

COmpact Detector for EXotics at LHCb: CODEX-b



Vladimir V. Gligorov, Simon Knapen,
Michele Papucci, **Dean Robinson**

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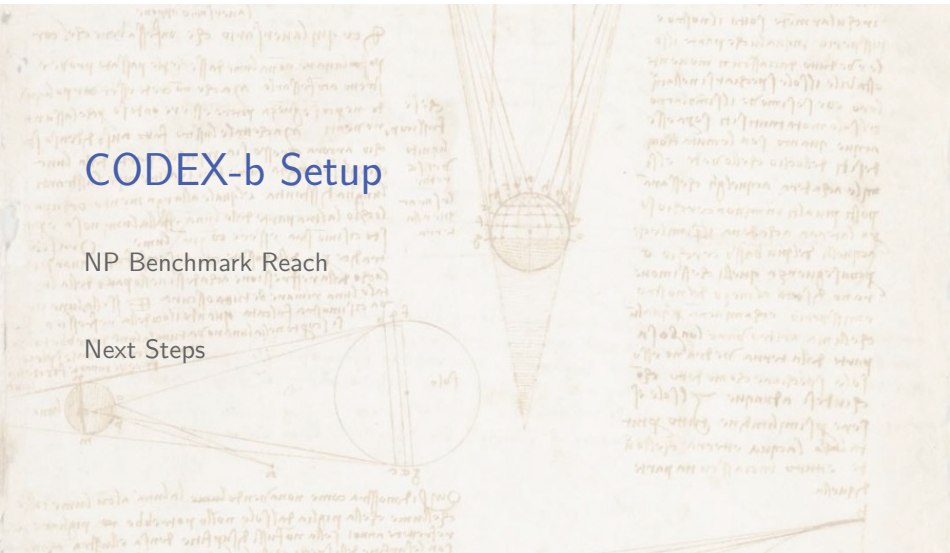
Leonardo da Vinci: Codex Leicester

