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Benchmarking FIMP signatures at future Higgs factories

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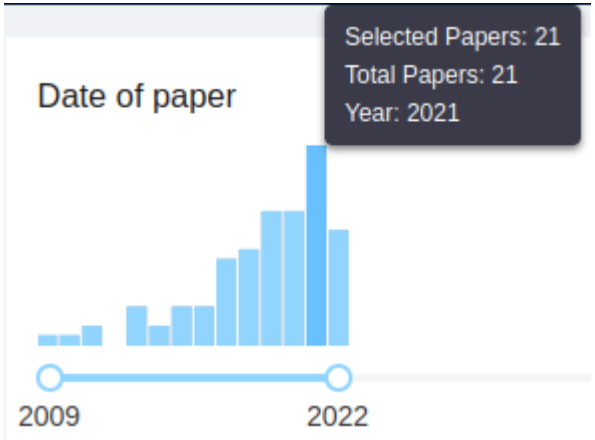
Feebly Interacting Massive Particles

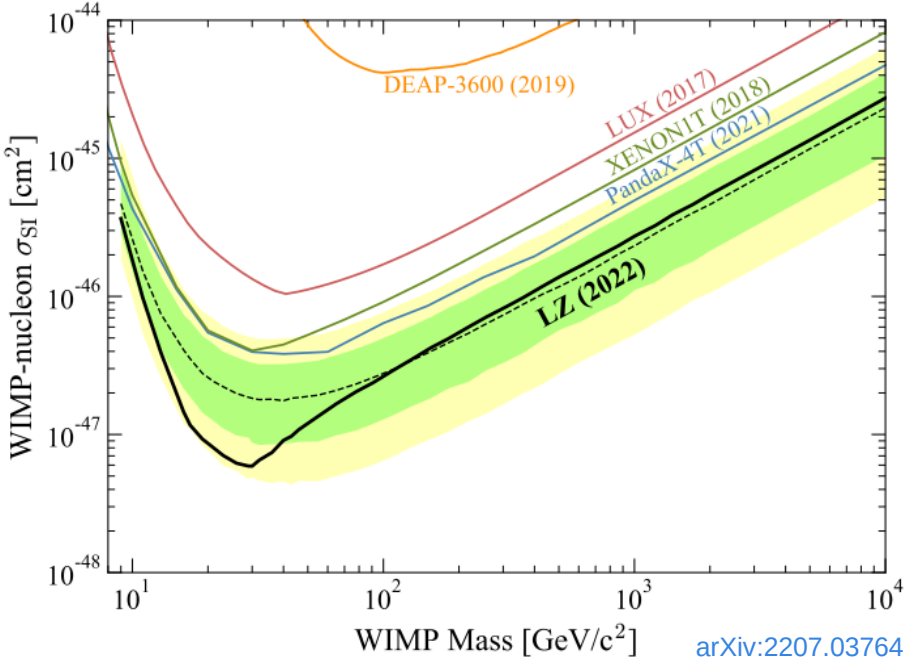
- Increasingly tightening constraints on WIMPs

  → Even smaller couplings start being considered

- Feeble couplings lead to **freeze-in** mechanism for dark matter, in contrast to freeze-out (WIMPs, neutrons)

