Multi-track Signals of LLPs from an EFT Perspective

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LLPs @ Belle II, DESY

Based on work with Brian Shuve, Albany Blackburn, Mason Acevedo and Mavis Stone (Harvey Mudd College)

Existing Searches for Long-Lived Particles

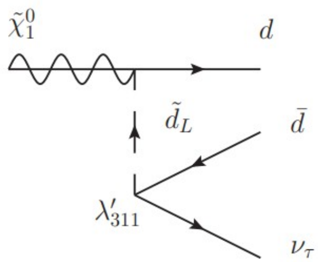
- Searches tailored for specific models:

  fixed production and decay channels/topologies

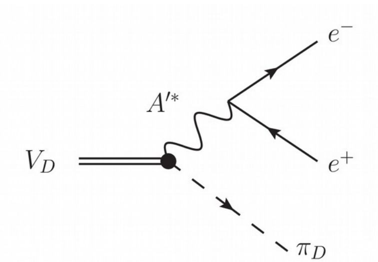
  E.g. heavy neutrinos (Belle – 1301.1105); two body decays (BaBar - 1502.02580), dark Higgses (BaBar - 2005.01885)

- Difficult or impossible to apply to slight variations

  Selections on total number of tracks, mass peaks, total energy in event prevent easy extension



RPV neutralinos
2012.00438
See talk by Wang

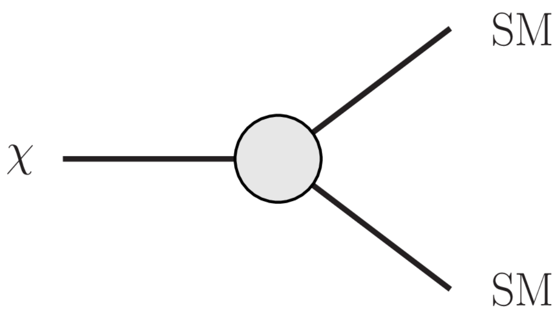


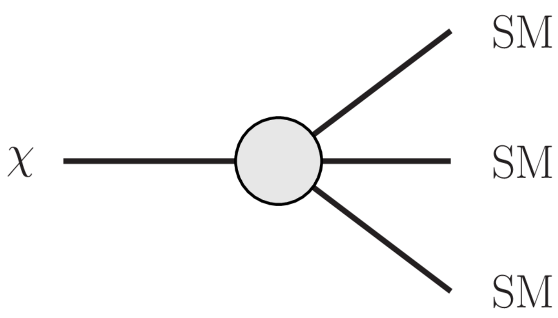
Strongly-interacting sectors
Inelastic DM: see talks by Cely and Longo

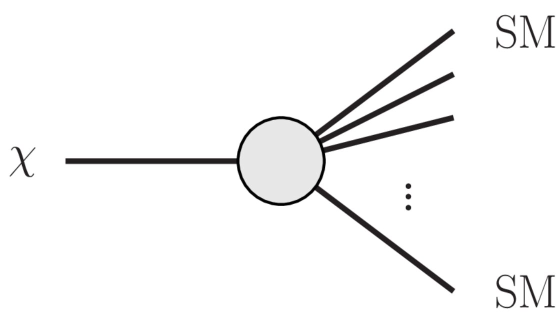
- How to ensure analyses remain relevant and widely applicable in the future?

LLPs in General

- Production and decay in general decoupled
- For a given production channel, many decays possible







Belle 1301.1105
BaBar 1502.02580
& 2005.01885

Dey *et al* 2012.00438

*Other BSM states can be present in final state too: e.g., iDM and SIMP-like decays (see, e.g., Duerr *et al* 1911.03176, Berlin *et al* 1801.05805)

Classifying Possible Final States

- Specialize to SM-only final states
- Interactions of LLP with SM must preserve
  1) Lorentz symmetry
  2) Gauge symmetries of SM

