Searches for Long Lived Particles at the LHC – Present and Future

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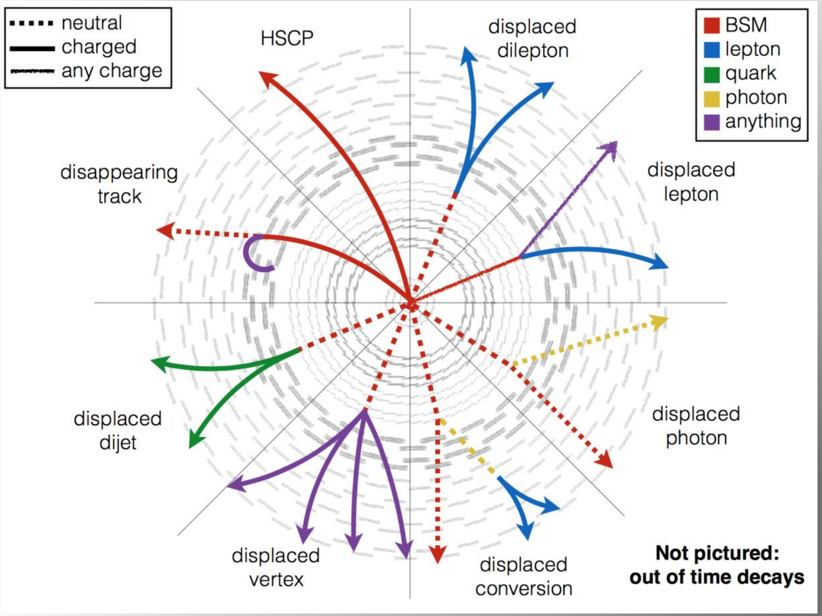
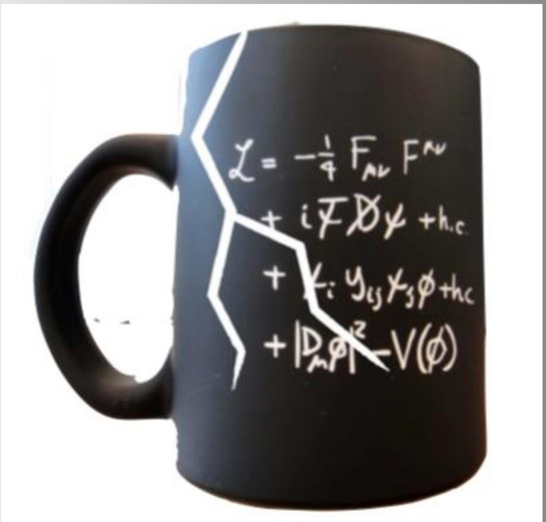
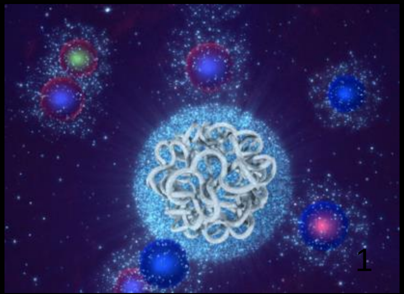




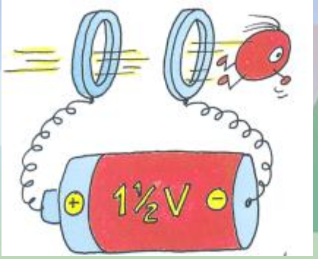
Outline

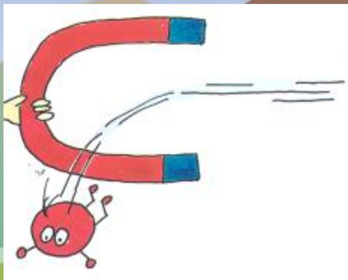
- Introduction to long lived exotic particles: why do we care?
- Challenges at and a few results from the LHC
- New experiments for the LHC?
- Other opportunities for LLPs searches
- Summary/Outlook

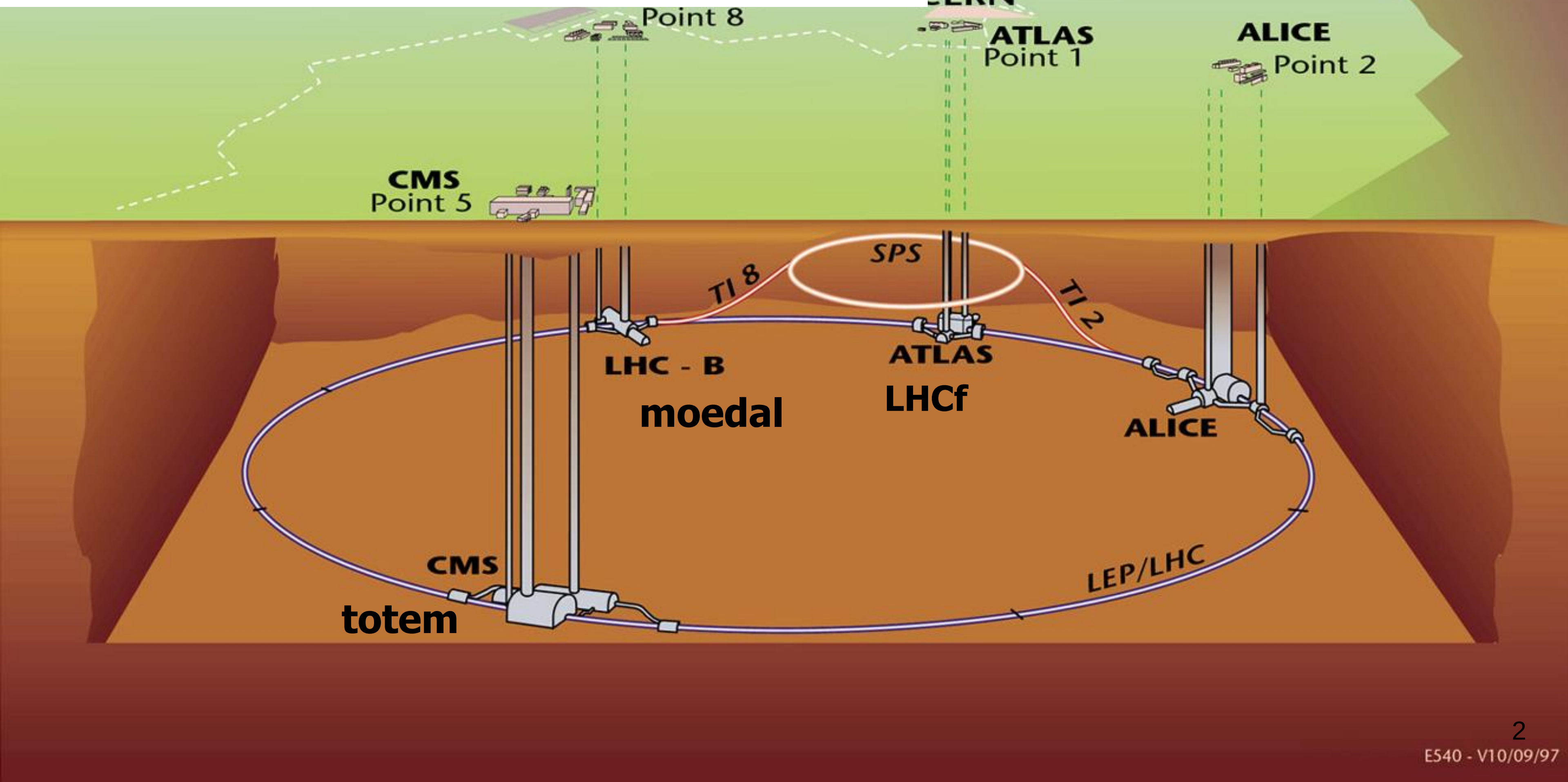


The Flagship Project of CERN: the Large Hadron Collider

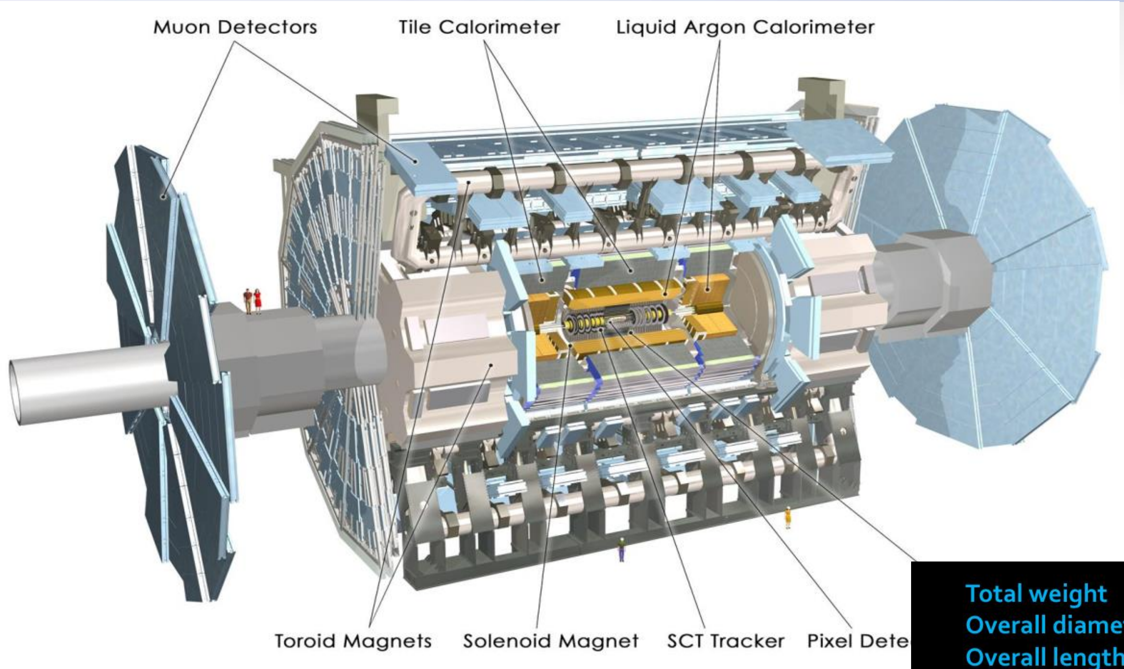
LHC is 100m underground and 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
Cost ~ 5 Billion USD
LHC has seven experiments





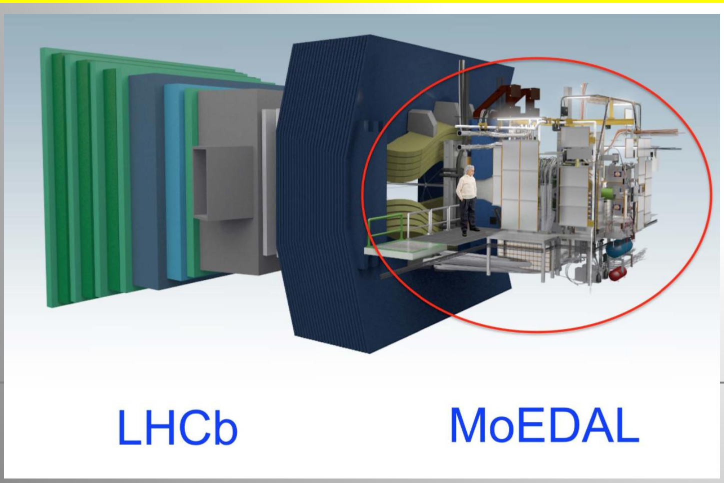


New Physics Hunters @ the LHC

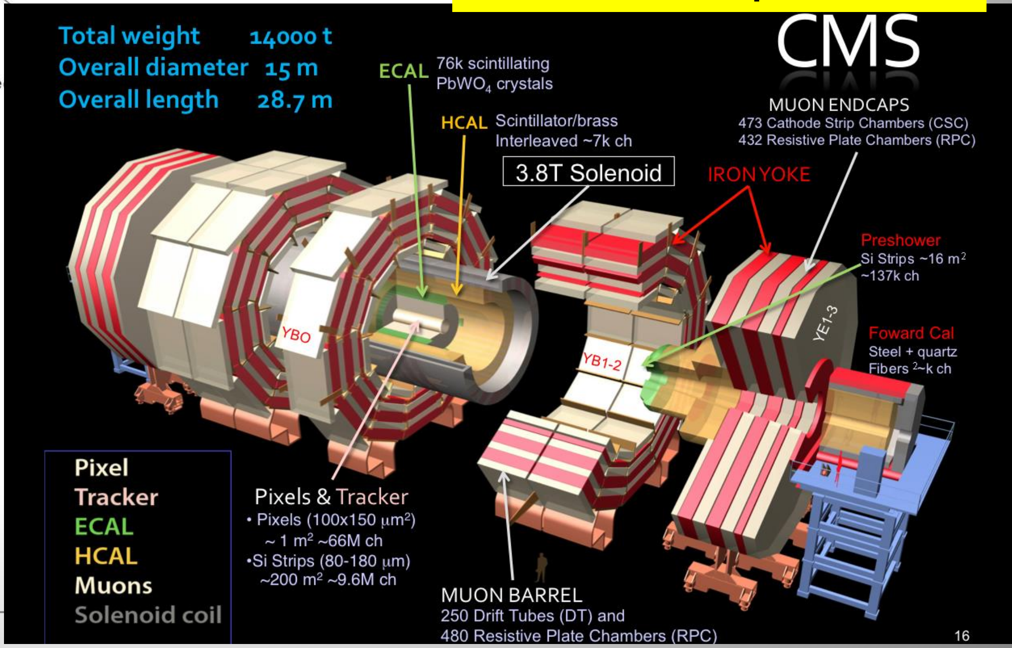


The ATLAS experiment

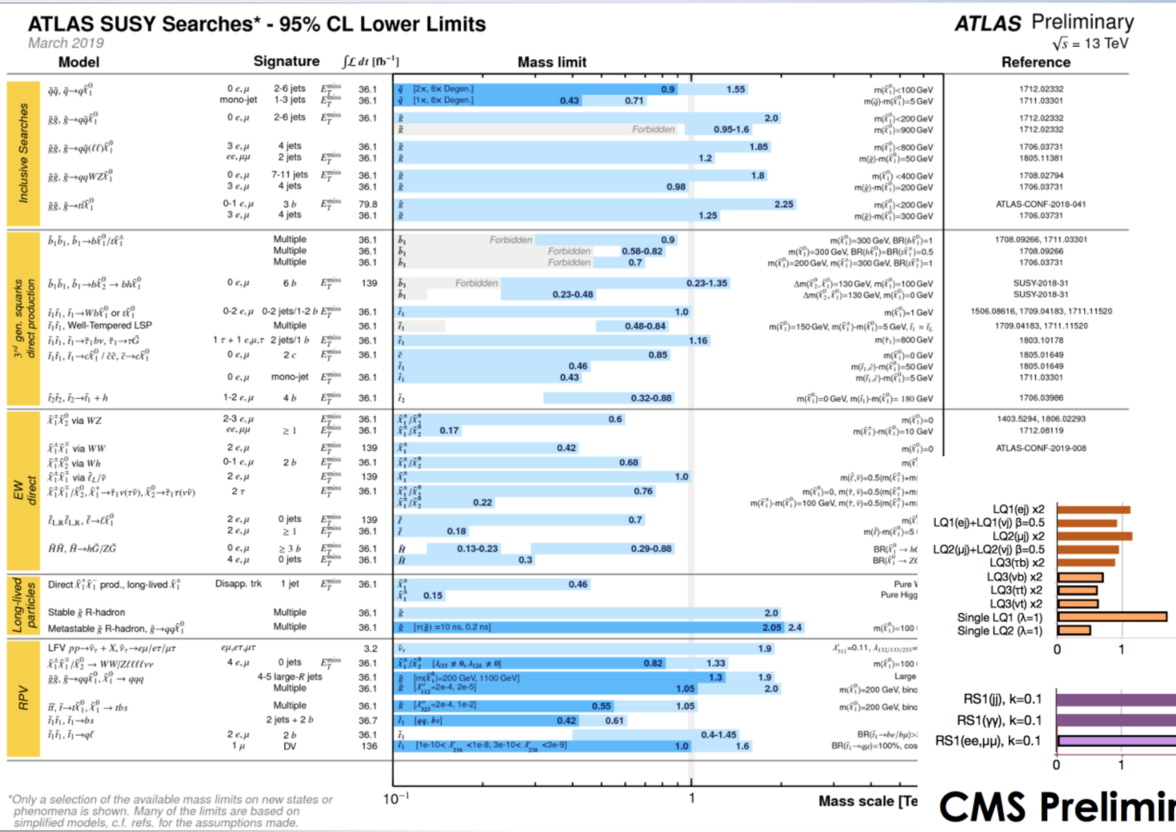
…And also LHCb and MoEDAL



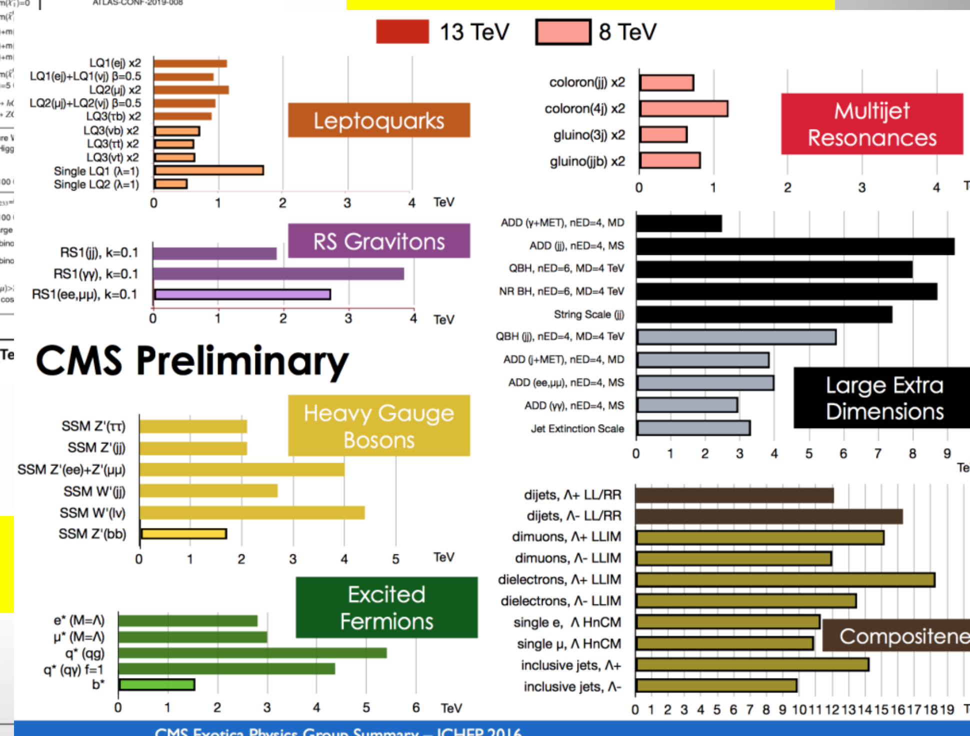
The CMS experiment



LHC: So far no new physics



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



No signal of new physics so far!!

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?

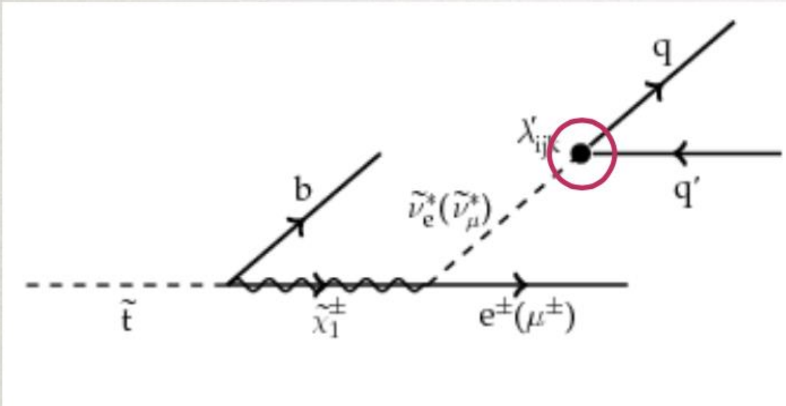
Leave no stone unturned!!

Searching for Long Lived Particles

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

LLP Models: Supersymmetry

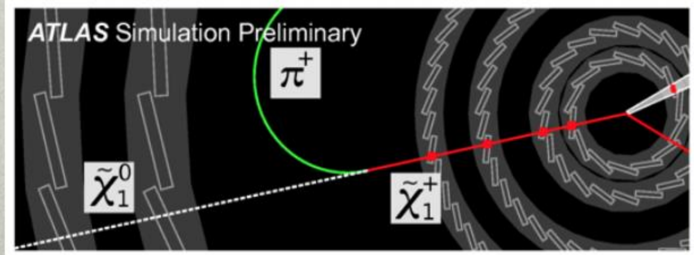
R-parity-violating SUSY:



$$|\lambda| \lesssim 10^{-8}$$

Pure weak-ino states:

- Electroweak symmetry gives degeneracy of NLSP-LSP masses if little mixing between Higgsino/gauginos

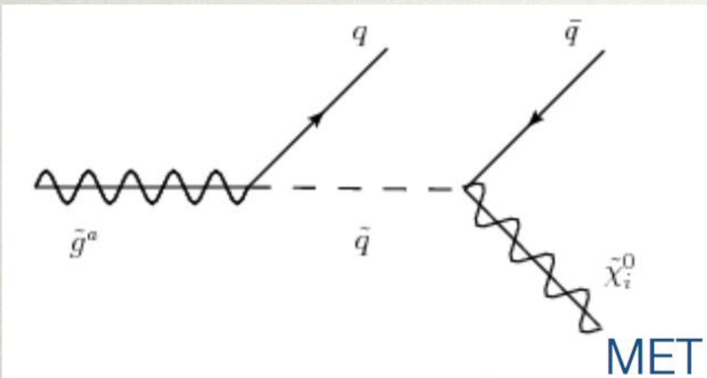


$$c\tau \approx 0.7\,\text{cm} \times \left(\frac{\Delta m}{340\,\text{MeV}}\right)^{-3}$$

LLP Models: Supersymmetry

Split SUSY:

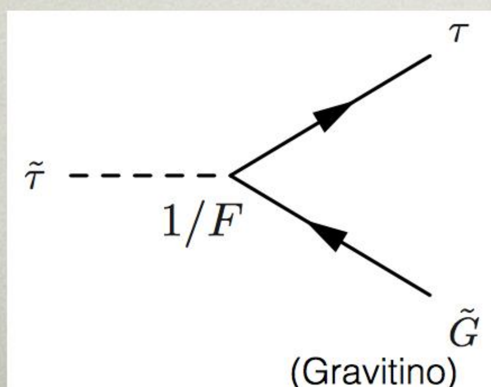
- Models with decoupled supersymmetric scalars



$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{10^3\,\mathrm{TeV}}\right)^4 \times \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

Gauge mediation:

- Decays to gravitino suppressed by SUSY-breaking scale

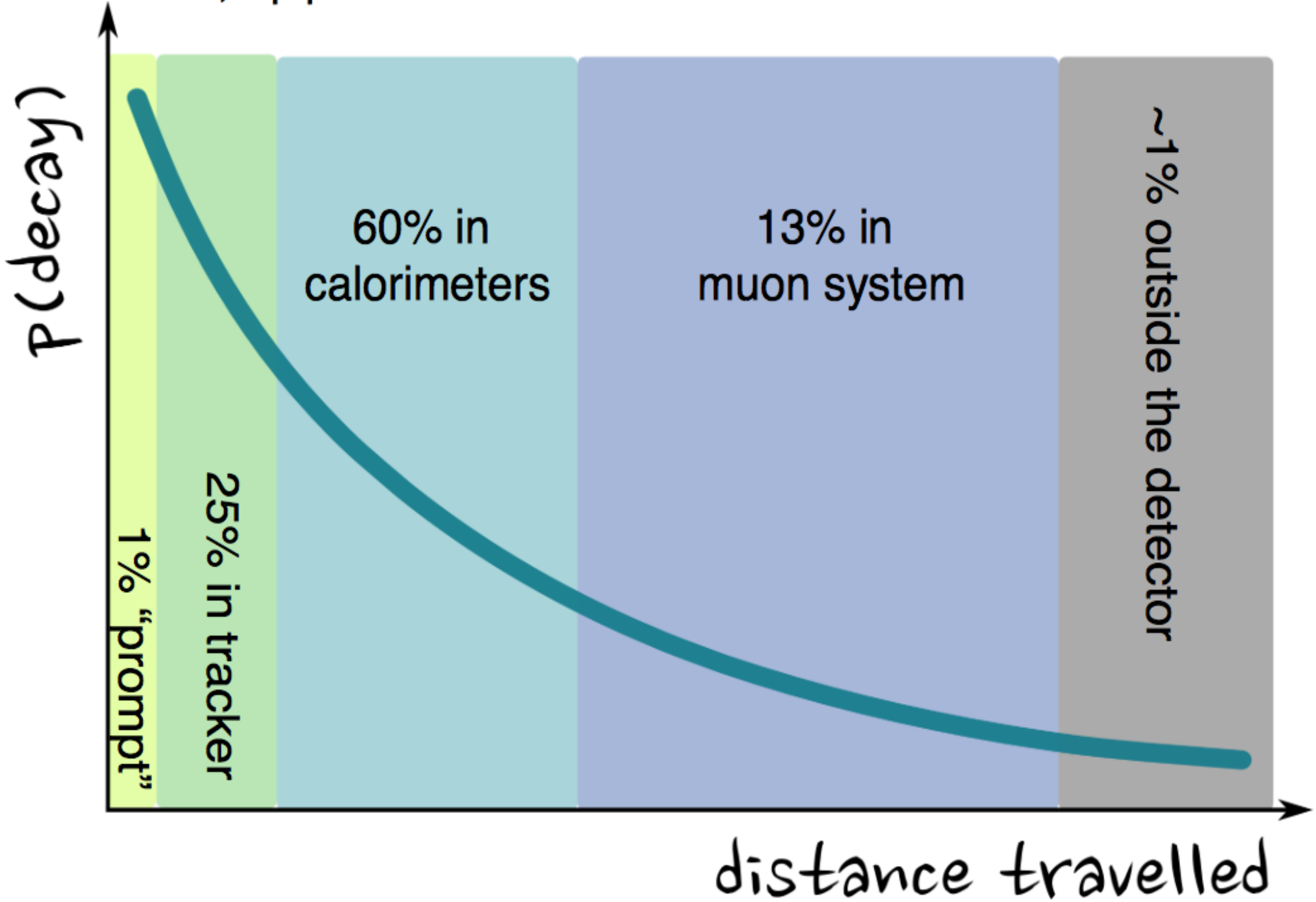


$$c\tau \approx 100\mu m \times \left(\frac{\sqrt{F}}{100\,\mathrm{TeV}}\right)^4 \times \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{\tau}}}\right)^5$$

why do we need so many searches?

