Exploring the lifetime frontier

Supplementary detectors

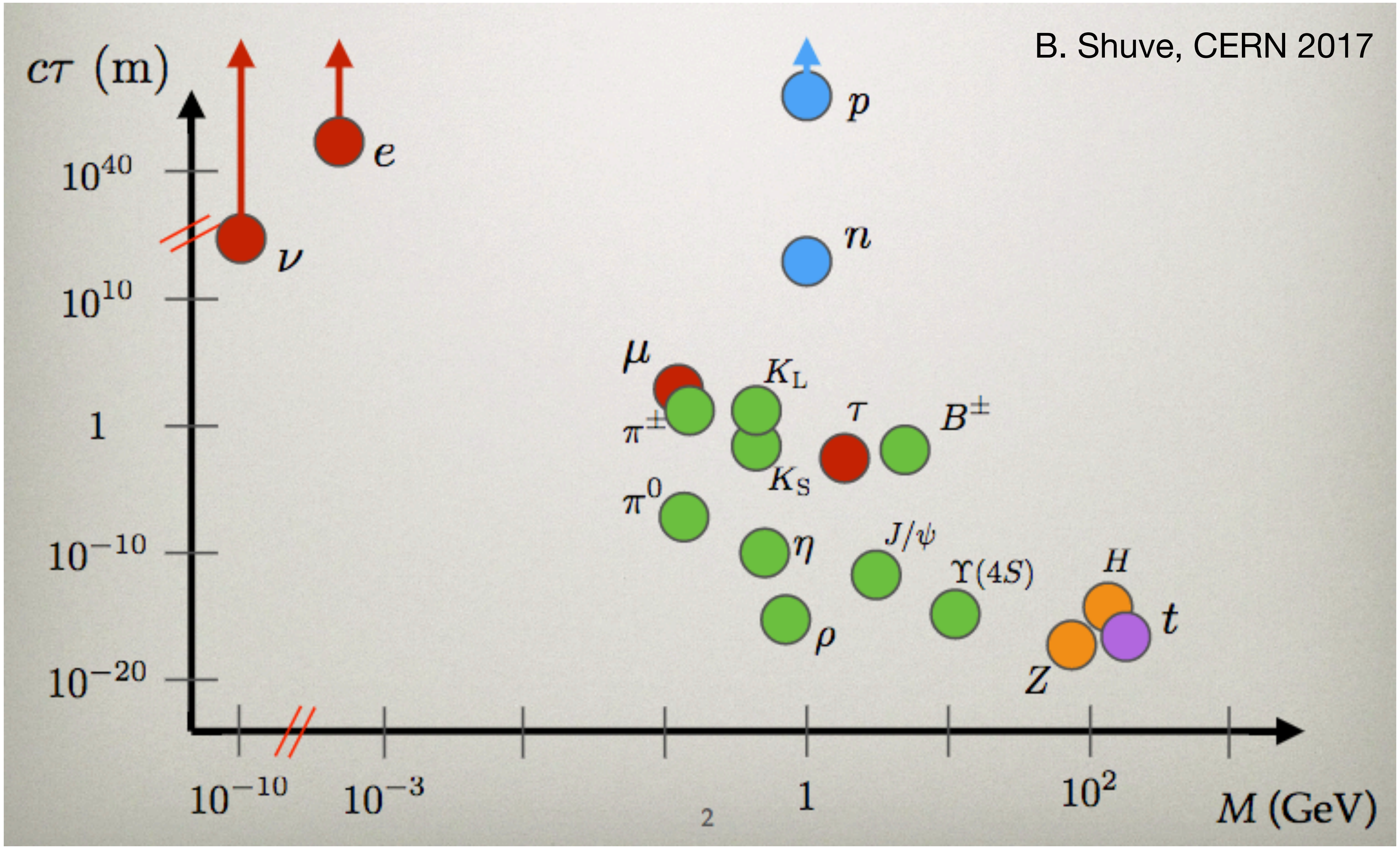
Simon Knapen
Institute for Advanced Study

@ Fermilab
09 / 18 / 18

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.09395
V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 18xx.xxxxx

Long-Lived Particles are generic

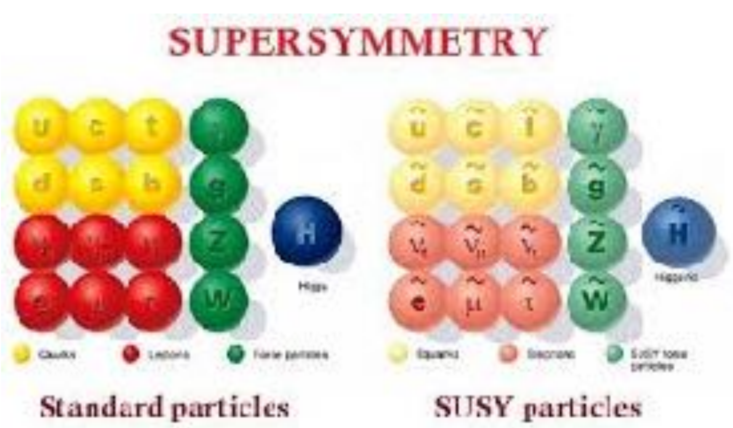
1. We already know many



Because $m_W >> \Lambda_{QCD}$

Long-Lived Particles are generic

2. Also generic in BSM



R-parity violation	Asymmetric Dark Matter	Baryogenesis
Gauge mediation	Freeze-in	Neutrino masses
(mini-)split SUSY	composite Dark Matter	Neutral Naturalness
stealth SUSY	…	Hidden Valleys
		…

Wide range of masses & lifetimes → no single experiment has comprehensive coverage

Theory priors

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

Three mechanisms:

- Off-shell decay (e.g. $\pi^{\pm}$)
- Small splitting (e.g. neutrons)
- Small coupling

small coupling

$$\Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

Set by symmetry structure, typically n ≥ 4

$m \ll M$

hierarchy of scales

➡ Lifetime strong function of mass

➡ Light (~ GeV) hidden states are generically long-lived

* could either be a hierarchy or loop suppression

Experimental Landscape (ATLAS/CMS)

Searches for long-lived particles at the Large Hadron Collider at CERN

September 24, 2017

Emmy Noether *Bryn Mawr College, Pennsylvania, USA*

Contact editors: lhc-llp-admin@cern.ch

Contents

1 *Introduction* 5
1.1 *Goals of the White Paper* 5
2 *Simplified Model Framework* 7
2.1 *Goals of the Present Simplified Model Framework* 9
4.4 *Current and Proposed Dedicated LLP Detectors* 27
5 *Recommendations for the Presentation of Search Results* 29
5.1 *Important Factors for Result Reinterpretation* 29

ely

ve

Fermilab theory:

Zhen Liu

Matthew Low

A growing subfield

Genera ... es ?

Experimental Challenges

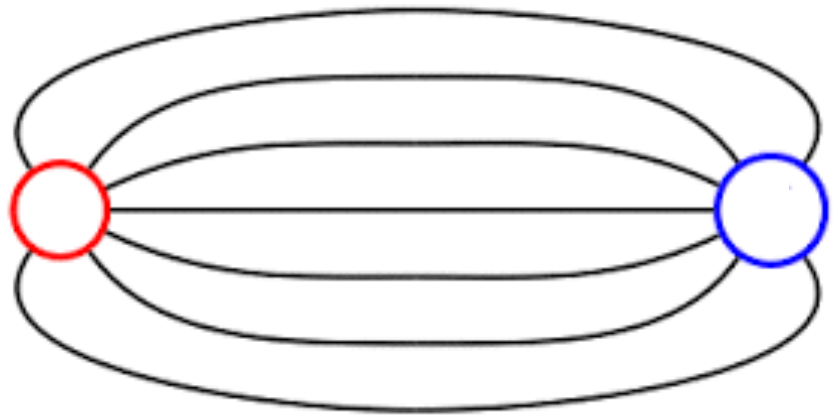
1. Triggers: Tracker detectors are very powerful for LLP's but difficult to trigger. (LHCb, CMS track trigger, …)

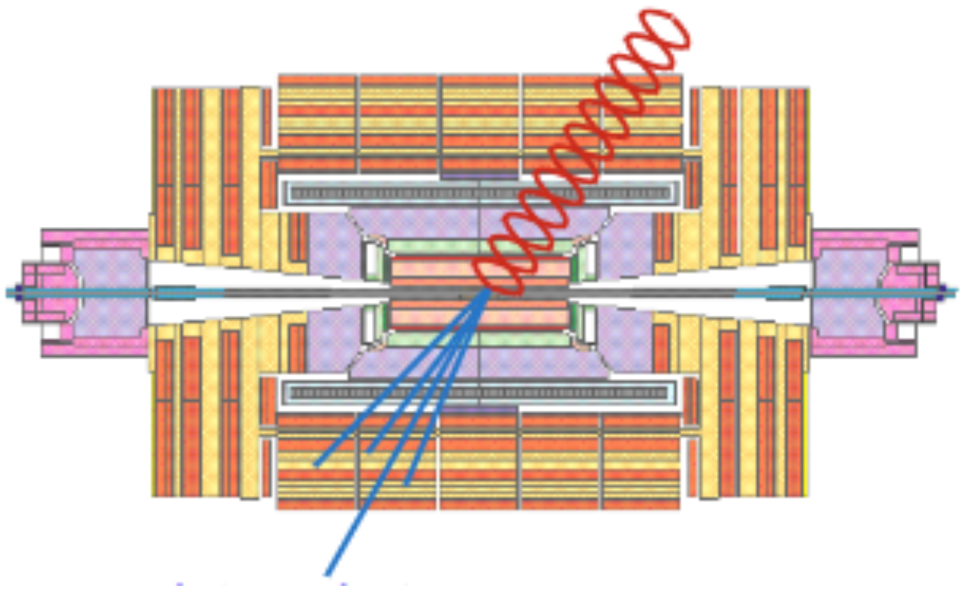
2. Backgrounds: Often low, but subtle (punch-through jets, cosmics, secondaries, …)

3. Reconstruction: Special tracking algorithms needed, large number of unassociated hits.

Tracking example: quirks

Essentially a flux tube of a dark confining sector





Oscillates, eventually annihilates

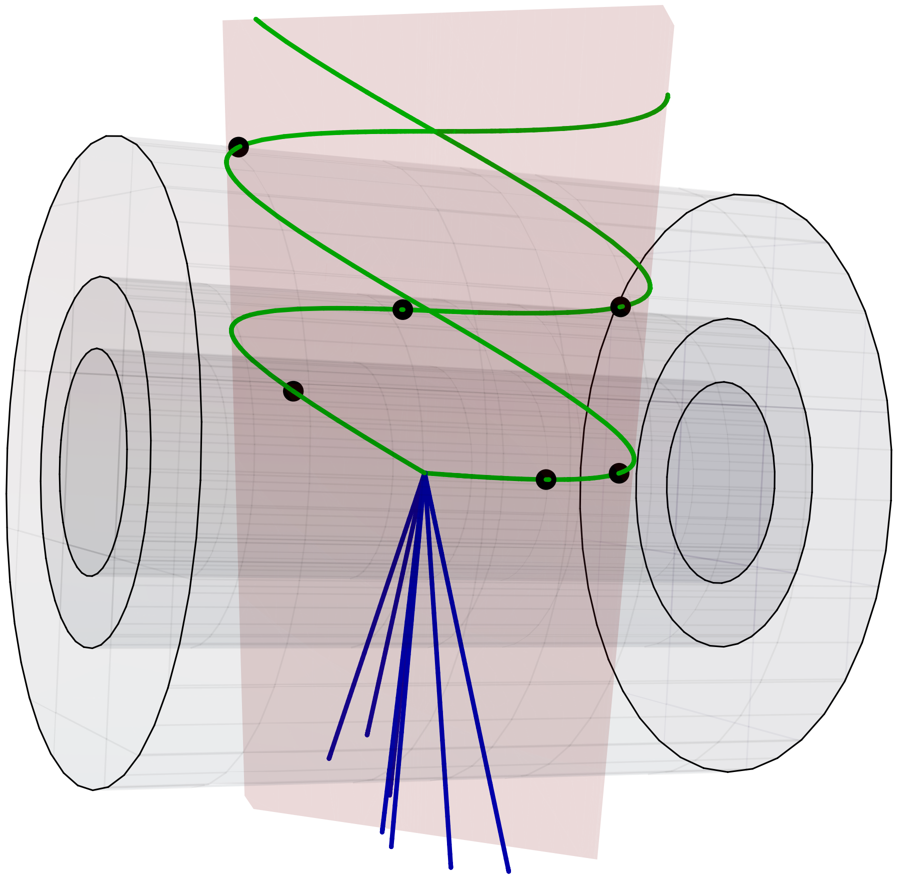
J. Kang, M. Luty: arXiv: 0805.4642

Quirk-antiquirk pairs cannot be created, flux tube never breaks

Need model-independent ways to find unconventional tracks

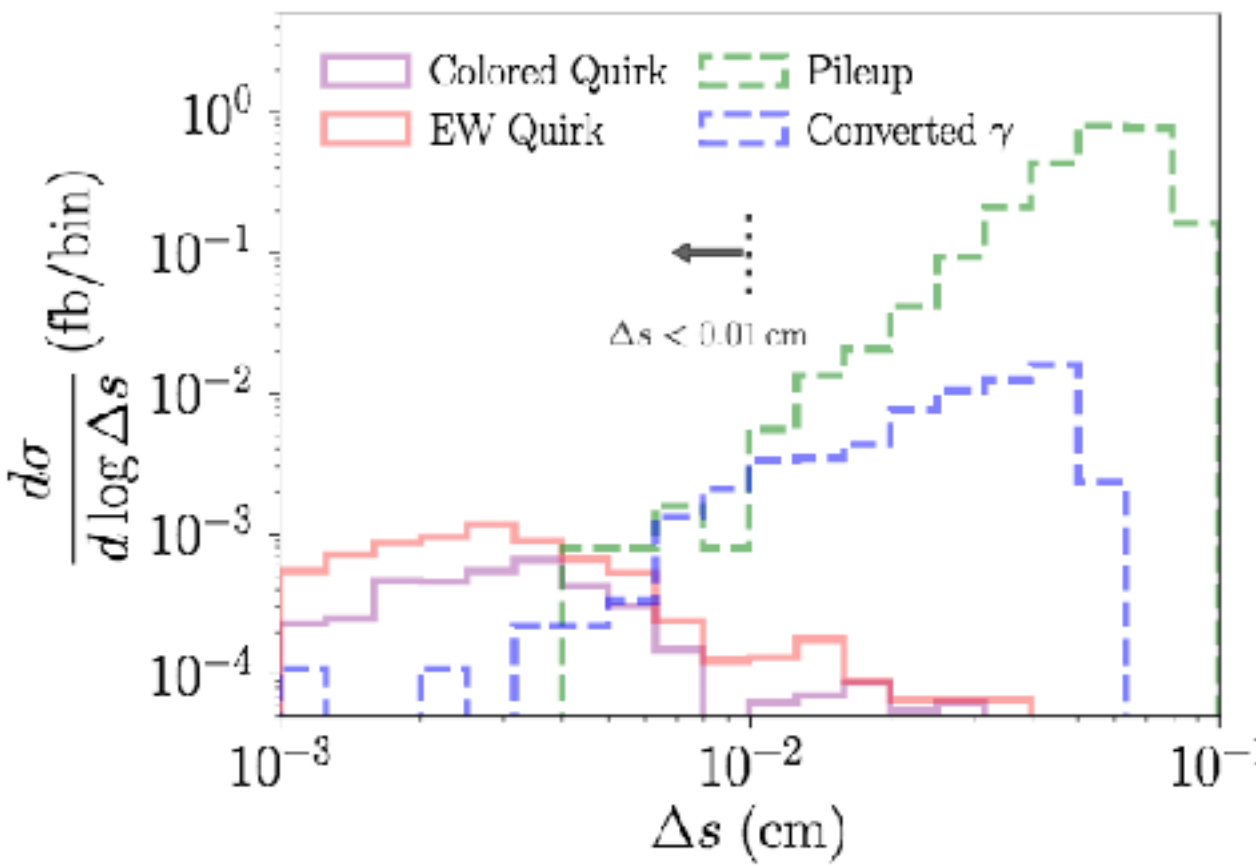
underneath pile-up background

“Tracking” Quirks



All hits lay in a plane

“thickness” of the plane



As long as the string tension >> Lorentz force, the trajectories will be planar

(valid for any central force)

SK, T. Lou, M. Papucci, J. Setford: 1708.02243

Finding Long-Lived Particles

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

… but for low masses they suffer from:

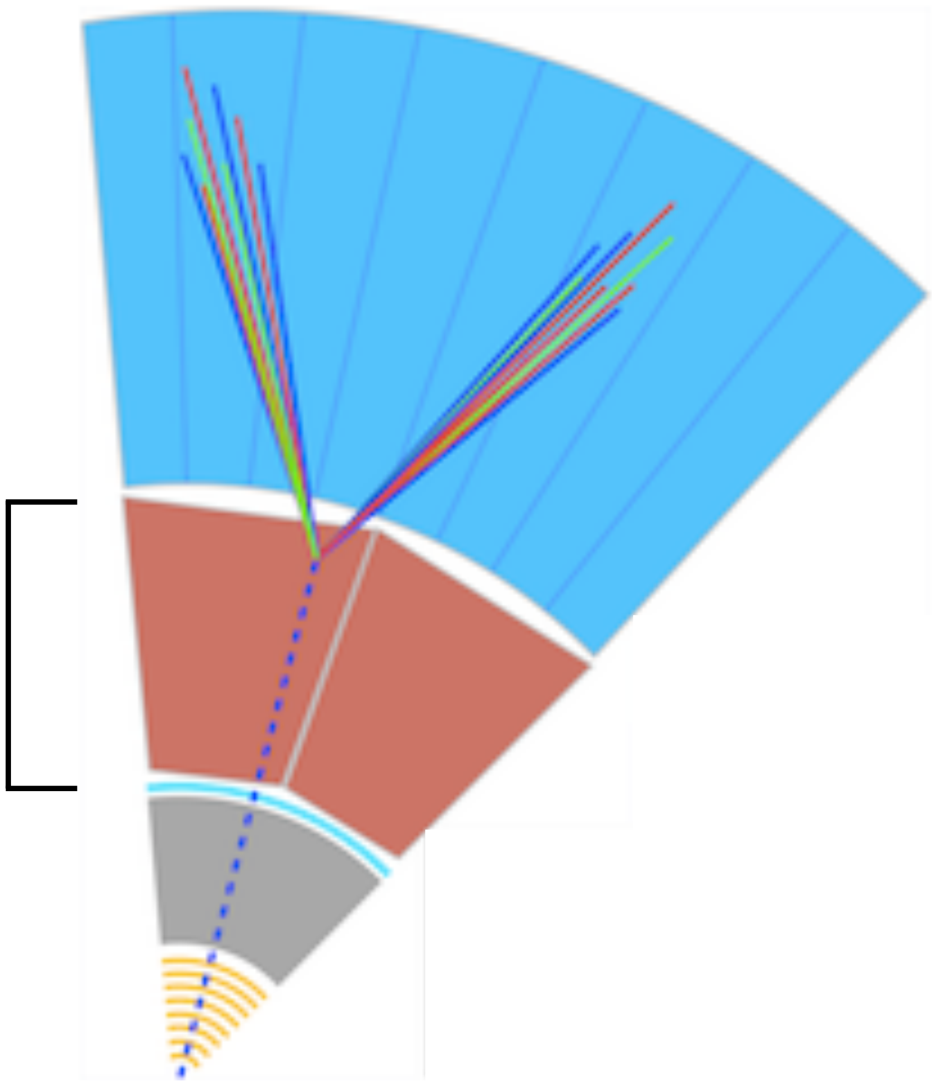
1. Tight trigger requirements
2. Backgrounds

A typical hadron has a chance of

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

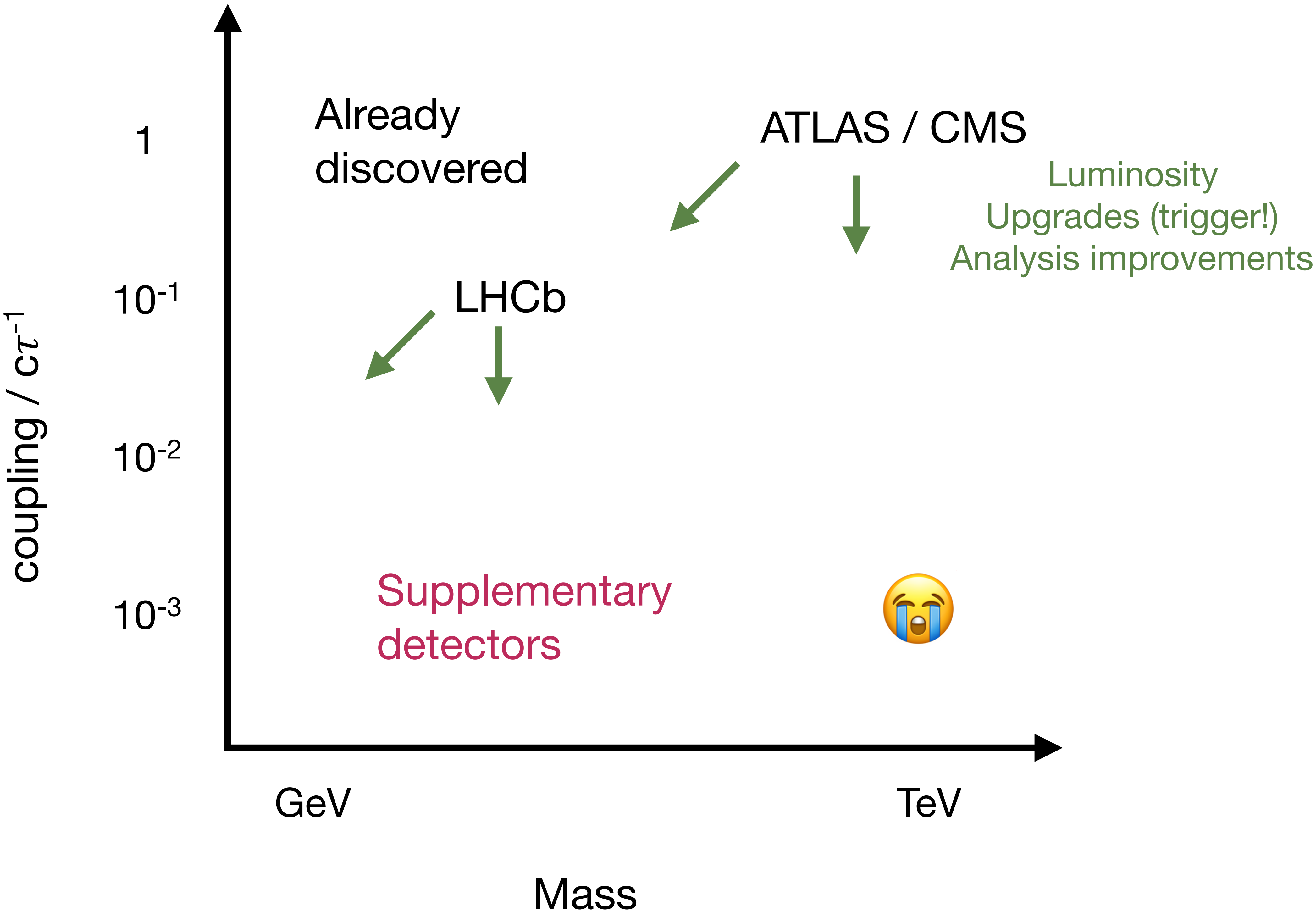
… but the LHC makes ~ 10^{9} K_L mesons /s

~ 10 nuclear interaction lengths (ATLAS)



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

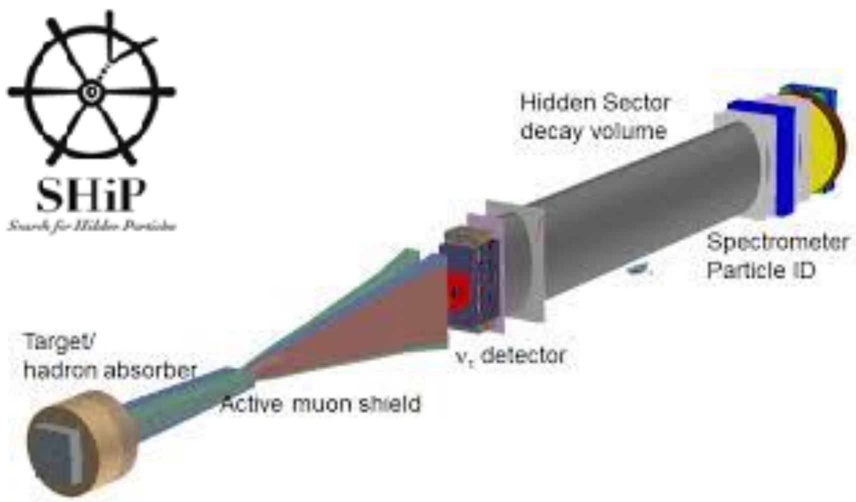
Lifetime frontier



(HIGHLY oversimplified!)

