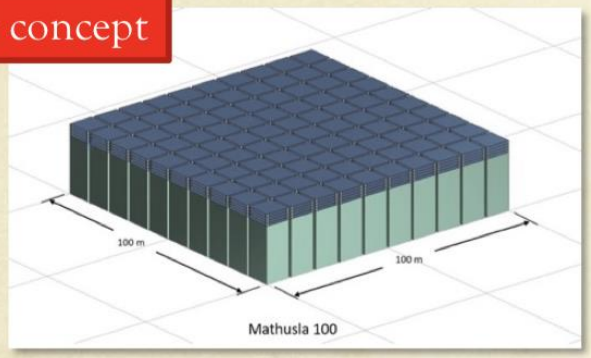
Recent developments

- Worked with Civil Engineers to define the **building and the layout of MATHUSLA at P5**
- **Layout restricted by existing structures** based on current concept and engineering requirements

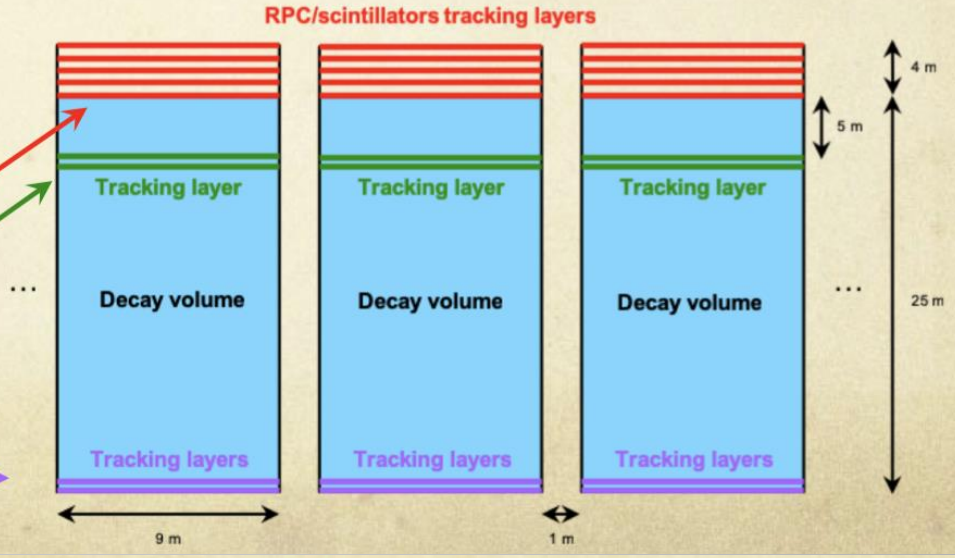


- 68 m to IP on surface and IP ~80m below surface
- ~7.5m offset to the beam line

Modular concept

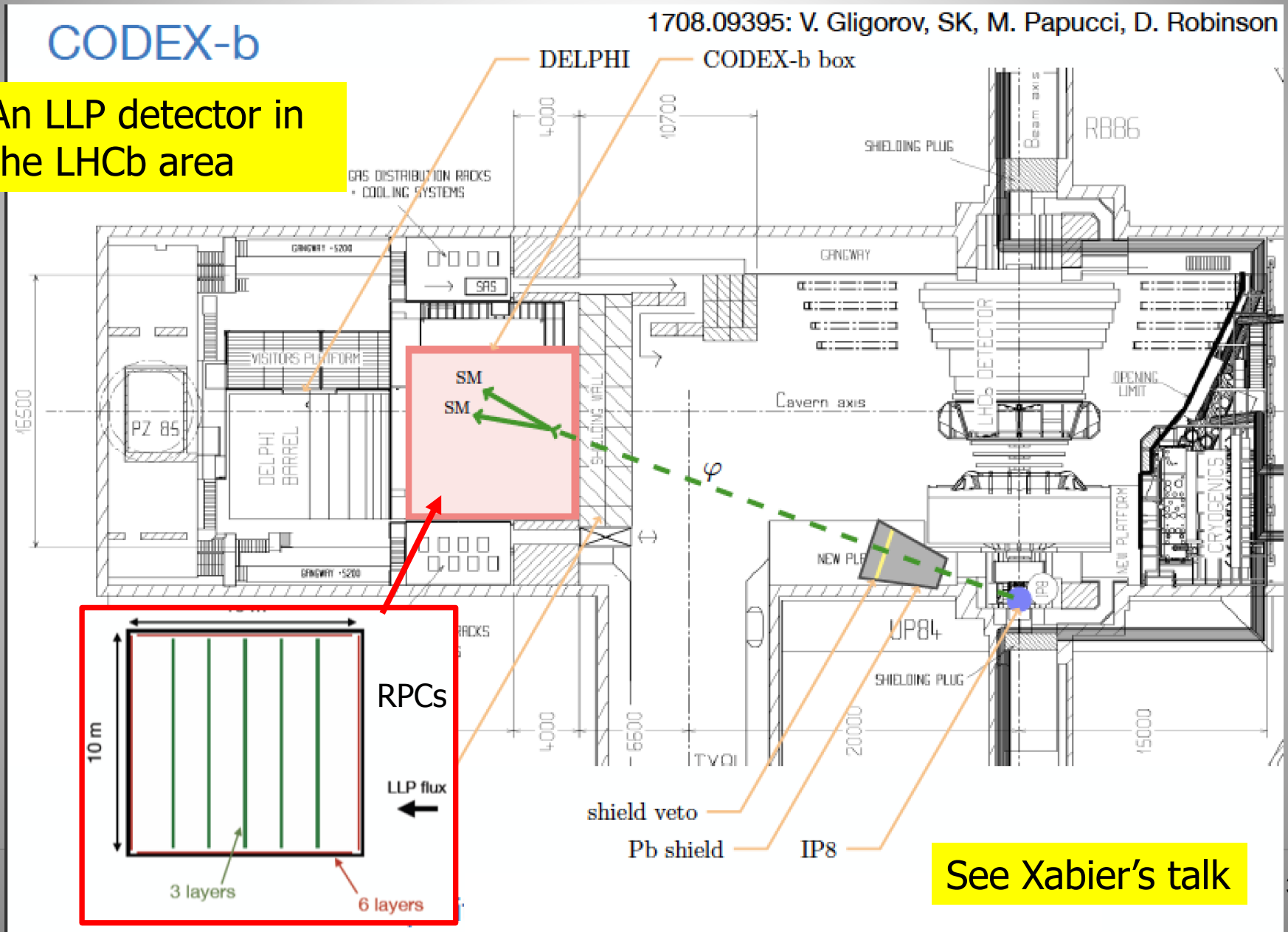


- Assume ~ 25 meter decay volume
- Individual detector units 9 x 9 x 30 m^3
- 5 layers of tracking/timing detectors separated by 1m
- Additional tracking/timing layer 5m
- Double layer floor detector (tracking/timing)