Even particles with a short proper lifetime can decay with a large lab-frame distance:

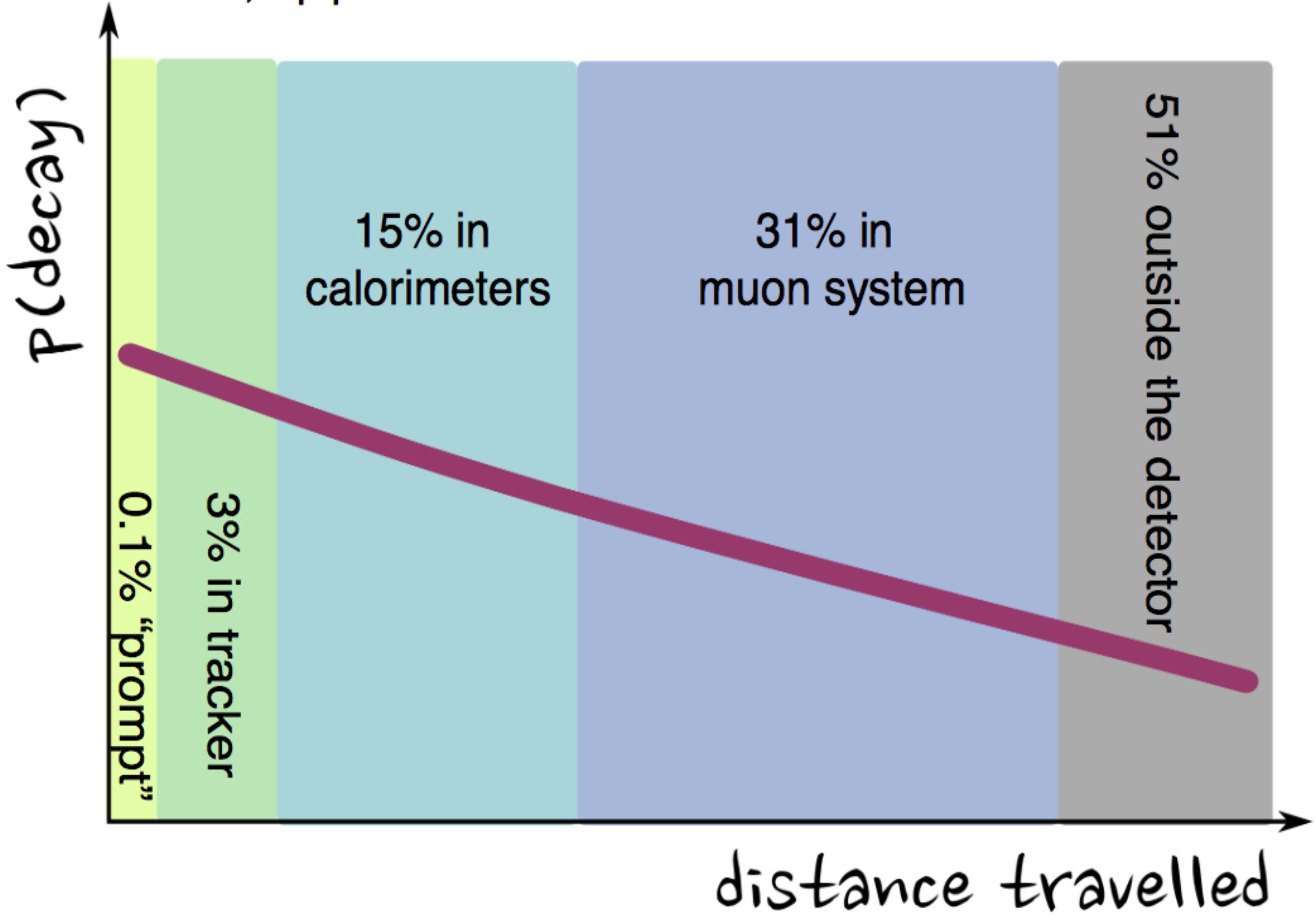
e.g. for $c\tau$ = 5 cm, $\langle\beta\gamma\rangle \sim 30$



why do we need so many searches?

But if we want to consider particles with a longer lifetime, need a dramatically different search strategy!

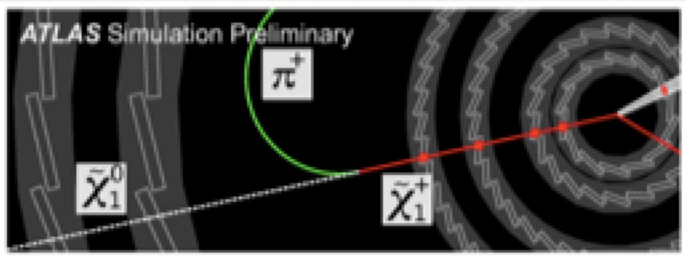
e.g. for cτ = 50 cm, <βγ> ~ 30

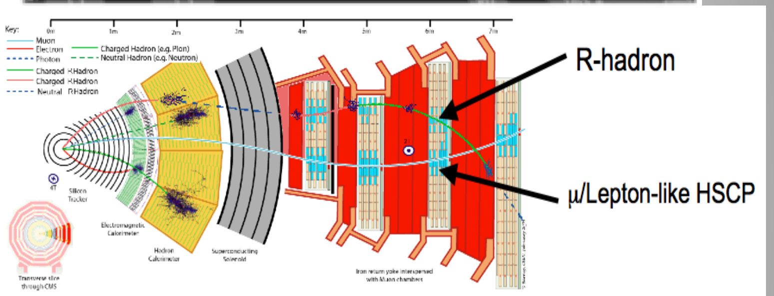


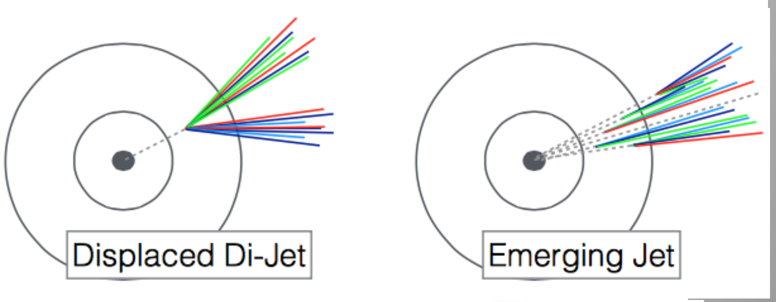
Long Lived Particles

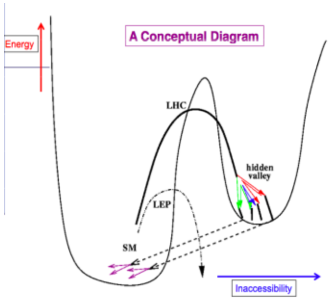
Long lifetimes arise from a hierarchy of scales or a small coupling

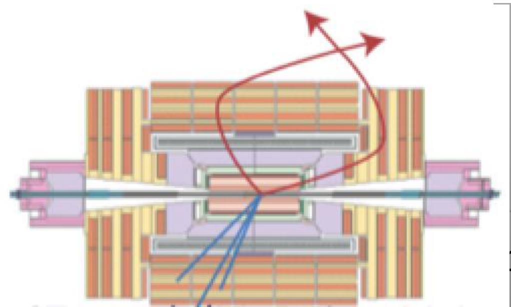
- RP Violating SUSY
- ASMB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ….





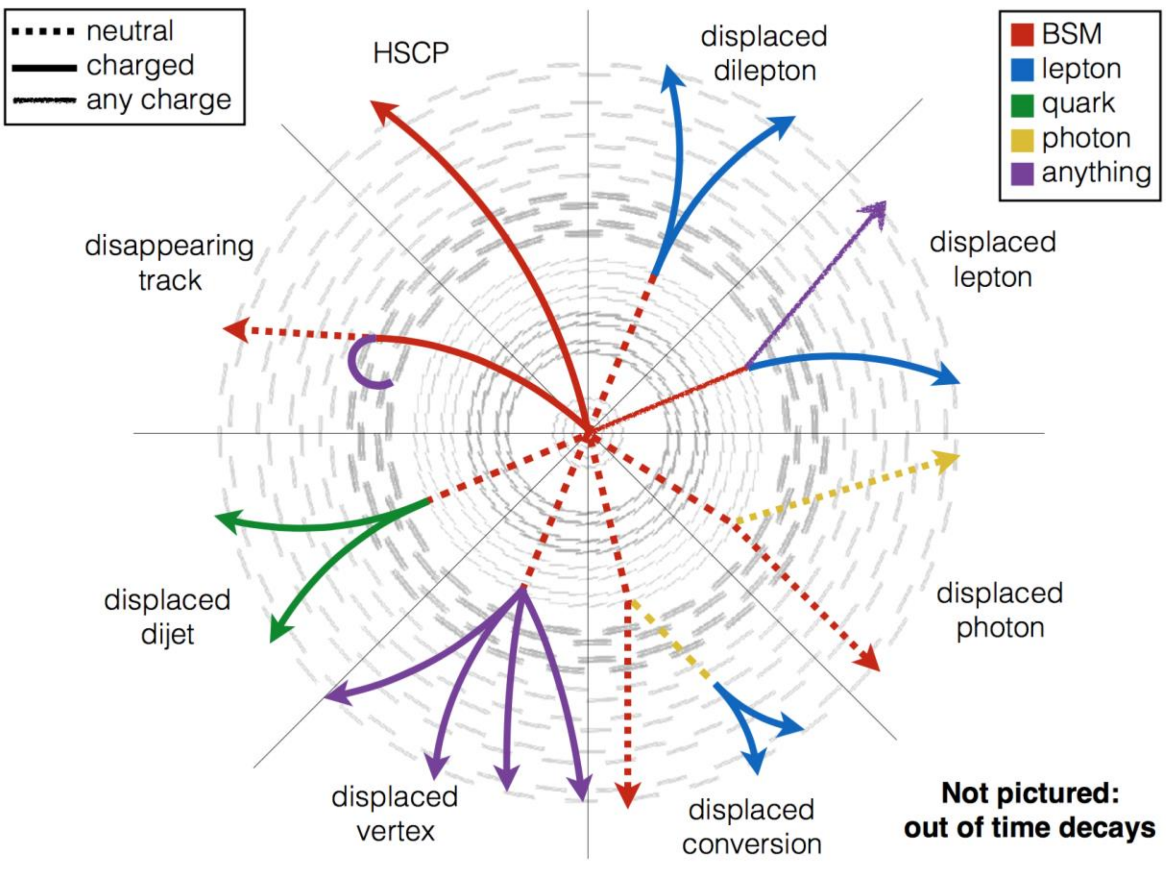






Long Lived Particles @LHC

Signatures



Some of the Challenges

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

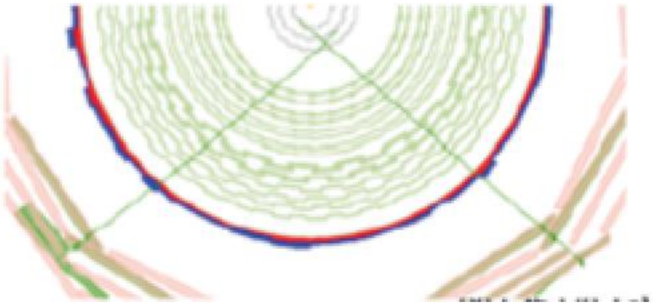
SM backgrounds often low. But need special studies (punch through, secondary interactions, tails, cosmics…)

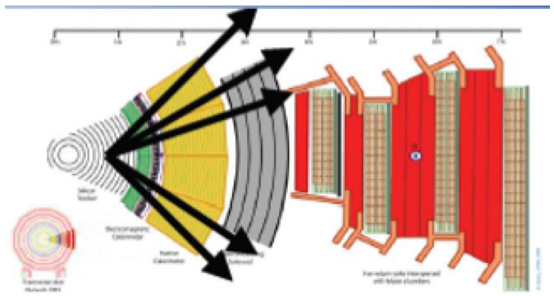
Special reconstruction is often needed

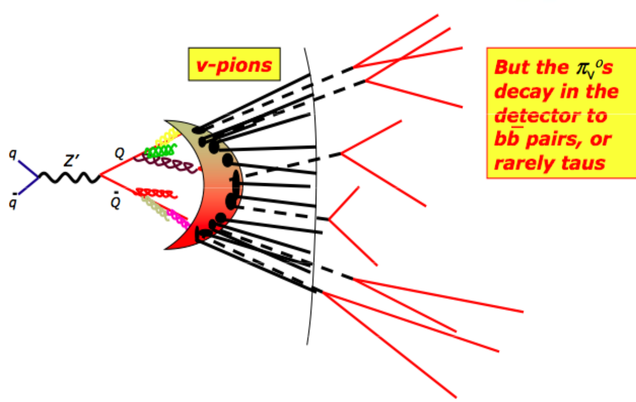
Some detector upgrades for High-Luminosity LHC (>2026) address these issues.

Long Lived Searches Overview

- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced leptons & lepton jets
- Displaced photons
- Dark photon decays
- Heavy Stable Charged Particles
- Stopped particles
- Emerging jets
- Monopoles stuck in material
- Heavy Neutral Lepton searches
- Strongly Interaction Massive Particles
- …. (others…new ideas…)

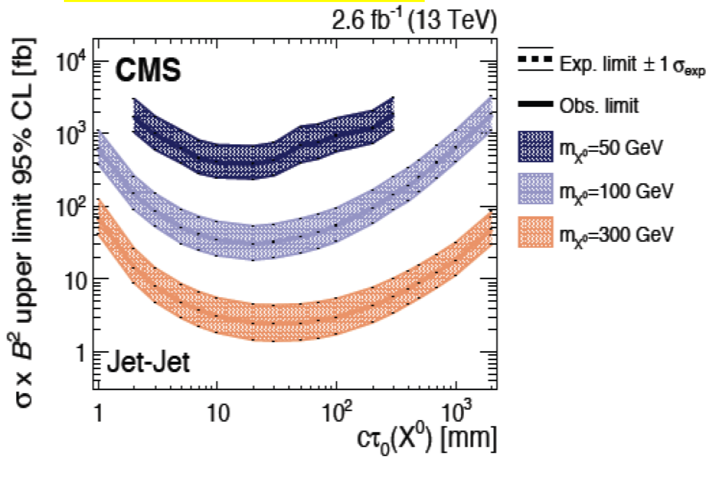




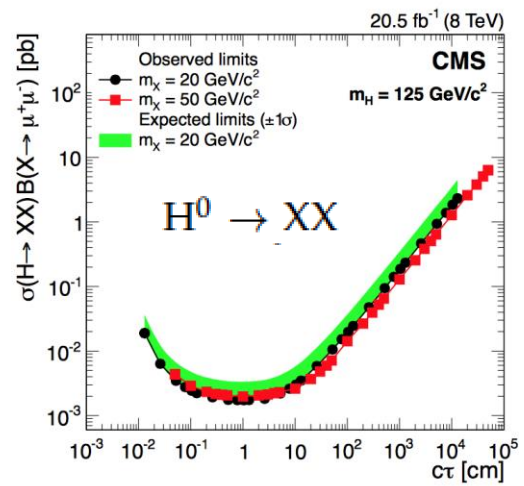


Long Lived Searches: Examples

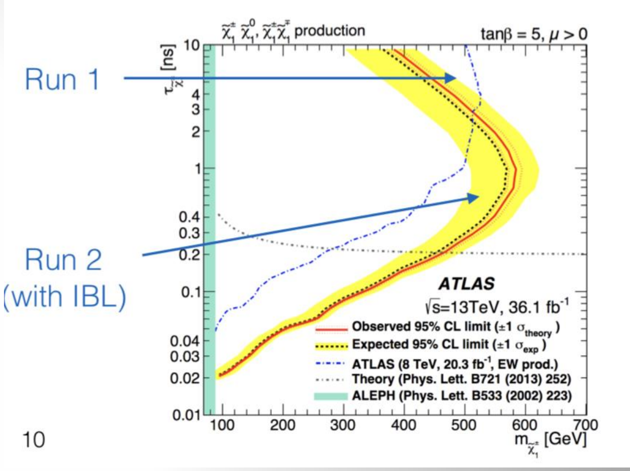
displaced jets



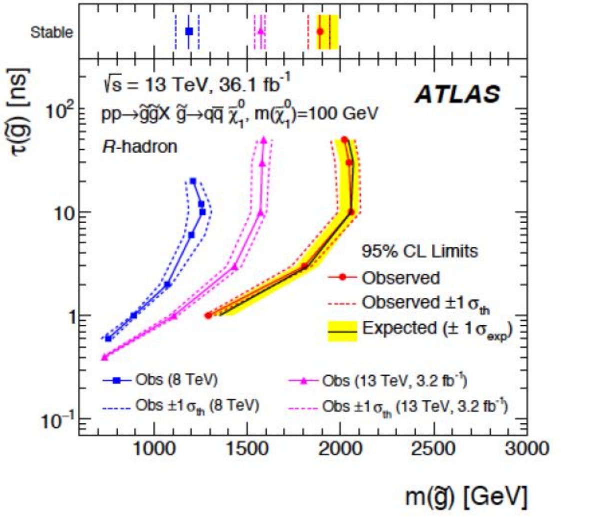
displaced leptons



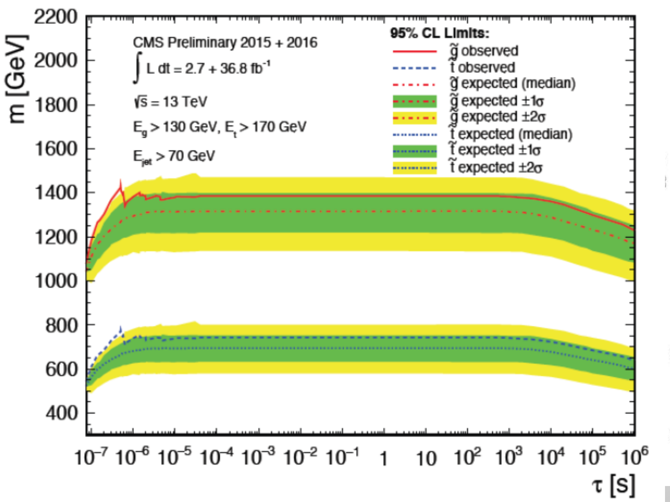
disappearing tracks



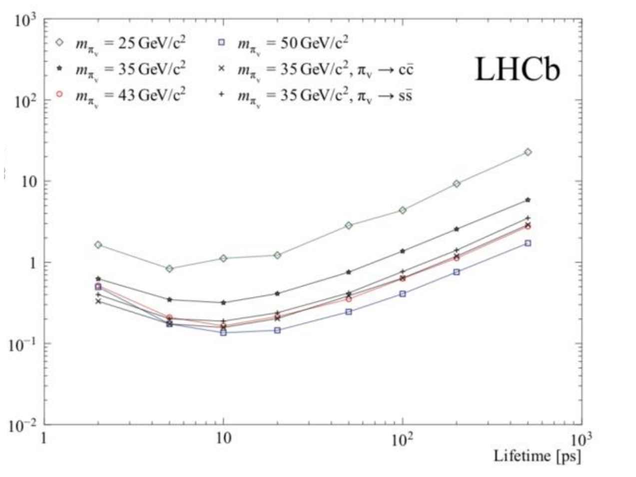
metastable R-hadrons



stopped particles

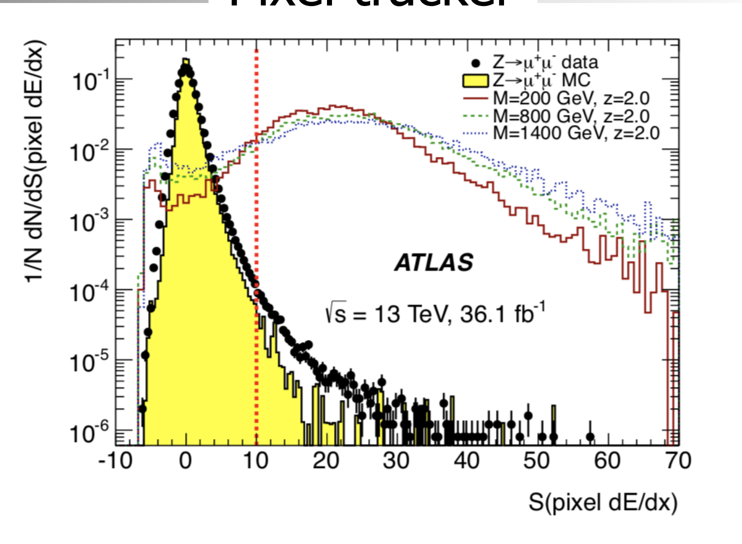


Hidden Valley searches

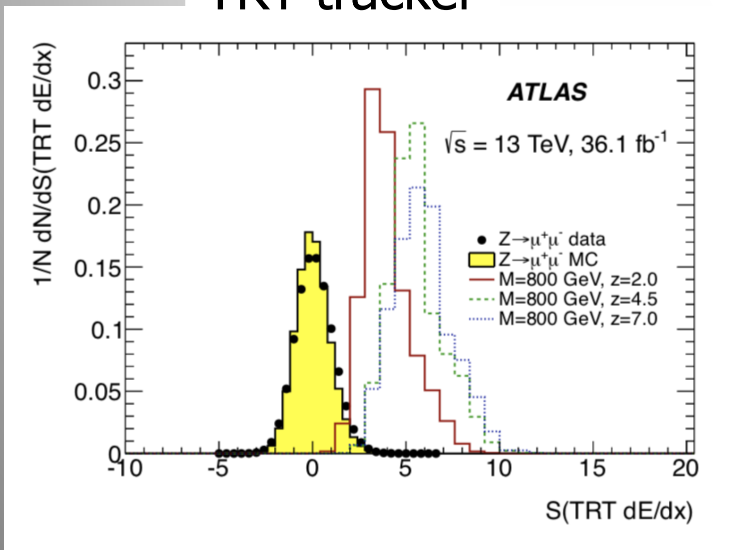


Multi Charged Particles

Pixel tracker

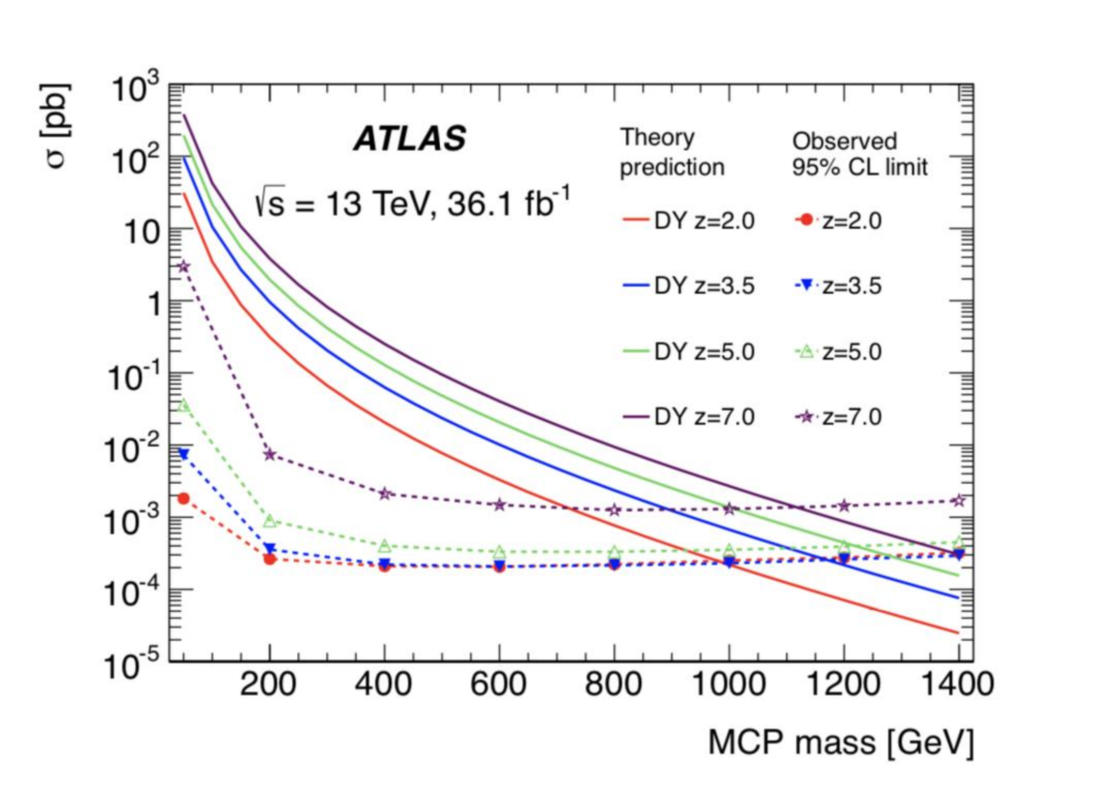


TRT tracker



Use central tracker and de/dx measurement to search for particles with electric charges of 2e to 7e