Detectors for the lifetime frontier

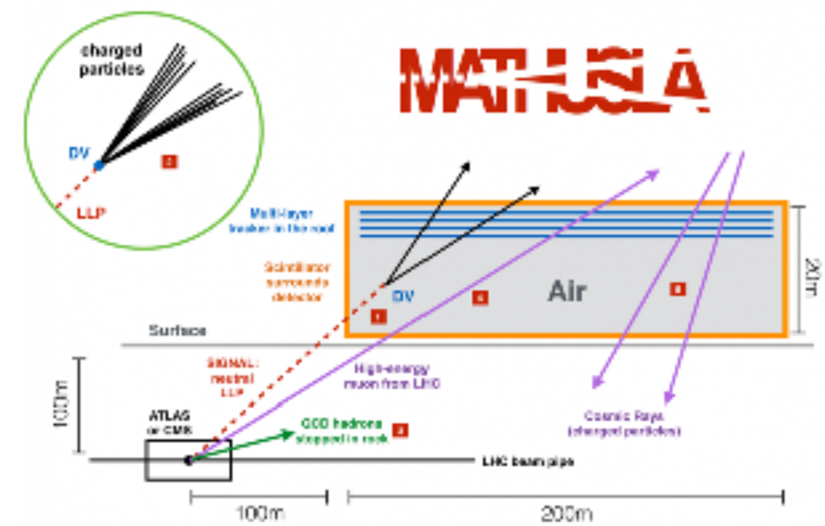
"Ambitious" proposals



SHiP

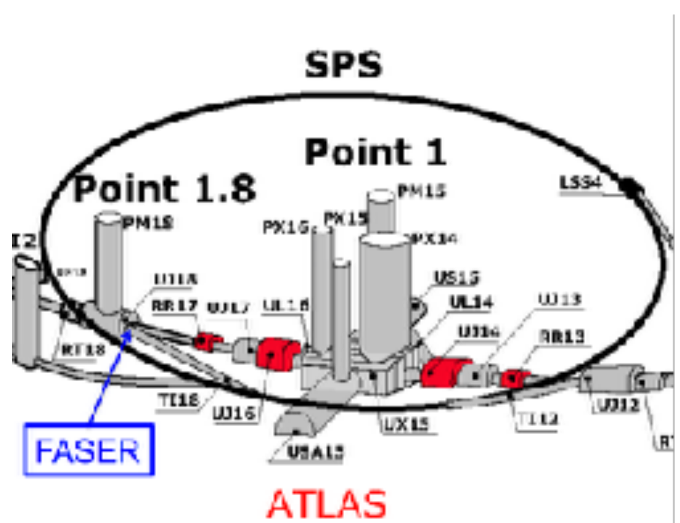
?

Other ideas



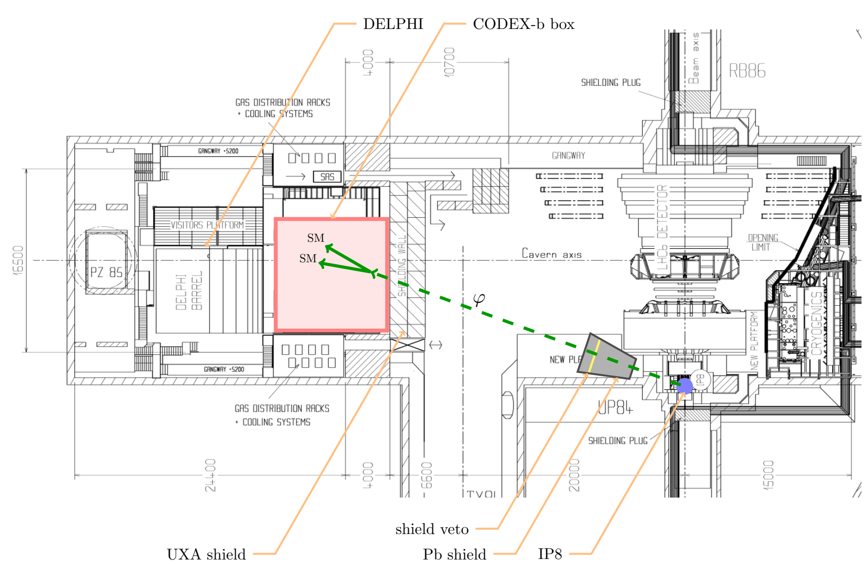
MATHUSLA

"Modest" proposals



FASER

Miliqan

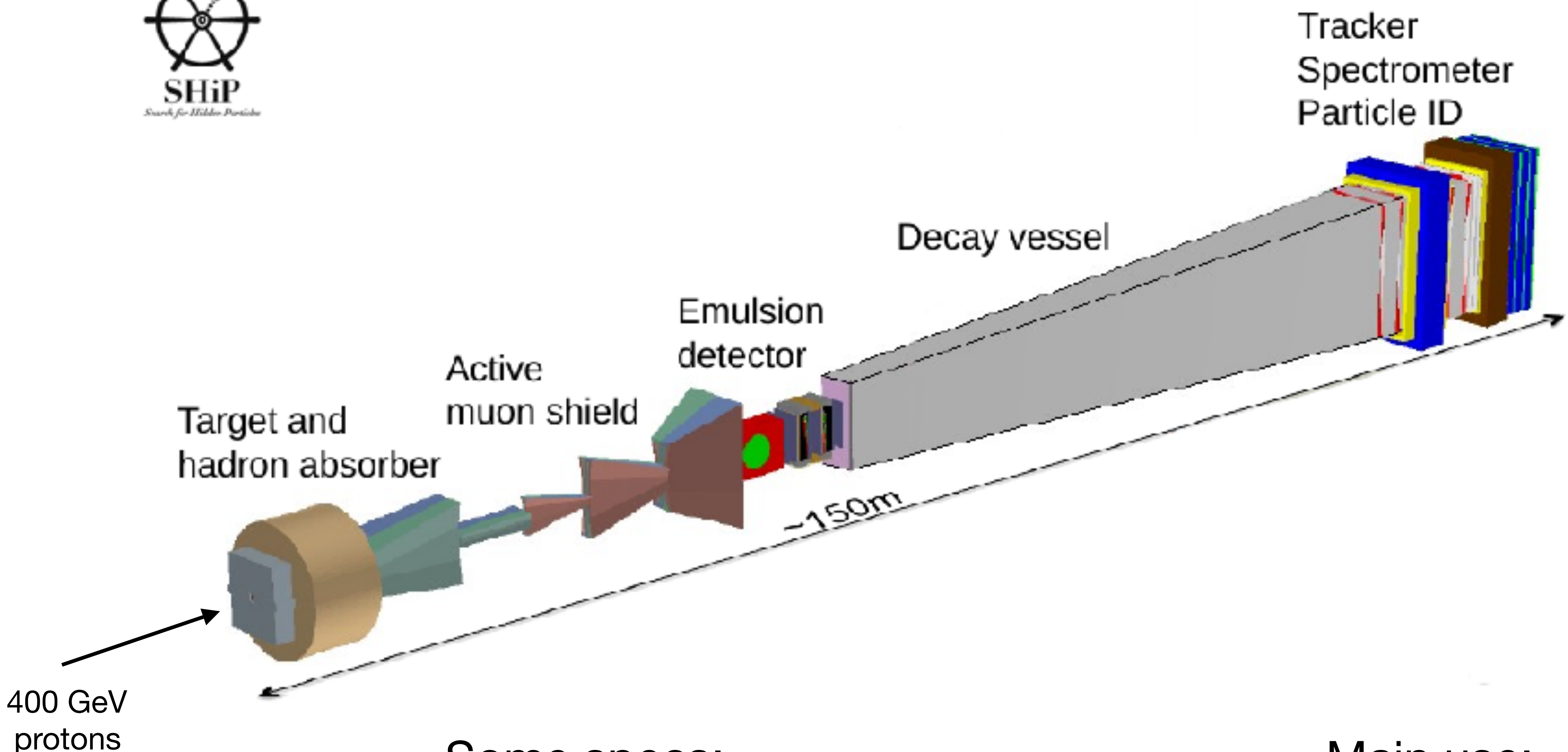


CODEX-b

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 $)

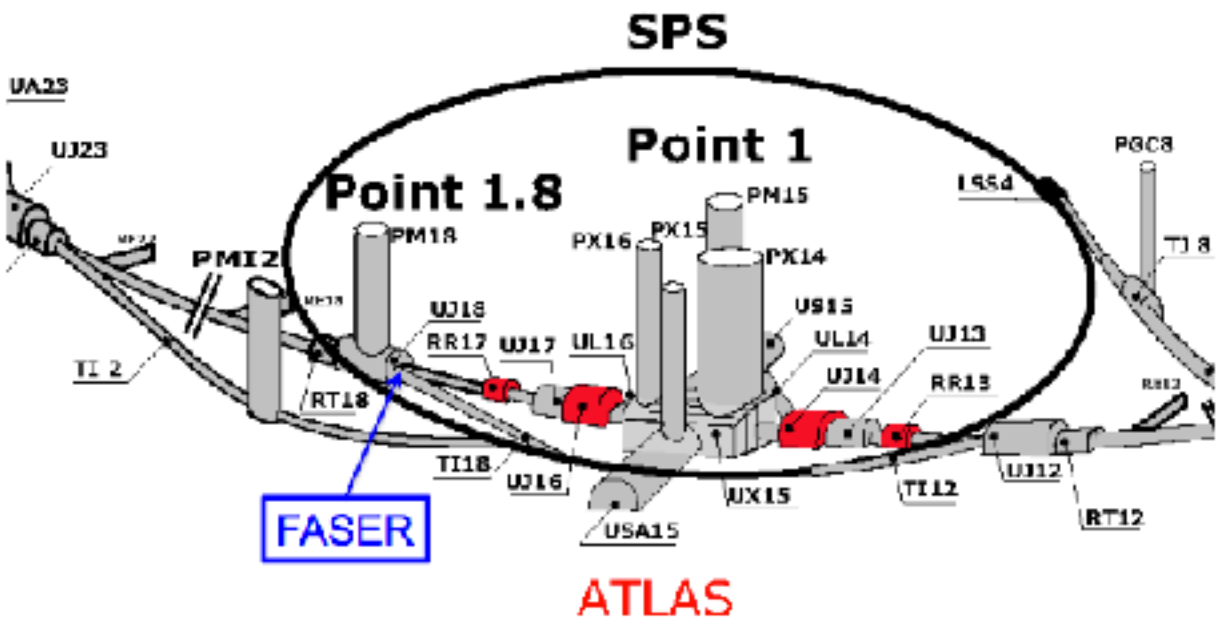
Main use:

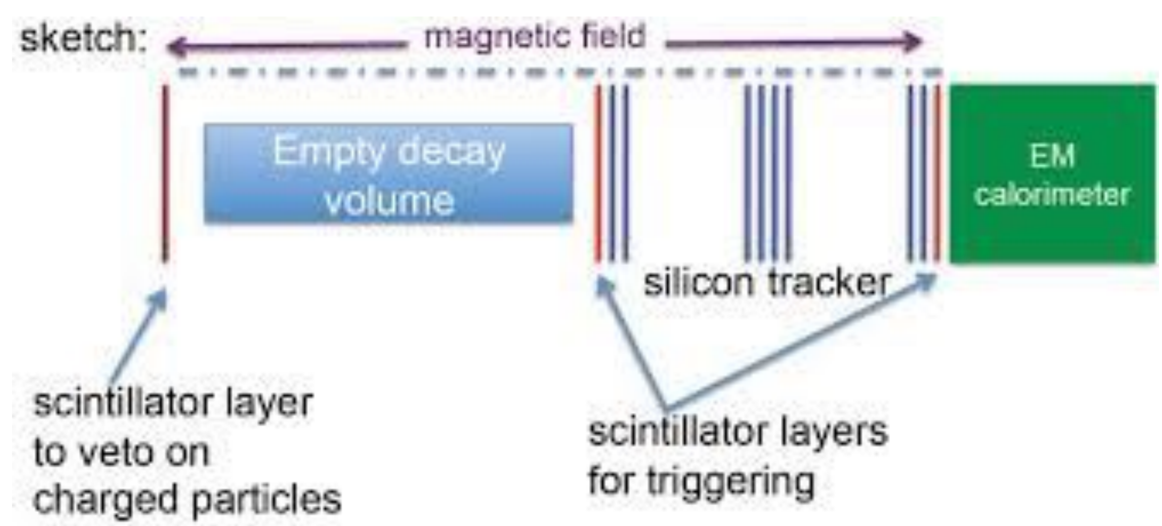
- tau neutrinos
- light sterile neutrinos
- dark photons
- other light LLPs

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:

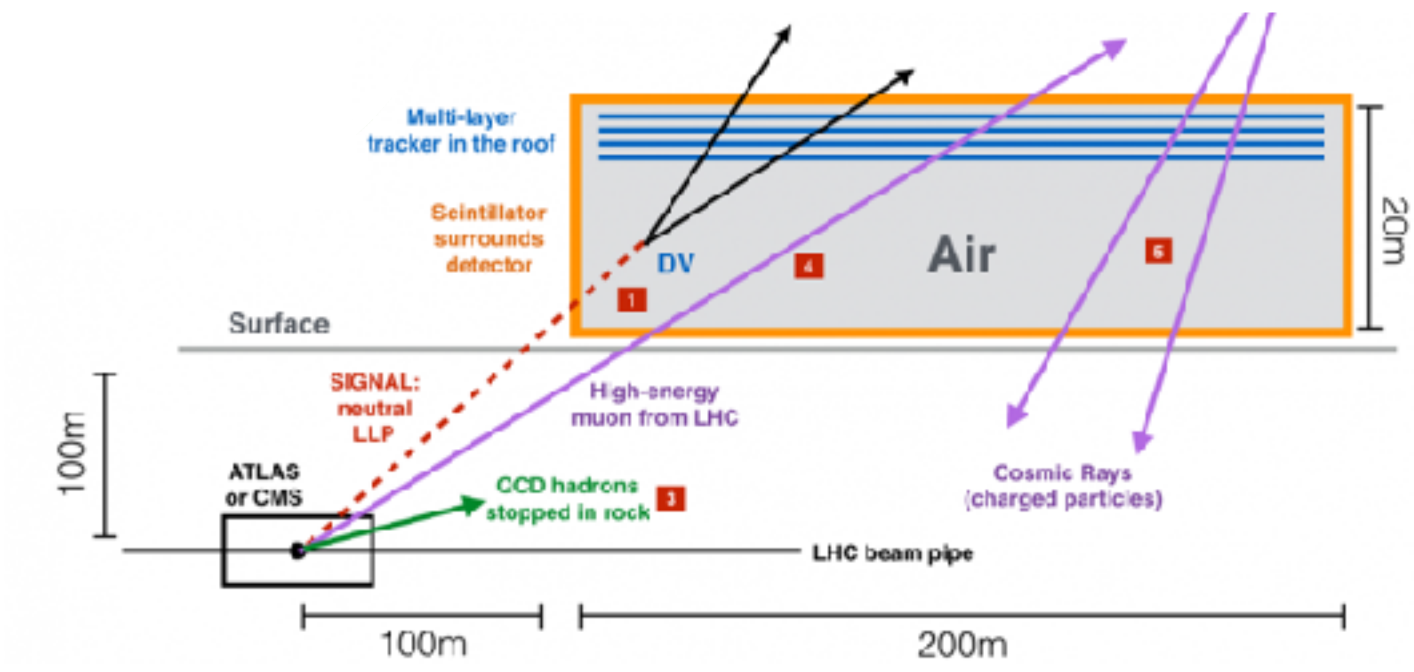
- light sterile neutrinos
- dark photons
- other light LLPs

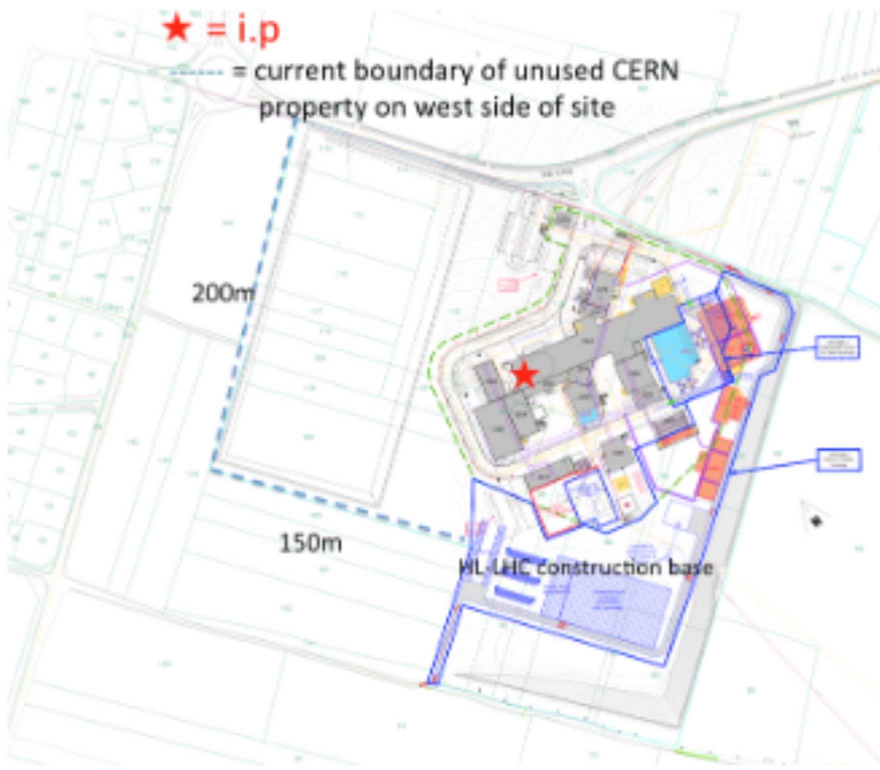
Substantially less reach than SHiP but much cheaper
(For some signals, competition from Fermilab's SeaQuest experiment)

MATHUSLA

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

(200 m)^2 detector, above CMS





Some specs:

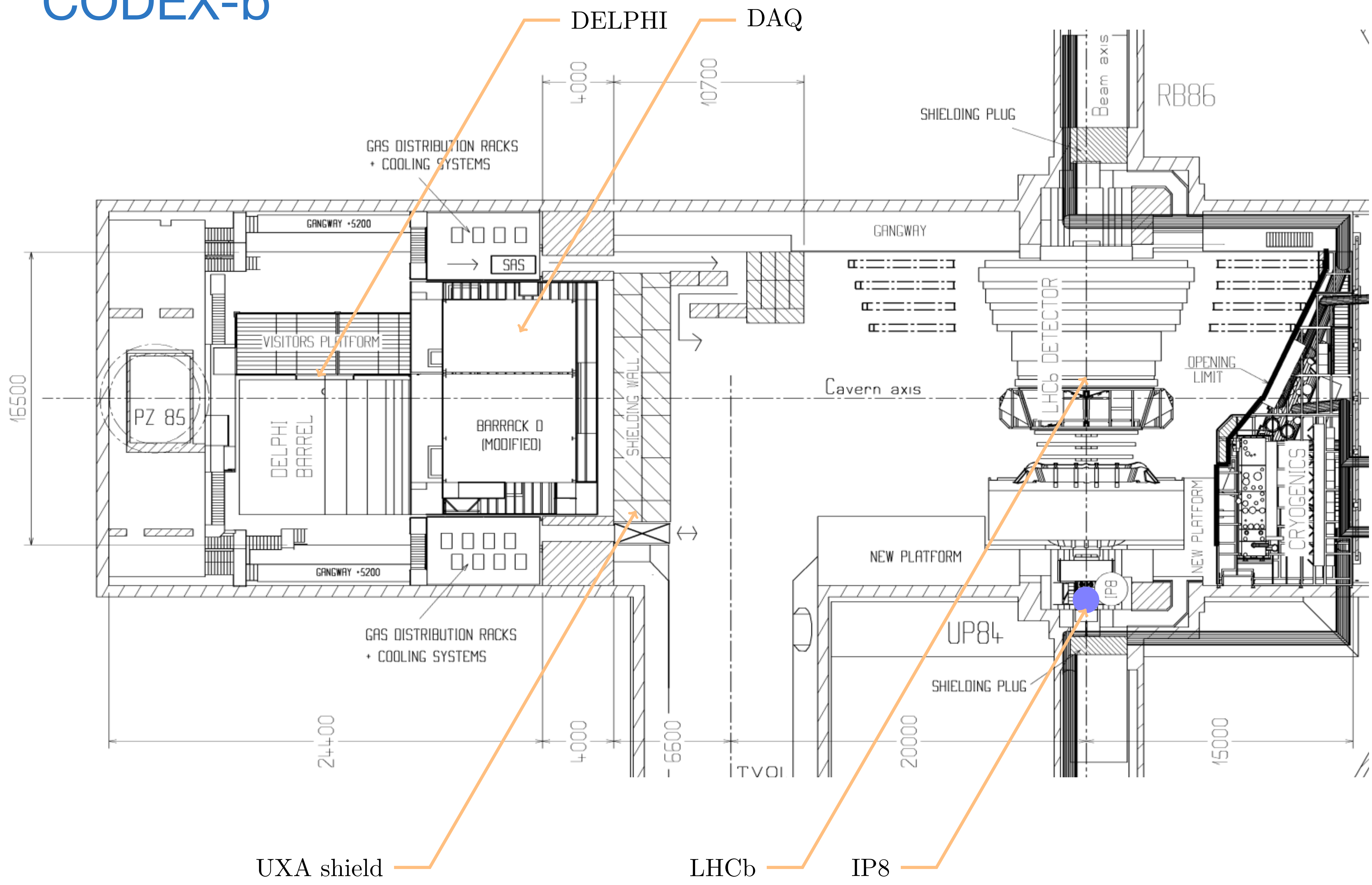
- 200 m x 200 m x 25 m
  (smaller designs considered)
- Construct in 9 m x 9 m x 25 m modules
- RPC’s for tracking
- Use timing to reject cosmic rays

