Long-Lived Particle Prospects with CODEX-b

Dean Robinson

LAPP

Mar 2018

Leonardo da Vinci: Codex Leicester (Codex Hammer)

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

18xx.xxxxx (J.Evans, S. Knapen, M. Papucci, H. Ramani, & DR)

BG WG: V. Coco, B. Dey, R. Dumps, T. Szumlak, H. Schindler

Why do we care about LLPs?

Long lived particles are generic consequence of theories with:

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

SM provides template weak decays: K_L or n!

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

broken sym
weak mixing/ marginal operator
technically natural

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

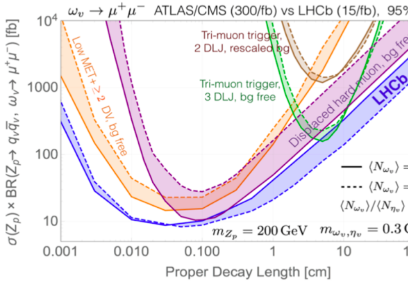
squeezed spectra
approx sym
multibody decays

Encompasses a very broad theory space. In terms of portals, can see these theories' 'LLP footprints' through e.g.

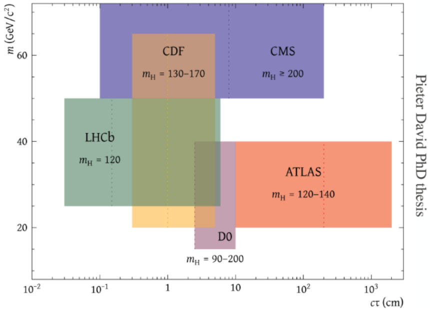
Kinetic mixing | Higgs mixing | Lepton yukawa

LHC coverage

- ATLAS/CMS will set best limits for charged, colored and/or heavy LLPs
- LHCb: $\mathcal{O}$(GeV) neutral LLPs with large muon BR and $c\tau \sim 1\,\mathrm{m}$
- In some cases, ATLAS, CMS, LHCb coverage is already complementary



1708.05389 [Pierce, Shakya, Tsai, Zhao]



M. Borsato, LLP WS 2017

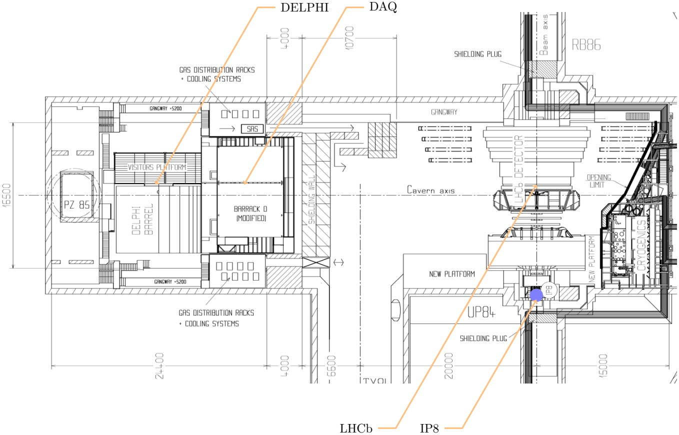
proper decay length $c\tau = L\,m/p$

- Large hadronic BGs: lighter, neutral, longer-lived LLPs are hard to see
- There are few good theory priors. Hard to build a single detector to cover all these cases: Complementarity is crucial!

CODEX-b proposal

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

largest shielded space at LHC near an IP!



CODEX-b proposal

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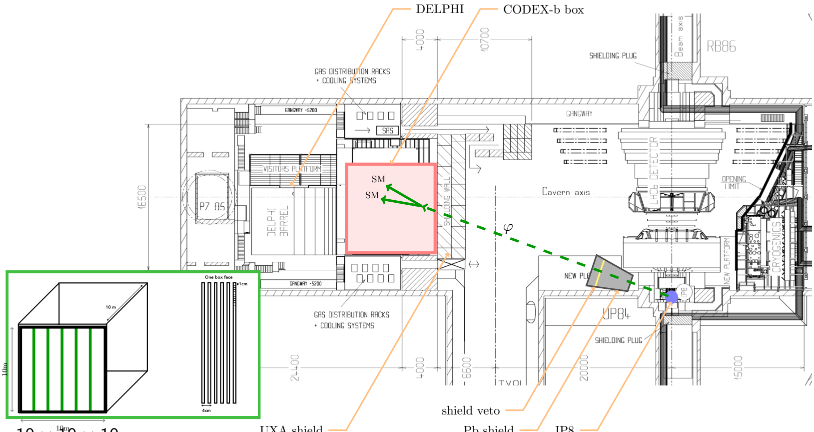


$10 \times 10 \times 10\,\mathrm{m}$

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

Tracking effs are typically $\mathcal{O}(1)$

Why is CODEX-b a good idea?