- The concept of FIMPs is getting attention in recent years



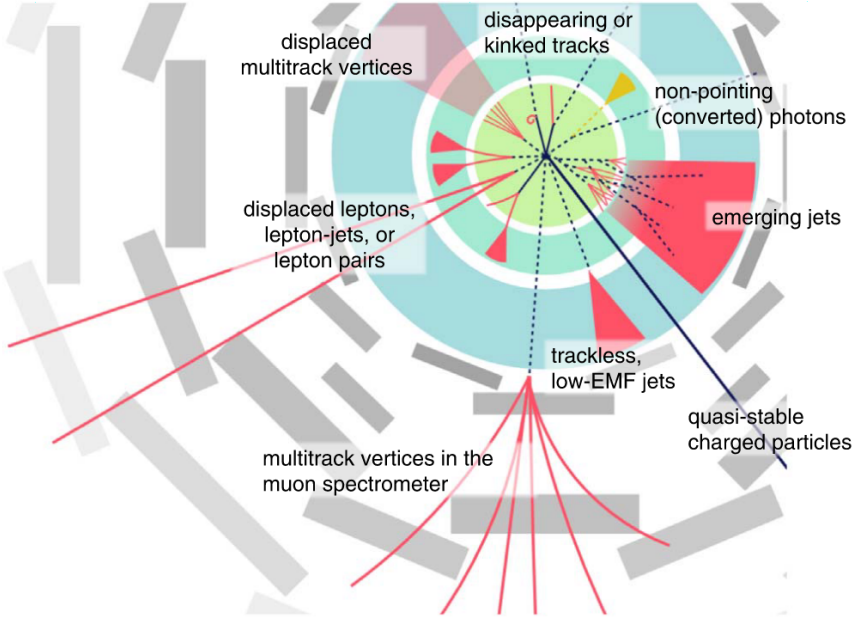


arXiv:2207.03764

Signatures and the reconstruction

- Due to the small couplings, **FIMPs** often appear alongside **long-lived particles**
- Can also be long-lived themselves!
- Variety of possible signatures at colliders

  → most of them can be described as tracks not pointing / not originating from the IP
- This talk: <u>focus on neutral long-lived states</u>



At the LHC: search for a given signature
At e^+e^- HF: **we can reconstruct full events** ← production/decay channels crucial!

Motivation and the strategy

- Variety of models offering **FIMP** (or **LLP**) candidates
- Such states seem perfect to **compare** different detector / collider options
- Difficult, if each experiment studies prospects for their favourite model
- **Main goal**: selection of the **"experimental" benchmark scenarios**

  → in a space of **physical properties of particles**, not a model parameter space

  → different signatures, **production** and **decay** channels have to be considered

- → "experimental" scenarios can be **translated** to benchmarks in the space of a given model

Signature examples in models with FIMPs

SUSY + axino DM (arXiv:1506.07532)

- Long-lived higgsino $\tilde{h}^0$ and frozen-in LSP axino $\tilde{a}$
- A higgsino pair-production with $\tilde{h}^0 \to Z\tilde{a}, h\tilde{a}$ gives a signature of two displaced vertices + $\not{E}$

Singlet-Doublet DM (arXiv:1805.04423)

- Additional fermions: long-lived $\chi_{2,3}$ and stable χ_1 DM FIMP (Z_2 symmetry)
- Pair production of $\chi_{2,3}$ and decays $\chi_{2,3} \to \chi_1 h, \chi_1 Z$ lead to a signature of two displaced vertices + $\not{E}$

Higgs portal (arXiv:1908.05685)

- Long-lived dark Higgs S that decays into DM or SM by mixing with SM Higgs
- With $h \to SS$ and $S \to \mathrm{SM\,SM}, \mathrm{DM\,DM}$ possible signatures of 2 (or 1) displaced vertices + Z boson (or Z + $\not{E}$)

Signature examples in models at this Workshop

Stau search – Teresa's talk

- For the stau-LSP mass difference < m_τ, stau becomes long-lived
- Displaced/kinked tracks + $\not{E}$

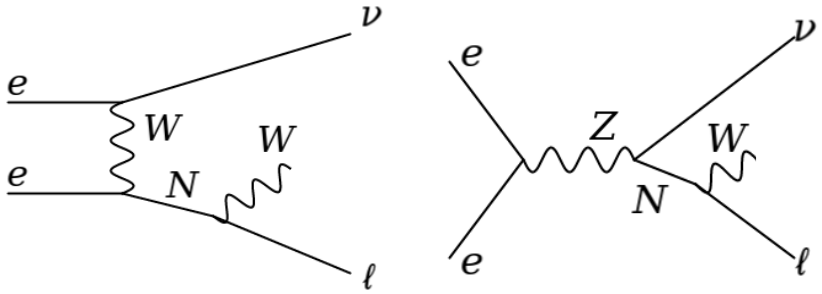
Double Dark Portal – Felix's talk

- Additional vector boson $\tilde{K}$ that can be long-lived
- Mono-photon channel or various displaced signatures e.g. in the Higgstrahlung(-like) process

