A COmpact Detector for EXotics at LHCb: CODEX-b

Carlos Vázquez Sierra 🗣 (IGFAE/USC) [https://cvazquez.notion.site/]

on behalf of the CODEX-b collaboration

8th Red LHC workshop, 29th of May 2024

IGFAE
Instituto Galego de Física de Altas Enerxías

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

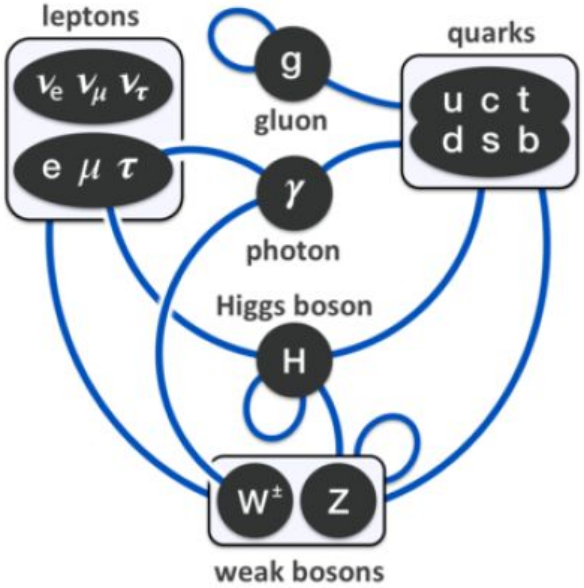
XUNTA
DE GALICIA

CODEX-b

The Standard Model (SM) of elementary particles:

- Most **successful theory** describing subatomic particles and their interactions.
- Accommodates strong, weak and electromagnetic interactions:

$$\mathrm{G}_{\mathrm{SM}} = \mathrm{G}_{\mathrm{QCD}} \times \mathrm{G}_{\mathrm{EW}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$



SM is strongly predictive and precise:

- t predicted (observed) on 1973 (95),
- W/Z predicted (observed) on 1962 (83),
- g predicted (observed) on 1962 (78),
- H predicted (observed) on 1964 (2012),
- Good agreement with experimental results.

The Standard Model (SM) of elementary particles:

- Most **successful theory** describing subatomic particles and their interactions.
- Accommodates strong, weak and electromagnetic interactions:

$$\mathrm{G}_{\mathrm{SM}} = \mathrm{G}_{\mathrm{QCD}} \times \mathrm{G}_{\mathrm{EW}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$

But also an incomplete theory:

- Inability to explain gravity.
- Dark matter and dark energy.
- Baryogenesis problem (BNV, CPV).
- Towards a GUT (gauge unification).
- Neutrino masses.
- Hierarchy problem and fine-tuning.

Still no New Physics?

Maybe…

The New Physics scale is higher than expected?

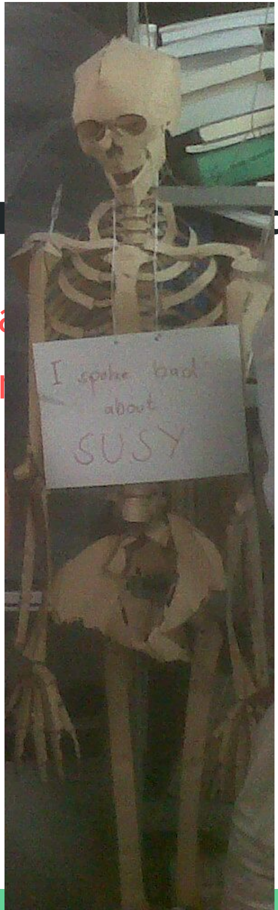
We need **bigger** colliders working at higher energies, with higher precisions…. large technological and financial requirements…

Still no New Physics?

Maybe…

The New Physics scale is higher t d?

We need **bigger** colliders working a rgies, with higher precisions…. large technological and financial requirer



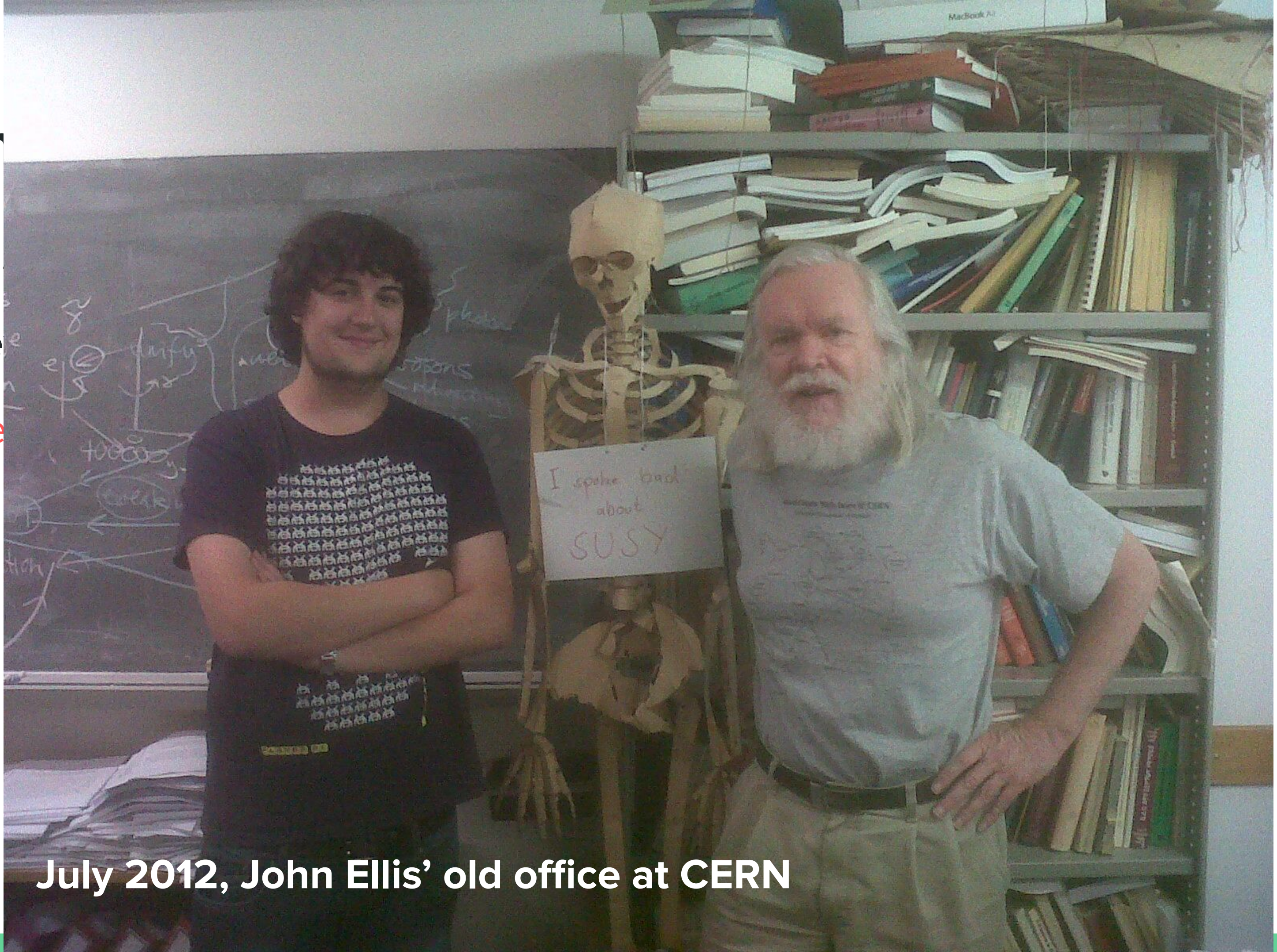
Still r

Maybe.

The Ne

We nee … large

technol



July 2012, John Ellis' old office at CERN

Still no New Physics?

Maybe...

The New Physics scale is higher than expected?

New Physics operates in *“Stealth”* mode?

New Physics exists at the electroweak scale, could be discovered in colliders, but with **heavy mediators, tiny couplings, large backgrounds...**

Still no New Physics?

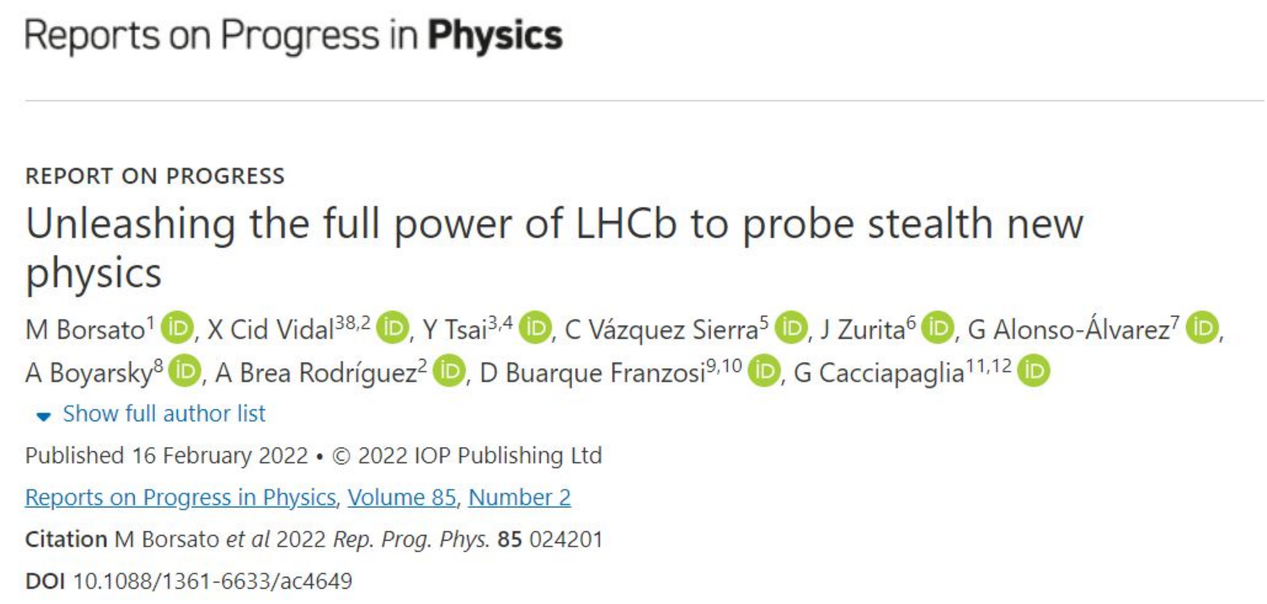
Maybe...

The New Pl

New Physic

New Physic iders, but

with **heavy**



Reports on Progress in **Physics**

REPORT ON PROGRESS

Unleashing the full power of LHCb to probe stealth new physics

M Borsato[1], X Cid Vidal[38,2], Y Tsai[3,4], C Vázquez Sierra[5], J Zurita[6], G Alonso-Álvarez[7], A Boyarsky[8], A Brea Rodríguez[2], D Buarque Franzosi[9,10], G Cacciapaglia[11,12]

▾ Show full author list

Published 16 February 2022 • © 2022 IOP Publishing Ltd

Reports on Progress in Physics, Volume 85, Number 2

Citation M Borsato *et al* 2022 *Rep. Prog. Phys.* **85** 024201

DOI 10.1088/1361-6633/ac4649

Still no New Physics?

Maybe…

The New Physics scale is higher than expected?

New Physics operates in *“Stealth”* mode?

New Physics requires of unconventional search strategies?

New phenomena does not happen strictly around the interaction point in colliders, or will not happen at such high energies?

CODEX-b

FASER

ANUBIS

THE MILLIQAN sub-detector

SHiP
Search for Hidden Particles

LHC-based

Non-LHC based

Xe
XENON
Dark Matter Project

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

ADMX
AXION DARK MATTER EXPERIMENT

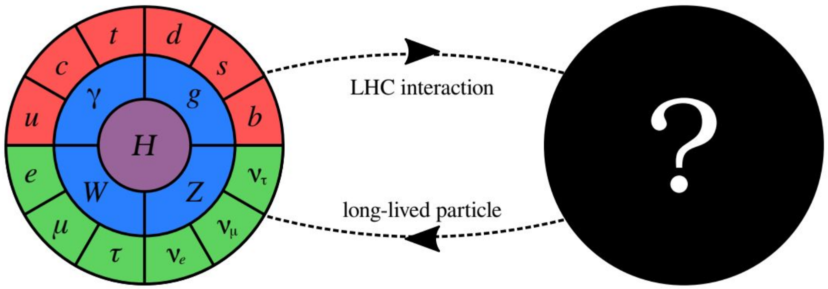
LZ

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

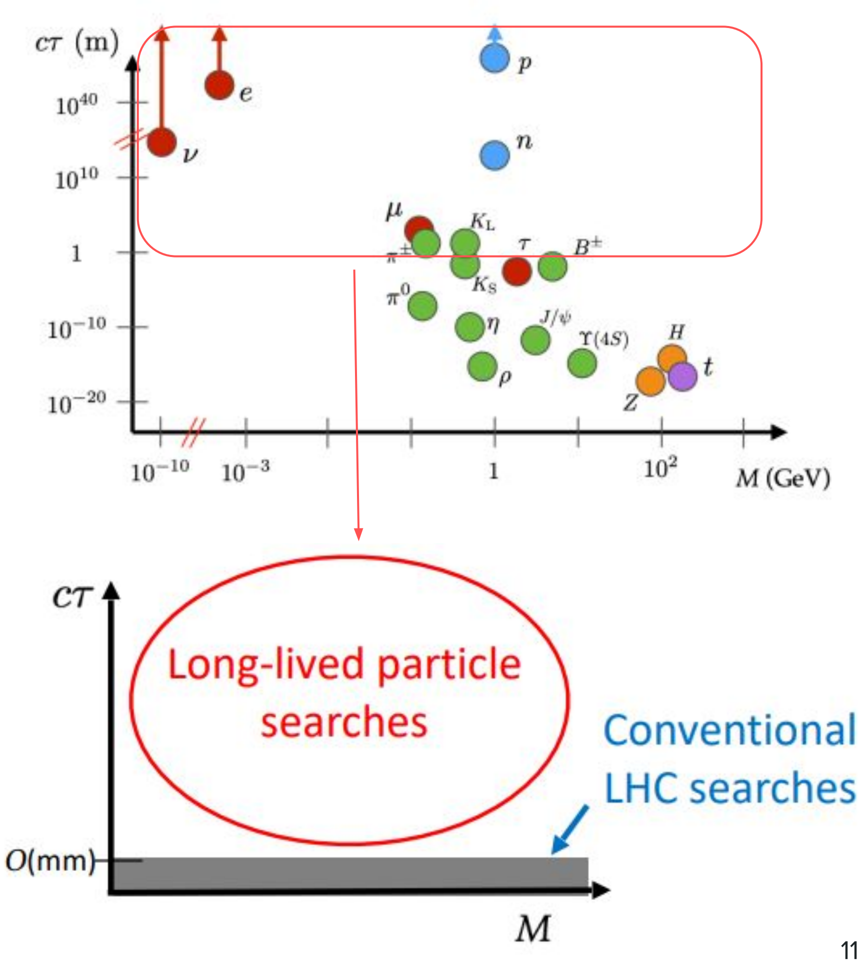
LUX-ZEPLIN (LZ)
DARK MATTER SEARCH

Search for feebly interacting long-lived particles (LLPs)

Small coupling with SM → large lifetime (e.g. dark sectors).



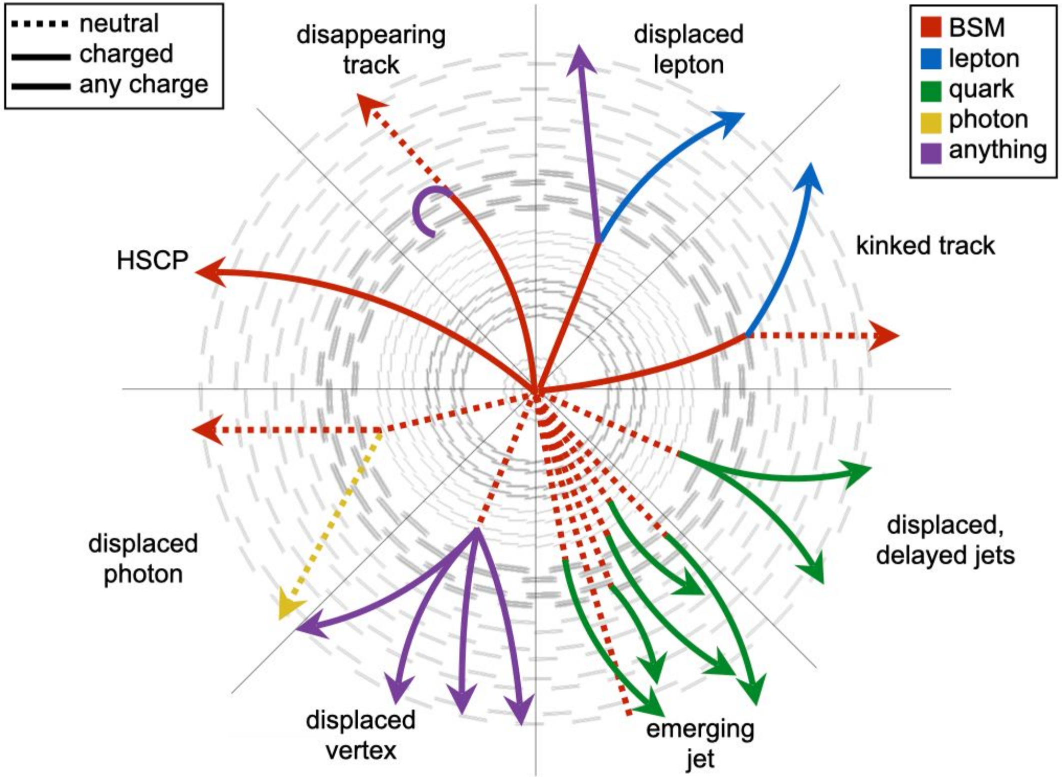
LHC conventional searches typically focused on shorter lifetimes, higher masses.



Complex and diverse model space → sometimes very complicated signatures.

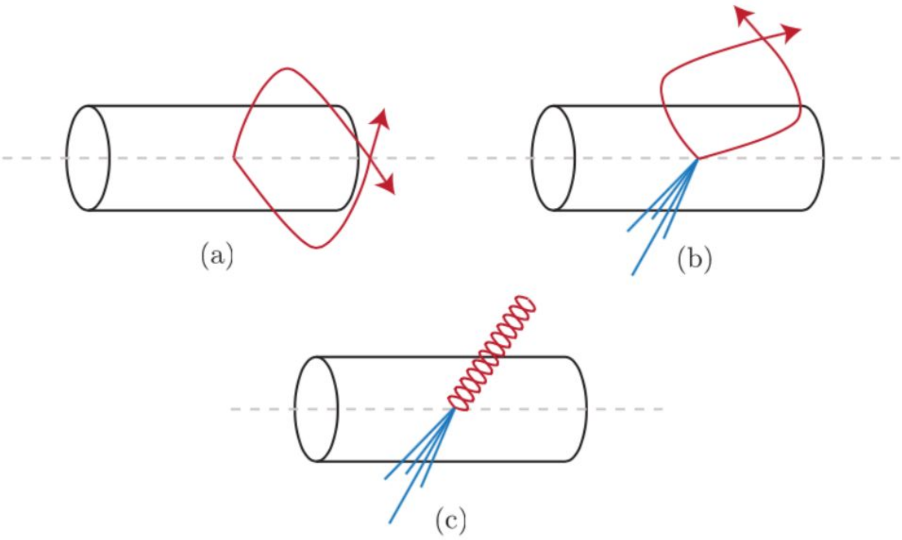
Huge efforts at major collaborations (ATLAS, CMS, LHCb) required to design and develop dedicated triggers, reconstruction algorithms, and even complicated simulation models.

These detectors were not originally designed for these kind of searches.

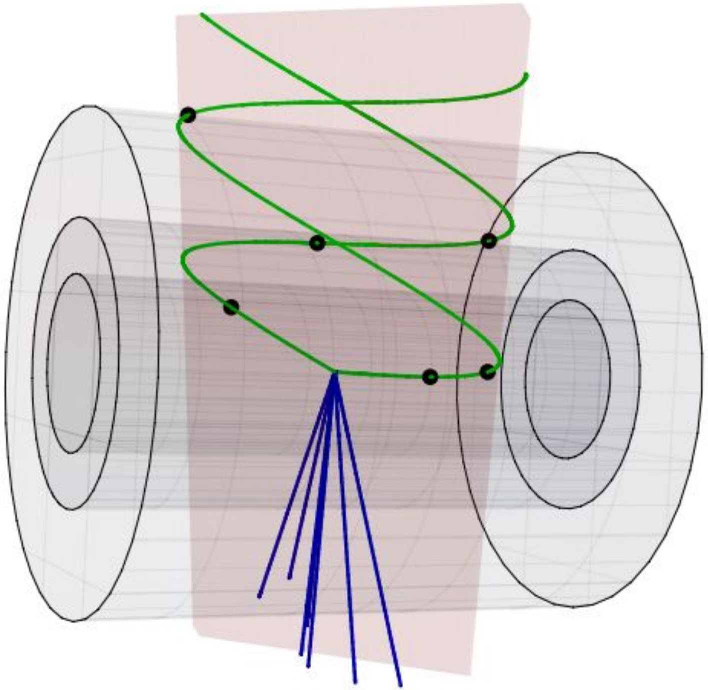


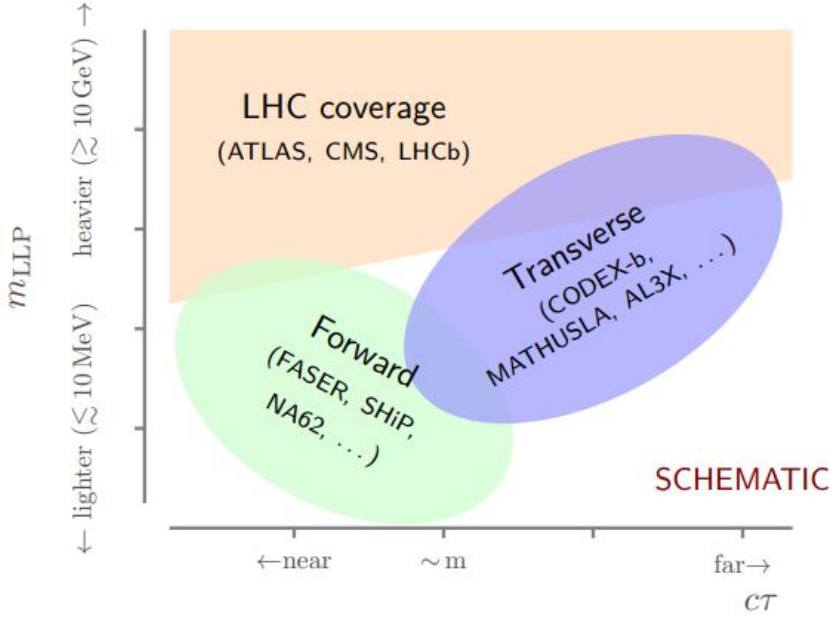
CMS schematic,
J. Antonelli (ICHEP 2016)

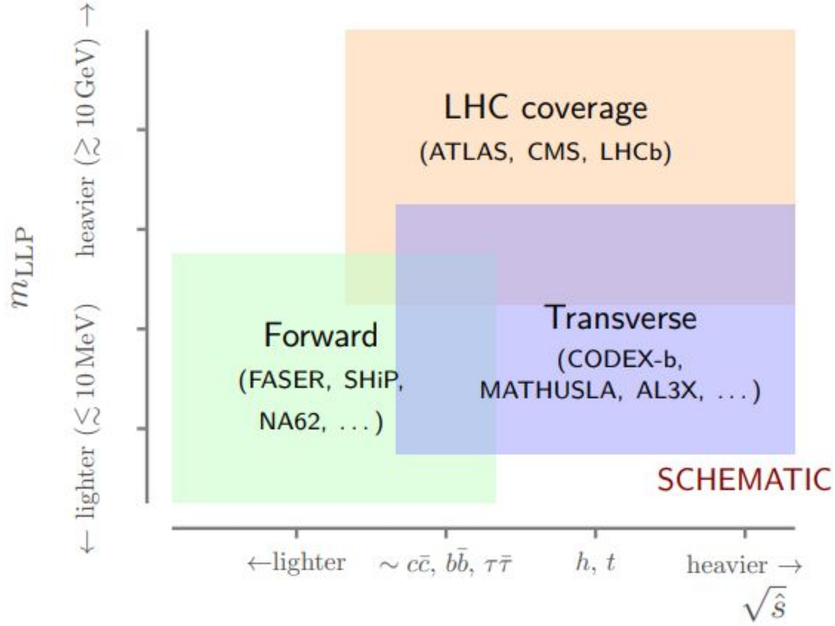
Complex and diverse model space → sometimes <u>very complicated</u> signatures.



arXiv:0805.4642 "Macroscopic strings and **quirks** at colliders"

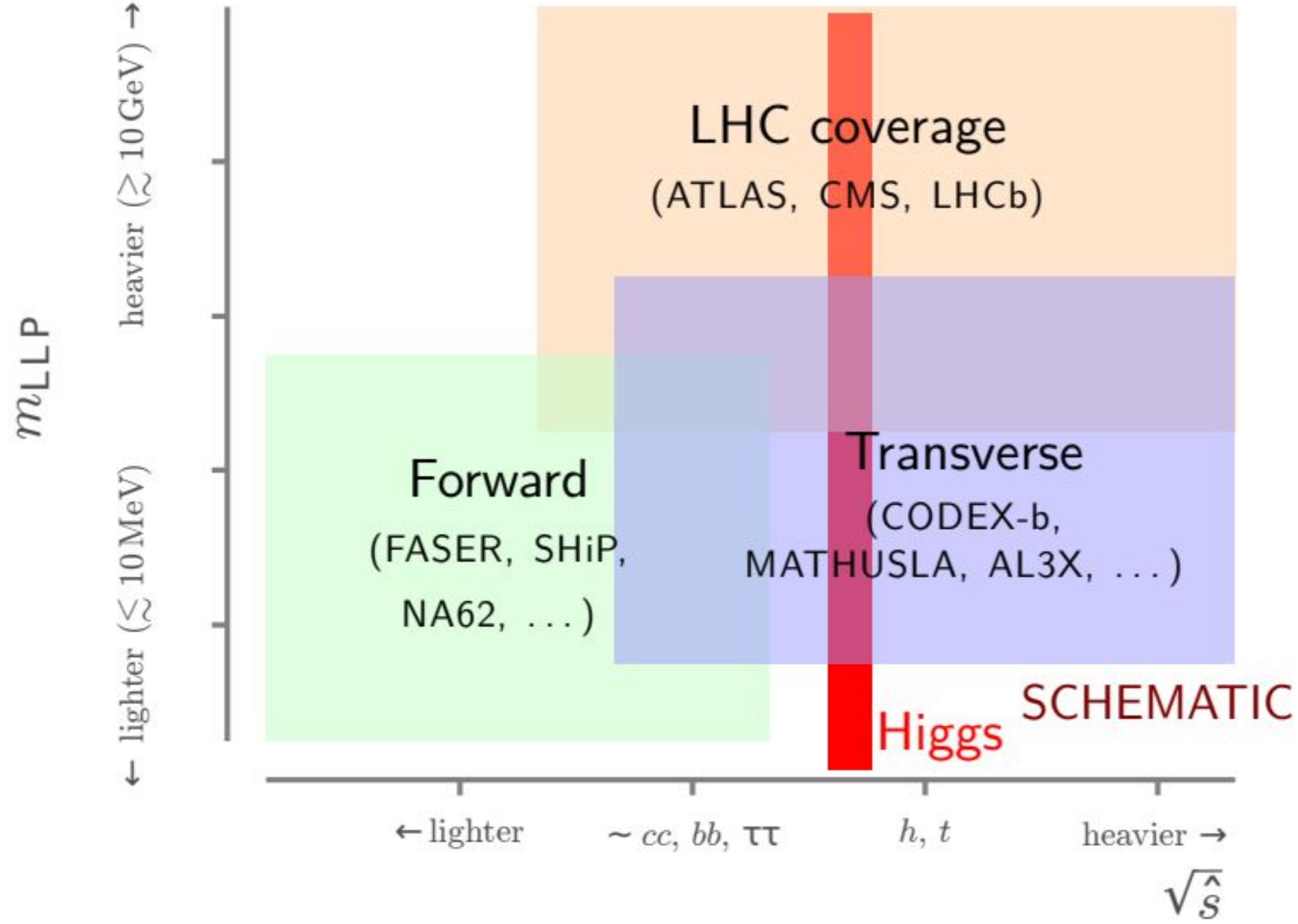






Propose new, dedicated LLP detectors to cover the inaccessible gaps of the parameter space.