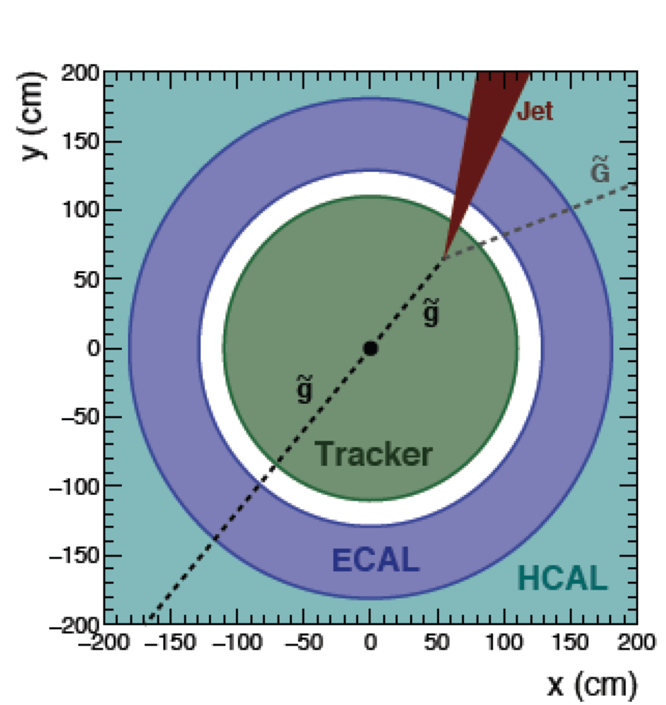
arXiv:1812.03673

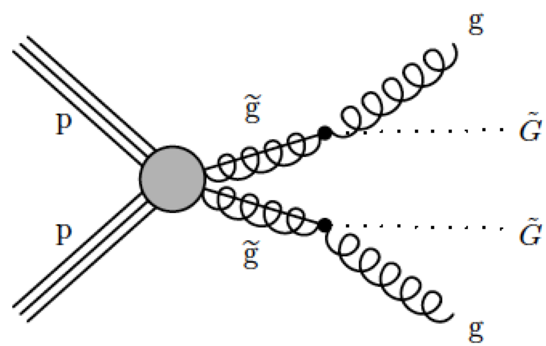


Exclusion between 50 GeV and 980-1220 GeV

Search for Delayed Jets

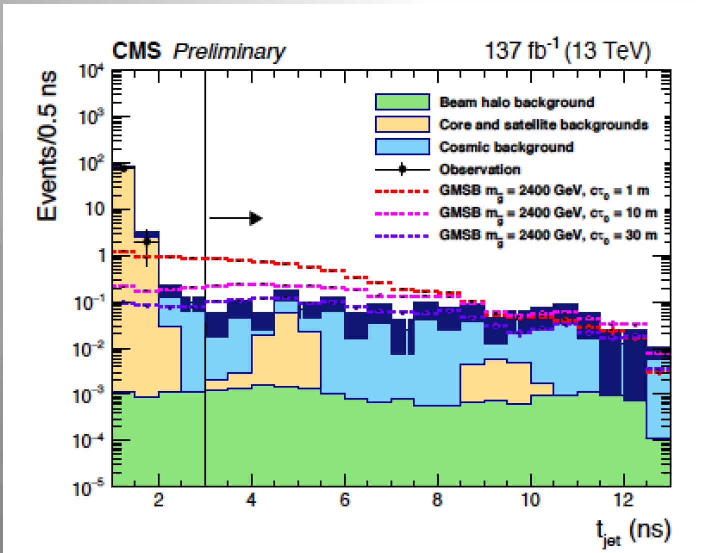
EXO-19-001

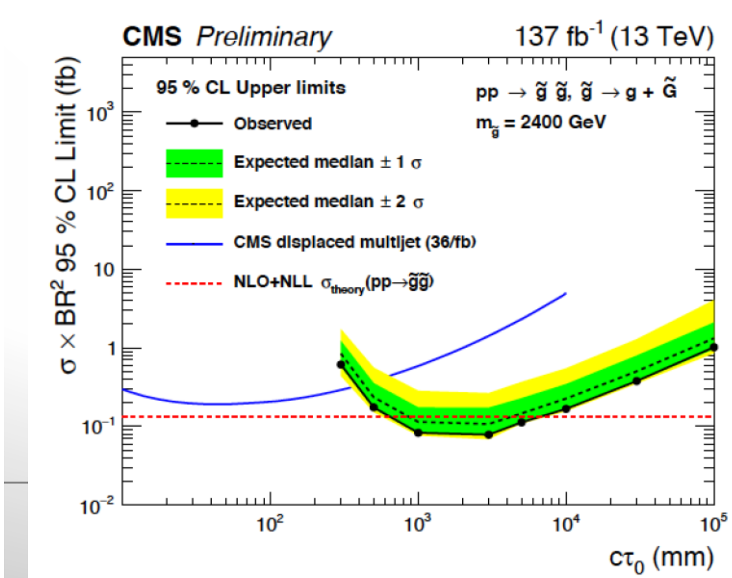




Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

- Using the ECAL precision timing ~200 ps
- Search for jets not connected to the primary vertex
- Data driven background estimate

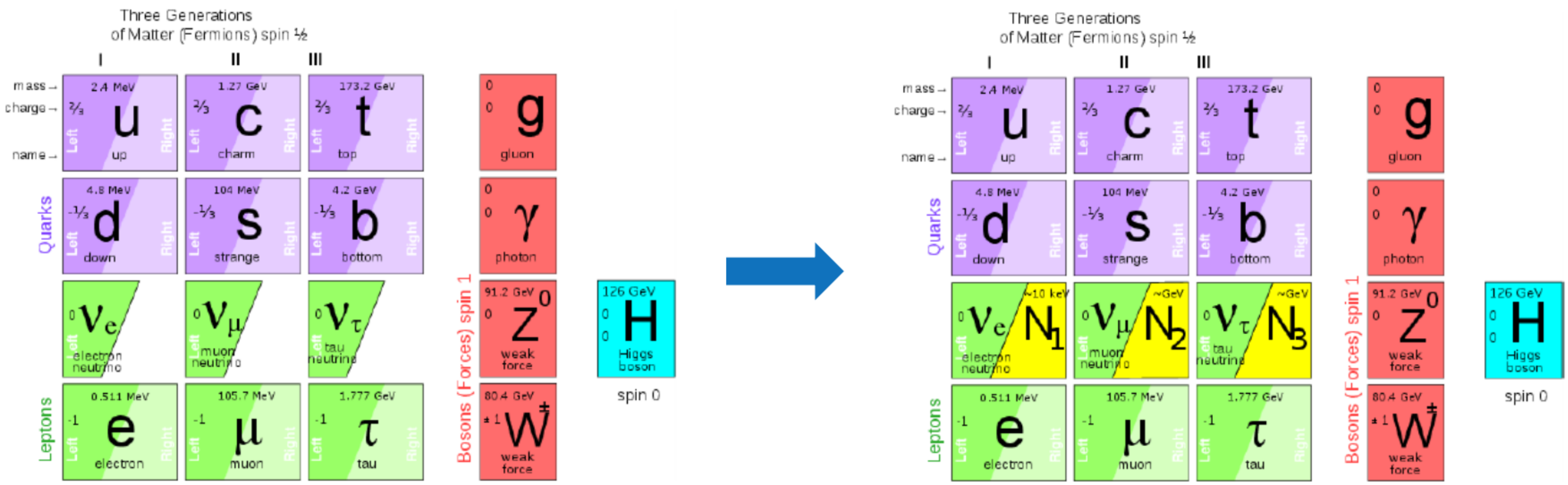




GMSB long-lived gluino model search. Mass limits up to 2500 GeV

Example Scenario

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by three Right Handed (Majorana) Heavy Neutral Leptons (HNL): N1, N2, N3.

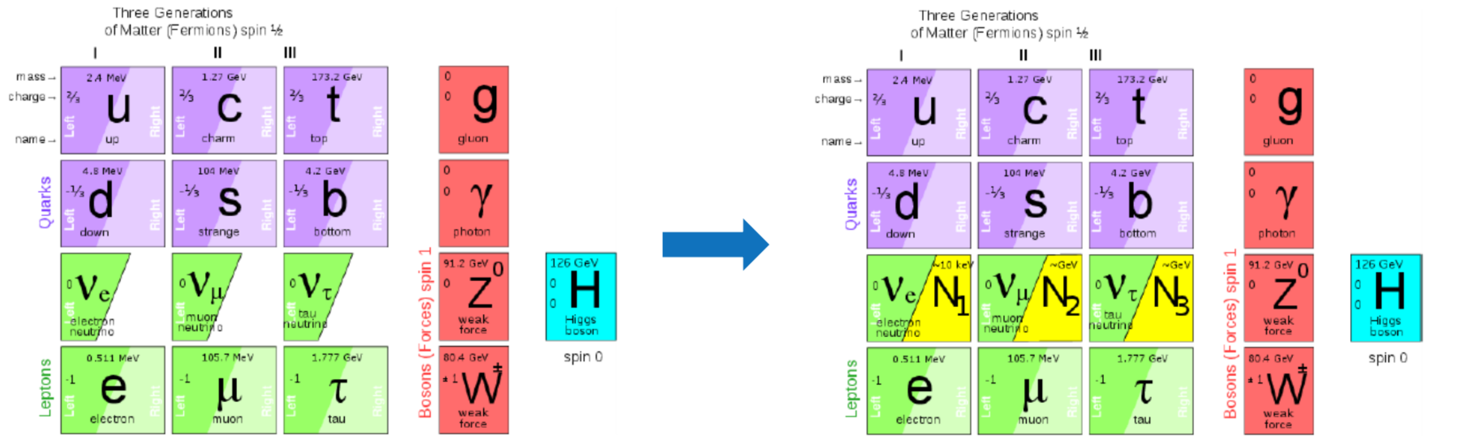


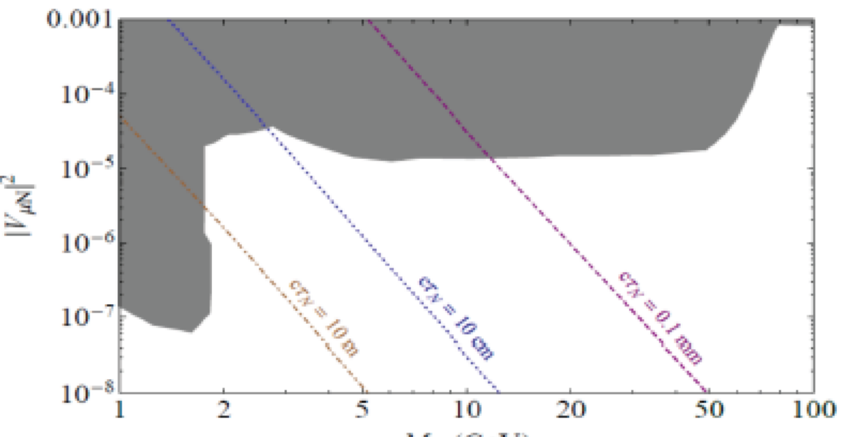
-The lightest singlet N_1 (mass ≈ KeV): good dark matter candidate.
-N_2, N_3 (mass in 100 MeV - GeV region):
- Mechanism to give masses to neutrinos
- Explain baryon asymmetry

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

Heavy Neutral Leptons

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





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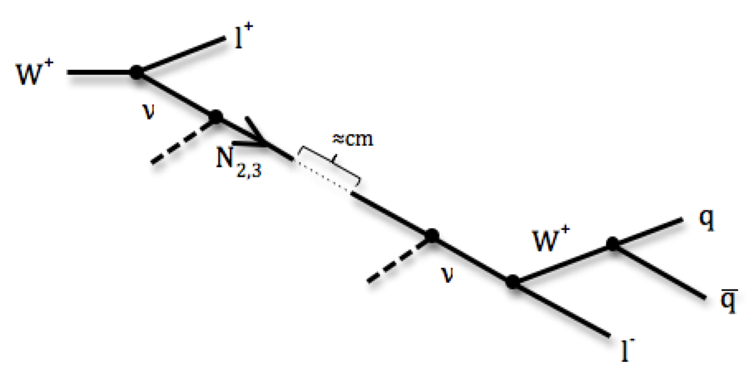
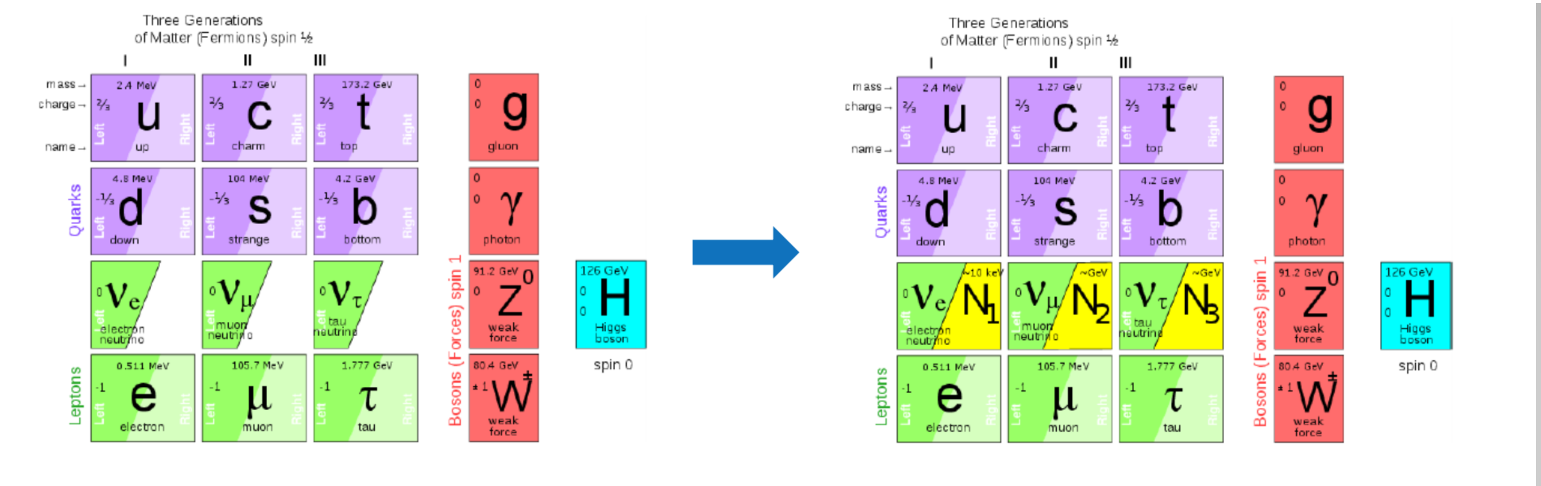


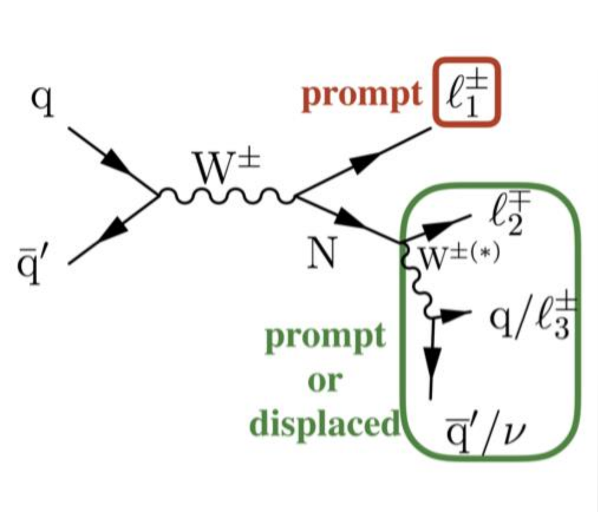
First LHC results on prompt studies
Majorana/Dirac? Now studies with displaced jets/lepton analyses. L~ 1m?

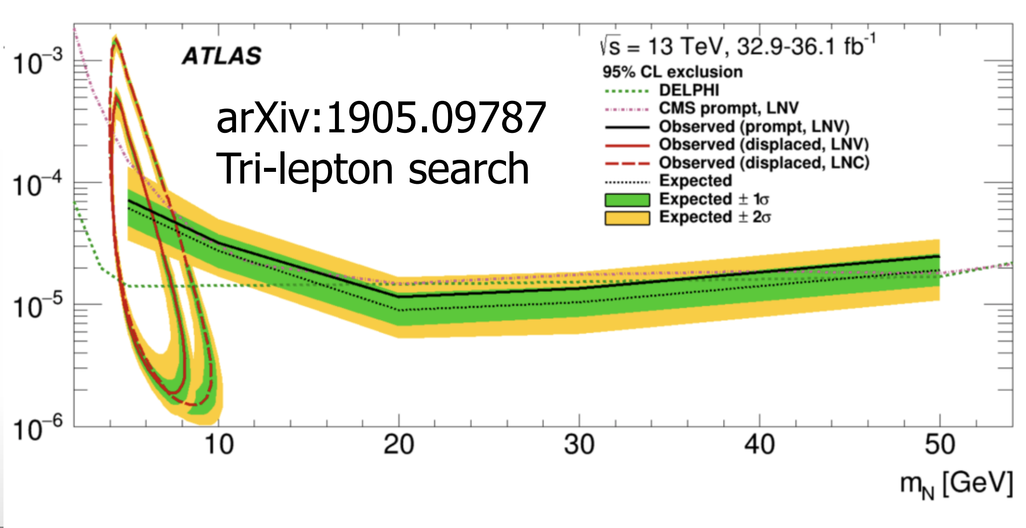
Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

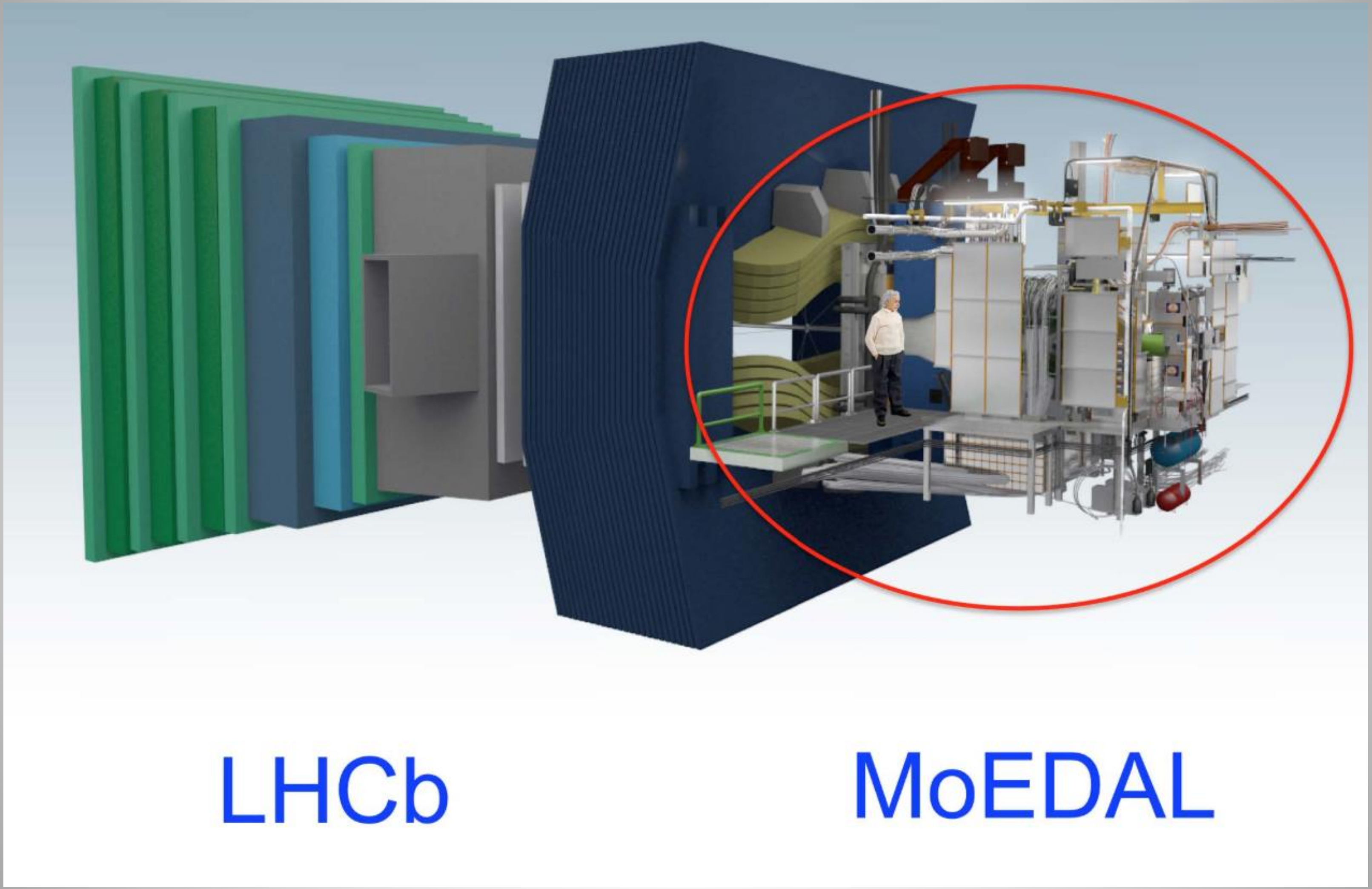
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.







