Long-lived particle searches with the ILD experiment

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D. Jeans[1], J. Klamka[2], A. F. Żarnecki[2]
[1]KEK, [2]University of Warsaw
jan.klamka@fuw.edu.pl

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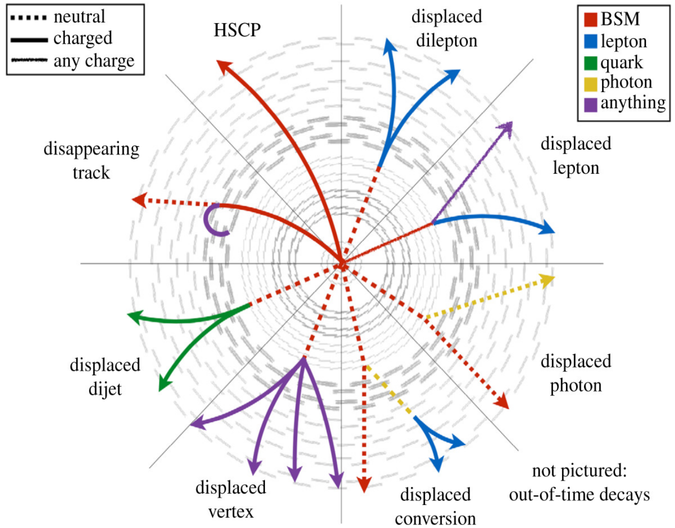
Motivation

Particles with macroscopic lifetimes naturally appear in numerous BSM models

Three main mechanisms are responsible for that...

1810.12602		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓



https://doi.org/10.1098/rsta.2019.0047

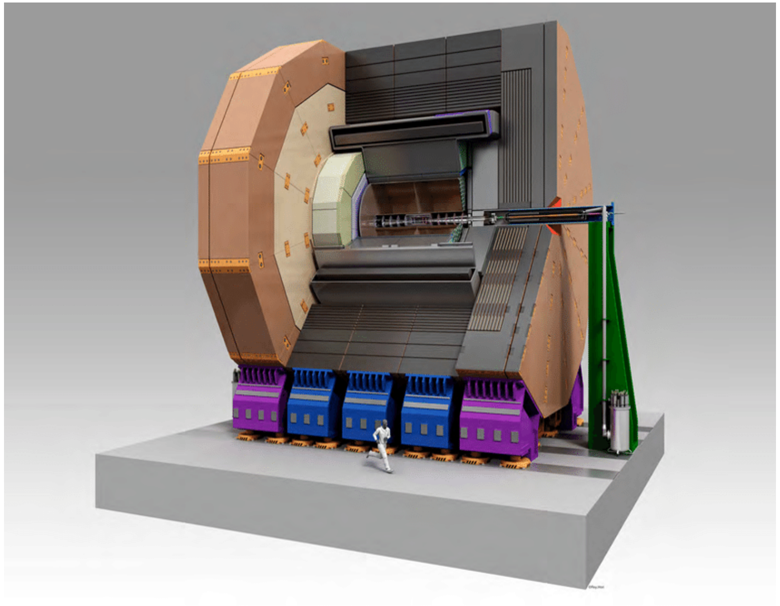
Multiple LLP searches at the LHC, sensitive to high masses and couplings

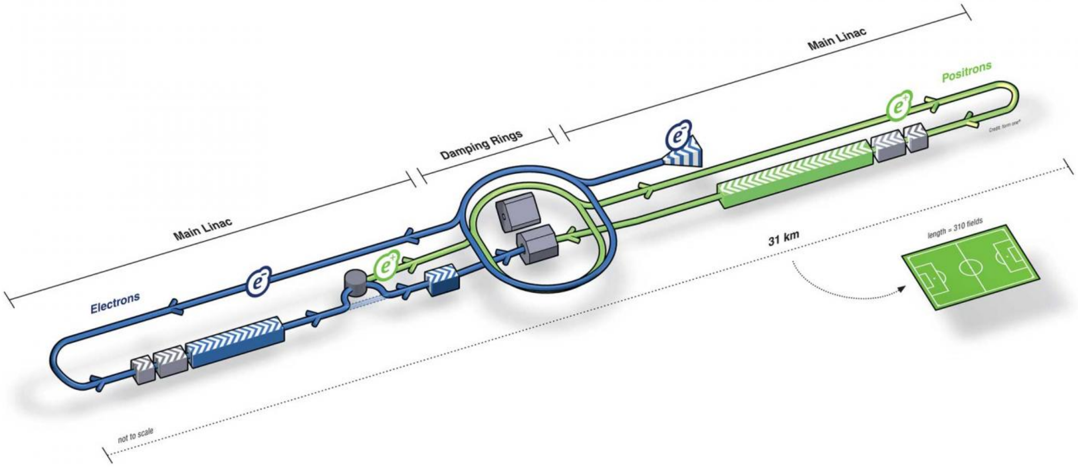
- **complementary region** could be probed at e^+e^- **colliders** (**small masses, couplings, mass splittings**)
- typical properties of feebly interacting massive particles (FIMPs) → challenging for hadron colliders

International Large Detector (ILD)

- Multi-purpose detector for an e^+e^- Higgs Factory (HF)
- Example: the International Linear Collider (ILC), with baseline c.m.s. energy **250**-500 GeV
- Possible operation at other HF proposals now under study (link1, link2)

