Long-lived particle searches with the ILD experiment

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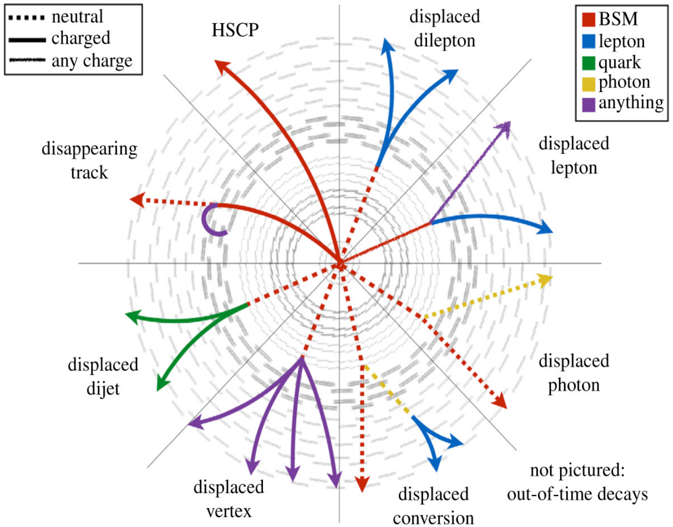
Motivation

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

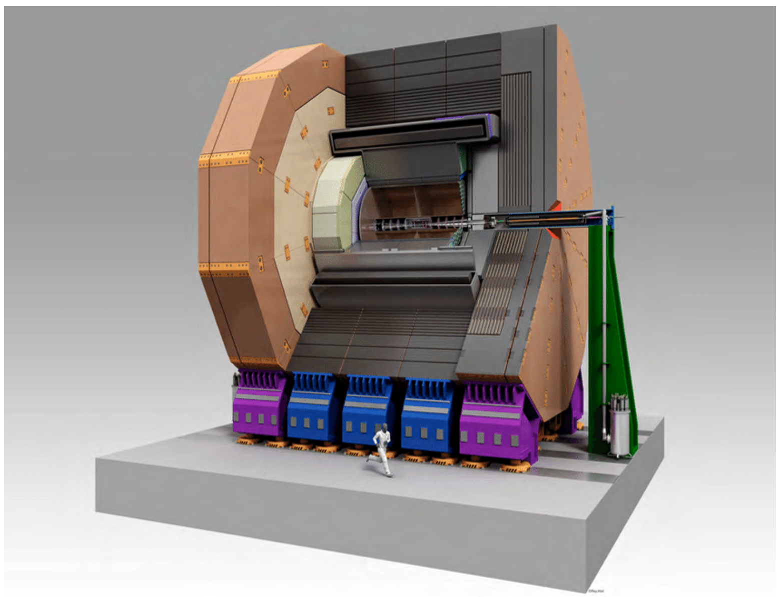
Multiple LLP searches at the LHC, sensitive to high masses and couplings

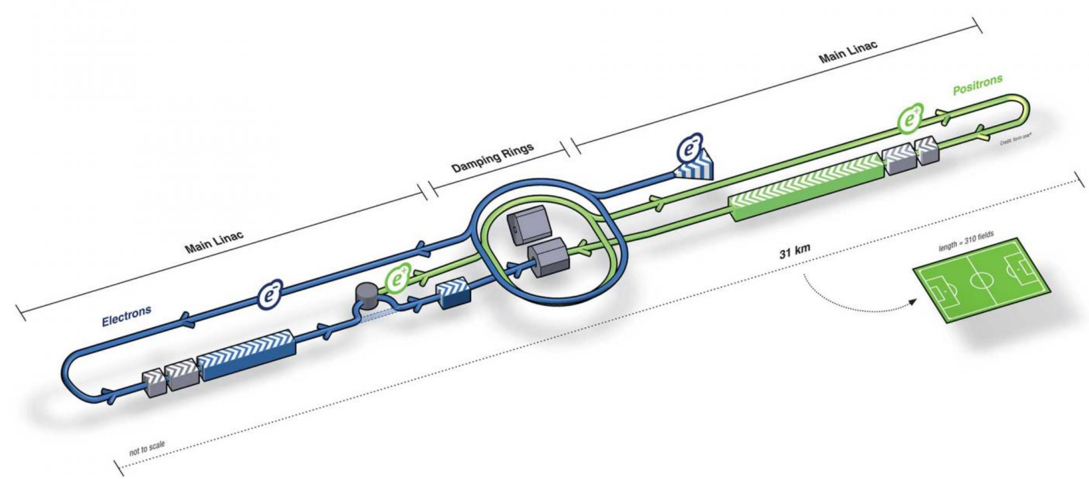
- **complementary region** could be probed at **e^+e^- colliders** (**small masses, couplings, mass splittings**)
- typical properties of feebly interacting massive particles (FIMPs) → challenging for hadron colliders

