FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

NATIONAL SCIENCE CENTRE POLAND

ILD

# Reconstructing long-lived particles with the ILD detector

SECOND • ECFA • WORKSHOP
on $e^+e^-$ Higgs / Electroweak / Top Factories

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# Long-lived particles

**Numerous BSM models predict LLPs**:

→ SUSY particles, axion-like particles, heavy neutral leptons, dark photons, exotic scalars...

| | | 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 | | | ✓ |

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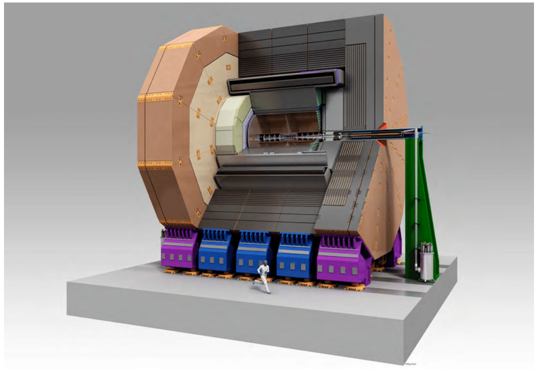
# LLPs at the Higgs factories

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

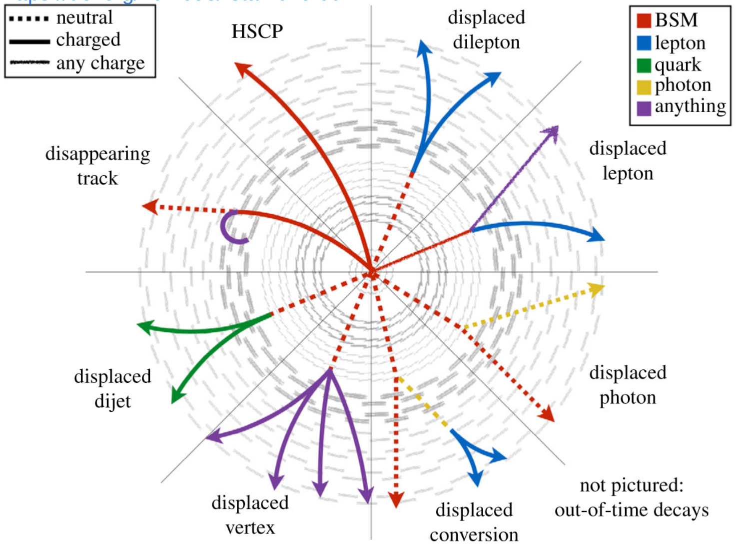
  → complementary region could be probed at $e^+e^-$ **colliders** (**small masses, couplings, mass splittings**)

  → typical properties of feebly interacting massive particles (FIMPs)

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



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



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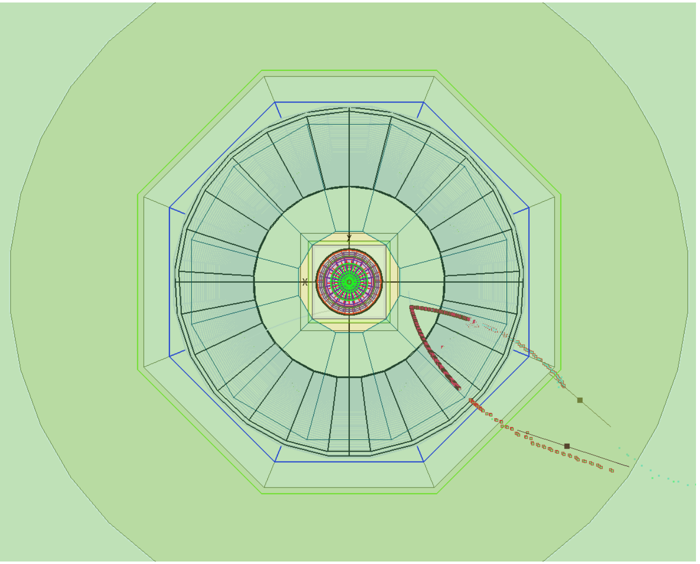
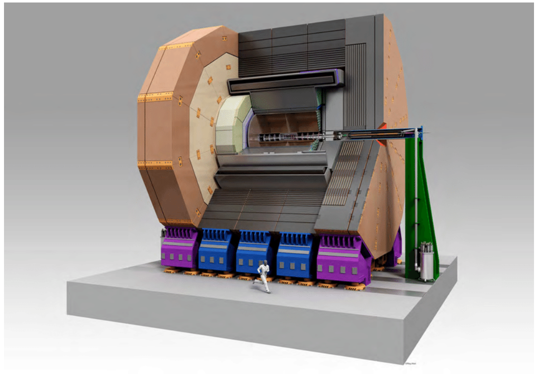




- Study such challenging signatures from the **experimental perspective**

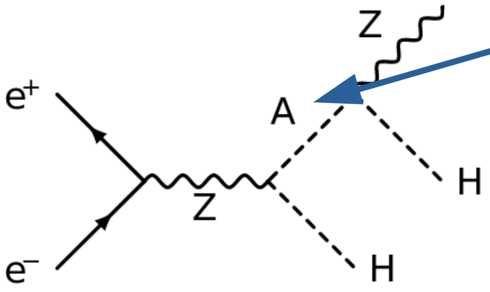
  → experimental/kinematic properties, not points in a model parameter space

- 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:

$\rightarrow$ (tuned) Inert Doublet Model sample with small mass splitting, $\mathrm{Z}^* \rightarrow \mu\mu$




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

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

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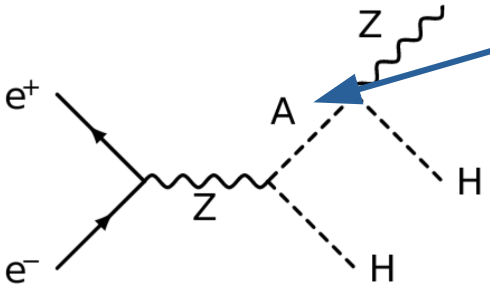
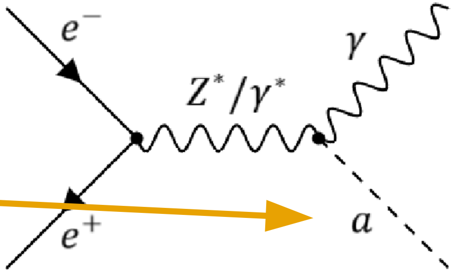



Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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, $a \to \mu\mu$

**Very simple vertex finding, based on a distance between track pairs**

# Overlay events

At the ILC, on average **1.05 low-pT hadrons** and **1 seeable $e^+e^-$ pair** events are produced in each bunch-crossing

In most analyses important as they **overlay** on physical events

→ but can look like signal on their own

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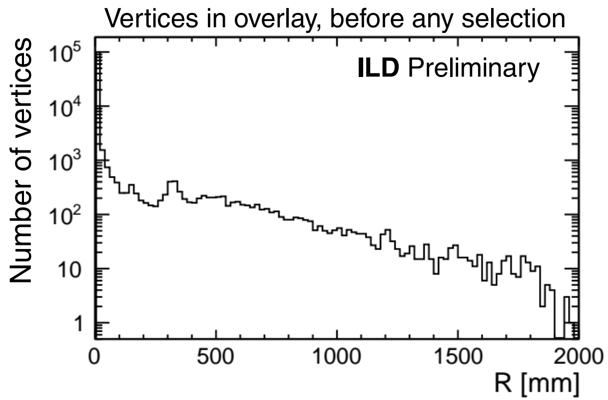
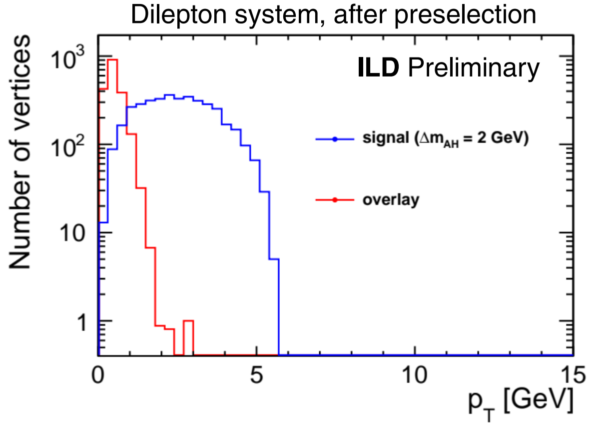
- ~$10^{11}$ bunch-crossings per year at ILC
- Overlay events can be busy
  → can also contribute to fake secondary vertices
- kinematics similar to signal
  → expected to give dominant contribution as a <u>separate background</u>



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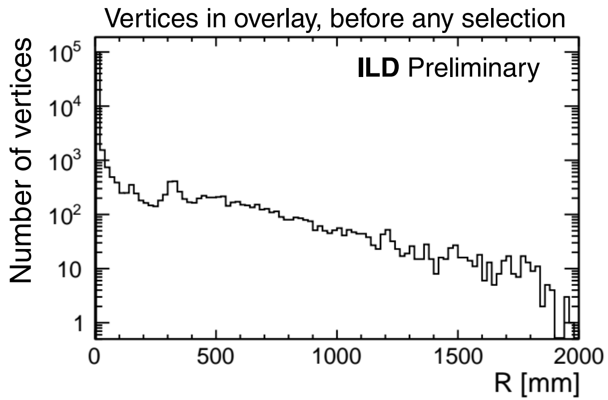
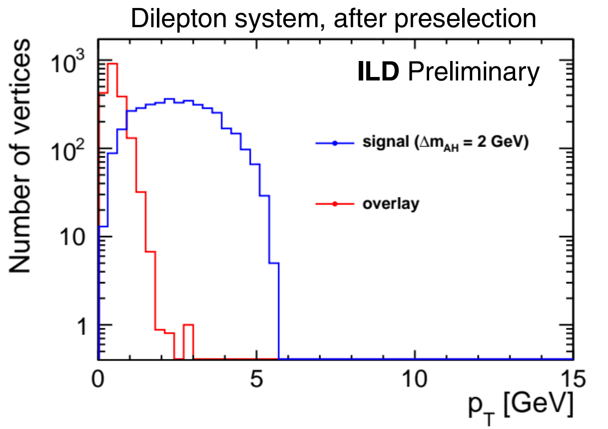
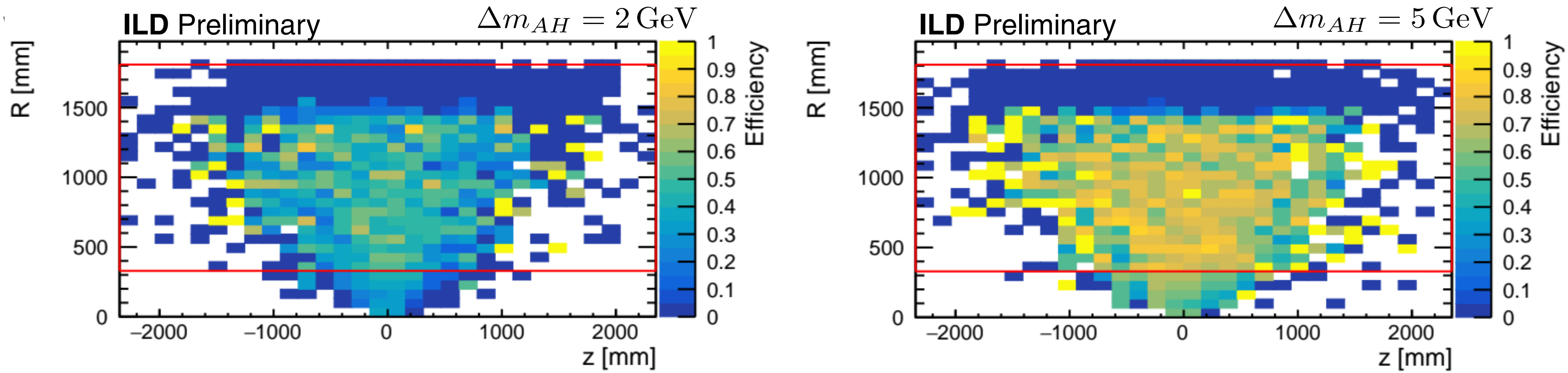