Goal to complete the Technical Design Report (TDR) by end 2020

CODEX-b Proposal

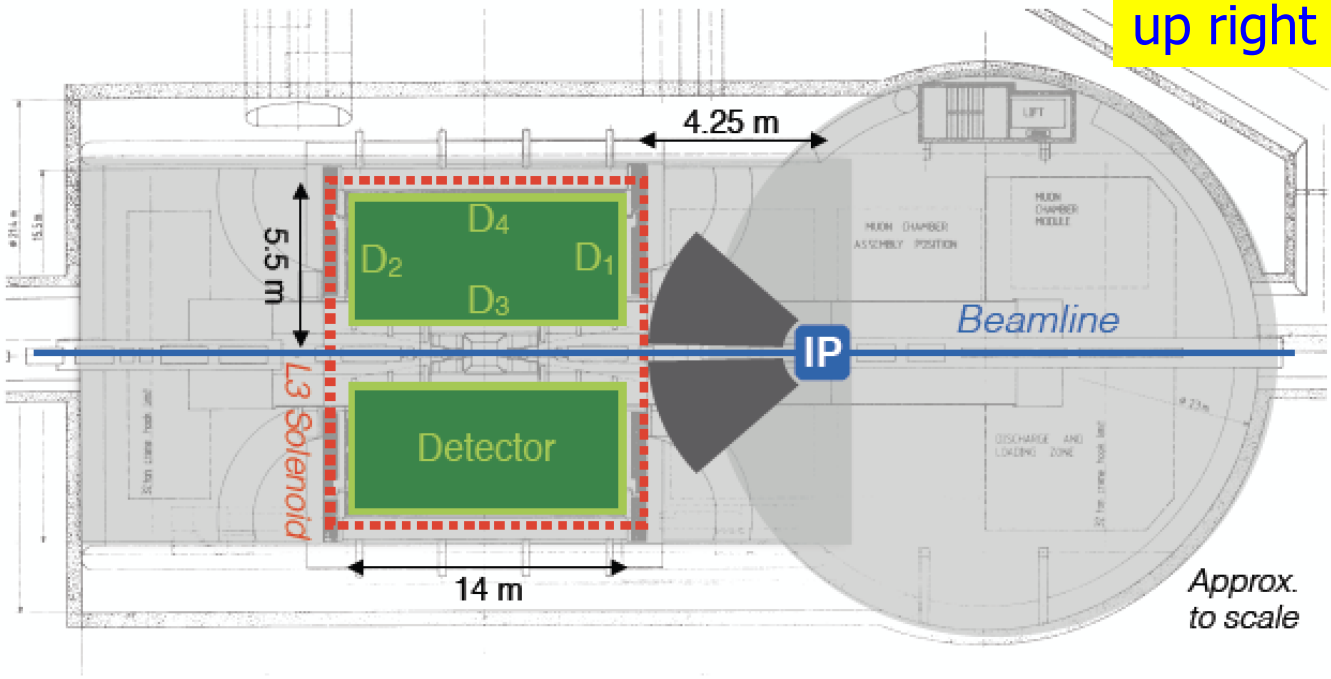


Re-using the ALICE detector?

A Laboratory for Long-Lived eXotics (AL3X)

For LHC Run 5??
So far just an idea
Not really followed up right now…

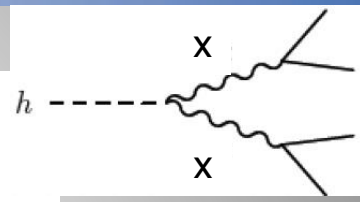
Reuse the L3 magnet and (perhaps) the ALICE TPC



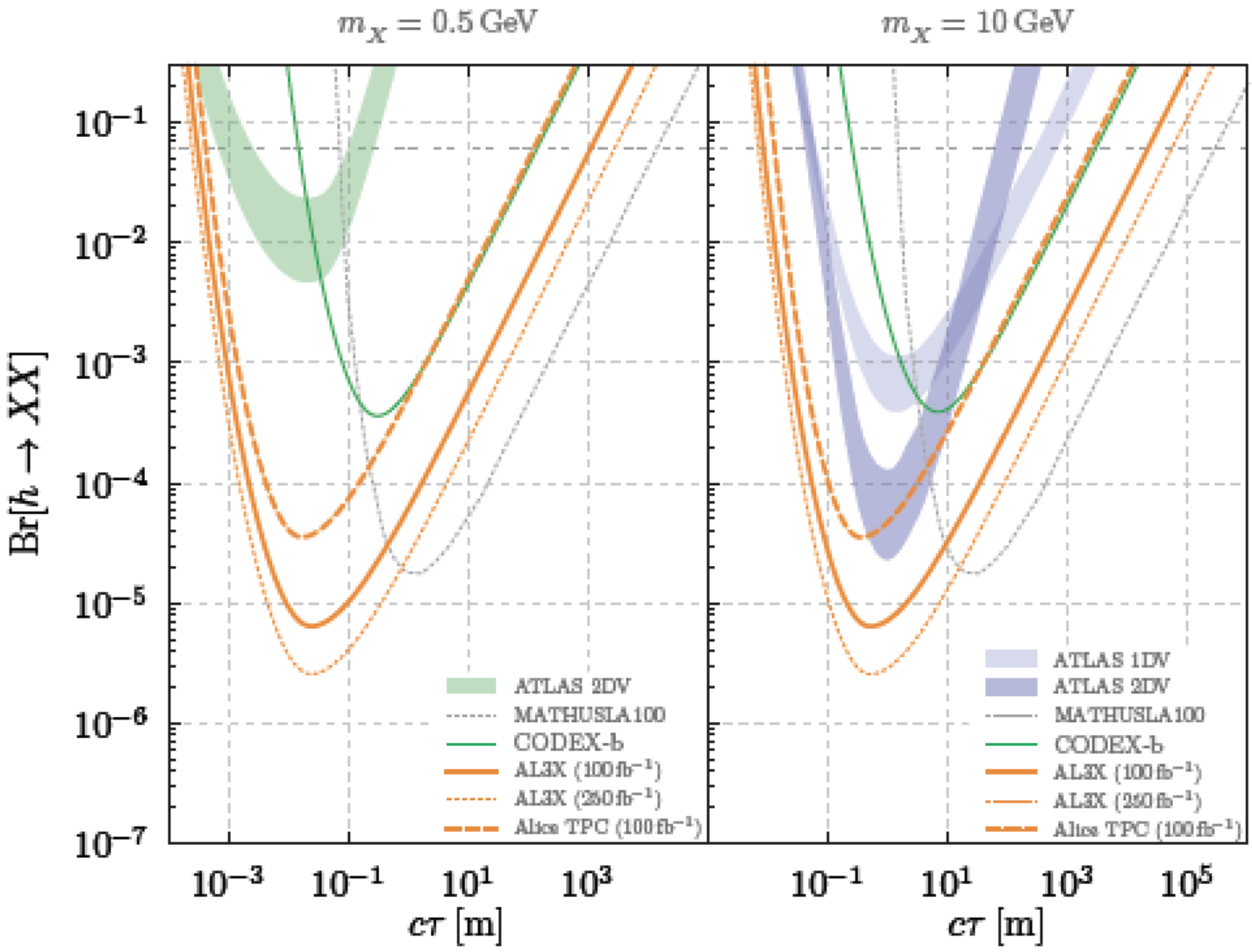
Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636