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

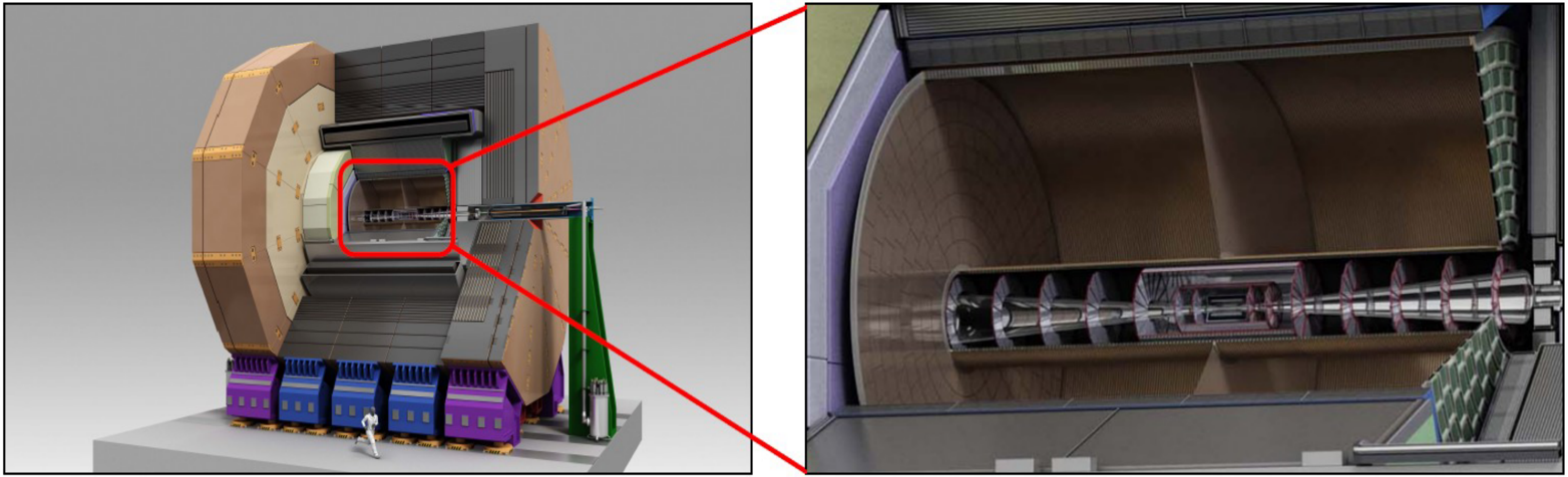
this study





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

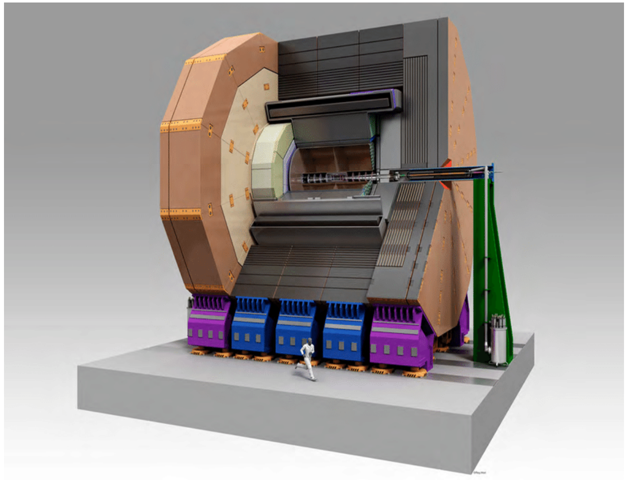
→ study based on full simulation

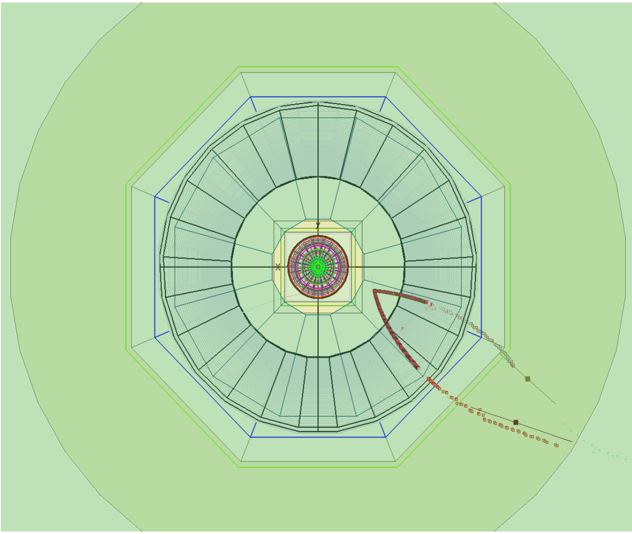
- Study such challenging signatures from the **experimental perspective**

  → 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**

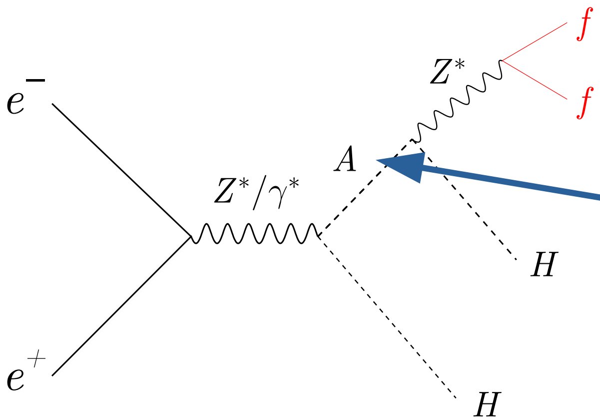




Framework and signatures

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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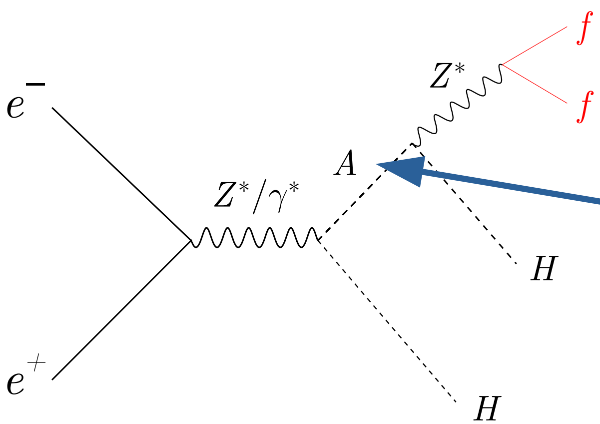


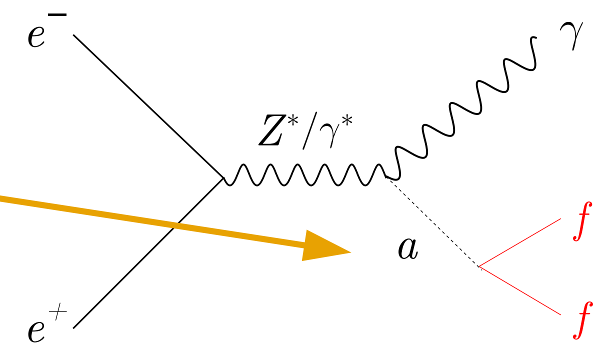
Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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