- Can be suppressed using cuts on the $p_T$ and geometry of track pair
- Total expected reduction factor at the level of **~$10^{-9}$** (**~$10^{-10}$**) for **low-pT had.** (**$e^+e^-$ pairs**)

# Results (heavy scalar signal)

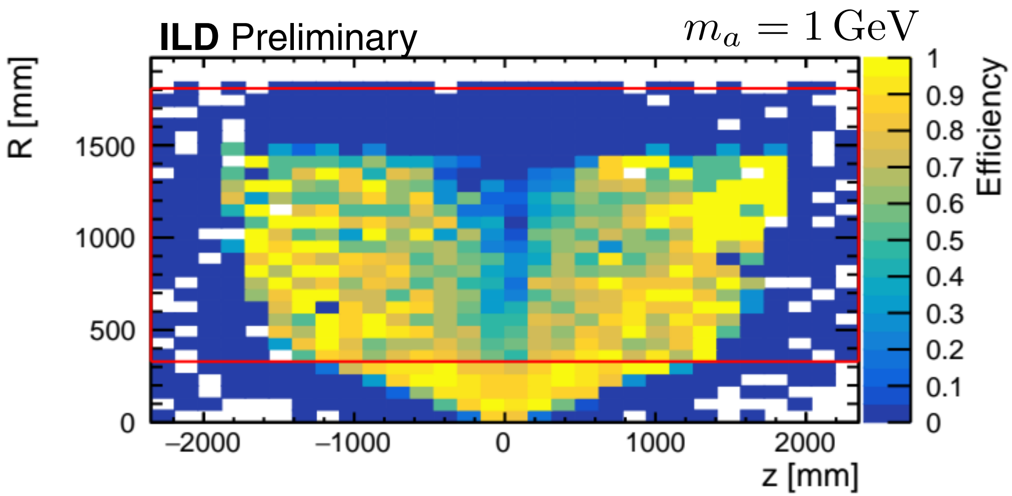
| Δm | 1 GeV | 2 GeV | 3 GeV | 5 GeV |
|---|---|---|---|---|
| TPC eff. (correct / decays within TPC acceptance) | 3.9% | 37% | 52.2% | 60.4% |
| Accuracy in TPC (correct / all found) | 99.1% | 99.5% | 99.5% | 99.7% |

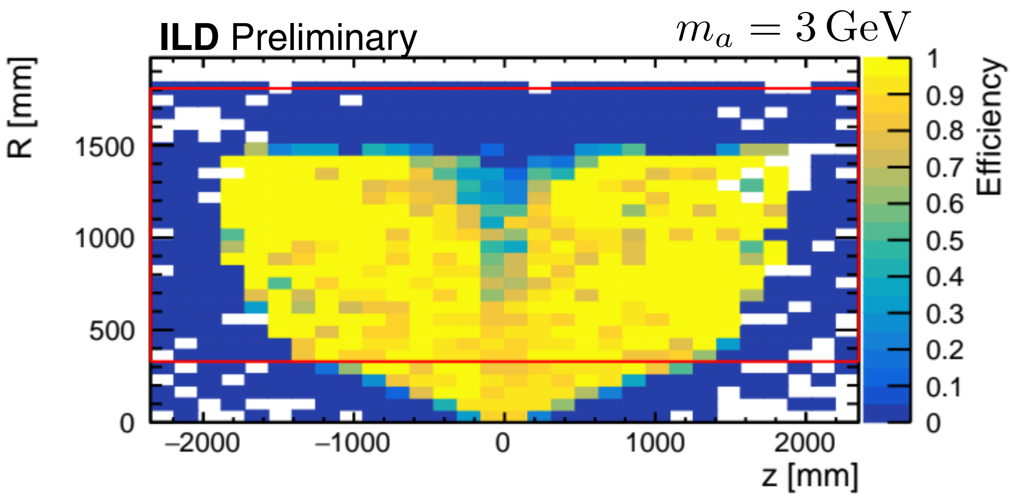



- Consider "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality)
- Δm = 1 GeV scenario needs dedicated approach

# 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** (work in progress for 0.3 GeV)

# Cross section limits

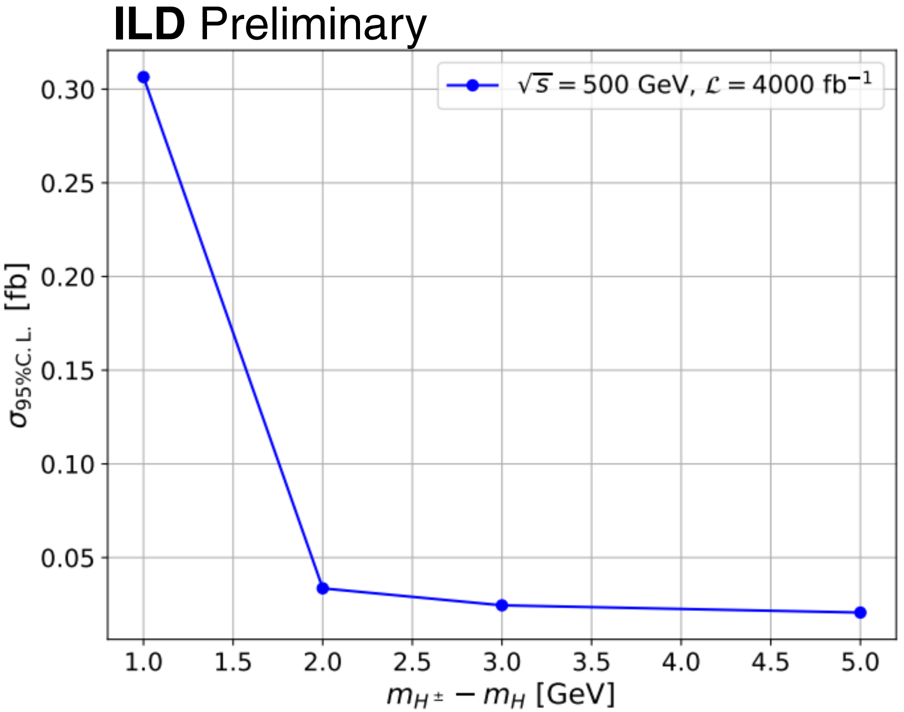
With the overlay events as the main background, we can also estimate expected 95% C.L. limits on the **signal production cross section**

