KIT
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Displaced vertex physics

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Belle II Trigger/DAQ Workshop 2022

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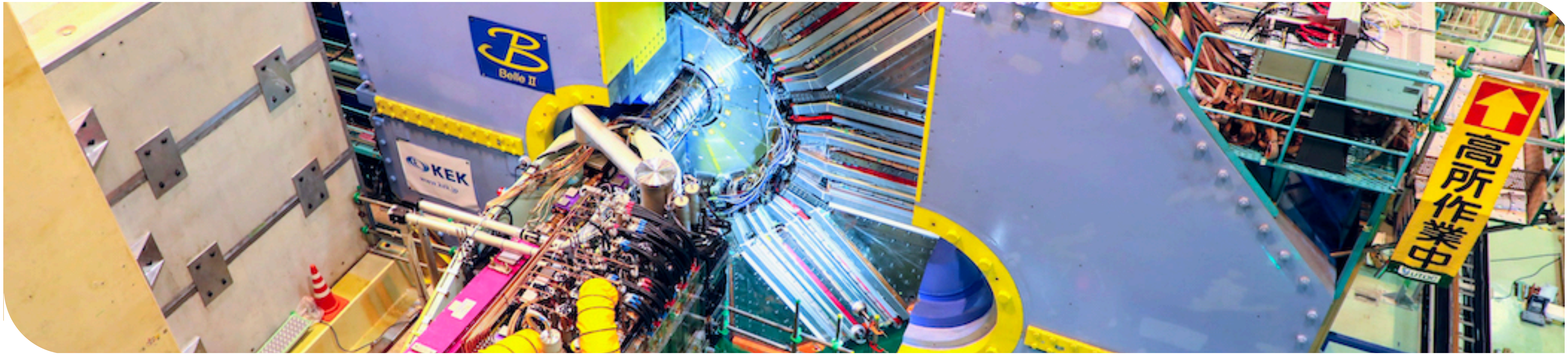
with input from Patrick Ecker, Chris Hearty, Tim Tueschen and theory collaborators



Introduction: Beyond Standard Model portals

- Most BSM collider searches are discussed in so called portal models:
  - $\mathscr{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{BSM}}$
  - O_{SM} is an operator composed from SM fields and O_{BSM} is an operator composed from new fields
- Only keep lowest dimensional renormalisable portals
  - this makes them rather simple theoretically, which in turn makes them very popular
- Keeps the theoretical structure (and all symmetries) of the SM intact

- Do the portal models appear in UV-complete models? Yes.
- Are the portals sufficient to cover all feebly interacting particle signatures? Probably not.
  - e.g. emerging jets (P. Schwaller et al., J. High Energ. Phys. 2015, 59 (2015)), quirks (G. D. Kribset al., Phys. Rev. D 81, 095001 (2010)), softbombs (S. Knapen et al., J. High Energ. Phys. 2017, 76 (2017)), dark showers (E. Bernreuther et al, https://arxiv.org/abs/2203.08824 , accepted by JHEP)

Portal Models

Portal	Coupling
Vector portal (**F** is the dark photon field which couples to the hypercharge field B)	$-\frac{\epsilon}{2\cos(\theta_W)} F'_{\mu\nu} B^{\mu\nu}$
Higgs portal (**S** is a scalar singlet that couples to the SM Higgs doublet H with **μ** (dim. less) and **λ** (dimensional))	$(\mu S + \lambda S^2) H^\dagger H$
ALP portal (**a** is a pseudoscalar axion that couples to a dimension-4 di-photon, di-fermion or di-gluon operator)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$
Neutrino portal (**N** is a neutral fermion that couples to one of the left-handed doublets L of the SM and the Higgs field H with a Yukawa coupling y_N)	$y_N LHN$

Physics Beyond Collider Benchmark Models

Benchmark	Name	Parameters	Signature
BC1	Dark Photon	$m_{A'}$, ε	$A' \to f\bar{f}$
BC2	Dark Matter (via A')	$m_{A'}$, ε, m_χ, α_D (α_D=0.1 and $m_{A'}/m_\chi$=3)	$A' \to \chi\bar{\chi}$
BC3	Millicharged (via A')	m_χ, Q_χ/e, ($m_{A'} \to 0$)	$A' \to \chi\bar{\chi}$
BC4	S (higgs mixing)	$\tan(\theta)$, m_S	$S \to f\bar{f}$
BC5	SS (higgs decay)	$\tan(\theta)$, m_S, λ	$h \to SS$
BC6	HNL (electron)	$\lvert U_e\rvert^2$, m_N, ($\lvert U_\mu\rvert^2 = \lvert U_\tau\rvert^2 = 0$)	ν_e or e
BC7	HNL (muon)	$\lvert U_\mu\rvert^2$, m_N, ($\lvert U_e\rvert^2 = \lvert U_\tau\rvert^2 = 0$)	ν_μ or μ
BC8	HNL (tau)	$\lvert U_\tau\rvert^2$, m_N, ($\lvert U_e\rvert^2 = \lvert U_\mu\rvert^2 = 0$)	ν_τ or τ
BC9	ALP with photon coupling	m_a, $g_{a\gamma\gamma}$	$a \to \gamma\gamma$
BC10	ALP with fermion coupling	m_a, g_{aff} ($g_{aff} = g_{aqq}$)	$a \to f\bar{f}$
BC11	ALP with gluon coupling	m_a, g_{agg}	$a \to$ hadrons

BCX1	U(1) (B-L)	$m_{A'}$, g_{B-L}	$A' \to f\bar{f}$
BCX2	Inelastic Dark Matter	$m_{A'}$, ε, $m_{\chi 1}$, $m_{\chi 2}$, α_D (α_D=0.1, $m_{A'}/m_\chi$=3, Δ =0.1 GeV)	$\chi_2 \to \chi_1 \ell\bar{\ell}$
BCX9	ALP with W coupling	m_a, g_{aWW}	$B \to Ka$, $a \to \gamma\gamma$

BC678X	HNL	Non-trivial combinations of $\lvert U_e\rvert^2$, $\lvert U_\mu\rvert^2$, $\lvert U_\tau\rvert^2$	

"The main goal of the Study Group remains to explore the **opportunities offered by CERN**'s unique accelerator complex (…) that complement the goals of the main experiments of the Laboratory's collider programme. Examples of physics objectives include (…) searches for feebly interacting particles. (…) The study group will primarily investigate, and, where appropriate, provide support to, projects expected to be **sited at CERN**. (…)"

https://pbc.web.cern.ch/mandate

https://pbc.web.cern.ch/fpc-mandate

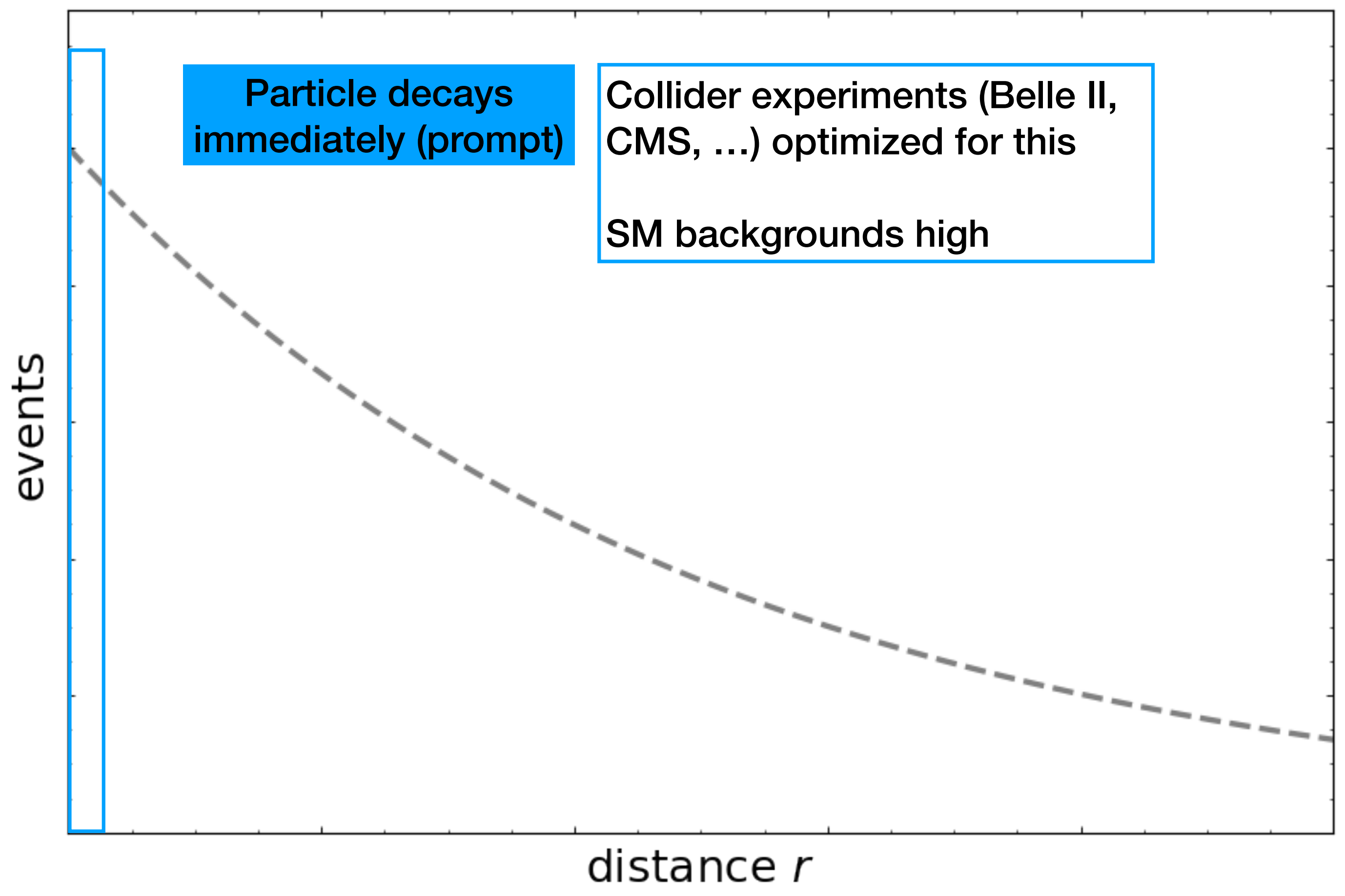
- New mediators with very small couplings in the range of Belle II sensitivity are naturally long-lived
- Lighter mediators have longer lifetimes in the experiment due to larger boost
- In the PBC/FPC: Only BC2 and BCX2 are actual DM models, many other are possible mediators to dark sectors

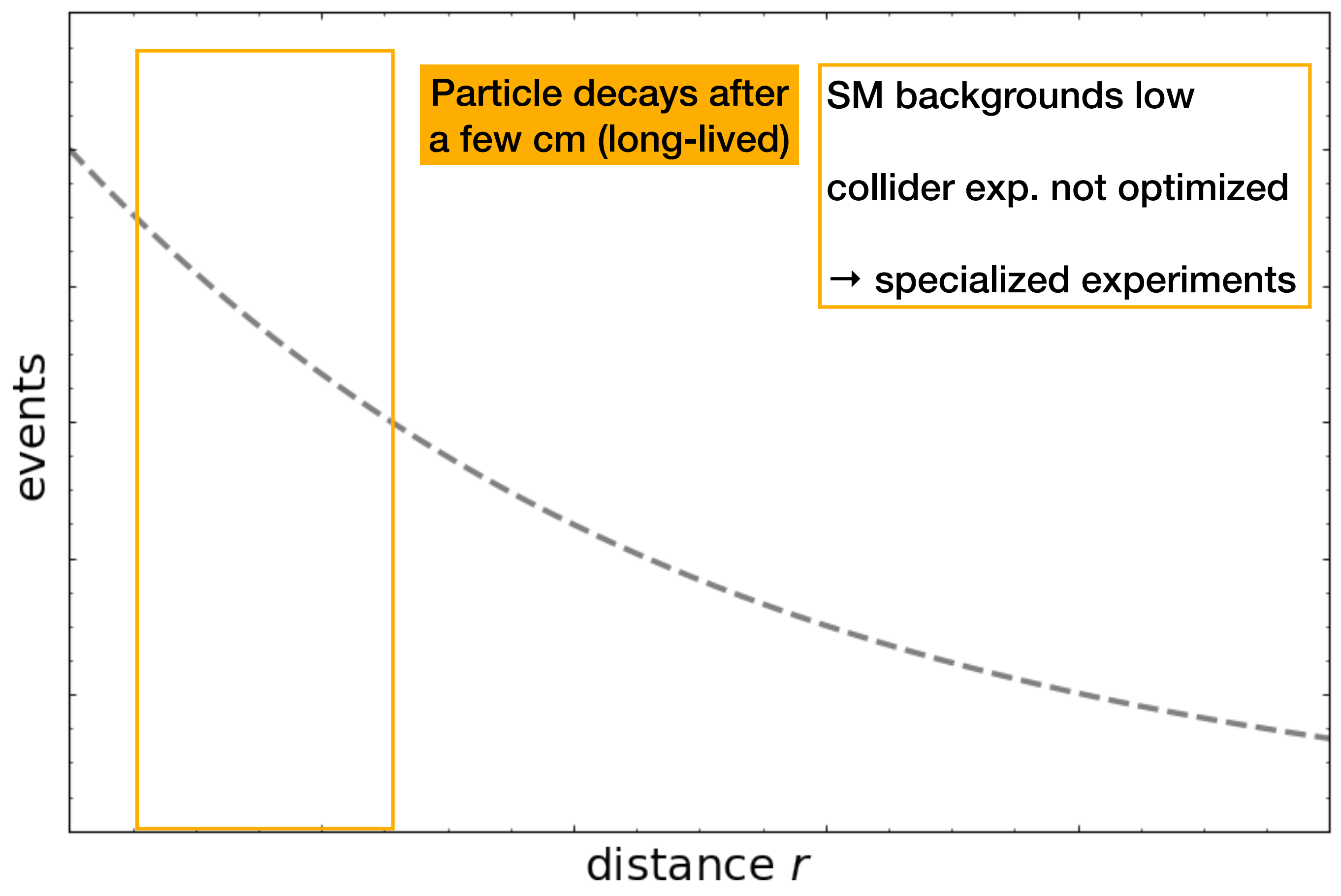
Introduction Dark Matter and relic targets

