Exploring the lifetime frontier

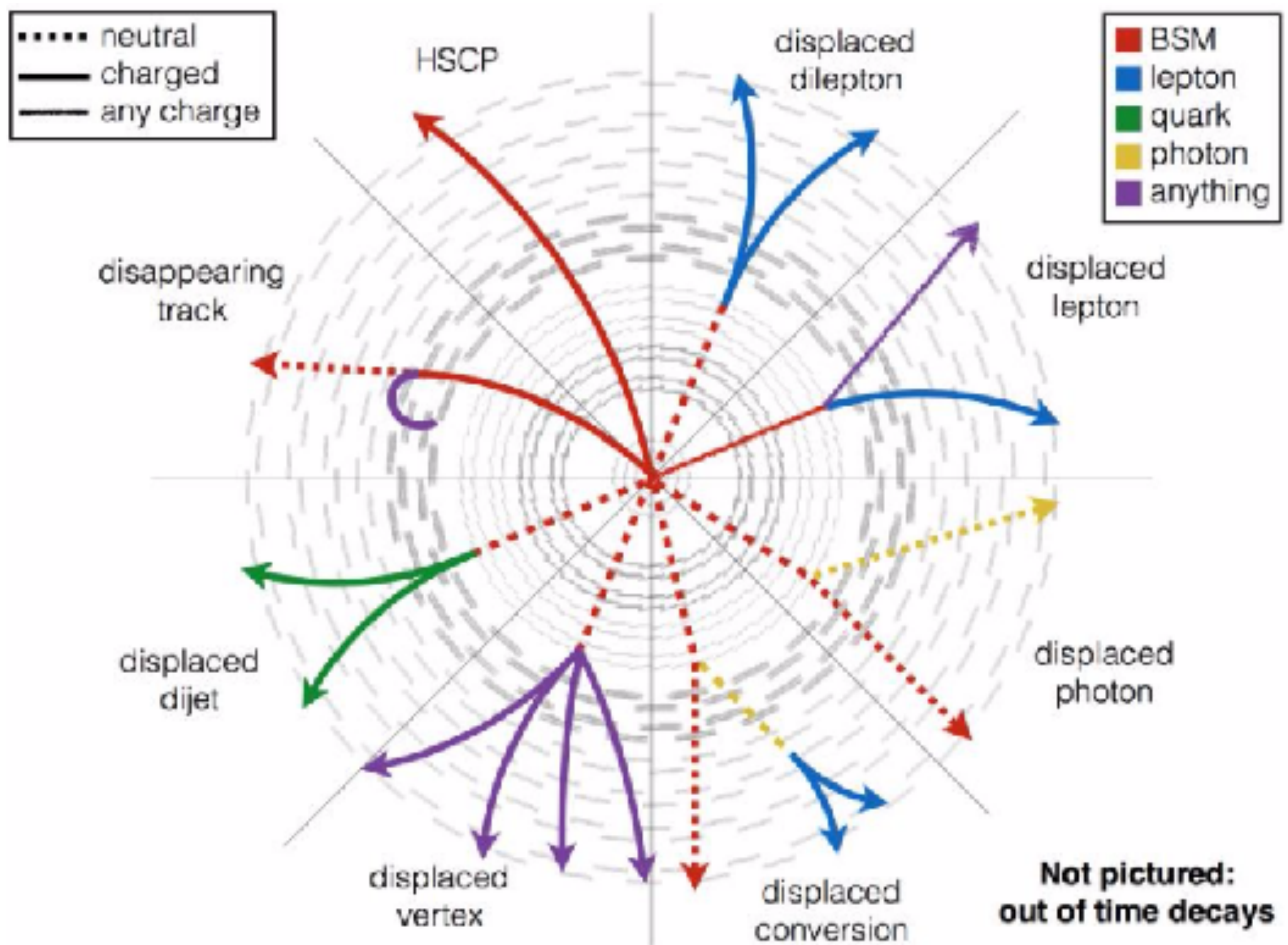
Supplementary detectors

Simon Knapen
Institute for Advanced Study
Princeton, USA

@ Winter Solstice EOS meeting
12 / 20 / 18

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.09395
V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636

Long-lived particles at the LHC



A. De Roeck, Trieste 2017

Many options, great progress in recent years

Large community white paper to appear soon

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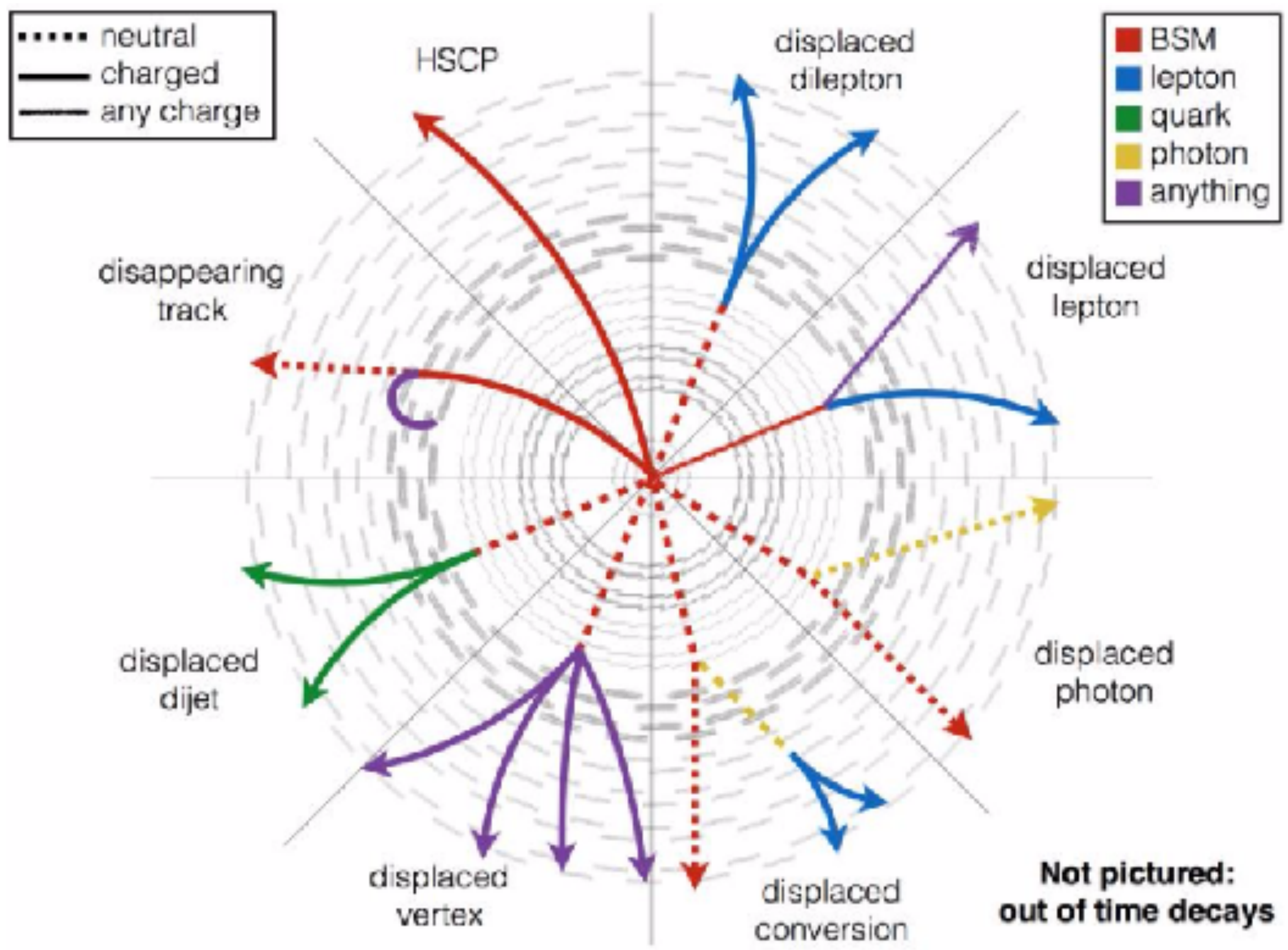

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Key questions:

- Where does a search break down & how to identify holes?
- Can we do low mass ($\lesssim$ 10 GeV) displaced decays?

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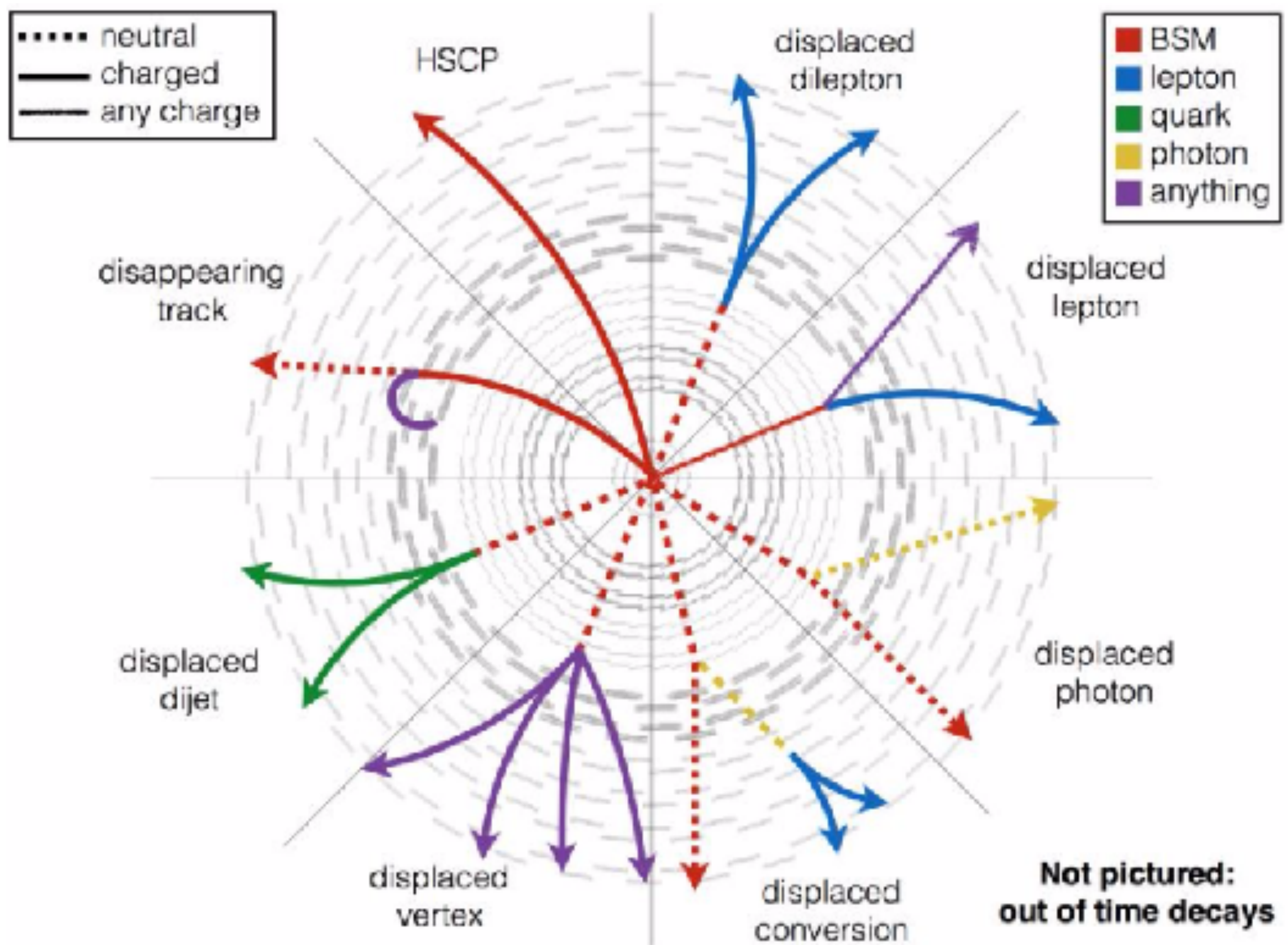

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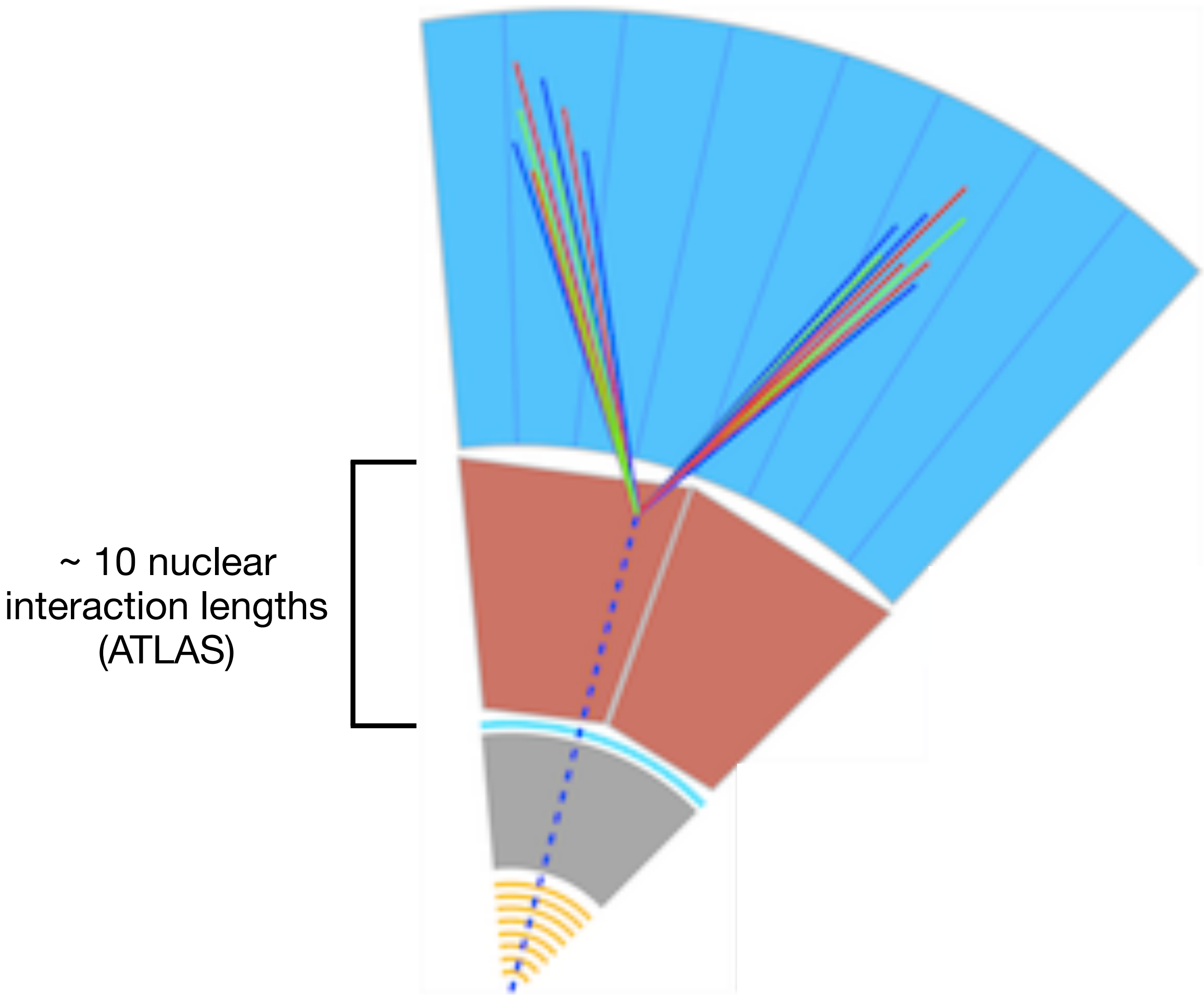
- Can we do low mass (≲ 10 GeV) displaced decays?

Finding Long-Lived Particles

ATLAS and CMS are very good at searching for high mass LLPs…

… but for low masses they suffer from:

1. Tight trigger requirements
2. Backgrounds



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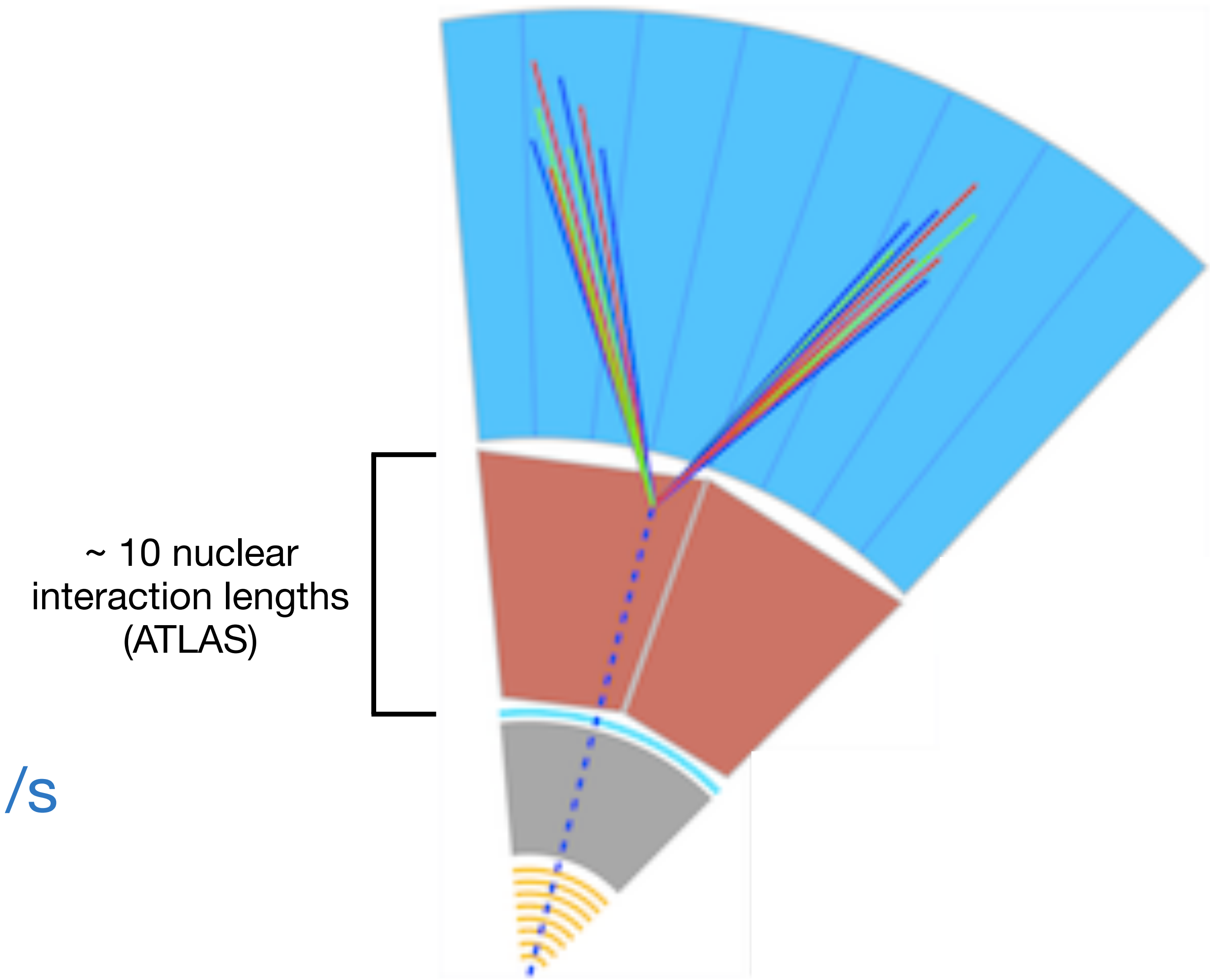
~ 10^{-5} to punch through calorimeter…

