Some more LHC experiments on the lifetime frontier

FASER & CODEX-b

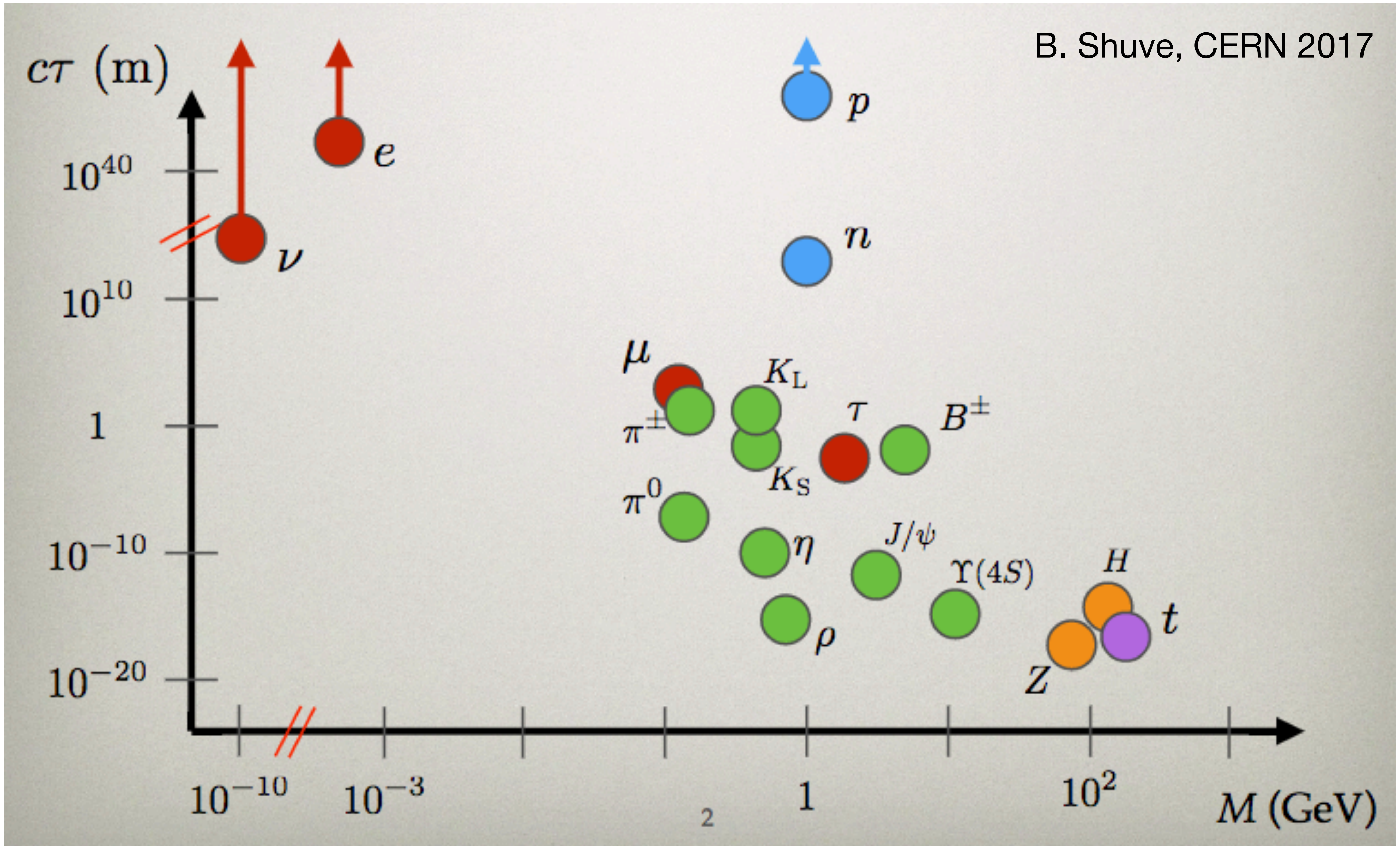
@ KITP, 05/23/2018

Simon Knapen

Lawrence Berkeley National Lab & UC Berkeley

FASER	1708.09389	F. Feng, I. Galon, F. Kling, S. Trojanowski
	1710.09387	F. Feng, I. Galon, F. Kling, S. Trojanowski
	1801.08947	F. Kling, S. Trojanowski
CODEX-b	1708.09395:	V. Gligorov, SK, M. Papucci, D. Robinson
	18xx.xxxxx:	J. Evans, SK, M. Papucci, H. Ramani, D. Robinson

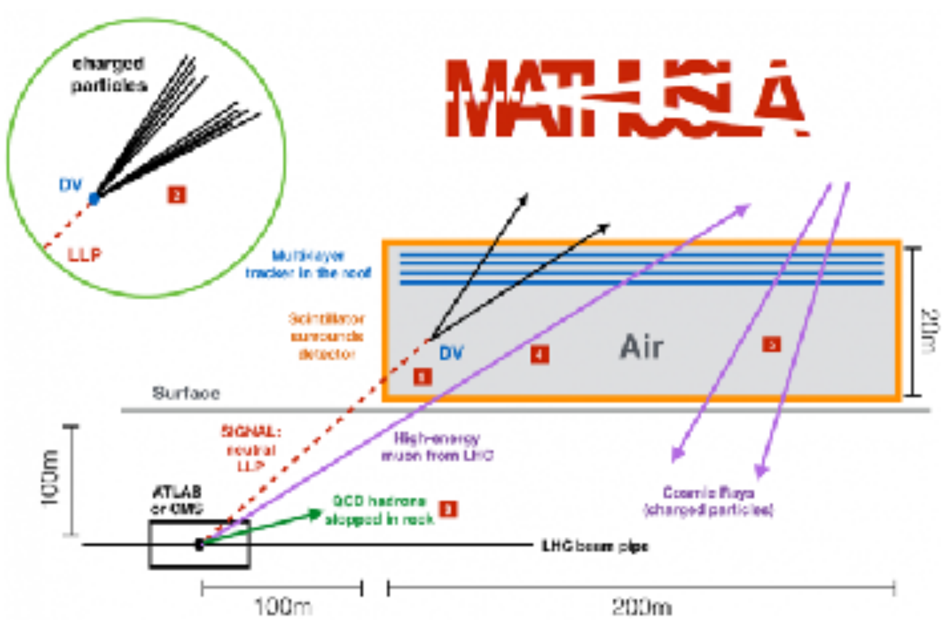
Long-Lived Particles are generic



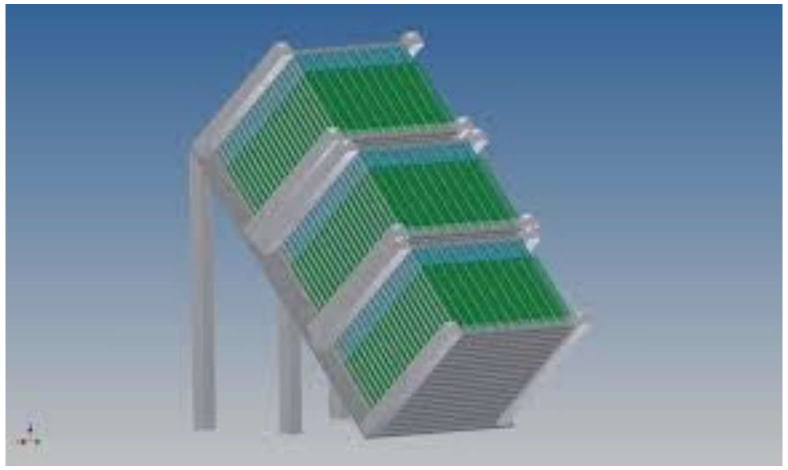
Because $m_W >> \Lambda_{QCD}$

Whenever there are multiple mass scales, expect long-lived particles

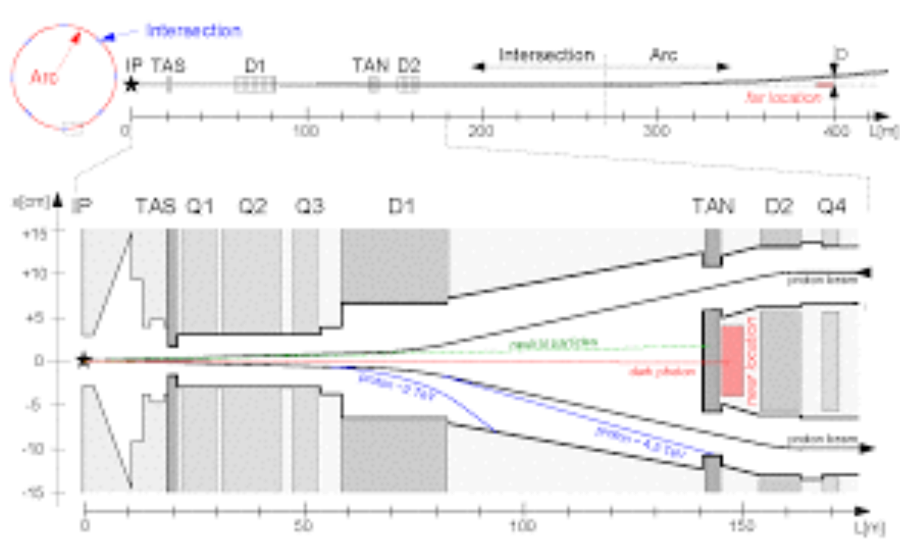
Proposals for shielded detectors



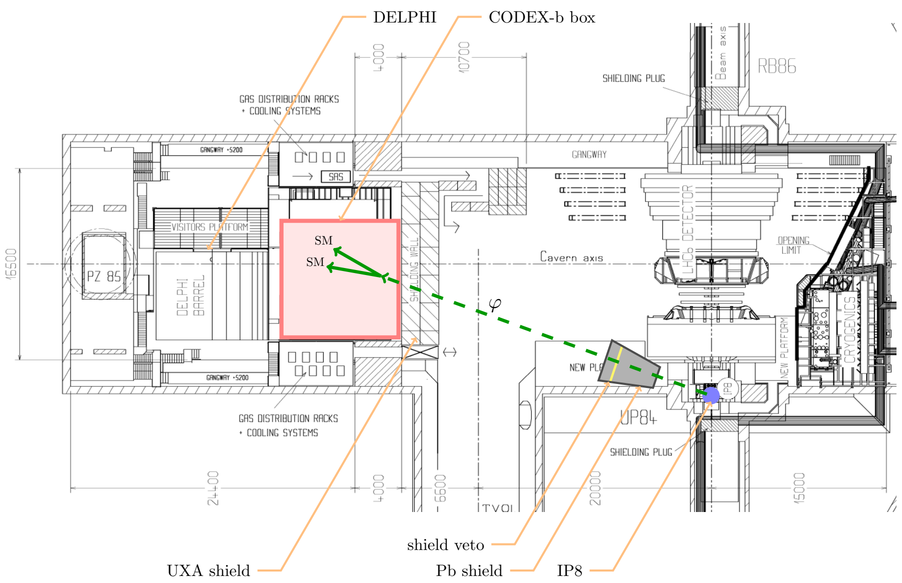
MATHUSLA



milliQan



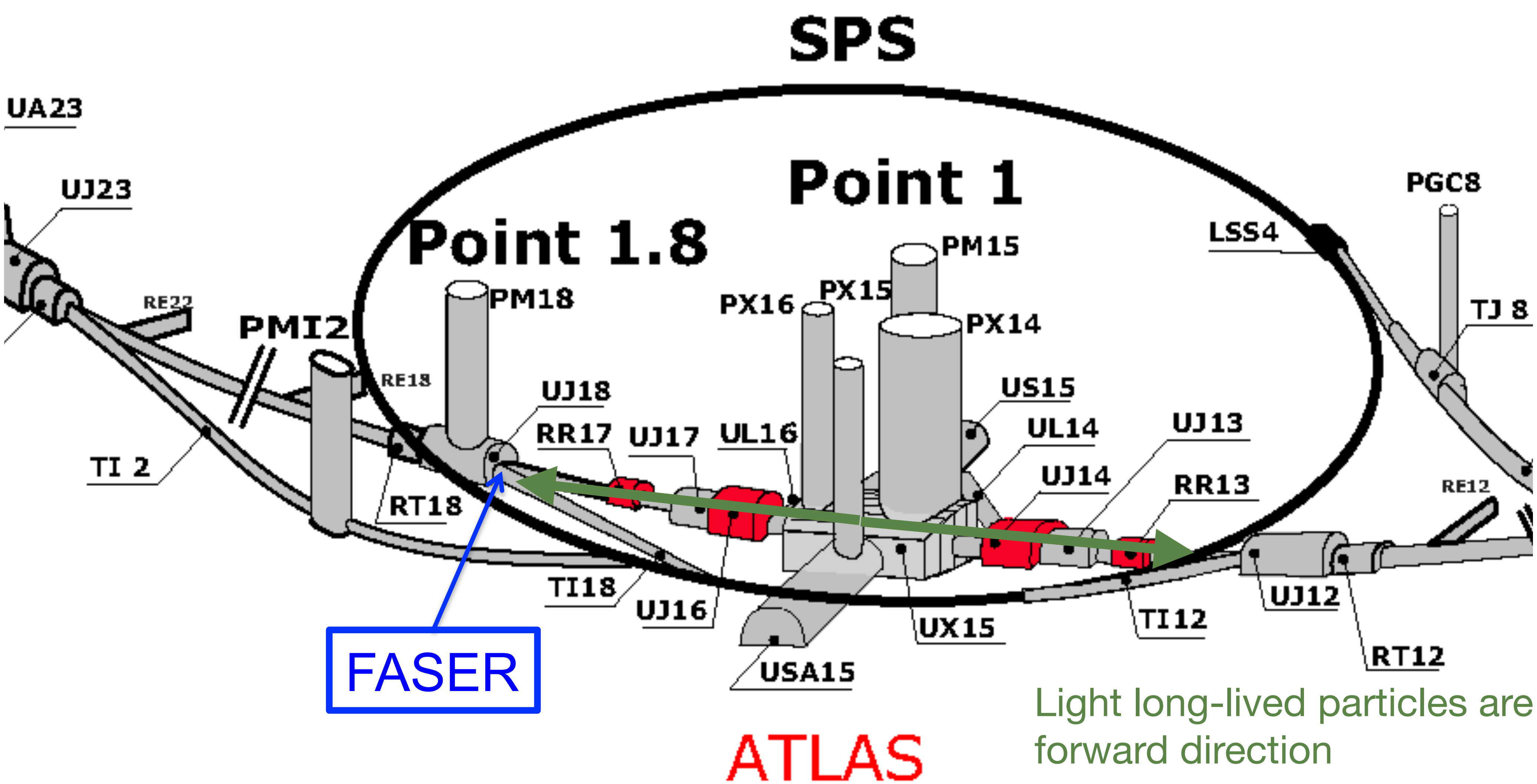
FASER



CODEX-b

Adapted from slides by Jamie Boyd
3th CERN LLP workshop 05/2018

SERVICE TUNNEL TI18



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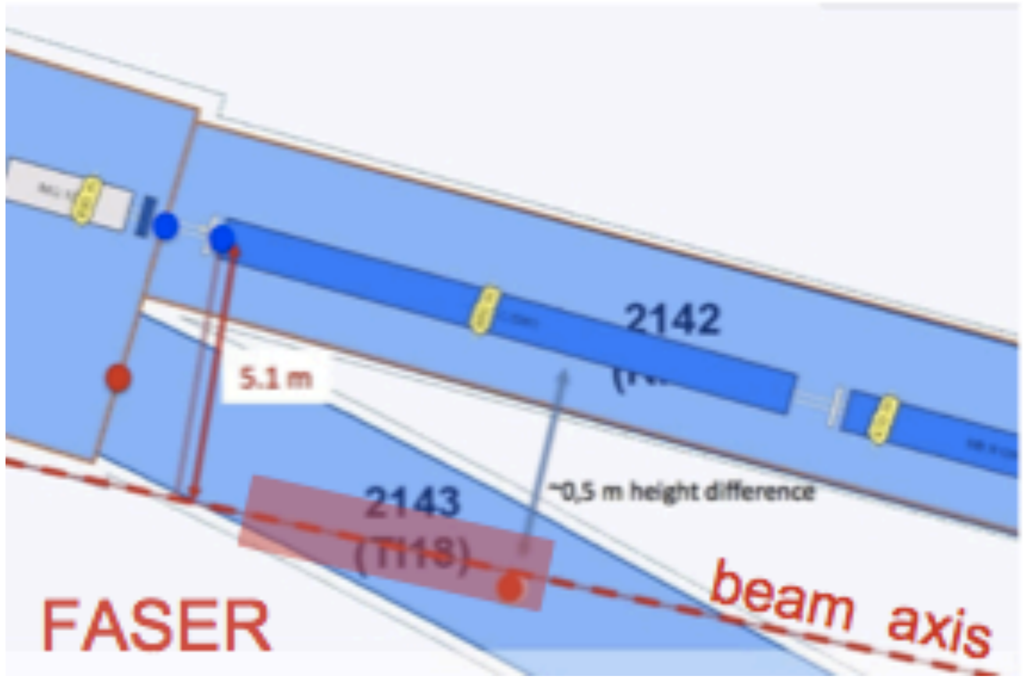
Slides by Jamie Boyd
3th CERN LLP workshop 05/2018

