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

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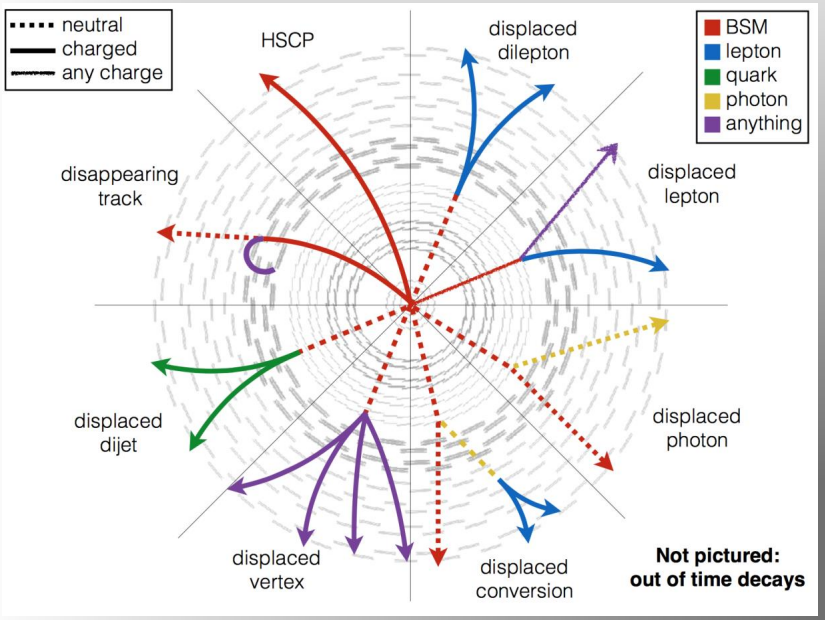
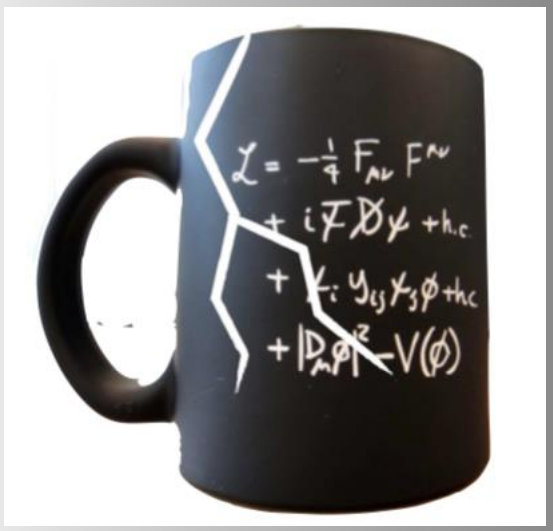
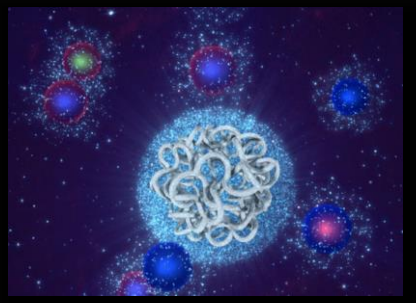
11th April 2019



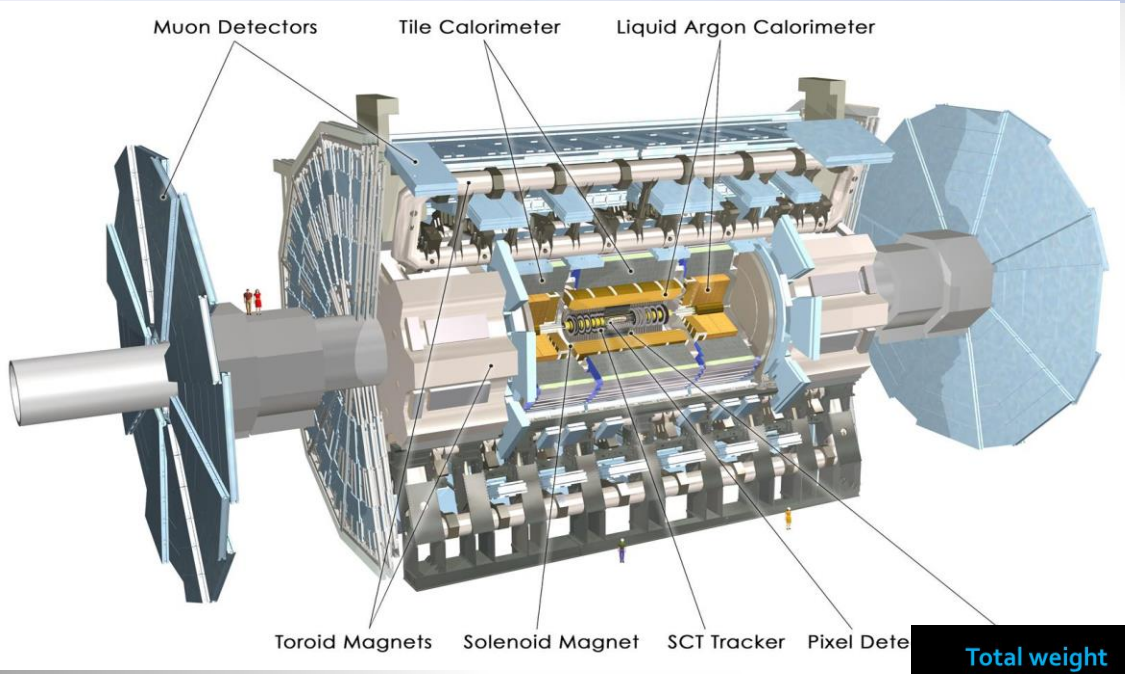
Outline

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



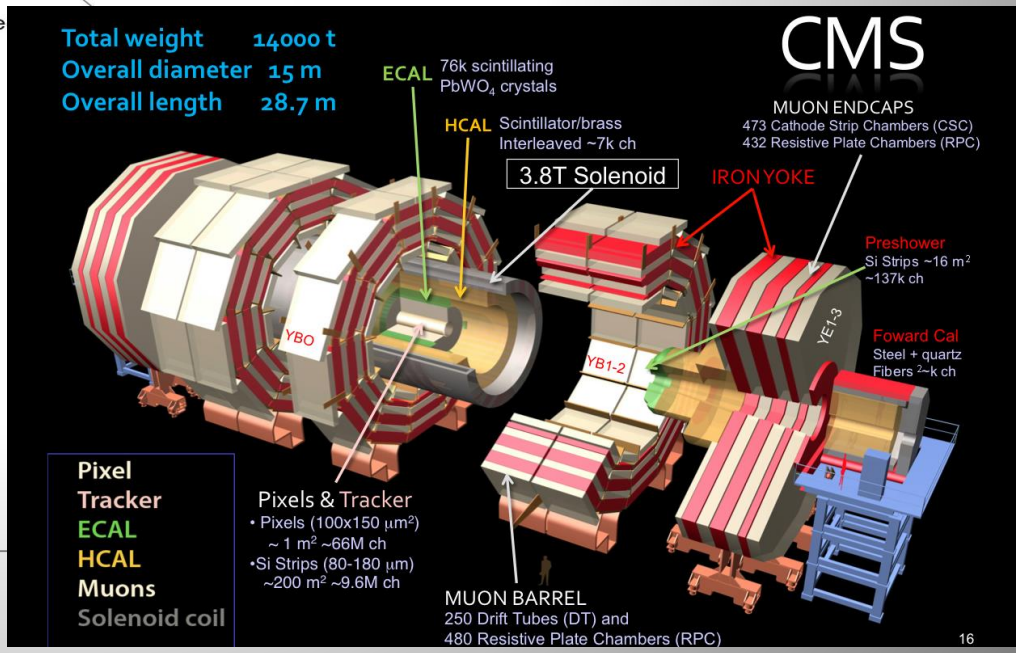


New Physics Hunters @ the LHC

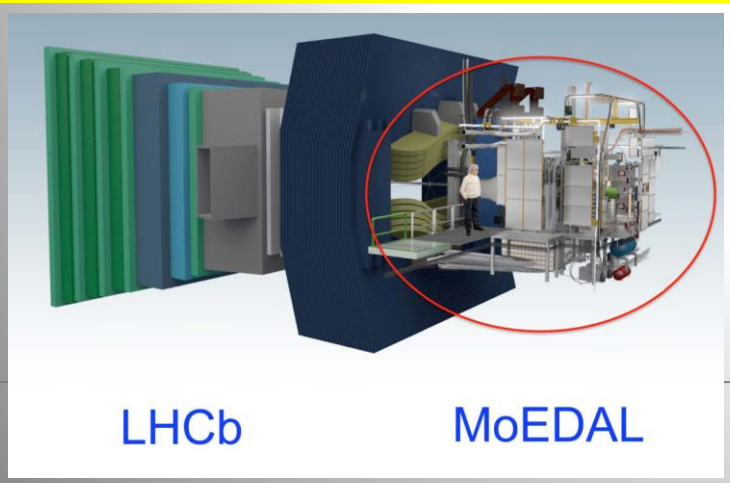


The ATLAS experiment

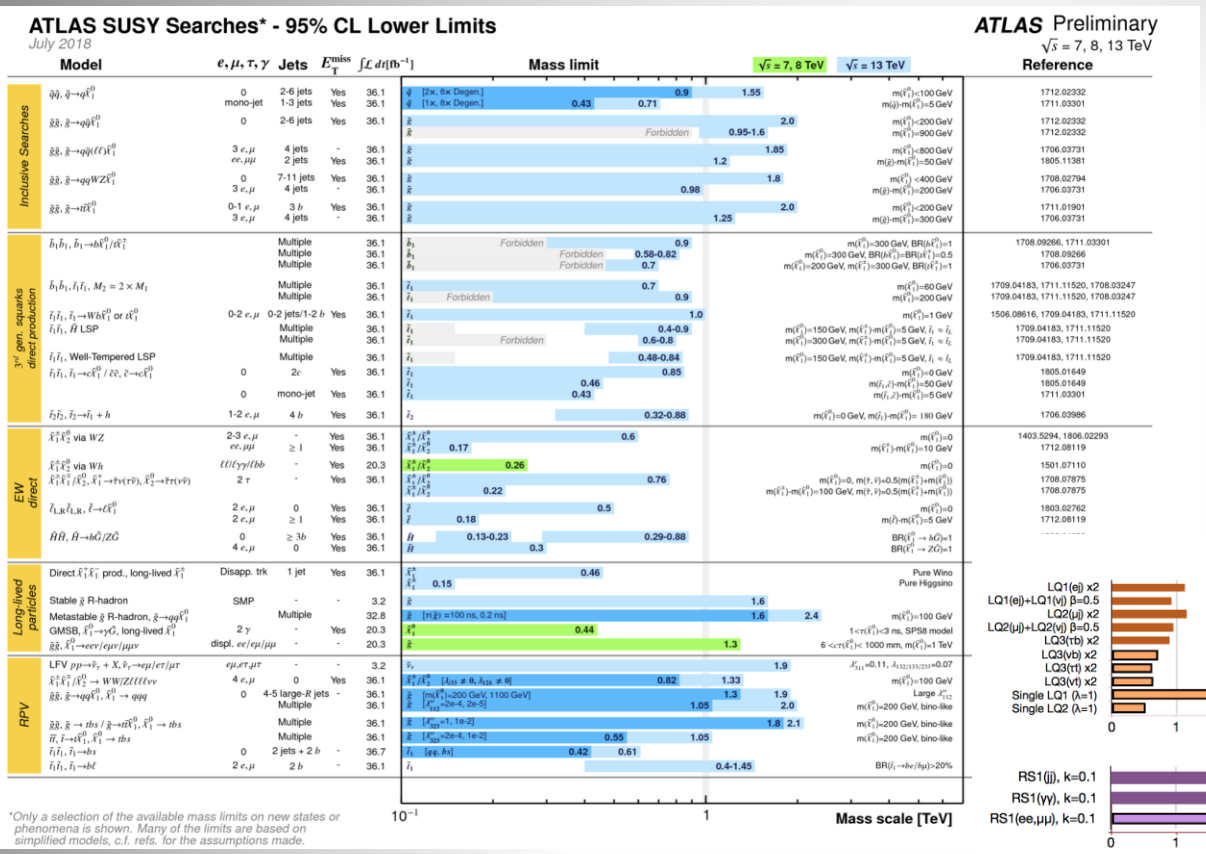
The CMS experiment



...And also LHCb and MoEDAL

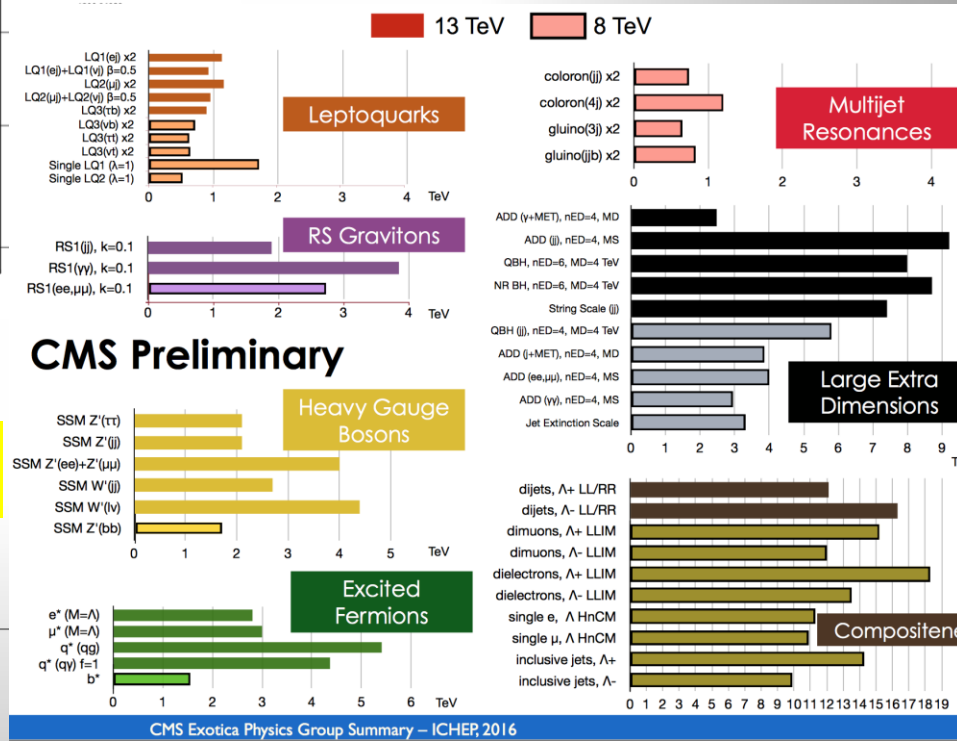


LHC: So far no new physics



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

No signal of new physics so far!!