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

$m_a = 0.3,\ 1,\ 3,\ 10\,\text{GeV}$



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

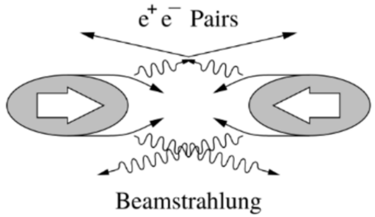
→ light pseudoscalar LLP $a \to \mu\mu$

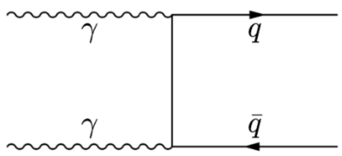
Very simple vertex finding (inside the TPC) based on a distance between track pairs

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 detector





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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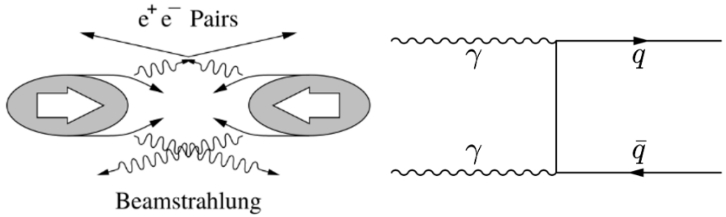

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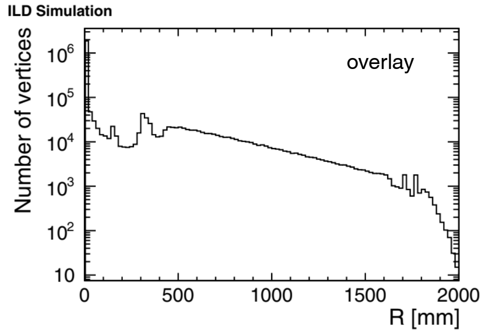
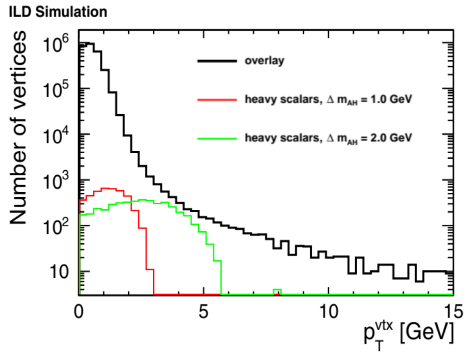
- ~10^{11} BXs per year at ILC → overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy

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

  → significant background





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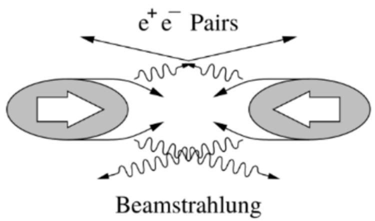

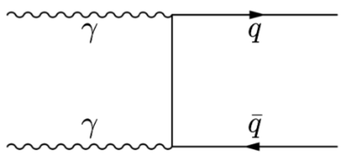

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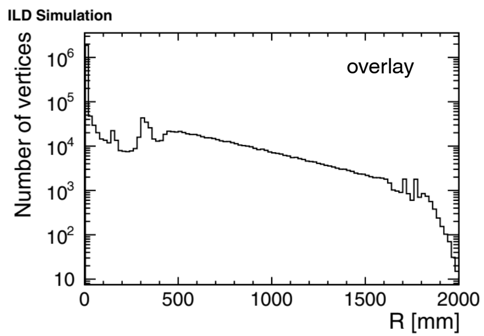

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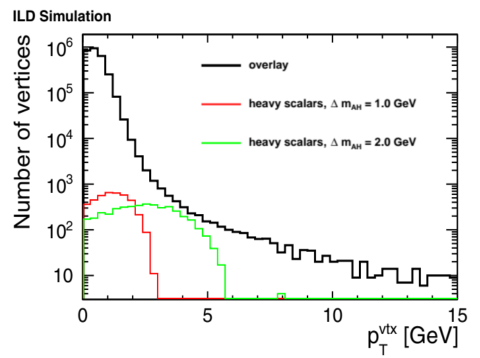

- Can be suppressed using cuts on the track pair geometry and $p_T^{vtx} > 1.9$ GeV
- Total expected reduction factor at the level of **~10^{-10}**

Background from high-p_T events

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

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

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

Selection eff. depends on number of jets, so:

Estimate efficiency based on full simulation

Use qq efficiency for the remaining processes

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

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

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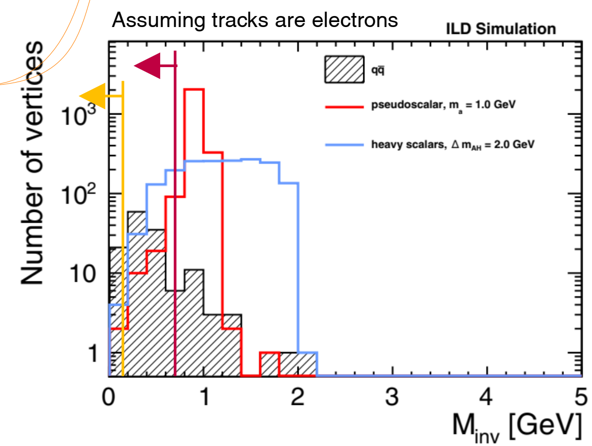
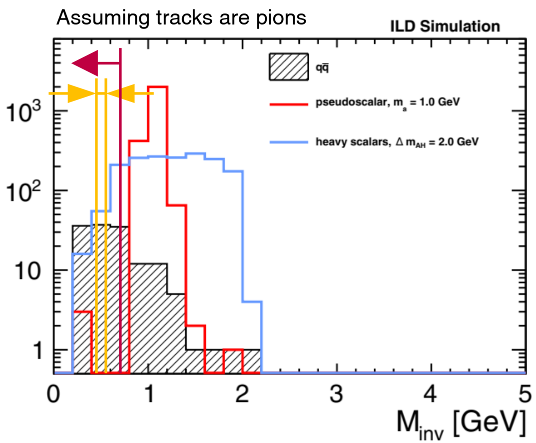
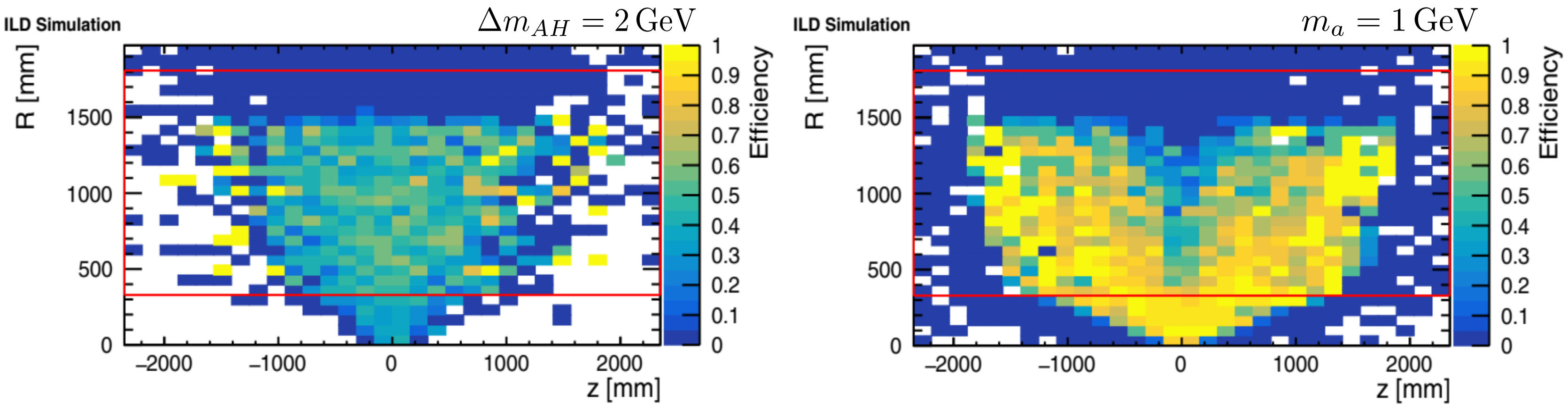




