# Long-lived particle searches with the ILD experiment

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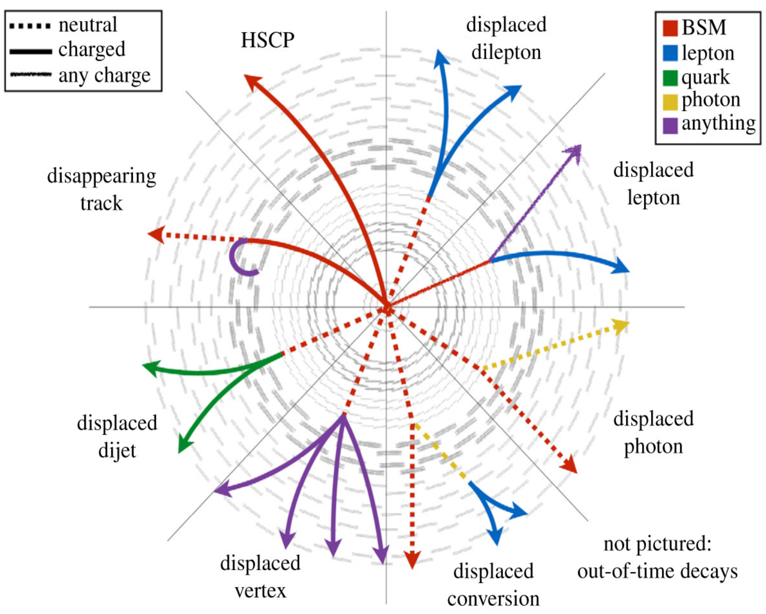
## Particles with macroscopic lifetimes naturally appear in numerous BSM models

Three main mechanisms are responsible for that...

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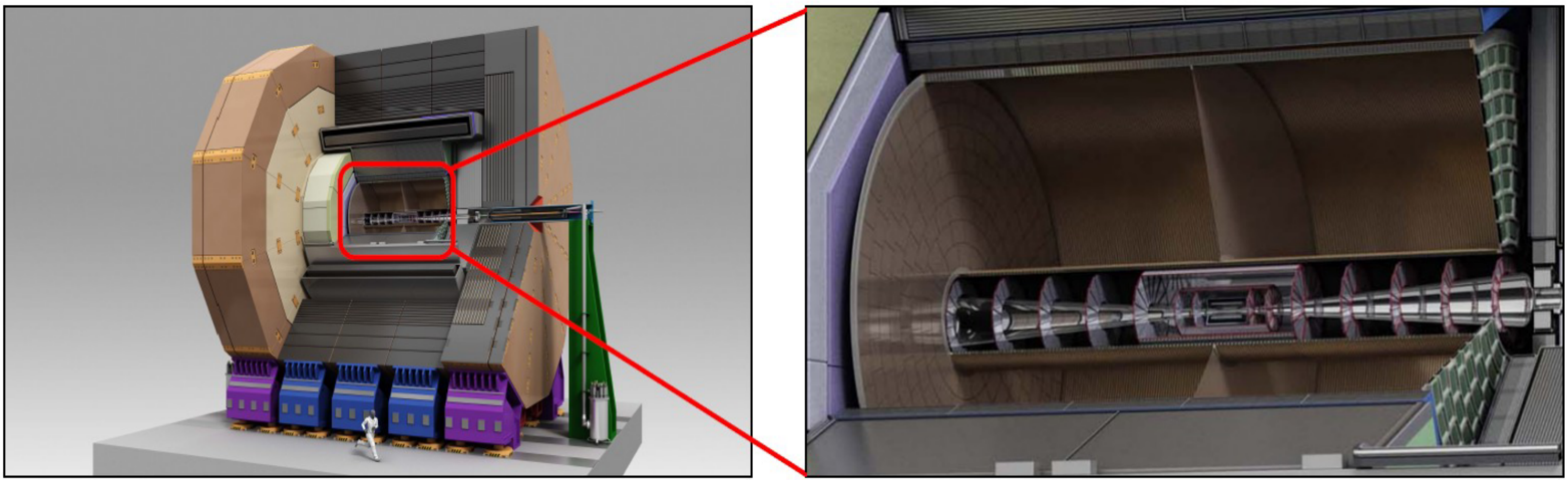
| | | Small coupling | Small phase space | Scale suppression |
|---|---|---|---|---|
| SUSY | GMSB | | | ✓ |
| | AMSB | | ✓ | |
| | Split-SUSY | | | ✓ |
| | RPV | ✓ | | |
| NN | Twin Higgs | ✓ | | |
| | Quirky Little Higgs | ✓ | | |
| | Folded SUSY | | ✓ | |
| DM | Freeze-in | ✓ | | |
| | Asymmetric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

1810.12602

→ ...but they authomatically make it challenging for hadron colliders to search for LLPs