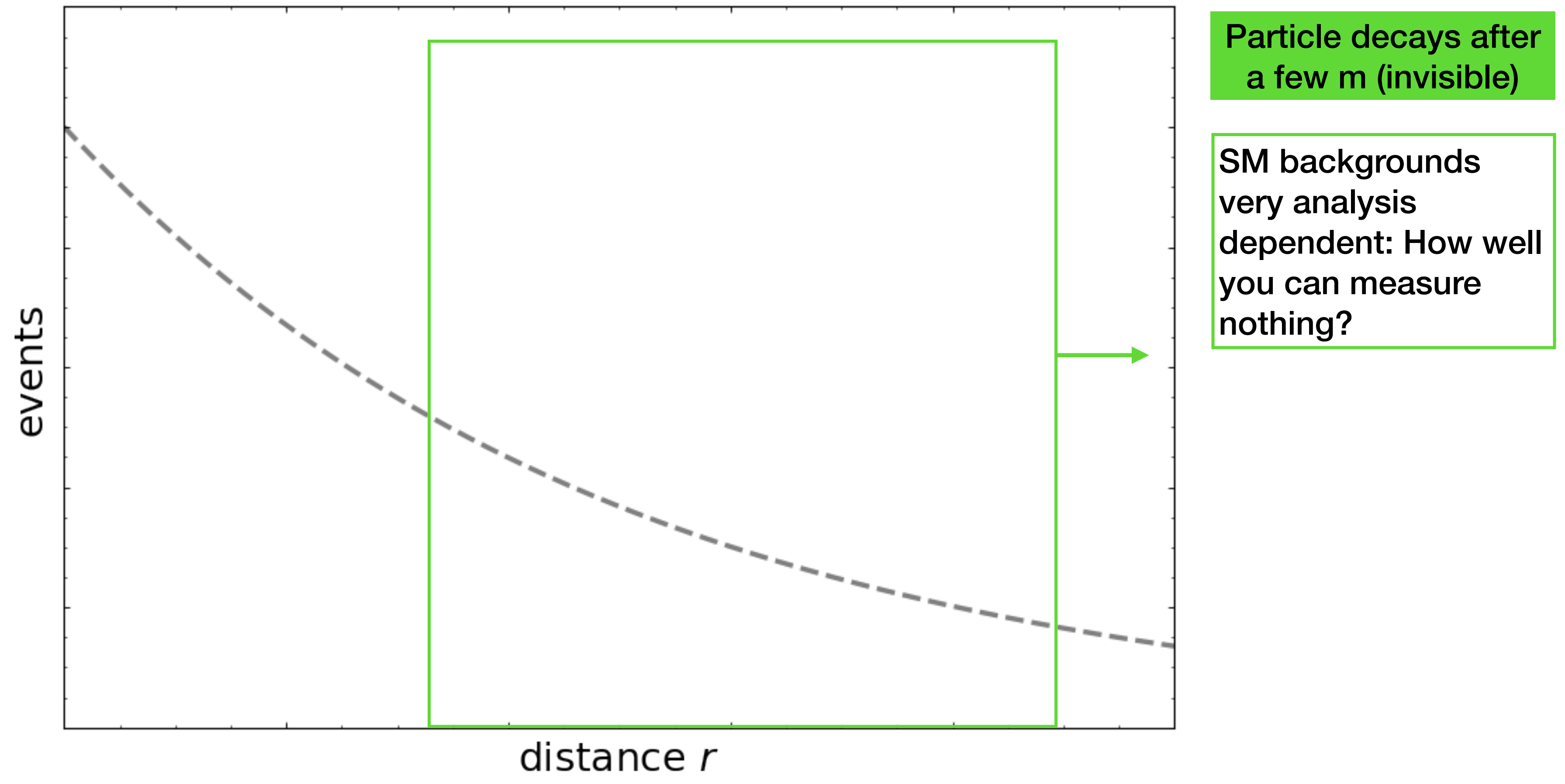
- Dark Matter particles χ are invisible in collider experiments
- Light Dark Matter (LDM), typically $m_\chi \lesssim 5$ GeV, requires a new mediator to the Standard Model if (!) there is any interaction beyond gravity
- Freeze-out Dark Matter models are predictive:
  "Relic targets" provide search target by using known dark matter density
  - Relic targets are model-dependent (at colliders this effect is often rather mild)
  - Relic target is a function of dark matter mass and coupling to the new mediator

At Belle II, searches for Dark Matter are always final states with missing energy.

Reminder: Exponential Decay Times



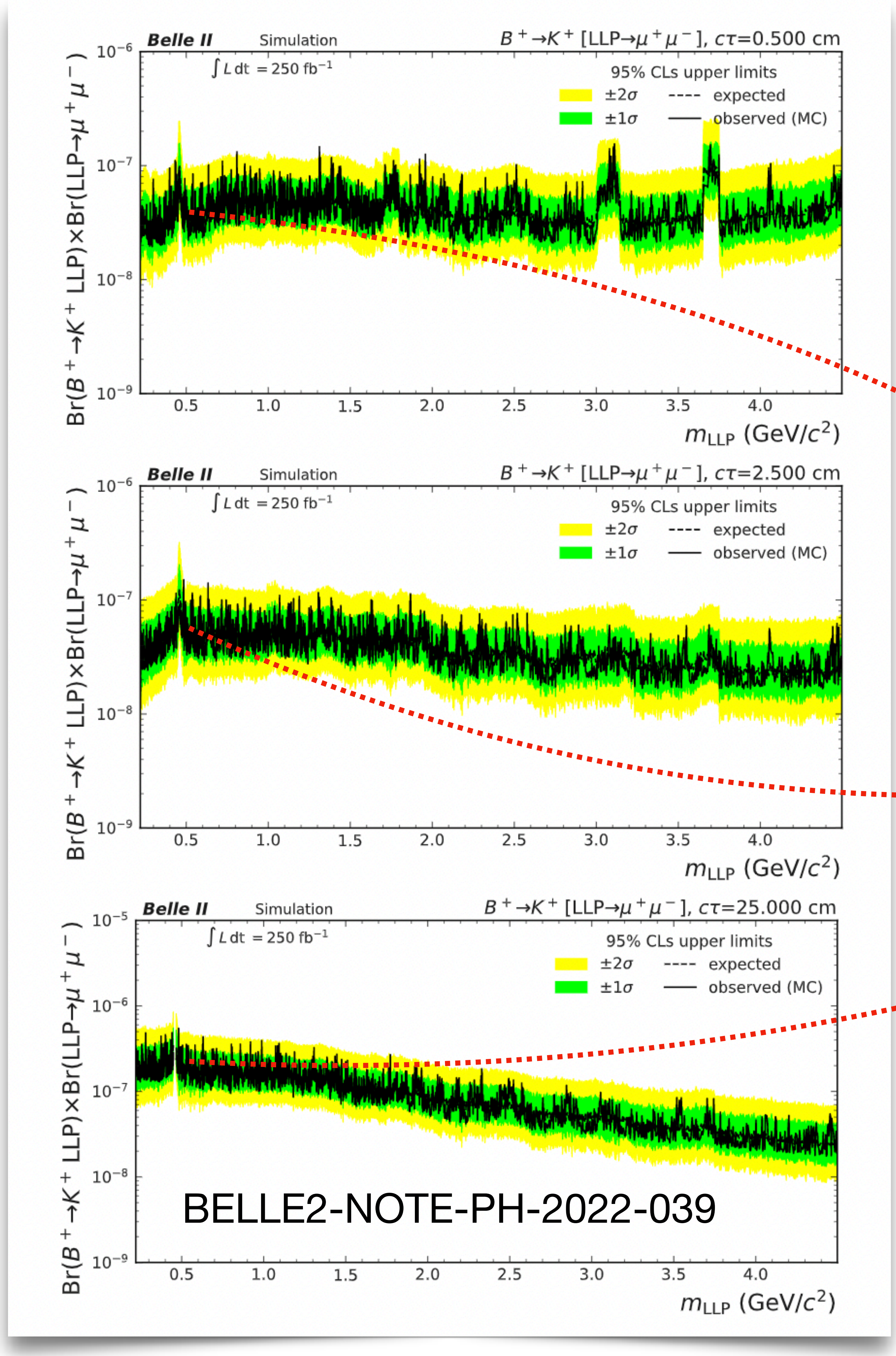




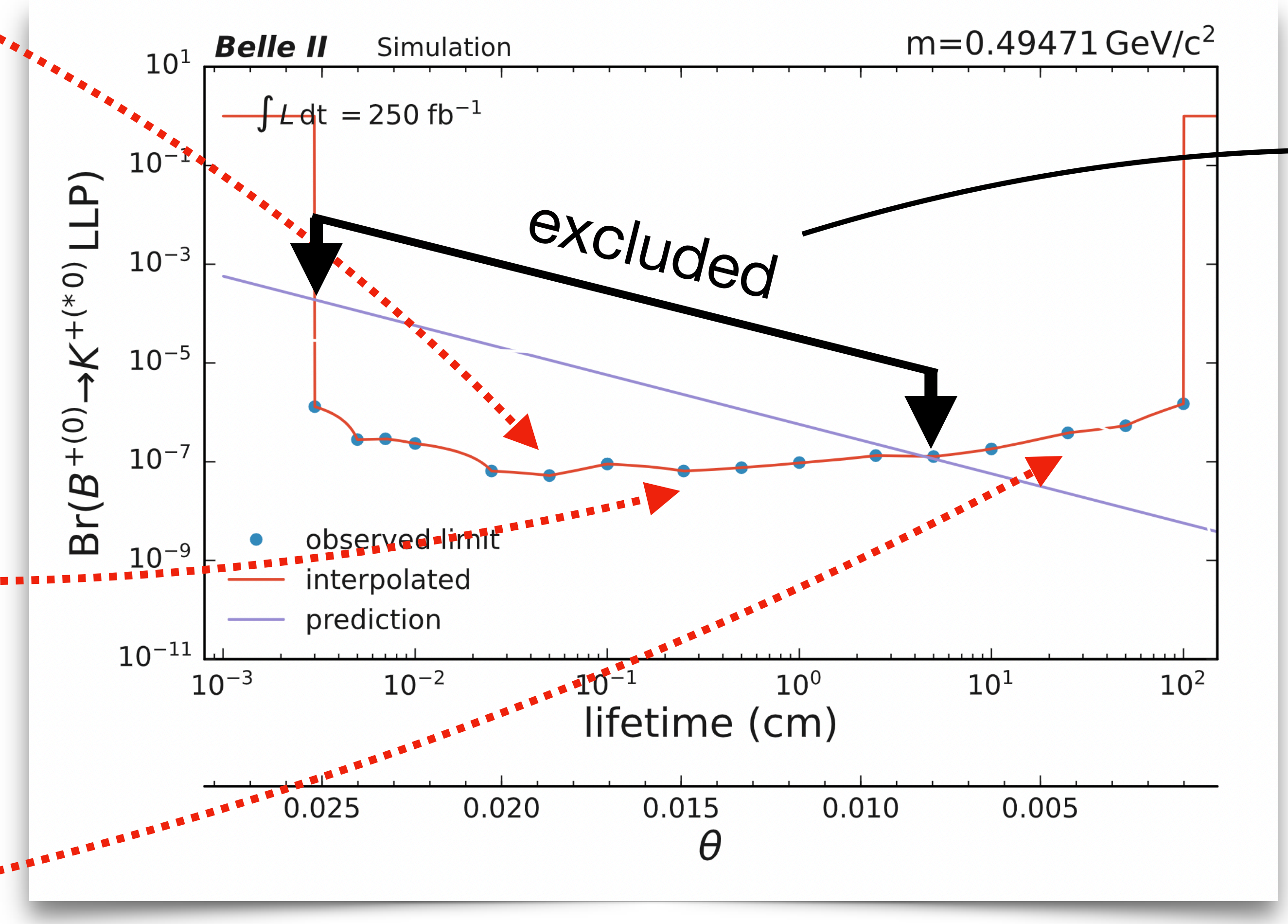
- Particles with lifetimes $\mathcal{O}$(cm) typically feature prompt, displaced, and invisible (==too long lived) signatures! (generally three different analyses)
- Generally: **Prompt** has good efficiency but high SM backgrounds, **invisible** has good efficiency and often small backgrounds but little information the final state, **displaced** has low efficiency and low backgrounds