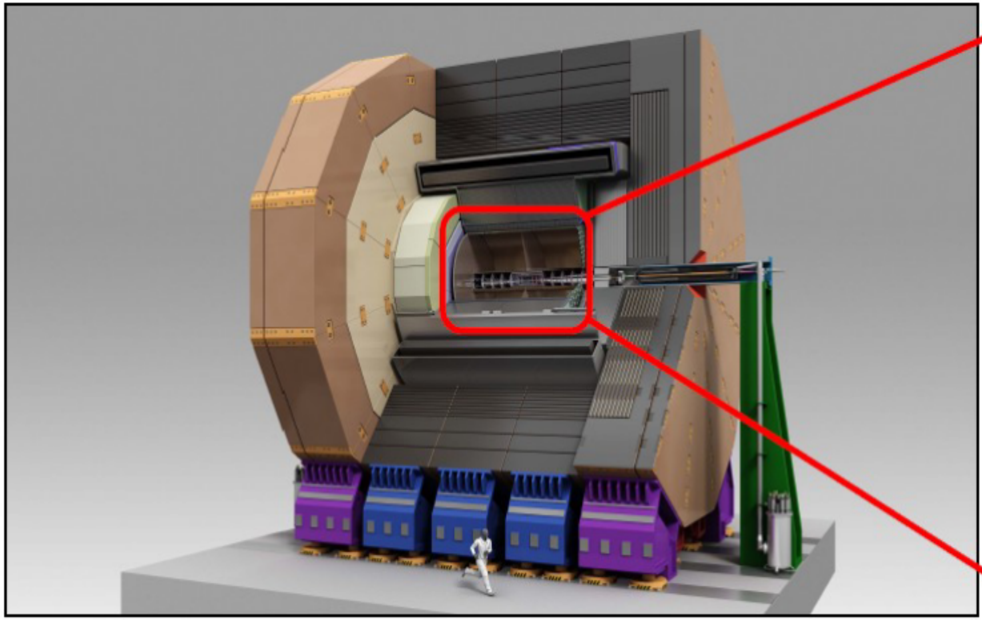
this study

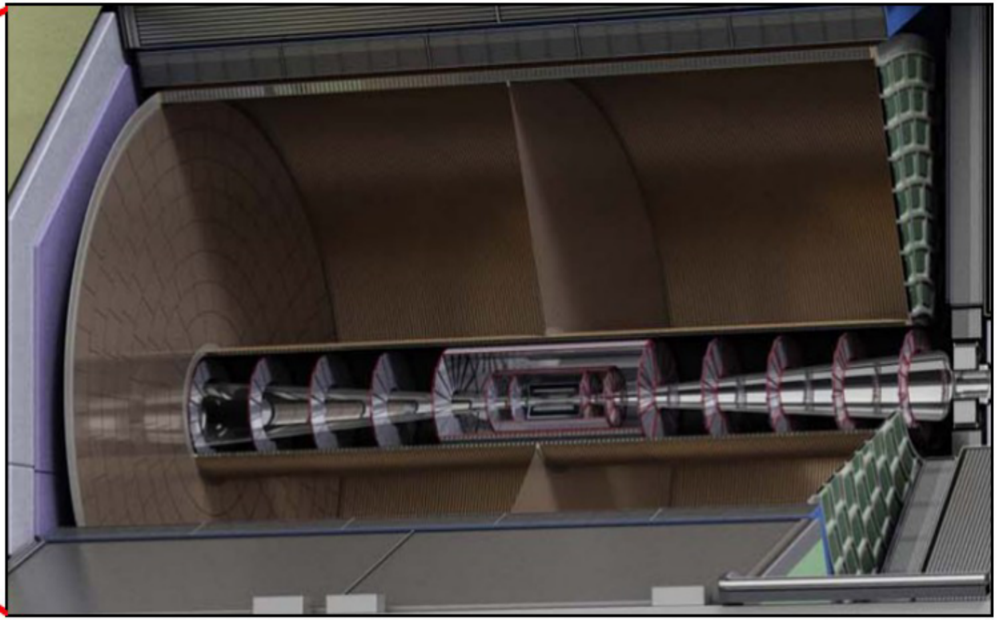




International Large Detector (ILD)

- Nearly 4π angular coverage, optimised for particle flow
- **Time projection chamber (TPC)** as the main tracker allows for continuous tracking and dE/dx PID
- High granularity calorimeter with minimal material in front of it inside 3.5 T solenoid