The MoEDAL Experiment



MoEDAL = ~ 70 physicists from 30 institutes and 14 countries
-> MoEDAL is a passive detector, sensitive to new physics

Magnetic Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla.\mathrm{E} = 4\pi\rho_e$$

$$\nabla.\mathrm{B} = 4\pi\rho_m$$

$$-\nabla\times\mathrm{E} = \frac{1}{c}\frac{\partial\mathrm{B}}{\partial t} + \frac{4\pi}{c}\mathrm{j_m}$$

$$\nabla\times\mathrm{B} = \frac{1}{c}\frac{\partial\mathrm{E}}{\partial t} + \frac{4\pi}{c}\mathrm{j_e}$$

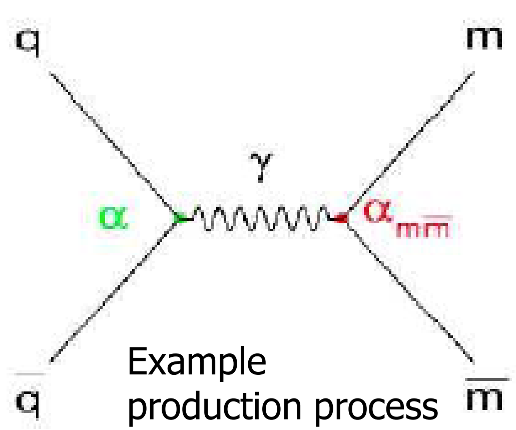
$$\mathrm{F} = q_e\left(\mathrm{E} + \frac{\mathrm{v}}{c}\times\mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathrm{v}}{c}\times\mathrm{E}\right)$$

$$g = \frac{q_m}{e} = \frac{n}{2\alpha_\mathrm{e}} = n\cdot g_\mathrm{D} \approx n\cdot 68.5$$

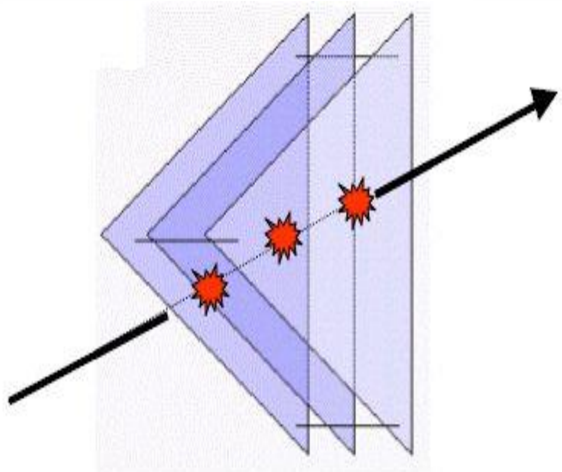
g_D is the Dirac unit magnetic charge

- Simplifies the Maxwell equations!
- Dirac: Charge quantization consequence of angular momentum quantization in the presence of monopole
- 't Hooft, Polyakov: GUT monopoles
- Cho-Maison: Electroweak monopoles in the TeV range. Recent discussion: arXiv:1602.01745

Collider signature: pair production of very highly ionizing particles!



Example production process



Monopoles will 'burn' through the plastic sheets of the experiment or get trapped in the dense material of the trapping detector

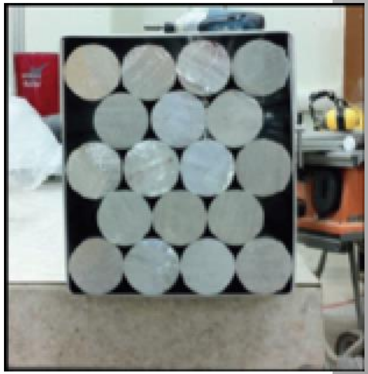
The MoEDAL Experiment

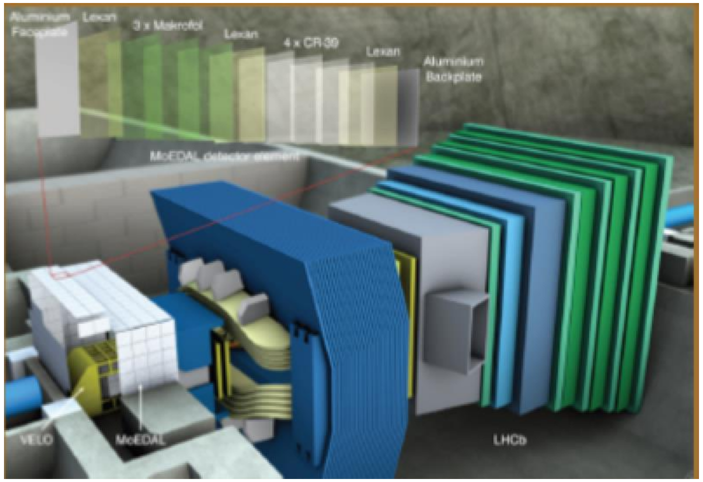
-> Three subdetector systems

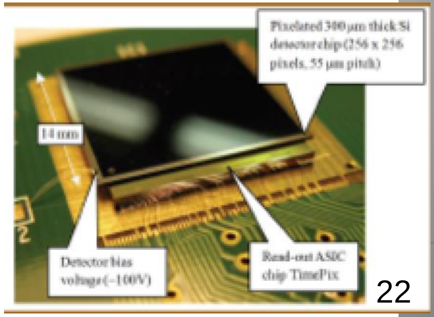
- Passive Nuclear Track-Etch Detectors (NTDs)
  - 120m^2 of CR39 and Makrofol (for very high ionization)
  - Detection threshold is “charge/β > 5”
- Passive Trapping Detectors (MMTs)
  - 794 kg of aluminium bars
- MediPix chip based online radiation monitor system

The NTD and MMT detectors are exchanged every year

The removed 2018 detector are being analysed







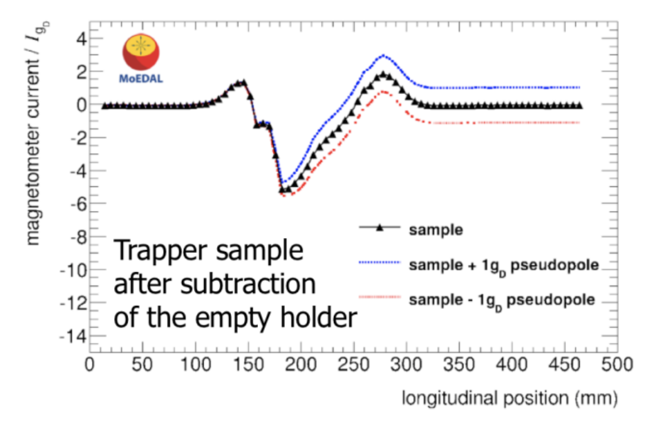
Magnetometer Measurements

Laboratory of Natural Magnetism, ETH Zurich

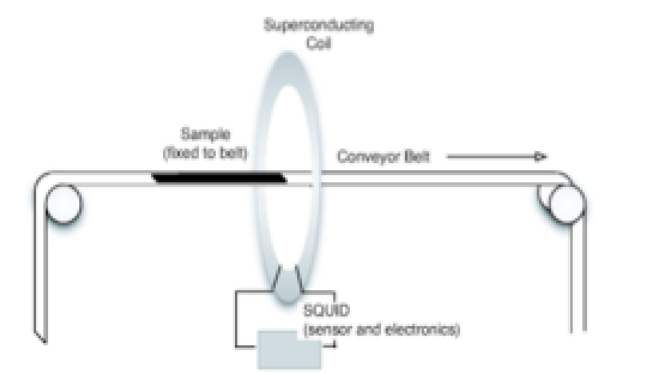
Magnetically shielded room

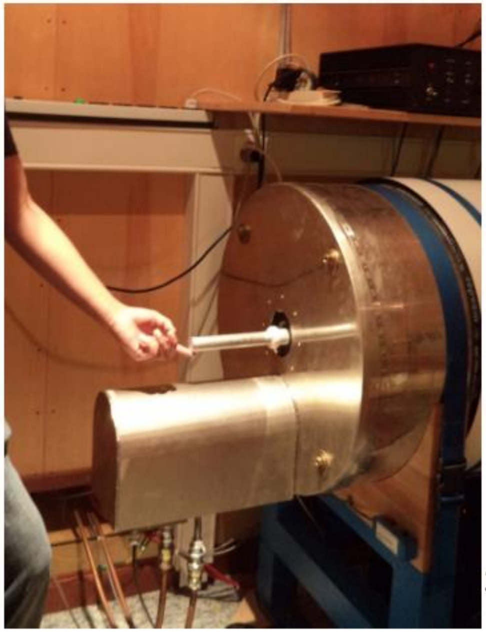
DC-SQUID magnetometer

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



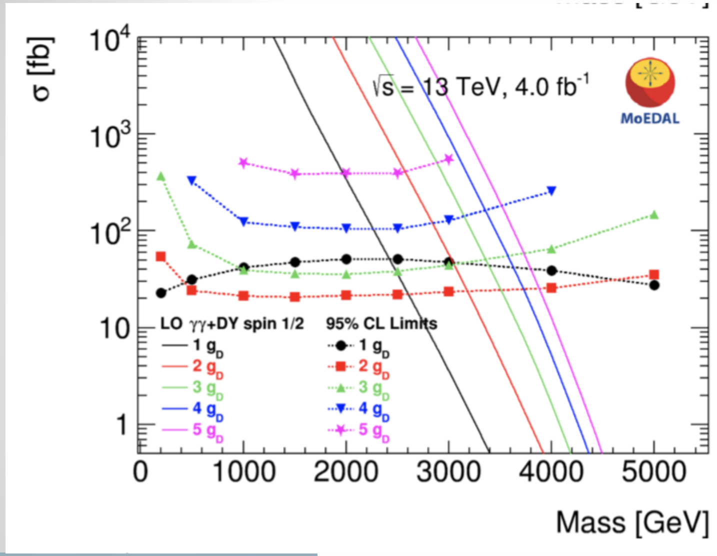
A DC-SQUID rock magnetometer (2G Enterprises model 755)

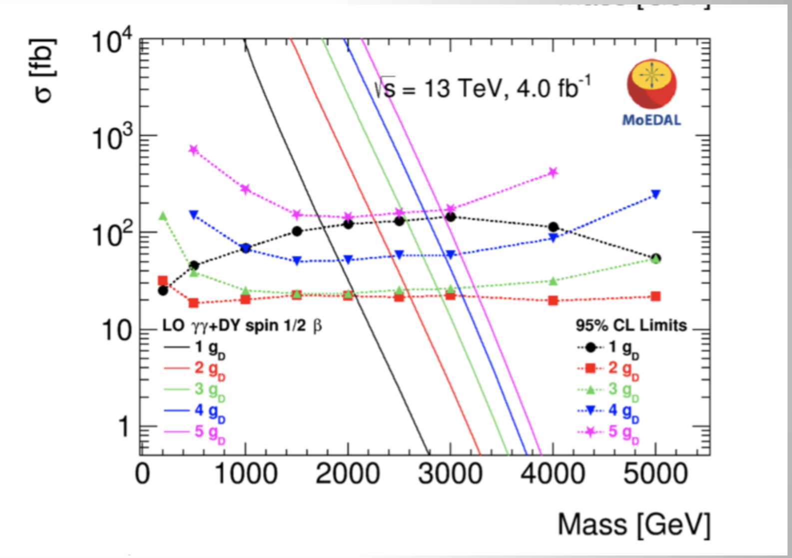


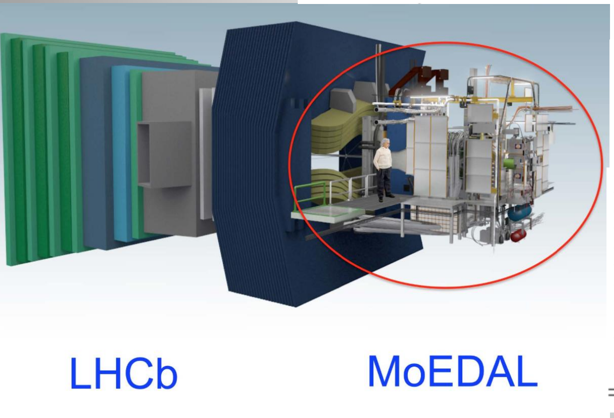


Monopole Searches: MoEDAL @ 13TeV

2016/2017 data analysis base on 794 kg Aluminium to "stop" the monopoles and search with a SQUID precision magnet ($4.0fb^{-1}$) arXiv:1903.08491







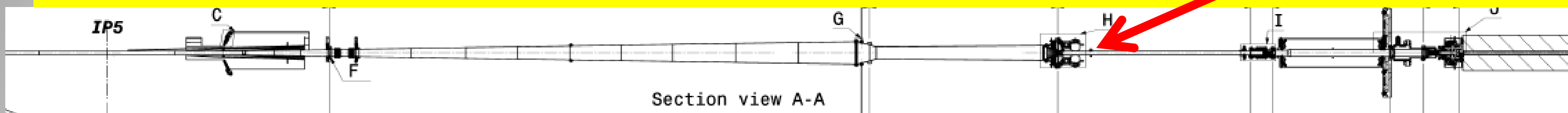
Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY+γγ	0	2190	2930	3120	3090	–
DY+γγ	1/2	2420	3180	3360	3340	–
DY+γγ	1	2920	3620	3750	3740	–
DY+γγ β-dep.	0	1500	2300	2590	2640	–
DY+γγ β-dep.	1/2	1760	2610	2870	2940	2900
DY+γγ β-dep.	1	2120	3010	3270	3300	3270

- 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



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

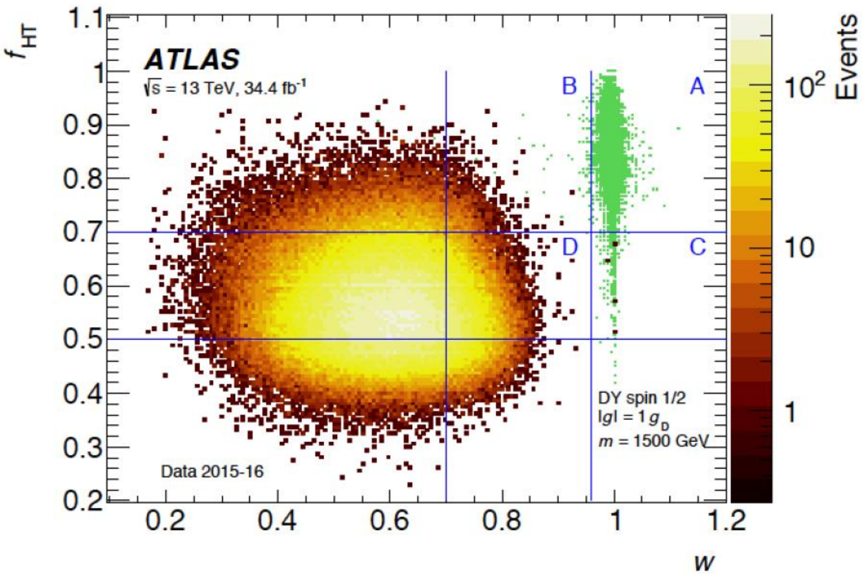
$|g| \geq 4g_D$

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…)

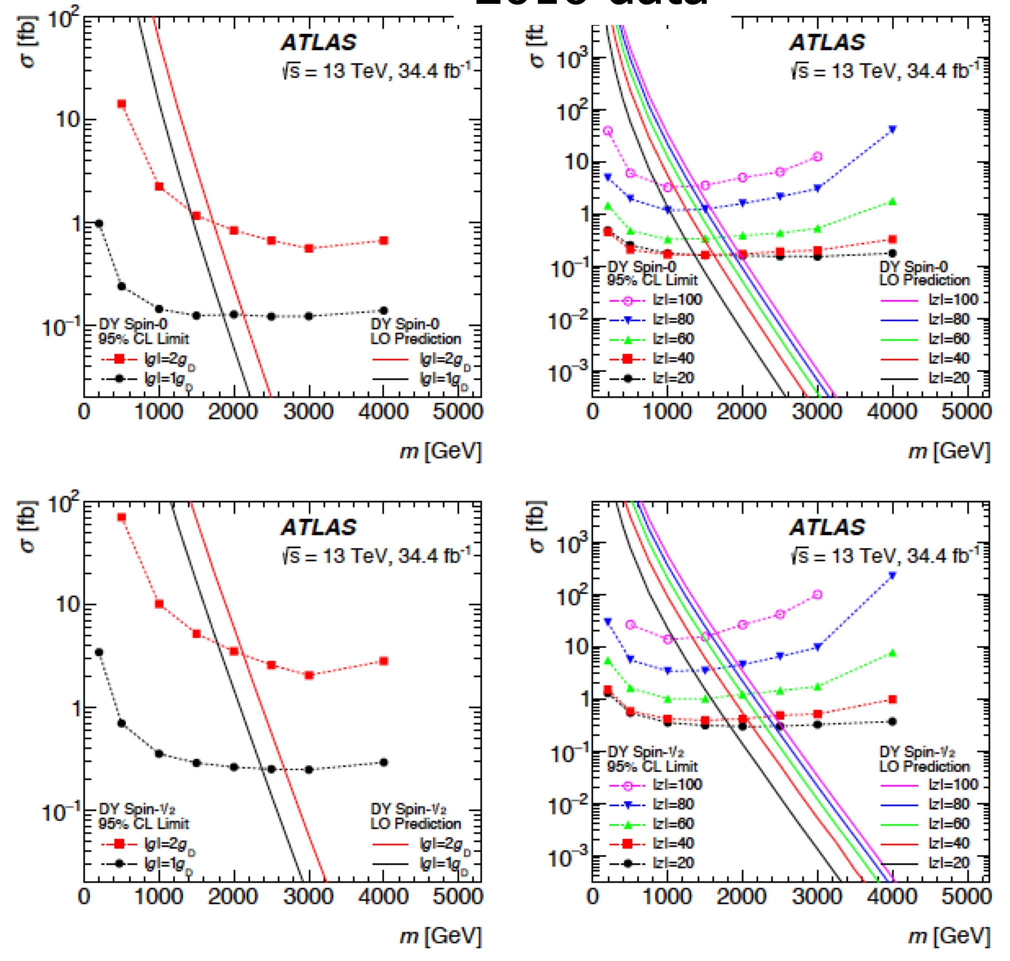
New: ATLAS Monopole Search

arXiv:1903.08491

Use high ionization in the transition radiation tracker and pencil-like energy deposit in the ECAL



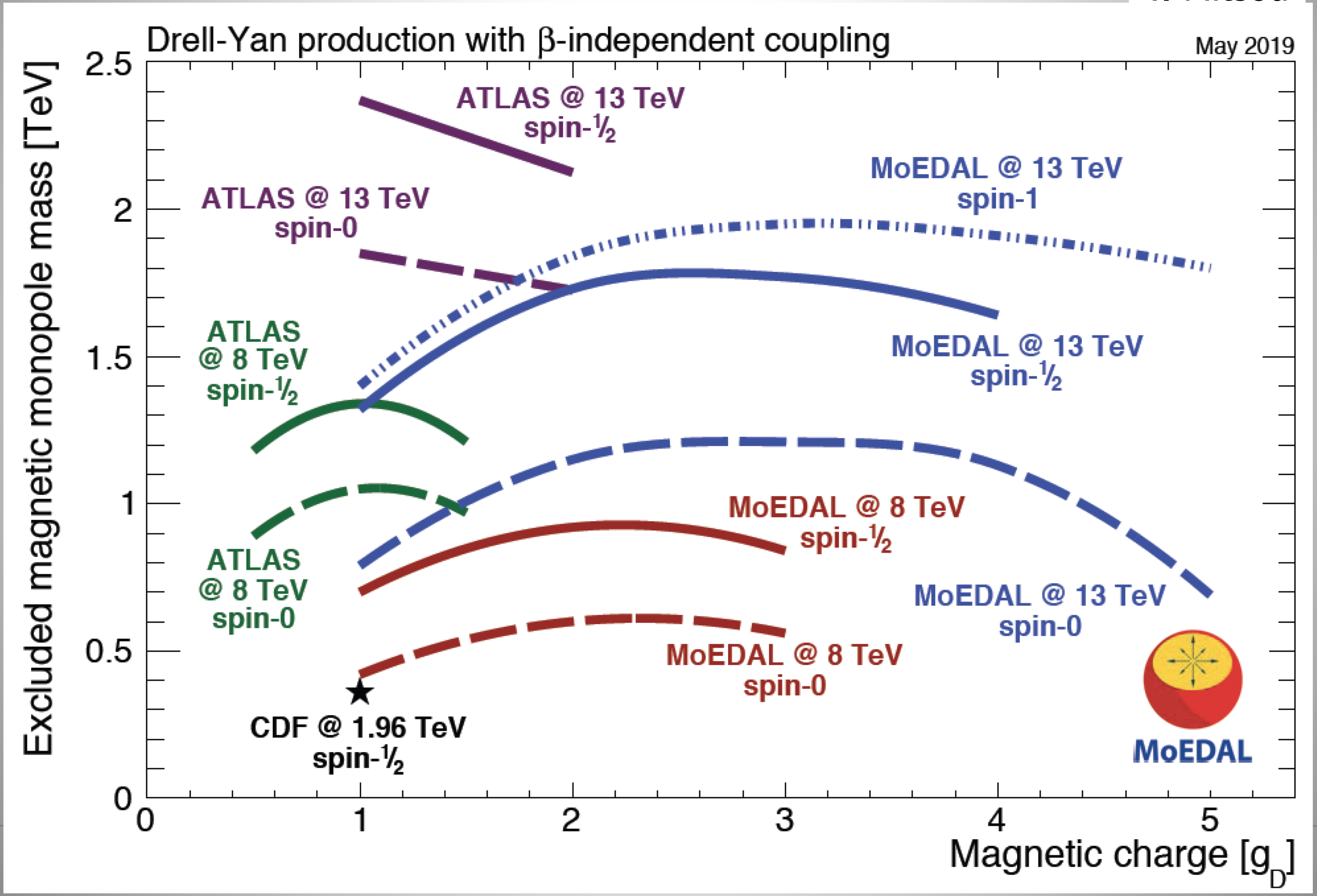
2016 data



Results interpreted via Drell-Yan production for Dirac charges 1 and 2

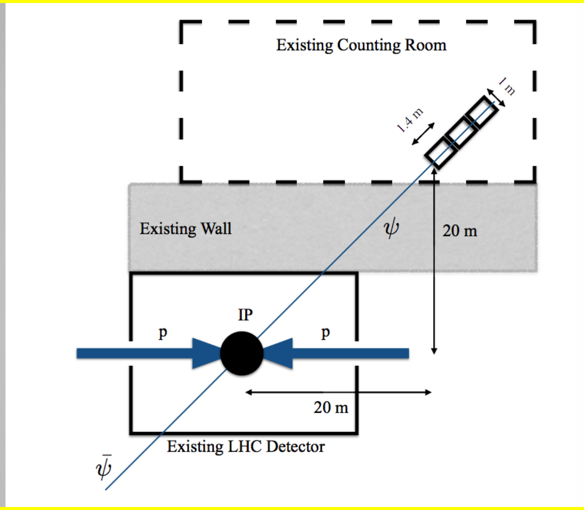
LHC Monopole Searches

V. Mitsou

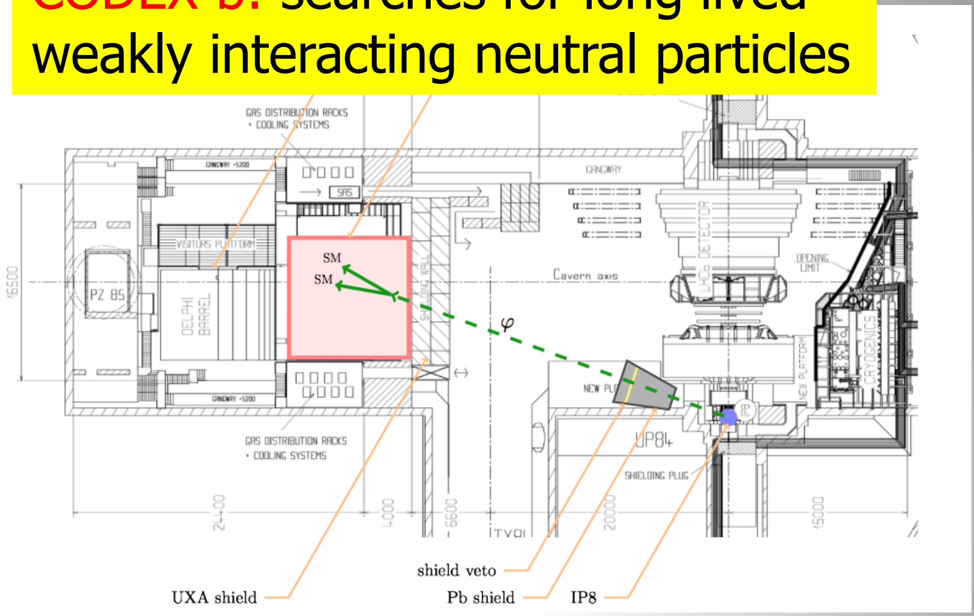


Proposals for New Experiments @LHC

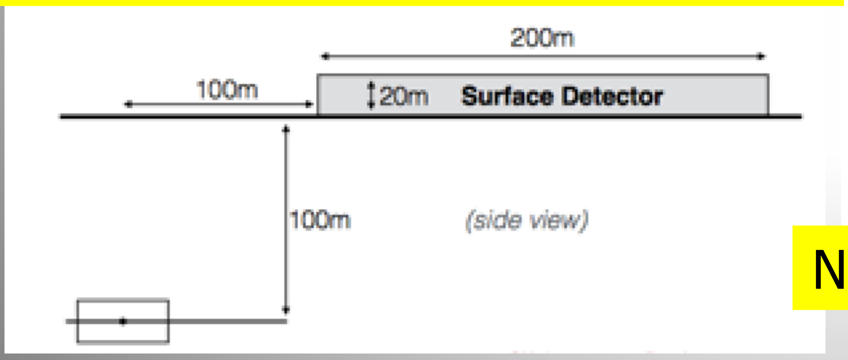
MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL



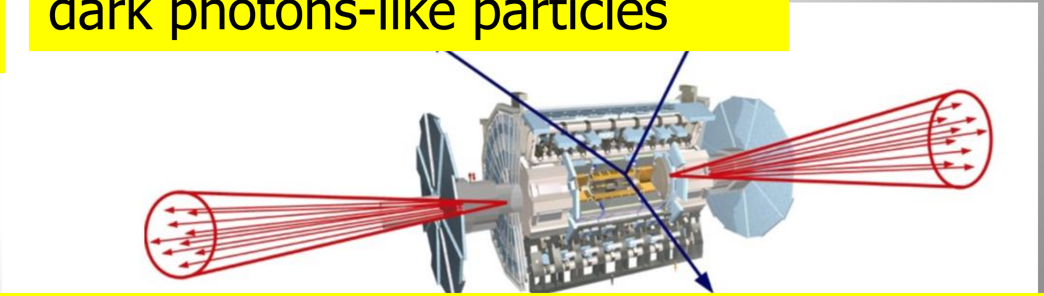
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



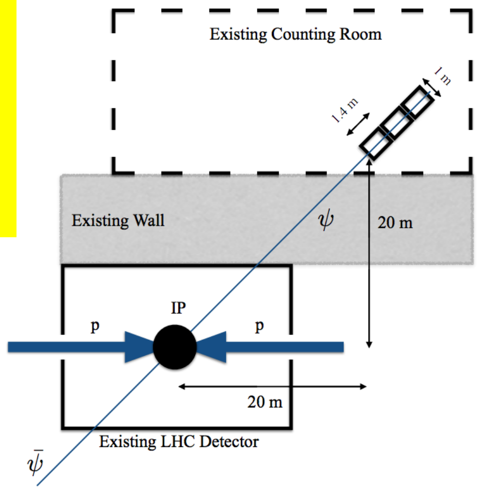
FASER: searches for long lived dark photons-like particles



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

Particles with Milli-Charges?