FASER: LOCATION



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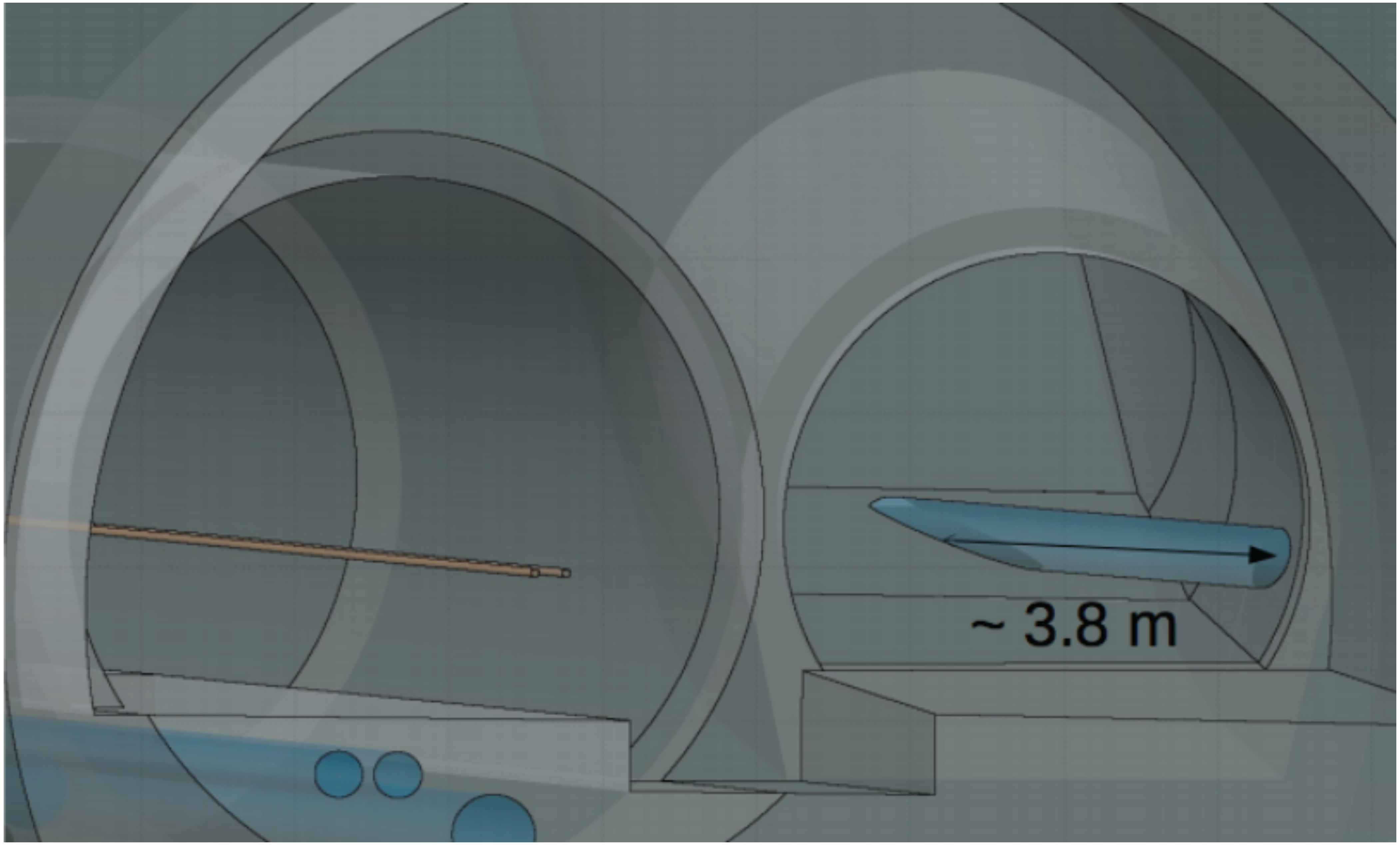
FASER: LOCATION



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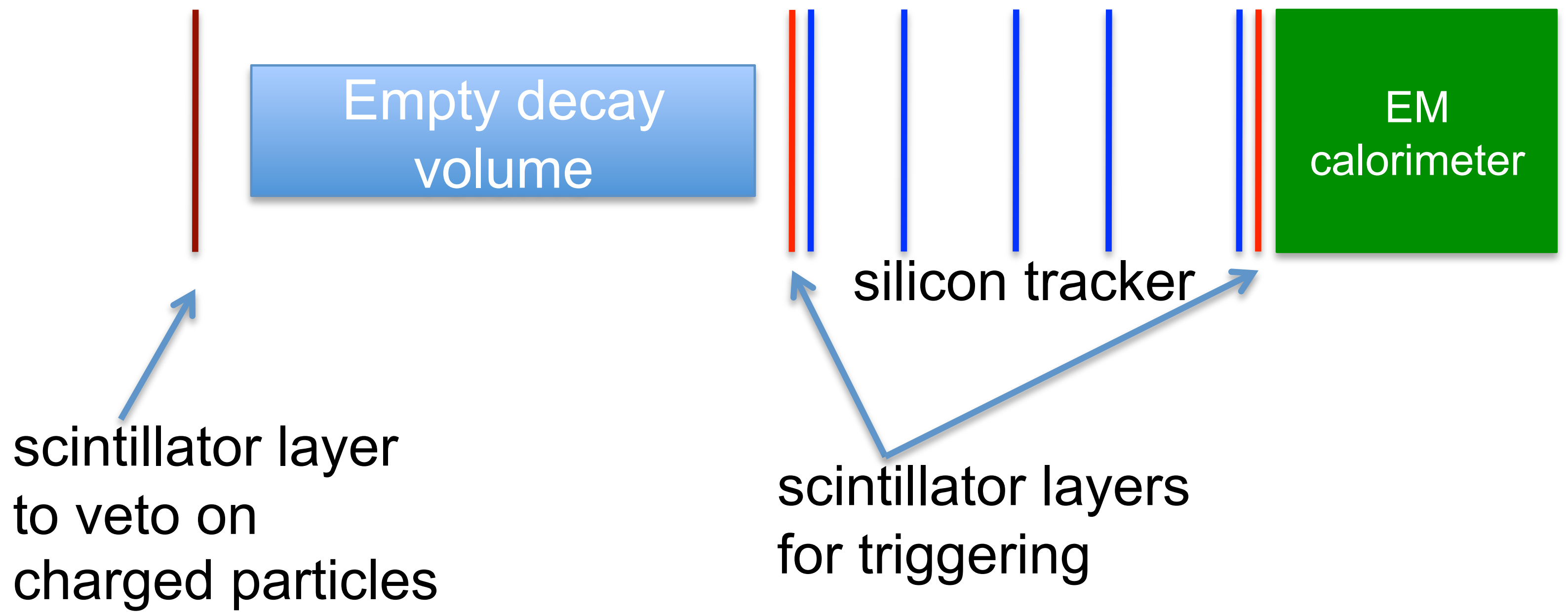
Slides by Jamie Boyd
3th CERN LLP workshop 05/2018

FASER: Detector considerations

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

sketch:



Currently optimizing the detector layout also based on re-using parts / spare-parts of existing detectors (e.g. for tracker).
Looking at different options for calorimeter.
Considering a permanent dipole magnet (suggested by CERN experts).
Detector needs to sit very close to the floor of the tunnel to lie on the line-of-sight, and needs to fit in available length (~4m, depends on crossing angle and possible digging).

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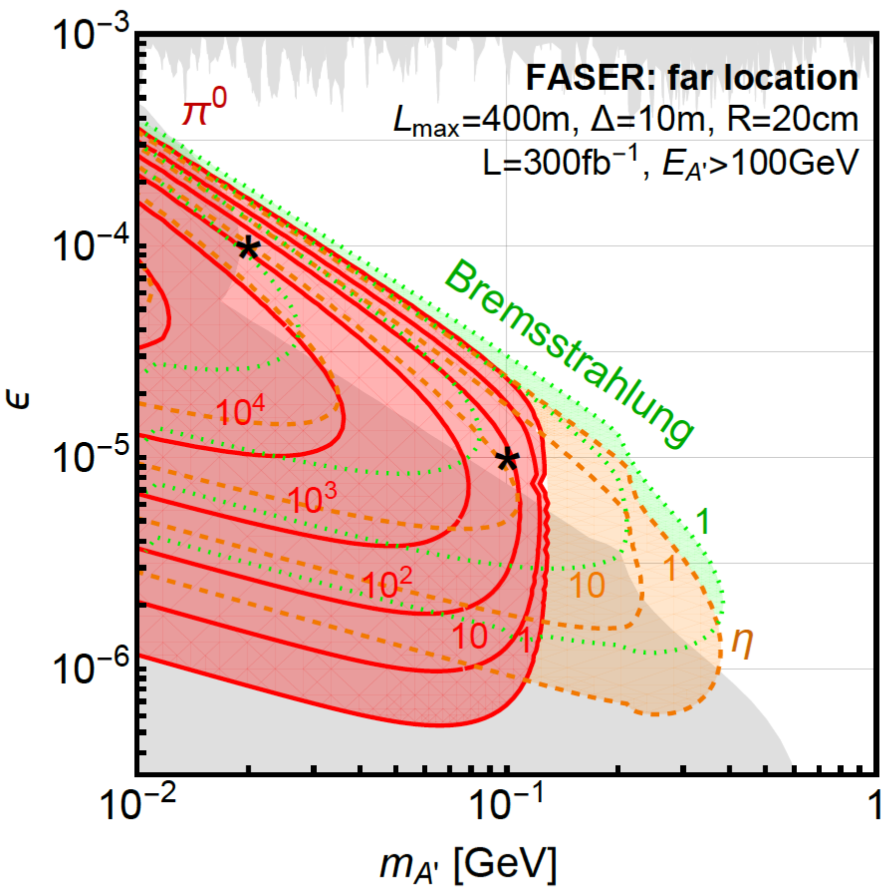
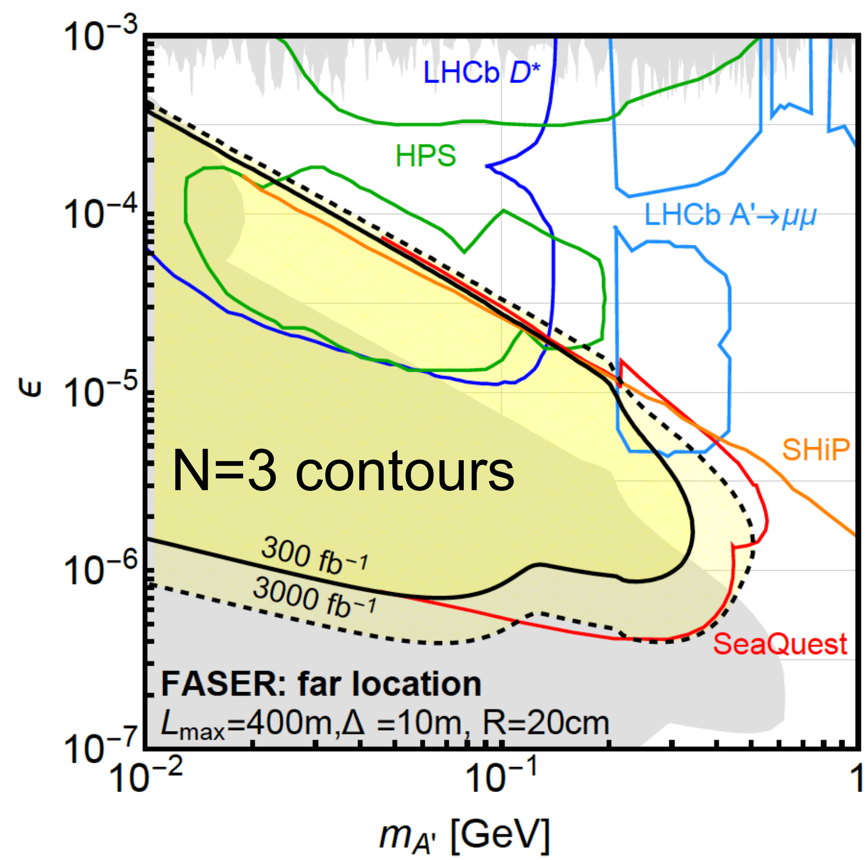
DARK PHOTON EVENT RATES AND REACH

