COmpact Detector for EXotics at LHCb: CODEX-b

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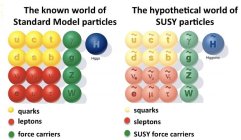
Leonardo da Vinci: Codex Leicester

Based on: 1708.09395 (V. Gligorov, S. Knapen, M. Papucci, & DR)

LLPs are generic!

Common consequence of: small couplings or; scale (or loop) hierarchies or; small mass splittings

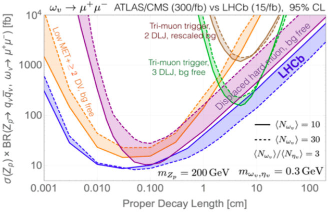


R-parity violation	Asym. Dark Matter	Baryogenesis
Gauge mediation	Freeze-in	Neutrino masses
(mini-)split SUSY	Composite Dark Matter	Flavor puzzle
stealth SUSY		Neutral Naturalness
		Hidden Valleys

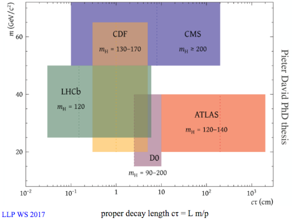
- LLP lifetimes as long as $\tau \lesssim 1\,\mathrm{s}$ are broadly consistent with BBN
- Masses can plausibly range from sub-MeV to $\mathcal{O}(100\,\mathrm{GeV})$.
- A large parameter space to explore!

LHC coverage

- ATLAS/CMS will set best limits for charged, colored and/or heavy LLPs
- LHCb: probes $\mathcal{O}$(GeV) neutral LLPs with significant muon BR and $c\tau \sim$ VELO scale: can trigger on softer μ's and softer DVs.
- In some cases, ATLAS, CMS, LHCb coverage is already complementary (See Carlos' talk)



Pierce, Shakya, Tsai, Zhao: 1708.05389



M. Borsato, LLP WS 2017

- Large BGs in hadronic collisions: lighter, neutral, longer-lived LLPs are hard for them to see!

Complementarity

There is a growing landscape of proposals for LLP searches: including MATHUSLA, MilliQan, FASER and CODEX-b.

- There are no good theory priors in the huge space of allowed LLP branching ratios, lifetimes or masses. Hard to build a single detector to cover all these cases!
- If we are building a LLP detection programme, rather than an exclusion programme, we need data from multiple experiments with decorrelated backgrounds

Complementarity is key for an LLP detection in the broadly unexplored parameter space!