Main use:

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

CODEX-b

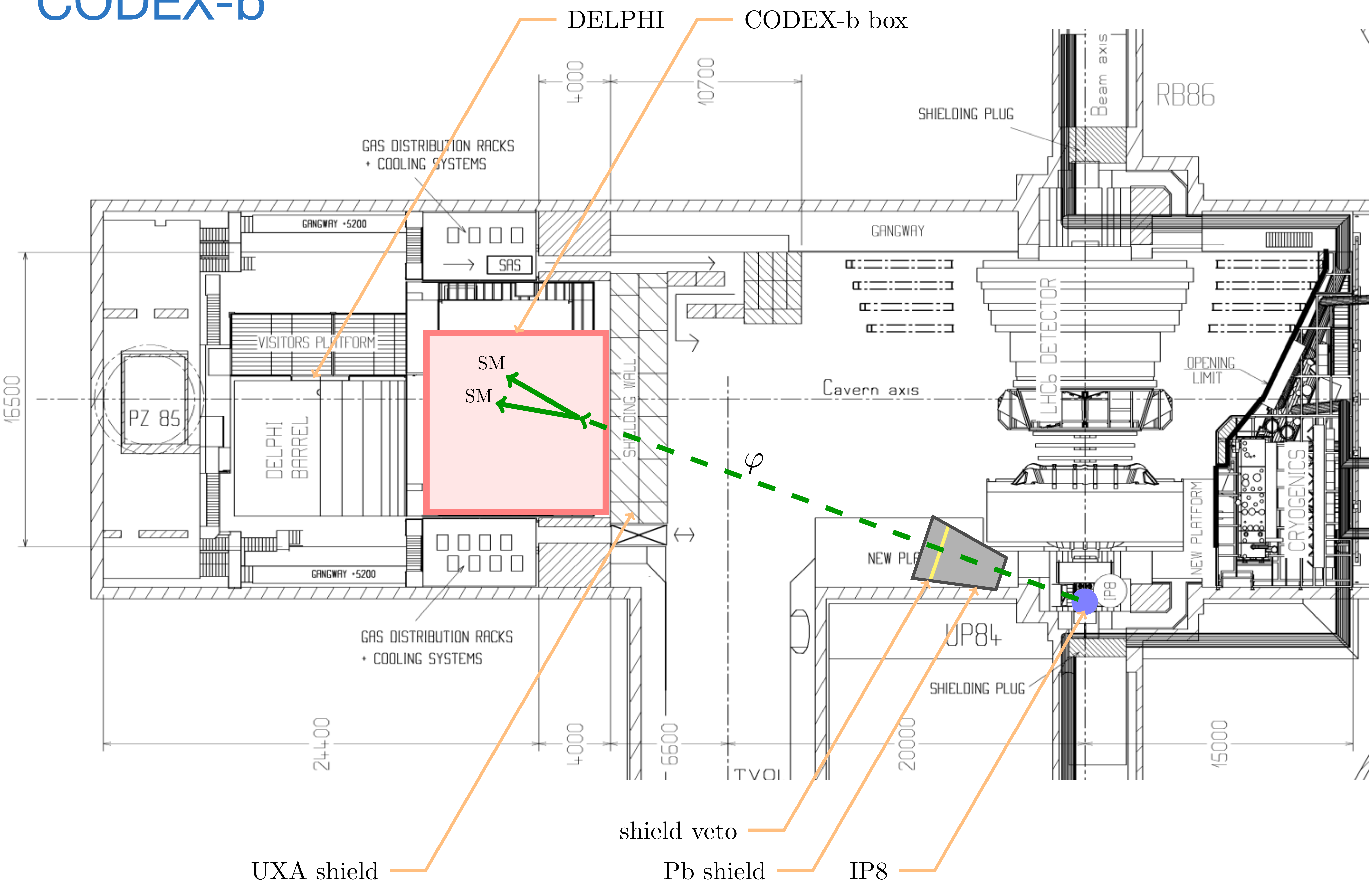
1708.09395: V. Gligorov, SK, M. Papucci, D. Robinson



Data acquisition will be moved to surface for run 3

CODEX-b

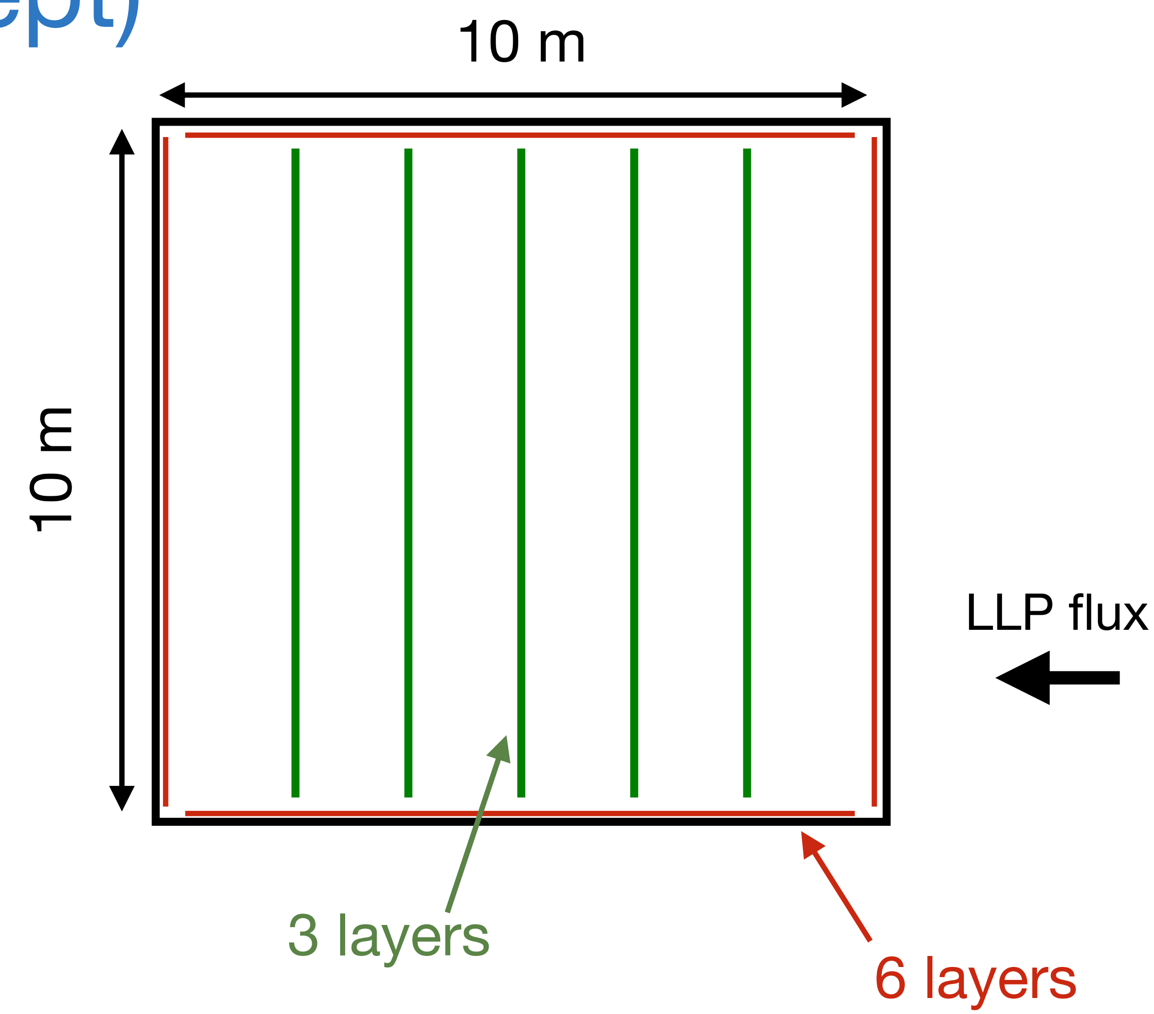
1708.09395: V. Gligorov, SK, M. Papucci, D. Robinson



Data acquisition will be moved to surface for run 3

Fiducial volume (proof of concept)

- 10m x 10m x 10m fiducial volume
  → 1-2% geometric coverage
  (double if DELPHI is removed)
- 6 RPC layers on each surface
- 5 set of 3 vertical RPC layers in the volume
- 1 cm granularity



Key points:

- recover acceptance for particles with low boost
- minimize distance to first tracked point

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

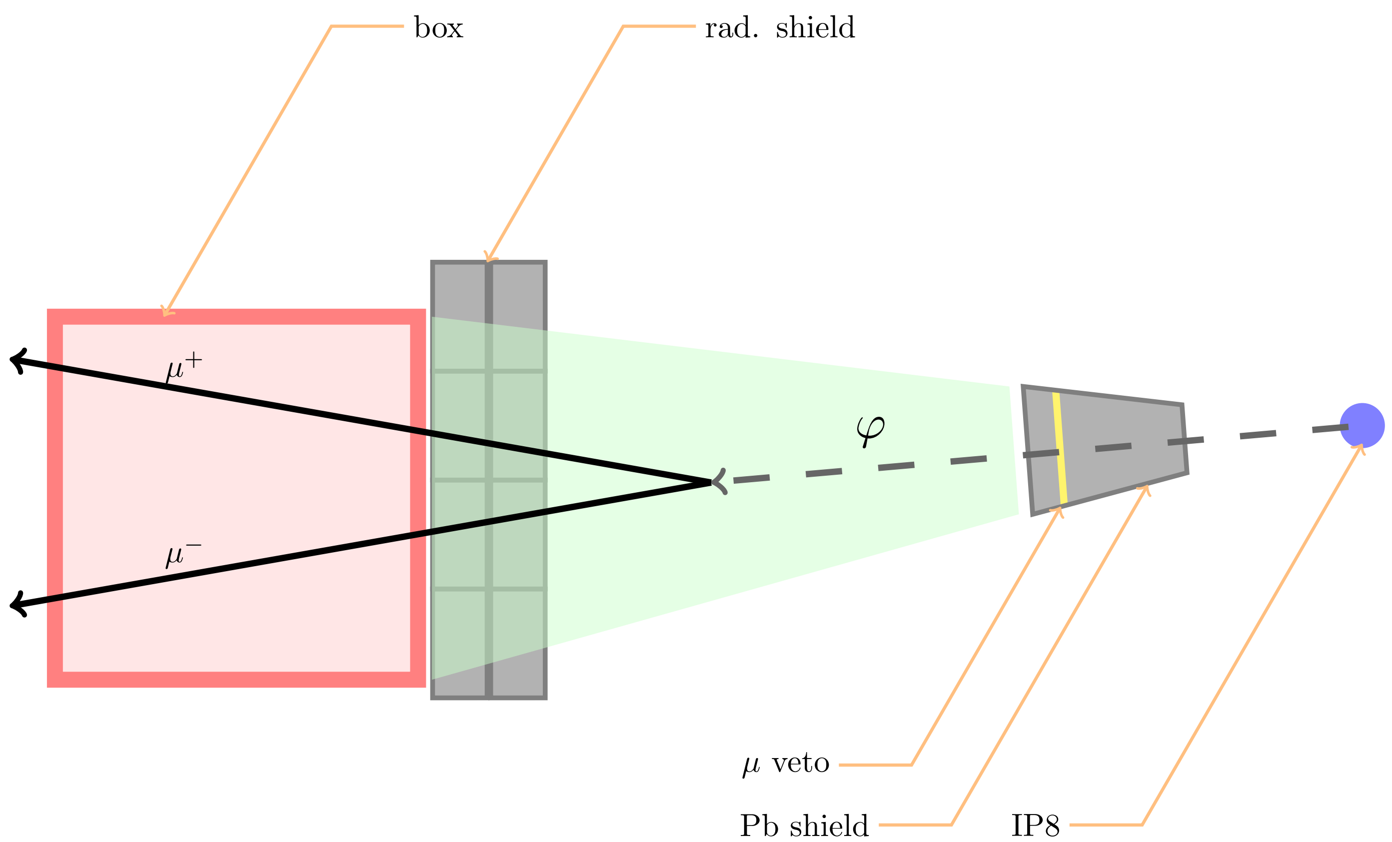
high boost

600 MeV cut

small opening angle,
overlapping decay products

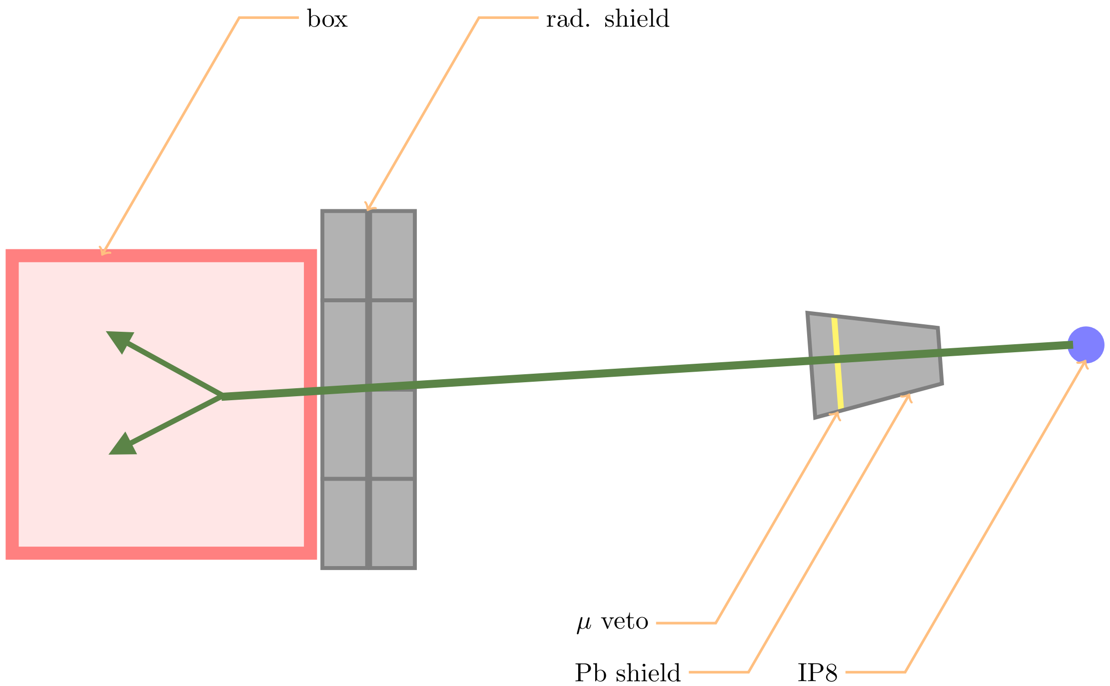
Possible features

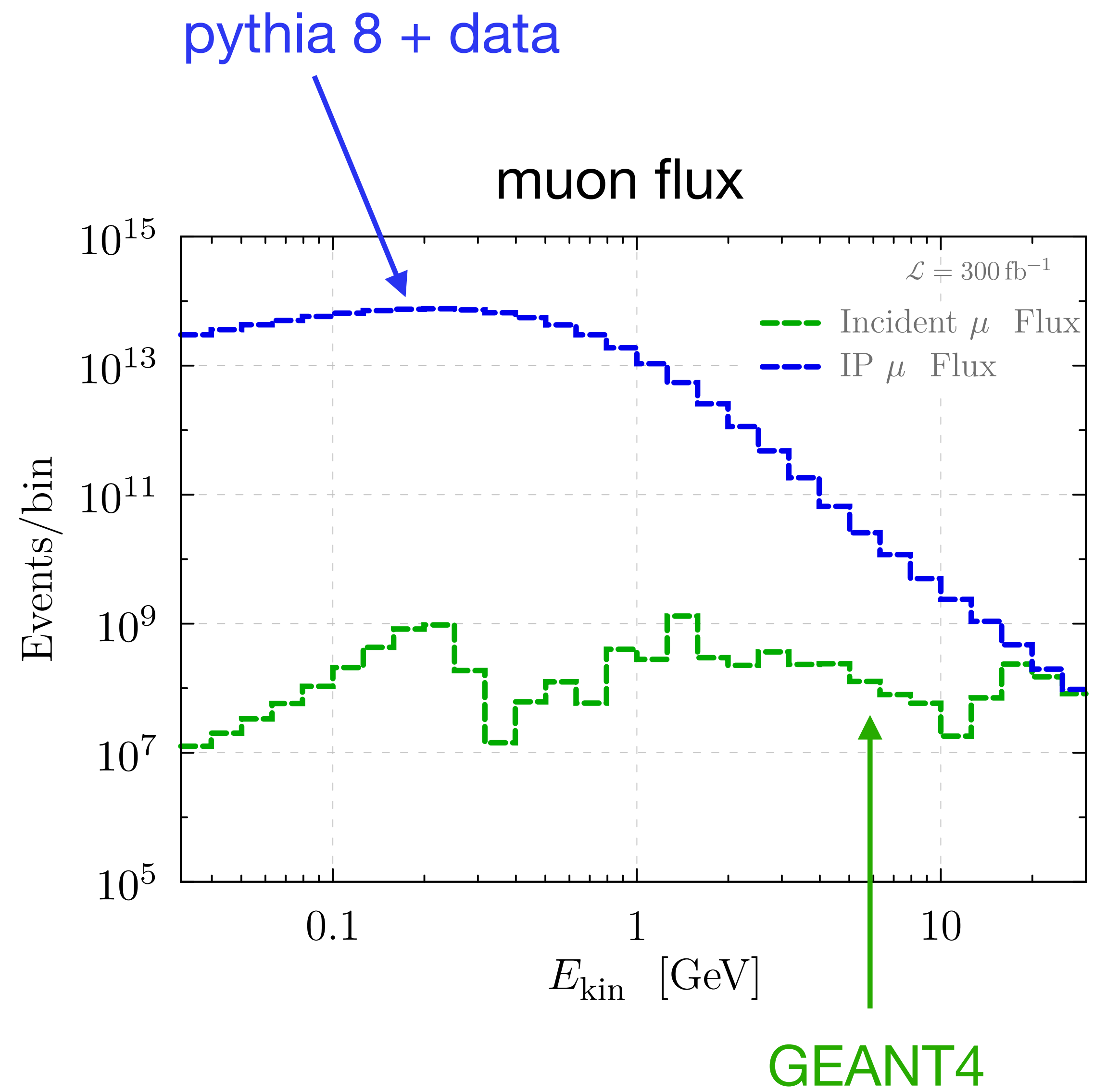
- Close to LHCb: ~ 4 bunch crossings for relativistic objects
  integrate CODEX-b in DAQ & readout as LHCb subdetector
- Relatively small, more ambitious design (timing, calorimetry, etc) may be possible
- Muon shadow may be exploited for more energetic signals