Rely on simpler reconstruction and tracking systems, much more flexible to accommodate unusual signatures.

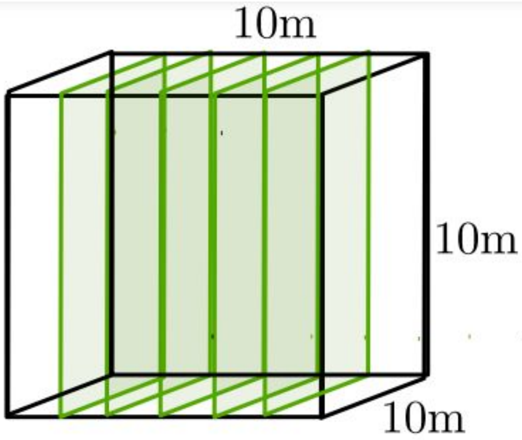

LHC coverage
(ATLAS, CMS, LHCb)
Forward
(FASER, SHiP, NA62, . . .)
Transverse
(CODEX-b, MATHUSLA, AL3X, . . .)
Higgs
SCHEMATIC
m_{LLP}
↓ lighter ($\lesssim 10\,\mathrm{MeV}$)
heavier ($\gtrsim 10\,\mathrm{GeV}$) ↑
← lighter
$\sim cc,\ bb,\ \tau\tau$
$h,\ t$
heavier →
$\sqrt{\hat{s}}$

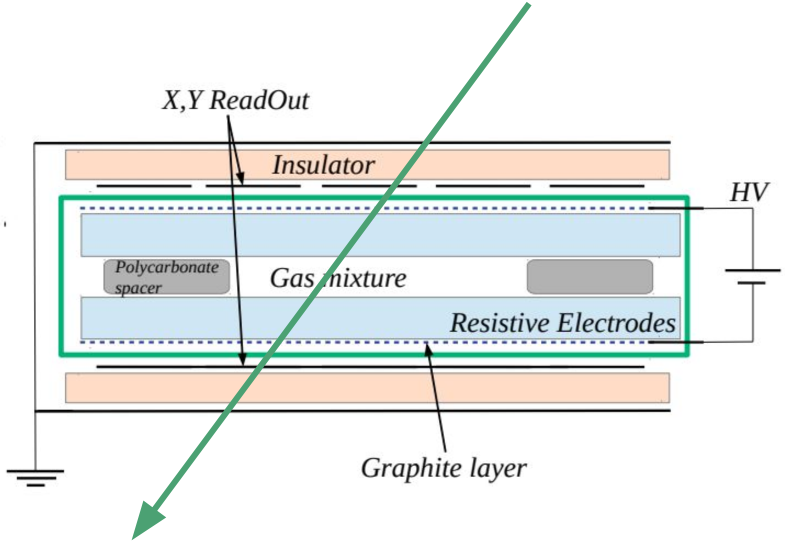
CODEX-b design

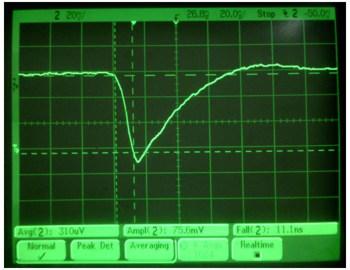
Forging a new detector

A COmpact Detector for EXotics at LHCb: CODEX-b

CODEX-b is a 10x10x10 m cube, with hundreds of **Resistive Plate Chamber (RPC) detectors** assembled in triplets and mounted in mechanical frames.





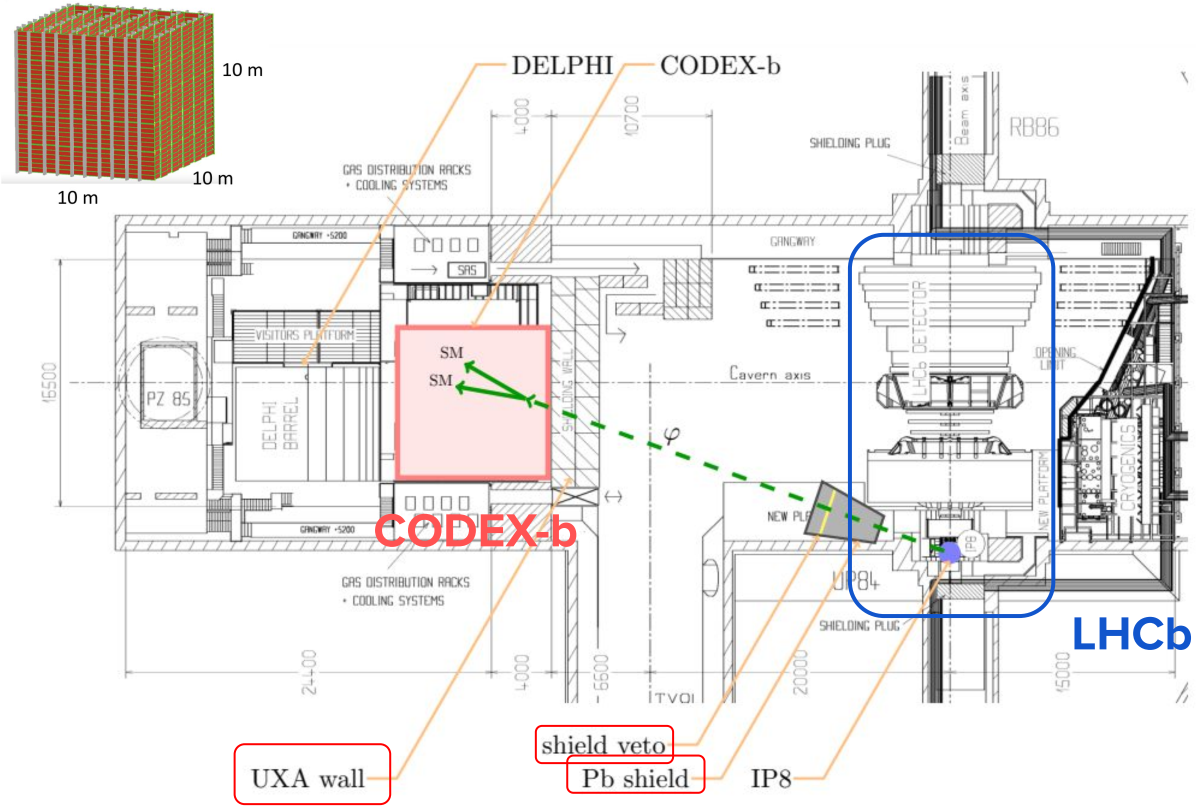


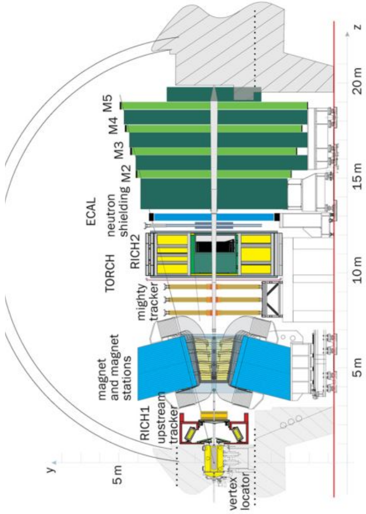
No civil work needed → will make use of existing facilities in the UXA85 cavern.

Relatively **cheap** detector, **O(10) M€**

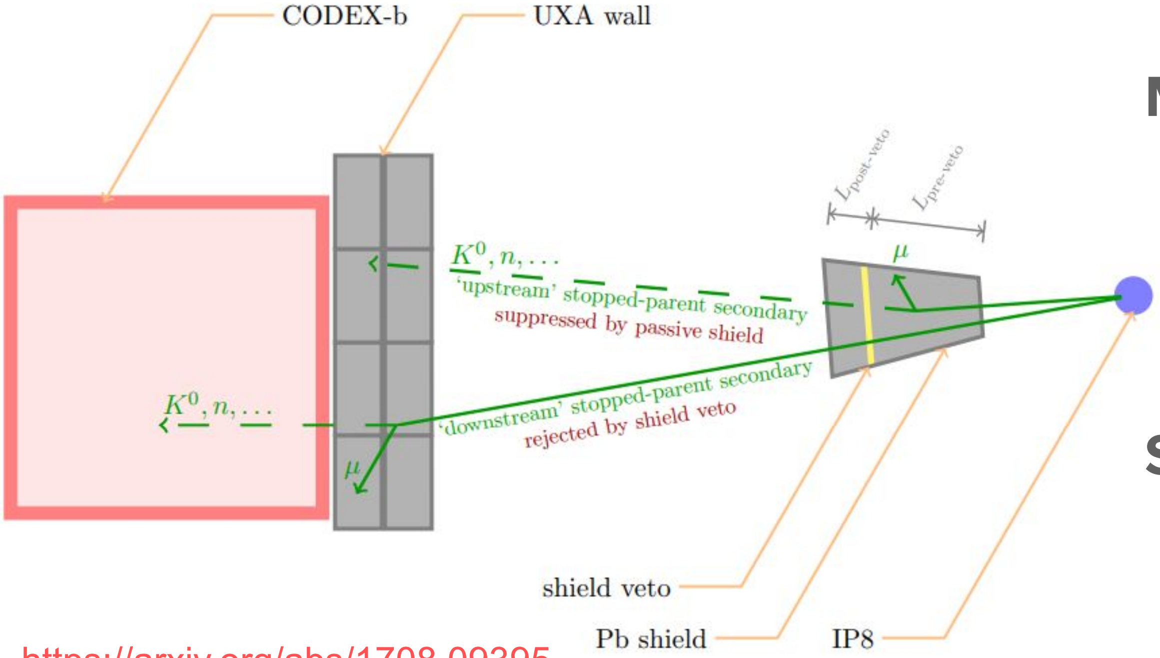
Located 25 m away from the IP8 (LHCb).

Zero-background: UXA wall + shield veto.





A background-free detector: shielding



https://arxiv.org/abs/1708.09395
https://arxiv.org/abs/1911.00481

Expect 10^{14} neutrons and KL^0 in 300 fb^{-1}.

Main backgrounds:

- ***n*, *KL^0* (main)** and ***μ***,
- **penetrating the wall,**
- or **from secondaries or stopped-parent decays**.

Shielding of 32λ/300 fb^{-1}:

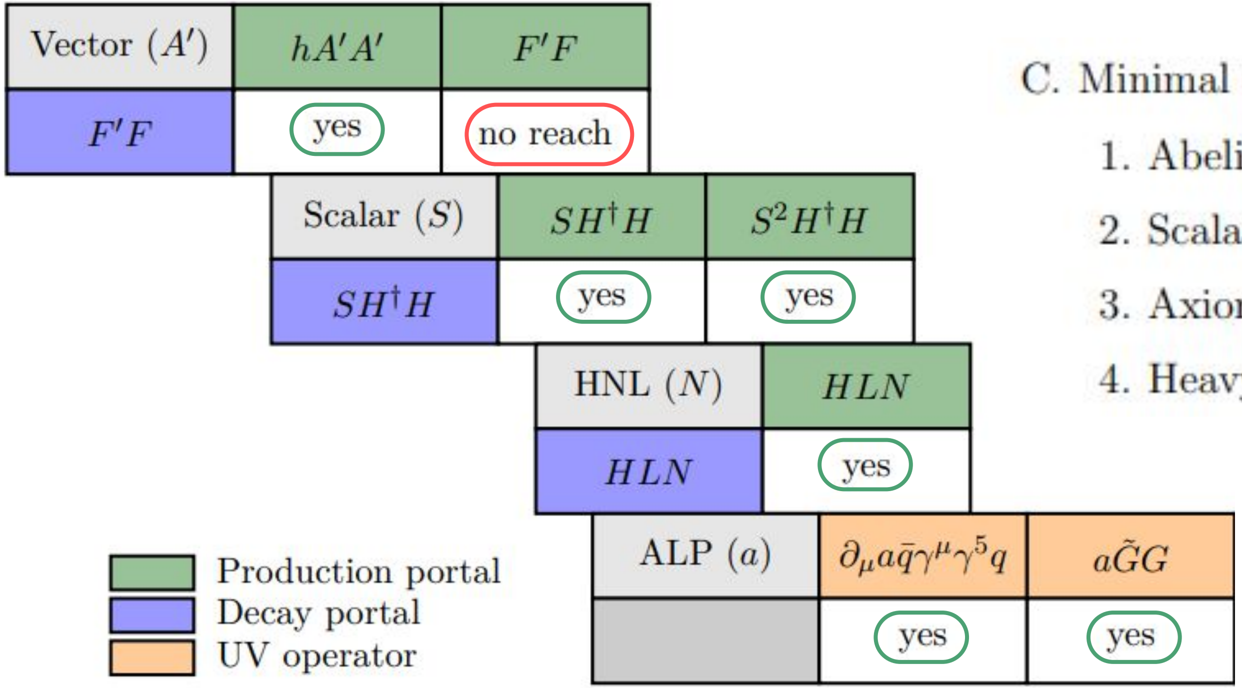
- **Pb shield (pre-veto) ~ 20λ,**
- **Shield veto,**
- **Pb shield (post-veto) ~ 5λ,**
- **UXA wall ~ 7λ.**

Physics reach

Unveiling the undiscovered

An overview of minimal models

https://arxiv.org/abs/1708.09395
https://arxiv.org/abs/1911.00481
https://arxiv.org/abs/2203.07316



Vector (A')	$hA'A'$	$F'F$
$F'F$	yes	no reach

Scalar (S)	$SH^\dagger H$	$S^2H^\dagger H$
$SH^\dagger H$	yes	yes

HNL (N)	HLN
HLN	yes

ALP (a)	$\partial_\mu a \bar{q}\gamma^\mu\gamma^5 q$	$a\tilde{G}G$
	yes	yes

🟩 Production portal
🟦 Decay portal
🟧 UV operator

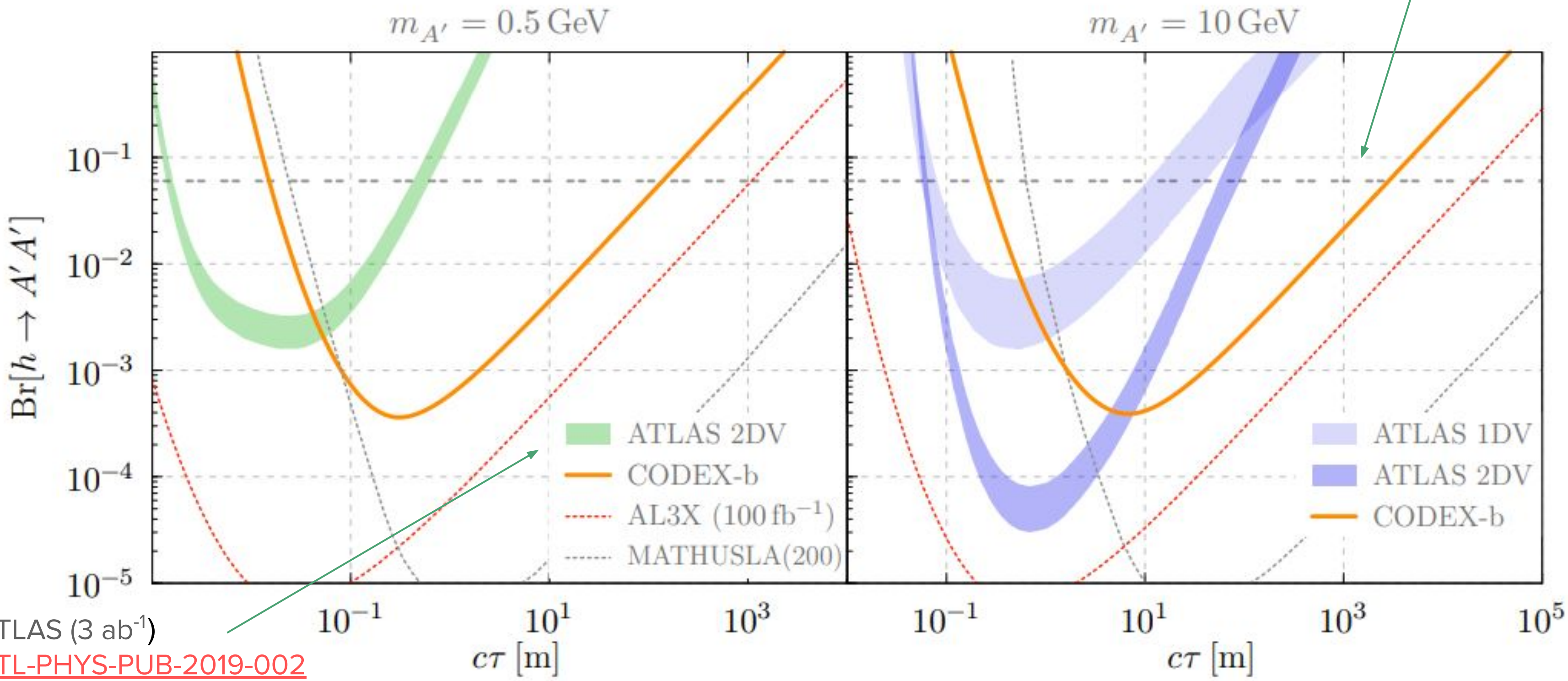
C. Minimal models

1. Abelian hidden sector
2. Scalar-Higgs portal
3. Axion-like particles
4. Heavy neutral leptons

(Only published studies)

Abelian hidden-sector: *dark photon*

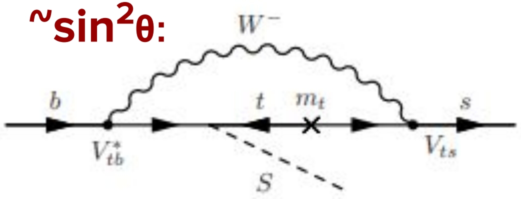
Higgs to invisible (HL-LHC) limit
arXiv:1902.00134



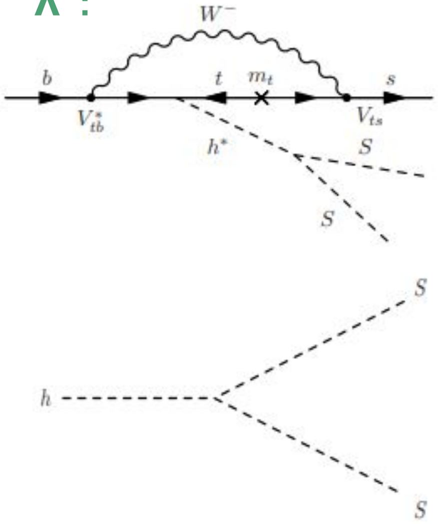
ATLAS (3 ab^{-1})
ATL-PHYS-PUB-2019-002
Phys. Rev. D 99, 052005

Scalar-Higgs portal

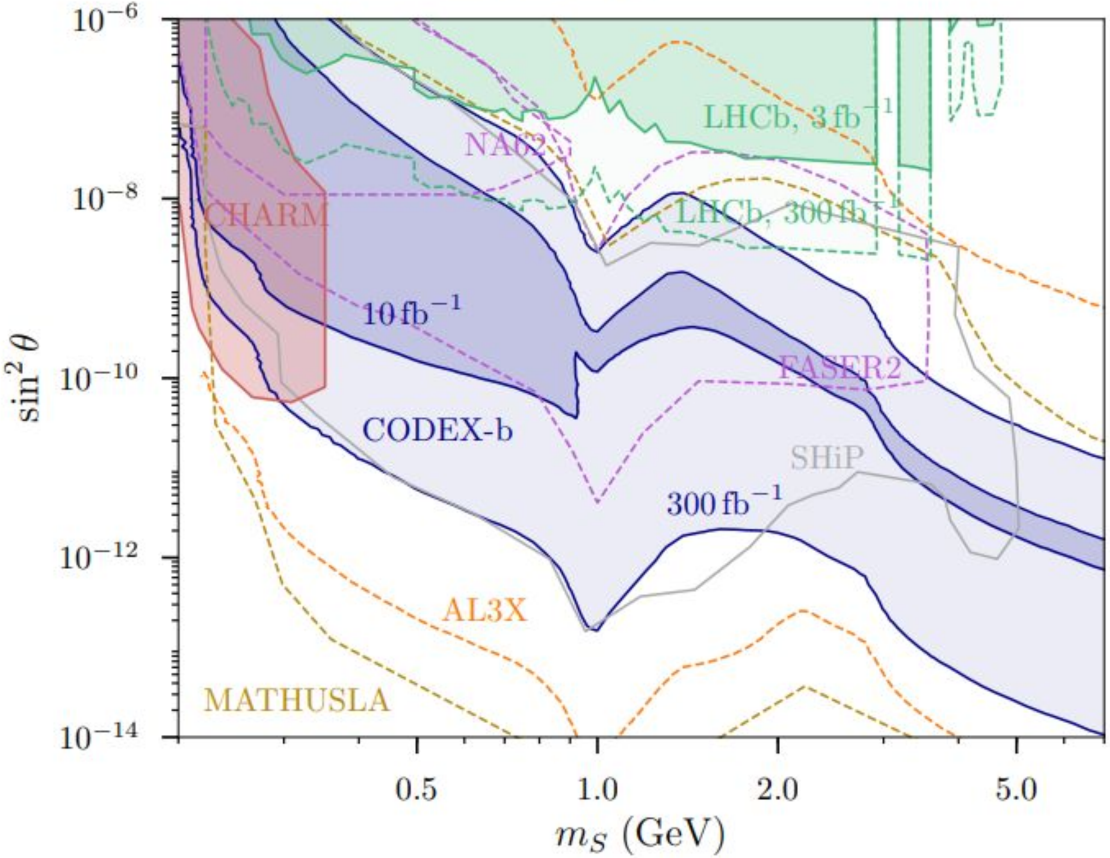
~$\sin^2\theta$:



~λ^2:

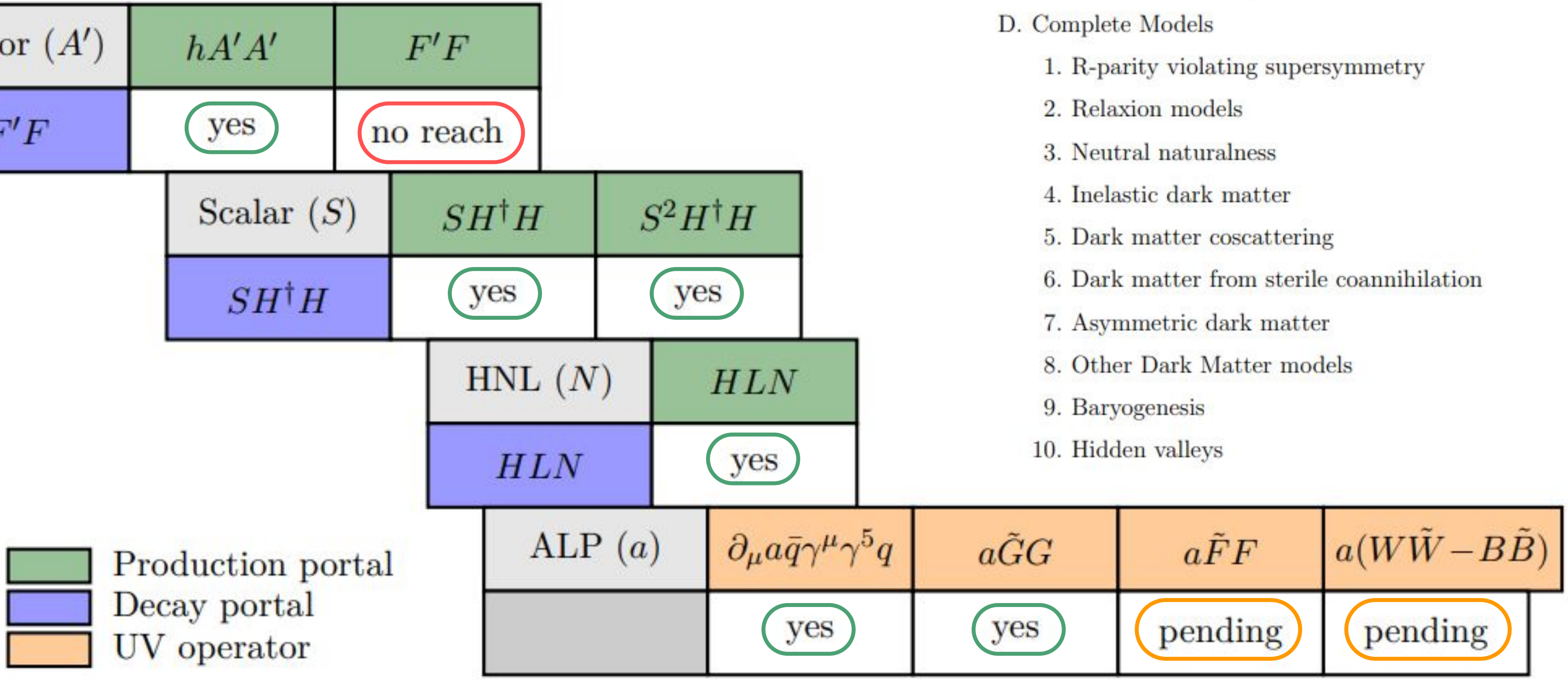


$\lambda = 1.6 \times 10^{-3}$ **From b-hadron decays**



An overview of (minimal) models

https://arxiv.org/abs/1911.00481



Vector (A')	$hA'A'$	$F'F$
$F'F$	yes	no reach

Scalar (S)	$SH^\dagger H$	$S^2H^\dagger H$
$SH^\dagger H$	yes	yes

HNL (N)	HLN
HLN	yes

ALP (a)	$\partial_\mu a\bar{q}\gamma^\mu\gamma^5 q$	$a\tilde{G}G$	$a\tilde{F}F$	$a(W\tilde{W}-B\tilde{B})$
	yes	yes	pending	pending

🟩 Production portal
🟦 Decay portal
🟧 UV operator

C. Minimal models
  1. Abelian hidden sector
  2. Scalar-Higgs portal
  3. Axion-like particles
  4. Heavy neutral leptons

D. Complete Models
  1. R-parity violating supersymmetry
  2. Relaxion models
  3. Neutral naturalness
  4. Inelastic dark matter
  5. Dark matter coscattering
  6. Dark matter from sterile coannihilation
  7. Asymmetric dark matter
  8. Other Dark Matter models
  9. Baryogenesis
  10. Hidden valleys

CODEX-β

CODEX-b v0.1

The need for a demonstrator

CODEX-b will be a **O(10) M€, near zero SM-background detector**, composed by **hundreds of RPCs arranged in a 10x10x10 m cube**.

Purpose of a demonstrator:

- **Test the technology, design and integration with LHCb.**
- **Measure the backgrounds accurately and validate our simulations,**
- **Perform physics measurements and update sensitivities projections.**

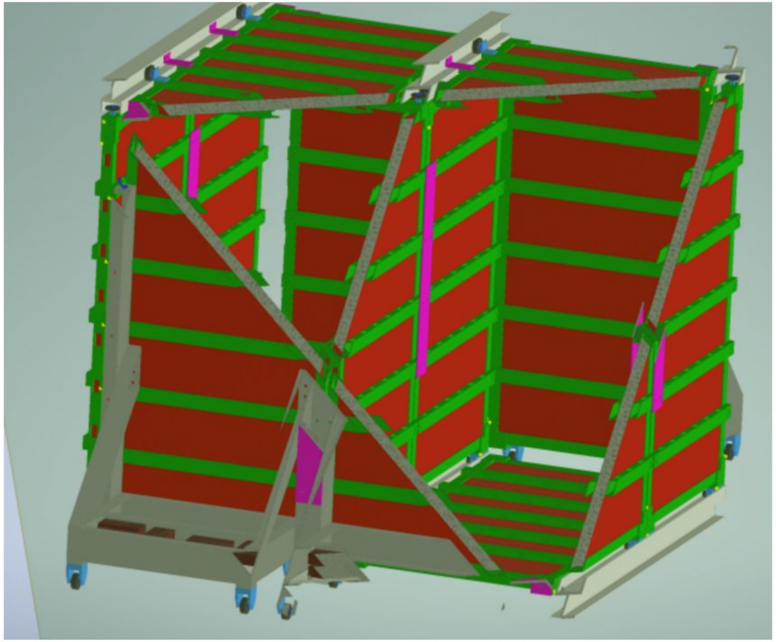
CODEX-β, a smaller version of CODEX-b, with 42 RPCs, integrated with LHCb and taking data during Run 3 (2025), costing ~1% of the full CODEX-b detector.

Designing the origins

CODEX-β is a 2 x 2 x 2 m cube:

- Each side is composed by 2 panels, 1 x 2 m each → **2x6 = 12 panels,**
- 2 panels inside → 12+2 = **14 total panels.**
- Each panel consists of a RPC triplet (3 singlets),
- **Design from BIS78 ATLAS upgrade project (as for CODEX-b).**

Mechanical frames completely redesigned by the CODEX-b team, built in the UC workshop.



Assembling and testing the RPCs

Target: assemble **14 panels**, with a RPC triplet each → **42 RPC singlets.**

Today: built 22 of 42 singlets, starting triplet characterization.

Began at BB5, but space needed by ATLAS start of 2024.

Migrated to B904 site, adjacent to CMS RPC workspace:

- Gas from CMS RPCs,
- Electronics and grounding ready to go,
- Trigger boards arrived and fully functional.

Huge thanks to ATLAS,
CMS and ANUBIS! 👏

Plan to complete installation and commissioning this year, and start the data-taking campaign by 2025.

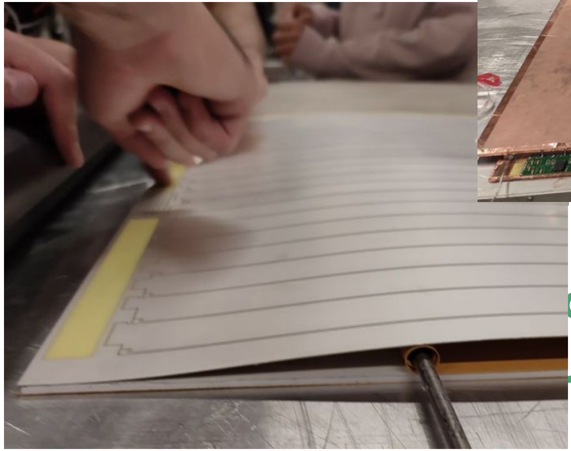
Assembling and testing the RPC

Target: assemble **14 panels**, with a RPC triplet

Today: built 22 of 43

Began at BB5, but sp

Migrated to B904 sit



nd fully functional.

o ATLAS,

BIS! 👏

an to complete installation
d commissioning this year,
and start the data-taking
campaign by 2025.

Assembling and testing the RPC

Targ

Tod

Beg

Mig

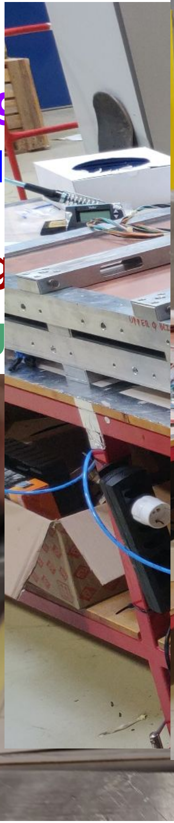
Assemb

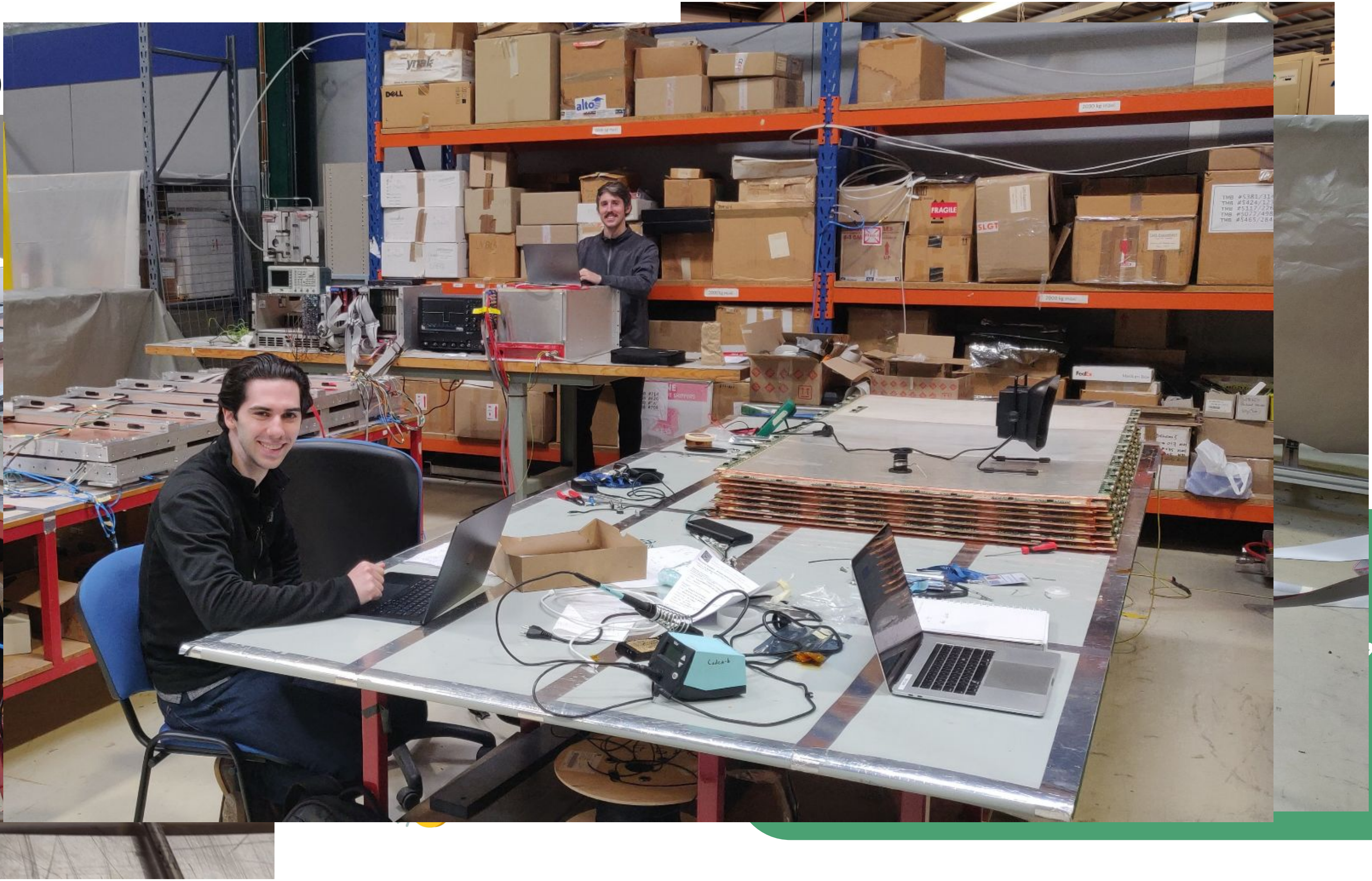
Targ

Tod

Beg

Mig





Assembling and testing the RPCs

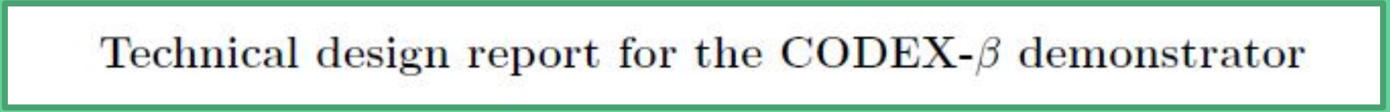
Target:

Today

Begar

Migra

- Gas
- Elec
- Trigg

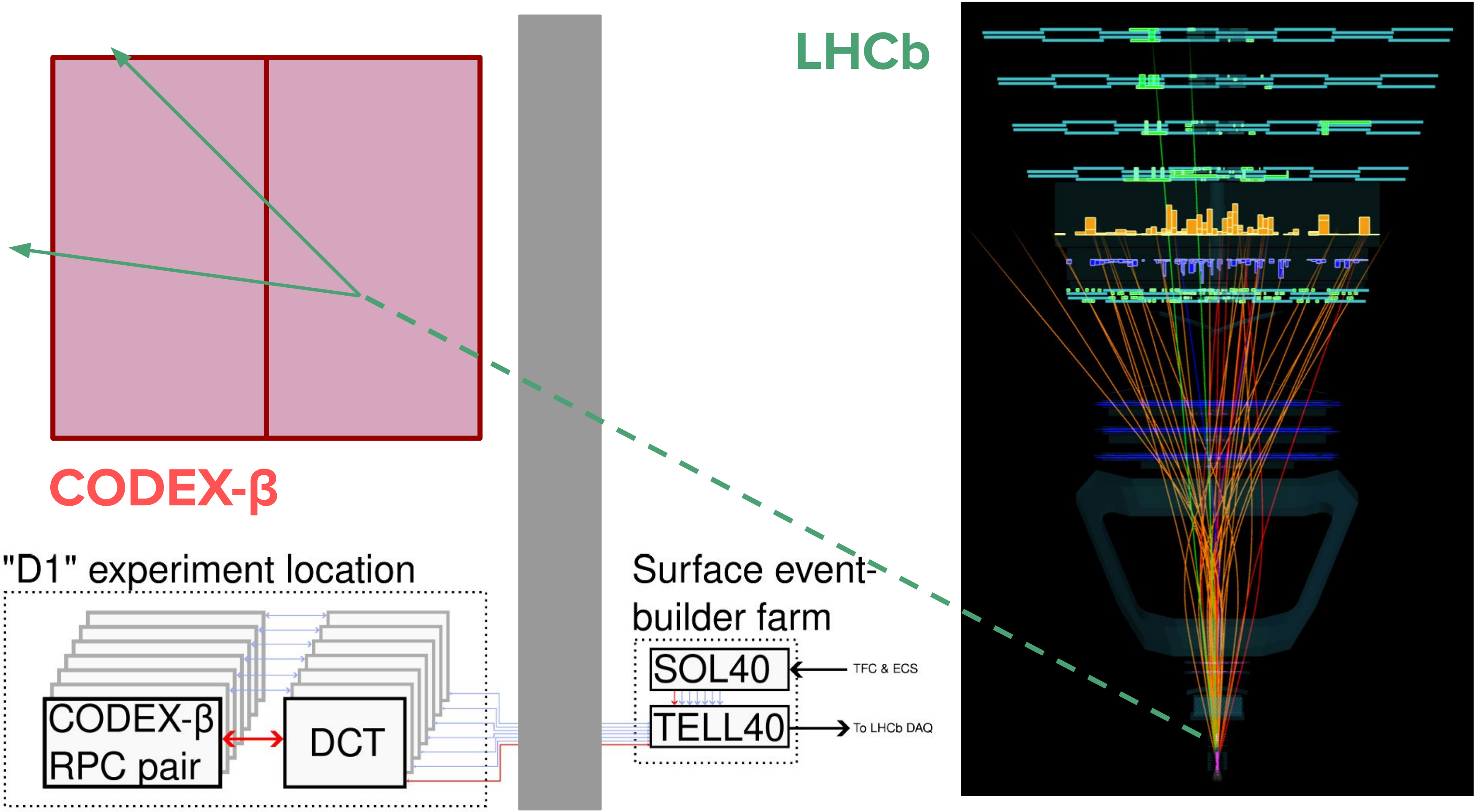

Technical design report for the CODEX-β demonstrator

Coming NEXT WEEK to the arXiv! Stay tuned!

A similar document on the physics plan with CODEX-β will be released as well in the next months!

:ion
/ear,
and start the data-taking campaign by 2025.

Huge thanks to ATLAS, CMS and ANUBIS! 👏

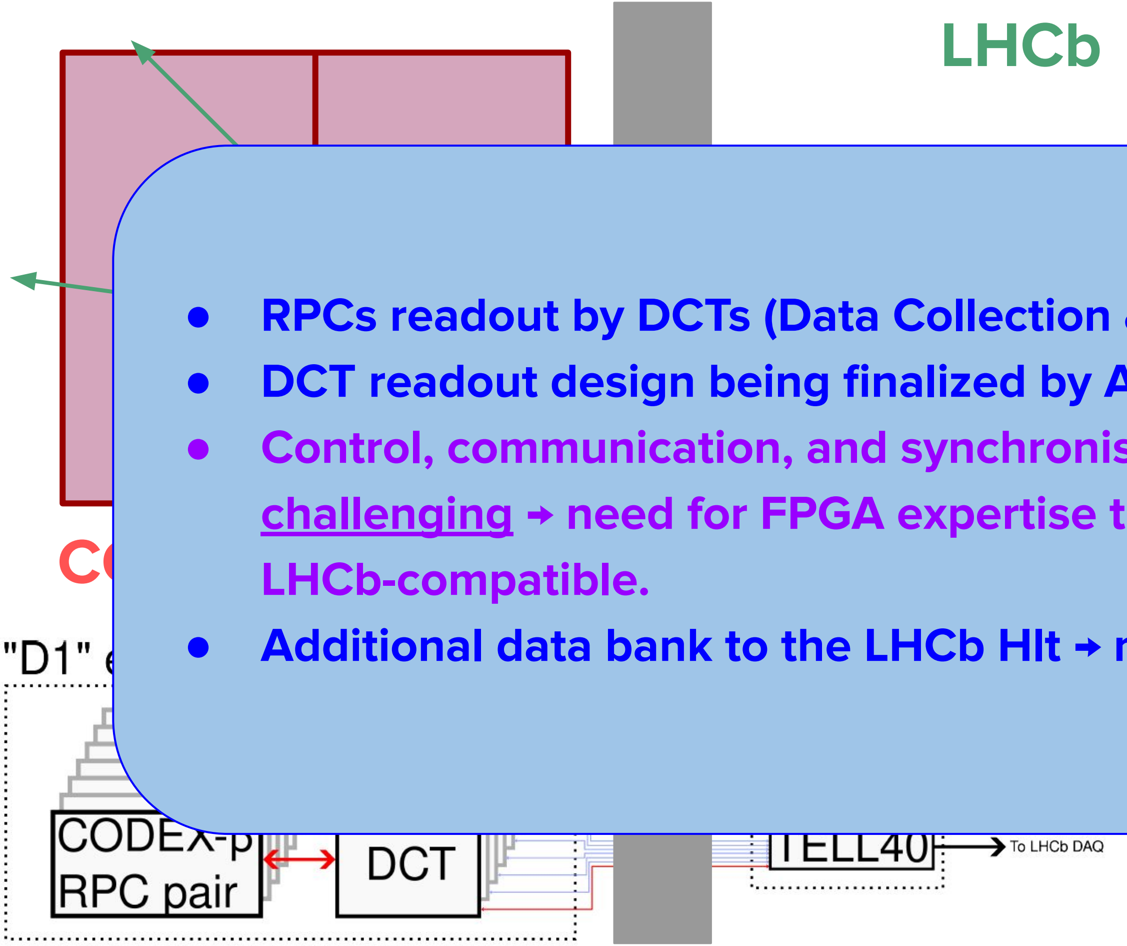


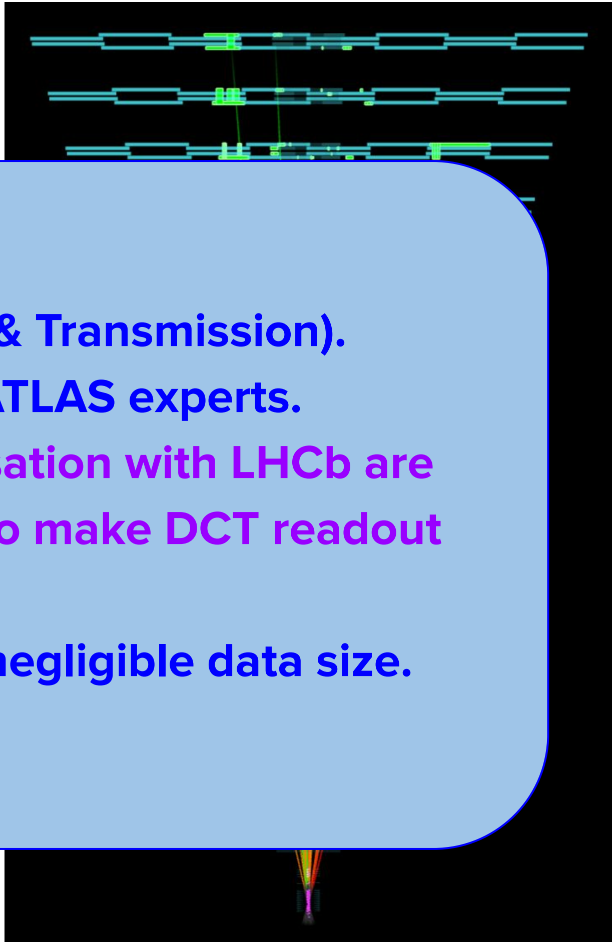
LHCb

CODEX-β

"D1" experiment location
CODEX-β RPC pair
DCT
Surface event-builder farm
SOL40
TELL40
TFC & ECS
To LHCb DAQ

LHCb





- **RPCs readout by DCTs (Data Collection & Transmission).**
- **DCT readout design being finalized by ATLAS experts.**
- **Control, communication, and synchronisation with LHCb are <u>challenging</u> → need for FPGA expertise to make DCT readout LHCb-compatible.**
- **Additional data bank to the LHCb Hlt → negligible data size.**

Summary

CERN
DESY.
Duke UNIVERSITY
LPNHE PARIS
SFU SIMON FRASER UNIVERSITY
香 港 大 學 THE UNIVERSITY OF HONG KONG
ELTE EÖTVÖS LORÁND UNIVERSITY
UNIVERSITÉ PIERRE & MARIE CURIE LA SCIENCE À PARIS
IGFAE Instituto Galego de Física de Altas Enerxías
USC
XUNTA DE GALICIA
中 山 大 學 SUN YAT-SEN UNIVERSITY
Massachusetts Institute of Technology
BERKELEY LAB
Berkeley UNIVERSITY OF CALIFORNIA
İSÜ İSTİNYE ÜNİVERSİTESİ ISTANBUL
UNIVERSITY OF BIRMINGHAM
UPPSALA UNIVERSITET
University of CINCINNATI
Caltech
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA
INFN Istituto Nazionale di Fisica Nucleare