Are we leaving no stone 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 if we still do not see more than a 2 sigma at the end of run 3, the HL-LHC will be likely mostly a precision physics machine, searching for subtle deviations or small couplings
- Are we looking at the right place? Time for more effort in thinking of complementary searches?

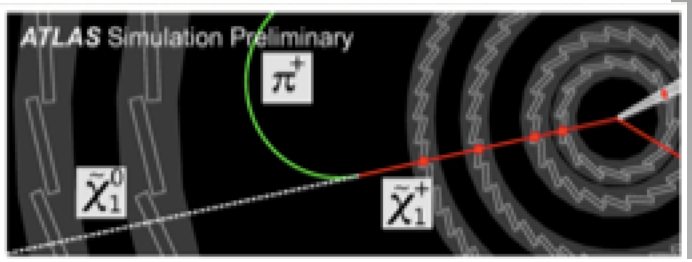
Are we looking at the right place?

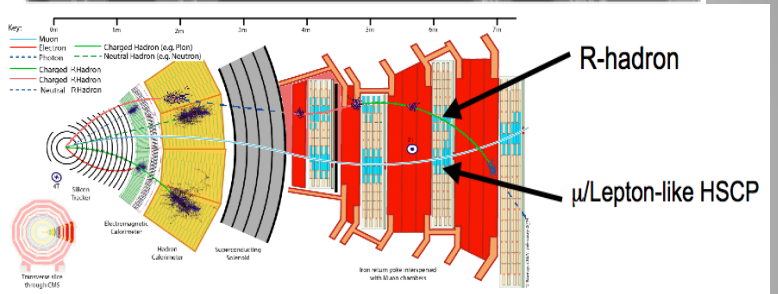
Leave no stone unturned!!

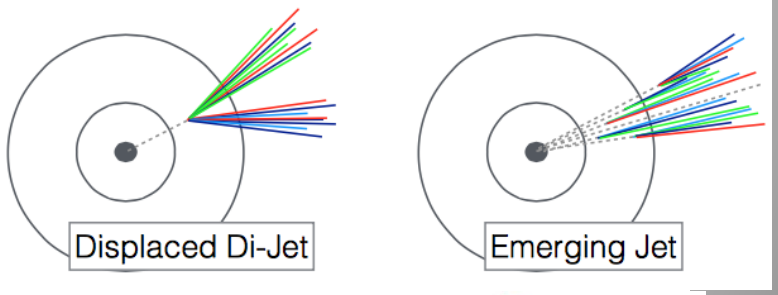
Long Lived Particles

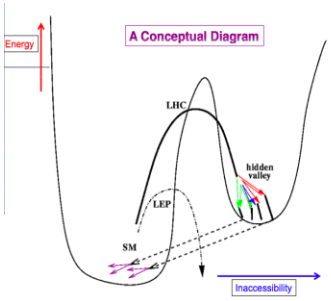
Long lifetimes arise from a hierarchy of scales or a small coupling

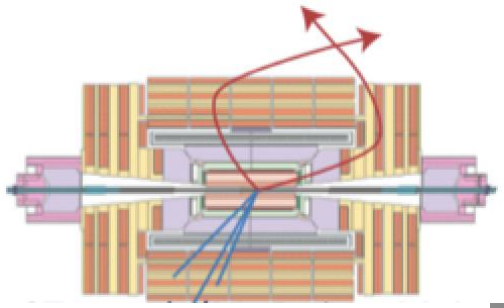
- RP Violating SUSY
- ASMB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ….





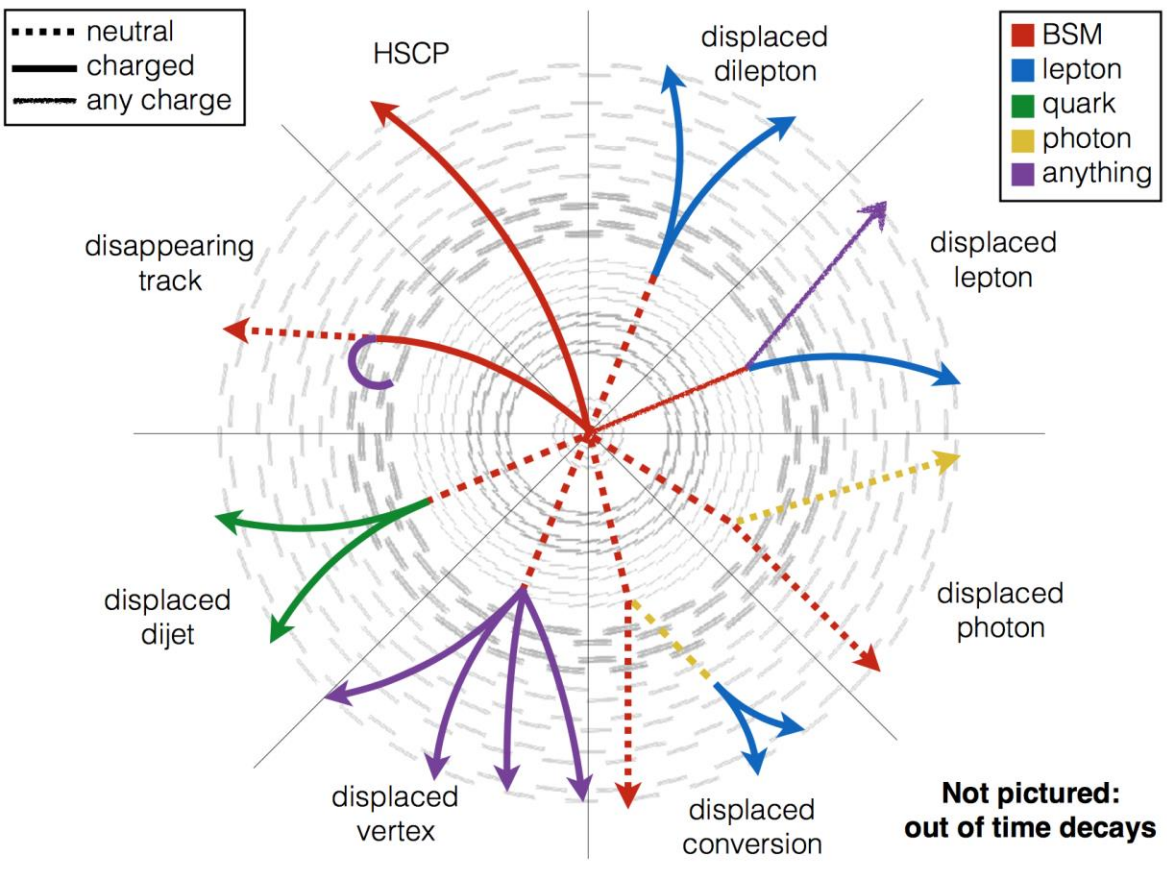






Long Lived Particles @LHC

Signatures



Some of the Challenges

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

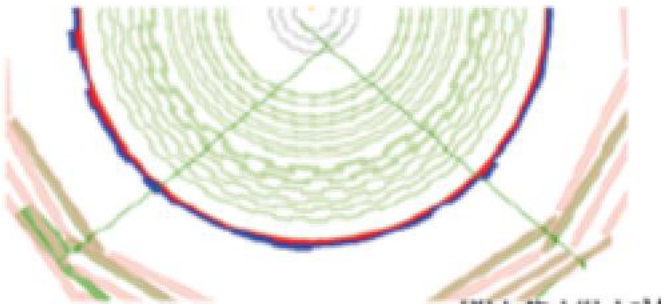
SM backgrounds often low. But need special studies (punch through, secondary interactions, tails, cosmics…)

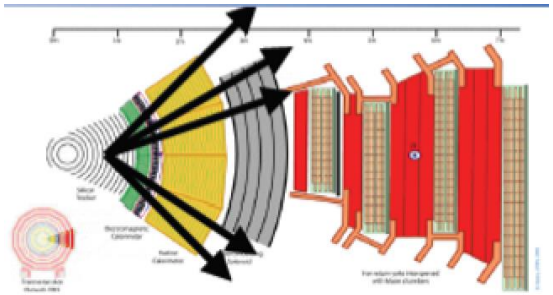
Special reconstruction is often needed

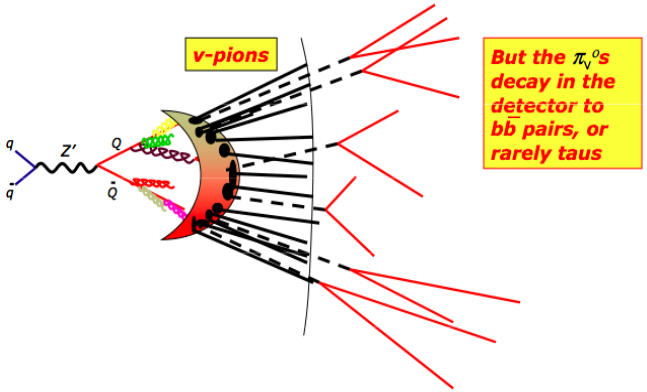
Some detector upgrades for High-Luminosity LHC (>2026) address these these issues.

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…)