- Instrumented volume is small: Consider more ambitious detection technologies such as calorimetry or time-of-flight compared to other proposals. (More later)

- Close to IP: Only $\sim$ 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.

- Backgrounds are controllable
  - Ample space for additional shielding
  - Also decorrelated wrt other experiments

- Competitive NP Reach!

Prelude & Setup

Benchmarks & Portals

BG Study

Outlook

Benchmark Scenarios

Five benchmark LLP scenarios

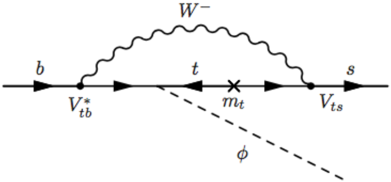
- Massive dark photon γ_{d} (kinetic mixing)
- Light $\mathcal{O}$(GeV) scalar φ (Higgs mixing)
- Heavy neutral lepton, N (mixing with the active neutrinos)
- $h \to$ dark glueballs (twin Higgs mixing portal)
- QCD coupled ALP $m_a < 3\pi$ (diphoton channel!)

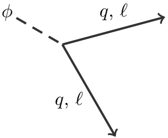
180x.xxxxx [Evans, Knapen, Papucci, Ramani, DR]

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

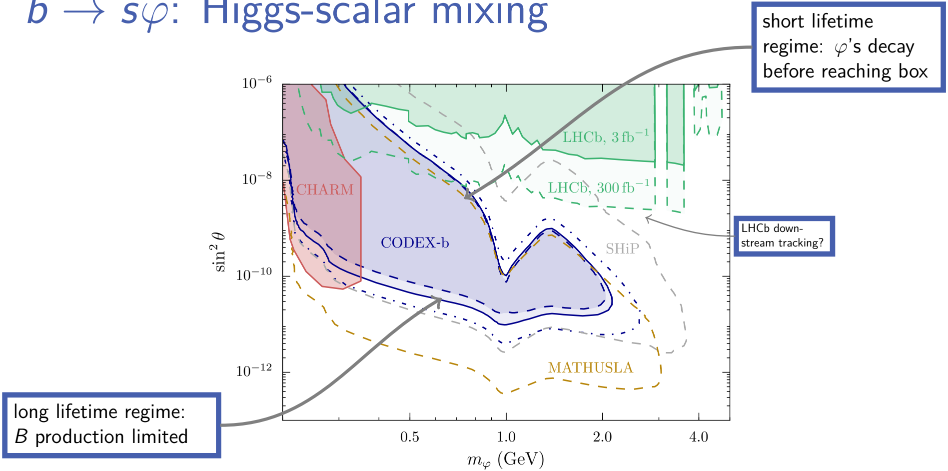
Single parameter portal: Higgs-scalar mixing angle, θ,

- In the mass basis, effective mixing $\sin\theta\,\varphi\, y_f \bar{f} f$
- For $m_\varphi \sim 1\,\text{GeV}$, dominant production from $b \to s$ decays, leveraging huge $\sigma_{b\bar{b}} \sim 500\,\mu\text{b}$
- Production and decay controlled by same portal