Effective Field Theory allows to organize all "valid" interactions

$$\mathcal{L} \supset \frac{1}{\Lambda^{n-4}} \chi \, O_{\mathrm{SM}}$$

Lifetime and Operator Dimensions

- Given an operator of dimension n

$$\Gamma \sim m_\chi \left(\frac{m_\chi}{\Lambda}\right)^{2(n-4)}$$

O(1) meter decay lengths obtained for

$$\Lambda \sim 10^{16/(2n-8)}\ \mathrm{GeV}$$

for n>8, Λ<100 GeV, so focus on

$$\dim \mathcal{O}_{\mathrm{SM}} \leq 8 - \dim \chi$$

Scale of new physics **charged** under SM

Available Operators

- Spin 0 LLP: $\mathcal{O}_{\rm SM} \in \rm SMEFT$

  use results of, e.g.,

  Grzadkowski *et al* (1008.4884)
  Lehman (1410.4193)
  Alonso *et al* (1405.0486)
  Passarino and Trott (1610.08356)...

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$$\dim \mathcal{O}_{\rm SM} = 6$$

- Spin ½ LLP: equivalent to SM + sterile neutrino

  see Liao & Ma 1612.04527

$(\bar{L}R)(\bar{L}R)(+\text{h.c.})$	
$\mathcal{O}_{LNLe}$	$(\bar{L}N)\epsilon(\bar{L}e)$
$\mathcal{O}_{LNQd}$	$(\bar{L}N)\epsilon(\bar{Q}d)$
$\mathcal{O}_{LdQN}$	$(\bar{L}d)\epsilon(\bar{Q}N)$

$$N = \chi \quad \dim \chi\mathcal{O}_{\rm SM} = 6$$

Available Final States

- Spin 0 LLP decay

dim $\chi\mathcal{O}_{\rm SM}$	leptonic	semi-leptonic	hadronic	photonic
5	$\bar{\ell}_i\ell_i$		$\bar{q}_i q_i$, gg	$\gamma\gamma$
6	$\nu\nu$			
7	$\bar{\ell}_i\ell_j\gamma$, $\bar{\ell}_i\ell_j\bar{\ell}_k\ell_l$, $\bar{\ell}_i\ell_j\bar{\nu}_k\nu_l$	$\bar{\ell}_i\ell_j\bar{q}_k q_l$, $\bar{\nu}\ell\bar{d}u$, $\ell_i u_j u_k d_l$	ggg, $\bar{q}_i q_j\gamma$, $\bar{q}_i q_j g$, $\bar{q}_i q_j\bar{q}_k q_l$, $\bar{\nu}_i\nu_j\bar{q}_k q_l$, $\nu_i u_j d_k d_l$	$\gamma\gamma$
8	$\bar{\ell}_i\ell_j\nu_k\nu_l$	$\bar{d}_i u_j\nu_k\ell_l$, $\bar{\ell}_i d_j d_k d_l$	$\bar{\nu}_i u_j d_k d_l$, $\bar{q}_i q_j\nu_k\nu_l$	$\nu_i\nu_j\gamma$

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dim $\chi\mathcal{O}_{\rm SM}$	leptonic	semi-leptonic	hadronic	photonic
6	$\bar{\ell}_i\ell_j\nu_k$	$\ell_i u_j\bar{d}_k$	$\bar{d}_i d_j\nu_k$, $\bar{u}_i u_j\nu_k$, $u_i d_j d_k$	$\nu\gamma$
7	$\bar{\ell}_i\ell_j\nu_k$, $\nu_i\bar{\nu}_j\nu_k$	$\ell_i u_j\bar{d}_k$	$\bar{d}_i d_j\nu_k$, $\bar{u}_i u_j\nu_k$, $u_i d_j d_k$	

Red: violates B or B-L

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- Spin ½ LLP decay

DVs with >2 charged tracks possible!

dim $\chi\mathcal{O}_{\rm SM}$	leptonic	semi-leptonic	hadronic	photonic
6	$\bar{\ell}_i\ell_j\nu_k$	$\ell_i u_j\bar{d}_k$	$\bar{d}_i d_j\nu_k,\ \bar{u}_i u_j\nu_k,\ u_i d_j d_k$	$\nu\gamma$
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Multiple Tracks from Displaced Vertices

- Displaced decays to multiple charged particles generic within the EFT framework