… but the LHC makes ~ 10^{9} K_L mesons /s



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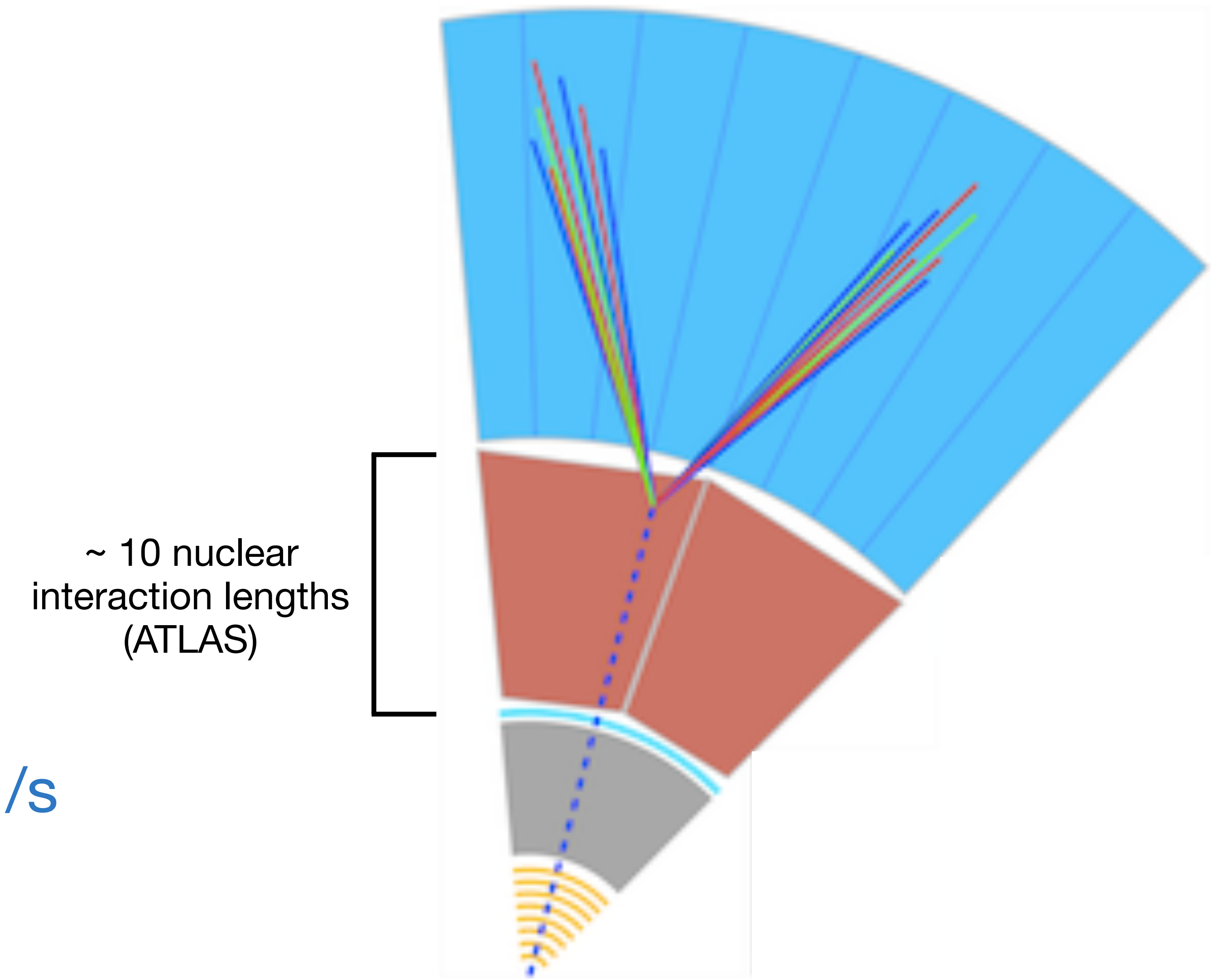
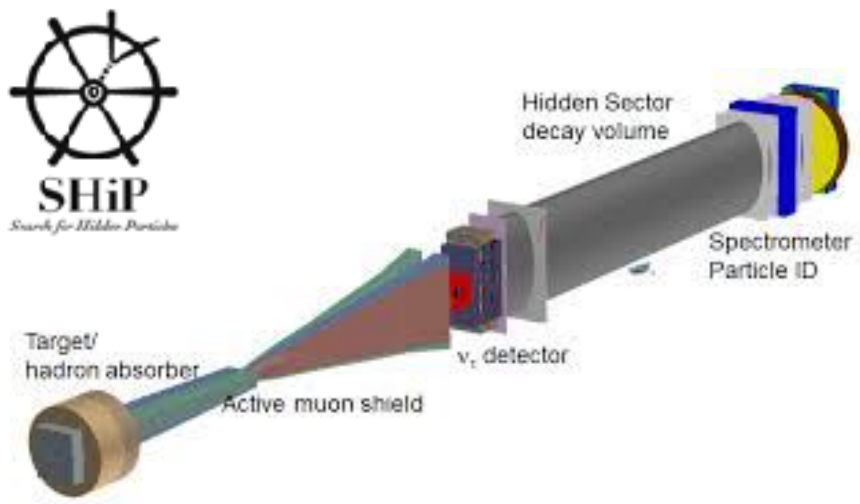


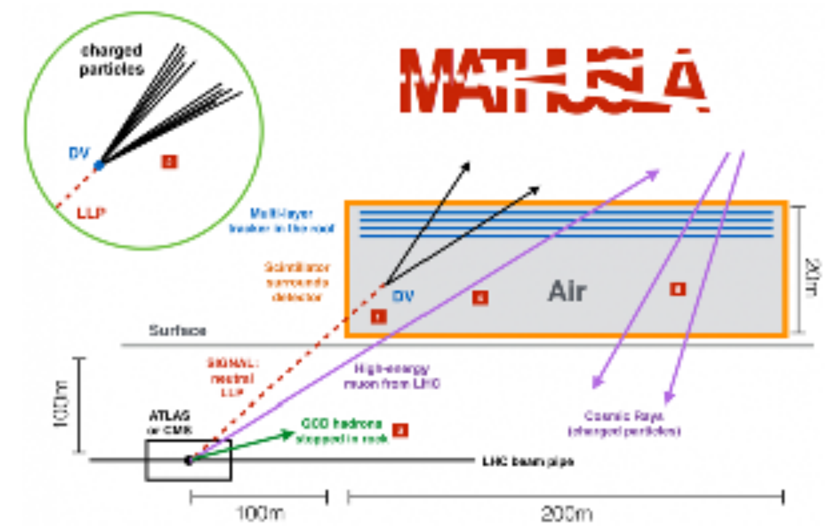
Solution:
Dedicated detector with ~ 3 to 4 times more shielding

Detectors for the lifetime frontier

"Ambitious" proposals



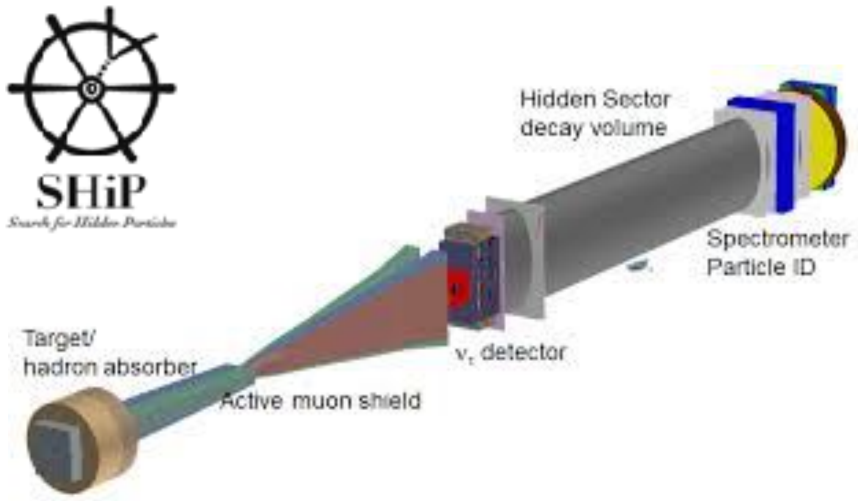
SHiP



MATHUSLA

Detectors for the lifetime frontier

“Ambitious” proposals



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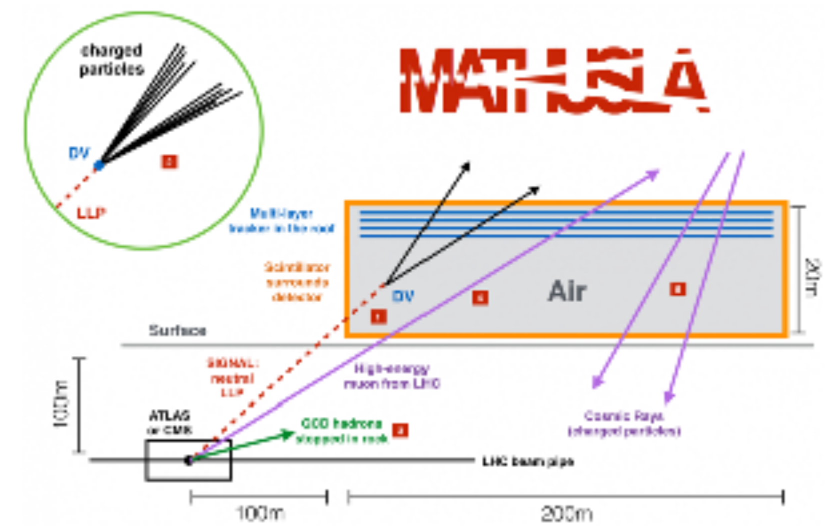
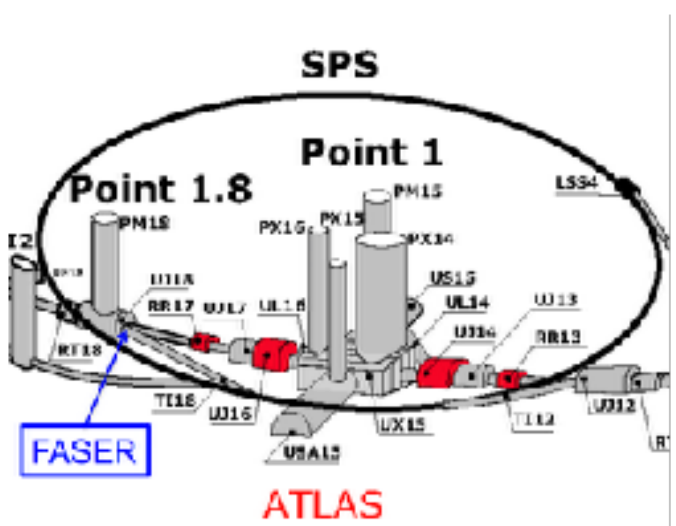


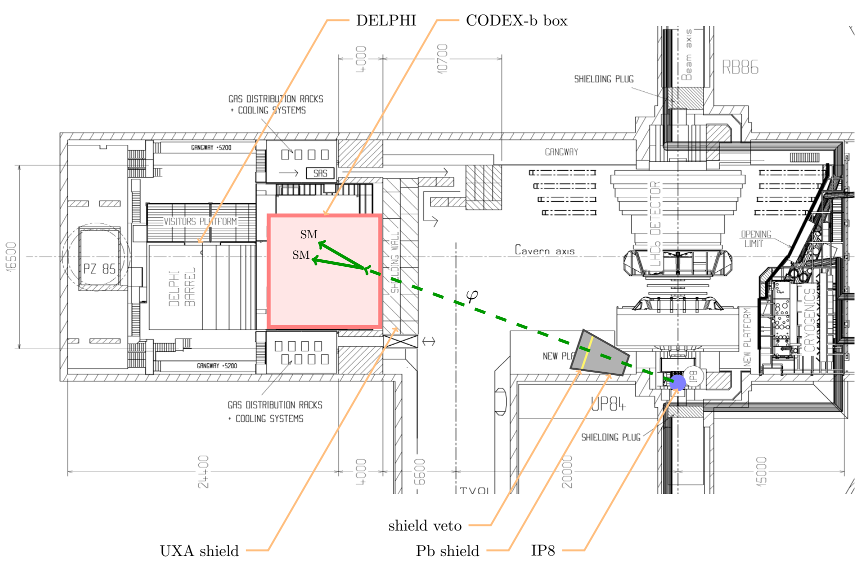
MATHUSLA

“Modest” proposals



FASER

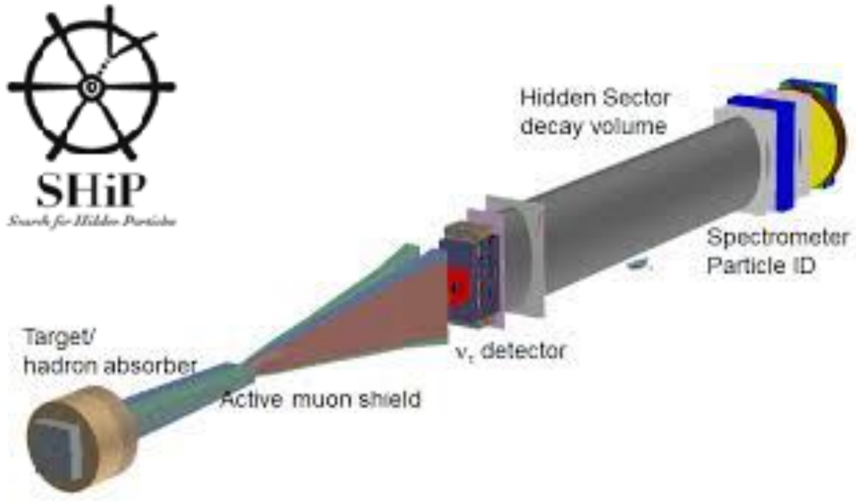
Miliqan



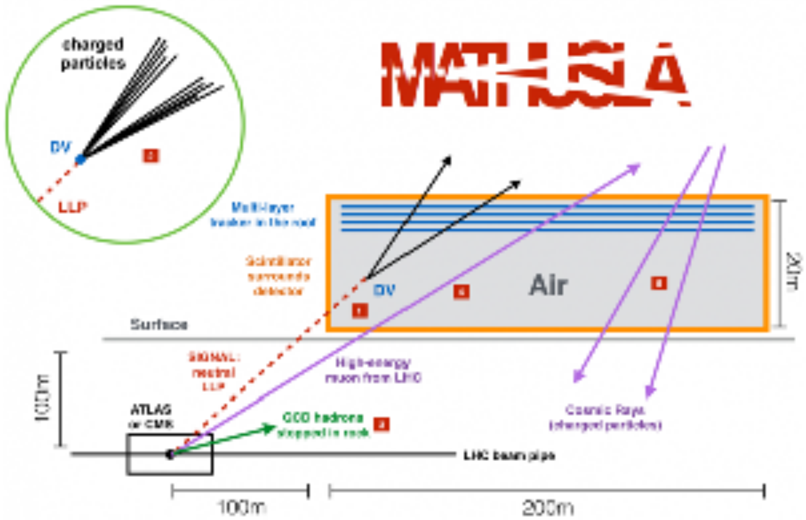
CODEX-b

Detectors for the lifetime frontier

“Ambitious” proposals



SHiP



MATHUSLA

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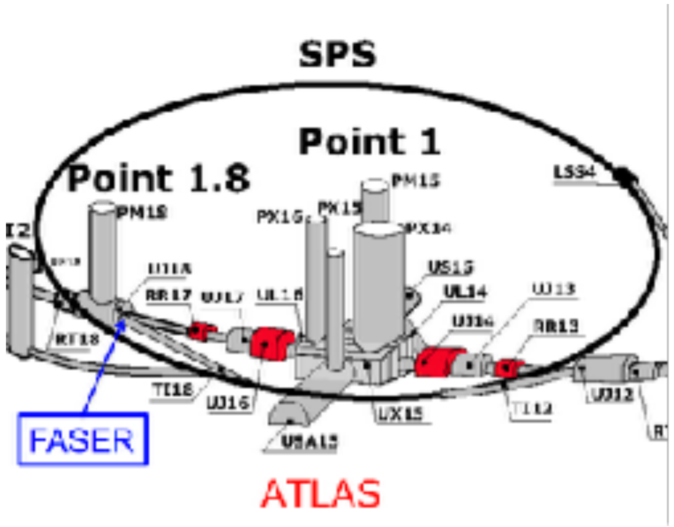

FASER

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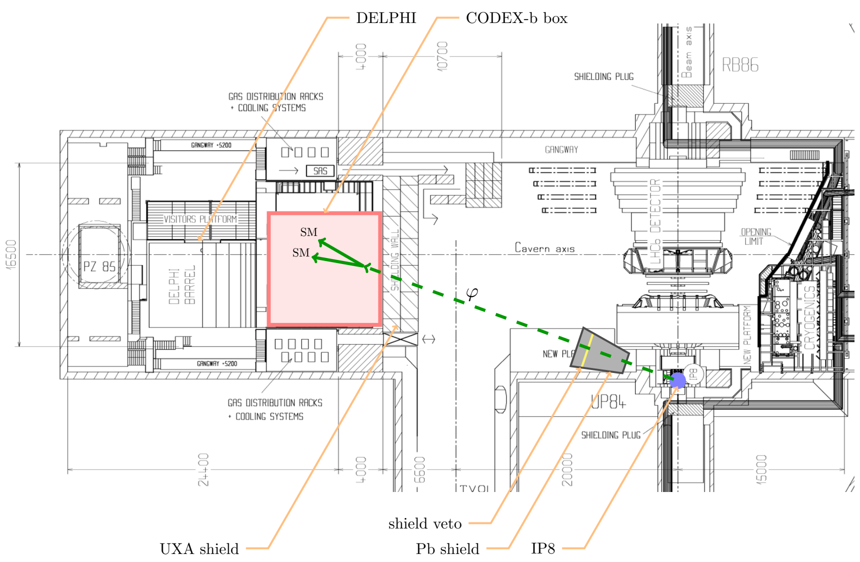
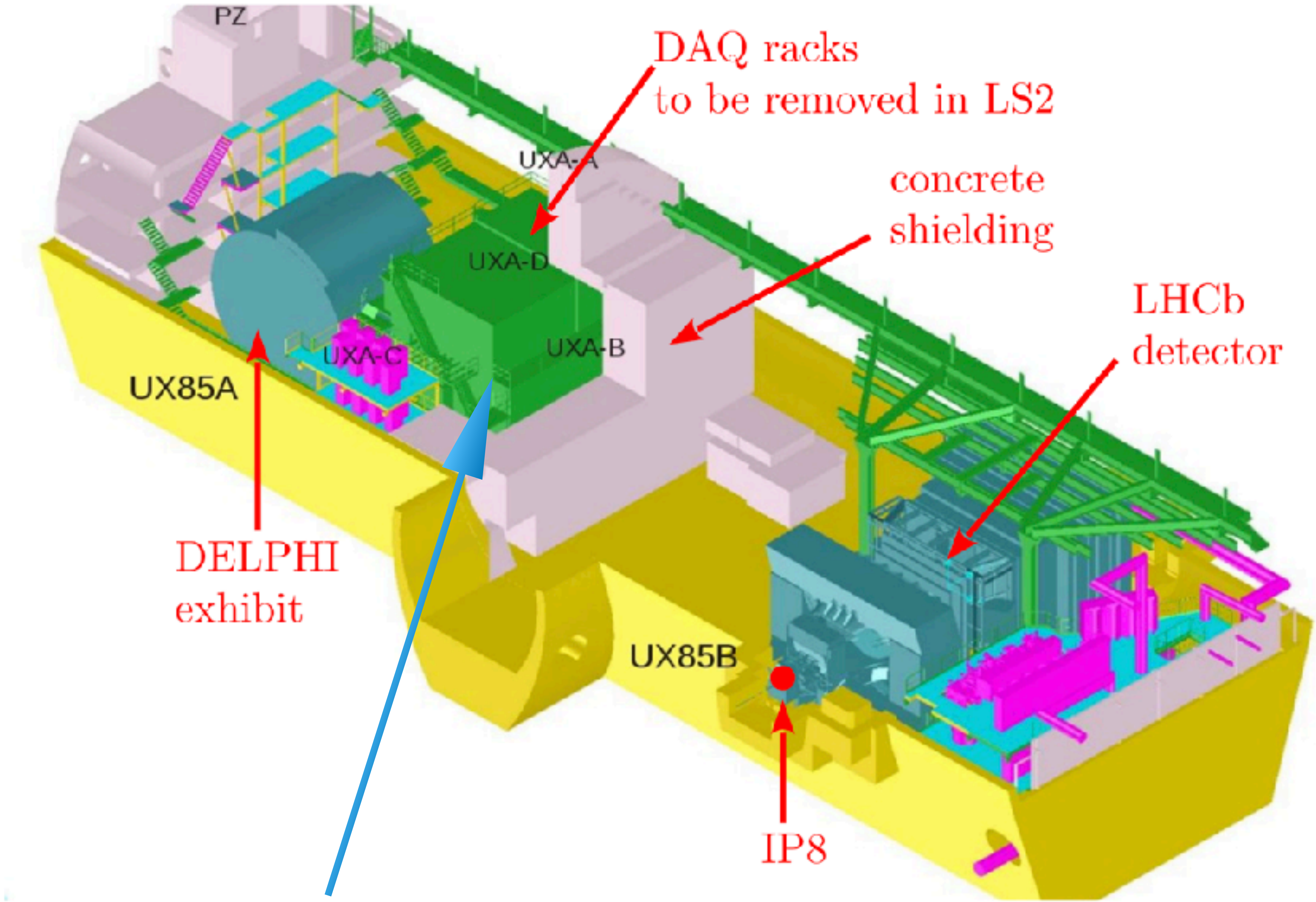