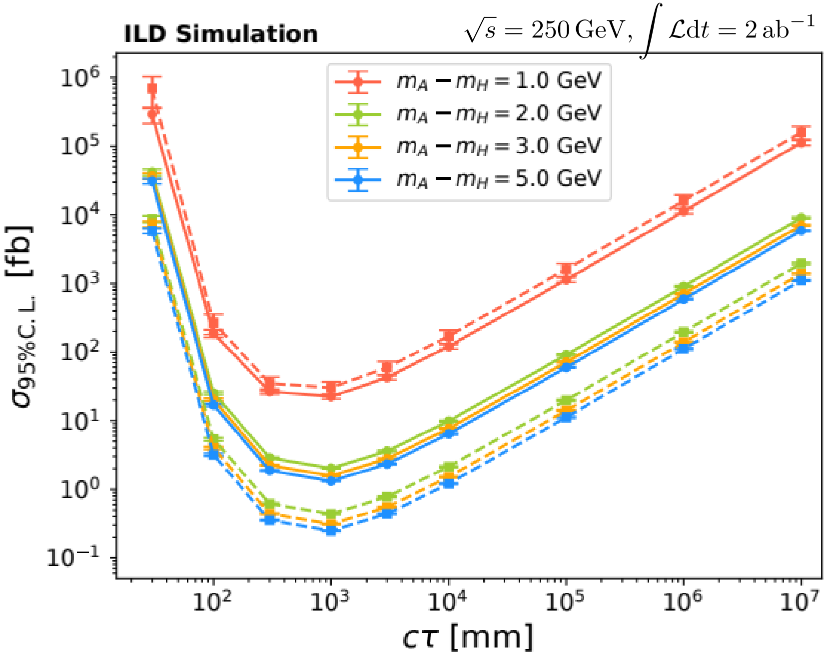
Vertex finding results



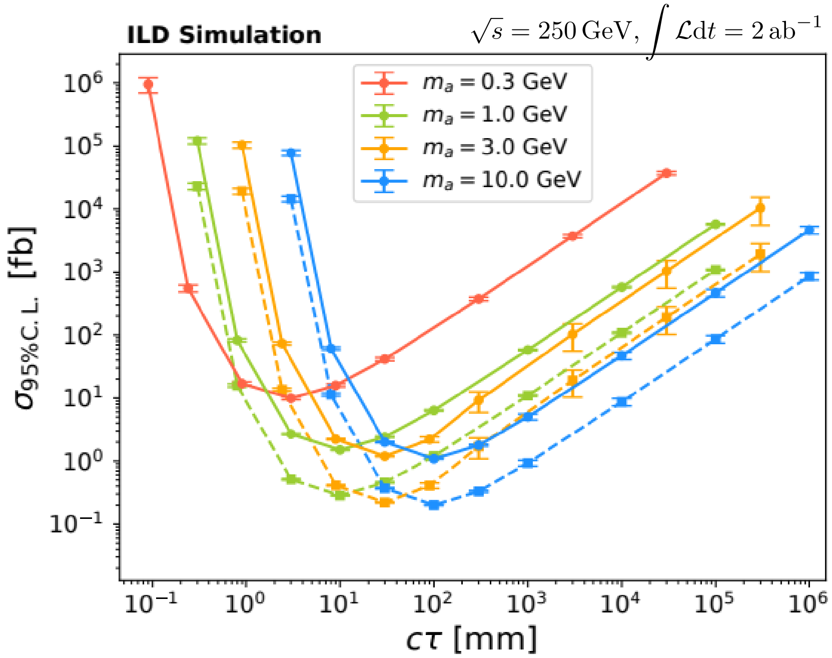
Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

- 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

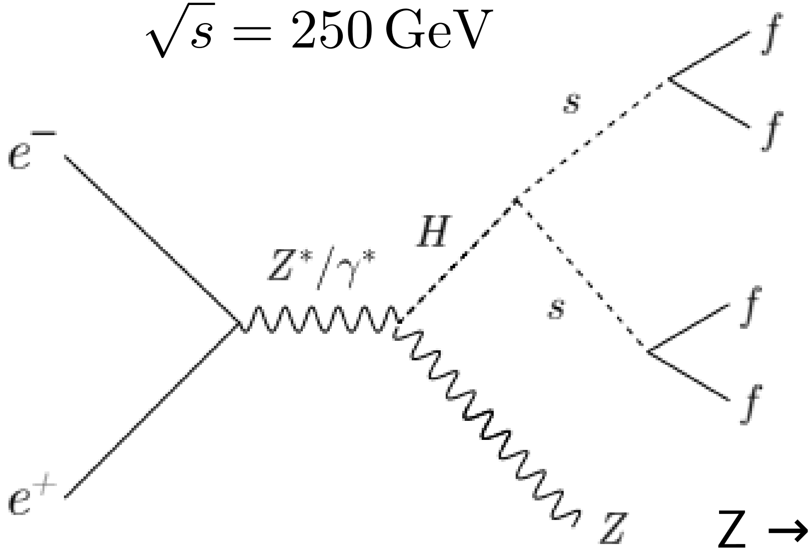
- Tight selection: dashed line, standard selection: solid line
- A wide range of models with heavy scalars with small mass splittings, or light pseudo scalar particles, can be excluded down to 0.1 fb