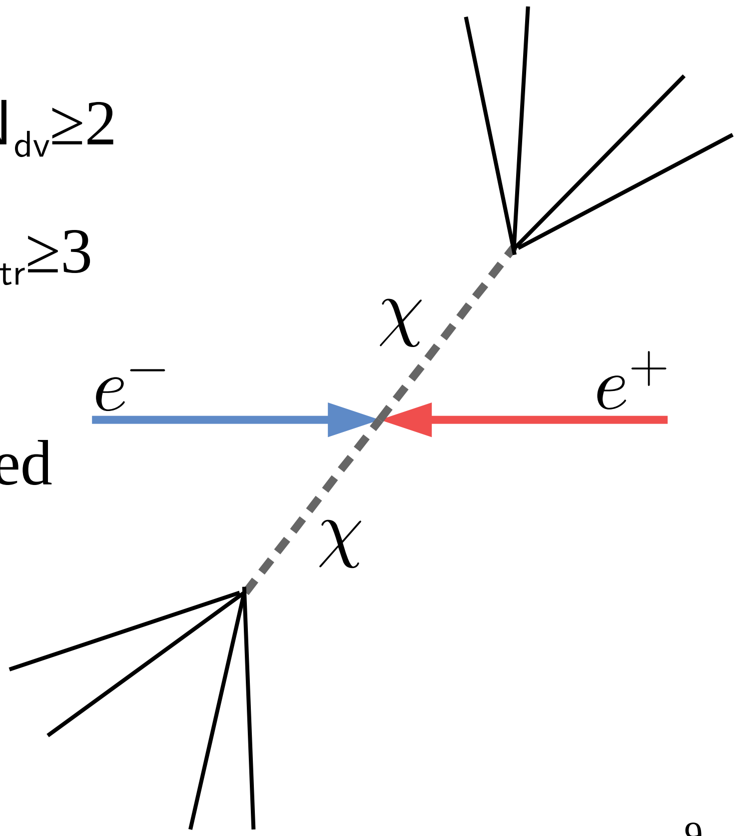
- An sample search:

   1) Number of displaced vertices, $N_{dv} \geq 2$

   2) Number of tracks per vertex, $N_{tr} \geq 3$

   3) $0.2\ \text{cm} \leq d \leq 60\ \text{cm}$

   4) $p_T > 100$ MeV, tracks well separated



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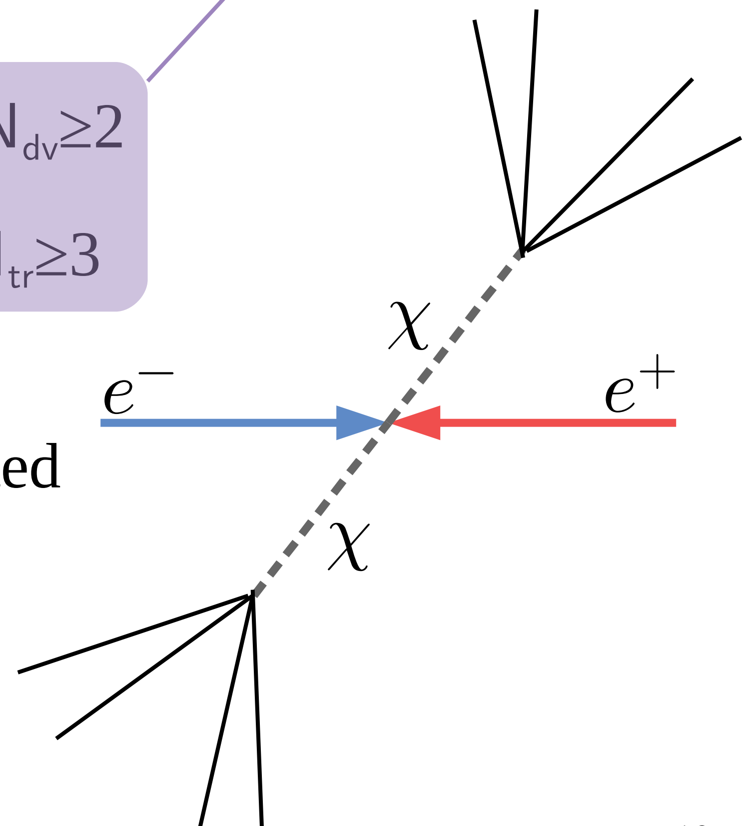
Relax if b/g under control



Backgrounds

- Genuine SM LLPs: $K^{\pm}$,$K_{L,S}$. These decay in fiducial region with probability ~0.05-0.9.

