Long-lived particle searches with the ILD detector

Jan Klamka, A.F. Żarnecki

University of Warsaw

jan.klamka@fuw.edu.pl

Motivation and goal

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

  → **e^+e^- competitive in complementary region**: small masses, couplings and mass splittings

  → typical properties of feebly interacting massive particles (FIMPs)
- For the LLPs, ILD potentially promising with the TPC
- Few analyses for Higgs factories using full simulation

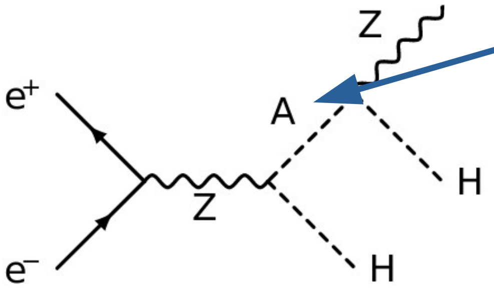
We take:

- **experiment-oriented approach**,
- a generic case – two muons coming from a **displaced vertex**,
- no other assumptions about the final state, **model-agnostic strategy**

Framework and signatures

As a challenging case (small boost, low-pT final state) we considered:

→ (tuned) Inert Doublet Model sample with small mass splitting, $Z^* \to \mu\mu$

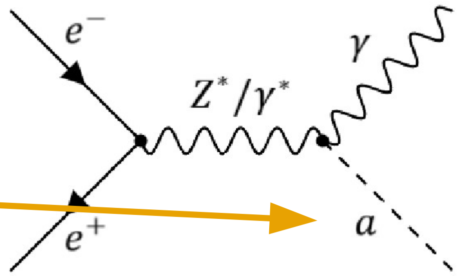


Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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)

→ (tuned) axion-like particle model sample, $a \to \mu\mu$

Simple vertex finding, based on a distance between track pairs

Vertex finding strategy

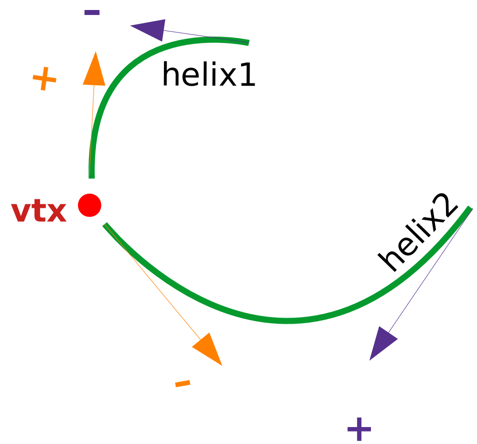
Approach as simple and general as possible:

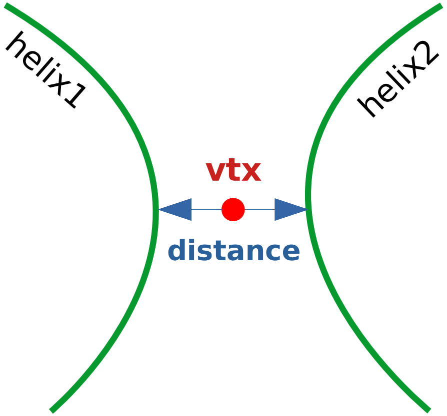
- Consider tracks in pairs
- As the TPC is not sensitive to track direction:

  → 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

At the ILC, on average **1.05 low-pT hadrons** and **1 seeable e^+e^- pair** events are overlaid per bunch-crossing

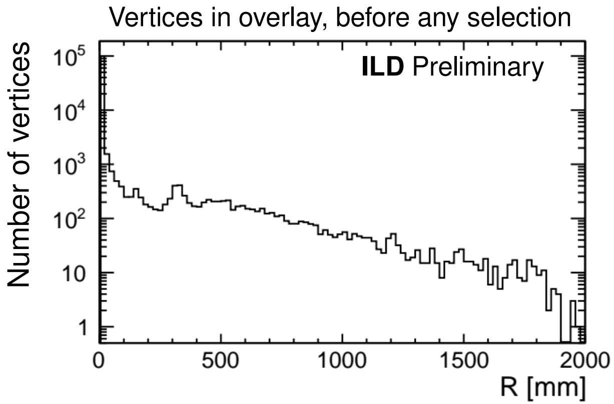
→ they can look like signal on their own

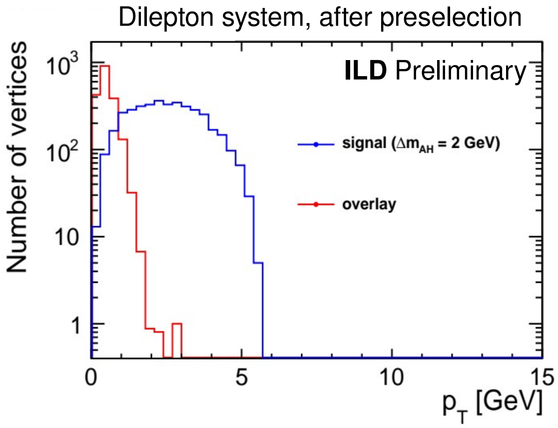
- ~10^{11} bunch-crossings per year at ILC
- Overlay events can be busy

  → can also contribute to fake secondary vertices
- kinematics similar to signal

  → expected to give dominant contribution as a separate background

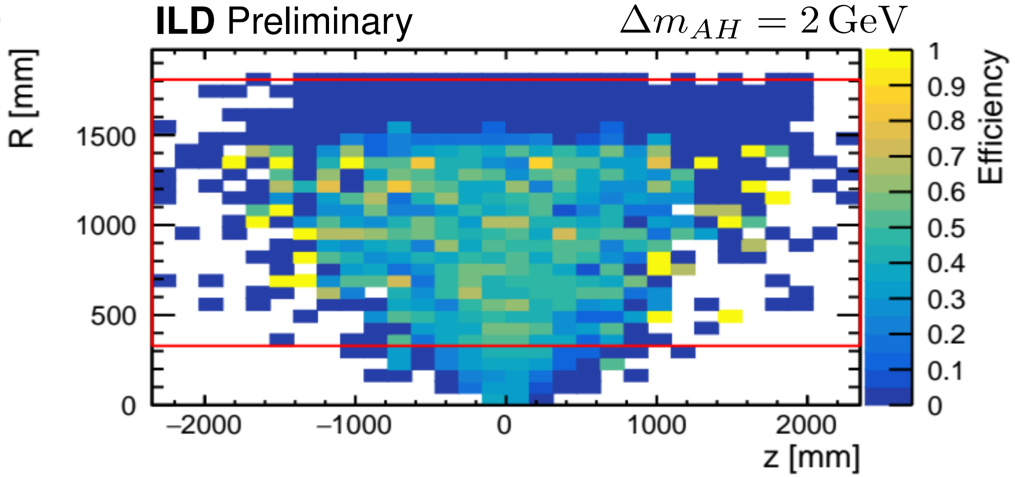
> - Can be suppressed using cuts on the p_T and geometry of track pair
> - Total expected reduction factor at the level of **~10^{-9}** (**~10^{-10}**) for **low-pT had.** (**e^+e^- pairs**)