Backgrounds

muons scattering on air





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

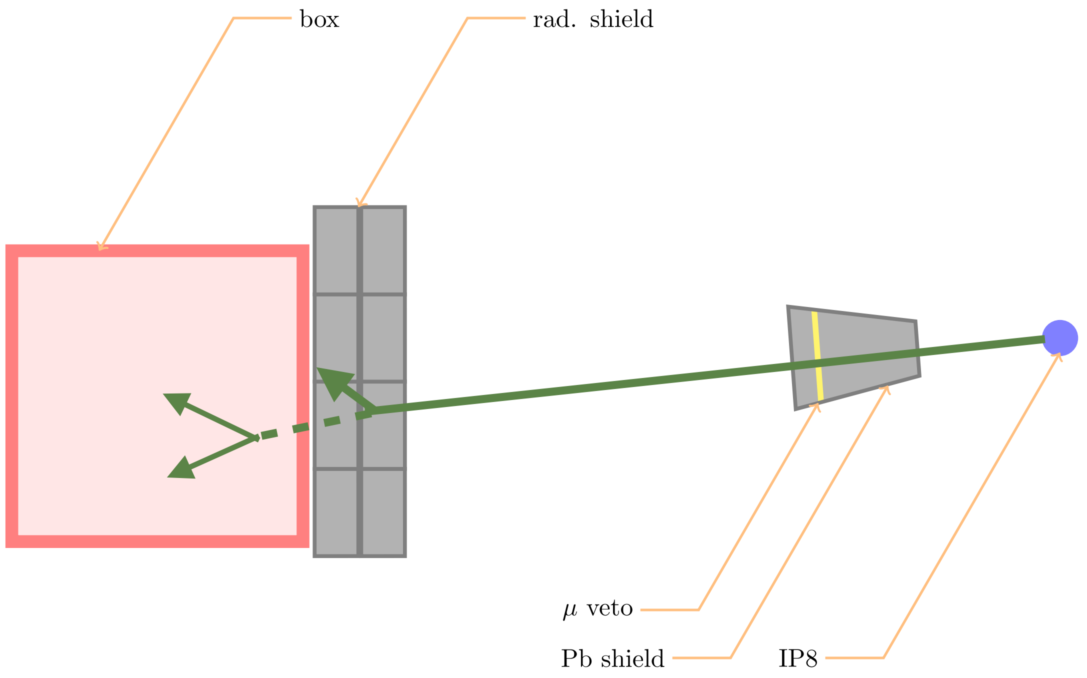
↓

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

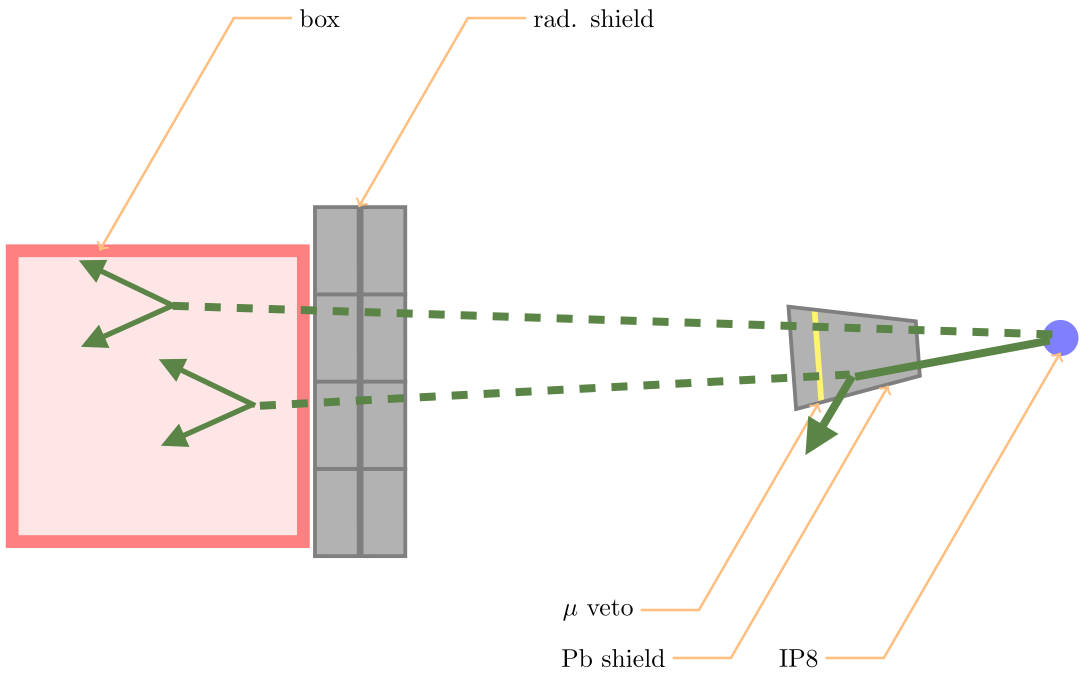
Backgrounds

neutrons / K_L + secondaries

prompt plus secondary from muons hitting shield



veto



irreducible

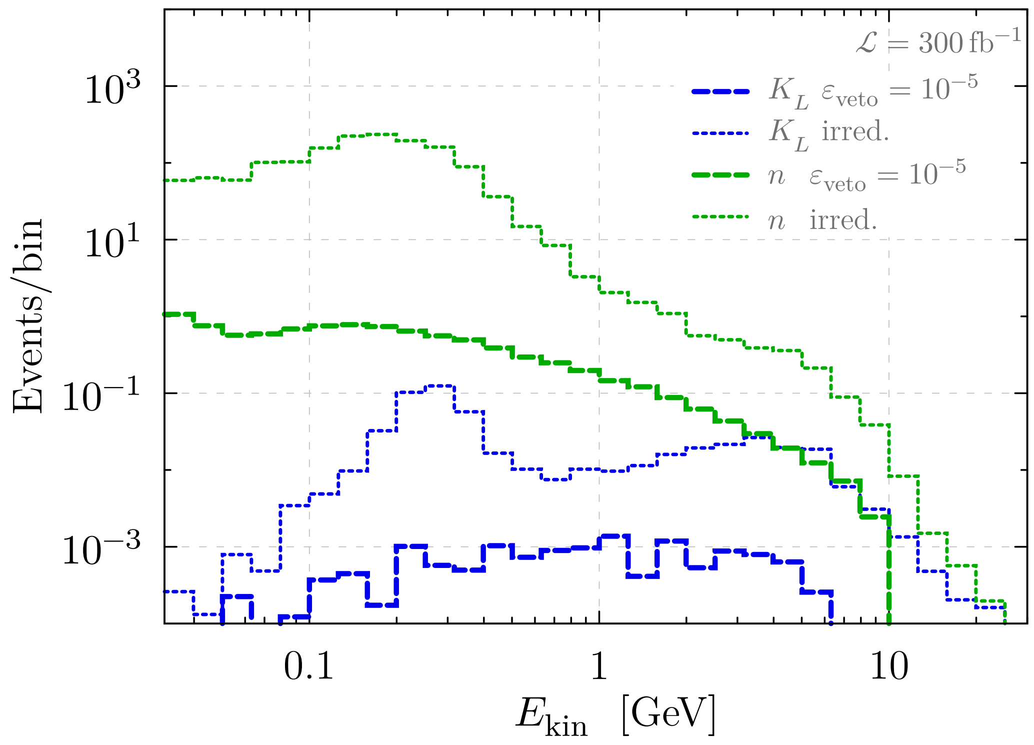
~ 32 interaction lengths (7 concrete + 25 Pb) ➞ roughly 4.5 m of Pb

Backgrounds

neutrons / K_L + secondaries

pythia 8 + GEANT 4 simulation

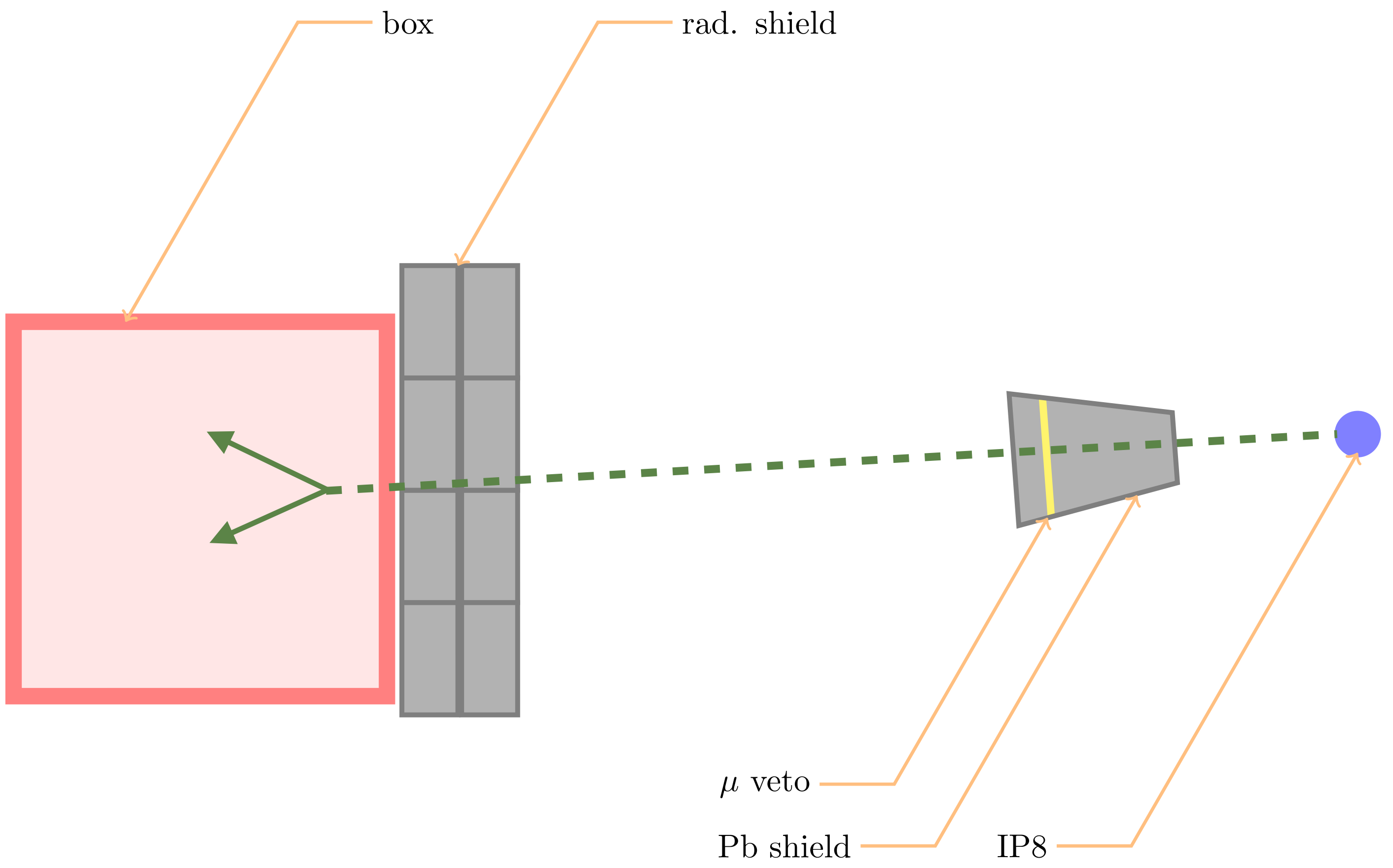
BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n + \bar{n}$	7	$5 \cdot 10^4$	$E_{\text{kin}} > 1\,\text{GeV}$
K_L^0	0.2	870	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\pi^\pm + K^\pm$	0.5	$3 \cdot 10^4$	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\nu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



- 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

Backgrounds

primary neutrinos



Very tricky to model, but with extremely conservative cuts, ~ 3 events

Likely to be overestimate with several orders of magnitude

Signal benchmarks

1. Light scalar mixing with Higgs
    - Produced in $B \rightarrow X_s\, \phi$ decays
    - Lifetime and production rate both set by mixing angle

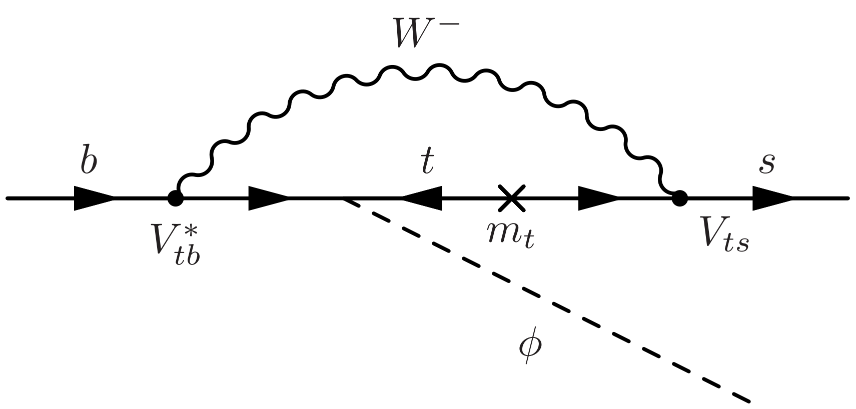
2. Dark photon
    - Produced in $h \rightarrow \gamma_d\, \gamma_d$ decays
    - Production rate and lifetime controlled by independent parameters

Light scalar mixing with Higgs

Production

$$\mathrm{Br}[B \to X_s \phi] \approx 6\ s_\theta^2\ (1 - m_\phi^2/m_B^2)^2$$

Roughly ~ 10^{14} B-mesons with 300 fb^{-1}



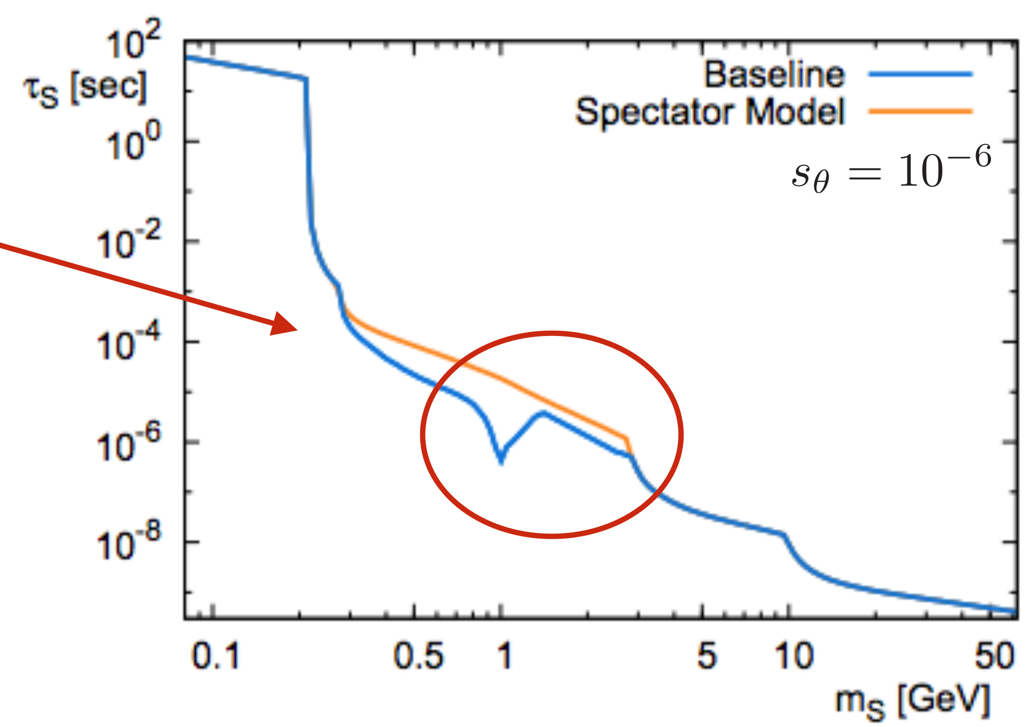
Decay

Large theory uncertainty

Different experiments make different assumptions to evaluate their reach

- LHCb, CODEX-b: “baseline” model
- SHiP: “spectator” model
- MATHUSLA: slight variation on “baseline” model

J. Evans: 1708.08503

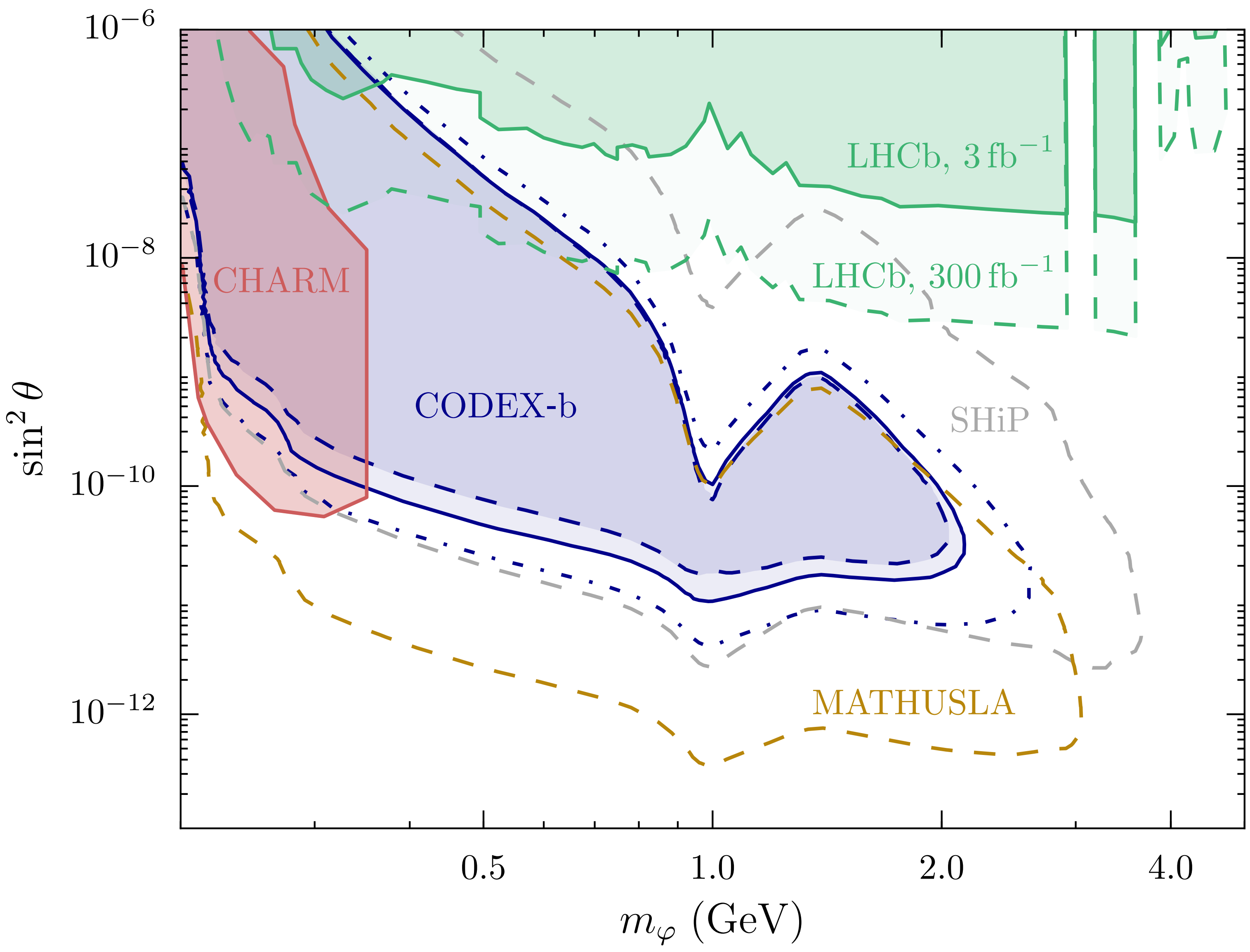


A. Fradette, M. Pospelov 1706.01920

J. F. Donoghue, et. al. , Nucl. Phys. B343, 341 (1990).

Light scalar mixing with Higgs

Reach

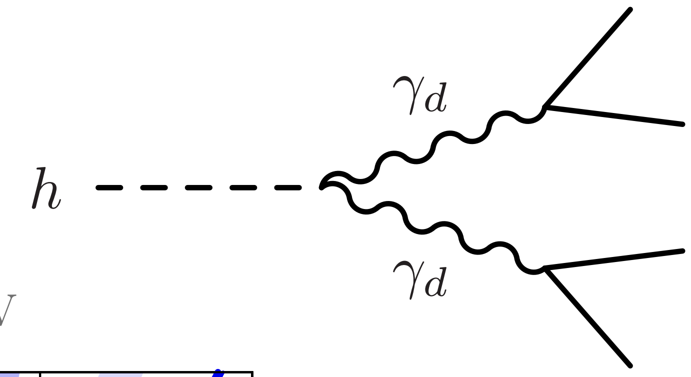


300 fb-1, excluding track efficiency
300 fb-1, including track efficiency
1 ab-1, excluding track efficiency

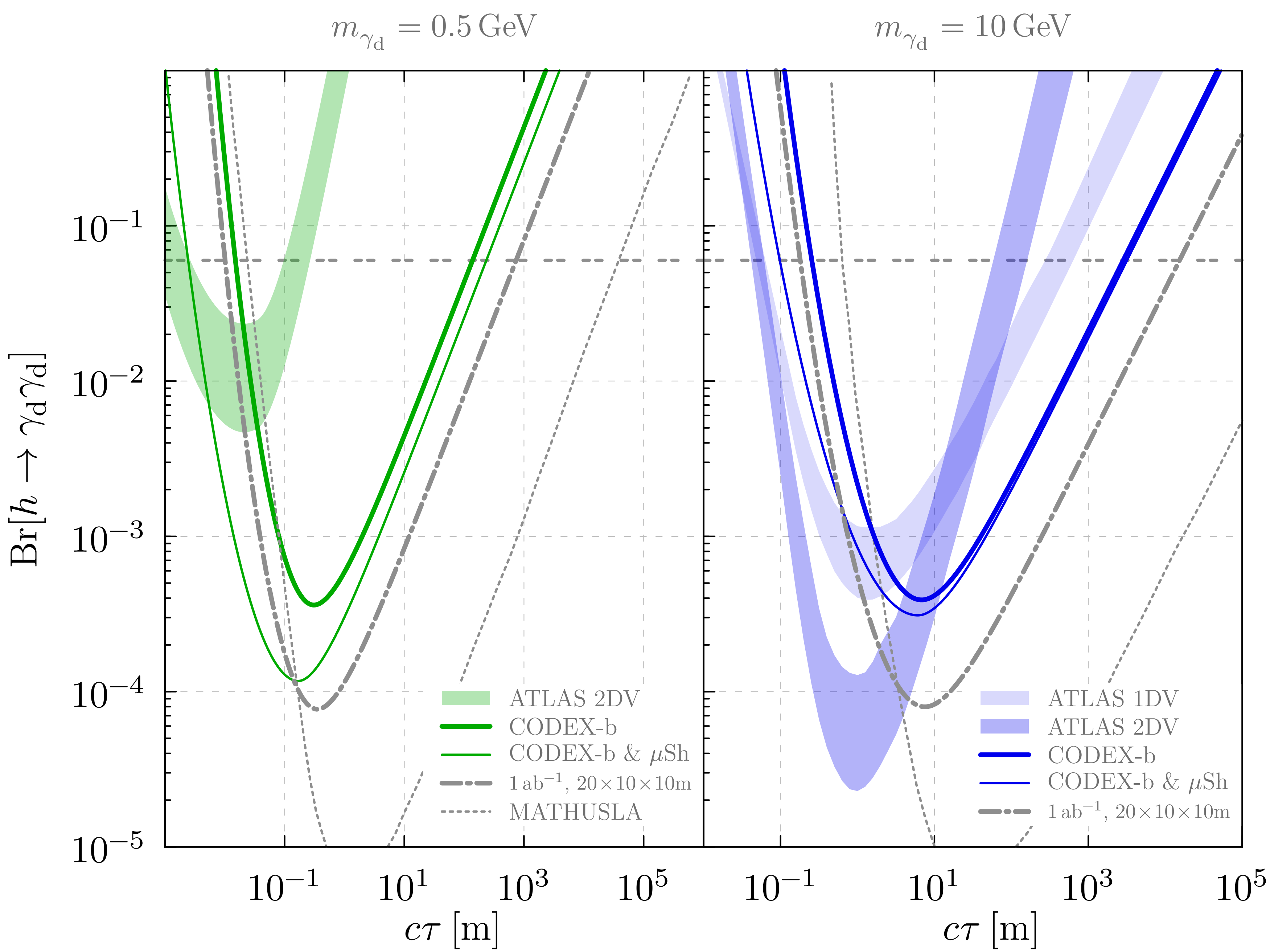
Probe sizable fraction of SHiP and MATHUSLA parameter space