CODEX-b

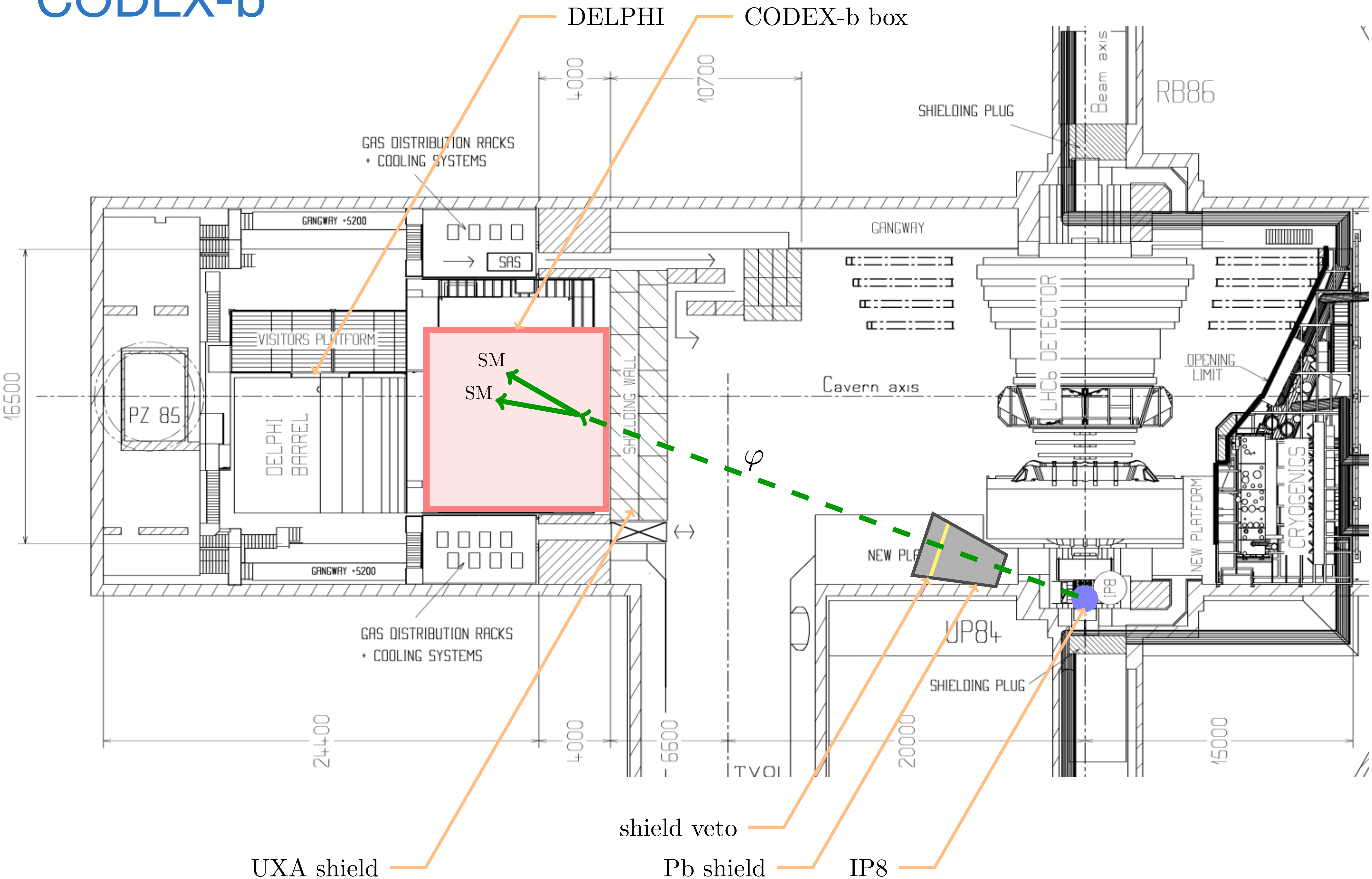
LHCb Cavern



Shielded space: 10m x 10m x 10m (20m x 10m x 10m if DELPHI is removed)
Roughly 25m from IP

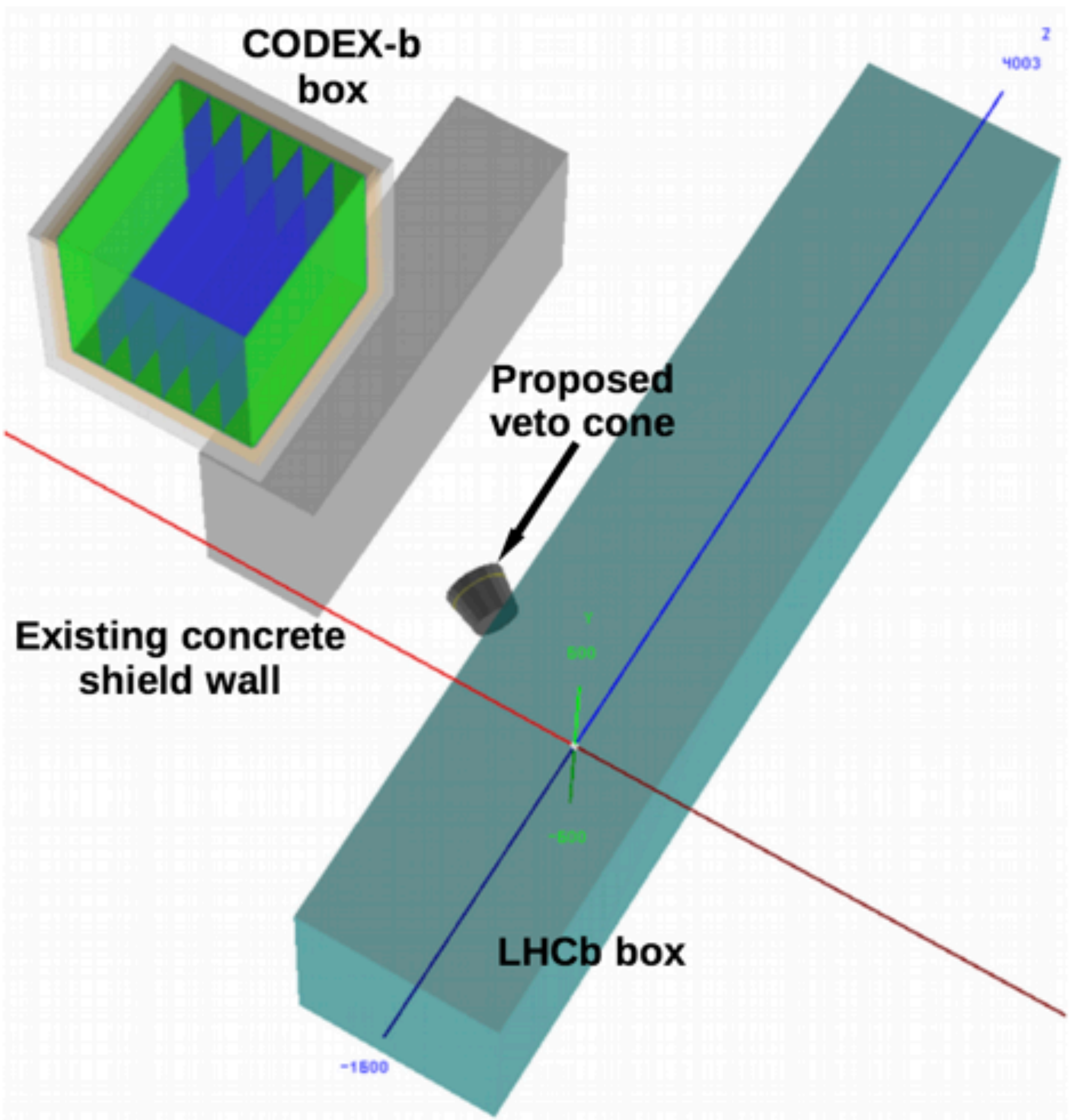
CODEX-b

1708.09395: V. Gligorov, SK, M. Papucci, D. Robinson



Data acquisition will be moved to surface for run 3

CODEX-b simulation framework



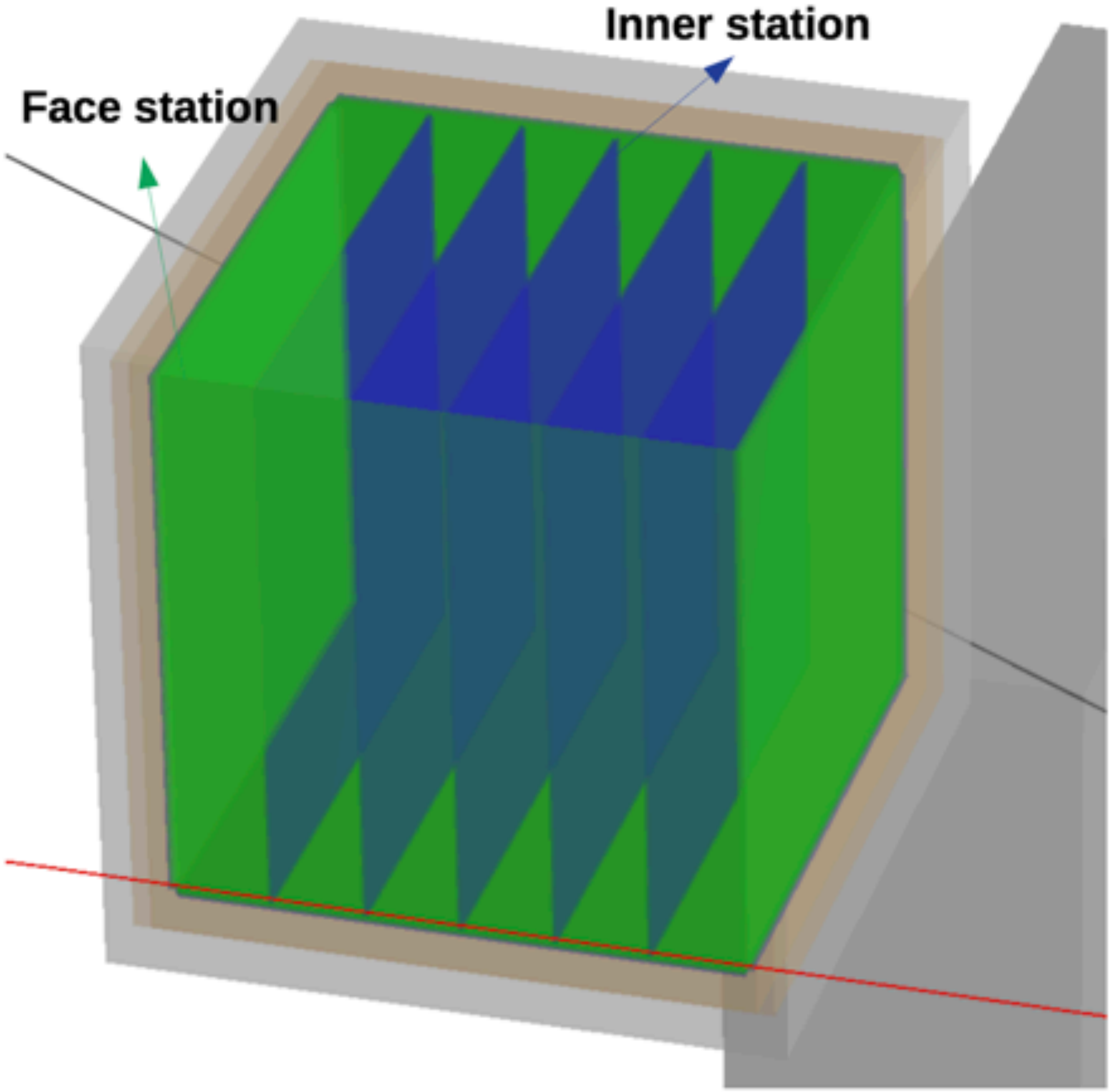
Implemented in DD4hep package
https://dd4hep.web.cern.ch/dd4hep/

- Veto cone
  - Two Pb absorbers
  - Active layer (Si)
- Concrete wall (3.2 m)
- CODEX-b detector

Tested with muon particle gun

By Biplab Dey, Markus Frank, Ben Couturier and Jongho Lee

Tentative geometry for tracking



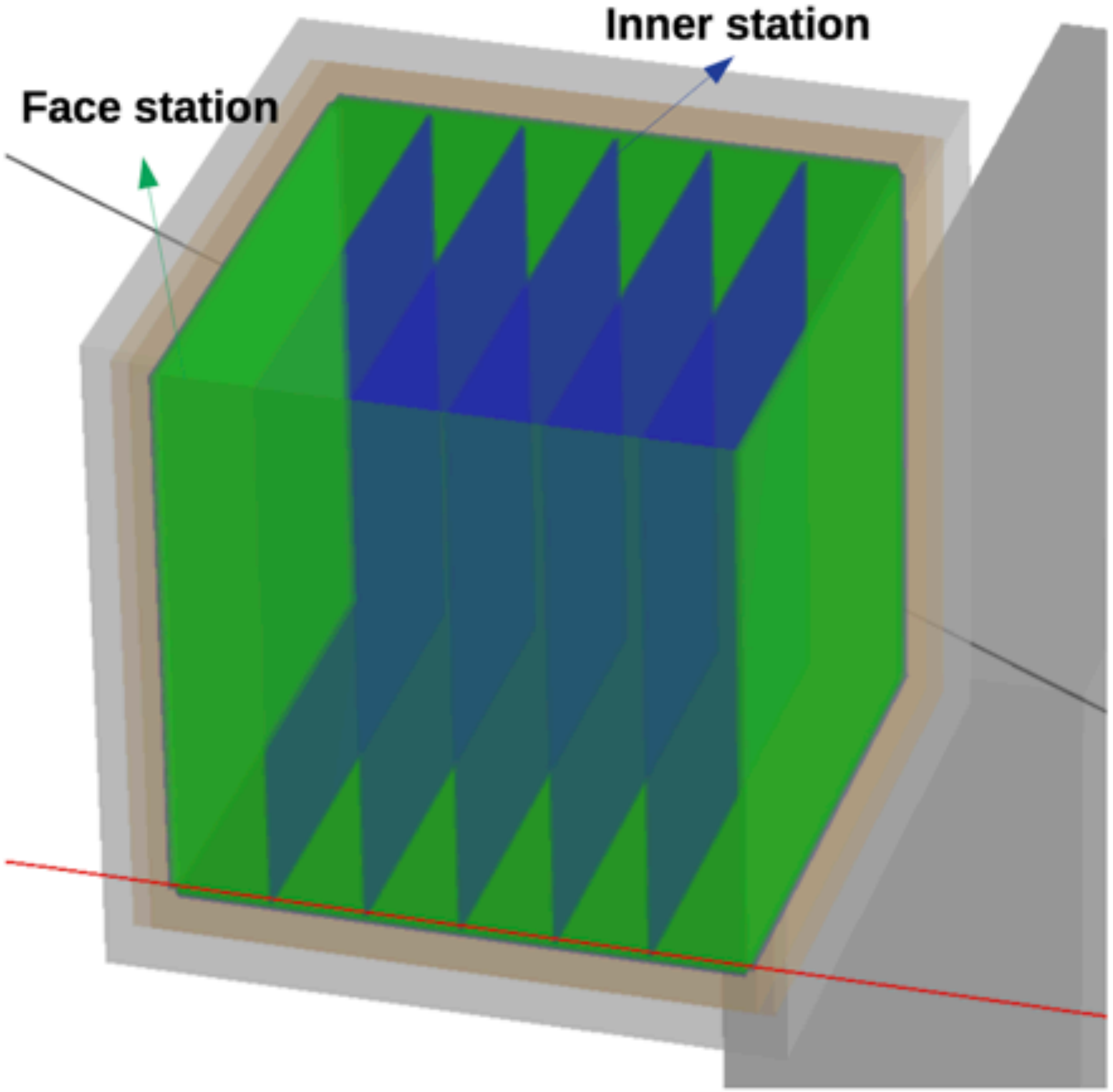
Face station (6x)

- 6 RPC layers on each surface
- 4 cm inter layer distance

Inner station (5x)

- 3 RPC layers on each surface
- 4 cm inter layer distance

Tentative geometry for tracking



Face station (6x)