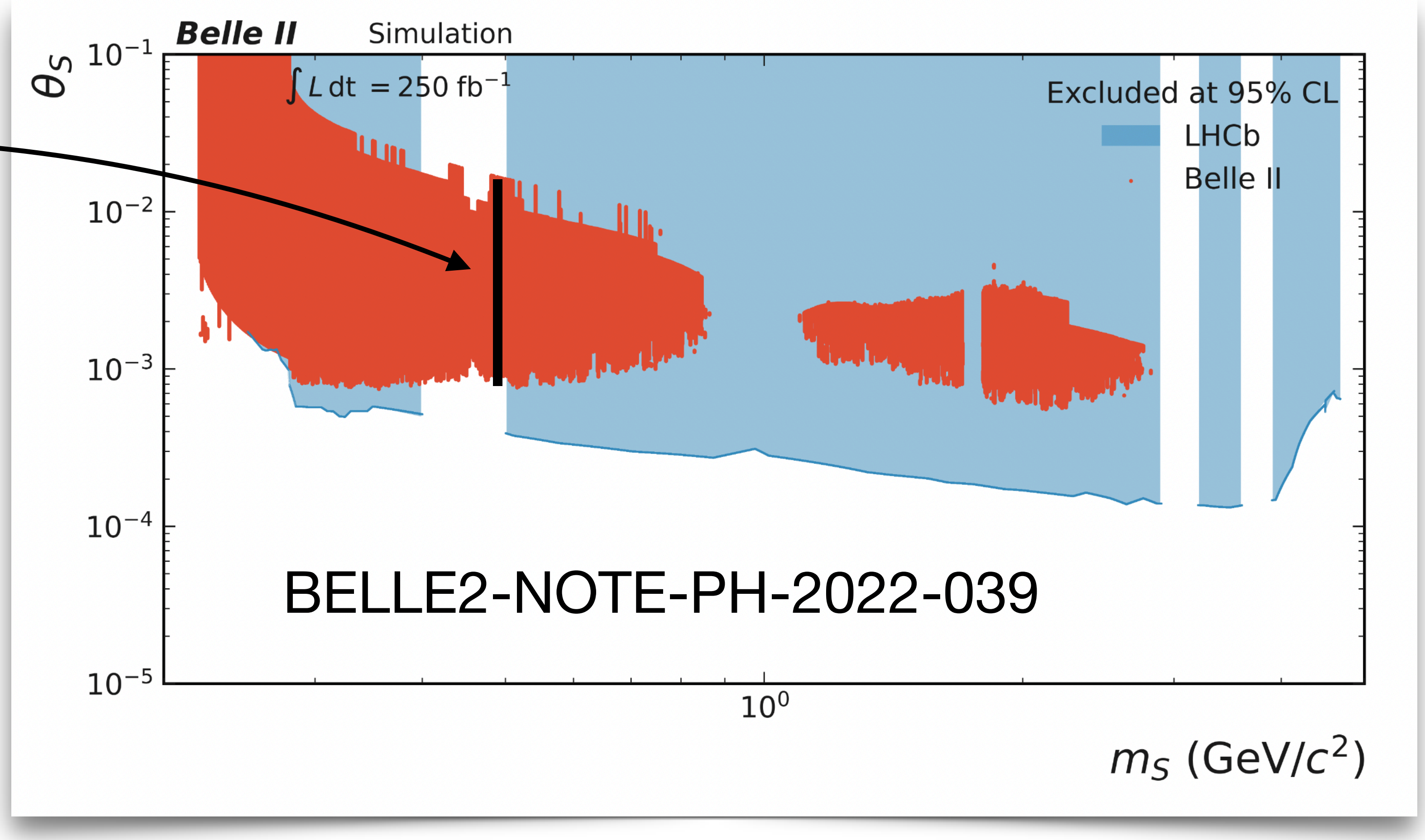
Signatures with long-lived particles

Example: $B \to KS, S \to \ell\ell/hh$



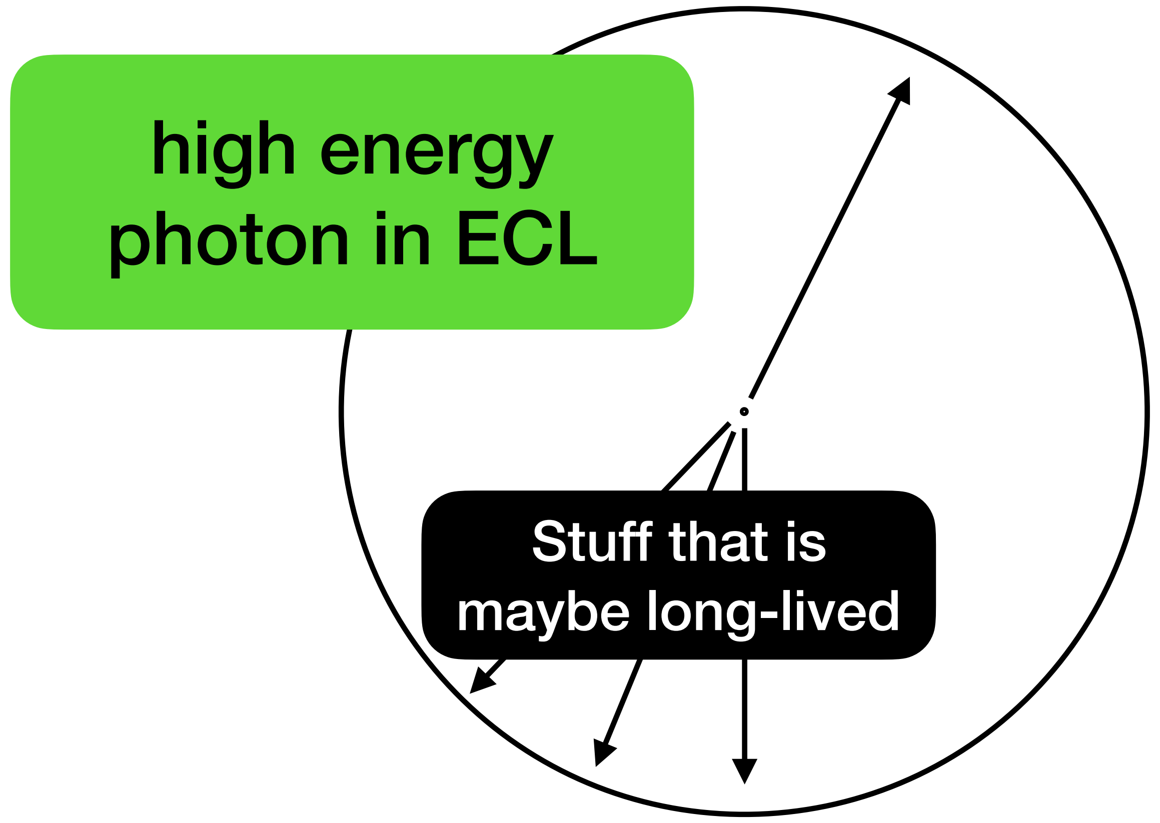
- General search strategy:
  - Resonant search for a fixed lifetime $c\tau$ → cross section limit $\sigma(m)$ for fixed lifetime
  - Scan for multiple different lifetimes → find model-dep. limit by interpolation

