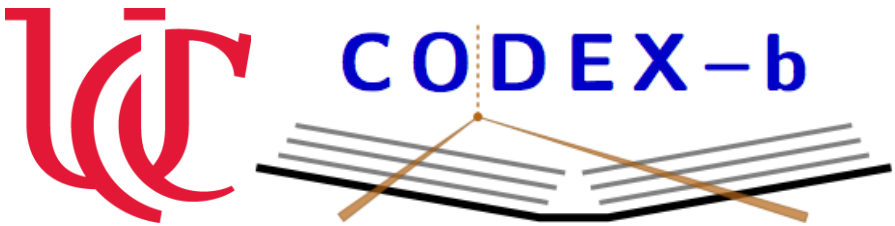


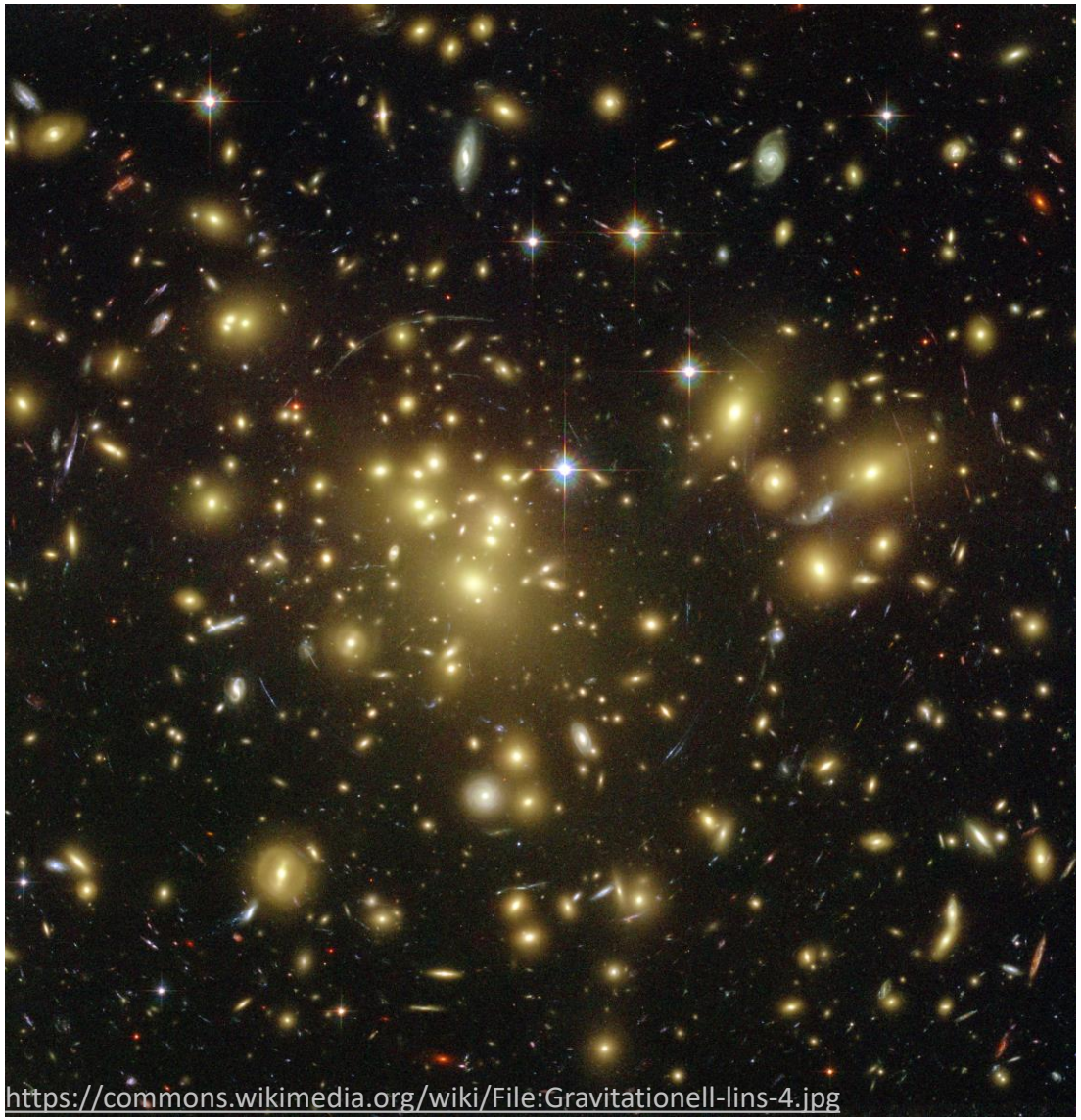
The CODEX-b Experiment: Status and Prospects

Michael K. Wilkinson
of the University of Cincinnati
on behalf of the CODEX-b collaboration

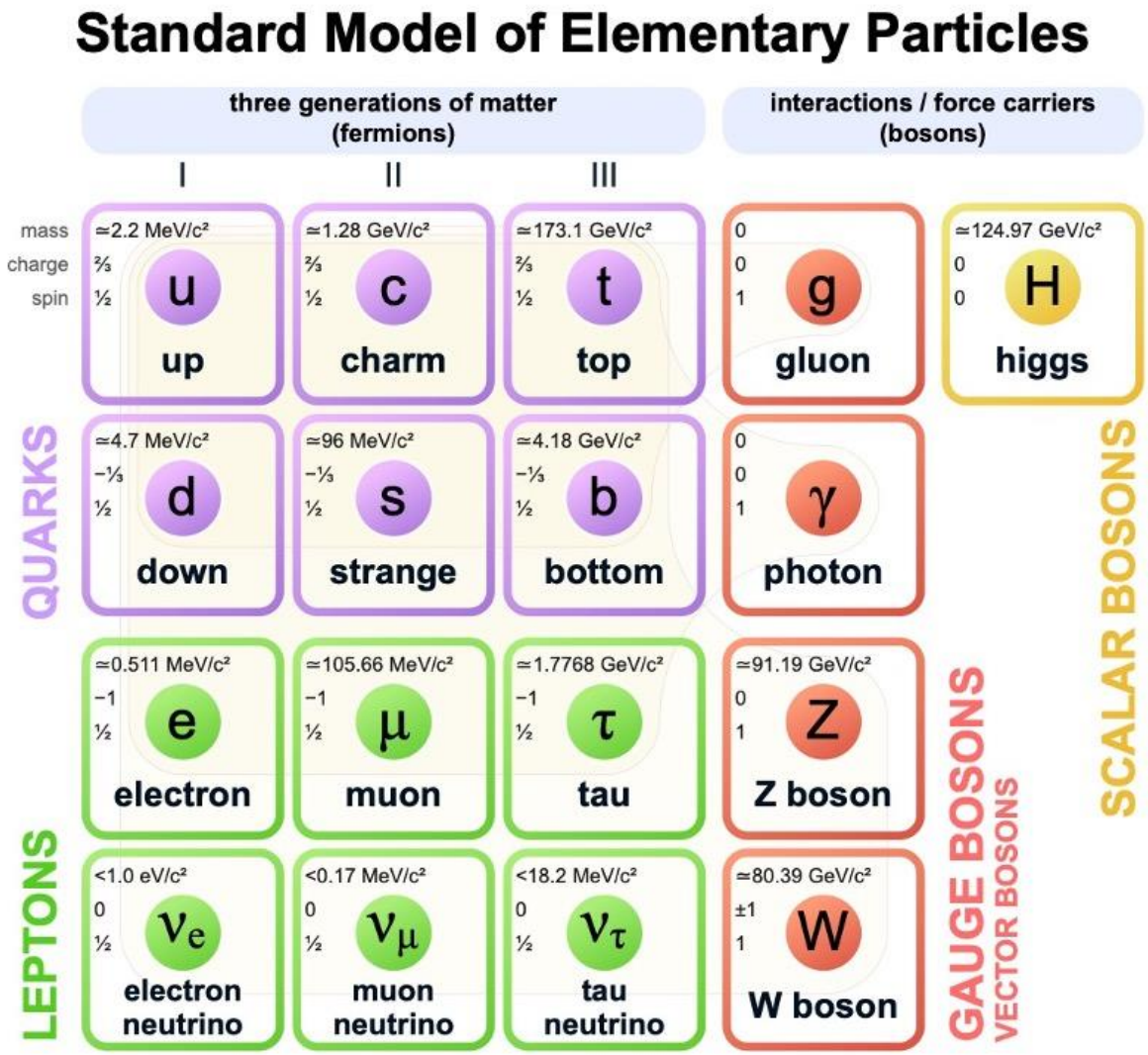
LHCP

5 June 2024

Dark Matter and the Standard Model

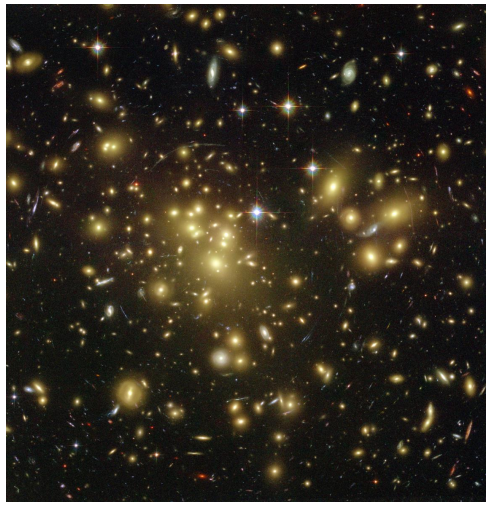


https://commons.wikimedia.org/wiki/File:Gravitationell-lins-4.jpg



https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

Dark Matter in the Standard Model



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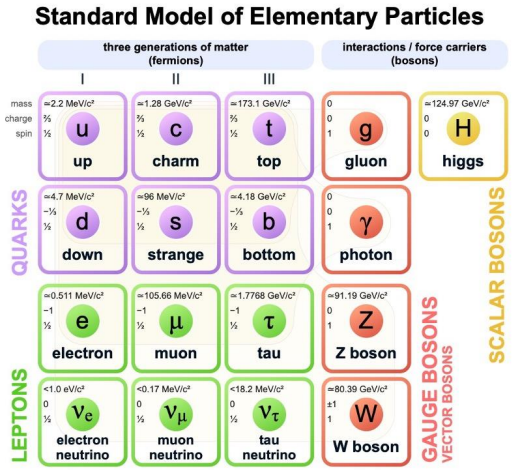
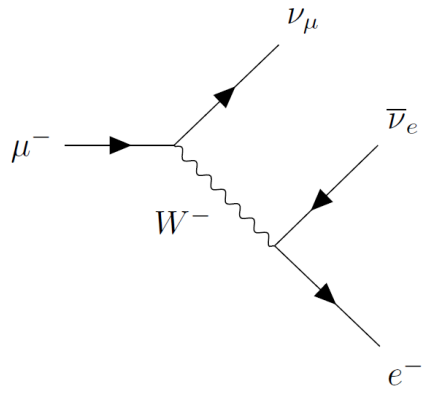
X

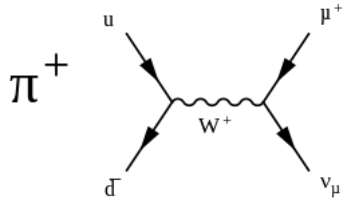


https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

Some famous LLPs in the SM:

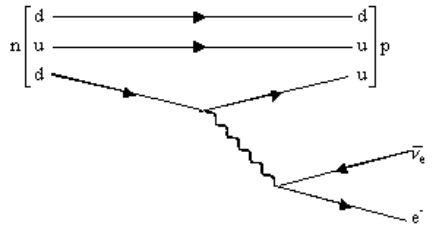


https://physics.stackexchange.com/q/517721



https://commons.wikimedia.org/wiki/File:PiPlus_muon_decay.svg

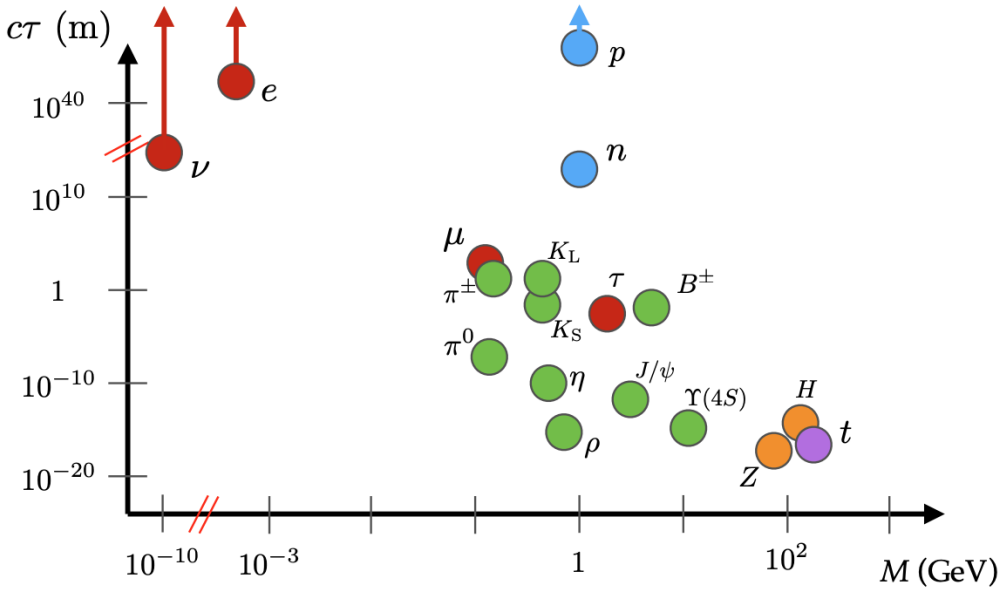
- DM and SM particles may feebly interact via mediators/portals
  - Scalar portal → Dark Higgs/scalars
  - Fermion portal → Heavy Neutral Leptons
  - Pseudoscalar portal → Axion-like particles
  - Vector portal → Dark photon
- Feebly interacting ⟹ long lived particles (LLP)



http://hst-archive.web.cern.ch/archiv/HST2002/feynman/examples.htm#Example%201

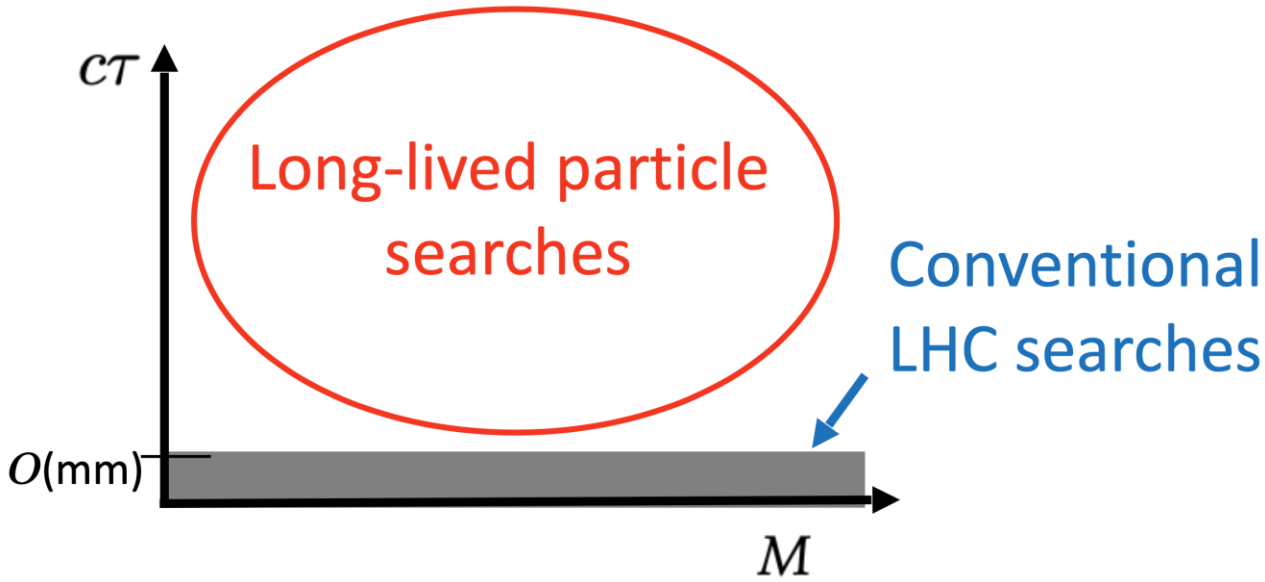
Long Lived Particles in the SM

Lifetimes span many orders of magnitude!



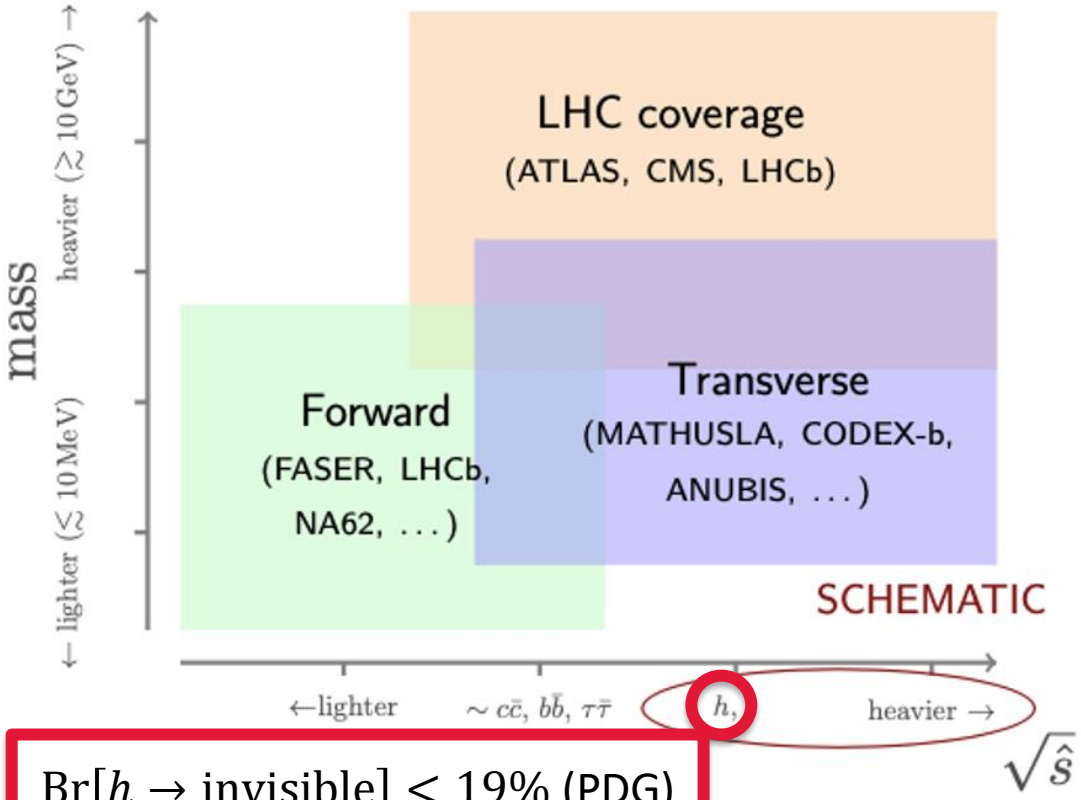
arXiv:1903.04497

…but conventional LHC searches focus on a small range.

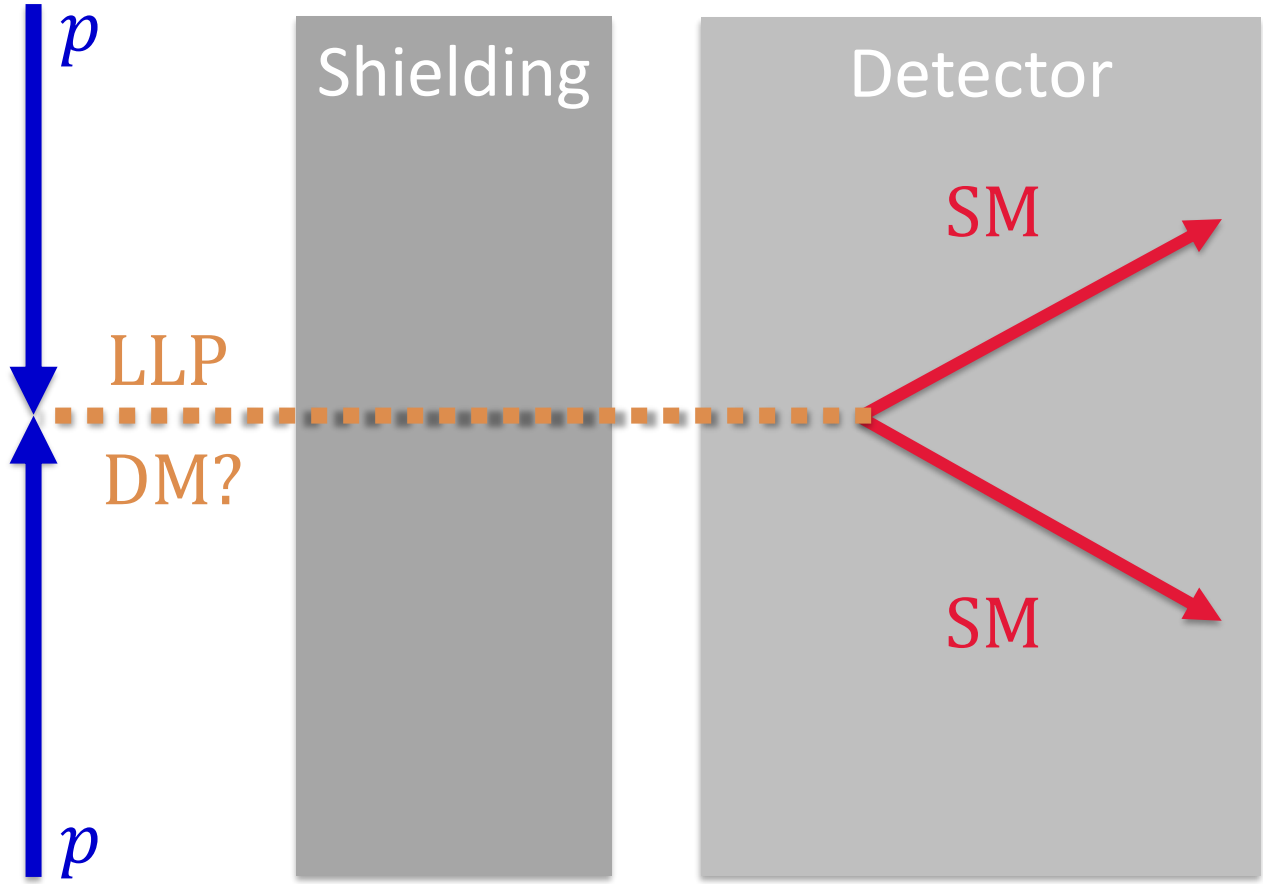


No compelling evidence for DM at colliders so far!