Long-Lived Particles at the FCC-ee – Juliette's talk

- Axion-Like Particles – displaced vertex or photon + h/Z/γ
- Exotic Higgs decays – 1 or 2 displaced vertices + Z (+$\not{E}$)
- Heavy Neutral Leptons – displaced vertex + $\not{E}$

Signature examples analysed by the Warsaw group



Heavy neutrinos – Krzysztof's talk

- Additional heavy neutrino
- If long-lived, a displaced vertex + $\not{E}$ signature available

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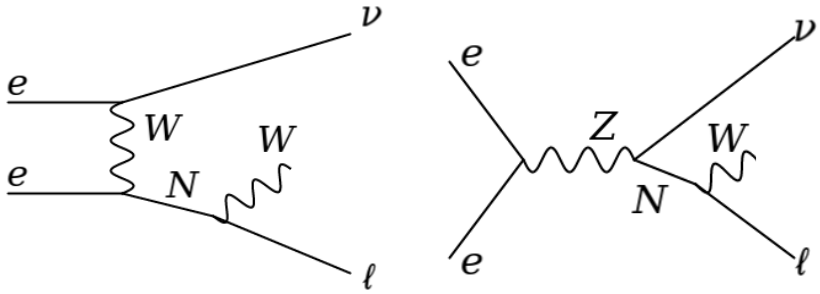

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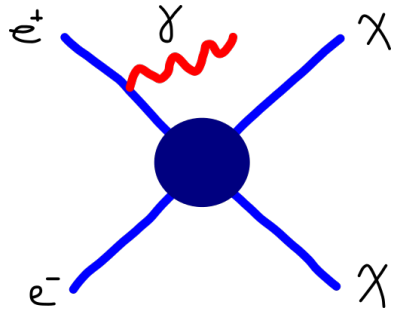
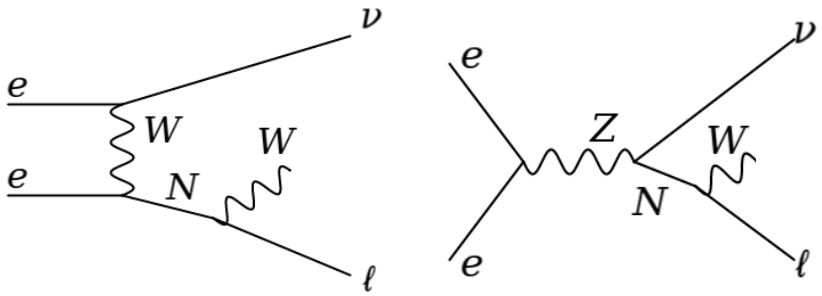


Mono-photon – Filip's talk

- Most general way for DM searches at the e+e- colliders; almost model-independent
- Invisible but for the ISR photon

Signature examples analysed by the Warsaw group



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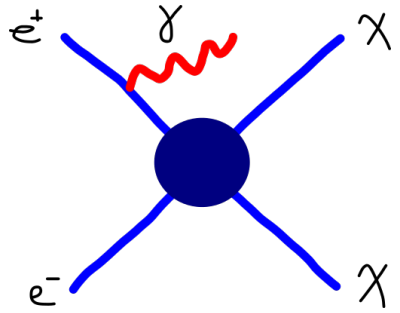

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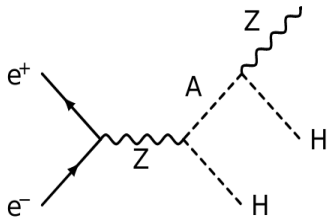

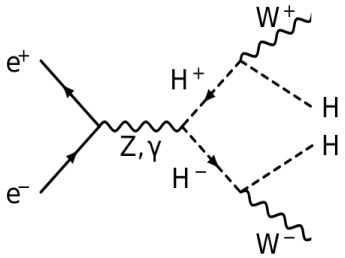

Inert Doublet Model (EPJ C 82, 738 (2022))