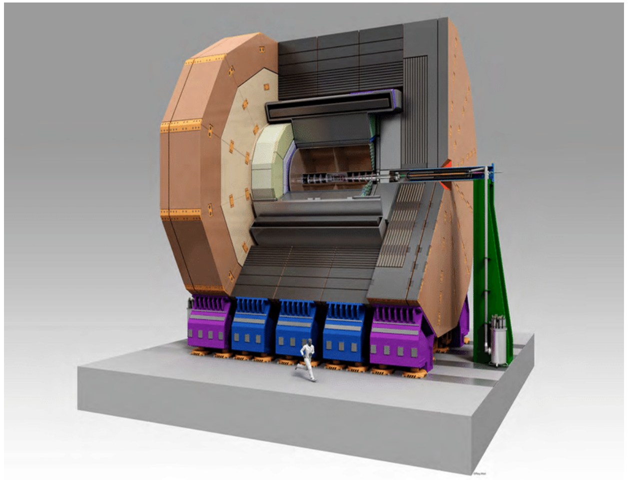


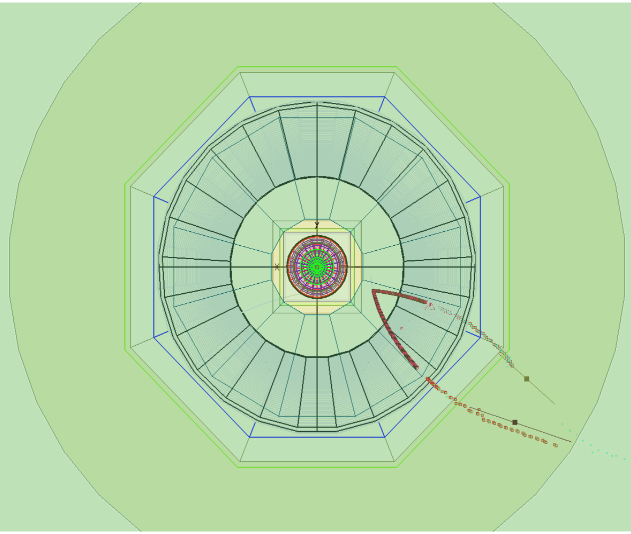
Strategy

ILD especially promising with a TPC as the main tracker

→ we want to investigate experimental aspects

→ study based on full simulation





- Study such challenging signatures from the **experimental perspective**

  → experimental/kinematic properties, not points in a model parameter space

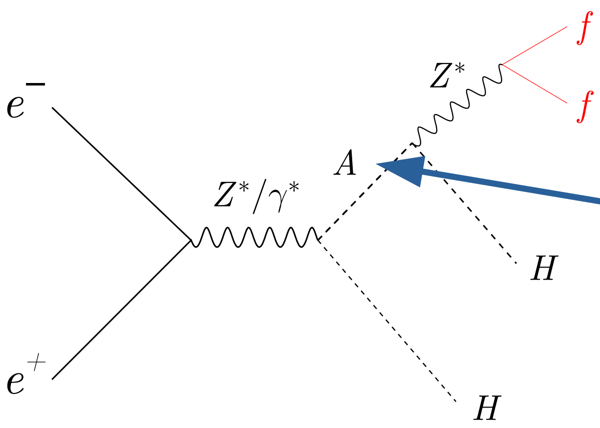
- Focus on a generic (and most challenging) case – two tracks from a displaced vertex

- No other assumptions about the final state, approach **as general as possible**

Framework and signatures

As a challenging case (small boost, low-pT final state) we considered: $\sqrt{s} = 250\,\mathrm{GeV}$

→ heavy scalar LLP (A) and DM (H) pair-production with small mass splitting, $\mathrm{Z}^* \to \mu\mu$



Long-lived, with $c\tau = 1\,\mathrm{m}$

$m_A = 75\,\mathrm{GeV}$

$m_A - m_H = 1, 2, 3, 5\,\mathrm{GeV}$

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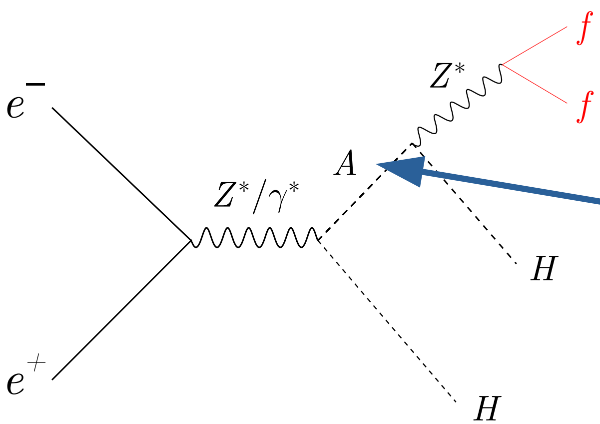
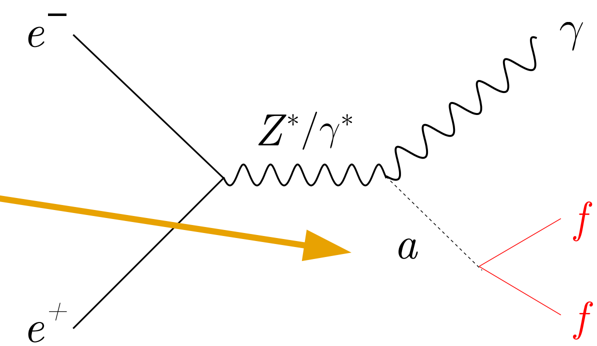


Long-lived, with $c\tau = 1\,\mathrm{m}$
$m_A = 75\,\mathrm{GeV}$
$m_A - m_H = 1, 2, 3, 5\,\mathrm{GeV}$

Long-lived, $c\tau = 10 \cdot m_a\,[\mathrm{mm}]$
$m_a = 0.3,\ 1,\ 3,\ 10\,\mathrm{GeV}$



The opposite extreme case, (large boost, high-pT final state)

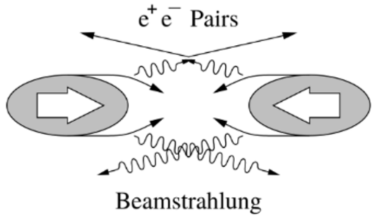
→ light pseudoscalar LLP $a \to \mu\mu$

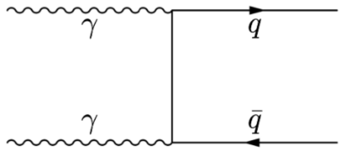
Very simple vertex finding (inside the TPC) based on a distance between track pairs

Overlay events background

At linear e^+e^- colliders beams are strongly focused and radiate photons, so $\gamma\gamma$ interactions also occur in detector. On average, in each bunch-crossing (BX) at ILC250, produced are:

- **1.55 $\gamma\gamma \rightarrow$ low-p_T hadrons** events
- **$O(10^5)$ incoherent e^+e^- pairs**, only a small fraction enters tracker





These events are soft, usually important because they **overlay** on physical events

...but can also look like signal on their own

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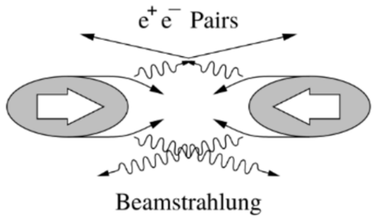

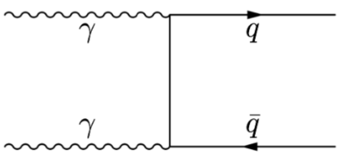

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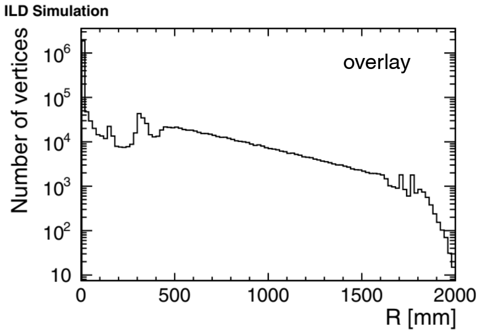