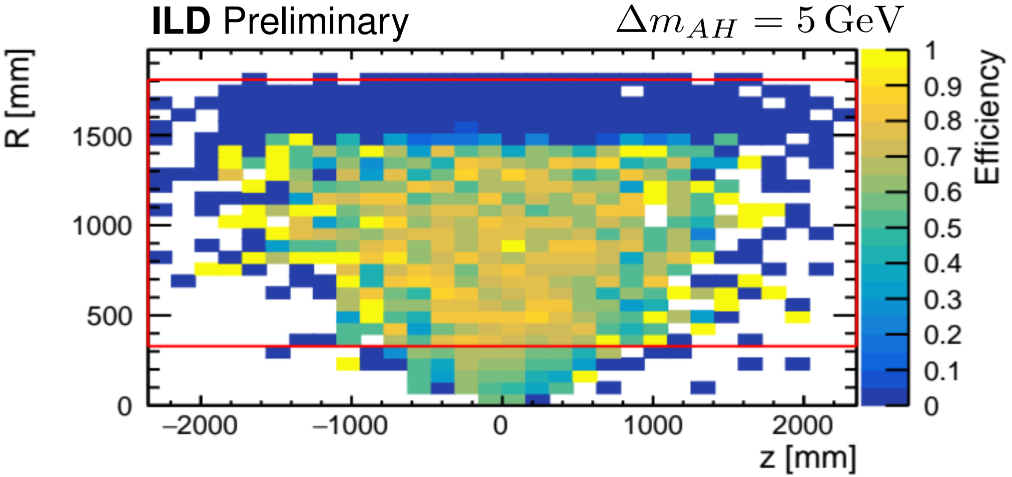




Results (heavy scalar signal)

Δm	1 GeV	2 GeV	3 GeV	5 GeV
TPC eff. (correct / decays within TPC acceptance)	3.9%	37%	52.2%	60.4%
Accuracy in TPC (correct / all found)	99.1%	99.5%	99.5%	99.7%

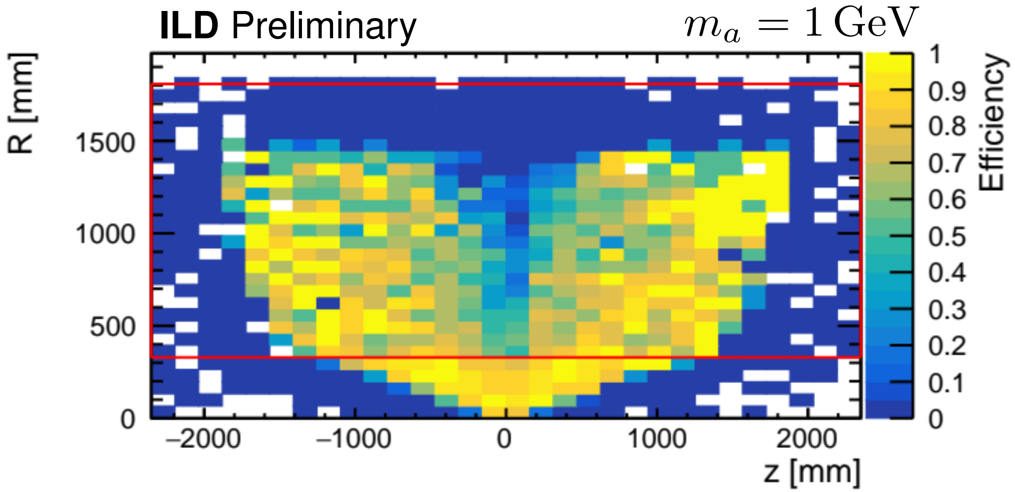


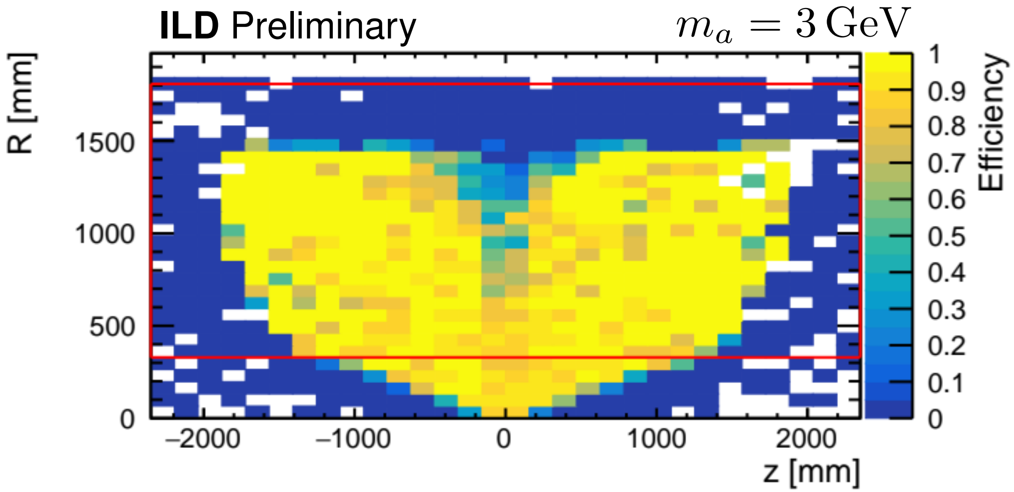


- Consider "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality)
- Δm = 1 GeV scenario needs dedicated approach

Results (ALP signal)

m_a	0.3 GeV	1 GeV	3 GeV	10 GeV
TPC eff. (correct / decays within TPC acceptance)	23.9%	53.8%	76.6%	78%
Accuracy in TPC (correct / all found)	42.7%	82.9%	97.4%	99%