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

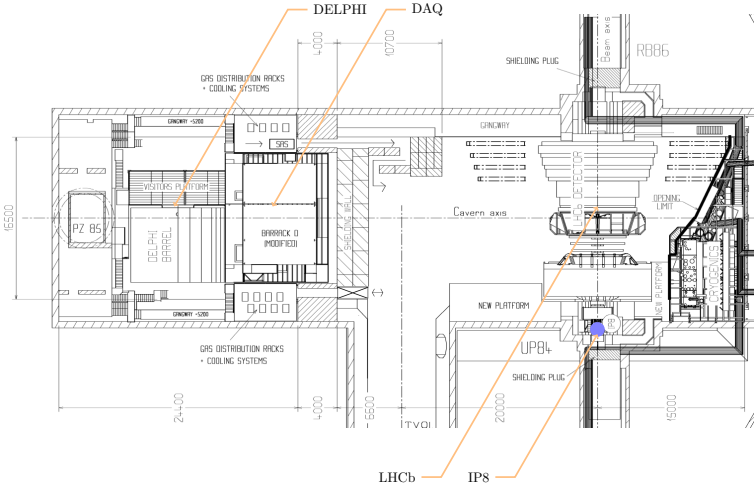
CODEX-b Setup

NP Benchmark Reach

Next Steps

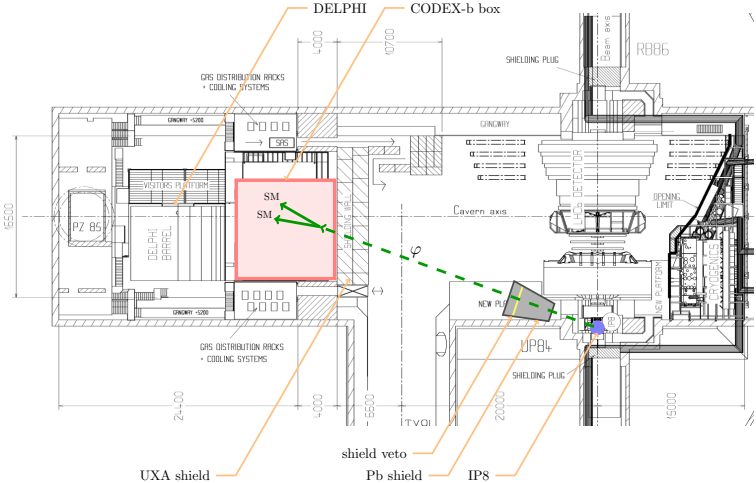


LHCb Cavern



LHCb Cavern

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

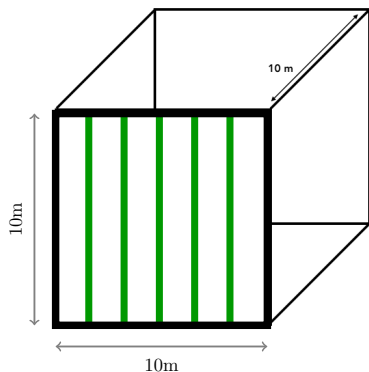


General strategy: Look for decays-in-flight of LLPs from IP8

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)

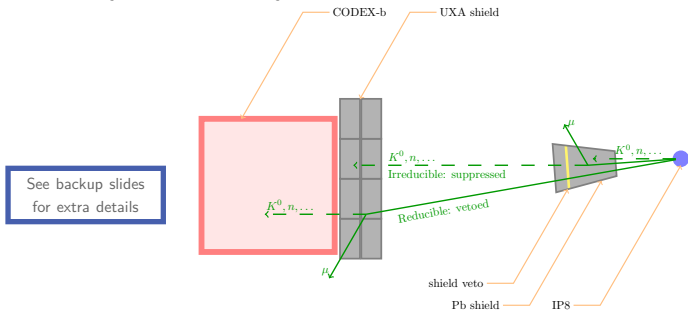
Capabilities and Possibilities

- **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.
- Modest **size** of the fiducial volume: Consider more ambitious detection technologies such as **calorimetry or time-of-flight**
- Precision timing and spatial resolution, **100 ps** or futuristic 50 ps resolution possible
 - Required for LLP mass reconstruction

Backgrounds

Modest amount of additional shielding is needed for CODEX-b

- Primary and secondary sources: **muons, kaons, neutrinos, and neutrons**



See backup slides
for extra details

- Conceptual study:
 - $(20 + 5)\lambda$ passive Pb shield attenuates muon & neutral hadron BGs
 - A thin veto layer rejects secondary production within the shield.
- To estimate BGs we use a (preliminary) Geant4 simulation.
- BGs are controlled in this proof-of-concept with active veto eff $\sim 10^{-5}$

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!

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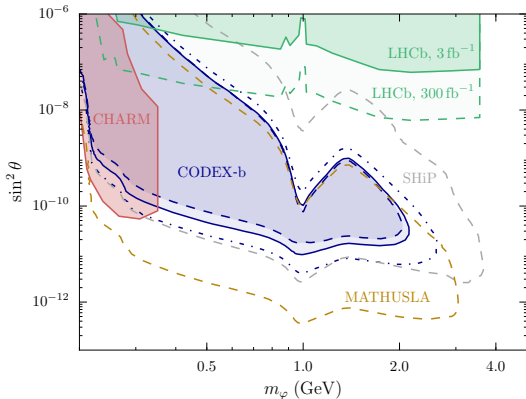
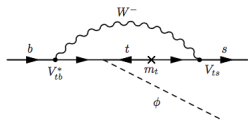
Benchmark Scenarios

Consider two benchmark LLP scenarios

- Spin-1 massive gauge boson γ_d
 - produced by **Higgs decays** $h \rightarrow \gamma_d \gamma_d$
 - γ_d decays via kinetic mixing with SM hypercharge
- light $\mathcal{O}(\text{GeV})$ scalar φ
 - produced in **inclusive B decays** $b \rightarrow s\varphi$ via Higgs mixing portal
 - φ decay through same Higgs portal

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

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

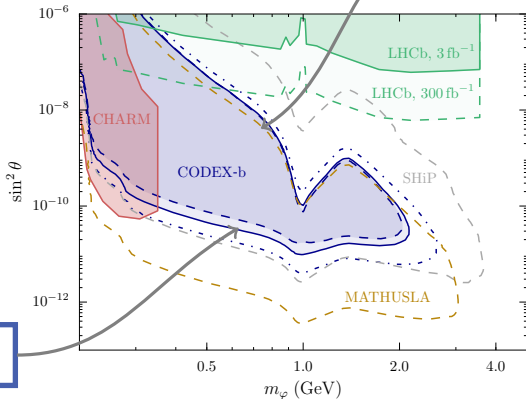
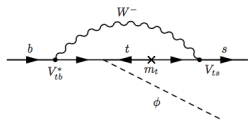