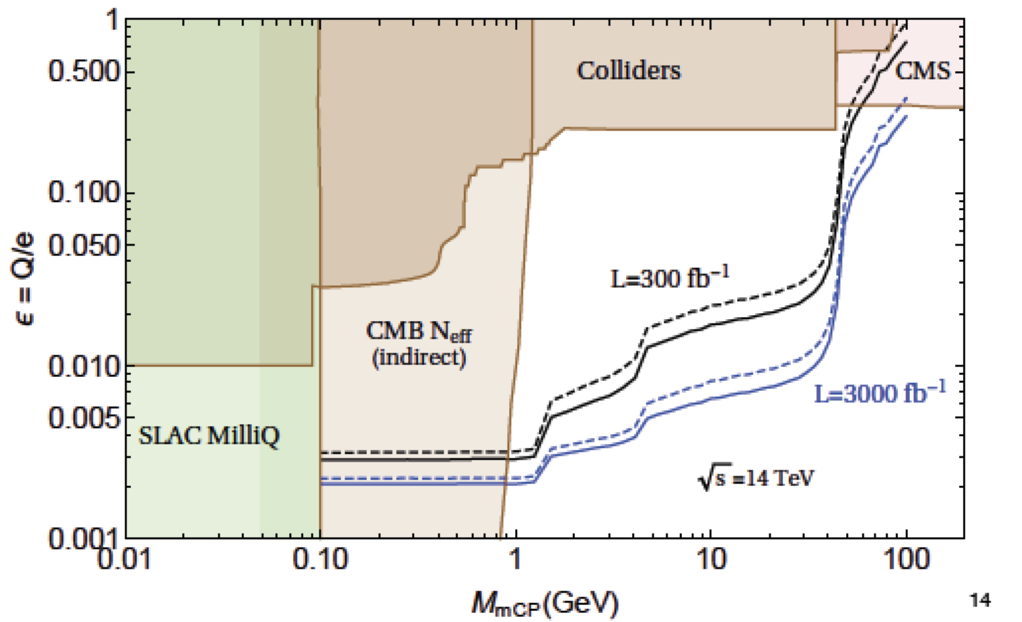
"New" idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017



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

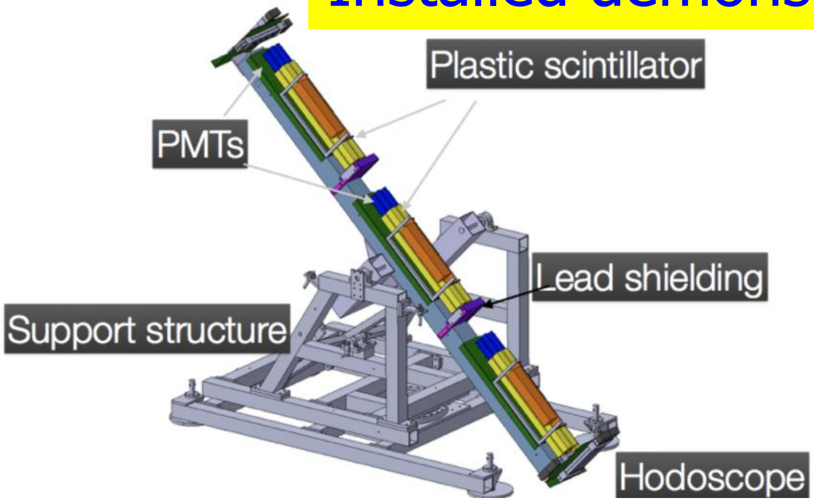
Motivation:

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

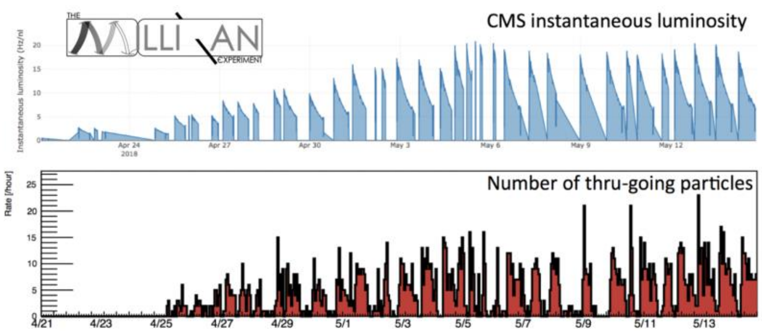
Detection technique:
scintillators-> low photon signals

MilliQan Experiment

Installed demonstrator in 2017



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”



- Took data since September 2017
  → ~100 fb^{-1} of data on tap
- First physics paper on these data?

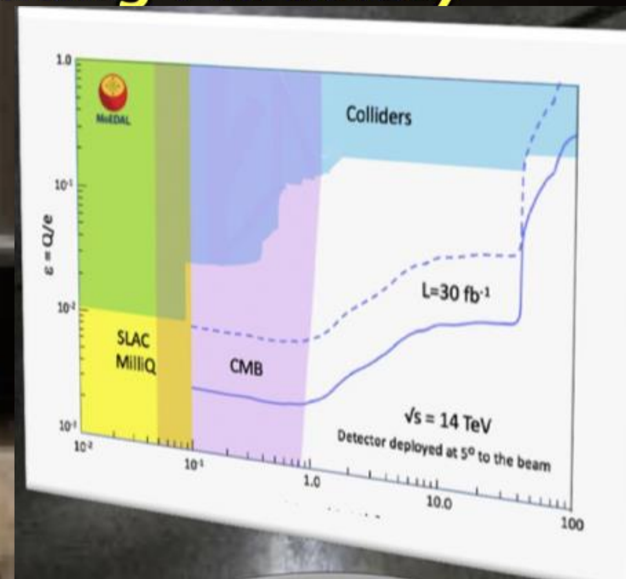
Dominant background: dark current pulses in the PMTs in coincidence with environmental radioactivity and cosmic rays

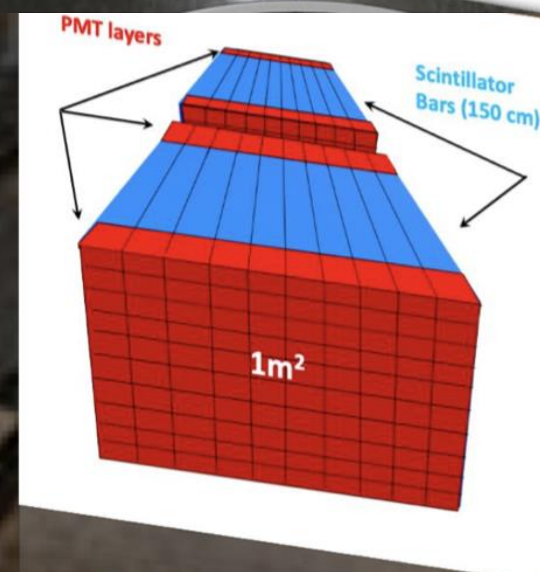
New design under study: 3 x 80cm → 4 x 60cm scintillator bars

MAPP* MoEDAL's Upgrade for RUN-3

*(MoEDAL Apparatus for Penetrating Particles)

- The Milli-charged particle (mQP) detector is a 1m x 1m x (2 x 1.5m) scintillator array, pointing to IP, in well shielded area of LHC Point 8 (LHCb)
  - Placed in UGC8 gallery ~100m underground Positioned at 55m from IP, 50m through rock, in the horizontal beam plane
  - Deployed from 5° to the beam (at 55m) to 25° to the beam (at 26 m)
  - 7-10m decay zones available in from of
  - Uses quadruple coincide between the two scintillator bars) sections (2 PMTs per bar)
  - Active veto against showers in rock
- Under construction during current shutdown
- Due to start data taking in LHC's RUN-3





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

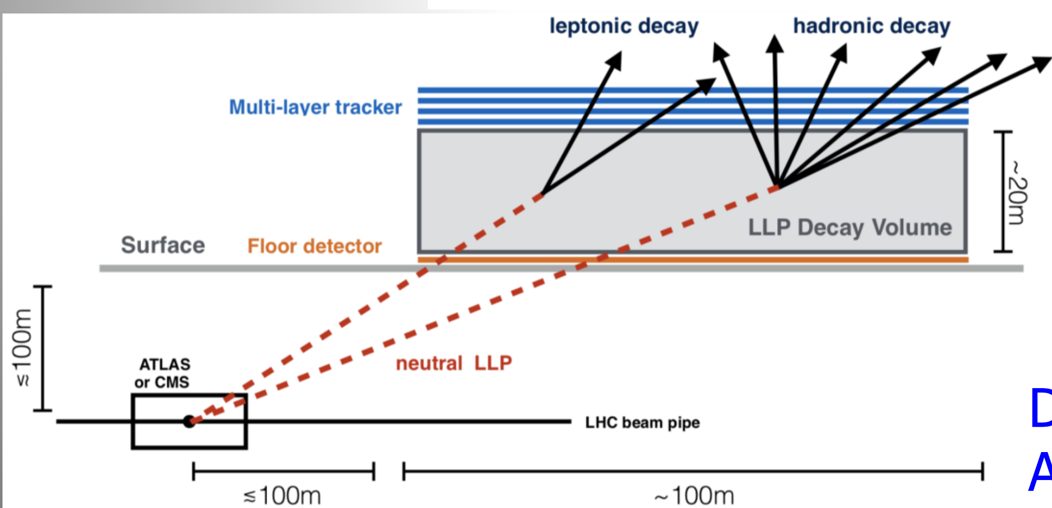
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

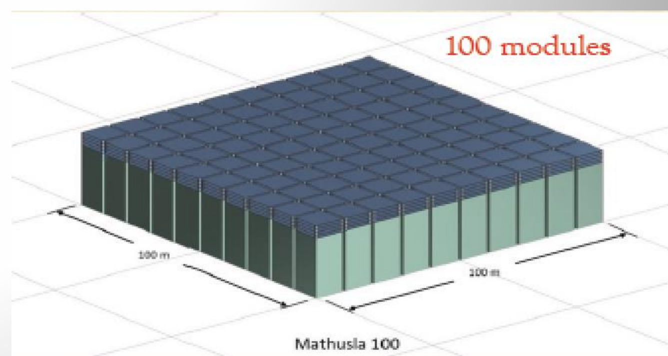
Aim to cover the range

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

~ BBN constrained inspired

Physic case arXiv:1806.07396





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

MATHUSLA

- **MATHUSLA: MAsive Timing Hodoscope for Ultra Stable neutraL pArticles**

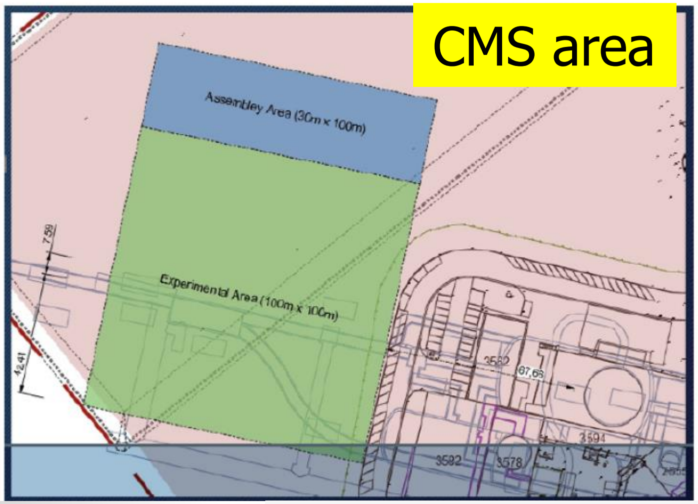
- The current MATHUSLA detector concept is 100x100 m^2 located at the surface of CMS
- Currently working with CERN civil engineers to:
  - determine the feasibility of excavating to install MATHUSLA slightly below surface
  - and feasibility of building a structure (building) with crane coverage to house MATHUSLA

Recent developments

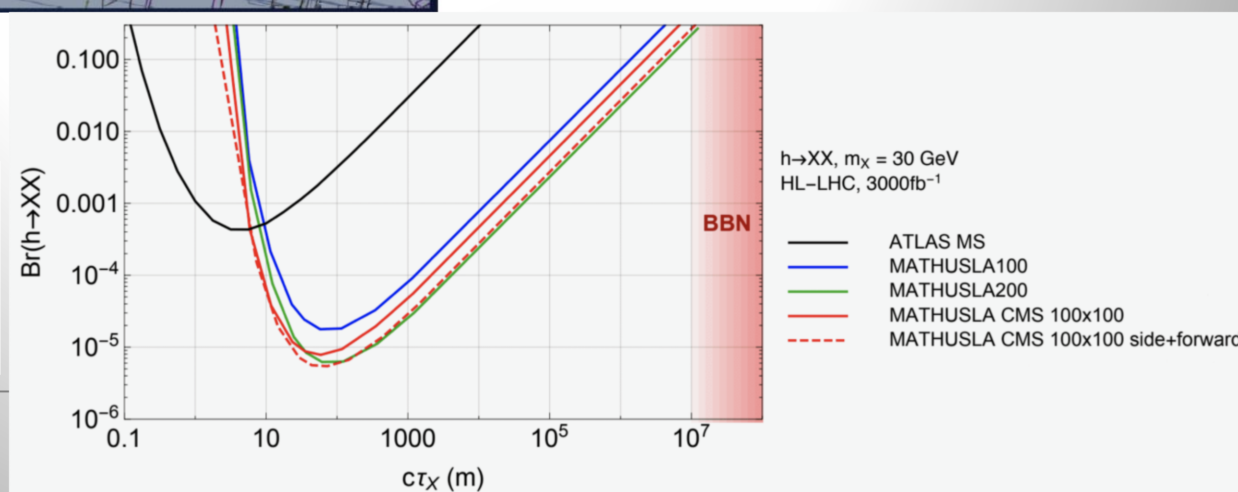
- Not on surface but make 5-10m deep hole to put it in.
- Size to 100mx100m
- Use scintillators instead of RPCs for the tracking stations

- 100m x 100m experimental area
- 30m x 100m assembly area
- ~7.5m offset to center of beam
- ~68m to IP

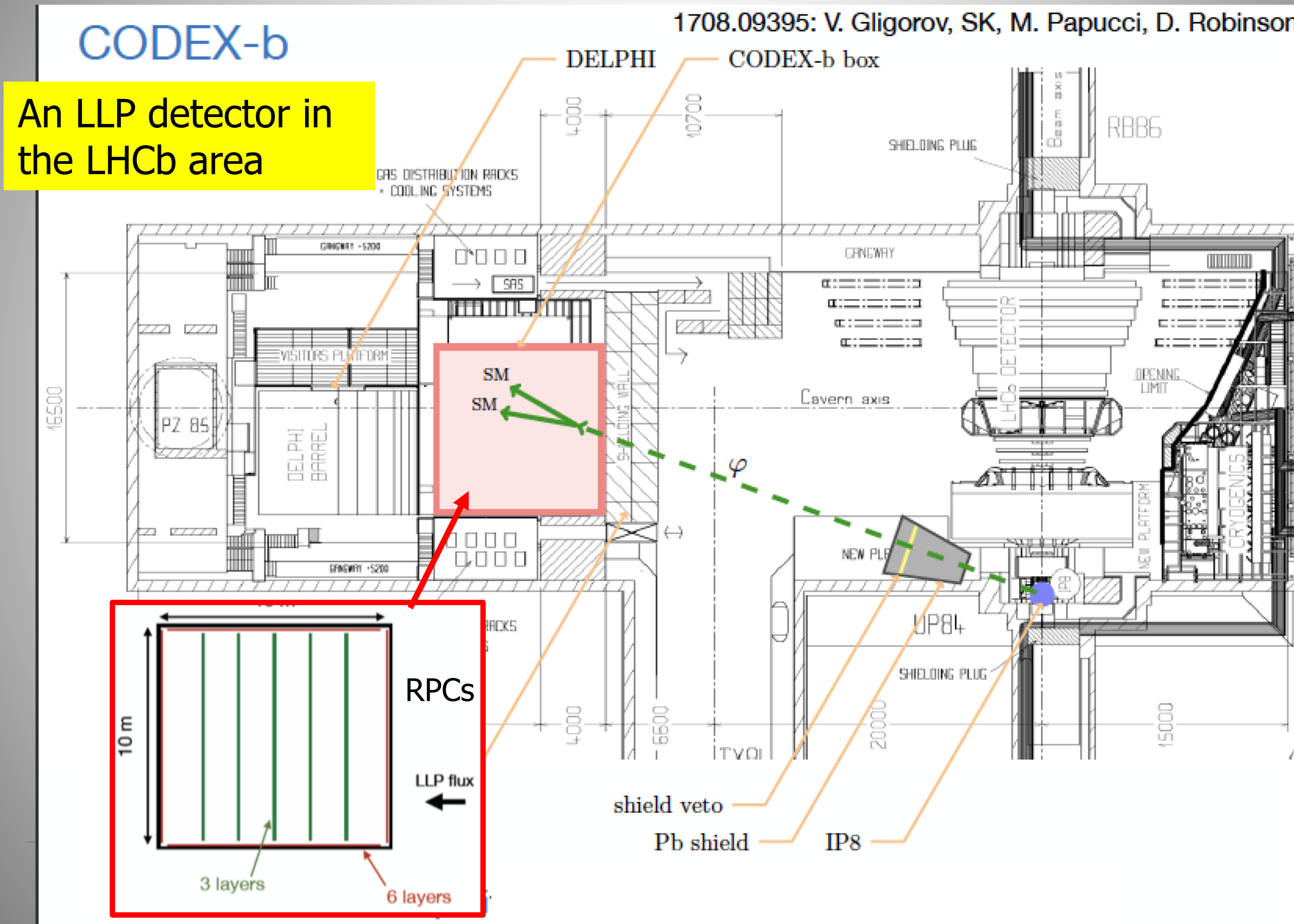
CMS area



MATHUSLA physics white paper arXiv:1806.07396



CODEX-b Proposal

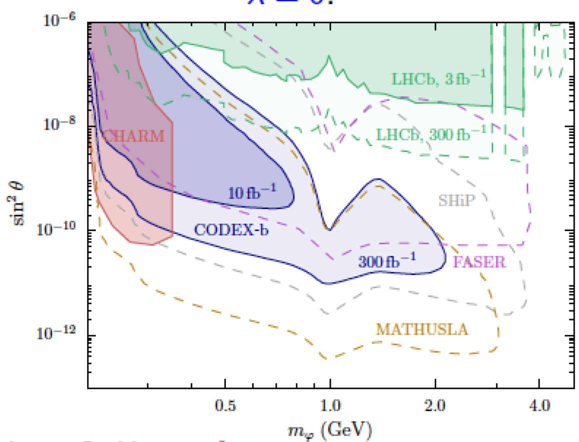


CODEX-b Proposal

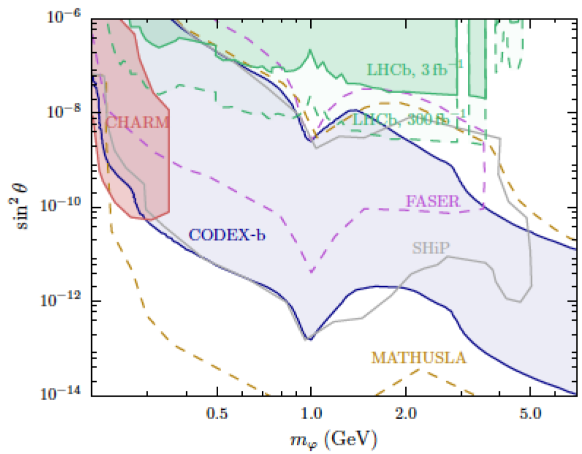
Example: Higgs-scalar mixing

- Minimal extension of Higgs sector: $\mathcal{L} \sim \mu\varphi HH^\dagger + \frac{\lambda}{2}\varphi^2 HH^\dagger$

$\lambda = 0$:

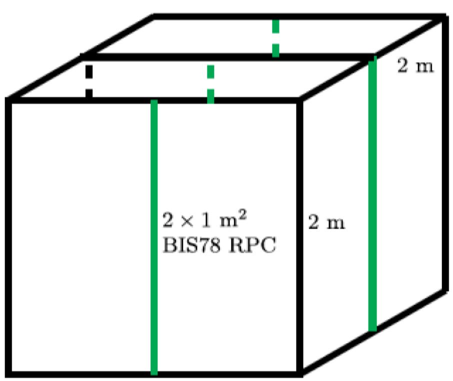


$\lambda = 1.6 \times 10^{-3}$:



[plots: S. Knapen]

- Scalar portal → Dark Higgs/scalars
- Neutrino portal → Heavy Neutral Leptons
- Pseudoscalar portal → Axion-like particles
- Vector portal → Dark photon



- $2 \times 2 \times 2$ m^3 demonstrator for Run 3 ⇒
- 6 faces + 1 inner station ⇒ 14 BIS78 triplet chambers.
- Enough space already in D1 area of the cavern once DAQ racks shifted out before EOY.
- Main goal: reconstruct K^0_L's in the volume from IP8 during 2021-23.