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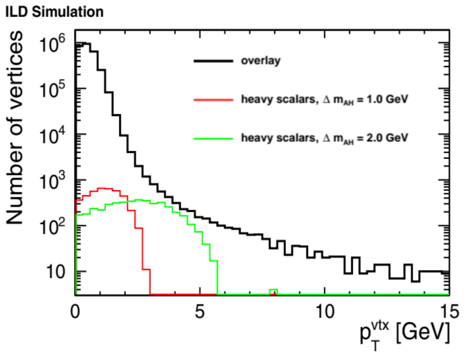
- ~10^{11} BXs per year at ILC → overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy

  → many secondary vertices (mostly fake, also V^0s and photon conversions)

  → significant background



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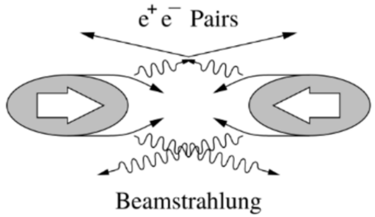

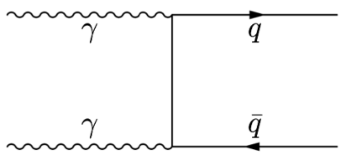

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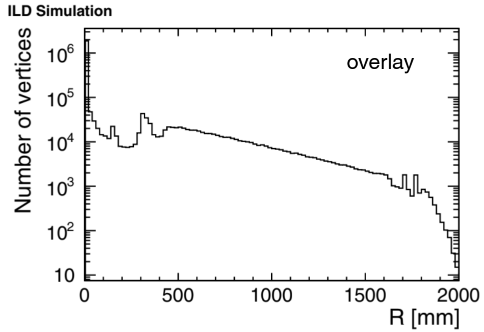

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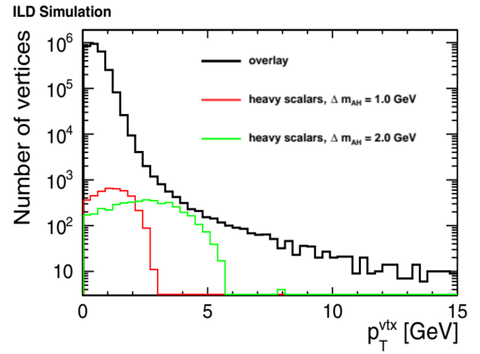


- Can be suppressed using cuts on the track pair geometry and $p_T^{vtx} > 1.9$ GeV
- Total expected reduction factor at the level of **~10^{-10}**

Background from high-p_T events

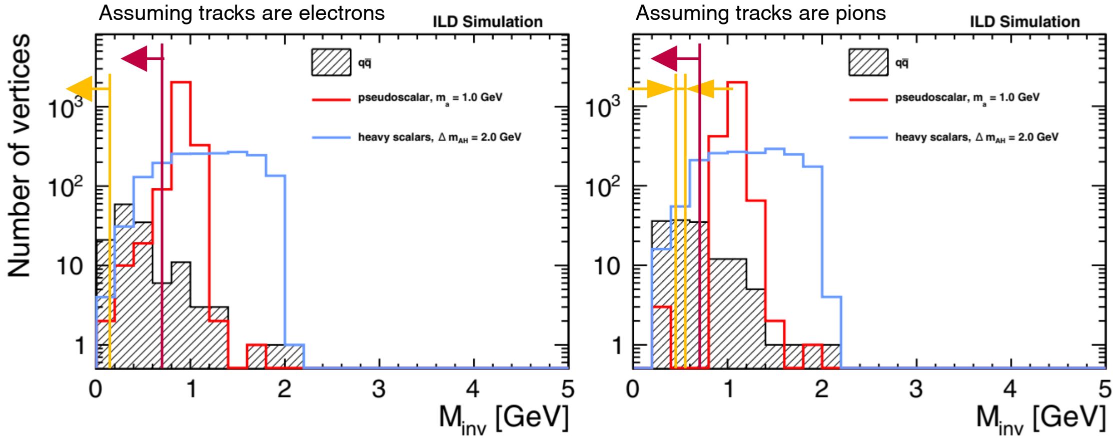
The following survive overlay selection in the hard e^+e^- processes:

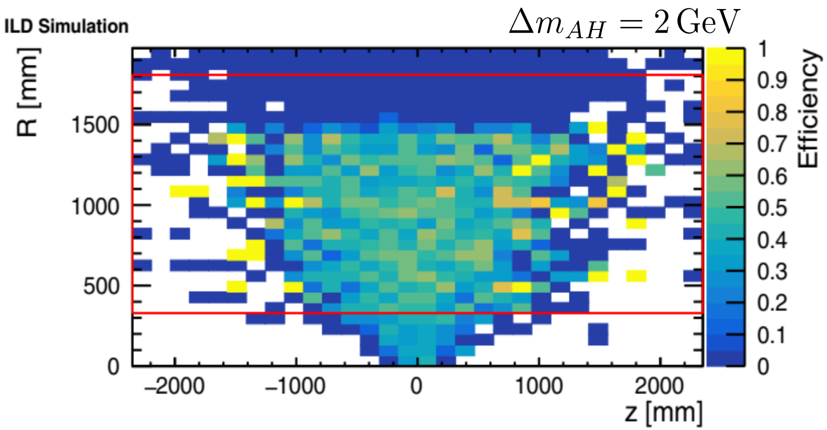
- Decays of kaons, lambdas, photon conversions
- Secondary tracks from interactions with detector material