- Large theory uncertainties for $m_\varphi \gtrsim 1$ GeV! (cf. Evans 1708.08503)
- Blue dashed includes tracking sim; dot-dashed for $\mathcal{L} = 1/\text{ab}$

$b \rightarrow s\varphi$: 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

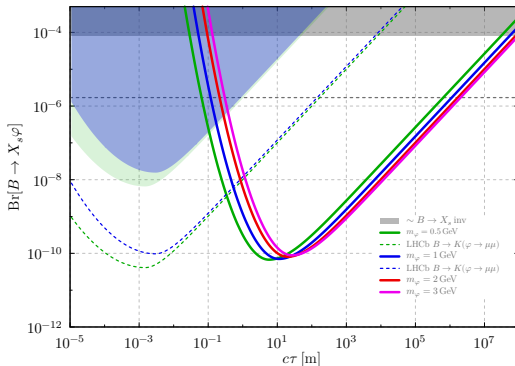


long lifetime regime: B production limited

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

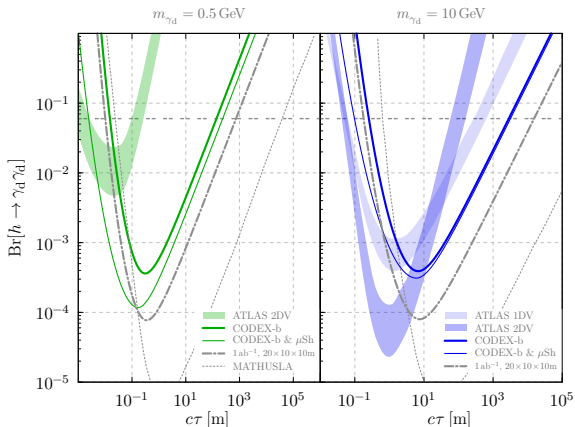
General $b \rightarrow s\varphi$ Reach

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.

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



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

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)	$m_\varphi [B \rightarrow X_s\varphi]$			$m_{\gamma_d} [h \rightarrow \gamma_d\gamma_d]$				
	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	-	-	-	-	-

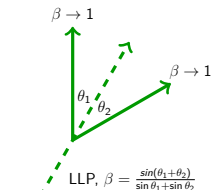
Dominated by opening angle resolution. Requires optimization using station spacing and granularity

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

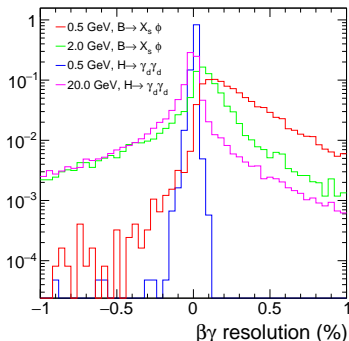
- Lesson: Proof-of-concept tracking effs are $\mathcal{O}(1)$. Can be further optimized.

Boost Resolution

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

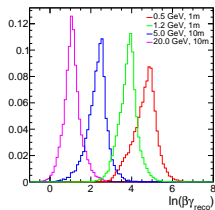
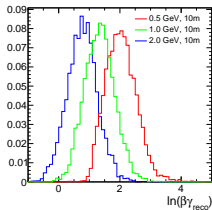


see also Curtin & Peskin:
1705.06327



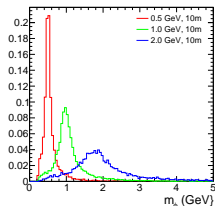
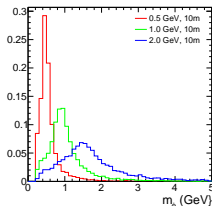
- The resolution is $< 1\%$ dominated by distance to first measured point, not detector granularity
- Boost distribution is dominated by the spread of boosts, not resolution.

