Higgs decays to long-lived particles with the ILD

J. Klamka, A. F. Żarnecki
University of Warsaw
jan.klamka@fuw.edu.pl

LLPs at the Higgs factories

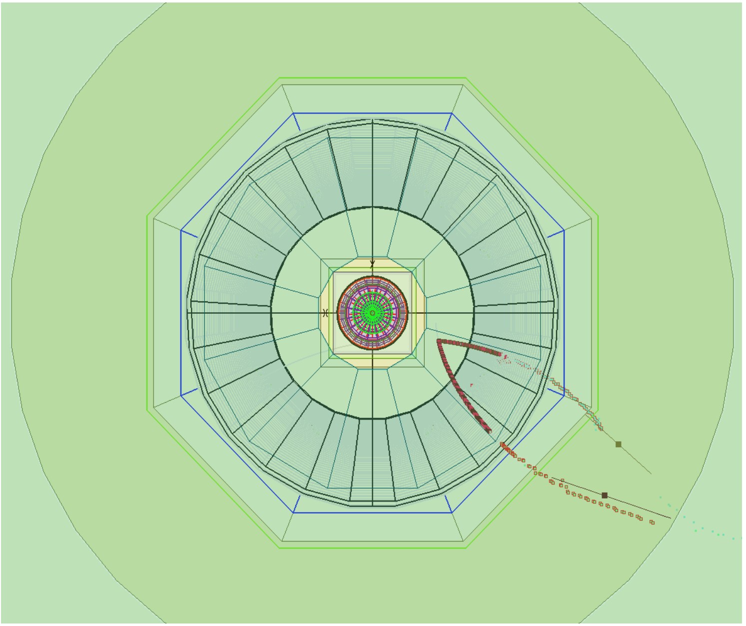
- Multiple LLP searches at the LHC, sensitive to high masses and couplings

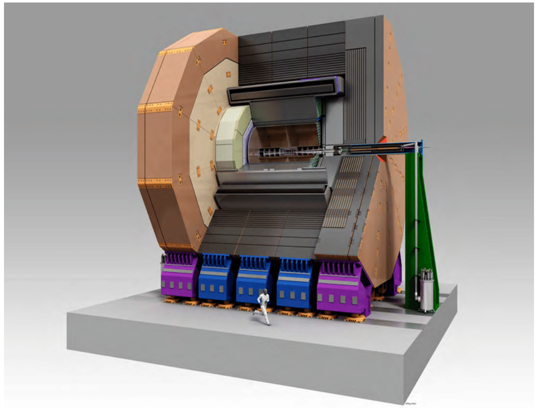
  → complementary region could be probed at **e^+e^- colliders** (**small masses, couplings, mass splittings**)

  → typical properties of feebly interacting massive particles (FIMPs)

- ILD especially promising with a TPC as the main tracker

  → study based on full simulation





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

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

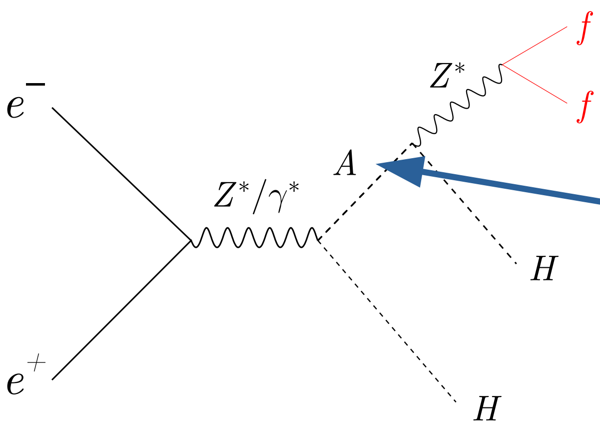
- Focus on a generic case – two tracks from a displaced vertex

- 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: $\sqrt{s} = 250\,\text{GeV}$

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



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

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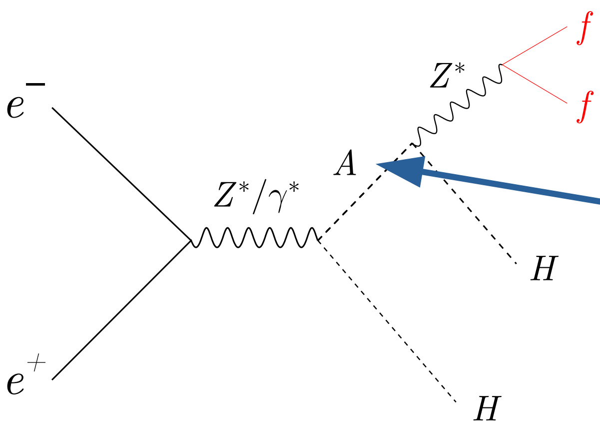


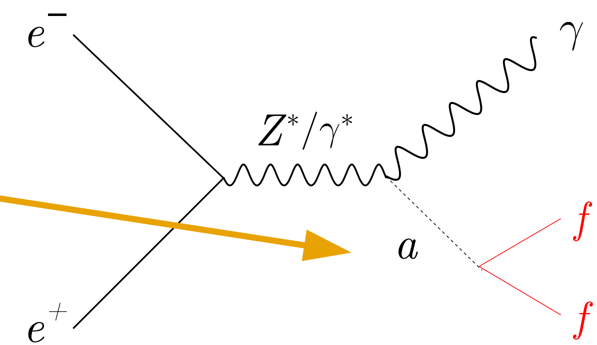
Long-lived, with $c\tau = 1\,\text{m}$

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

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

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

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



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

Backgrounds

Two types of backgrounds considered separately:

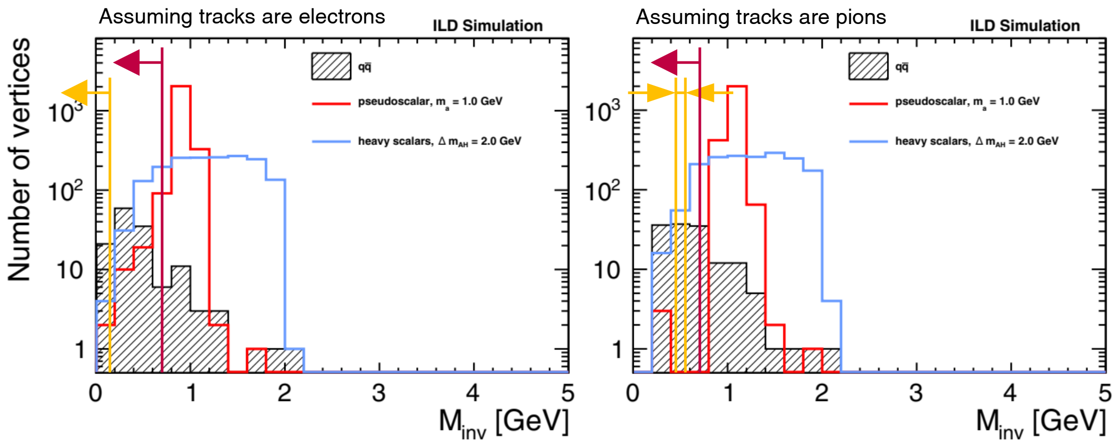
- Overlay events, as a standalone background
  → Very tight selection including vertex quality cuts (fake vtx rejection) and cuts on total vtx p_T
  → Overlay suppression ~10^{-10}, but for Higgs decays overlay negligible (more details later)

- High-p_T physics events with sources that survive overlay selection:
  → Decays of kaons, lambdas, photon conversions (V0s)

High-p_T background

- Matching with V0Finder does not remove sufficient events
- Also semileptonic K0 decays, or poorly reconstructed tracks survive

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



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

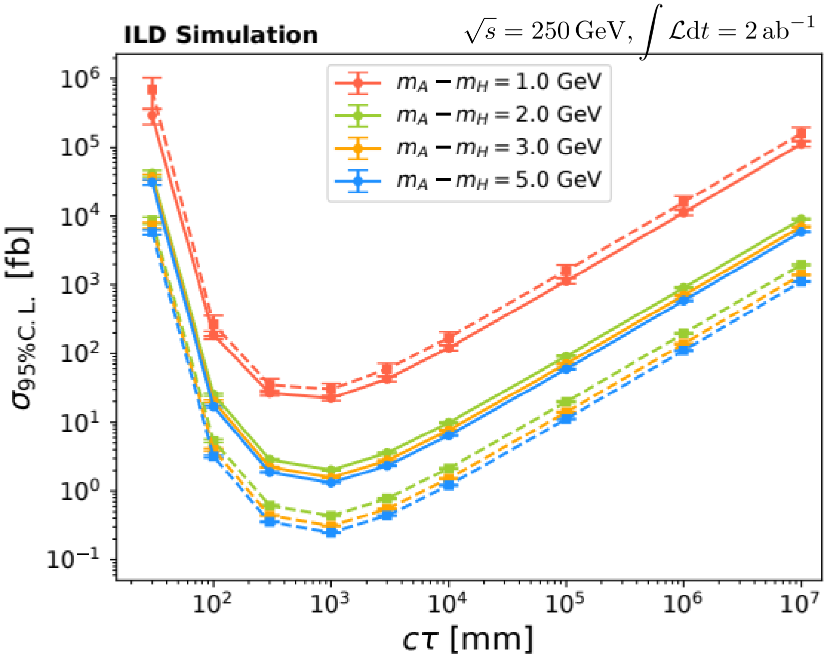
Selection eff. depends on number of jets, so:

Estimate selection efficiency based on full simulation

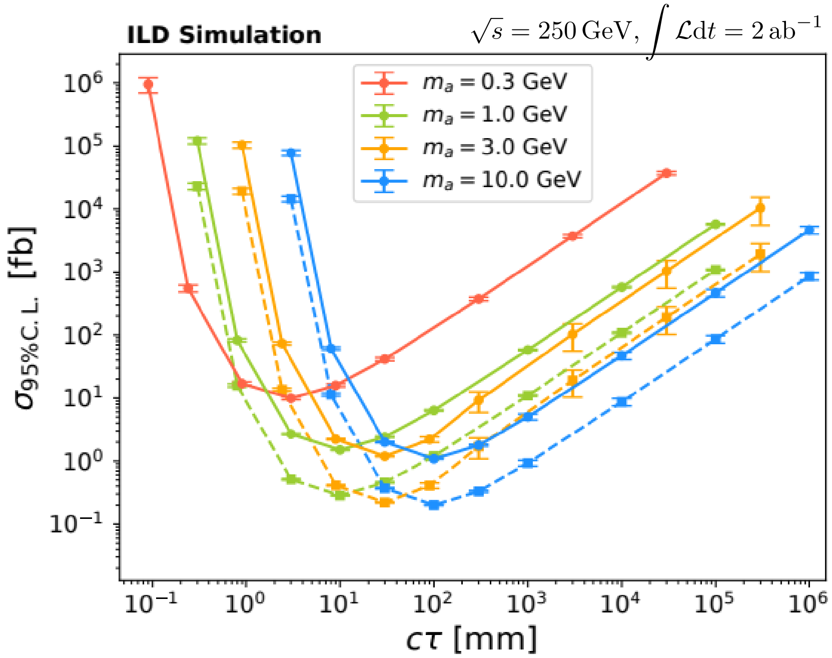
Use qq efficiency for the remaining processes

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

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

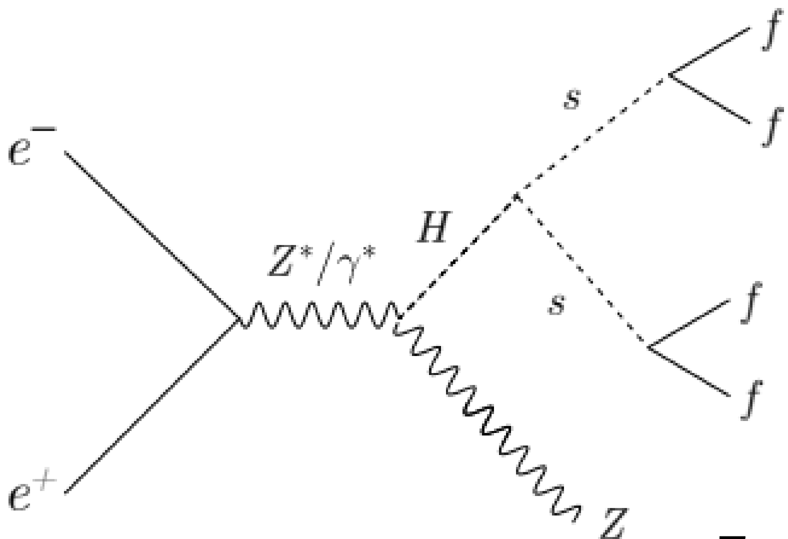
arXiv:2409.13492

Higgs decays to LLPs

Signal scenarios

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

Note: here overlay not added before the reconstruction

Use the same analysis procedure, but further optimise for this channel

Strategy

This time add constraints to optimise the search for HZ → Hνν channel

→ we expect at least one displaced vertex and nothing else

On top of all previous cuts, in each event require no prompt tracks with:

- $p_T > 2$ GeV
- $R_{fhit} < 20$ mm (barrel), or $R_{fhit} < 155$ and $215 < |Z_{fhit}| < 225$ (endcap)
- $|d0| < 10$ or $|z0| < 10$

In addition, for each vertex require total $p_T^{vtx} > 10$ GeV of tracks forming the vtx
→ allows to fully neglect hard γγ and overlay events

Because the statistics in samples becomes very low, assume the cuts above are orthogonal to cuts on invariant mass windows corresponding to V0 particles

→ estimate the efficiencies independently and combine

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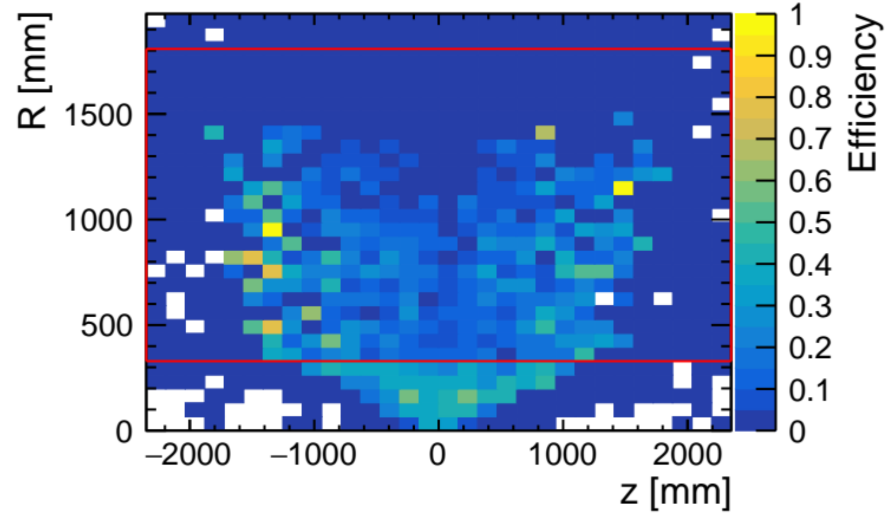
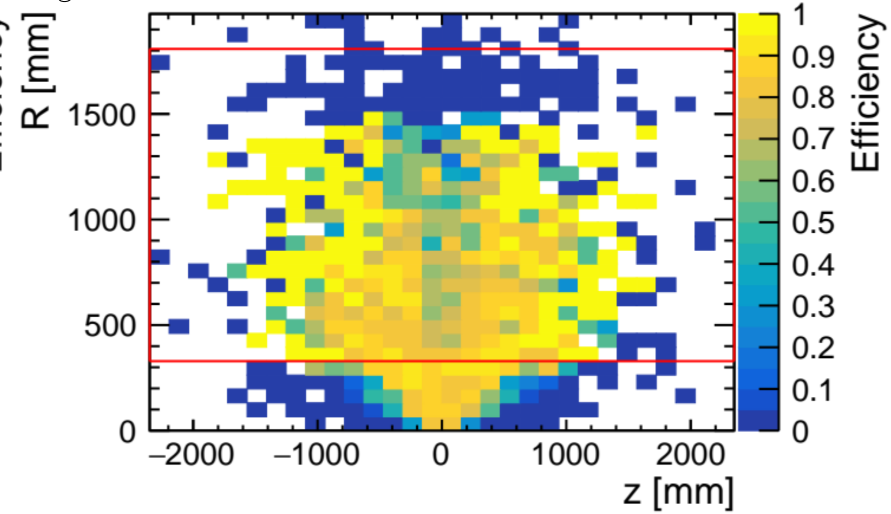
Even with this approach, the number of events after the above cuts is 0 in all simulated samples
→ conservatively assume 3 events remaining in each MC sample (95% C.L.) → ~16 bg. ev. expected

Vertex finding results

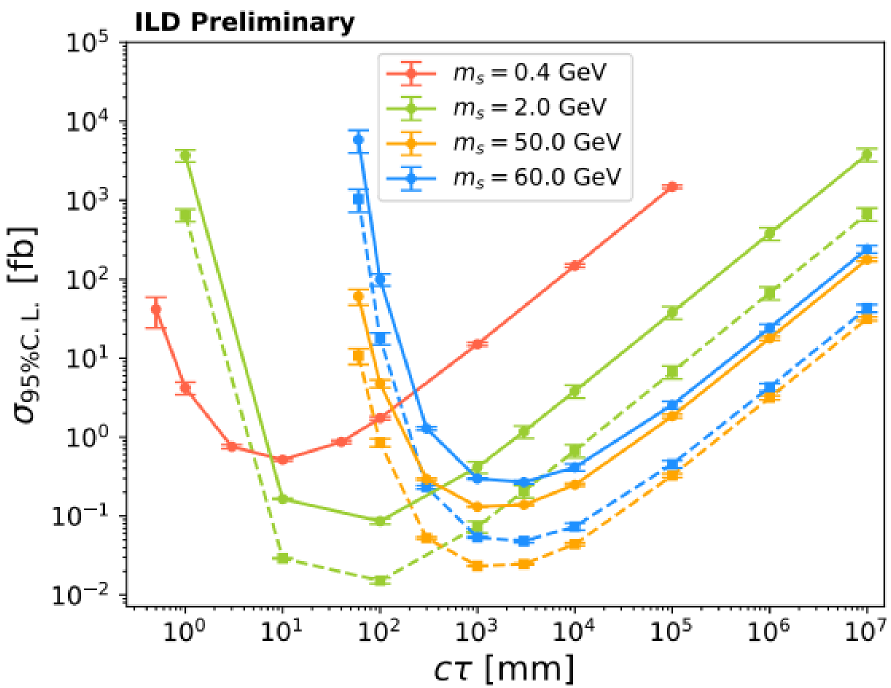
m_s	0.4 GeV	2 GeV	50 GeV	60 GeV
Efficiency (standard)	7.8%	52.2%	34.6%	18.5%
Efficiency (tight)	0%	52.2%	34.3%	18.1%