Proposed detector scheme

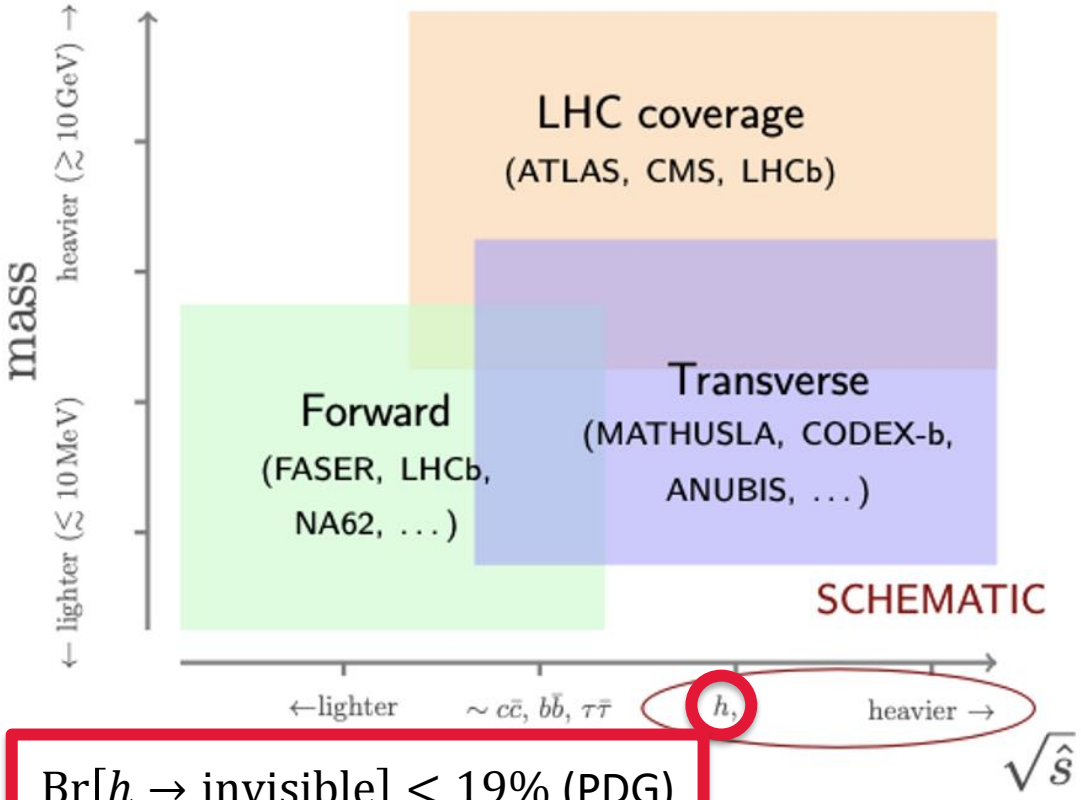


$\mathrm{Br}[h \to \text{invisible}] < 19\%$ (PDG)
Tantalizing area for new physics!
Only produced at LHC



Higgs boson produced in pp collision could couple to DM particle, which could then decay to SM particles

Proposed detector scheme



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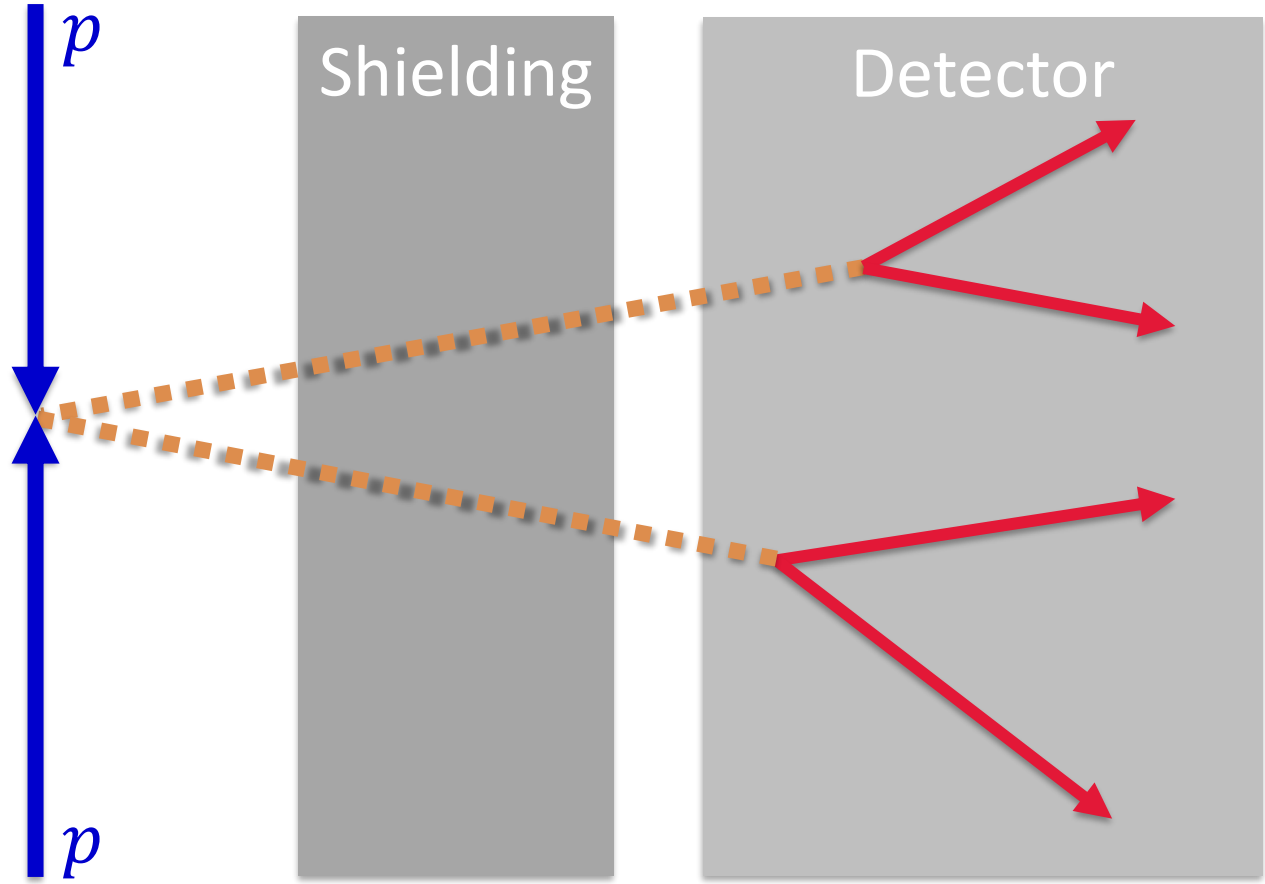

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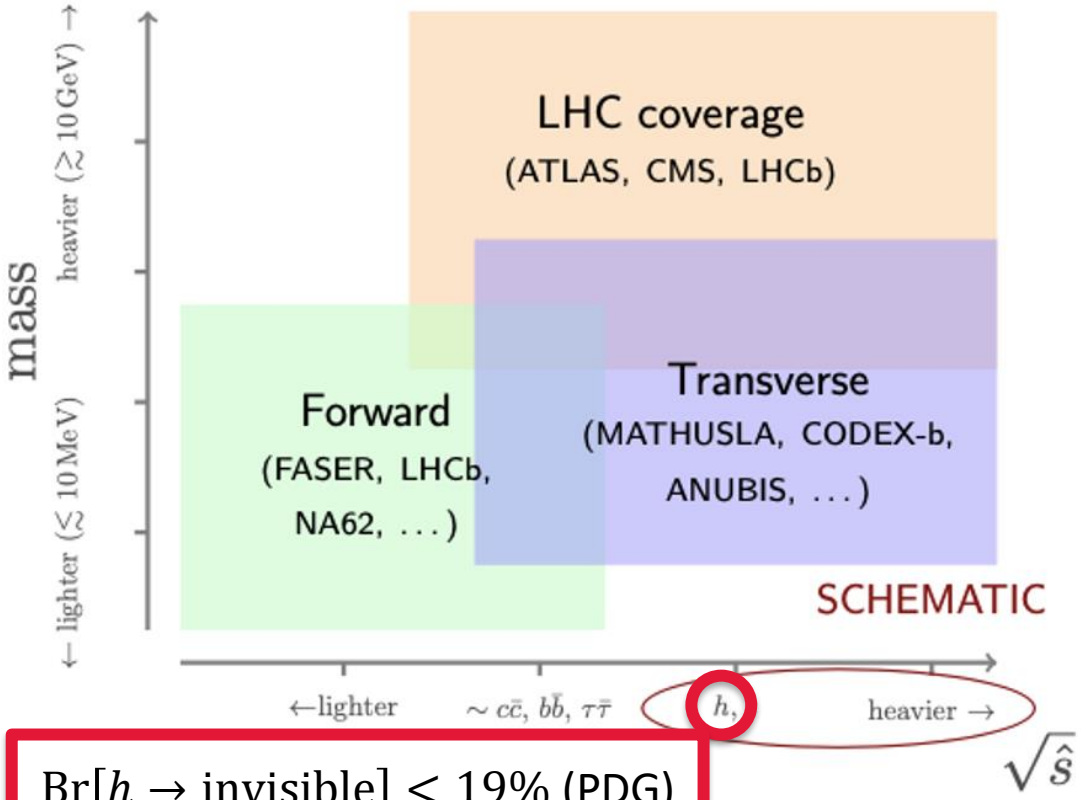

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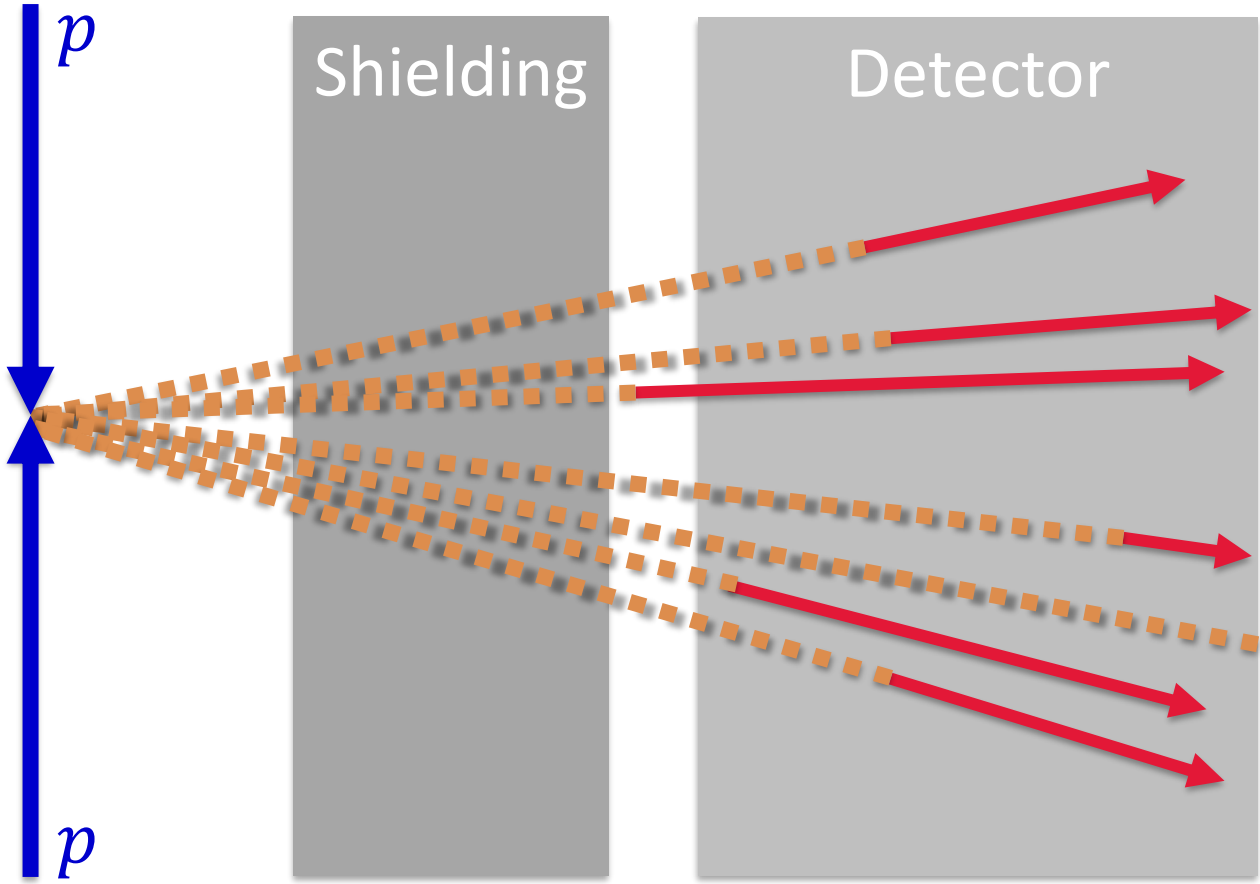
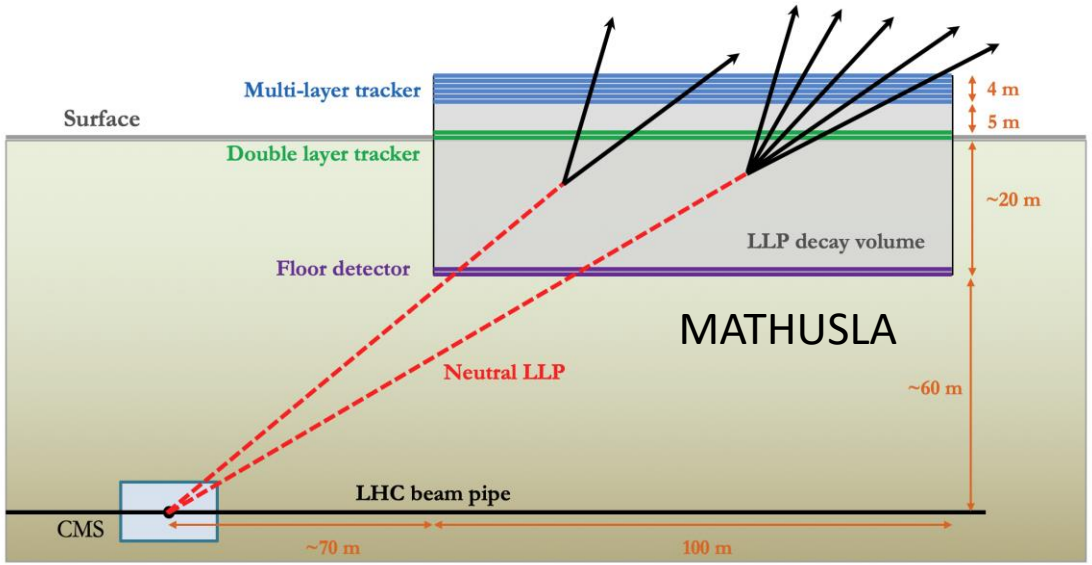
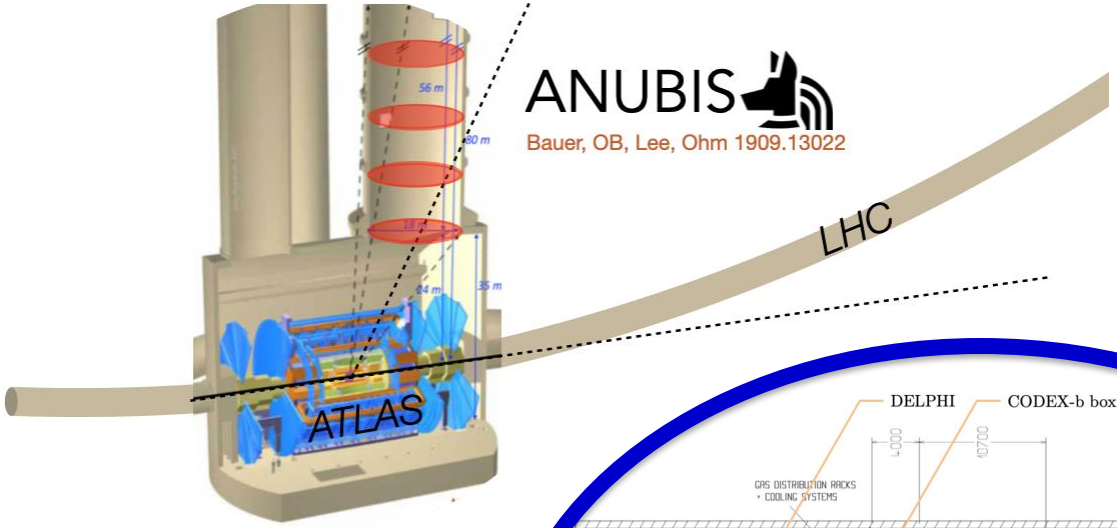


Higgs boson produced in pp collision could couple to DM particle, which could then decay to SM particles

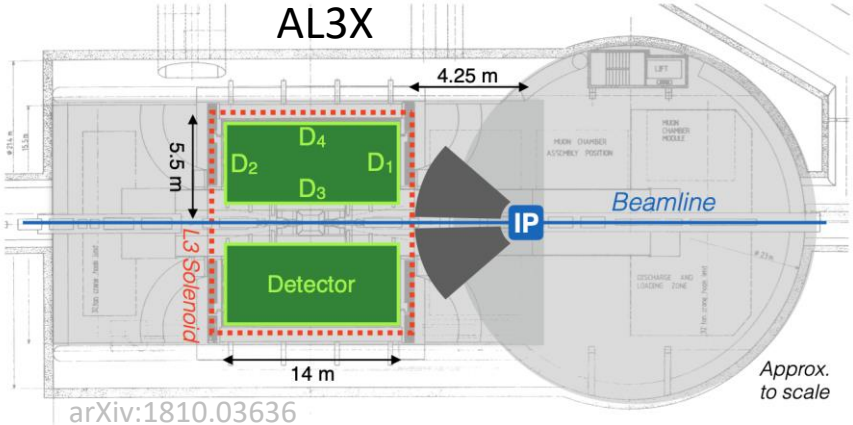
Transverse LLP Detectors Proposed at the LHC



https://mathusla-experiment.web.cern.ch

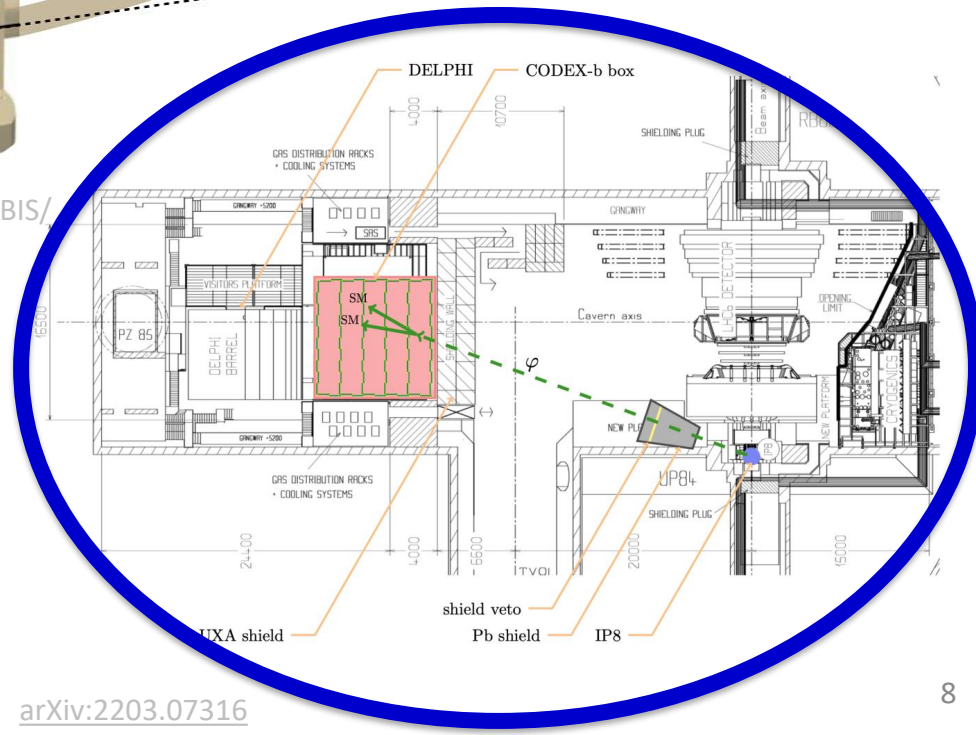


https://twiki.cern.ch/twiki/bin/view/ANUBIS/



arXiv:1810.03636

CODEX-b

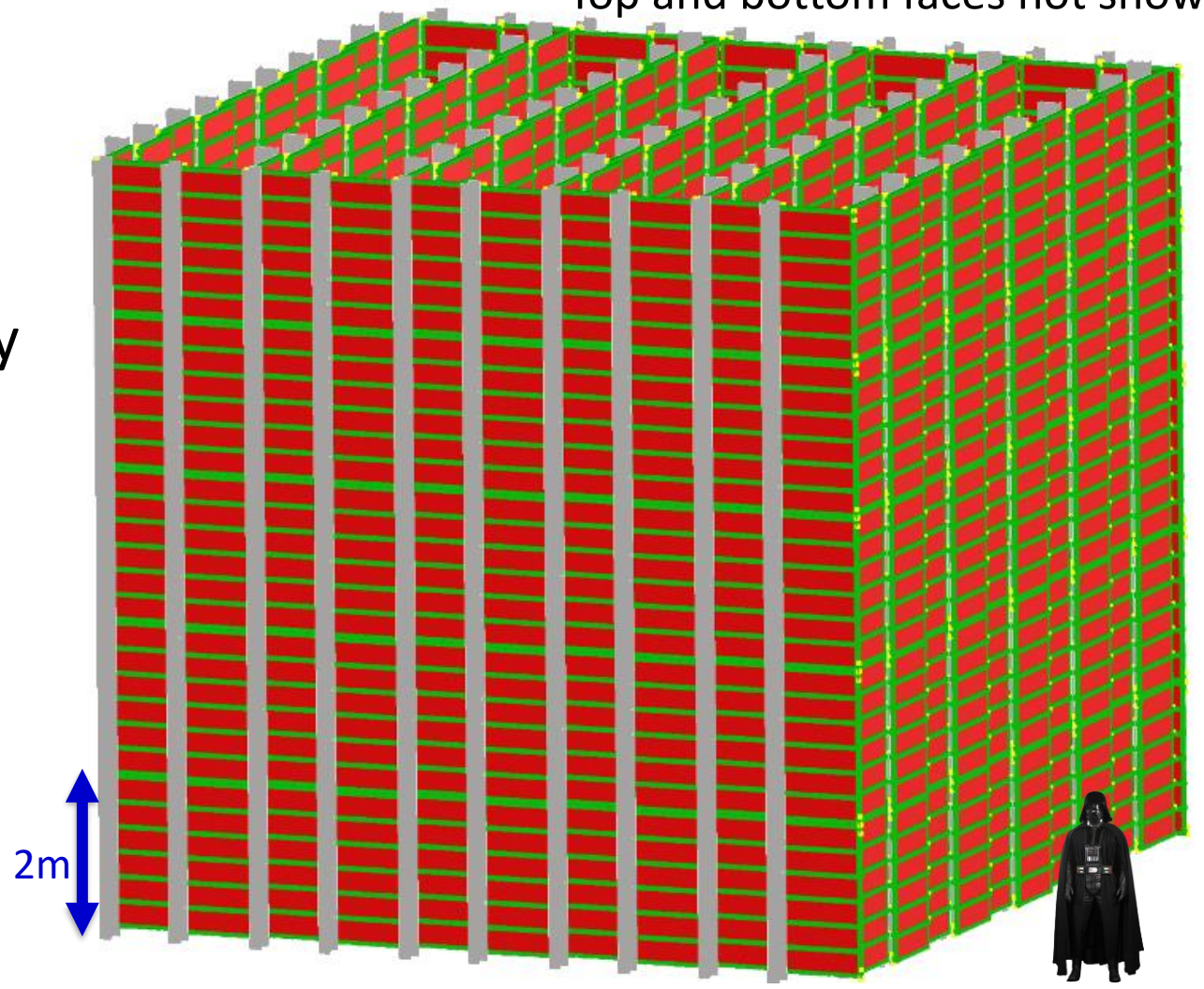


arXiv:2203.07316

CODEX-b Detector Baseline Design

- COmpact Detector for EXotics at LHCb
- 10 m cube of 500 2 m x 1 m **triplet Resistive Plate Chamber (RPC)** panels
  - Follows the ATLAS phase-II RPC design [1]
  - Established technology, inexpensive
- LHCb cavern already has many necessary services in place
- **Integration with LHCb trigger** allows possibility of distinguishing interesting events [2]
- **Zero background**, ensured by shielding
- No B-field or calorimeter—statistical mass measurement from geometry [3]

Top and bottom faces not shown



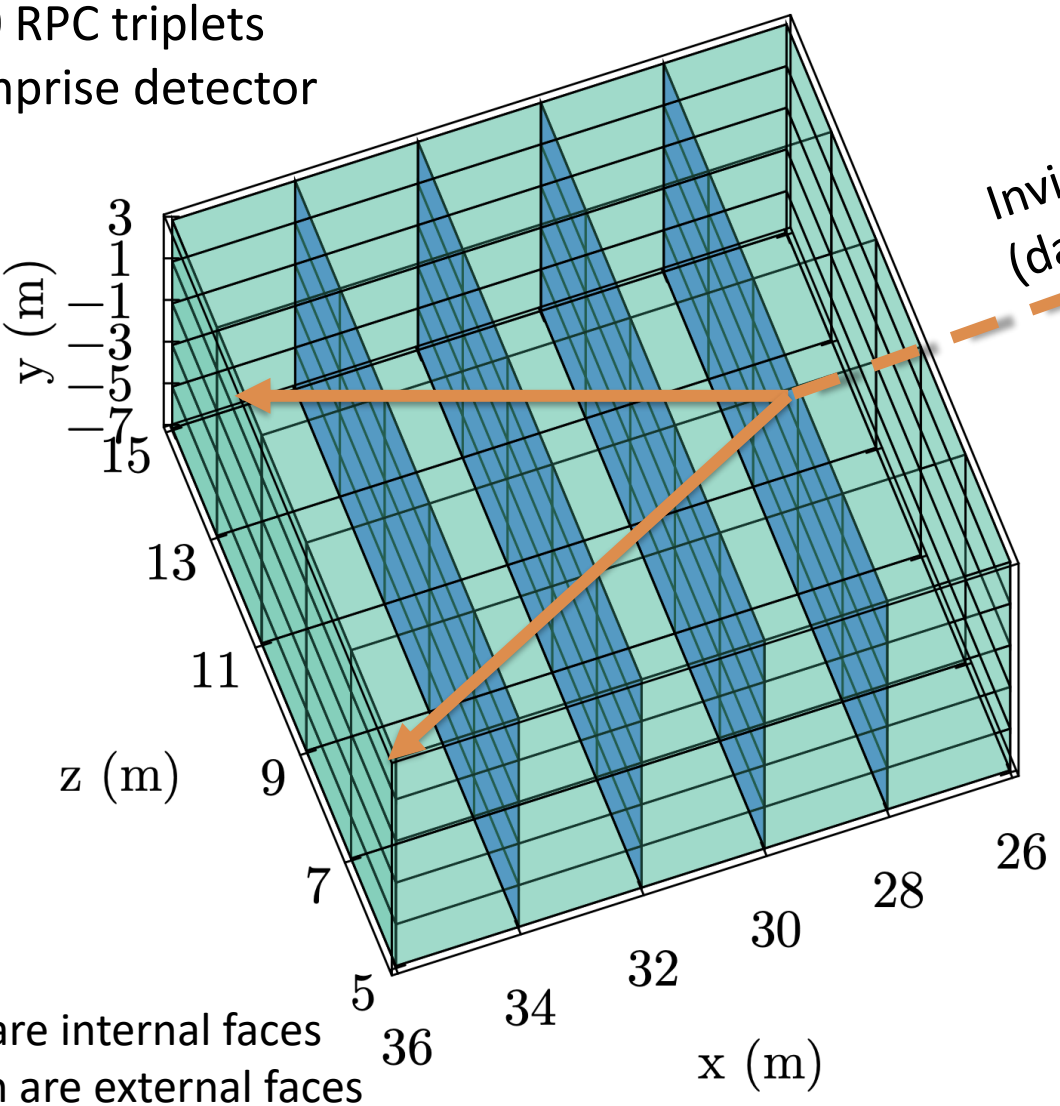
arXiv:2203.07316

https://en.wikipedia.org/wiki/File:Darth_Vader.png
https://www.cbr.com/darth-vader-anakin-height/

1. Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, Tech. Rep. CERN-LHCC- 2017-017. ATLAS-TDR-026 (CERN, Geneva, 2017).
2. G. Aielli et al., (2019), arXiv:1911.00481 [hep-ex].
3. V. V. Gligorov, S. Knapen, M. Papucci, and D. J. Robinson, Phys. Rev. D97, 015023 (2018), arXiv:1708.09395 [hep-ph].