# 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



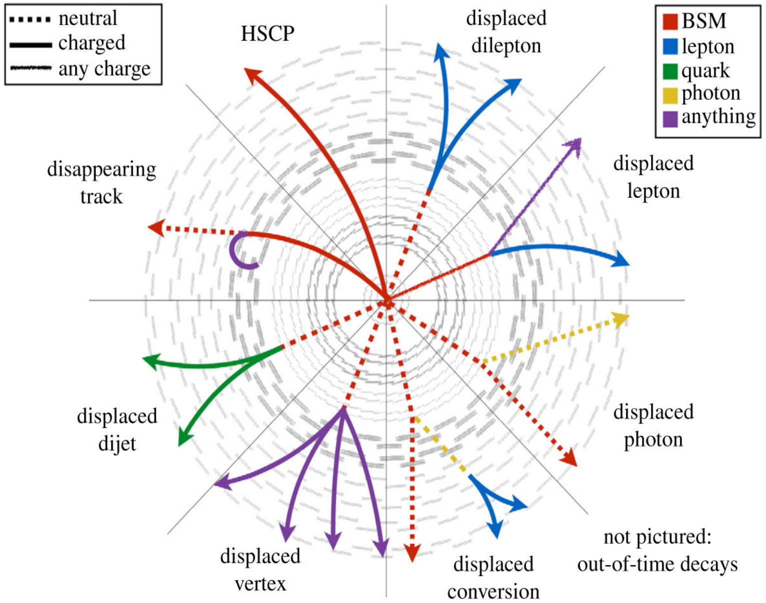
# LLPs at the Higgs factories

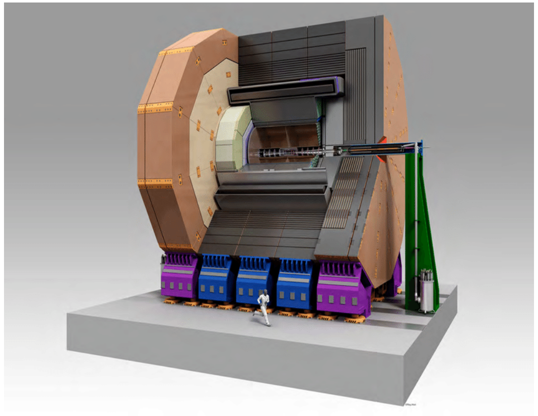
- Multiple LLP searches at the LHC, sensitive to high masses and couplings

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

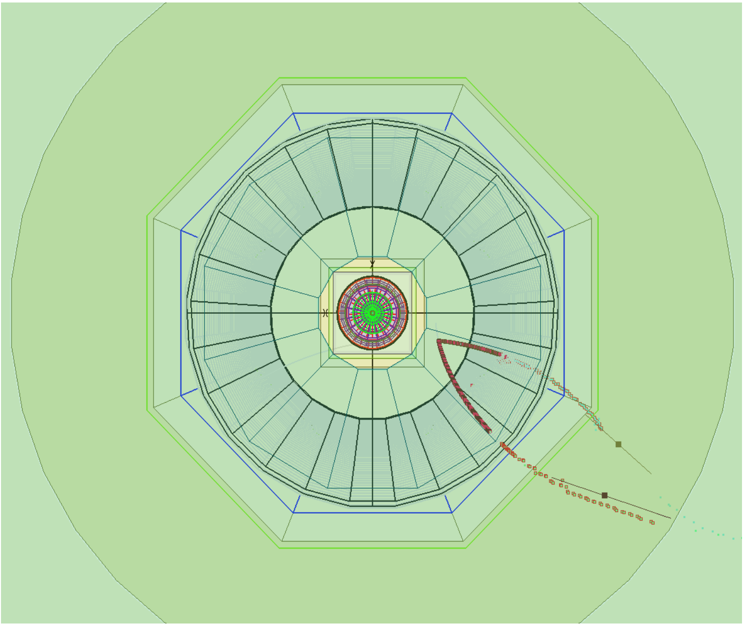
  → typical properties of feebly interacting massive particles (FIMPs)

- ILD potentially promising with a TPC as the main tracker (almost continous tracking)



# LLPs at the Higgs factories



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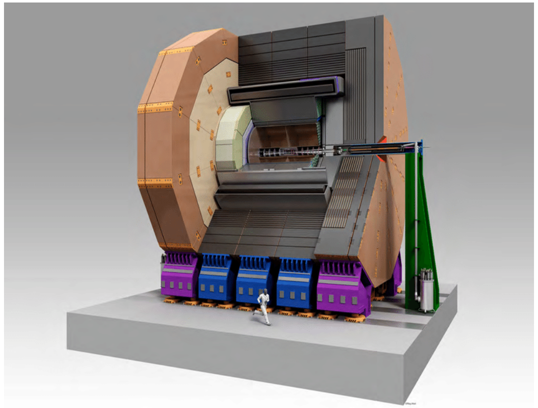


- Study such challenging signatures from the **experimental perspective**

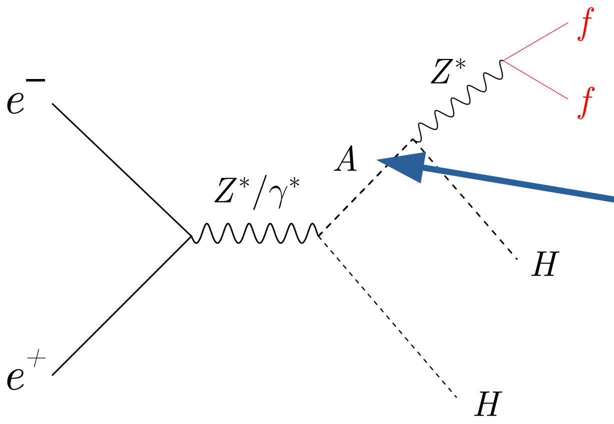
  → experimental/kinematic properties, not points in a model parameter space

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

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




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

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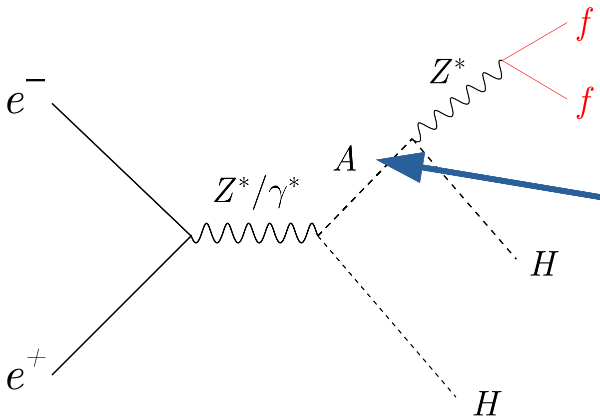