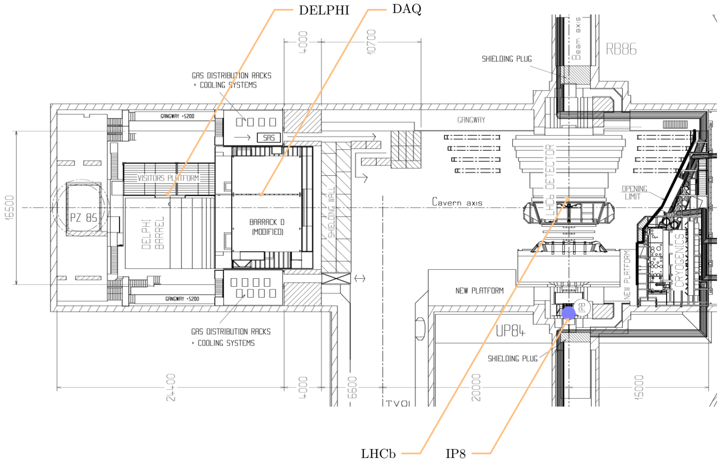
LLP Prelude

CODEX-b Setup

NP Benchmark Reach

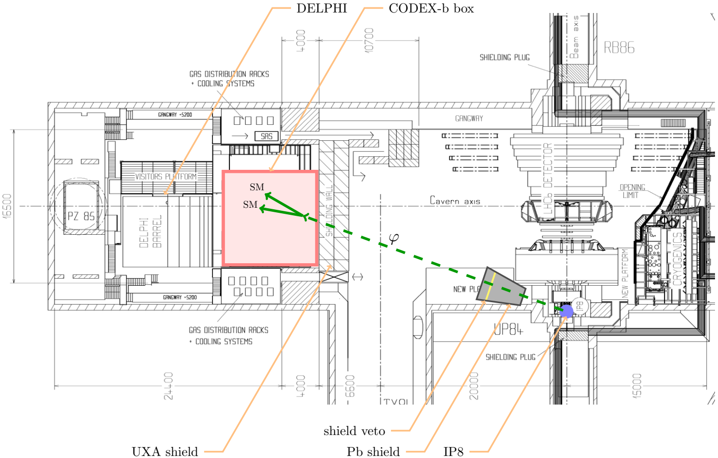
Next Steps

LHCb Cavern


DELPHI
DAQ
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
SHIELDING PLUG
RB86
GANGWAY
SAS
VISITORS PLATFORM
PZ 85
DELPHI BARREL
BARRACK D (MODIFIED)
SHIELDING WALL
Cavern axis
LHCb DETECTOR
OPENING LIMIT
CRYOGENICS
NEW PLATFORM
UP84
IP8
Beam axis
LHCb
IP8

LHCb Cavern

Pre-Run 3 (2020): Data AcQuistion will be moved to surface

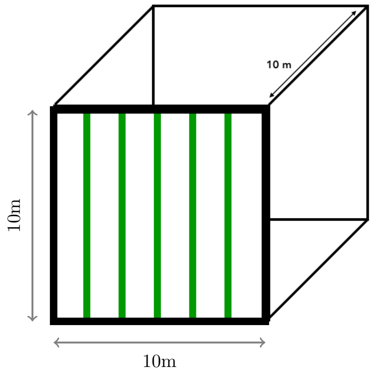


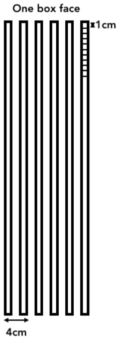
General strategy: Look for decays-in-flight of LLPs from IP8

Instrumentation

As a proof-of-concept:

- Fiducial volume ('the box') is $10 \times 10 \times 10$ m; angular acceptance 1%.
- 6 (RPC) tracking layers on all faces
- 5 sets of 3 vertical tracking layers equally spaced in box
- 1cm strip granularity





Tracking simulation:

- Tracking effs are all $\mathcal{O}(1)$ for benchmarks we consider (more later)

Capabilities and possibilities

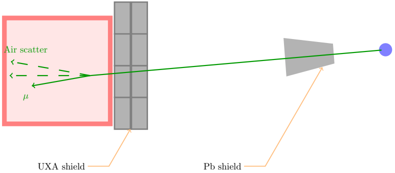
- Distance is only ~ 4 bunch crossing times for relativistic objects: Integrate CODEX-b into the DAQ & readout, and treat as subdetector
  - Identification and at least partial reconstruction of the LLP event.
  - E.g. tag a VBF jet for Higgs decays, or an associated $K^{(*)}$ for B decays.
  - Phase II pileup is manageable with precise enough timing info

- Modest size of the fiducial volume: Consider more ambitious detection technologies such as calorimetry or time-of-flight
  - Momentum reconstruction and particle identification
  - Aids confirmation of a discovery!

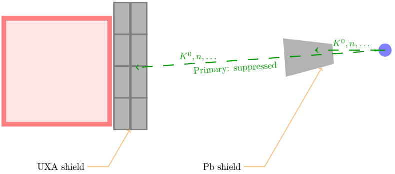
- Precision timing and spatial resolution, 100 ps or futuristic 50 ps resolution possible
  - Required for LLP mass reconstruction

Primary Backgrounds

- Primary muons may scatter on air. Attenuated with extra shielding, and remainder vetoable by front tracking faces



- Primary neutral hadrons suppressed with additional shielding

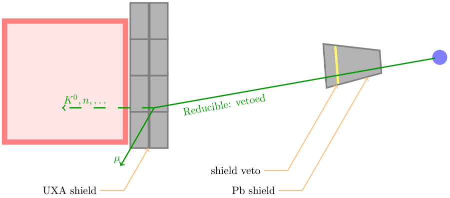


(In practice Pb is not ideal for neutrons: other materials to be considered)

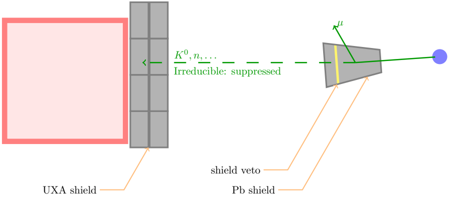
- ν-air inclusive inelastic σ: $\sim \mathcal{O}(3)$ events, but actual fake rate likely much smaller.