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:

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

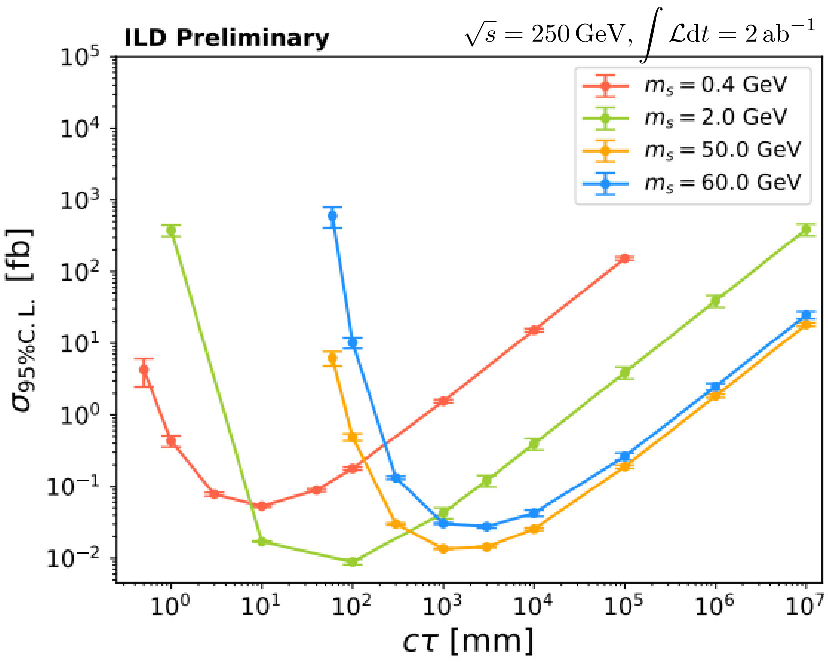
Z → νν, s → μμ decays used to simplify the simulation

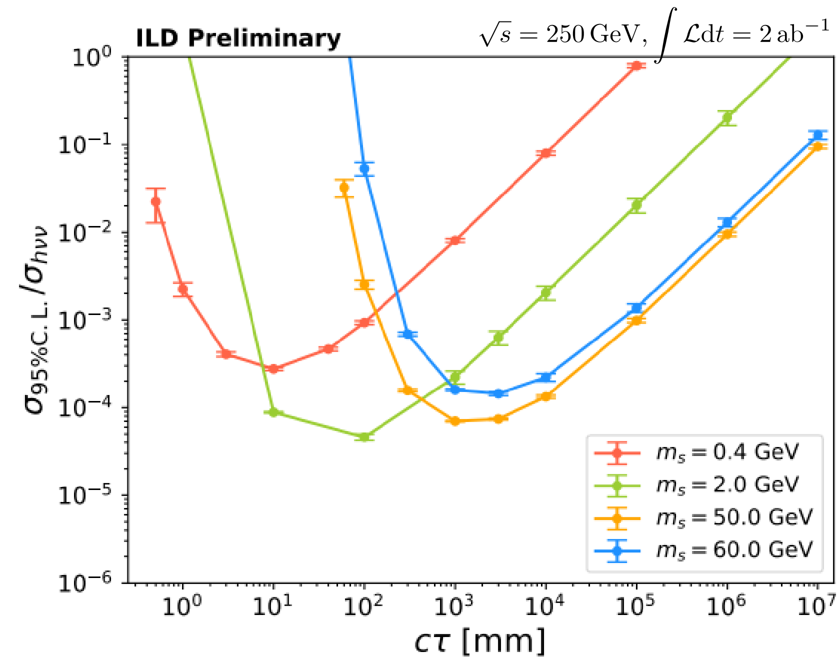
Use the **same analysis procedure**, but further **optimise for this channel** by requiring:

→ no additional prompt tracks with pT > 2 GeV

→ total pT > 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

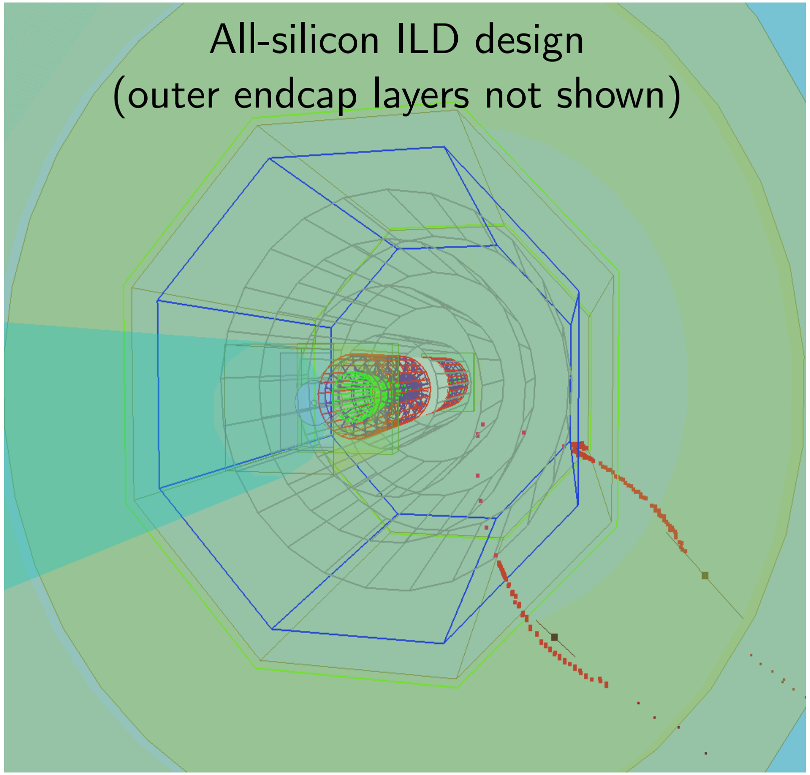
- ILD has a good potential to study long-lived particles, considering the model-independent approach and extreme signatures tested
- TPC plays the key role by enhancing the acceptance, allowing to probe very high lifetimes
- Additional selection utilizing features of a given signature can greatly improve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