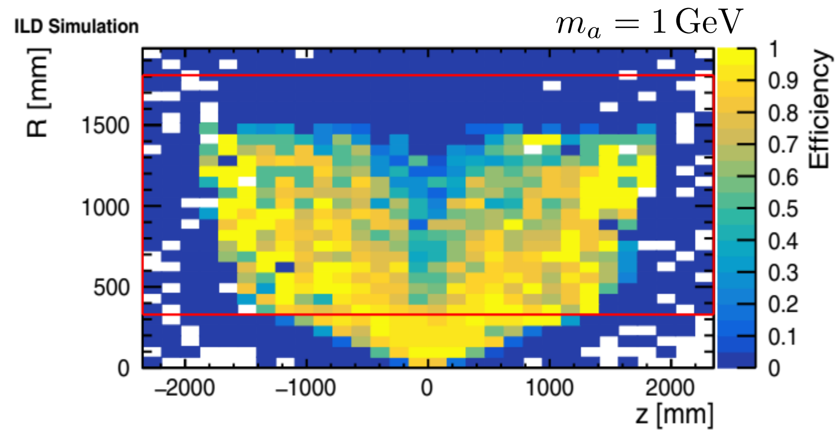
sgn(P(e⁻), P(e⁺))	(−,+)	(+,−)	(−,−)	(+,+)
channel	σ [fb]			
qq	127,966	70,417	0	0
qqqq	28,660	970	0	0
$qq\ell\nu$	29,043	261	191	191
$ZZ \to qq\ell\ell, qq\nu\nu$	838	467	0	0
$Z\nu_e\nu_e \to qq\nu_e\nu_e$	454	131	0	0
$Zee \to qqee$	1,423	1,219	1,156	1,157
process	BB	BW	WB	WW
hard $\gamma^{B/W}\gamma^{B/W}$	42,150	90,338	90,120	71,506

Backg. sources occur mainly inside jets, so we consider (hard) e^+e^- and $\gamma\gamma$ processes with jets in final state

→ Additional cuts on invariant mass are applied, with two working points: **standard** and **tight** (tight involving also **isolation** criterium)



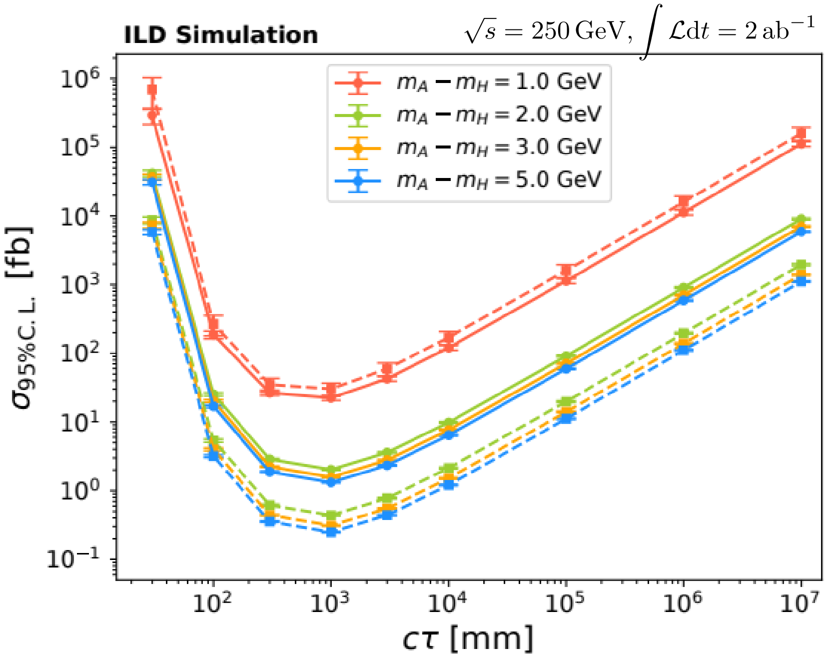




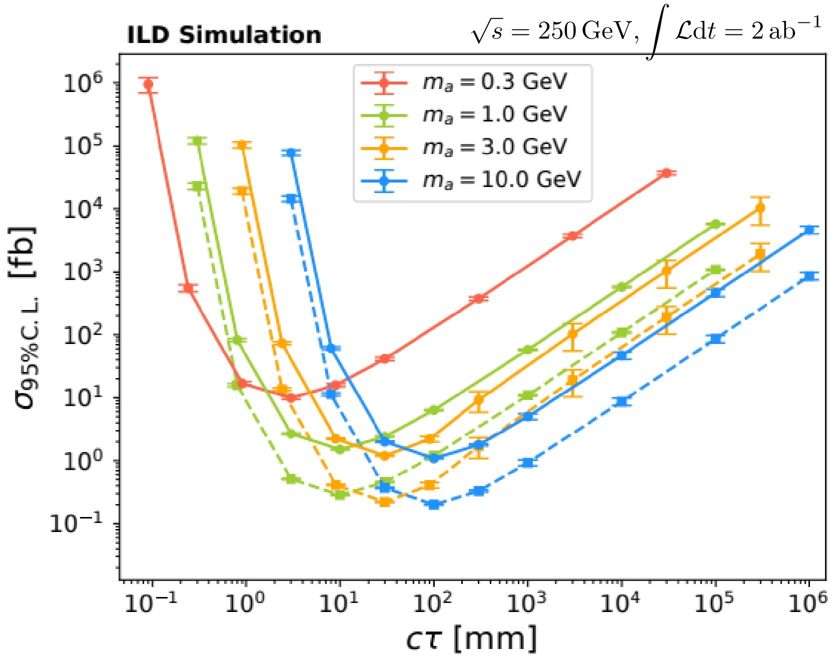
Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

- Efficiency = (correct / decays within TPC acceptance), "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality) and **mass** of *a* (final state boost)
- A dedicated approach could enhance sensitivity for Δm_{AH} = 1 GeV and m_a = 300 MeV scenarios