Long-lived, with $c\tau = 1\,\mathrm{m}$

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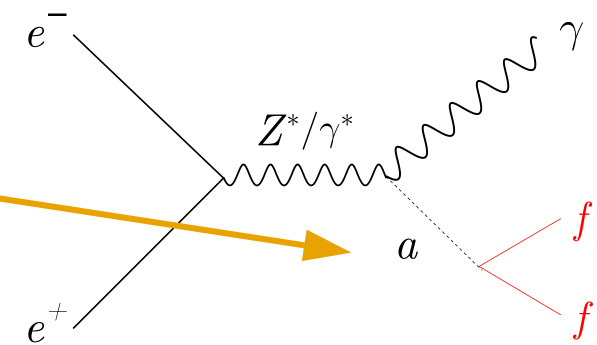
Long-lived, $c\tau = 10 \cdot m_a\,[\mathrm{mm}]$

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




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**

# Vertex finding strategy

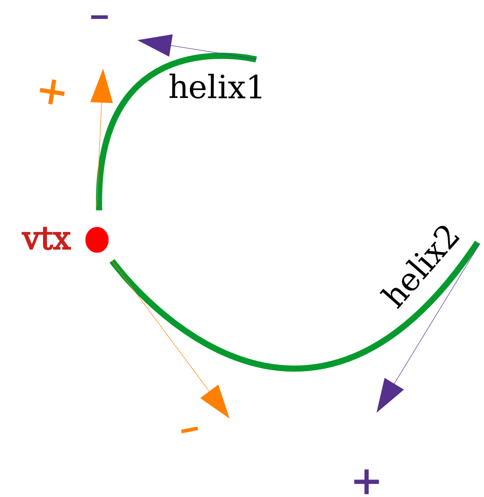
<u>Approach as simple and general as possible:</u>

- 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

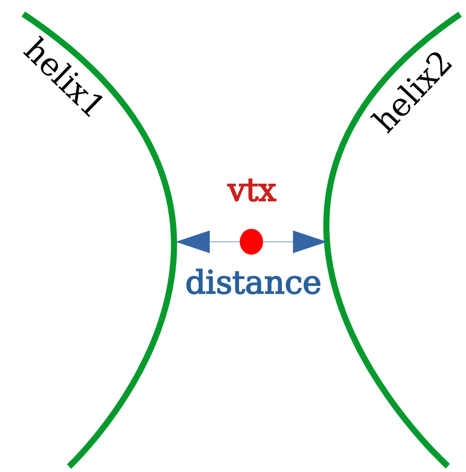
  → select pair with **closest starting points**




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

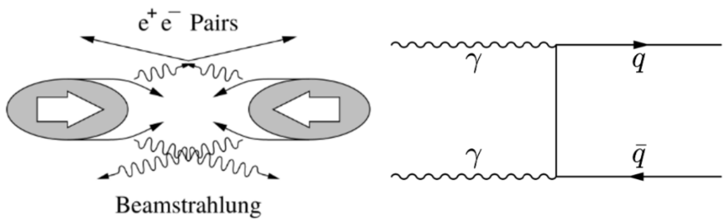
  → Require distance < 25 mm

- Cuts for background suppression (slides 9-12) improve quality
- Vtx reconstructed from two tracks, but more tracks starting nearby are allowed



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 $\gamma\gamma \to$ 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 "hard" events

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

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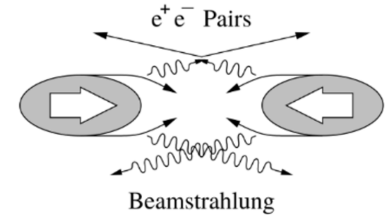


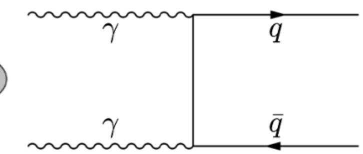


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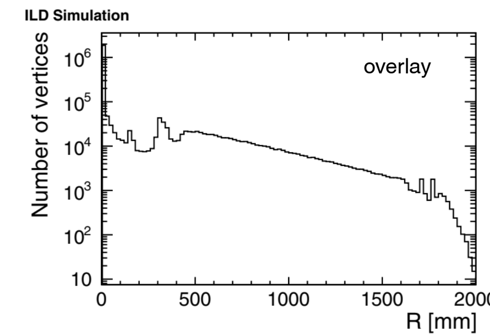
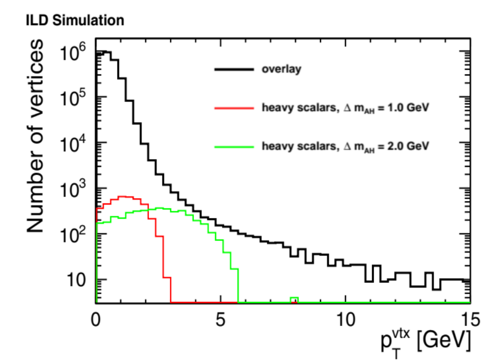
- ~$10^{11}$ BXs per year at ILC → overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy

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

  → significant background



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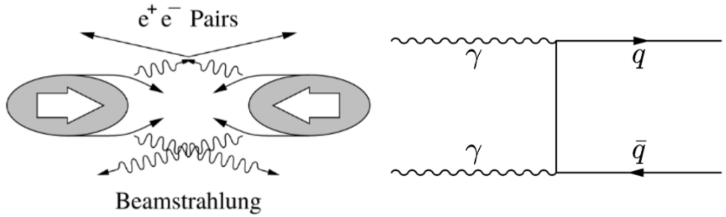


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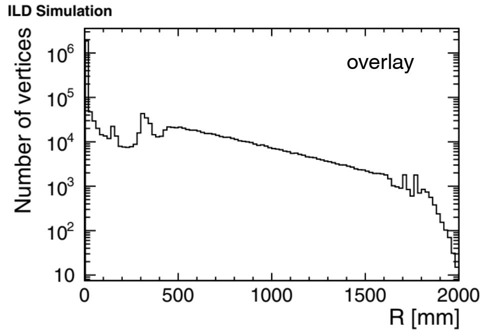
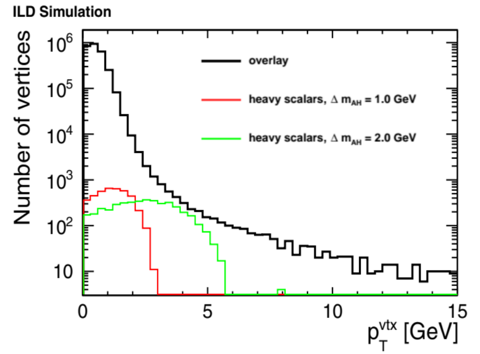



- Can be suppressed using cuts on the track pair geometry and $p_T > 1.9$ GeV
- Total expected reduction factor at the level of **~$10^{-9}$**

# 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

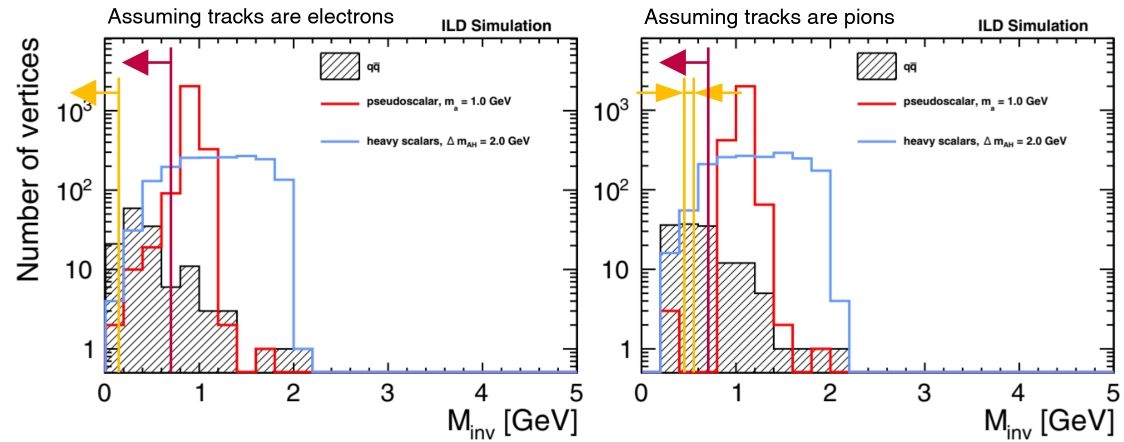
They occur mainly inside jets, so we consider (hard) $e^+e^-$ and $\gamma\gamma$ processes with jets in final state

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

Selection eff. depends on number of jets, so:

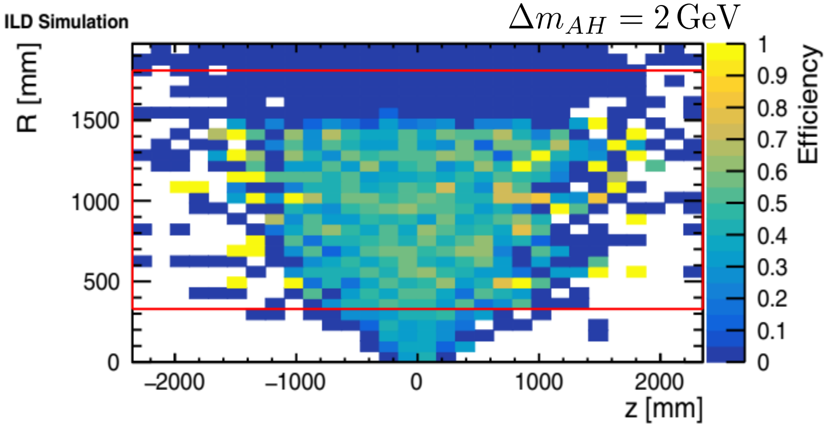
Estimate selection efficiency based on full simulation

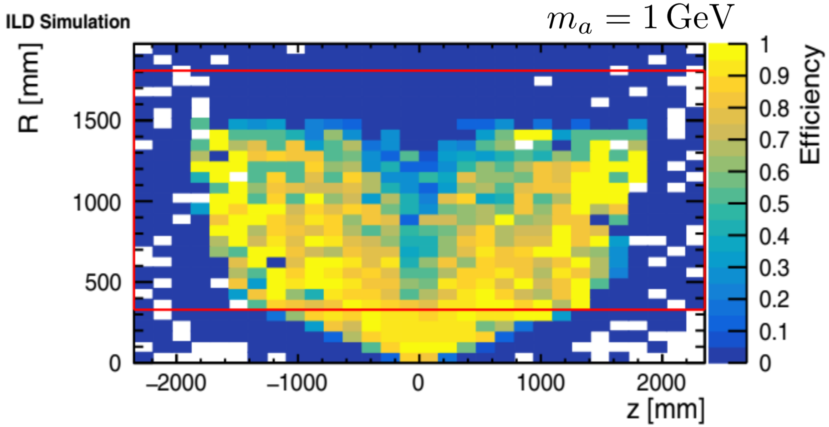
Use qq efficiency for the remaining processes




| sgn(P($e^-$), P($e^+$)) | $(-,+)$ | $(+,-)$ | $(-,-)$ | $(+,+)$ |
|---|---|---|---|---|
| channel | | $\sigma$ [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 |