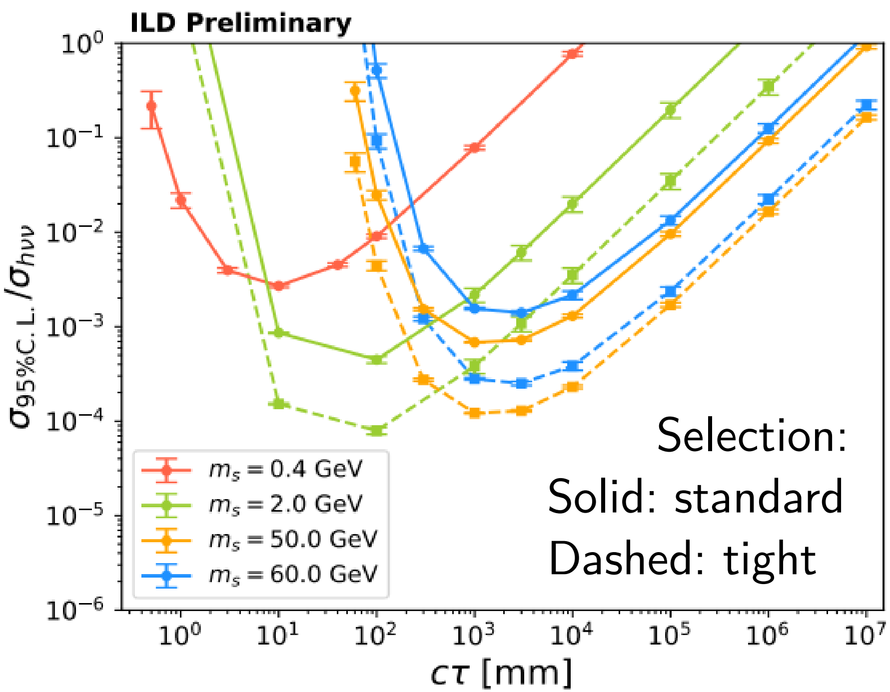




- Efficiency = (correct / decays within TPC acceptance), "correct" if distance to the true vtx < 30 mm
- Tight selection cut on invariant mass assuming tracks are pions/electrons, M > 700 MeV, "kills" the 400 MeV scenario, the rest of scenarios remain almost intact

