Reconstructing long-lived particles with the ILD detector

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Long-lived particles

Numerous BSM models predict LLPs:

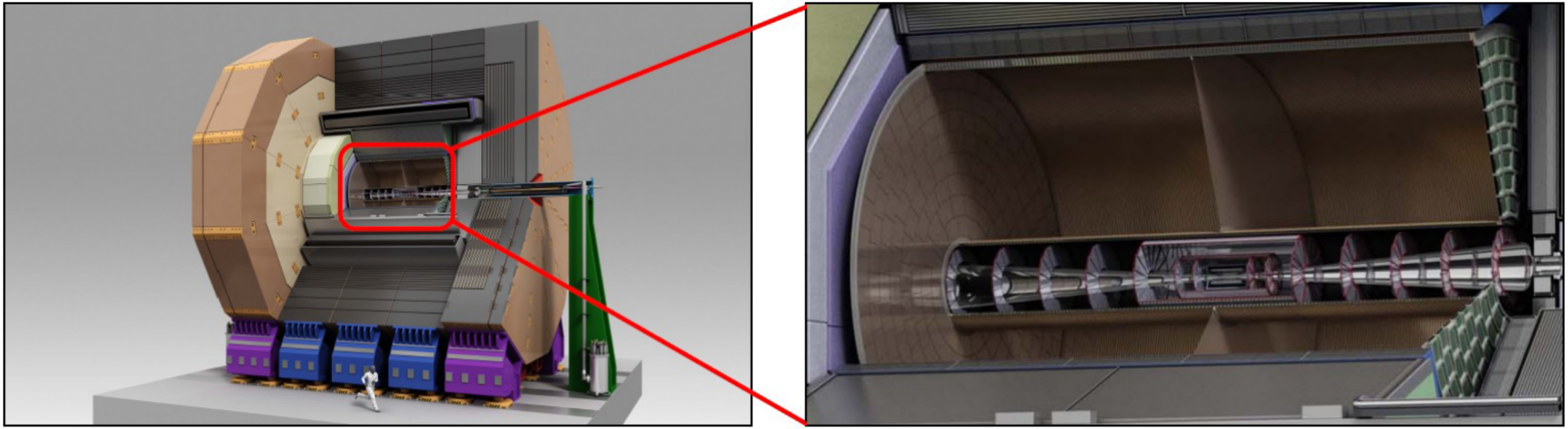
$\rightarrow$ SUSY particles, axion-like particles, heavy neutral leptons, dark photons, exotic scalars...

		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			✓

1810.12602

International Large Detector (ILD)

- Multi-purpose detector for an e^+e^- Higgs factory, nearly 4π angular coverage, optimised for particle flow
- Time projection chamber (TPC) as 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



See: general ILD status and plans talk by Uli Einhaus

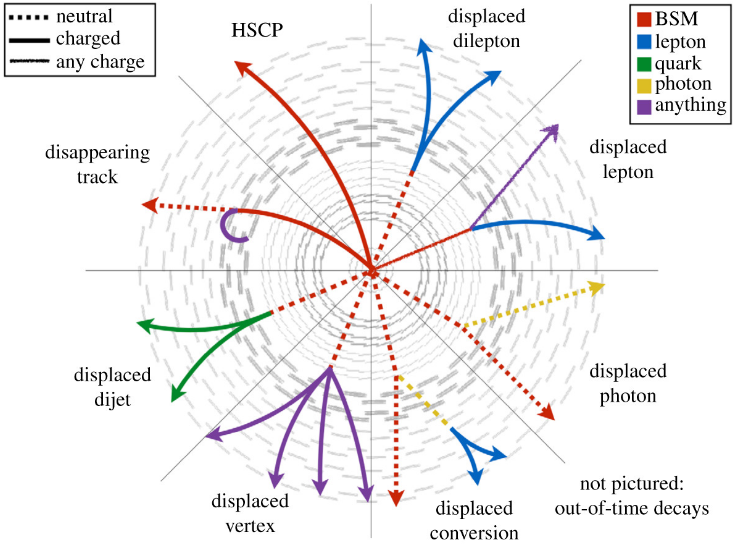
LLPs at the Higgs factories

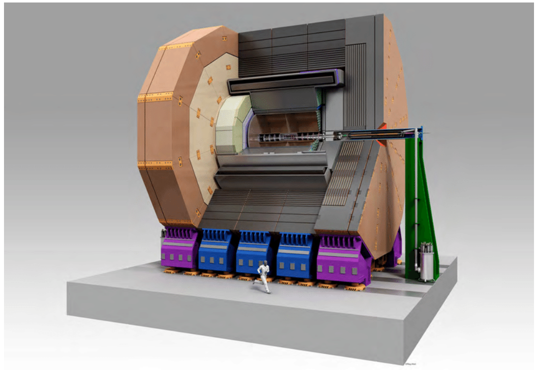
- Multiple LLP searches at the LHC, sensitive to high masses and couplings

  → 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)