About 1 K per hadronic event: ~10^{11} K for 50 ab^{-1}

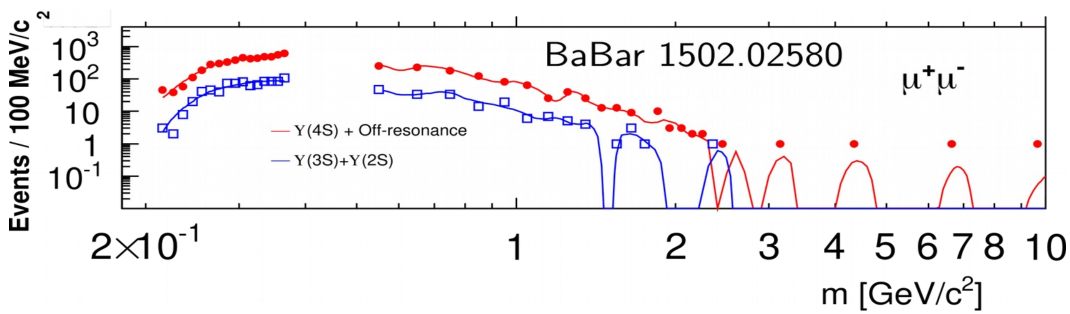
BaBar (1306.2895)

$$\mathrm{Br}\left(K^{+} \rightarrow \pi^{+}\pi^{-}\pi^{+}\right) \sim 0.06$$

$$\mathrm{Br}\left(K^{+} \rightarrow \pi^{+}\pi^{-}e^{+}\nu_{e}\right) \sim 10^{-5}$$

Other dangerous branching fractions similar ^

- Random track crossings: from BaBar 1502.02580, probability of fake *single*, *two-track* vertices $\sim 10^{-6}$



Corresponds to 10^5 two-track fakes at 50 ab^{-1}!

Demanding N_{dv}≥2, N_{tr}≥3 should reduce b/g to O(1) level

Radiative Return Example

$$e^+e^- \to \gamma_{\rm ISR} A', \underbrace{A' \to \chi\chi,}_{\text{prompt}} \underbrace{\chi \to \text{SM}}_{\text{displaced}}$$