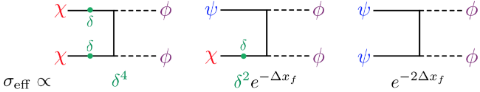
$b \to s\varphi$: Higgs-scalar mixing

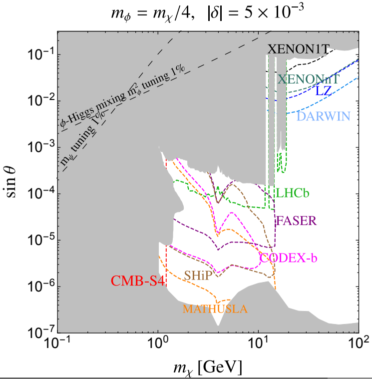


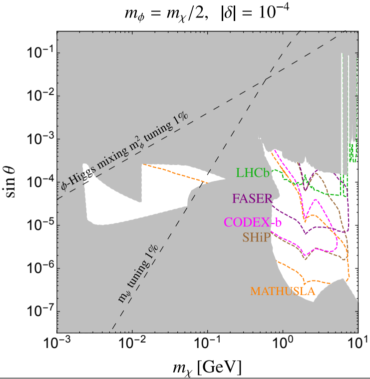
- LHCb reach scaled from $B \to K(\varphi \to \mu\mu)$ results, assuming no BG
- Reach/size exceeds most other proposals!
- NB large theory uncertainties for $m_\varphi \gtrsim 1$ GeV! (cf. 1708.08503 [Evans])

Application: Sterile Coannihilating DM

DM χ mixes with a heavier state ψ that coannihilate to the Higgs mixing scalar φ. 1803.02901 [Tito D'Agnolo, Mondino, Ruderman Wang]







Heavy Neutral Lepton: N

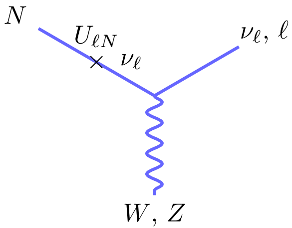
A heavy 4th (Dirac or Majorana) neutrino: effective mixing via extended PMNS matrix elements: U_{eN}, $U_{\mu N}$, or $U_{\tau N}$.

Production channels

- $c \to s\ell N$, $D_s \to \ell N$ $(\sigma_{c\bar{c}} \sim 5\text{mb!})$
- $b \to c\ell N$, $B_c \to \ell N$
- $W/Z \to \ell/\nu N$ (Large GB sample vs fixed target!)

Decay channels

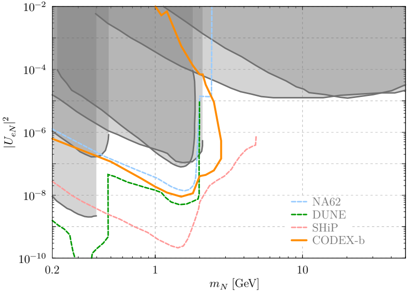
- $N \to 3\nu$ (Z channel; always present!)
- $N \to \nu\ell\ell$ (Z or W channel)
- $N \to \ell$ had (W channel)