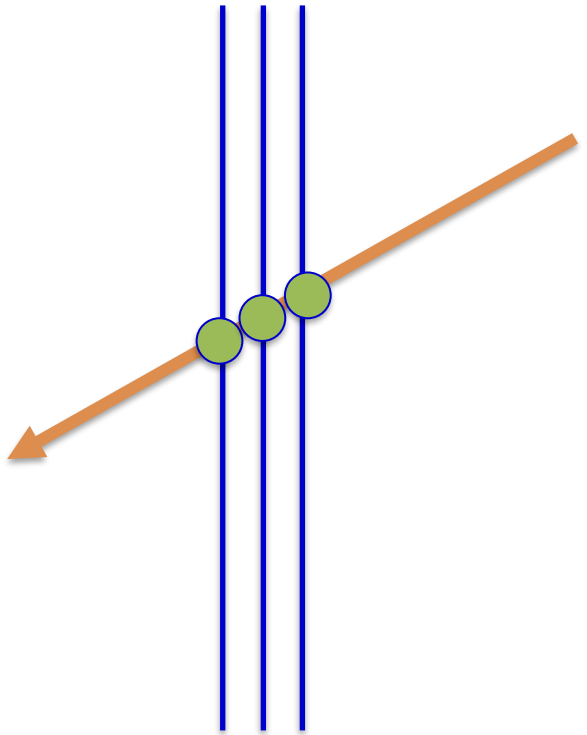
CODEX-b Baseline Configuration

500 RPC triplets comprise detector



Search for 2 charged SM tracks originating in detector volume

RPC triplet—3 hits



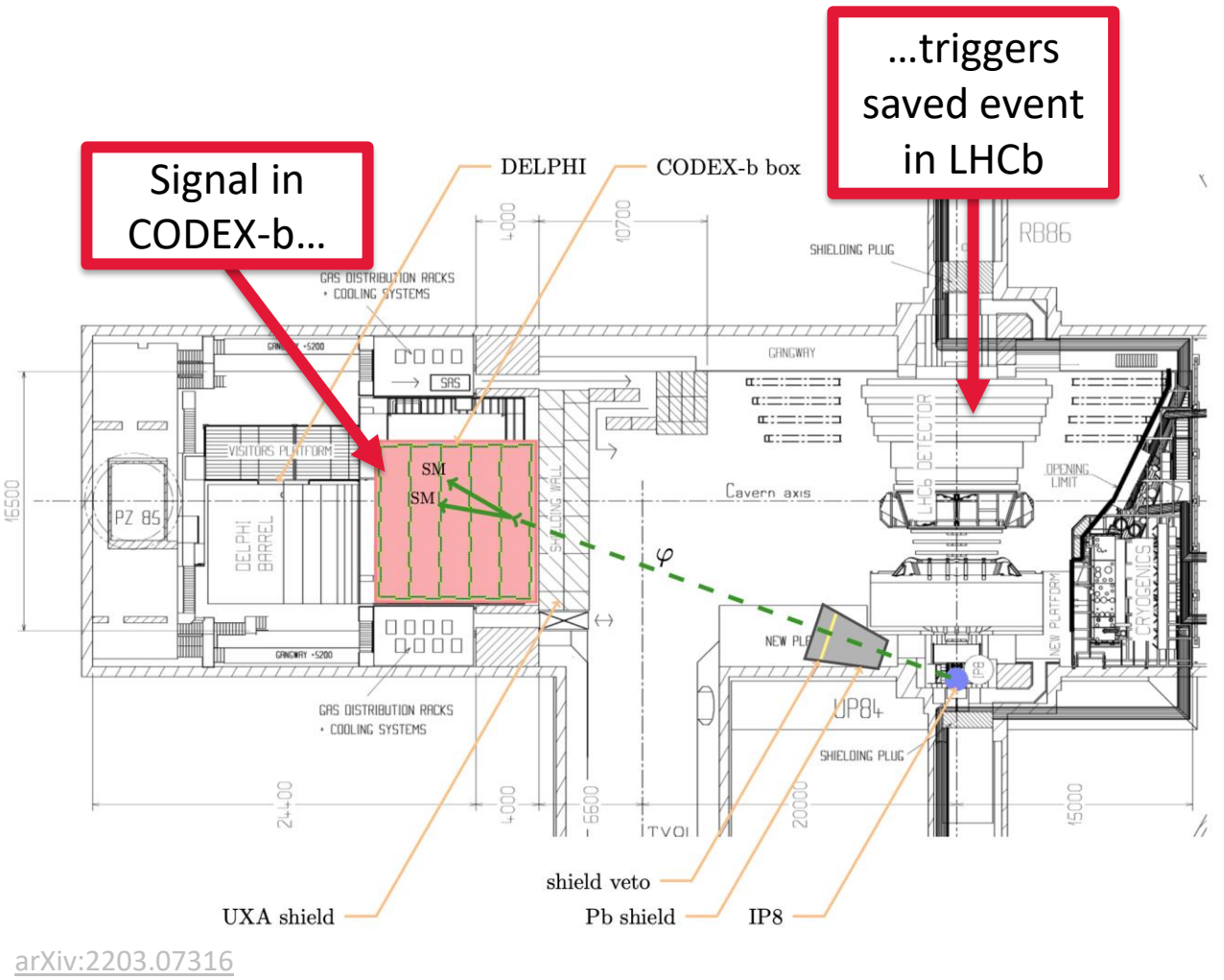
Reduces noise

Blue are internal faces
Green are external faces

arXiv:2203.07316

Integration with LHCb Trigger

- In Run 3, LHCb moved to a software-only trigger system
  - Read out every event
  - Real-time (with buffering) reconstruction enables flexible decisions about which events to keep
- CODEX-b readout would integrate with LHCb [1]
  - Use existing LHCb computing infrastructure
  - Access LHCb data along with CODEX-b data to further probe event

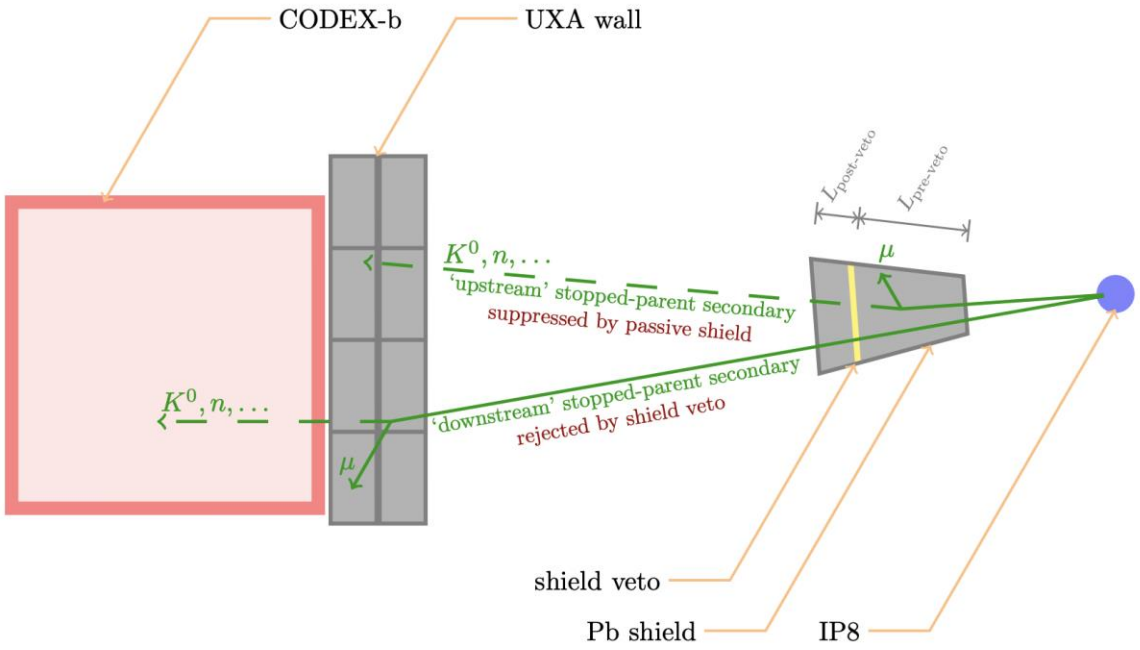


arXiv:2203.07316

1. G. Aielli et al., (2019), arXiv:1911.00481 [hep-ex].

Zero Background

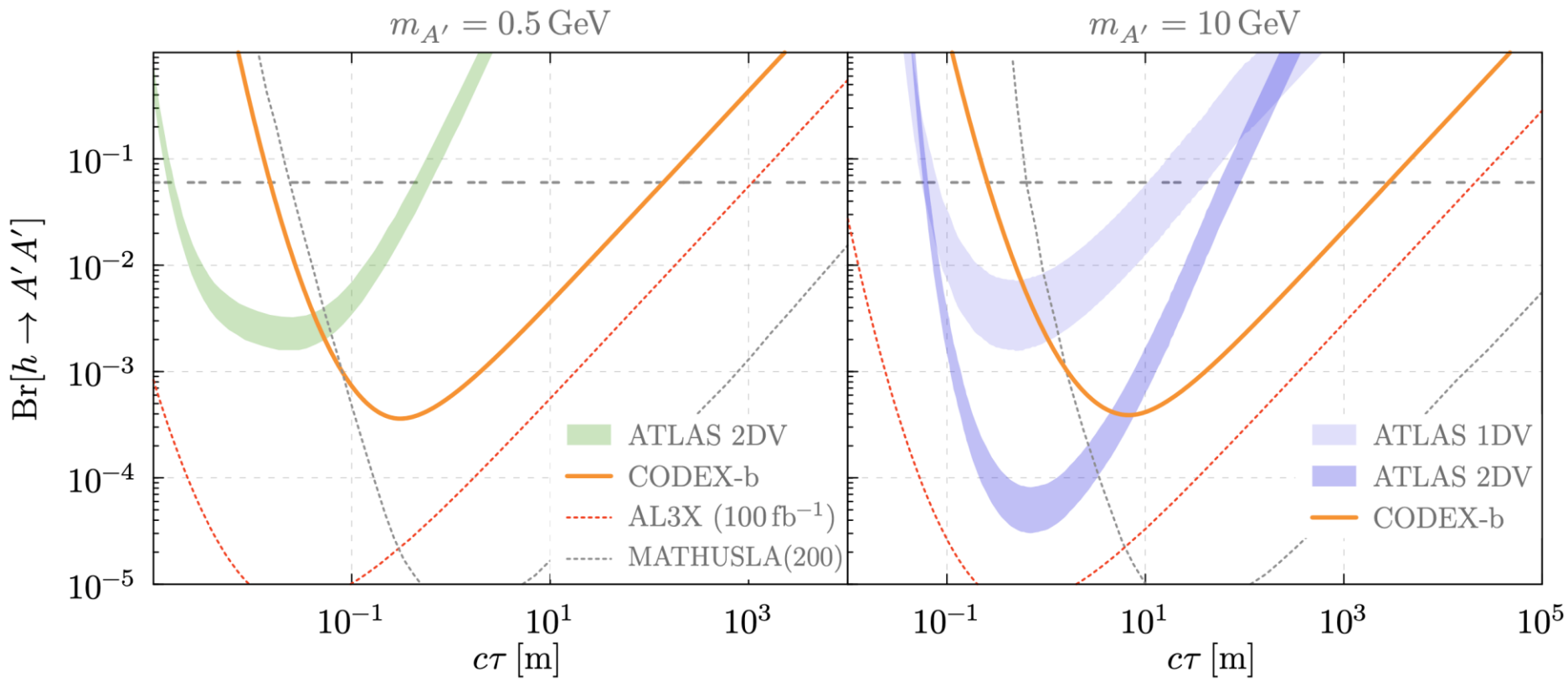
- Primary-produced n and K_L^0 can enter detector and mimic signal decay
- 3 m concrete wall and 4.5 m Pb shield can produce secondary decays
- Shield veto to remove most of these
  - Single layer scintillator (or similar)
  - Embedded in Pb shield
- Shield veto location optimized using conservative simulation, verified by measuring flux rate in cavern
- Further background studies to be conducted by CODEX-β demonstrator



arXiv:2203.07316

Abelian Hidden Sector

- Minimal model with one new particle (and its Higgs)
- $h \to A'A'$
  - $h =$ SM Higgs boson
  - $A' =$ dark photon
- Dominant A' production mode in some scenarios



Estimated upper limits on $\mathrm{Br}[h \to A'A']$ from simulation as a function of A' lifetime

horizontal dashed line = estimated HL-LHC limit on $\mathrm{Br}[h \to \mathrm{invisible}]$
ATLAS estimates range from conservative to optimistic
DV = Displaced Vertex
arXiv:1911.00481

CODEX-b Model Sensitivity

- Abelian hidden sector
- Scalar-Higgs portal
- Axion-like particles
- Heavy neutral leptons
- R-parity violating supersymmetry
- Relaxion models
- Neutral naturalness
- Inelastic dark matter
- Dark matter coscattering
- Dark matter from sterile coannihilation
- Asymmetric dark matter
- Other Dark Matter models
- Baryogenesis
- Hidden valleys

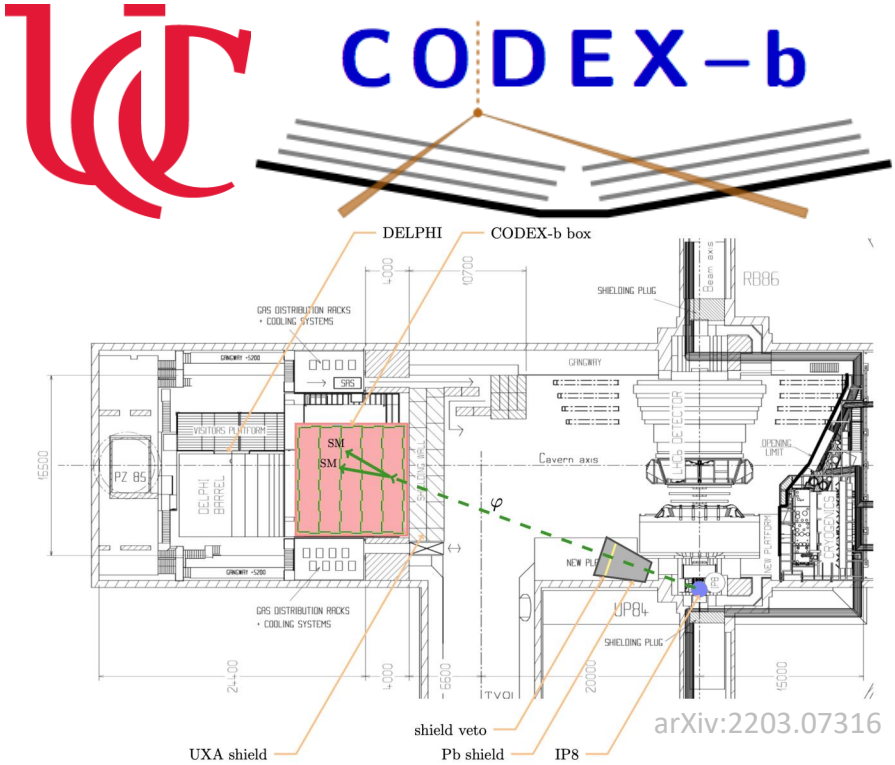
AND MORE!

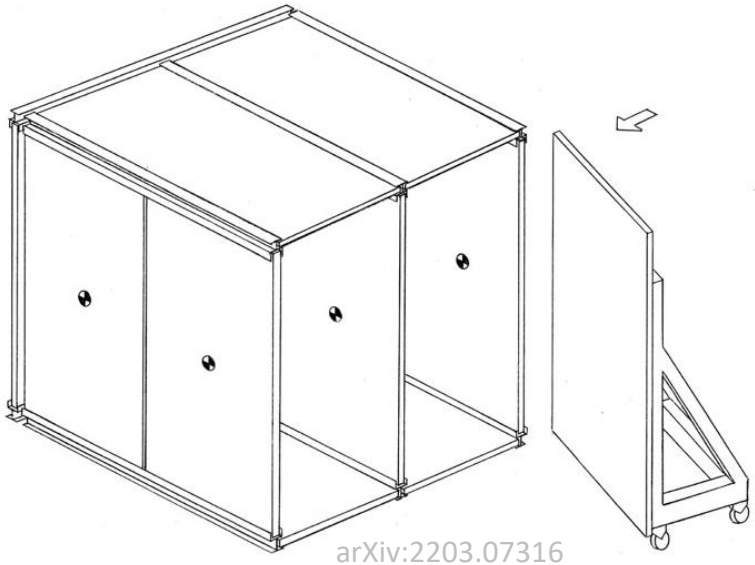
Complementary coverage to other proposed detectors at lower cost with simplified construction and shorter installation time

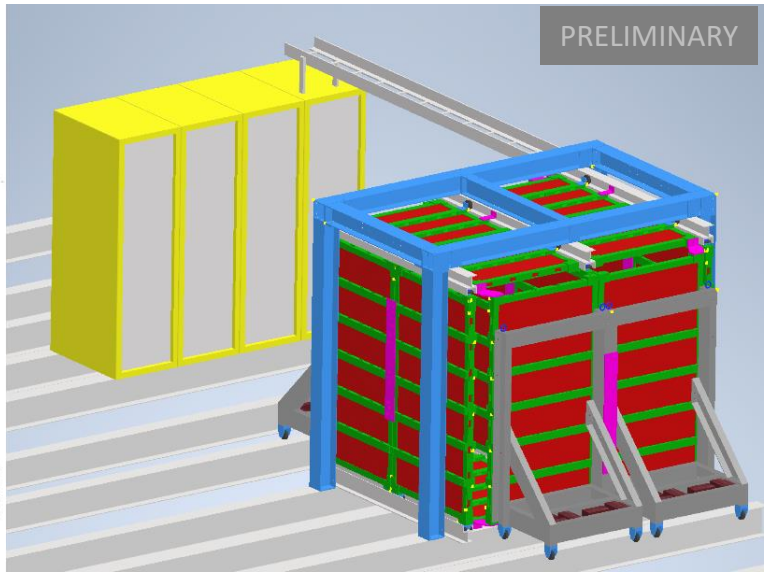
arXiv:1911.00481

CODEX-β Design

- LHCb R&D project
- 2 m cube in LHCb server room (approximate proposed location of CODEX-b)
- Integrated with LHCb software-only trigger
- Comprises fourteen 2m x 1m triplet RPC panels (same RPC design as for CODEX-b)
- No Pb or shield veto in place, only 3 m concrete shield wall

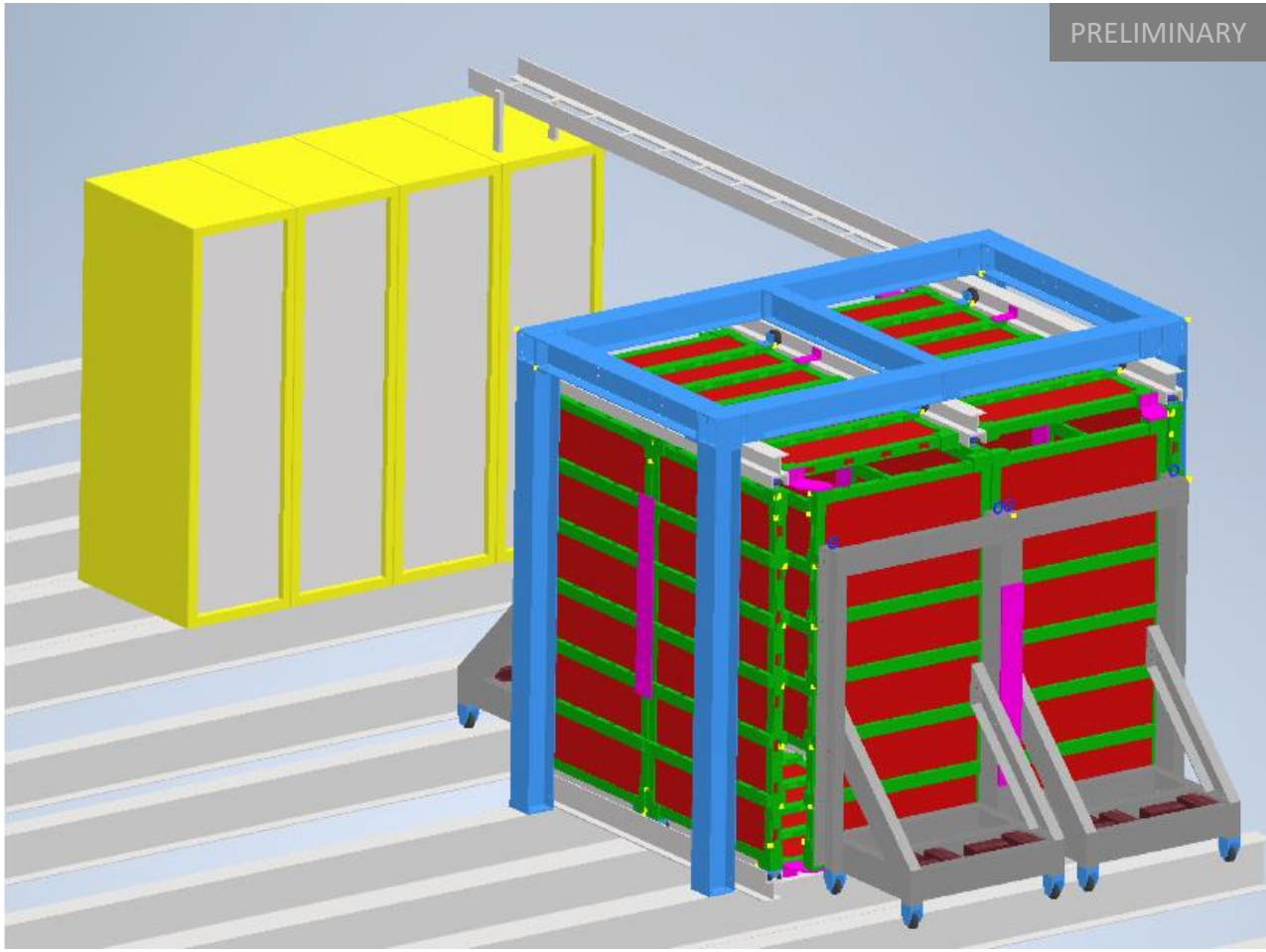






CODEX-β Goals

1. Validate background estimates
2. Integrate with LHCb readout/trigger
3. Demonstrate suitability of RPCs
4. Validate simulation by reconstructing SM backgrounds
5. Validate scalable mechanical support structure for RPCs