- 6 RPC layers on each surface
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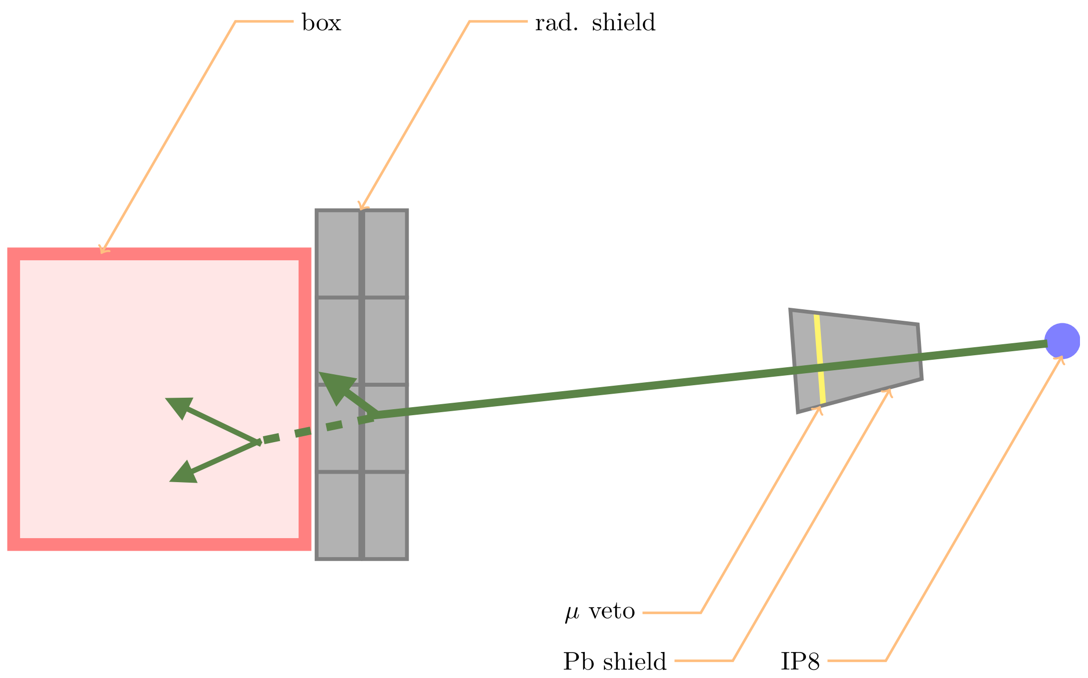
Inner station (5x)

- 3 RPC layers on each surface
- 4 cm inter layer distance

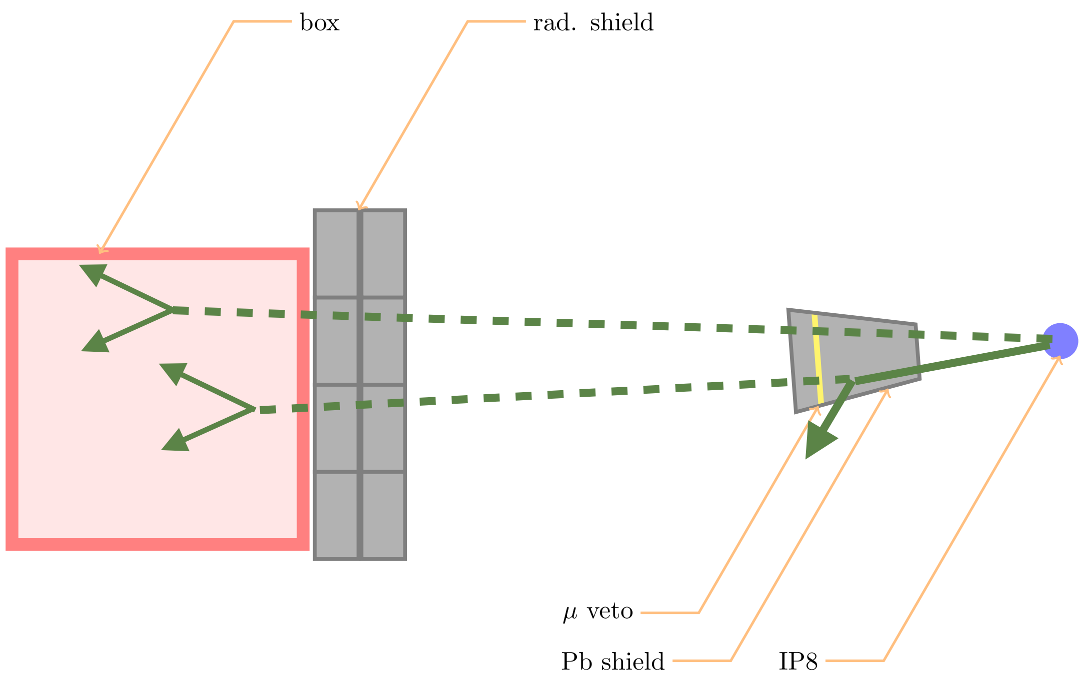
Motivation

- Faces stations: recover acceptance for particles with low boost
- Inner stations: minimize distance to first tracked point

Main backgrounds



veto



irreducible

Needed for full background suppression:

- need 10^{-4} - 10^{-5} muon veto
- ~ 32 interaction lengths (7 concrete + 25 Pb) ➞ roughly 4.5 m of Pb

(Verified with pythia 8 + GEANT 4 simulation, numbers and figures in back-up slides)

Background calibration

- Measured charged flux at different points in UX85A
- Good amount of data: 50k hits in 17 days
  (results for later day)
- Use to calibrate background simulation

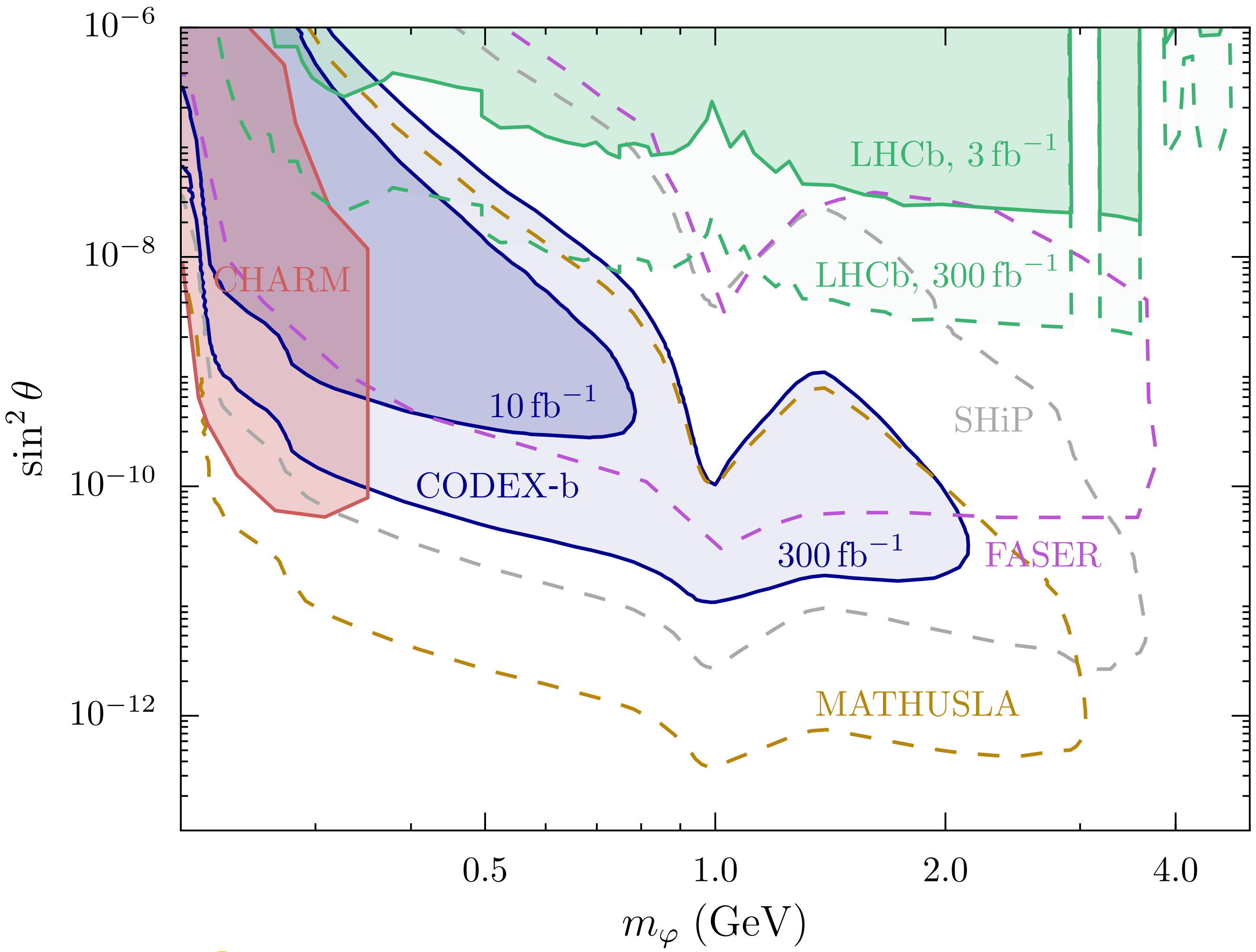
By Biplab Dey, Heinrich Schindler, Victor Coco, Raphael Dumps and Jongho Lee*

* CERN summer student

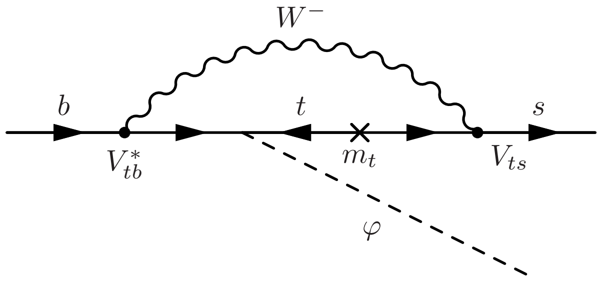
Exotic B decays

Model: $$\mathcal{L} \supset \mu\,\varphi H H^\dagger + \frac{\lambda}{2}\varphi^2 H^\dagger H$$

With $\lambda = 0$



Production



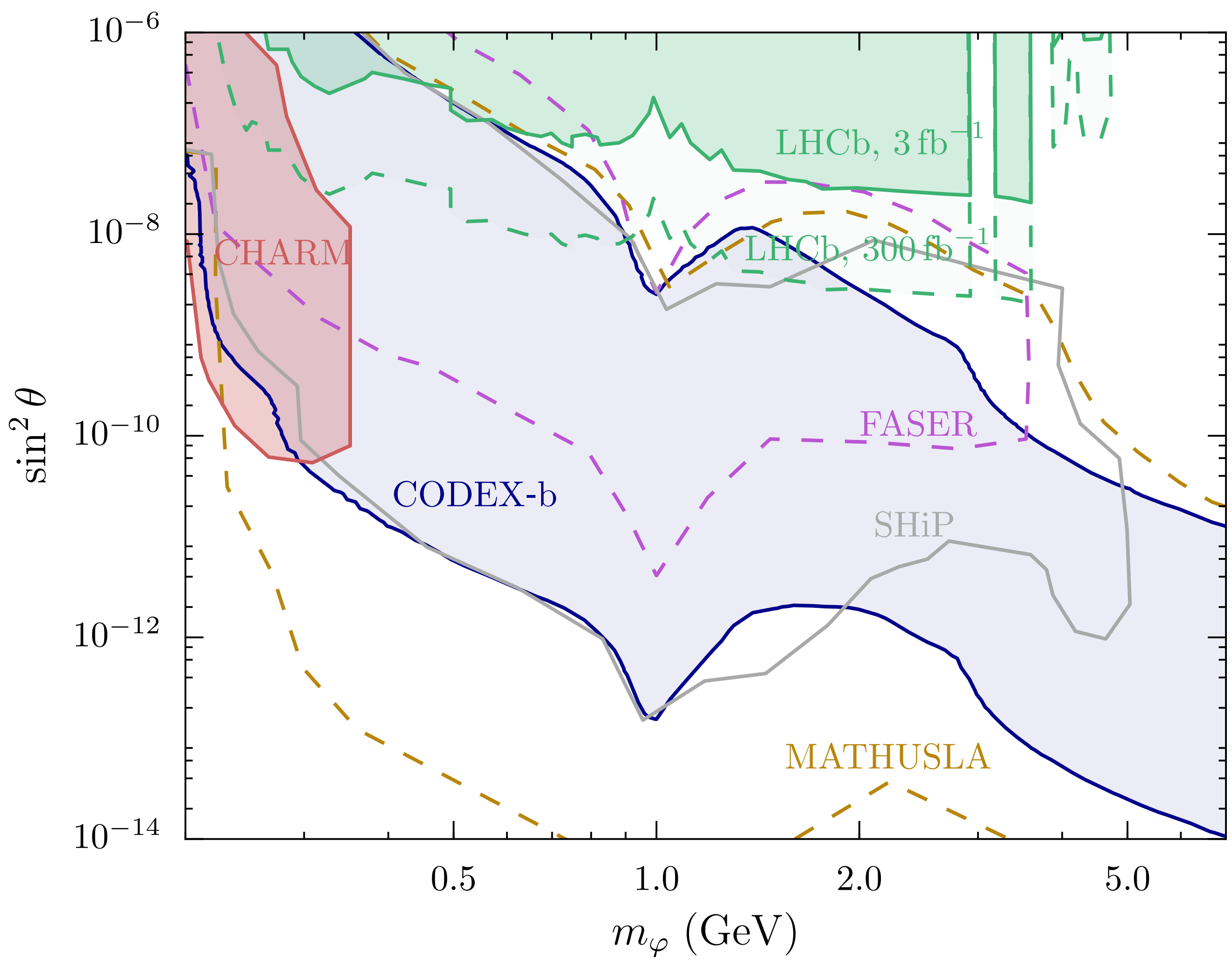
Different assumptions for lifetime in literature, need to recast the limits when comparing experiments!

Exotic B + Higgs decays

Model: $\mathcal{L} \supset \mu\,\varphi H H^\dagger + \frac{\lambda}{2}\,\varphi^2 H^\dagger H$

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

$\mathrm{Br}(h \to 2\varphi) \approx 0.01$



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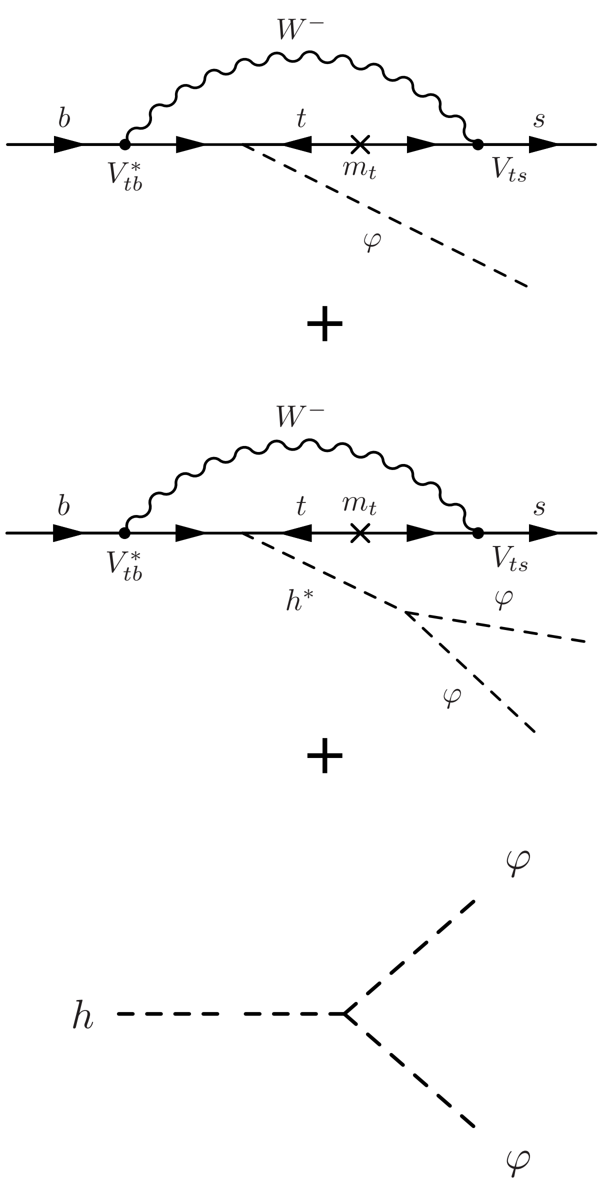
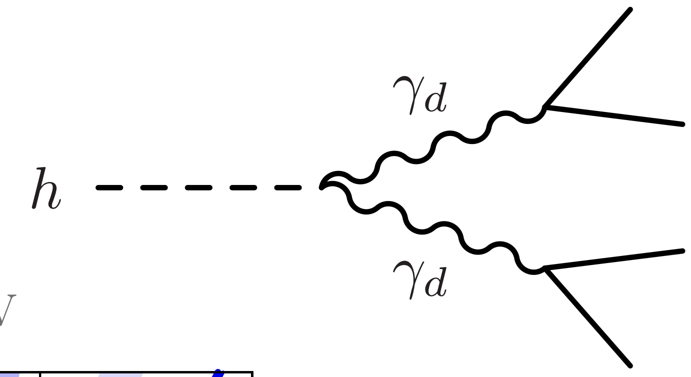
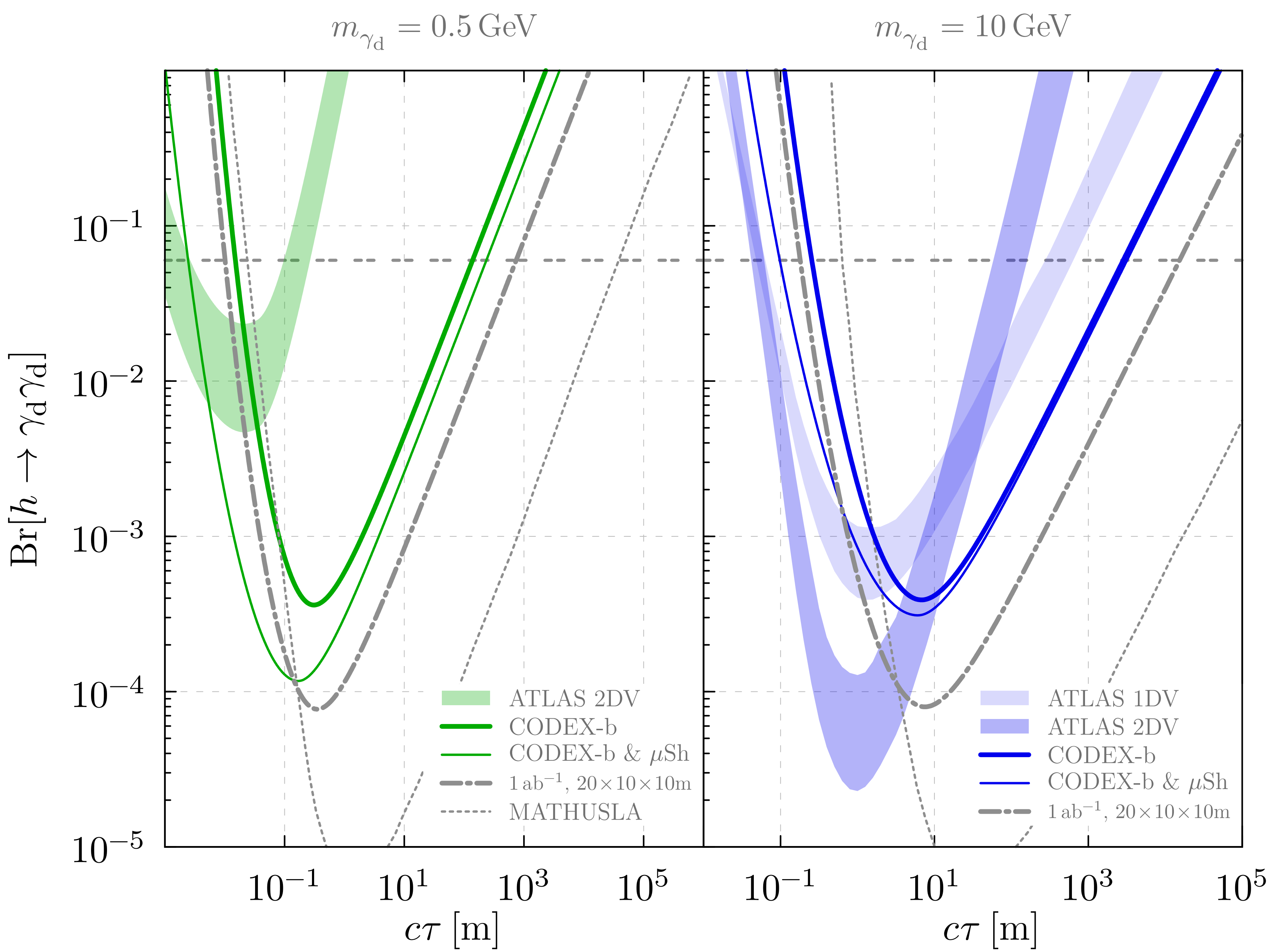


See back-up slides or “Physics for beyond colliders” report for axion-like particles and heavy neutral leptons.

