

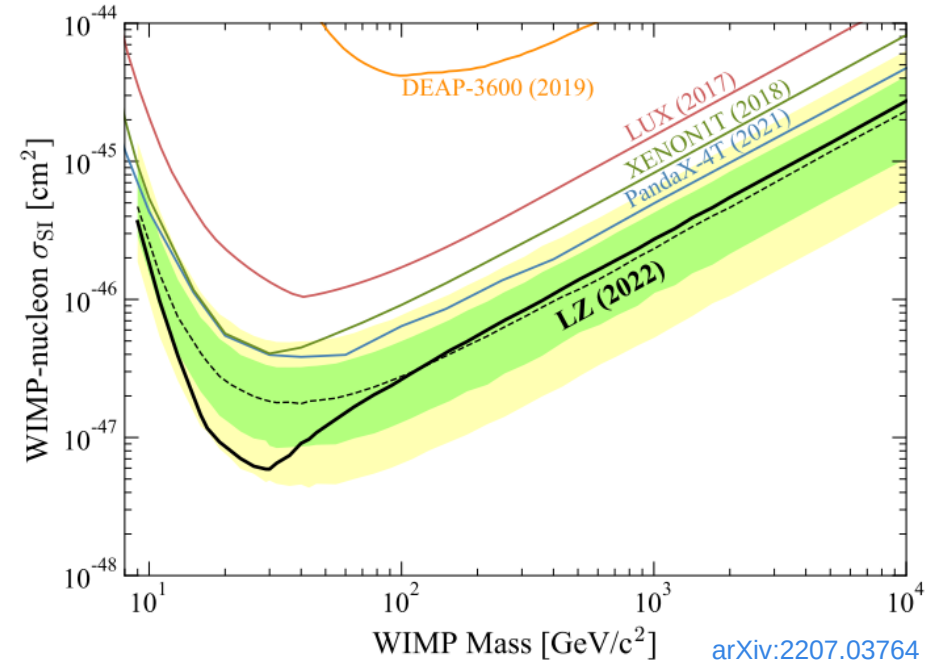
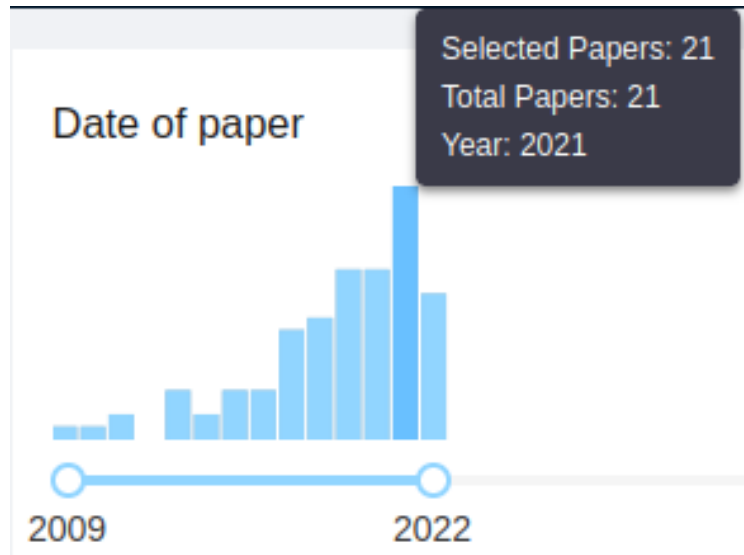
Benchmarking LLP signatures at future Higgs factories

Twelfth Workshop of the Long-Lived
Particle Community
1 November 2022

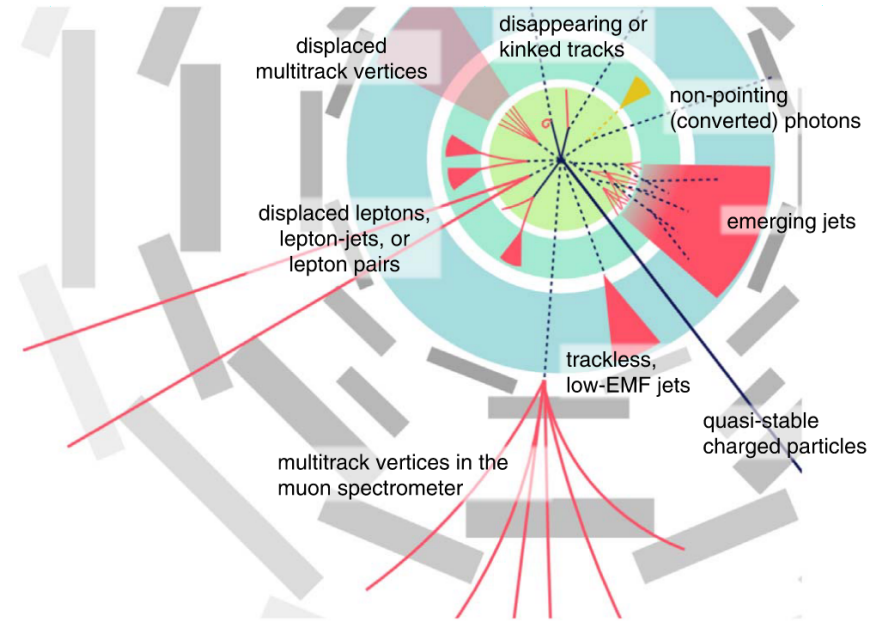
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- Increasingly tightening constraints on WIMPs
- Masses and couplings below the weak scale start being considered
- The concept of FIMPs is getting attention in recent years