SHiP and MATHUSLA recast to “baseline” model

Exotic Higgs decays



Reach



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

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

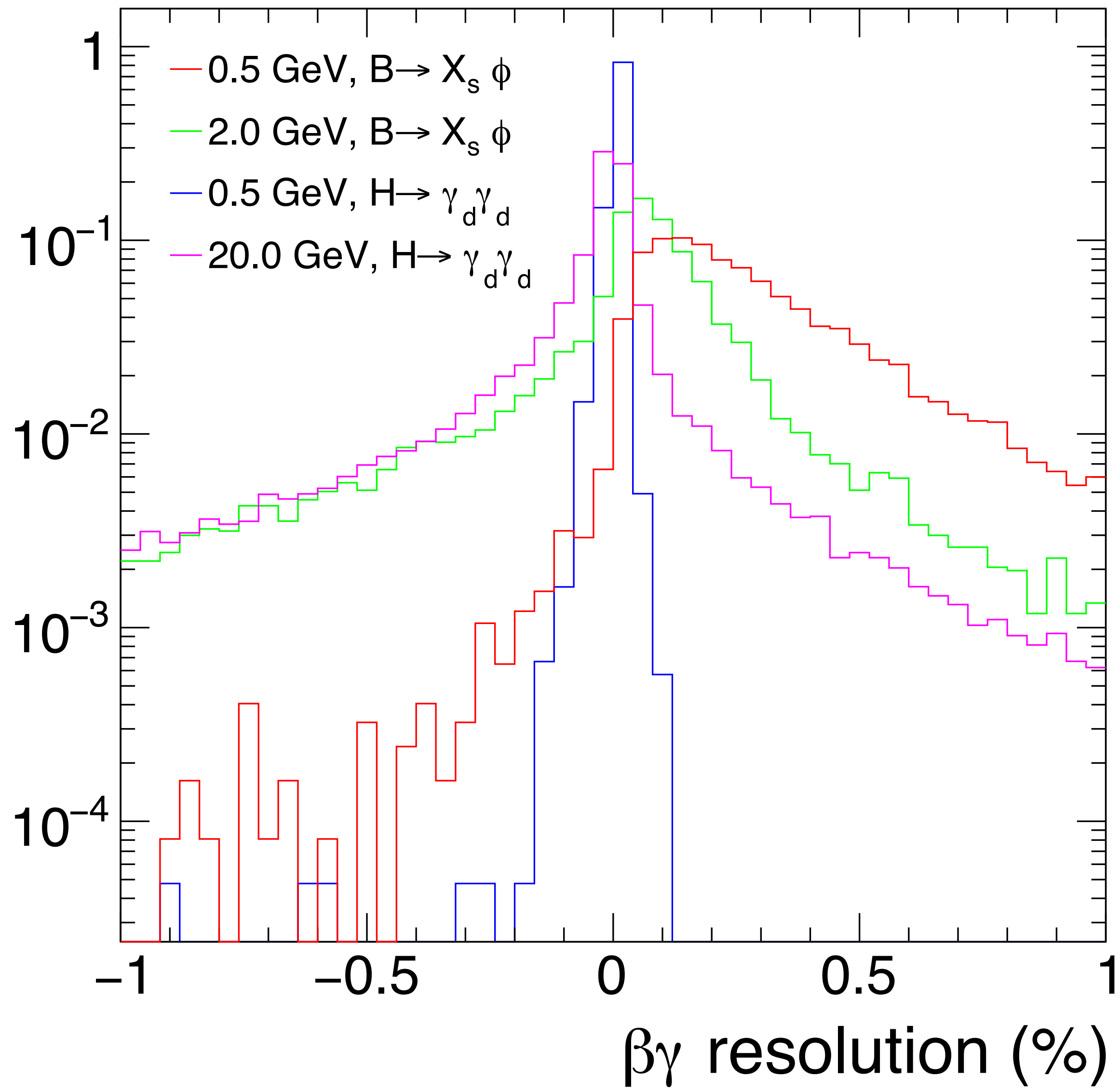
Characterizing the signal

Parent boost reconstruction

Boost reconstruction

D. Curtin, M. Peskin: 1705.06327

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

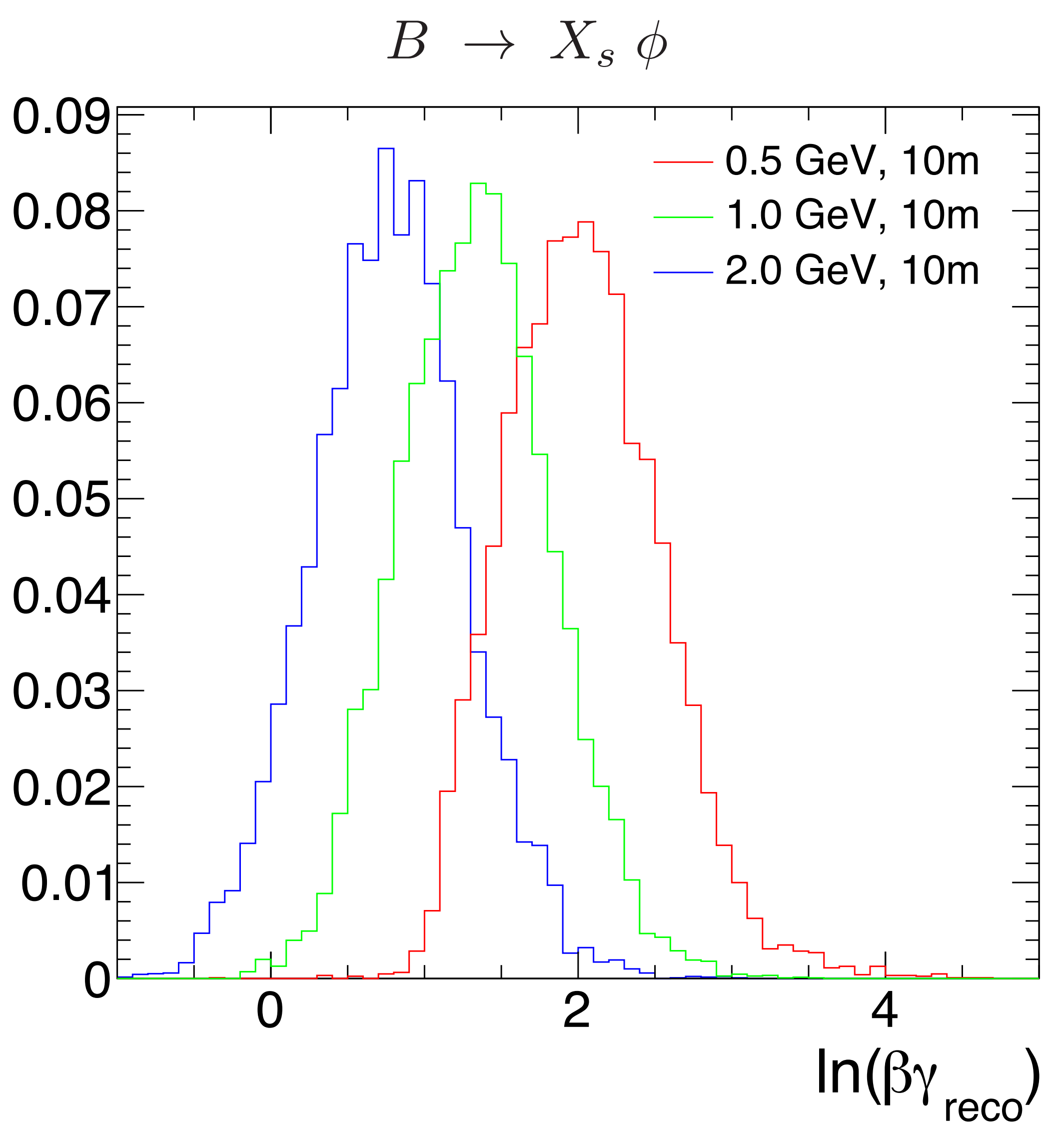


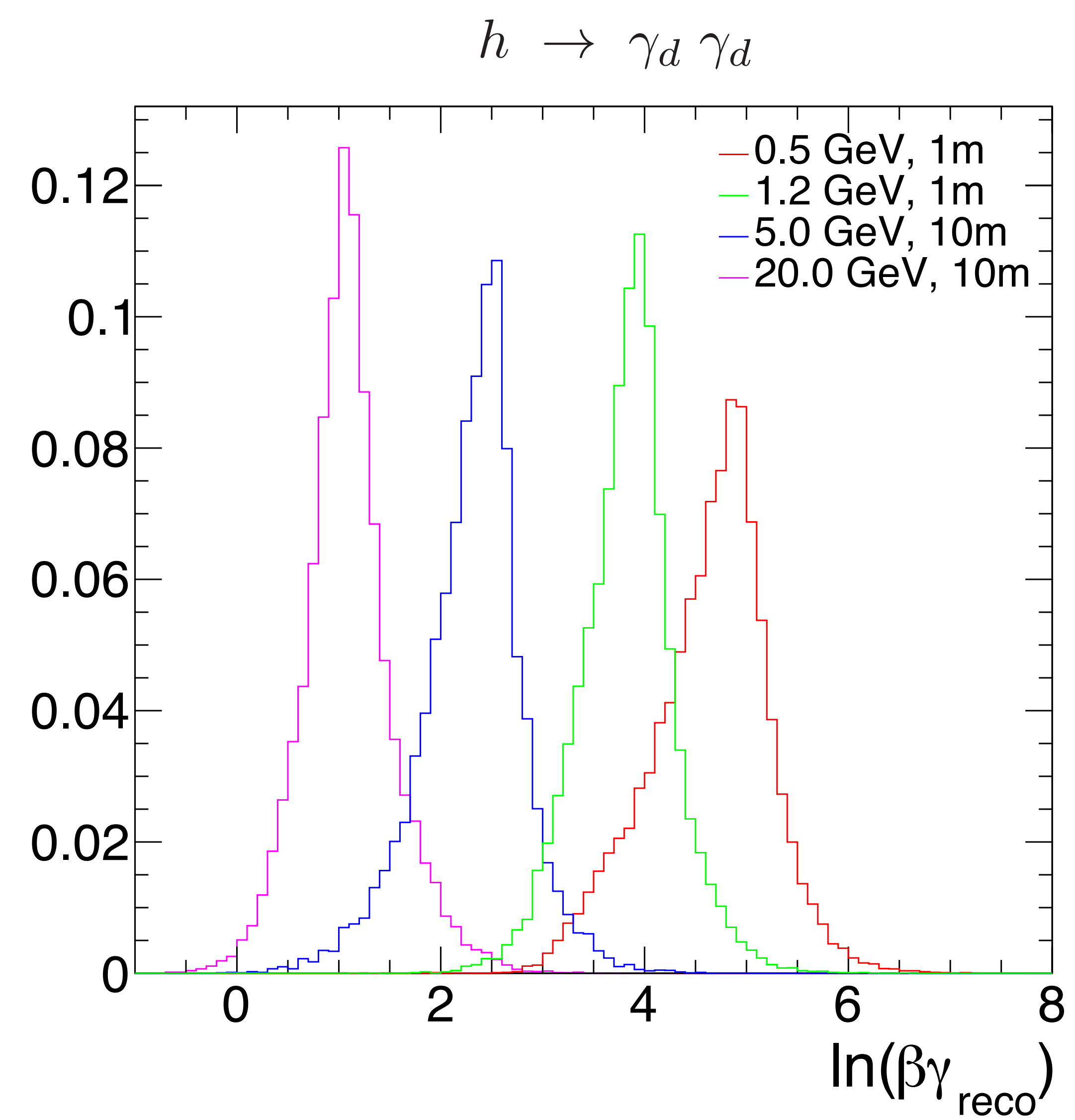
For relativistic decay products, only need spatial information

Most important parameter is distance to first measured point

Mass measurement

Only spatial information

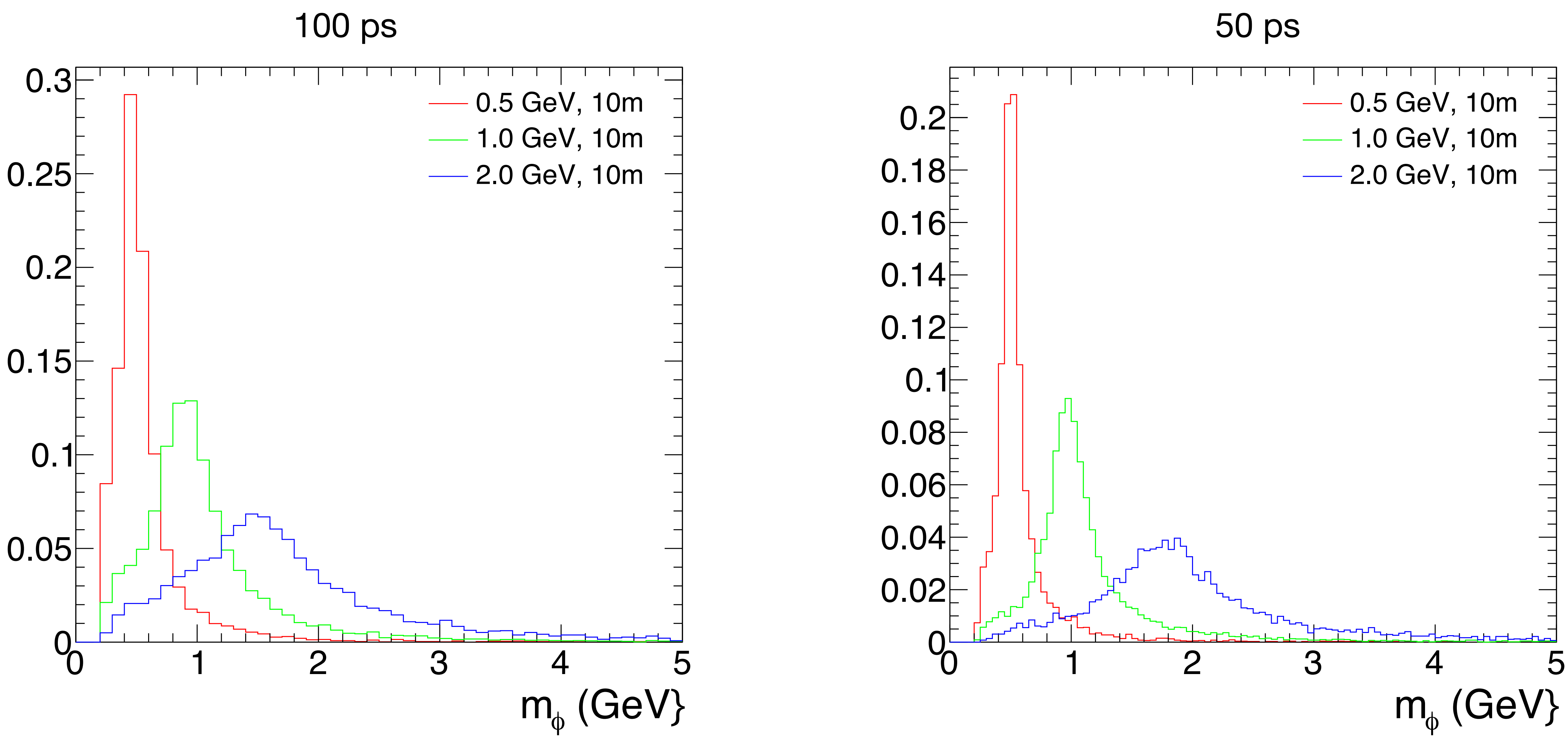




Rudimentary mass measurement possible even without calorimetry

Mass measurement

Include timing



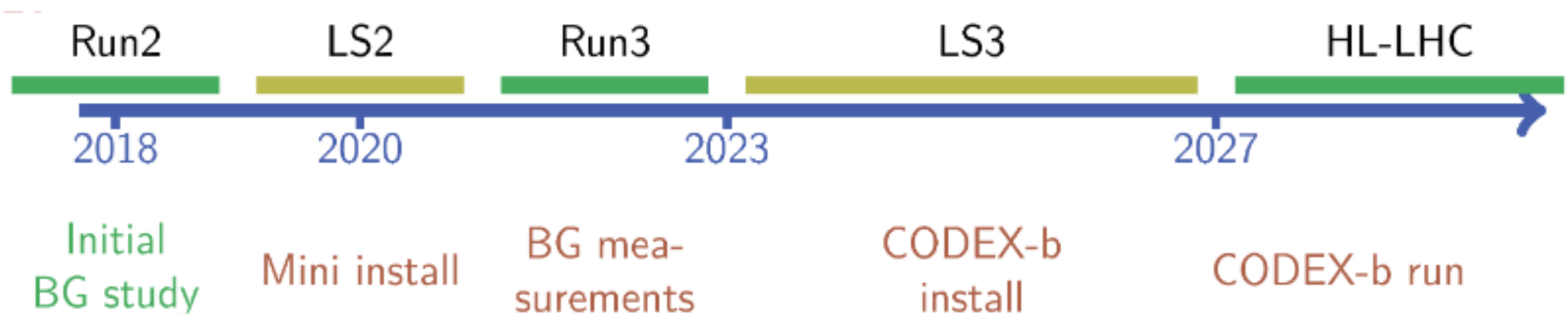
For exotic B decays, mass separation can be improved by including time-of-flight information

Moving forward

Ongoing work on theory side: more benchmark models
(back-up slides, see also upcoming PBC report)

Ongoing work on the LHCb side

- Data driven background estimate →
- Detector design and add to LHCb simulation
- On track for a detector paper in Fall / early Spring



Team

V. Coco	LHCb
J. Evans	Theory
B. Dey	LHCb
R. Dumps	LHCb
V. Gligorov	LHCb
S. Knapen	Theory
J. Lee	LHCb
M. Papucci	Theory
H. Ramani	Theory
D. Robinson	Theory
H. Schindler	LHCb
T. Szumlak	LHCb
X. Vidal	LHCb

Still growing, and we welcome new collaborators!

What would an “ideal” detector look like?

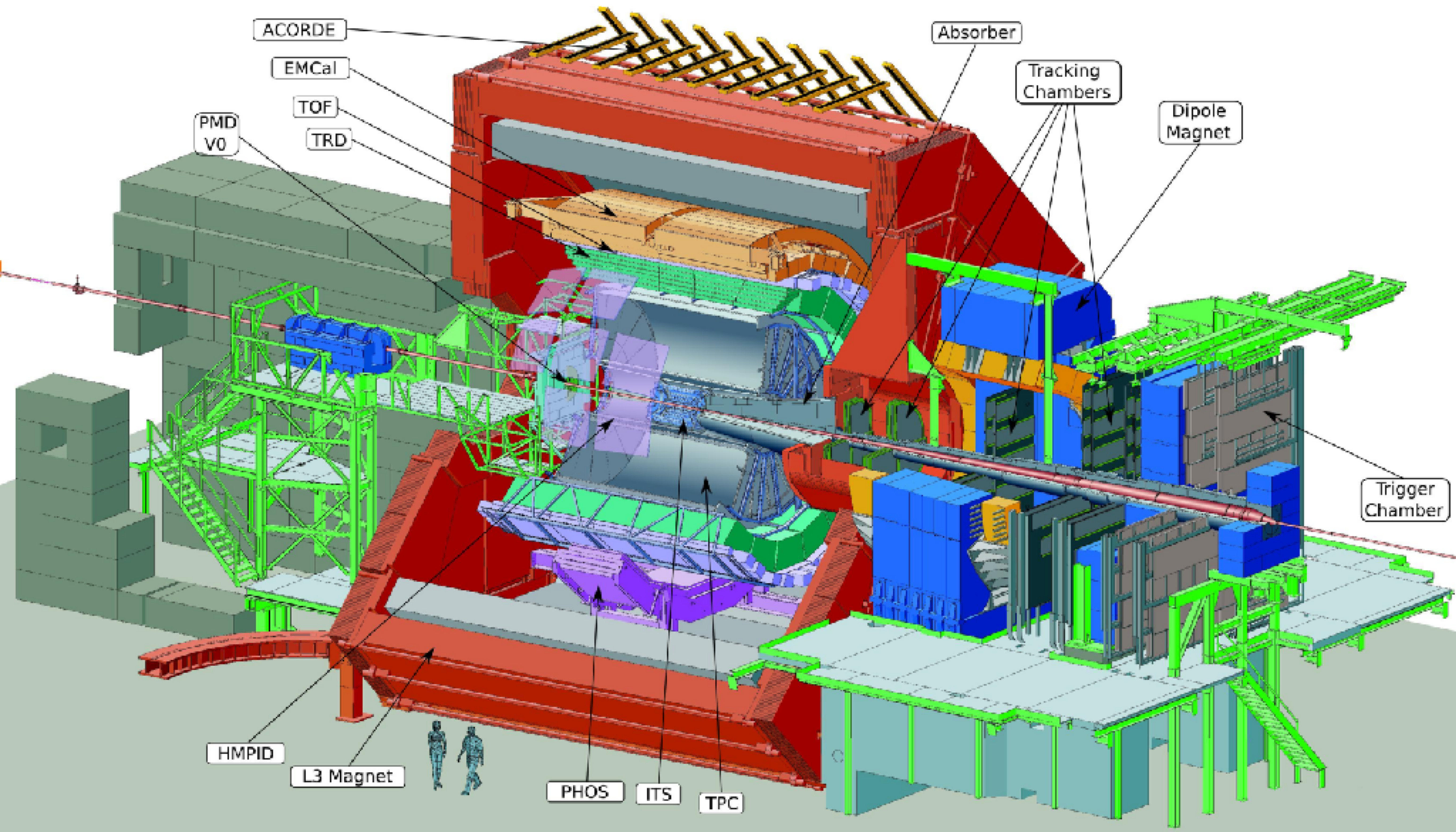
- $\sqrt{s}$ = 13 TeV ✔
- As close as possible to IP ✔
- B field for momentum measurement ✔
- High resolution tracker (vertex reco) ✔
- as high lumi as possible

L3 magnet (0.5 T)

Most of this is present in ALICE cavern

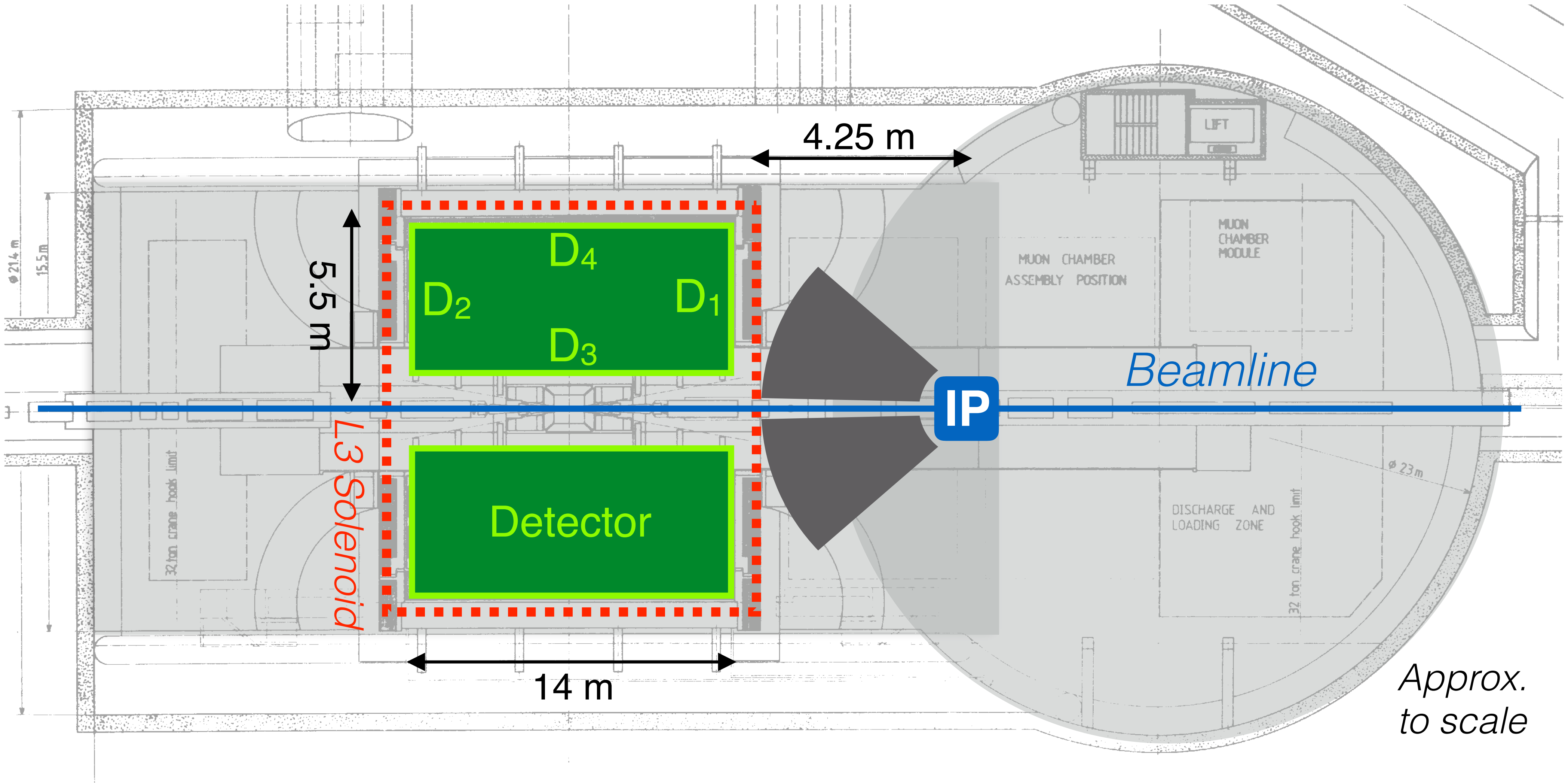
(At this time, there is no (public) ALICE heavy ion program during run 5)