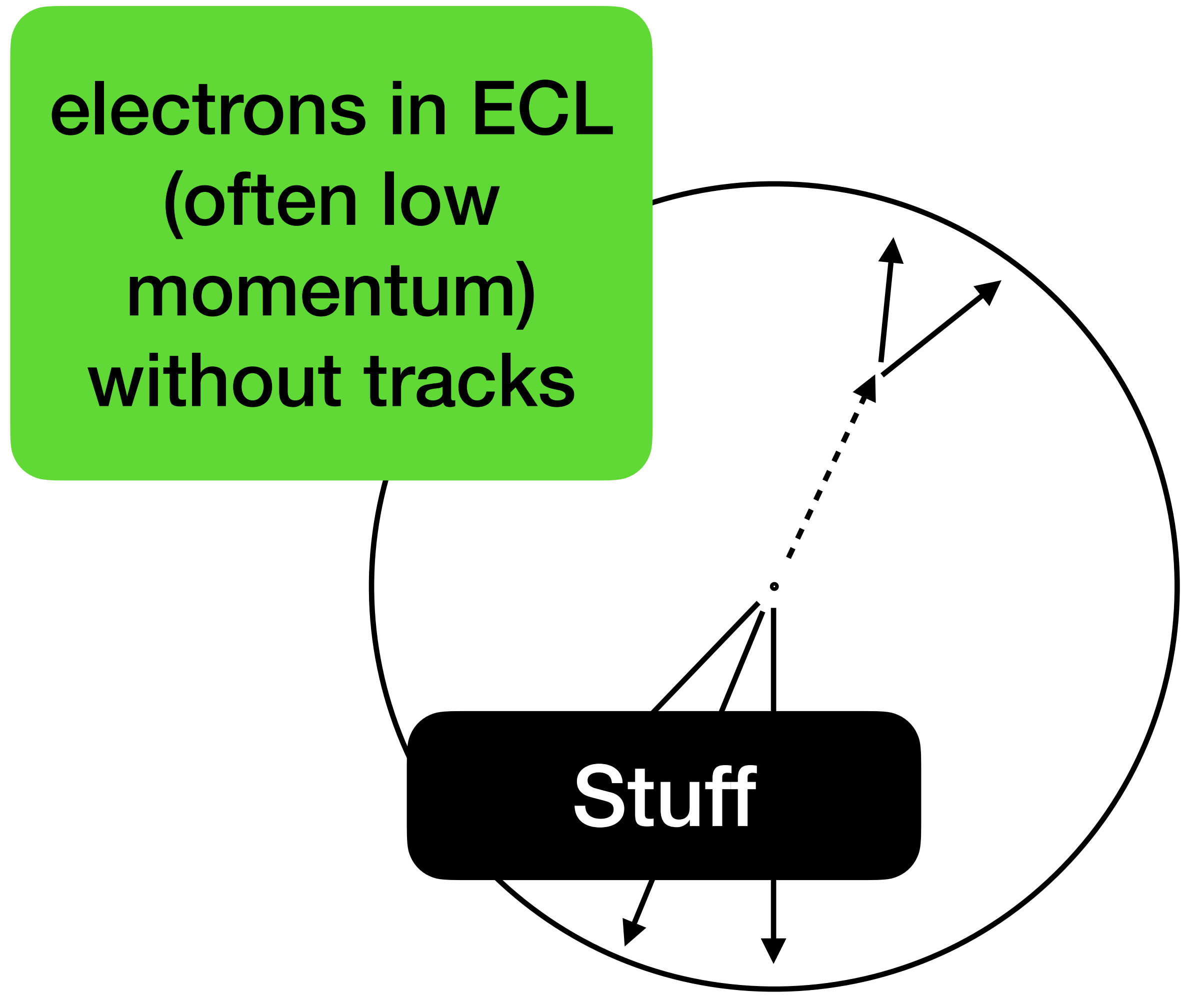


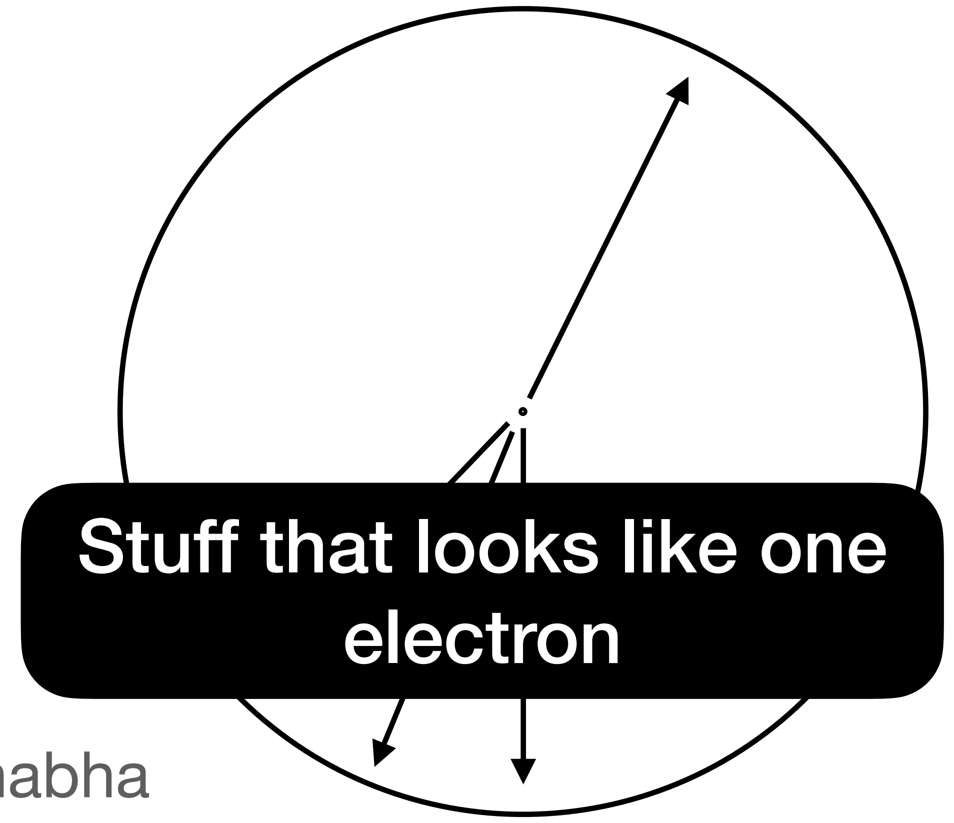


Triggers for long-lived particles

ECL based triggers

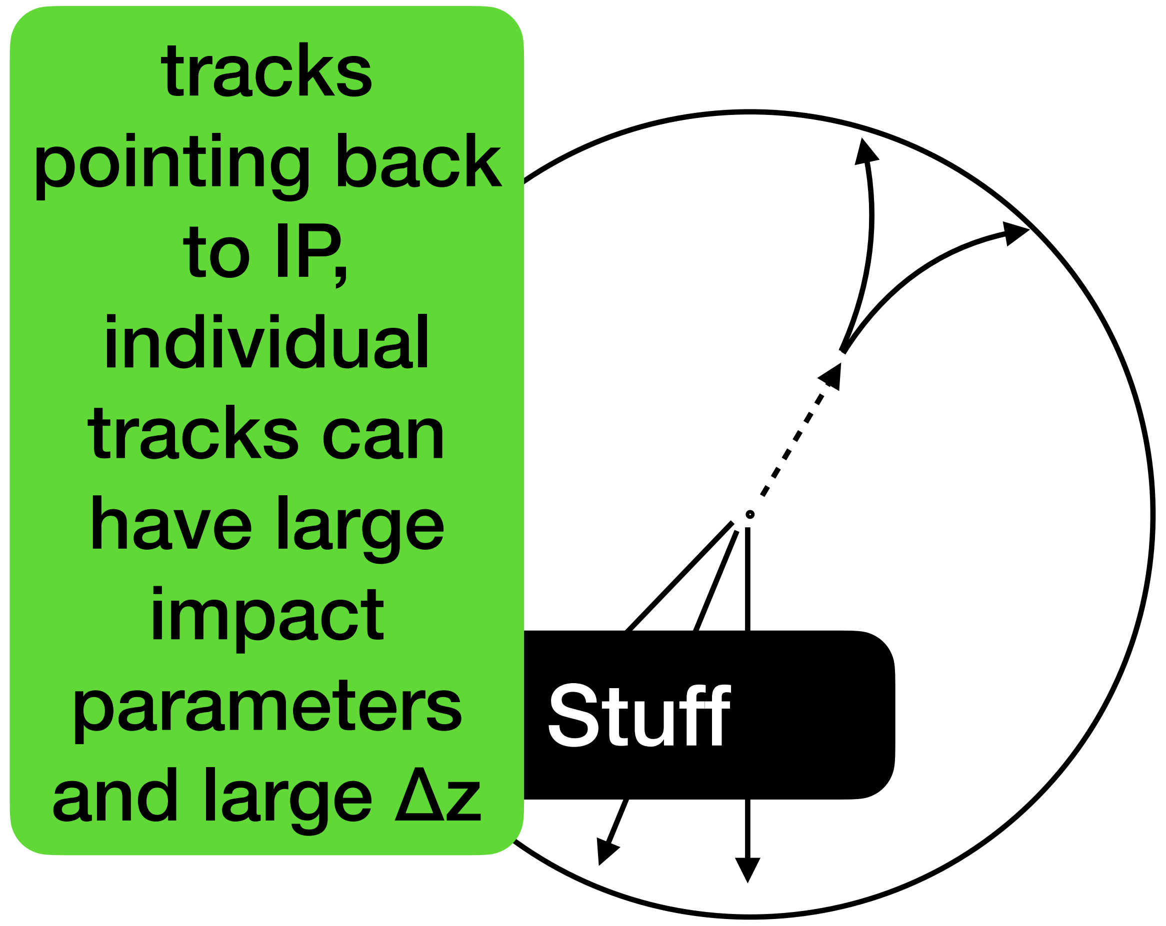


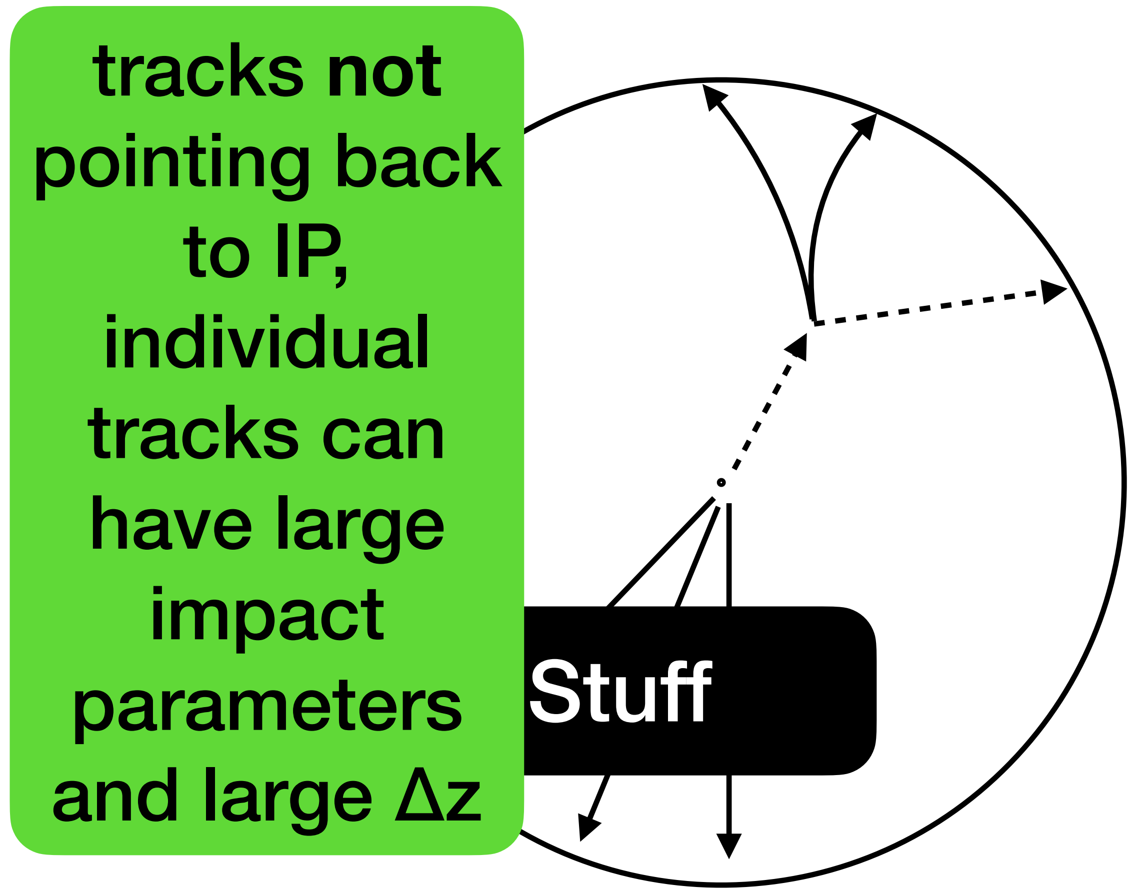


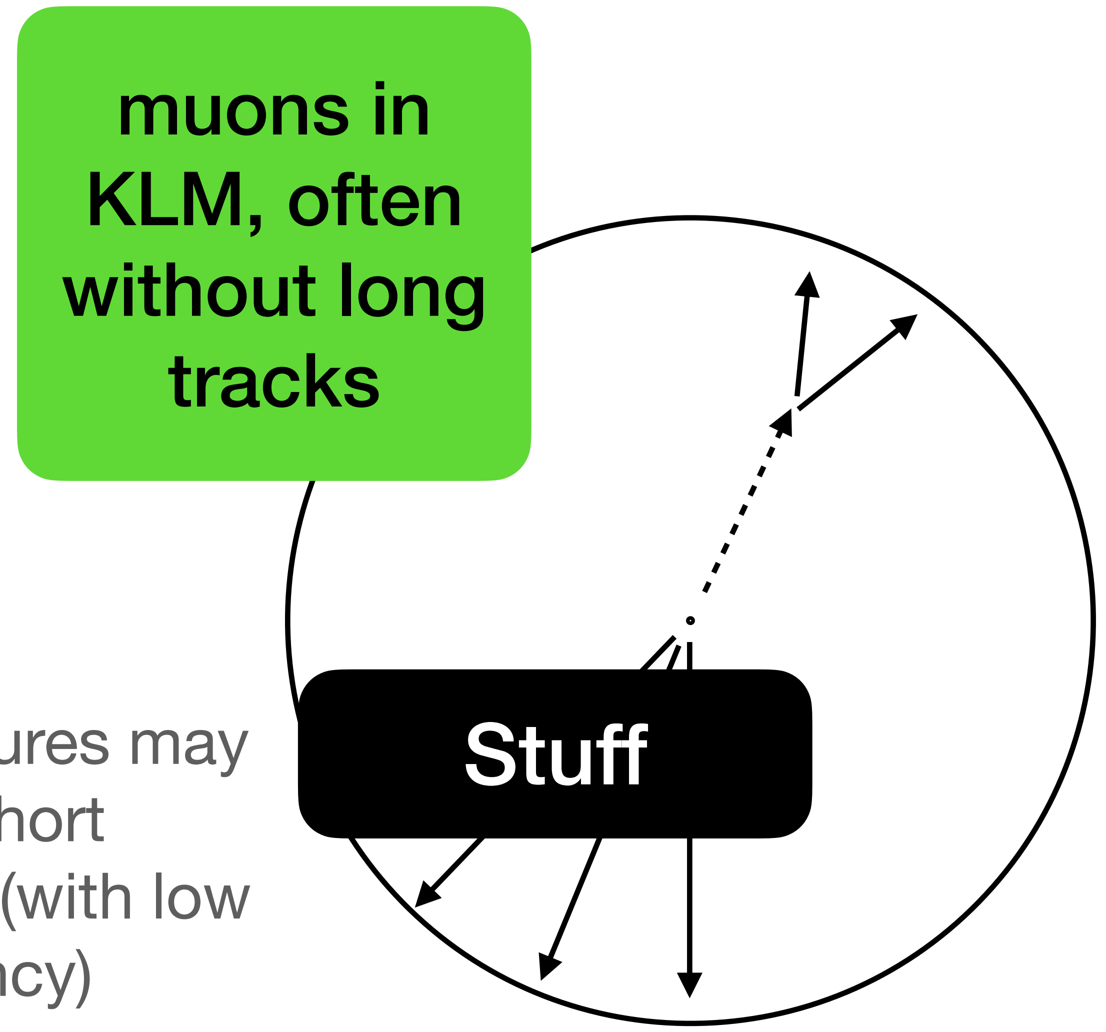


Are Bhabha vetoes specific enough to not veto those?

Track based triggers



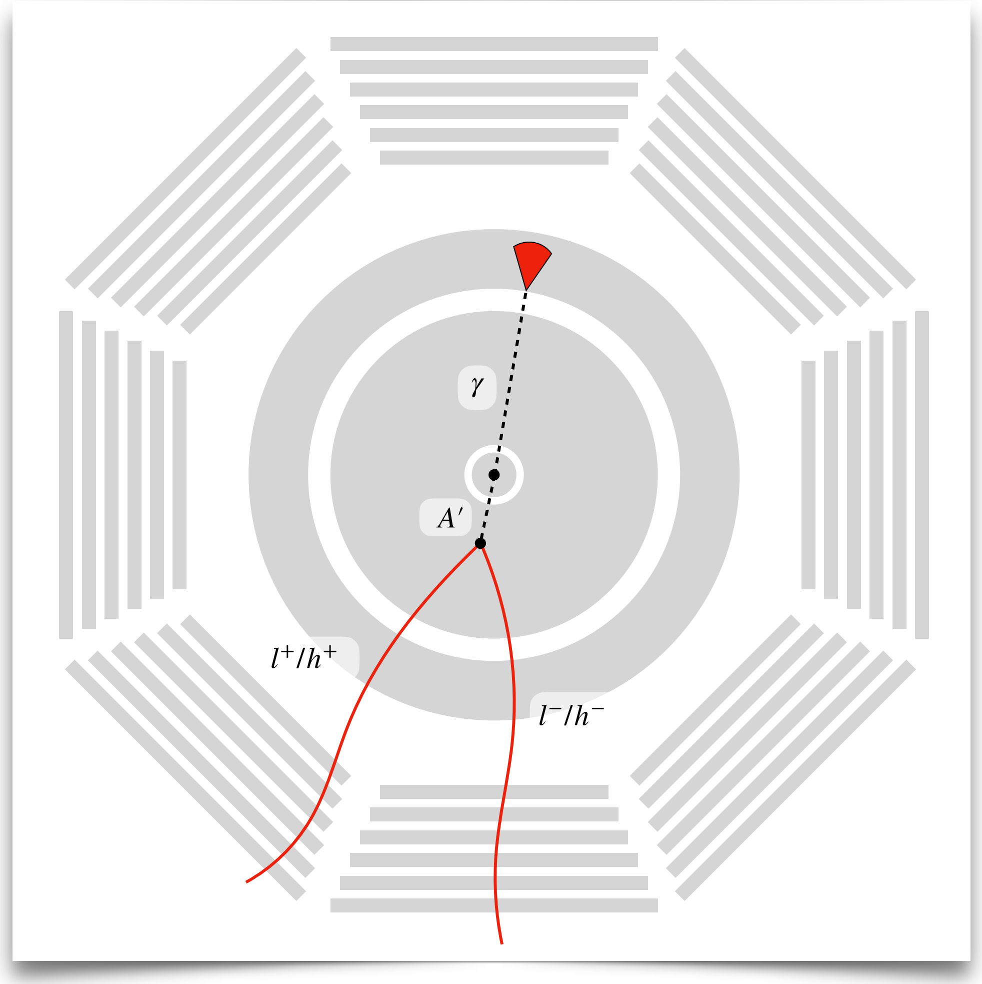


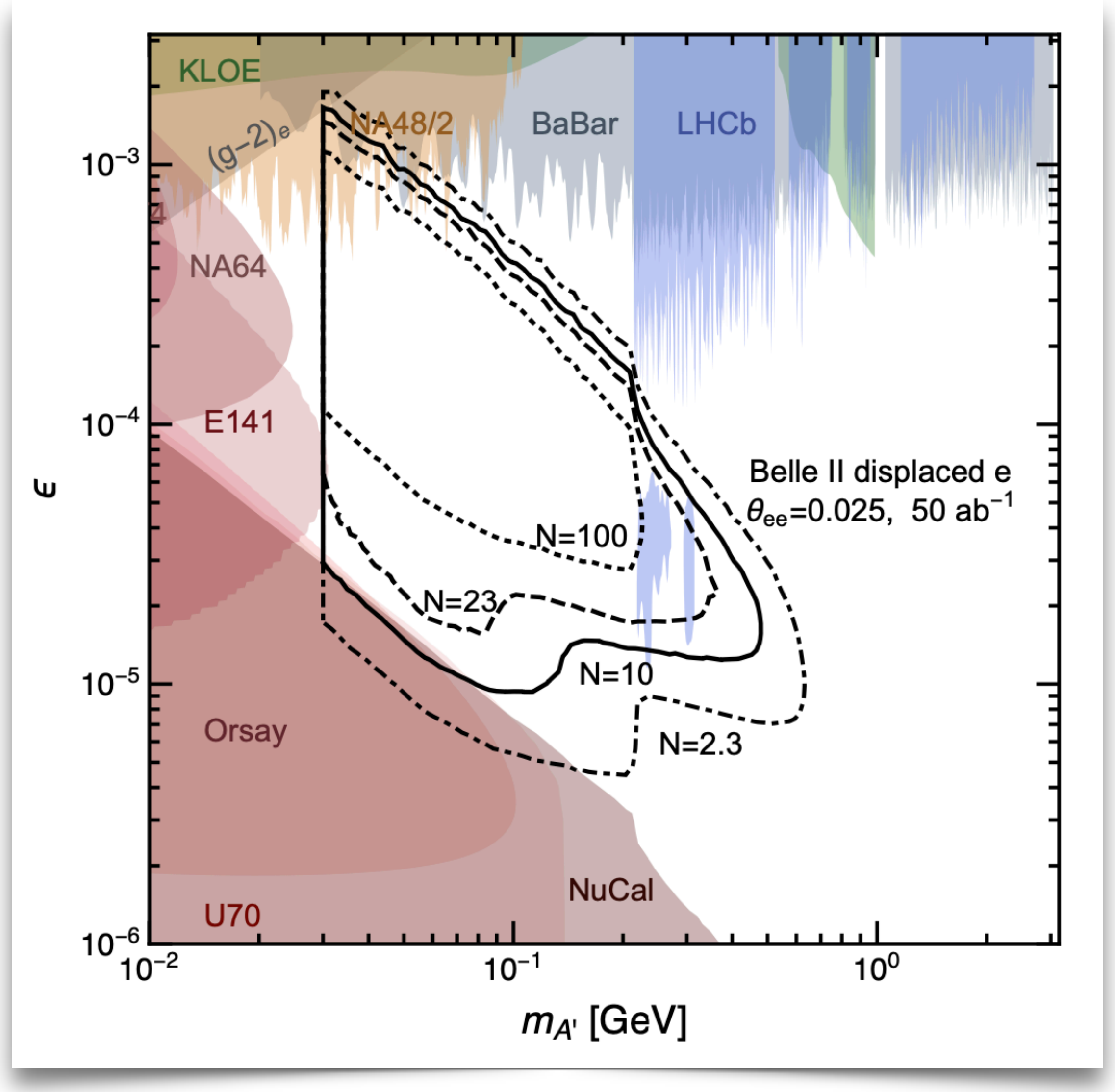


Signatures may have short tracks (with low efficiency)

These triggers keep displaced tracks “by chance”, not by design. But parameter space is huge (see next slides).