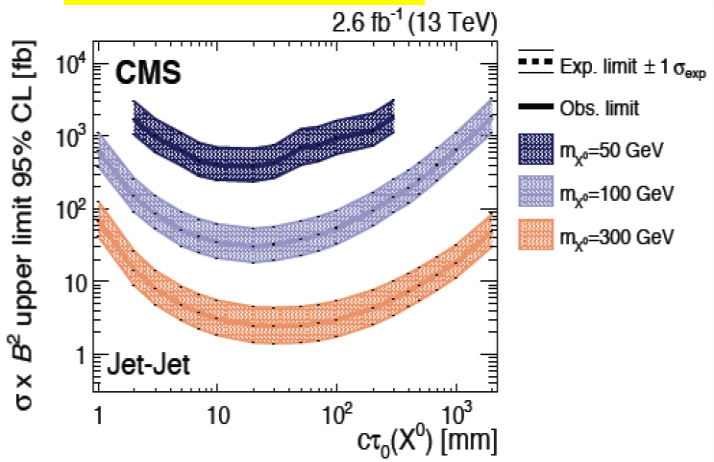




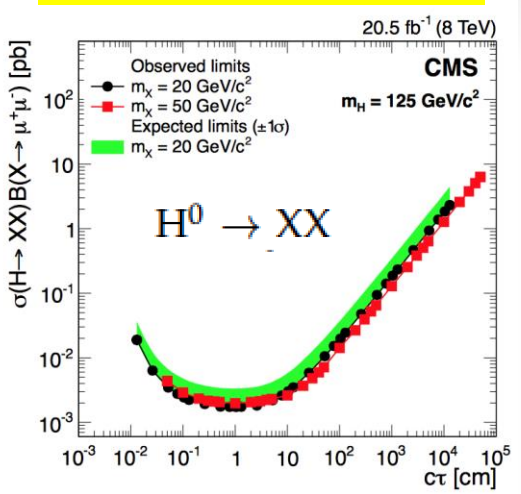


Long Lived Searches: Examples

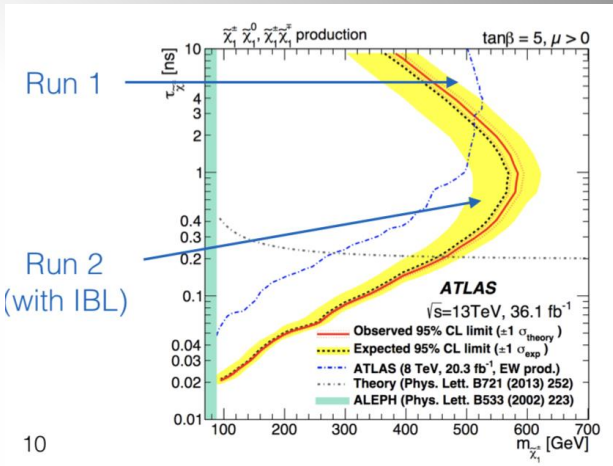
displaced jets



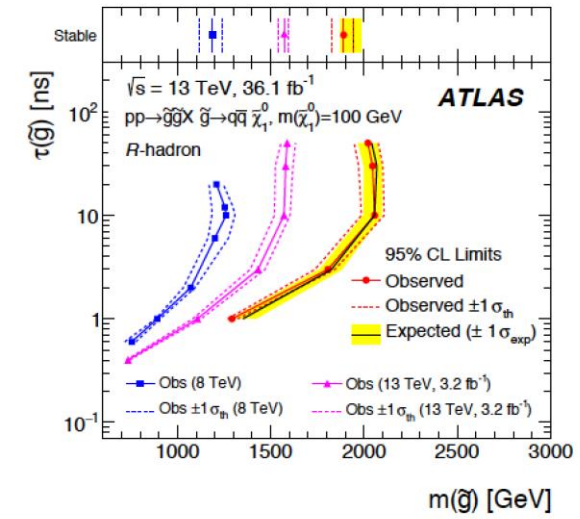
displaced leptons



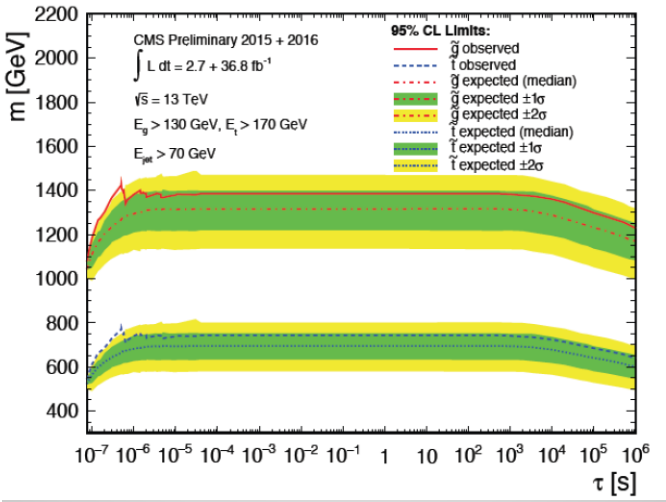
disappearing tracks



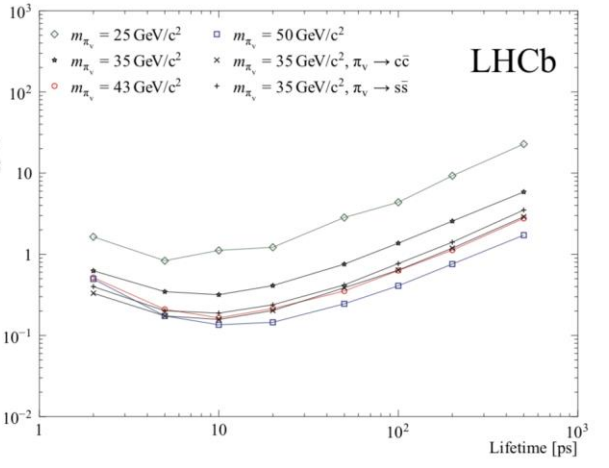
metastable R-hadrons



stopped particles

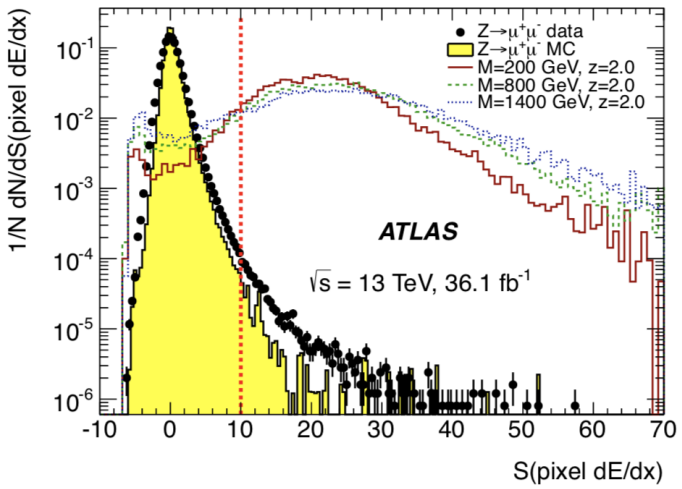


Hidden Valley searches

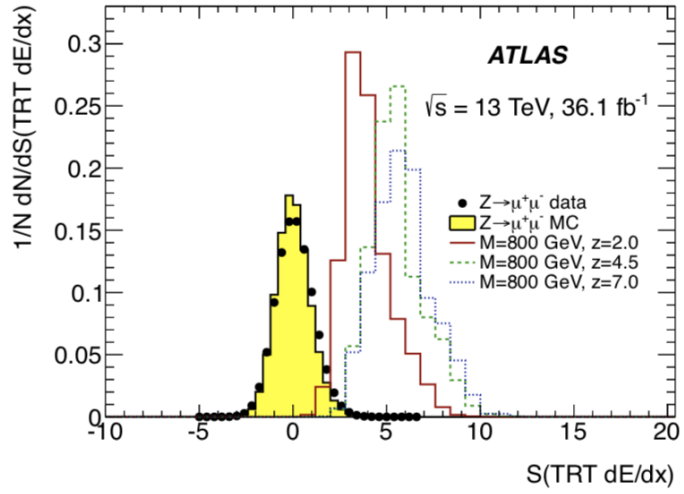


Multi Charged Particles

Pixel tracker

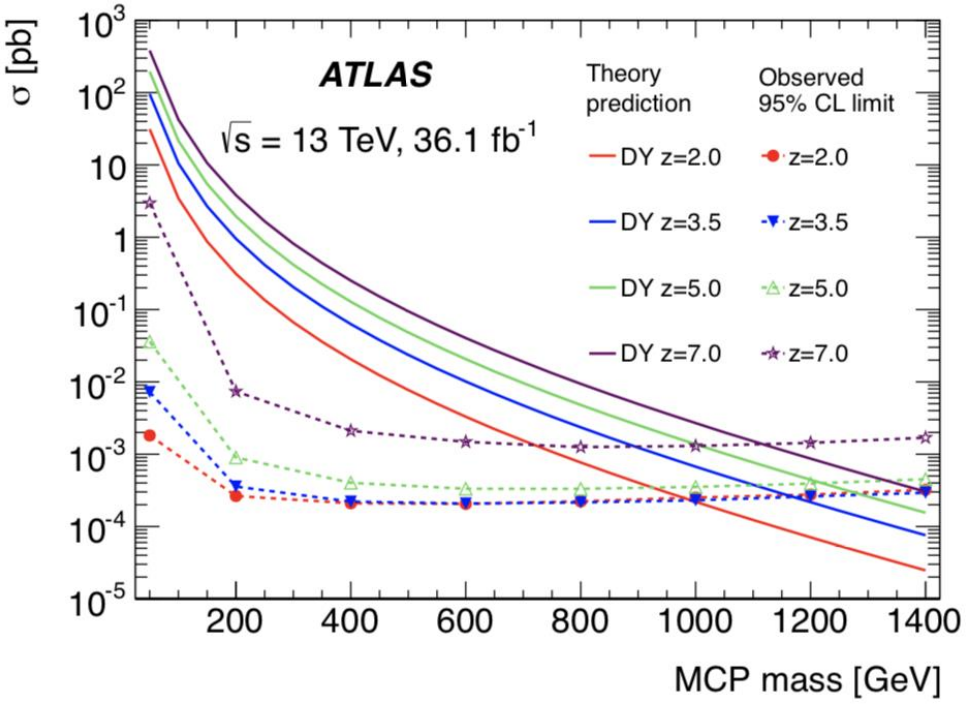


TRT tracker



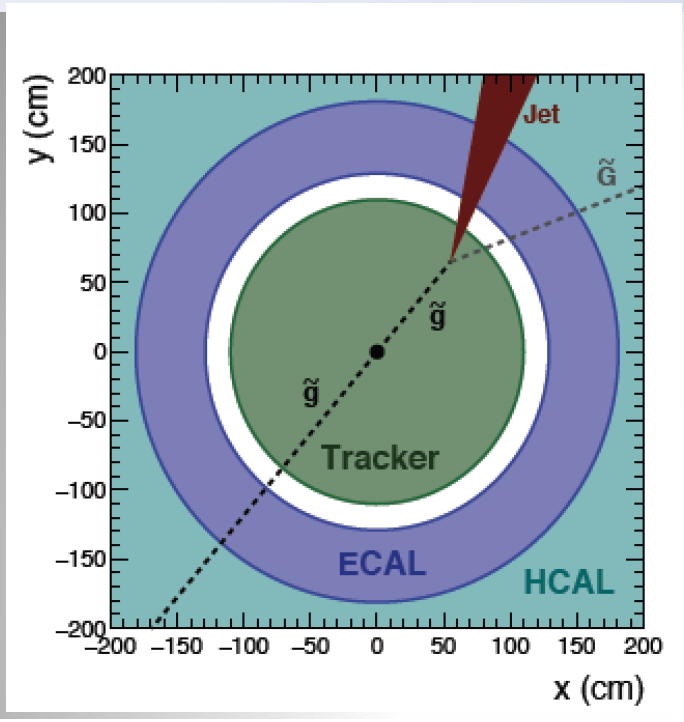
Use central tracker and de/dx measurement to search for particles with electric charges of 2e to 7e