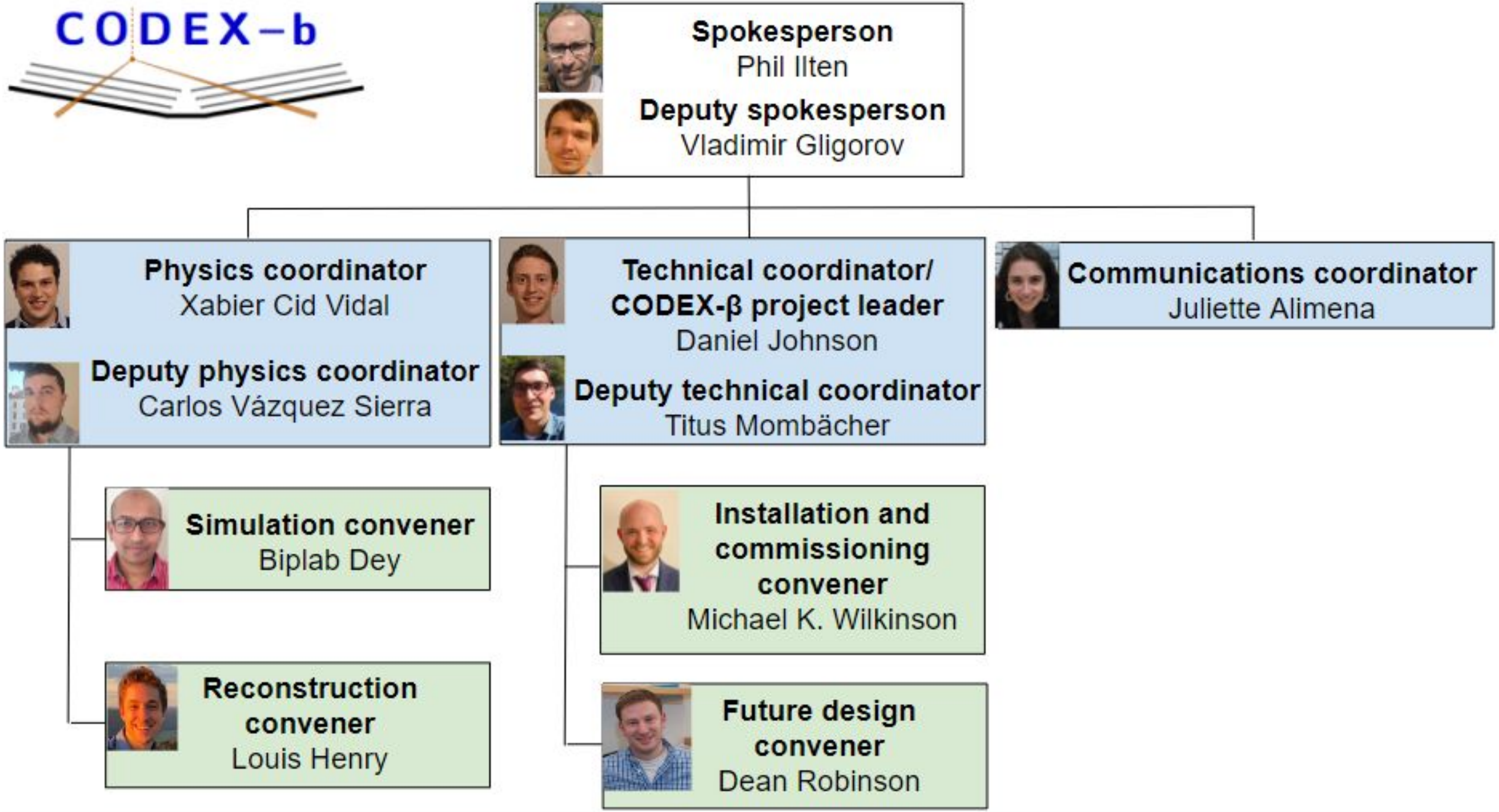
growing team with 22 institutes with 53 members

theory (5), engineering (4), ATLAS (10), CMS (5), LHCb (29)

leadership from all 5 categories

https://codex-b.web.cern.ch/

CODEX-b



Spokesperson
Phil Ilten

Deputy spokesperson
Vladimir Gligorov

Physics coordinator
Xabier Cid Vidal

Deputy physics coordinator
Carlos Vázquez Sierra

Technical coordinator/ CODEX-β project leader
Daniel Johnson

Deputy technical coordinator
Titus Mombächer

Communications coordinator
Juliette Alimena

Simulation convener
Biplab Dey

Reconstruction convener
Louis Henry

Installation and commissioning convener
Michael K. Wilkinson

Future design convener
Dean Robinson

Summary

- **Intense and fruitful year for the CODEX-b team (and for everyone).**
- **Finalize the construction and installation of CODEX-β by 2024.**
- Take data by the end of 2024/beginning of 2025.
- **Challenges ahead:** DAQ/readout design, LHCb integration.
- **Collaboration in a healthy status → 10 talks in 2023 (EPS, LLP13, Higgs…), 2 talks in 2024 plus 1 poster and 2 secured talks (LHCP @ Boston, LLP14 @ Tokyo).**

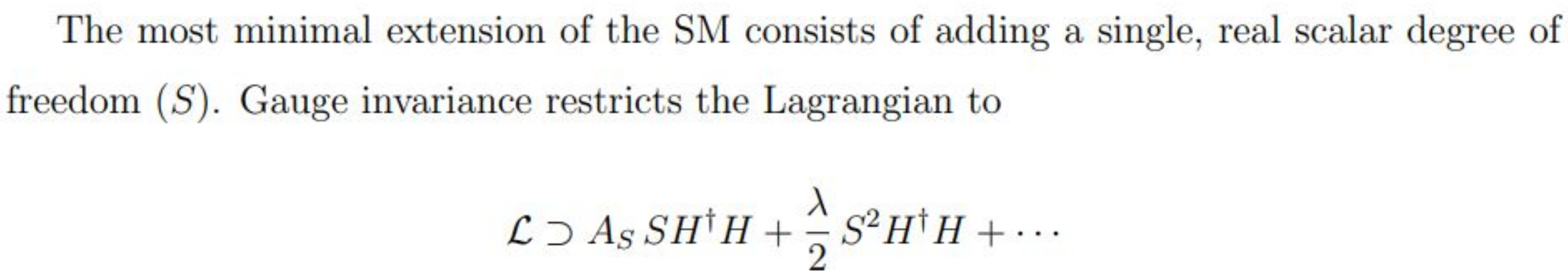
However, we would benefit from personpower to cover specific gaps we need to reinforce (see above), if you would like to join us let us know!

Here are the Victorian-era particle physicist images you requested, capturing the moment of discovering dark matter in CODEX-b. If you need any adjustments or additional elements, feel free to let me know!

Thank you! Questions? Coffee?

Backup

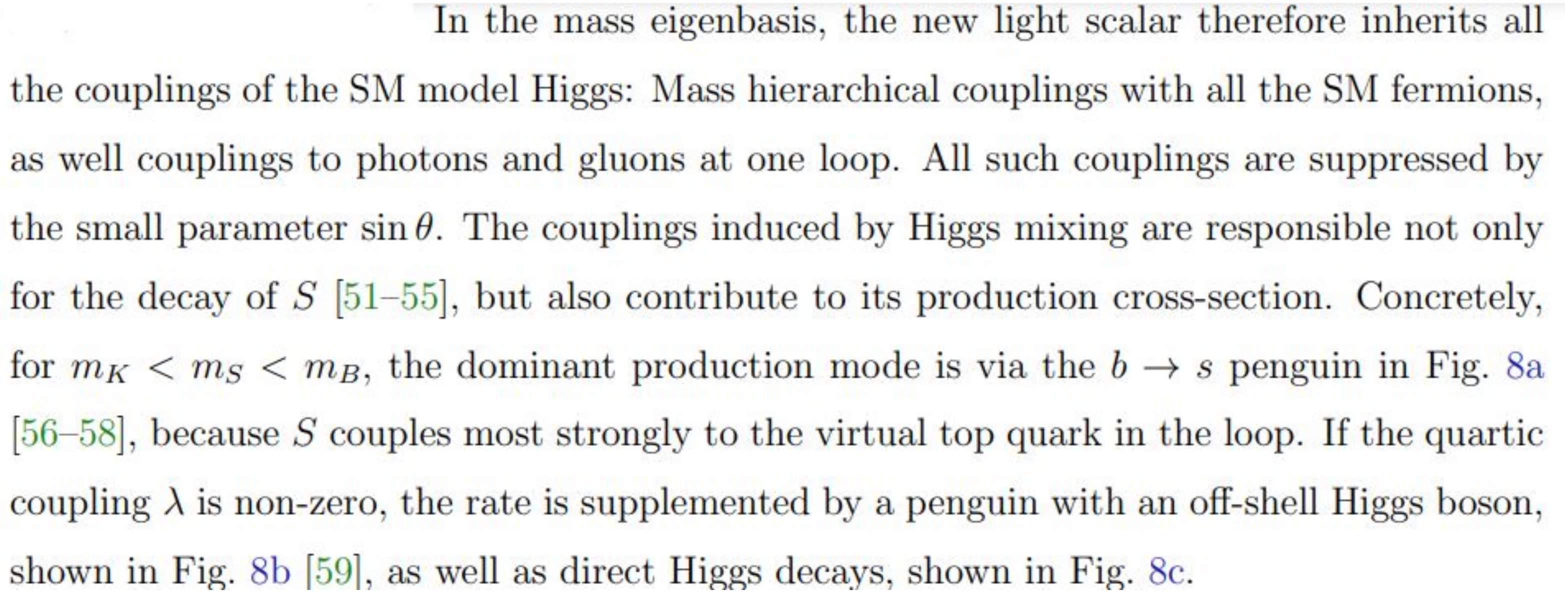
Physics



The most minimal extension of the SM consists of adding a single, real scalar degree of freedom (S). Gauge invariance restricts the Lagrangian to

$$\mathcal{L} \supset A_S \, S H^\dagger H + \frac{\lambda}{2} S^2 H^\dagger H + \cdots$$

https://arxiv.org/abs/1911.00481

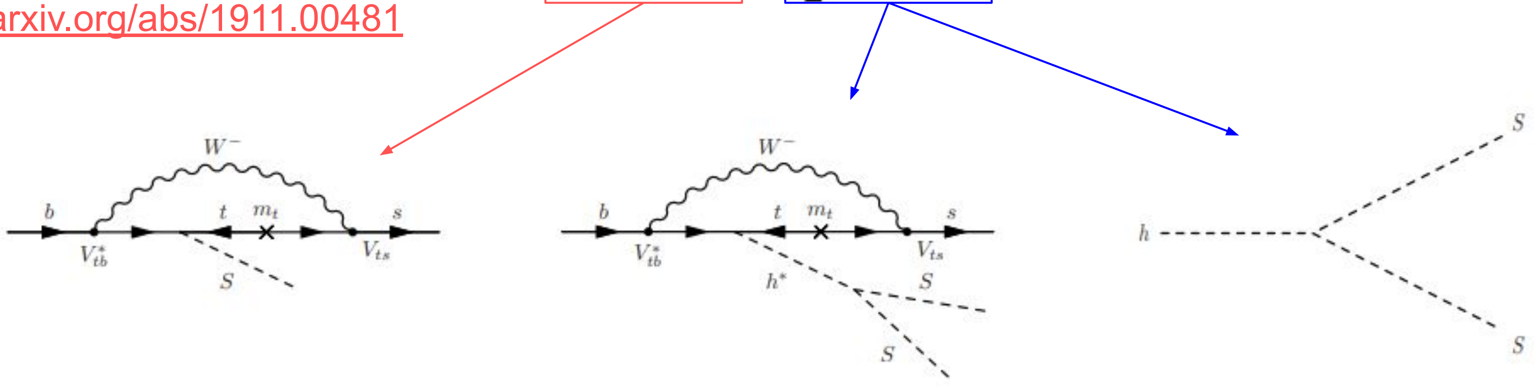


In the mass eigenbasis, the new light scalar therefore inherits all the couplings of the SM model Higgs: Mass hierarchical couplings with all the SM fermions, as well couplings to photons and gluons at one loop. All such couplings are suppressed by the small parameter $\sin\theta$. The couplings induced by Higgs mixing are responsible not only for the decay of S [51–55], but also contribute to its production cross-section. Concretely, for $m_K < m_S < m_B$, the dominant production mode is via the $b \to s$ penguin in Fig. 8a [56–58], because S couples most strongly to the virtual top quark in the loop. If the quartic coupling λ is non-zero, the rate is supplemented by a penguin with an off-shell Higgs boson, shown in Fig. 8b [59], as well as direct Higgs decays, shown in Fig. 8c.

The most minimal extension of the SM consists of adding a single, real scalar degree of freedom (S). Gauge invariance restricts the Lagrangian to

$$\mathcal{L} \supset \boxed{A_S\, S H^\dagger H} + \boxed{\frac{\lambda}{2}\, S^2 H^\dagger H} + \cdots$$

https://arxiv.org/abs/1911.00481



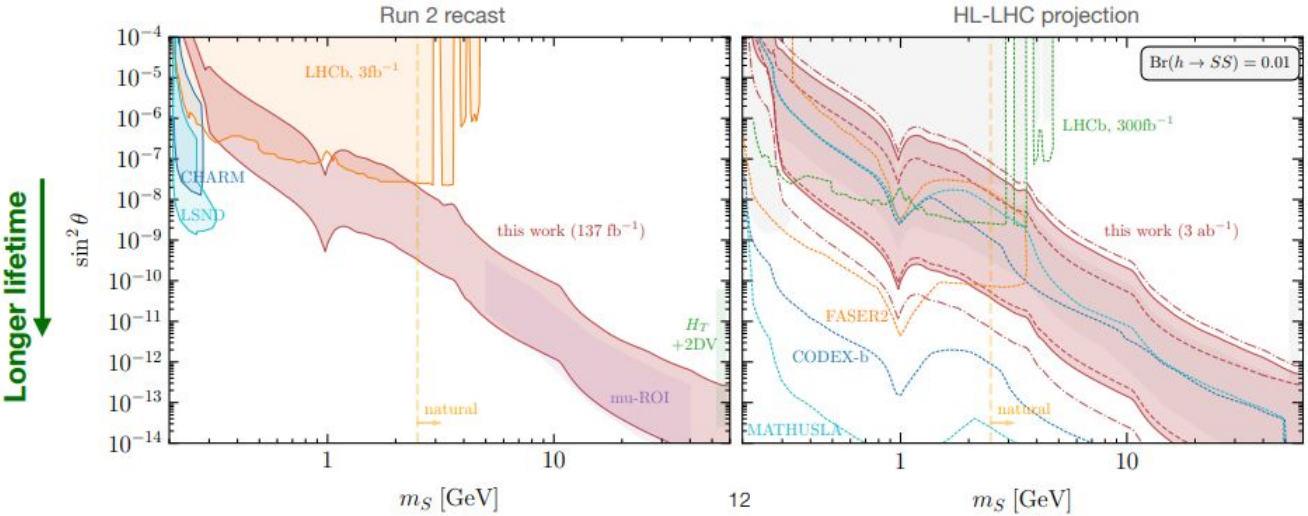
(a) (b) (c)

FIG. 8: Diagrams responsible for S production in a minimal extended Higgs sector. (a) is proportional to the mixing between S and Higgs, $\sin^2\theta$, while (b) and (c) are proportional to the square of the quartic coupling, λ^2.

Reinterpretation with Delphes

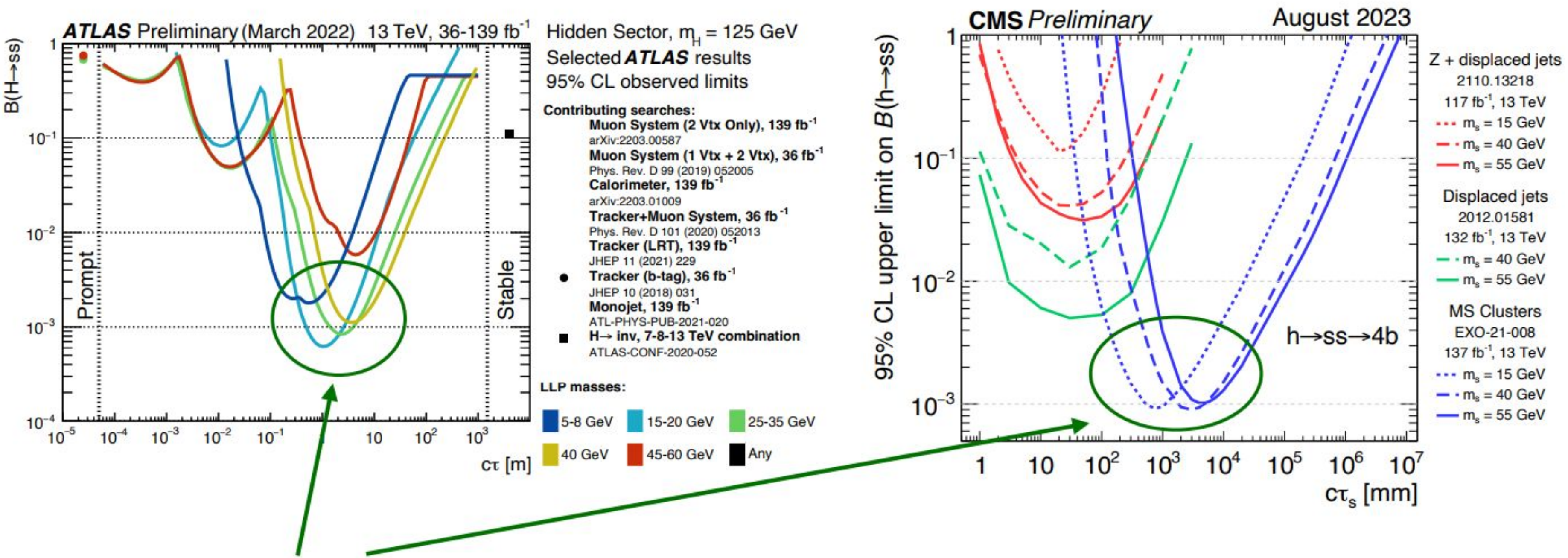
JHEP 02 (2023) 011
Phys. Rev. D 108, 05504
JHEP 07 (2023) 07

- **MDS detector response is calorimetric**
  - Only depends on generator-level LLP hadronic energy, EM energy, and decay positions → release parameterized functions as supplementary materials on HEPData
- Integrated the CSC cluster detector response functions to Delphes: https://github.com/delphes/delphes/pull/103
- Recasted the analysis and projected sensitivity in a number of models: dark scalar, dark photon, ALPs, inelastic DM, hidden valley models, HNL, and VLL
  - These recasting efforts inspired the ongoing CMS analyses mentioned earlier



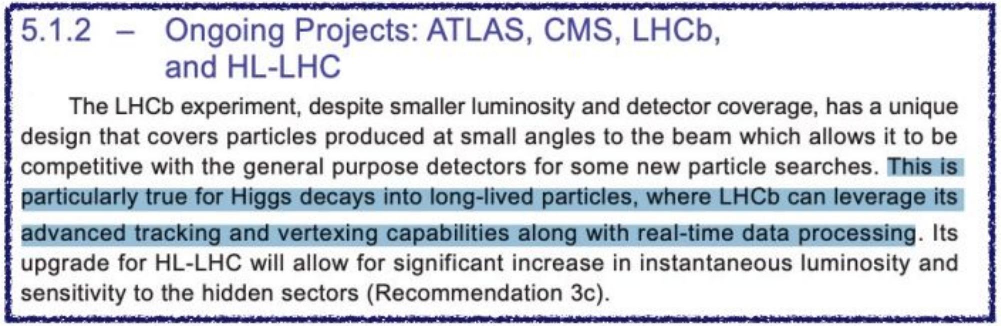
Dark scalar model

https://indico.cern.ch/event/1340162/contributions/5809466



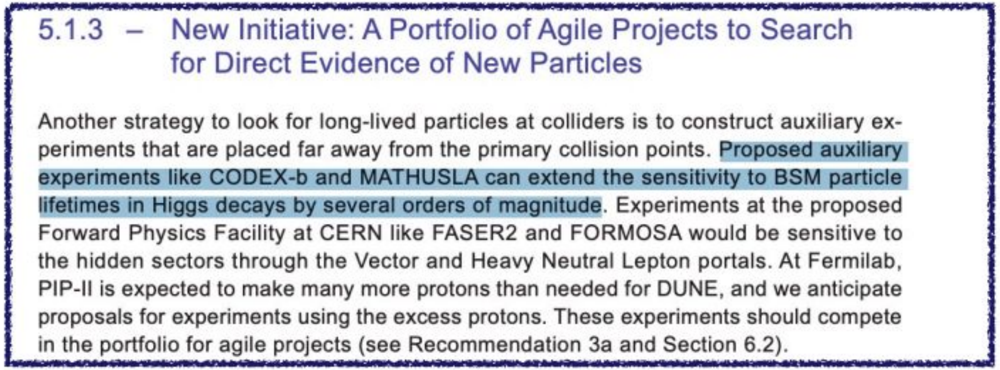
- Muon system analyses are among the most sensitive searches for both ATLAS and CMS

https://indico.cern.ch/event/1340162/contributions/5809466



5.1.2 – Ongoing Projects: ATLAS, CMS, LHCb, and HL-LHC

The LHCb experiment, despite smaller luminosity and detector coverage, has a unique design that covers particles produced at small angles to the beam which allows it to be competitive with the general purpose detectors for some new particle searches. This is particularly true for Higgs decays into long-lived particles, where LHCb can leverage its advanced tracking and vertexing capabilities along with real-time data processing. Its upgrade for HL-LHC will allow for significant increase in instantaneous luminosity and sensitivity to the hidden sectors (Recommendation 3c).



5.1.3 – New Initiative: A Portfolio of Agile Projects to Search for Direct Evidence of New Particles

Another strategy to look for long-lived particles at colliders is to construct auxiliary experiments that are placed far away from the primary collision points. Proposed auxiliary experiments like CODEX-b and MATHUSLA can extend the sensitivity to BSM particle lifetimes in Higgs decays by several orders of magnitude. Experiments at the proposed Forward Physics Facility at CERN like FASER2 and FORMOSA would be sensitive to the hidden sectors through the Vector and Heavy Neutral Lepton portals. At Fermilab, PIP-II is expected to make many more protons than needed for DUNE, and we anticipate proposals for experiments using the excess protons. These experiments should compete in the portfolio for agile projects (see Recommendation 3a and Section 6.2).