Long-lived Dark Photon A'





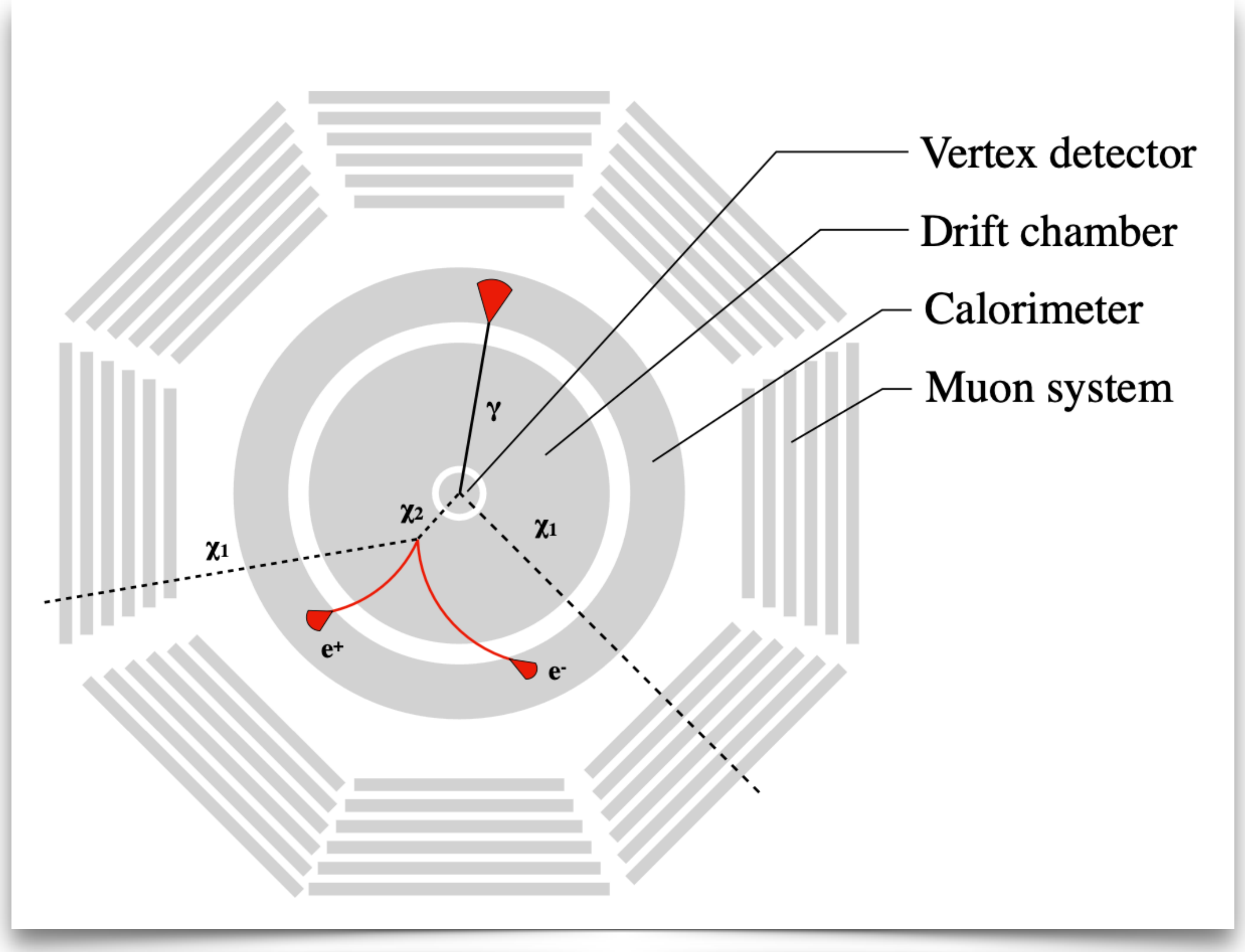
- Generic dark photon model BC1 predicts long lifetimes only for light, very weakly coupled dark photons
- Sensitivity dominated by $A' \to e^+e^-$
- **Trigger**:
  - L1 high energy photon. 'dpee' introduced in exp26 to keep $e(e)\gamma$ signatures.
  - HLT: high energy photon
- **Background**: Mis-reconstructed pair conversions (note that it is "easy" to reject correctly reconstructed pair conversions)

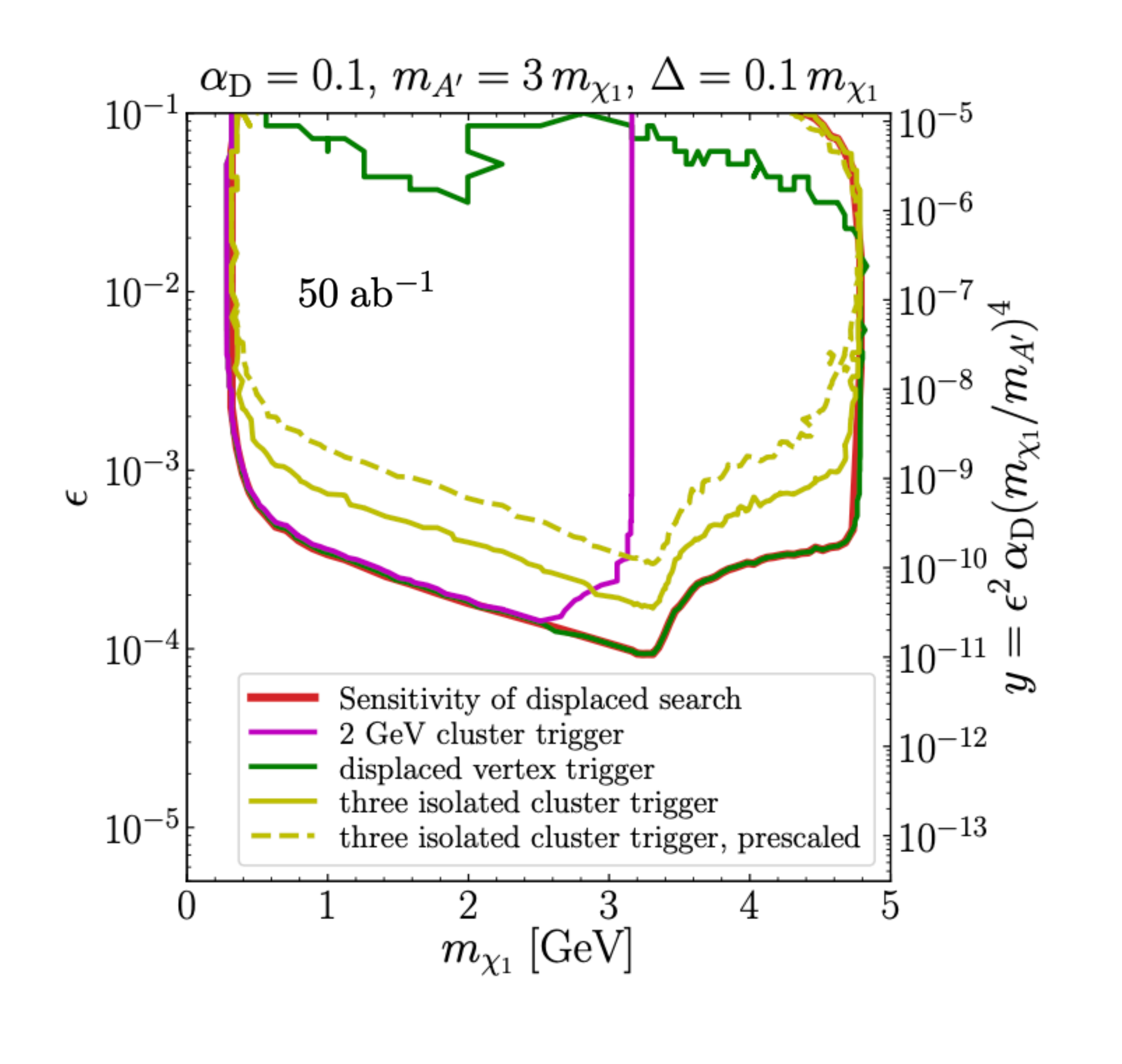
TF, C. Garcia-Cely, K. Schmidt-Hoberg, "Belle II sensitivity to long–lived dark photons", Phys.Lett.B 833 (2022) 137373, https://arxiv.org/abs/2202.03452

Inelastic Dark Matter (iDM)

*Recently an extended variant of this model (i2DM) is discussed where $\chi_1\chi_1, \chi_1\chi_2, \chi_2\chi_2$ final states are possible, see e.g. https://indico.cern.ch/event/1119695/contributions/5033899/attachments/2530332/4354339/talk_FIPs_SJ.pdf

- 5* free parameters
  $m_{A'}, m_{\chi_1}, \Delta m = m_{\chi_2} - m_{\chi_1}, \epsilon, \alpha_D$
- χ_1 is a dark matter candidate
- χ_2 is an unstable dark sector particle decaying into $\chi_2 \to \chi_1 \to \chi_1 e^+ e^-$
- **Trigger**:
  - L1: high energy photon, but removing endcap hie or lml2 will reduce efficiency. Needs displaced vertex trigger for high masses and small couplings (for very large datasets)
  - HLT: high energy photon
- **Background**: Rare hadronic interactions in τ events (based on full MC study, pheno paper assumes zero bkgd)





M. Duerr, TF, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, "Invisible and displaced dark matter signatures at Belle II", JHEP 02 (2020) 039, https://arxiv.org/abs/1911.03176