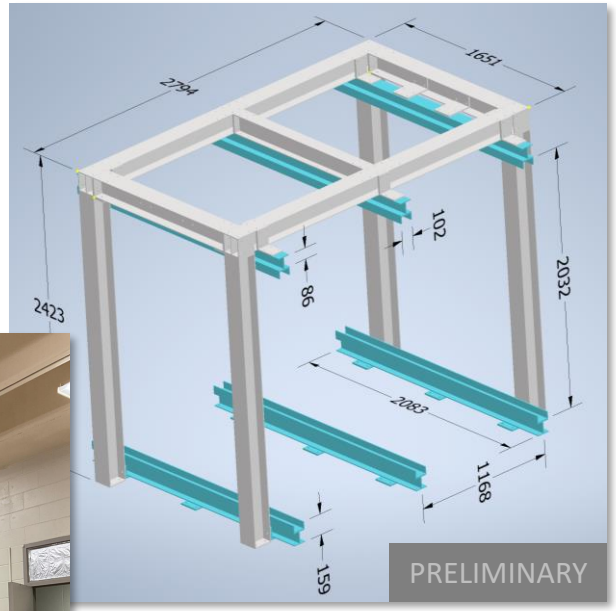


CODEX-β Production Pipeline

UC

RPC frame production

Support structure production



CERN RPC lab

RPC production

Module assembly

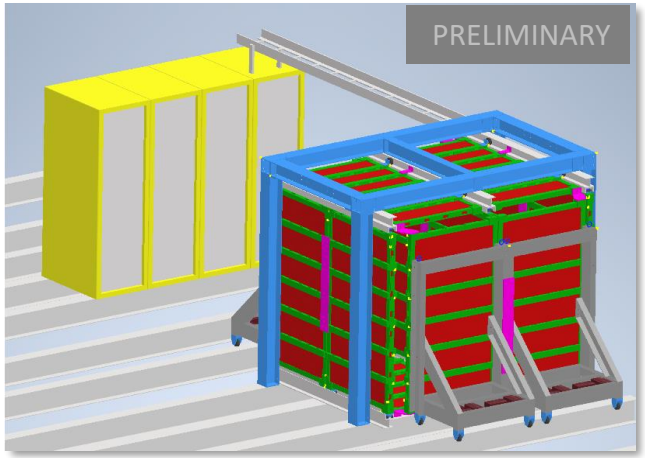
CERN IP8

Support structure assembly

Module insertion

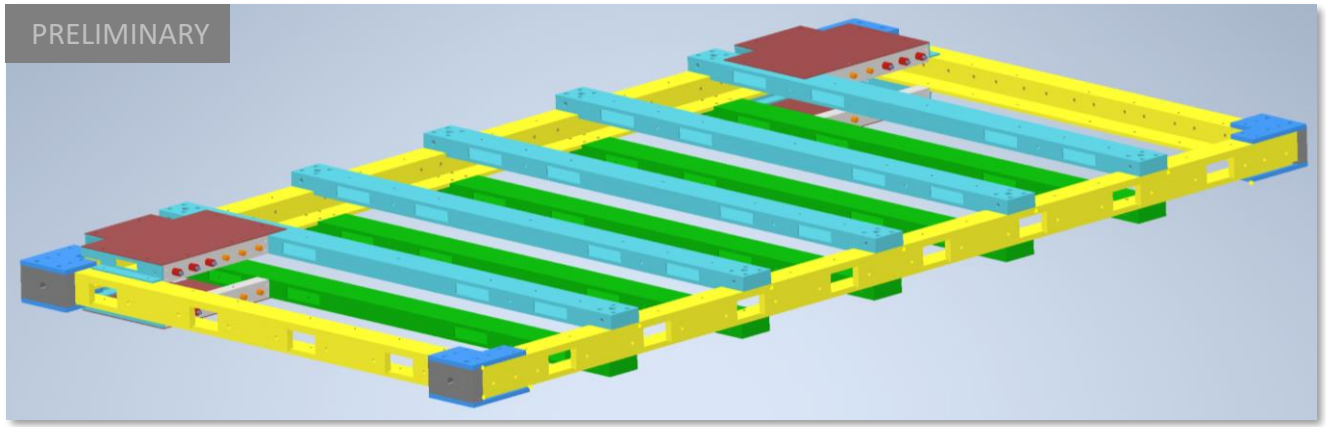
Services installation

Data taking



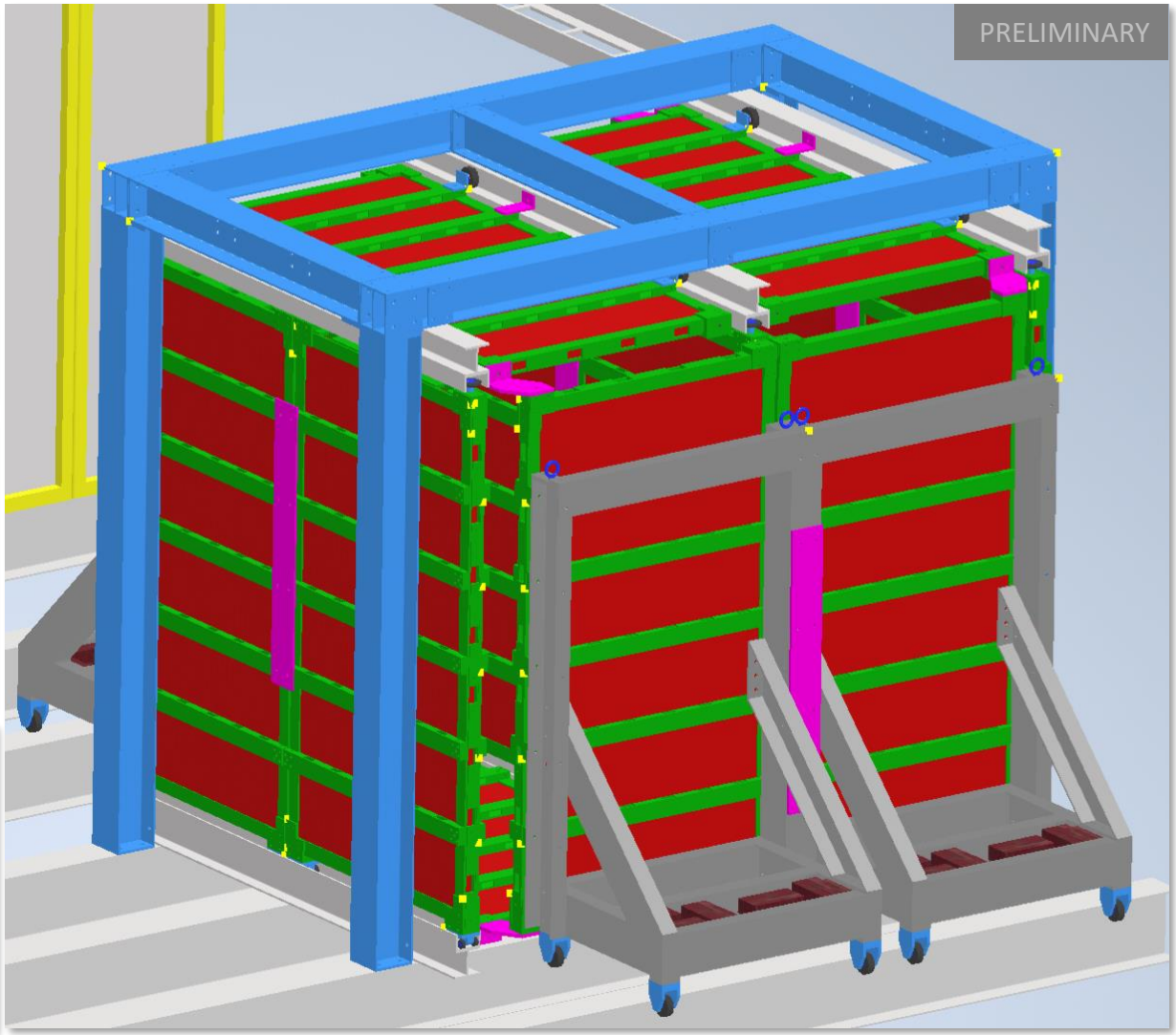
CODEX-β Mechanics

PRELIMINARY

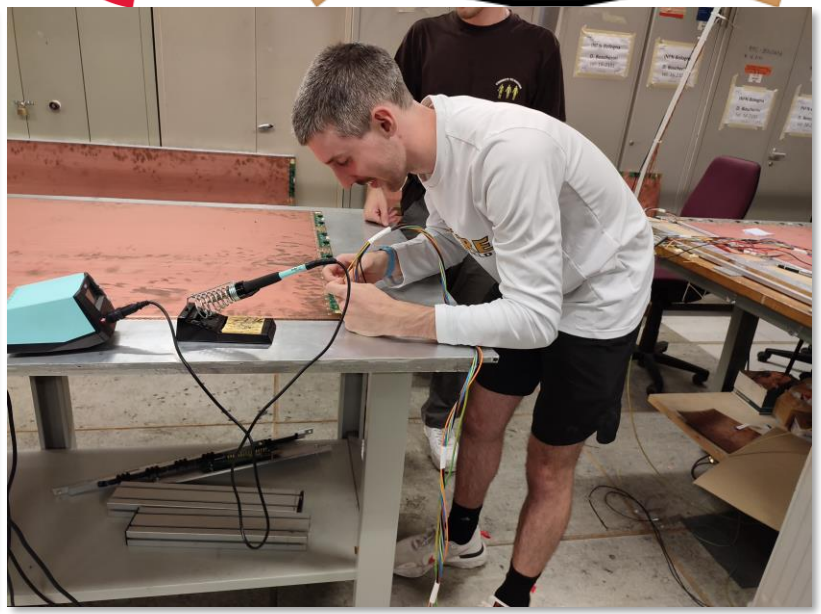


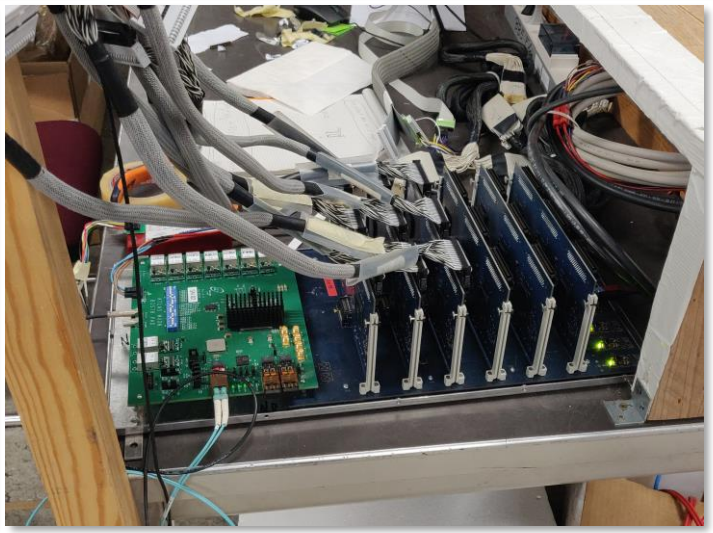
RPC frames and support structure machined, tested, and shipped from UC.

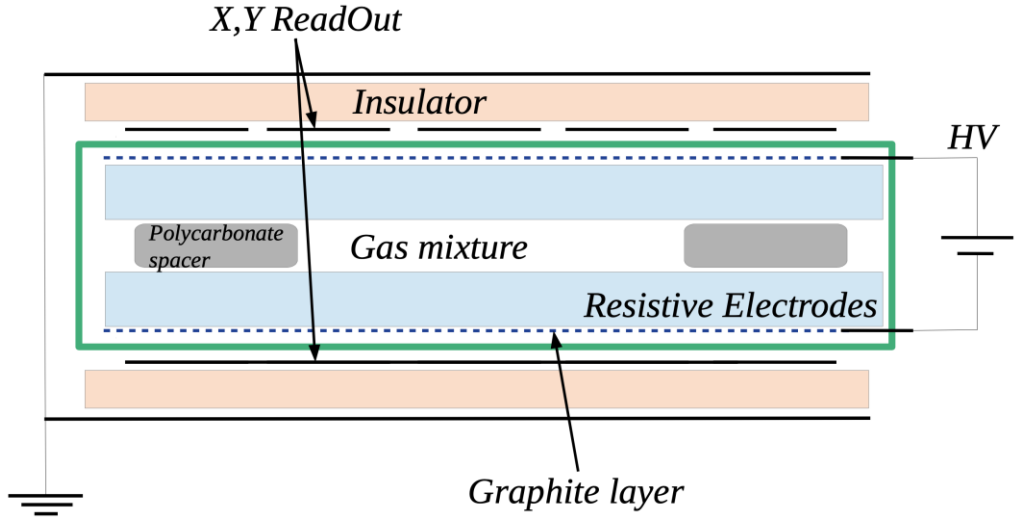
PRELIMINARY



CODEX-β RPCs and Electronics



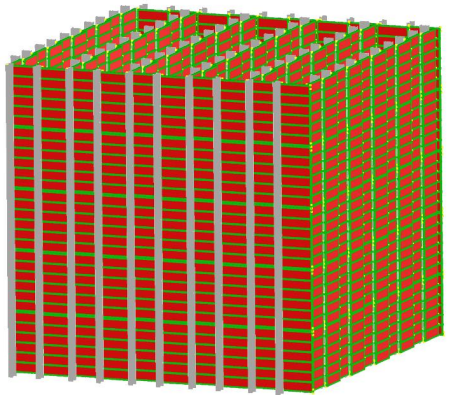


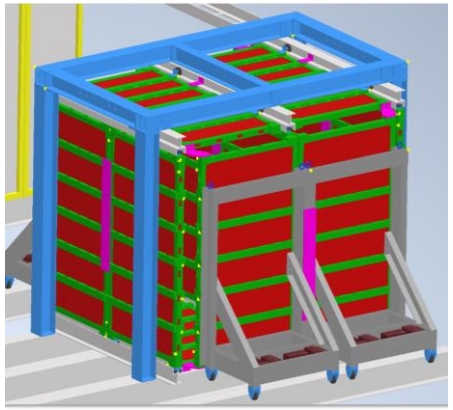


Summary

- We need a zero-background, transverse, LLP detector at the LHC
- CODEX-b would be such a detector
  - Potential sensitivity to a wide range of BSM scenarios
  - Complementary coverage to other proposed detectors
  - Lower construction and maintenance cost, relatively short construction timeline
  - Aiming for partial installation and data-taking by Run 4 (2030) and full installation by Run 5 (2035)

- CODEX-β is a prototype
  - Under construction, aiming for installation during Run 3 (ongoing)
  - TDR forthcoming
  - Demonstrate feasibility, gain expertise
  - Validate background estimates
  - Maybe probe new physics!





Call for Collaborators

https://gitlab.cern.ch/groups/codex-b/-/wikis/Collaboration-photo

Growing collaboration—
come join us!

https://gitlab.cern.ch/groups/codex-b/-/wikis/Logos-of-participating-institutions

Proposal: arXiv:1708.09395

Expression of Interest: arXiv:1911.00481

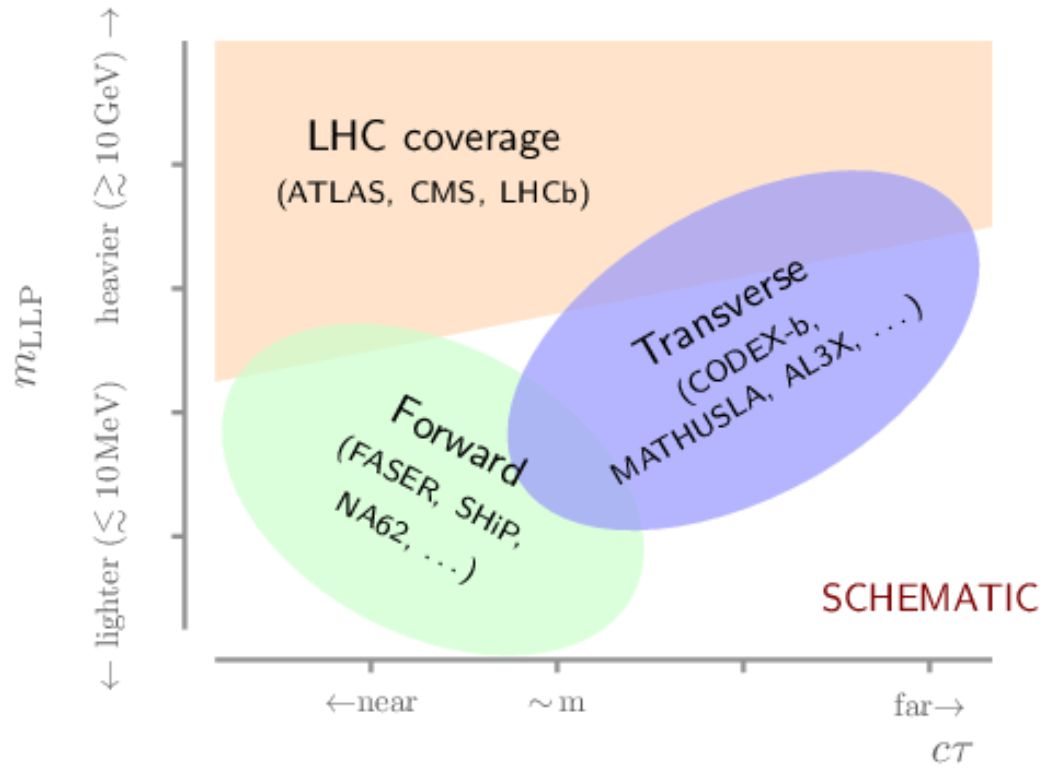
Snowmass whitepaper: arXiv:2203.07316

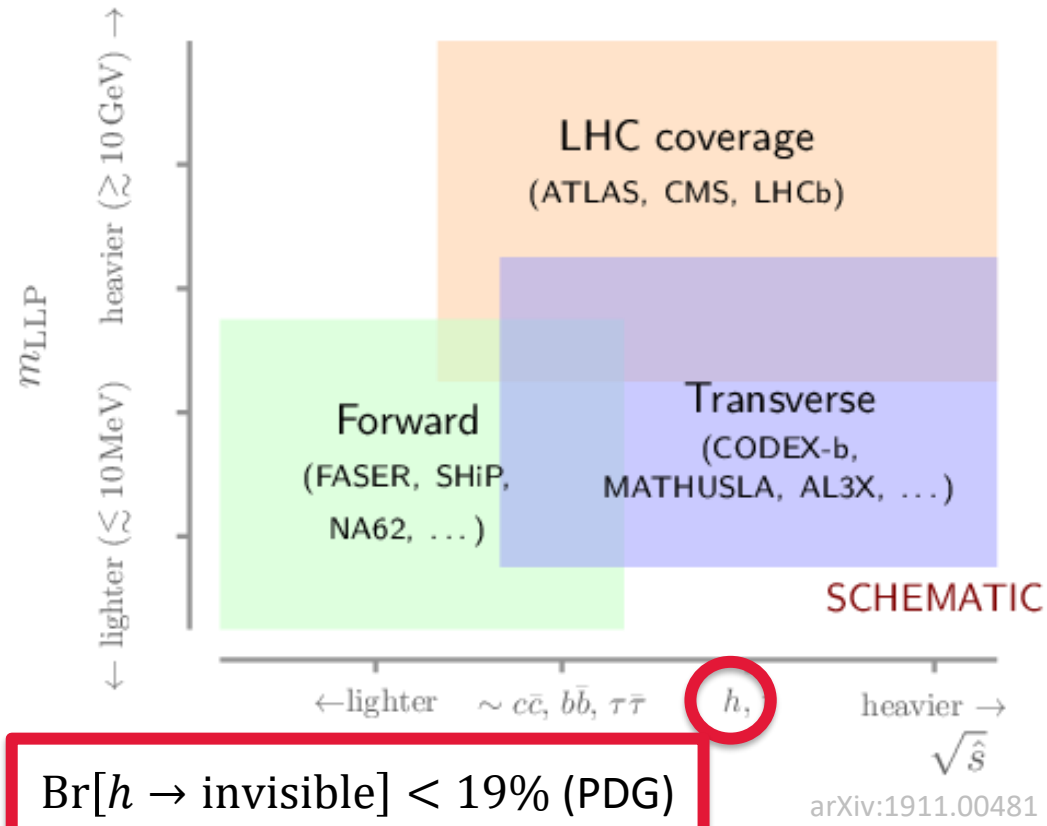
CODEX-β TDR: arXiv:nnnn.nnnnn (forthcoming)

FIN

BACKUP

LLP Detector Landscape

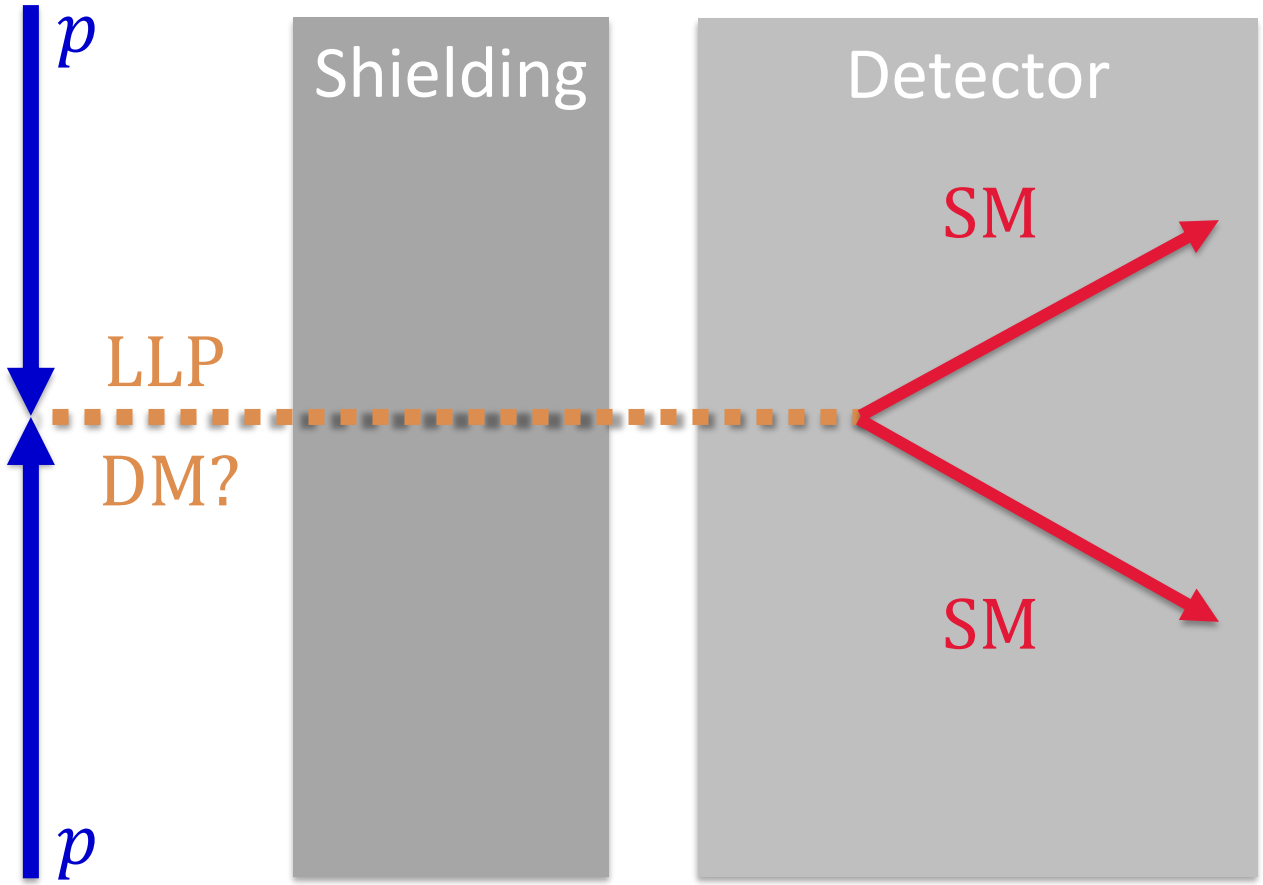


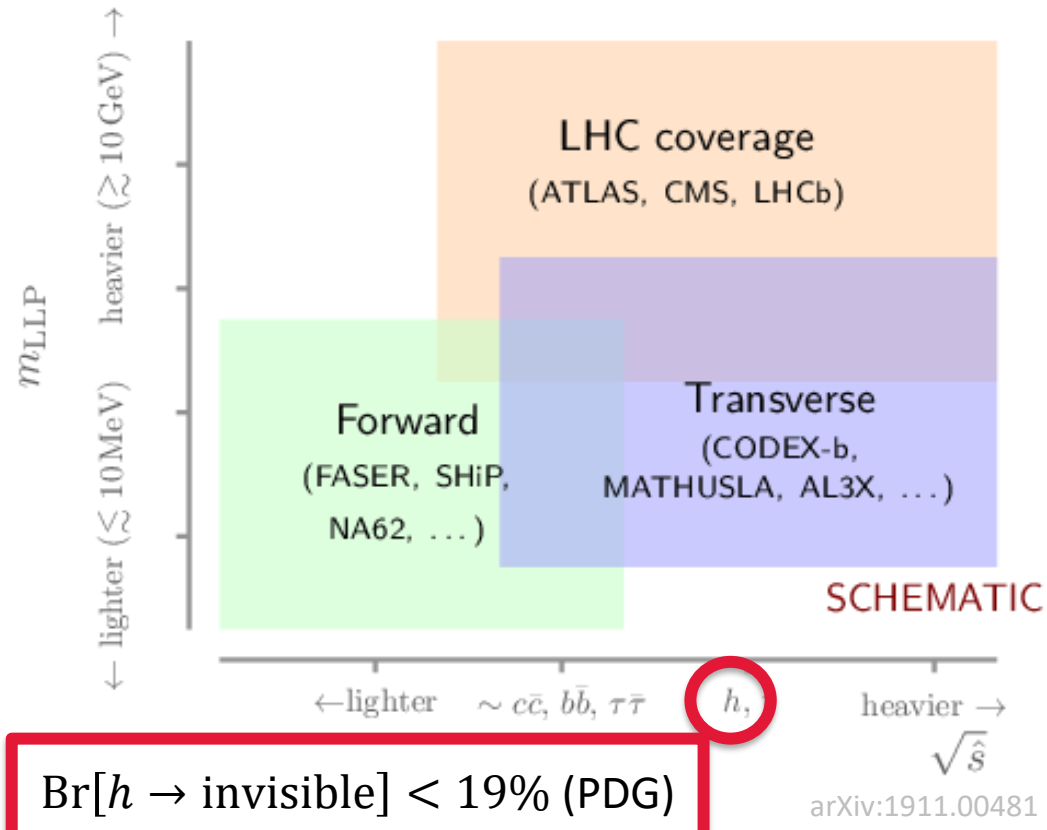


arXiv:1911.00481

$\mathrm{Br}[h \to \text{invisible}] < 19\%$ (PDG)
Tantalizing area for new physics!
Only produced at LHC