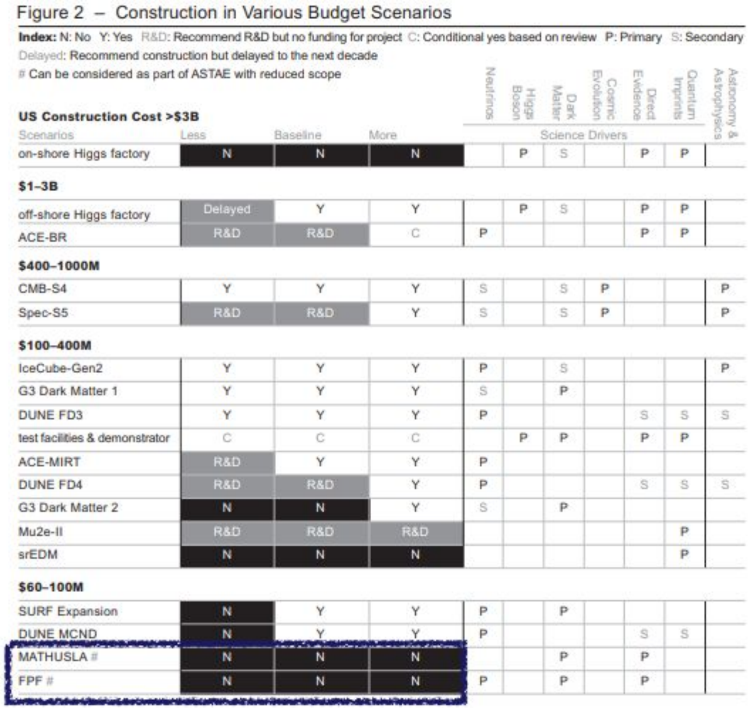


Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

Can be considered as part of ASTAE with reduced scope

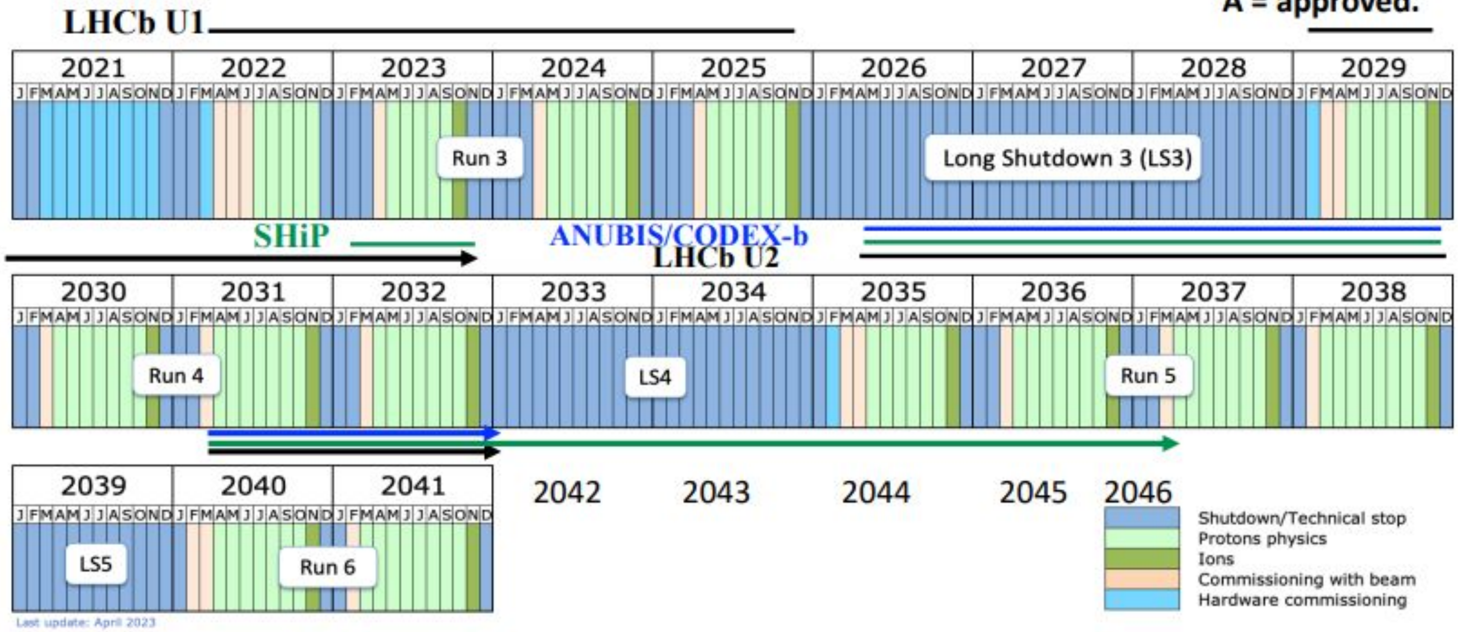
US Construction Cost >$3B				Science Drivers						
Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

Experiments and timescales

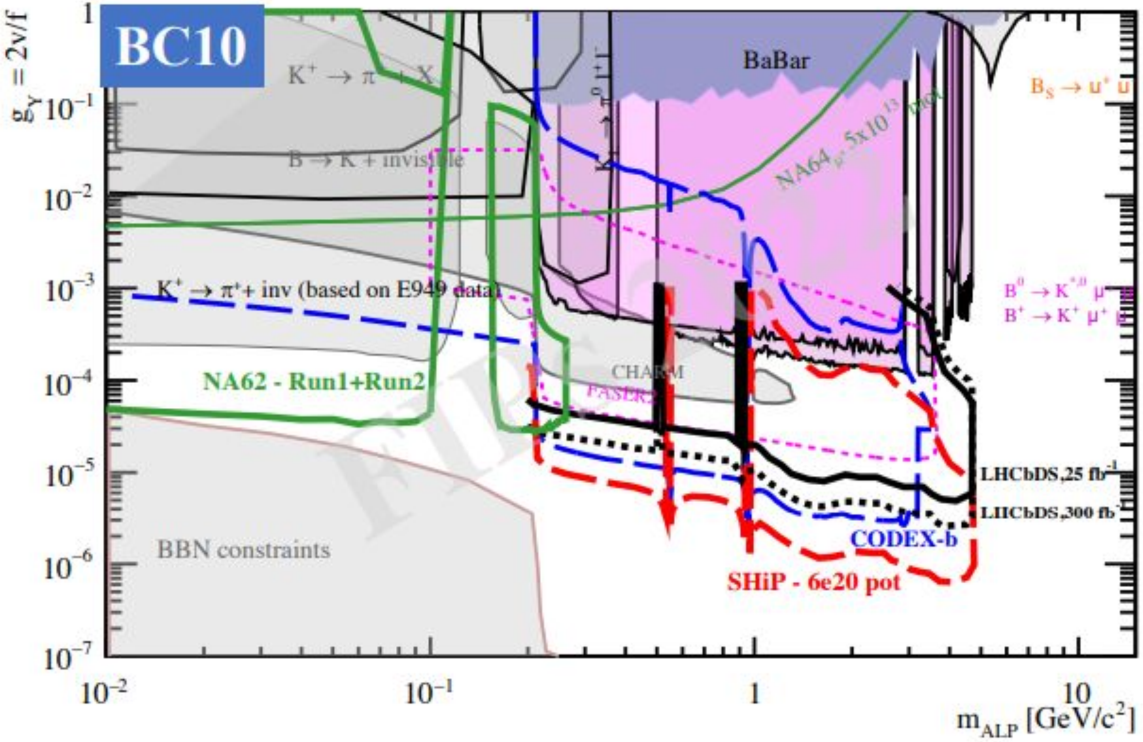
LHCb-U1 (2022-2032): **50 fb^{-1} (A)**
LHCb-U2 (2035-2041): **300 fb^{-1}**
ANUBIS (2035-2041): **3 ab^{-1} (ATLAS)**
CODEX-b (2035-2041): **300 fb^{-1}**

SHiP (2031-2046): **6x10^{20} pot (A)**
NA64-e: 2022-2025 (Run3) **(A)**
NA64-mu: 2029-2032 (Run4) (Pilot run approved)
LDMX (SLAC): approved, start run in 2028 **(A)**

A = approved.

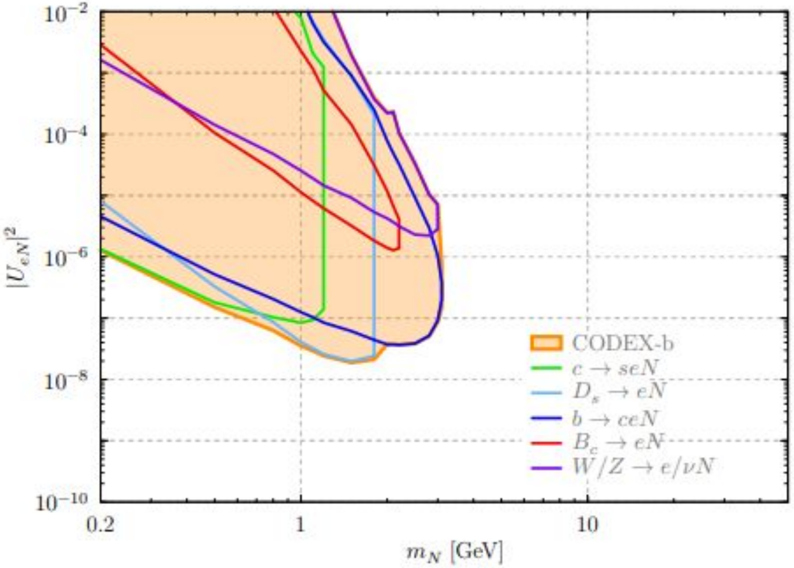


ALP mediator with fermion couplings

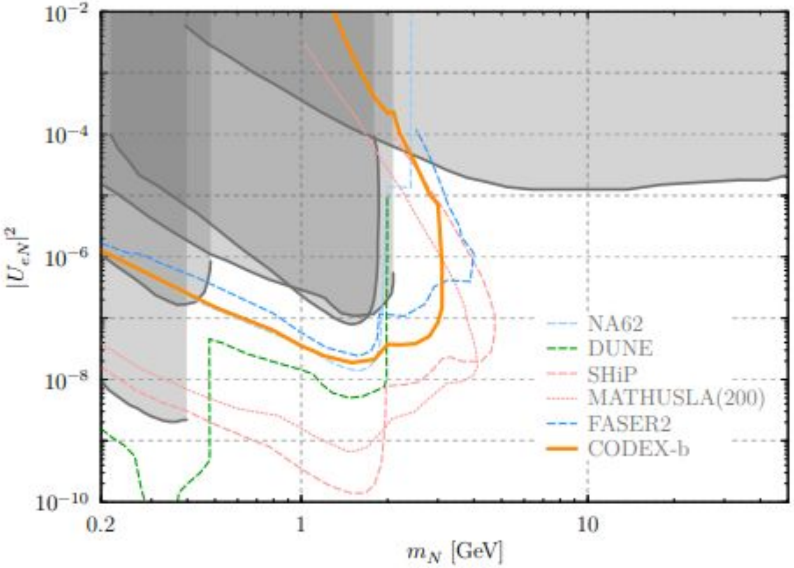


Worldwide leading project < 10 years: LHCb-U1 with 25 fb^{-1}

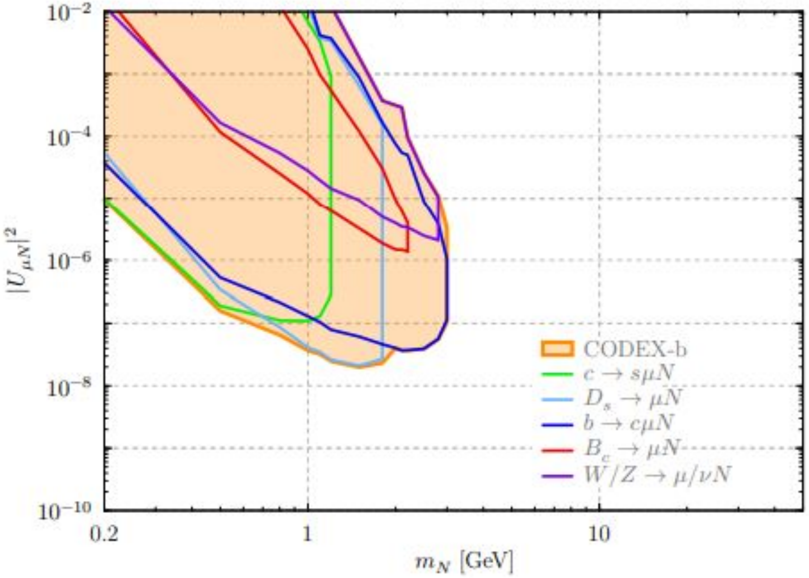
Worldwide leading projects > 10 years: LHCb-U1/U2 & CODEX-b, SHiP



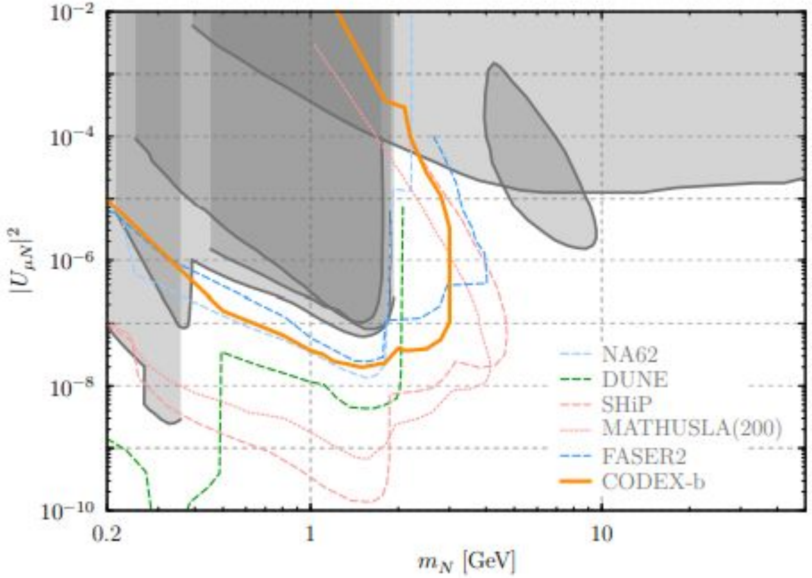
(a) $U_{eN} \gg U_{\mu N}, U_{\tau N}$ (Channels)



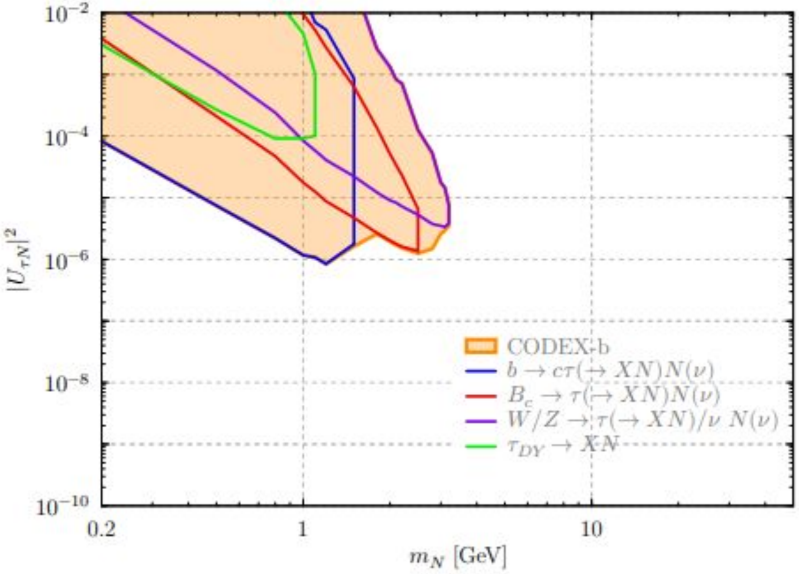
(b) $U_{eN} \gg U_{\mu N}, U_{\tau N}$ (Combined)



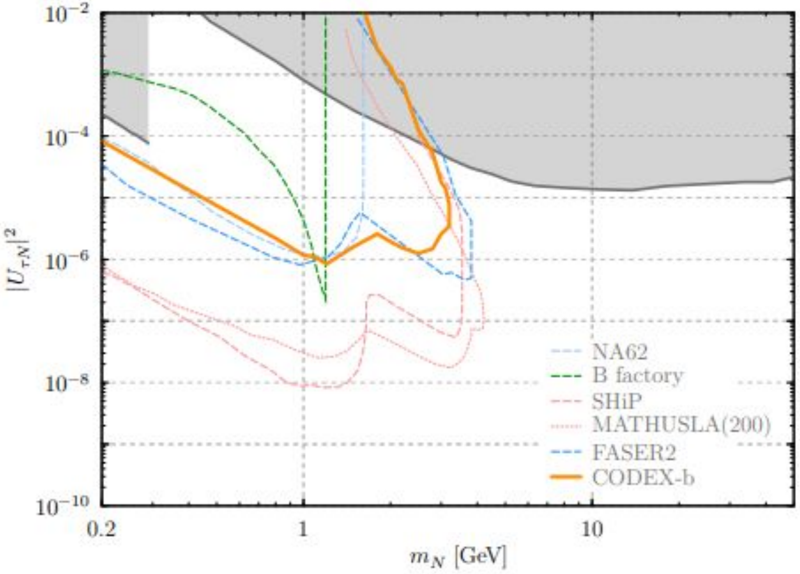
(c) $U_{\mu N} \gg U_{eN}, U_{\tau N}$ (Channels)



(d) $U_{\mu N} \gg U_{eN}, U_{\tau N}$ (Combined)

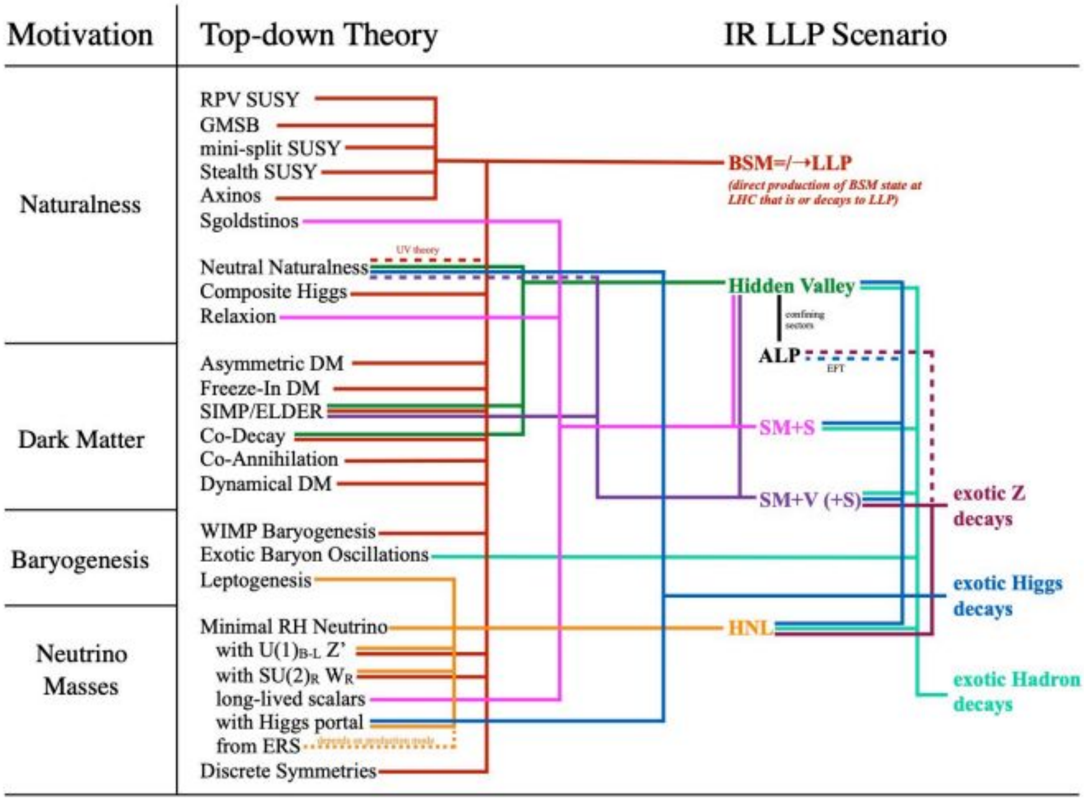


(e) $U_{\tau N} \gg U_{eN}, U_{\mu N}$ (Channels)



(f) $U_{\tau N} \gg U_{eN}, U_{\mu N}$ (Combined)

Mathusla physics case
arxiv:1806.07396



Motivation | Top-down Theory | IR LLP Scenario

Naturalness
RPV SUSY
GMSB
mini-split SUSY
Stealth SUSY
Axinos
Sgoldstinos
Neutral Naturalness
UV theory
Composite Higgs
Relaxion

Dark Matter
Asymmetric DM
Freeze-In DM
SIMP/ELDER
Co-Decay
Co-Annihilation
Dynamical DM

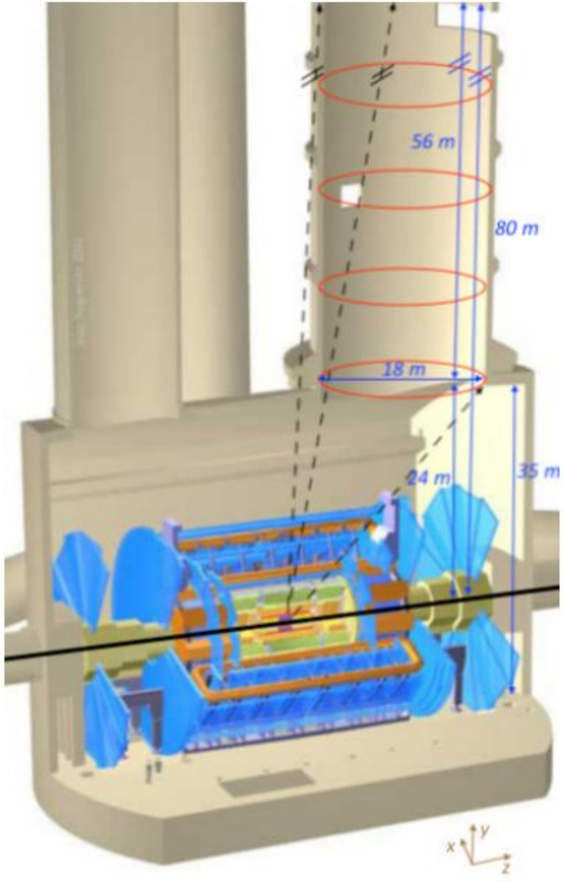
Baryogenesis
WIMP Baryogenesis
Exotic Baryon Oscillations
Leptogenesis

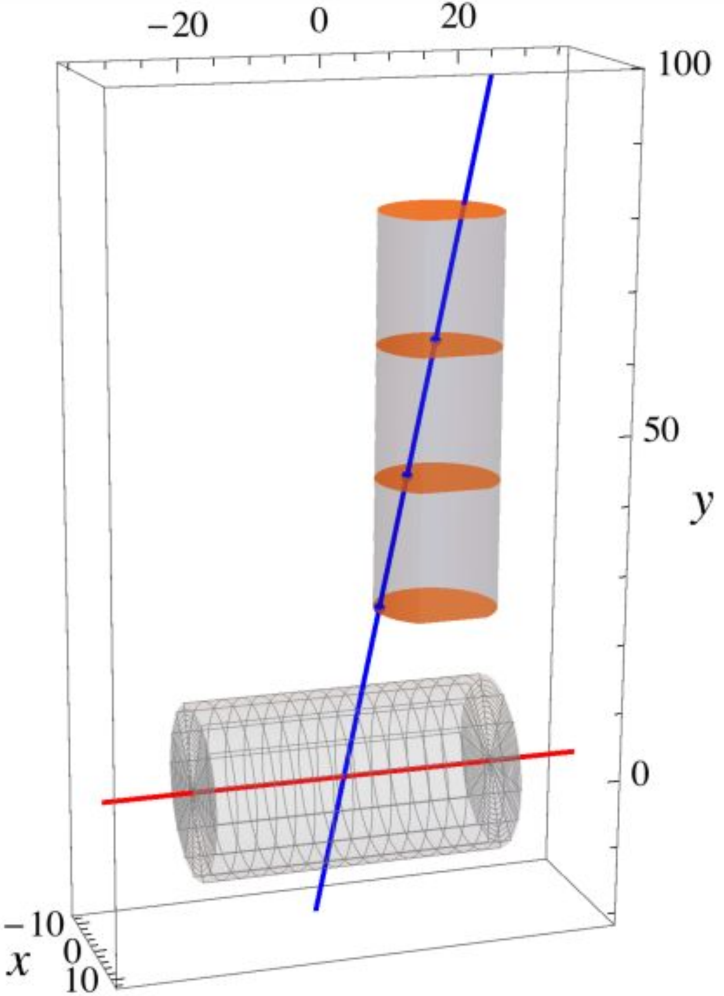
Neutrino Masses
Minimal RH Neutrino
with U(1)$_{B-L}$ Z'
with SU(2)$_R$ W$_R$
long-lived scalars
with Higgs portal
from ERS
depends on production mode
Discrete Symmetries

BSM=/→LLP
(direct production of BSM state at LHC that is or decays to LLP)

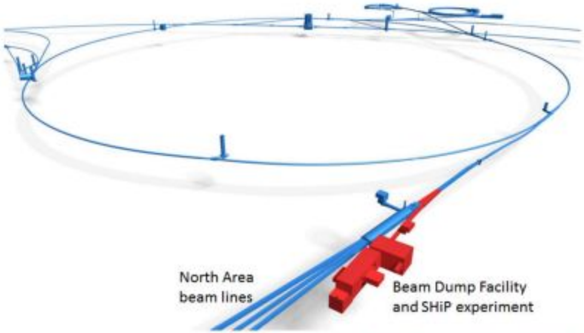
Hidden Valley
confining sectors
ALP
EFT
SM+S
SM+V (+S)
HNL

exotic Z decays
exotic Higgs decays
exotic Hadron decays

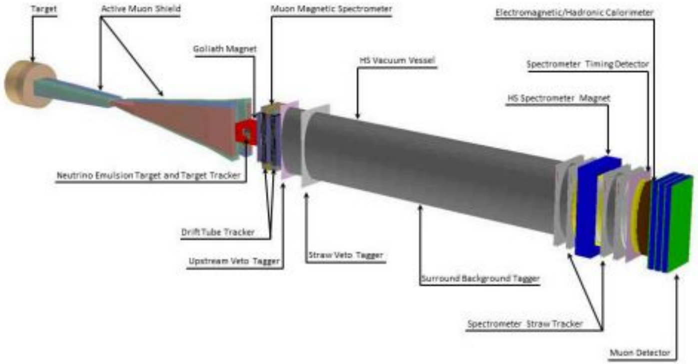

56 m
80 m
18 m
24 m
35 m
x
y
z


−20
0
20
100
50
y
0
−10
0
10
x

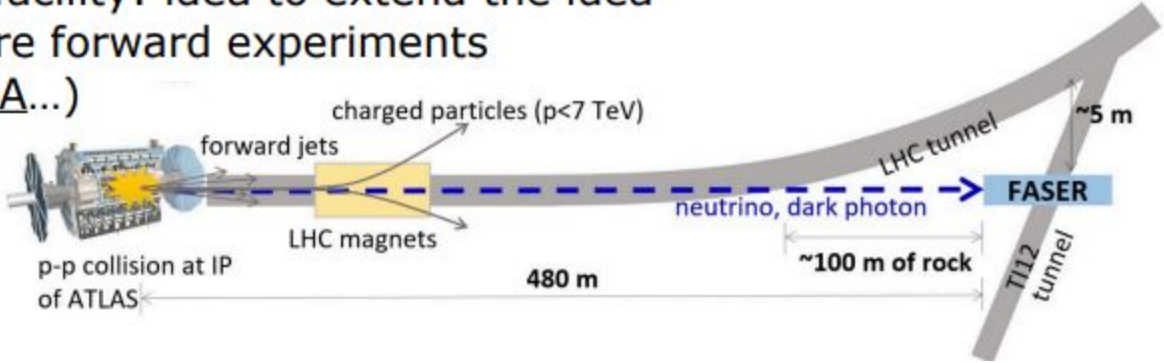
- Relies the new proposed SPS Beam Dump Facility (BDF), would provide huge statistics (5 years of BDF, 2×10^{20} protons on target!)
  - Search for Hidden Particles (SHIP) designed for discovery and measurement of super-weakly interacting new particles
  - Ultra-low background environment. First part of SHiP: muons and hadron absorbers
  - A long vacuum chamber of about 50m allows long-lived particles to disintegrate
  - Detect leptons and mesons, a muon detector and an electromagnetic calorimeter are placed downstream