- 4 new scalars, 1 stable DM candidate H
- Displaced vertex + $\not{E}$ signature possible; (Kinked tracks + $\not{E}$ for charged channel)

Possible signatures at e^+e^- colliders – single X production

Assuming generic **long-lived particle X** and one **DM candidate***, the signatures can be categorised based on the possible production and decay channels:

production \ decay	X → SM SM	X → SM SM	X → SM DM	X → DM DM
$e^-e^+ \to X$	• 2 tracks/jets/γ from IP ◆	• 2 tracks/jets/γ from IP • $\not{E}$	• 1 track/jet/γ from IP • $\not{E}$	Invisible ◆
$e^-e^+ \to X\,DM$	• displaced vertex • $\not{E}$	• displaced vertex • $\not{E}$ ◇	• displaced track/jet/γ • $\not{E}$ ◇	Invisible
$e^-e^+ \to X\,Z/h/\gamma$	• displaced vertex • $Z/h/\gamma$ ◆	• displaced vertex • $Z/h/\gamma$ • $\not{E}$	• displaced track/jet/γ • $Z/h/\gamma$ • $\not{E}$	• $Z/h/\gamma$ • $\not{E}$ ◆

▭ - predicted by models mentioned on the slides 5-9

If Z_2 is imposed:

◇ - X odd under Z_2

◆ - X even under Z_2

* branches with neutrinos also marked as DM

- Invisible final states correspond to the mono-photon signature
- Diagrams used only for visualisation, other channels also taken into account

Possible signatures at e^+e^- colliders – X pair production

Assuming generic **long-lived particle X** and one **DM candidate***, the signatures can be categorised based on the possible production and decay channels:

production \ decay	X → SM SM	X → SM SM DM	X → SM DM DM	X → DM DM
$e^+e^- \to XX$	• 2 displaced vertices ◆	• 2 displaced vertices • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • $\not{E}$ ◇	Invisible ◆
$e^+e^- \to Xx \to XSM$	• 2 displaced vertices • $\not{E}$	• 2 displaced vertices • $\not{E}$	• 2 displaced tracks/jets/γ • $\not{E}$	Invisible
$e^+e^- \to Xx \to XZ/h/\gamma$	• 2 displaced vertices • $Z/h/\gamma$ ◆	• 2 displaced vertices • $Z/h/\gamma$ • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • $Z/h/\gamma$ • $\not{E}$ ◇	• $Z/h/\gamma$ • $\not{E}$ ◆

▭ - predicted by models mentioned on the slides 5-9

If Z_2 is imposed:

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* branches with neutrinos also marked as DM

- The cells in the table can be referred back to signatures in particular models
- Mixed channel $(XX \to 2SM + 2DM)$ also possible

Possibly interesting signatures yet to be considered

- **$e^+e^- \to X\,DM,\ X \to SM\,DM$** (one displaced photon/jet)
  – scenario similar to stau search, but with a single X production

- **$e^+e^- \to 2X,\ X \to 2SM$** (two displaced vertices)
  – standard search, could be interesting if X is long-lived

- **$e^+e^- \to 2X\ Z/h/\gamma,\ X \to 2SM\ DM$** (two displaced vertices + $Z/h/\gamma + \not{E}$)
  – associated production of two long-lived states

- **$e^+e^- \to 2X\ Z/h/\gamma,\ X \to SM\ DM$** (two displaced jets/photons + $Z/h/\gamma + \not{E}$)
  – associated production of two long-lived states with missing energy

Summary

- **Higgs factories** offer a good prospect for studying models with **FIMPs** and **long-lived particles** with a possibility of full-event reconstruction
- To allow for more direct comparison between different experiments we plan to propose a set of **“experimental” benchmark scenarios**
- Different signatures have to be considered – **classification** made based on **production**/**decay** channel
- **Selection of points** in the space of physical particle properties (not model parameter space) as **the next step**
- Various models predict many of the presented signatures