Assume

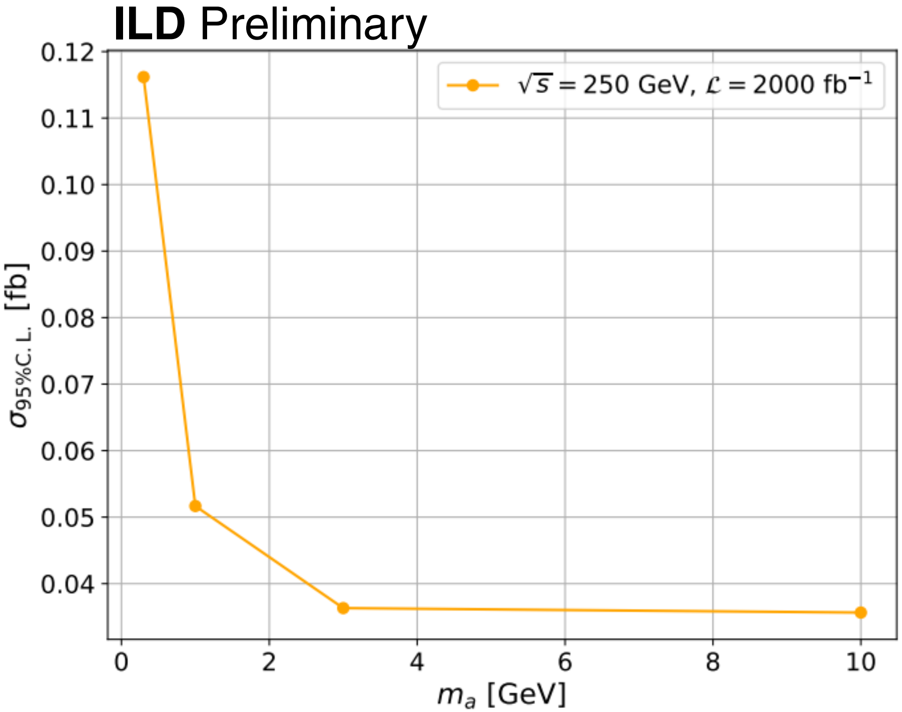
- **2 ab$^{-1}$** of data at **250 GeV** and **4 ab$^{-1}$** at **500 GeV** ILC,
- **10 yr** and **8.5 yr** $\times$ $10^{11}$ bunch-crossings (BXs),
- **1.05** (**1.00**) **$\gamma\gamma \rightarrow$ had.** (**seeable $e^+e^-$ pairs**) events per BX,
- total background rejection of **$10^{-9}$** (**$10^{-10}$**) $\rightarrow$ ~**1150** expected bg. events

# Cross section limits

Heavy scalars (IDM)




Light pseudoscalar (ALP)

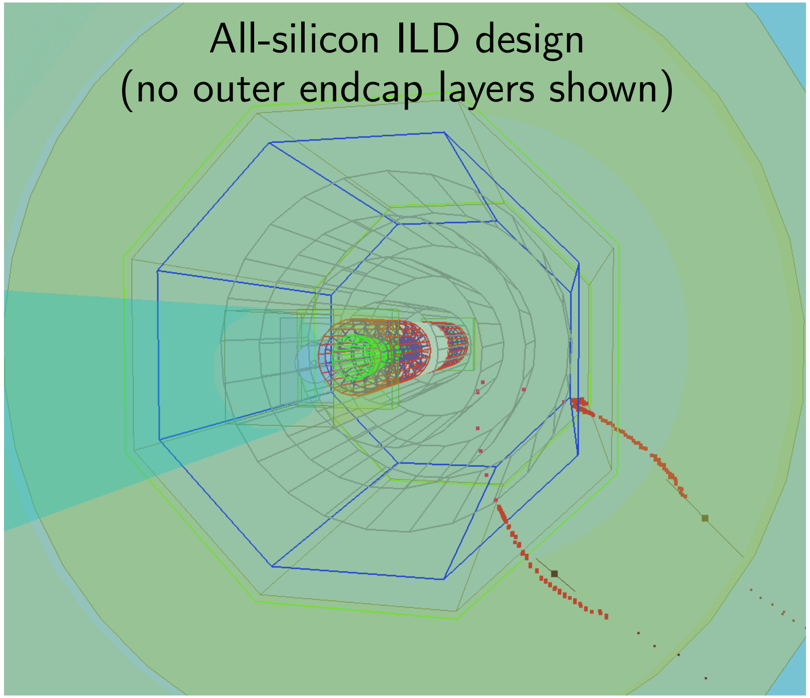



- Valid for kinematic region $p_T^{vtx} > 1.9$ GeV and decays inside TPC volume
- Conservative limit, not using reconstructed invariant mass