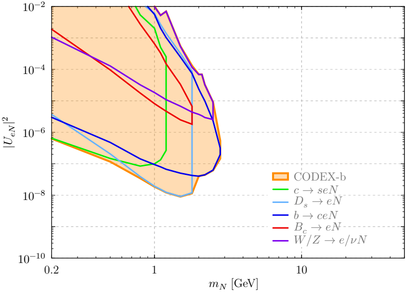


mass range
$0.1 \le m_N \le 10\,\text{GeV}$

Consider U_{eN}, $U_{\mu N}$, $U_{\tau N}$ one at a time

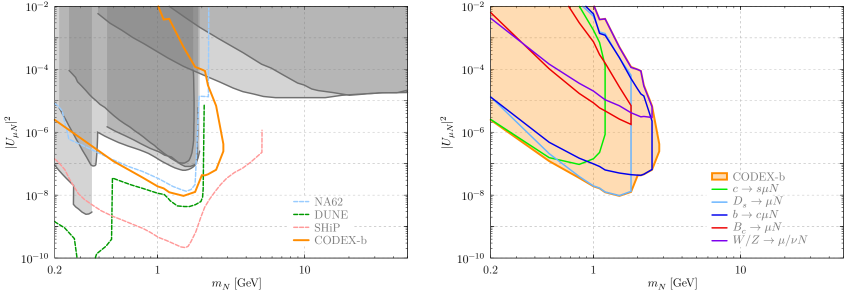
HNL: U_{eN}





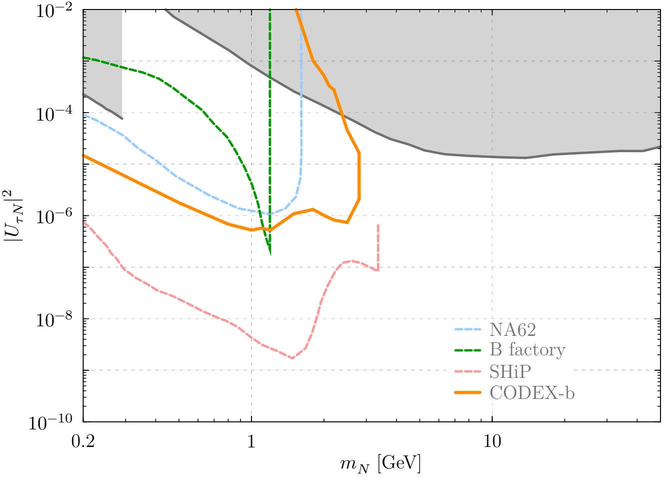
- Reach dominated by charm decays, B decays at high masses
- Strong limits set by current data
- cf. similar analysis by 1803.02212 [Heo, Hirsch Wang]

HNL: $U_{\mu N}$



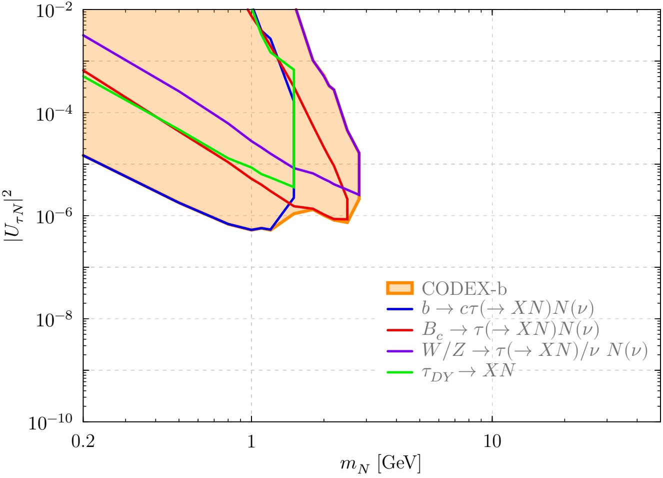
- Reach dominated by charm decays; B decays at high masses; W, Z in short lifetime regime
- Strong limits set by current data
- cf. similar analysis by 1803.02212 [Heo, Hirsch Wang]

HNL: $U_{\tau N}$



- Only weak limits set by current data!

HNL: $U_{\tau N}$



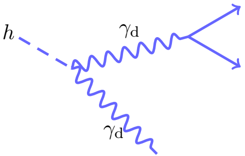
- Only weak limits set by current data!
- Reach dominated by B, B_c decays; W, Z in short lifetime regime

$h \to \gamma_d \gamma_d$

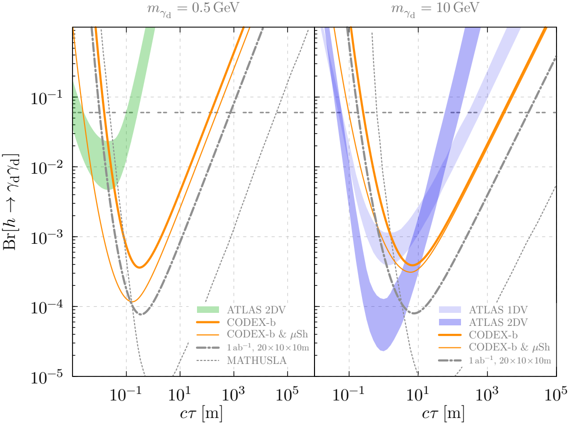
Higgs-Dark photon portal:

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

- $\mathrm{Br}[h \to \gamma_d \gamma_d]$ and γ_d lifetime controlled by separate parameters
- γ_d branching ratios fixed by e^+e^- data
- GF Higgs production, simulated with `Pythia8`



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



- For $m_{\gamma_d} = 10$ GeV, ATLAS disp. dijet reach dominates

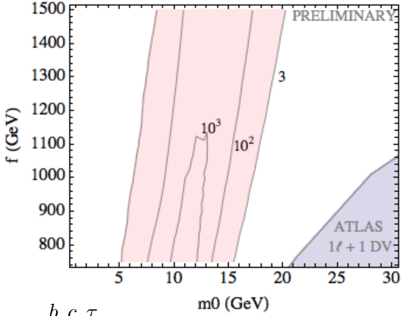
  1605.02742 [Coccaro, Curtin, Lubatti, Russell, and Shelton]