Exotic Higgs decays





For low masses, ATLAS/CMS are background limited, CODEX-b and MATHUSLA have an edge

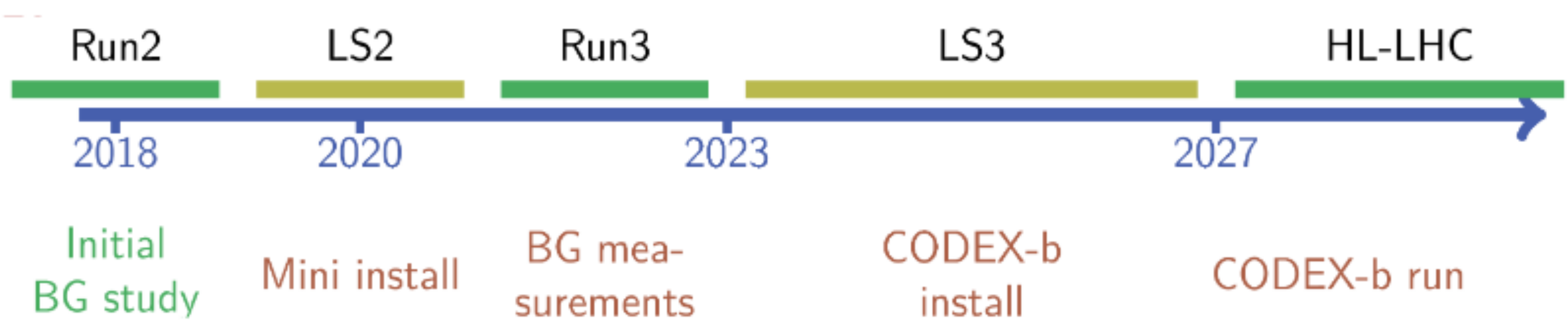
ATLAS reach: A. Coccaro, et al.: 1605.02742

Moving forward

Ongoing work on theory side: finishing benchmark models
(back-up slides, see also upcoming "Physics Beyond Colliders" report)

Ongoing work on the LHCb side

- Background data analysis
- Detector design and simulation
- On track for a detector paper in Summer 2019



CODEX-b Team

Theory: J. Evans, SK, M. Papucci, H. Ramani, D. Robinson

LHCb: J. Lee, V. Coco, B. Dey, R. Dumps, V. Gligorov, H. Schindler, P. Ilten, T. Szumlak, X. Vidal + many others...

Support from LHCb computing & simulation:
M. Frank, B. Couturier, D. Muller, G. Corti

Still growing, and we welcome new collaborators!

What would an “ideal” detector look like?

- $\sqrt{s}$ = 13 TeV
- As close as possible to IP
- B field for momentum measurement
- High resolution tracker (vertex reco)
- as high lumi as possible

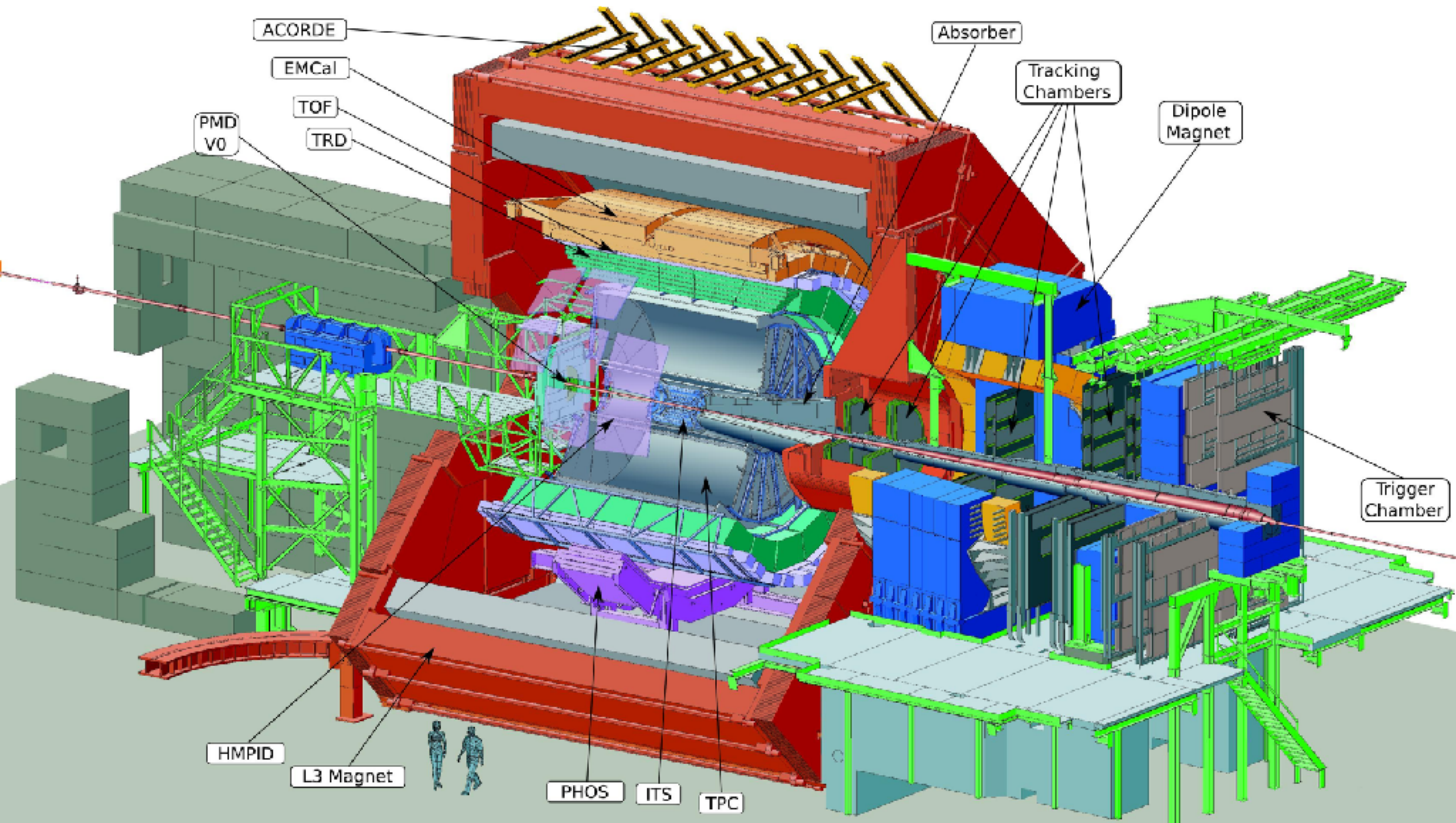
What would an “ideal” detector look like?

- $\sqrt{s}$ = 13 TeV ✔
- As close as possible to IP ✔
- B field for momentum measurement ✔
- High resolution tracker (vertex reco) ✔
- as high lumi as possible

Most of this is present in ALICE cavern

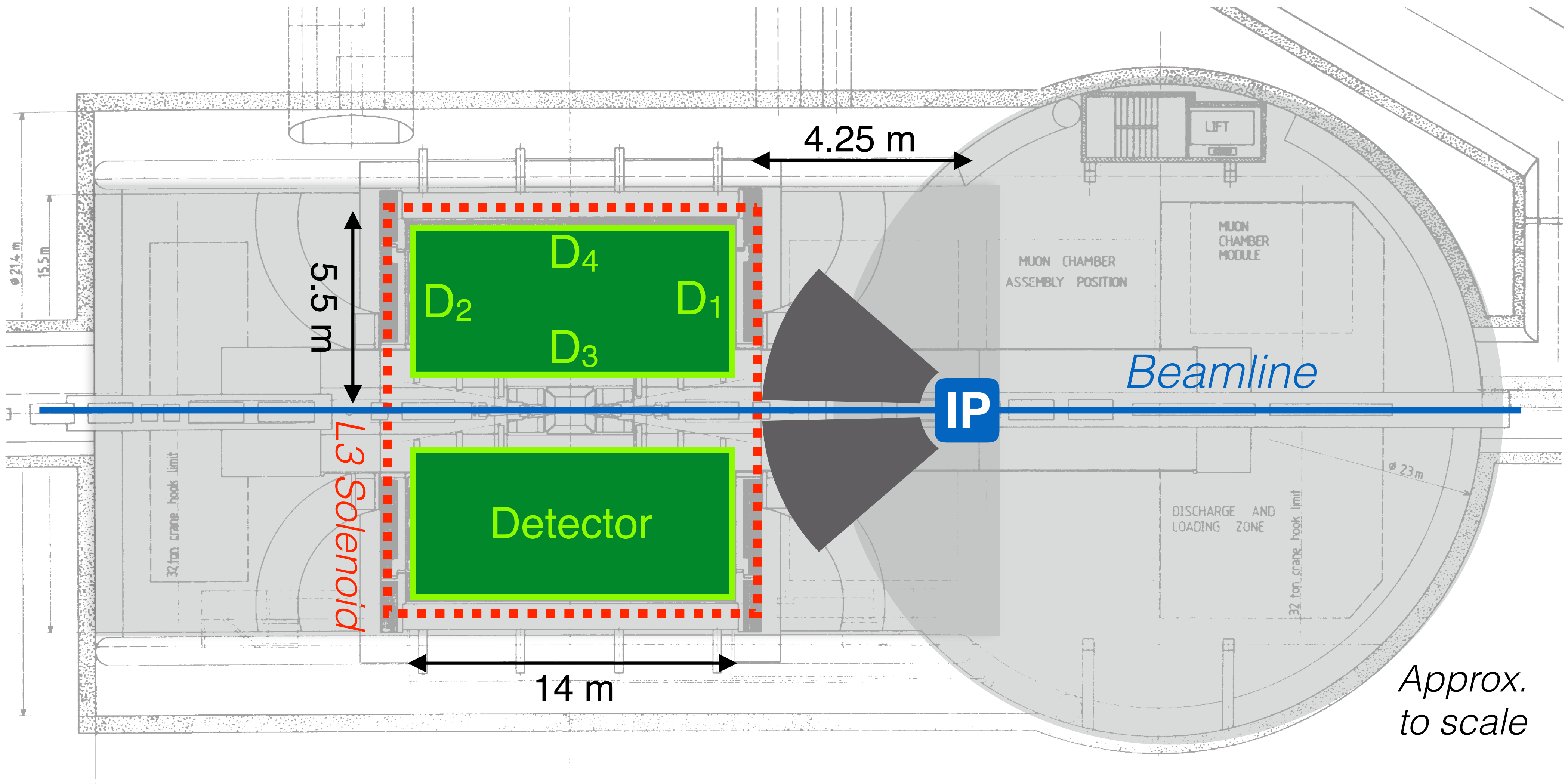
(At this time, there is no firm plan for a ALICE heavy ion program during run 5)

ALICE detector



A Laboratory for Long-Lived eXotics (AL3X)

Reuse the L3 magnet and (perhaps) the ALICE TPC



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

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

Upgrading Interaction Point 2

Needed:

- move the IP with 11.25 m
- ~ 100 fb^{-1}

Similar to IP8 (LHCb)

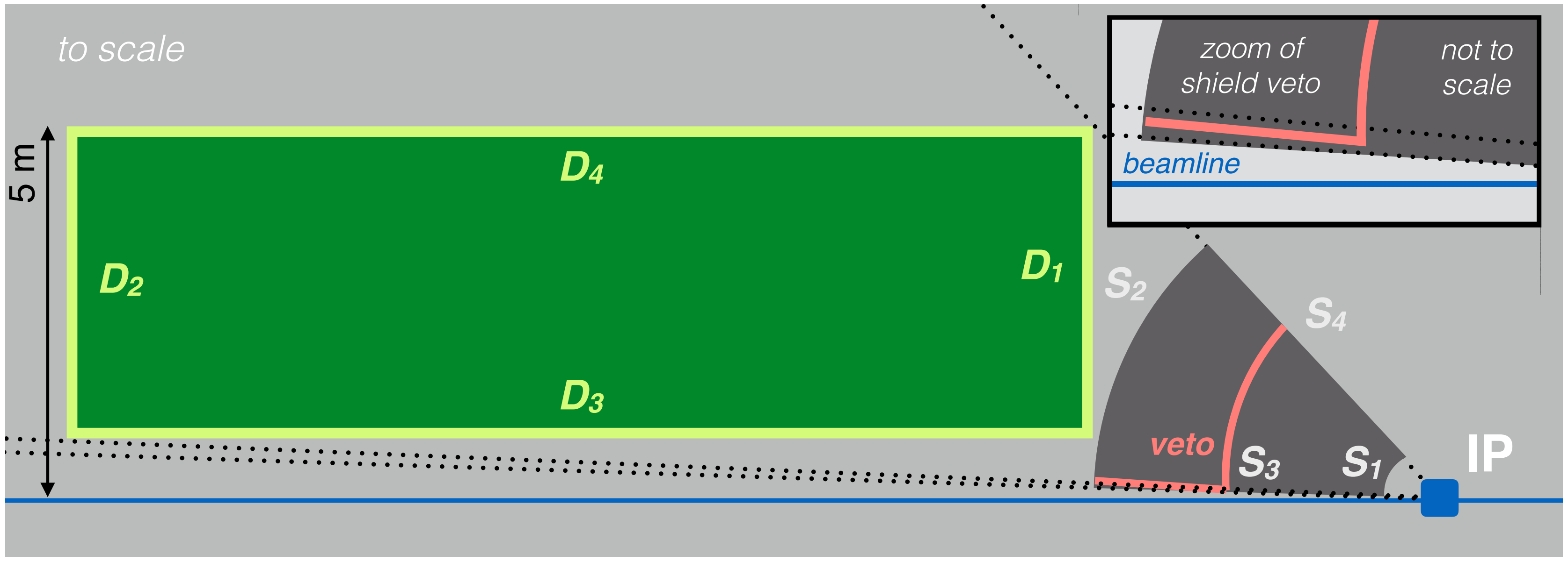
Possible challenges:

- luminosity sharing
- beam optics
- cost?

Most obvious failure mode at this moment

Backgrounds

More complicated than for CODEX-b, due to beam pipe

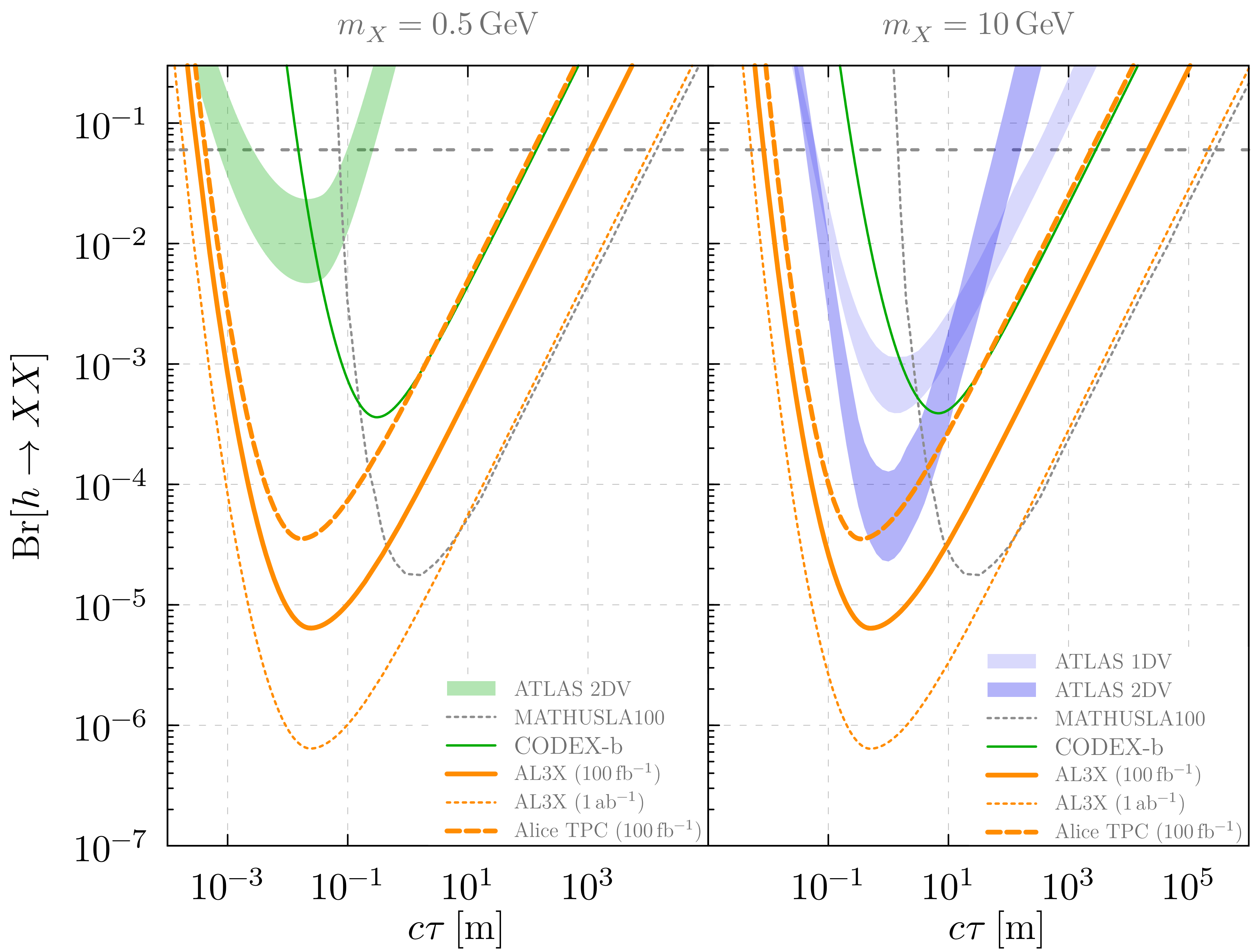


Needed for full background suppression:

- need 10^{-8} muon veto
- fast trigger layers for the TPC (few muons per collision)
- ~ 40 interaction lengths (e.g 1 m Fe from magnet doors + 9 m steel + 2.5 m W)

(Verified with pythia 8 + GEANT 4 simulation)