Secondary Backgrounds

- Muon or neutron secondary production in shield can be large!
Vetoable – 'reducible' – by active veto in shield



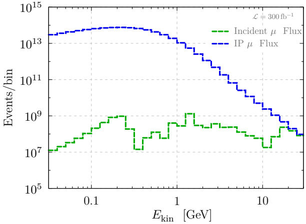
- Active veto placed so that active veto eff/rejection rate is minimized, while neutral 'irreducible' BGs are suppressed



Geant4 $(20+5)\lambda$ simulation

To estimate BGs we use a (preliminary) `Geant4` simulation. Includes muons, kaons, pions, neutrinos, neutrons, gammas, protons,....

BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n+\bar{n}$	7	$5\cdot10^4$	$E_{\text{kin}} > 1$ GeV
K_L^0	0.2	870	$E_{\text{kin}} > 0.5$ GeV
$\pi^\pm + K^\pm$	0.5	$3\cdot10^4$	$E_{\text{kin}} > 0.5$ GeV
$\nu+\bar{\nu}$	0.5	$2\cdot10^6$	$E > 0.5$ GeV



These are yields not scattering rates! n–air scattering prob. $\sim 5\%$

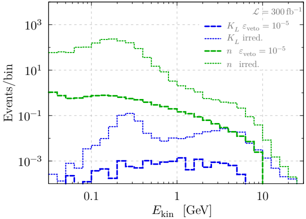
Normalization is set for min bias $\sigma \sim 100$ mb

Muon-air interactions can be vetoed using front detector faces

Shield veto event rejection rate $\sim 10^{-4}$

No use (yet) of timing or spatial information

Estimates validated with simplified propagation model using muon CSDA and kaon scattering length, and scattering/muoproduction cross-sections, from data



Data-driven BG calibration

- Cosmics will be used for spatial & time detector alignment.
  (Signal is from horizontally displaced source, not vertical!)

- Backgrounds can be measured by putting a small telescope in the LHCb cavern
  - Measure background rates with different shield thicknesses
  - Is being considered for an engineering run well ahead of full detector construction. Looks promising to do very soon!

Benchmark Scenarios

Consider two benchmark LLP scenarios

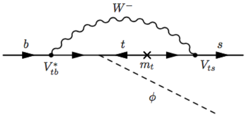
- Spin-1 massive gauge boson γ_{d}
  - produced by Higgs decays $h \to \gamma_{\text{d}}\gamma_{\text{d}}$
  - γ_{d} decays via kinetic mixing with SM hypercharge

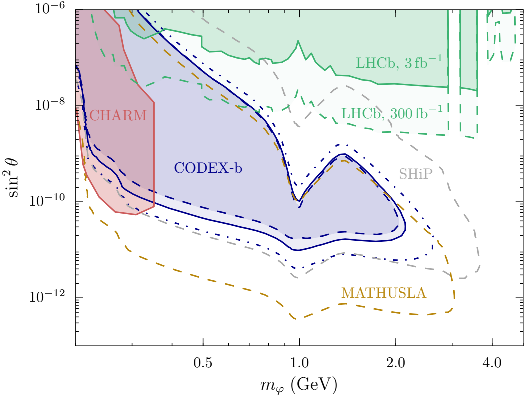
- light $\mathcal{O}$(GeV) scalar φ
  - produced in inclusive B decays $b \to s\varphi$ via Higgs mixing portal
  - φ decay through same Higgs portal

- Coming soon: $h \to$ dark glueballs, twin Higgs mixing portal
  - Suggestions for other portals/signatures welcome!

$b \to s\varphi$: Higgs-scalar mixing

Single parameter portal: Higgs-scalar mixing angle, θ, controls production rate and lifetime

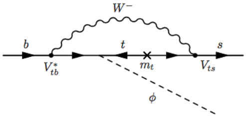




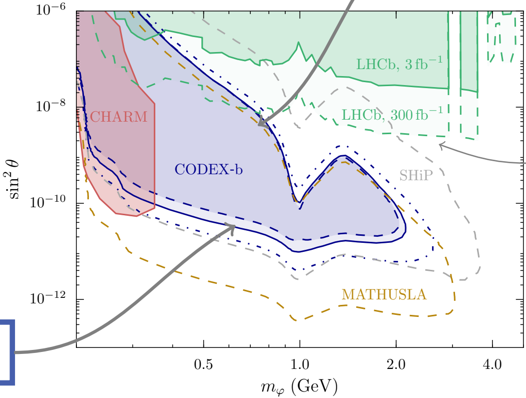
- Large theory uncertainties for $m_\varphi \gtrsim 1$ GeV! (cf. Evans 1708.08503)
- Blue dashed includes tracking sim; dot-dashed for $\mathcal{L} = 1/\text{ab}$