# Vertex finding results

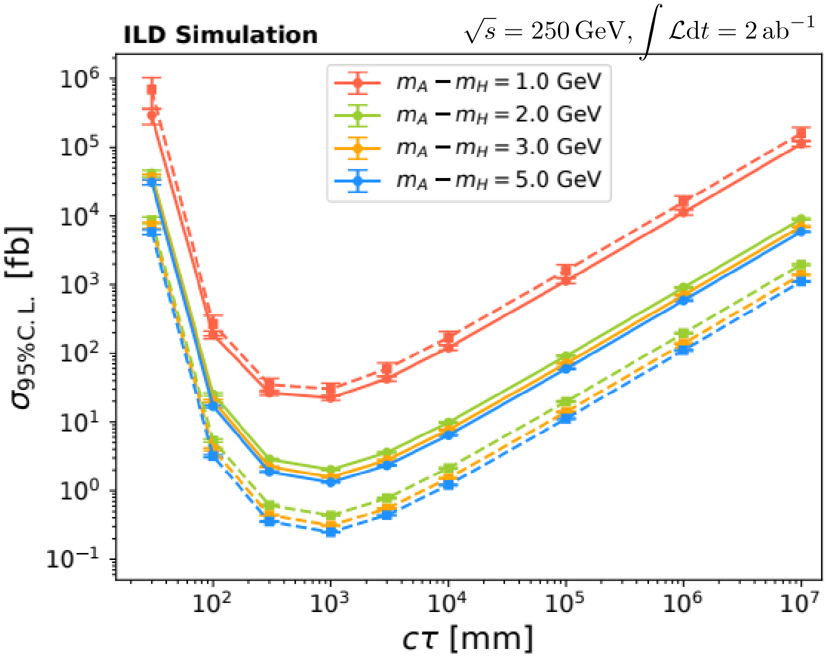


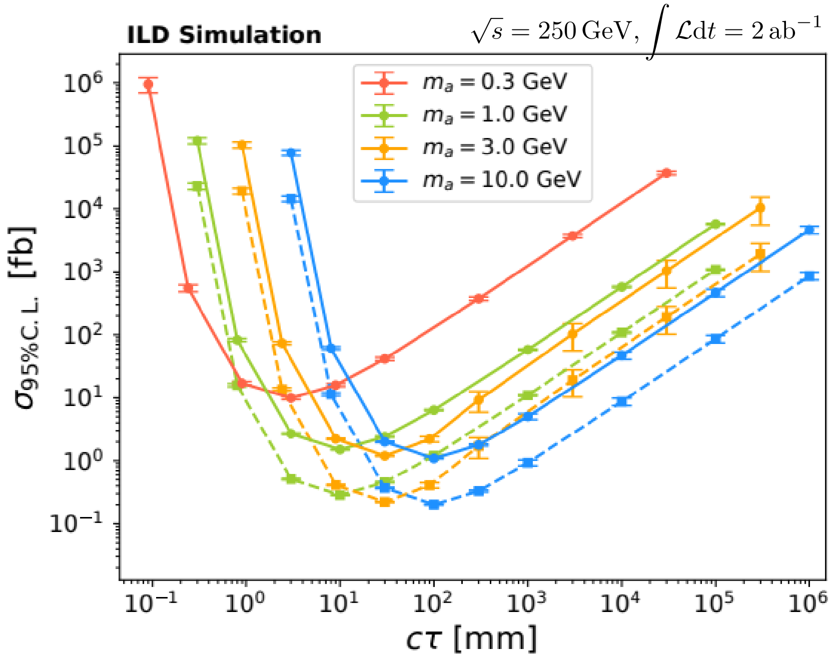

| $\Delta m_{AH}$ [GeV] | 1 | 2 | 3 | 5 |
|---|---|---|---|---|
| Efficiency (standard) [%] | 3 | 33.2 | 43.4 | 51.1 |
| Efficiency (tight) [%] | 0.4 | 28.3 | 40.7 | 50.2 |
| $m_a$ [GeV] | 0.3 | 1 | 3 | 10 |
| Efficiency (standard) [%] | 7.4 | 48.4 | 61.7 | 65.8 |
| Efficiency (tight) [%] | – | 47.3 | 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 $\Delta m_{AH}$ = 1 GeV and $m_a$ = 300 MeV scenarios