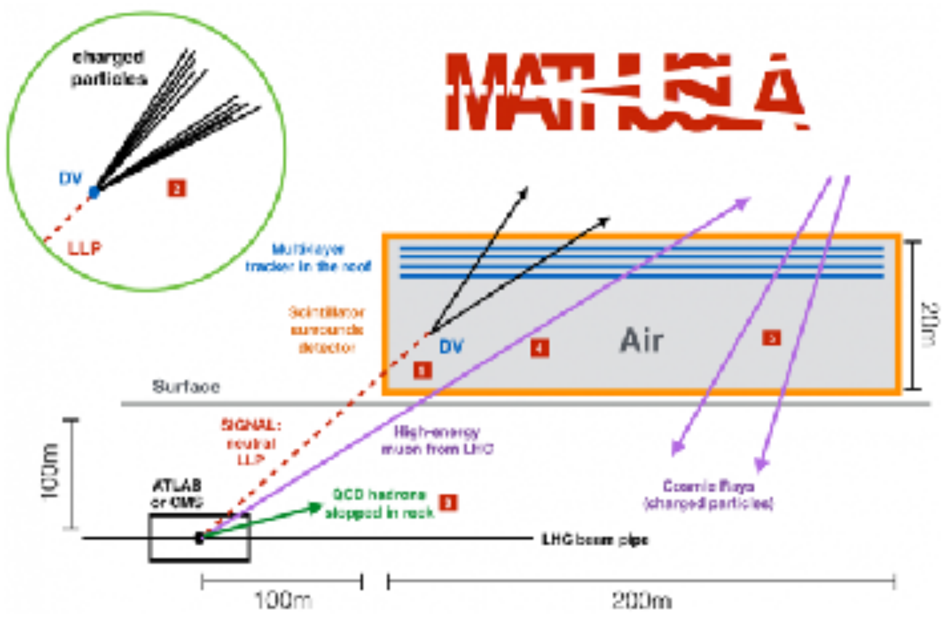
- Up to 10^5 dark photons decay in FASER in 300 fb^{-1} in parameter regions with $m_{A'} \sim 10 - 500$ MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$



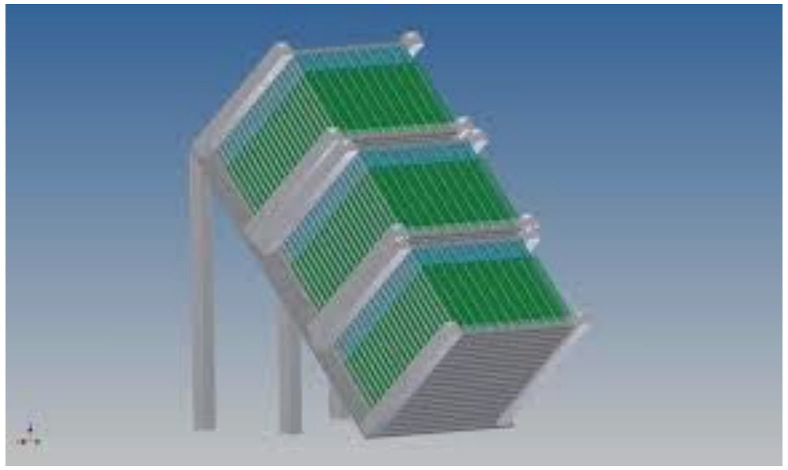


- Note that at upper ε boundary, rates are extremely sensitive to ε and the reach is quite insensitive to background, provided it is known