BACKUP

Alternative all-silicon ILD design

Alternative ILD design implemented for tests

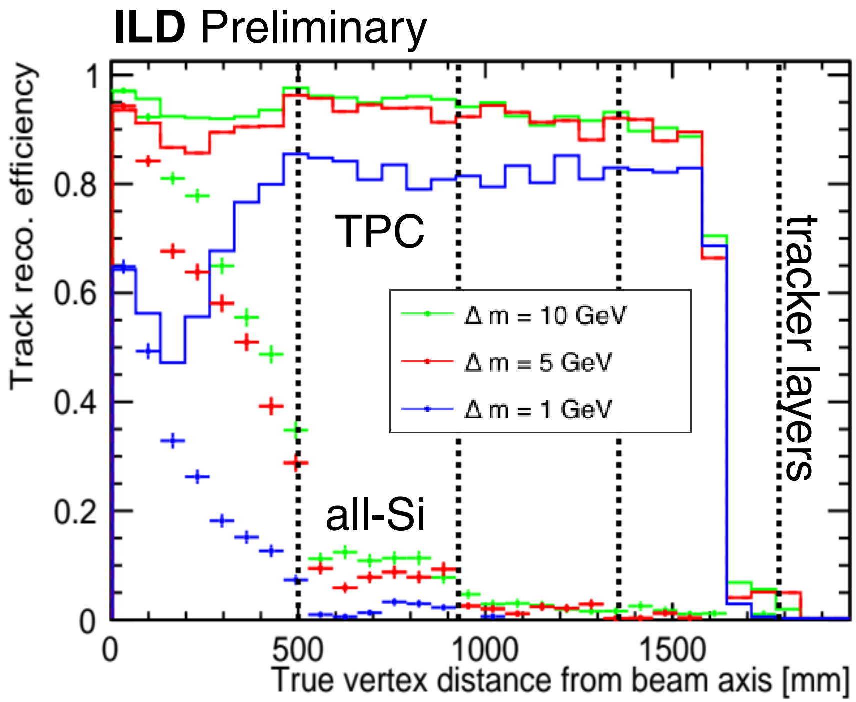
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ 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:

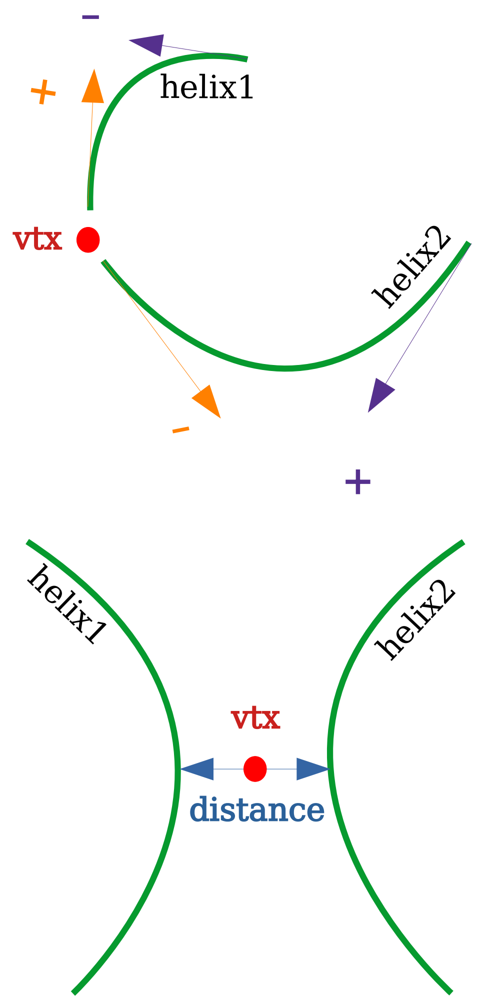
  → use **both track direction** (charge) **hypothesis** for vertex finding

  → consider opposite-charge track pairs only

  → select pair with **closest starting points**

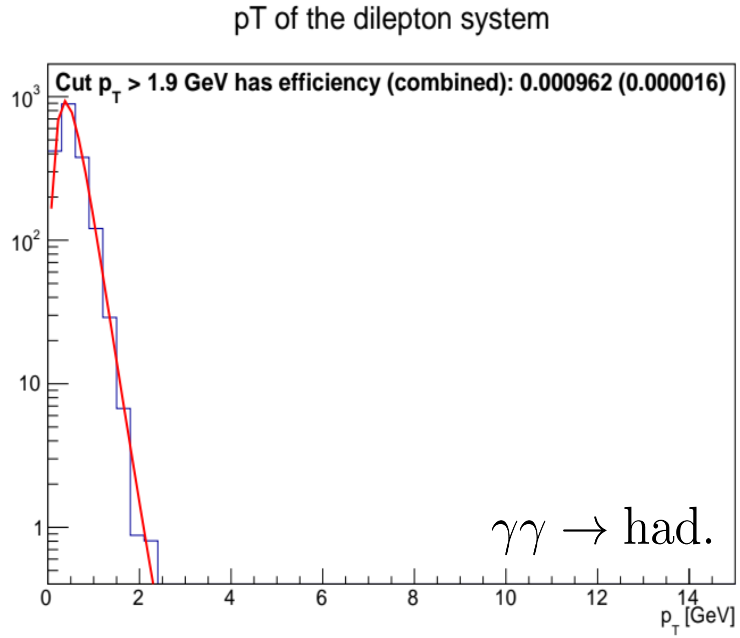
- Reconstruct vertex in **between points of closest approach** of helices