Boost and Mass Reco



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

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



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Thoughts

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**

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

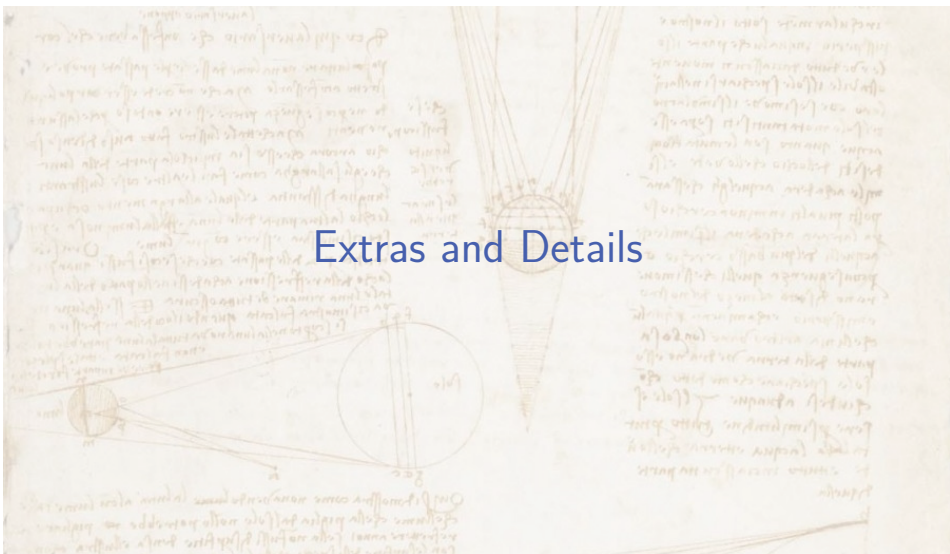
Next steps

Many angles to pursue:

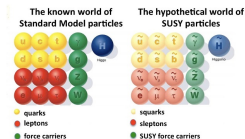
- Develop a more realistic proposal for the detector, including BG shield analysis and tracking setup/other technologies
- Understand better how low we can realistically track in momentum, achievable resolution for vertex reconstruction
- Develop the NP physics case for other models: Leverage possible special capabilities of CODEX-b

Thank you!

Extras and Details



LLPs are generic!



R-parity violation

Gauge mediation

(mini-)split SUSY

stealth SUSY

Asym. Dark Matter

Freeze-in

Composite Dark Matter

Baryogenesis

Neutrino masses

Flavor puzzle

Neutral Naturalness

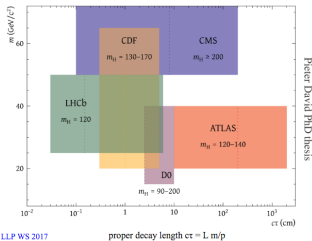
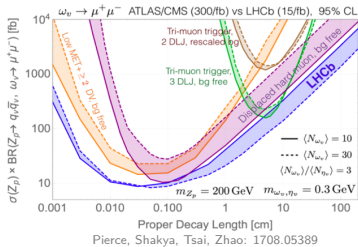
Hidden Valleys

LLPs with lifetimes as long as $\tau \lesssim 1$ s are broadly consistent with BBN bounds. Masses can plausibly range from sub-MeV to $\mathcal{O}(100$ GeV).

A large parameter space to explore!

LHC coverage

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



M. Borsato, LLP WS 2017

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

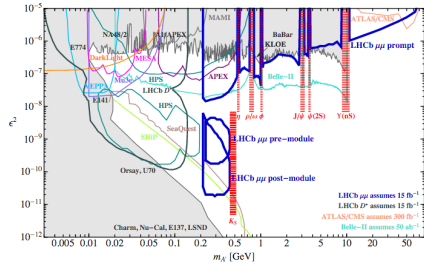
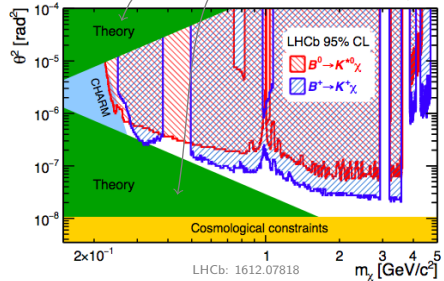
LHCb (projected) reaches

Two example portals:

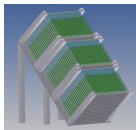
- Higgs mixing portal:
 $B \rightarrow K^{(*)}(\varphi \rightarrow \mu\mu)$
- Dark photon portal:
 $D^* \rightarrow DA'$

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)



Some LLP Proposals



MilliQan: 1607.04669

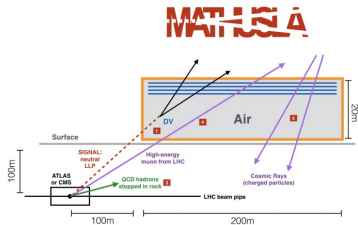
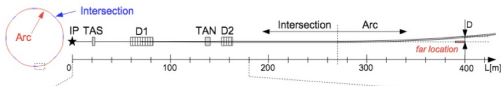
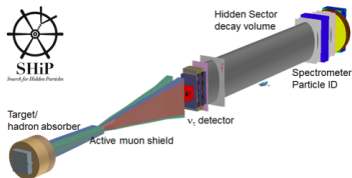


Image: D.Curtin & R. Sundrum

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/fb
or more!