Demonstrator for Run 3

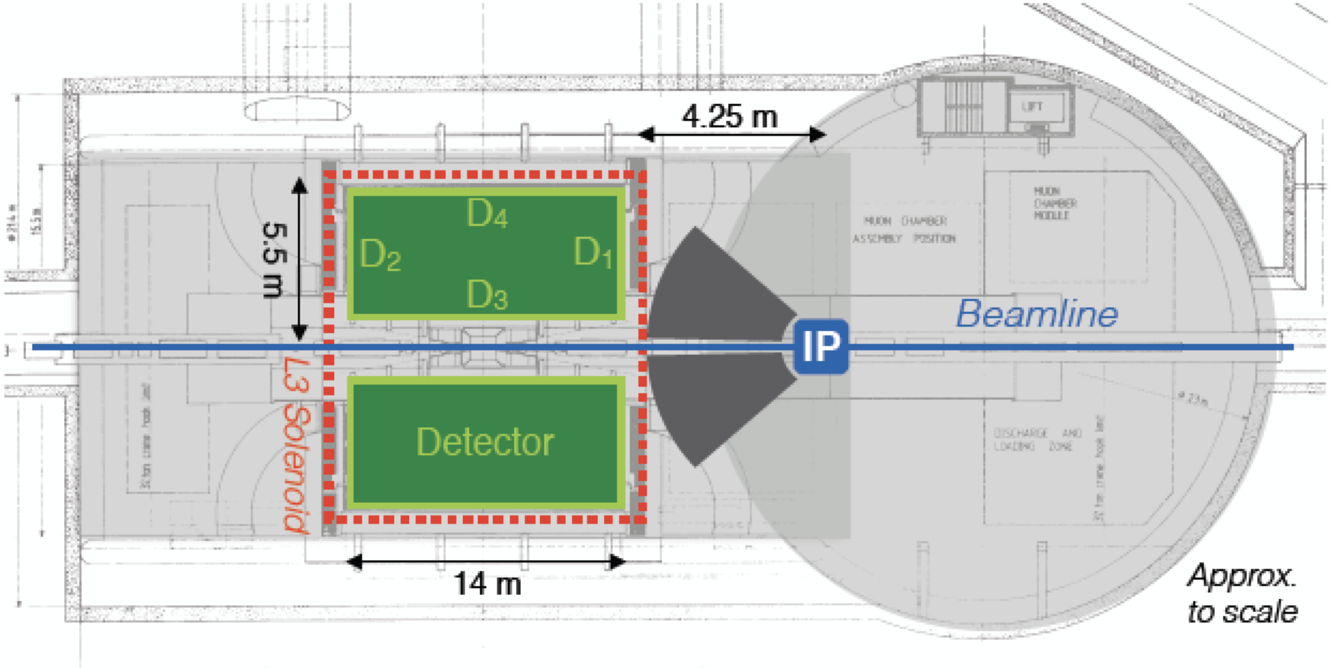
Limited background campaign in 2018 did not show nasty surprises

Re-using the ALICE detector?

A Laboratory for Long-Lived eXotics (AL3X)

Reuse the L3 magnet and (perhaps) the ALICE TPC

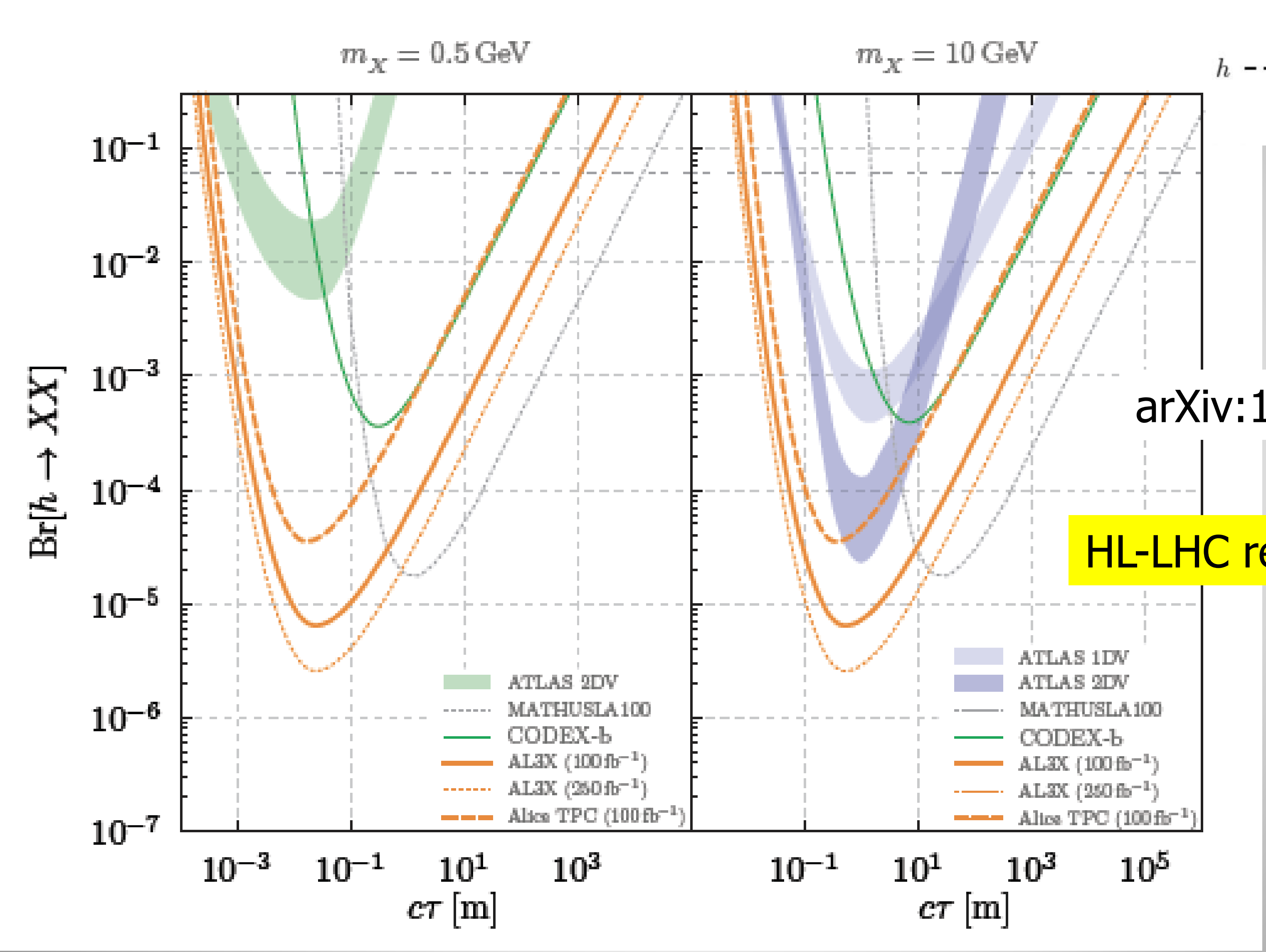
For LHC Run 5 or later??

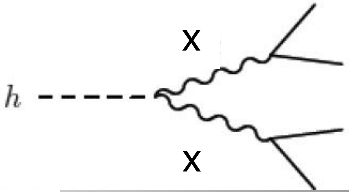


Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

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

Physics Reach: Example



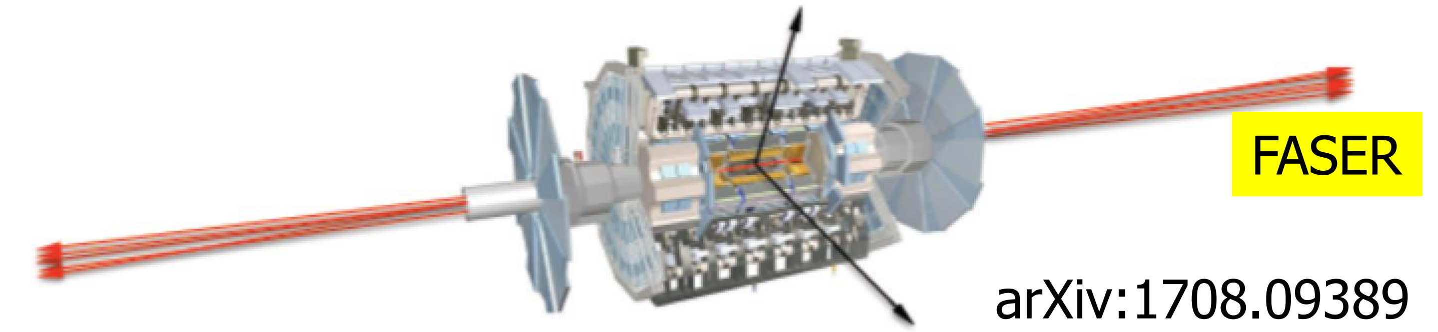


arXiv:1810.03636

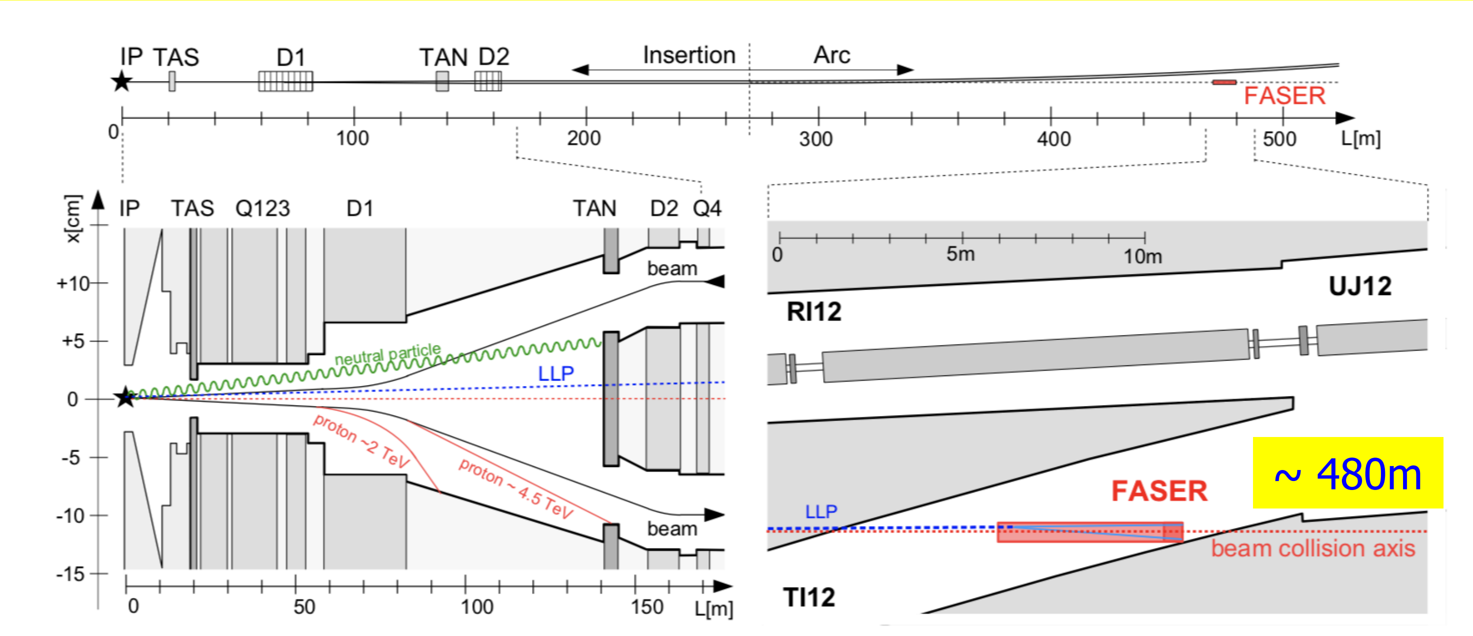
HL-LHC reach

For low masses: MATHUSLA, CODEX-b and AL3X have a leading edge

The FASER Experiment



FASER, ForwArd Search ExpeRiment, will search for light, extremely weakly-interacting particles at the LHC



FASER is in the line-of-sight, behind 100m of rock shielding. The LHC magnets sweep away charged particle backgrounds hence low radiation and low beam backgrounds

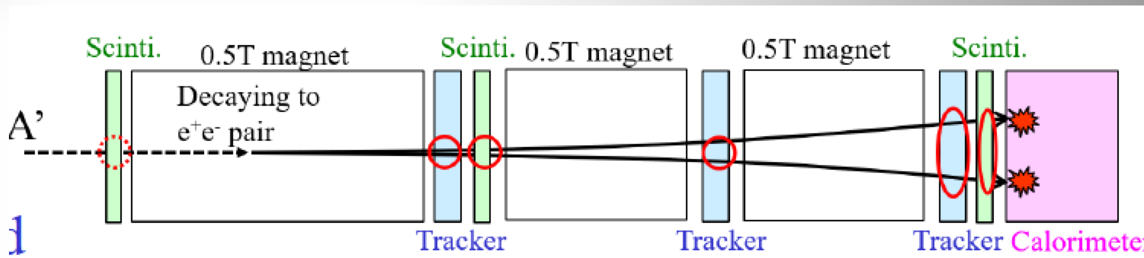
FASER Phase 1 Approval

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

INTERACTIONS.ORG
PARTICLE PHYSICS NEWS AND RESOURCES

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

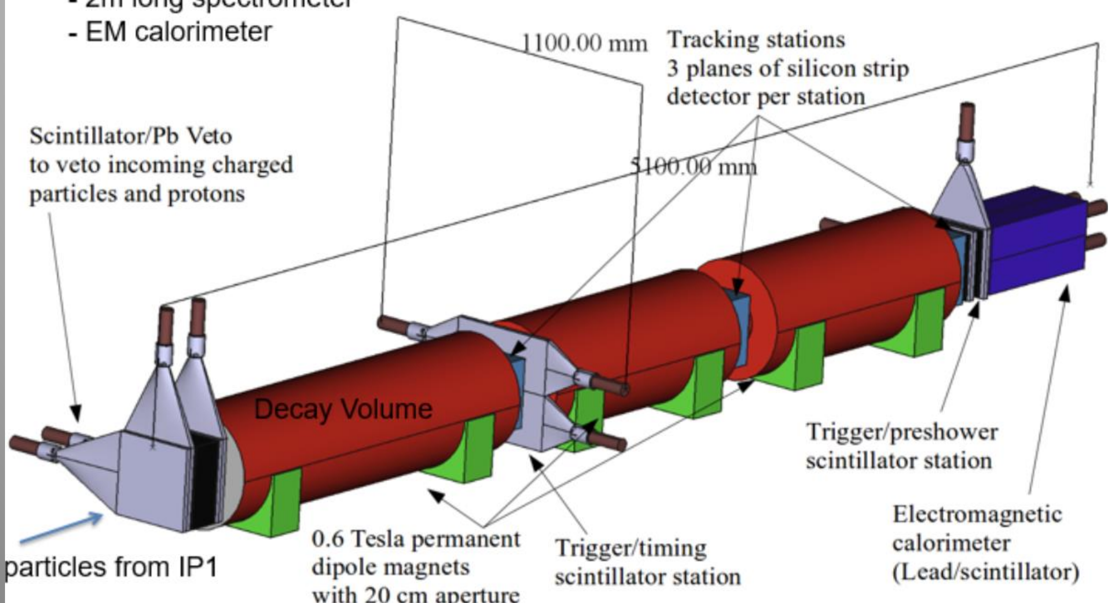
Date Issued
March 5th, 2019



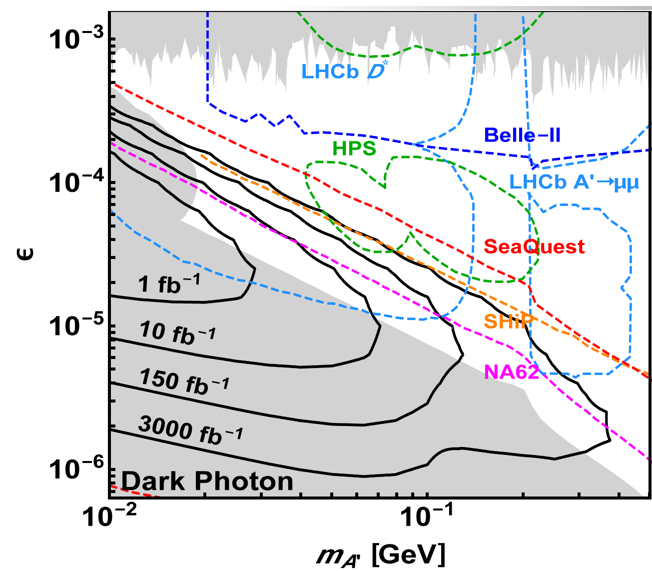
arXiv:1901.04468

THE FASER DETECTOR

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



Re-use spare ATLAS SCT silicon tracking modules and LHCb EM calorimeter modules

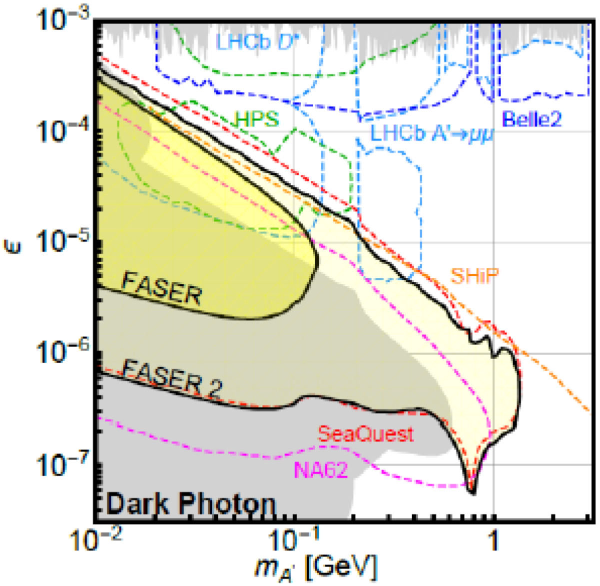


FASER Phase 2

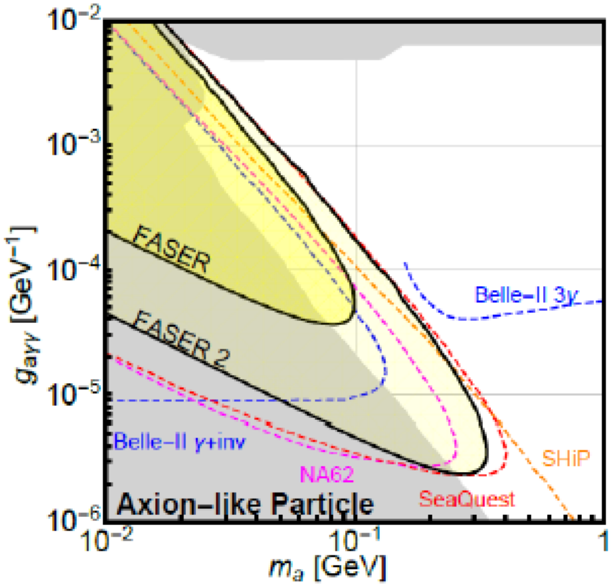
For the HL-LHC run..

- FASER2 is a potential upgrade to run in HL-LHC with bigger dimensions of the detector.
  - Radius: 1 m — To open the acceptance for decays from Ds & Bs
  - Decay volume length: 5 m
- FASER2 can explore much larger parameter space in dark sectors.

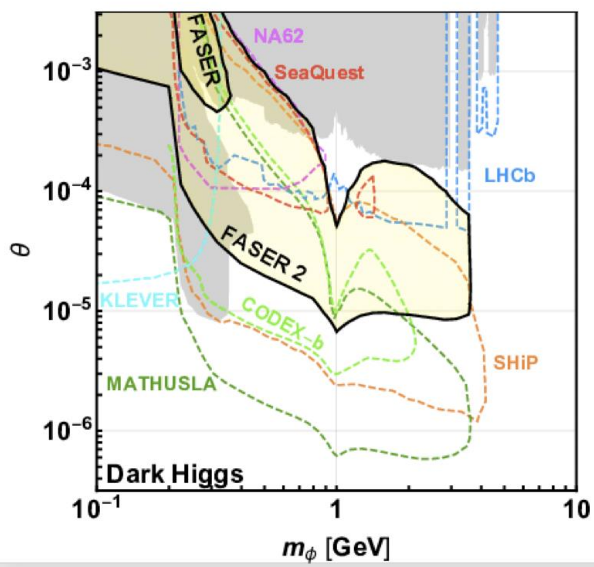
Dark Photon



Axion like particle



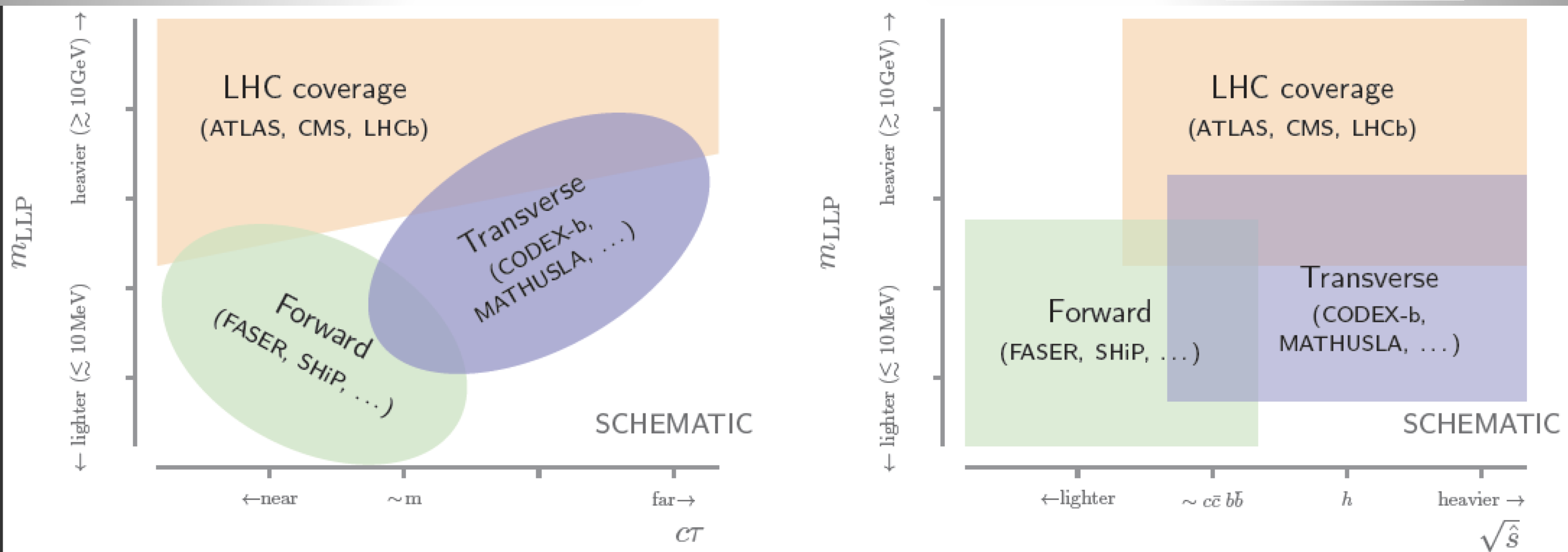
Dark Higgs



Experimental Complementarity

A rough sketch for the coverage for feebly interacting particles

V. Gligorov



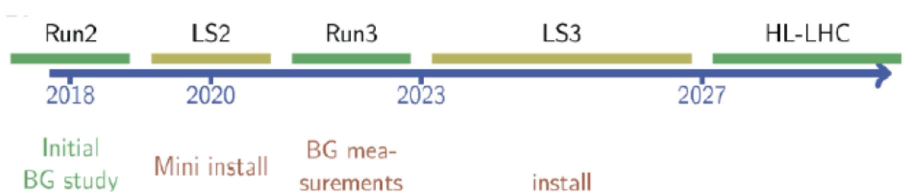
Status of the Various Projects

Lifetime frontier

Supplementary detectors

Based on Simon Knapen FNAL seminar fall 2018 (*)