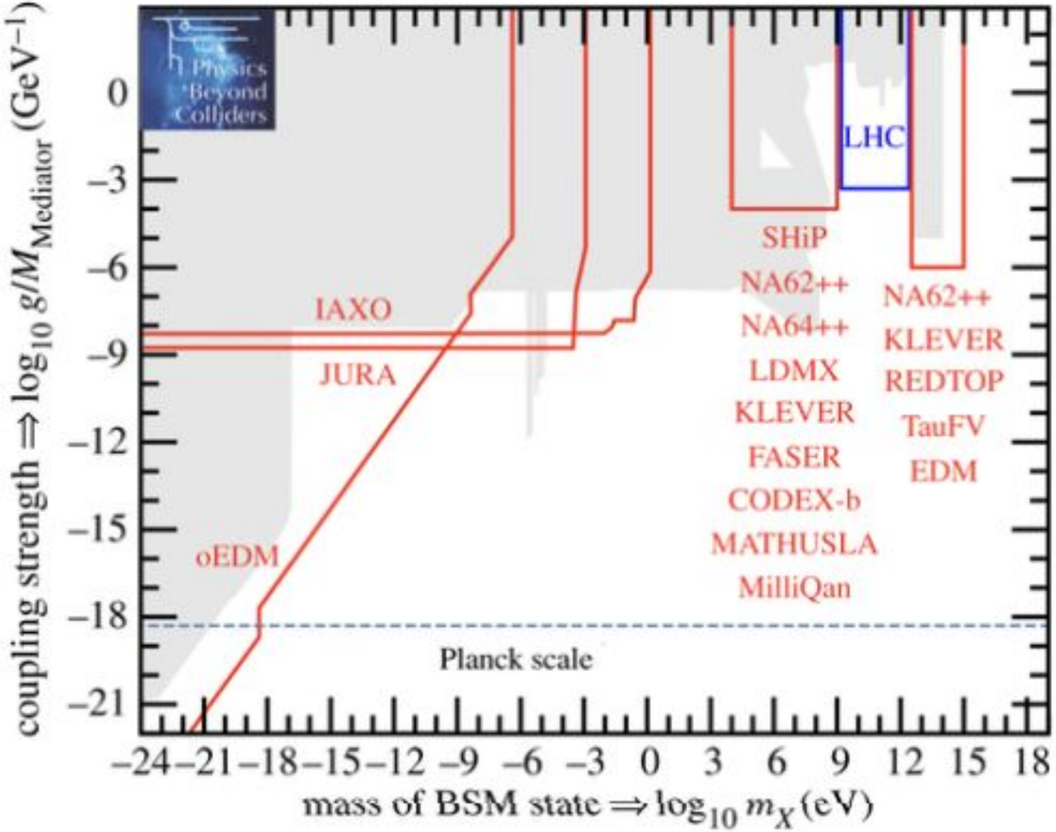


[JINST 14 (2019) no.03, P03025]
[CERN-PBC-REPORT-2018-001]



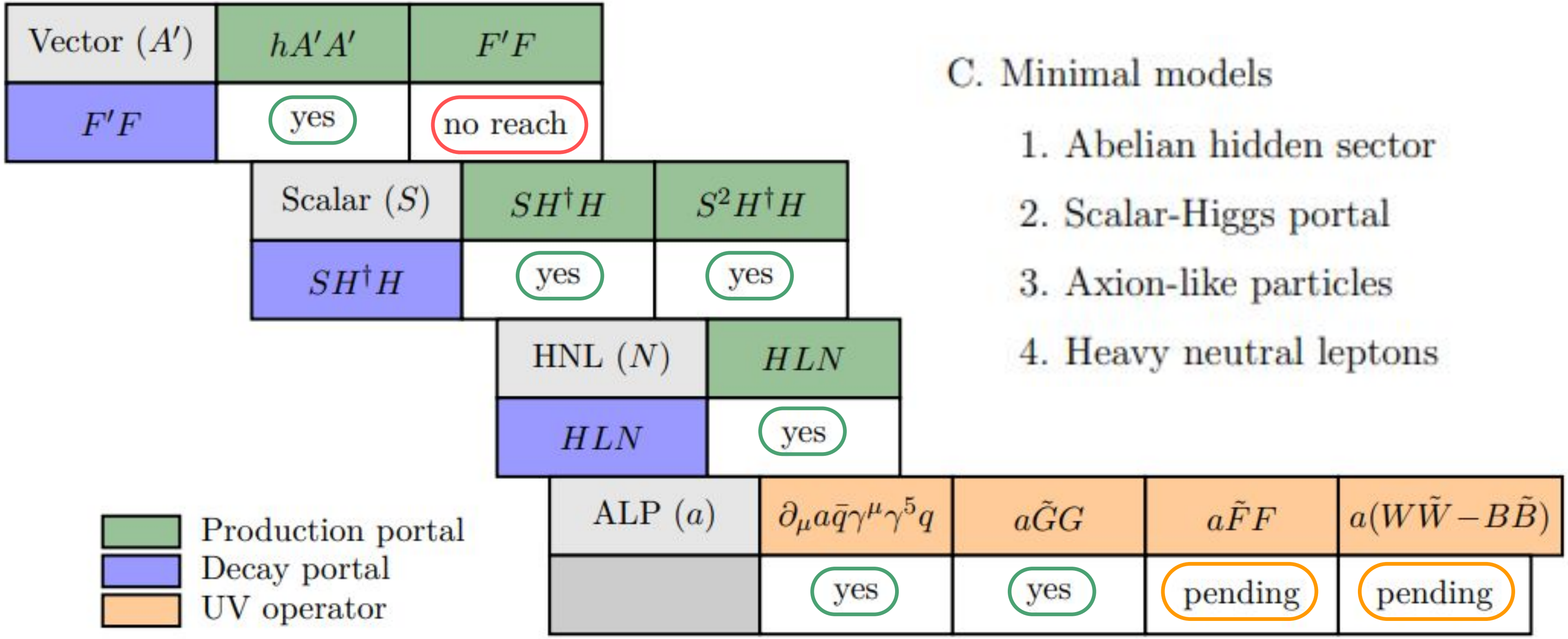
- ForwArd Search ExpeRiment (FASER) new small LLP experiment in an old LEP injector tunnel (TI12)
  - Most advanced proposal: FASER experiment (phase-I) has been approved March 2019
  - Designed to collect 150 fb^{-1} from 2021-2023
  - FASERν, potential extension to detect (for the first time) LHC neutrinos!
  - LHC forward physics facility: idea to extend the idea of FASER to build more forward experiments (SND@LHC, FORMOSA...)




Physics Beyond Colliders
coupling strength ⇒ $\log_{10} g/M_{\mathrm{Mediator}}$ (GeV^{-1})
0
−3
−6
−9
−12
−15
−18
−21
IAXO
JURA
oEDM
LHC
SHiP
NA62++
NA64++
LDMX
KLEVER
FASER
CODEX-b
MATHUSLA
MilliQan
NA62++
KLEVER
REDTOP
TauFV
EDM
Planck scale
−24
−21
−18
−15
−12
−9
−6
−3
0
3
6
9
12
15
18
mass of BSM state ⇒ $\log_{10} m_X$ (eV)

An overview of minimal models

https://arxiv.org/abs/1708.09395
https://arxiv.org/abs/1911.00481
https://arxiv.org/abs/2203.07316



Vector (A')	$hA'A'$	$F'F$
$F'F$	yes	no reach

Scalar (S)	$SH^\dagger H$	$S^2H^\dagger H$
$SH^\dagger H$	yes	yes

HNL (N)	HLN
HLN	yes

ALP (a)	$\partial_\mu a \bar{q}\gamma^\mu\gamma^5 q$	$a\tilde{G}G$	$a\tilde{F}F$	$a(W\tilde{W}-B\tilde{B})$
	yes	yes	pending	pending

🟩 Production portal
🟦 Decay portal
🟧 UV operator

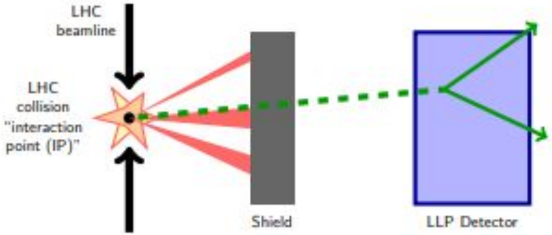
C. Minimal models

1. Abelian hidden sector
2. Scalar-Higgs portal
3. Axion-like particles
4. Heavy neutral leptons

Background studies

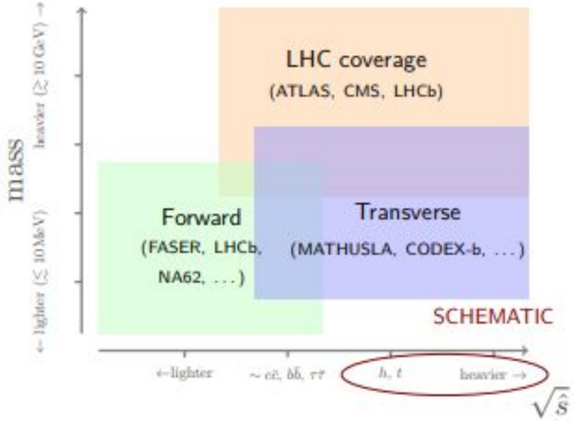
Main LHC experiments will efficiently probe 'heavy' ($m \gtrsim 10\,\text{GeV}$) LLPs, but backgrounds become impossible for lighter states.

Comprehensive LHC search for LLPs requires new, special purpose, shielded detectors

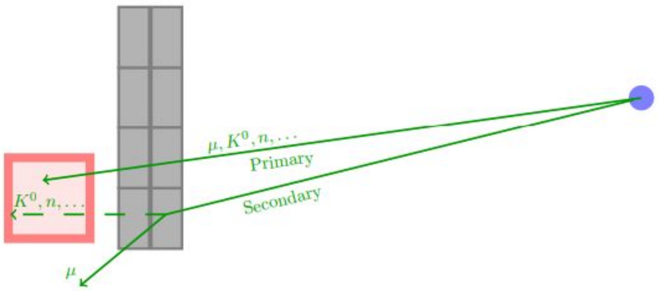


Background-free environment: searches beyond LHC main experiments' capability

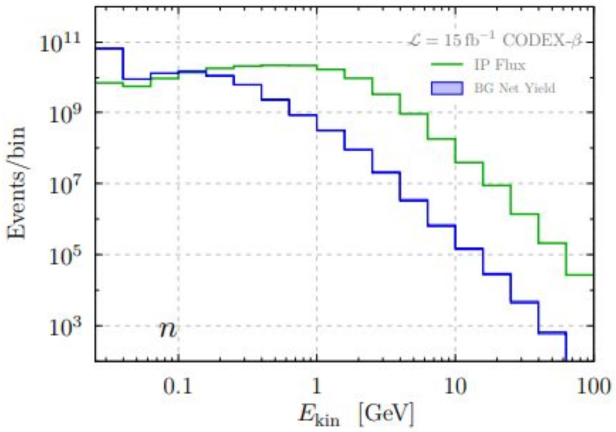
Transverse detectors are needed to probe heavy mediators (including the Higgs)

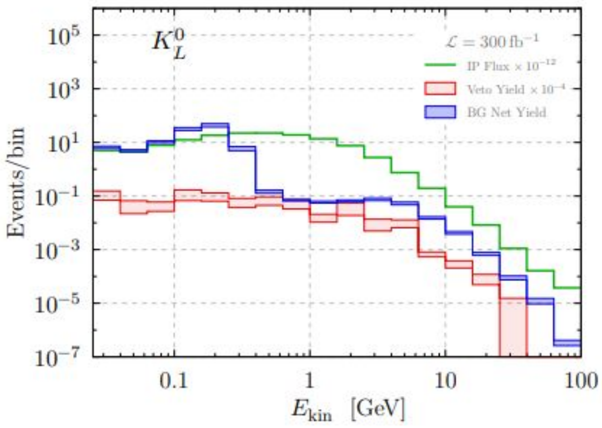


Background studies



- Fluxes of SM LLPs from IP over $\log(E_{kin})$ with Pythia + G4 for shield response.
- Measure fluxes of **primary plus secondary** backgrounds versus **simulation.**
- Generate data-driven background sim framework ➜ **optimize shielding design.**

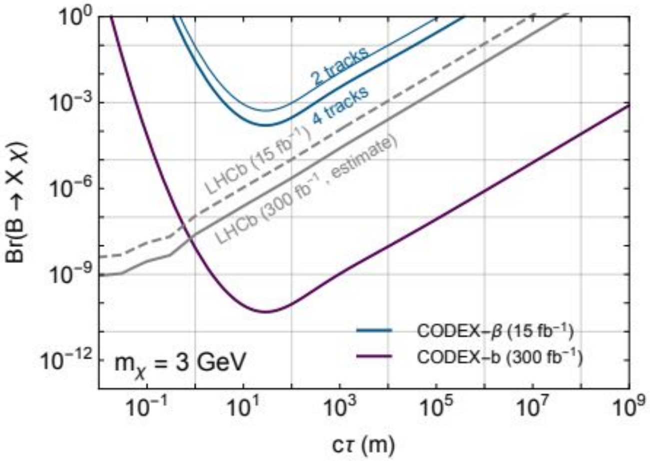




Multitrack production from LLPs

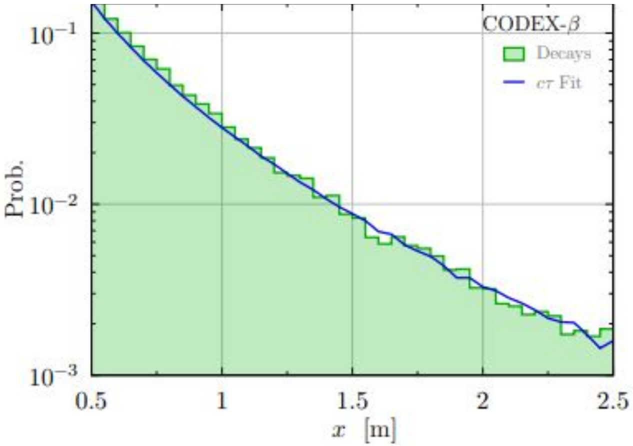
Tracks	Total	K_L^0 contribution
1	$(3.9 \pm 0.1) \times 10^8$	$(2.9 \pm 0.1) \times 10^8$
2	$(4.1 \pm 0.1) \times 10^7$	$(3.7 \pm 0.1) \times 10^7$
3	$(6 \pm 1) \times 10^5$	$(2.9 \pm 0.4) \times 10^5$
4+	$(9 \pm 2) \times 10^4$	$(7 \pm 2) \times 10^4$

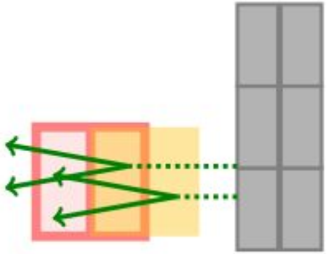
- Example: χudd interaction, $\chi \to 4h$ decay (Motivated by baryogenesis scenario)



Can conduct a trial NP analysis with CODEX-β

KS0 lifetime measurement





Toy CODEX-β example: **(Ks0 lifetime measurement)**

- Azimov dataset of 10^6 events (i.e. $\sim 10\%$ efficiency) binned with 5 cm resolution
- Vertexing $0.5 \leq x \leq 2.5$ m from UXA wall (assumes vertexing in 'detector shadow')
- Toy χ^2 fit: Recover $c\tau = 0.030^{+0.003}_{-0.007}$ cf. $c\tau = 0.02686(1)$ m.

Goals and roadmap from reconstruction

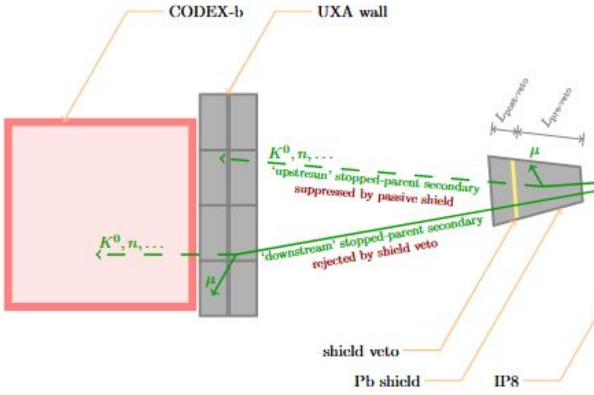
Three main goals:

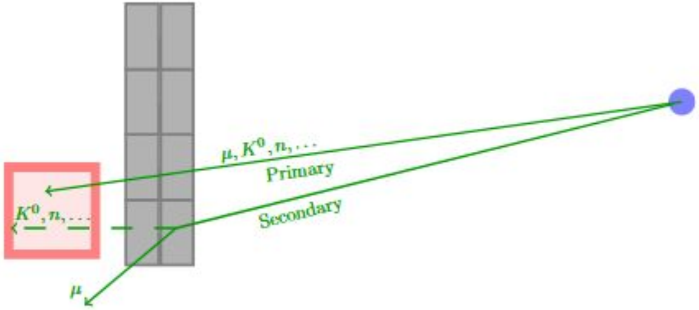
1. Trigger on interesting events → **no need to be reconstructed** (anomaly detection),
2. Provide a **set of tracks for physics analysis,**
3. Provide estimates of **efficiencies and resolutions on physics quantities.**

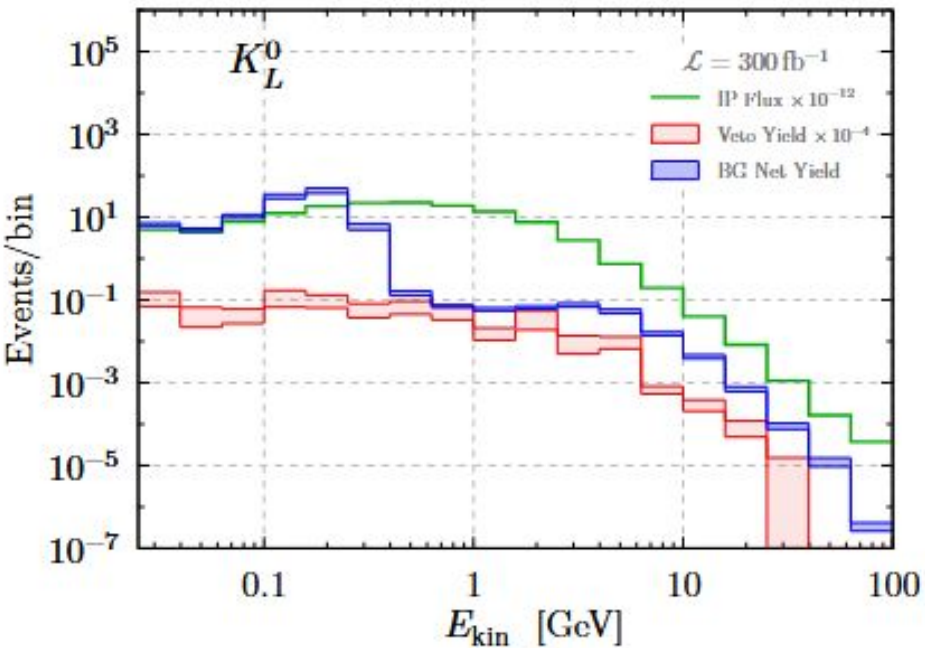
Goals 1 and 2 can be decoupled if we use different techniques, but **dependent on memory storage** – can we afford to store triggered events offline.

Personpower much needed to help with reconstruction efforts!

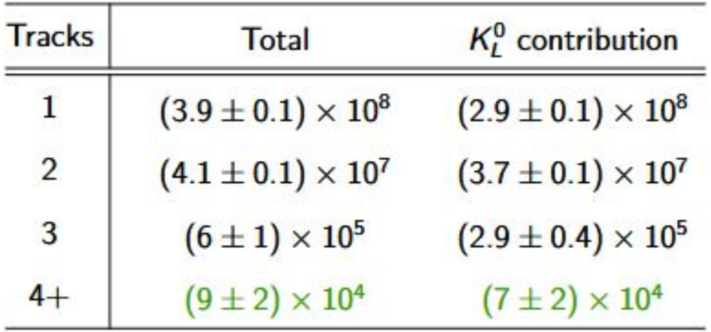
Physics with CODEX-β: Background studies





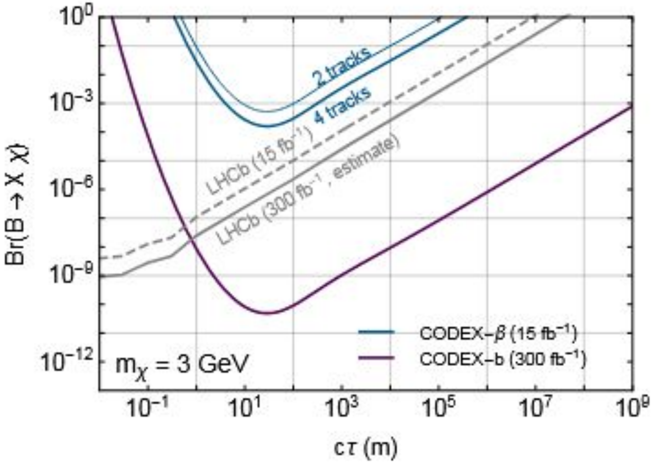


Physics with CODEX-β: Trial NP analysis



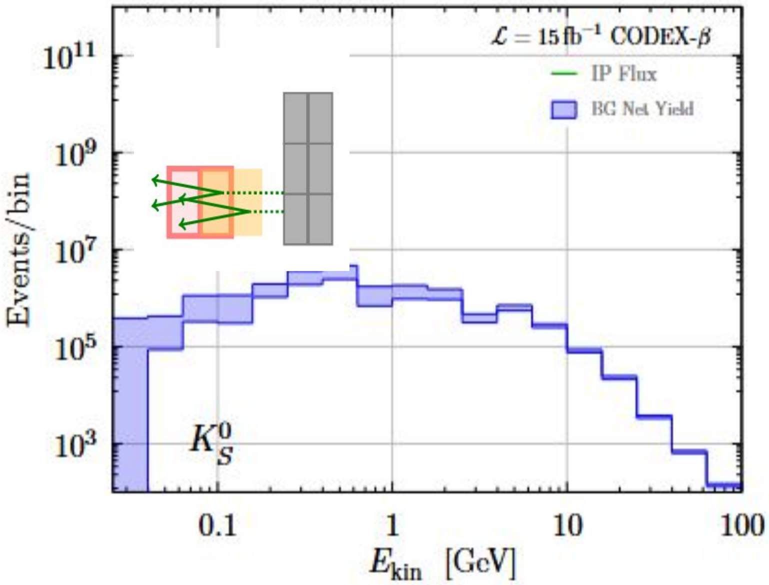
Tracks	Total	K_L^0 contribution
1	$(3.9 \pm 0.1) \times 10^8$	$(2.9 \pm 0.1) \times 10^8$
2	$(4.1 \pm 0.1) \times 10^7$	$(3.7 \pm 0.1) \times 10^7$
3	$(6 \pm 1) \times 10^5$	$(2.9 \pm 0.4) \times 10^5$
4+	$(9 \pm 2) \times 10^4$	$(7 \pm 2) \times 10^4$

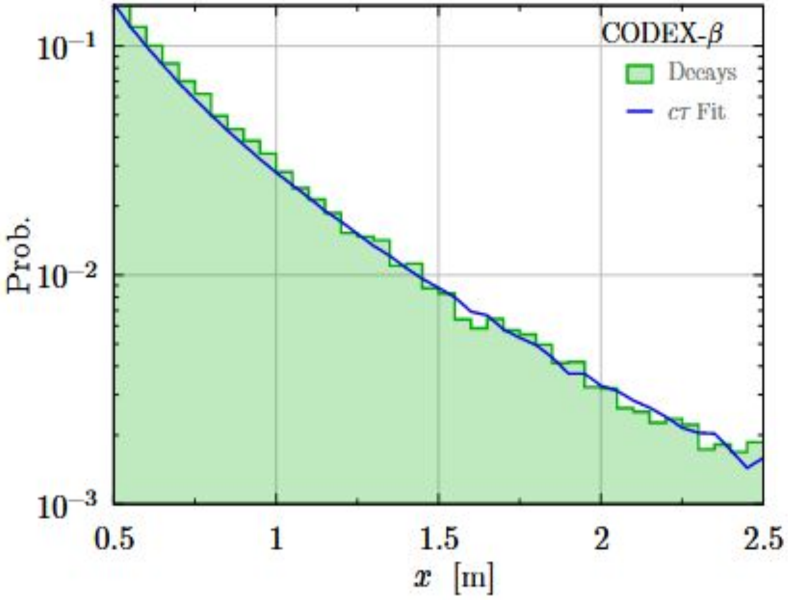
- Example: χudd interaction, $\chi \to 4h$ decay (Motivated by baryogenesis scenario)



Physics with CODEX-β: KS0 lifetime measurement

GEANT4-based sim





Simulation and reconstruction software

We had some hackathons during our first CODEX-b week:

Simulation:

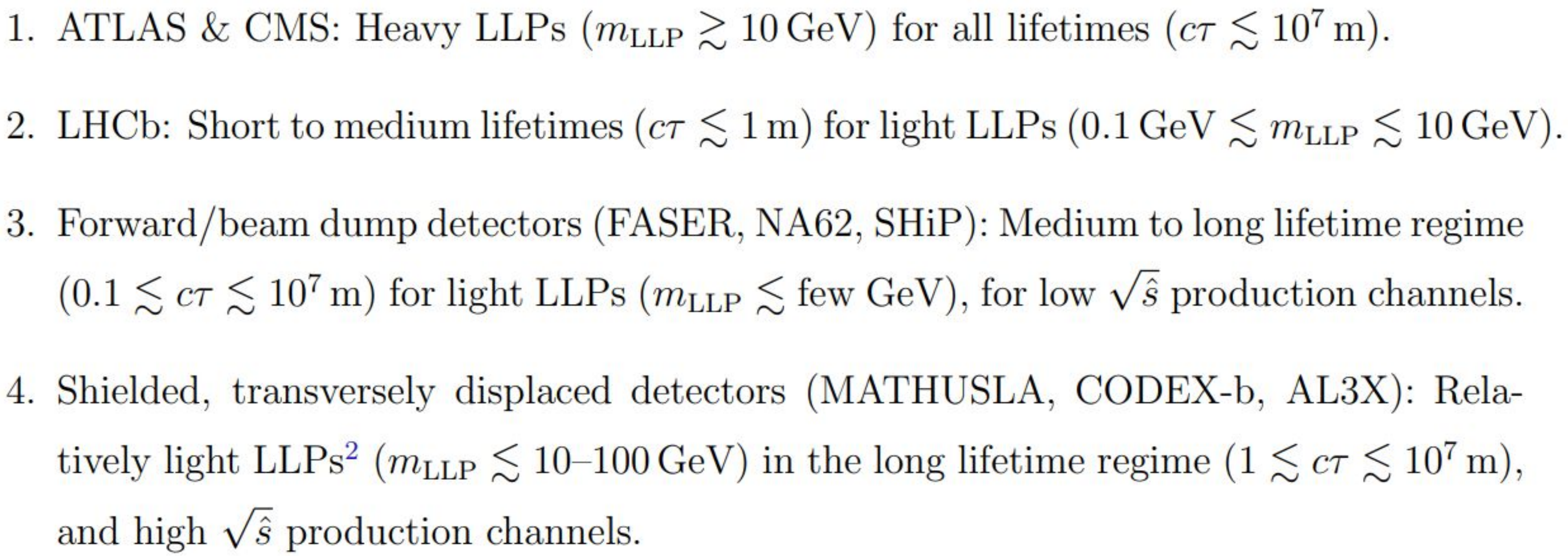
Implementations in Detector and Gauss. **Still need to validate CODEX-β geometry, and write the digitalisation in Boole.**

Reconstruction:

Prepare simulation samples → set of tracks for physics analyses, and obtain quantities of interest from these. **Still in early phase.**

These are the first steps towards developing a full analysis framework embedded in the LHCb software stack.