Cross section limits



Heavy scalars



Light pseudoscalar

- Tight selection: dashed line, standard selection: solid line
- A wide range of models with heavy scalars with small mass splittings, or light pseudo scalar particles, can be excluded down to 0.1 fb

arXiv:2409.13492

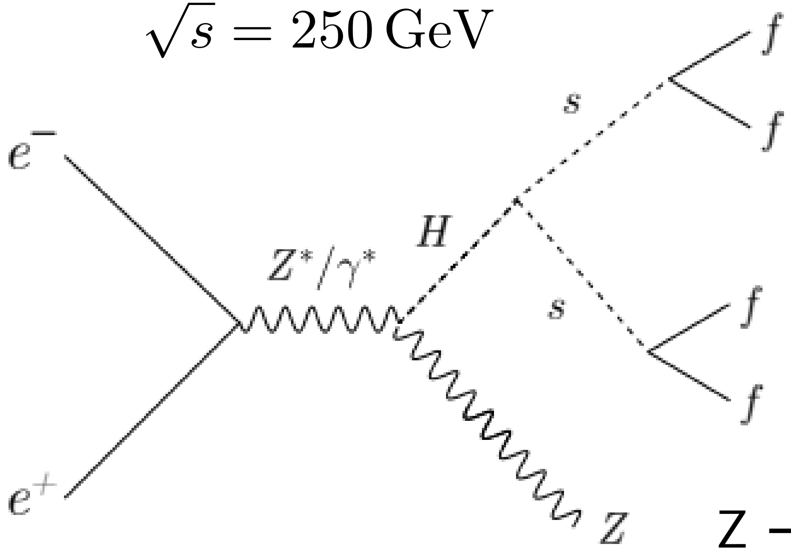
Exotic Higgs decays

Higgs decays to LLPs

Higgsstrahlung with H(125) decay to two long-lived scalars

Generated using the Triple Real Singlet Higgs model with fixed lifetimes of s

$\sqrt{s} = 250\,\mathrm{GeV}$



Generated scenarios:

$$m_s = 400\,\mathrm{MeV},\ c\tau = 10\,\mathrm{mm}$$
$$m_s = 2\,\mathrm{GeV},\ c\tau = 10\,\mathrm{mm}$$
$$m_s = 50\,\mathrm{GeV},\ c\tau = 1\,\mathrm{m}$$
$$m_s = 60\,\mathrm{GeV},\ c\tau = 1\,\mathrm{m}$$

Z → νν, s → μμ decays used to simplify the simulation

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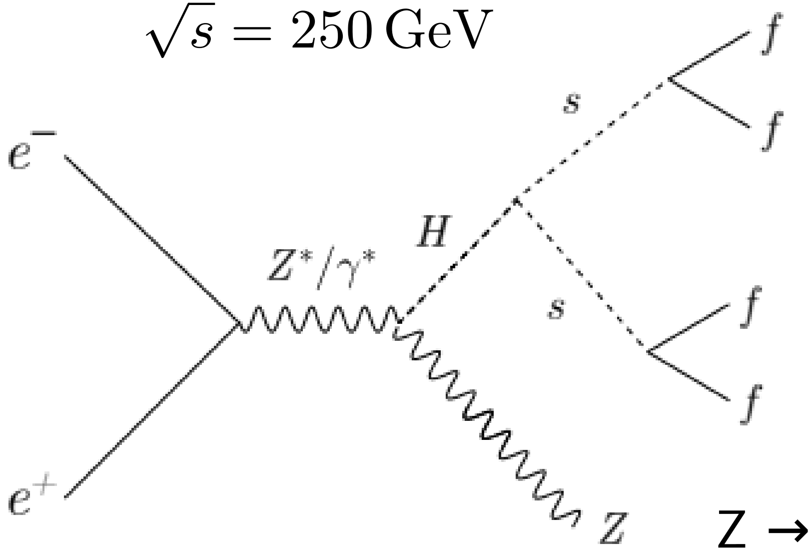

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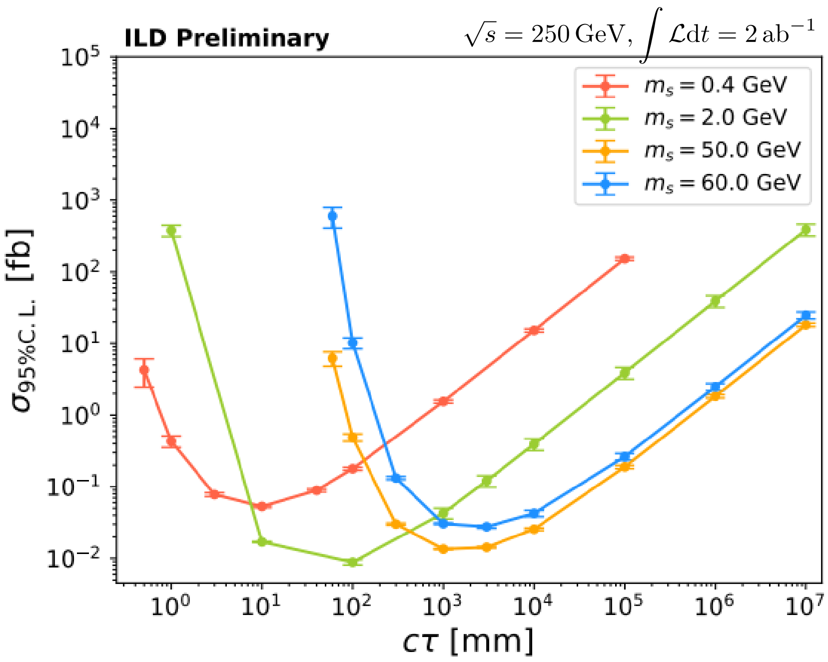
Z → νν, s → μμ decays used to simplify the simulation