- Efficiency increases with mass (decreasing boost)
- Better performance for smaller radii (as opposed to heavy scalar case)
- **High efficiency** for masses from **1 GeV**

Cross section limits

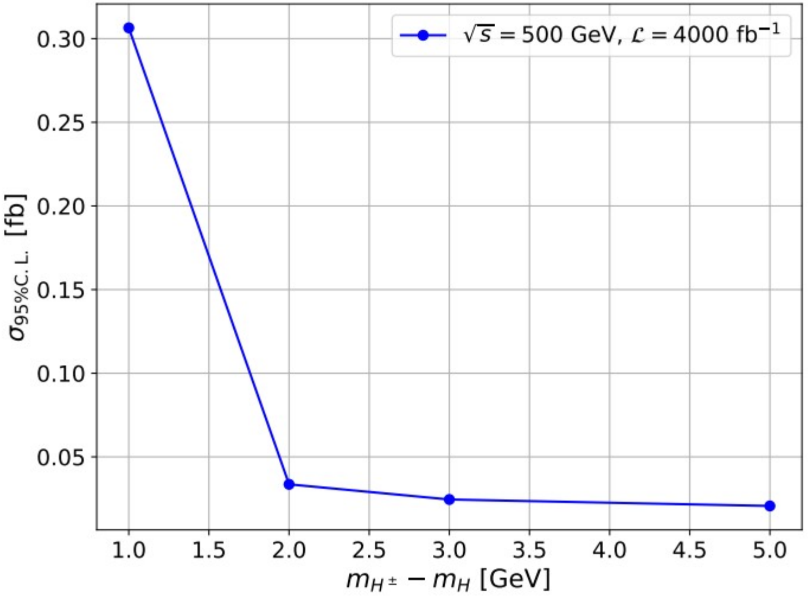
With the overlay events as the main background, we can also estimate expected 95% C.L. limits on the **signal production cross section**

Assume

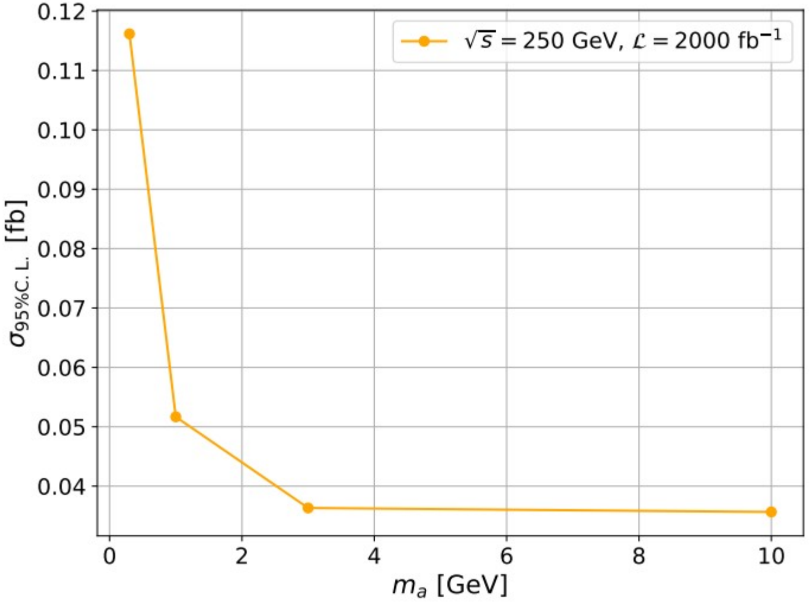
- **2 ab^{-1}** of data at **250 GeV** and **4 ab^{-1}** at **500 GeV** ILC,
- **10 yr** and **8.5 yr** × 10^{11} bunch-crossings (BXs),
- **1.05** (**1.00**) **$\gamma\gamma$ → had.** (**seeable e^+e^- pairs**) events per BX,
- total background rejection of **10^{-9}** (**10^{-10}**) → ~**1150** expected N_{bg} events for **250 GeV**
- No. of signal ev. corresponding to the limit: $N_{sig} = 1.64 \cdot \sqrt{N_{bg}}/\epsilon_{sel}$

Cross section limits (so far)

Heavy scalars (IDM)



Light pseudoscalar (ALP)



- Valid for kinematic region $p_T^{vtx} > 1.9$ GeV and only for decays inside TPC volume
  → Correct for the TPC acceptance
  → Get predictions for different lifetimes - reweight the events using probability distributions

Cross section limits (new)

- For different lifetimes, $\boldsymbol{\tau}$', reweight the events by ratio of exponential PDFs:

  $\mathbf{w} = \mathbf{P}(\mathbf{t}, \boldsymbol{\tau}')/\mathbf{P}(\mathbf{t}, \boldsymbol{\tau}_0)$ (with $\boldsymbol{\tau}_0$ used for **sample generation**; for $\tau' = \tau_0$, $w = 1$)

Cross section limits (new)

- For different lifetimes, $\boldsymbol{\tau}$', reweight the events by ratio of exponential PDFs:

  $\mathbf{w} = \mathbf{P(t, \boldsymbol{\tau}')/P(t, \boldsymbol{\tau}_0)}$ (with $\boldsymbol{\tau}_0$ used for **sample generation**; for $\tau' = \tau_0$, $w = 1$)

- Limited statistics in the samples for decays at large distances - problem for higher τ':

  → <u>cutoff</u> at a large distance ($L_{max} = 3$ m) above which finding a vertex is impossible