# Alternative all-silicon ILD design

Alternative ILD design implemented for tests

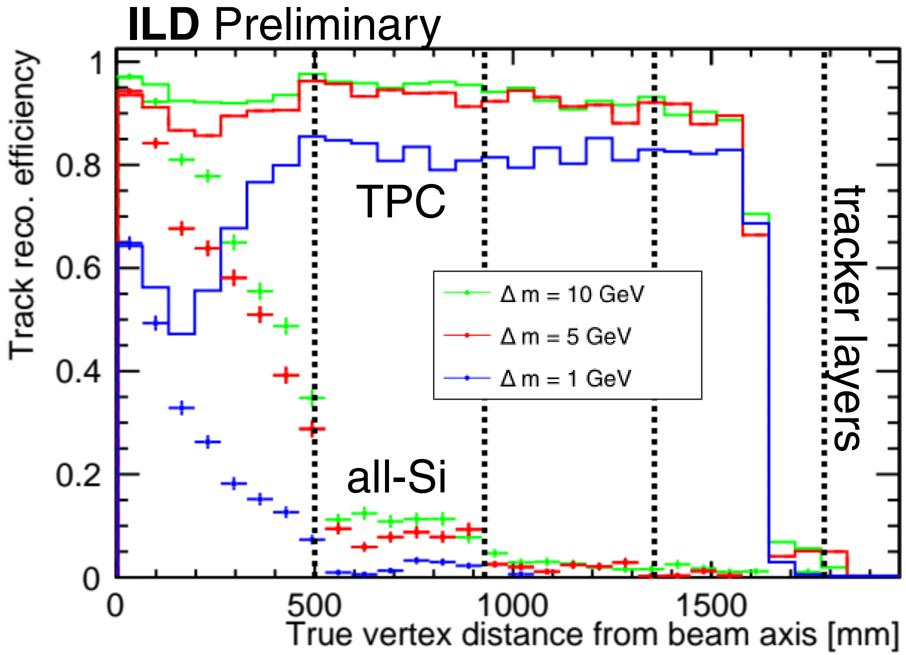
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD




→ 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
- Events with **two tracks** from a **displaced vertex** analysed

  → a simple algorithm developed, background from the overlay events taken into account; **not a background-free analysis**

- For heavy scalars production, with **small mass splittings** between LLP and DM and **low-momenta decay products**, good sensitivity from $\mathbf{\Delta m = 2}$ **GeV**
- Reconstruction of **highly boosted**, **light** ALPs decaying into muons performed with the same algorithm and procedure indicates good sensitivity for **masses** $\geq$ **1 GeV**
- Estimated 95% CL limit on signal cross section below 0.05 fb for most scenarios

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

  → tracking tests for heavy scalars confirm **higher reach of TPC** in LLP searches

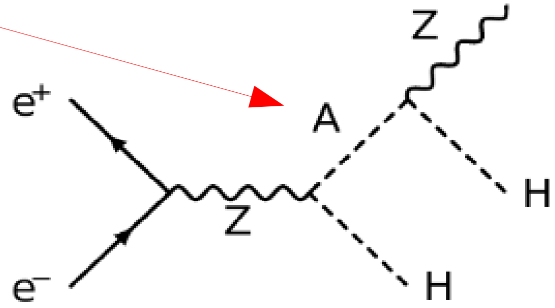
# BACKUP

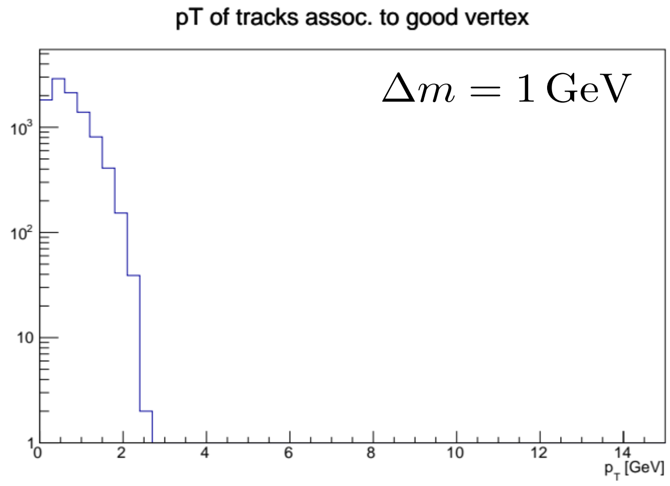
# Test signal scenarios

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

- pair production of heavy, neutral scalars 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: $A \to HZ^*;\ Z^* \to \mu\mu$ decay used for vertex reconstruction studies

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




Low-pT tracks prevail

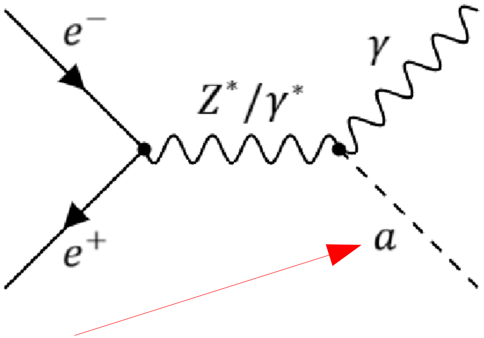
Benchmark scenarios:

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

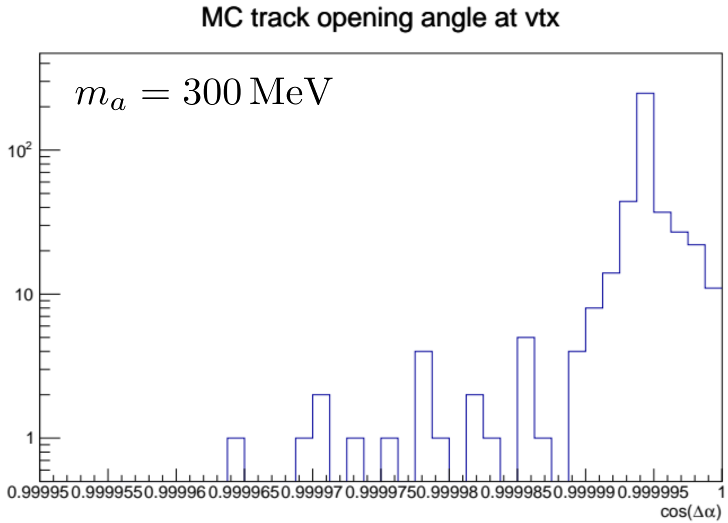
# Test signal scenario – highly boosted light LLPs