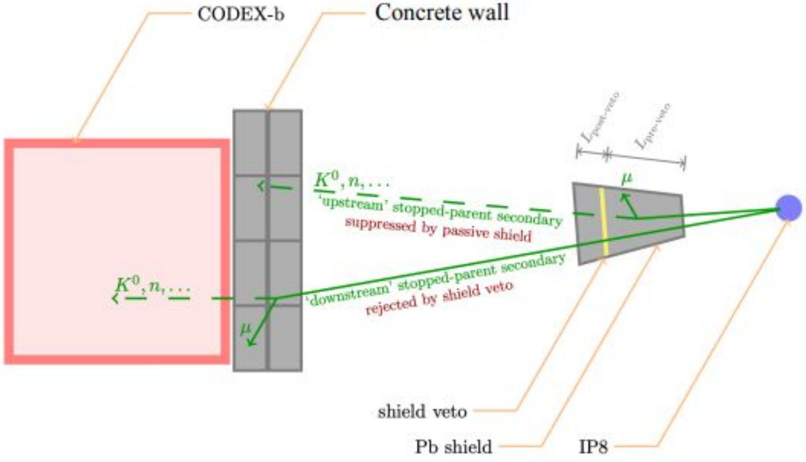
Coverage mockup plots



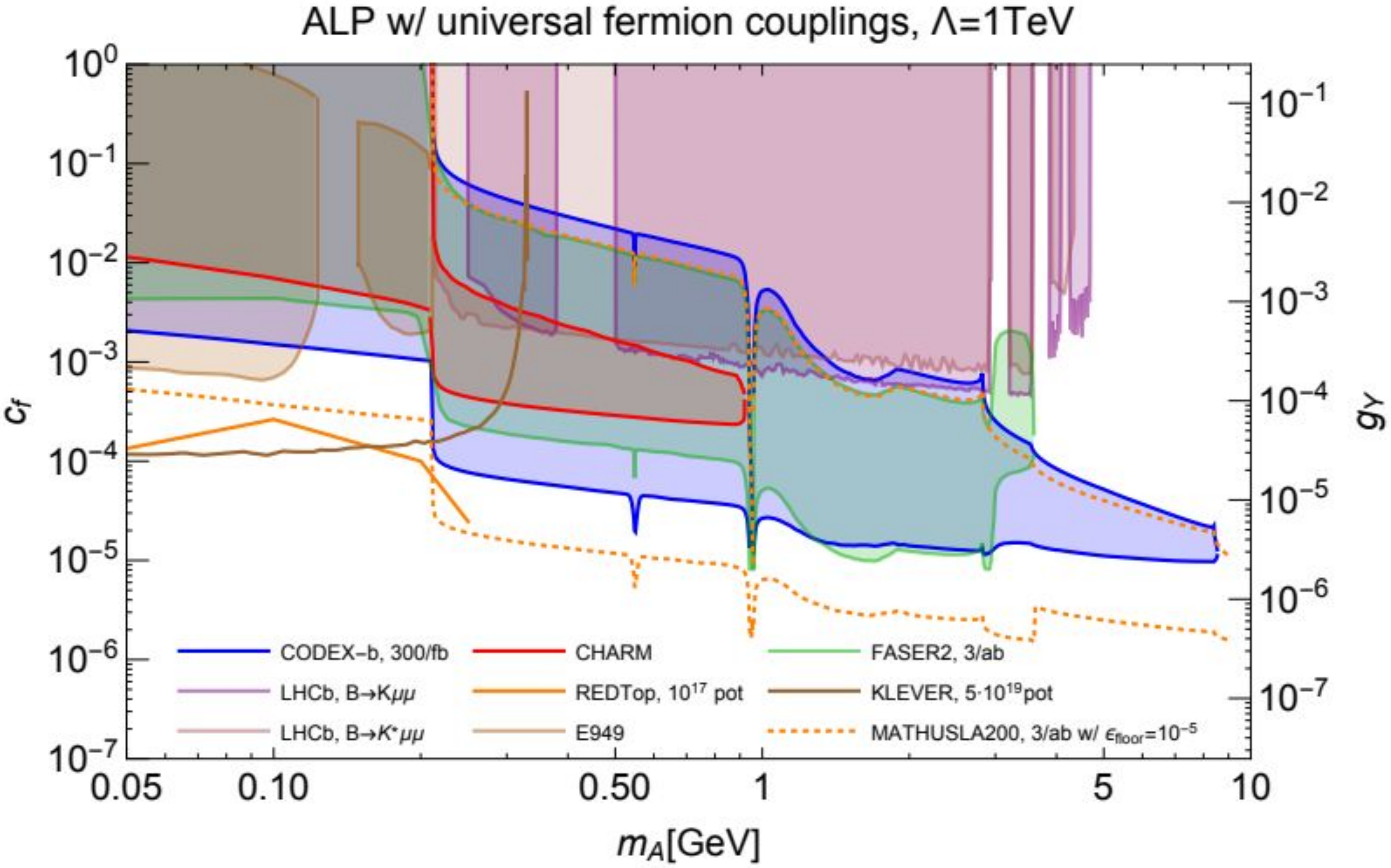
1. ATLAS & CMS: Heavy LLPs ($m_{\text{LLP}} \gtrsim 10\,\text{GeV}$) for all lifetimes ($c\tau \lesssim 10^7\,\text{m}$).
2. LHCb: Short to medium lifetimes ($c\tau \lesssim 1\,\text{m}$) for light LLPs ($0.1\,\text{GeV} \lesssim m_{\text{LLP}} \lesssim 10\,\text{GeV}$).
3. Forward/beam dump detectors (FASER, NA62, SHiP): Medium to long lifetime regime ($0.1 \lesssim c\tau \lesssim 10^7\,\text{m}$) for light LLPs ($m_{\text{LLP}} \lesssim$ few GeV), for low $\sqrt{\hat{s}}$ production channels.
4. Shielded, transversely displaced detectors (MATHUSLA, CODEX-b, AL3X): Relatively light LLPs[2] ($m_{\text{LLP}} \lesssim 10$–$100\,\text{GeV}$) in the long lifetime regime ($1 \lesssim c\tau \lesssim 10^7\,\text{m}$), and high $\sqrt{\hat{s}}$ production channels.

Backgrounds in CODEX-b

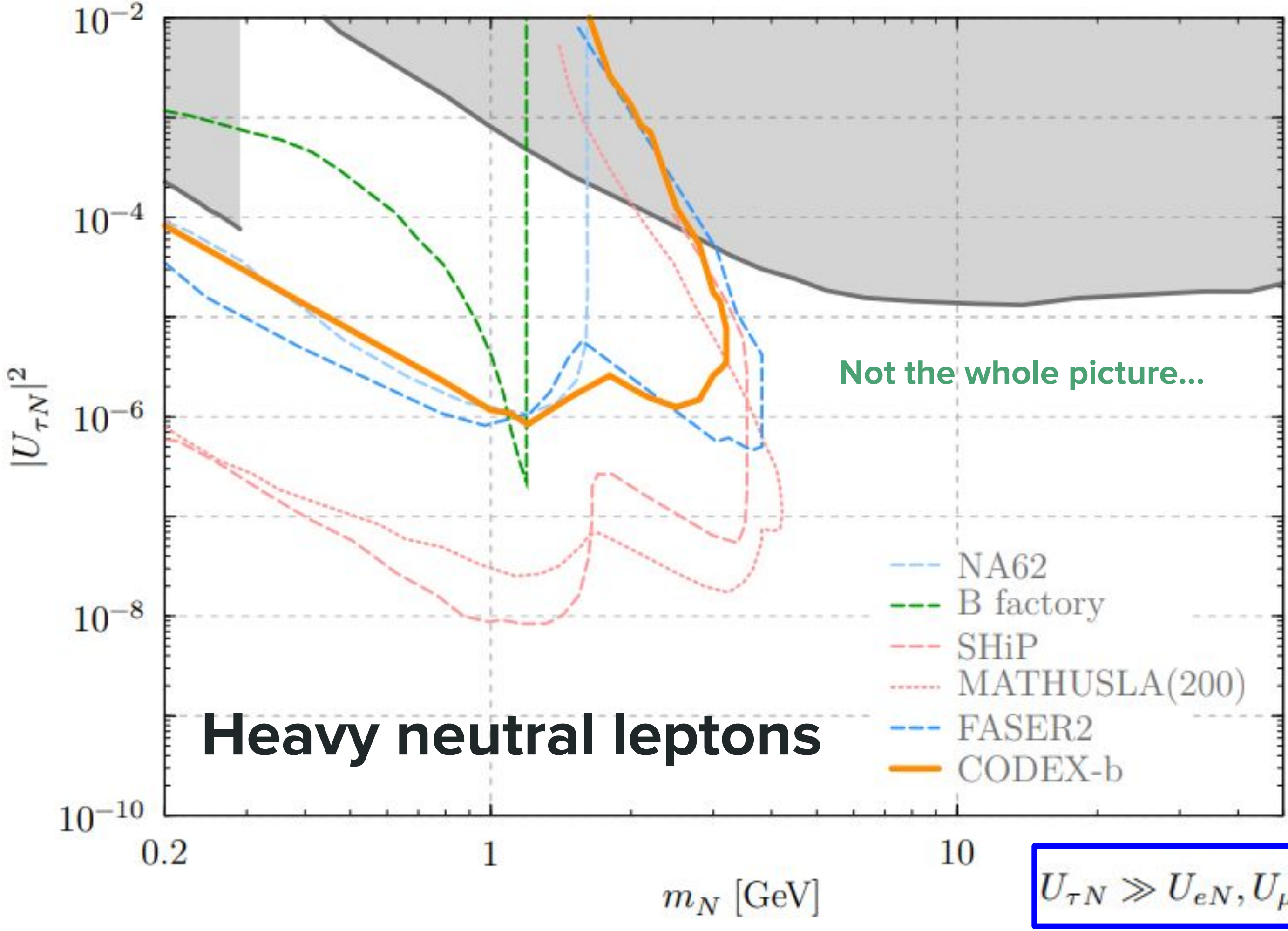
- **Main backgrounds:**
  - μ (primary or secondary) that can penetrate concrete+Pb shield
  - n/$\pi^{\pm}$/$\mathrm{K}^{\pm}$/$\mathrm{K}_{\mathrm{L}}^{0}$
- **Additional potential sources:**
  - LHC machine-induced, Thermal neutrons, Neutrinos



- **Detailed bkg simulation:**
  - arXiv:1708.09395, arXiv:1911.00481
  - **Bkg levels reduced to < $\mathcal{O}$ (1 event) in 300 fb^{-1} with shields + active/ topological vetoes**
- Shield + 3.2m concrete wall crucial to achieve 0 backgrounds
- Measured backgrounds in D1 area in 2018:
  - arXiv:1912.03846
- FLUKA campaign from CERN Radiation Protection validated Pythia simulation


ALP w/ universal fermion couplings, Λ=1TeV
c_f
g_Y
m_A[GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.05
0.10
0.50
1
5
10
CODEX-b, 300/fb
CHARM
FASER2, 3/ab
LHCb, B→Kμμ
REDTop, 10^{17} pot
KLEVER, $5\cdot10^{19}$pot
LHCb, B→K*μμ
E949
MATHUSLA200, 3/ab w/ $\epsilon_{\rm floor}=10^{-5}$

Heavy neutral leptons

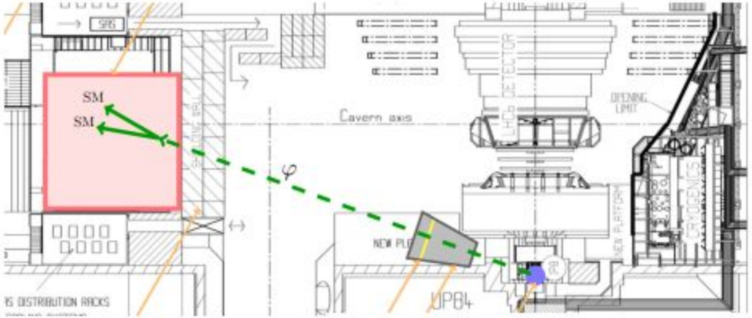


Not the whole picture...

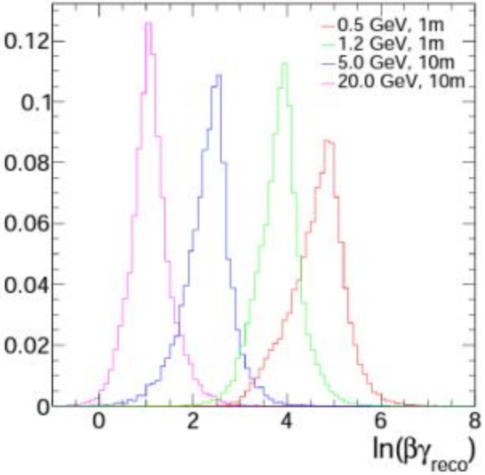
$U_{\tau N} \gg U_{eN}, U_{\mu N}$

arXiv:1705.06327
arXiv:1708.09395

LLP Mass Determination



Reco LLP boost for $h \to \gamma_d\gamma_d$

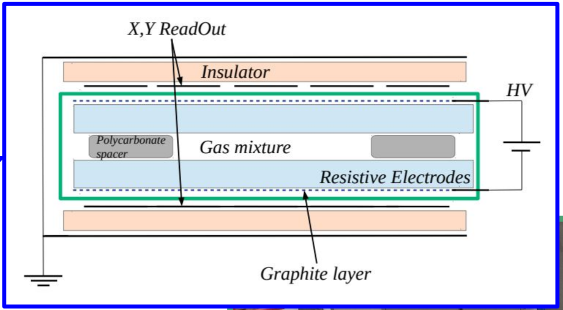


- **Design decisions** made in order to look for **GeV-scale LLPs**:
  - produced in LHC collisions at LHCb,
  - travel some distance, and then
  - decay within the CODEX-b tracking volume
- **Crucial** that the **displaced vertex** is **well-reconstructed** in CODEX-b
- CODEX-b should also be able to **measure the LLP velocity, boost, and mass**
  - Assuming a production mechanism
- **Boost distribution provides good discrimination between LLP masses and lifetimes**

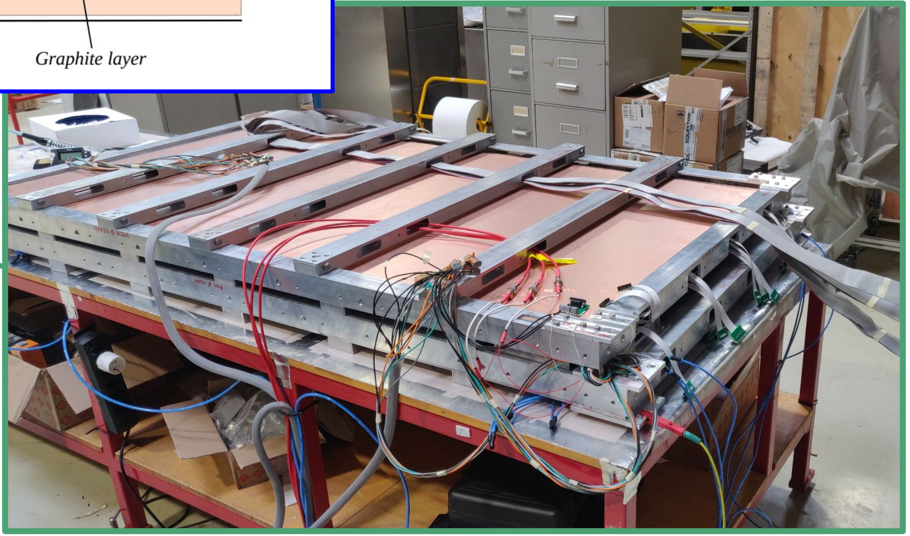
Technologies

A tale of triplets and singlets

RPC singlets rely on BIS-78 technology (ATLAS muon upgrade).

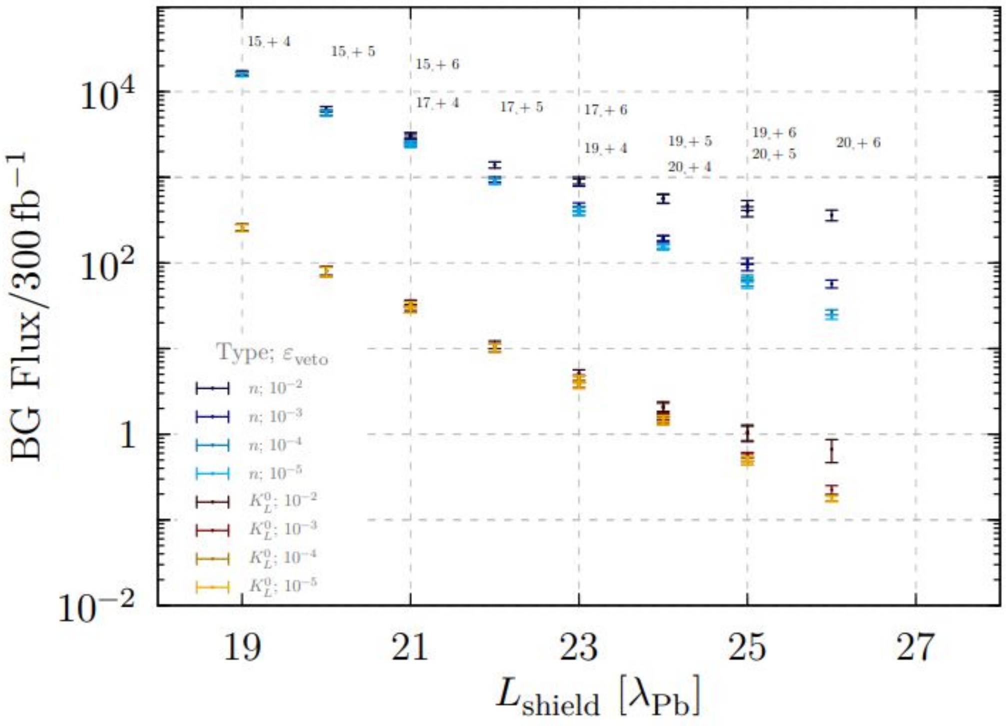


RPC triplets (2 x 1 m) with 1 mm spatial resolution and 100 ps timing resolution.



More details later...

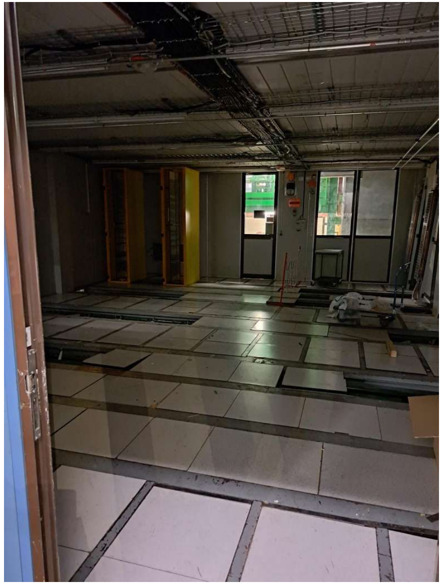
A background-free detector: shielding



Measurement campaign of backgrounds in D1 barracks during 2018.
https://arxiv.org/abs/1912.03846

Detailed simulations with Pythia, **consistent with FLUKA predictions by CERN Radiation Protection.**

Preparing the D1 barracks



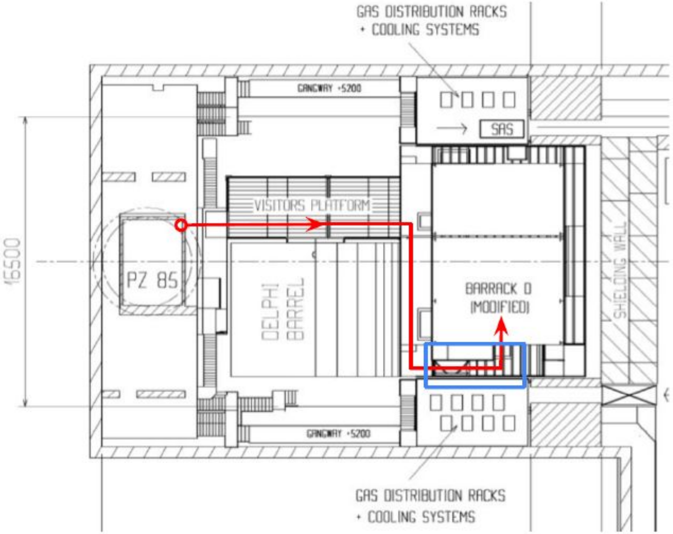
D1 barracks are empty now, power supply available.