$b \to s\varphi$: Higgs-scalar mixing

Single parameter portal: Higgs-scalar mixing angle, θ, controls production rate and lifetime



short lifetime regime: φ's decay before reaching box



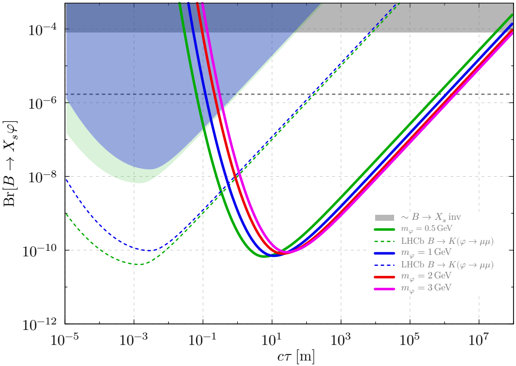
LHCb downstream tracking?

long lifetime regime: B production limited

- Large theory uncertainties for $m_\varphi \gtrsim 1$ GeV! (cf. Evans 1708.08503)
- Blue dashed includes tracking sim; dot-dashed for $\mathcal{L} = 1/\mathrm{ab}$

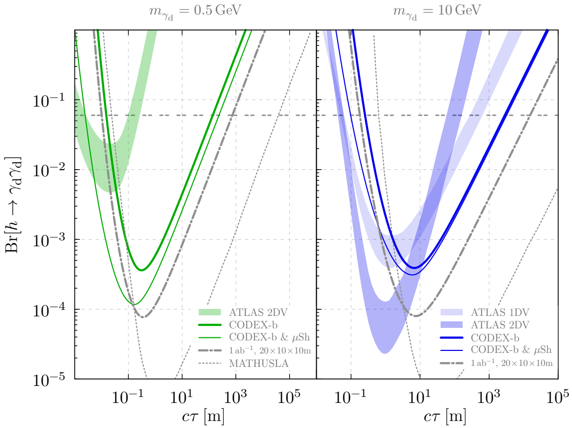
General $b \to s\varphi$ Reach

Relax constraint between lifetime and inclusive BR



- Max efficiency at $c\tau \sim 10$ m: parent B's and daughter φ's only mildly boosted.

$h \to \gamma_d\gamma_d$: Higgs-Dark photon portal



- For $m_\varphi = 0.5\,\mathrm{GeV}$, ATLAS reach is sys limited: Assume factor of 5 improvement. (Could scale as much as $\sqrt{L}$)
- $h \to$ inv reach anticipated to be $\sim$ few%

Tracking Efficiencies

Implement a tracking simulation for above geometry:

- Six hits required for a track
- Assume sensitivity down to 600 MeV momentum

$c\tau$ (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	–	–	–	–	–

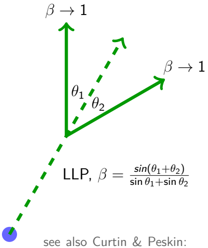
Dominated by assumption $p > 600$ MeV. Needs proper simulation of turn-off.

Dominated by opening angle resolution. Requires optimization using station spacing and granularity

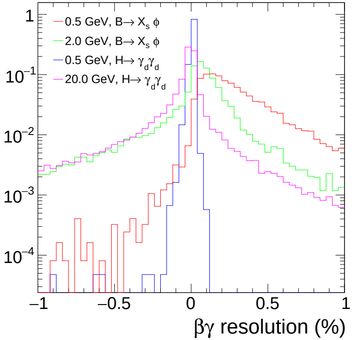
- Lesson: Proof-of-concept tracking effs are $\mathcal{O}(1)$. Can be further optimized.

Boost Resolution

- Reconstruct parent boost from the measured decay vertex (no timing!), assuming 2-body decay with relativistic products (only need spatial info!)

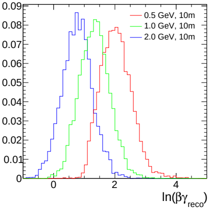


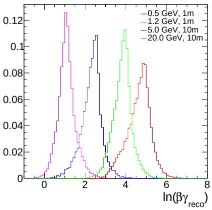
see also Curtin & Peskin: 1705.06327



- The resolution is $< 1\%$ dominated by distance to first measured point, not detector granularity
- Boost distribution is dominated by the spread of boosts, not resolution.