See Schmidt-Hoberg's talk for a discussion of the dark photon

Existing searches for dark photons require γ in ECAL acceptance

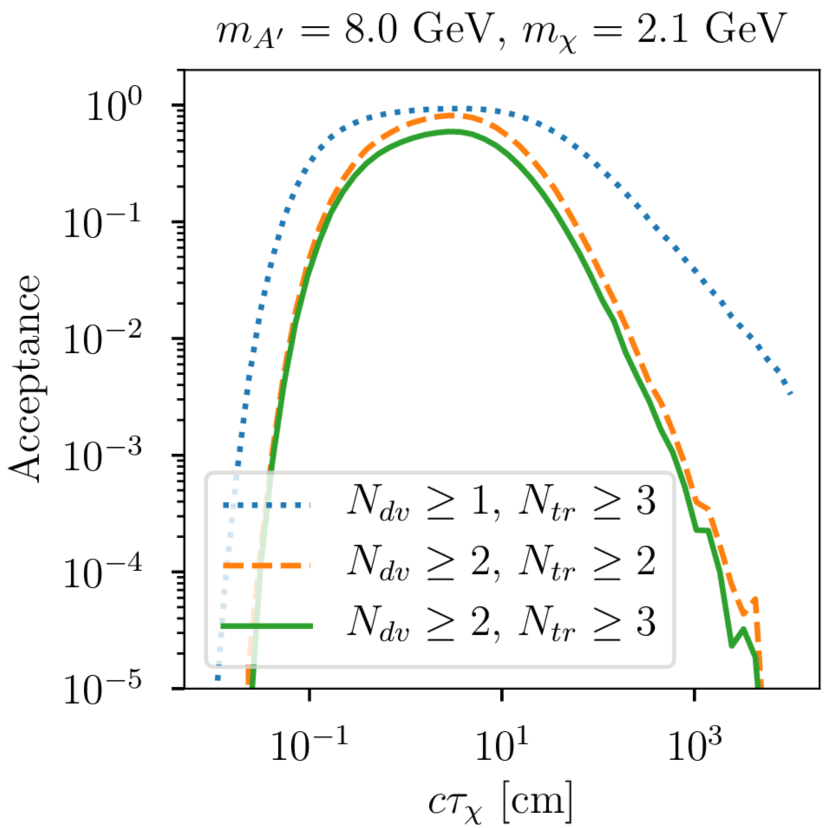
BaBar 1406.2980, 1702.03327

Rates a factor $\sim$ 20 larger if no γ tag required

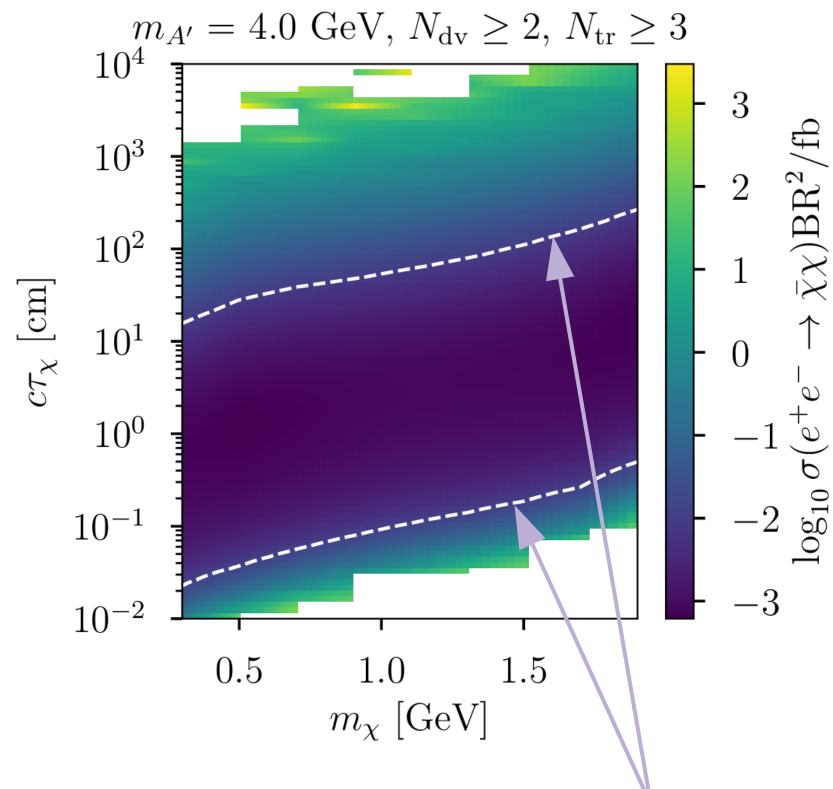
$\log s/m_e^2$

Leptonic Decays

$$\chi \mathcal{O}_{SM} = \chi(\bar{e}_R \gamma_\mu e_R)(\bar{\mu}_R \gamma^\mu \mu_R)$$