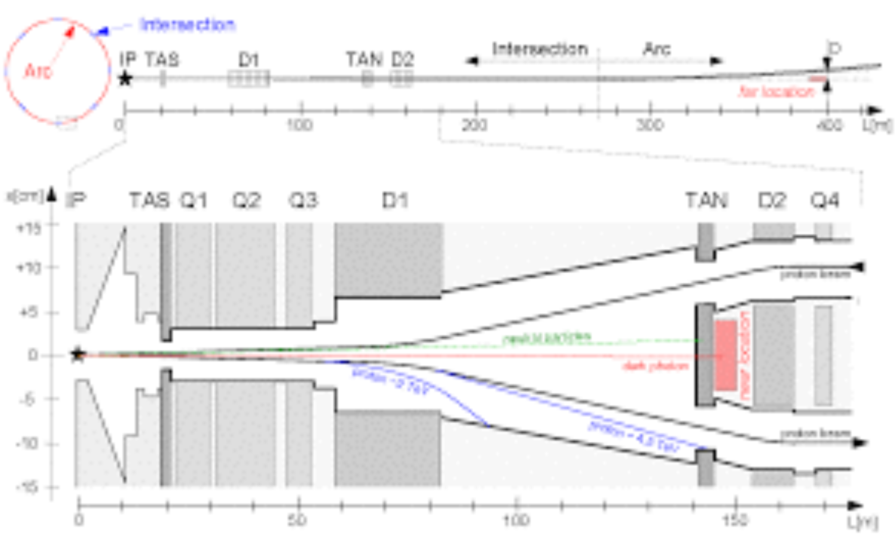
Proposals for shielded detectors



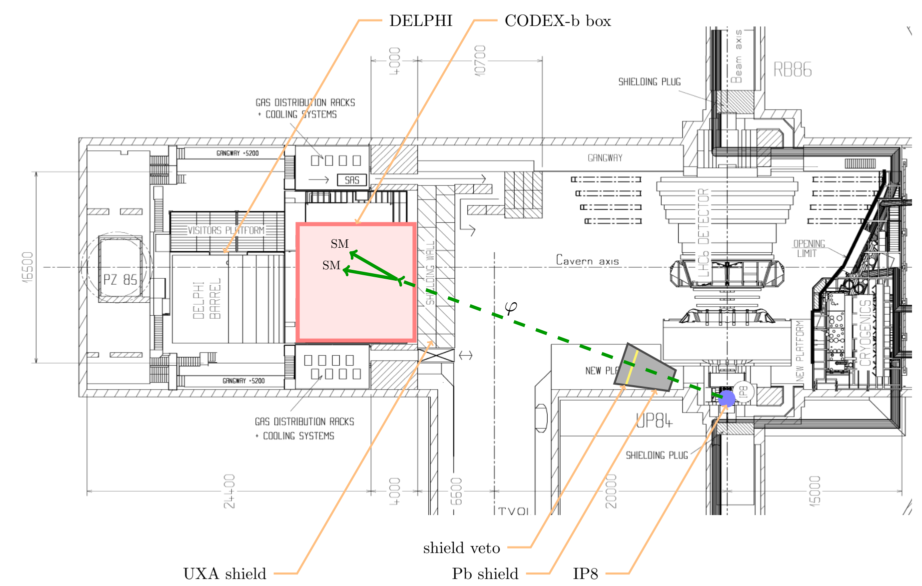
MATHUSLA



milliQan

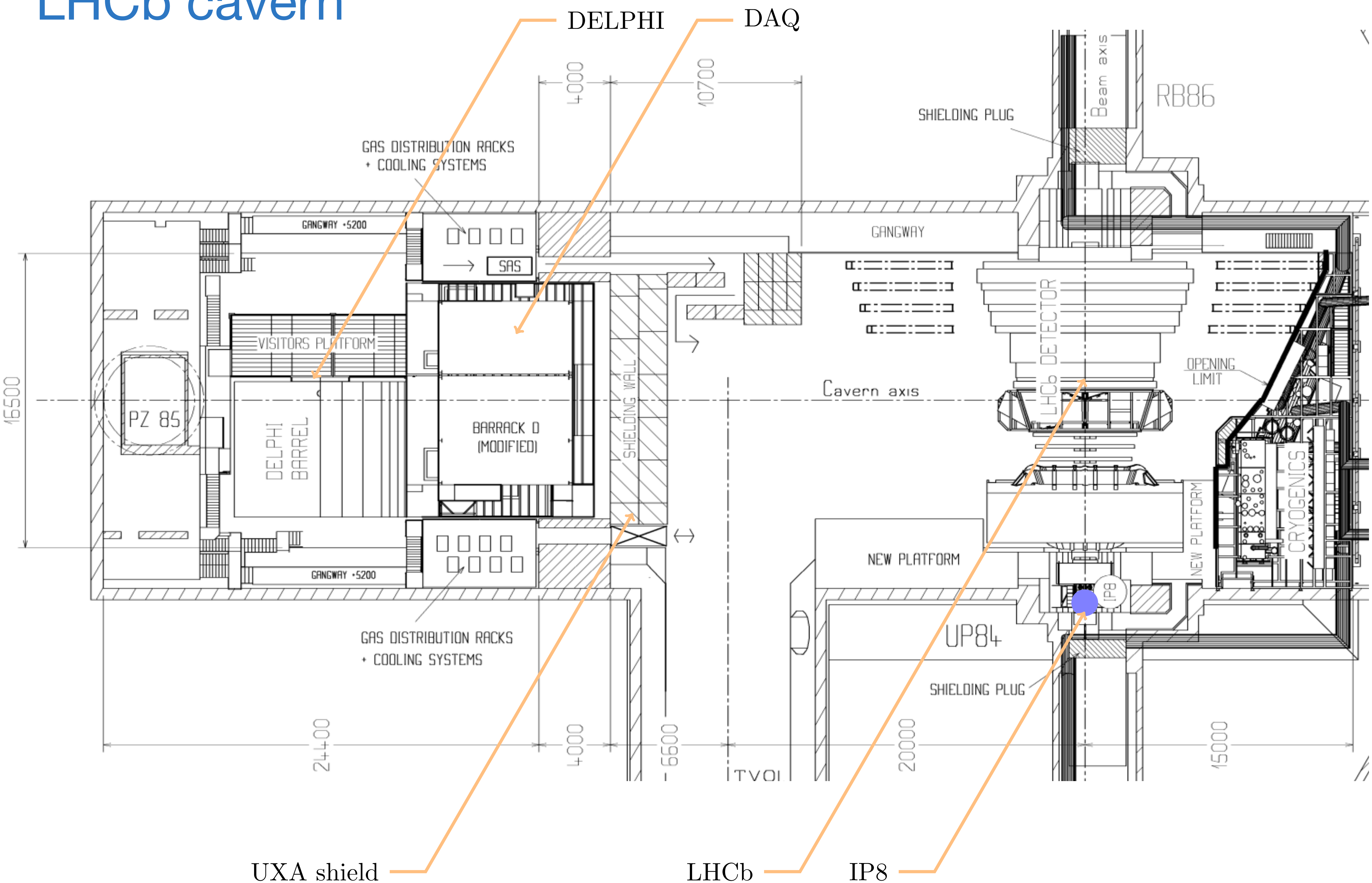


FASER



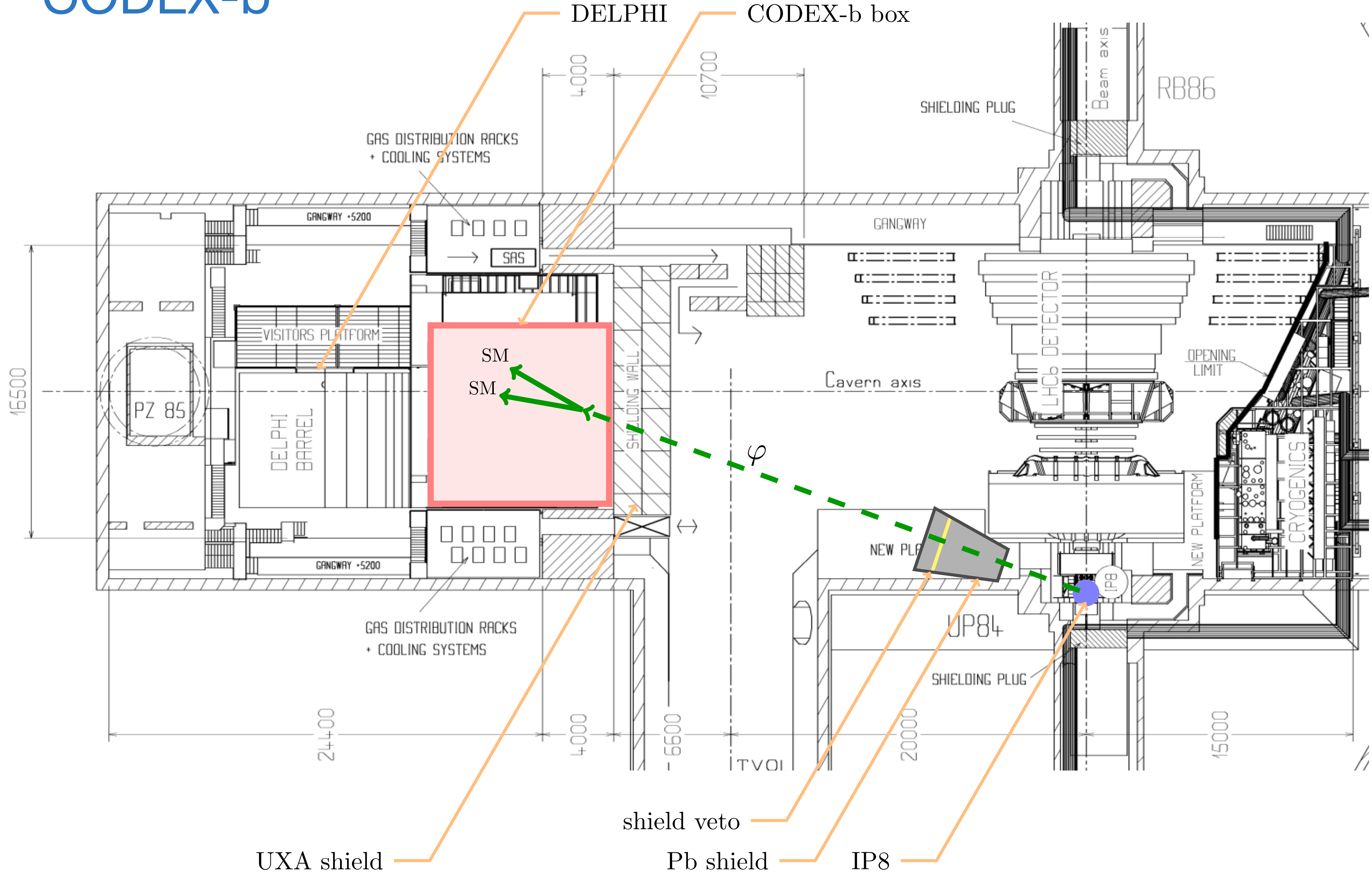
CODEX-b

LHCb cavern



Data acquisition will be moved to surface for run 3

CODEX-b



Data acquisition will be moved to surface for run 3

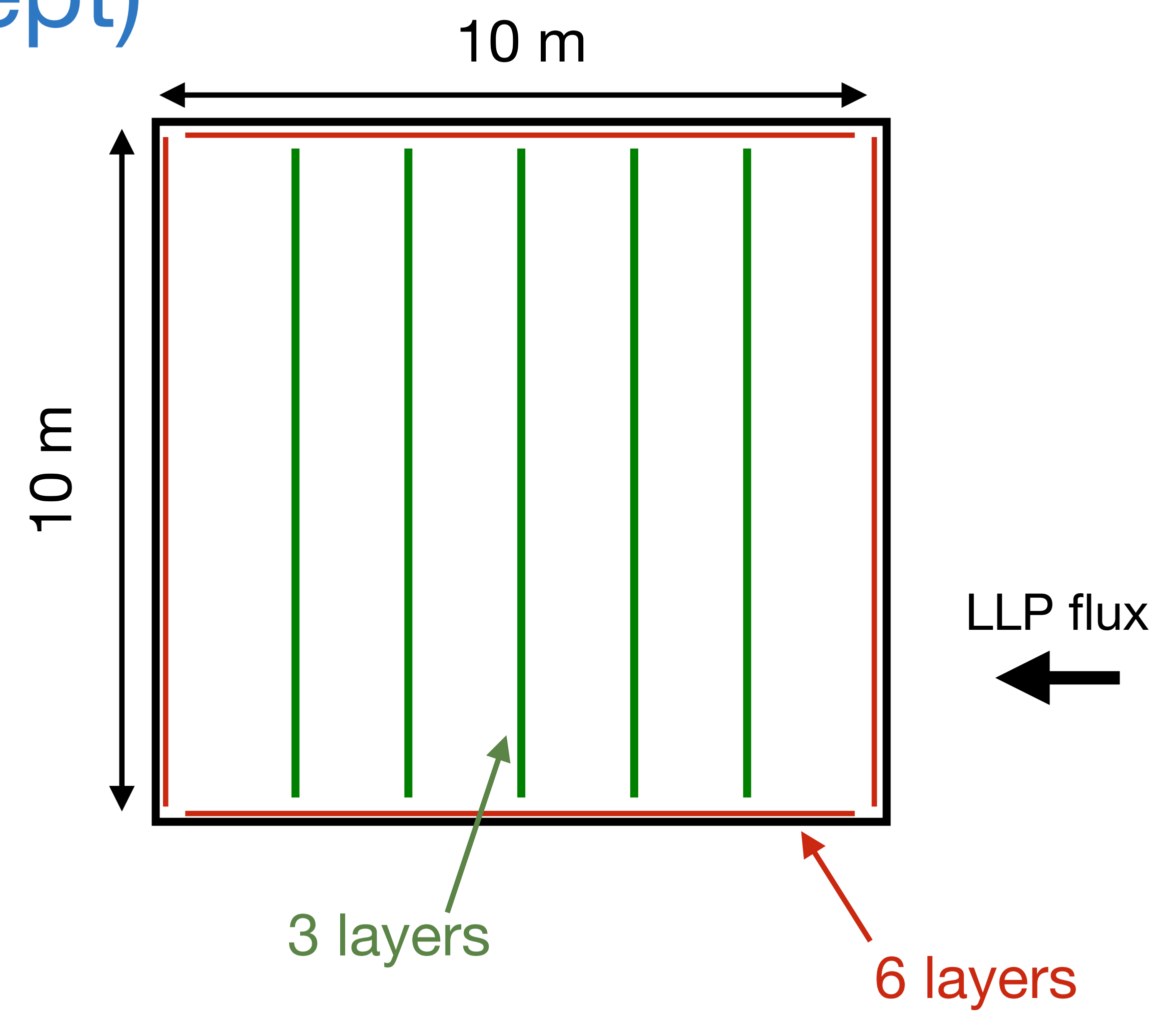
Fiducial volume (proof of concept)

- 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:

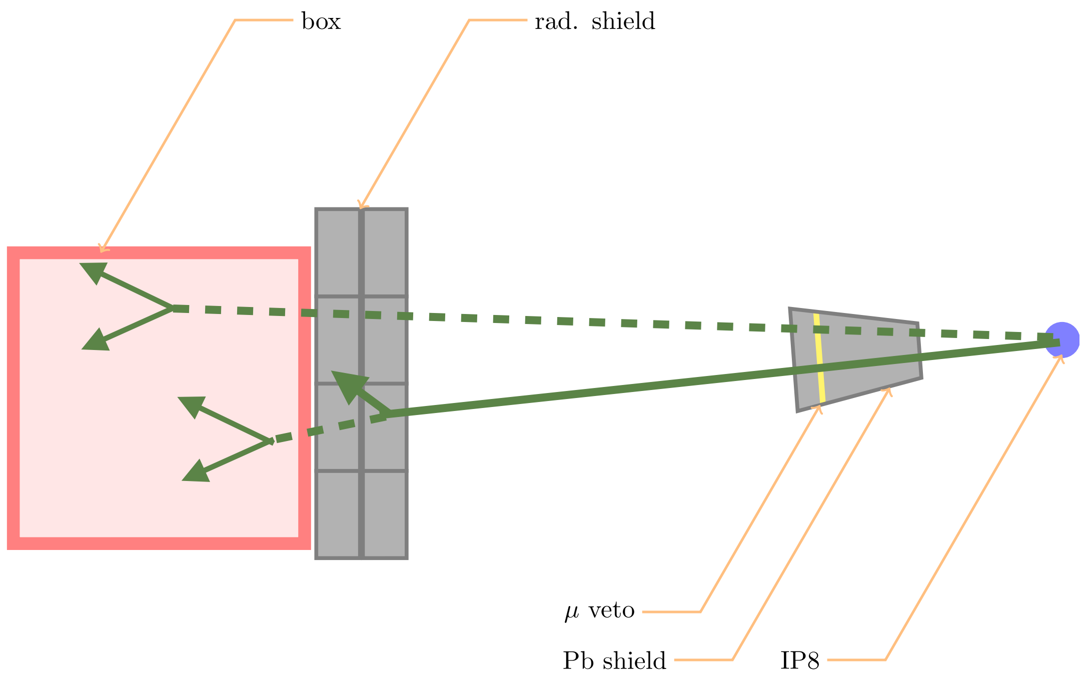
- recover acceptance for particles with low boost

- minimize distance to first tracked point

Backgrounds

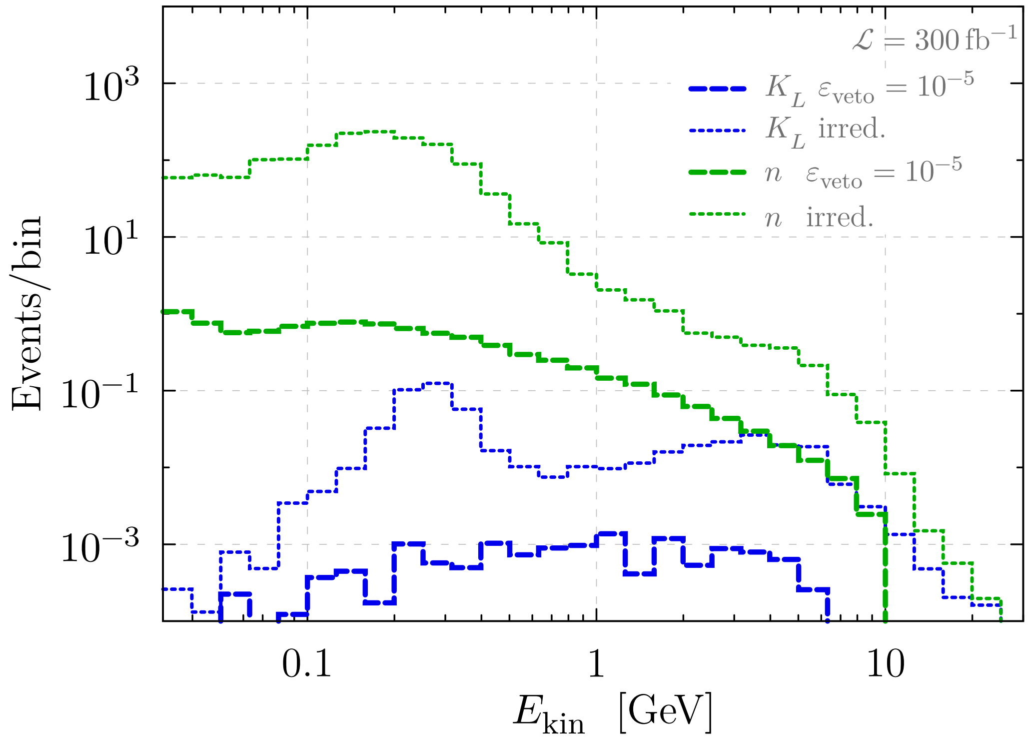
- Absorb neutral hadrons in shield
  (irreducible background)

- Veto muon-induced backgrounds with muon veto + front face of the detector (reducible background)



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	$2 \cdot 10^6$	$E > 0.5\,\text{GeV}$

Simulation: pythia 8 + GEANT 4



Need about 4.5m of Pb shielding

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

Example models

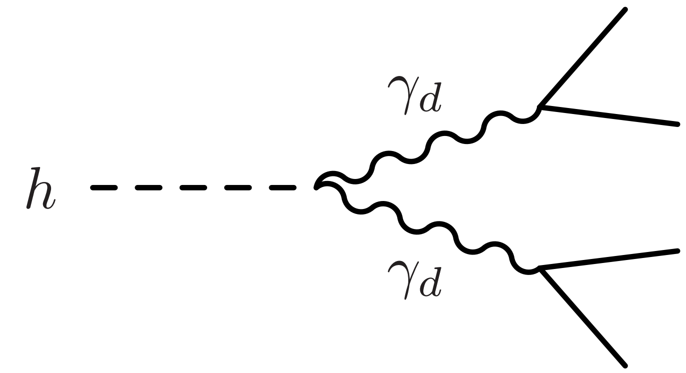
High energy portals

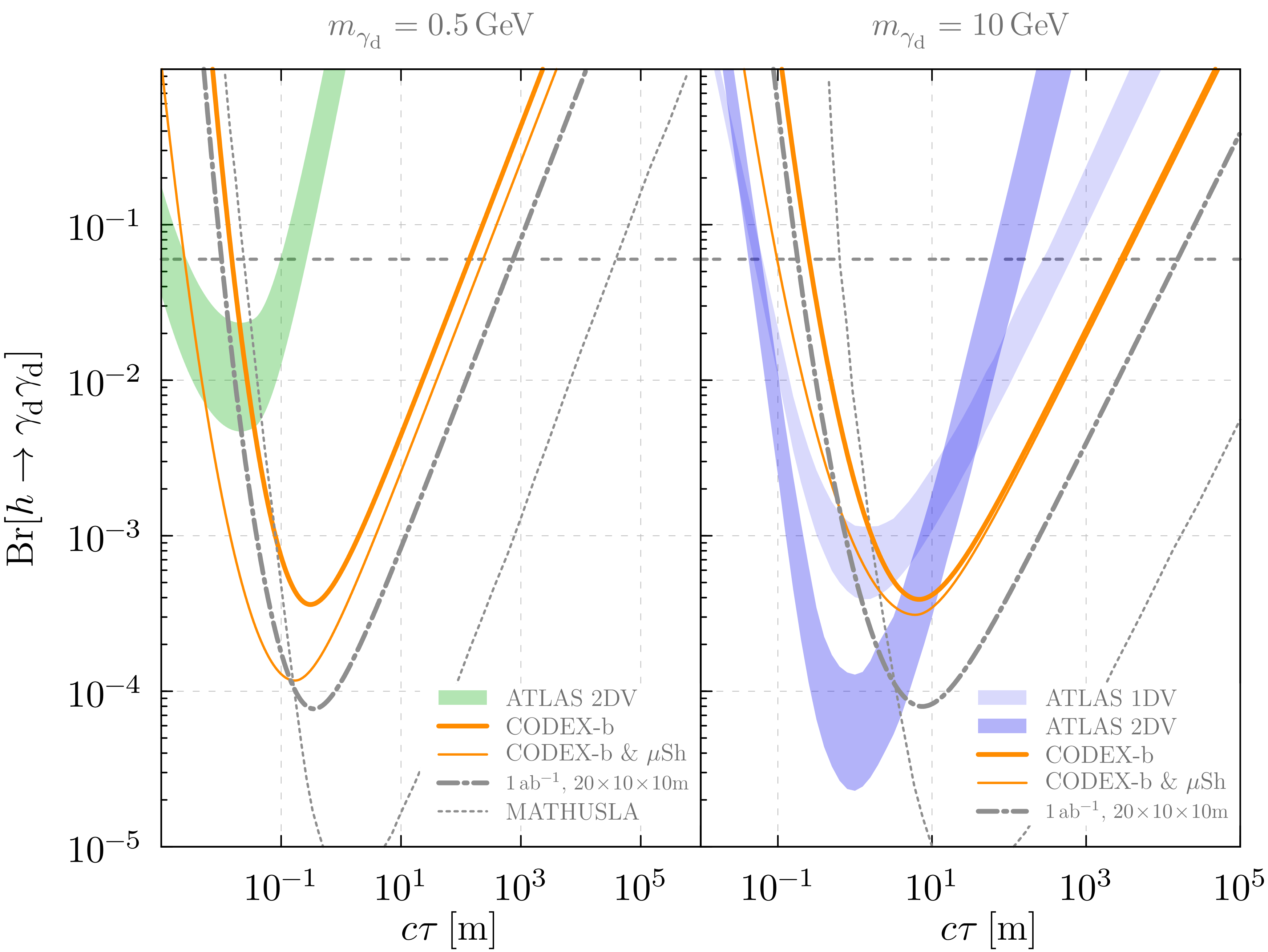
1. Exotic Higgs decays: $h \rightarrow A' A'$
2. Z decay to RPV neutralinos (back-up slides)
3. Hidden sector glueballs as in Neutral Naturalness (back-up slides)

Low energy portals

1. Exotic B decays: $B \rightarrow K \varphi$
2. Heavy Neutral leptons
3. Axion-like particles (back-up slides)

Exotic Higgs decays





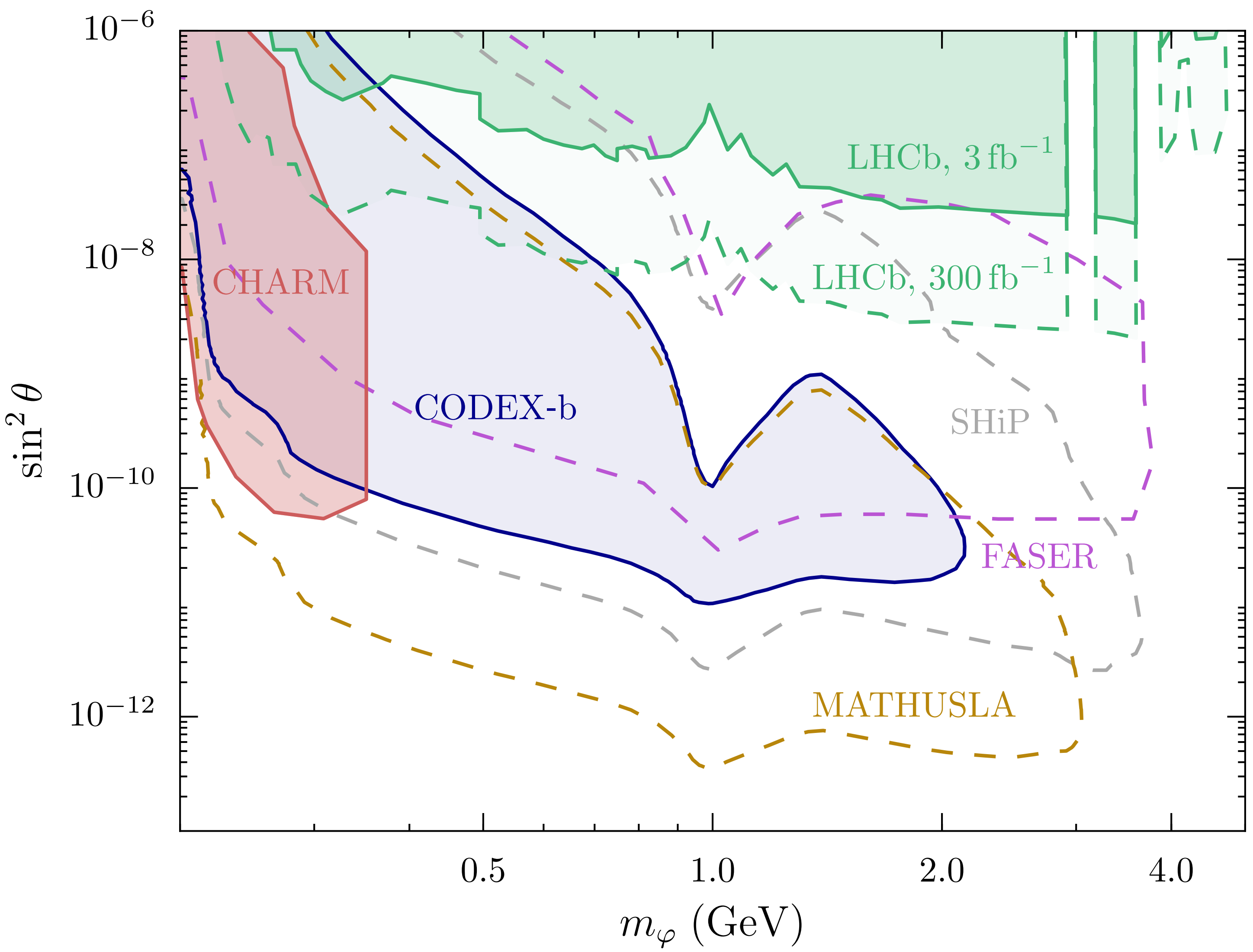
Application:
Neutral Naturalness
(See back-up material)