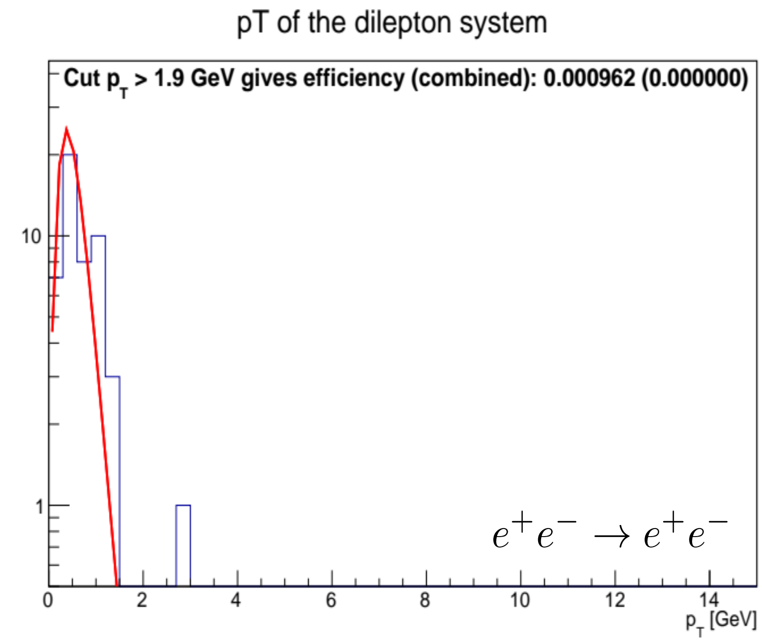
  → Require distance < 25 mm



Final selection – pT

- We consider **γγ → had.** and **e^+e^- samples** separately
- Estimated background eff. from fitted distributions ~10^{-3} (**~10^{-5}–10^{-7}** with preselection)
- Very **small statistics** in **e^+e^- sample** after preselection → fit shape from **γγ → had.** with floating normalisations



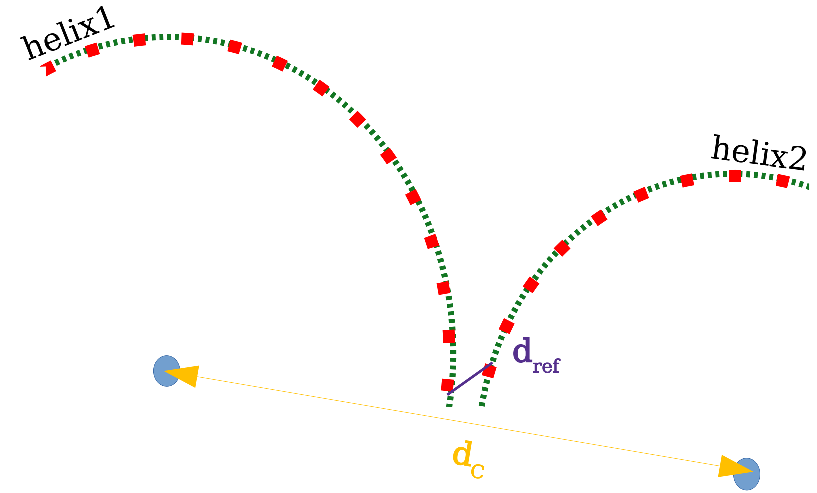


Norm = number of events, scaled by corresponding Poisson expectation values

Final selection – other variables

- At least one more (independent) variable needed to achieve the assumed reduction
- We expect that **signal** tracks should come out of a single point → **reference points should be close**
- In busier backgound events, still many tracks evade the cuts – e.g. curlers, secondary decays

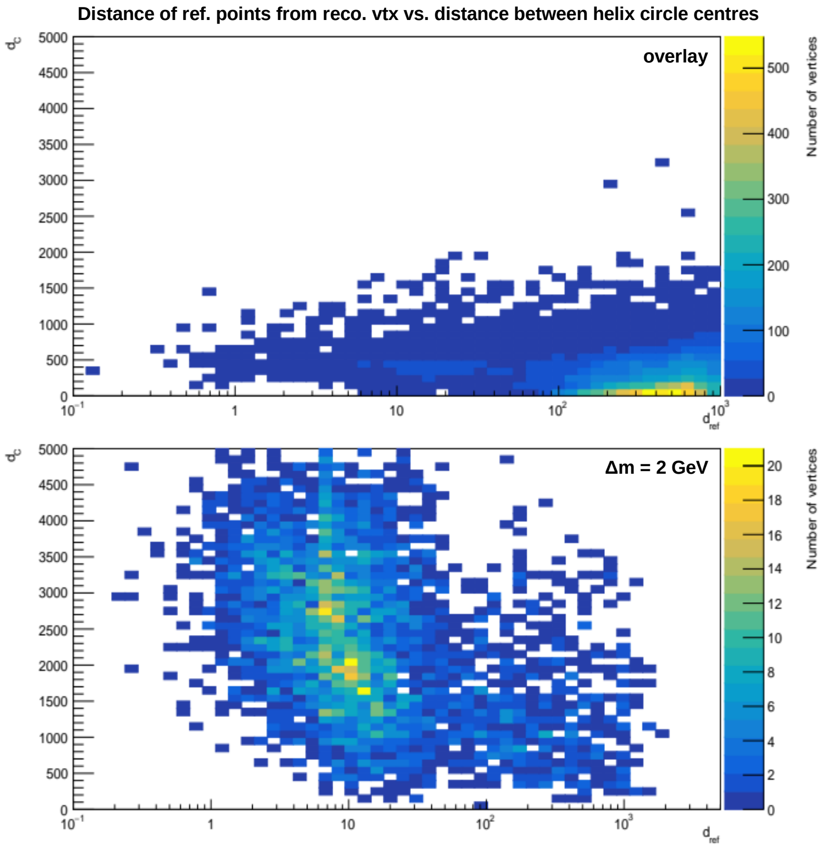
→ either **far reference points** or **close centres of helices**