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: 18xx.xxxxx

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

Reduced by the shield:

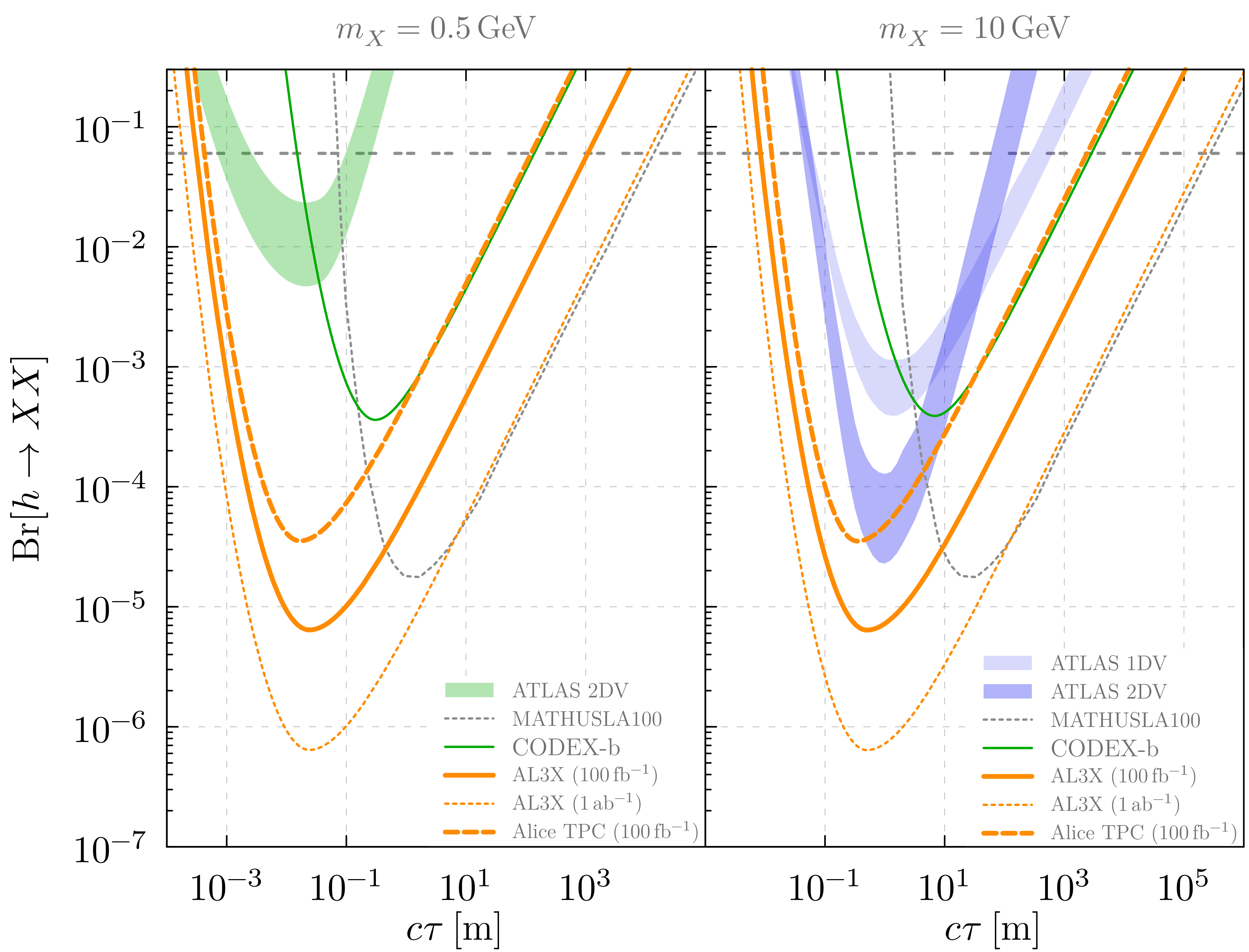
- neutrons scattering on air
- K_L

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	$\lesssim 10$

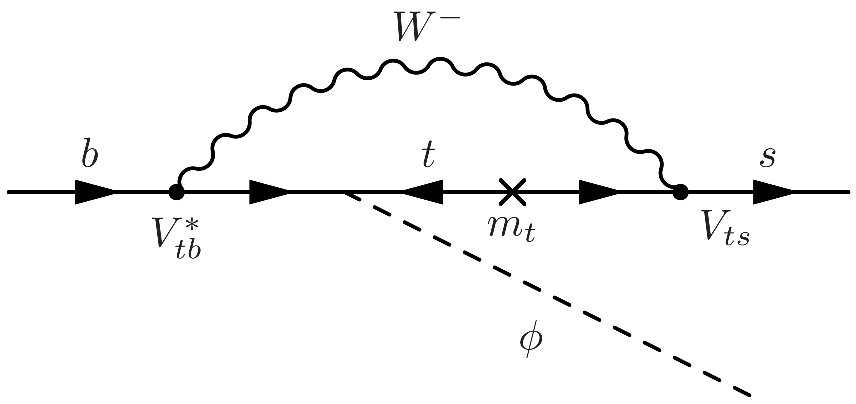
GEANT4 simulation: Low background setup appears possible

Reach for Higgs decays

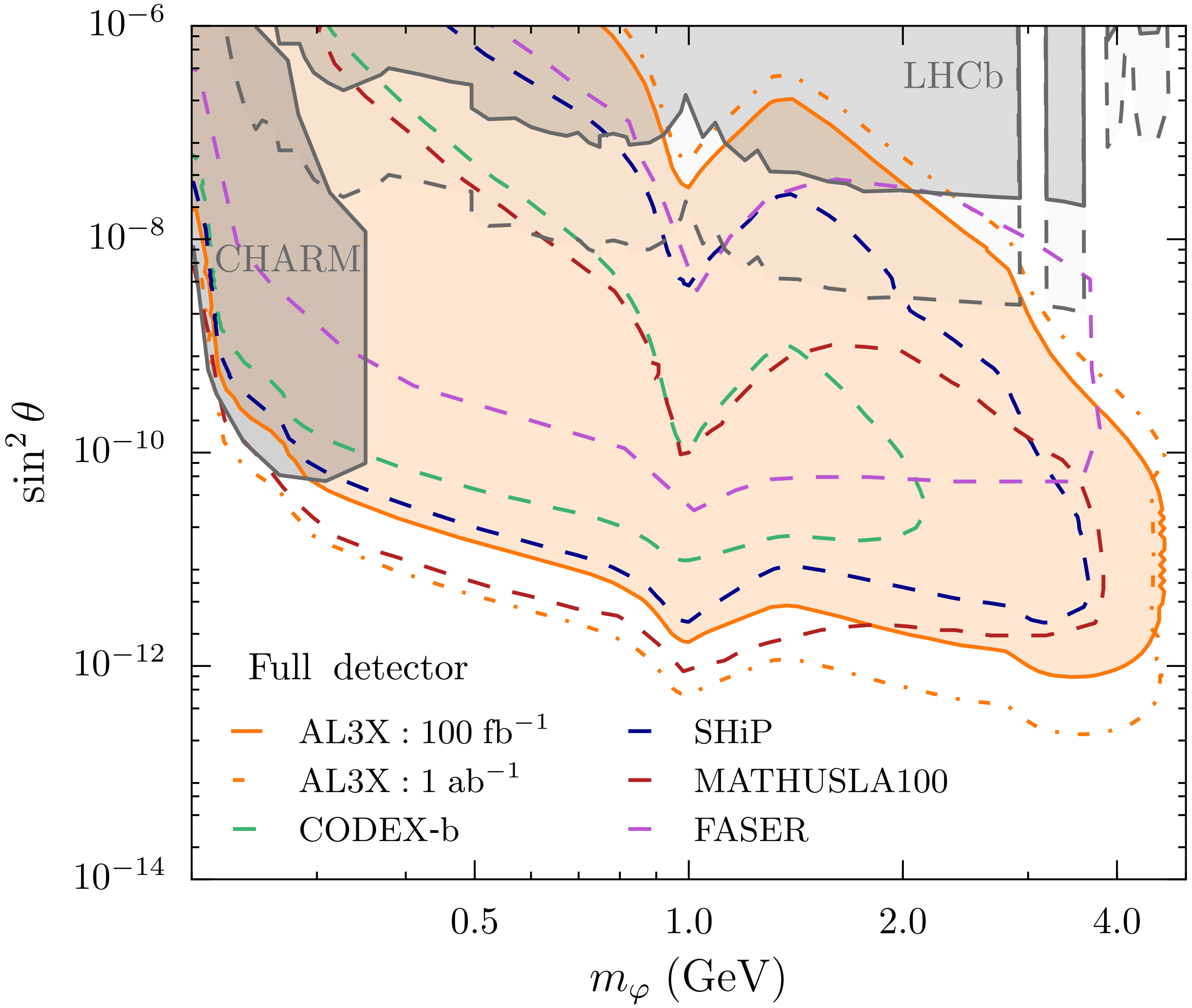


ATLAS reach: A. Coccaro, et al.: 1605.02742

Reach for B decays



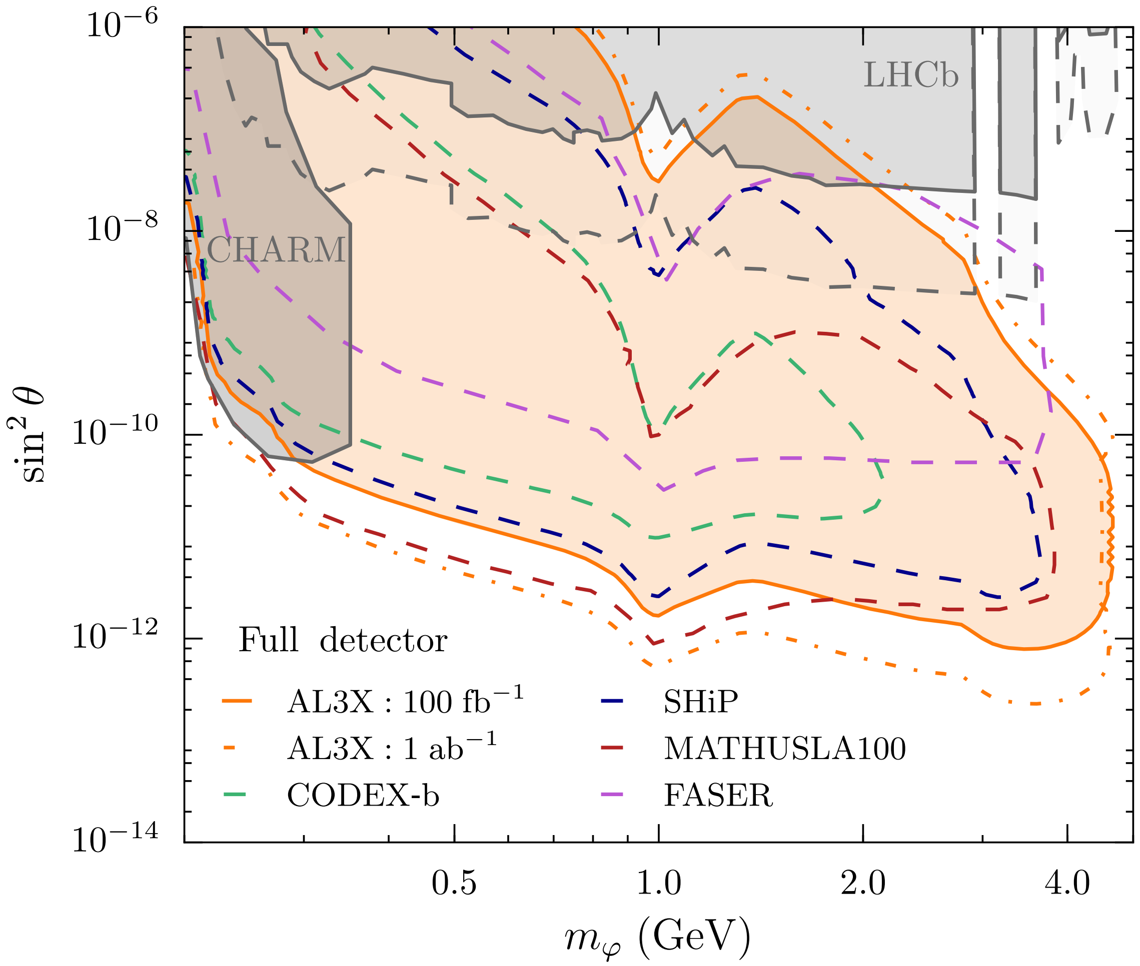
(Scalar mixed with Higgs)



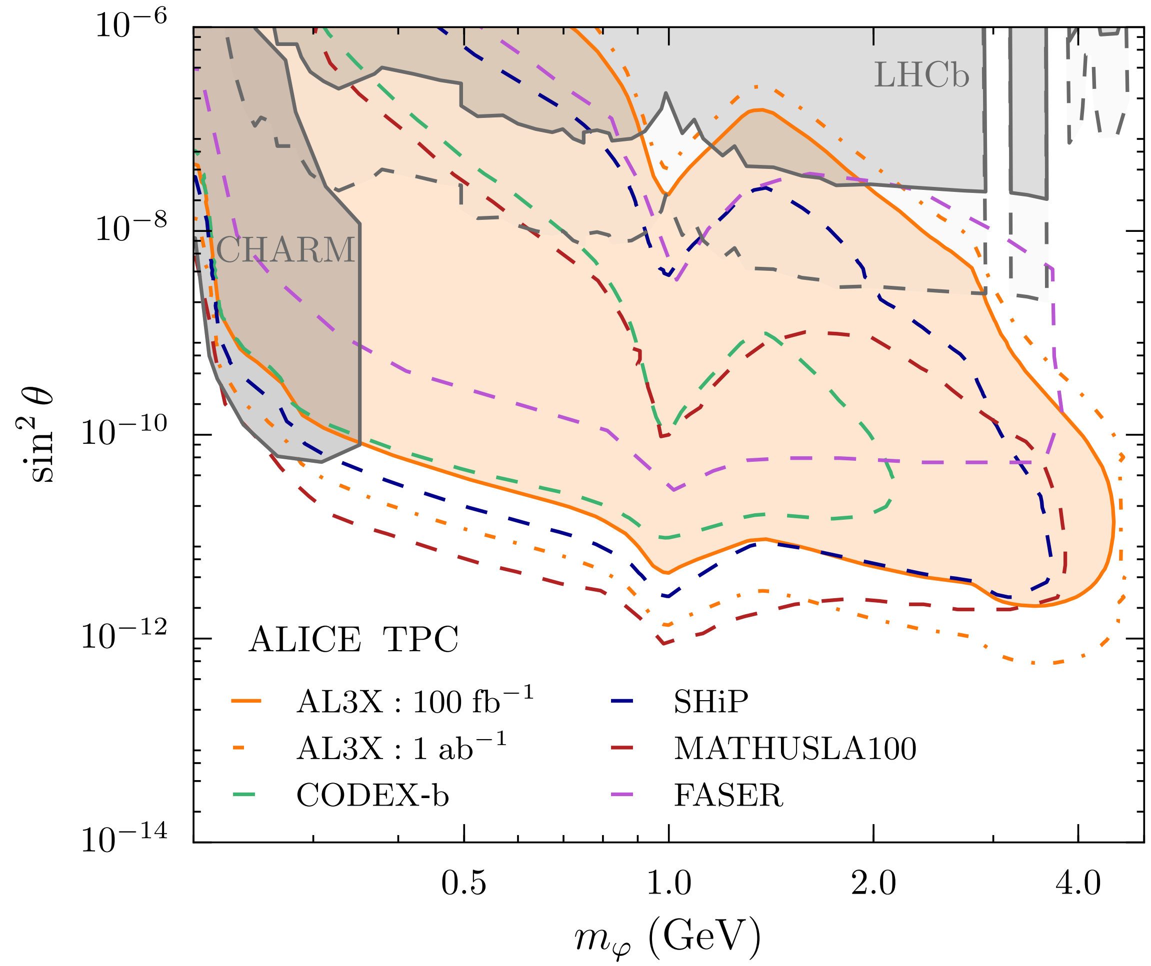
For exotic B decays, AL3X easily has the best sensitivity of all proposals

Reach for B decays

Full detector

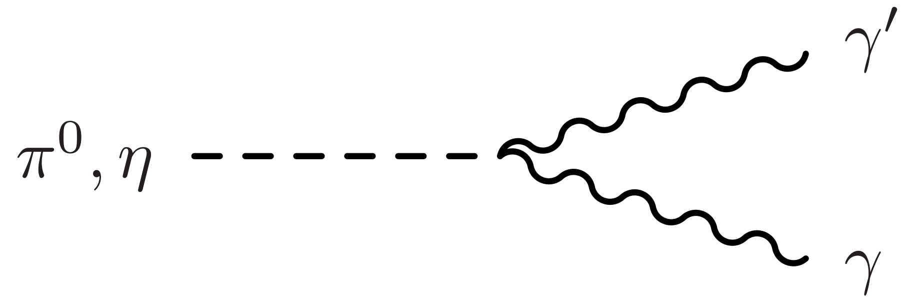


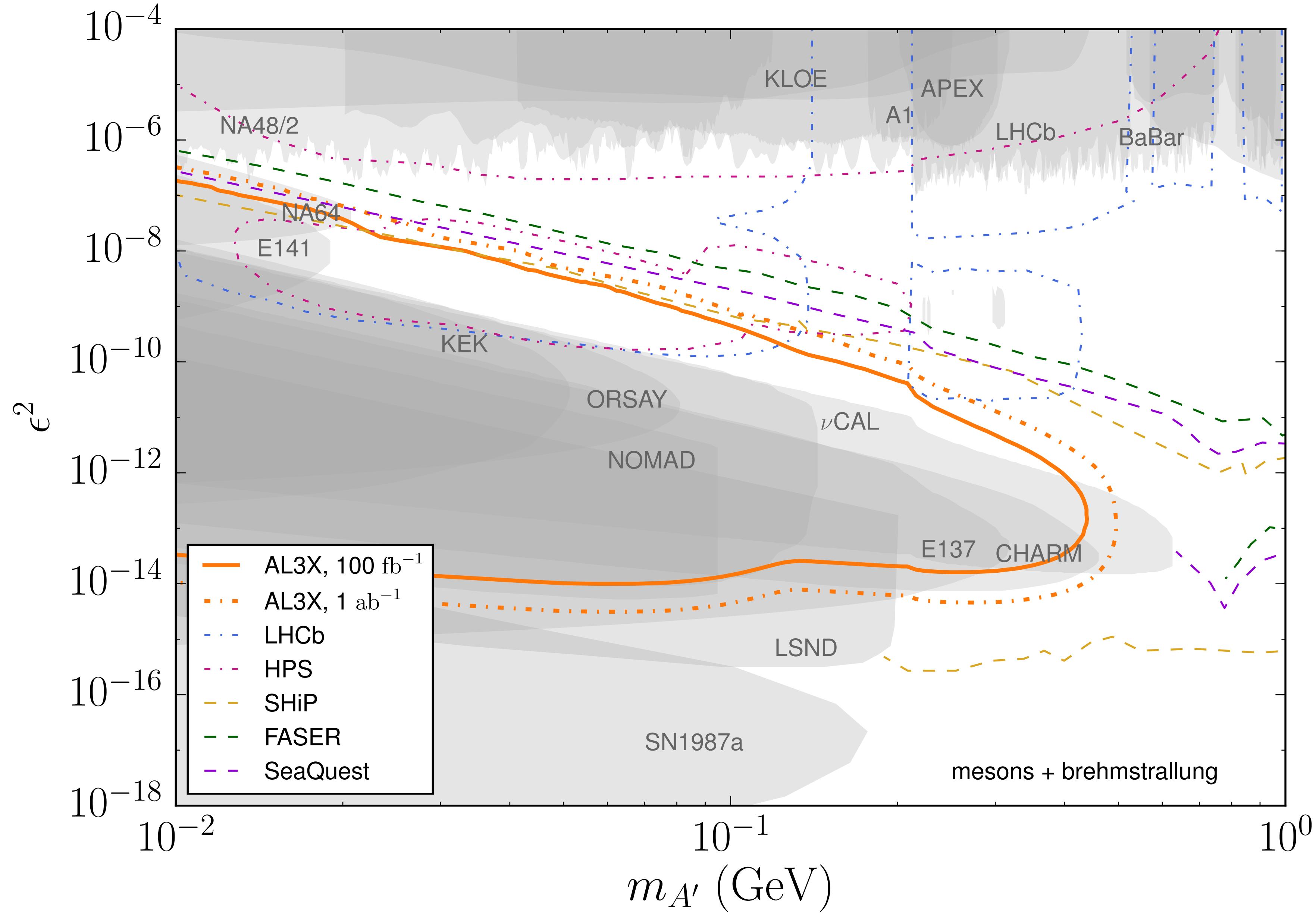
Reuse ALICE TPC



For exotic B decays, AL3X easily has the best sensitivity of all proposals

Reach for π, η decays





AL3X has sensitivity for kinetically mixed dark photons, but it's not the best

(Basically because there is no brehmstrallung contribution)

People & moving forward

V. Gligorov	LHCb
S. Knapen	Theory
B. Nachman	ATLAS
M. Papucci	Theory
D. Robinson	Theory

Just getting started, so we welcome ideas and collaborators

Find me if you want to know more

Moving forward

- Finish proof-of-concept study (next few weeks)
- More detailed background studies
- Study beam optics (expertise needed)

Lifetime frontier

Supplementary detectors

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

MOEDAL: monopoles, already running

MiliQan: milicharged particles, phase 1 detector in place

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?)