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

portal dependent
sensitive to η, ϕ, β distribution

Fiducial efficiency:

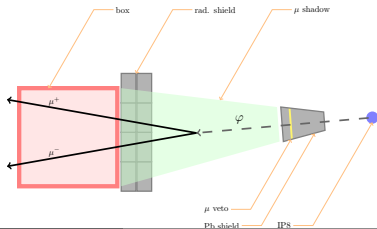
$$\varepsilon_{\text{box}} = \int_{\text{box}} \frac{dV}{2\pi r^2 c\tau} \int d\beta w(\beta, \eta) \times \frac{e^{-r/(c\tau\beta\gamma)}}{\beta\gamma}$$

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

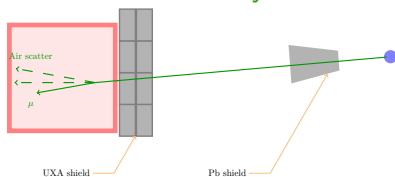
Other Capabilities and Possibilities

- 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 $\varphi \rightarrow fl\nu$ or $\varphi \rightarrow \varphi' ff$
- Empty space ('**muon shadow**') between IP8 and UXA shield **might** also be exploited if $BR(LLP \rightarrow \mu\mu) \sim 1$.

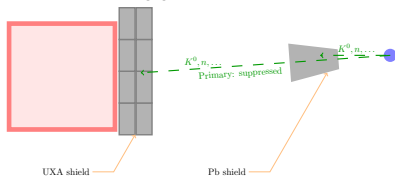


Primary Backgrounds

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



- Primary neutral hadrons suppressed with additional shielding

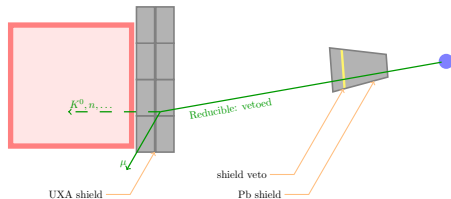


(In practice Pb is not ideal for neutrons: other materials to be considered)

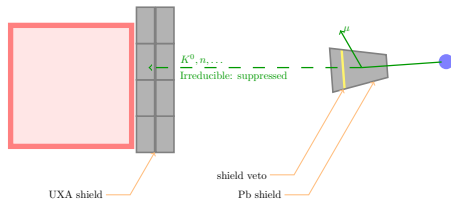
- ν -air inclusive inelastic σ : $\sim \mathcal{O}(3)$ events, but actual fake rate likely much smaller.

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) λ simulation

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

BG species	Particle yields		Baseline Cuts
	irreducible by shield veto	reducible by shield veto	
$n + \bar{n}$	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	$2 \cdot 10^6$	$E > 0.5 \text{ GeV}$

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

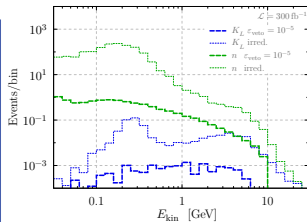
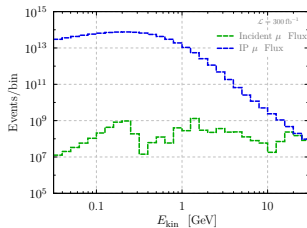
Normalization is set for min bias $\sigma \sim 100 \text{ mb}$

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



$b \rightarrow s\varphi$

Single parameter portal: Higgs-scalar mixing angle, θ

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

$$\text{Br}[B \rightarrow X_s\varphi] \simeq 6 \cdot s_\theta^2 (1 - m_\varphi^2/m_b^2)^2$$

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

$$h \rightarrow \gamma_d \gamma_d$$

Higgs-Dark photon portal:

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

- $\text{Br}[h \rightarrow \gamma_d \gamma_d]$ 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 $\text{Br}[\gamma_d \rightarrow \mu\mu]$ is significant