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 $c\tau = 10\,\mathrm{mm}$




Tracks almost collinear

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

# 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:

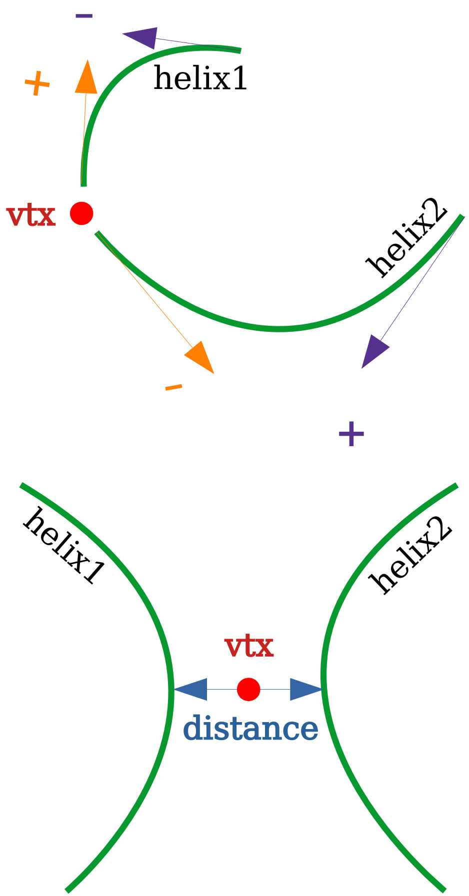
  → use **both track direction** (charge) **hypothesis** for vertex finding

  → consider opposite-charge track pairs only

  → select pair with **closest starting points**

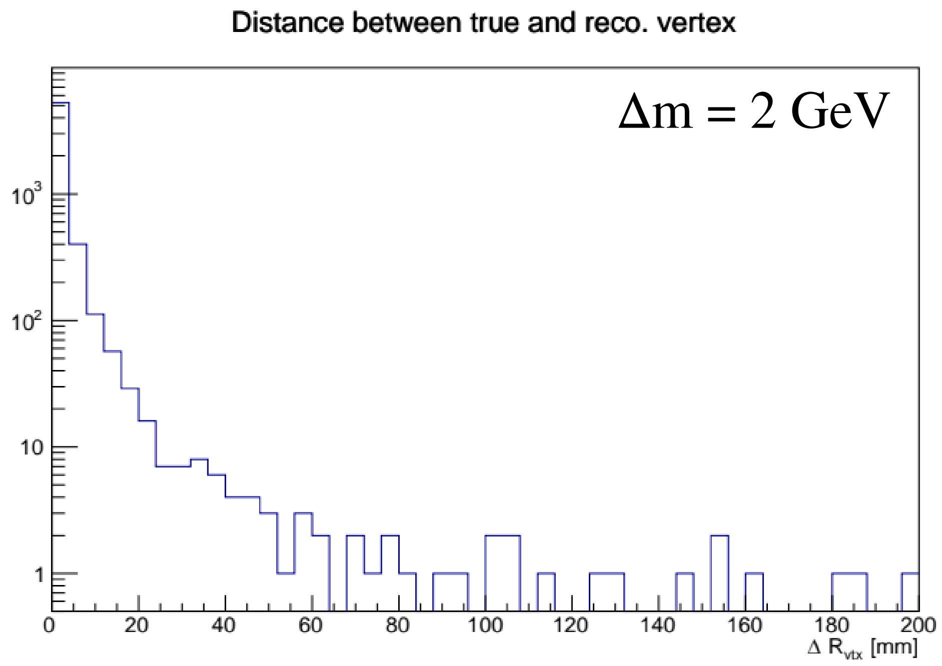
- Reconstruct vertex in **between points of closest approach** of helices

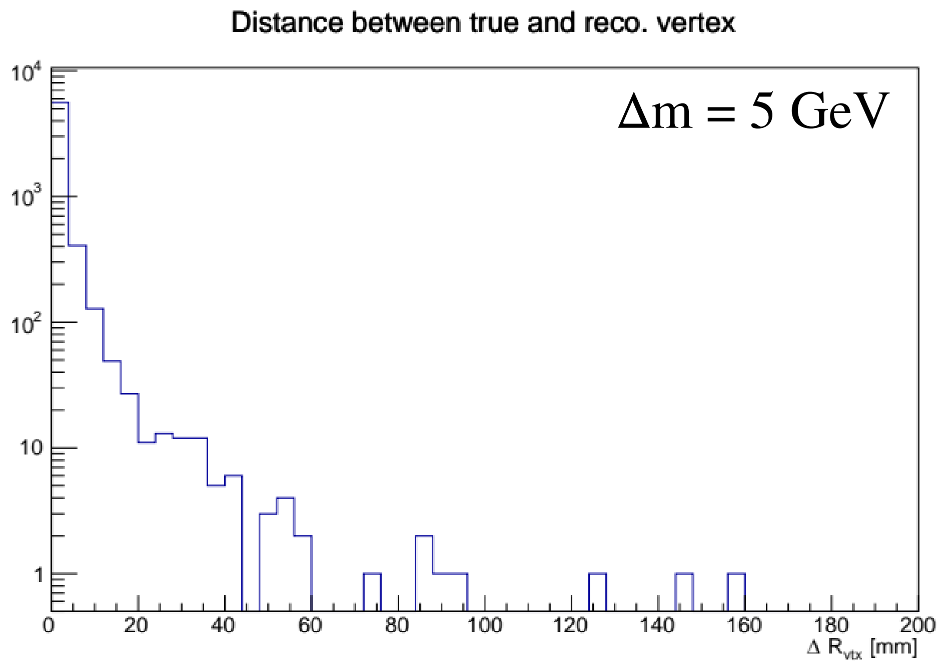
  → Require distance < 25 mm



# Distance to the true vertex

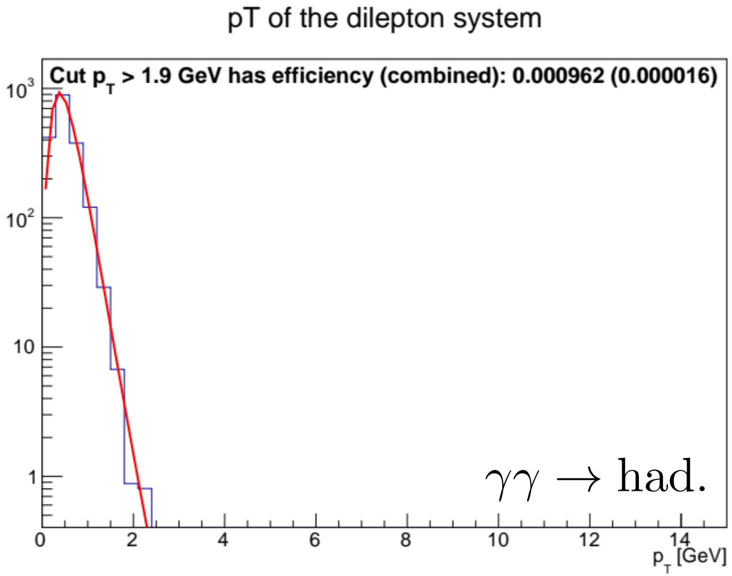
Consider a vertex „correct” if distance to the true vtx < 30 mm