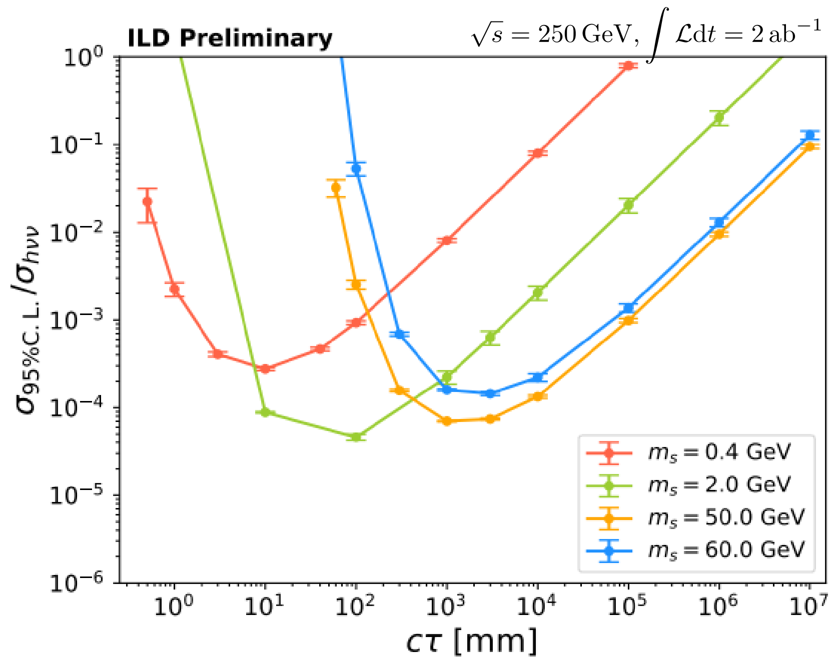
Use the **same analysis procedure**, but further **optimise for this channel** by requiring:

→ no additional prompt tracks with $p_T > 2$ GeV

→ total $p_T^{vtx} > 10$ GeV of tracks forming a vertex (to neglect the overlay)

Higgs decays to LLPs





- ILD can improve the current constraints and probe higher lifetimes already @ ILC250 thanks to higher TPC acceptance
- The limits could be further improved by dedicated searches using vertex detector and by more data at higher energy stages

Conclusions

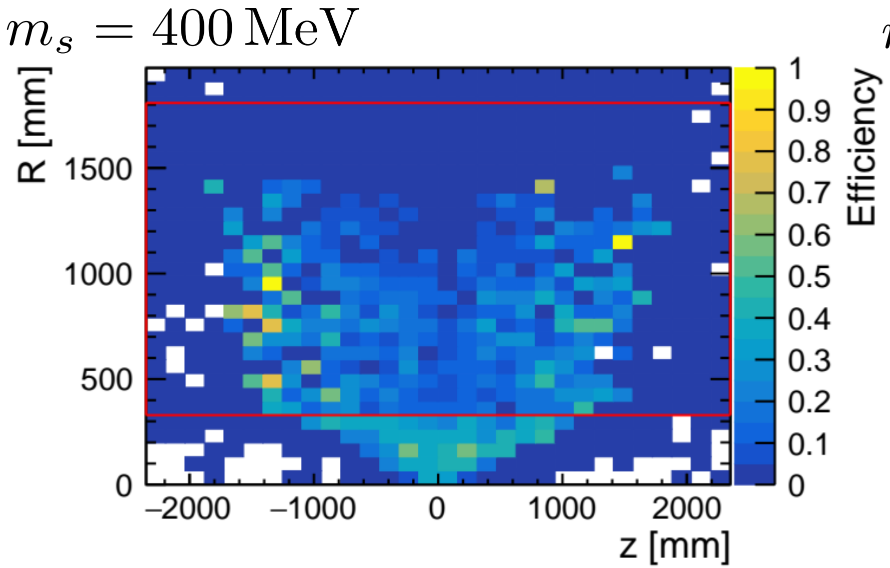
- ILD has a good potential to study long-lived particles, considering the model-independent approach and extreme signatures tested
- TPC plays the key role by enhancing the acceptance, allowing to probe very high lifetimes
- Additional selection utilizing features of a given signature can greatly improve sensitivity
- Presented expected limits on SM-like Higgs decays to LLPs would improve current constraints by order of magnitude or probe longer lifetimes

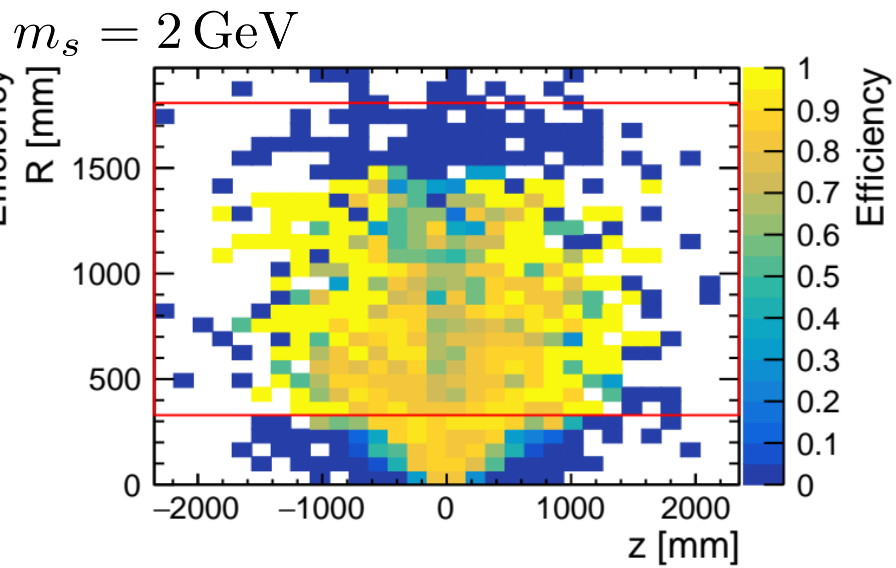
Thank you!