Physics Reach: Example

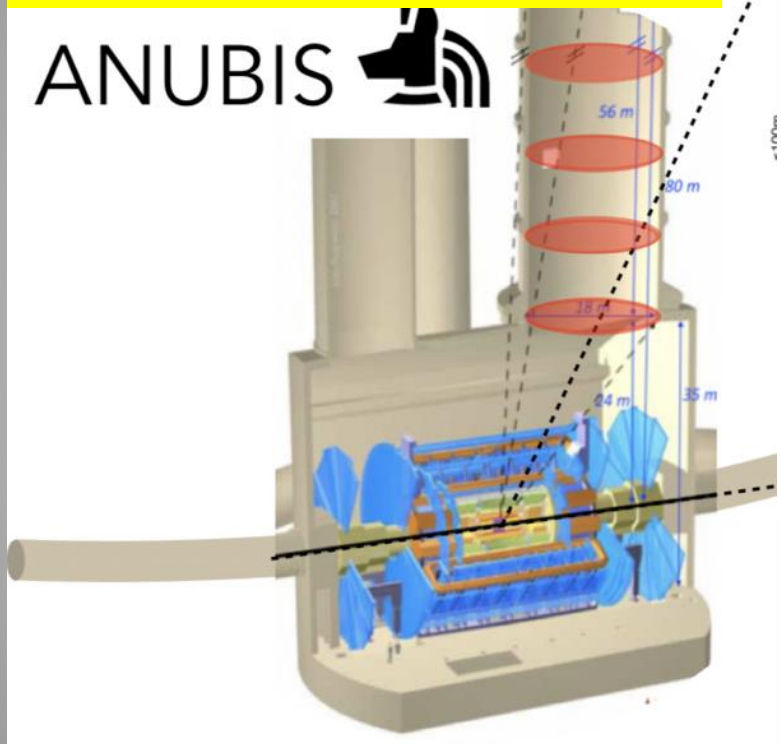


1810.03636



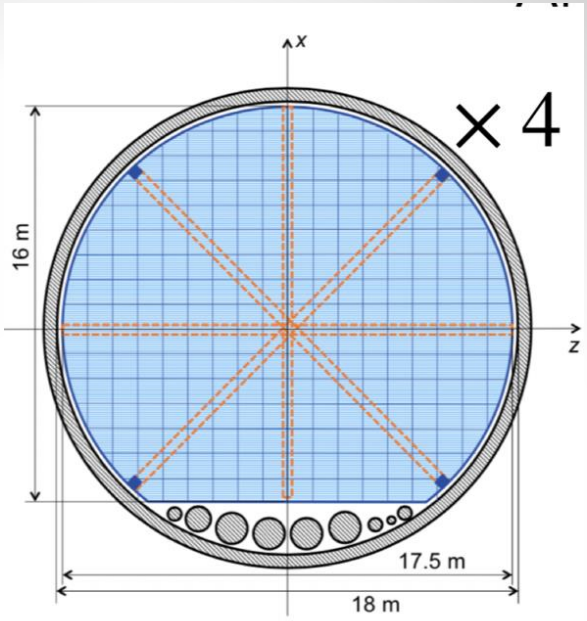
Proposals for New Experiments @LHC

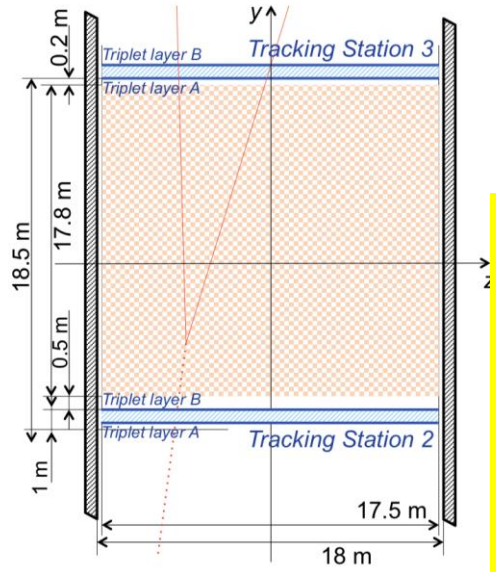
ANUBIS: searches for long lived weakly interacting neutral particles



We propose to instrument the ATLAS service shaft

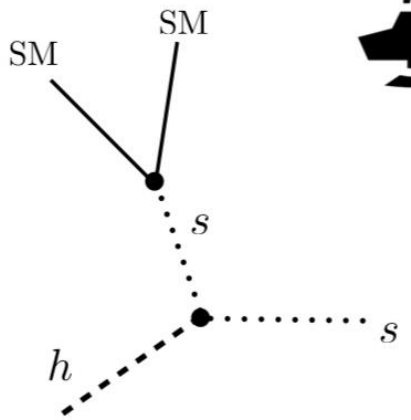
Bauer, OB, Lee, Ohm 1909.13022





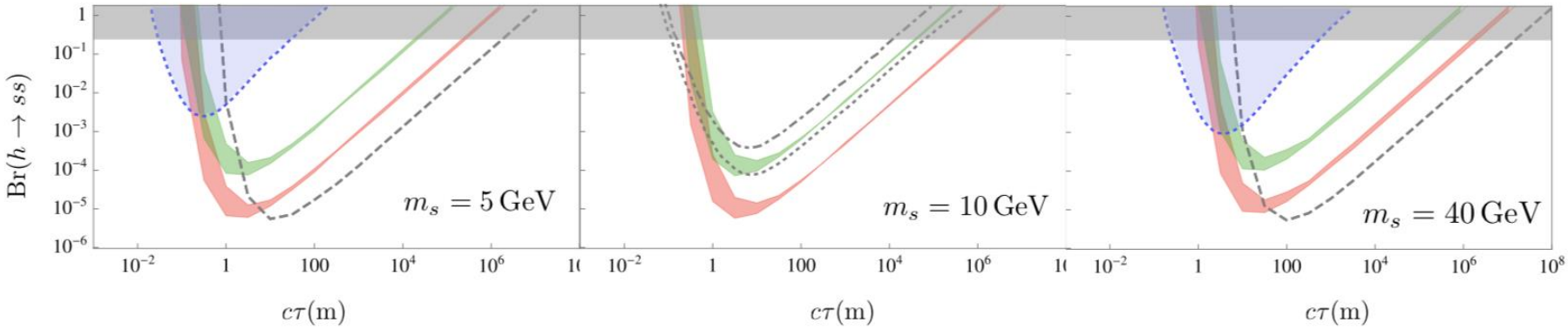
- 4 tracking stations of RPCs
- Propose to have $1x1m^2$ test set-up
- Could also be in the CMS shaft