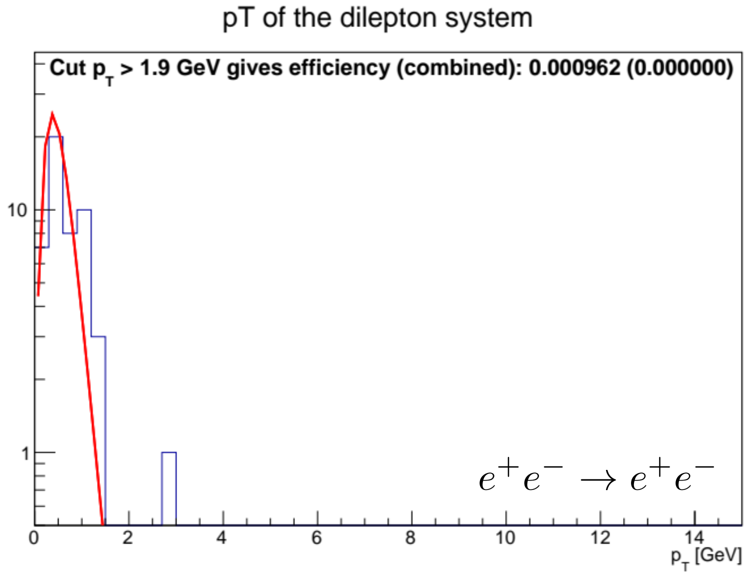


# Final selection – pT

- 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

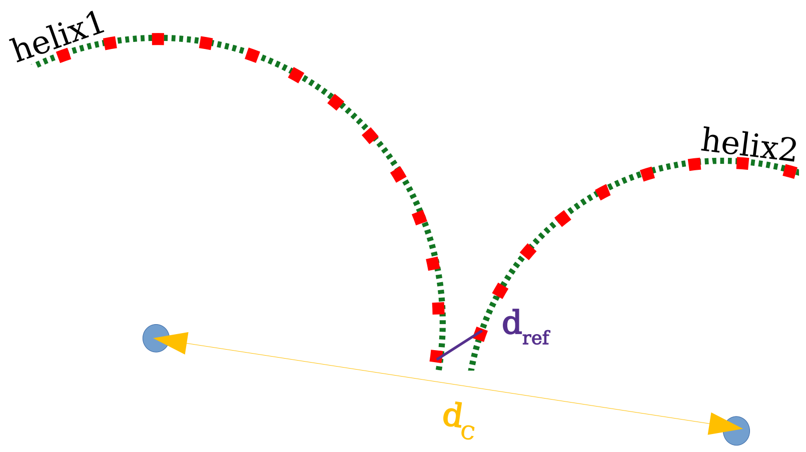
# Final selection – other variables

- 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**

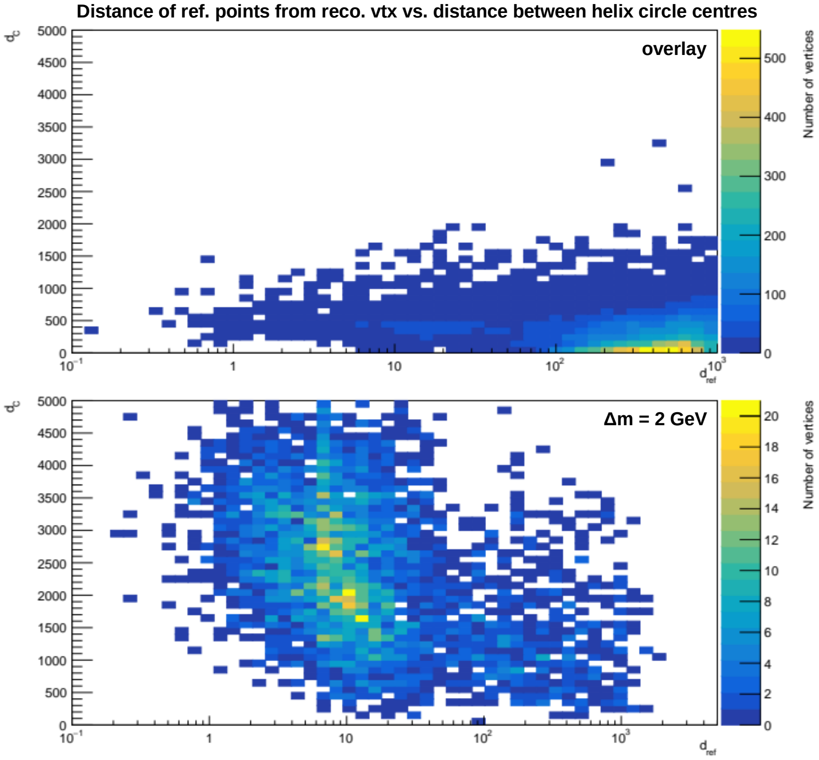



- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)