Upgrades

- Timing detectors
- CMS high granularity forward calorimeter

Analysis improvements

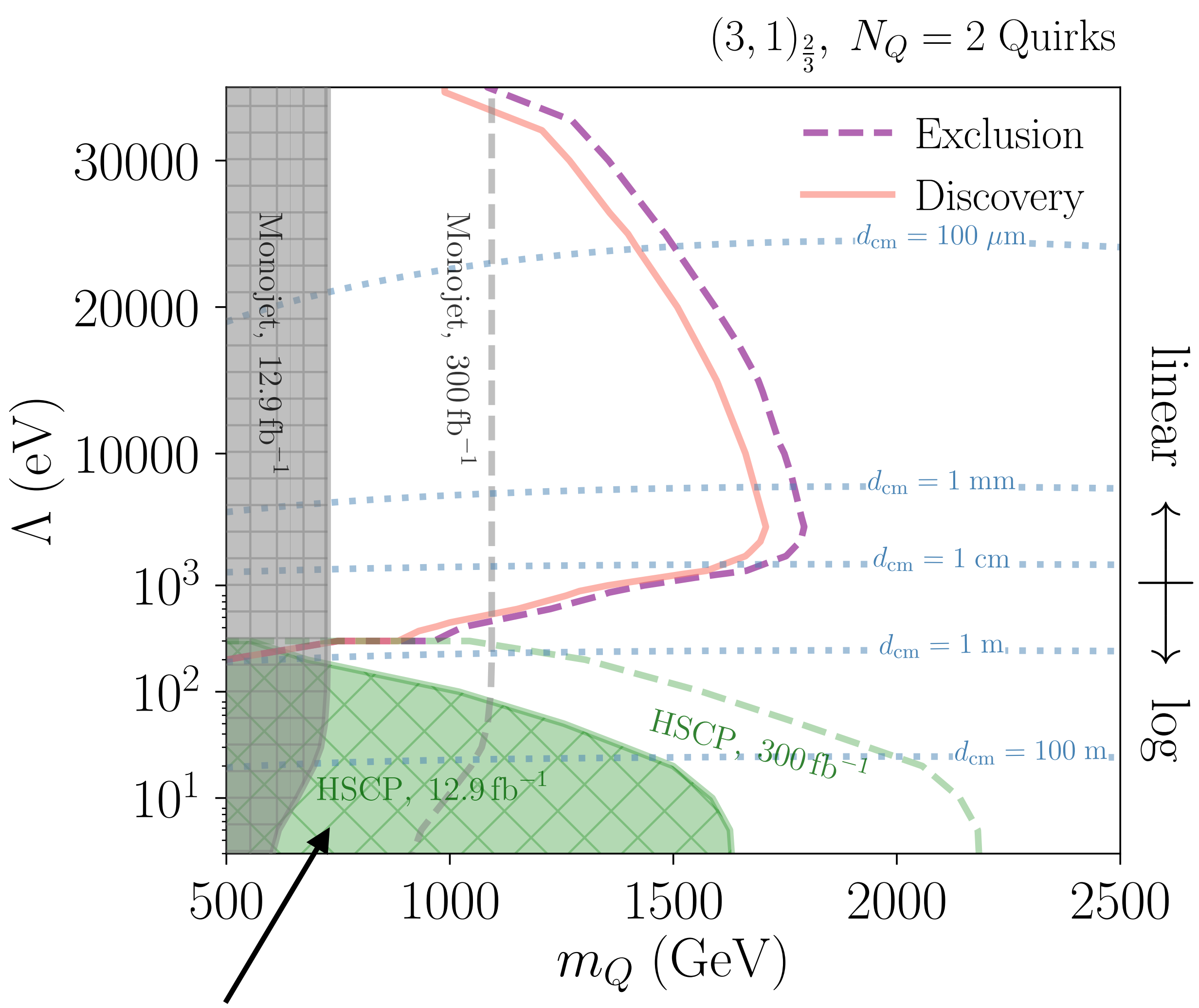
- Dark showers / hidden valleys (now largely a theory problem in my opinion)
- Quirks (GEANT implementation appears to be the bottleneck)

Greenland shark, lifespan up to 400 years

Back-up

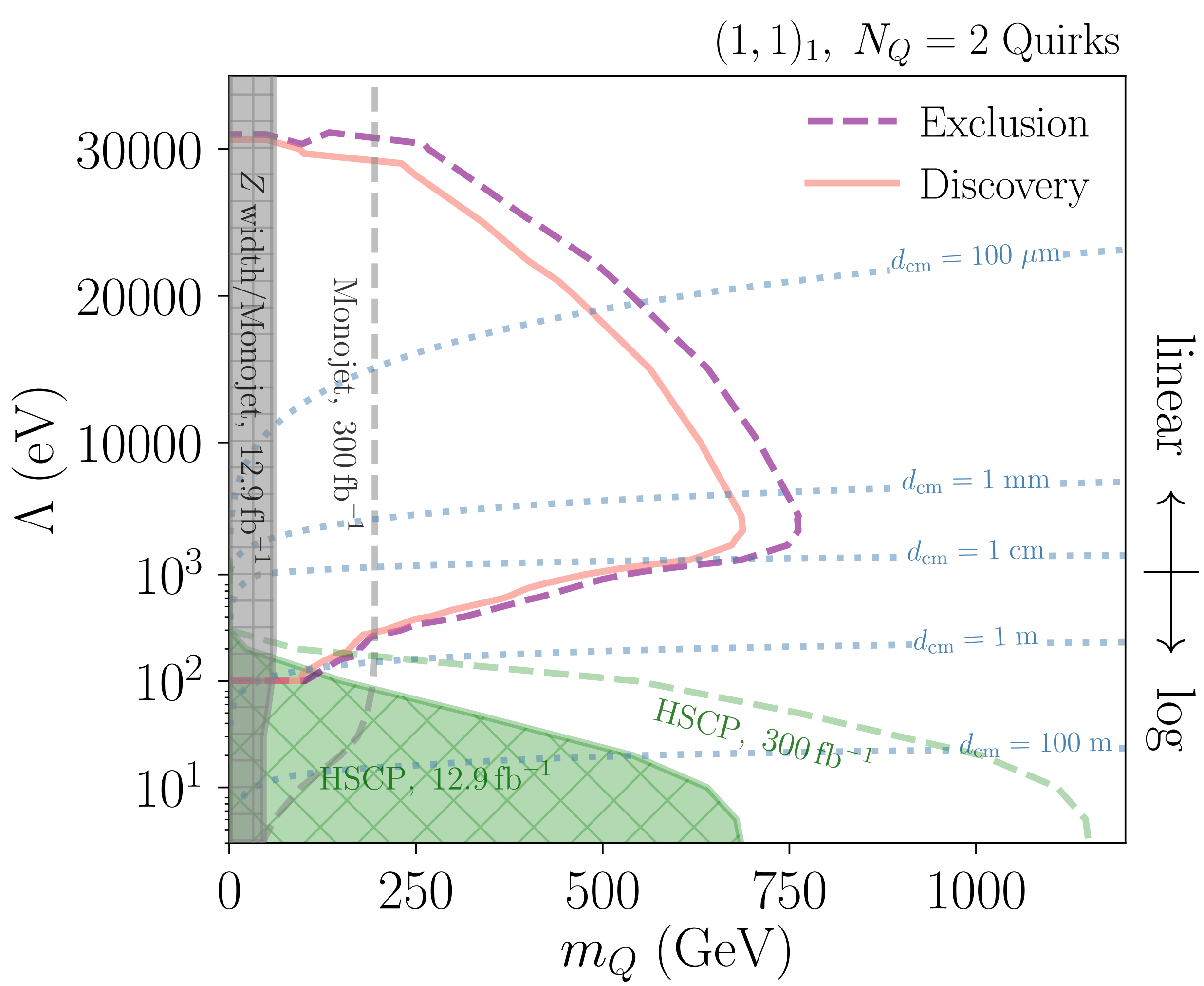
Projected reach

Colored production



M. Farina, M. Low: 1703.00912

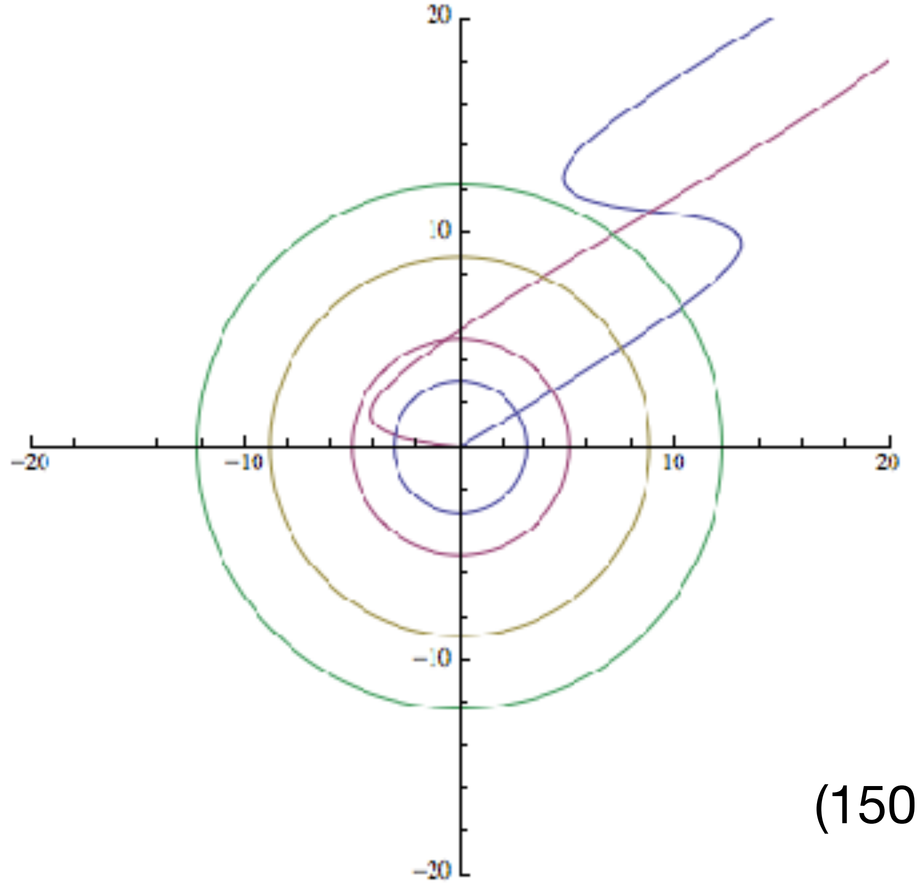
Drell-Yan production



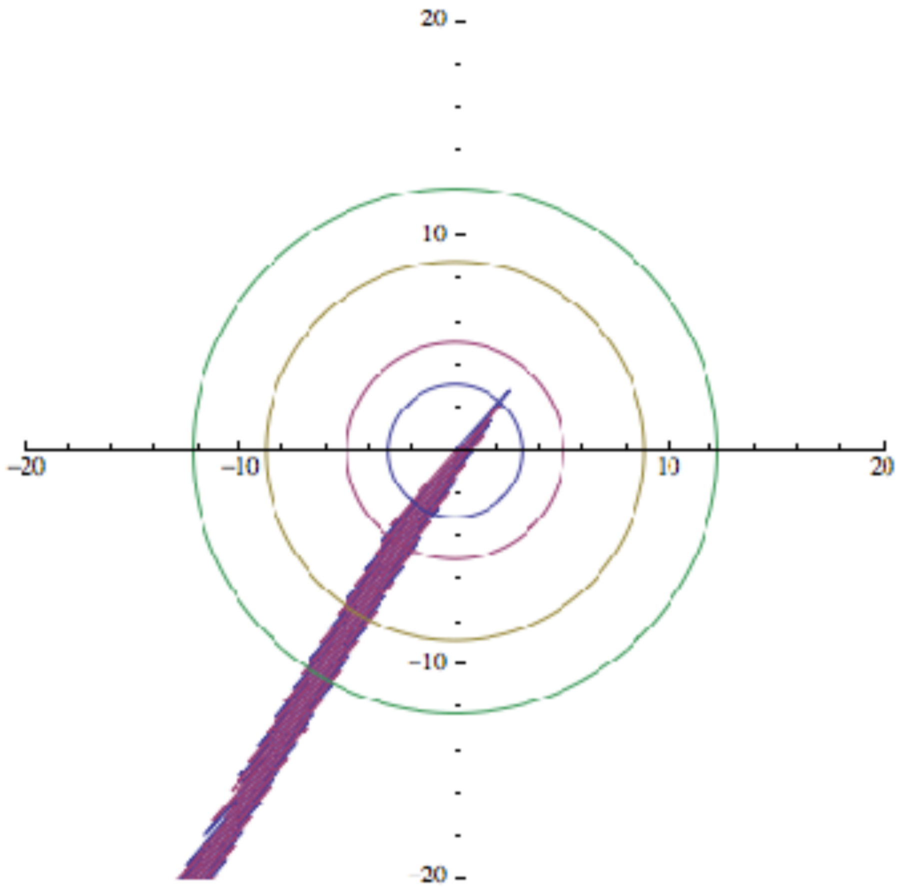
SK, T. Lou, M. Papucci, J. Setford: 1708.02243

Why is this hard?

- Signature depends strongly on m_Q and Λ
- Even for same model point (m_Q, Λ), strong dependence on ISR



(150 GeV, 500 eV)



Both trajectories must be fit together, in total 8 degrees of freedom in the fit!

- Tons of unassociated hits from pile-up

Need a model-independent way to reject pile-up background to 10^{-9}, while maintaining signal efficiency

LHCb coverage for LLP's

- Higgs mixing portal

  LHCb: 1612.07818

- Dark photon portal

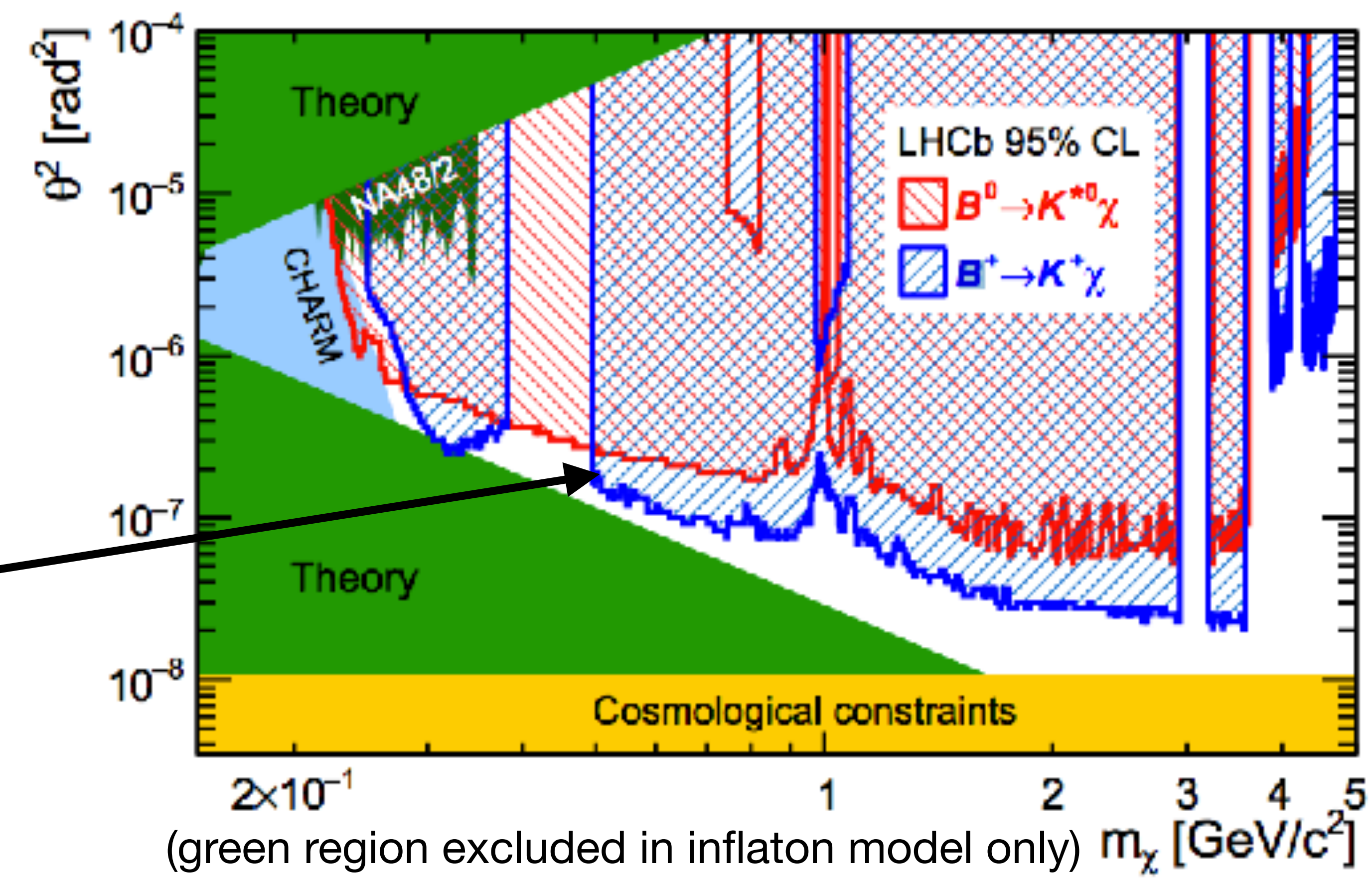
  P. Ilten, J. Thaler, M. Williams, W. Xue: 1509.06765
  P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue: 1603.08926

- Hidden valleys

  A. Pierce, B. Shakya, Y. Tsai, Y. Zhao: 1708.05389

LHCb: 1612.07818

$c\tau \sim 1\,\mathrm{mm}$

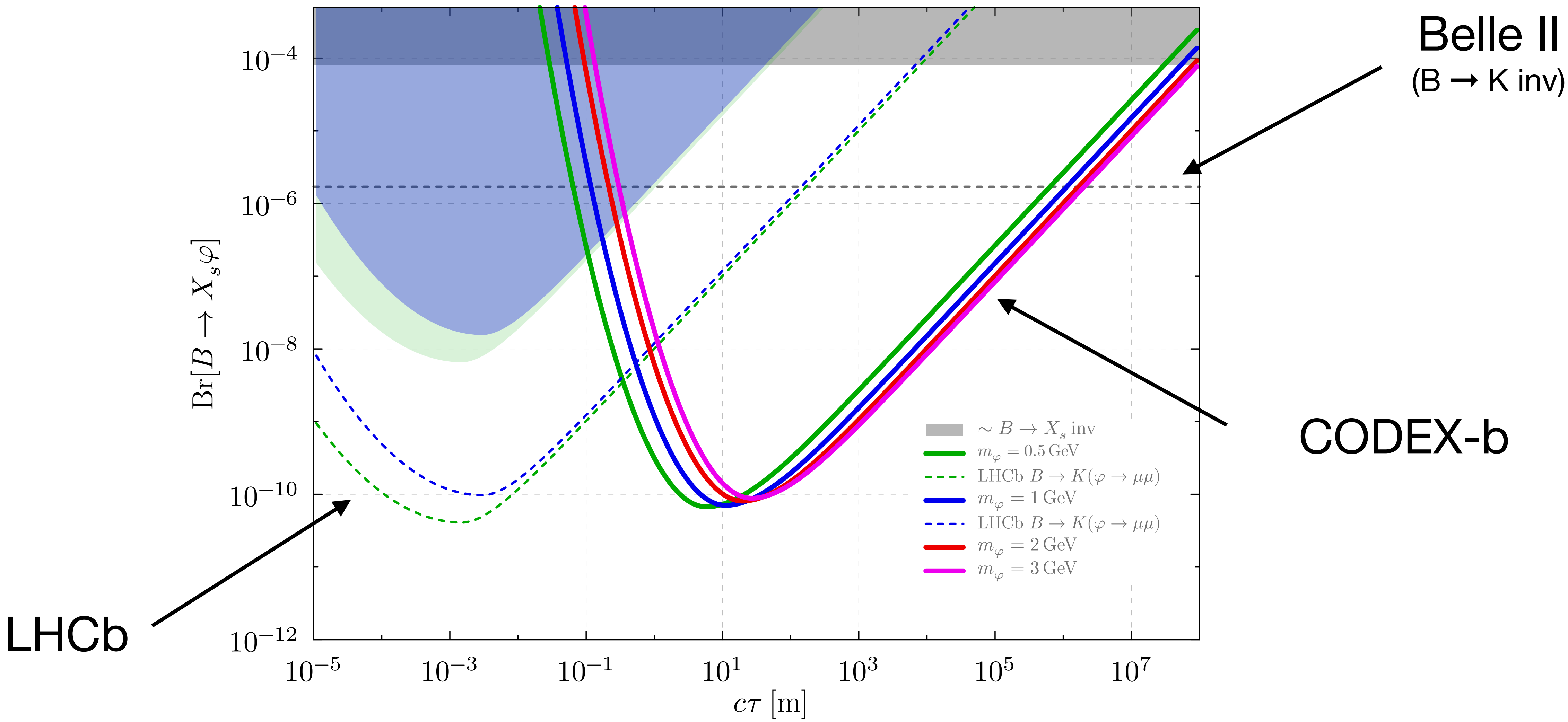


(green region excluded in inflaton model only)

Large boost and rather small VELO (~ 1m) reduce sensitivity to long lifetimes

More general models

Reach



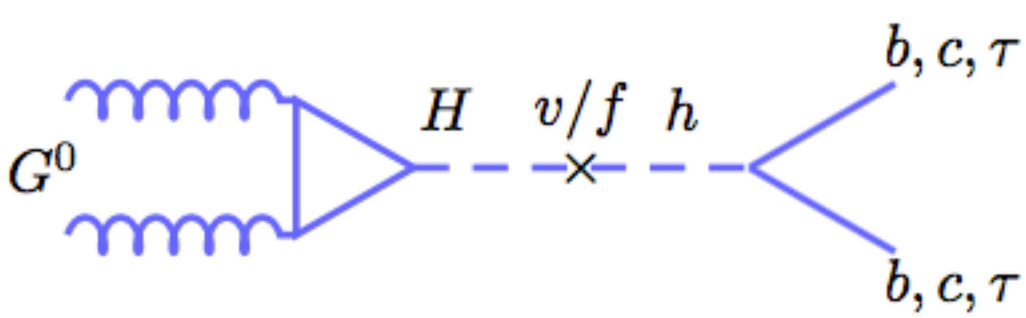
Complementary reach compared to main LHCb detector