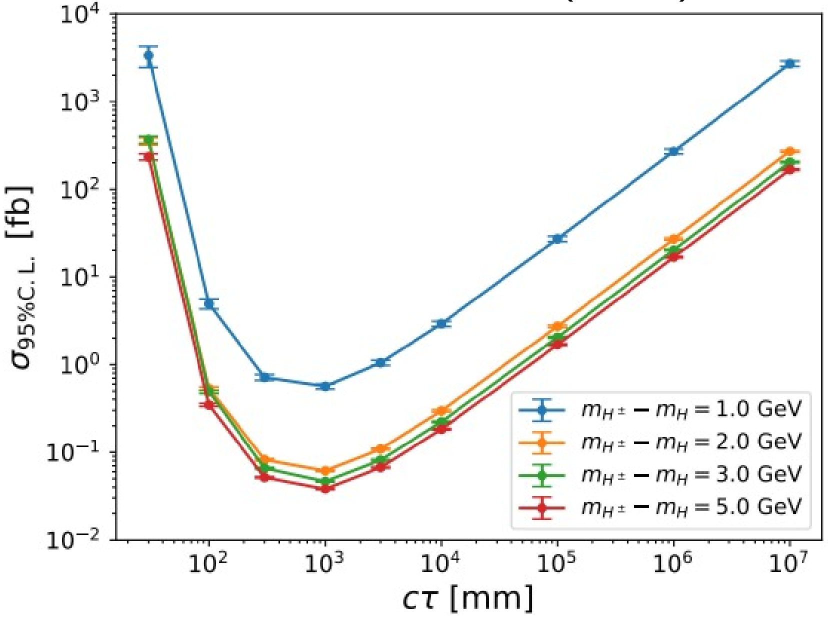
  → $\mathbf{N_{all} = \Sigma w / w_{max}}$ where $\mathbf{w_{max}}$ = **tot. probability that LLP decays before** $\mathbf{L_{max}}$

  → $\mathbf{N_{pass} = \Sigma w}$ for events passing selection in TPC

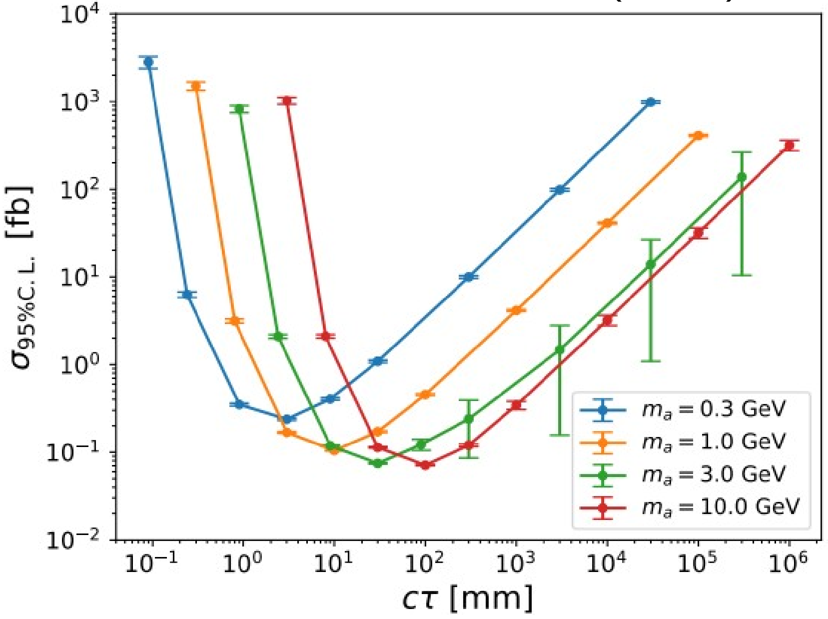
Now with $\epsilon_{sel} = N_{pass}/N_{all},\ N_{sig} = 1.64 \cdot \sqrt{N_{bg}}/\epsilon_{sel}$

Cross section limits (new)

Heavy scalars (IDM)



Light pseudoscalar (ALP)



- Good sensitivity, even for high lifetimes
- Limits still conservative due to the model-independent approach (not using e.g. invariant mass or missing energy)

Summary

- LLPs studied for challenging parameter space regions complementary to LHC searches, **two tracks** from a **displaced vertex** analysed in a model-agnostic way
- Heavy scalars production considered, with **small O(1 GeV) mass splittings** between LLP and DM and **low-momenta decay products**
- Reconstruction of **highly boosted**, **light** ALPs, with O(1 GeV) masses, performed with the same algorithm and procedure
- Estimated 95% CL limit on signal **cross section $\lesssim$ 1 fb** for many scenarios, with $c\tau$ between 1 mm and 100 m

Next steps under consideration:

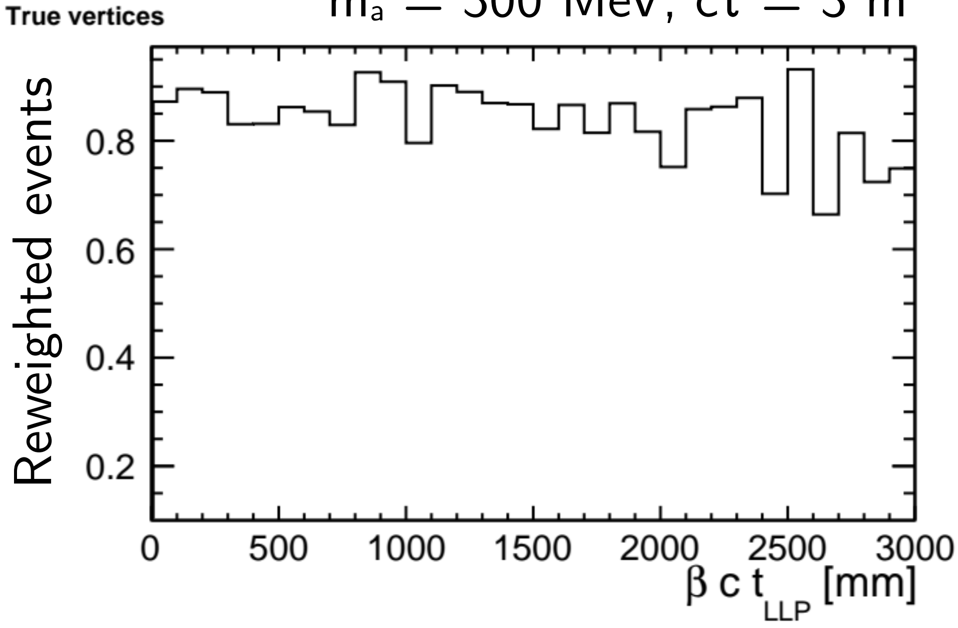
- Analysis extension to displaced jets (Higgs decays to LLPs?)
- In parallel ongoing tests of other ILD designs - TPC with pixel readout

  → tracking performance still needs improvement (any contributions more than welcome)