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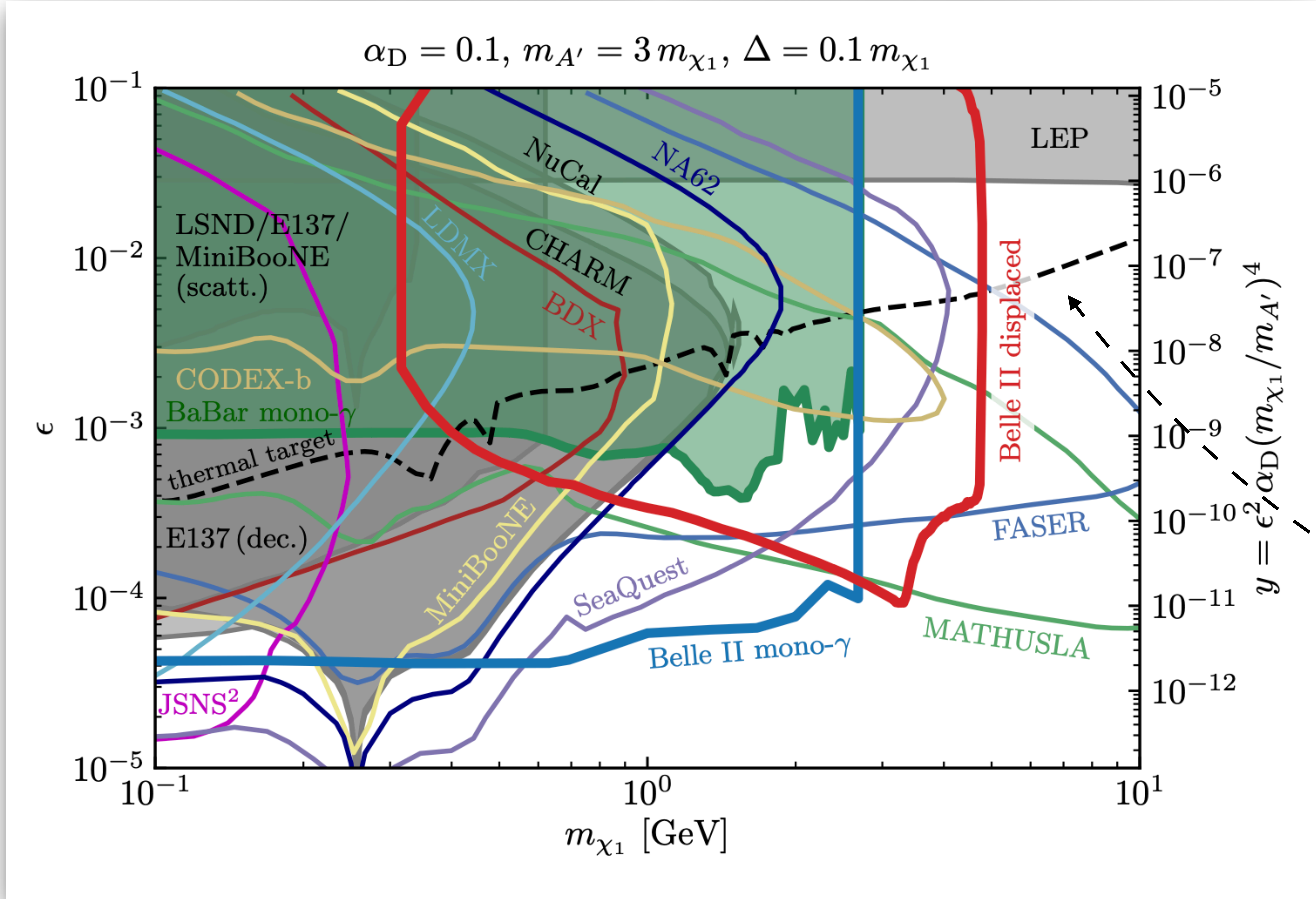
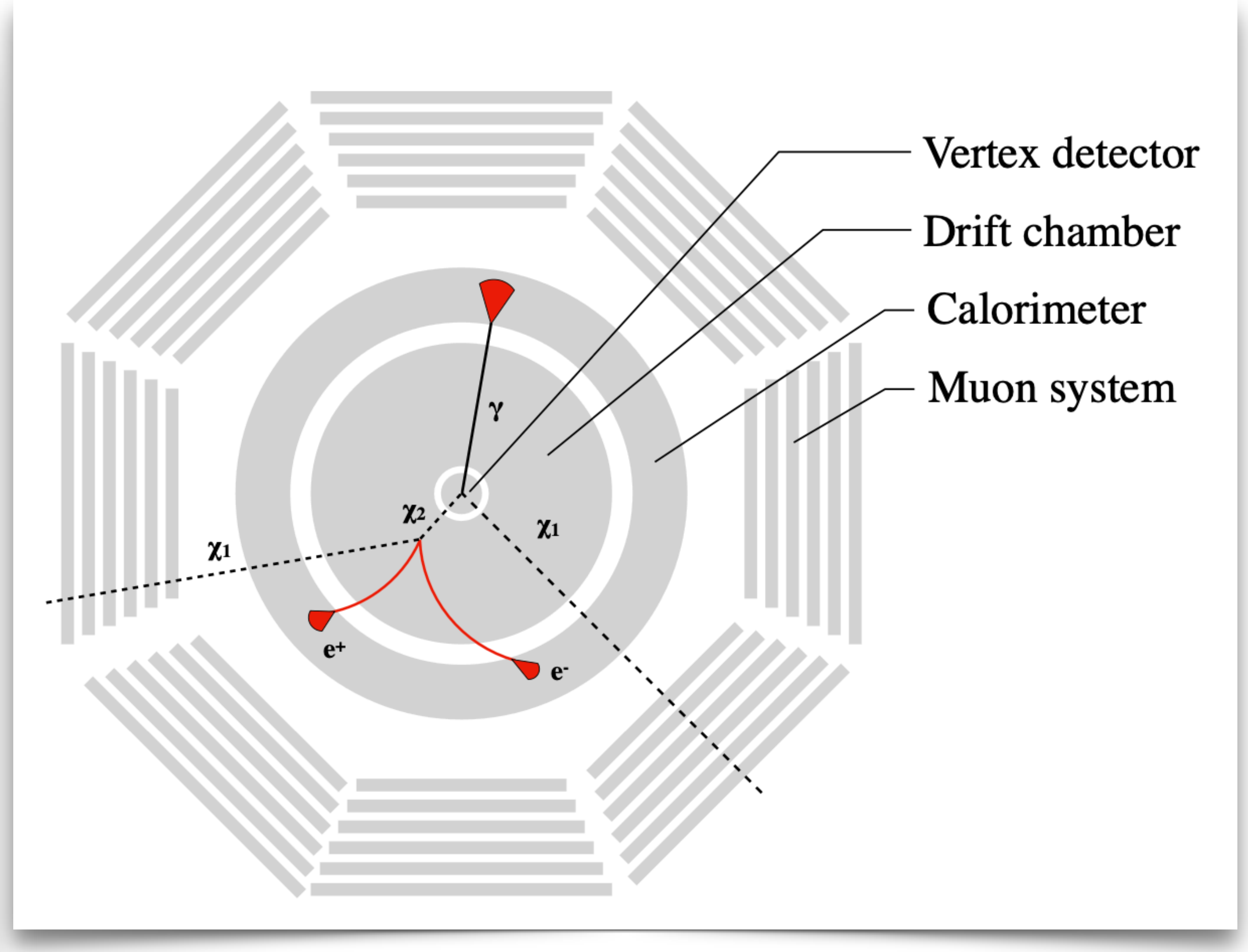


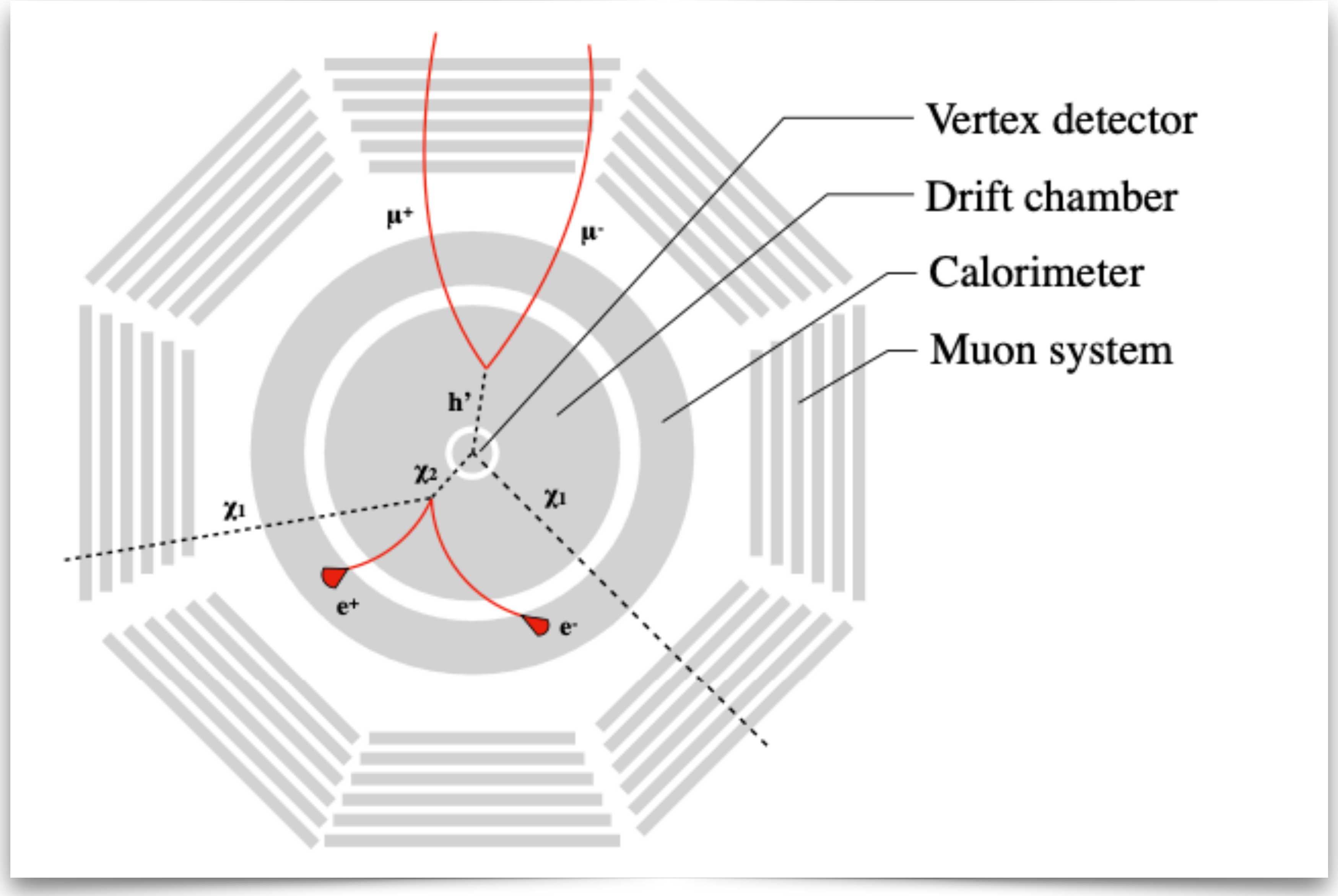


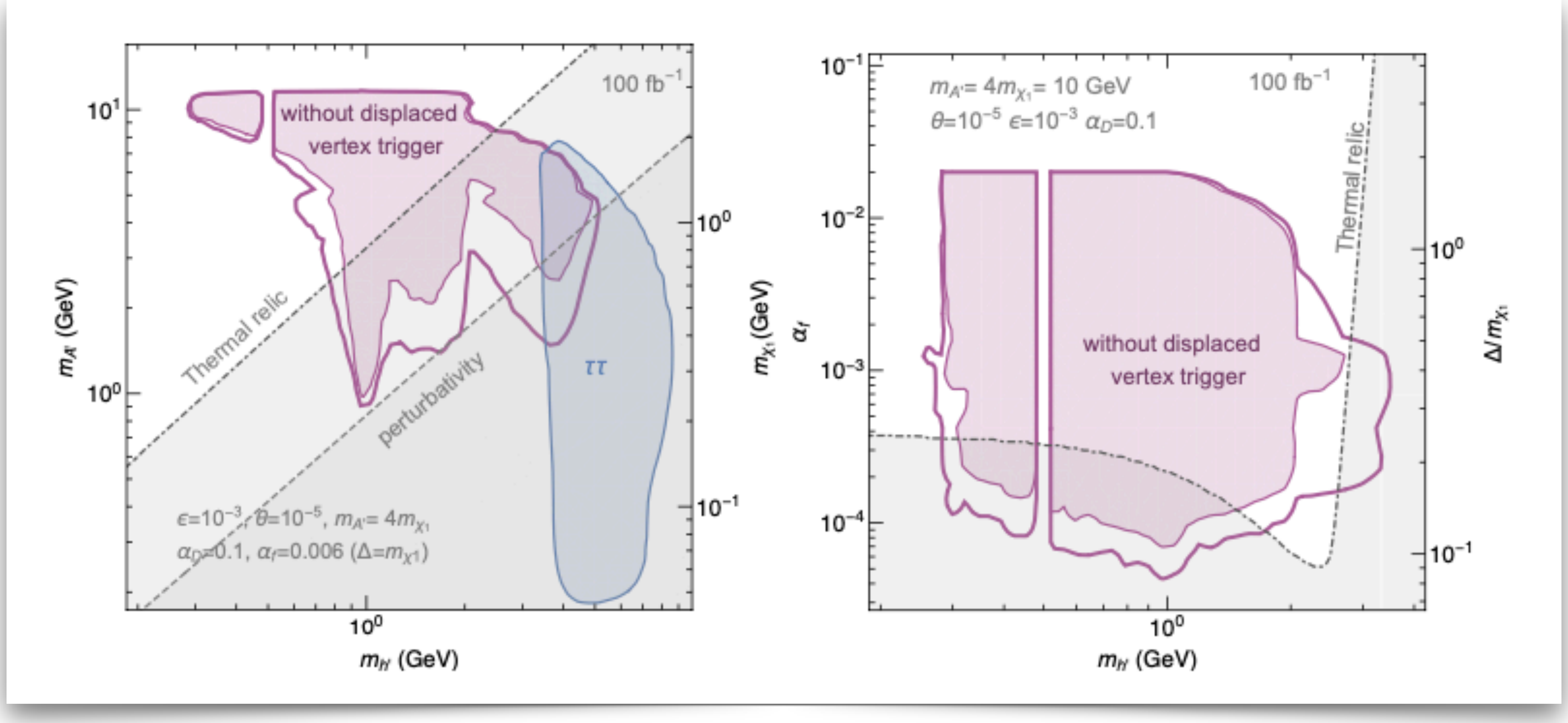
Thermal (relic) target (Freeze-out DM)

M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, "Invisible and displaced dark matter signatures at Belle II", JHEP 02 (2020) 039, https://arxiv.org/abs/1911.03176

Inelastic Dark Matter with a Dark Higgs (iDMDH)

- 7 free parameters
  $m_{h'}, m_{A'}, m_{\chi_1}, \Delta m = m_{\chi_2} - m_{\chi_1}, \epsilon, \alpha_D, \theta$
- χ_1 is a dark matter candidate
- **Trigger**:
  - L1L: Complex: Calorimeter for large Δm, STT for short livestimes. Needs displaced vertex trigger for large lifetimes and small mass splittings (see next slide)
  - HLT: under study, potential issue from non-IP tracks.
- **Background**: Very small, dominated by random track combinations (pheno paper assumes zero bkgd)





M. Duerr, TF, C. Garcia-Cely, C. Hearty, K. Schmidt-Hoberg, "Long-lived Dark Higgs and Inelastic Dark Matter at Belle II", JHEP 04 (2021) 146, https://arxiv.org/abs/2012.08595