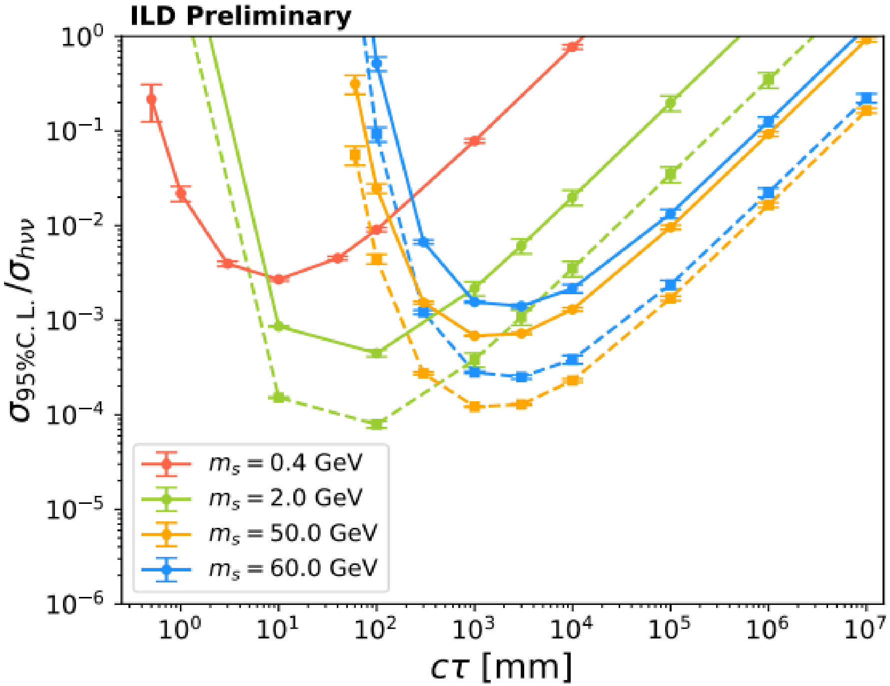
95% C.L. limits

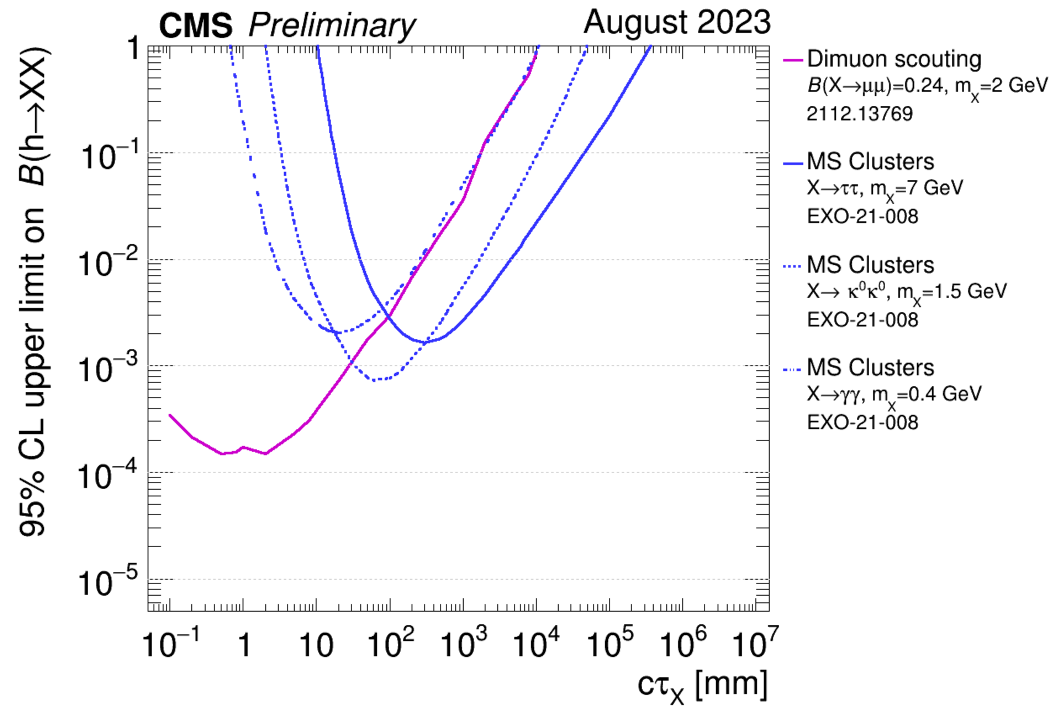




- As before: event reweighting performed to obtain limits for a range of scenarios
- Branching ratios at 10^{-4} can be probed even up to decay lengths above 10 m

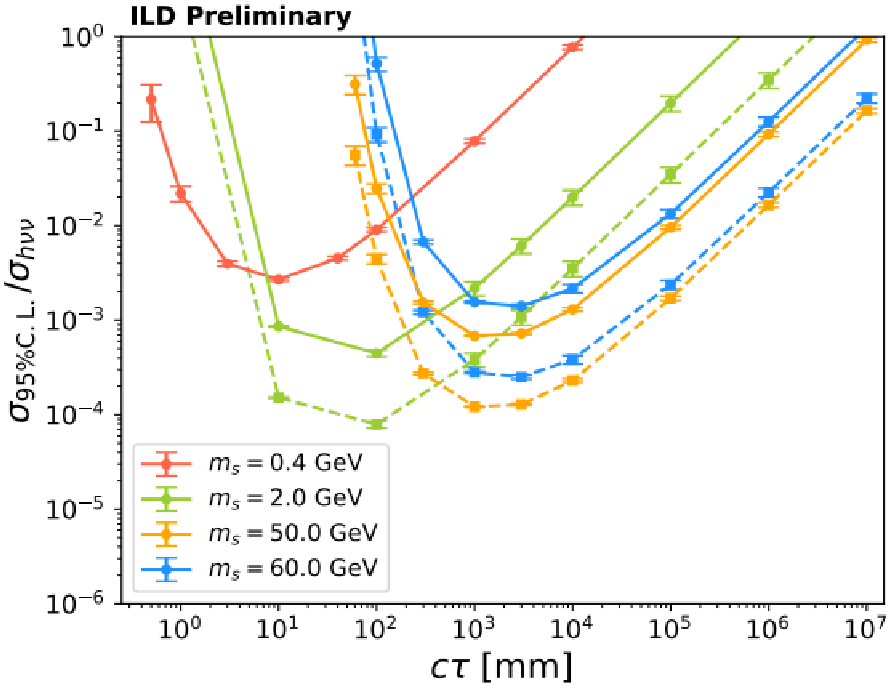
95% C.L. limits

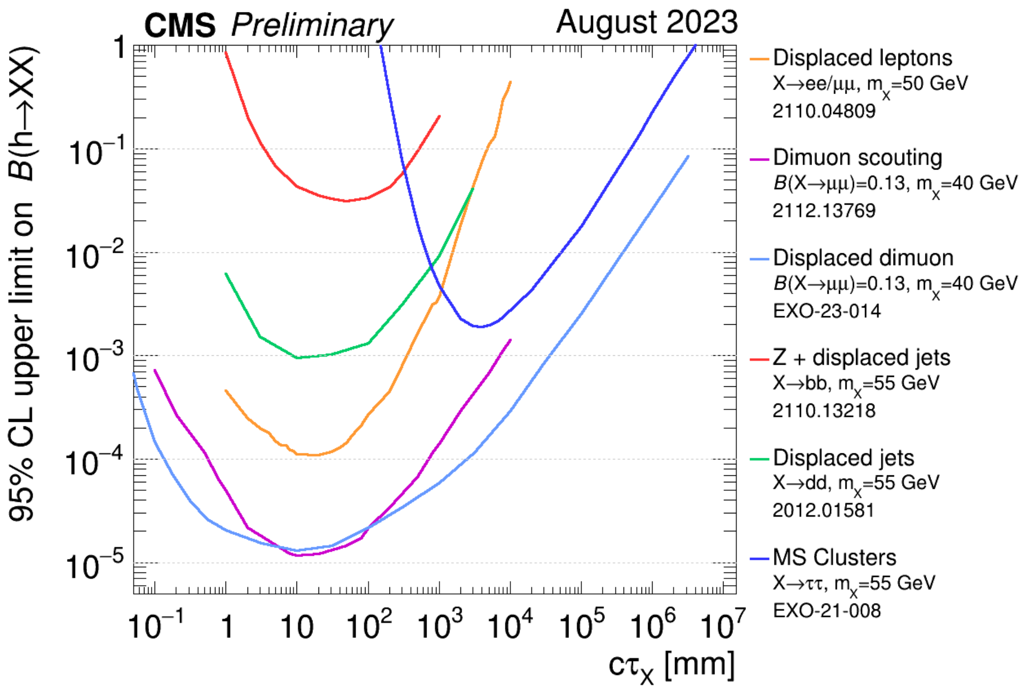




- ILD @ ILC250 can improve the CMS reach for higher lifetimes thanks to TPC acceptance, but does not go down with the current limit
- This could be improved by searches using vertex detector and more data at higher energies

95% C.L. limits





- With different assumptions, CMS can provide even better limits
- For higher masses, ILD again improves the reach for higher lifetimes