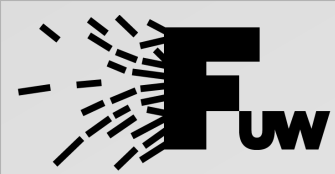
- Due to the small couplings, **FIMPs** often appear alongside **long-lived particles**
- Can also be long-lived themselves!
- Variety of possible signatures at colliders
 - most of them can be described as tracks **not pointing to** / **not originating from** the IP
- This talk: focus on neutral long-lived states



At the LHC: search for a given signature
 At e^+e^- HF: **we can reconstruct full events**

← production/decay channels crucial!

- Variety of models offering **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 analysed in the context of e^+e^- colliders



Long-Lived Particles at the FCC-ee - [LLPs at the FCCee talk](#)

- Axion-Like Particles - displaced vertex or photons + $h/Z/\gamma$
- Exotic Higgs decays - 1 or 2 displaced vertices + $Z (+\cancel{E})$
- Heavy Neutral Leptons - displaced vertex + \cancel{E}

Double Dark Portal ([arXiv:1704.00730](#))

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

Dark photons at Belle II ([arXiv:2202.03452](#))

- Simple SM extension with additional $U(1)_X$ symmetry
- Displaced vertex + hard photon signature

SUSY + axino DM ([arXiv:1506.07532](#))

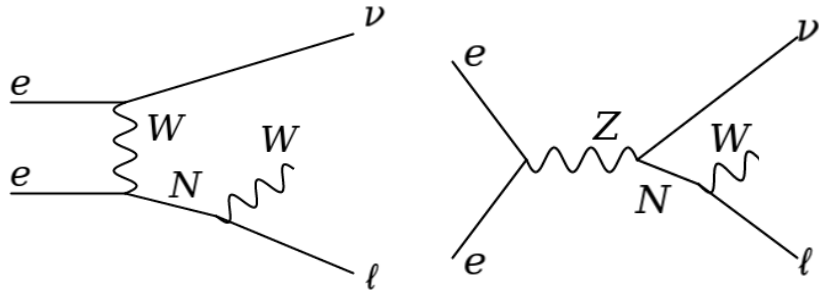
- Long-lived higgsino \tilde{h}^0 and frozen-in LSP axino \tilde{a}
- A higgsino pair-production with $\tilde{h}^0 \rightarrow Z\tilde{a}, h\tilde{a}$ gives a signature of two displaced vertices + \cancel{E}

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 $\chi_{2,3} \rightarrow \chi_1 h, \chi_1 Z$ lead to a signature of two displaced vertices + \cancel{E}

Higgs portal ([arXiv:1908.05685](#))

- Long-lived dark Higgs S that decays into DM or SM by mixing with SM Higgs
- With $h \rightarrow SS$ and $S \rightarrow \text{SM SM}, \text{DM DM}$ possible signatures of 2 (or 1) displaced vertices + Z boson (or Z + \cancel{E})

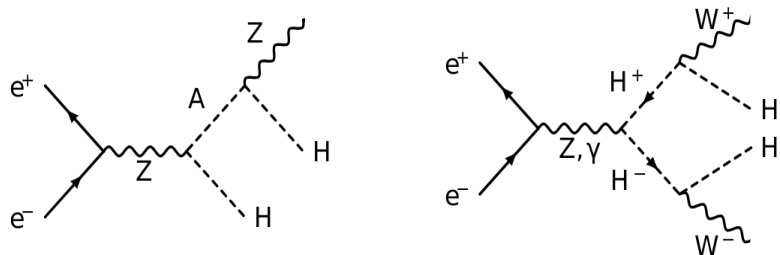
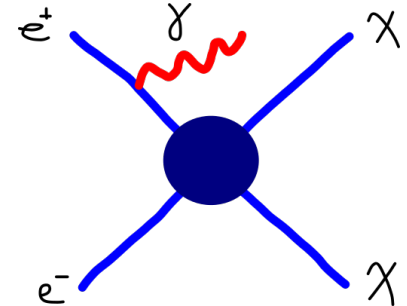