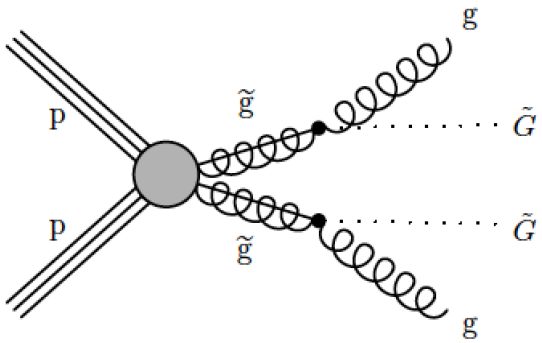
arXiv:1812.03673



Exclusion between 50 GeV and 980-1220 GeV

Search for Delayed Jets

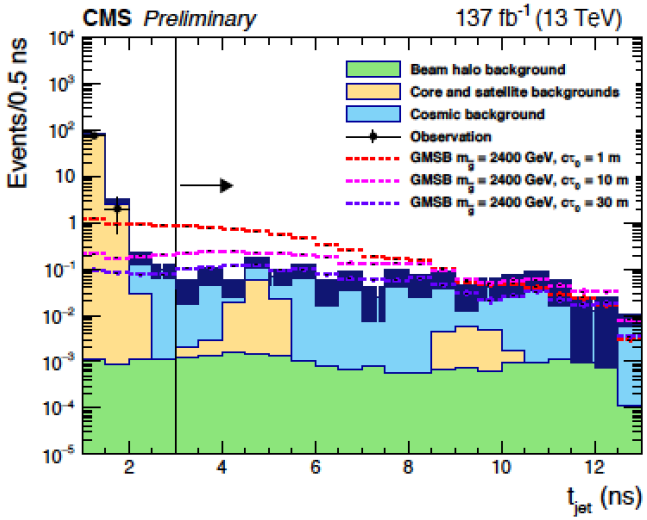


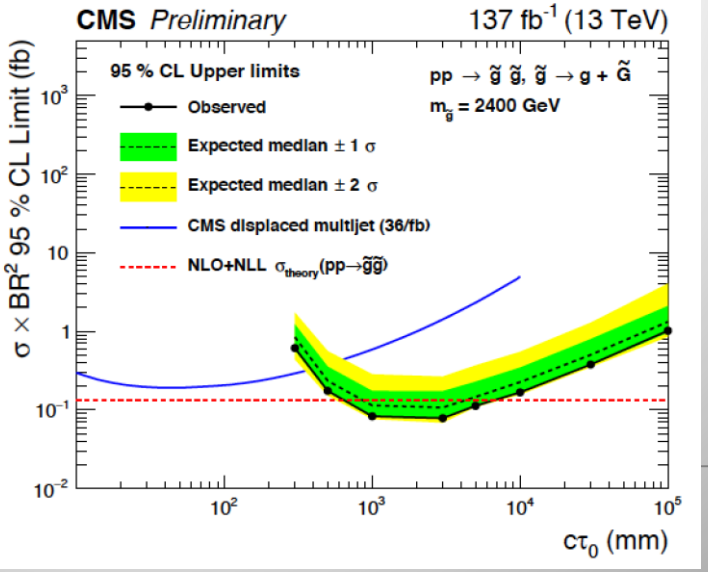


Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

EXO-19-001

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

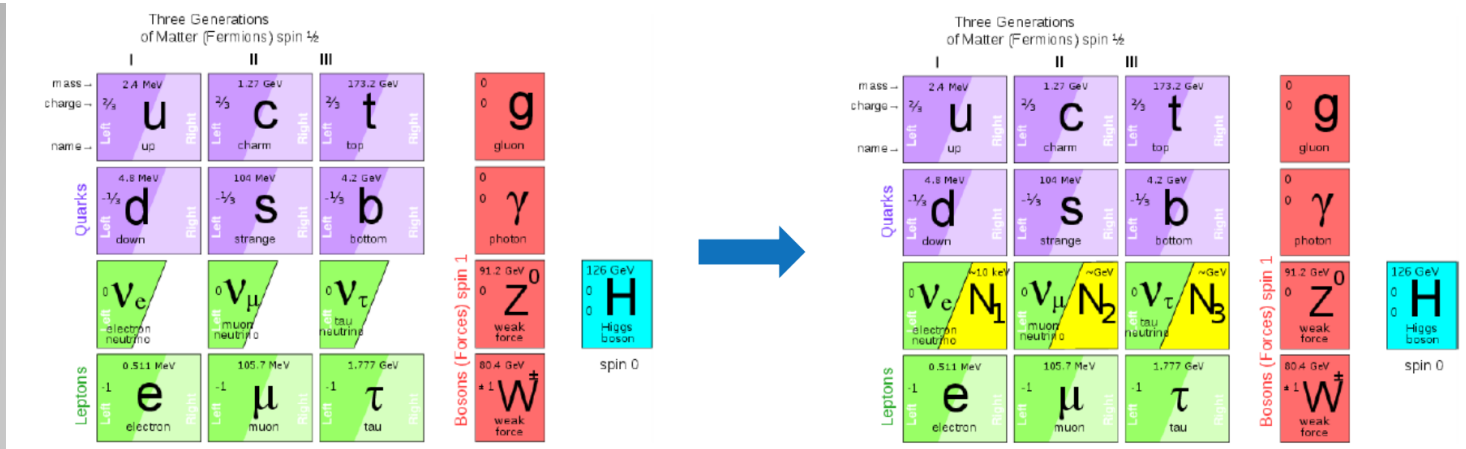


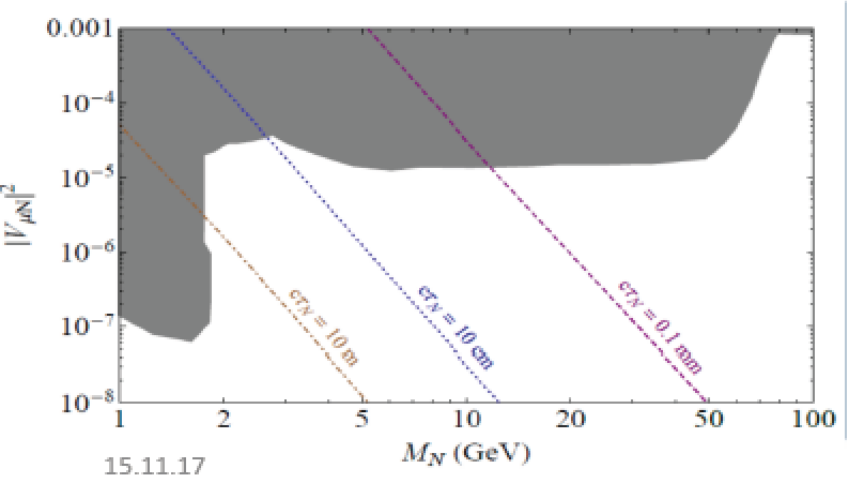


GMSB long-lived gluino model search. Mass limits up to 2500 GeV

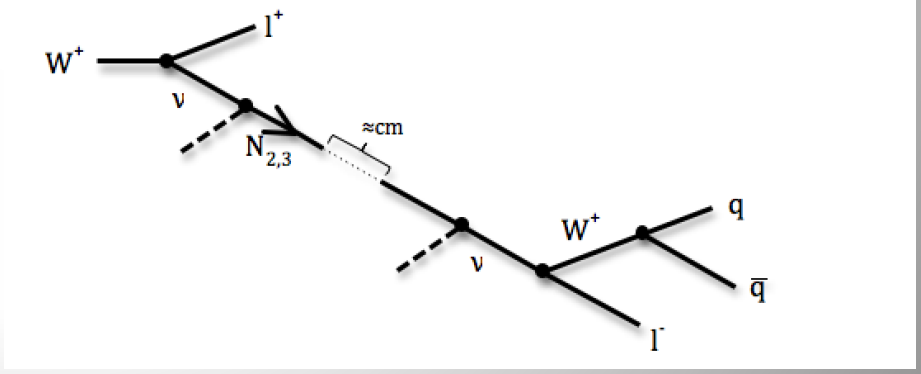
Heavy Neutral Leptons

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





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

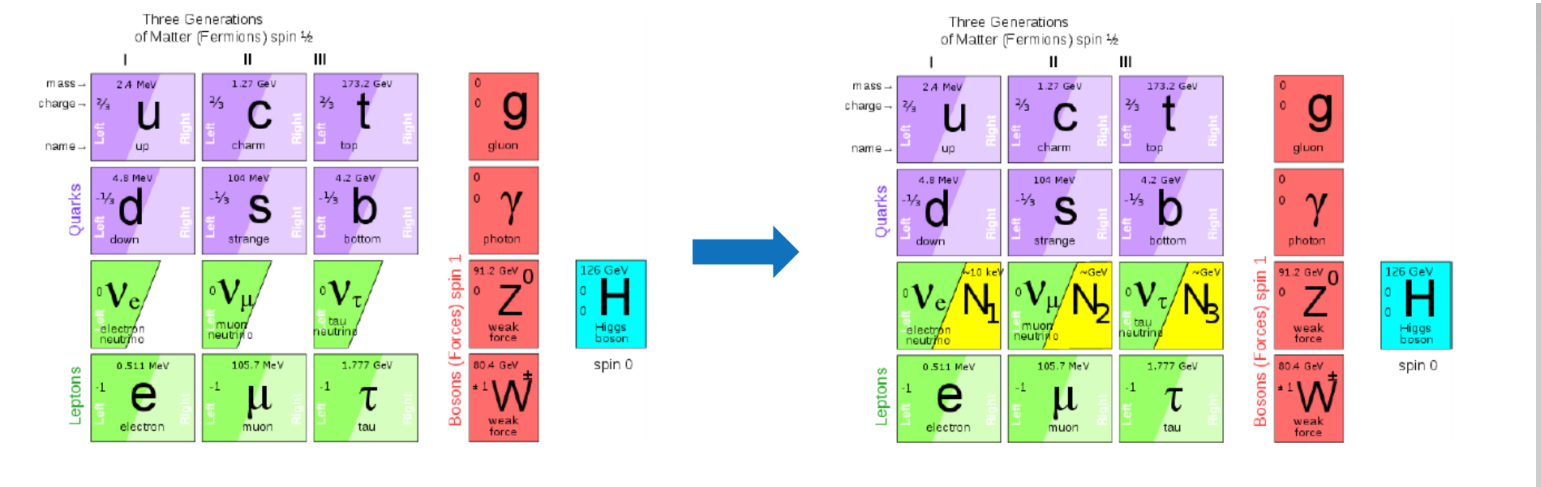


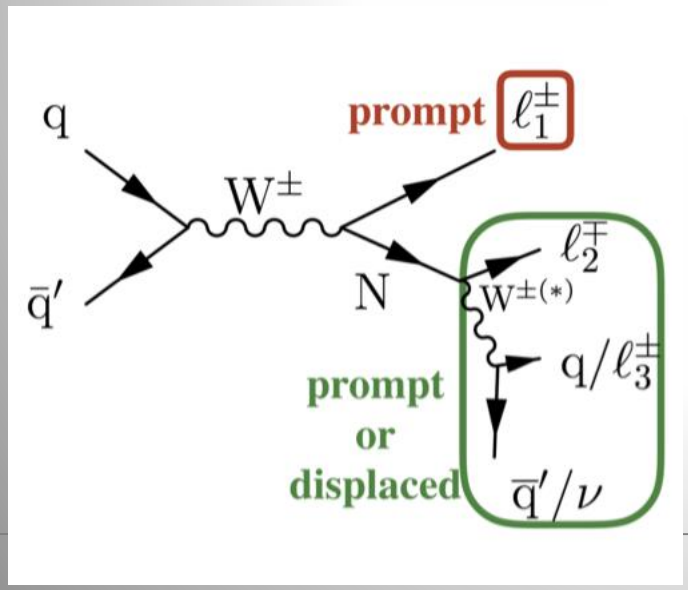
First LHC results on prompt studies
Majorana/Dirac? Now studies with displaced jets/lepton analyses. L~ 1m?

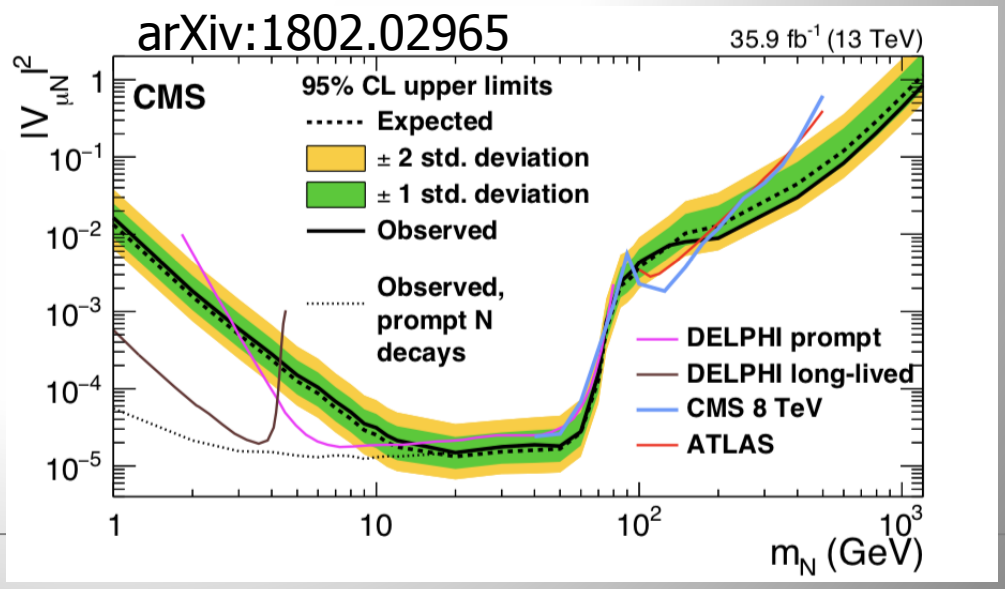
Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

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







Monopoles

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

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

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

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

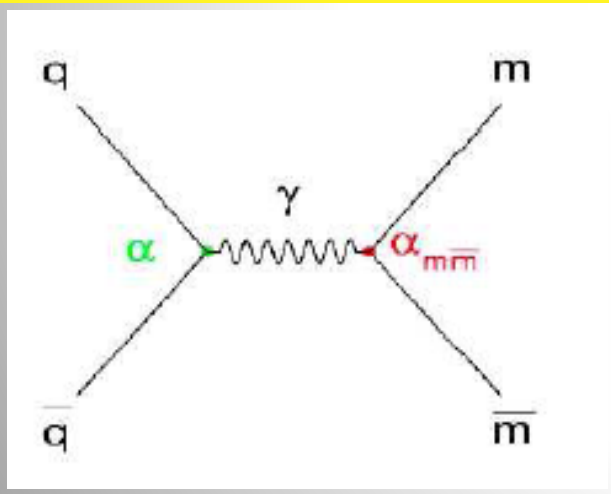
$$\nabla\times\mathbf{B} = \tfrac{1}{c}\tfrac{\partial\mathbf{E}}{\partial t} + \tfrac{4\pi}{c}\mathbf{j_e}$$

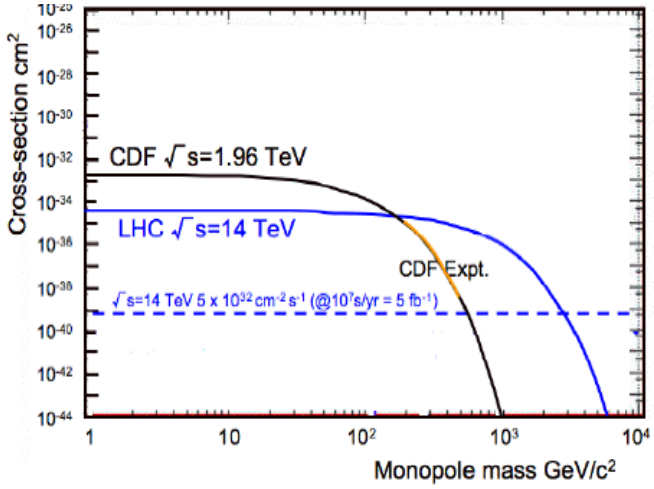
$$\mathbf{F} = q_e\left(\mathbf{E} + \tfrac{\mathbf{v}}{c}\times\mathbf{B}\right) + q_m\left(\mathbf{B} - \tfrac{\mathbf{v}}{c}\times\mathbf{E}\right)$$

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

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

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





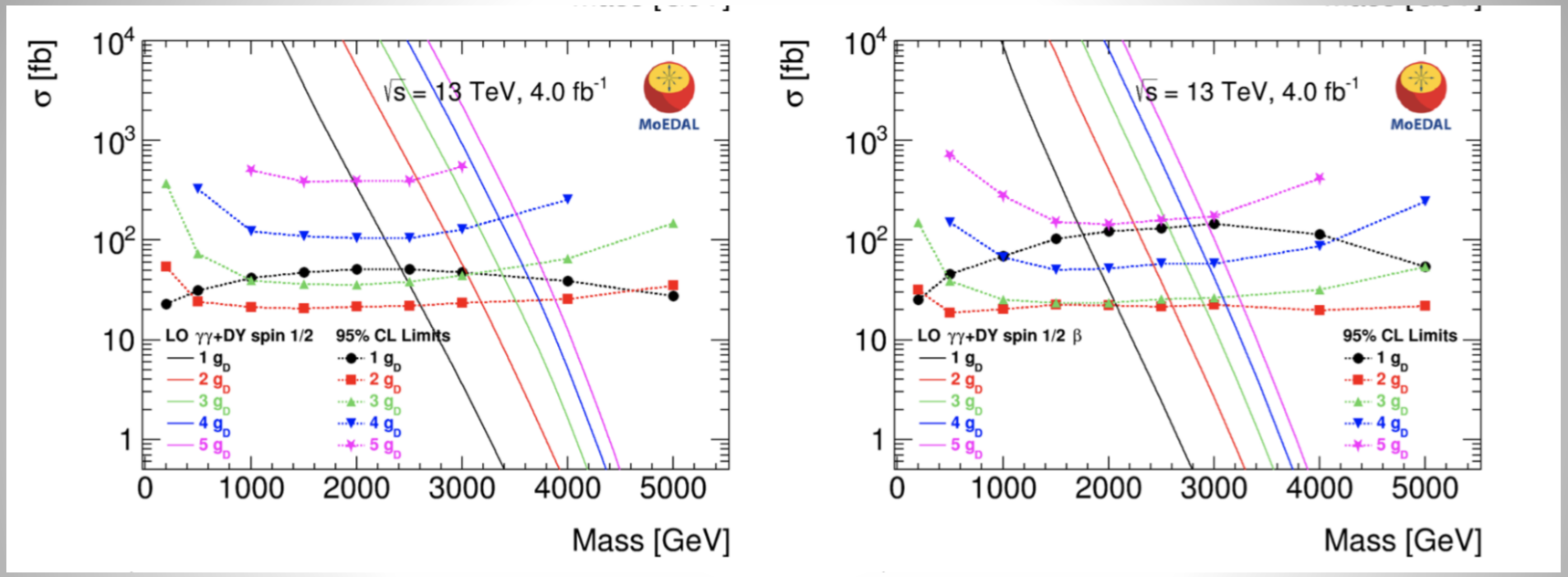
Sensitivity of LHC experiments to exotic highly ionising particles

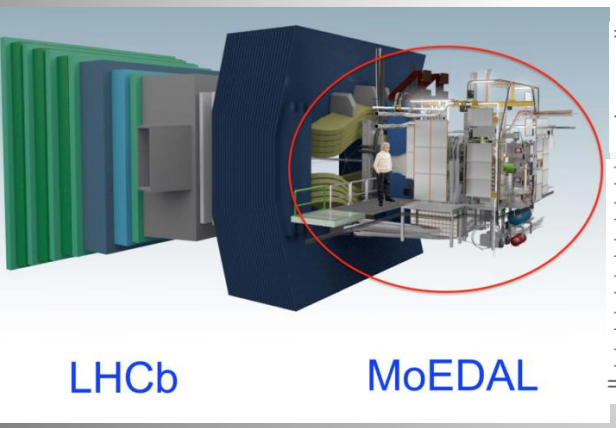
A. De Roeck[1,2,3], A. Katre[4], P. Mermod[a,4,5], D. Milstead[6], T. Sloan[7]

arXiv: 1112.2999

Monopole Searches: MoEDAL @ 13TeV

2016 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





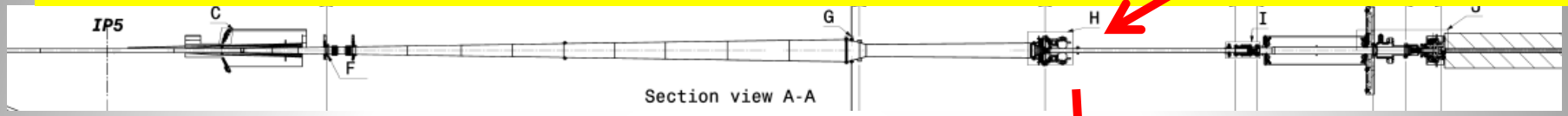
Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY+γγ	0	2190	2930	3120	3090	–
DY+γγ	1/2	2420	3180	3360	3340	–
DY+γγ	1	2920	3620	3750	3740	–
DY+γγ β-dep.	0	1500	2300	2590	2640	–
DY+γγ β-dep.	1/2	1760	2610	2870	2940	2900
DY+γγ β-dep.	1	2120	3010	3270	3300	3270