Summary

- LLP analysis extended to Higgs decays to long-lived scalars
- Channel-specific cuts added assuming $HZ \rightarrow H\nu\nu$ decay
- Conservative estimates show ILD @ ILC250 can extend existing limits to higher lifetimes with minimal assumptions
- In more optimistic scenario with zero-background regime, the limits could be improved by almost an order of magnitude

BACKUP

Vertex finding strategy

Approach as simple and general as possible:

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

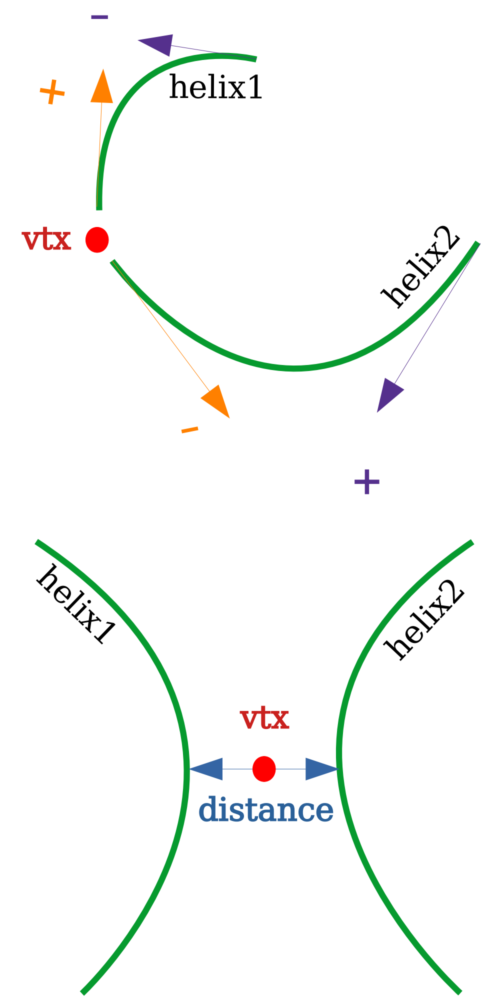
  → use **both track direction** (charge) **hypothesis** for vertex finding

  → consider opposite-charge track pairs only

  → select pair with **closest starting points**

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

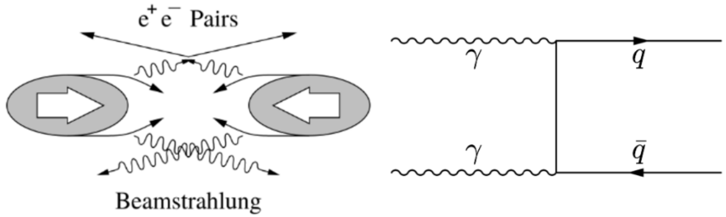
  → Require distance < 25 mm



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 (BXs) at ILC, produced are:

- **1.55 $\gamma\gamma$ → 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

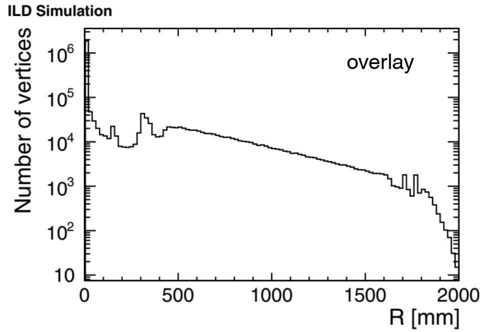
...but can also look like signal on their own

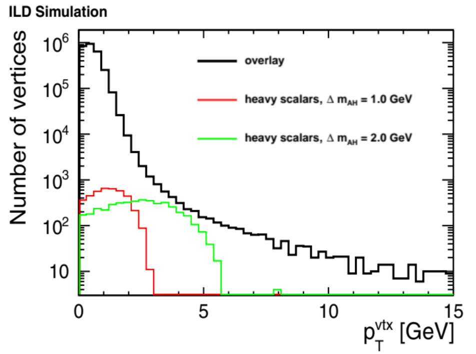
- ~10^{11} BXs per year at ILC → overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy

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

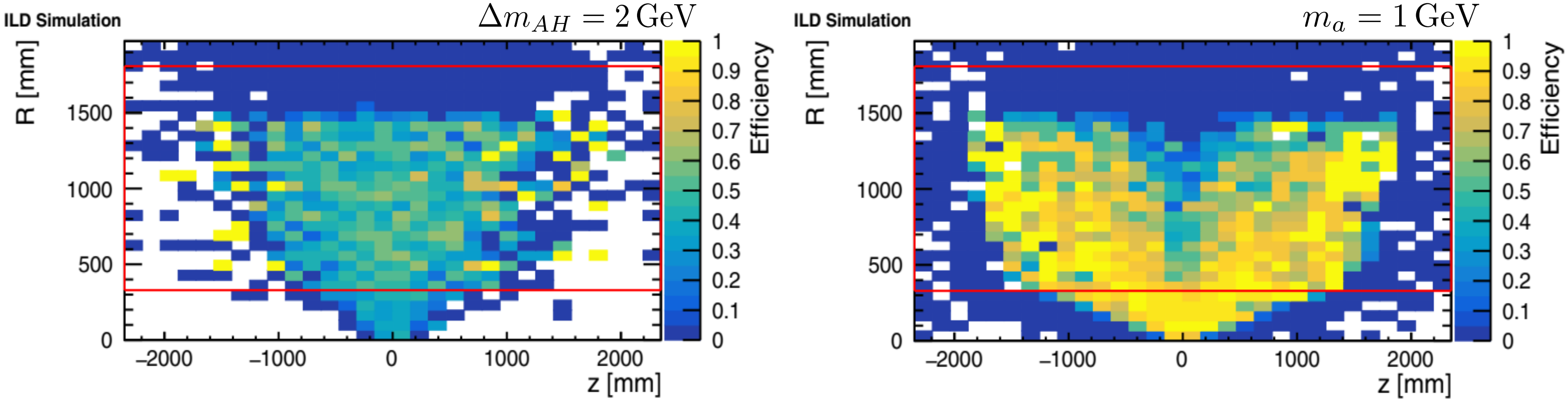
  → significant background

- 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^{-9}**





Vertex finding results

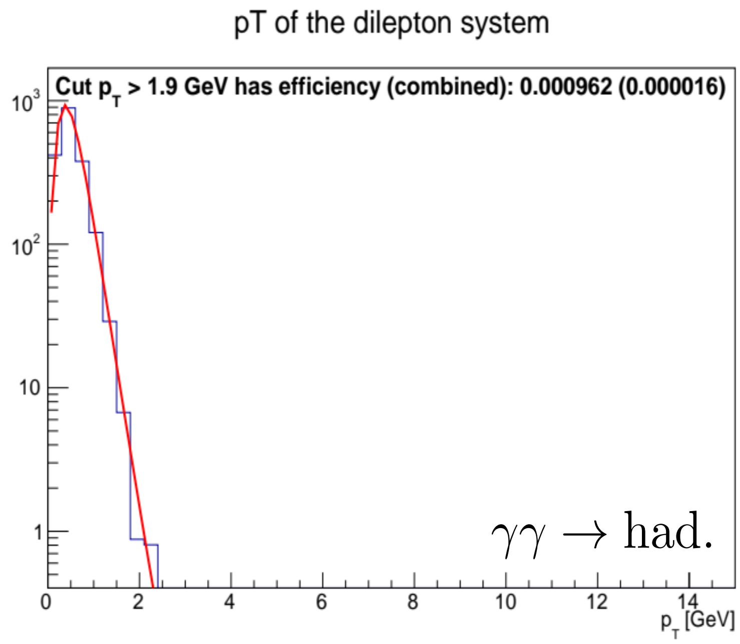


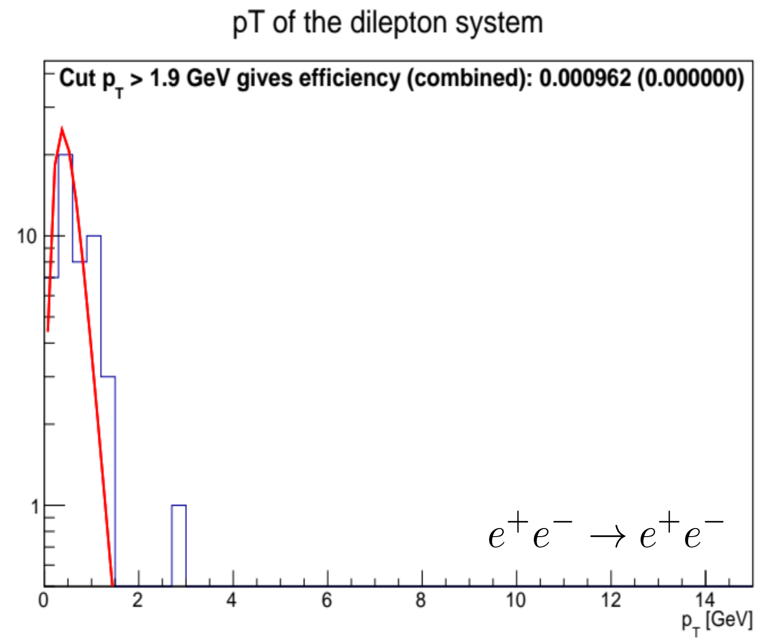
Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

- 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

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



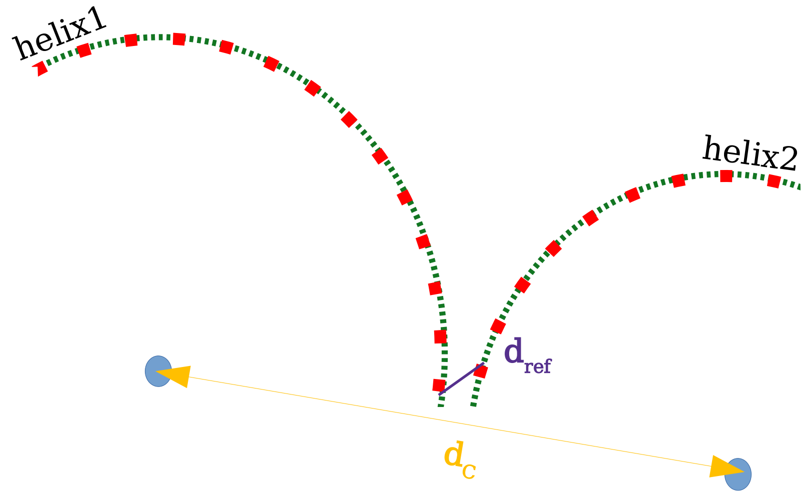


Norm = number of events, scaled by corresponding Poisson expectation values

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

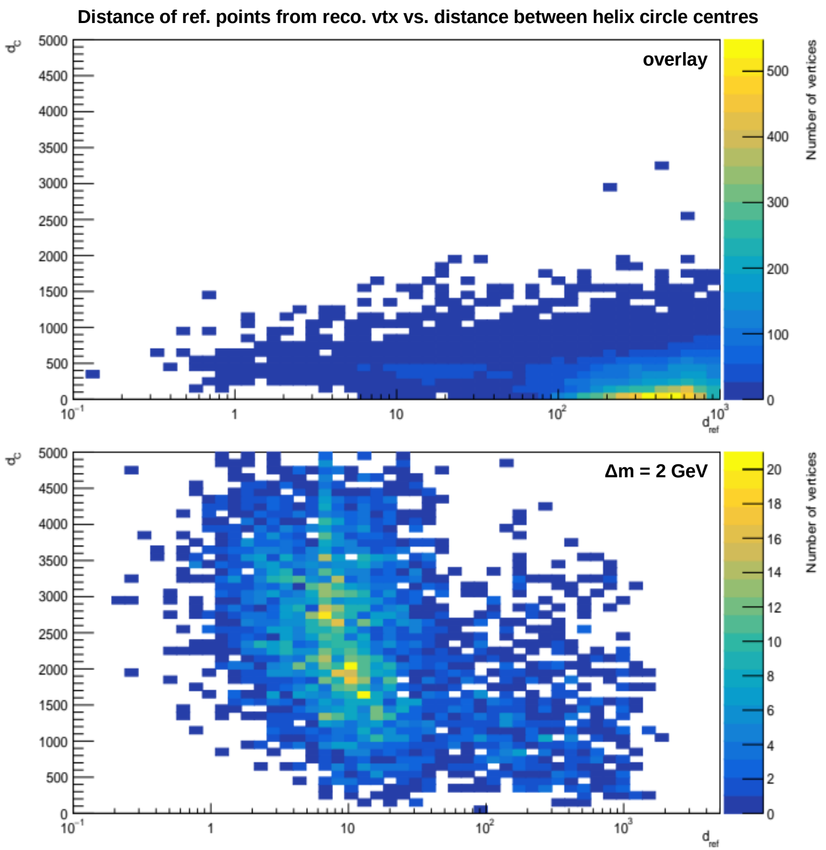
→ either **far reference points** or **close centres of helices**