ANUBIS



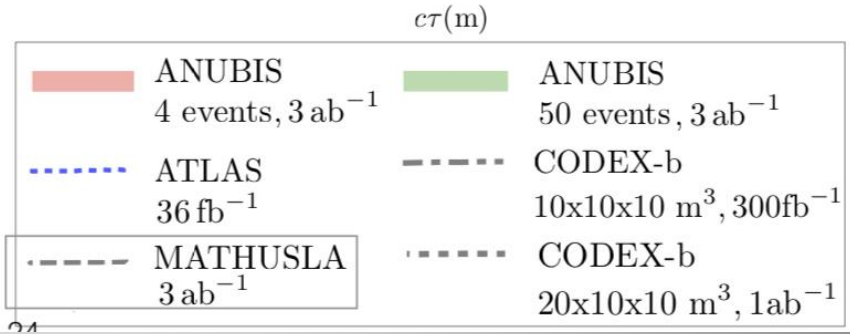
Sensitivity study for exotic Higgs decays

$$\mathcal{L} = \lambda s^2 H^\dagger H \qquad h \to ss, s \to \mathrm{SM\,SM}$$



arXiv:1909.13022

200 x 200 x 20 m³ decay volume →

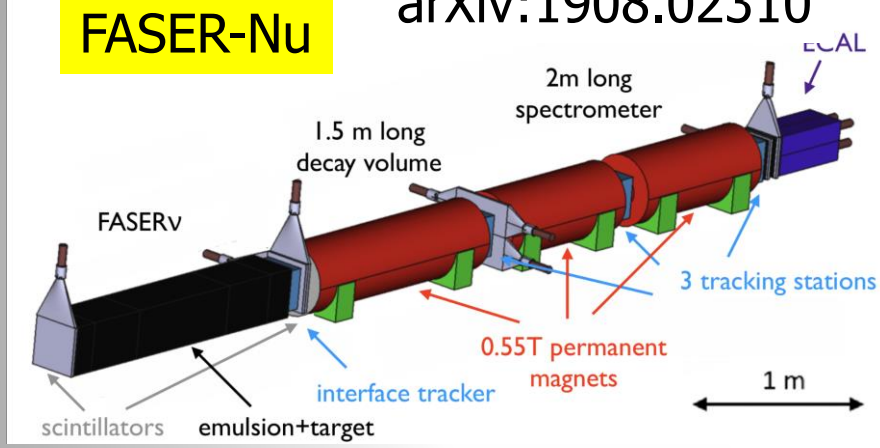


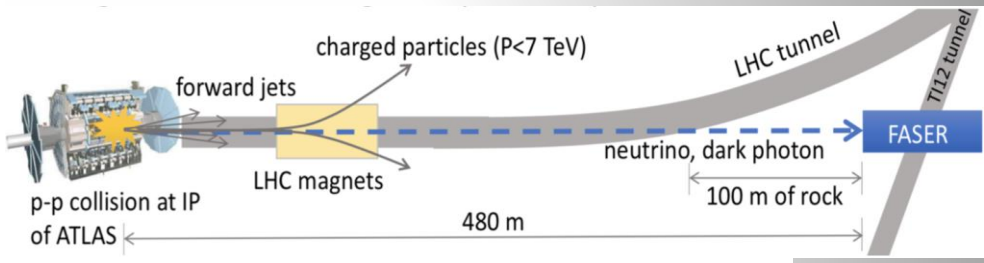
TeV Neutrinos at the LHC

No neutrinos at the LHC have been seen so far. Recent proposals for experiments 400m forward of the IPs to study TeV-neutrinos from forward meson decays with emulsion detectors: FASER-Nu and XSEN