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

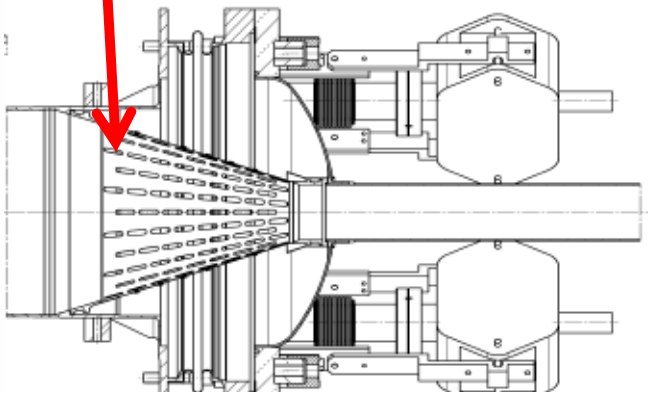
Monopoles Stopped in the Beampipe

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



$|g| \geq 4g_D$

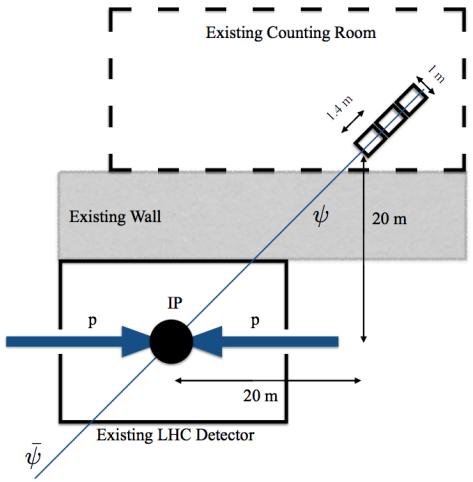


Faulty connecting "fingers" were removed and scanned in a SQUID in Zurich

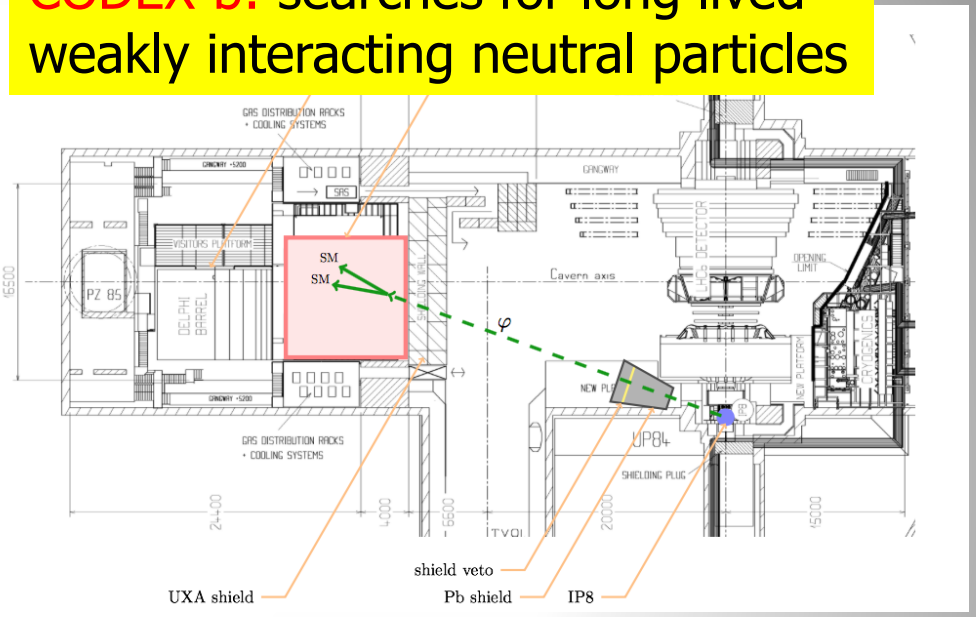
Want to use the 2012 CMS beampipe! MoEDAL officially got it since 18/2/2019!!
A beampipe analysis effort is put into place in MoEDAL
-> The analysis preparation effort is starting now

Proposals for New Experiments @LHC

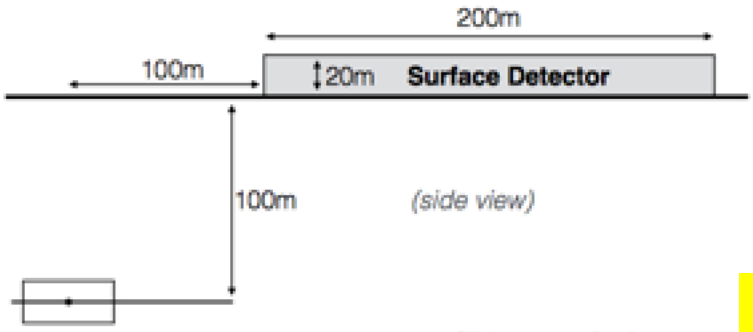
MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL



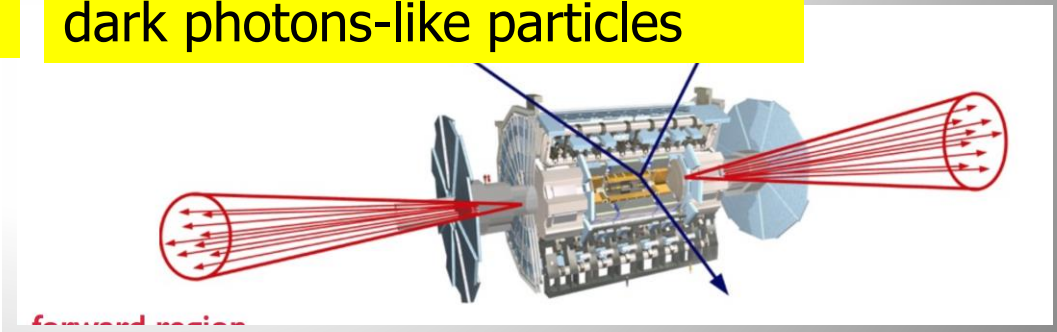
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



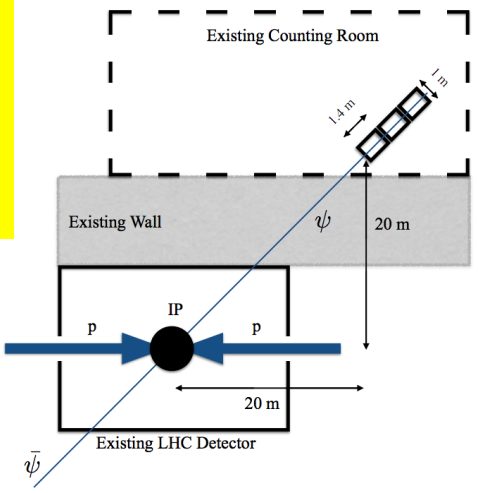
FASER: searches for long lived dark photons-like particles



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

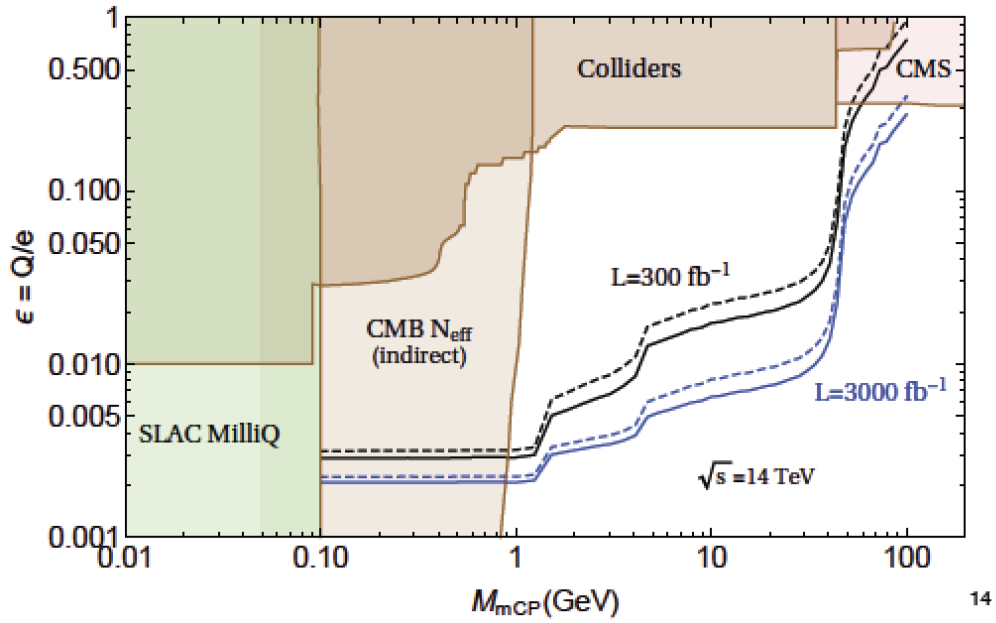


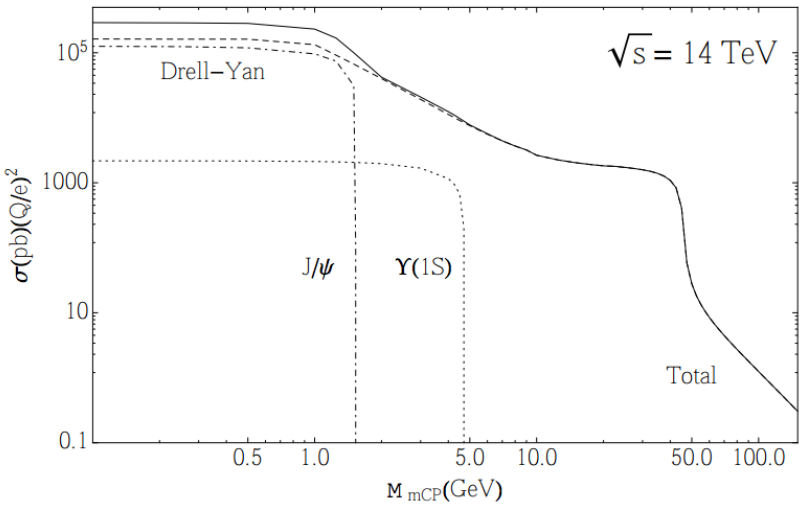
A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

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





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]

CERN-LHCC-2018-25

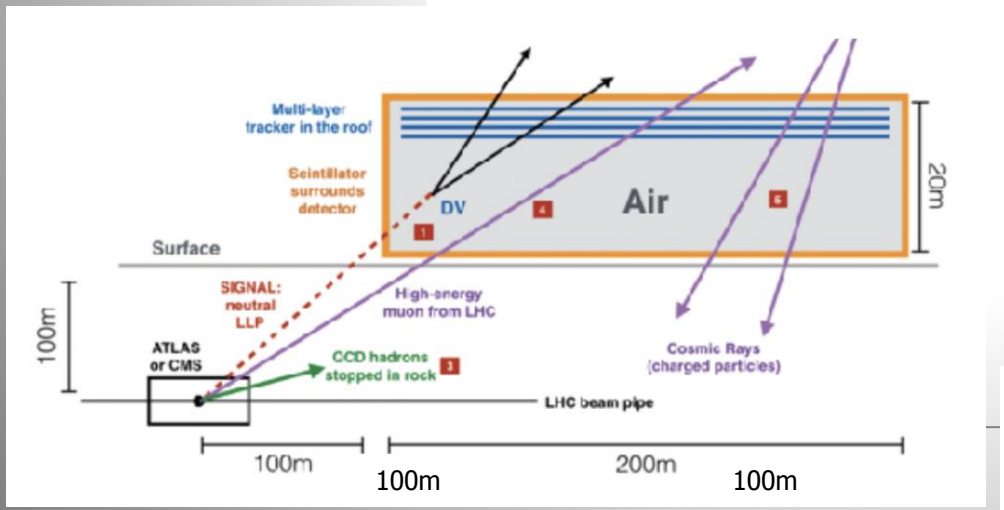
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