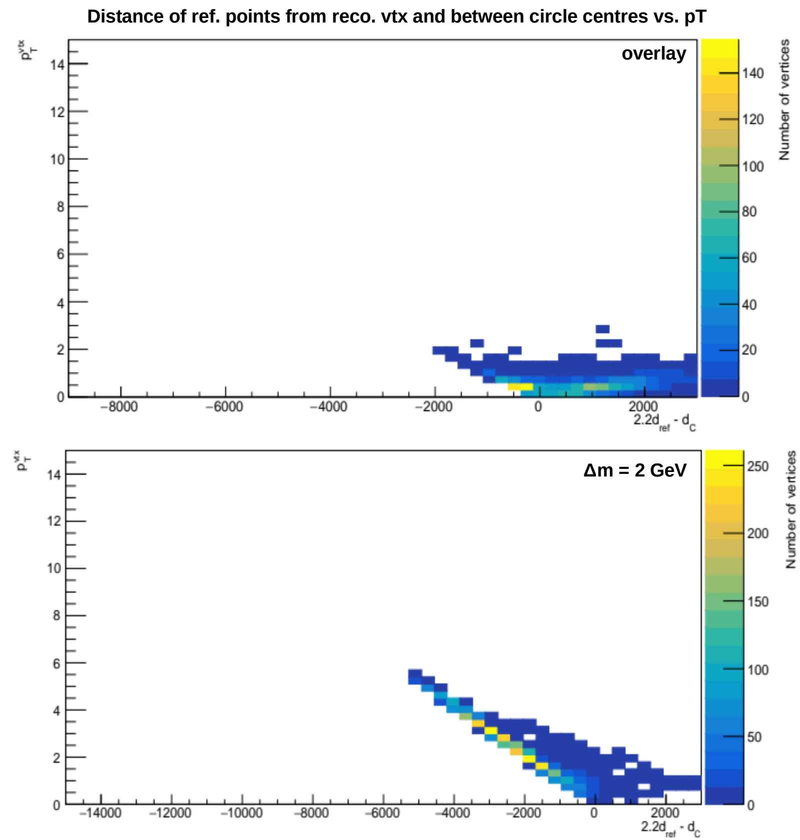
- $\mathbf{d}_{\mathbf{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d}_{\mathbf{C}}$ – distance between centres of helices projections into XY plane

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



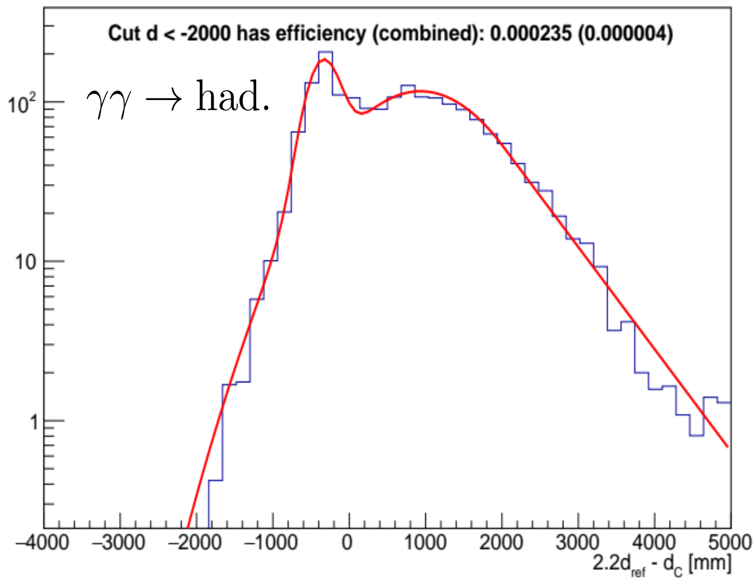
Warp and check correlation with p_T

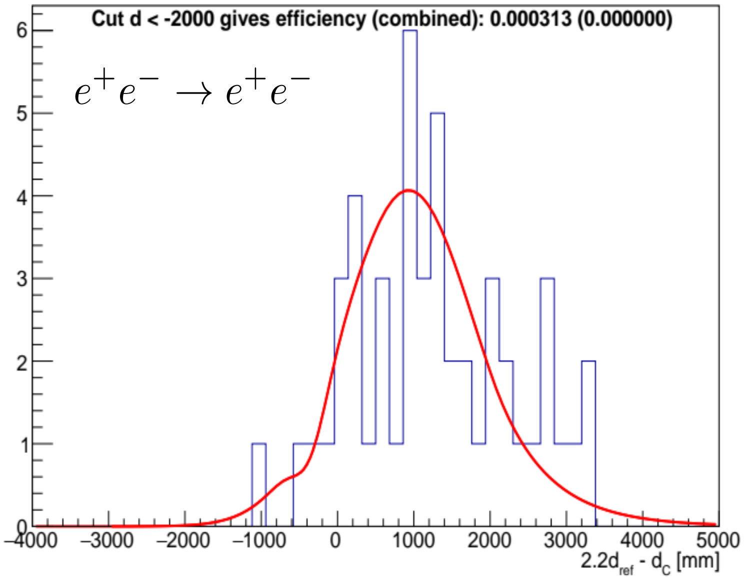


- Small correlation for the background
- Signal strongly correlated

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 **$\gamma\gamma \rightarrow$ had.** (**e^+e^- pairs**)





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

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