Proposed detector scheme





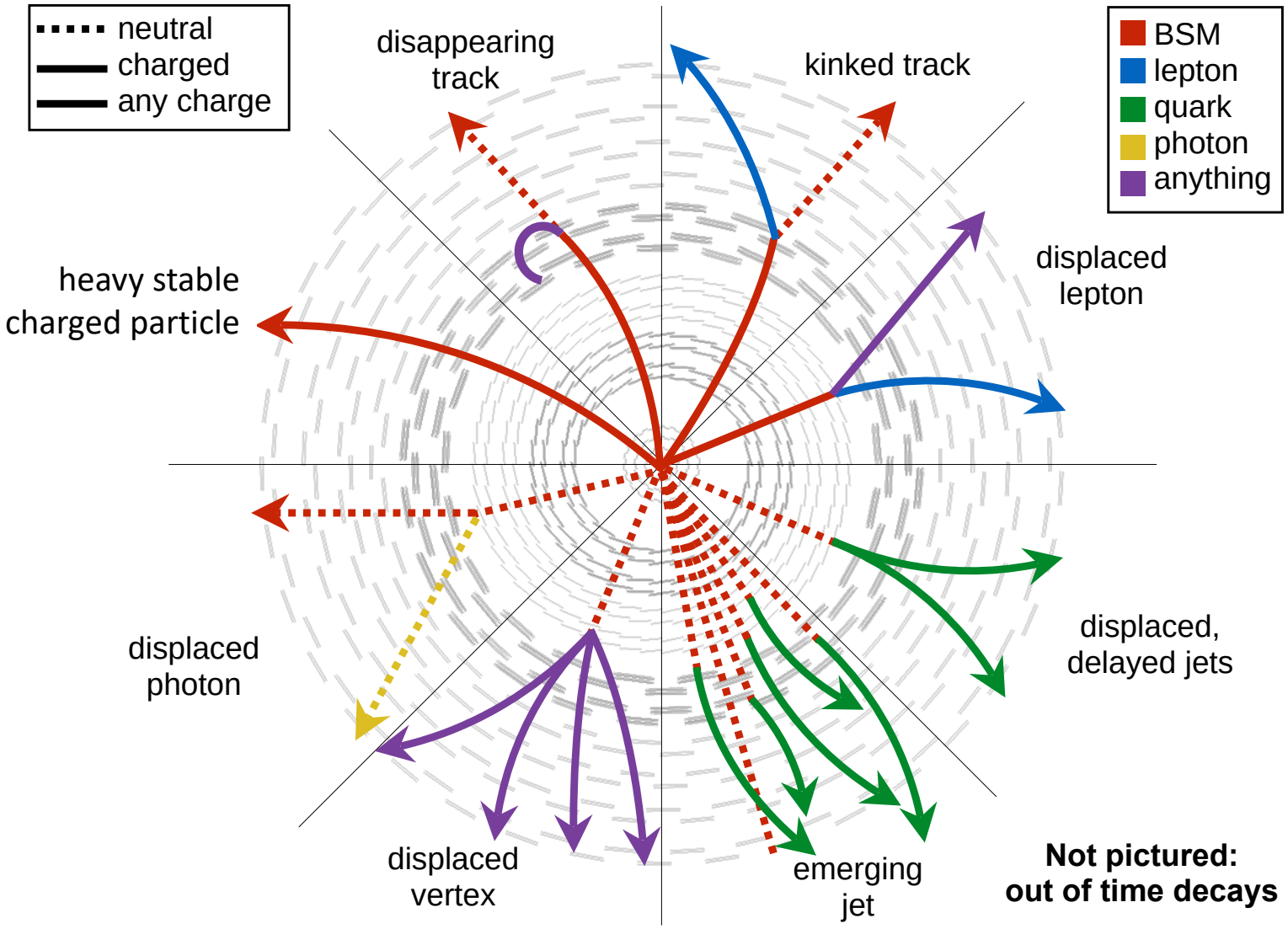
Higgs boson produced in pp collision could couple to DM particle, which could then decay to SM particles

$\mathrm{Br}[h \to \text{invisible}] < 19\%$ (PDG)
Tantalizing area for new physics!
Only produced at LHC

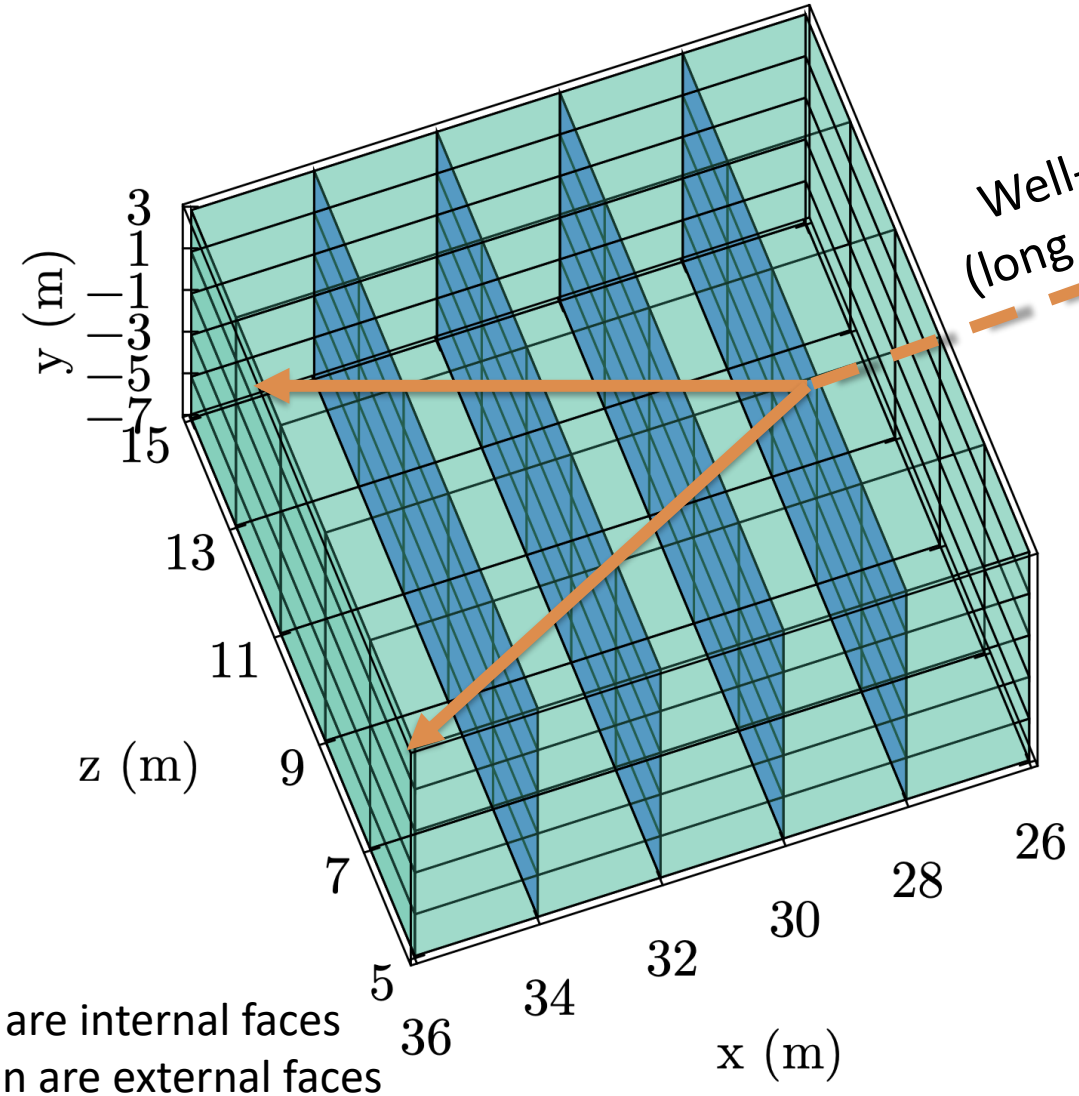
Signatures of Beyond SM LLPs

There are many potential characteristic signatures of Beyond SM (BSM) LLPs at LHC experiments

They are often difficult/impossible to distinguish from SM backgrounds in the detector



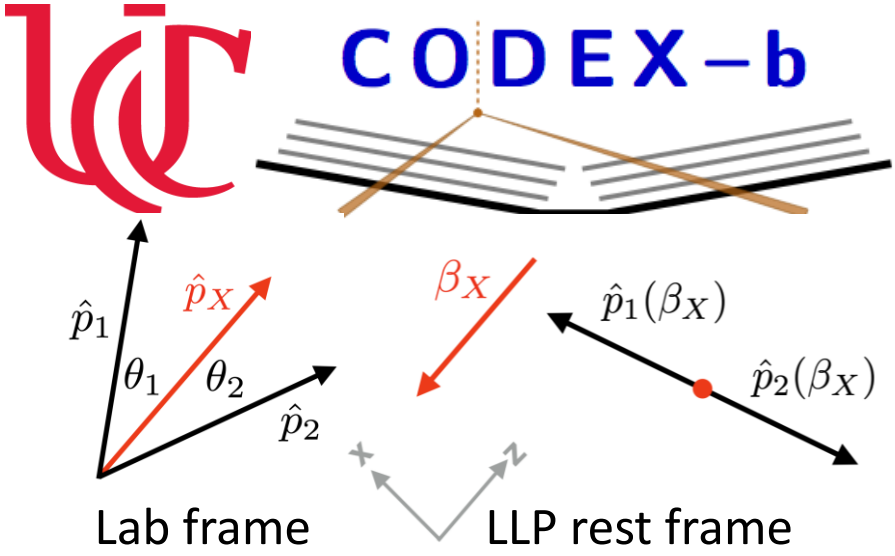
Mass from geometry



Well-known vector
(long distance to PV)

Search for 2 charged SM tracks originating in detector volume

Blue are internal faces
Green are external faces



$$p_i = E_i(1, \pm\beta_i \sin\theta_i, 0, \beta_i \cos\theta_i)$$

$$E_1\beta_1 \sin\theta_1 = E_2\beta_2 \sin\theta_2$$

$$\beta_X = \frac{\beta_1\beta_2 \sin(\theta_1 + \theta_2)}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2}$$

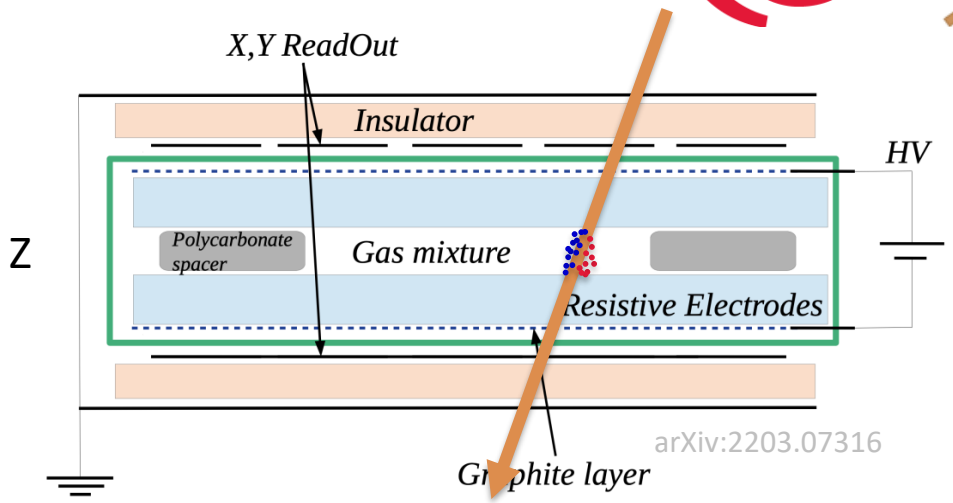
β_i from RPC timing information
(or from assuming $\beta_i = 1$)

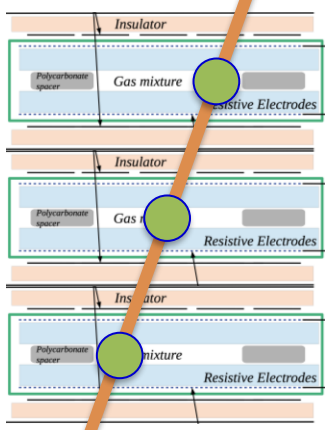
arXiv:2203.07316

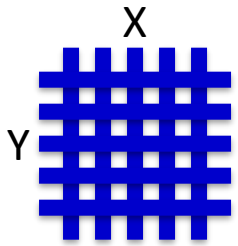
arXiv:1705.06327

Resistive Plate Chambers: BIS-7

- Developed by ATLAS for High Luminosity Large Hadron Collider (HL-LHC) upgrade
- Thoroughly tested, inexpensive
- $\mathcal{O}(1\ \mathrm{mm})$ spatial resolution
- $\mathcal{O}(100\ \mathrm{ps})$ timing resolution
- Module comprises three RPC singlets (triplet), service connections, and support structure







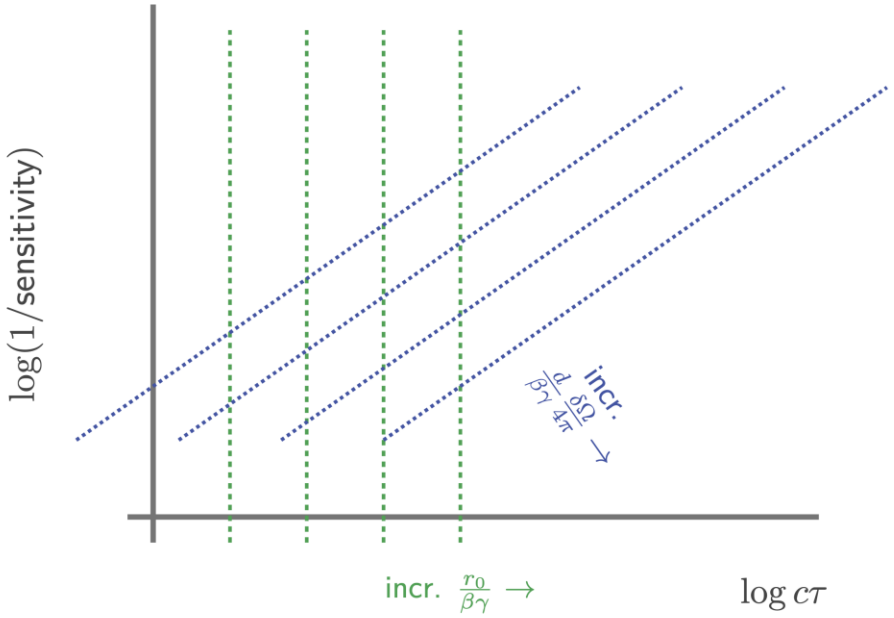
BIS-7 triplet

RPC 2020 talk by Y. Sun

Sensitivity scaling intuition 1

Sensitivity scaling intuition

- Long lifetime: contours of $d/\beta\gamma \times \delta\Omega/4\pi$, sensitivity scales as $1/c\tau$.

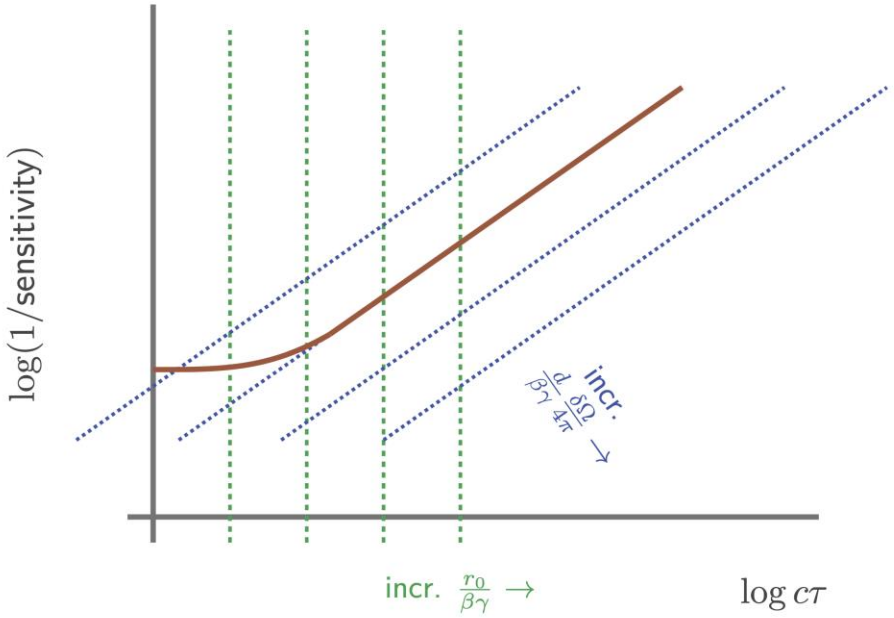


https://indi.to/xkRTz

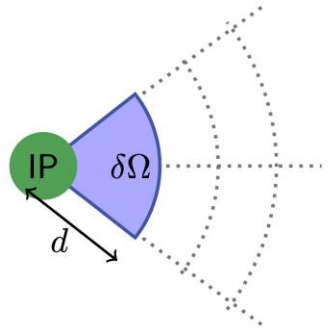
Sensitivity scaling intuition 2

Sensitivity scaling intuition

- Long lifetime: contours of $d/\beta\gamma \times \delta\Omega/4\pi$, sensitivity scales as $1/c\tau$.



Case 1: Wedge of constant $\delta\Omega$ from IP to depth d.



- Max sensitivity set by $\delta\Omega/(4\pi)$ acceptance
- Flattens out at $r/\beta\gamma \sim 1/c\tau$

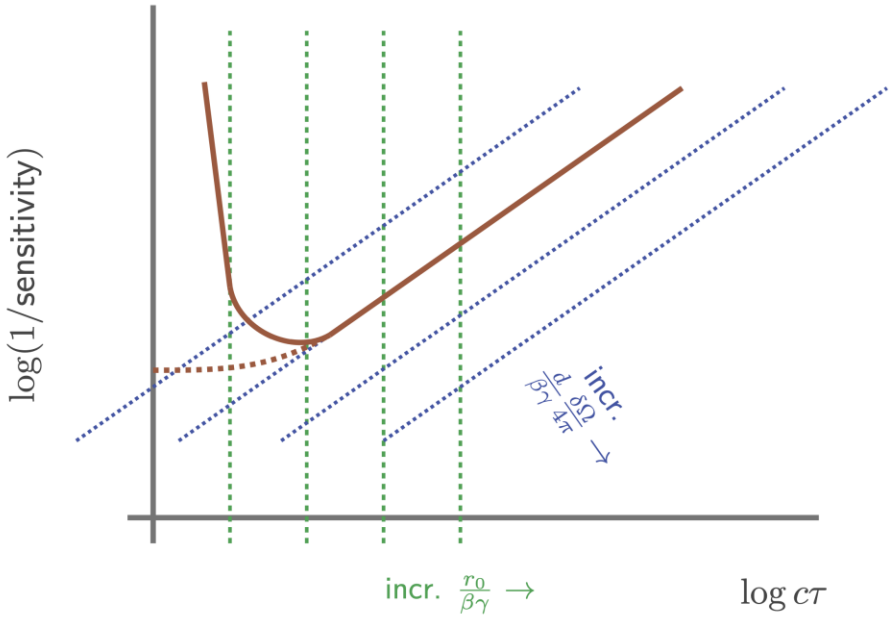
Dean Robinson drobinson@lbl.gov | CODEX-b/β | 6 | 30

https://indi.to/xkRTz

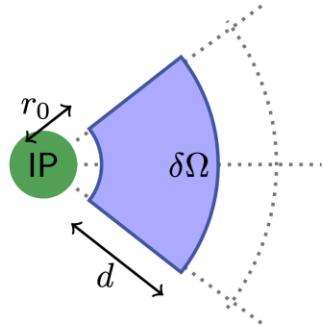
Sensitivity scaling intuition 3

Sensitivity scaling intuition

- Short lifetime: contours of $r_0/\beta\gamma$, characteristic suppression of sensitivity for $r_0/\beta\gamma \sim 1/c\tau$.



Case 2: Wedge of constant $\delta\Omega$ and depth d, distance r_0

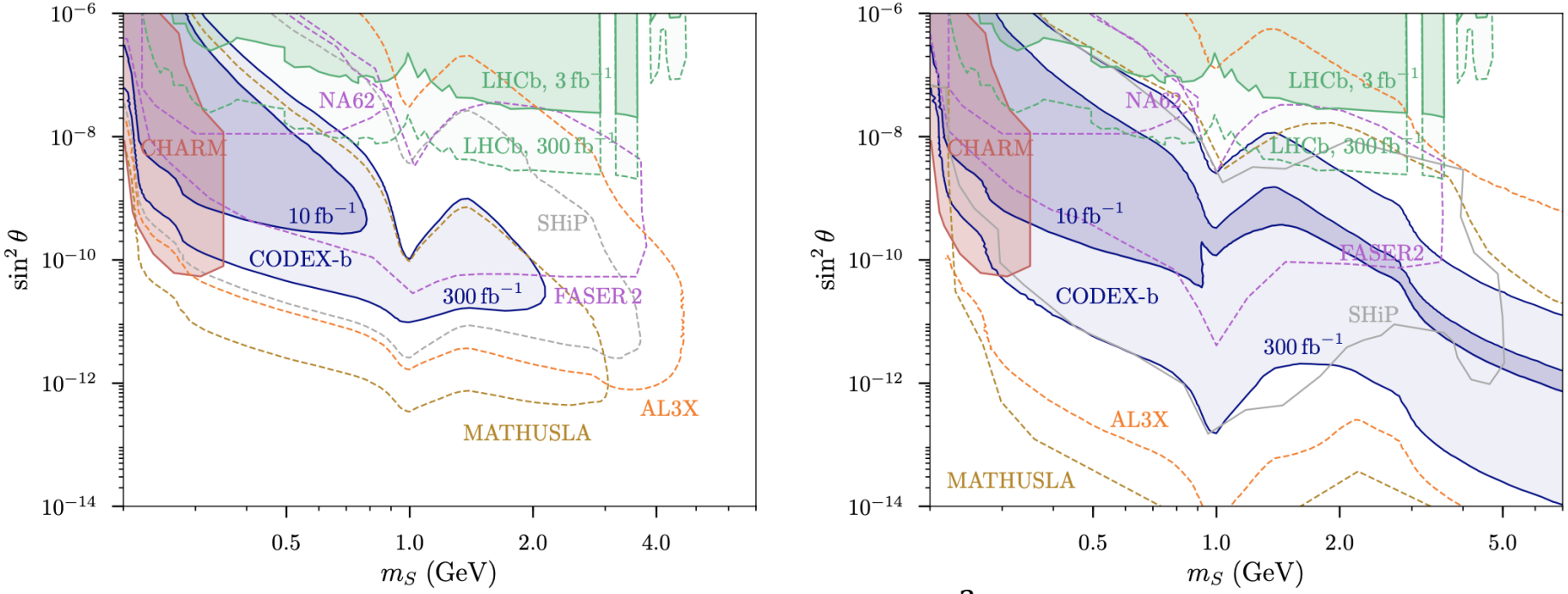


- Flattens out at $r/\beta\gamma \sim 1/c\tau$

https://indi.to/xkRTz

Scalar-Higgs Portal

- Most-minimal model: introduce single scalar S with mass m_S
- Mixing angle θ with SM Higgs, suppressed as $\sin\theta$
- $\lambda =$ quartic coupling $(\frac{\lambda}{2} S^2 H^\dagger H)$



(a) $\lambda = 0$

Reach for measuring $\sin^2\theta$, estimated from simulation

(b) $\lambda = 1.6 \times 10^{-3}$

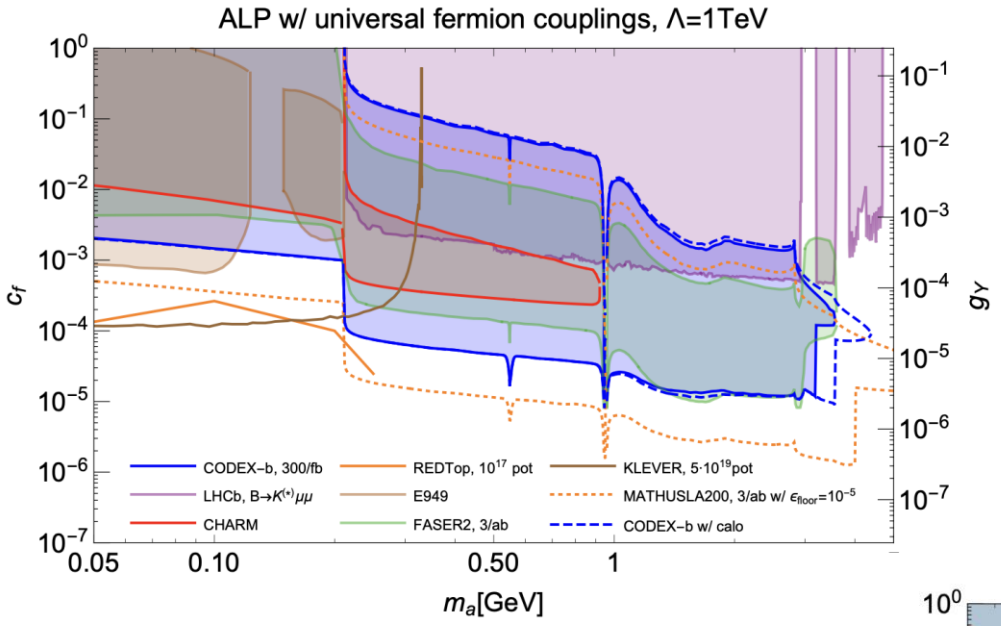
arXiv:1911.00481

Most conservative scenario

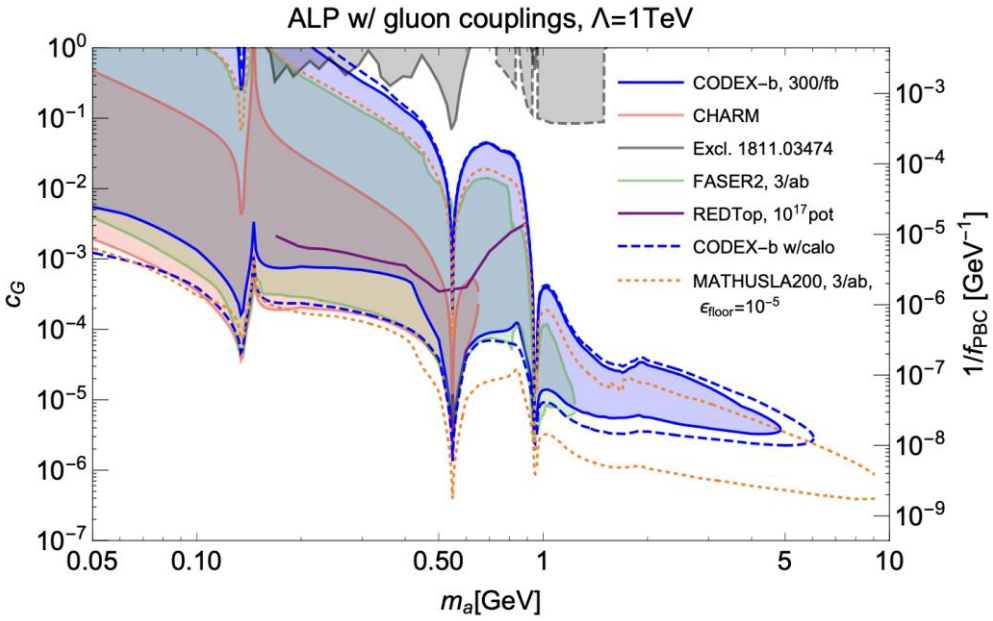
Most optimistic scenario
$\Rightarrow \mathrm{Br}[h \to SS] = 0.01$