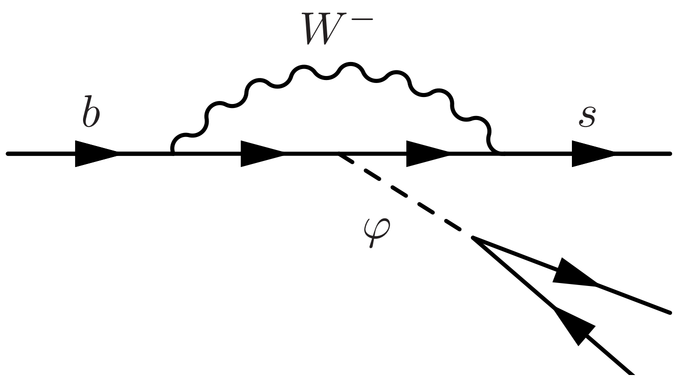
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

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

Light scalar mixing with Higgs





Beware of theory uncertainties on the lifetime!

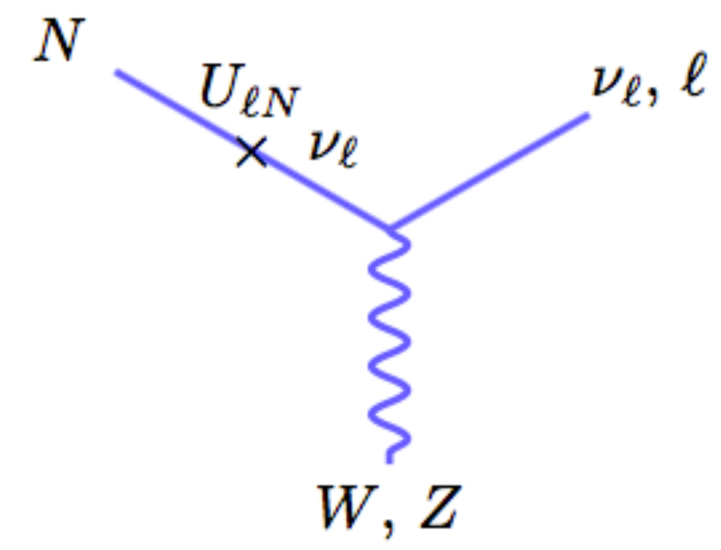
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

For application to coannihilating dark matter:
R. Tito D'Agnolo, C. Mondino, J. Ruderman. P. Wang: 1803.02901

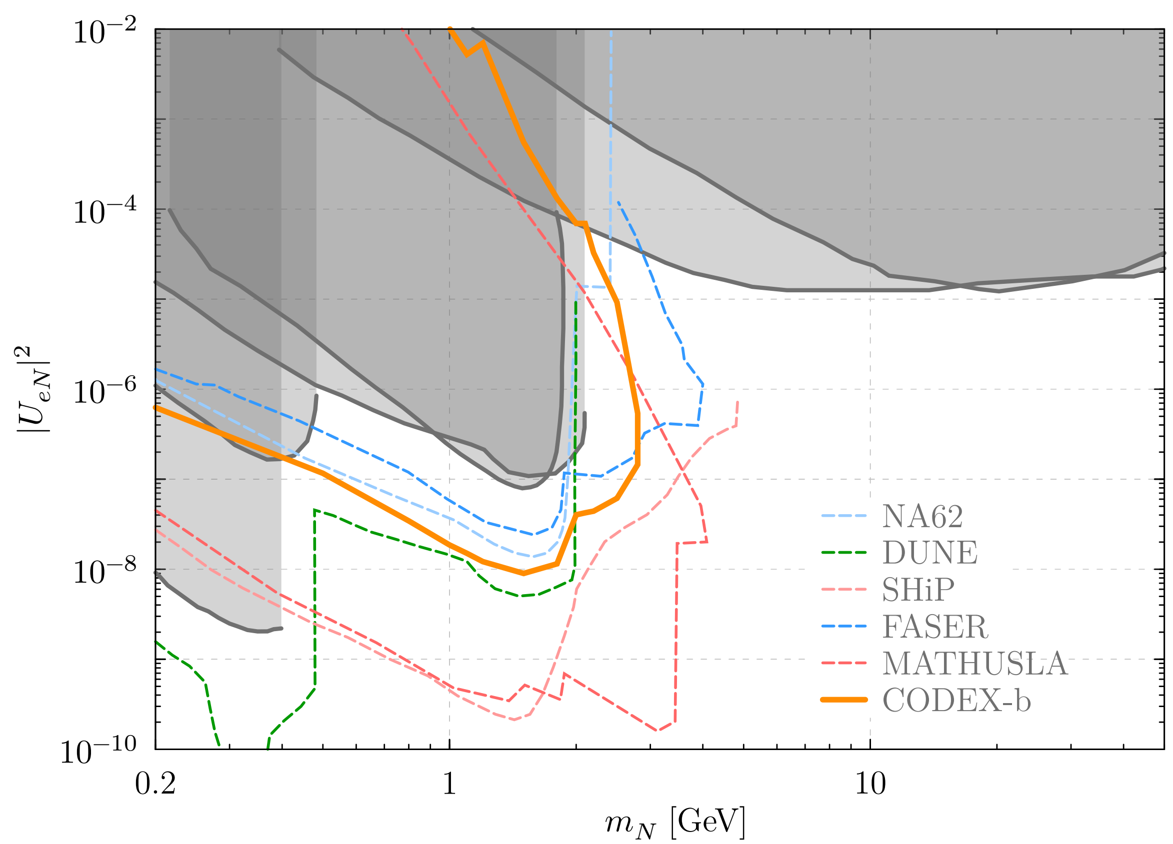
Heavy neutral leptons

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

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



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

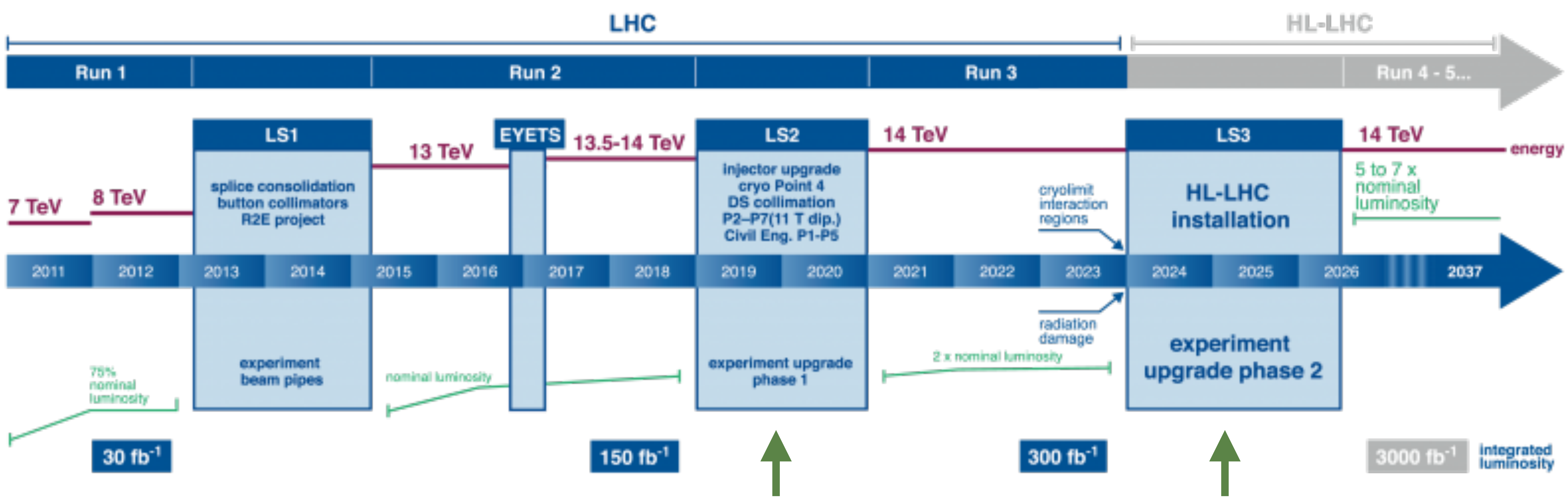
see also: Heo, Hirsch, Wang: 1803.02212

Moving forward

Ongoing work on theory side: more benchmark models

Ongoing work on the LHCb side

- Data driven background estimate →
- Considering different detector layouts
- Preparing a concrete proposal for the phase 2 upgrade



DAQ moves to surface

Install CODEX-b

Back-up

Finding Long-Lived Particles

* LHCb is an important exception

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

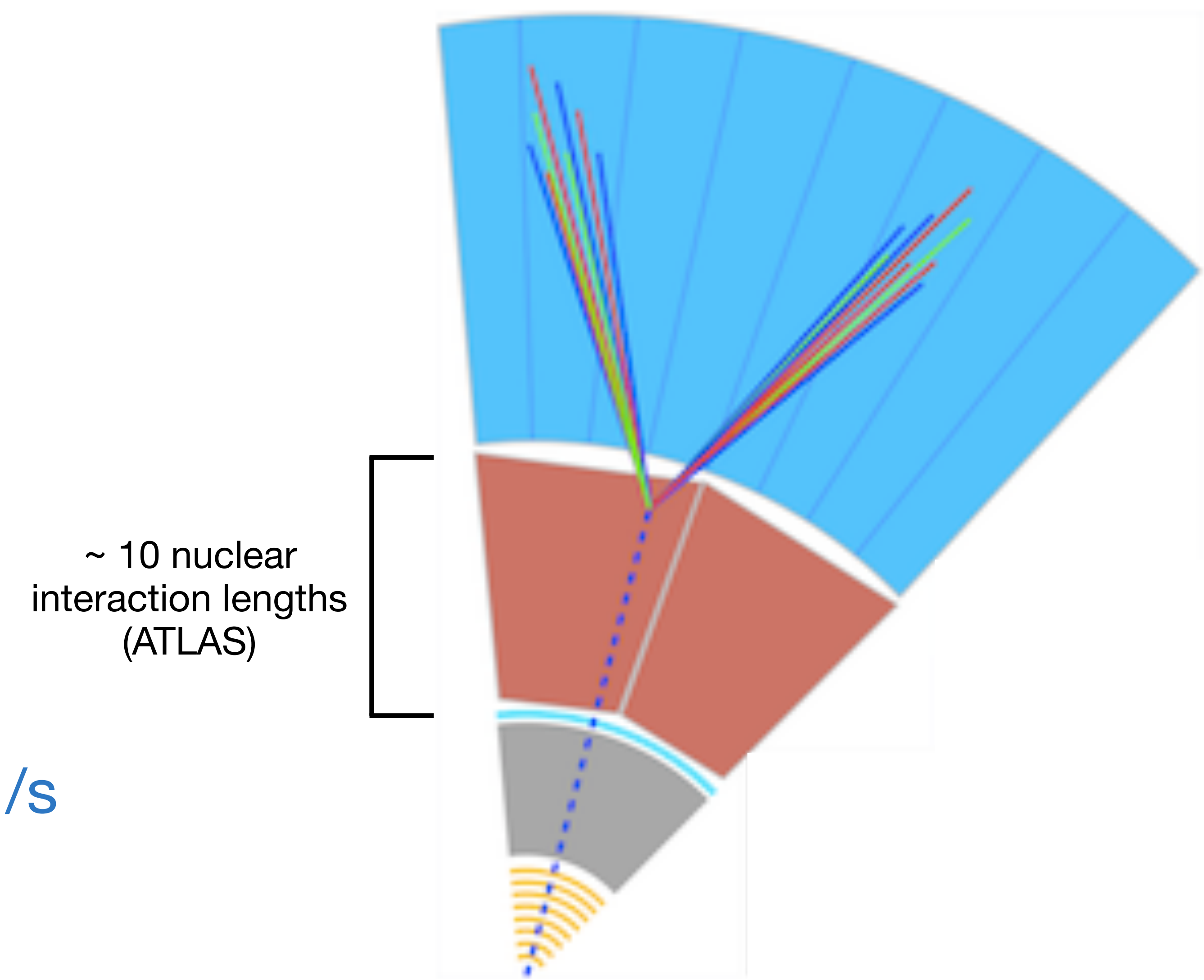
… but for low masses they suffer from*:

1. Tight trigger requirements
2. Backgrounds

A typical hadron has a chance of

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

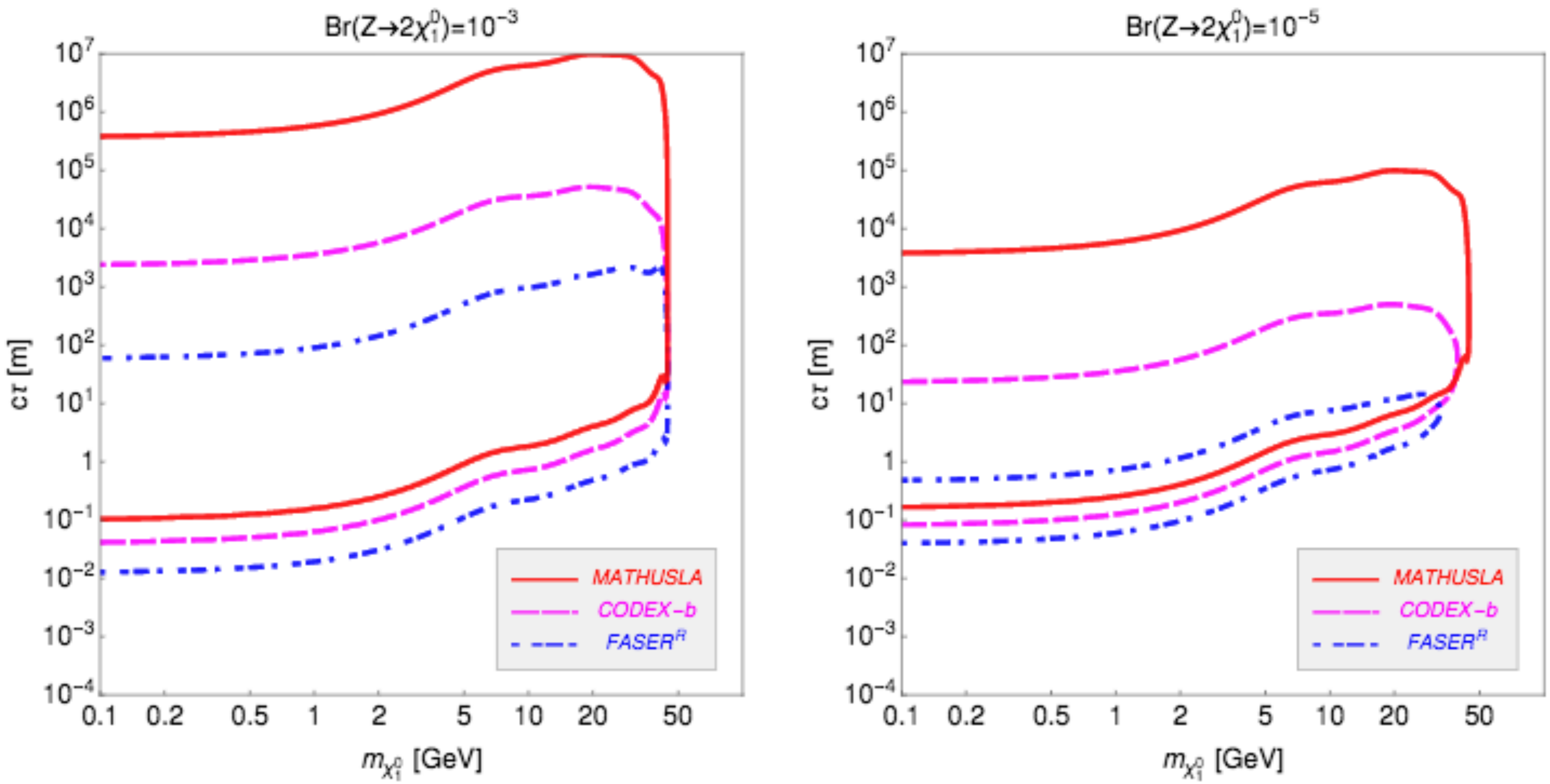
… but the LHC makes ~ 10^9 K_L mesons /s



Solution:
Dedicated detector with more shielding

RPV neutralinos

Take advantage of the large number of Z bosons

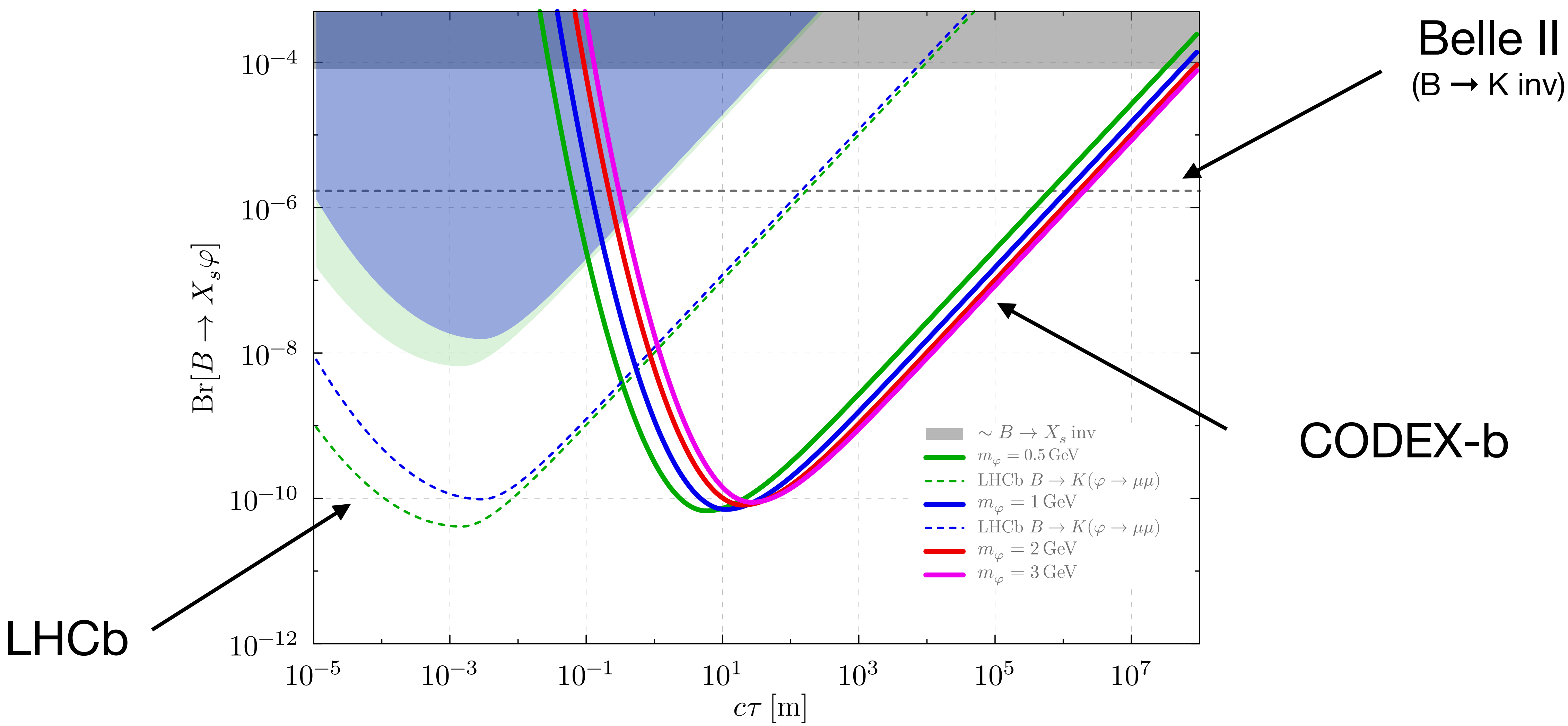


Maximum sensitivity:

	$\mathrm{Br}(Z \to \chi_1\chi_1)$
MATHUSLA	1×10^{-8}
CODEX-b	6×10^{-7}
FASER	5×10^{-6}

Heo, Hirsch, Wang: 1803.02212

More general exotic B decays



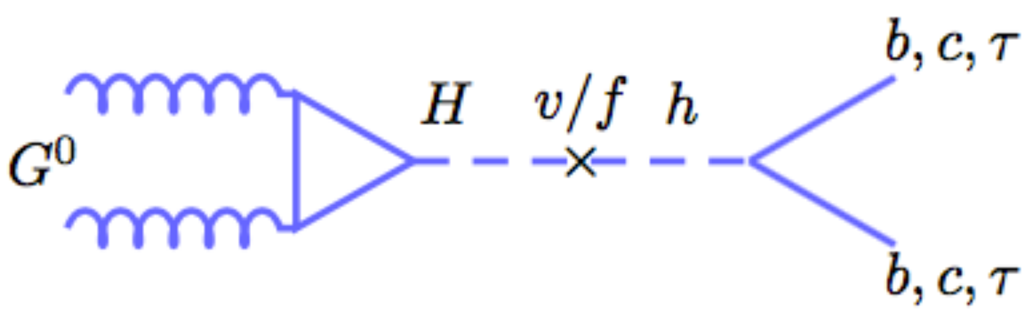
Complementary reach compared to main LHCb detector

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

Hidden glueballs (Neutral Naturalness)

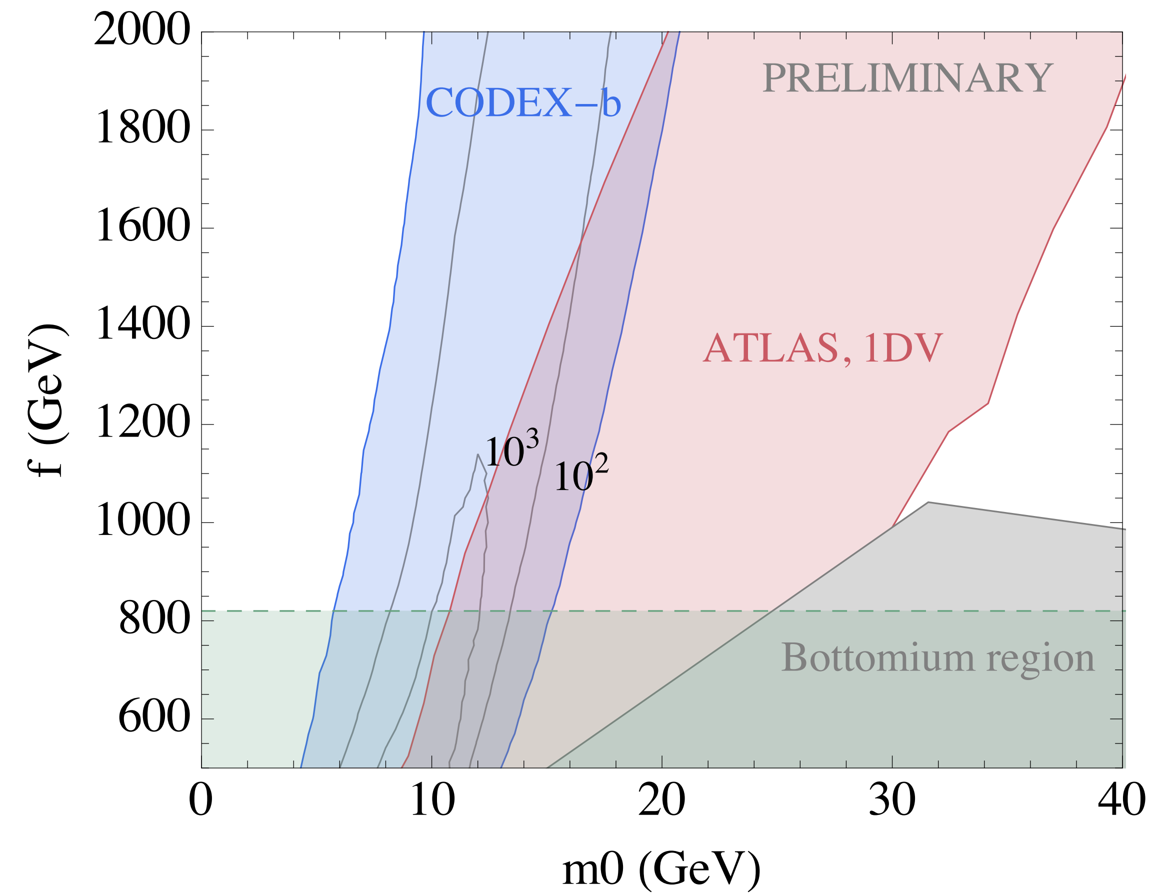
Production: exotic Higgs decay

Decay: through Higgs mixing:



Lifetime very strong function

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



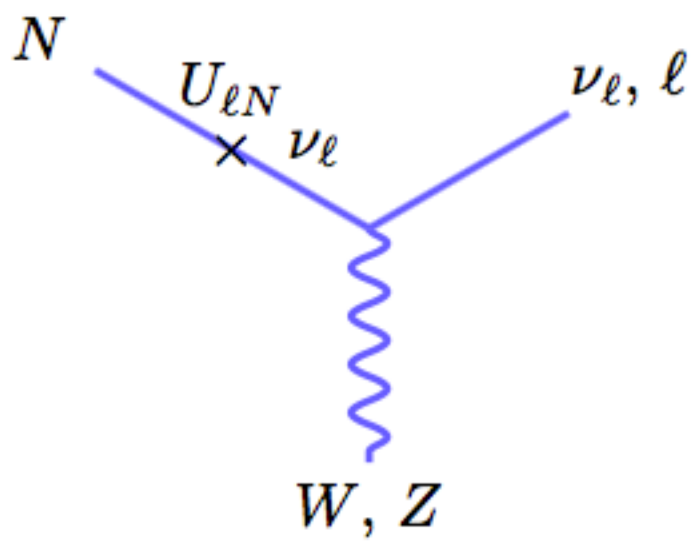
ATLAS / CMS pay double penalty at low mass:

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

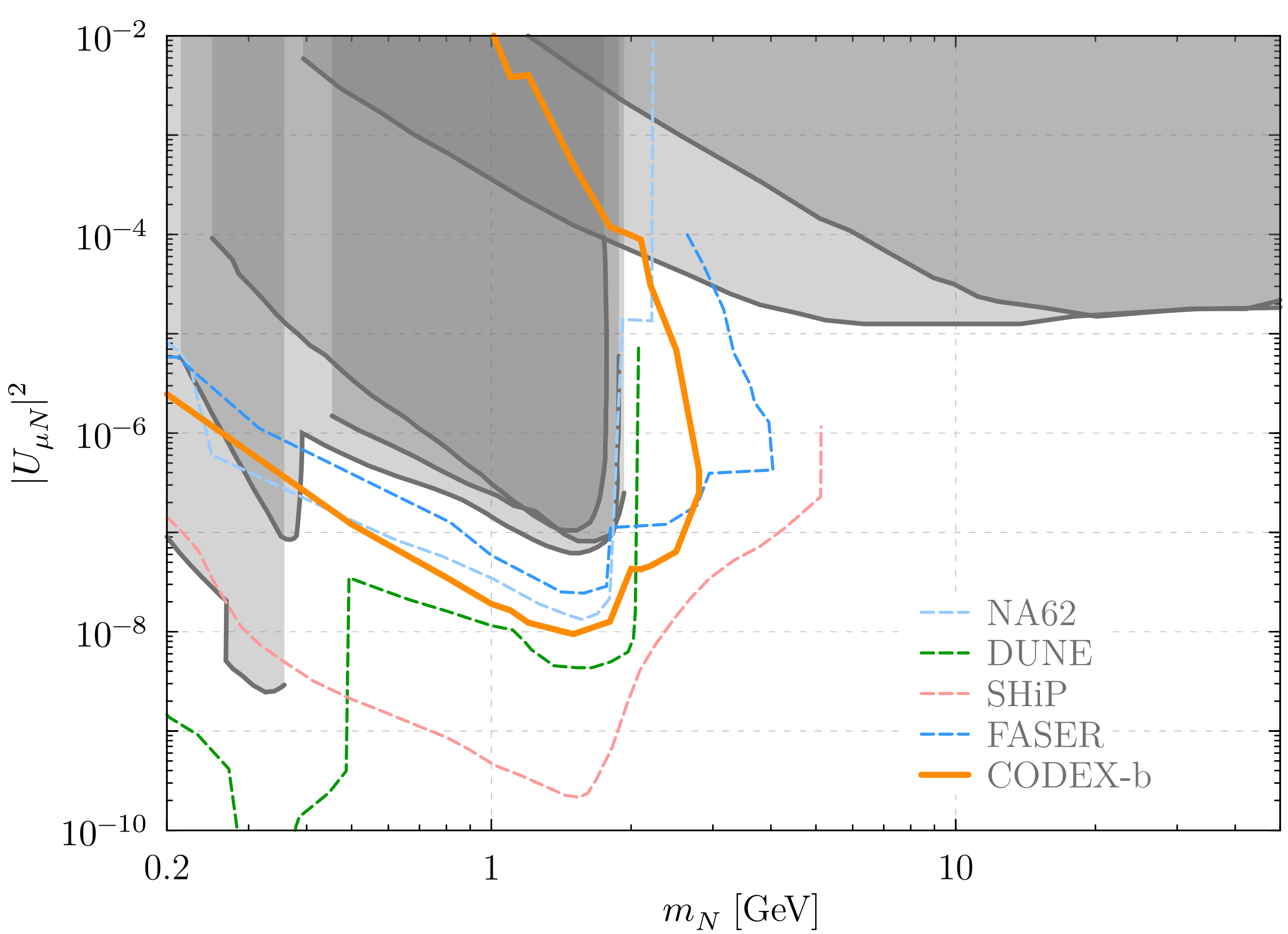
Heavy neutral leptons

- 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: $U_{\mu N}$



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

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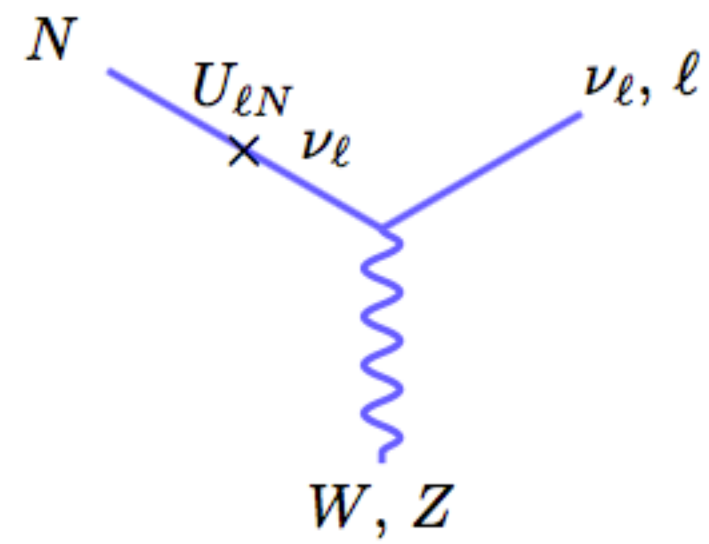
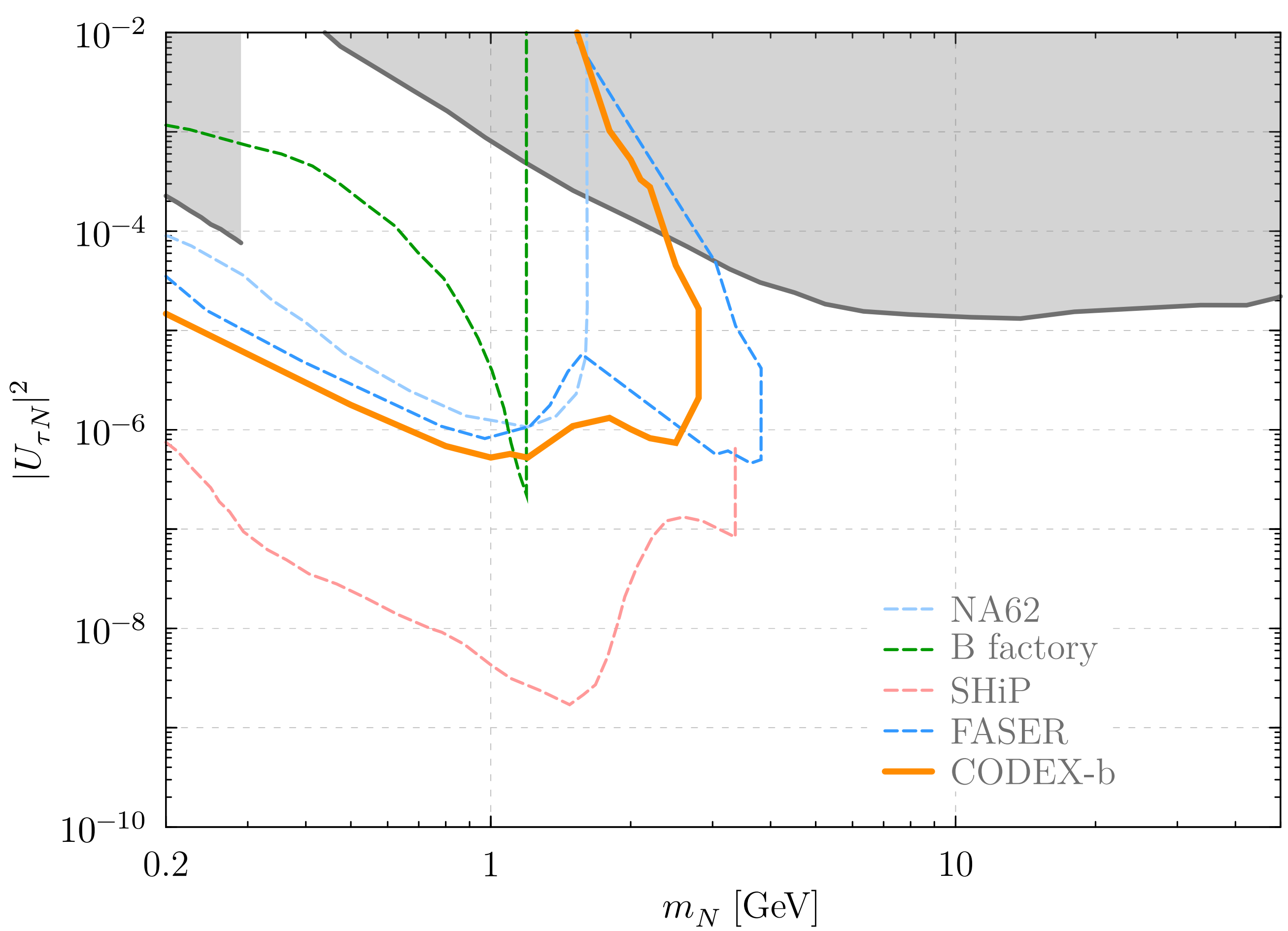


Example: $U_{\tau N}$



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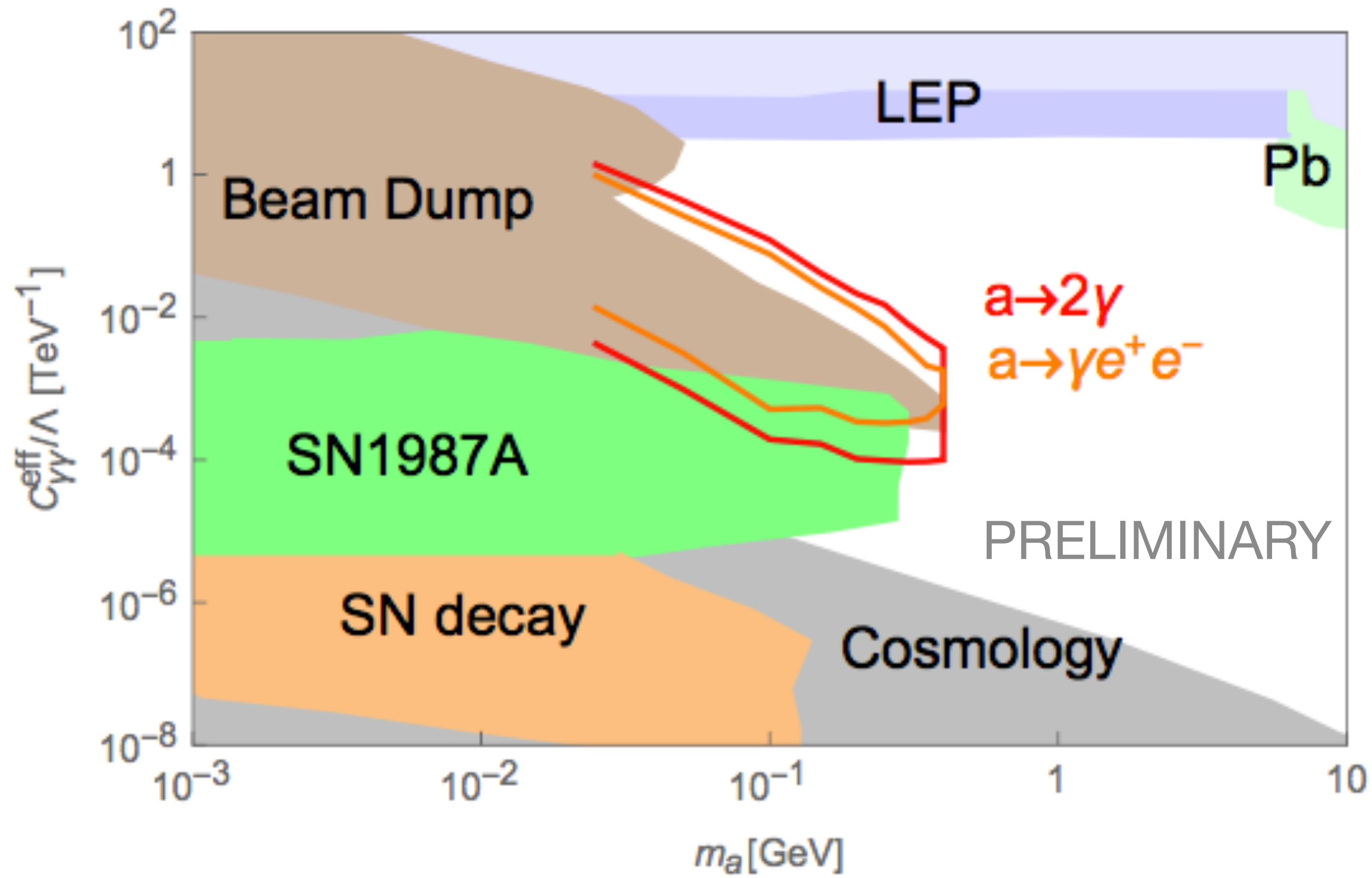
see also: Heo, Hirsch, Wang: 1803.02212

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

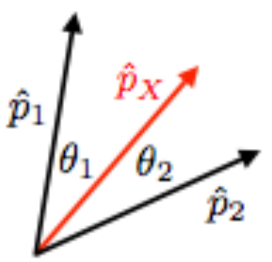
It is non-trivial but perhaps not impossible for CODEX-b to see the 2γ mode
(Will depend on final design choices.)

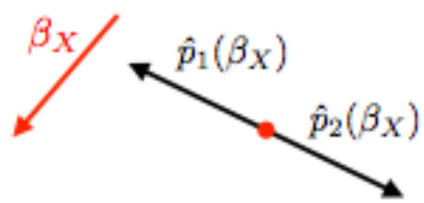
18xx.xxxxx: J. Evans, SK, M. Papucci, H. Ramani D. Robinson