Heavy neutrinos (JHEP 06 (2022) 010)

- Additional heavy neutrino
- If long-lived, a displaced vertex + \cancel{E} signature available

Mono-photon (EPJ C 81, 955 (2021))

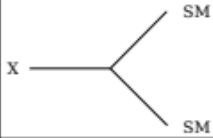
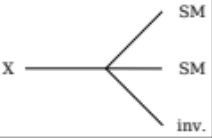
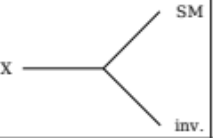
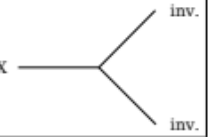
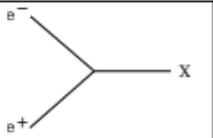

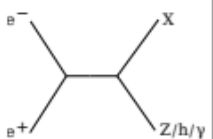
- Most general way for DM searches at the e^+e^- colliders; almost model-independent
- Invisible but for the ISR photon



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

- 4 new scalars, 1 stable DM candidate H
- Displaced vertex + \cancel{E} signature possible; (Kinked tracks + \cancel{E} for charged channel)

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				
	<ul style="list-style-type: none"> • 2 tracks/jets/γ from IP 	<ul style="list-style-type: none"> • 2 tracks/jets/γ from IP • \mathcal{E} 	<ul style="list-style-type: none"> • 1 track/jet/γ from IP • \mathcal{E} 	Invisible
	<ul style="list-style-type: none"> • displaced vertex • \mathcal{E} 	<ul style="list-style-type: none"> • displaced vertex • \mathcal{E} 	<ul style="list-style-type: none"> • displaced track/jet/γ • \mathcal{E} 	Invisible
	<ul style="list-style-type: none"> • displaced vertex • $Z/h/\gamma$ 	<ul style="list-style-type: none"> • displaced vertex • $Z/h/\gamma$ • \mathcal{E} 	<ul style="list-style-type: none"> • displaced track/jet/γ • $Z/h/\gamma$ • \mathcal{E} 	<ul style="list-style-type: none"> • $Z/h/\gamma$ • \mathcal{E}

- predicted by models mentioned on the slides 5-8

If Z_2 is imposed:

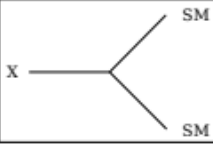
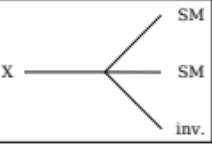
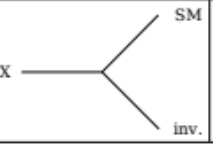
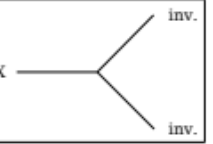
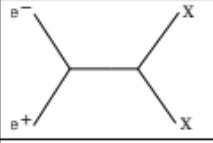
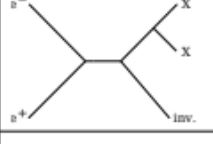
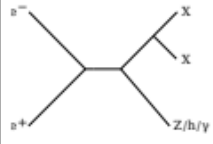
- X odd under Z_2


- X even under Z_2

* marked by “inv.”; can be also a neutrino

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

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				
	<ul style="list-style-type: none"> • 2 displaced vertices 	<ul style="list-style-type: none"> • 2 displaced vertices • \mathcal{E} 	<ul style="list-style-type: none"> • 2 displaced tracks/jets/γ • \mathcal{E} 	Invisible
	<ul style="list-style-type: none"> • 2 displaced vertices • \mathcal{E} 	<ul style="list-style-type: none"> • 2 displaced vertices • \mathcal{E} 	<ul style="list-style-type: none"> • 2 displaced tracks/jets/γ • \mathcal{E} 	Invisible
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 - predicted by models mentioned on the slides 5-8

If Z_2 is imposed:

 - X odd under Z_2

 - X even under Z_2

* marked by “inv.”; can be also a neutrino

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

- $e^+e^- \rightarrow X+\text{inv.}, X \rightarrow \text{SM}+\text{inv.}$ (one displaced photon/jet)
 - scenario similar to typical SUSY search, but with a single X production
- $e^+e^- \rightarrow 2X, X \rightarrow 2\text{SM}$ (two displaced vertices)
 - standard search, could be interesting if X is long-lived
- $e^+e^- \rightarrow 2X+Z/h/\gamma, X \rightarrow 2\text{SM}+\text{inv.}$ (two displaced vertices + Z/h/ γ + \cancel{E})
 - associated production of two long-lived states
- $e^+e^- \rightarrow 2X+Z/h/\gamma, X \rightarrow \text{SM}+\text{inv.}$ (two displaced jets/photons + Z/h/ γ + \cancel{E})
 - associated production of two long-lived states with missing energy

- **Higgs factories** offer a good prospect for studying **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