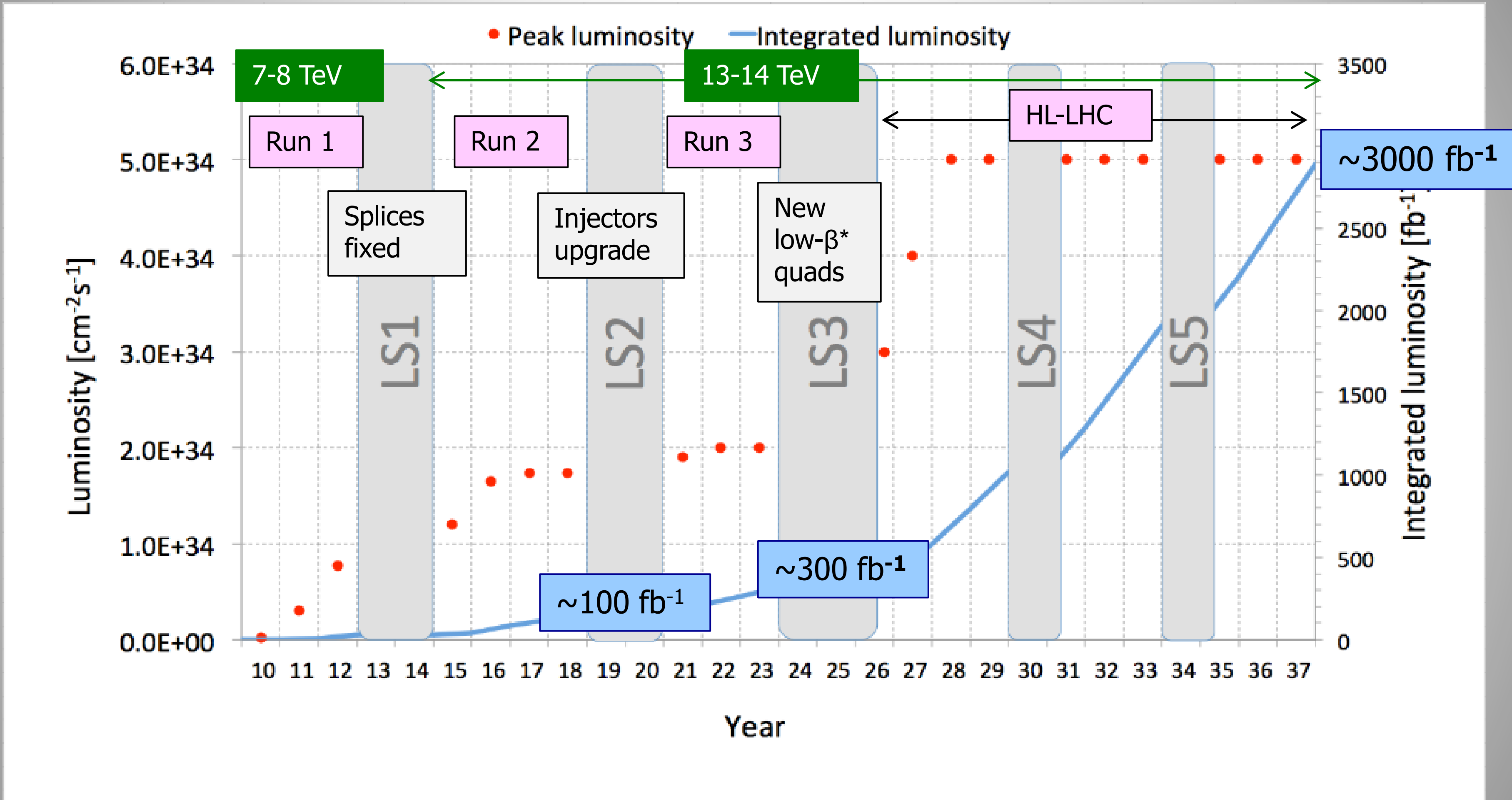
	Higgs Decay	B meson decay	π, η- decay dark photon	Progress	Cost
FASER		(✓)	✓	First phase approved and funded	$
CODEX-b	✓	✓		Sub-collaboration formed	$
MilliQan		(✓)		Sub-collaboration formed	$
AL3X	✓	✓	✓	Proof of concept	$$
MATHUSLA	✓	(✓)		Letter of Intent	$$
SHIP		✓	✓	Conceptual design report	$$$



- FASER1/MilliQan(?) installation by 2021
- MATHUSLA, CODEX-b, FASER2 for HL-LHC

(*) Experiments have different capabilities for measuring the LLPs

LHC Future Running till ~2037



Approved program at CERN to collect 3-4 ab^{-1} with the LHC (HL-LHC)

Maximize the reach for searches and for precision measurements (eg Higgs)

CERN High Beam Intensity Initiative

Status and Prospects of PHYSICS BEYOND COLLIDERS at CERN

Study Group mandated by the CERN Management
to prepare the next European HEP strategy update (2019-20
(coordination: J. Jäckel, M. Lamont, C.V.)

Excerpt from the mandate:

"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."

Time scale: next 2 decades

Physics Beyond Colliders at CERN 1

Many studies on
long lived particles

Summary plots of the
reach are being completed
for the European Strategy
Document (November)

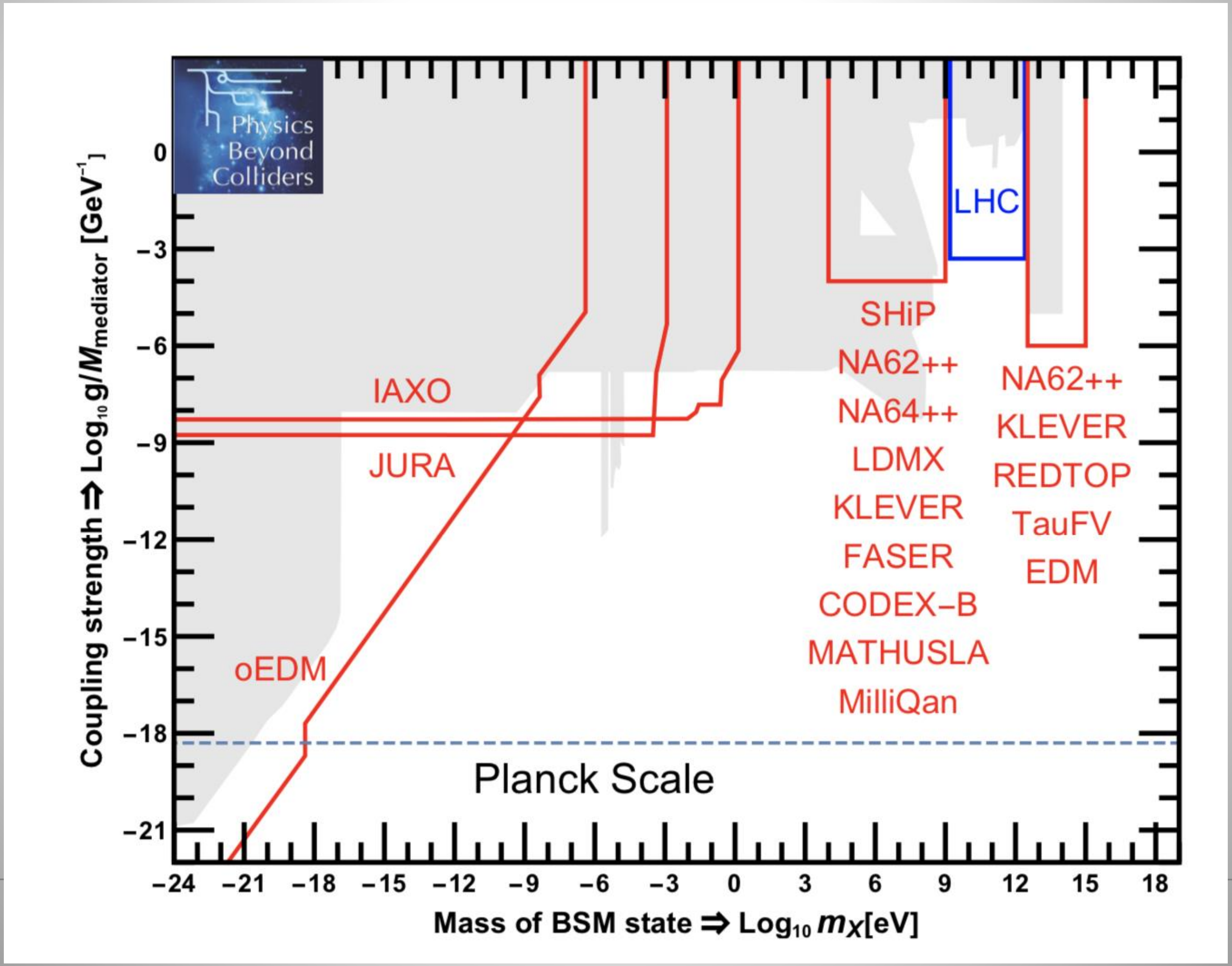
Last workshop (January '19)
https://indico.cern.ch/event/755856/

Next workshop November 5-6

NA62, NA64, SHIP, LHC new experiments…

New Possible Experiments

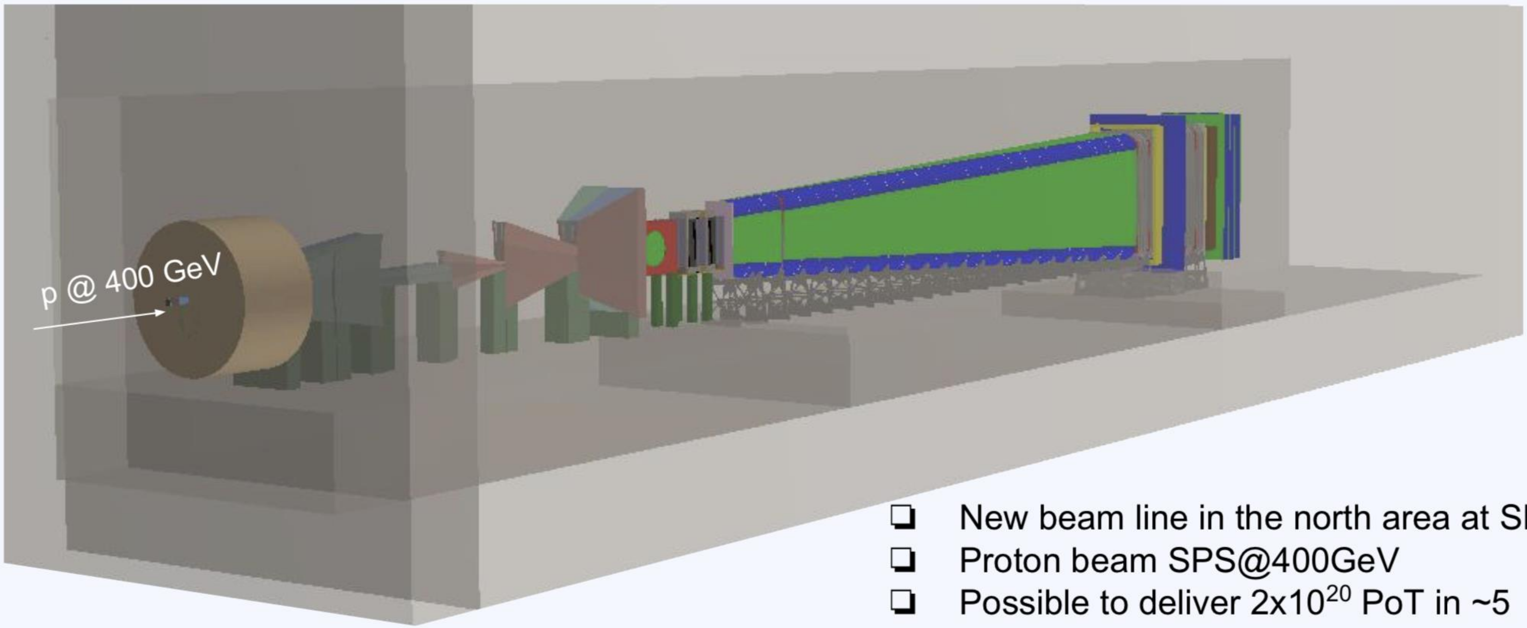
From the beyond collider study document: arXiv:1902.00260



SHiP Beam Dump Experiment Proposal

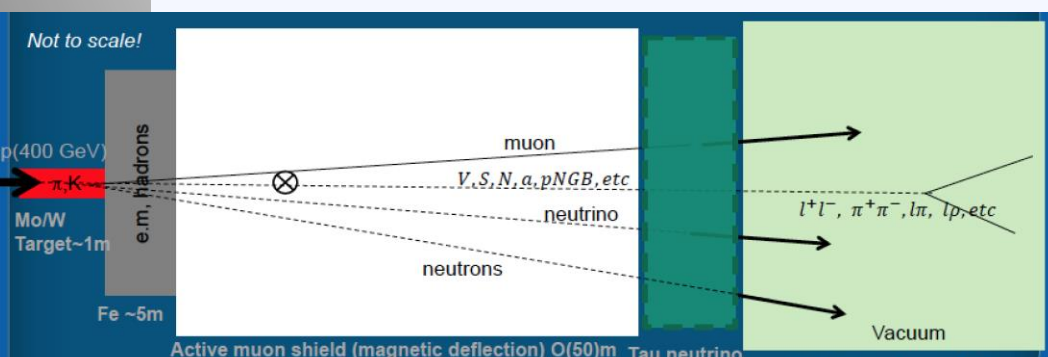
SHiP is a proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to O(10) GeV and weak couplings, down to 10^{-10} .

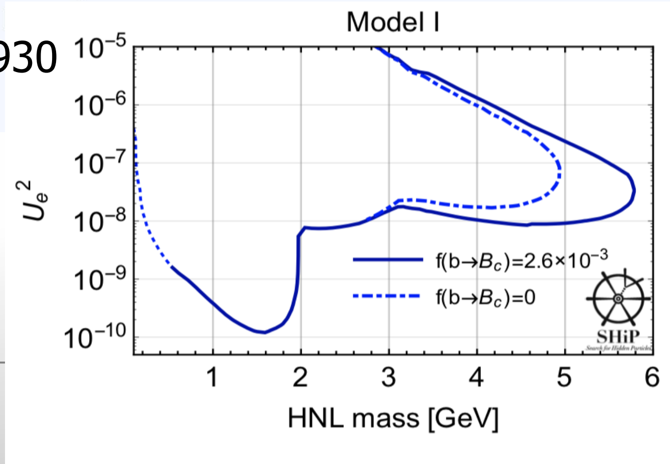
arXiv:1504.04956



- New beam line in the north area at SPS
- Proton beam SPS@400GeV
- Possible to deliver 2×10^{20} PoT in ~5 years

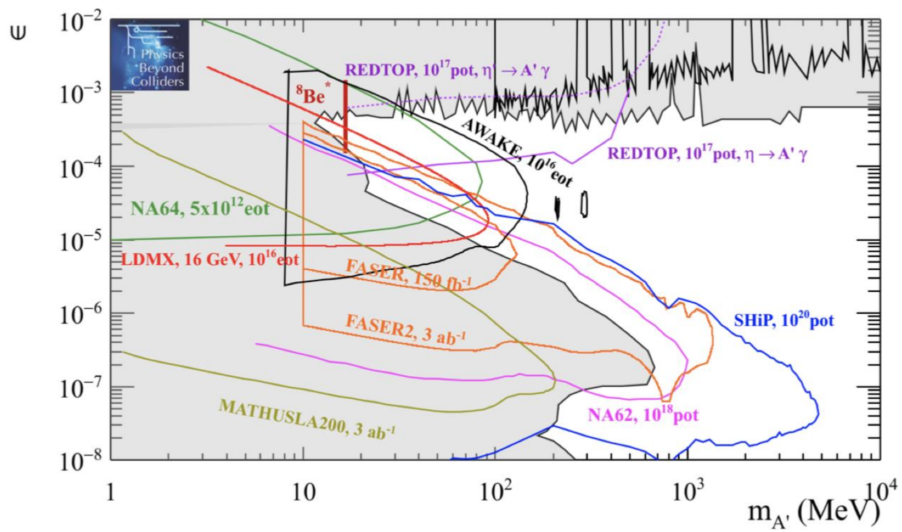
arXiv:1811.00930



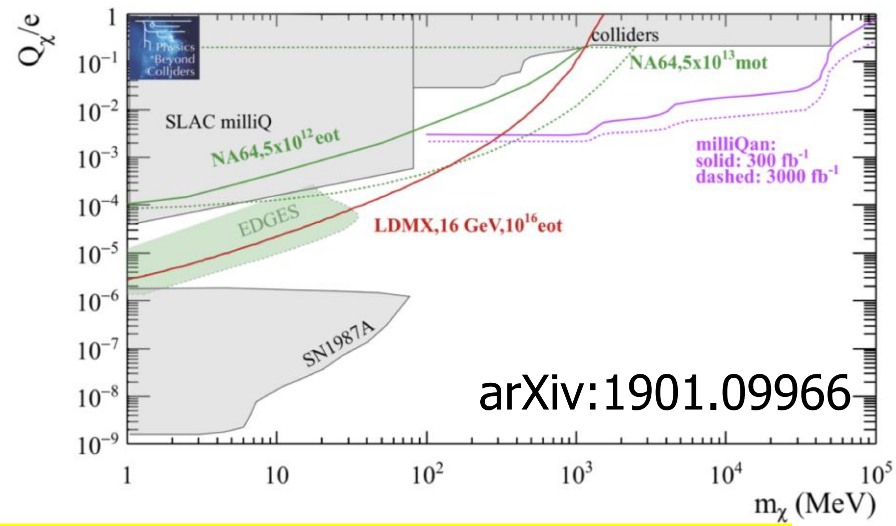


Sensitivity Summaries

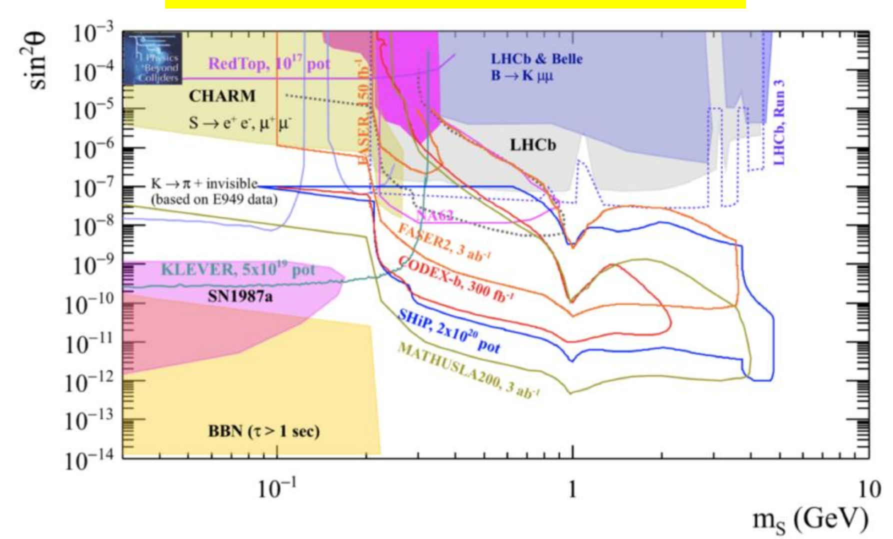
Search for dark photons (visible mode)



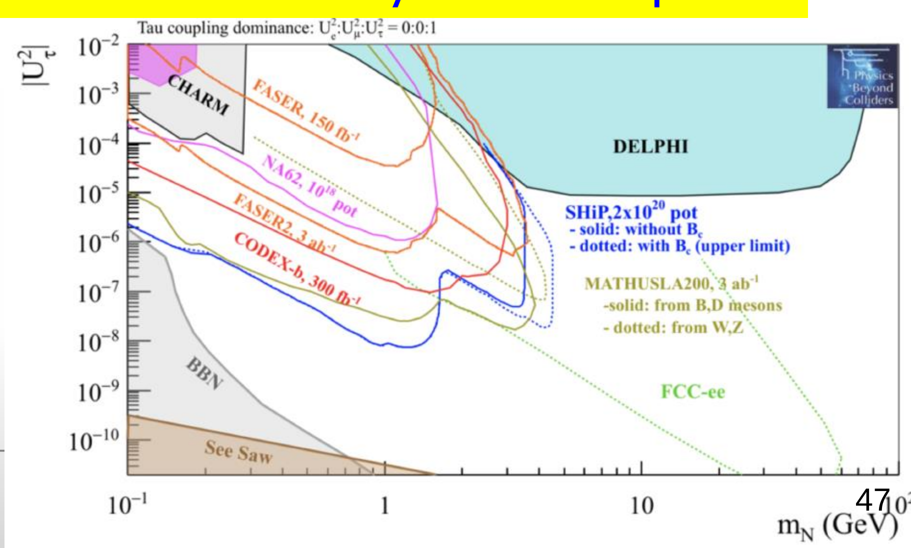
Search for millicharges



Search for dark scalars

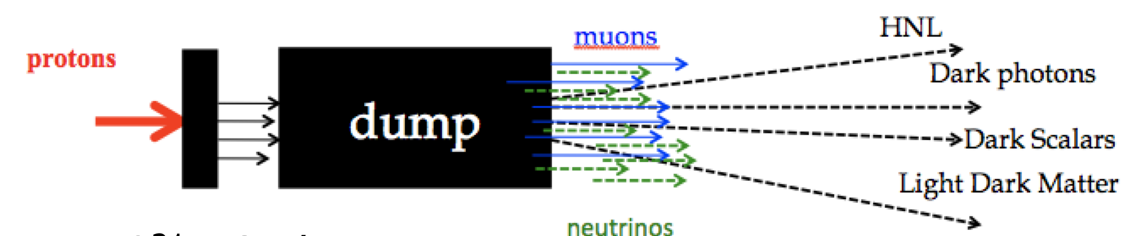


Search for heavy neutral leptons



Beam Dump Experiments

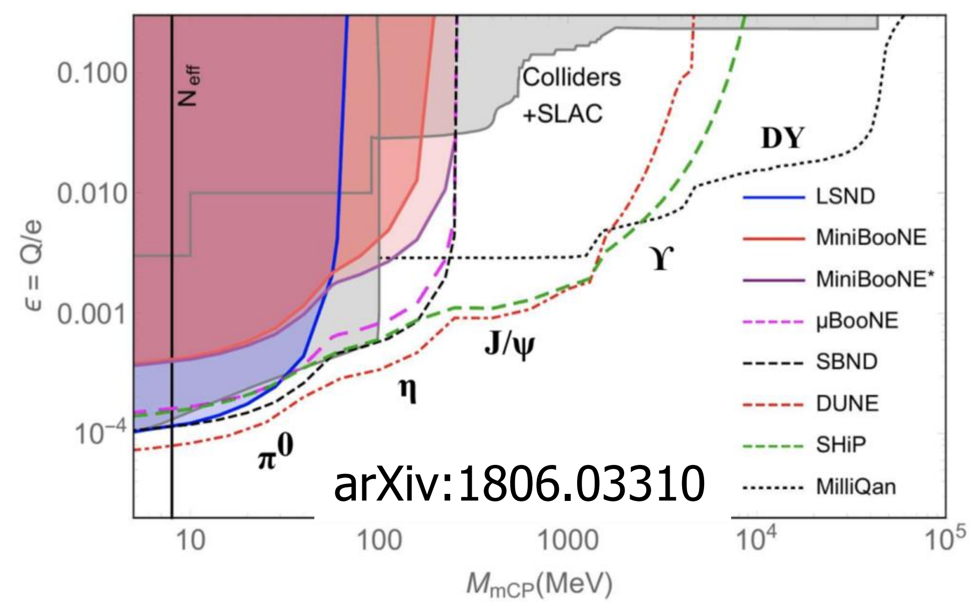
High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



> 10^{21} POT/Year

Near Detector: few 100m away from the dump

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?