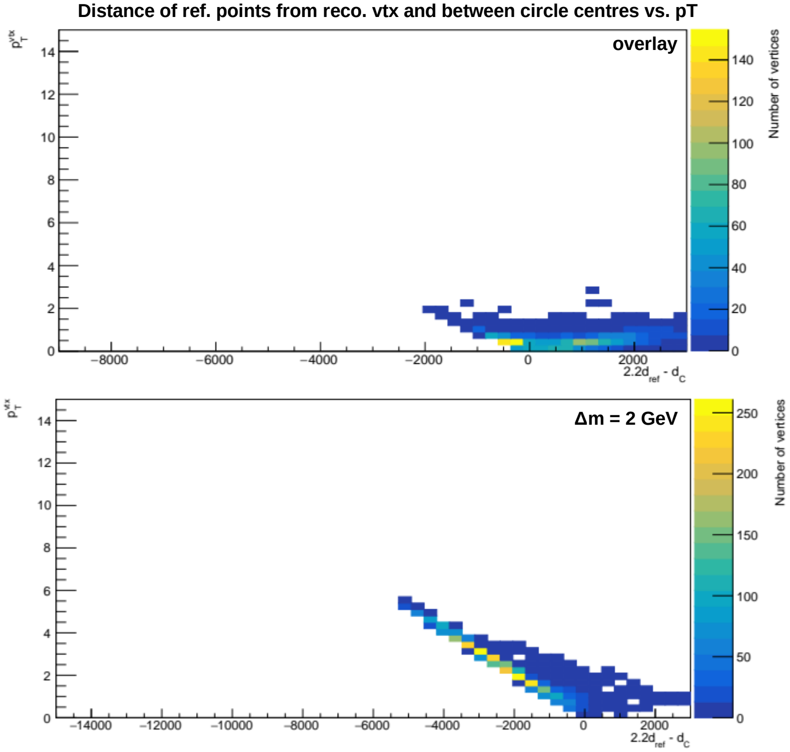
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

# 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



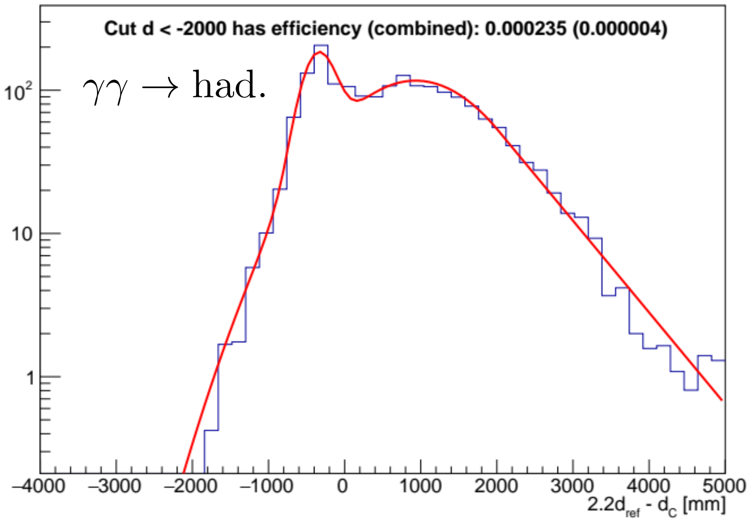

Warp and check correlation with $p_T$

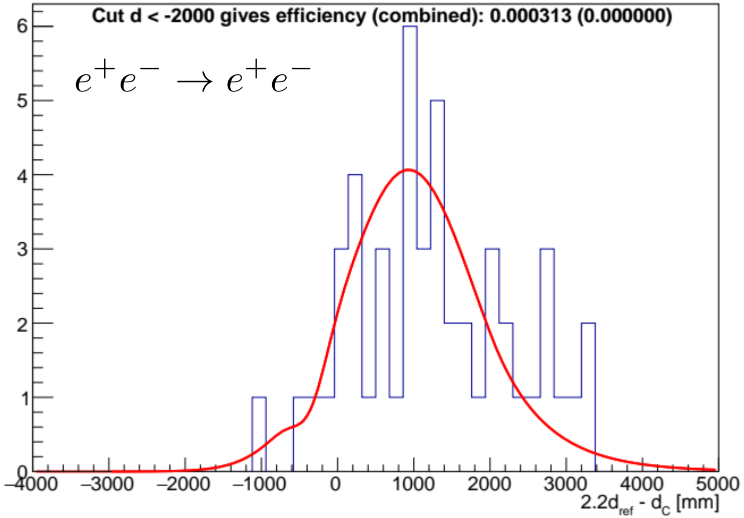



- Small correlation for the background
- Signal strongly correlated

# 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 ~$10^{-4}$ (**~$10^{-6}$–$10^{-7}$** 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

# Overlay events – final selection

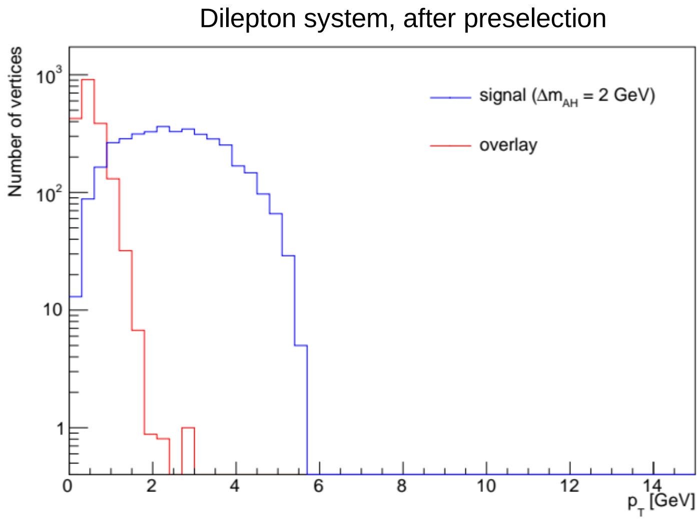
- **~$10^{10}$ events expected per year:** reduction by ~$10^{-9}$ needed
- Limited MC statistics → high uncertainties already at a reduction factor of ~$10^{-5}$

The idea: find independent cuts that **combined** give highest possible efficiency

First (obvious) variable: $\mathbf{p_T}$

Second variable: combination of **distances between reference points** and centres of helices projections into XY plane (**helix circles**)

→ Total expected reduction factor at the level of **~$10^{-9}$** (**~$10^{-10}$**) for **γγ → had.** (**$e^+e^-$ pairs**)



# 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 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