FASER-Nu

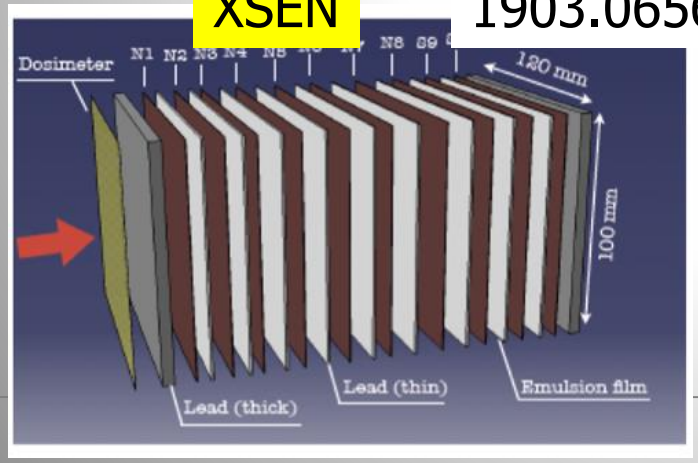
arXiv:1908.02310

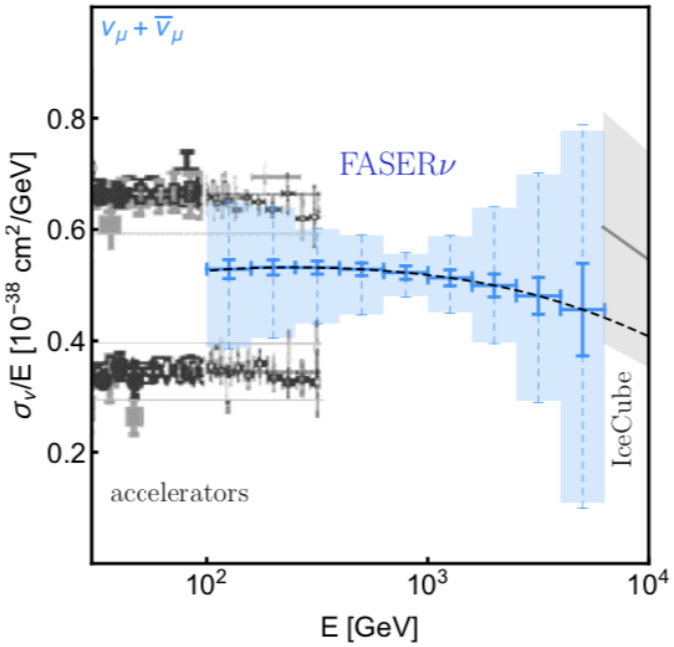




XSEN

1903.06564

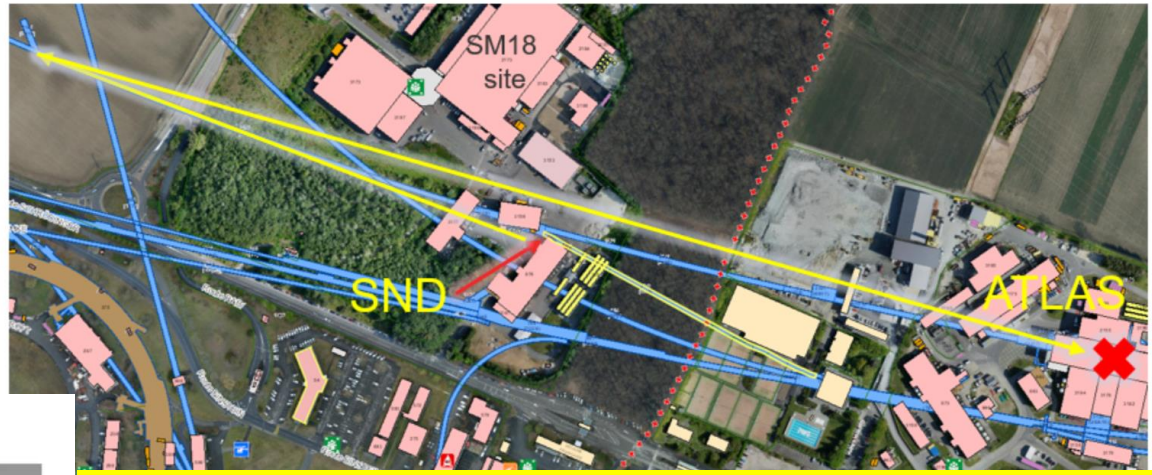




SND@LHC: LHC neutrinos

Proposal (LOI) prepared for the LHCC this week
SND= Ship Neutrino Detector

Aim for :
-Test run in 2021
-Full run in 2022 +..



Some acceptance Light Dark Matter etc..

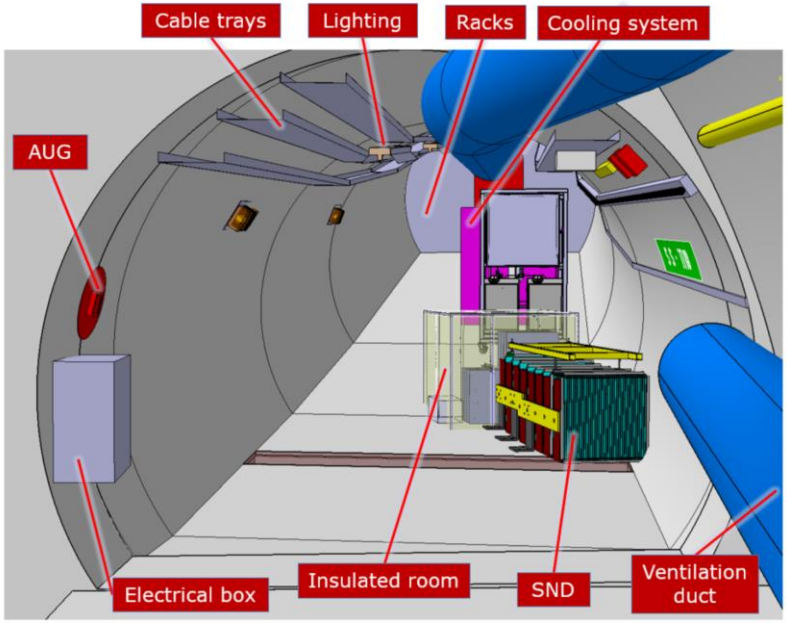
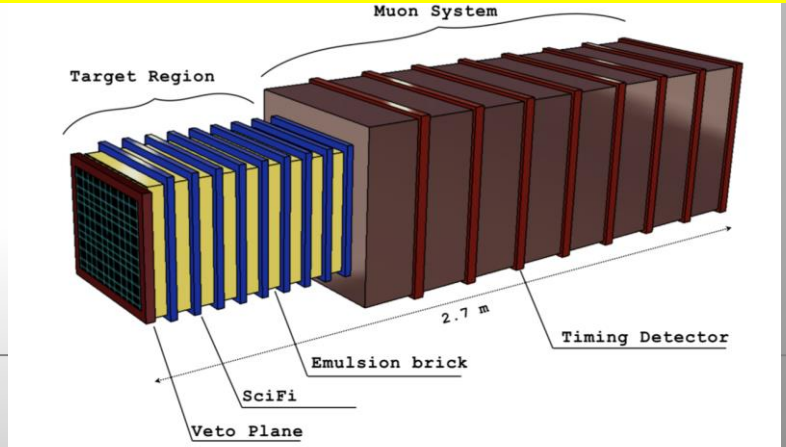