# Cross section limits




Heavy scalars



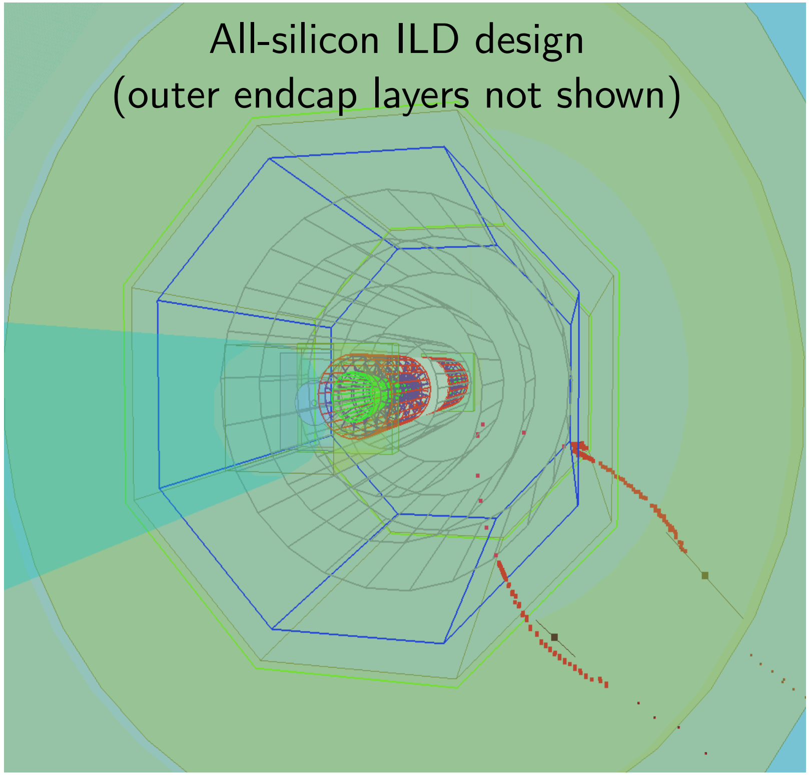

Light pseudoscalar

- 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

# Alternative all-silicon ILD design

Alternative ILD design implemented for tests

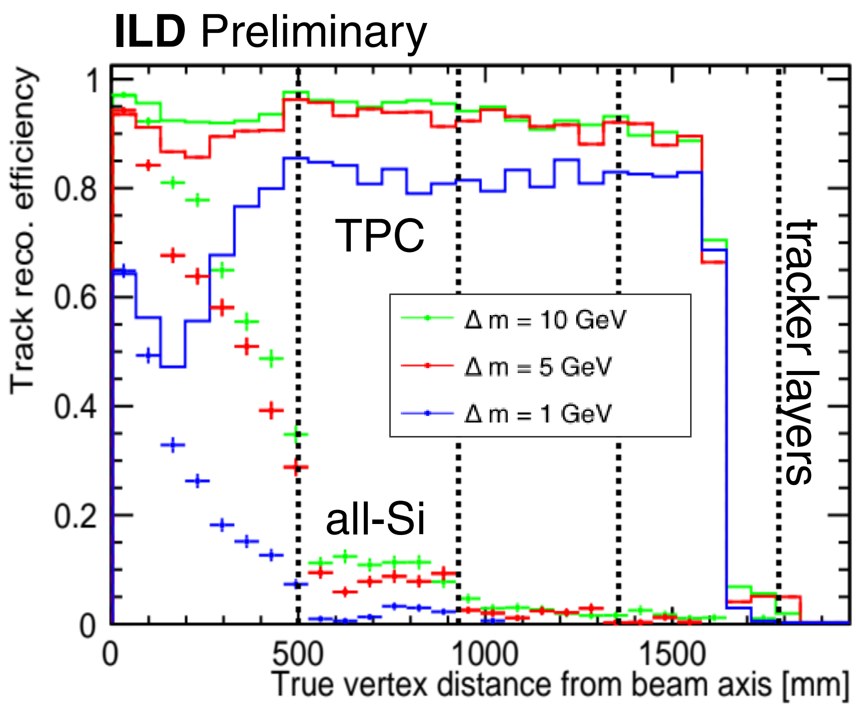
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD




→ 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**



# Summary

- We study LLPs in parameter space regions complementary to LHC searches
- Inclusive search for **two tracks** from a **displaced vertex** (more complex signatures allowed)

  → a simple vertex-finding algorithm developed, with a set of cuts aimed to suppress background from the overlay events and hard SM processes

- For heavy scalars production, with **small mass splittings** between LLP and DM and **low-momenta decay products**, good sensitivity from $\Delta \mathbf{m} = \mathbf{2}$ **GeV**
- Reconstruction of **highly boosted**, **light** pseudoscalar decaying into muons performed with the same algorithm and procedure indicates good sensitivity for **masses** $\geq$ **1 GeV**
- Estimated 95% CL limits on signal cross section indicate ILD's high reach for a wide range of lifetimes (0.003-10 m, depending on a scenario)

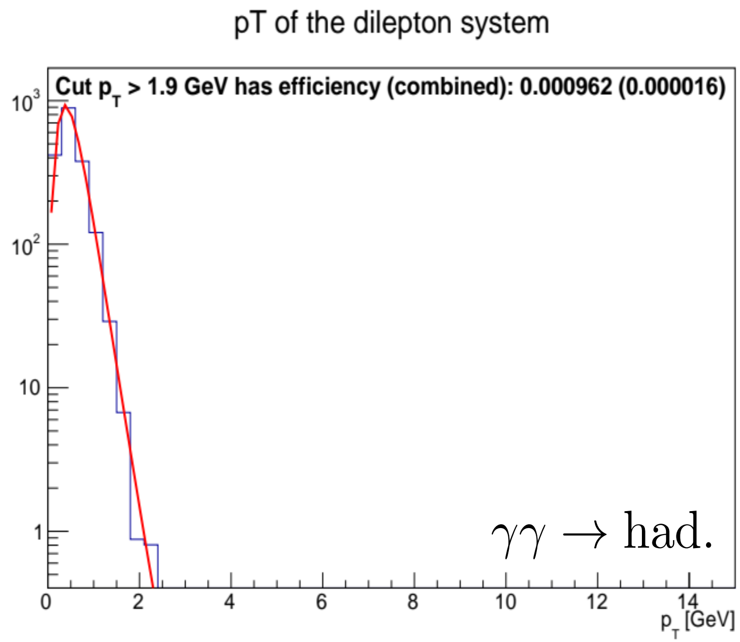
- Alternative ILD design used for comparison between all-silicon tracker and TPC