10 signal event sensitivity, no b/g

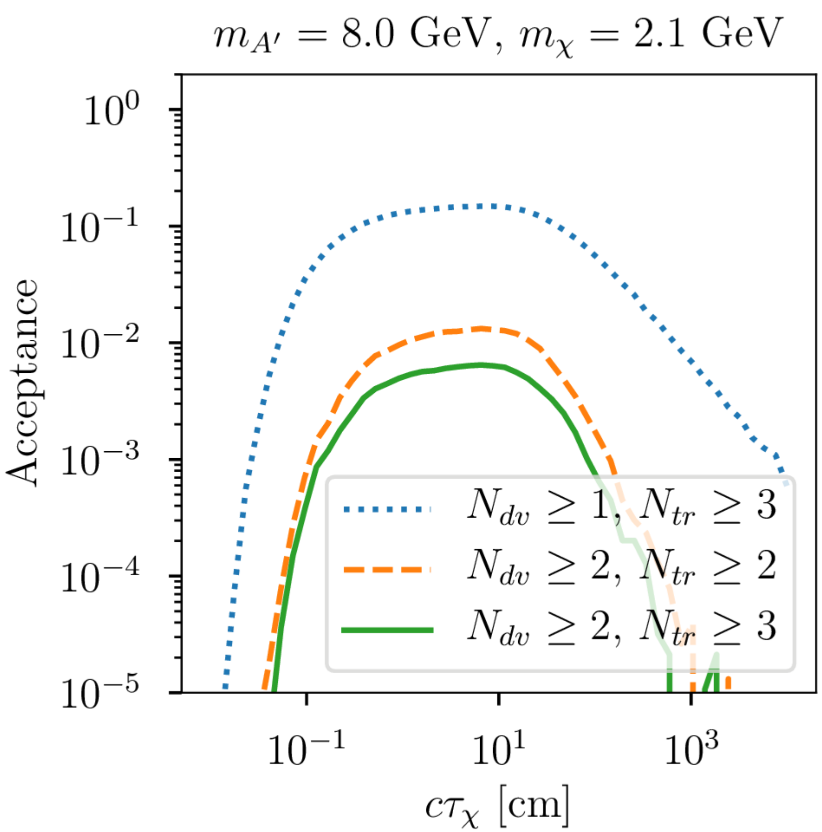


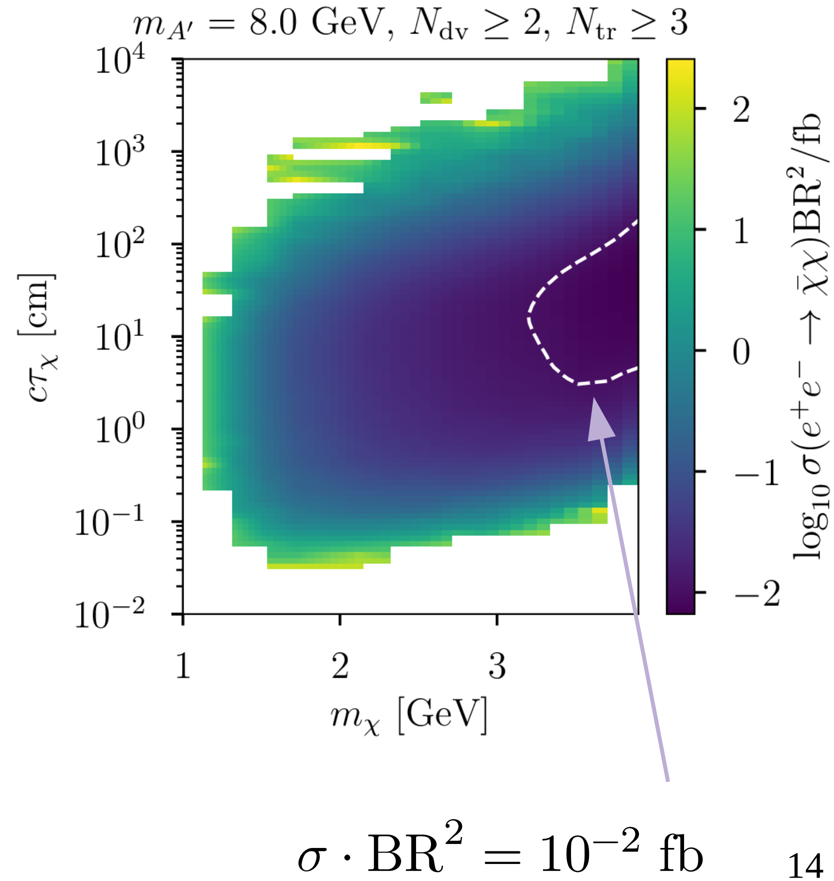
$\sigma \cdot \mathrm{BR}^2 = 10^{-2}$ fb