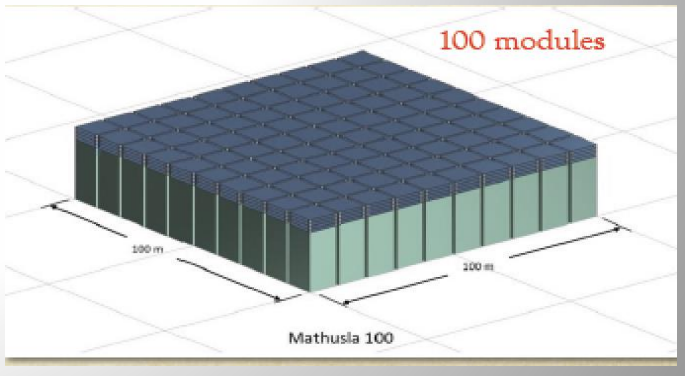
Aim to cover the range

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

~ BBN constrained inspired

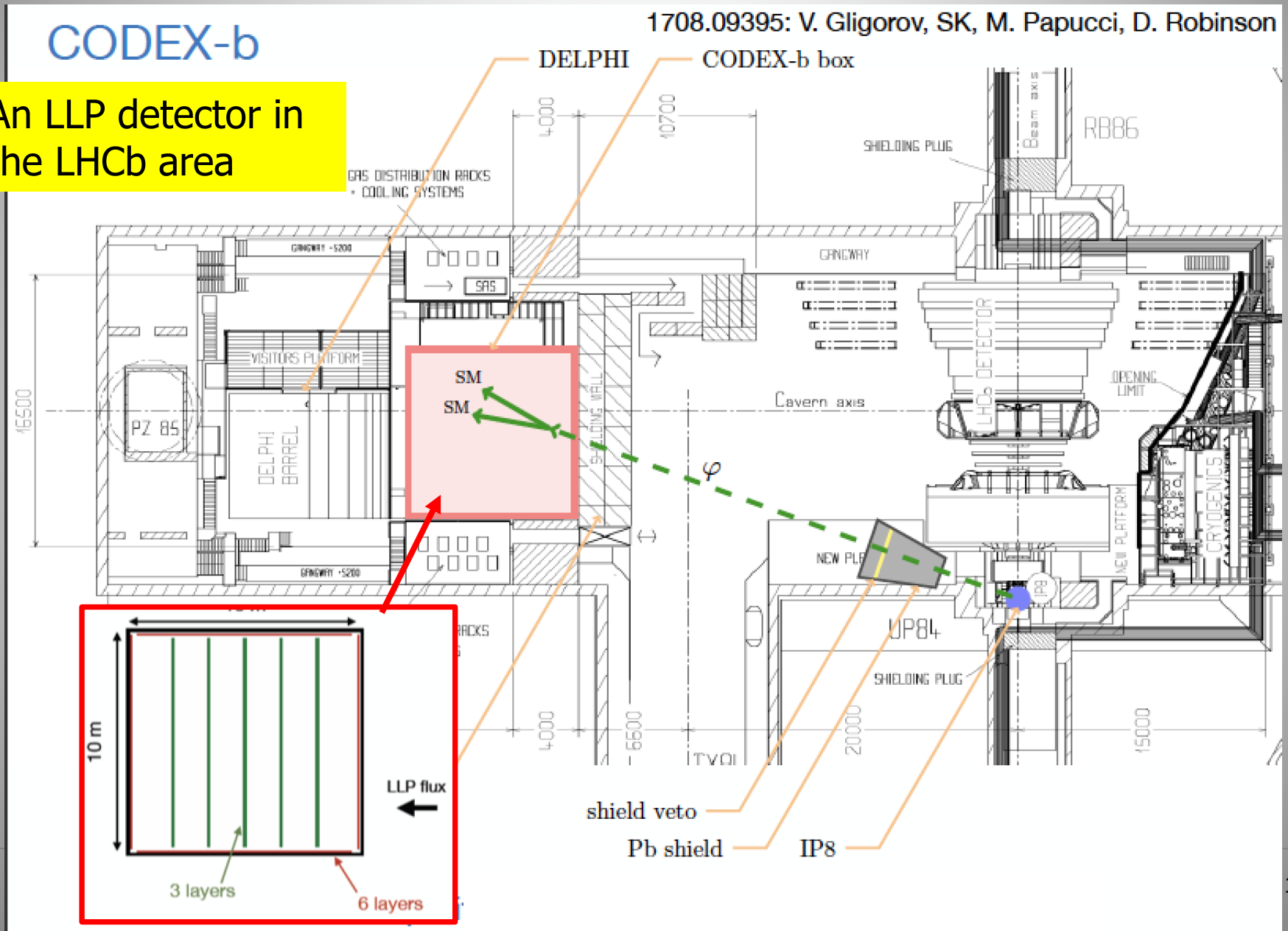
Physic case arXiv:1806.07396





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

CODEX-b Proposal

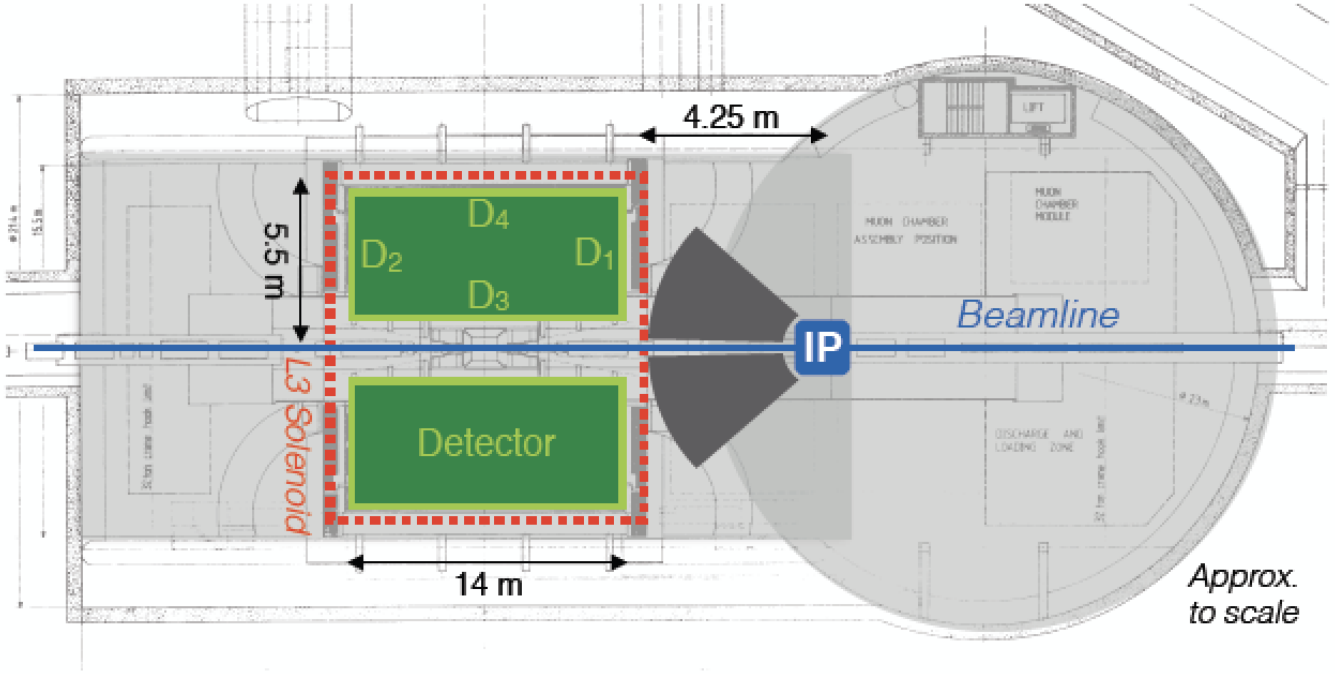


Re-using the ALICE detector?

A Laboratory for Long-Lived eXotics (AL3X)

Reuse the L3 magnet and (perhaps) the ALICE TPC

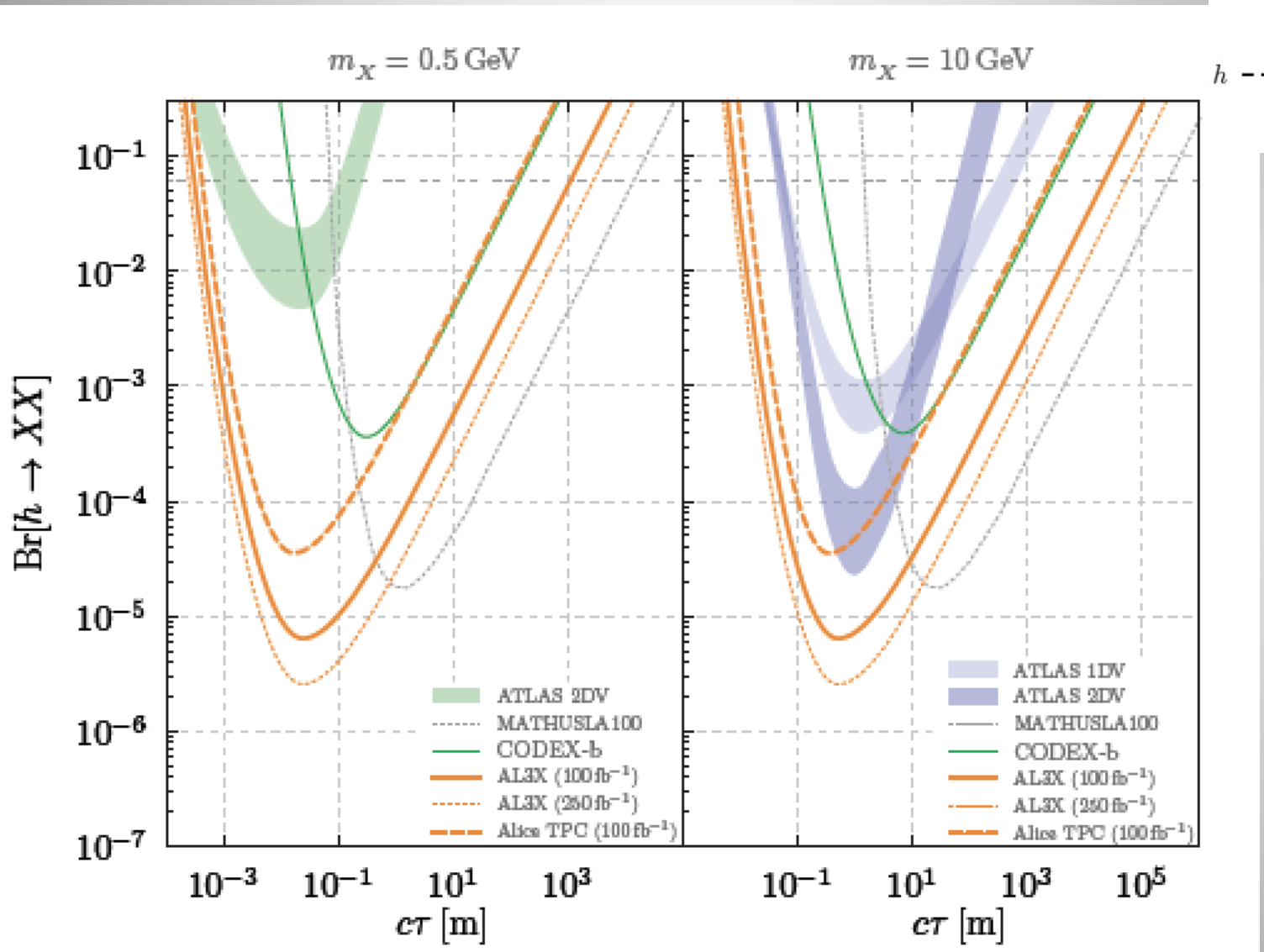
For LHC Run 5??

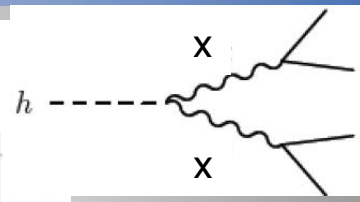


Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

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

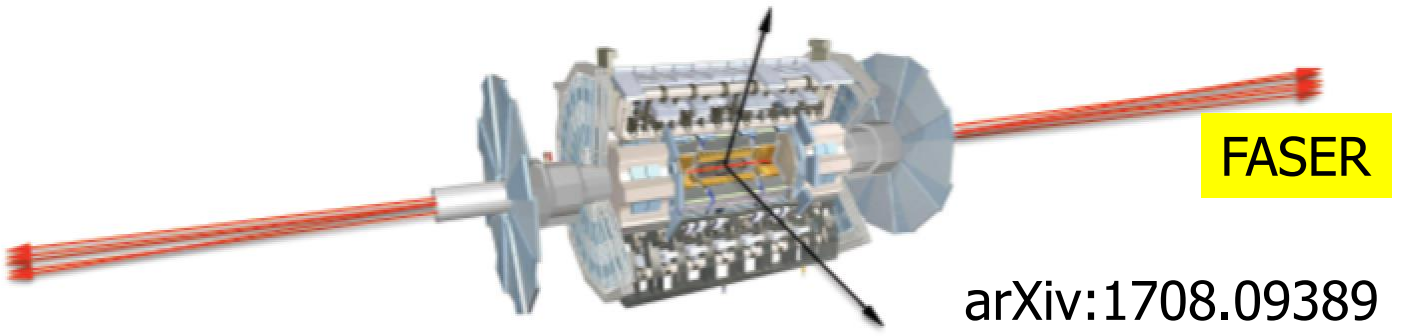
Physics Reach: Example



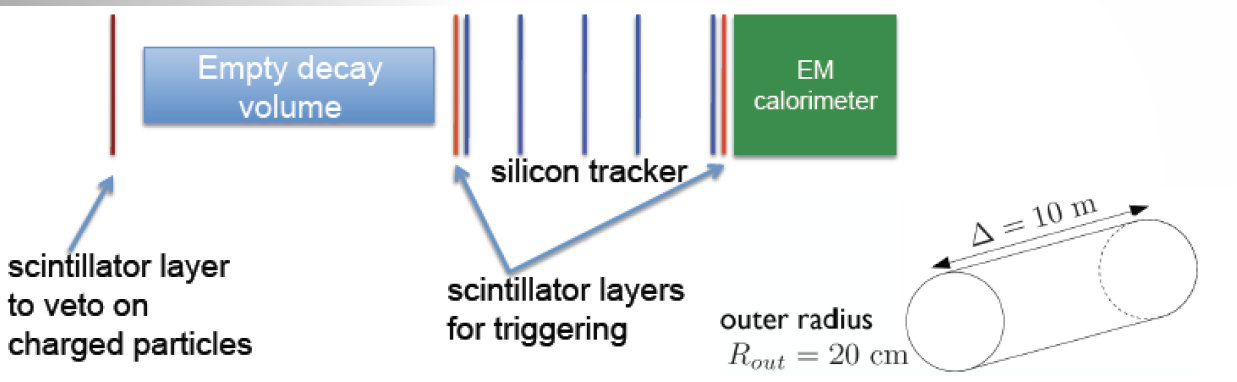


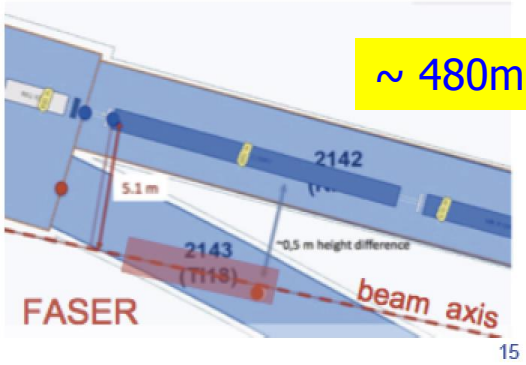
For low masses: MATHUSLA, CODEX-b and AL3X have a leading edge

FASER Proposal



arXiv:1708.09389





- 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.

- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.