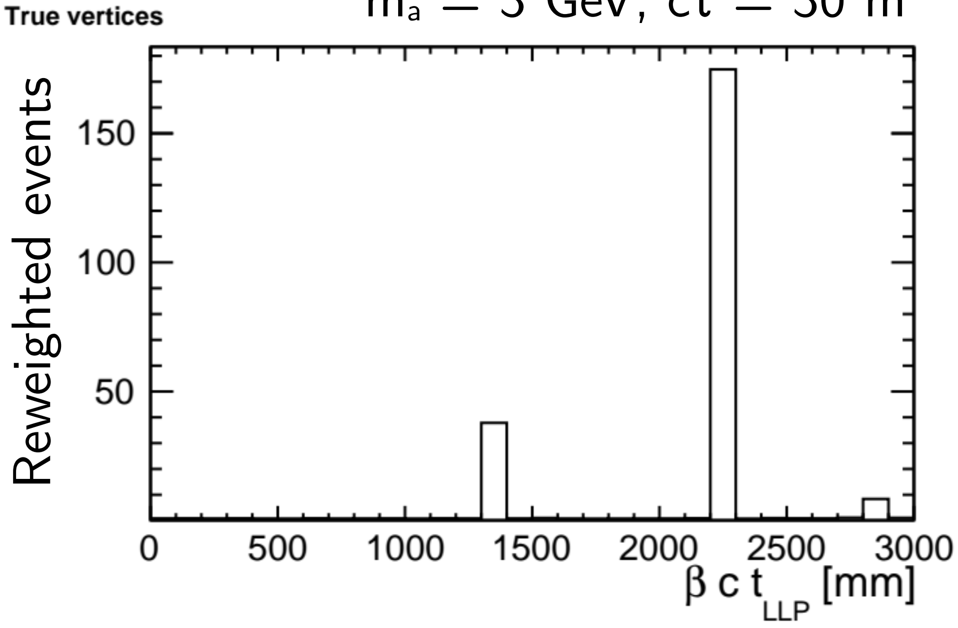
BACKUP

Reweighted events

$m_a = 300$ MeV, $c\tau = 3$ m



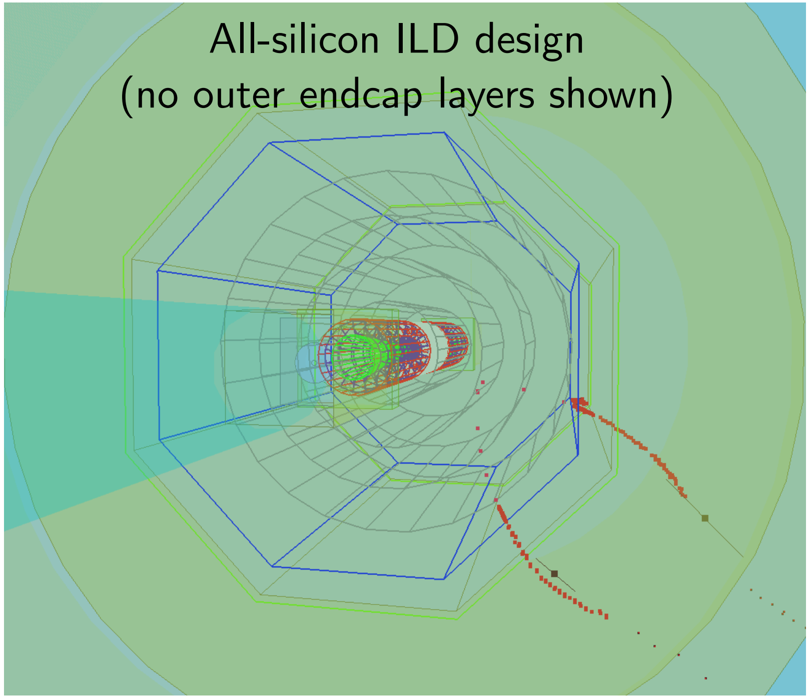
$m_a = 3$ GeV, $c\tau = 30$ m



Alternative all-silicon ILD design

Alternative ILD design implemented for tests

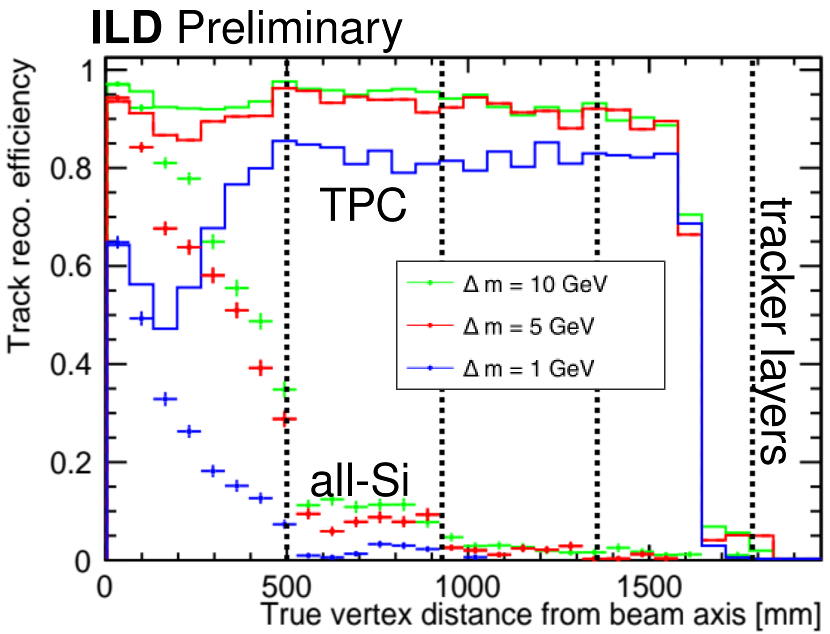
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ 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**



Test signal scenarios

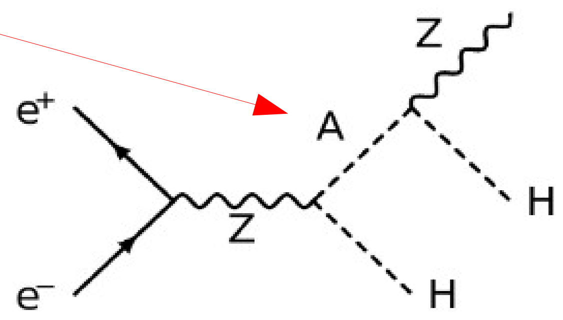
First challenging scenario (**small-boost**, **low-p_T** track pair, **not pointing towards IP**):