Axion-Like Particles

- Pseudoscalars coupled to the SM through dimension-5 operators
- Potential couplings to quarks, gluons, leptons, and photons



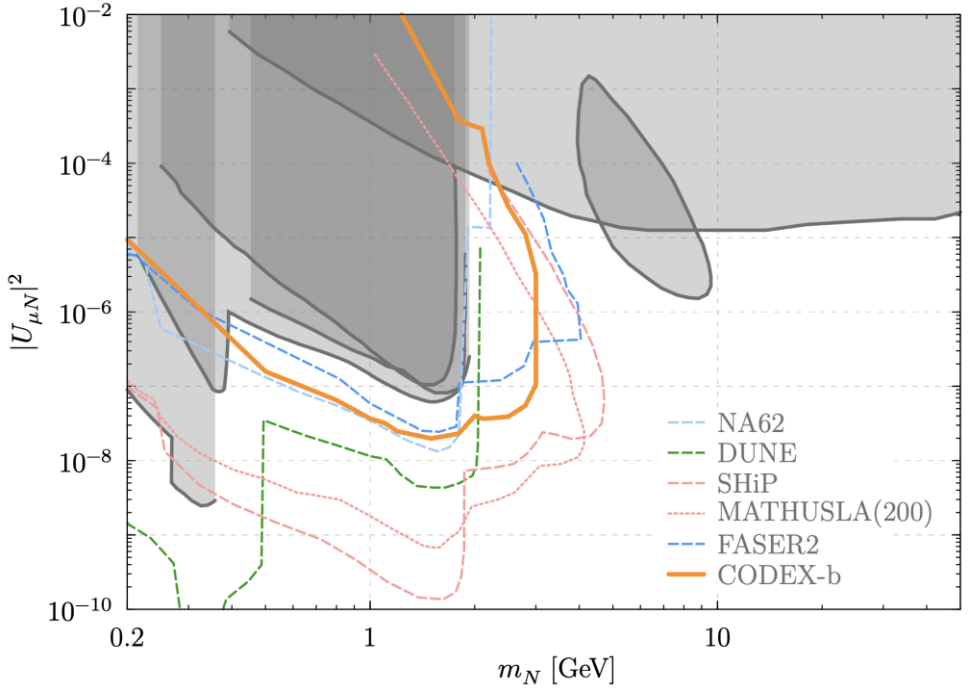
Reach for measuring couplings (left axis) and normalizations (right axis) as functions of ALP mass taken from simulation



arXiv:1911.00481

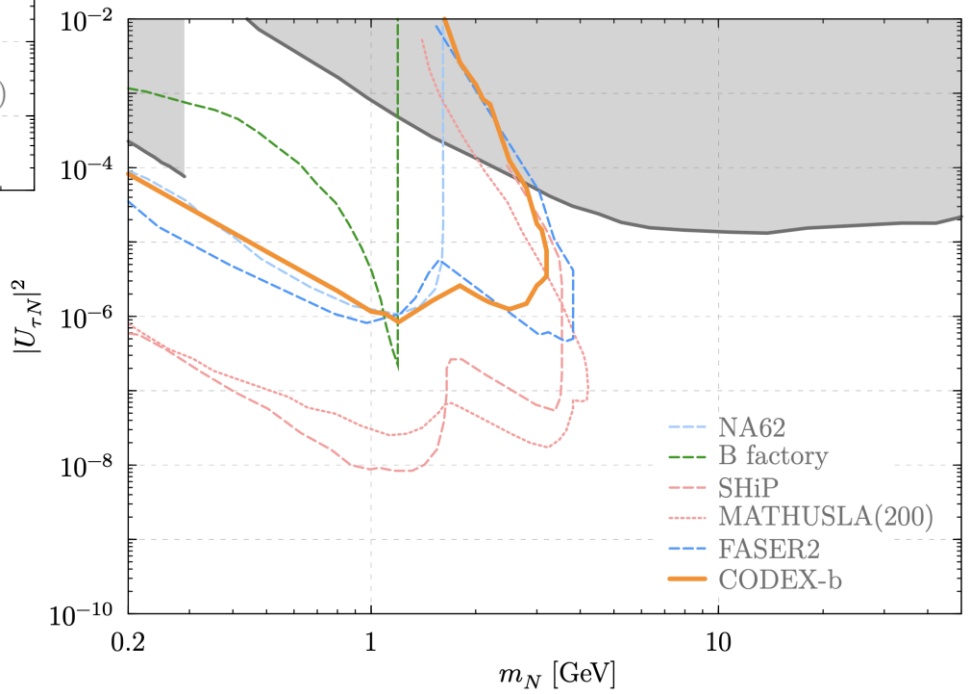
Heavy Neutral Leptons

- Feature in a range of Beyond Standard Model (BSM) scenarios
- Motivated by, e.g., neutrino masses, DM, or semileptonic anomalies



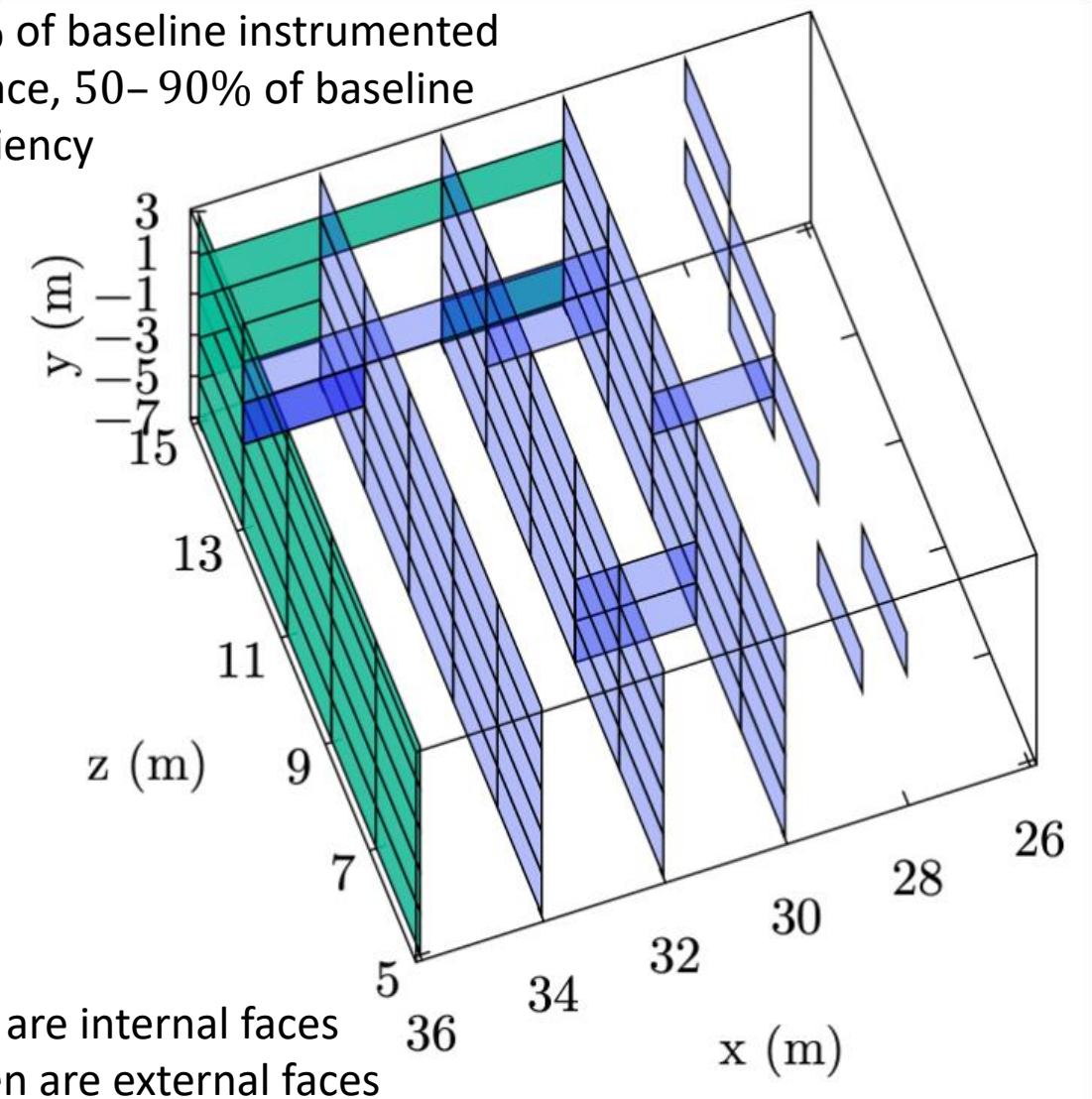
arXiv:1911.00481

Reach for measuring couplings between HNLs and leptons as functions of HNL mass taken from simulation



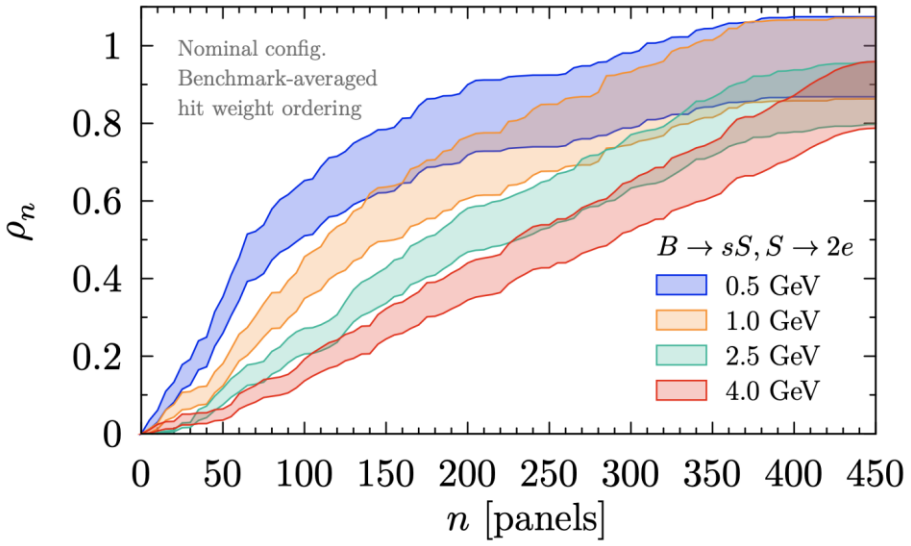
CODEX-b Optimized Configuration

43% of baseline instrumented surface, 50– 90% of baseline efficiency

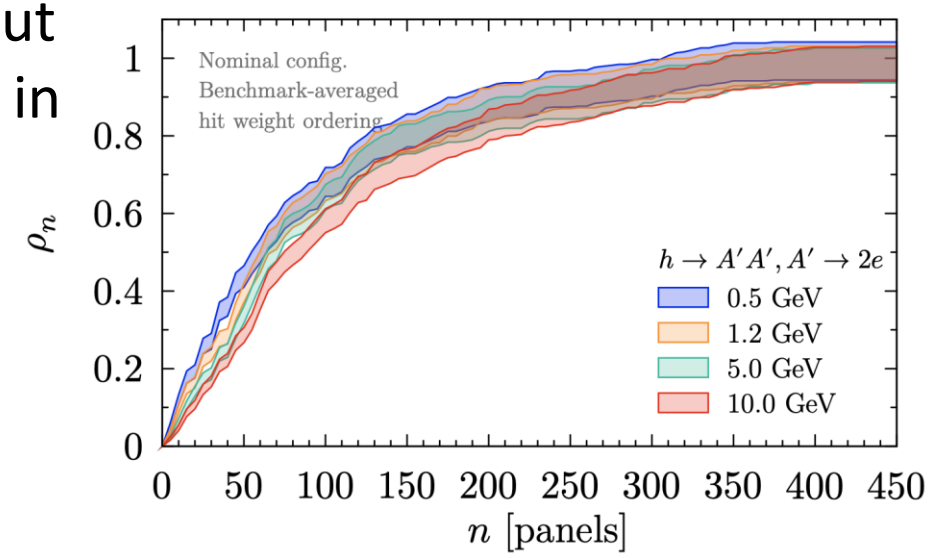


Blue are internal faces
Green are external faces

ρ_n = relative efficiency w.r.t. baseline
1σ CL bands



Large reduction in panels without large reduction in efficiency!



arXiv:2203.07316, arXiv:2211.08450

Background Simulation

- Simulated background, detector, and shielding using Pythia and Geant4
- Considered backgrounds from $\gamma, e^{\pm}, p^{\pm}, n^{\pm}, \pi^{\pm,0}, K^{\pm}, K^0_{S,L}, \mu^{\pm}, \nu$
- All found to result in $< \mathcal{O}(1)$ signal-like yield in the detector volume (after shielding) with $\mathcal{L} = 300\ \mathrm{fb}^{-1}$
- Simulation of machine-induced background ongoing

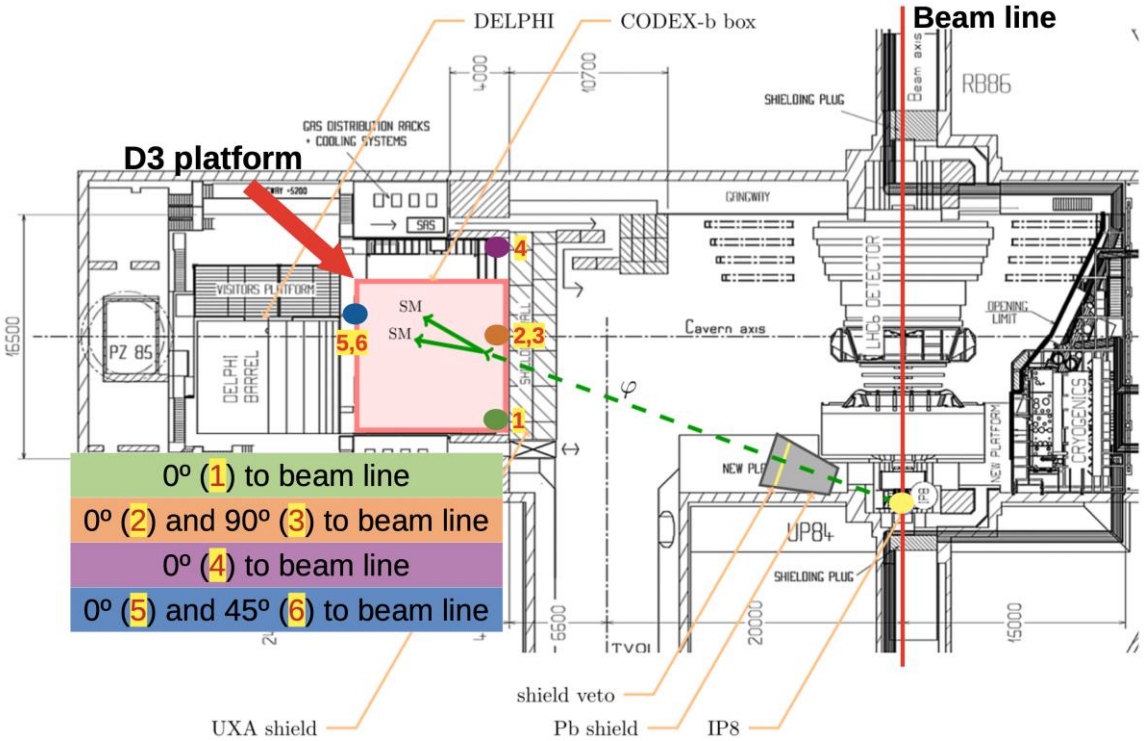
BG species	Particle yields: Net ($E_{\mathrm{kin}}^{\mathrm{neutral}} > 0.4\,\mathrm{GeV}$)	Particle yields: Shield veto rejection (total)	Particle yields: Shield veto rejection (±/0 correlation)	Net yield
γ	0.54 ± 0.12	$(8.06 \pm 0.60) \times 10^4$	$(2.62 \pm 1.03) \times 10^3$	–
n	58.10 ± 4.63	$(4.59 \pm 0.15) \times 10^5$	$(3.44 \pm 0.51) \times 10^4$	–
n ($> 0.8\,\mathrm{GeV}$)	2.78 ± 0.25	$(1.03 \pm 0.06) \times 10^5$	$(7.45 \pm 1.92) \times 10^3$	$\lesssim 1$
$\bar{n}$ (no cut)	$(3.24 \pm 0.72) \times 10^{-3}$	34.40 ± 25.80	$(7.12 \pm 2.19) \times 10^{-2}$	$\ll 1$
K_L^0	0.49 ± 0.05	$(1.94 \pm 0.74) \times 10^3$	54.40 ± 19.20	$\lesssim 0.1$
K_S^0	$(6.33 \pm 1.39) \times 10^{-3}$	93.90 ± 45.80	0.74 ± 0.19	$\ll 1$
$\nu + \bar{\nu}$	$(5.69 \pm 0.00) \times 10^{13}$	$(7.35 \pm 0.12) \times 10^6$	$(7.31 \pm 0.11) \times 10^6$	–
$p^{\pm}$	$(2.07 \pm 0.26) \times 10^2$	$(9.24 \pm 0.36) \times 10^5$	$(9.24 \pm 0.36) \times 10^5$	–
$e^{\pm}$	$(4.53 \pm 0.02) \times 10^3$	$(4.38 \pm 0.02) \times 10^7$	$(4.38 \pm 0.02) \times 10^7$	–
π^+	34.70 ± 2.27	$(2.96 \pm 0.20) \times 10^5$	$(2.96 \pm 0.20) \times 10^5$	–
π^-	31.40 ± 2.12	$(2.68 \pm 0.19) \times 10^5$	$(2.68 \pm 0.19) \times 10^5$	–
K^+	0.83 ± 0.30	$(3.08 \pm 1.24) \times 10^3$	$(3.08 \pm 1.24) \times 10^3$	–
K^-	0.23 ± 0.12	$(1.12 \pm 0.63) \times 10^3$	$(1.12 \pm 0.63) \times 10^3$	–
μ^+	$(1.04 \pm 0.00) \times 10^6$	$(1.04 \pm 0.00) \times 10^{10}$	$(1.04 \pm 0.00) \times 10^{10}$	–
μ^-	$(8.07 \pm 0.01) \times 10^5$	$(8.07 \pm 0.01) \times 10^9$	$(8.07 \pm 0.01) \times 10^9$	–

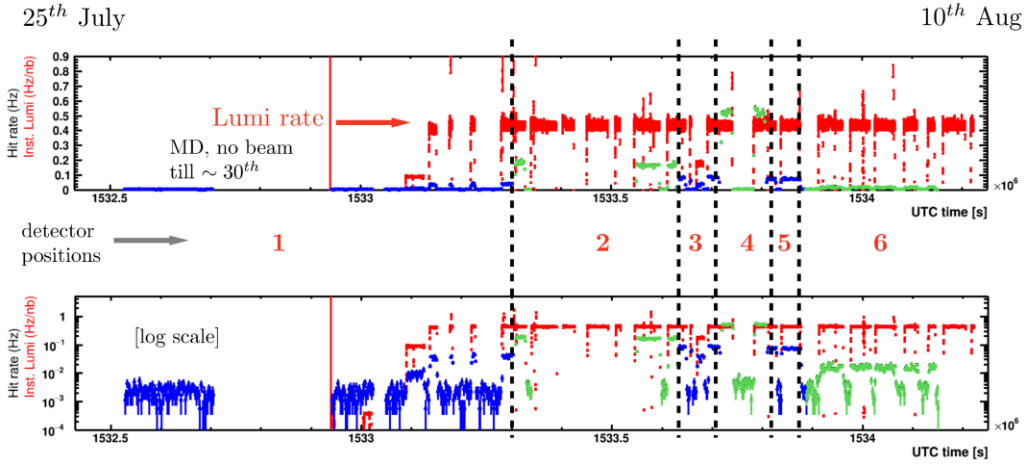
arXiv:1911.00481

Initial background validation

- Measured hit rates in LHCb cavern behind concrete shield wall
- Used existing scintillators
- Background rates less than predicted

  At point 2:
  - ≈ 5 Hz predicted
  - ≈ 0.2 Hz measured
- CERN rad. group will also test during Run 3—thermal neutrons [1]





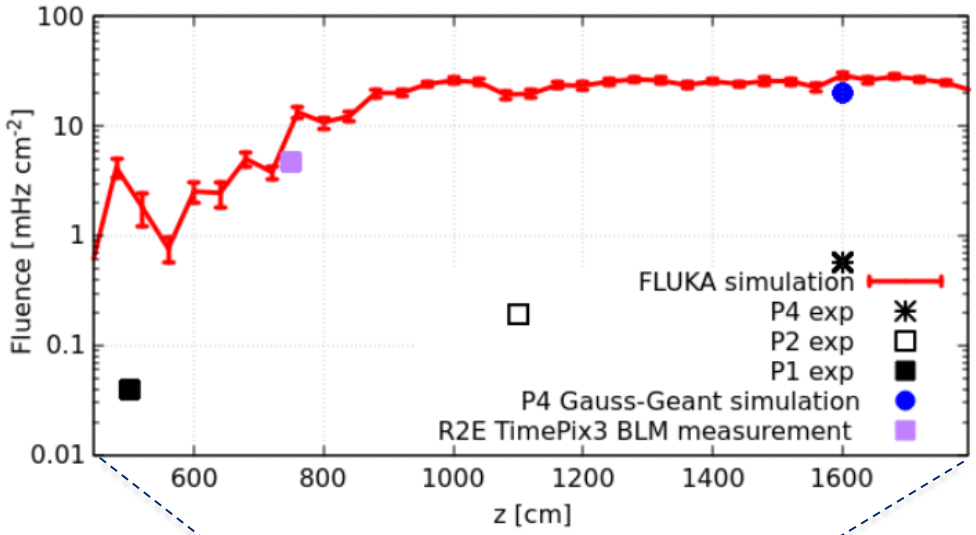
arXiv:1912.03846

1. The Road Ahead for CODEX-b, arXiv:2203.07316.

Further background validation

- CERN radiation group tested in same location
- Radiation monitor
  - Total ionizing dose
  - Particle fluence (including thermal neutrons)
  - After 82 days, still no radiation above threshold—electronics safe
- Beam loss monitor
  - Acts as tracking detector
  - Count muon fluence
  - Validates simulation, disagrees with previous measurement–possibly trigger issue

Preliminary results—paper forthcoming
https://indico.cern.ch/event/1239064/contributions/5439527/



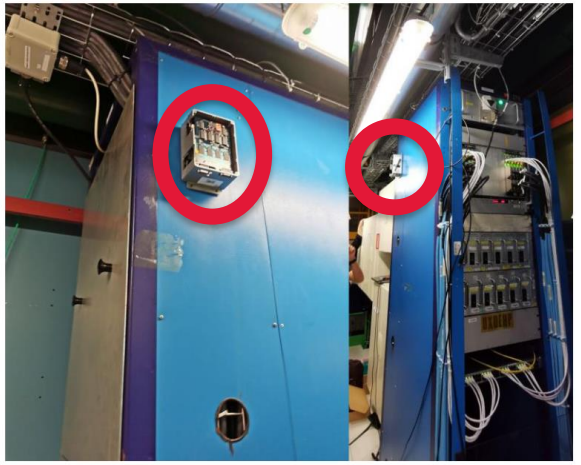
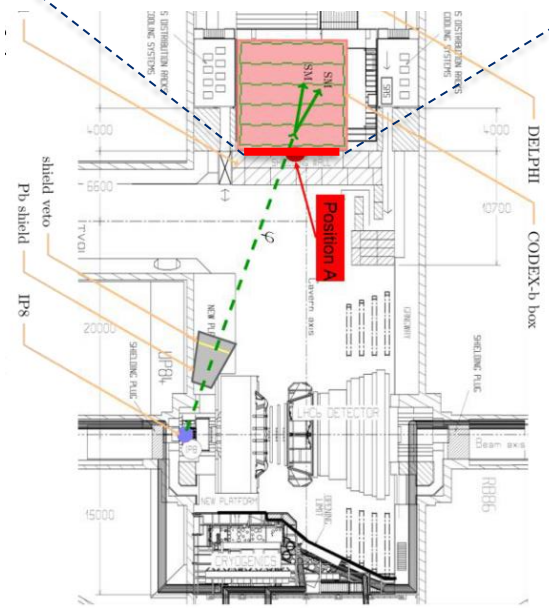
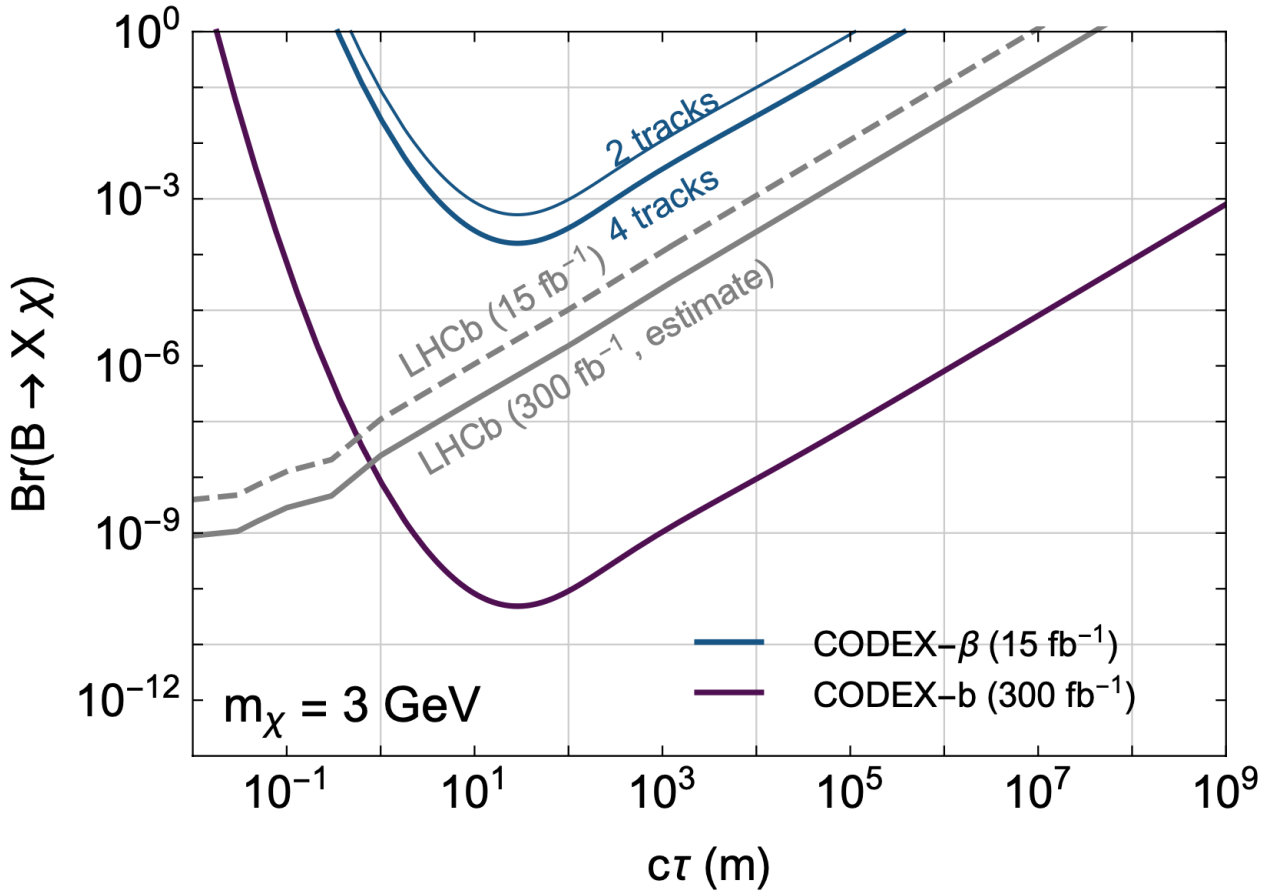