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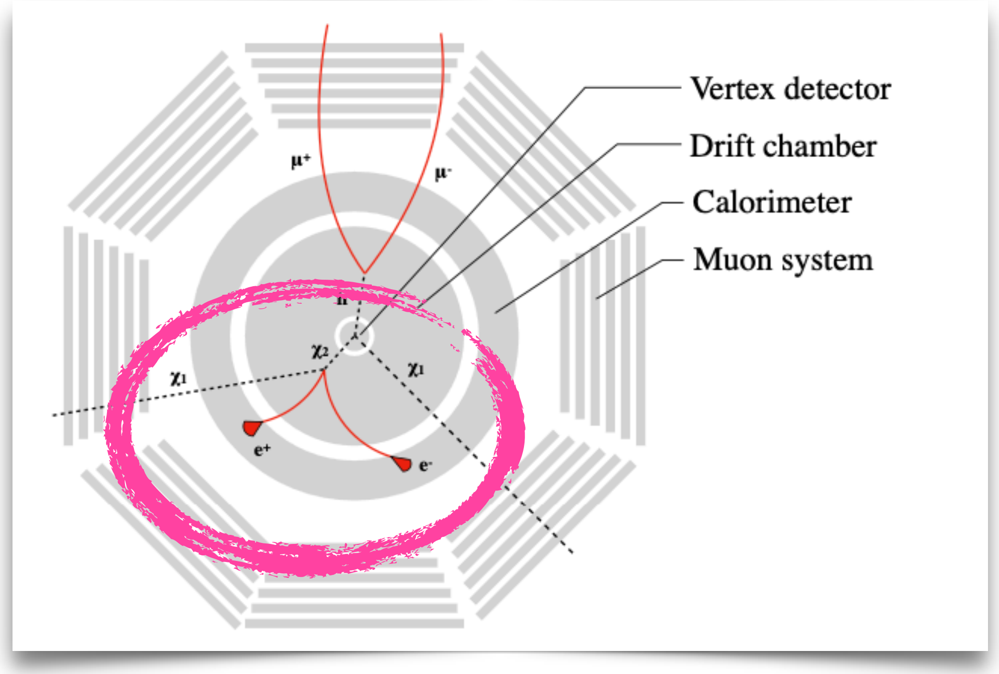
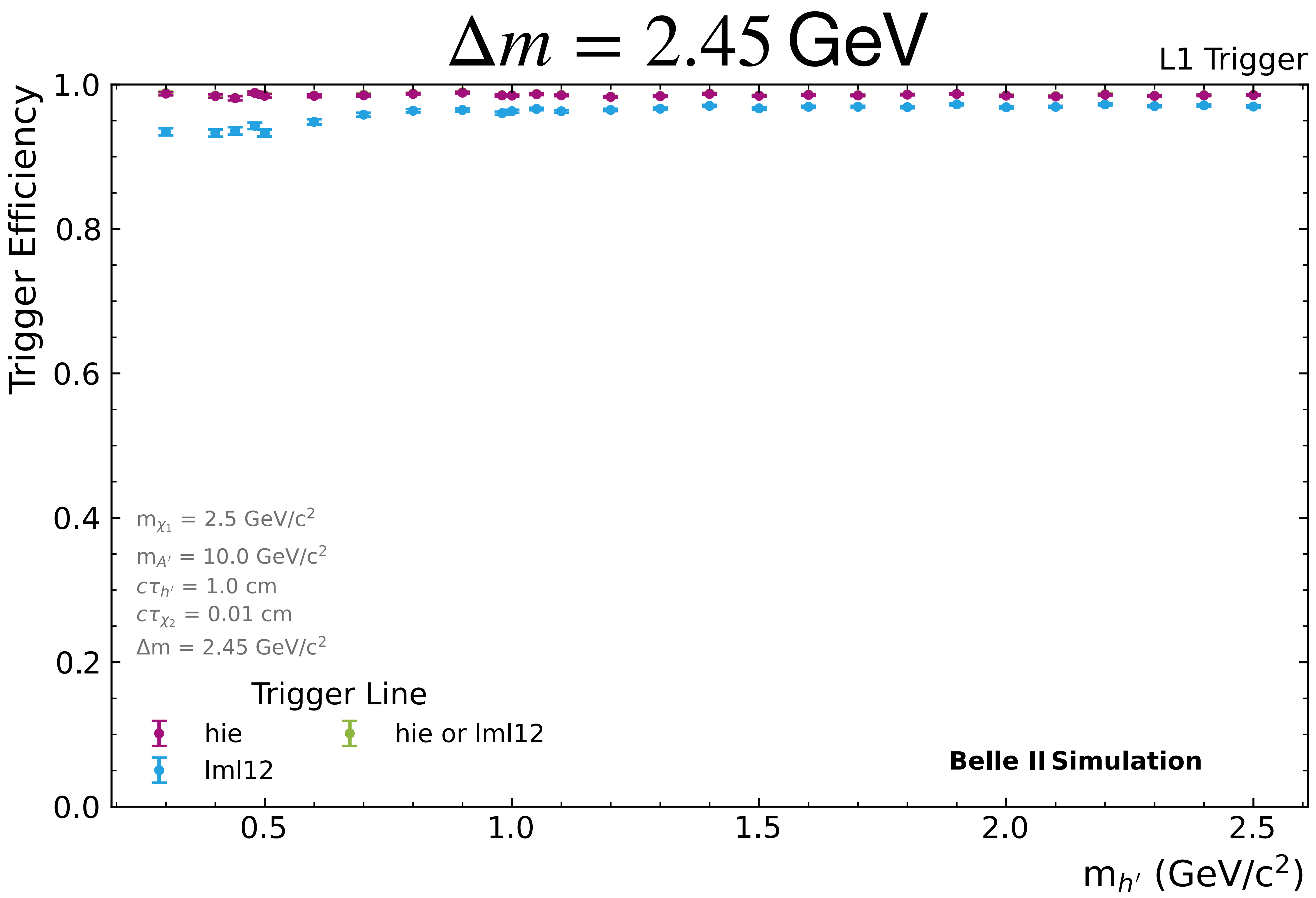
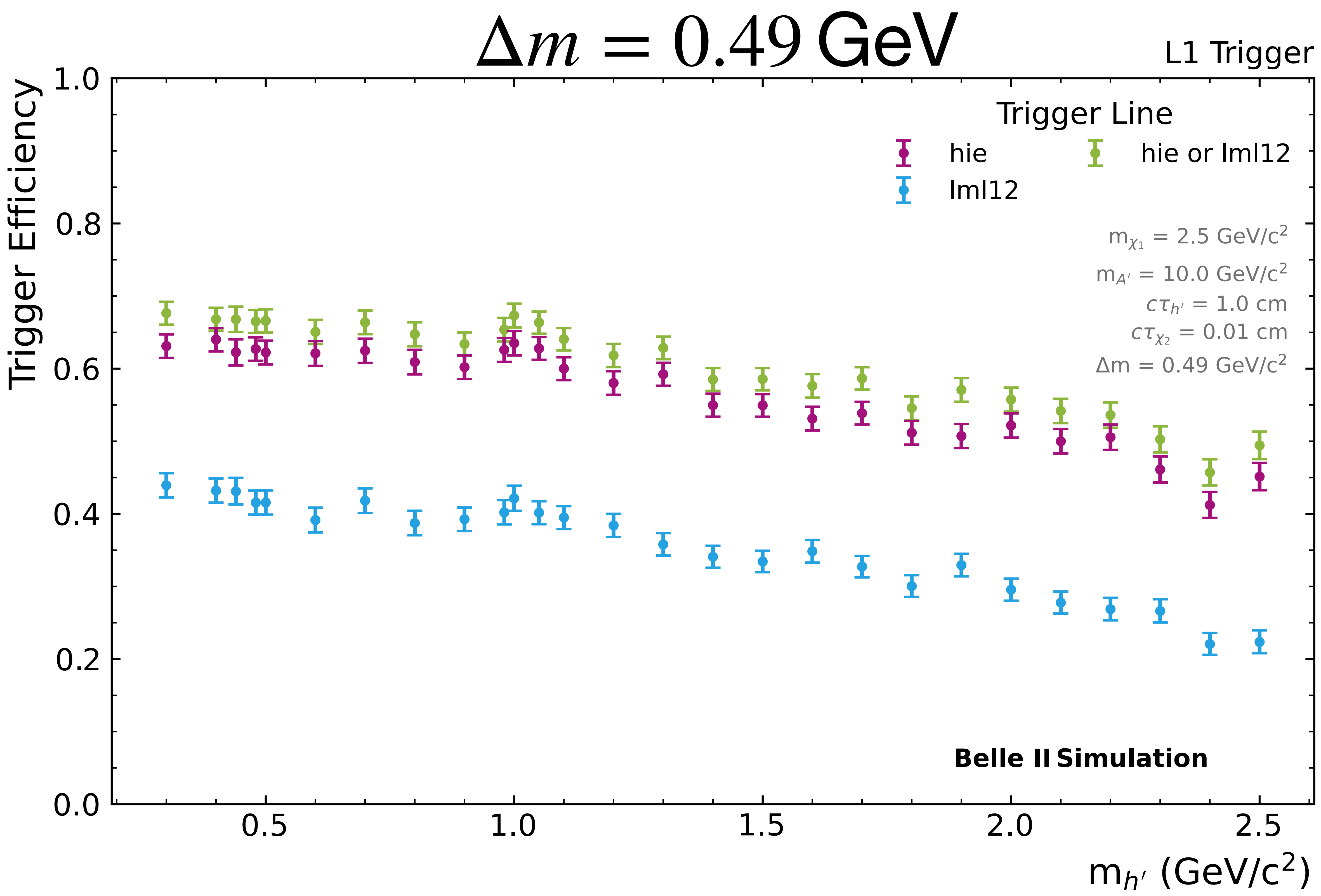


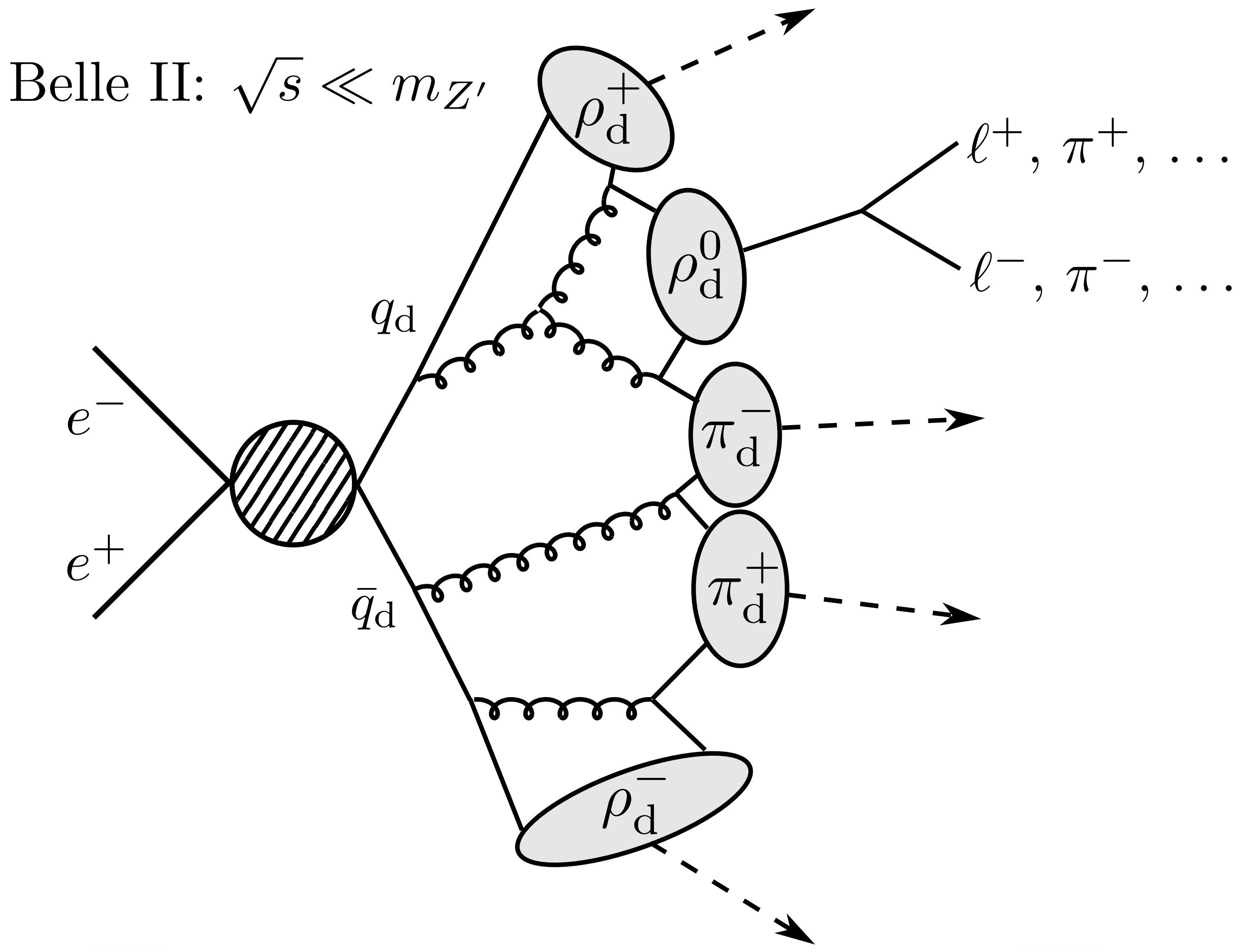
- e^+e^- decay products from χ_2 decay have low energies for small values $\Delta m = m_{\chi_2} - m_{\chi_1}$
  → L1 calorimeter trigger looses efficiency