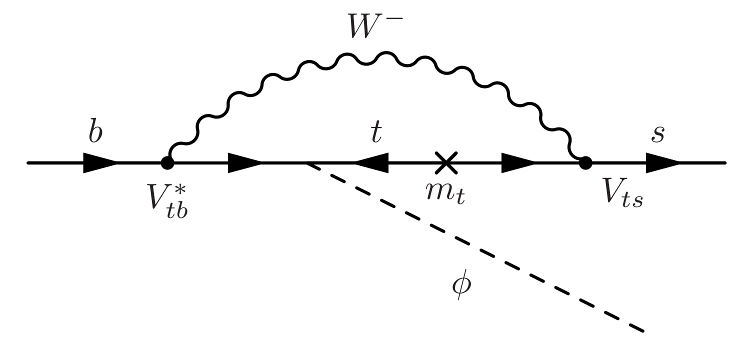
Reach for Higgs decays



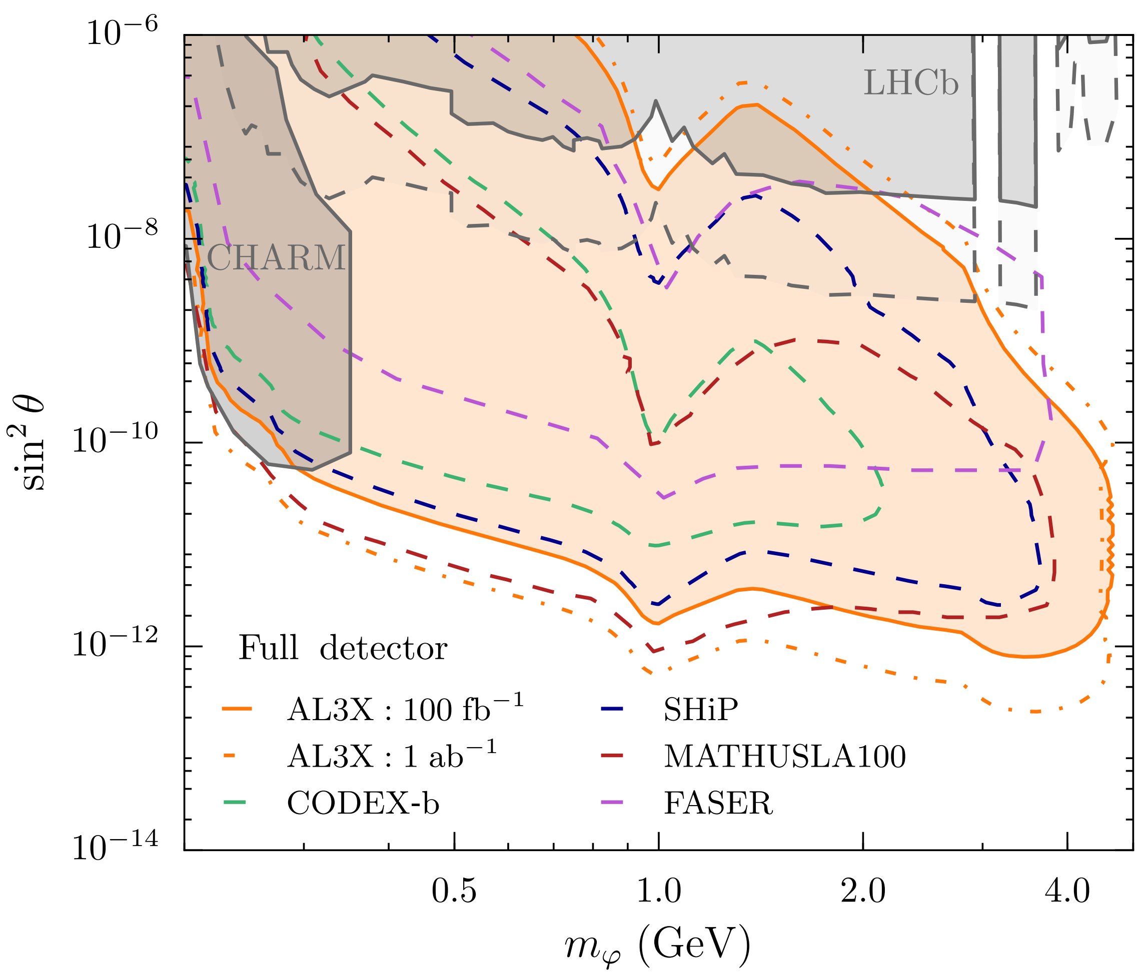
Comparable sensitivity to MATHUSLA

ATLAS reach: A. Coccaro, et al.: 1605.02742

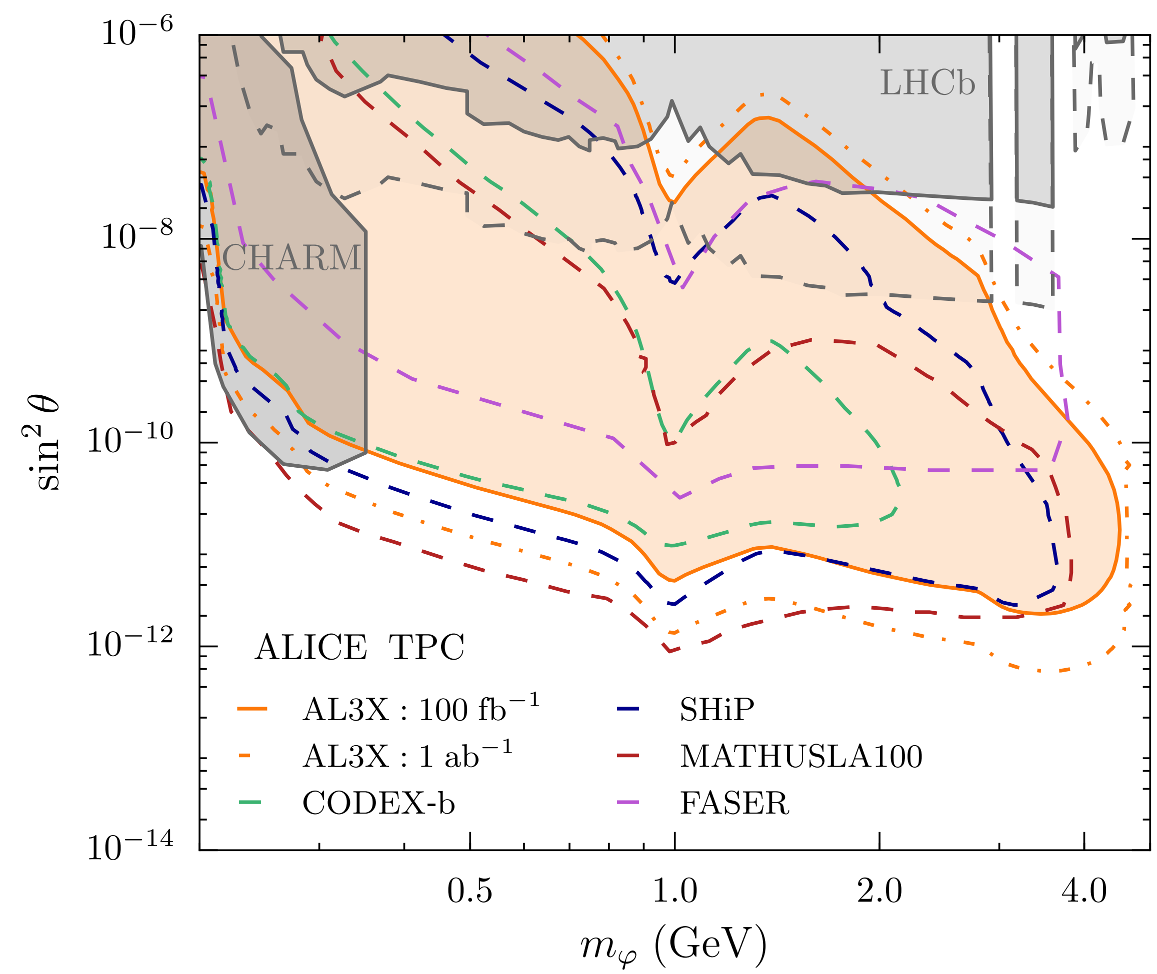
Reach for B decays



New detector



Reuse ALICE TPC



For exotic B decays, AL3X = SHiP + MATHUSLA

Lifetime frontier

Supplementary detectors

CODEX-b:

- Probe decent fraction of SHiP + MATHUSLA parameter space
- Simple, relatively inexpensive detector

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AL3X:

- Probe all or more of SHiP + MATHUSLA parameter space
- Contingent upon:
  - ALICE heavy ion program
  - Upgrade of the interaction point

Interesting developments also for MATHUSLA, SHiP, FASER, MOEDAL and MiliQan

Lifetime frontier

very non-exhaustive list!

Existing detectors & upgrades

Triggers!

- LHCb triggerless readout
- CMS track trigger, ATLAS FTK
- HLT keeps getting smarter (e.g. track multiplicity triggers?)

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Upgrades

- Timing detectors
- CMS high granularity forward calorimeter

Lifetime frontier

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Upgrades

- Timing detectors
- CMS high granularity forward calorimeter

Analysis improvements

- Dark showers / hidden valleys (now largely a theory problem in my opinion)
- Quirks (GEANT implementation appears to be the bottleneck)

Thanks!

Greenland shark, lifespan up to 400 years

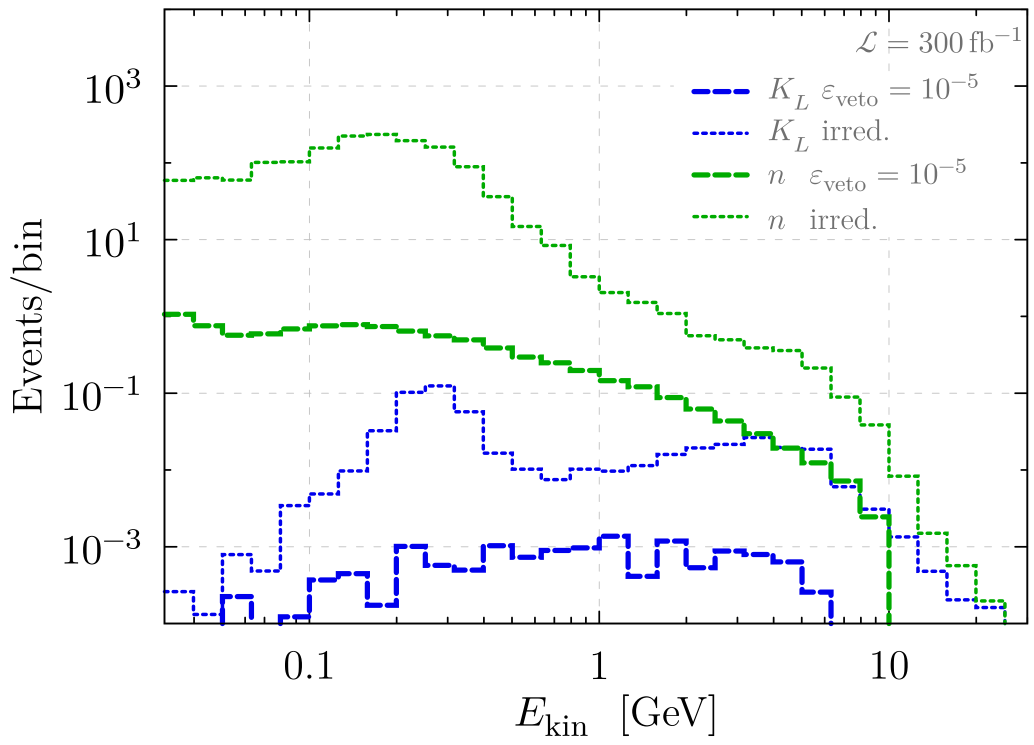
Back-up

Backgrounds

neutrons / K_L + secondaries

pythia 8 + GEANT 4 simulation

BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n + \bar{n}$	7	$5 \cdot 10^4$	$E_{\rm kin} > 1\,{\rm GeV}$
K_L^0	0.2	870	$E_{\rm kin} > 0.5\,{\rm GeV}$
$\pi^\pm + K^\pm$	0.5	$3 \cdot 10^4$	$E_{\rm kin} > 0.5\,{\rm GeV}$
$\nu + \bar{\nu}$	0.5	$2 \cdot 10^6$	$E > 0.5\,{\rm GeV}$

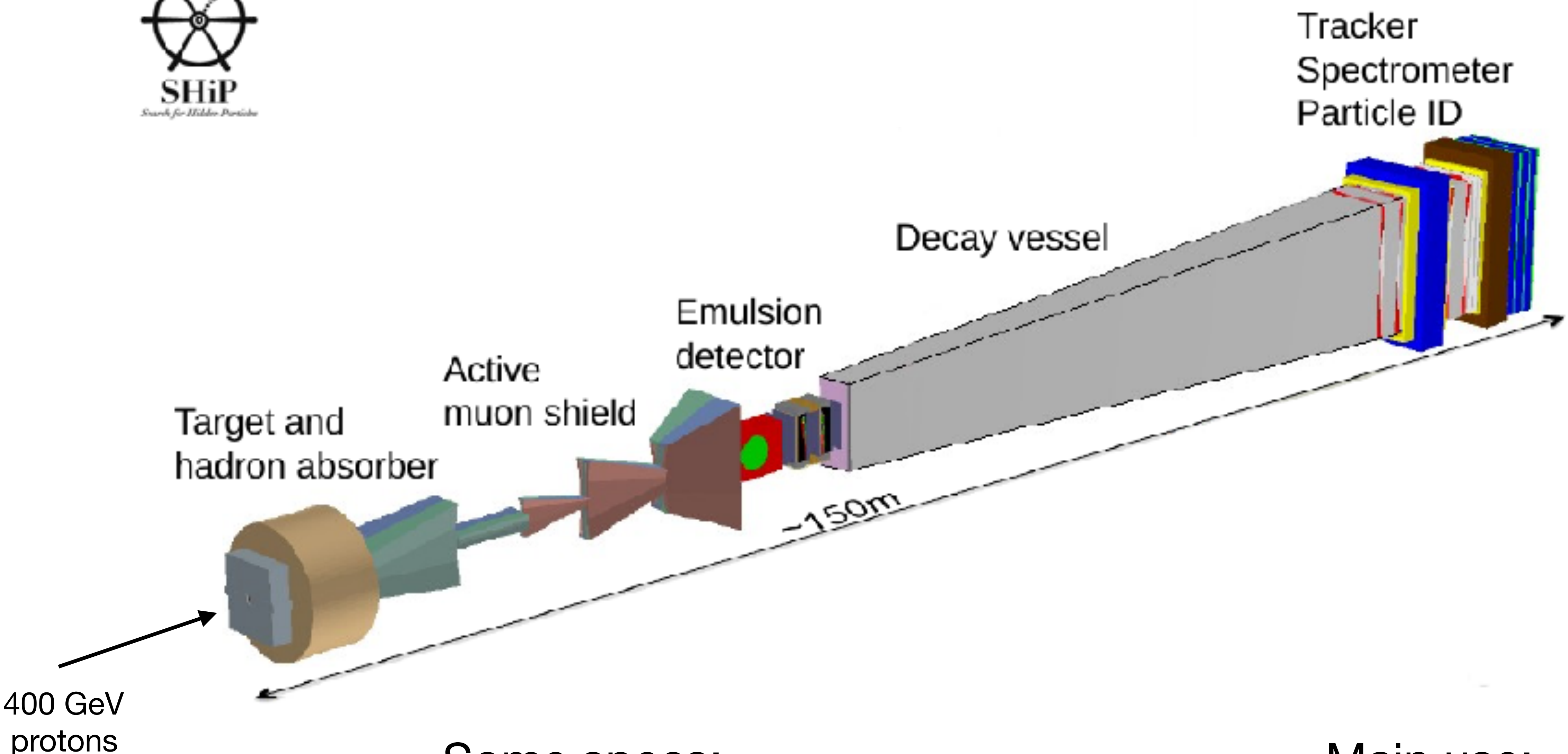


- need 10^{-4} - 10^{-5} muon veto, easily achieved with a few redundant layers
- neutrons dominate, with ~ 5% chance of scattering on air in the box
- secondary neutrinos completely negligible

SHiP

1504.04956: M. Anelli et. al.

Beam dump experiment at the SPS accelerator



Some specs:

- 10^{20} protons on target
- $\sqrt{s}$ = 20 GeV
- New beam line needed
- Aiming for 2025 (~ 200 million $)

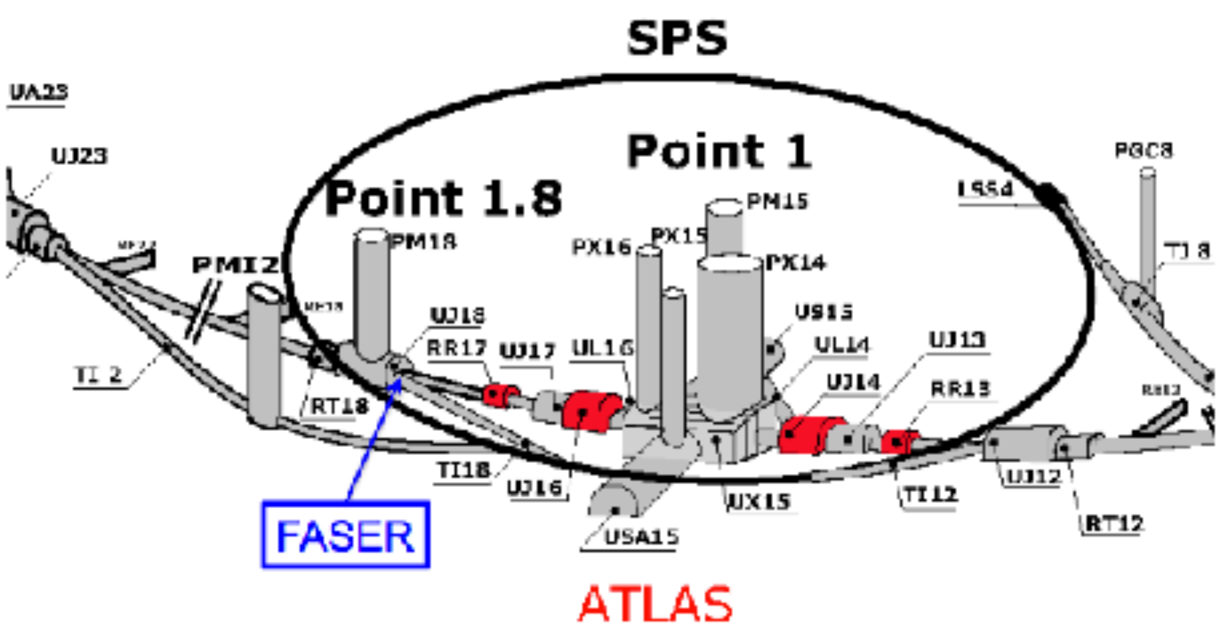
Main use:

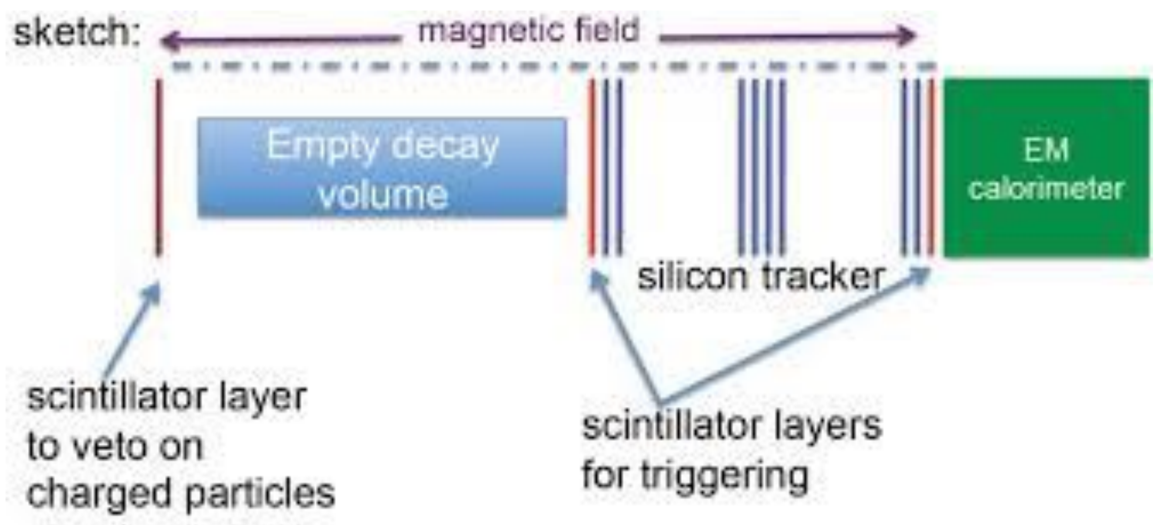
- tau neutrinos
- light sterile neutrinos
- dark photons
- other light LLPs

FASER

1708.09389: J. Feng et. al.