***Figure 3**: BatMons installed in the position of interest.*



CODEX-β Novel Physics

- CODEX-β may probe some Beyond Standard Model (BSM) scenarios
- Billions of b-hadrons will be produced at LHCb while CODEX-β is in place
- If a B meson decays to an LLP χ ($B \rightarrow X\ \chi$), CODEX-β will be sensitive to a multi-track SM decay, even with relatively high levels of background
- Could be the first to set limit; neat to have new physics reach for the prototype at all!



arXiv:1911.00481

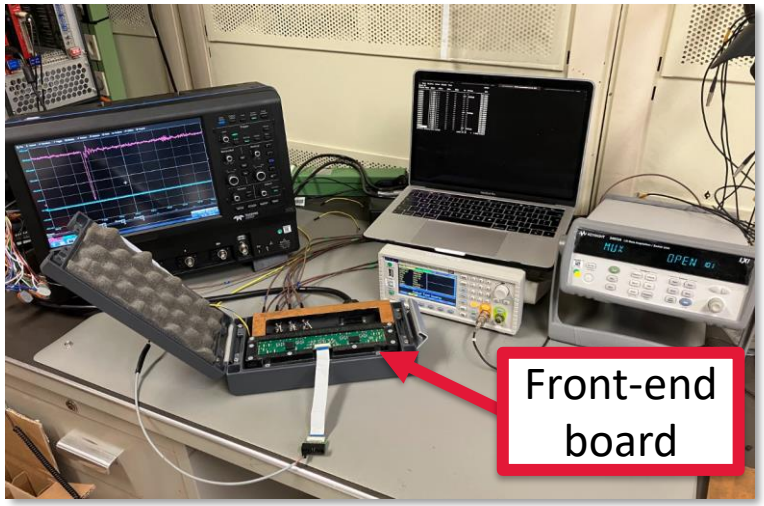
Shielding Optimization

- Baseline assumptions:
  - Angular distribution of particle scattering is not exploited
  - Detector response to neutral secondaries is 100%
  - Longer path lengths from non-zero angles of incidence on the shield wall are not included
  - The shield veto is a single layer and does not use tracking information
- Relaxing these assumptions may allow a more efficient veto and reduction in the size of the Pb shield [1]

1. The Road Ahead for CODEX-b, arXiv:2203.07316.

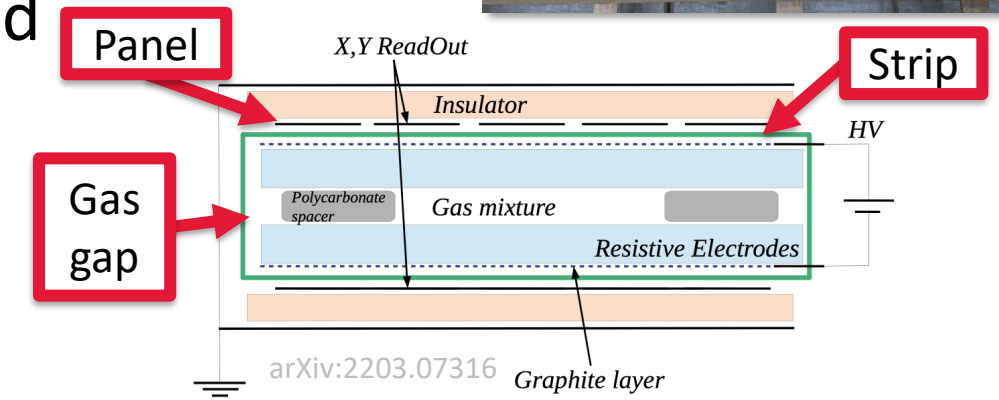
CODEX-β RPC and electronics QA

- RPC components and electronics commercially available
- Gas gaps, strip panels, and strips have all been procured
- Strip panels inspected
- Front-end boards procured and tested
- First triplet manufactured!

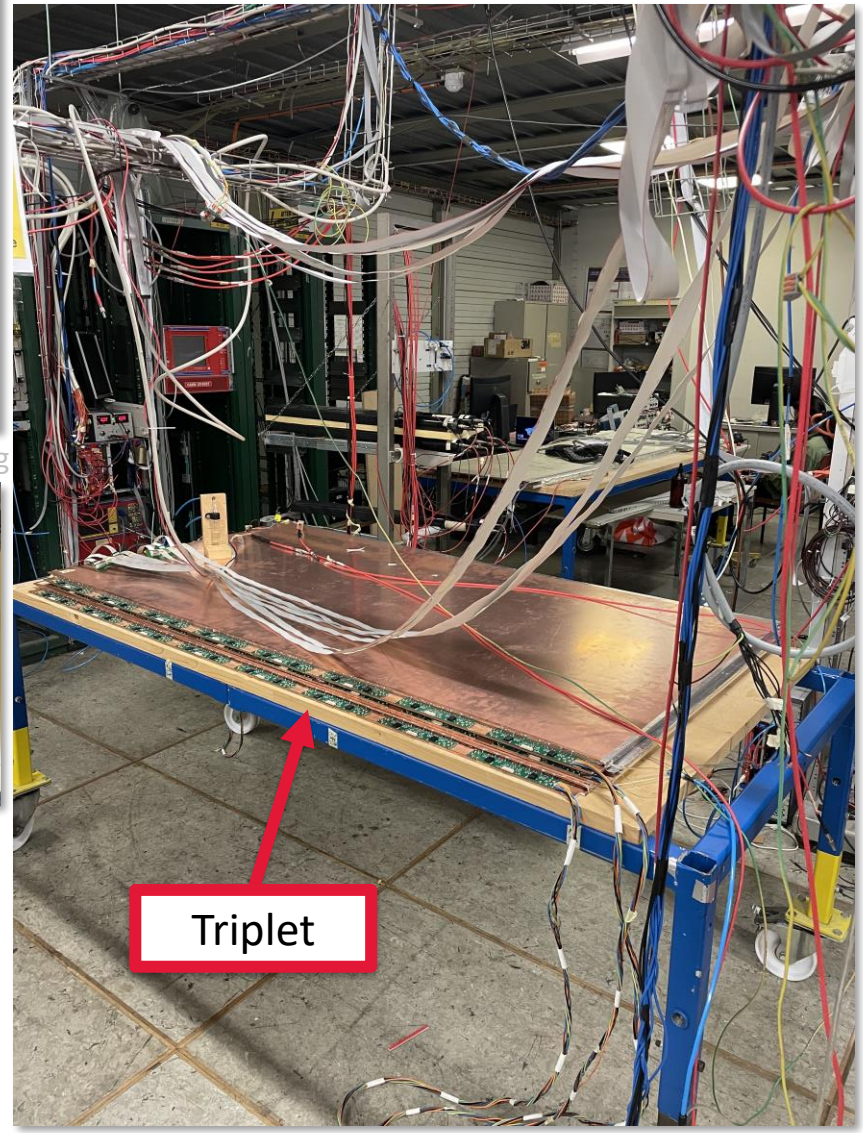


https://gitlab.cern.ch/groups/codex-b/-/wikis/readout-board-testing

https://gitlab.cern.ch/groups/codex-b/-/wikis/Assessment-of-damaged-panels

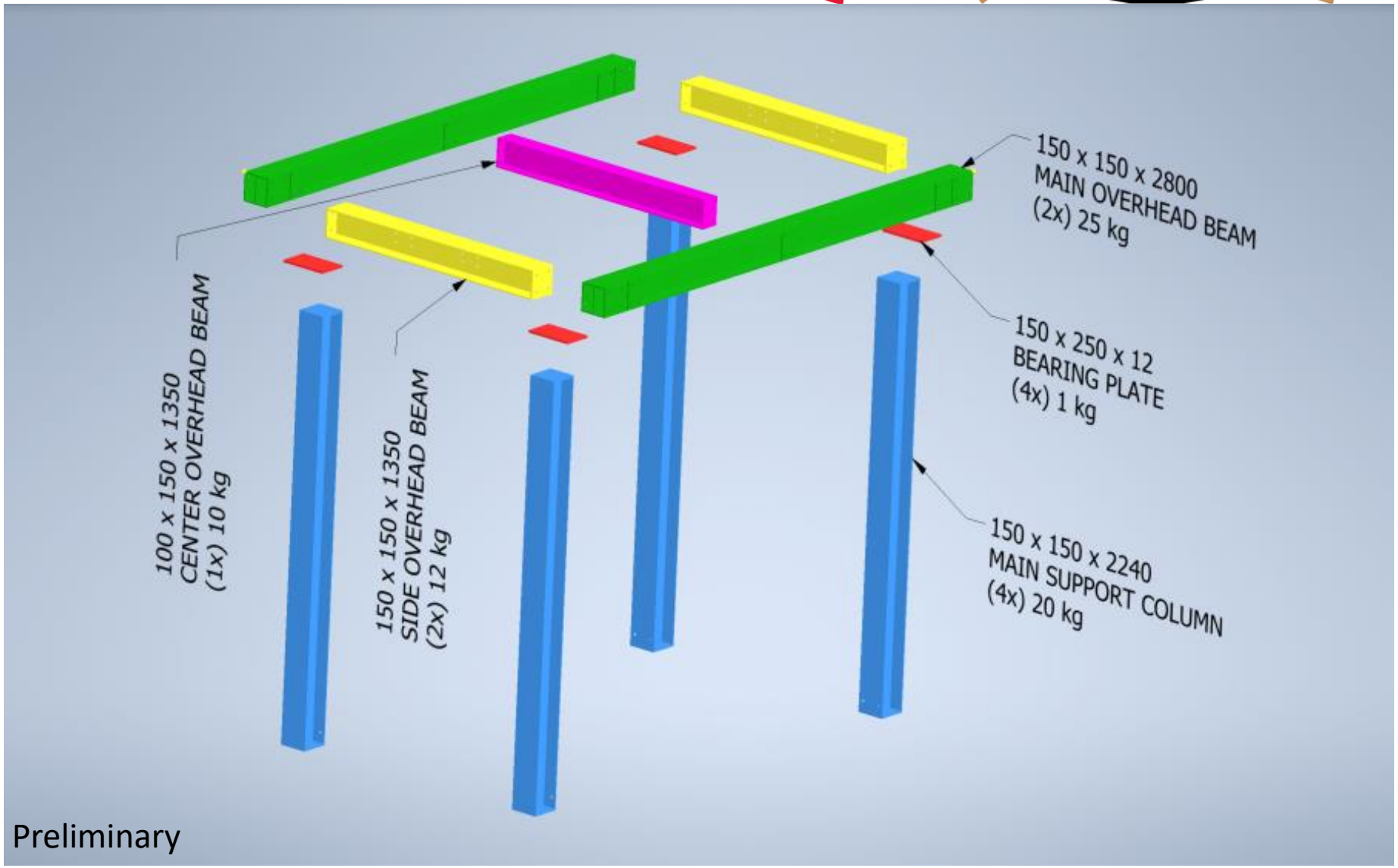


arXiv:2203.07316



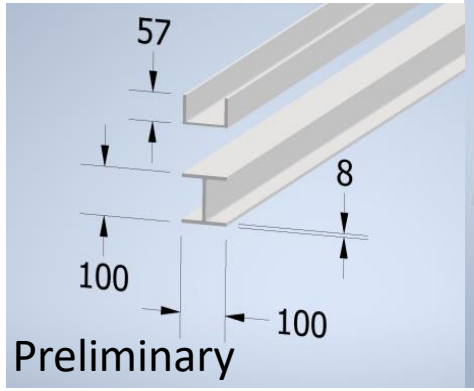
CODEX-β Support Structure Design 1

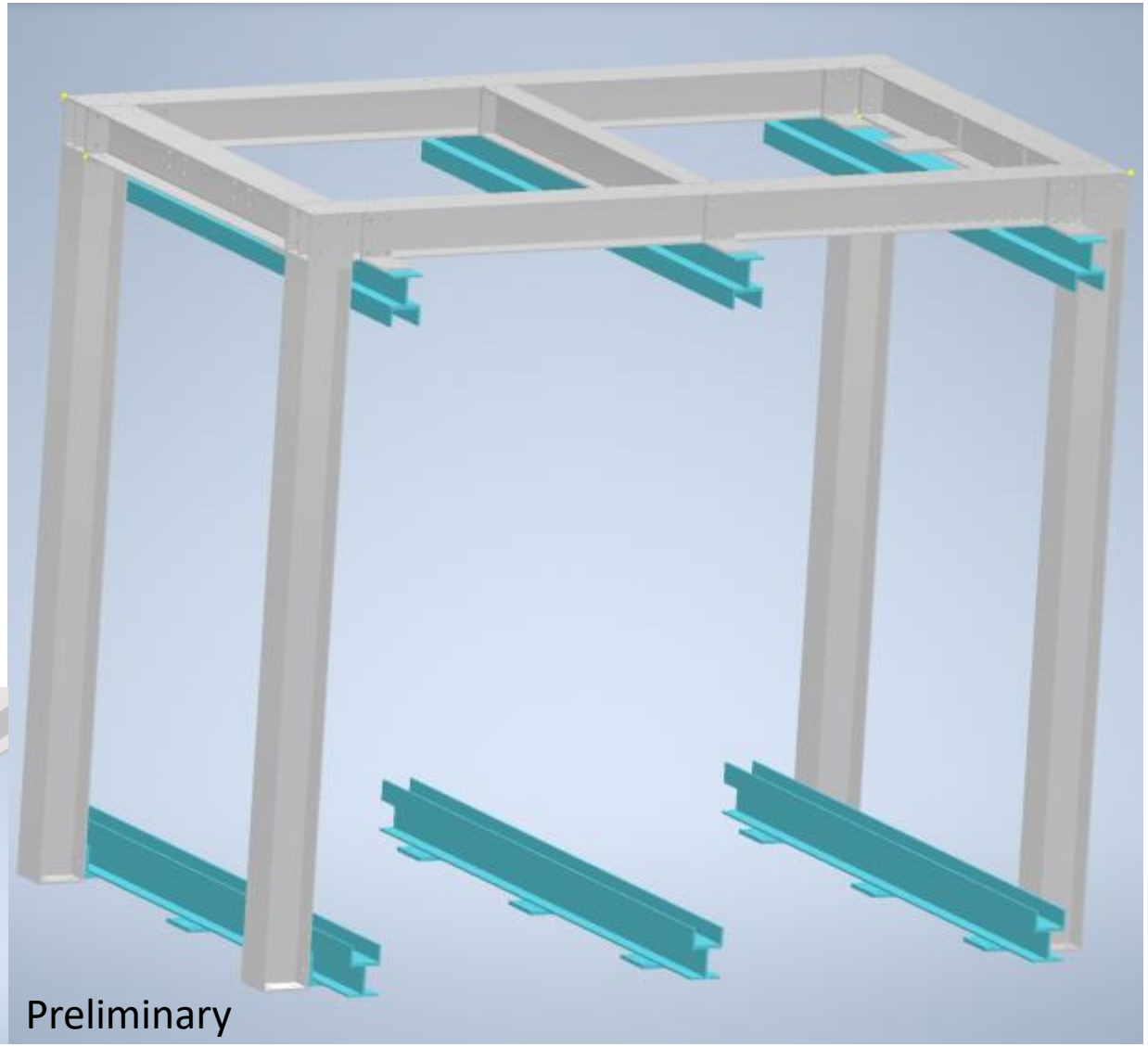
- Comprises Al I-beams
- Plates welded to ends or sides
- Exploded view shows primary structural supports



CODEX-β Support Structure Design 2

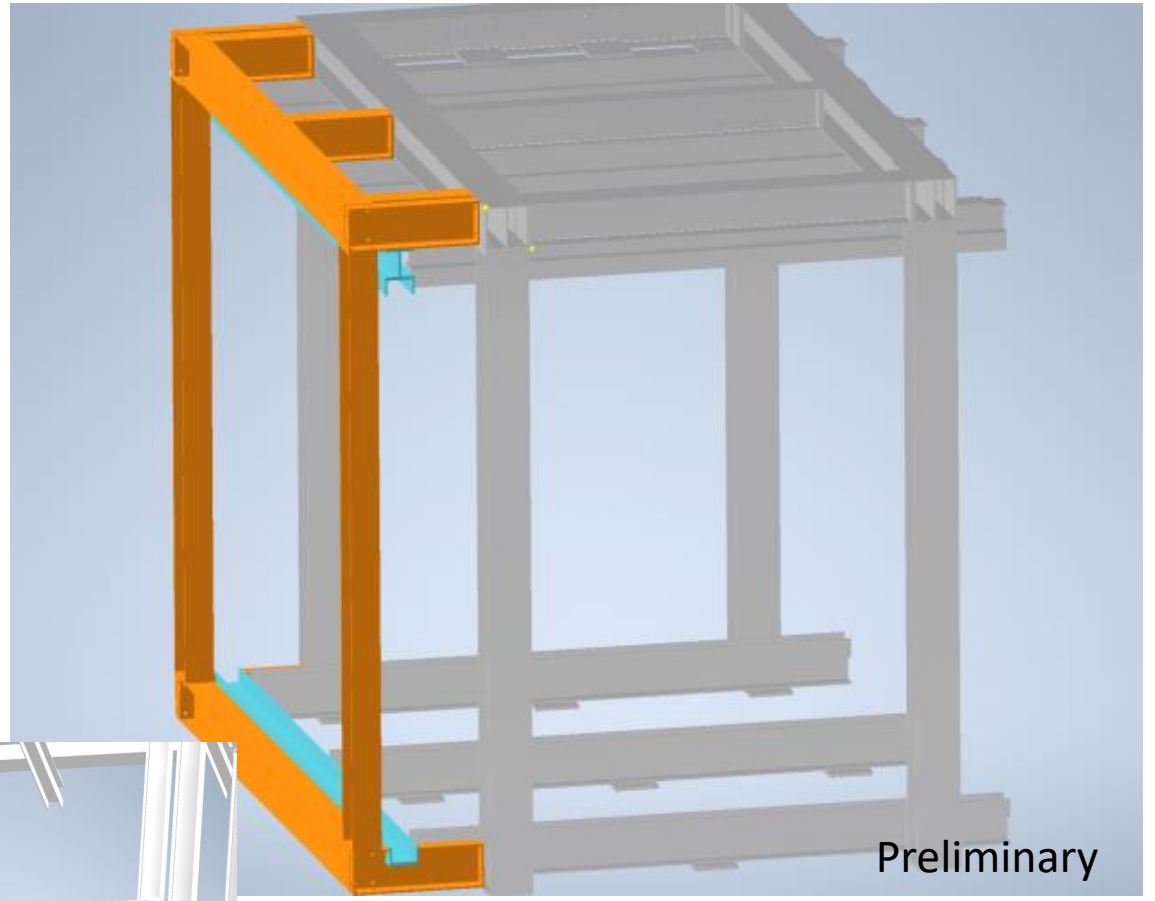
- Al channel and I-beam welded together to allow multi-plane assembly
- Channels do not bear any load

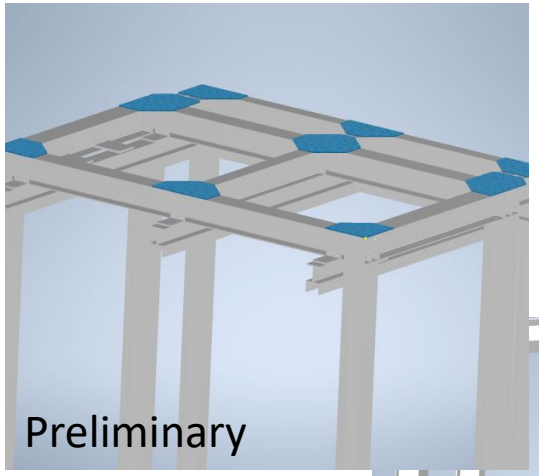


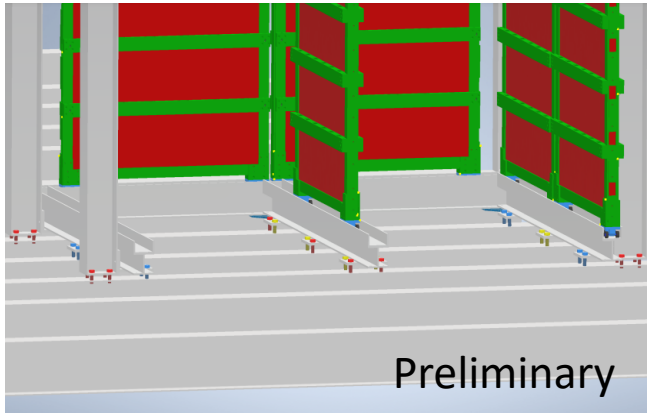


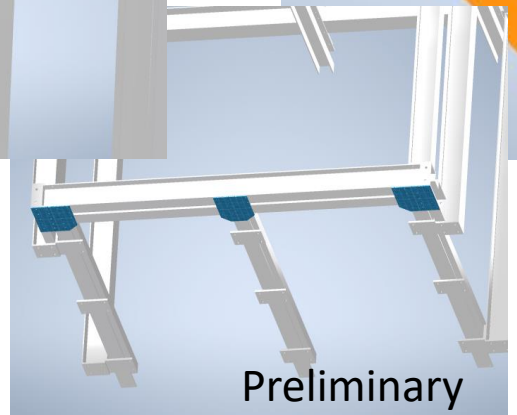
CODEX-β Support Structure Design 3

- Orange “porch” structure adds rigidity and supports one cube face
- Steel gusset plates add rigidity and help fix alignment
- Whole structure bolted to existing floor beams



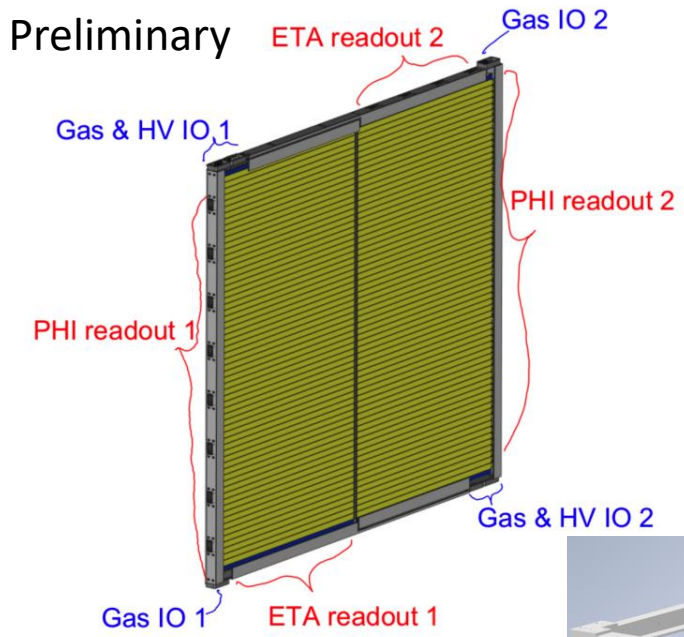


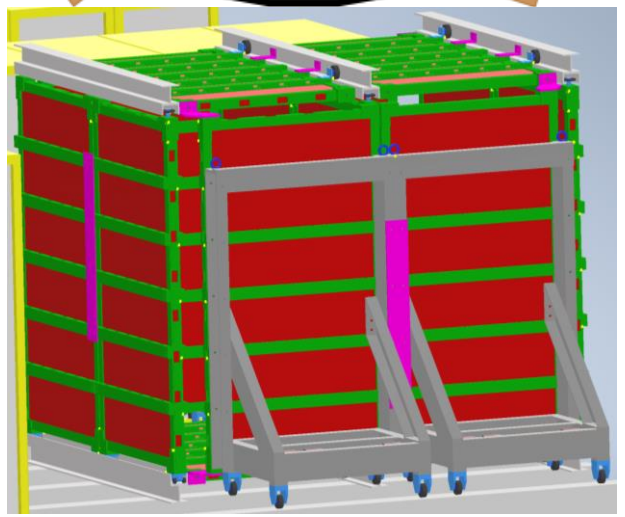




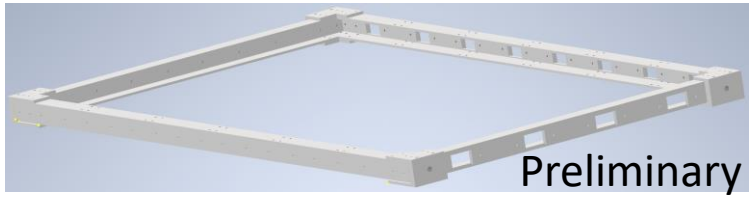
CODEX-β RPC Frame Design

- Holds RPC triplet
- Made of Al 6063 with stainless steel fasteners
- Similar design to BIS-7 triplet frame
  - Thicker Al and larger cross-supports
  - More pick-points for hoisting
  - Fewer space constraints
- Preliminary Finite Element Analysis (FEA) shows robust under load
- Services connected via four boxes (two on front and two on back)