Figure 16: SND integration inside TI18

Target: Nuclear emulsion/lead +SciFi tracker
Bulk: muon system+timing detector

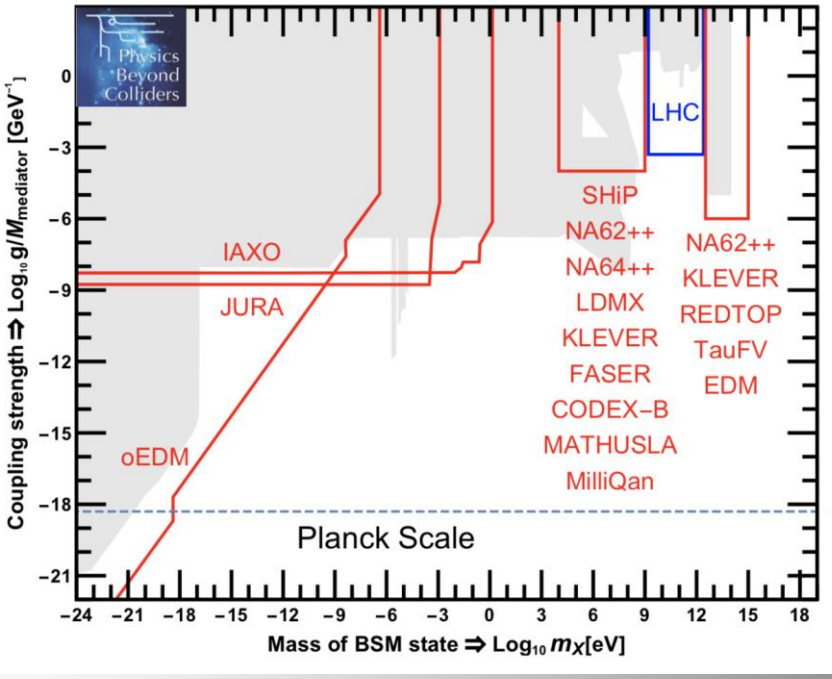


Physis Beyond Colliders

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

arXiv:1901.09966

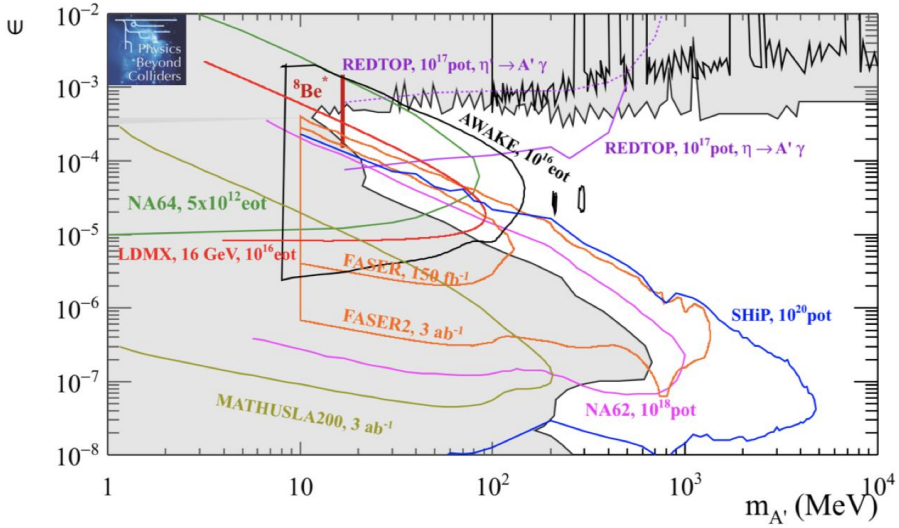
J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].



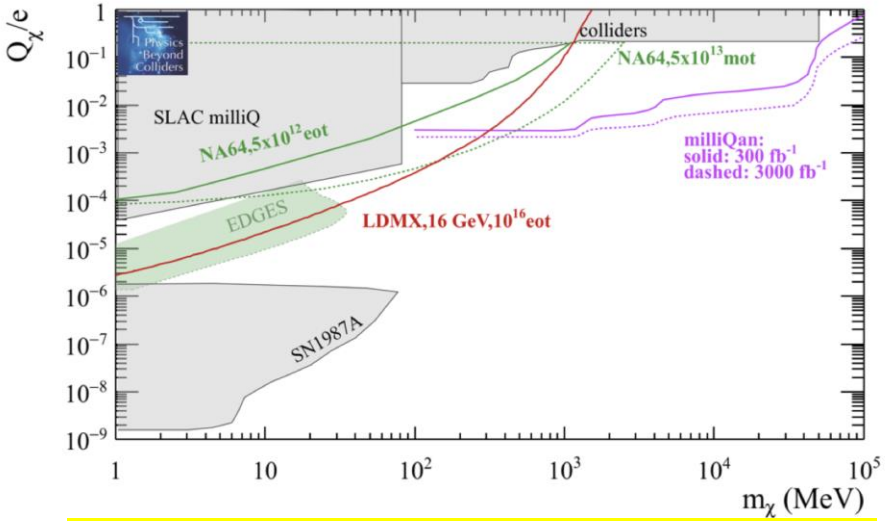
Summarize sensitivities of experiments now and for the next 10-15 years

Sensitivity Summaries

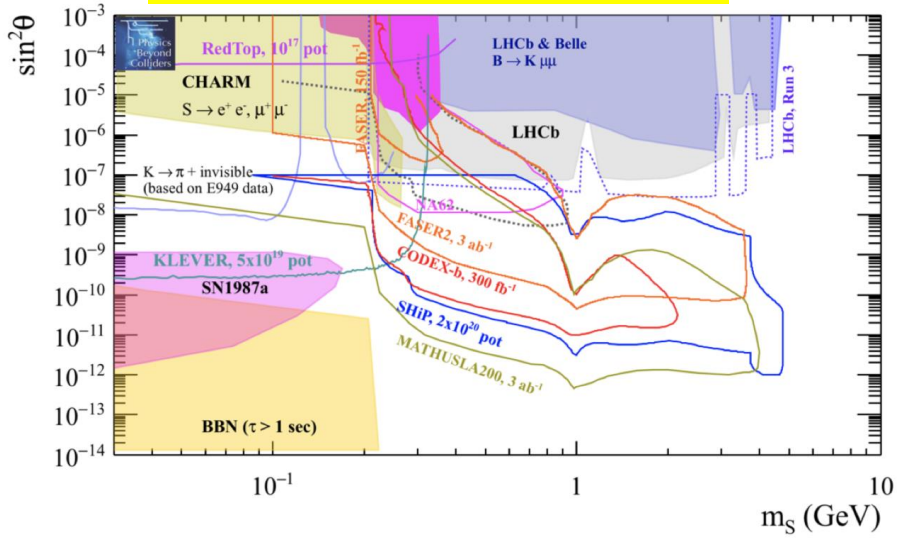
Search for dark photons (visible mode)