Corresponds to kinetic mixing ~ 10^{-5}

Semi-Leptonic Decays

$$\chi\mathcal{O}_{SM} = \chi(\bar{Q}u_R)\cdot(\bar{L}e_R) \to \chi\left[\bar{e}_L e_R \bar{u}_L u_R + \bar{\nu}_L e_R \bar{d}_L u_R\right]$$





Future Work and Conclusion

Searches for displaced vertices + tracks offer sensitivity to broad classes of LLPs

- More reliable background estimates needed (in progress)
- Quantify hadronization uncertainties (compare chiral PT + vector mesons vs Pythia – in progress)
- Any other model-independent constraints on EFT operators (or from their UV completions)?

Thank you!

Appendix

Hadronization

- Even operators with only two quarks can lead to multiple charged tracks. E.g.,

$$\chi(\bar{\nu}_L e_R)(\bar{d}_L u_R) \to B\chi(\bar{\nu}_L e_R)\mathrm{tr}\,\Sigma^\dagger C$$

$$\supset B\chi(\bar{\nu}_L e_R)\left[\frac{\pi^+}{f_\pi} + \frac{\eta\pi^+}{f_\pi^2} + \frac{\pi^+\pi^-\pi^+}{f_\pi^3}\right]$$

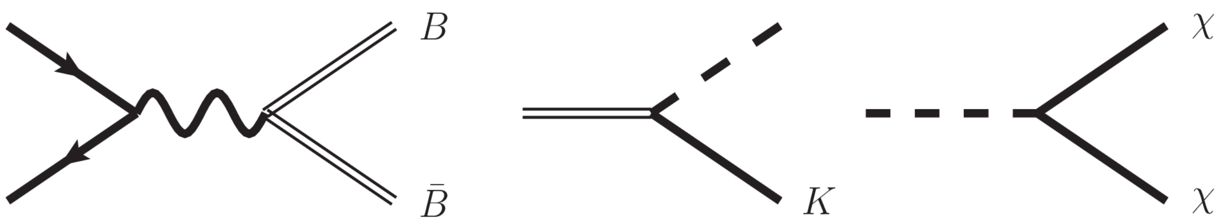
- To produce events, use Pythia to hadronize or chiral perturbation theory (+ vector mesons)

LLP Production Channels

- Search can be adapted to any production channel.

1) Radiative return

2) Rare B decays



3) … (many other possibilities, e.g., associated heavy lepton flavour production, neutrino portal production)

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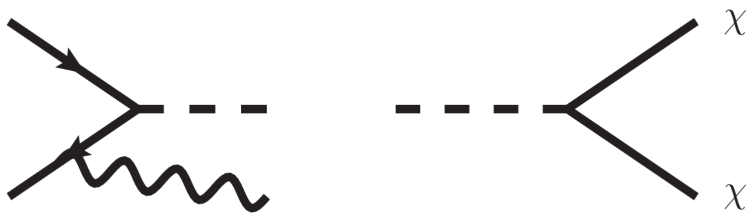

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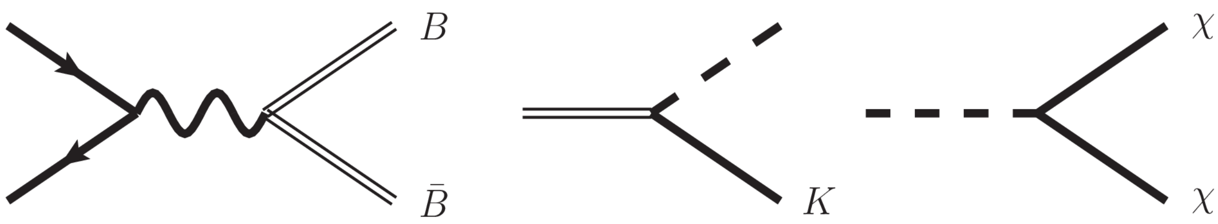

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Hadronic Decays

$$\chi\mathcal{O}_{SM} = \chi(\bar{u}_R\gamma_\mu u_R)(\bar{u}_R\gamma^\mu u_R)$$