BACKUP

Vertex finding results (h → ss)

m_s	0.4 GeV	2 GeV	50 GeV	60 GeV
Efficiency (standard)	7.8%	52.2%	34.6%	18.5%
Efficiency (tight)	0%	52.2%	34.3%	18.1%



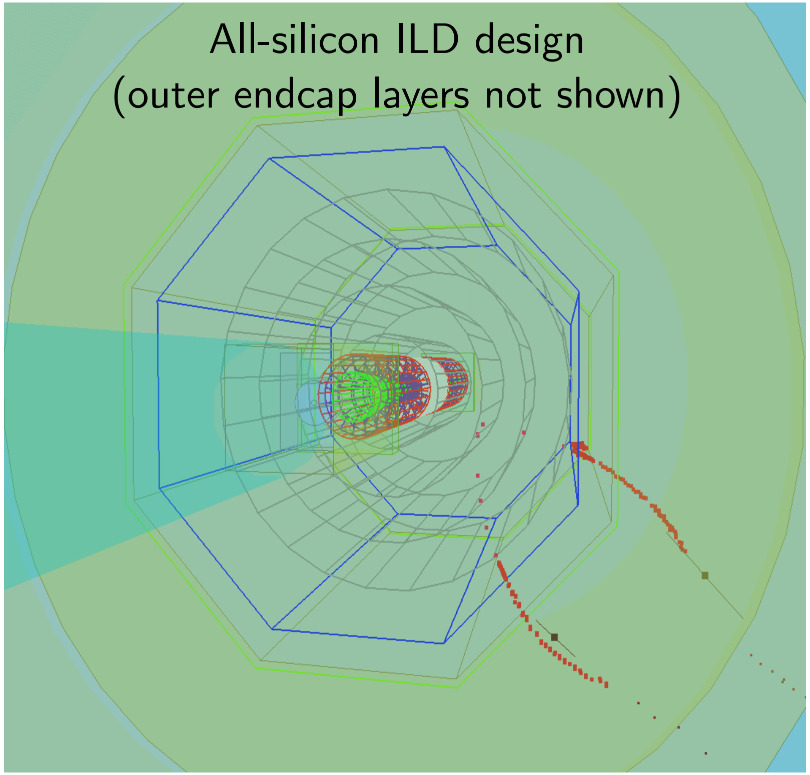


- Efficiency = (correct / decays within TPC acceptance), "correct" if distance to the true vtx $<$ 30 mm
- Tight selection cut on invariant mass assuming tracks are pions/electrons, M $>$ 700 MeV, "kills" the 400 MeV scenario, the rest of scenarios remain almost intact

Alternative all-silicon ILD design

Alternative ILD design implemented for tests

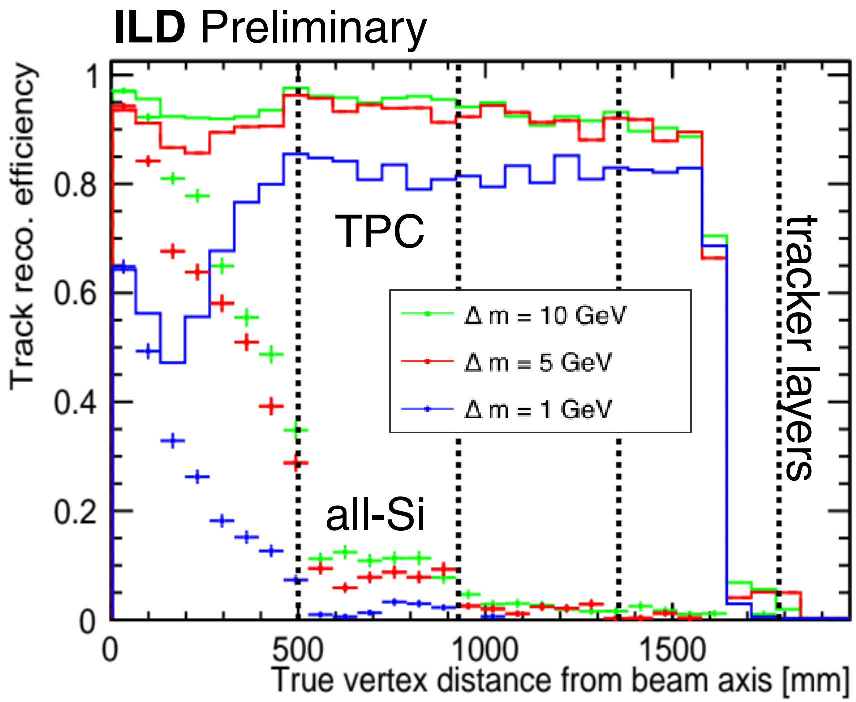
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ Check how the **results** for heavy scalars are influenced by a **change of tracker** design

Heavy scalars at all-silicon ILD

- Vertex reconstruction driven by **track reconstruction efficiency**
- Performance similar to baseline design (TPC) near the beam axis
- Smaller number of hits available → **efficiency drops faster** with vertex displacement
- At least **4 hits required** for track reconstruction → limited reach
- For large decay lengths, **efficiency significantly higher** for "standard" ILD with **TPC**



Vertex finding strategy

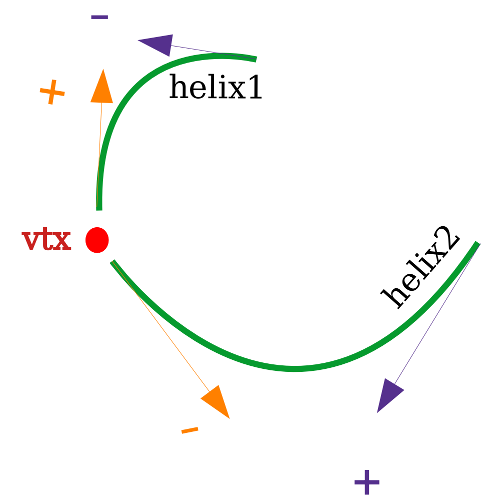
<u>Approach as simple and general as possible:</u>

- Consider tracks in pairs
- As the TPC is not sensitive to track direction:

  → use **both track direction** (charge) **hypothesis** for vertex finding

  → consider opposite-charge track pairs only

  → select pair with **closest starting points**



- Reconstruct vertex in **between points of closest approach** of helices

  → Require distance < 25 mm