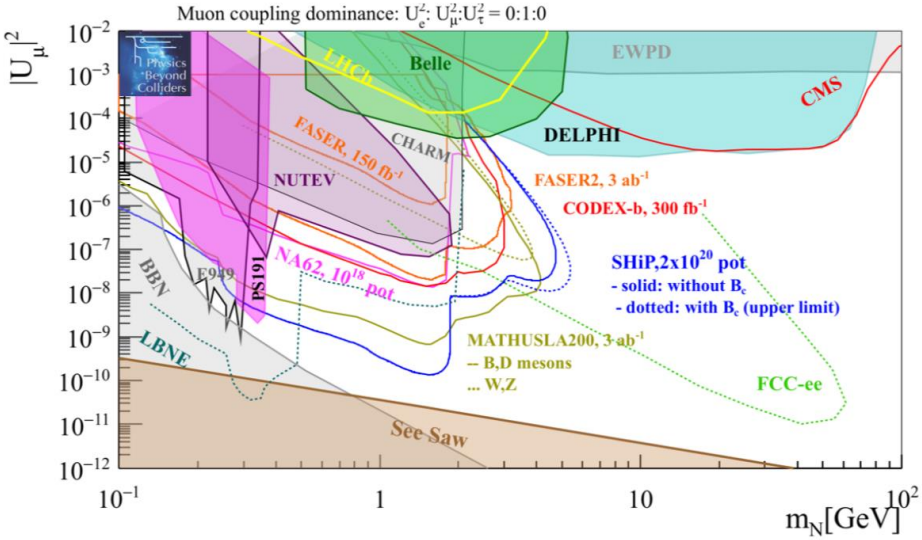
Search for millicharges



Search for dark scalars

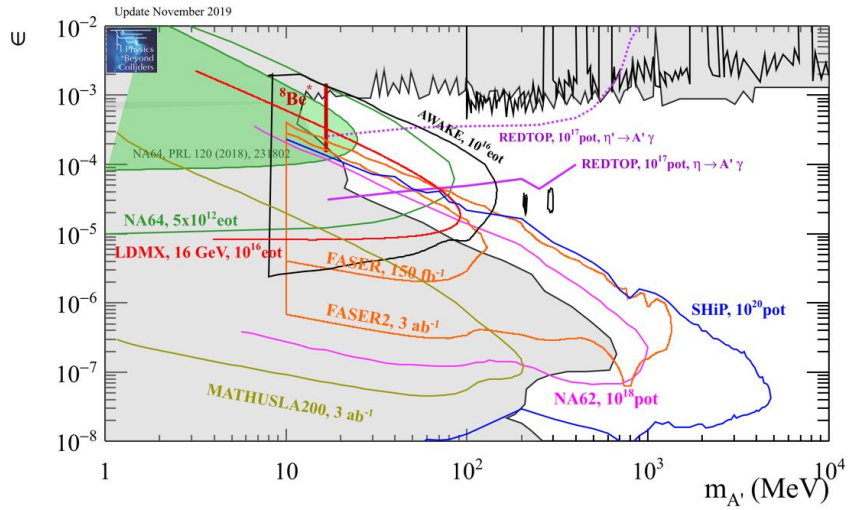


Search for heavy neutral leptons

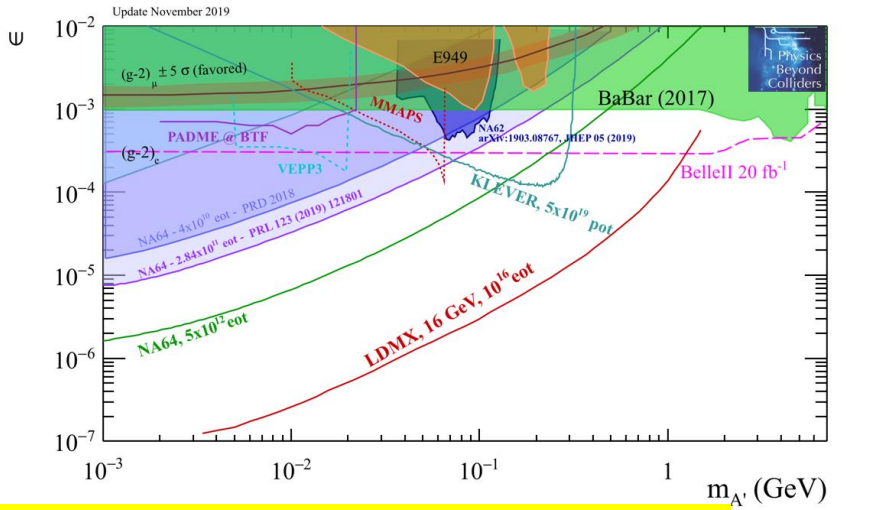


Sensitivity Summaries (Updates)

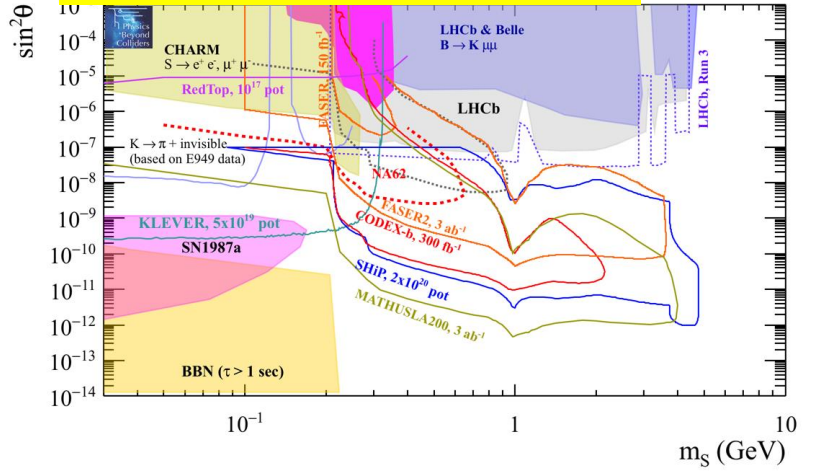
Search for dark photons (visible mode)



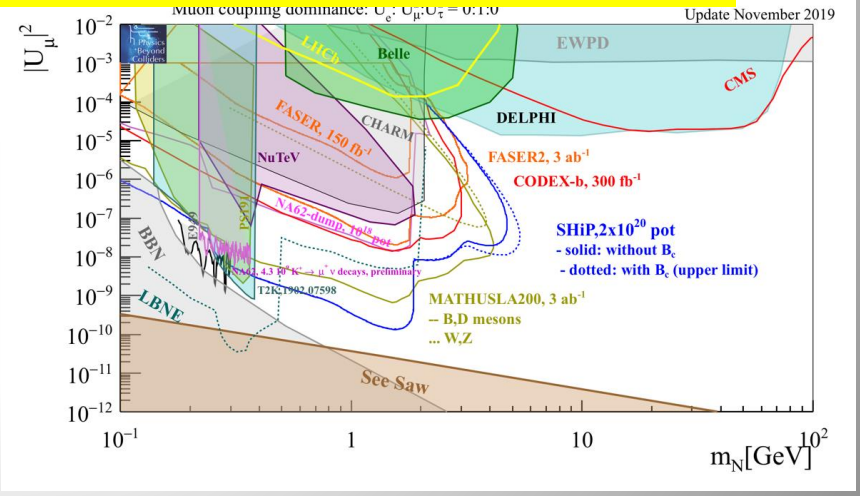
Search for dark photons (invisible)