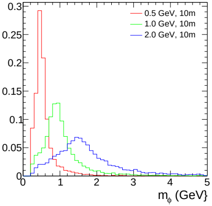
Boost and Mass Reco

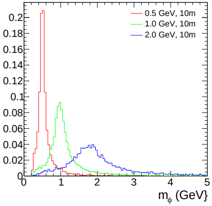




Mild resolution even for $b \to s\varphi$!

For $b \to s\varphi$, use time-of-flight to reconstruct LLP mass. Assume 100 ps and 50 ps resolution per hit. LLPs slow enough for mild mass reconstruction!





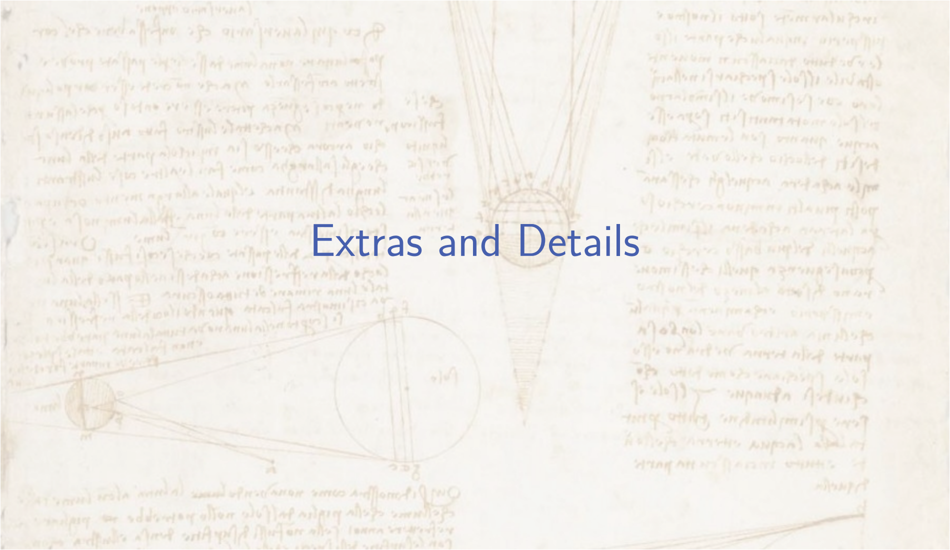
Thoughts & Next Steps

No showstoppers so far. CODEX-b can significantly enhance the NP reach and capabilities of the LLP programme, complementing or exceeding the reach of other LHC experiments, with largely decorrelated backgrounds

Lots to do:

- Develop a more realistic proposal for the detector, including BG shield analysis and tracking setup/other technologies, and achievable resolution for reconstruction
- Develop the NP physics case for other models
- Participation welcome!

Thank you!



Extras and Details

Why do we care about LLPs?

Long lived particles are generic consequence of theories with:

- Small couplings
- Scale (or loop) hierarchies
- Phase space suppression

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

broken sym
weak mixing/ marginal operator
technically natural

$m \ll M$, typically $n \geq 4$
loop factors

squeezed spectra
approx sym
multibody decays

SM provides a template in weak decays:

Multiple scales (G_F)

Approx symmetries (e.g. isospin)

3-body final states

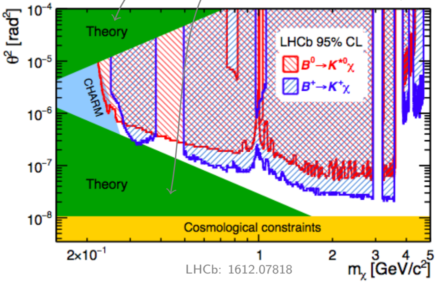
LHCb (projected) reaches

Two example portals:

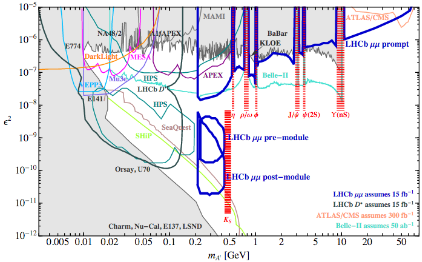
- Higgs mixing portal: $B \to K^{(*)}(\varphi \to \mu\mu)$
- Dark photon portal: $D^* \to DA'$

Reach in $c\tau$ is limited by size of VELO/TT distance and/or statistics

Generically not excluded: Applies for light inflaton (Bezrukov and Gorbunov 1303.4395)