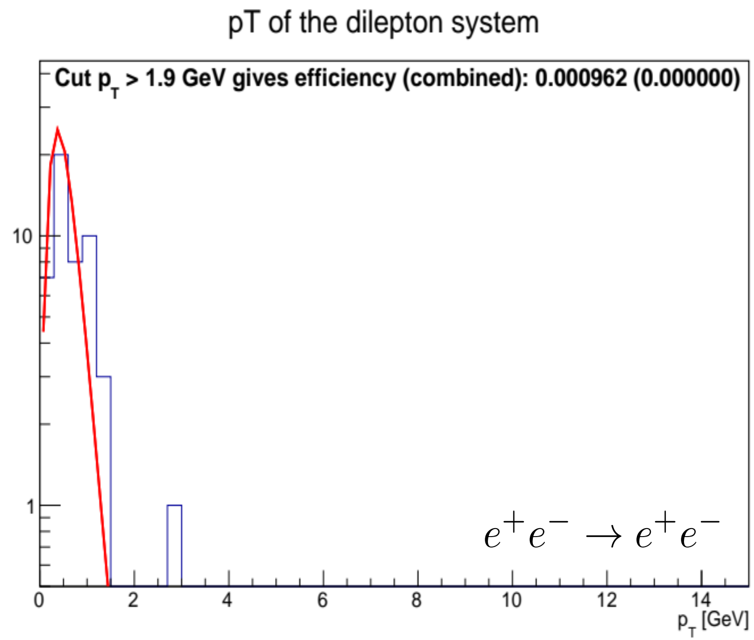
  → tracking tests for heavy scalars confirm **TPC can improve the reach** in LLP searches

# BACKUP

# 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



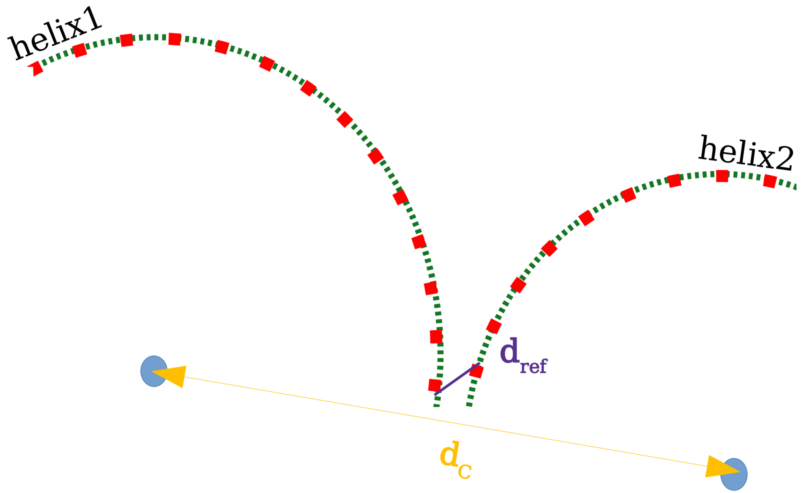




Norm = number of events, scaled by corresponding Poisson expectation values

# 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

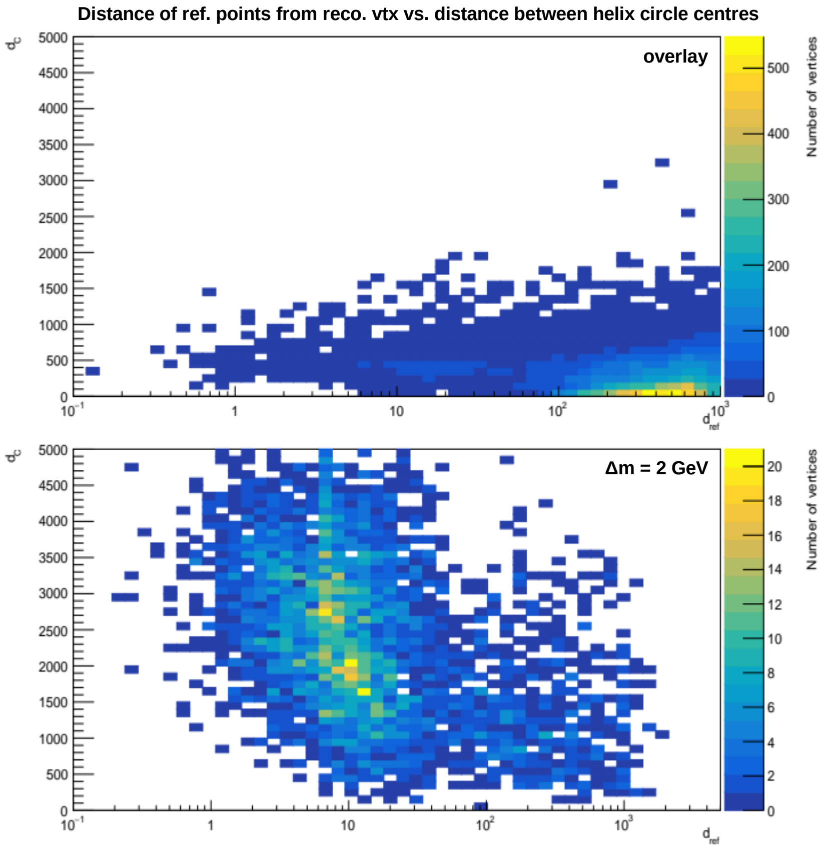
→ either **far reference points** or **close centres of helices**