Ultra-forward detector on LHC beam line





Some specs:

- ~ 5-10 meters long
- ~ 400 meters from IP
- Need small but good tracker

Main use:

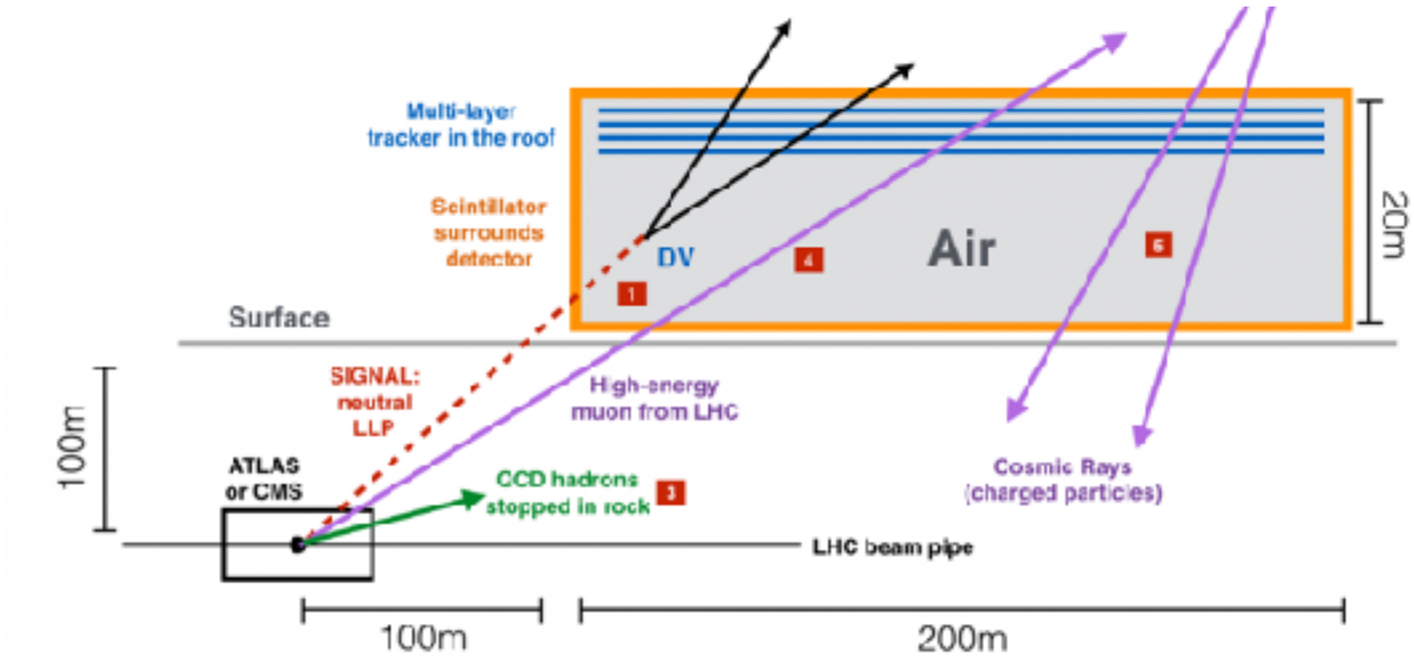
- light sterile neutrinos
- dark photons
- other light LLPs

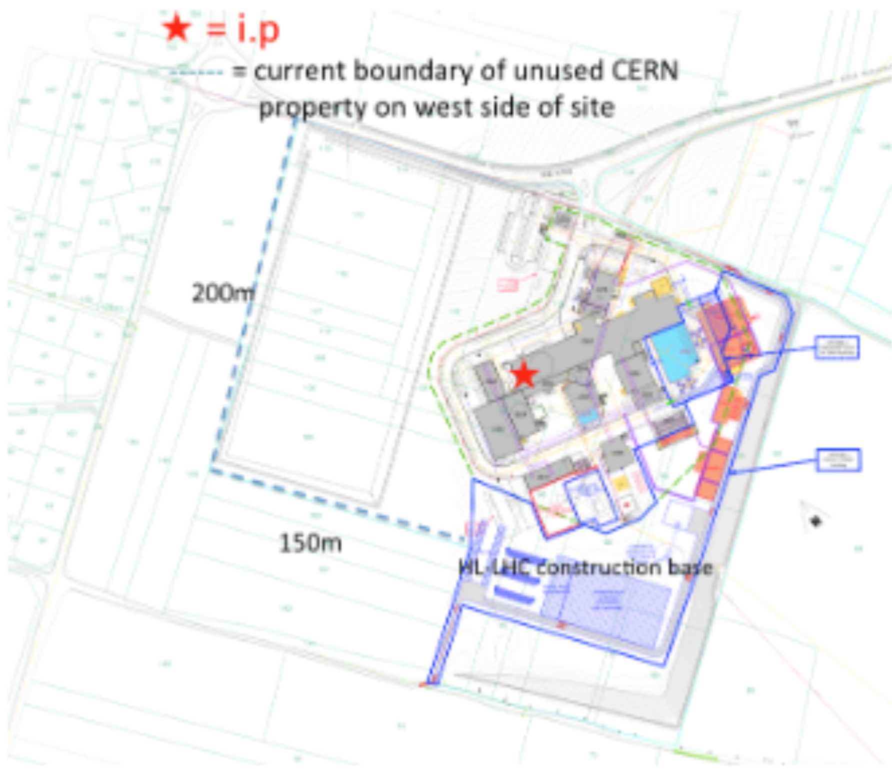
Substantially less reach than SHiP but much cheaper
(For some signals, competition from Fermilab's SeaQuest experiment)

MATHUSLA

CERN-LHCC-2018-025: C. Alpigiani et. al.

(200 m)^2 detector, above CMS





Some specs:

- 200 m x 200 m x 25 m
  (smaller designs considered)
- Construct in 9 m x 9 m x 25 m modules
- RPC's for tracking
- Use timing to reject cosmic rays

Main use:

- Exotic Higgs decays
- LLPs which require high $\sqrt{s}$
- Most light LLPs
  (except dark photon)

Reconstruction efficiency (proof of concept)

- Require 6 hits per track
- Require minimum momentum of 600 MeV per track

$c\tau$ (m)	m_φ $[B \to X_s\varphi]$			m_{γ_d} $[h \to \gamma_d\gamma_d]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
10.0	0.49	0.58	0.74	0.59	0.75	0.84	0.86	0.88
50.0	0.38	0.48	0.74	0.57	0.75	0.82	0.87	0.88
100.0	0.39	0.45	0.73	0.62	0.77	0.83	0.87	0.89
500.0	0.33	0.40	0.75	–	–	–	–	–

low boost — high boost

Reconstruction efficiency (proof of concept)

- Require 6 hits per track
- Require minimum momentum of 600 MeV per track

$c\tau$ (m)	m_φ $[B \to X_s \varphi]$			m_{γ_d} $[h \to \gamma_\mathrm{d}\gamma_\mathrm{d}]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
10.0	0.49	0.58	0.74	0.59	0.75	0.84	0.86	0.88
50.0	0.38	0.48	0.74	0.57	0.75	0.82	0.87	0.88
100.0	0.39	0.45	0.73	0.62	0.77	0.83	0.87	0.89
500.0	0.33	0.40	0.75	–	–	–	–	–

low boost — high boost

600 MeV cut

Reconstruction efficiency (proof of concept)

- Require 6 hits per track
- Require minimum momentum of 600 MeV per track

$c\tau$ (m)	m_φ $[B \to X_s \varphi]$			m_{γ_d} $[h \to \gamma_d \gamma_d]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
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100.0	0.39	0.45	0.73	0.62	0.77	0.83	0.87	0.89
500.0	0.33	0.40	0.75	–	–	–	–	–

low boost

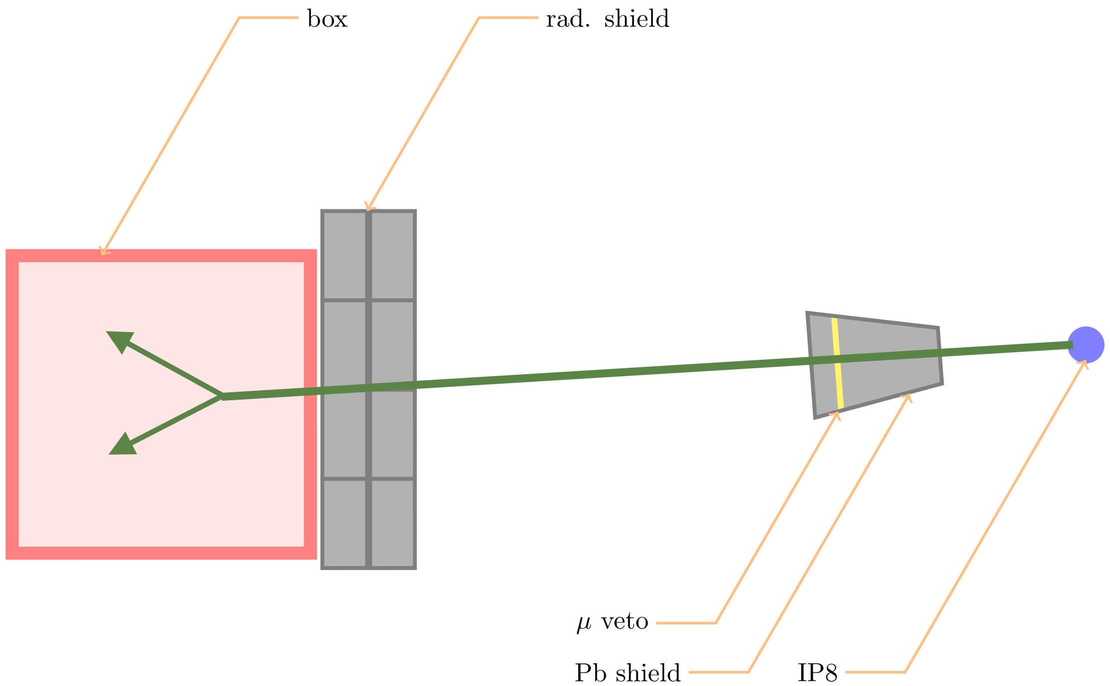
high boost

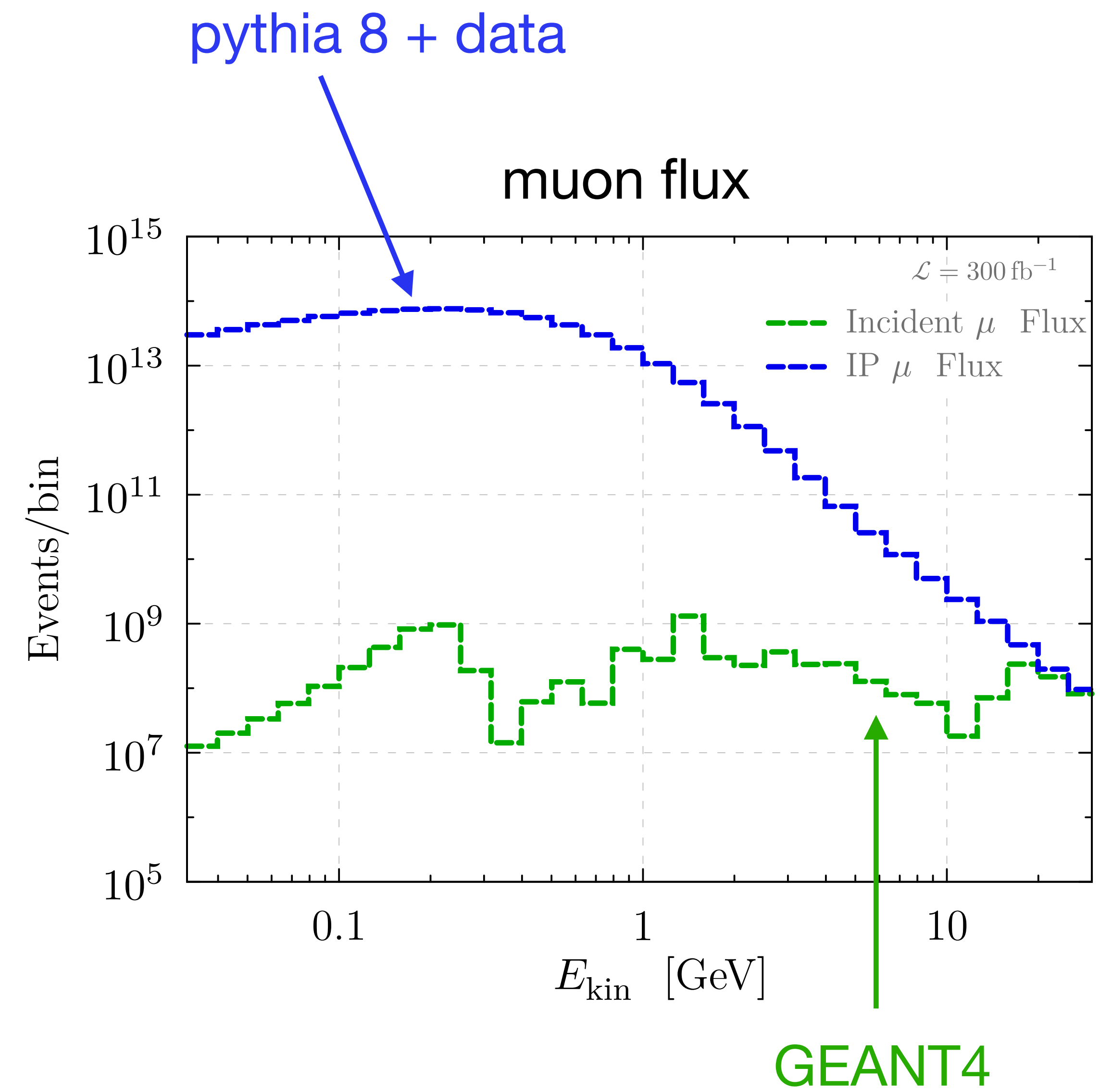
600 MeV cut

small opening angle,
overlapping decay products

Backgrounds

muons scattering on air





with mb crosssection, scattering probability is ~ 10^{-3}

↓

~ 10^7 events but can be veto-ed with shield veto + front face of the box

Backgrounds

Reduced by the shield:

- neutrons scattering on air
- K_L

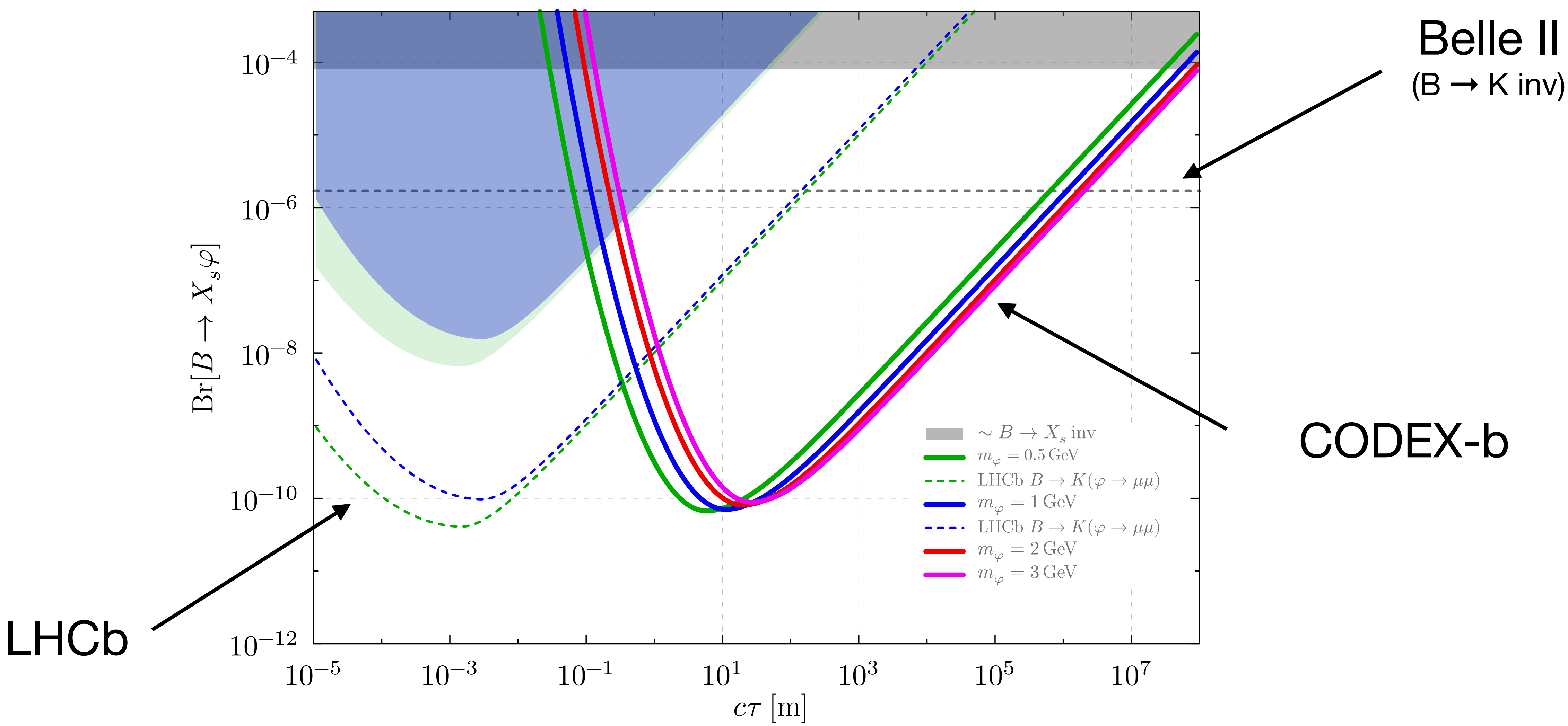
Need ~ 40 interaction lengths + 10^{-8} muon veto

BG species	Full shield (S_1–S_2)		Evade shield	Net BG flux/event into detector	BG rate per 100 fb^{-1}
	shield veto rate	BG flux/event	BG flux/event		
$n+\bar{n}$ (> 0.5 GeV)	—	$3. \times 10^{-14}$	—	$2. \times 10^{-7}$	$\lesssim 10$
$p+\bar{p}$	$2. \times 10^{-6}$	$4. \times 10^{-15}$	—	$2. \times 10^{-7}$	—
μ	0.008	$1. \times 10^{-11}$	0.007	0.008	—
e	$3. \times 10^{-7}$	$2. \times 10^{-15}$	—	$2. \times 10^{-7}$	—
K_L^0	—	$5. \times 10^{-17}$	—	$4. \times 10^{-9}$	$\ll 1$
K_S^0	—	$1. \times 10^{-17}$	—	$1. \times 10^{-9}$	$\ll 1$
γ	—	$6. \times 10^{-16}$	—	$3. \times 10^{-8}$	—
$\pi^\pm$	$1. \times 10^{-6}$	$5. \times 10^{-15}$	—	$2. \times 10^{-7}$	—
$\nu+\bar{\nu}$ (> 0.25 GeV)	—	0.2	0.02	0.2	$\lesssim 10$