Characterizing the signal

Parent boost reconstruction

Boost reconstruction

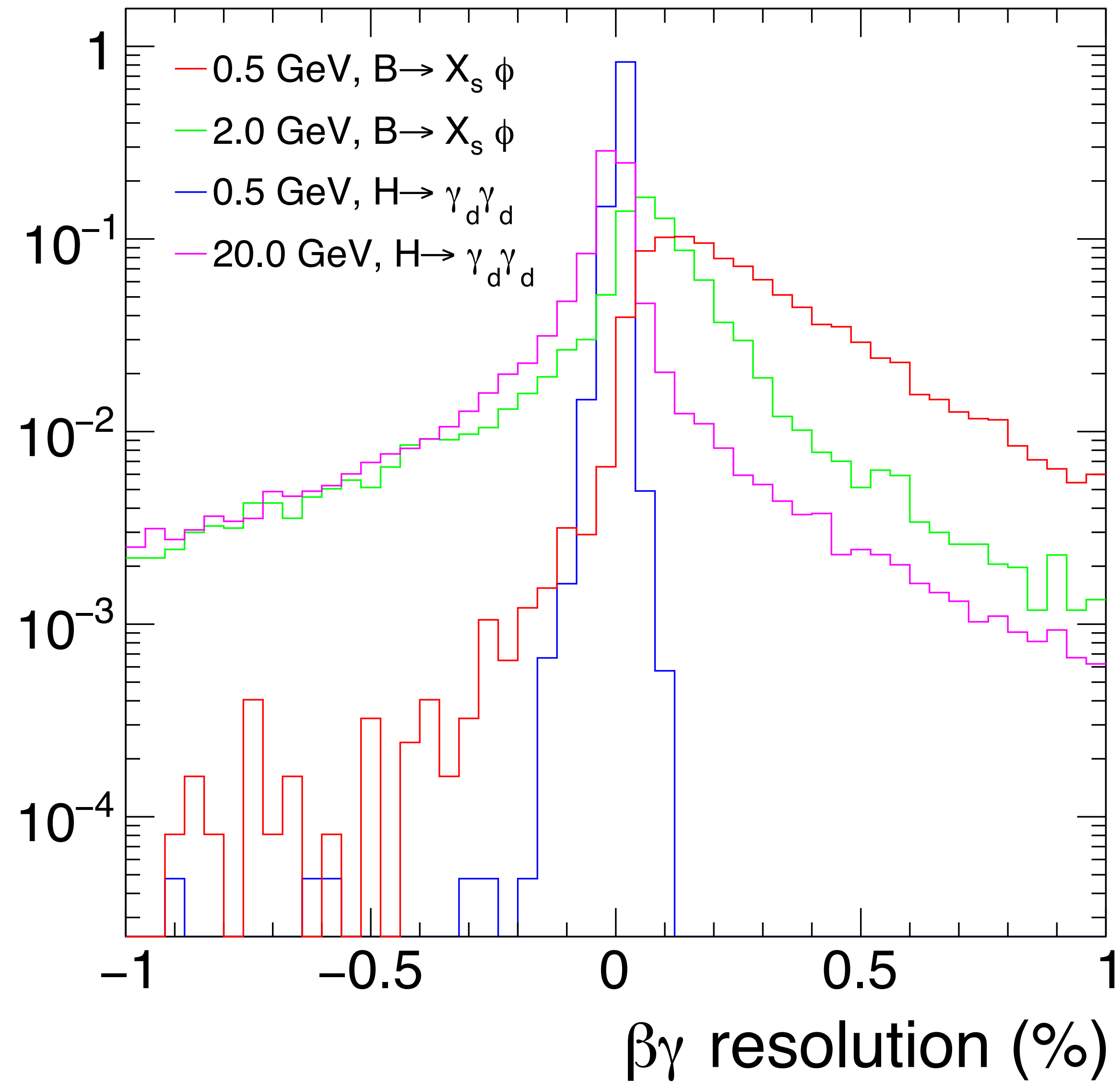




D. Curtin, M. Peskin: 1705.06327

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

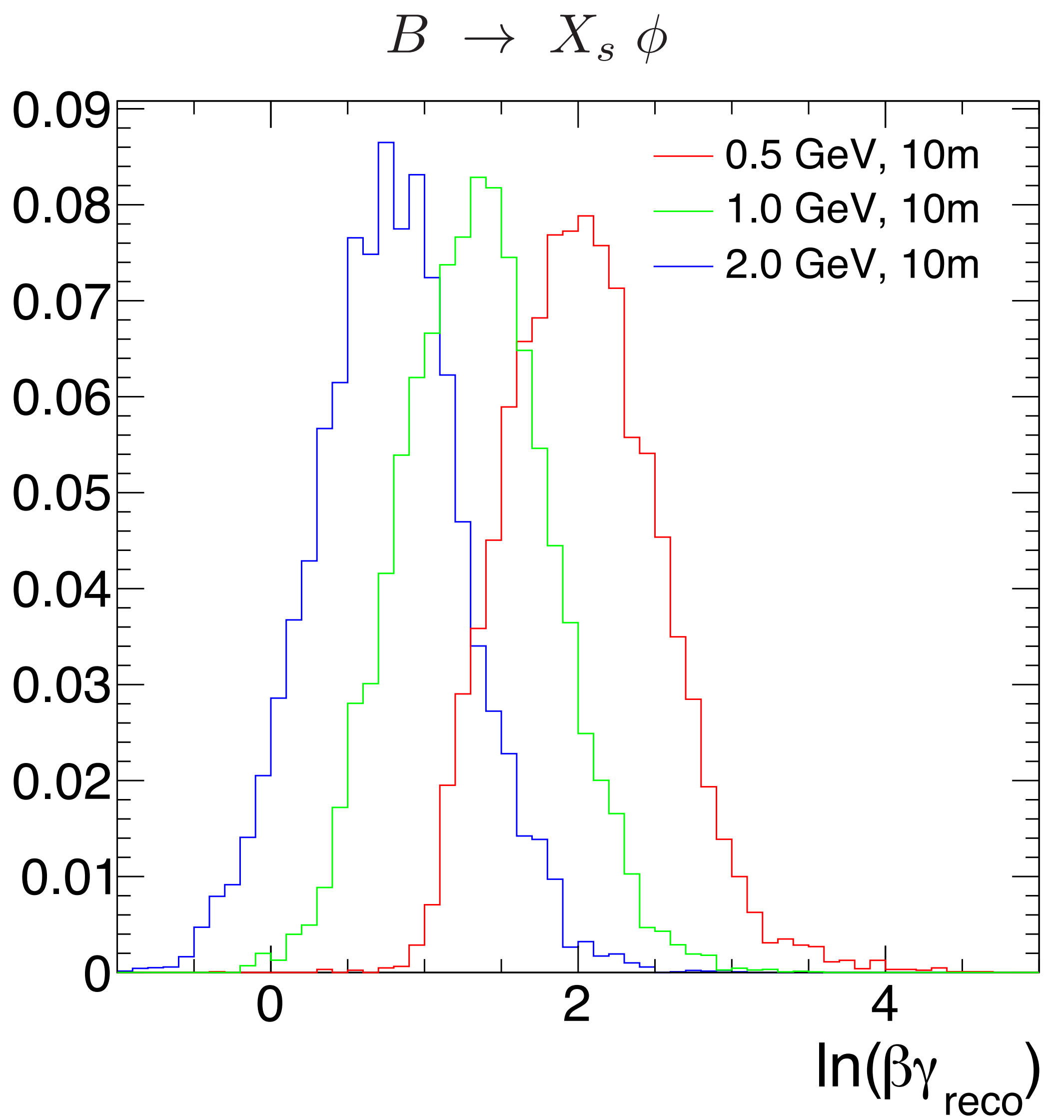
For relativistic decay products, only need spatial information

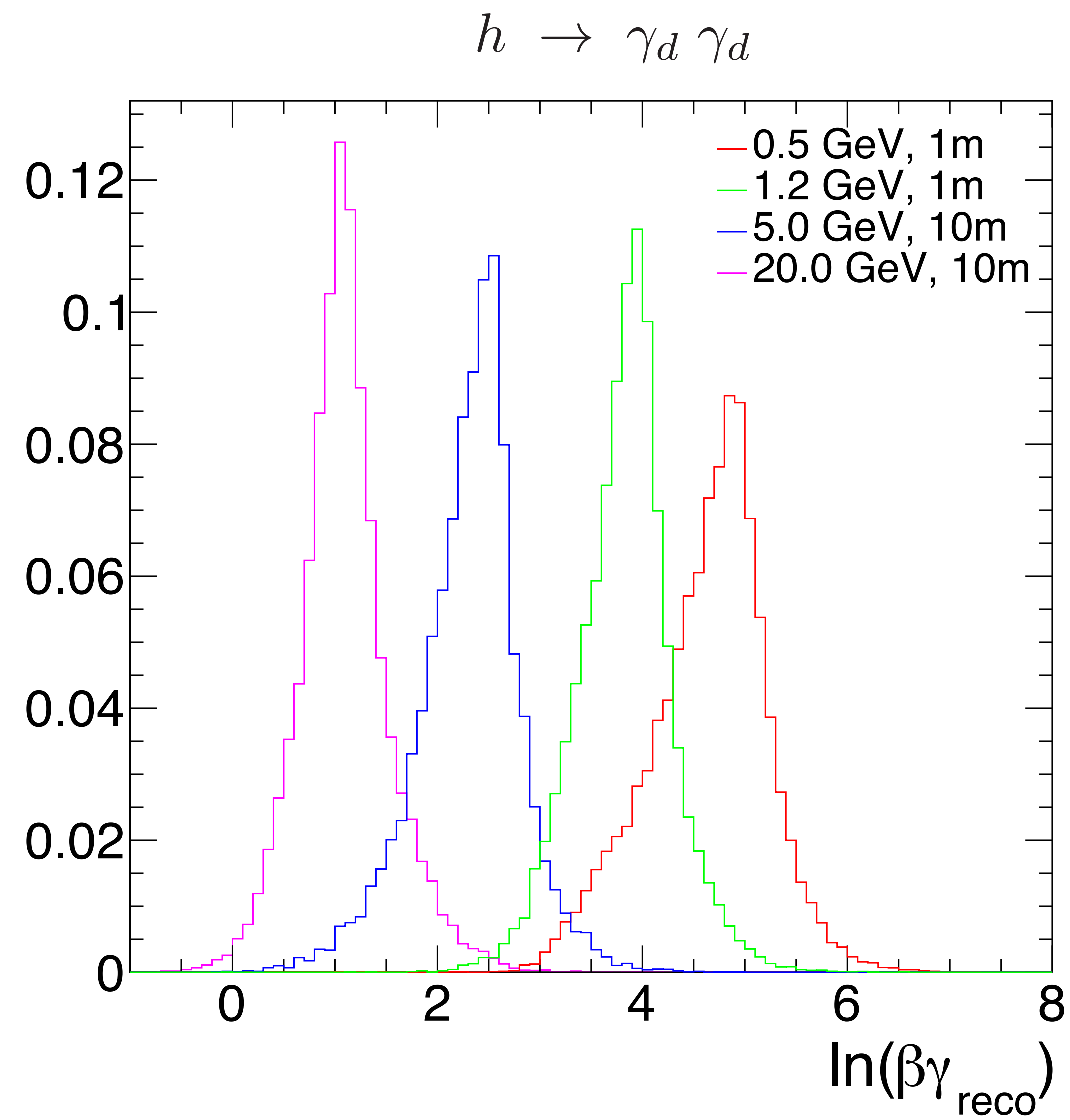


Most important parameter is distance to first measured point

Mass measurement

Only spatial information

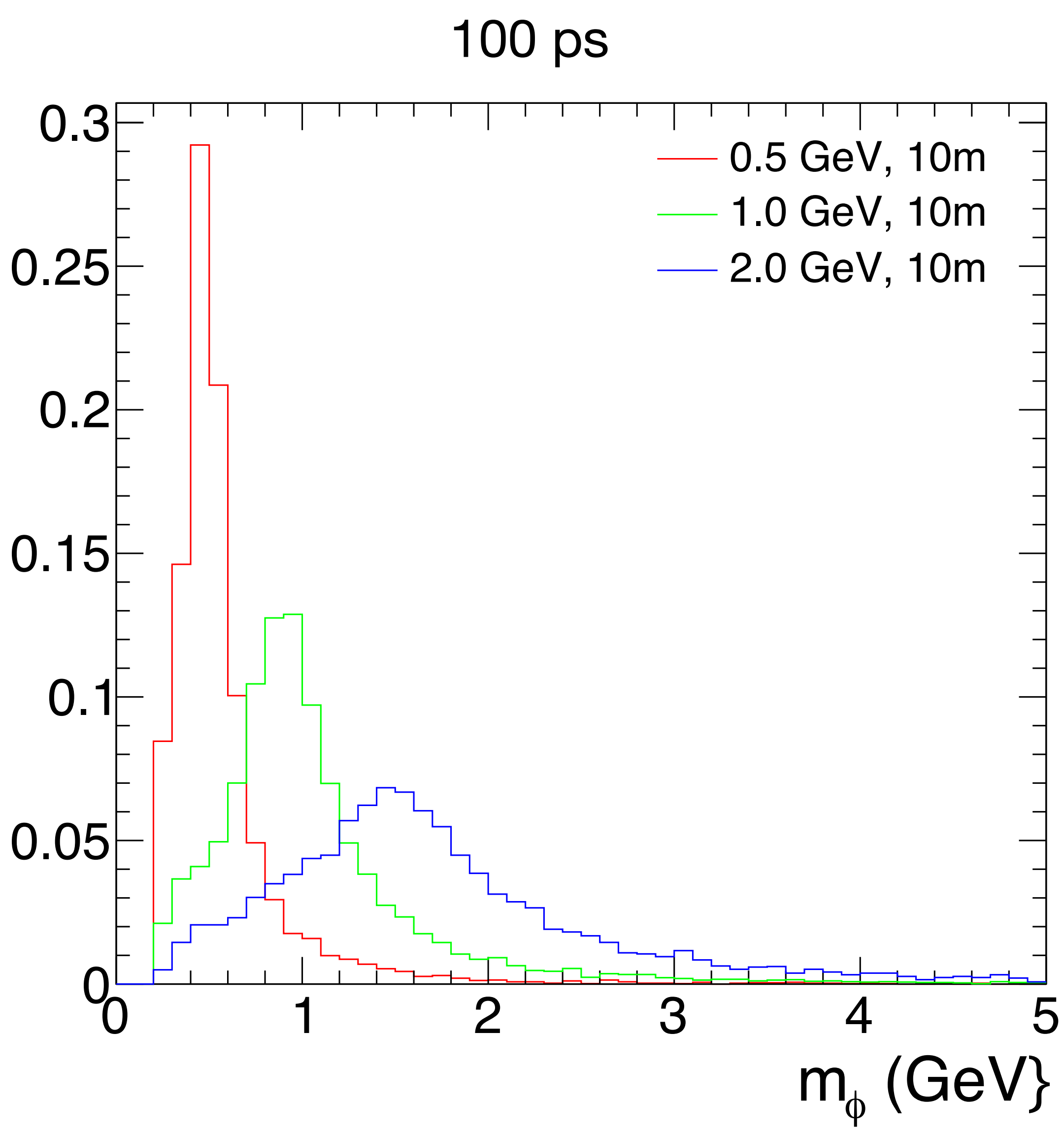


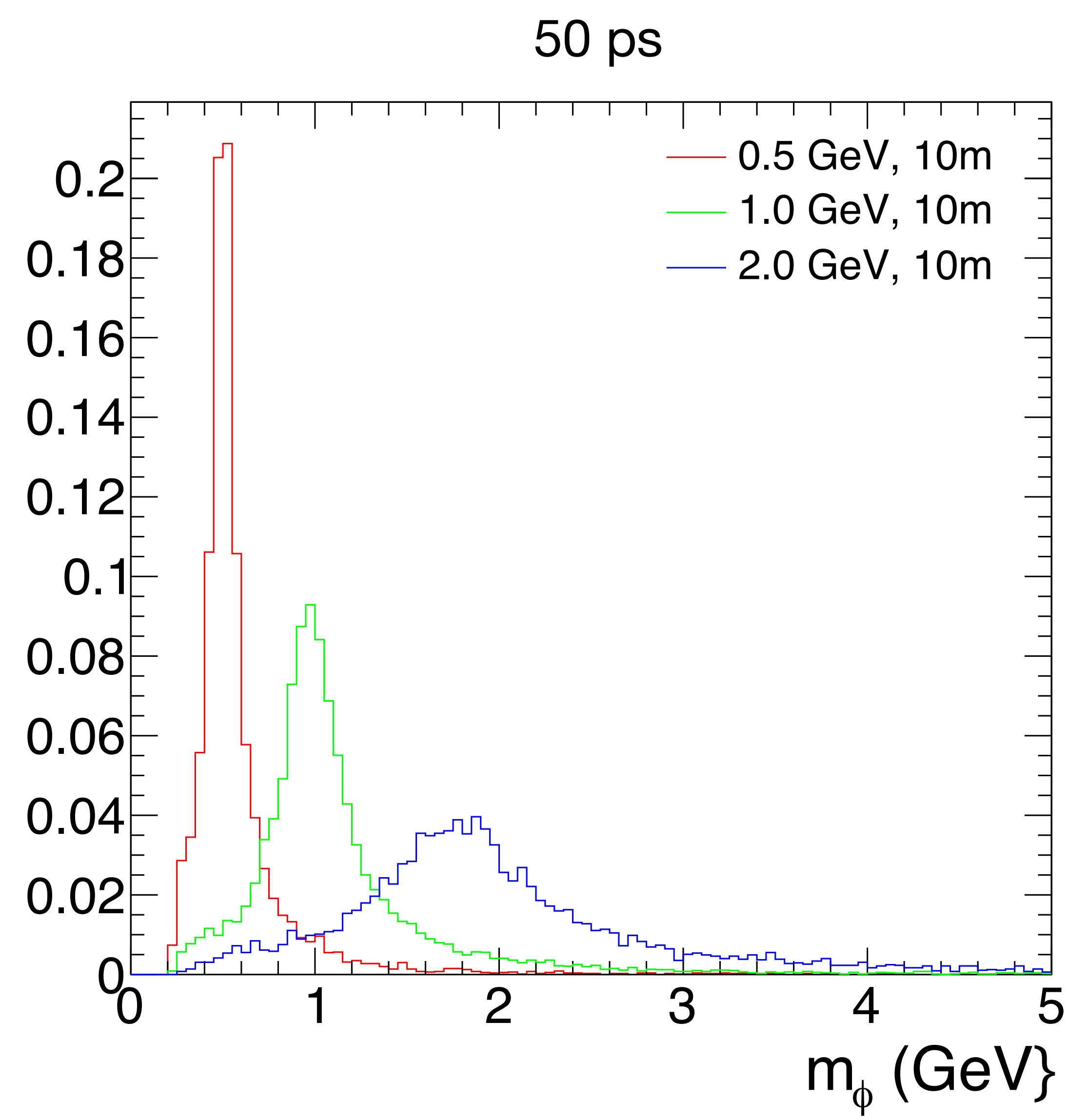


Rudimentary mass measurement possible even without calorimetry

Mass measurement

Include timing





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