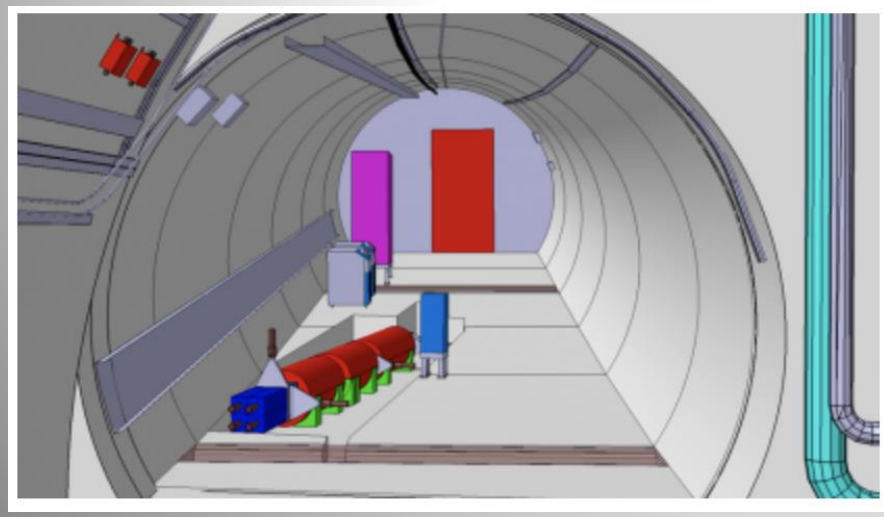
FASER Approval

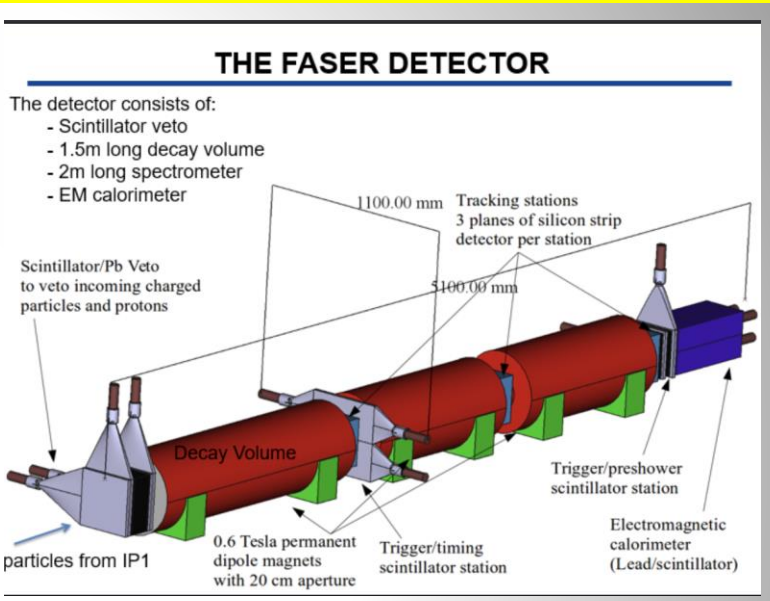
Breaking news: the FASER experiment (phase-I) has been approved March 5th

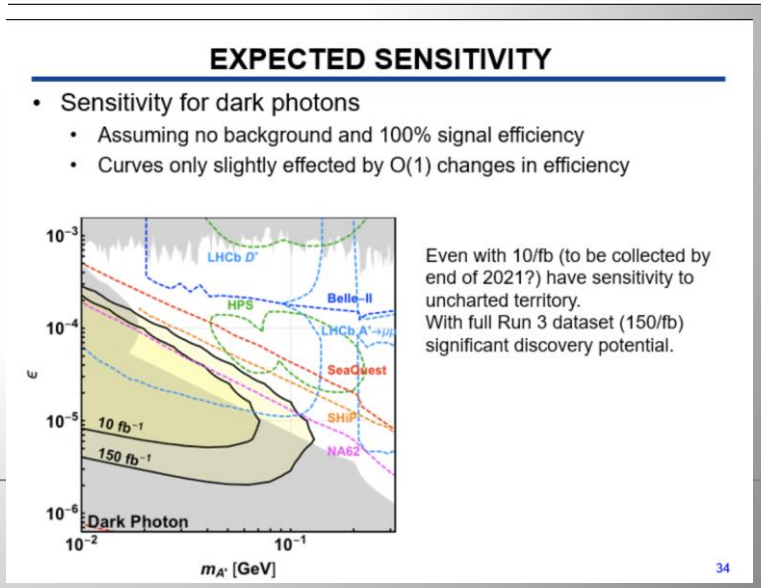
INTERACTIONS.ORG
PARTICLE PHYSICS NEWS AND RESOURCES

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

Date Issued
March 5th, 2019







Status of the Various Projects

Simon Knapen FNAL seminar fall 2018

Lifetime frontier

Supplementary detectors

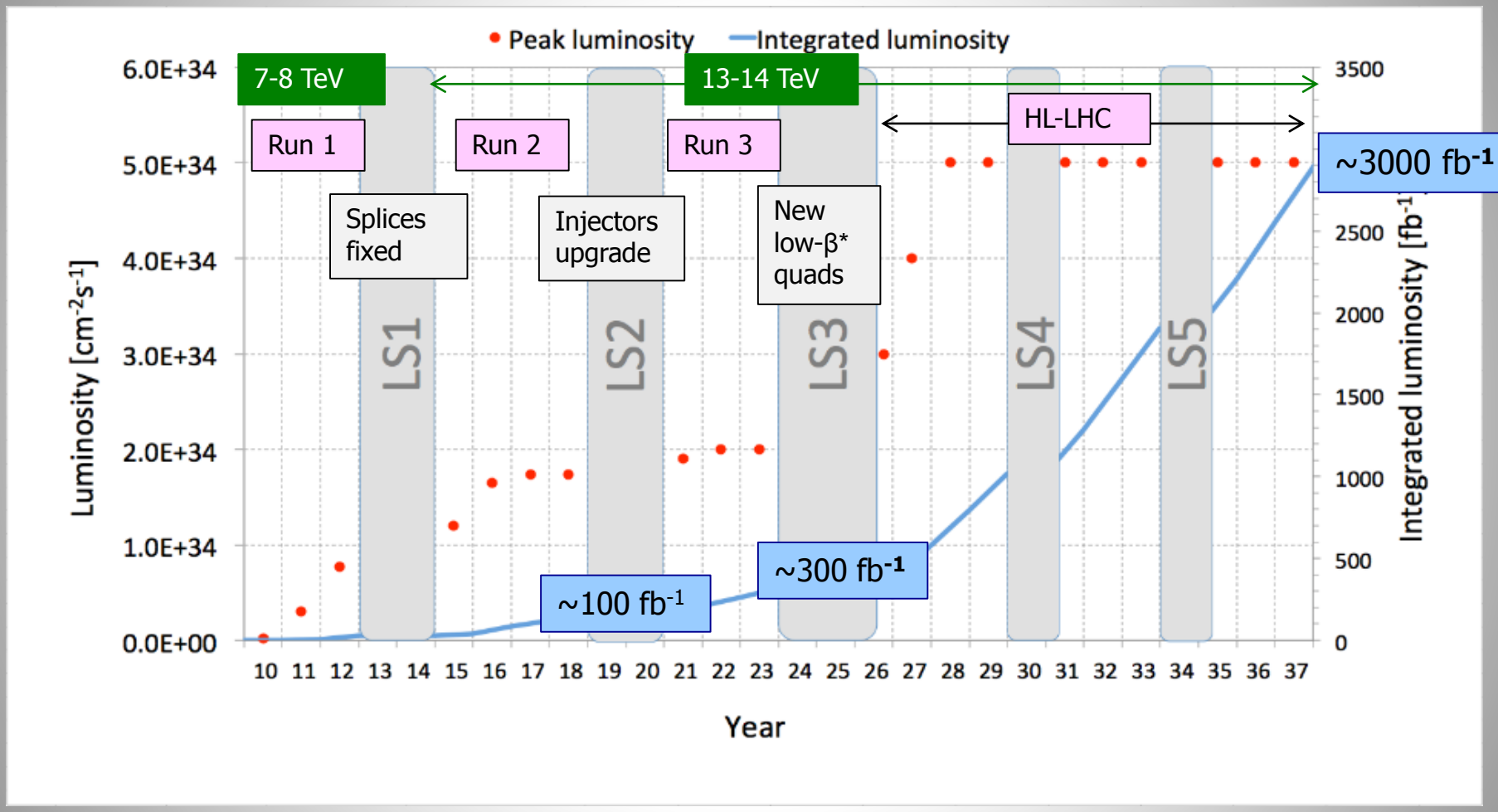
	Higgs decay	B-meson decay	π,η-decay (dark photon)	Progress	Cost
FASER		✔	✔	Collaboration formed	$
CODEX-b	✔	✔		sub-collaboration formed	$
SeaQuest			✔	experiment exists	$
AL3X	✔	✔	✔	Proof of concept	$$
MATHUSLA	✔	(✔)		Letter of intent	$$
SHiP		✔	✔	Technical design report	$$$

MOEDAL: monopoles, already running

MiliQan: milicharged particles, phase 1 detector in place

Similar timelines for MATHUSLA, MilliQan CODEX-b, FASER

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

1(

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/

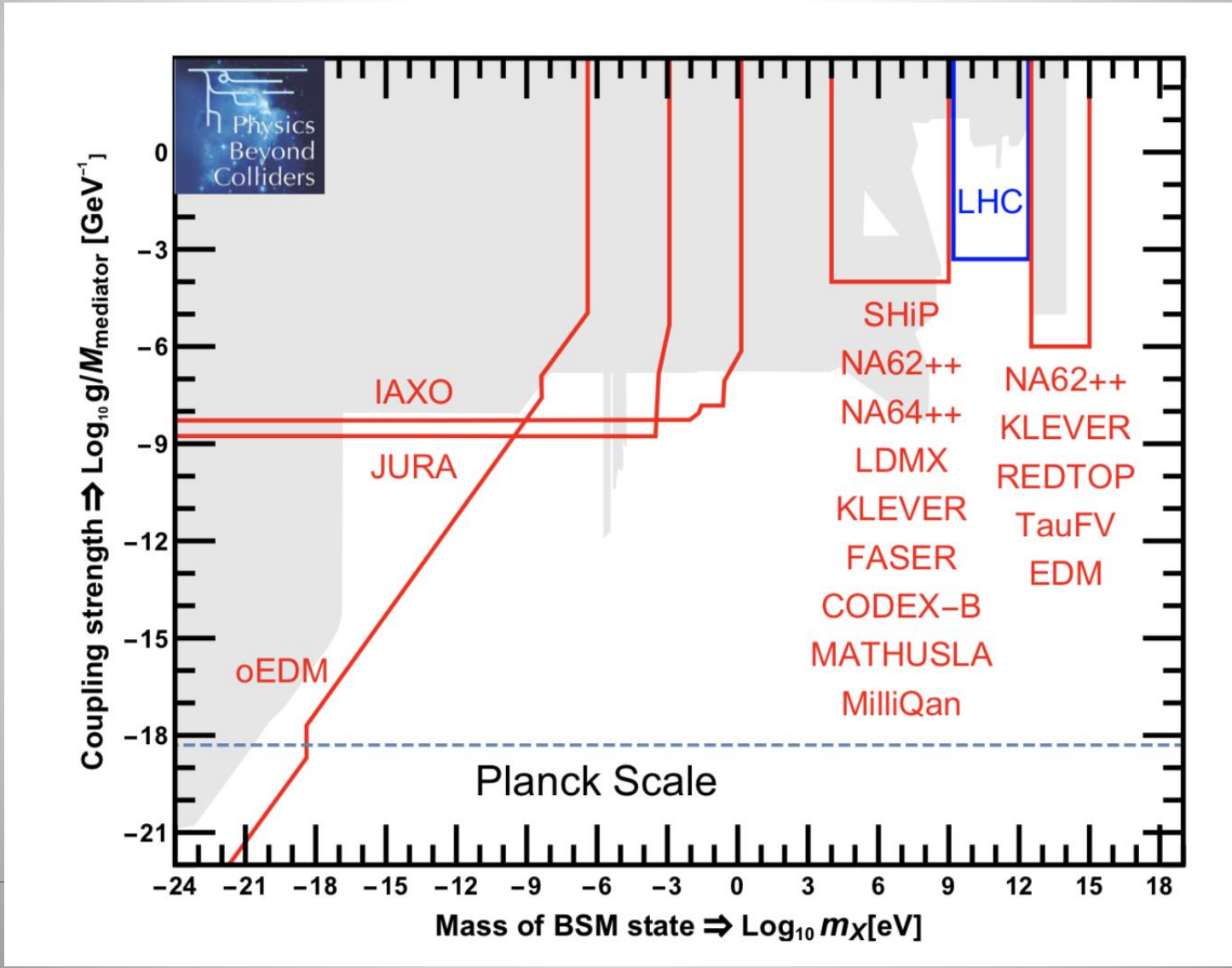
Next workshop November 5-6

CERN Physics Beyond Colliders

NA62, NA64, SHIP, LHC new experiments…

New Possible Experiments

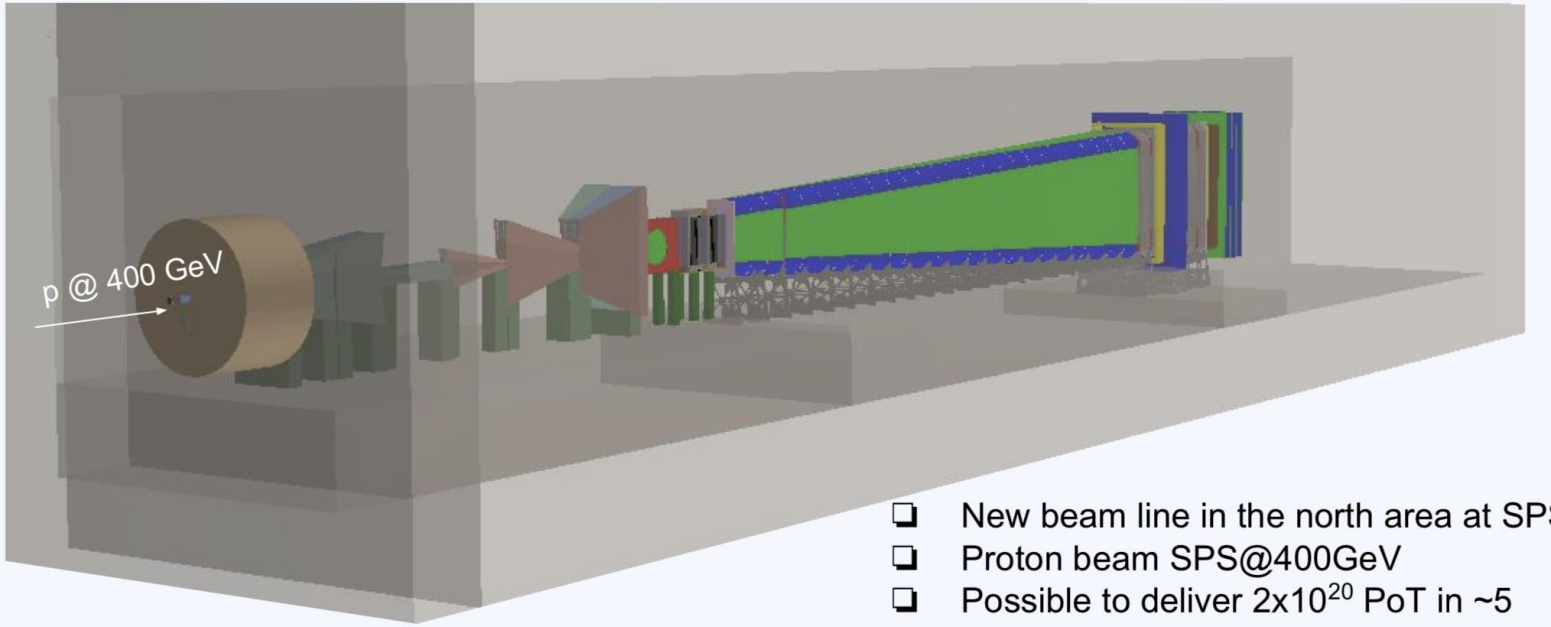
From the beyond collider study document: arXiv:1902.00260



SHiP Beam Dump Experiment Proposal

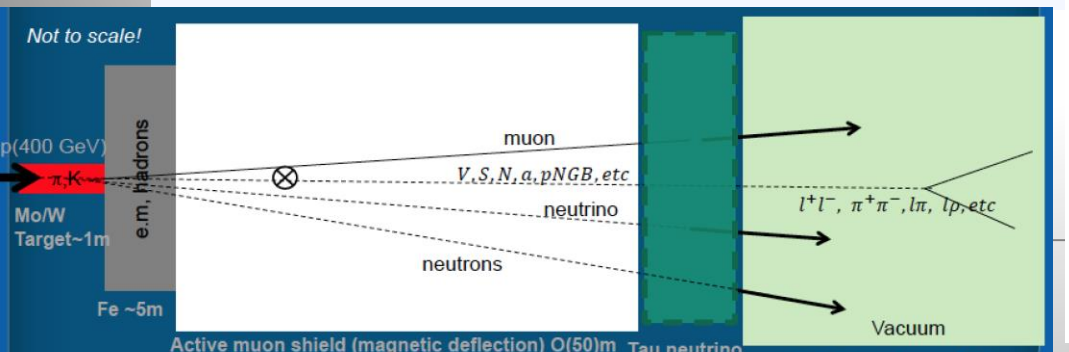
SHiP is a proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to O(10) GeV and weak couplings, down to 10^{-10} .