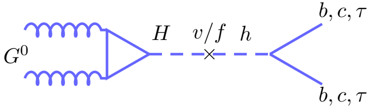
  1412.0018 [Curtin, Essig, Gori, and Shelton]
- For $m_{\gamma_d} = 0.5$ GeV, ATLAS reach is sys limited: Assume factor of 5 improvement. (Could scale as much as $\sqrt{L}$)

Dark glueballs: G^0 (preliminary)

'Fraternal' Twin Higgs (neutral naturalness) setup:

- Heavy-light Higgs mixing via $f/v \gtrsim 3$.
- One heavy flavor dark QCD sector: glueball lightest state
- Decays to SM, $G^0 \to qq$, via higgs portal. Loop and yukawa suppressed, $\Gamma \sim m_0^7/f^4 m_h^2$!



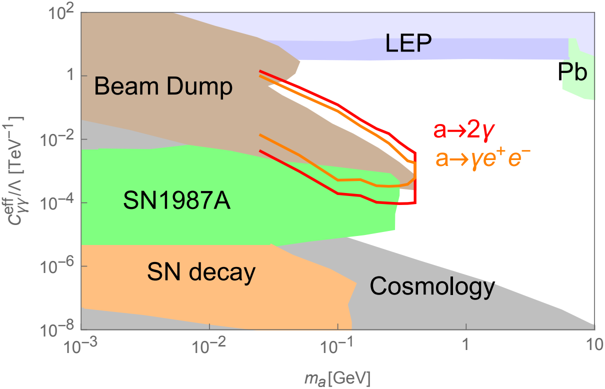


- ATLAS/ CMS reach limited by VH production: trigger on 1DV + 1 lepton/ associated hard object 1506.06141 [D. Curtin, C. Verhaaren]
- Can access lighter glueball regime, over broad range of f values!

Axion-like Particles, a (preliminary)

Well-motivated over broad range of hidden valley type theories

- UV coupling to $aG\widetilde{G}$
- Induces $\alpha a F\widetilde{F}$ operator and mixing with SM π^0!
- For $m_a < 3\pi$, production through π^0-a mixing, decay to $\gamma\gamma$!



- Reach leverages huge π^0 production rate, modulo exponential fragmentation penalty (a la Lund: $\sim e^{-(m_a^2 - m_\pi^2)\pi/\kappa}$)
- Reach supplements beam dump in vital coupling/mass regime!
- Effective reach even for $a \to ee\gamma$ [Br $\sim 1\%$] But can CODEX-b see photons?!?

Prelude & Setup

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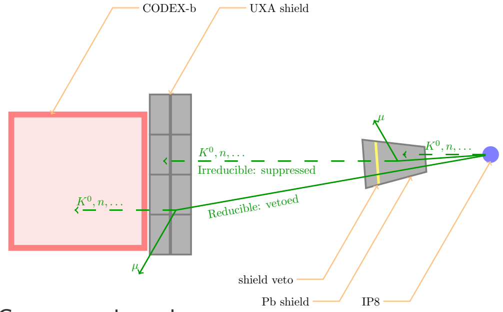
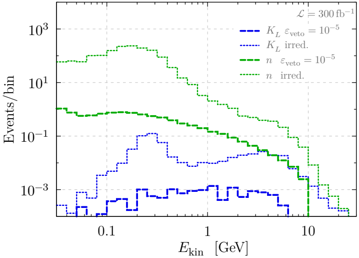
Backgrounds

Modest amount of additional shielding is needed for CODEX-b

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

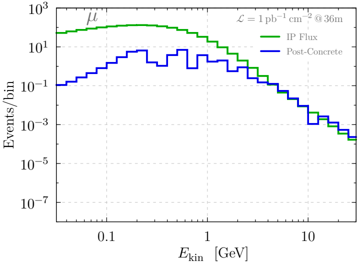




- Conceptual study:
  - Passive Pb shield attenuates muon & neutral hadron BGs
  - A thin veto layer rejects secondary production within the shield.
- To estimate BGs we use a (preliminary) `Geant4` simulation, validated with simplified propagation model
- BGs are controlled in this proof-of-concept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