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

Hidden glueballs (Neutral Naturalness)

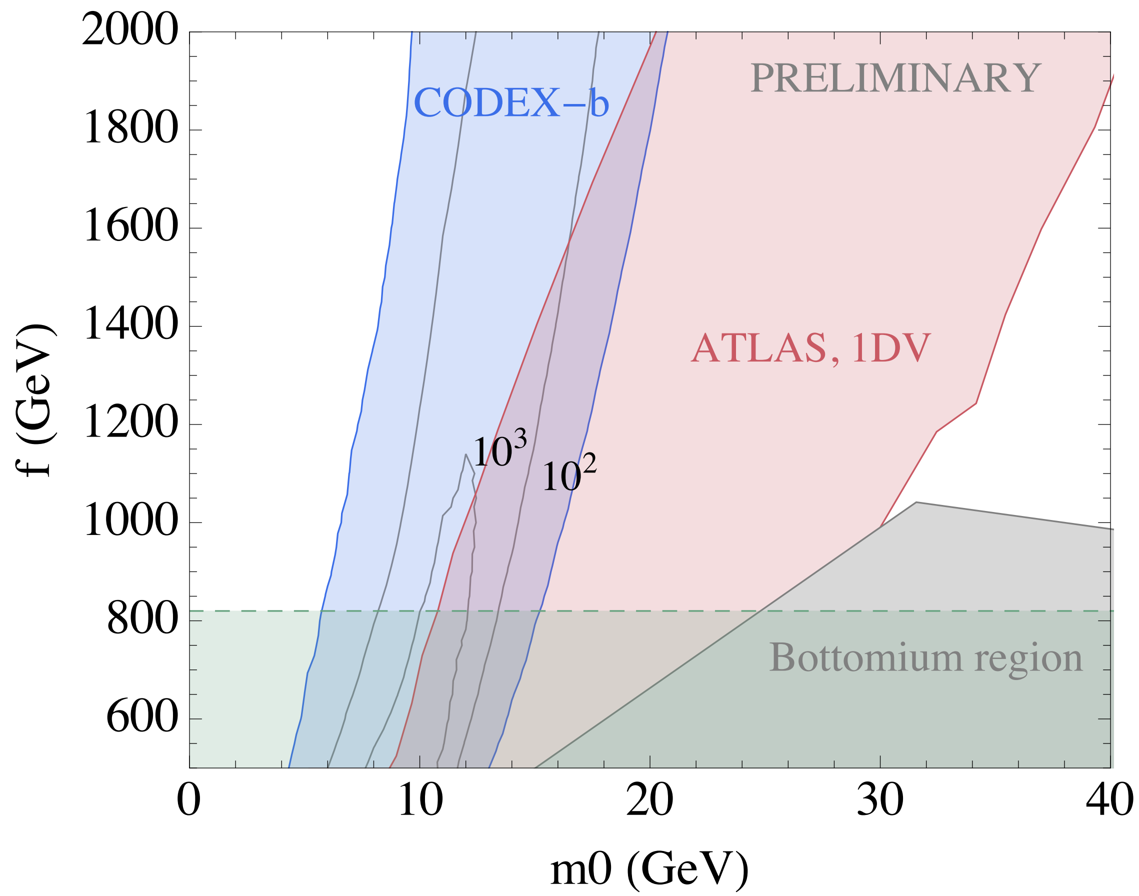
Production: exotic Higgs decay

Decay: through Higgs mixing:



Lifetime very strong function

of glueball mass $c\tau \sim m_0^{-7}$



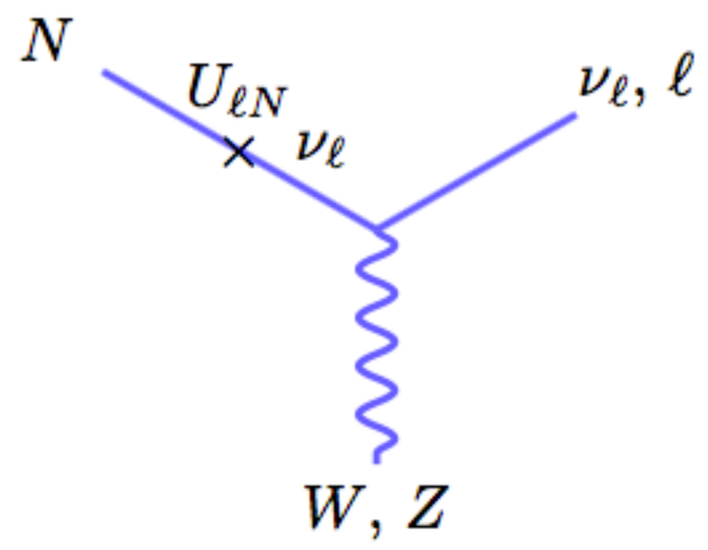
ATLAS / CMS pay double penalty at low mass:

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

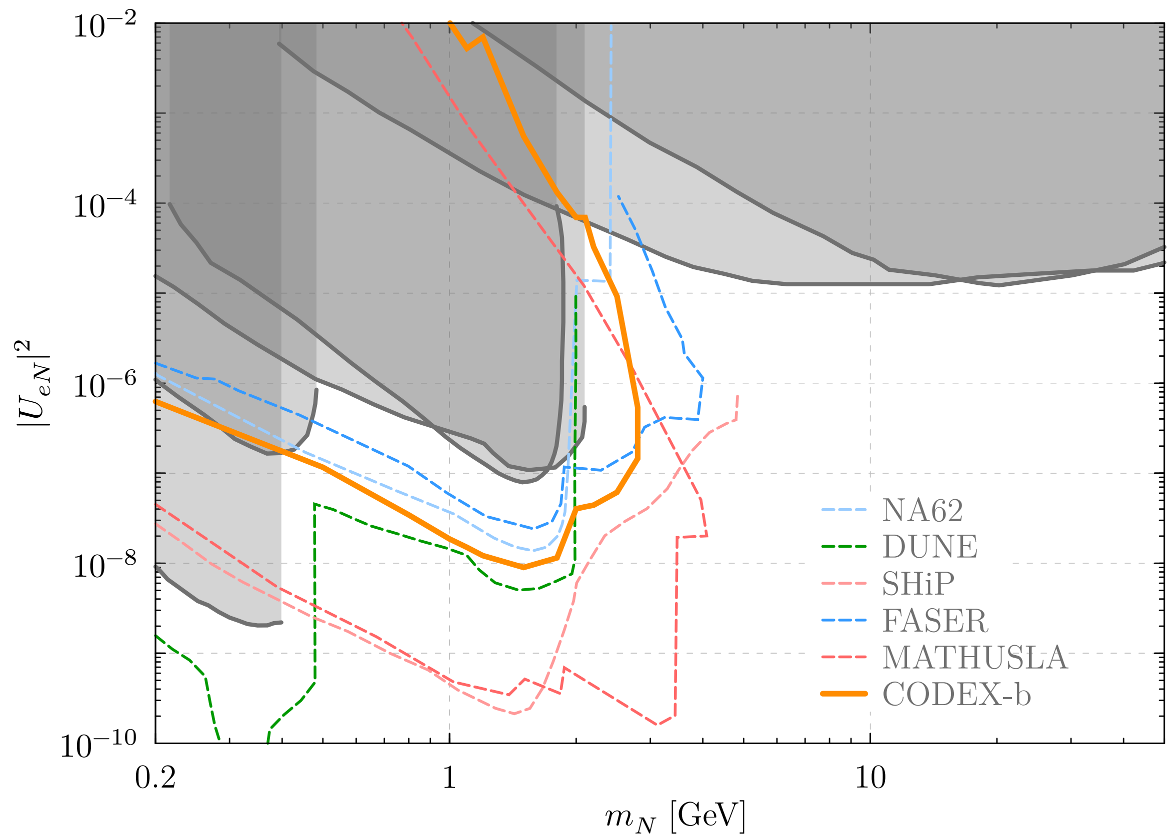
Heavy neutral leptons

- 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

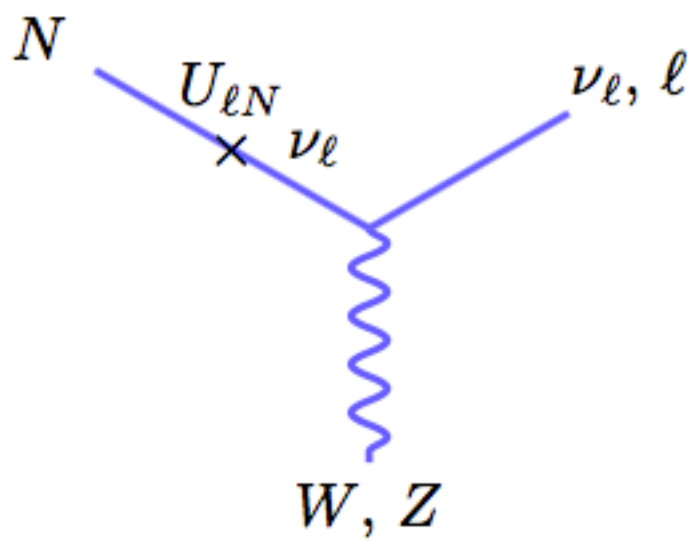
18xx.xxxxx: J. Evans, SK, M. Papucci, H. Ramani D. Robinson

see also: Heo, Hirsch, Wang: 1803.02212

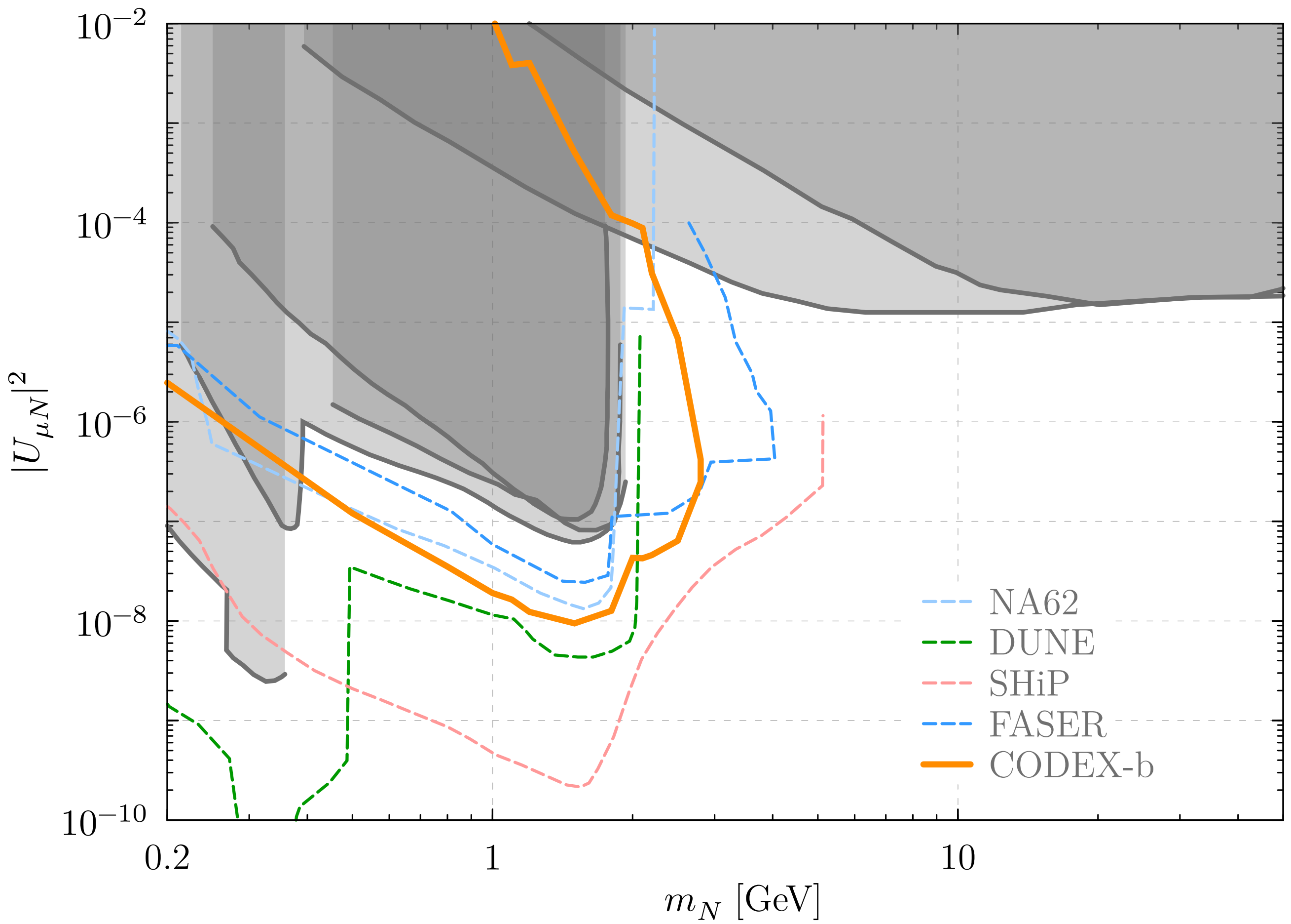
Heavy neutral leptons

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

- Decay: Mix back to off-shell SM neutrino
  (N→3ν, N→ℓ hadrons, N→νℓℓ)



Example: $U_{\mu N}$

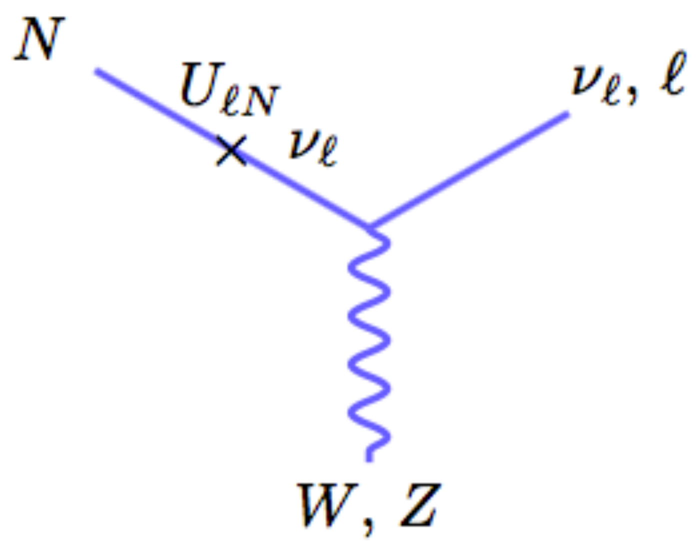


18xx.xxxxx: J. Evans, SK, M. Papucci, H. Ramani D. Robinson

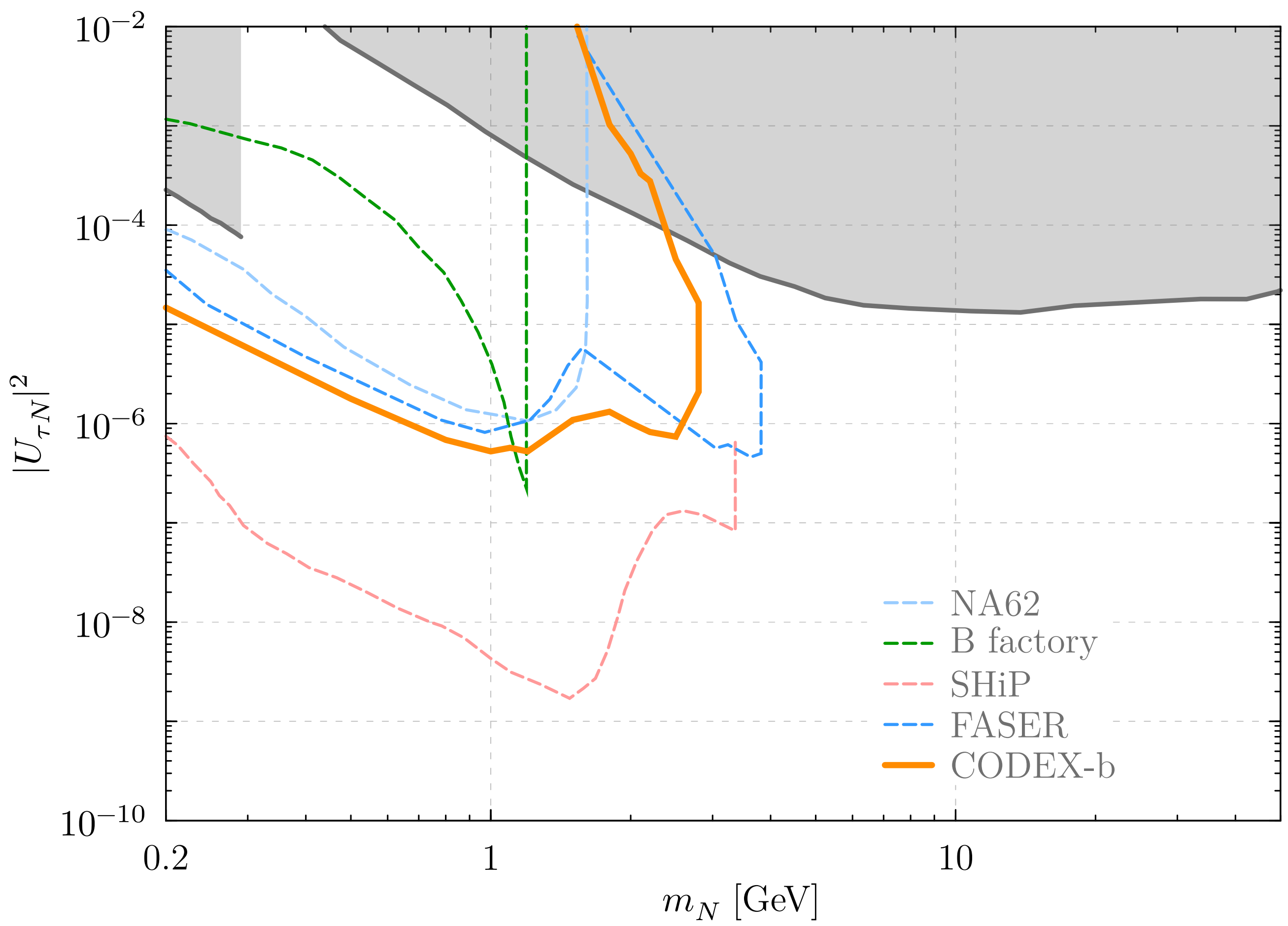
see also: Heo, Hirsch, Wang: 1803.02212

Heavy neutral leptons

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



Example: $U_{\tau N}$



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

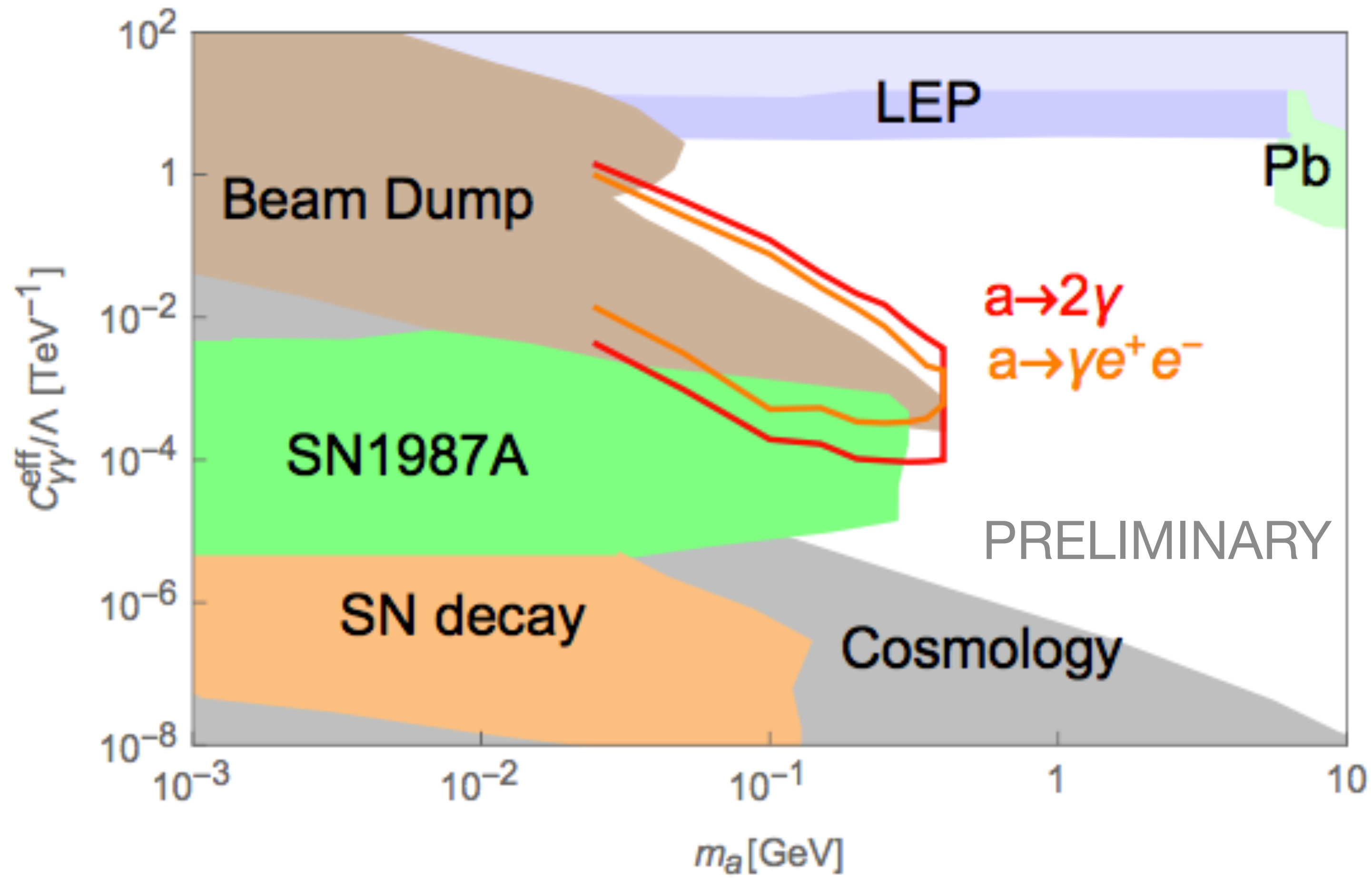
see also: Heo, Hirsch, Wang: 1803.02212

Axion-like particles

Assume only $aG\tilde{G}$ coupling in UV

↓

Induces $aF\tilde{F}$ coupling in IR
& mixing with SM π^0



Below the 3π threshold, the lifetime is enhanced

It is non-trivial but perhaps not impossible for CODEX-b to see the 2γ mode
(Will depend on final design choices.)

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