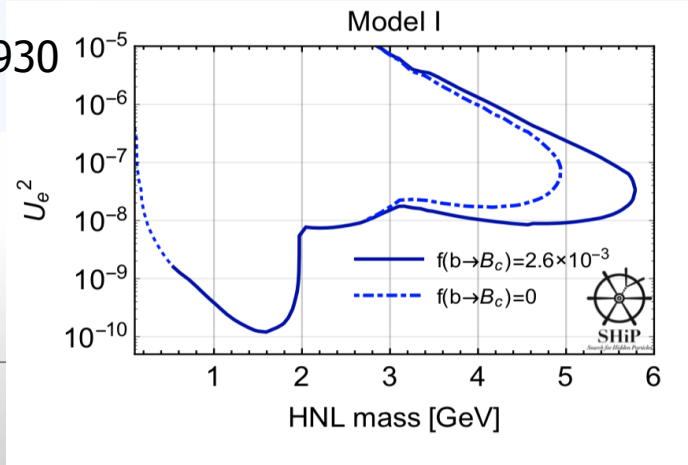
arXiv:1504.04956



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

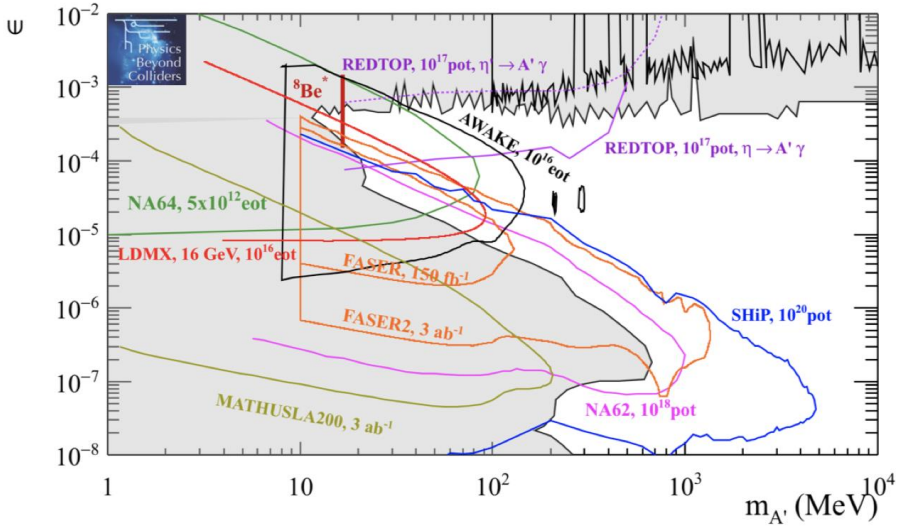
arXiv:1811.00930



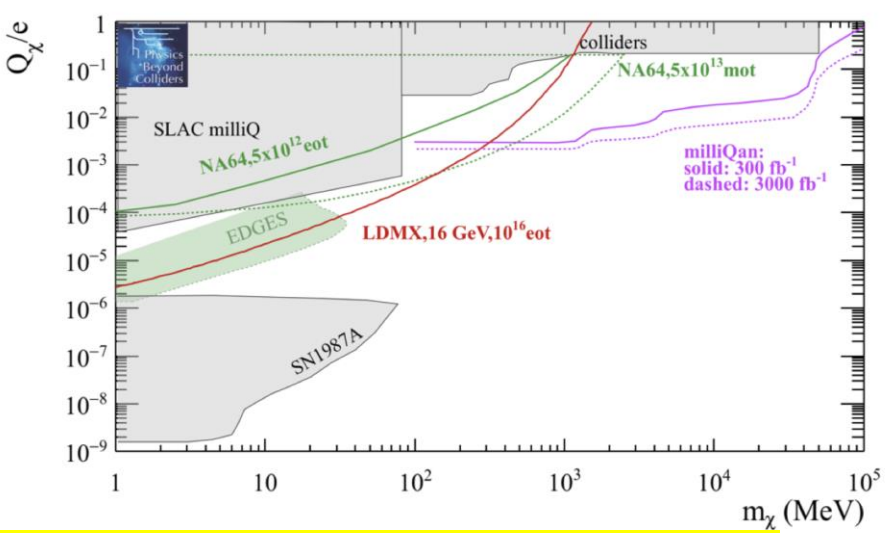


Sensitivity Summaries

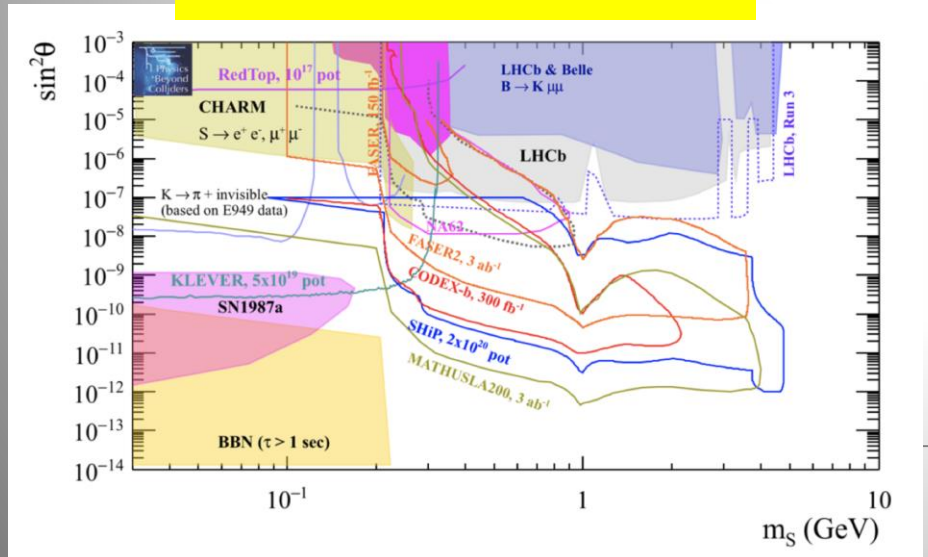
Search for dark photons (visible mode)



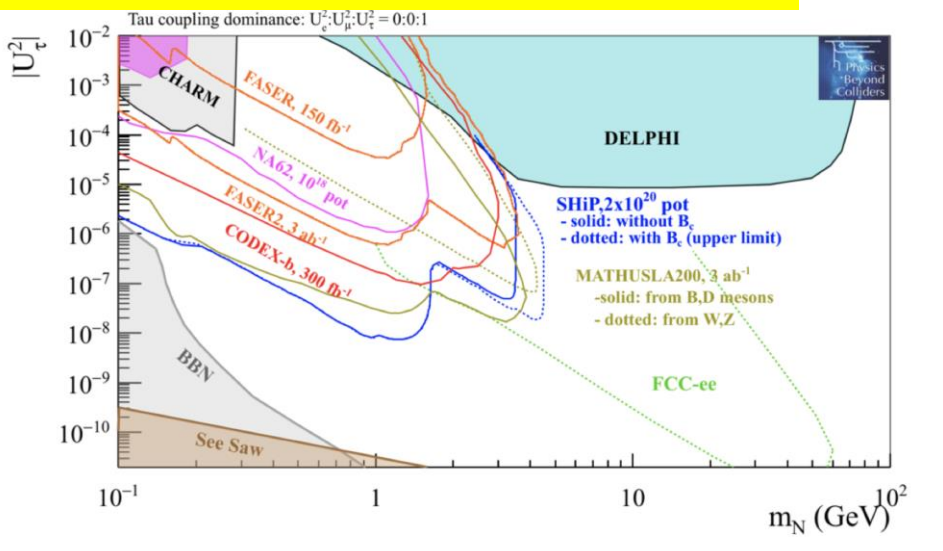
Search for millicharges



Search for dark scalars

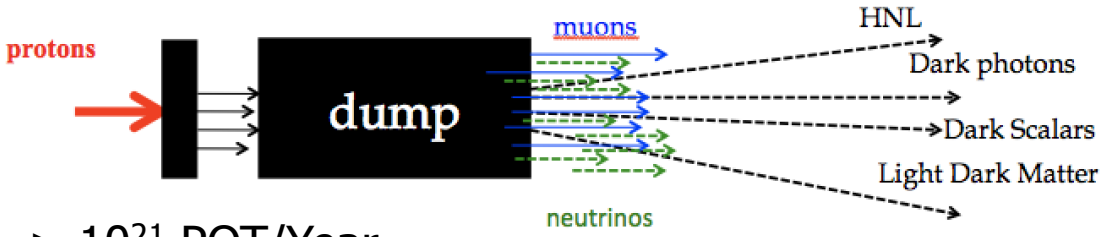


Search for heavy neutral leptons



Beam Dump Experiments

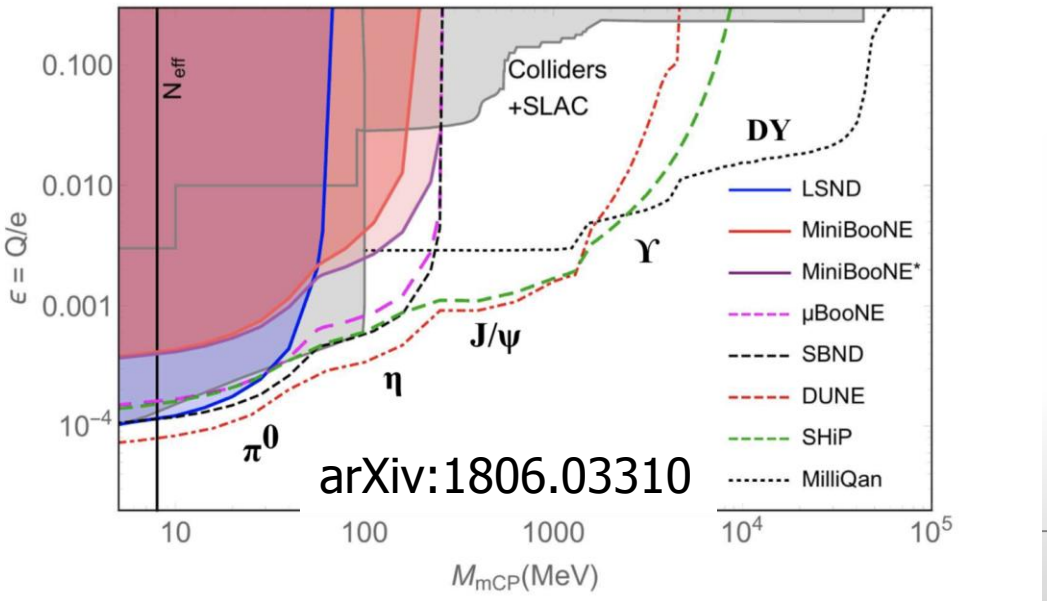
High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



> 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?

Current Neutral LLP Searches

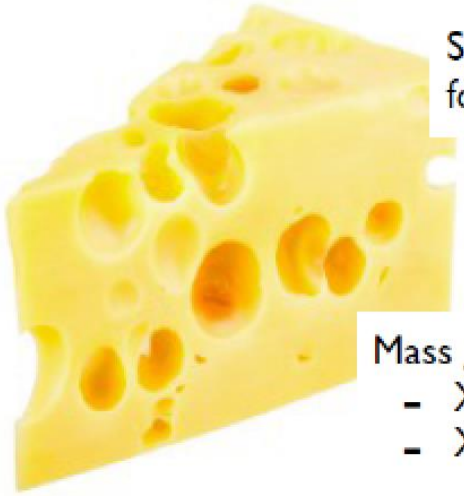
2016

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

Need a more systematic approach

not yet

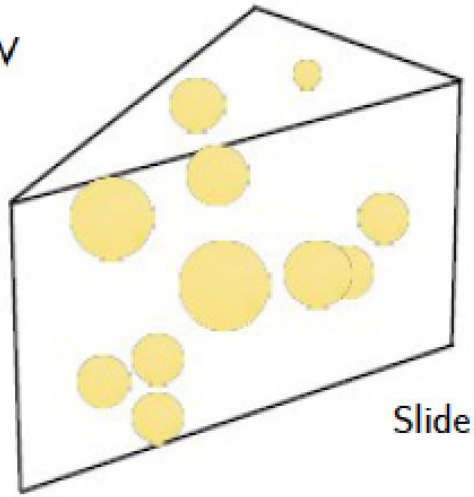


Shorter lifetimes: identify DV for < ~ mm displacements

Mass gaps in current searches:

- X→ leptons: 2 - 20 GeV
- X→ hadrons: < 10 GeV

more like



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)

Next workshop: 27-29 May 2019 CERN

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

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

Report of the CERN Physics Beyond Colliders Working group

CERN-PBC-REPORT-2018

arXiv.org > hep-ex > arXiv:1902.00260

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. Martin 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. Schache G. Schnell[11], P. Schuster[22], Y. Semertzidis[14], A. Siemko[1], T. Spadaro[7], S. Stapnes[1], A. Stocch 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 in are progress. No signal observed yet, but only top of the iceberg covered so far.
- LLP White Paper released! (LHC). Many ideas for new analyses yet to be analysed for the LHC data
- New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, MATHUSLA, CODEX-b, FASER, AL3X. Future beam dump experiments (SHiP). LLPs also focus in the Physics Beyond Collider studies
- Of interest to study in detail the complementarity with LLP searches at Neutrino Near Detectors. Can these be further optimized?
- More opportunities at future projects (FCC…)