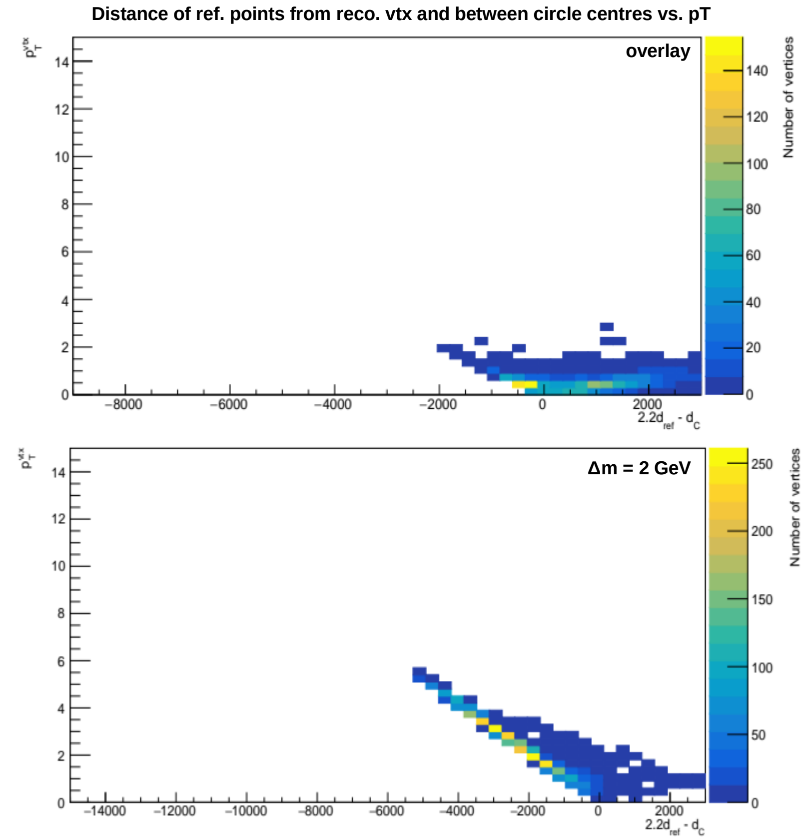
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

Final selection – second variable

- New variable(s) should be uncorrelated with pT to make the cuts independent
- $2.2d_{ref} - d_C$ good for optimal signal-background separation → use it to look for correlation



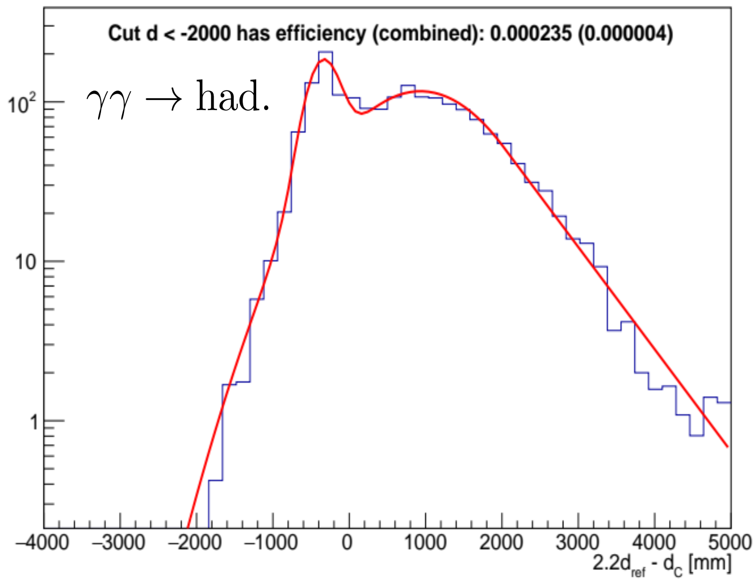
Warp and check correlation with p_T

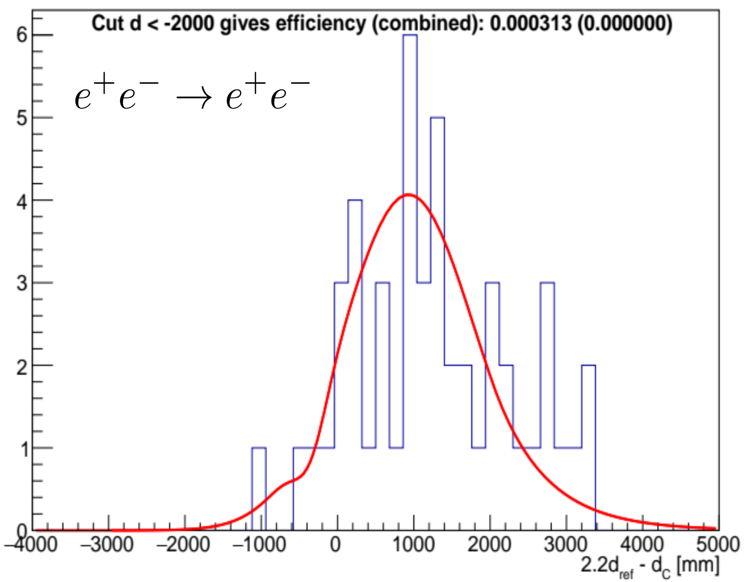


- Small correlation for the background
- Signal strongly correlated

Final selection – second variable

- Same approach as for the pT
- For $2.2d_{ref} - d_C < -2000$ mm, **signal eff. ~37%** ($\Delta m = 2$ GeV)
- Estimated background eff. from fitted distributions ~10^{-4} (**~10^{-6}–10^{-7}** with preselection)
- Total expected efficiency at the level of **~10^{-9}** (~10^{-10}) for **$\gamma\gamma \to$ had.** (**e^+e^- pairs**)





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Selection assuming correlations

For small correlations r between x and y, total selection efficiency can be described as

$$\epsilon_{xy} = \epsilon_y^{(1-r)} \epsilon_x, \ \epsilon_x > \epsilon_y$$

For cuts on $\mathbf{p_T}$ and $\mathbf{2.2d_{ref} - d_C}$ (slide 5), assuming **30% correlation**, for $\gamma\gamma \rightarrow$ had. (e^+e^- pairs) that gives:

- $2.8 \cdot 10^{-6}$ ($3.4 \cdot 10^{-6}$)
- $4.6 \cdot 10^{-8}$ ($1.7 \cdot 10^{-9}$) ← combined with preselection