Search for dark scalars



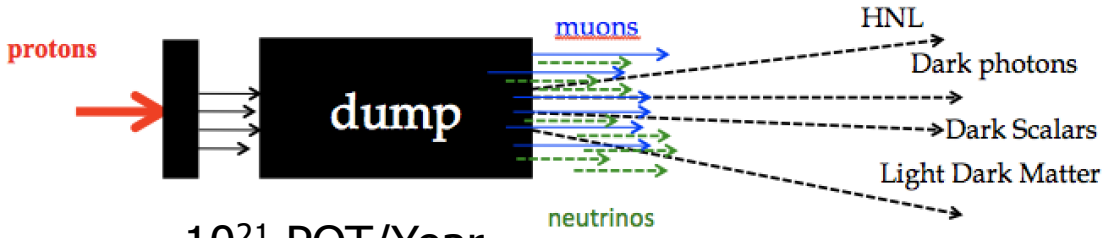
Search for heavy neutral leptons



November 2019: updates from NA64, NA62, REDTOP, Belle II, T2K…

Neutrino Experiments

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

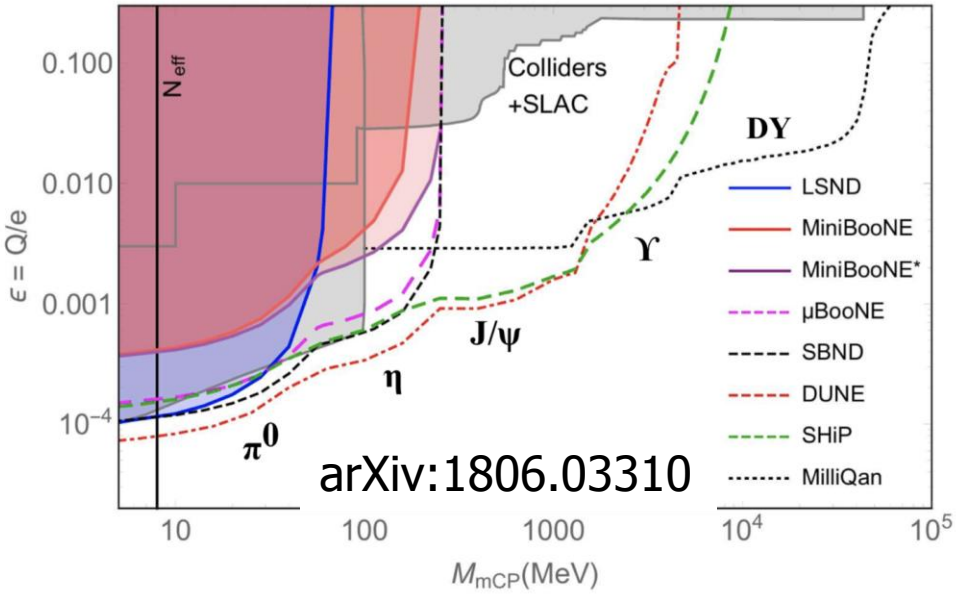


~ 10^{21} POT/Year

Near Detector: few 100m away from the dump

White paper 2019!
arXiv:1907.08311

https://indico.fnal.gov/event/18430/



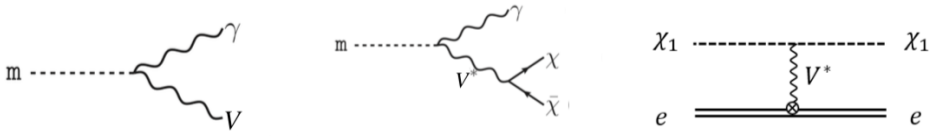
arXiv:1806.03310

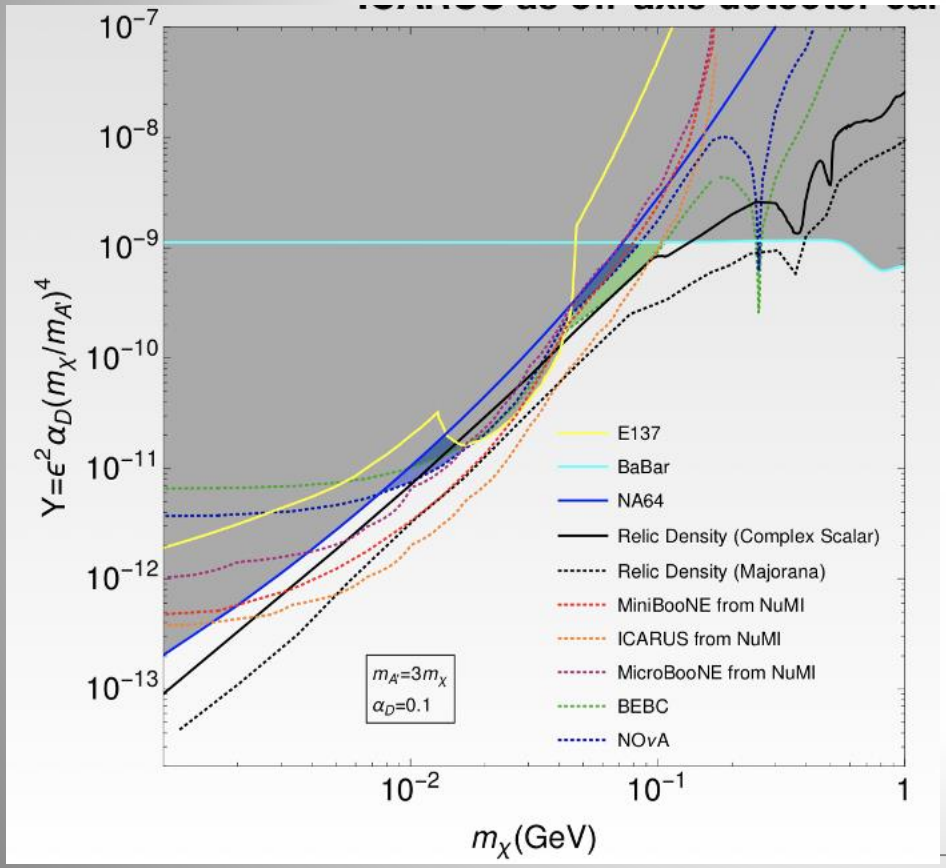
These experiments can perform searches for low mass New Physics particles eg
-HNL/sterile neutrinos
-dark photons
-ALPs
-mini/millicharges
...

<- Example for millicharges
FerMINI @FNAL?

Example: Low Mass Dark Matter

Light DM produced in meson decays, eg π^0s





ICARUS Experiment at SBN
Use the FNAL NuMi beam!
Angle to CARUS is ~6 degrees
120 GeV protons on target

Results available in a few years

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.
- LHC-LLP White Paper released! arXiv:1903.04497
- New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, MAPP, MATHUSLA, CODEX-b, FASER, AL3X, ANUBIS,.. New: LHC neutrino experiments! LLPs also focus in the Physics Beyond Collider studies.
- Of interest to study in detail the complementaritv with LLP searches at Neutrino Near Detectors. Can the optimized? (tentative workshop in Pittsburgh spring
- If we would observe one significant anomaly

Coming Soon @ CERN

https://indico.cern.ch/event/864648