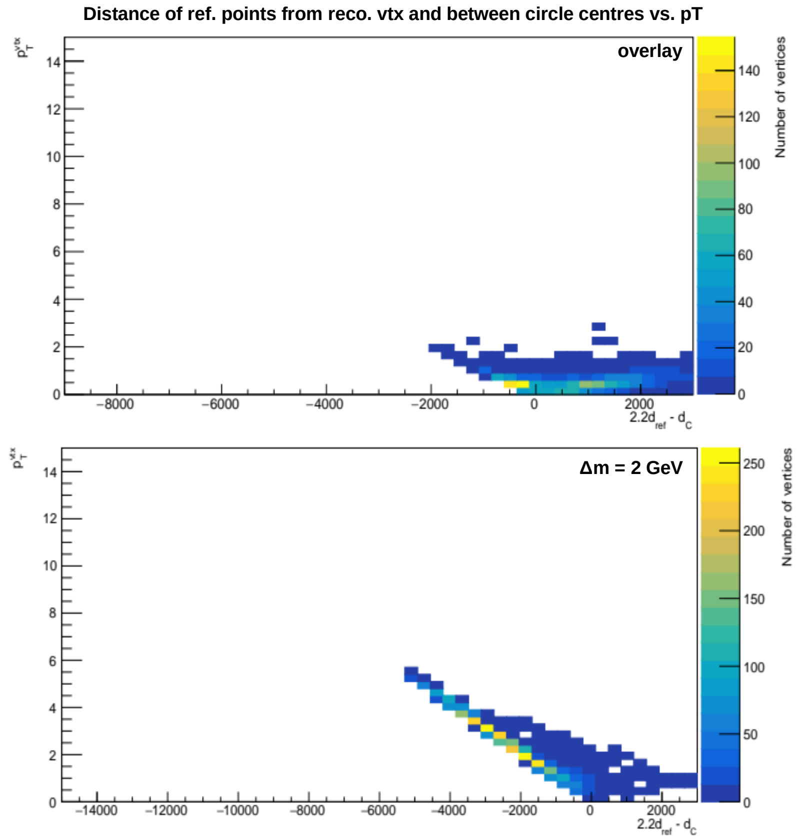

- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

# 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



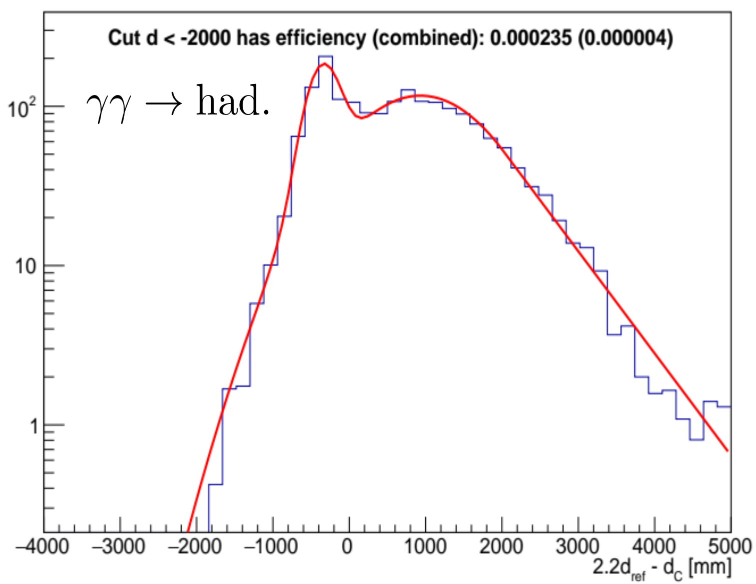

Warp and check correlation with $p_T$

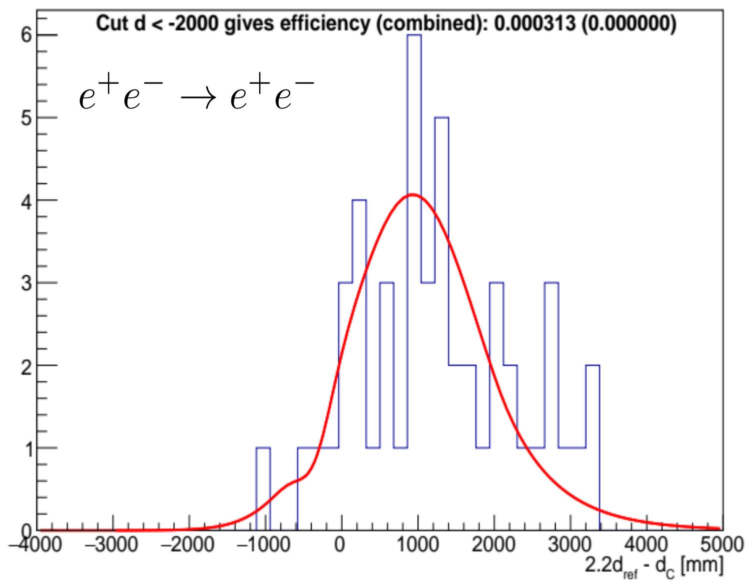



- Small correlation for the background
- Signal strongly correlated

# 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 $\sim 10^{-4}$ (**$\sim 10^{-6}$–$10^{-7}$** with preselection)
- Total expected efficiency at the level of **$\sim 10^{-9}$** (**$\sim 10^{-10}$**) 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