Data-driven BG calibration

- Data-driven BG measurement in the LHCb cavern
  - Measure background charged flux behind the UXA wall (later: different shield thicknesses/materials)
  - Allows us to begin to properly calibrate MC estimates



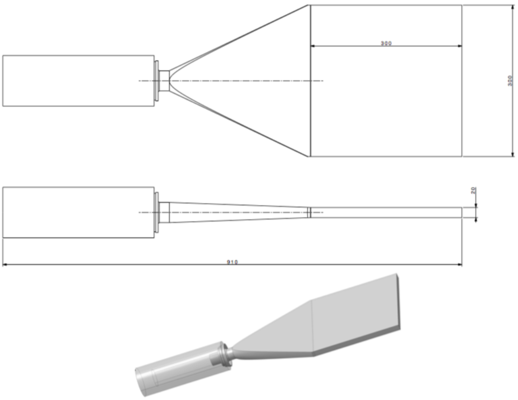
- Happening this year!

A BG calibration with scintillator+PMT: Plan to install behind UXA wall for engineering run

BG Calibration

Wrapped scintillator panel: $30 \times 30 \times 2\,\mathrm{cm}$.

Measure charged flux through UXA wall

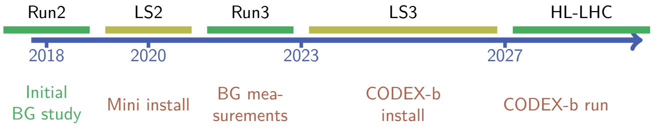


Courtesy of Raphael Dumps

Thoughts & Questions

CODEX-b significantly enhances the NP reach and capabilities of the LLP programme, complementing or exceeding the reach of other LHC experiments, with largely decorrelated backgrounds

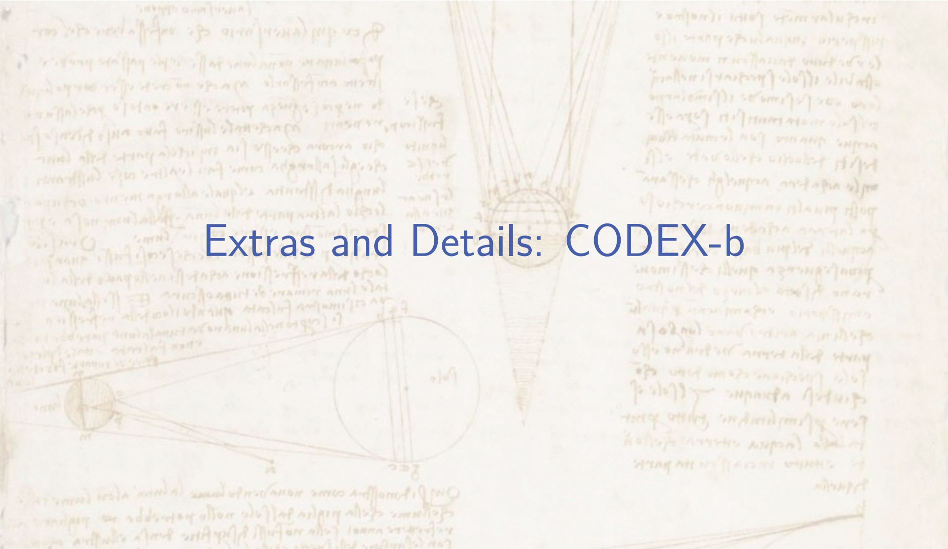
Timeline:



Questions for the workshop:

- $a \to \gamma\gamma$: Is there a plausible calorimetry solution at CODEX-b?
- More reach: If LHCb dismantles the shield wall to bring out DELPHI, can the shield wall be rebuilt closer to LHCb to buy even more decay volume?
- Tracking: Is a NOVA based techonology a better approach?

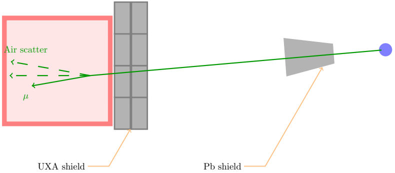
Thank you!