More Milli-Charge Hunting

A proposal for milli-charges at FNAL @ MINOS near detector
Submitted end of May

FerMINI: Fermilab Search for Milicharged Particle

J. F. Hirschauer, (Principle Investigator) and Y.-D. Tsai (Co-Investigator)

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

A. Haas (Co-Investigator)

New York University, New York, NY 10003, USA

C. Hill (Co-Investigator)

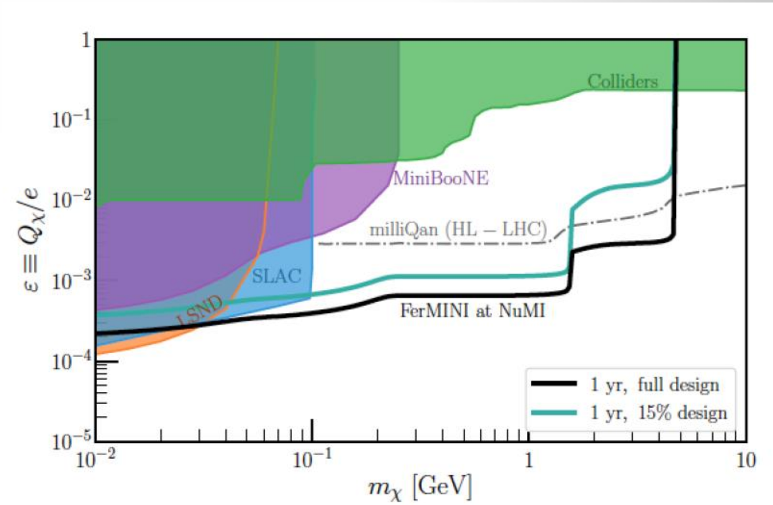
Ohio State University, Columbus, OH 43210, USA

D. Miller (Co-Investigator)

University of Chicago, Chicago, IL 60637, USA

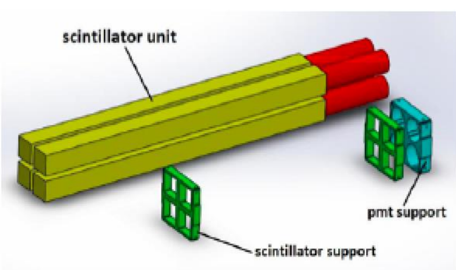
D. Stuart (Co-Investigator)

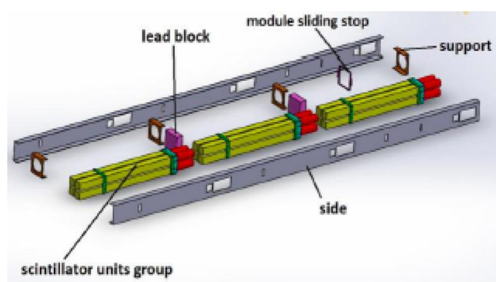
University of California, Santa Barbara, CA 93106-9530, USA

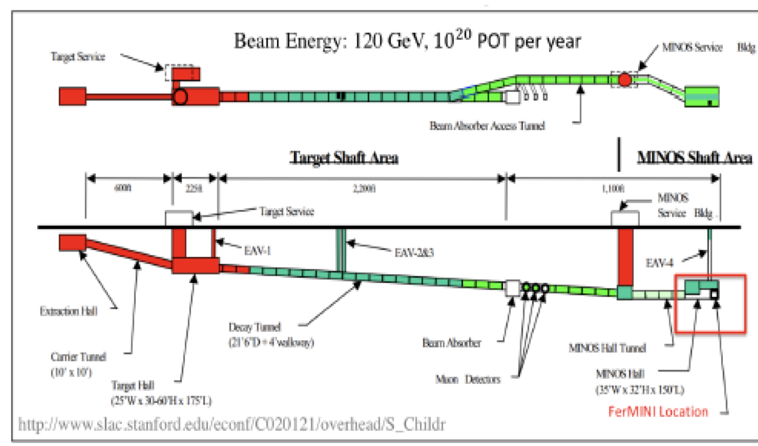


See also: arXiv:1806.03310

Based on the MilliQan design







Current Neutral LLP Searches

2016

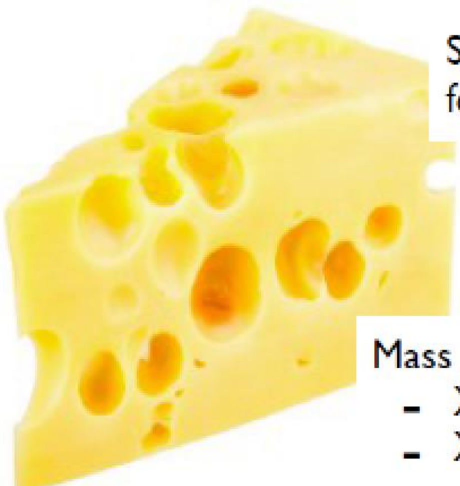
at the LHC

Exp	Search	run	signal	LLP Daughters	LLP Scale	Parent Scale	Associated Objects	# LLP Decays	decay Location	decay Detector	L1 trigger
CMS	EXO-12-035-pas	8 TeV	GMSB neutralino → γ + G	γ + MET	100-300 GeV	x2 + ~ 50	jets, MET	1	tracker	ECAL (timing)	one photon
	EXO-14-017-pas	8 TeV	GMSB neutralino → γ + G	γ + MET	200-300 GeV	x2 + ~ 50	MET	2	tracker	tracker (convers▸	diphoton
	1211.2472	7 TeV	H->XX	2 leptons	20+ GeV	100+ GeV	none	2	tracker	same	dilepton
	1411.6530v2	8 TeV	H->XX, RPV SUSY	2 jets	50+ GeV	200+ GeV	none or jets	1	tracker	same	HT > 300 GeV
	1411.6977	8 TeV	H->XX, RPV SUSY	2 leptons	20+ GeV	100+ GeV	none	1	tracker	same	dilepton
	1409.4789	8 TeV	RPV SUSY	e and mu	0.5 – 1 TeV	x2	none	2	tracker	tracker, MS	one muon
ATLAS	1504.03634	8 TeV	H->XX, HV Z', Stealth SUSY	2x ~ anything	10+ GeV	100+ GeV	none	2	Muon System	same	Muon RoI
	1501.04020	8 TeV	H->XX	2x ~ anything	10+ GeV	100+ GeV	none	2	HCAL	same	CalRatio
	1409.0746	8 TeV	H → HV .. → X X	2 leptons	0.4 – 2 GeV	~ 100 GeV	none	2	tracker	same	standard lepton(s)
	1504.05162	8 TeV	SUSY (split, rpv, gmsb)	2 leptons or 5+ charges	10+ GeV	600+ GeV	various		tracker	same	HARD MET, Jet, lepton
LHCb	1412.3021	7tev 0.62/fb	H->XX	2 quarks	25 – 50 GeV	100 GeV	none	1	0.4-4.8mm From beam	tracker	single track > 1.5 – 3.5 GeV

not yet

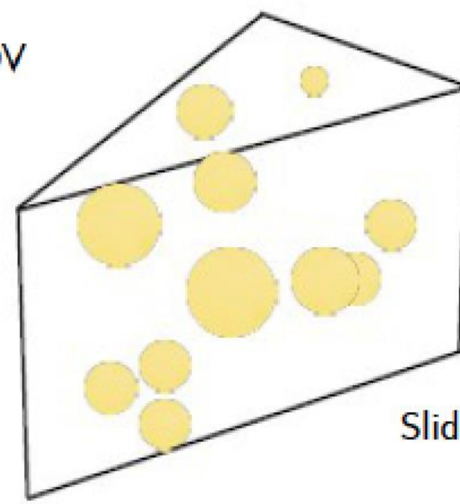
Need a more systematic approach

more like



Shorter lifetimes: identify DV for < ~ mm displacements

Mass gaps in current searches:
- X→ leptons: 2 - 20 GeV
- X→ hadrons: < 10 GeV



Slide from D. Curtin

LHC Community White Paper

Web page: https://indico.cern.ch/event/649760

Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community

17 Oct 2017, 16:00 → 20 Oct 2017, 18:00 Europe/Zurich

Giambiagi Lecture Hall (ICTP, Trieste, Italy)

Albert De Roeck (CERN), Bobby Samir Acharya (Abdus Salam Int. Cent. Theor. Phys. (IT)), Brian Shuve (SLAC National Accelerator Laboratory), James Beacham (Ohio State University (US)), Xabier Cid Vidal (Universidade de Santiago de Compostela)

Recent workshop: 27-29 May 2019 CERN

ICTP 2017

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

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

White Paper being finalized

Input from ATLAS, CMS, LHCb, proposed specialized experiments and theory
Completed March 2019
(~ 300 pages)

Also meetings with
LHC Dark Matter group

Recent Reviews/Reports

arXiv.org > hep-ex > arXiv:1903.04497

High Energy Physics – Experiment

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

White paper of the LHC long-lived particle community
Accepted by J.Phys.G

CERN-PBC-REPORT-2018-003

Physics Beyond Colliders

arXiv.org > hep-ex > arXiv:1902.00260

Report of the CERN Physics Beyond Colliders Working group

Summary Report of Physics Beyond Colliders at CERN

*R. Alemany[1], C. Burrage[2], H. Bartosik[1], J. Bernhard[1], J. Boyd[1], M. Brugger[1], M. Calviani[1], C. Carli[1], N. Charitonidis[1], D. Curtin[23], A. Dainese[34], A. de Roeck[1], M. Diehl[3], B. Döbrich[1], L. Evans[1], J.L. Feng[24], M. Ferro-Luzzi[1], L. Gatignon[1], S. Gilardoni[1], S. Gninenko[19], G. Graziani[32], E. Gschwendtner[1], B. Goddard[1], A. Hartin[16], I. Irastorza[20], J. Jaeckel[*4], R. Jacobsson[1], K. Jungmann[5], K. Kirch[6], F. Kling[24], W. Krasny[13], M. Lamont[*1], G. Lanfranchi[7], J-P. Lansberg[27], A. Lindner[3], K. Long[12], A. Magnon[1], G. Mallot[1], F. Martinez Vidal[21], M. Moulson[7], M. Papucci[1], J. M. Pawlowski[4], I. Pedraza[25], K. Petridis[18], M. Pospelov[8], S. Pulawski[31], S. Redaelli[1], S. Rozanov[9], G. Rumolo[1], G. Ruoso[10], J. Schacher[29], G. Schnell[11], P. Schuster[22], Y. Semertzidis[14], A. Siemko[1], T. Spadaro[7], S. Stapnes[1], A. Stocchi[28], H. Ströher[15], G. Usai[30], C. Vallée[*9], G. Venanzoni[26], G. Wilkinson[33], and M. Wing[16]*

Collider Searches for Long-Lived Particles Beyond the Standard Model

Lawrence Lee[1], Christian Ohm[2,3], Abner Soffer[4], Tien-Tien Yu[5,6]

arXiv.org > hep-ph > arXiv:1810.12602

Present LHC coverage paper

Summary

- Clearly and increased interest in LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. Many analyses done or are in progress. No signal observed yet, but only the top of the iceberg has been covered so far.
- MoEDAL is a small dedicated experiment for a search for highly ionizing particles, such as monopoles, using unique detection techniques at the LHC.
- New ideas for additional new experiments at the LHC to increase the LHC coverage: MilliQan, MAPP, MATHUSLA, CODEX-b, FASER, AL3X…
- These proposals are at a different stage of progress, approval and funding right now. FASER1 is approved/funded.
- We are still hunting for new physics! It takes only one significant deviation to show the way… . and maybe one day soon…

BACKUP

Neutrino Detector & Program

Note: anti-ν_τ has never been observed

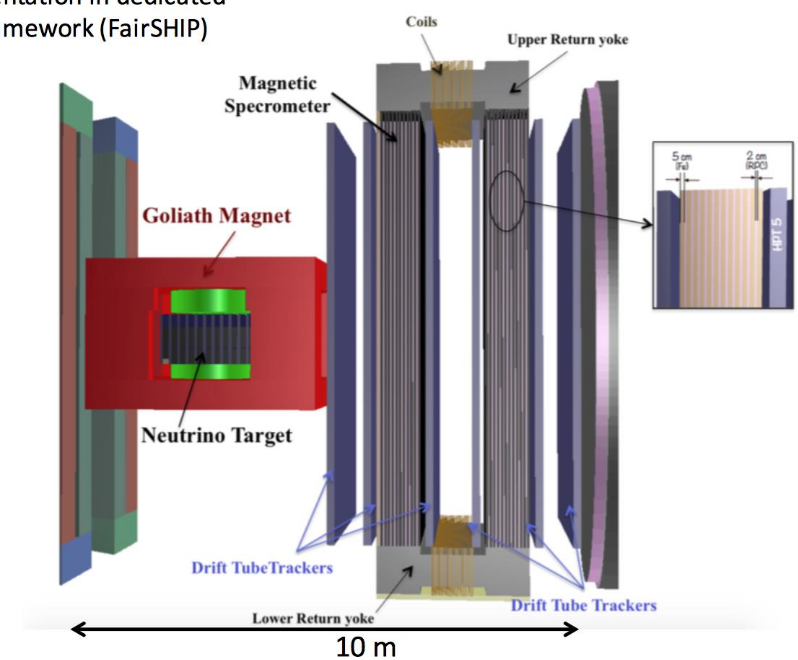
SHiP neutrino program

~8k expected ν_τ and ~4k anti-ν_τ interactions in the target

- First observation of anti-ν_τ
- Sufficient statistics to perform ν_τ and anti-ν_τ cross section measurement.
- First measurement of structure function F_4 and F_5 entering in DIS neutrino-nucleon cross section

Follows the OPERA concept

Implementation in dedicated CERN framework (FairSHIP)



	<E> (GeV)	Interactions
N_{ν_e}	46	2.5×10^5
N_{ν_μ}	29	1.7×10^6
N_{ν_τ}	59	7.4×10^3
$N_{\bar{\nu}_e}$	46	9.0×10^4
$N_{\bar{\nu}_\mu}$	28	6.7×10^5
$N_{\bar{\nu}_\tau}$	58	3.7×10^3

Neutrino interactions for 5 year running

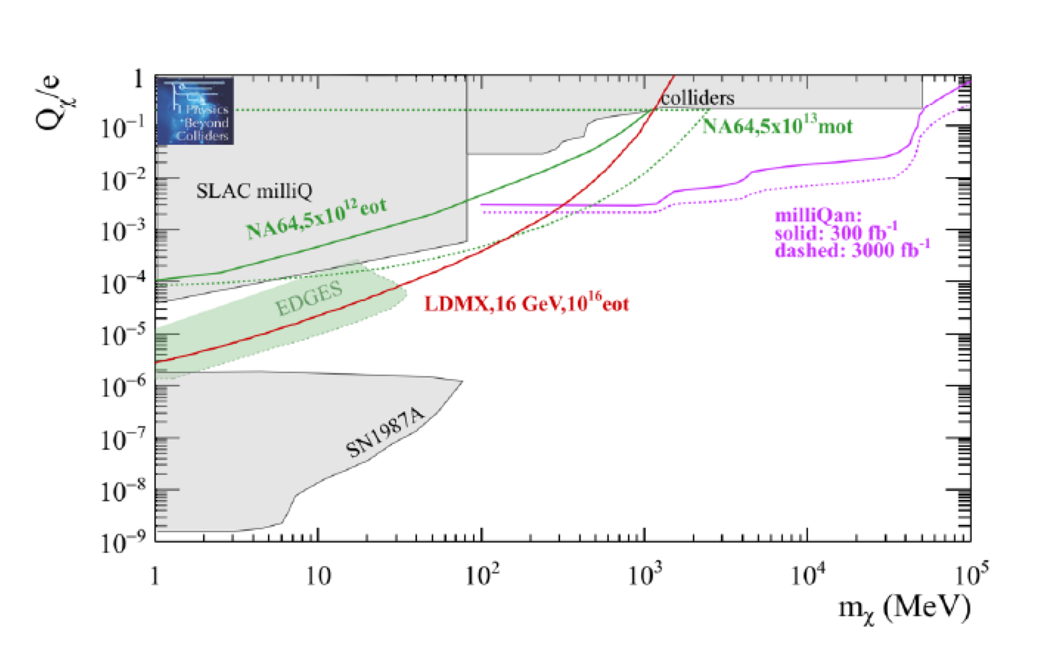
More Milli-Charge Activities

Physics Beyond Collider Study

arXiv:1901.09966

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

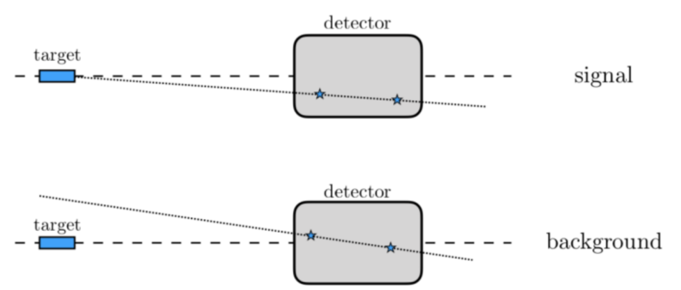
J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], 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].



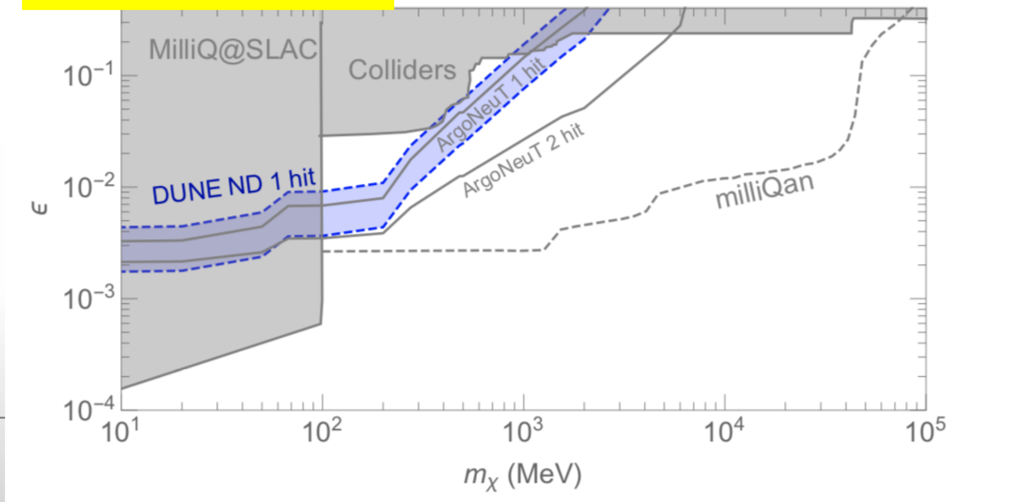
Millicharged Particles in Liquid Argon Neutrino Experiments

Roni Harnik[1], Zhen Liu[2], and Ornella Palamara[1]
[1] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[2] Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742-4111 USA

arXiv:1902.03246

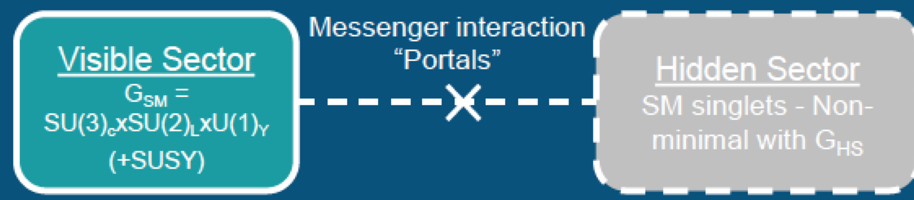


LArTPC study



Physics Goals

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$

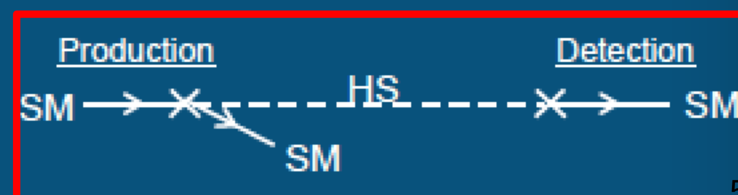


New physics prospects in the hidden sector

Explore Hidden Portals and extensions of the Standard Model incorporating long lived and very weakly interacting particles

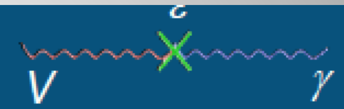
- Vector portals: motivated by 'mirror world', constituting dark matter, g-2 anom.
- Scalar portals: right handed neutrinos,dark matter, inflation,"dark naturalness"
- Neutrino portals: neutrino oscillations, dark matter, baryon asymmetry…
- Axion portals: extended Higgs, SUSY breaking, dark matter, inflation…
- SUSY portals…

- Two search methods:
  1. "Indirect detection" through portals in (missing mass)
  2. "Direct detection" through both portals in and out



Details on the Portals

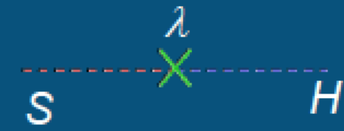
- **D = 2: Vector portal**



  - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F_{\mu\nu}^{SM} F_{HS}^{\mu\nu}$

  ➔ Motivated in part by idea of "mirror world" restoring left and right symmetry, constituting dark matter, g-2 anomaly, …
  - Production: proton bremsstrahlung, direct QCD production $q\bar{\bar{q}} \to V, qg \to Vq$, meson decays ($\pi^0, \eta,\ \omega,\ \eta', \dots$)

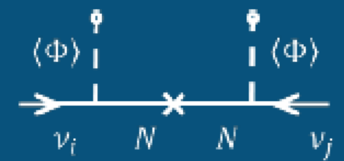
- **D = 2: Scalar portal**



  - Mass mixing with dark singlet scalar χ : $(gS + \lambda S^2)H^\dagger H$

  ➔ Mass to Higgs boson and right-handed neutrino, inflaton, dark phase transitions BAU, dark matter, "dark naturalness",…
  - Production: Direct $p + target \to X + S$, meson decays e.g. $B \to KS,\ K \to \pi S$

- **D = 5/2: Neutrino portal**



  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^\dagger \bar{N}_I L_\ell$

  ➔ Neutrino oscillation, baryon asymmetry, dark matter
  - Production: Leptonic, semi-leptonic decays of heavy hadrons

- **D = 4: Axion portal**
  - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors a : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

  ➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

  ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…
- Production: Primakoff production, mixing with pions and heavy meson decays

- **And higher dimensional operator portals**
  - Chern-Simons portal (vector portal)

Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla . \mathrm{E} = 4\pi\rho_e$$

$$\nabla . \mathrm{B} = 4\pi\rho_m$$

$$-\nabla \times \mathrm{E} = \frac{1}{c}\frac{\partial \mathrm{B}}{\partial t} + \frac{4\pi}{c}\mathrm{j_m}$$

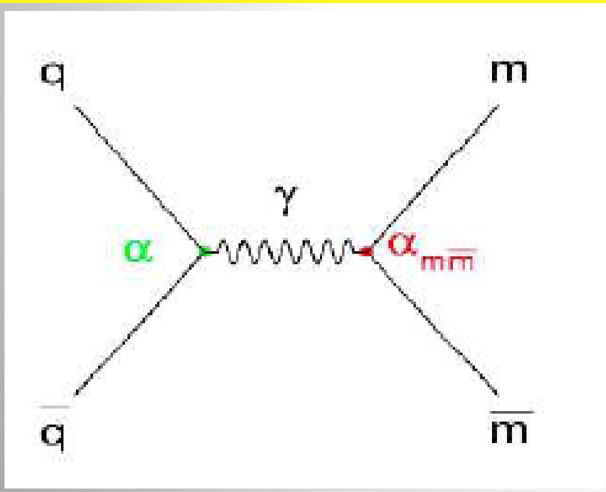
$$\nabla \times \mathrm{B} = \frac{1}{c}\frac{\partial \mathrm{E}}{\partial t} + \frac{4\pi}{c}\mathrm{j_e}$$

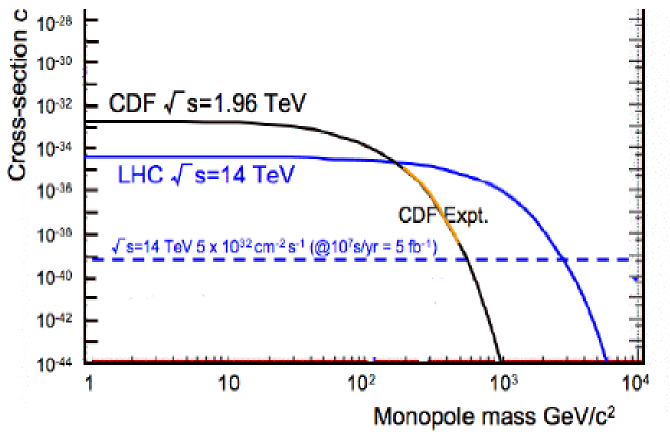
$$\mathrm{F} = q_e\left(\mathrm{E} + \frac{\mathrm{v}}{c} \times \mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathrm{v}}{c} \times \mathrm{E}\right)$$

$$eg = n\hbar c/2 = n g_D$$ = n 68.5e

$$\sigma_{D(m)} = \left(\frac{g_D}{e}\right)^2 \times \sigma_{\mu\mu}(> 2m) \times (1 - 4\frac{m^2}{s})$$

Simplifies Maxwell equations
Searched for at all colliders
Tevatron direct limits ~ 400-800 GeV





Sensitivity of LHC experiments to exotic highly ionising particles

A. De Roeck[1,2,3], **A. Katre**[4], **P. Mermod**[a,4,5], **D. Milstead**[6], **T. Sloan**[7]

arXiv: 1112.2999