GEANT4 simulation: Low background setup appears possible

More general models

Reach



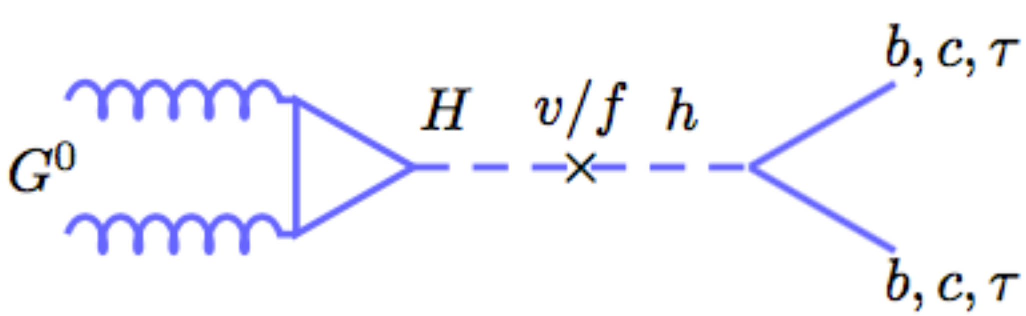
Complementary reach compared to main LHCb detector

(Branching ratio to muons is irrelevant for CODEX-b)

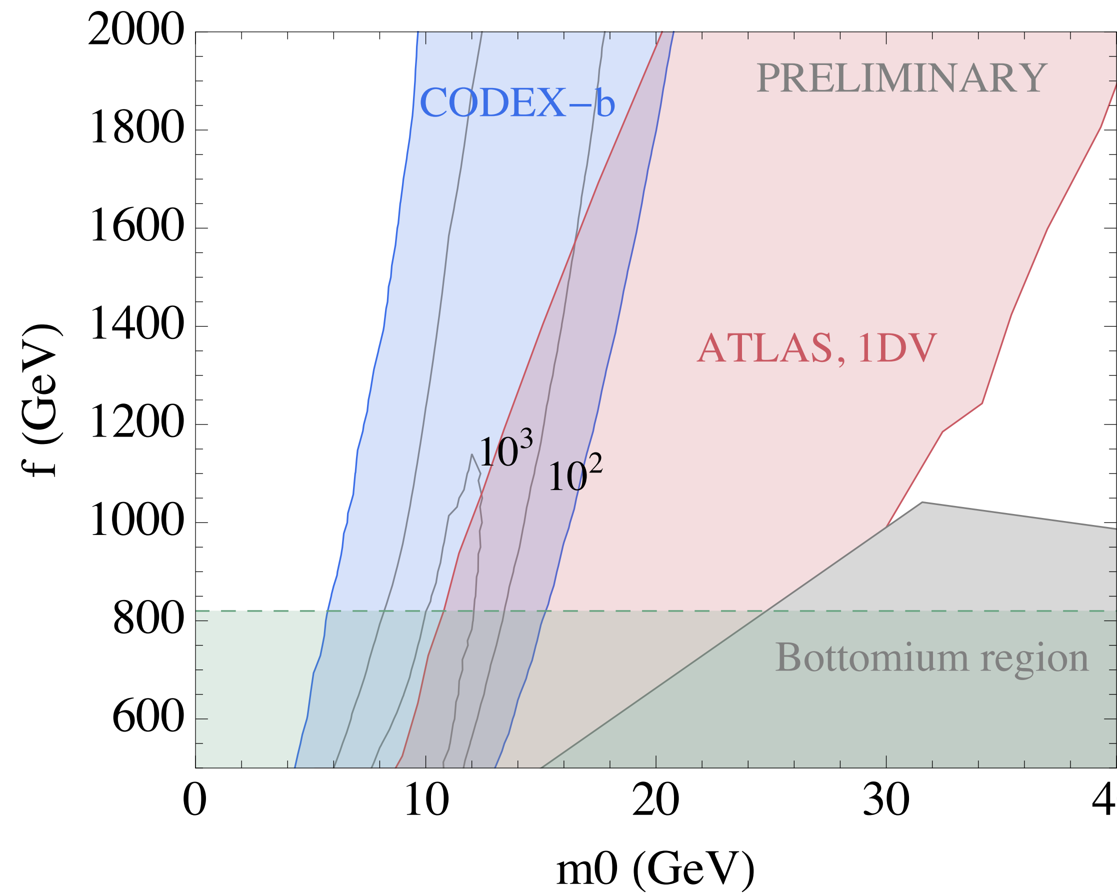
Hidden glueballs (Neutral Naturalness)

Production: exotic Higgs decay

Decay: through Higgs mixing:



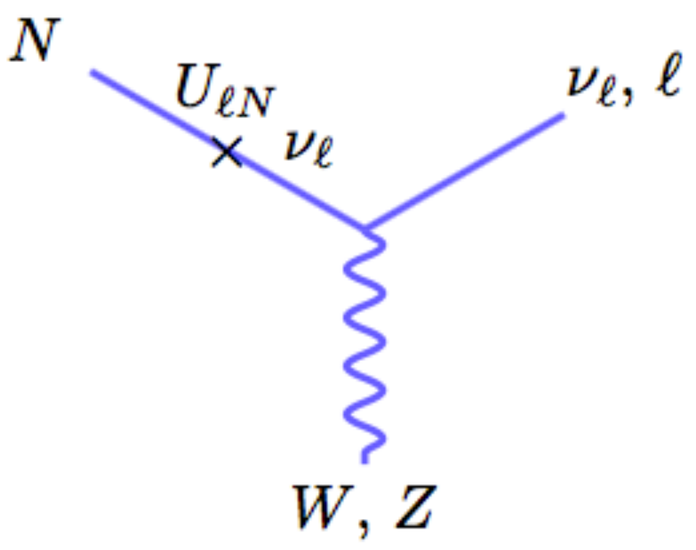
Lifetime very strong function of glueball mass $c\tau \sim m_0^{-7}$



ATLAS / CMS pay double penalty at low mass:

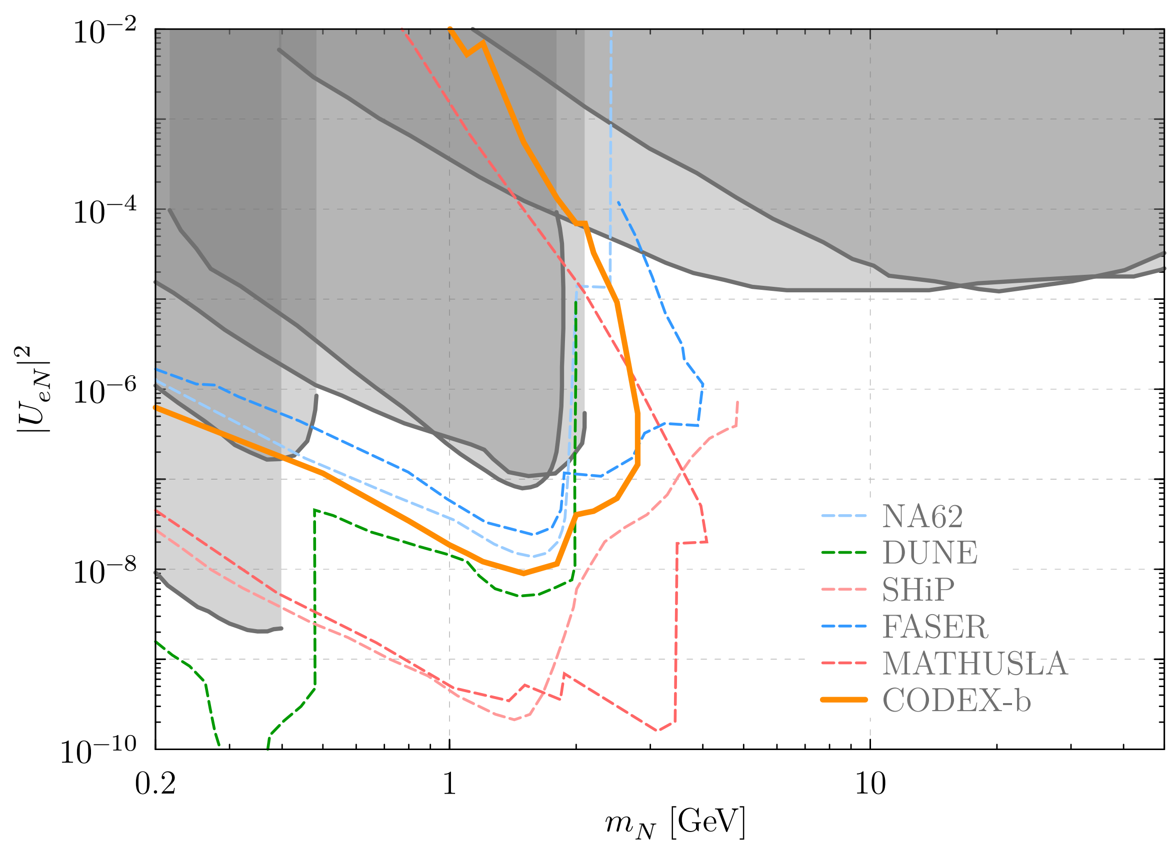
- Backgrounds go up
- Requiring a second displaced vertex kills the signal rate

Heavy neutral leptons



- Production: any SM decay with neutrinos
  (c, b, τ, W & Z decays)
- Decay: Mix back to off-shell SM neutrino
  (N→3ν, N→ℓ hadrons, N→νℓℓ)

Example: U_{eN}



$U_{\mu N}$ and $U_{\tau N}$ in the back-up material

18xx.xxxxx: J. Evans, SK, M. Papucci, H. Ramani D. Robinson

see also: Heo, Hirsch, Wang: 1803.02212

Heavy neutral leptons

- Production: any SM decay with neutrinos
  (c, b, τ, W & Z decays)

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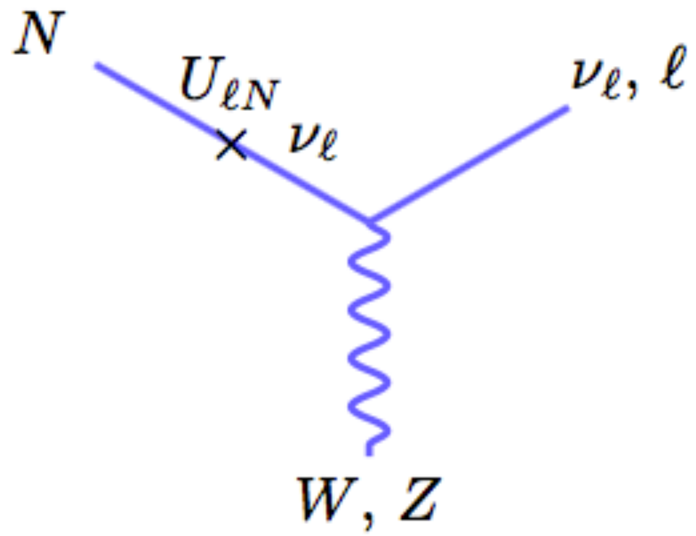
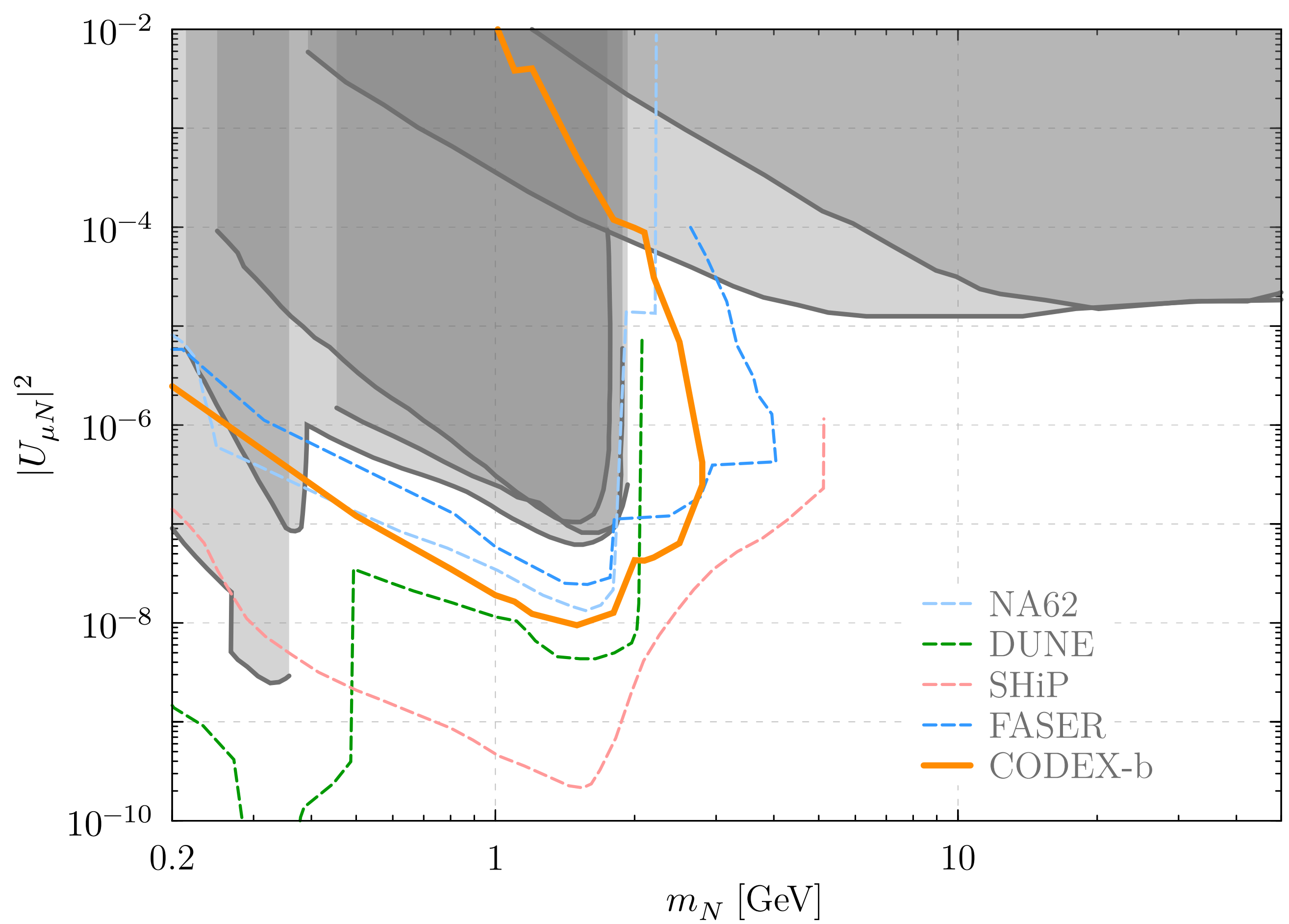


Example: $U_{\mu N}$



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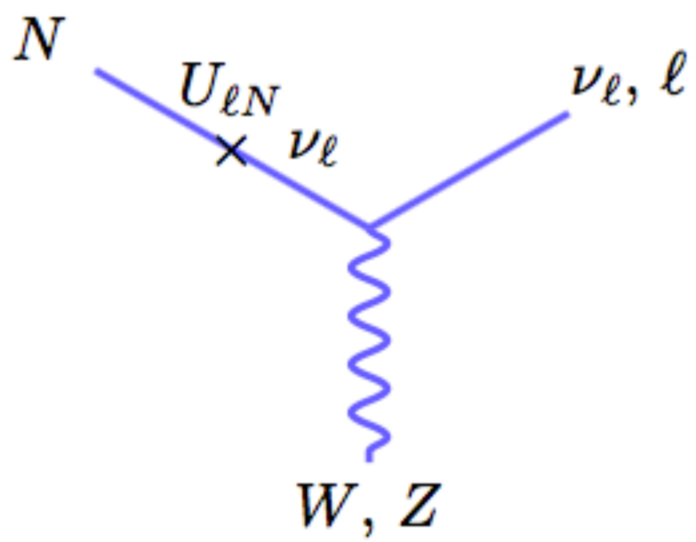
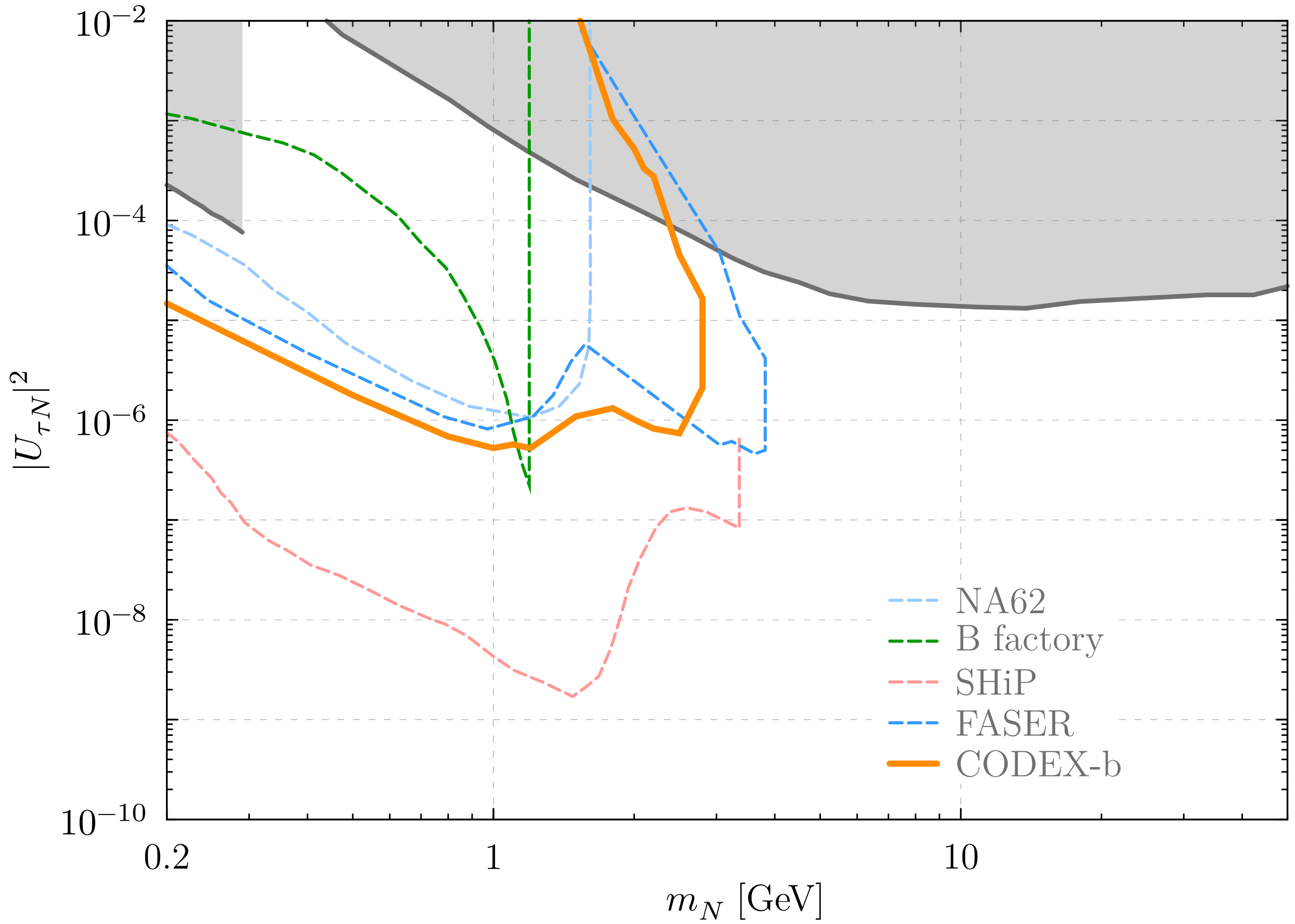


Example: $U_{\tau N}$



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