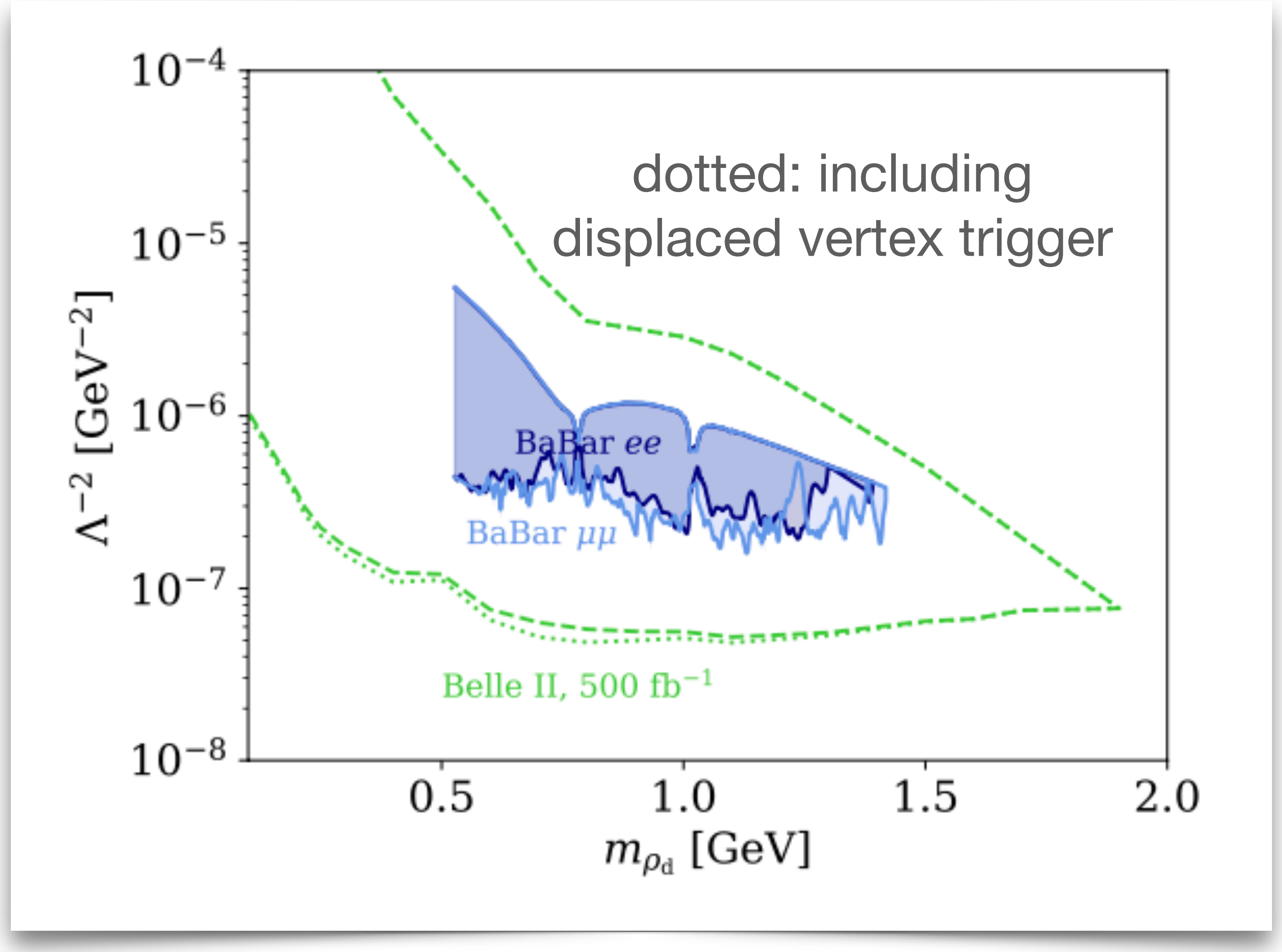




Dark Showers

- Only two effective parameters $m_{\rho D}$, Λ^{-2} (or lifetime)
- **Trigger:**
  - L1: Complex: Calorimeter for electrons, STT and two track triggers for muons and hadrons. Benefits slightly from displaced vertex L1 trigger for small couplings.
  - HLT: issue from non-IP tracks (see next slide)
- **Background**: random combinations and material interactions in ττ events (pheno paper assumes zero bkgd)





E. Bernreuther, K. Böse, **TF**, C. Hearty, F. Kahlhoefer, A. Morandini, K. Schmidt-Hoberg, "Forecasting dark showers at Belle II", submitted to JHEP (2022), https://arxiv.org/abs/2203.08824

Dark Showers

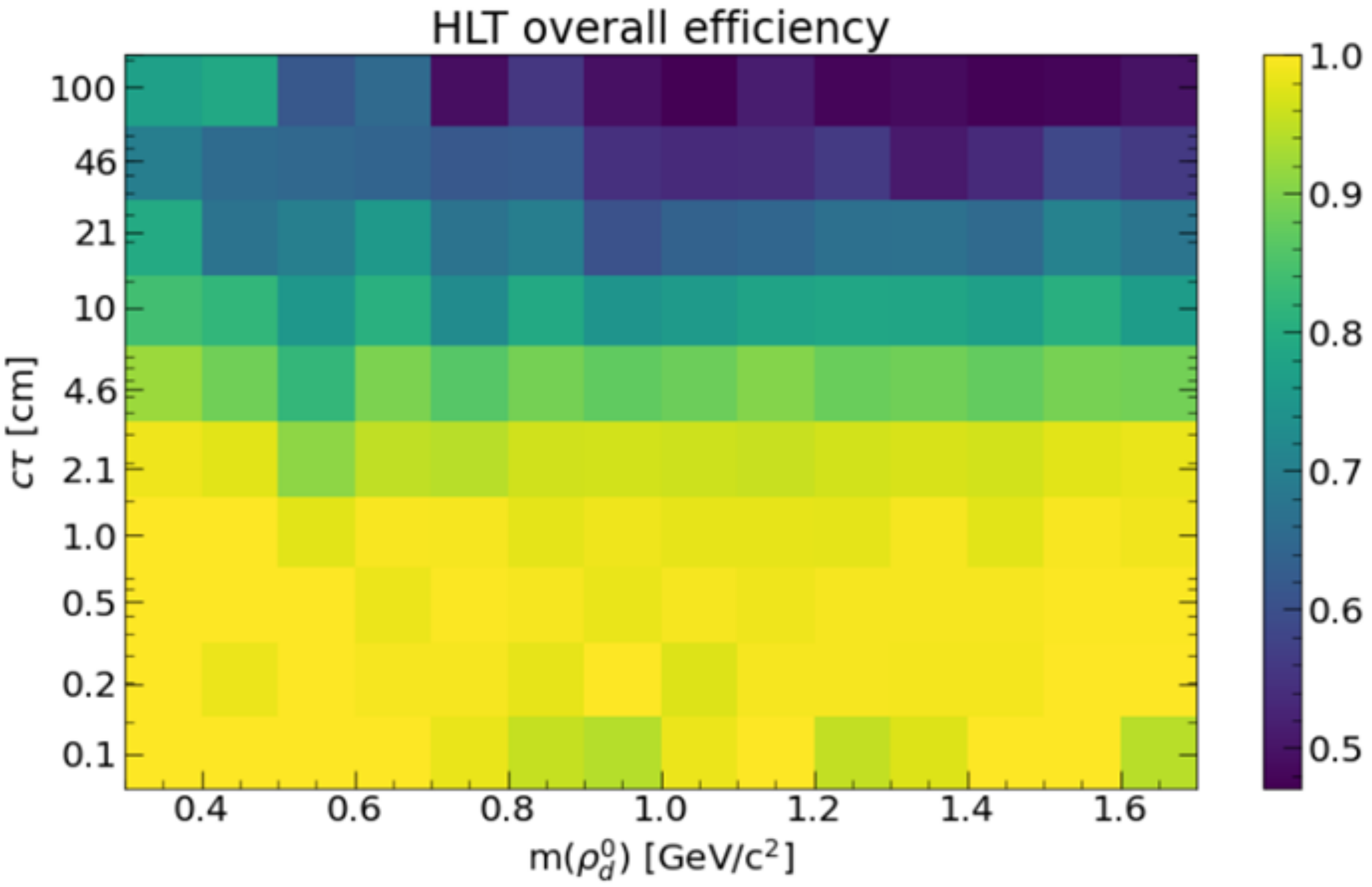


Figure 4.14: HLT efficiency after L1 Triggers have been applied.

T. Tueschen, MSc thesis, UBC 2022

Summary

- For completeness:
  - LLP signatures in B decays are kept by L1 and HLT
  - ALP (3γ) is very boosted and looks like γγ on trigger level ("hie OR ggsel" is efficient)
- Parameter space for some searches is huge and event selection optimization is subtle → quick checks if trigger modifications are problematic are a serious effort for LLP searches!
- HLT needs modification for low multiplicity final state with tracks not coming from the IP
- **Displaced vertex trigger is needed** for:
  - (Very) long lived region of parameter space in non-electron or low momentum electron final states
  - redundancy: STT and hie provide generally rather high efficiencies, but we are using them for signatures that they were not designed to trigger

Backup

Literature: Experiment

Invisible

BaBar collaboration, "Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BaBar", *Phys. Rev. Lett. 119, 131804 (2017)*, https://arxiv.org/abs/1702.03327

B-decays

BaBar collaboration, "Search for $B \to K^{(*)}\nu\bar{\nu}$ and invisible quarkonium decays", *Phys. Rev. D 87, 112005 (2013)*, https://arxiv.org/abs/1303.7465

BaBar collaboration, "Search for an Axion-Like Particle in B Meson Decays", *Phys.Rev.Lett.* 128 (2022) 13, 131802, https://arxiv.org/abs/2111.01800

Low multiplicity

BaBar collaboration, "Search for a Dark Leptophilic Scalar at BaBar", *Phys. Rev. Lett. 125, 181801 (2020),* https://arxiv.org/abs/2005.01885

BaBar collaboration, "Search for Long-Lived Particles in e^+e^- Collisions", *Phys.Rev.Lett.* 114 (2015) 17, 171801, https://arxiv.org/abs/1502.02580

Literature: Phenomenology

Invisible

M. J. Dolan, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, “Revised constraints and Belle II sensitivity for visible and invisible axion-like particles”, JHEP 12 (2017) 094, JHEP 03 (2021) 190 (erratum), https://arxiv.org/abs/1709.00009

B-decays

A. Filimonova, R. Schäfer, S. Westhoff, “Probing dark sectors with long-lived particles at Belle II”, *Phys.Rev.D* 101 (2020) 9, 095006, https://arxiv.org/abs/1911.03490

E. Bertholet, S. Chakraborty, V. Loladze, T. Okui, A. Soffer, K. Tobioka, “Heavy QCD axion at Belle II: Displaced and prompt signals”, *Phys.Rev.D 105 (2022) 7, L071701*, https://arxiv.org/abs/2108.10331

TF, A. Filimonova, R. Schäfer, S. Westhoff, “Displaced or invisible? ALPs from B decays at Belle II”, submitted to JHEP (2022), https://arxiv.org/abs/2201.06580

Low multiplicity

E. Bernreuther, K. Böse, **TF**, C. Hearty, F. Kahlhoefer, A. Morandini, K. Schmidt-Hoberg, “Forecasting dark showers at Belle II”, submitted to JHEP (2022), https://arxiv.org/abs/2203.08824

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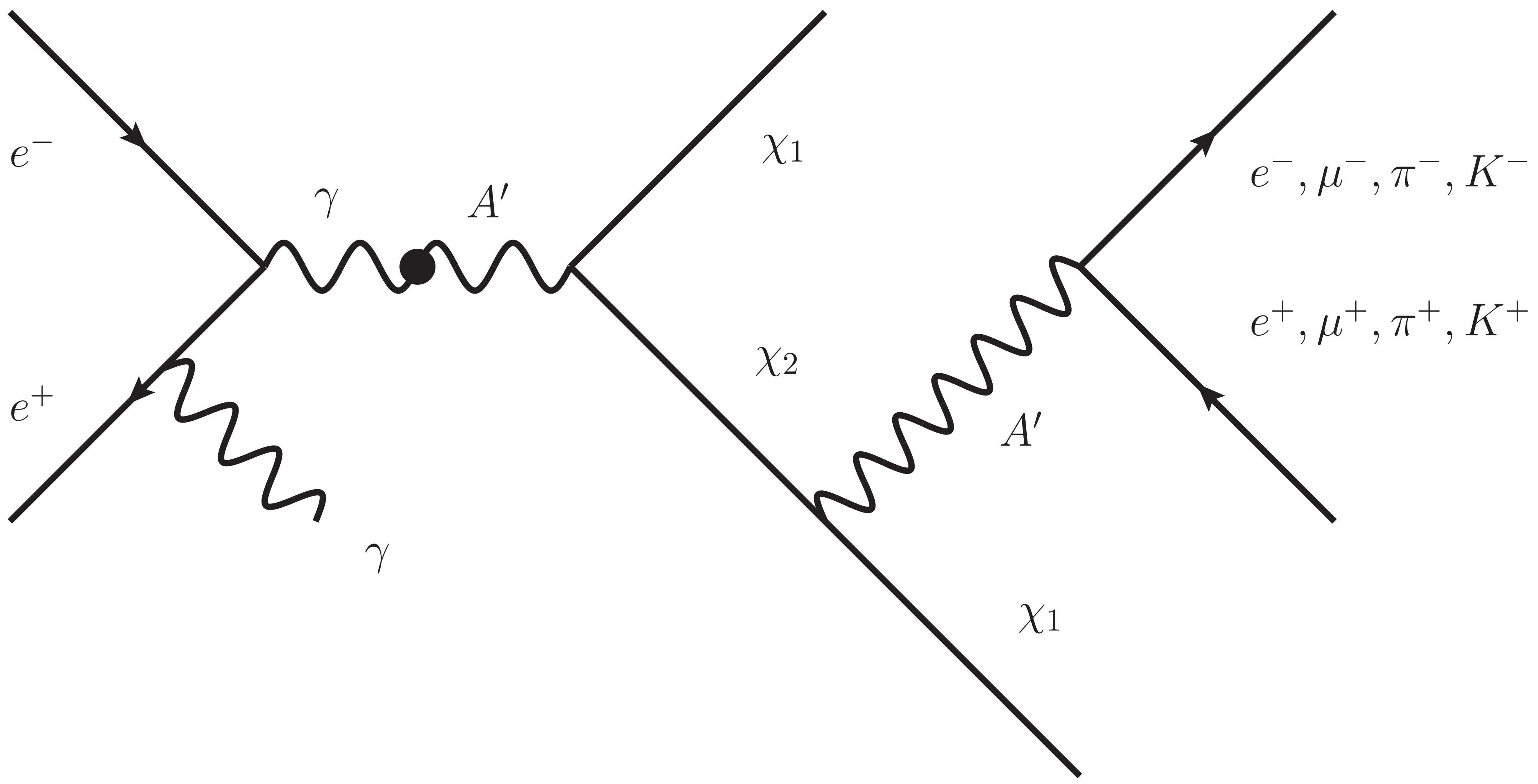
M. Duerr, **TF**, C. Garcia-Cely, C. Hearty, K. Schmidt-Hoberg, “Long-lived Dark Higgs and Inelastic Dark Matter at Belle II”, JHEP 04 (2021) 146, https://arxiv.org/abs/2012.08595

New experiment

S. Dreyer, **TF**, A. Filimonova, C. Garcia-Cely, C. Hearty, S. Longo, R. Schäfer, K. Schmidt-Hoberg, M. Tammaro, K. Trabelsi, S. Westhoff, J. Zupan, “Physics reach of a long-lived particle detector at Belle II”, contribution to Snowmass 2021, https://arxiv.org/abs/2105.12962

Feynman diagrams

iDM



iDM+DH