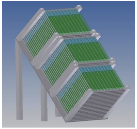


LHCb: 1612.07818



Ilten, Soreq, Thaler, Williams, Xue: 1603.08926

Some LLP Proposals



MilliQan: 1607.04669

MATHUSLA

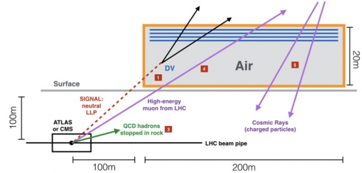
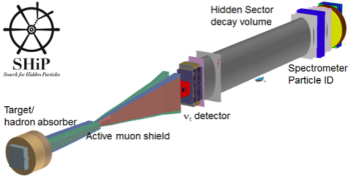
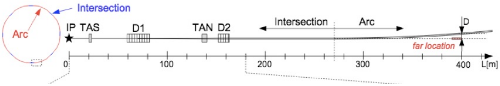


Image: D.Curtin & R. Sundrum

CODEX-b physics reach will be most directly comparable to MATHUSLA. The LLP detection strategies and technologies necessarily have various commonalities, though the backgrounds and configuration will differ in several critical aspects





FASER: 1708.09389

LLP Reach Intuition

Number of LLP decay vertices

lumi $\sim 300/\text{fb}$
or more!

$$N_{\text{box}} = \mathcal{L}_{\text{LHCb}} \times (\sigma \times \text{Br})_{pp\to\varphi X} \times \varepsilon_{\text{box}}$$

portal dependent
sensitive to η, ϕ, β distribution

Fiducial efficiency:

$$\varepsilon_{\text{box}} = \int_{\text{box}} \frac{dV}{2\pi r^2 c\tau} \int d\beta\, w(\beta,\eta) \times \frac{e^{-r/(c\tau\beta\gamma)}}{\beta\gamma}$$

for distance $\ll c\tau\langle\beta\gamma\rangle$
$\varepsilon \sim |\text{depth}|/c\tau\langle\beta\gamma\rangle$
linear suppression
at long lifetimes

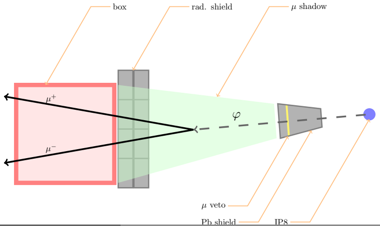
for distance $\gg c\tau\langle\beta\gamma\rangle$
$\varepsilon \sim e^{-r_{\text{near}}/c\tau\langle\beta\gamma\rangle}$
exponential suppression
at short lifetimes

Other Capabilities and Possibilities

- If DELPHI is removed, fiducial volume doubles!

- Precision timing and spatial resolution, 100 ps or futuristic 50 ps resolution possible
  - Multi-track signatures could be very compelling signals of NP
  - Can fully reconstruct events even with one light invisible state: semileptonic $\varphi \to f\ell\nu$ or $\varphi \to \varphi' ff$

- Empty space ('muon shadow') between IP8 and UXA shield might also be exploited if BR(LLP $\to \mu\mu$) ~ 1.



$b \to s\varphi$

Single parameter portal: Higgs-scalar mixing angle, θ

- Inclusive $b \to s\varphi$ branching ratio

$$\mathrm{Br}[B \to X_s\varphi] \simeq 6.\, s_\theta^2 (1 - m_\varphi^2/m_b^2)^2$$

- φ width also set by s_θ^2, from data-driven estimate (Fradette and Pospelov 1706.01920). Somewhat large theory uncertainties for $m_\varphi \gtrsim 1\,\mathrm{GeV}$! (cf. Evans 1708.08503)
- B distribution generated with `Pythia8` hardQCD; inclusive decays modelled by $B \to K\varphi$ exclusive
- $b\bar{b}$ production cross-section $\sim 500\,\mu\mathrm{b}$

$h \to \gamma_d \gamma_d$

Higgs-Dark photon portal:

$$yhF'_{\mu\nu}F'_{\mu\nu} + \epsilon F'_{\mu\nu}B_{\mu\nu}$$

- $\mathrm{Br}[h \to \gamma_d \gamma_d]$ and γ_d lifetime controlled by separate parameters
- γ_d branching ratios fixed by e^+e^- data
- GF Higgs production, simulated with `Pythia8`
- Daughter muons can be quite hard, can use muon shadow if $\mathrm{Br}[\gamma_d \to \mu\mu]$ is significant