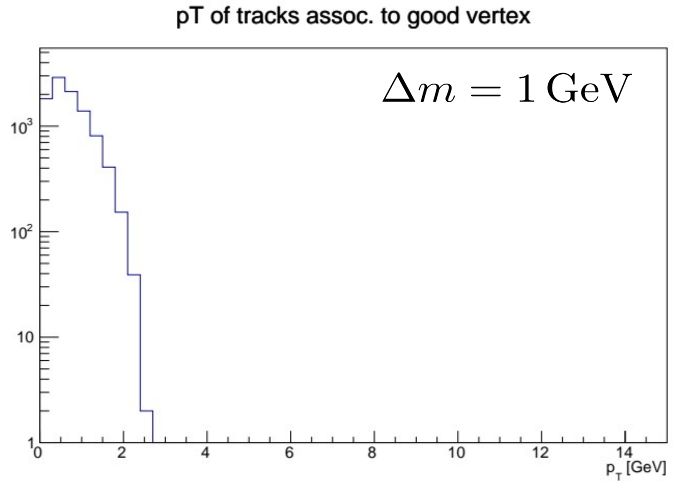
- pair production of <u>heavy, neutral scalars</u> from Inert Doublet Model (IDM):
  A (heavier) and **H** (lighter; stable dark matter candidate)

- A can be long-lived for **small mass splittings** between A and H

- dominant decay: $\mathrm{A} \to \mathrm{HZ}^*;\ \mathrm{Z}^* \to \mu\mu$ decay used for vertex reconstruction studies

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





Low-pT tracks prevail

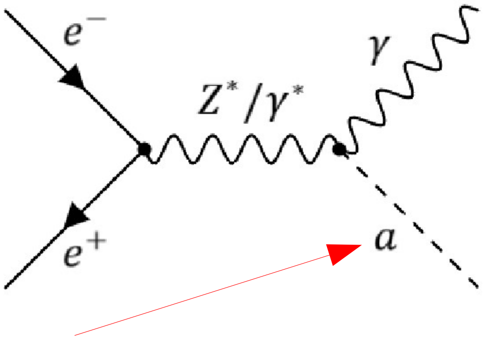
<u>Benchmark scenarios</u>:

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

Test signal scenario – highly boosted light LLPs

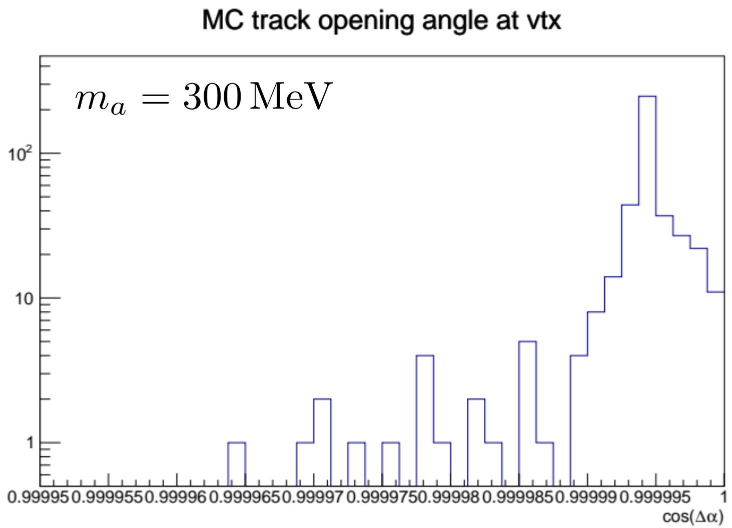
Exactly the opposite extreme scenario (**small LLP mass**, very **high pT**, **collinear tracks**):

- **axion-like particle** (ALP) produced alongside hard photon
  (UFO model by R. Schafer, S. Bruggisser, S. Westhoff)
- Use the **same procedure** as for IDM (same algorithm, cuts), $a \to \mu\mu$ decay used for studies
- Number of decays within acceptance strongly varies between signal scenarios



Long-lived, with $c\tau = 10\,\mathrm{mm}$

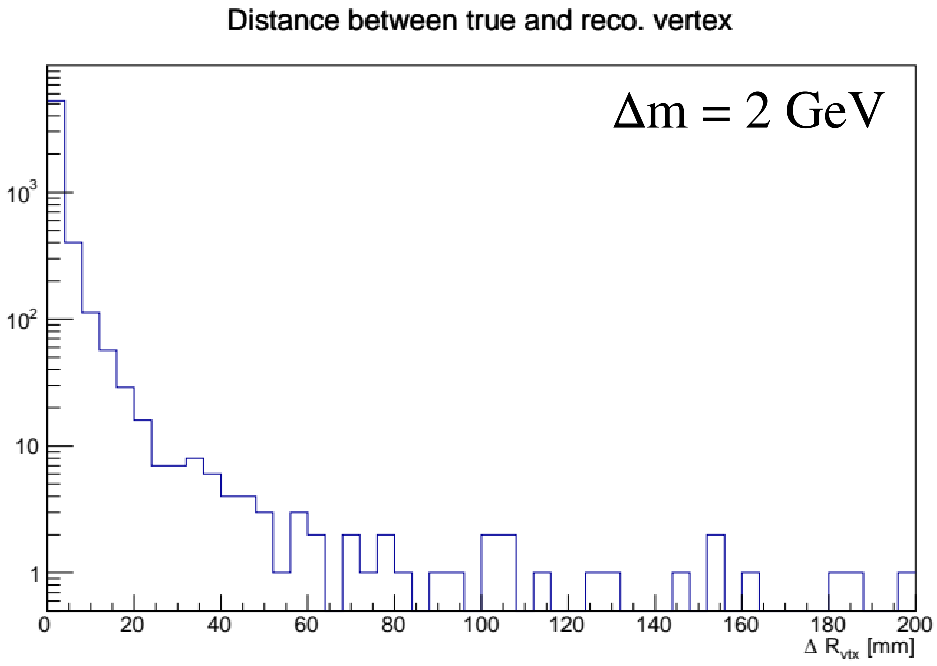
<u>Benchmark scenarios</u>: $m_a = 0.3, 1, 3, 10\,\mathrm{GeV}$