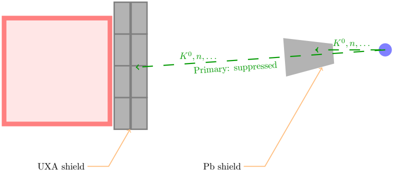
Extras and Details: CODEX-b

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

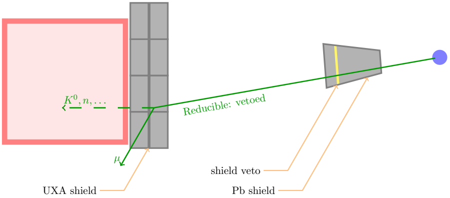


(In practice Pb is not ideal for neutrons: other materials to be considered)

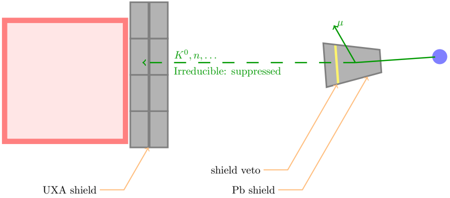
- ν-air inclusive inelastic σ: $\sim \mathcal{O}(3)$ events, but actual fake rate likely much smaller.

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

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

BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n+\overline{n}$	7	$5 \cdot 10^4$	$E_{\text{kin}} > 1$ GeV
K_L^0	0.2	9×10^2	$E_{\text{kin}} > 0.5$ GeV
$\pi^{\pm}+K^{\pm}$	0.5	$3 \cdot 10^4$	$E_{\text{kin}} > 0.5$ GeV
$\nu+\overline{\nu}$	0.5	$2 \cdot 10^6$	$E > 0.5$ GeV

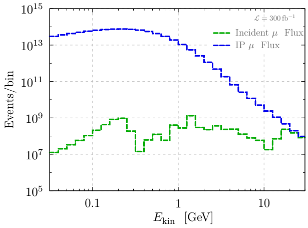
These are yields not scattering rates! n–air scattering prob. $\sim 5\%$

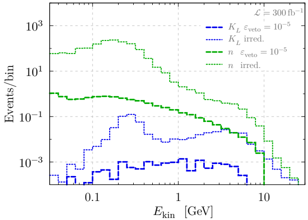
Normalization is set for min bias $\sigma \sim 100$ mb

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





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	–	–	–	–	–

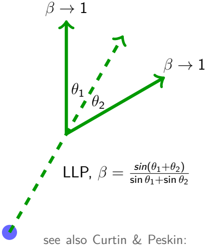
Dominated by opening angle resolution. Requires optimization using station spacing and granularity

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

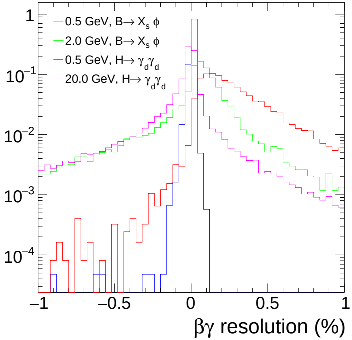
- Lesson: Proof-of-concept tracking effs are $\mathcal{O}(1)$. Can be further optimized.

Boost Resolution

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



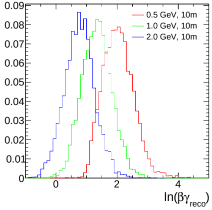
see also Curtin & Peskin: 1705.06327

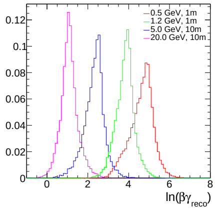


- The resolution is $< 1\%$ dominated by distance to first measured point, not detector granularity
- Boost distribution is dominated by the spread of boosts, not resolution.

Boost and Mass Reco

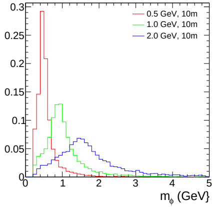
Using only geometry of tracks, can reconstruct parent:

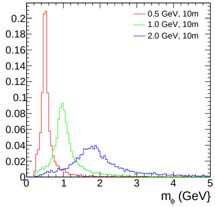




Mild resolution even for $b \to s\varphi$!

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!





Dark glueballs Lifetime