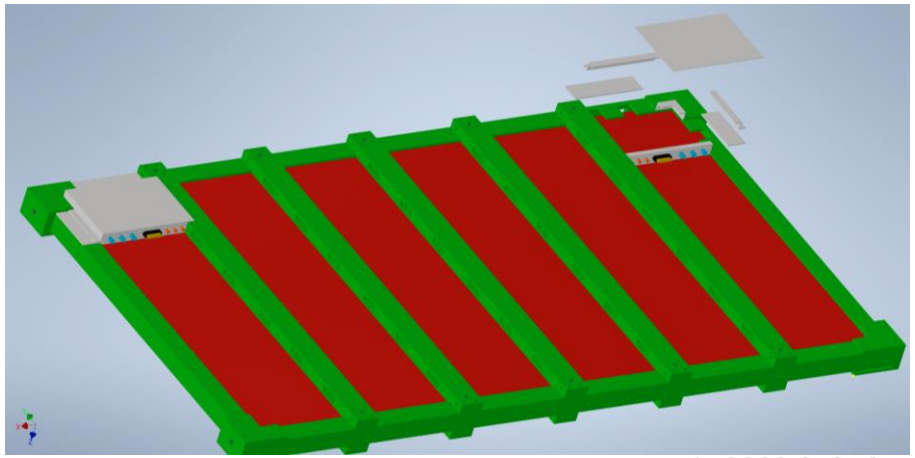




arXiv:2203.07316



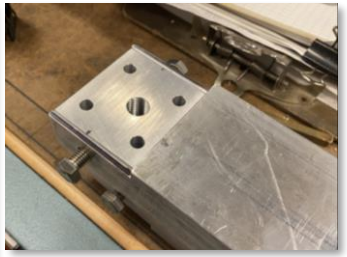
Preliminary

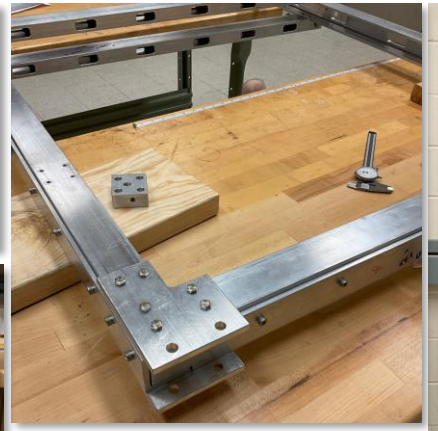


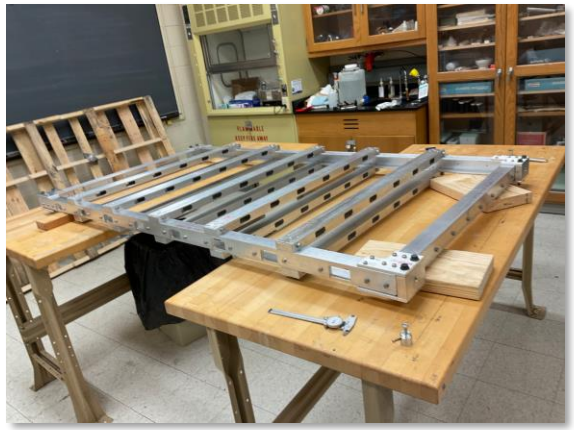
arXiv:2203.07316

CODEX-β RPC Frame Assembly







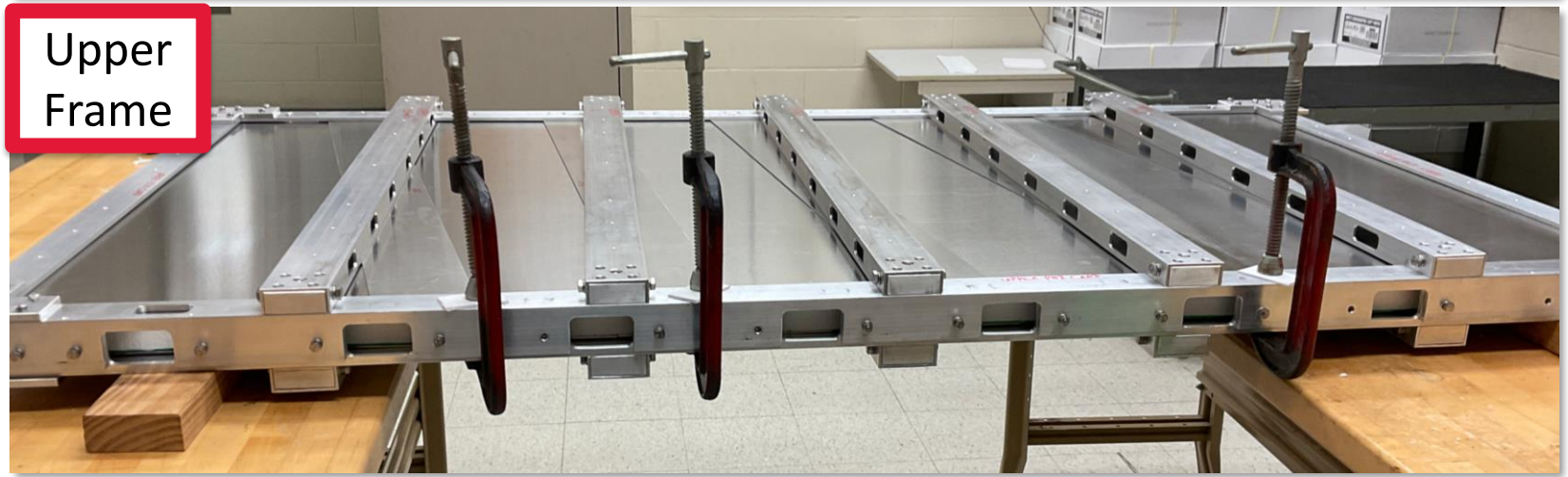




- 6063 Al extrusions machined at UC
- All screw assembly—no welding
- ≈ 3 hours for inexperienced team to assemble using written procedure
- High precision

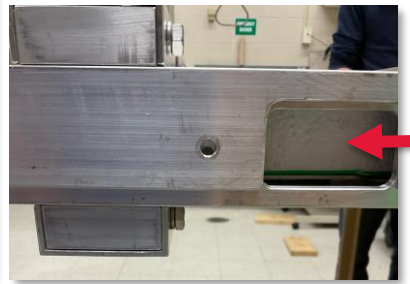
CODEX-β RPC Frame Suspension

- Two eye-hook pick-points on both short sides
- Additional points at each end of each crossbar
- Provide many options for manipulating frames
  - Flexibility for small installation space
  - Useful for mounting to carts (see later)

CODEX-β Mock RPC Insertion

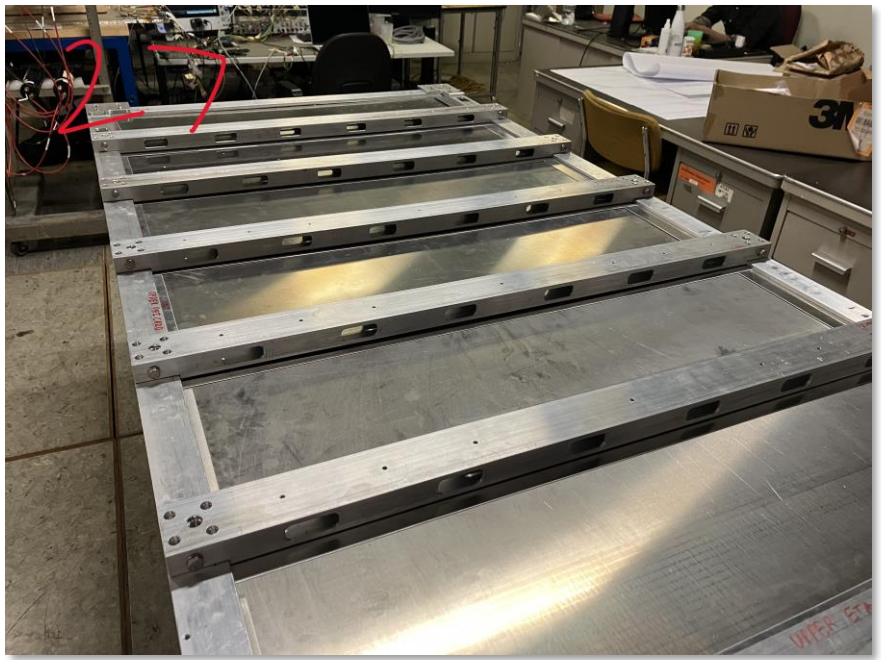


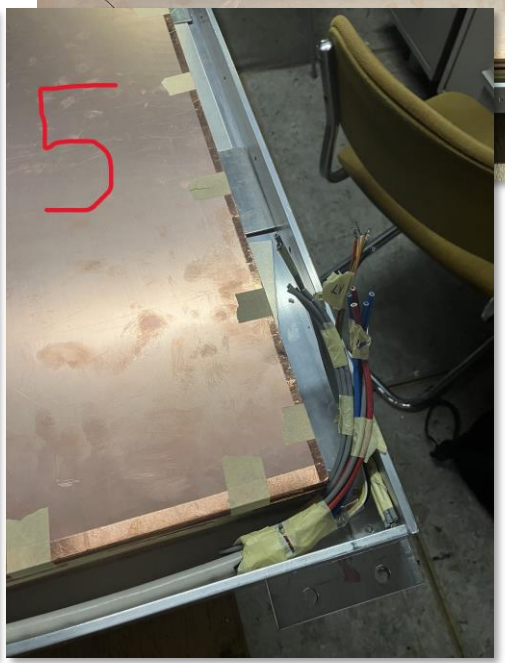
- .090” Al skins create Faraday cage
- Al shims ensure RPC triplet is compressed
- Attempted mock insertion using foam
  - Foam compression required clamping with $2 \times .090$” Al shims
  - Need variety of shims for RPC triplet



CODEX-β triplet RPC insertion

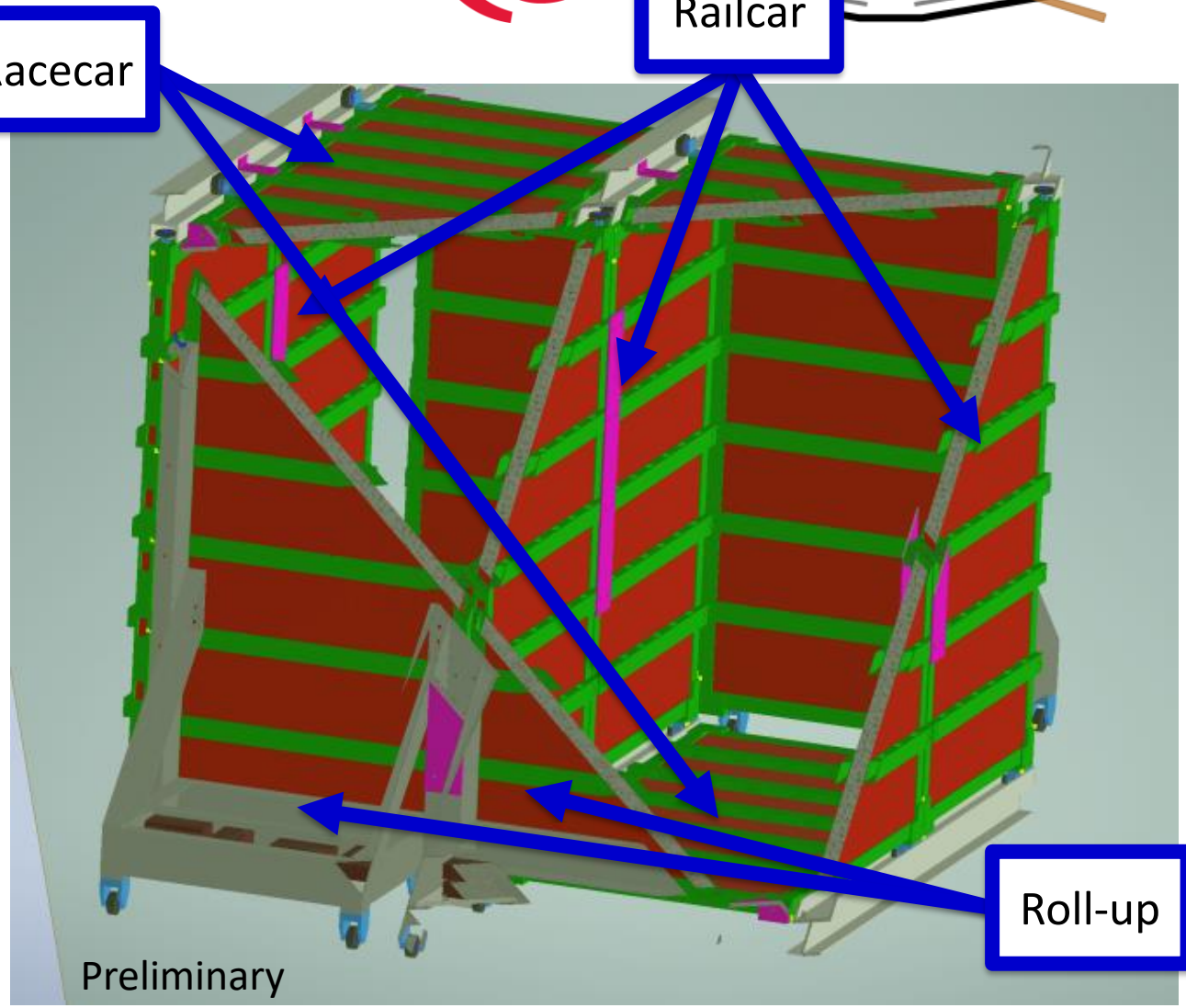
- Sent prototype RPC frame to CERN
- Inserted triplet RPC
  - Tested cable routing
  - Monitored HV readout during closure for spikes





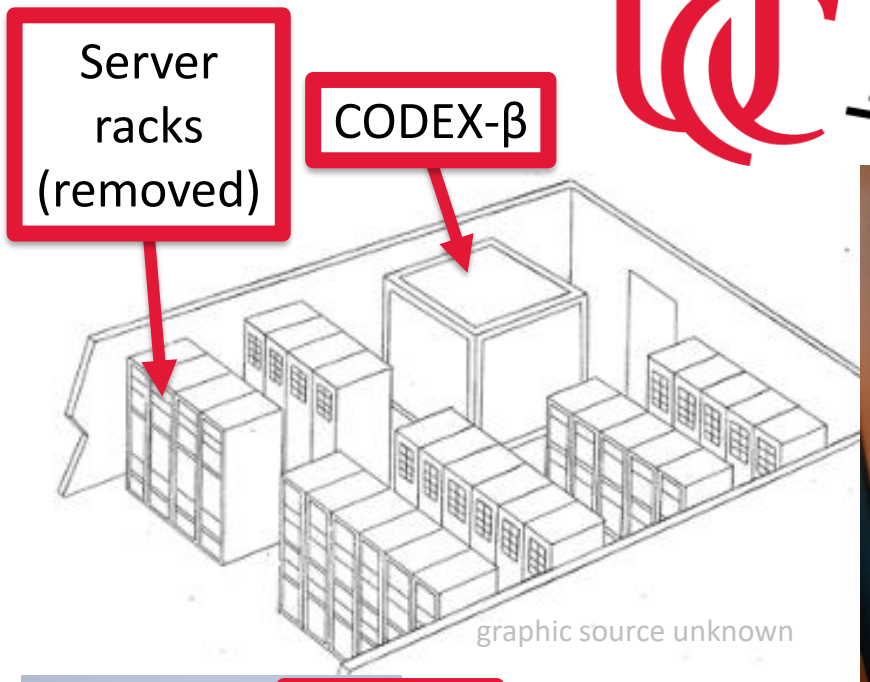
CODEX-β Support Structure Overview

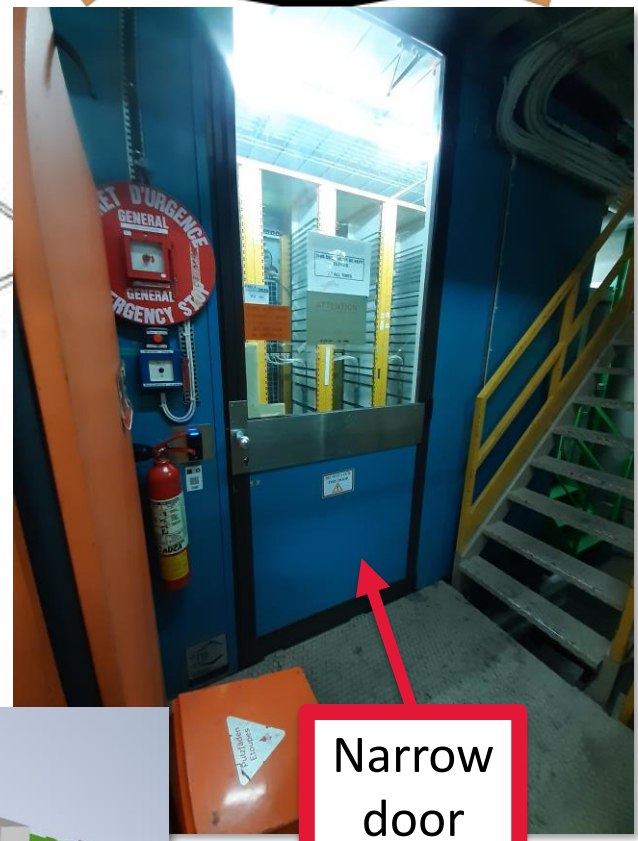
- To be assembled in situ
- $14 \times \approx 200\ \mathrm{kg}$ modules, different orientations ⇒ 3 different installation procedures
- Vertically mounted (“railcar”) with rollers on bottom, guides on top
- Horizontally mounted (“racecar”) with rollers projecting out on both sides
- Vertically mounted (“roll-up”) on permanent carts, not supported by structure

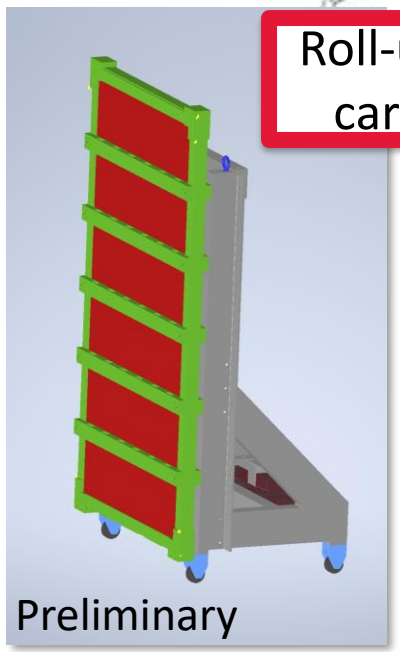


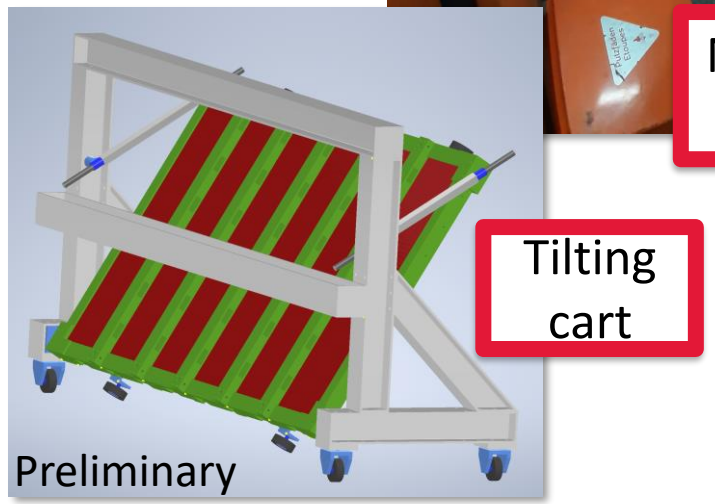
CODEX-β Installation

- All components must fit through narrow door
- Roll-up carts transport most modules and permanently support two modules
- Tilting carts transport horizontal modules, allowing passage through the door and smooth lowering from an angle to horizontal
- Support-structure assembly (except welding) in situ



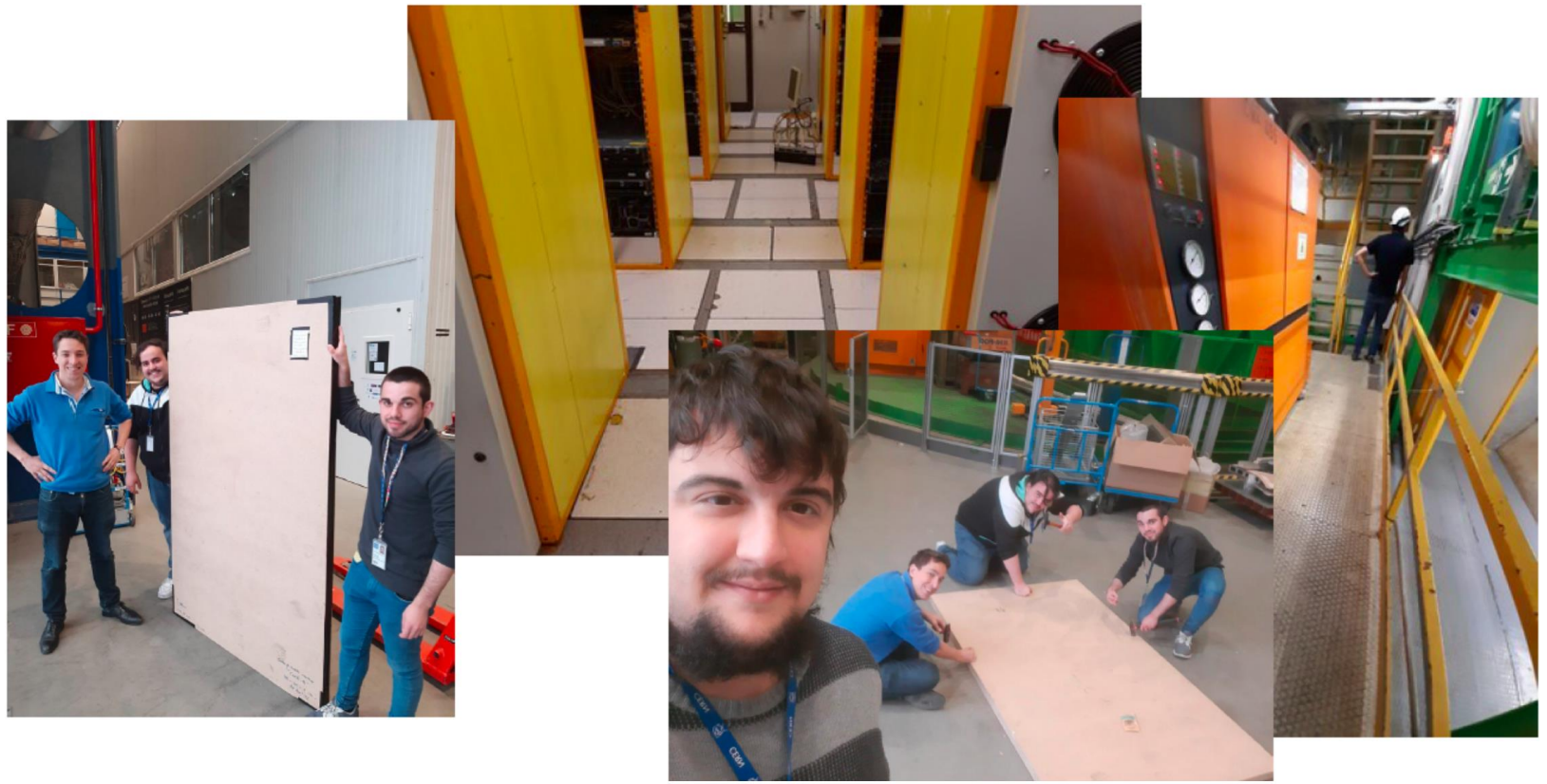






CODEX-β Progress

- Support structure designed
- Service box and installation cart design underway
- Gas and electronics design mature
- Mock transport and location measurements complete
- Electronics procured and validated
- RPC components procured and validated
- Module frames validated; construction ongoing
- RPC construction ongoing; first triplet complete!



https://gitlab.cern.ch/groups/codex-b/-/wikis/More-photos