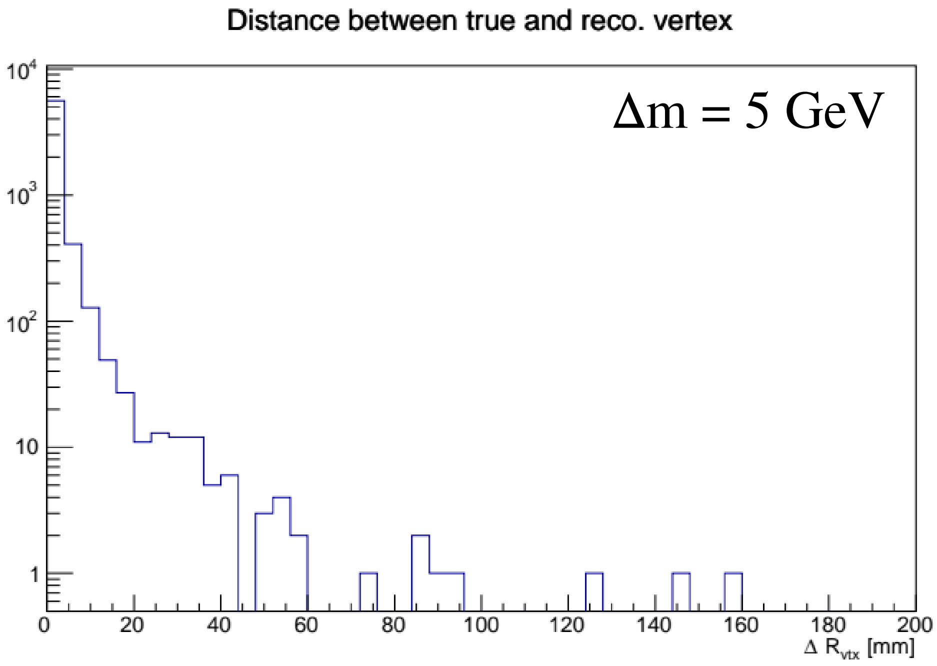


Tracks almost collinear

Distance to the true vertex

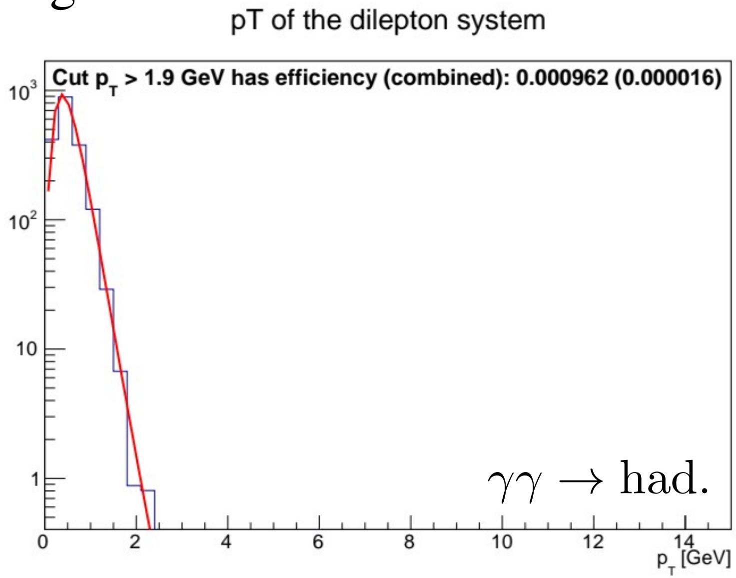
Consider a vertex „correct" if distance to the true vtx < 30 mm