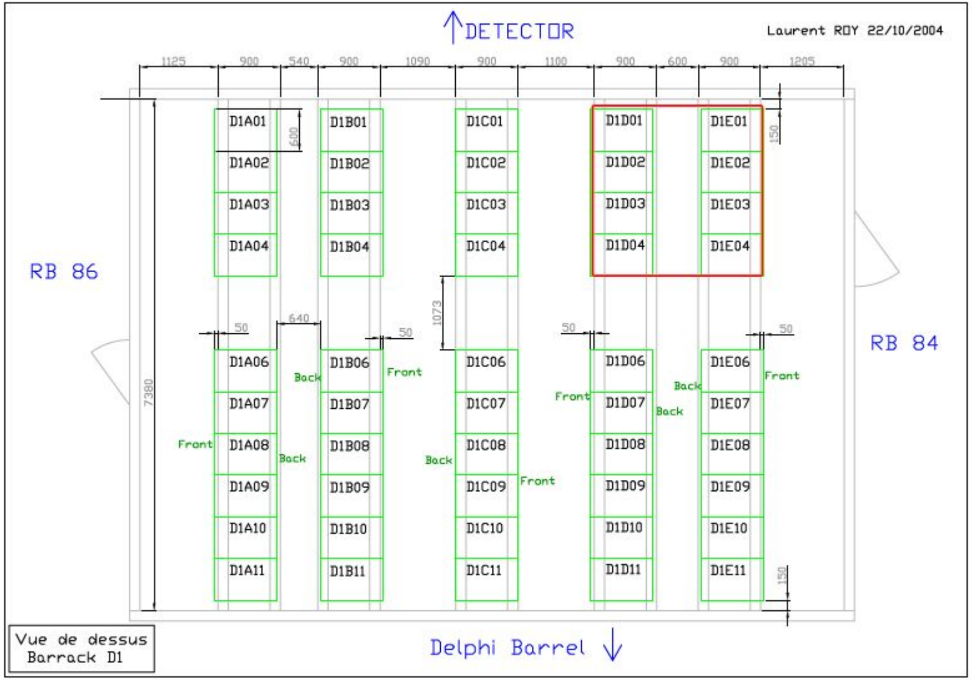
Working now on:

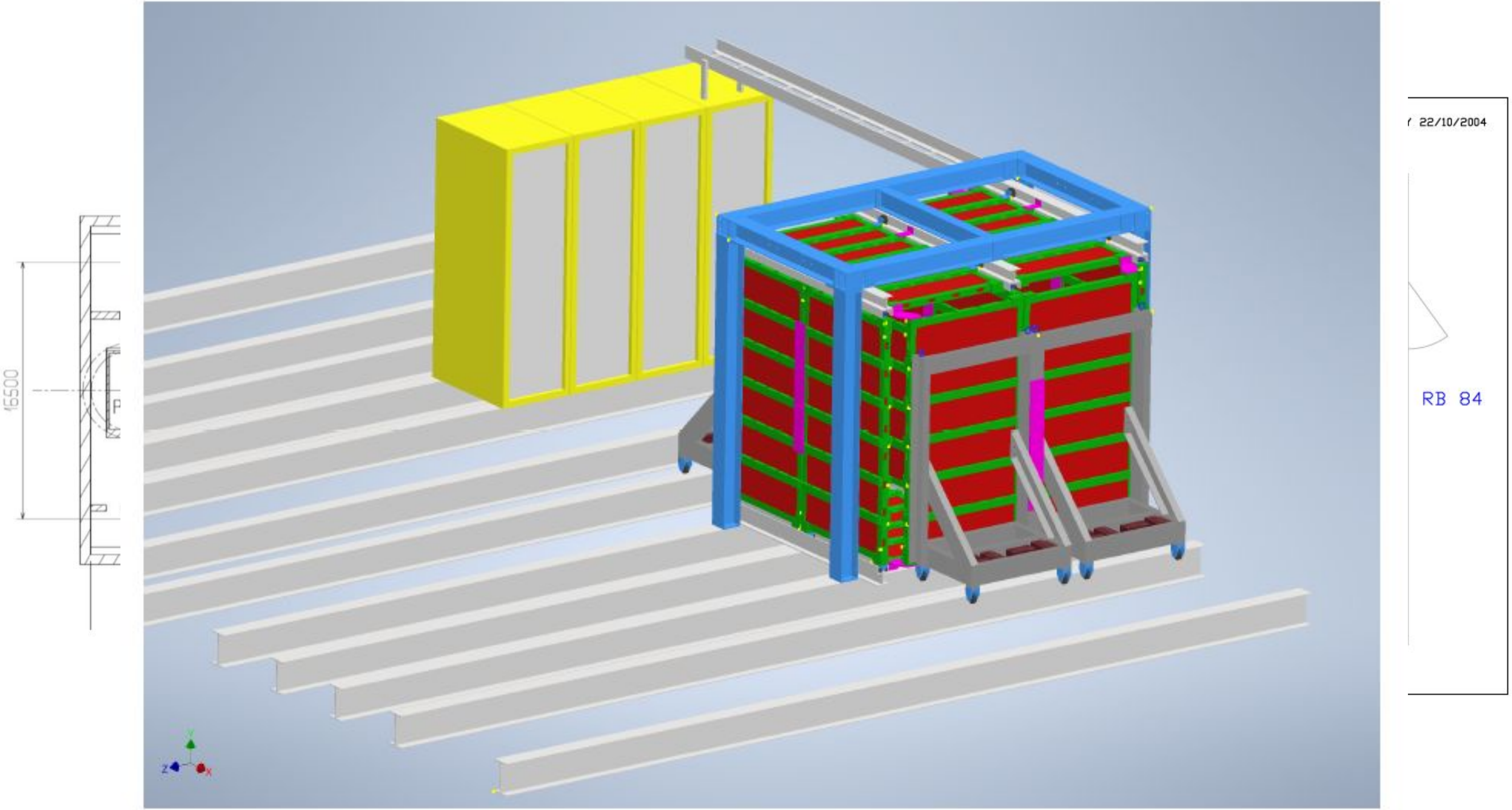
- **Providing a gas line for RPCs,**
- Preparing the safety procedure for working in D1.
- Transport from B904 to P8 (300 kg/frame), use of PZ lift.

Gas system:

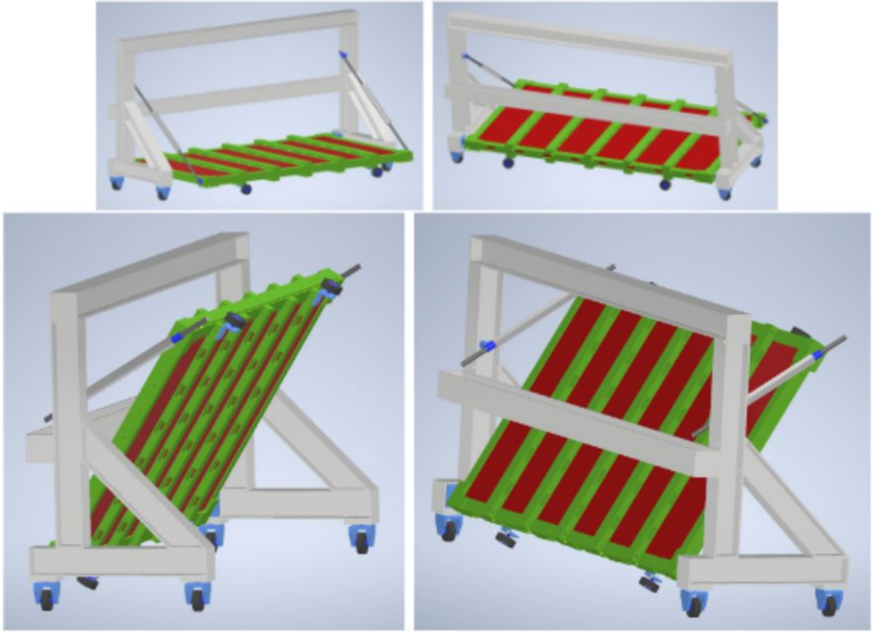
- **Mixer + recirculation system ordered and underway.**
- **GHG emissions not scalable for CODEX-b → R&D in search for an ecomixture.**

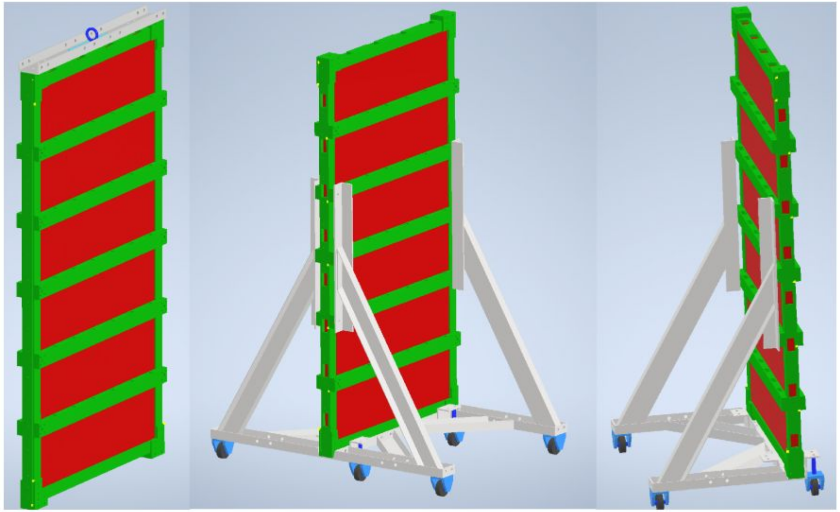

GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
GANGWAY +5200
SAS
VISITORS PLATFORM
16500
PZ 85
DELPHI
BARREL
BARRACK D
(MODIFIED)
SHIELDING WALL
GANGWAY +5200
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS


DETECTOR
Laurent ROY 22/10/2004
1125
900
540
900
1090
900
1100
900
600
900
1205
D1A01
D1A02
D1A03
D1A04
D1B01
D1B02
D1B03
D1B04
D1C01
D1C02
D1C03
D1C04
D1D01
D1D02
D1D03
D1D04
D1E01
D1E02
D1E03
D1E04
600
150
RB 86
RB 84
1073
50
640
50
50
50
D1A06
D1A07
D1A08
D1A09
D1A10
D1A11
D1B06
D1B07
D1B08
D1B09
D1B10
D1B11
D1C06
D1C07
D1C08
D1C09
D1C10
D1C11
D1D06
D1D07
D1D08
D1D09
D1D10
D1D11
D1E06
D1E07
D1E08
D1E09
D1E10
D1E11
Back
Front
Front
Back
Back
Front
Front
Back
Back
Front
7380
150
Vue de dessus
Barrack D1
Delphi Barrel


16500
22/10/2004
RB 84
Y
Z
X

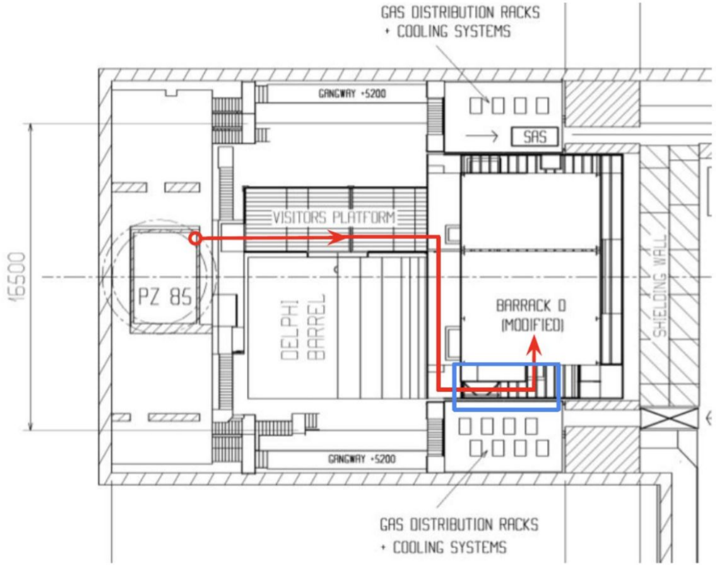
Transporting the frames to the barracks





Moving the frames to D1 barracks.

Transporting the frames to the barracks

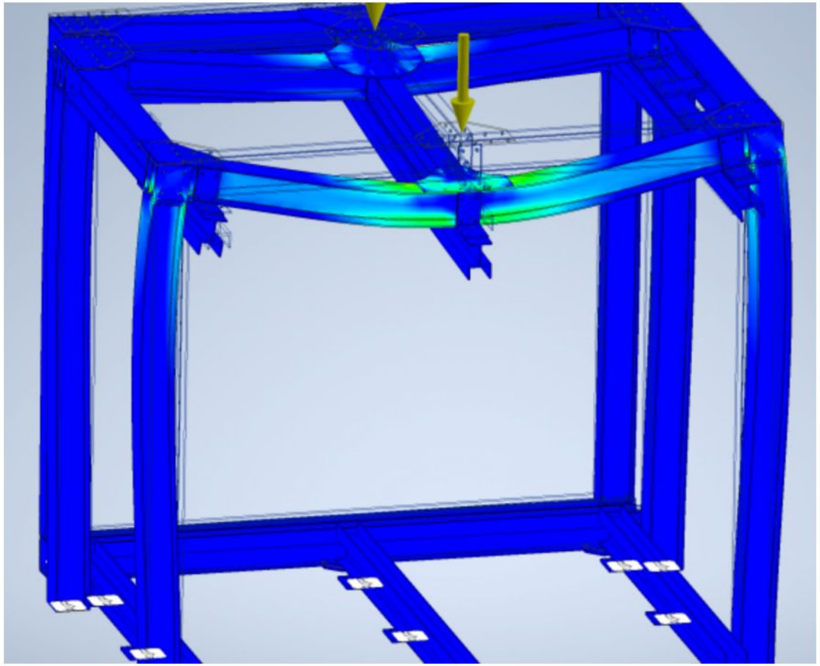


- **Shipped from B904 to P8.**
- Weight per triplet inc. cart ~ 300 kg. **Transported with PZ lift.**

Assembling CODEX-β

- Cubic, aluminium structure + 2 racks
- Consists of I-beams, C-channels, and angles, bolted in situ
- 12 chambers mounted on structure; 2 roll-up
- Load on the structure from the two chambers on the top face
- Support structure development closely followed by CERN HSE

Once assembled, test the chambers: repeat all RPC testing after installation, plus cosmics, powering, etc.



(exaggerated FEA - actual deflection $\mathcal{O}(1)$mm)

Assembling and testing the RPCs

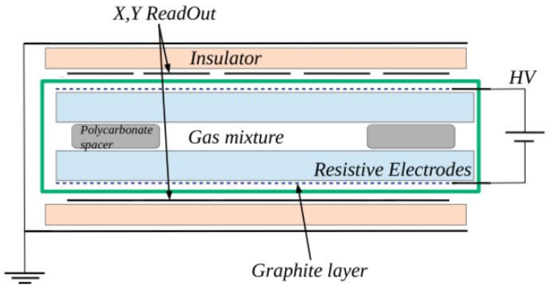
Target: assemble **14 panels**, with a RPC triplet each → **42 RPC singlets.**

Assemble one RPC singlet: prepare the **panels,** attach **readout cards** (solder LV and readout connections), **add the gas gap** and **close the Faraday cage.**

Test that one RPC singlet: test **each resistor** in the panels, the **LV**, the **readout**, the **Faraday cage,** an **IV test** with external power supply, and a **gas** and **HV leak** test.

Same RPC design as BIS78 ATLAS upgrade project:

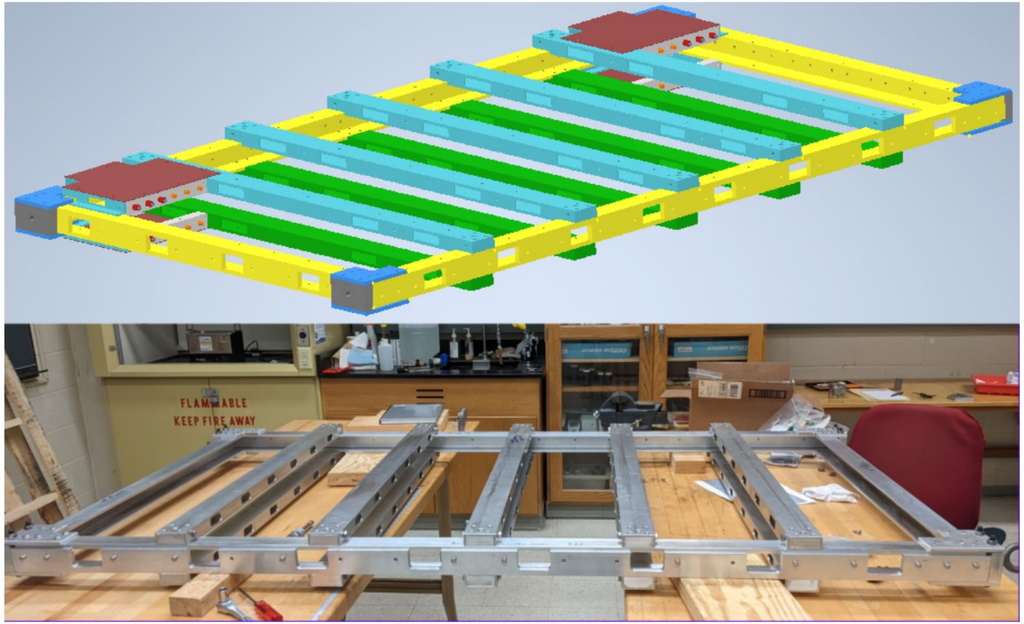
- 1mm gas gap
- Matrix of polycarbonate spacers 1cm diameter; 7cm spacing
- 1.2mm HPL, graphite-coated electrodes
- Sandwich between insulated, orthogonal strip panels (∼25 mm pitch)
- Panels glued to insulating FOREX material
- Faraday cage case: low noise and shield FE



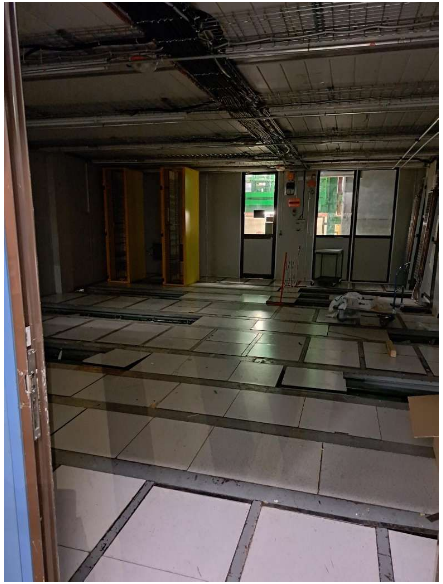
Assembling and testing the RPCs

Target: assemble **14 panels**, with a RPC triplet each → **42 RPC singlets.**

1. **Assemble and test RPC singlets individually.**
2. **Assemble three RPC singlets, and then one RPC triplet:** insert three singlets into a frame → **each triplet weighs 150 kg.**
3. **Test the RPC triplet.**



Preparing the D1 barracks



D1 barracks are empty now, power supply available.

Working now on:

- **Providing a gas line for RPCs,**
- Preparing the safety procedure for working in D1.
- Transport from B904 to P8 (300 kg/frame), use of PZ lift.

Gas system:

- **Mixer + recirculation system ordered and underway.** Extensive discussions with CERN gas group. 64% R134a, 30% CO2, 5% isobutane, 1% SF6.
- **GHG emissions not scalable for CODEX-b → R&D in search for an ecomixture.**

DAQ, readout and integration with LHCb

- RPCs readout by DCTs (Data Collection & Transmission).
- **DCT readout design being finalized by ATLAS experts.**
- Development with LHCb experts on slow control (LV, HV, Gas, monitoring).
- **Control, communication, and synchronisation with LHCb are challenging:**
  - Firmware for RPCs to be developed to make the output LHCb compatible.
  - **Need for FPGA expertise to make DCT readout LHCb-compatible.**

Locations

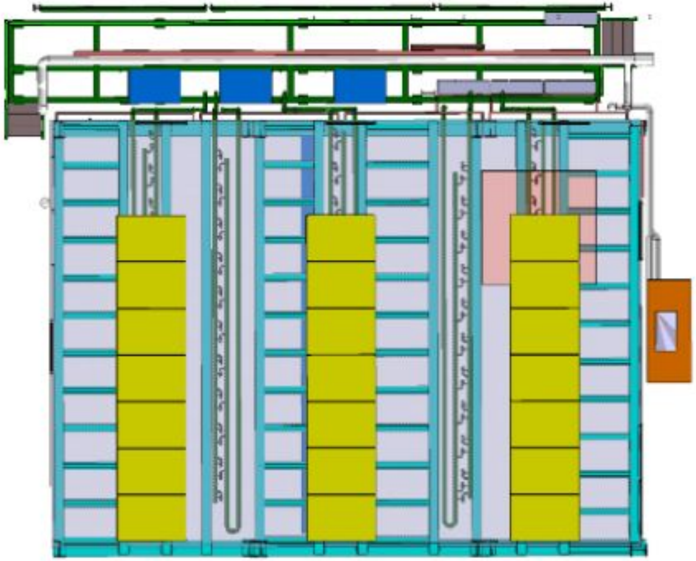
CODEX-b locations from LHCb perspective

Would the active veto/Pb shield block access to VELO/RICH1/UT/Magnet?

On D1-D3 counting rooms:

- D1/D2 housed event-filter farm and control system during Run 1 and 2.
- System will be relocated to UX85 during Upgrade Ib/II.
- Refurbishment of D1/D2 during LS3, D3 will be used for electronics rack.

Wishful thinking: can we come up with an idea to prevent the need to refurbish D1/D2?

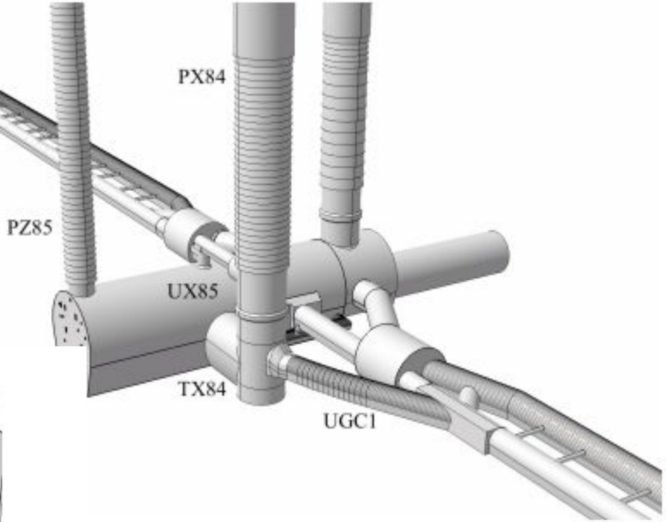


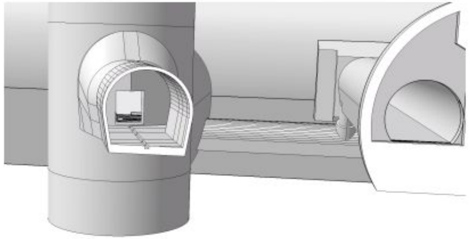
Draft layout for D1 refurbishment in LS3.

CODEX-b locations from LHCb perspective

On UGC1 gallery:

- Unused but in an unfinished state. Not planned to be used by LHCb.
- **Require civil engineering, ventilation, safety systems, access (cost estimate).**
- **Not accessible when beam is on.**





CODEX-b locations from LHCb perspective

Between shielding wall and counting rooms:

- Position of shielding wall **must be compatible with handling of detector parts**, *e.g.* transport between PX84 shaft and UX85B cavern through TX84 gallery.
- **Moving the concrete blocks would create a gap that needs to be covered.**
- **Metallic structure, supporting services and cable/trays have to stay.**

Must leave some passing way, for instance, underneath the detector!

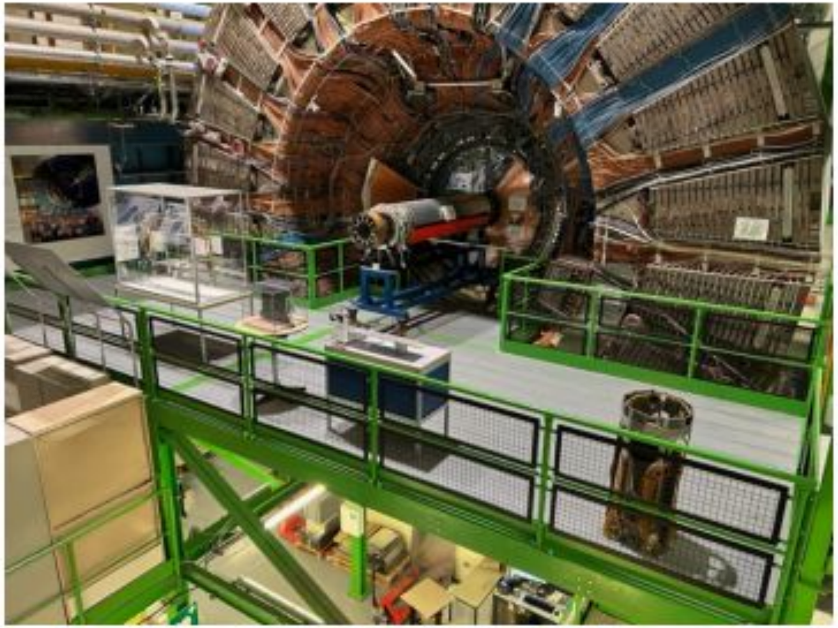
CODEX-b locations from LHCb perspective

Dismantling Delphi: likely to be unviable in terms of safety and operation.

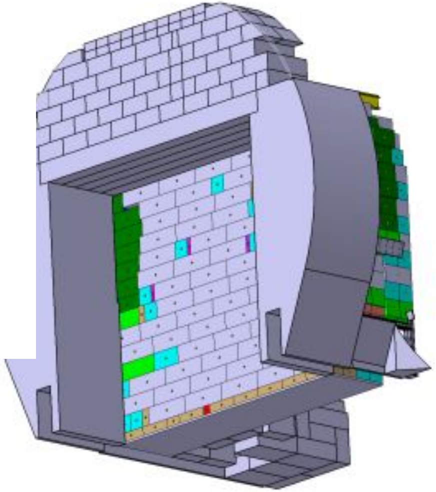
Using Delphi's visitor platform:

- 11 x 3 m surface area with possible height limitations.
- Metallic structure needs to be reinforced.
- Might also be needed in LHCb for Upgrade II (*e.g.* cooling plants).

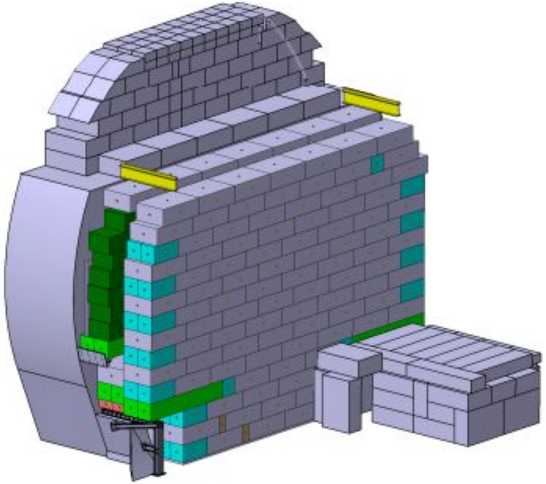
CODEX-b locations from LHCb perspective



CODEX-b locations from LHCb perspective



View from UX85A.



View from UX85B.