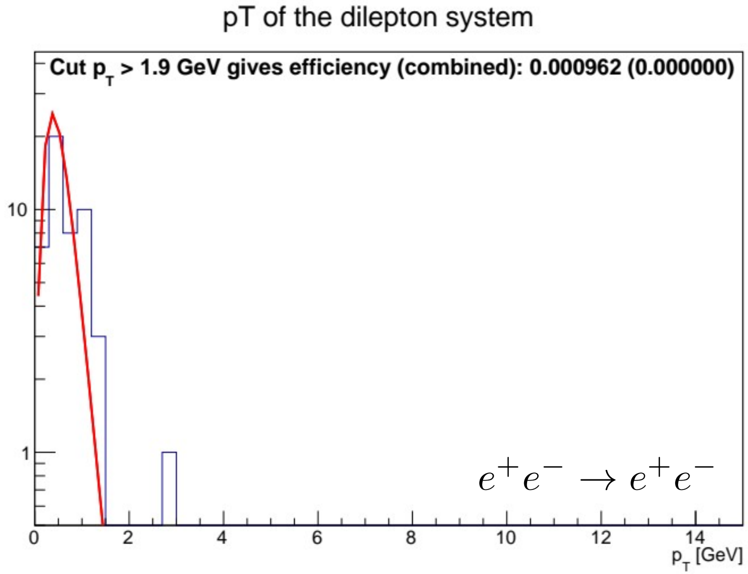




Final selection – pT

- 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

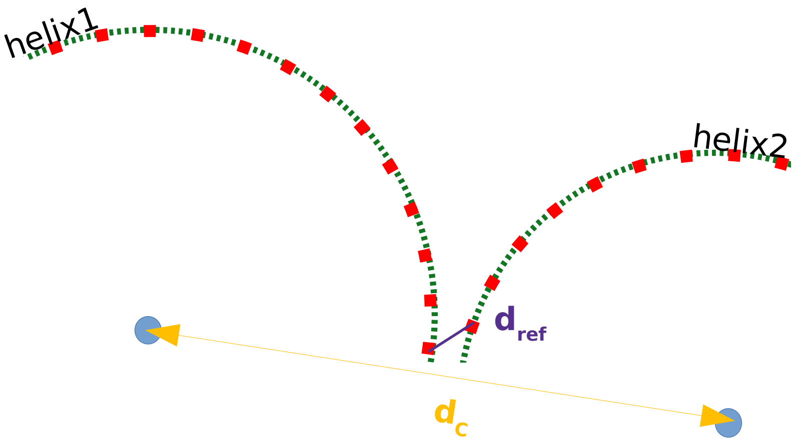
Final selection – other variables

- 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**

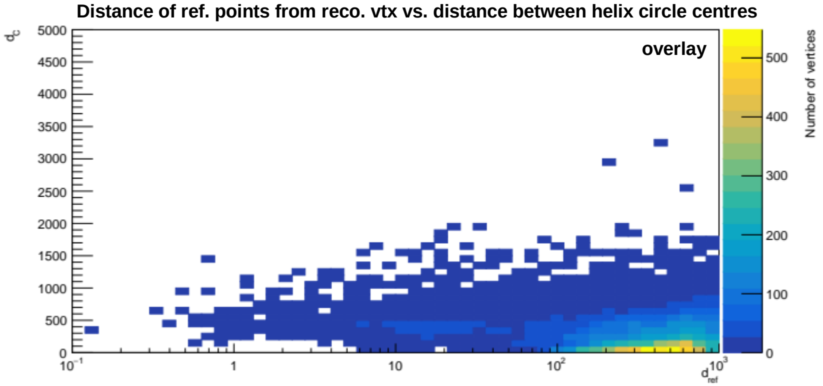


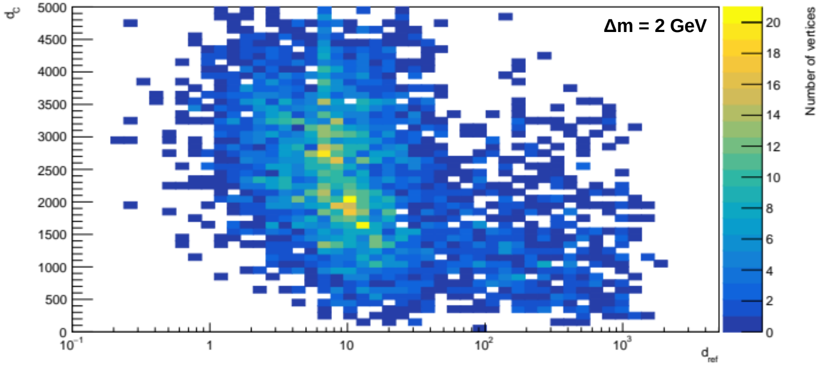
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)

- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

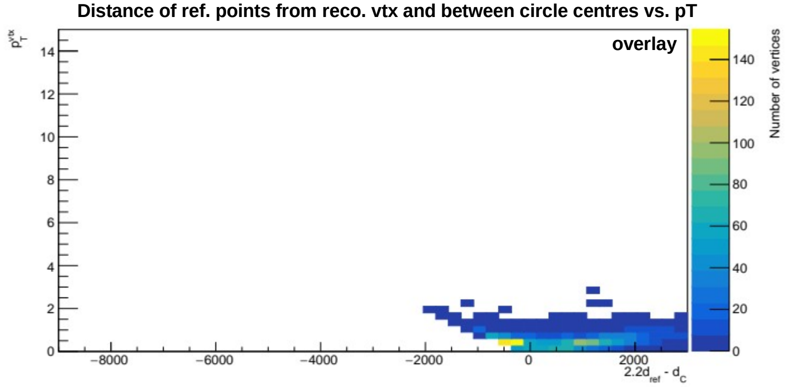
Final selection – second variable

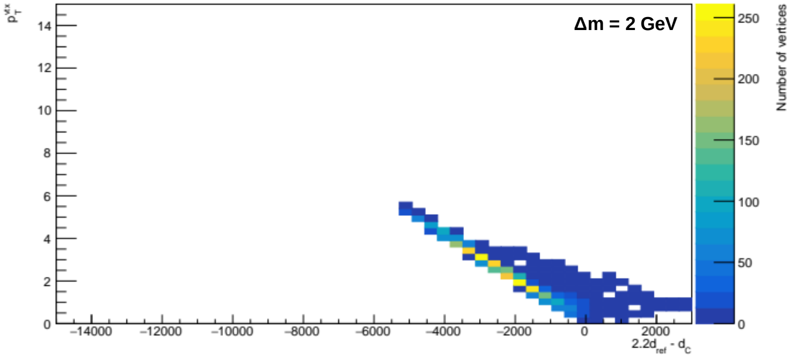
- New variable(s) should be uncorrelated with pT to make the cuts independent
- $2.2d_{ref} - d_C$ good for optimal signal-background separation → use it to look for correlation





Warp and check correlation with p_T

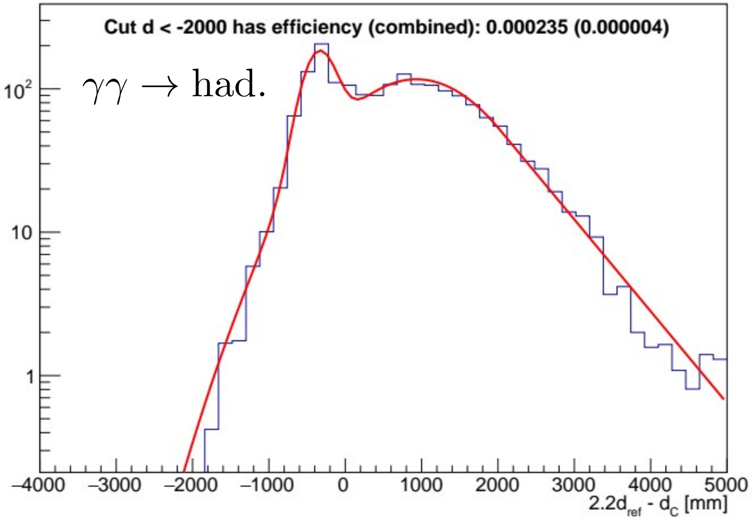


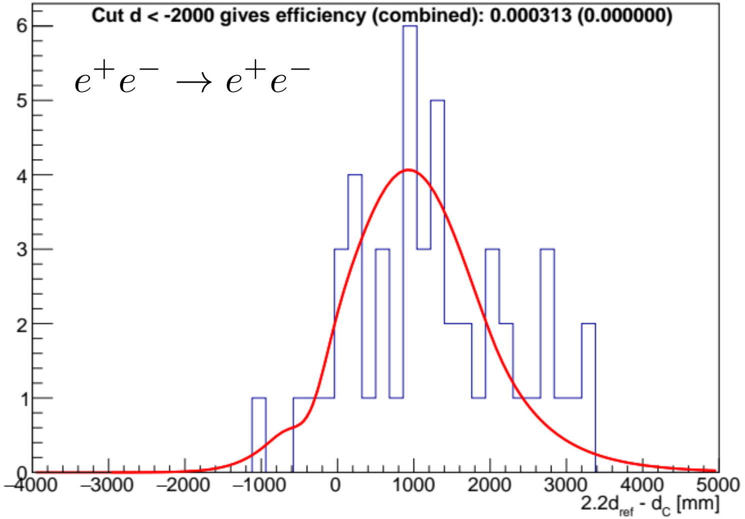


- Small correlation for the background
- Signal strongly correlated

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 $\sim 10^{-4}$ (**$\sim 10^{-6}$–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**)





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 $\mathbf{2.2d_{ref} - d_C}$, assuming **30% correlation**, for γγ → 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