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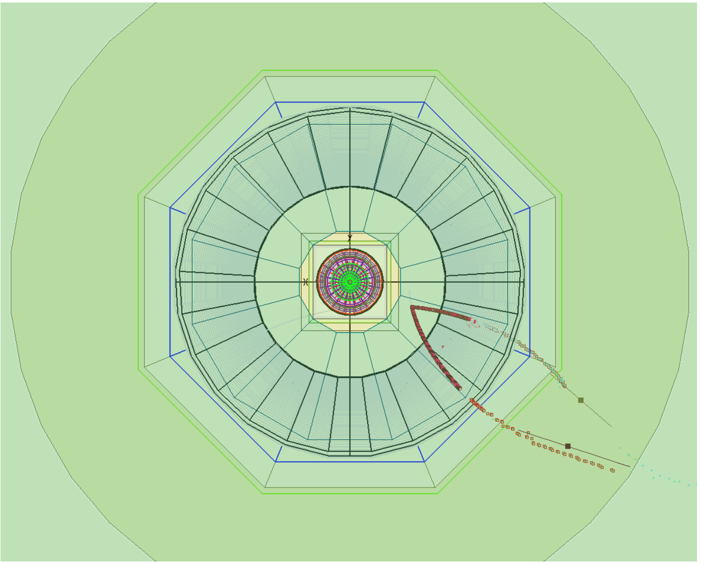
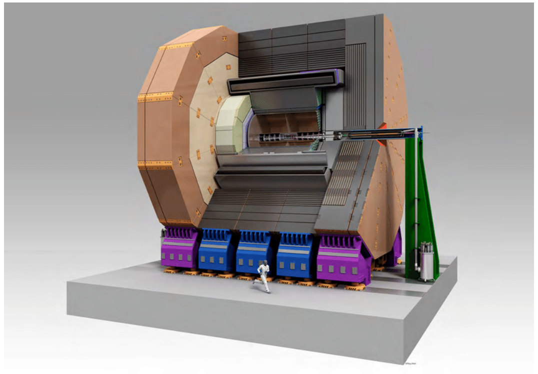




- Study such challenging signatures from the **experimental perspective**

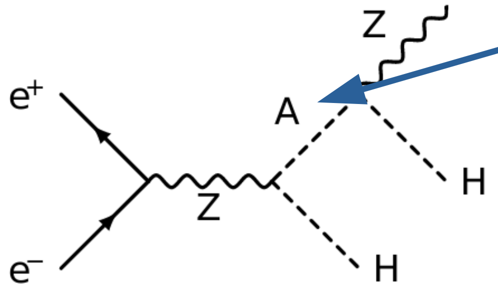
  → experimental/kinematic properties, not points in a model parameter space

- 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:

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



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

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

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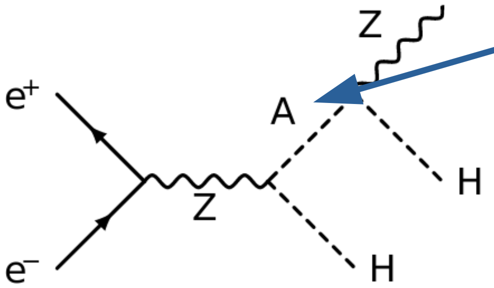
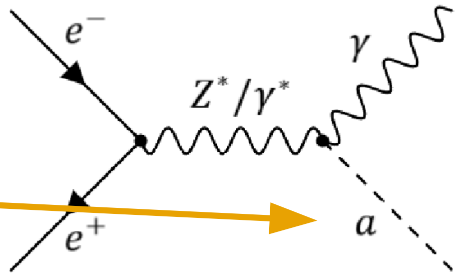


Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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)

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

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

Overlay events

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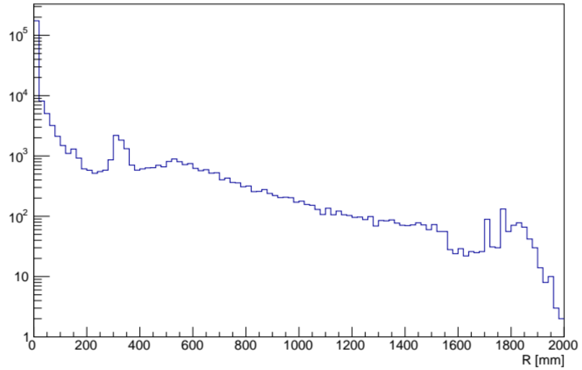
- ~10^{11} bunch-crossings per year at ILC
- Overlay events can be busy

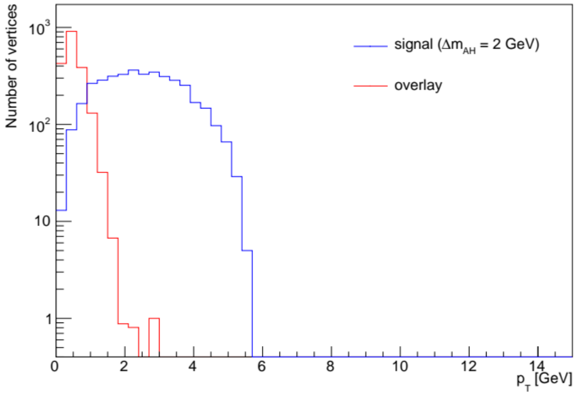
  → easy to find fake vertices by using a simple approach
- kinematics similar to signal

  → expected to give dominant contribution as a separate background

Vertices in overlay, before any selection



Dilepton system, after preselection



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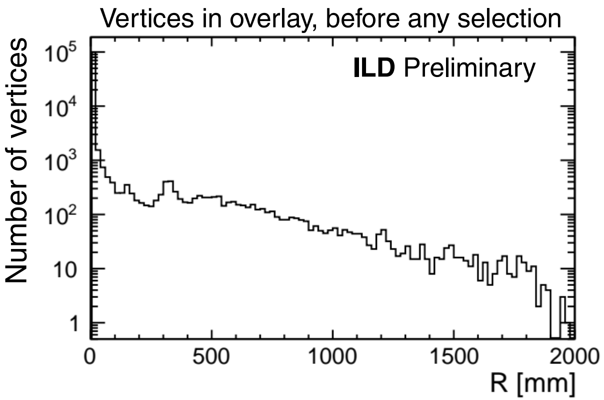
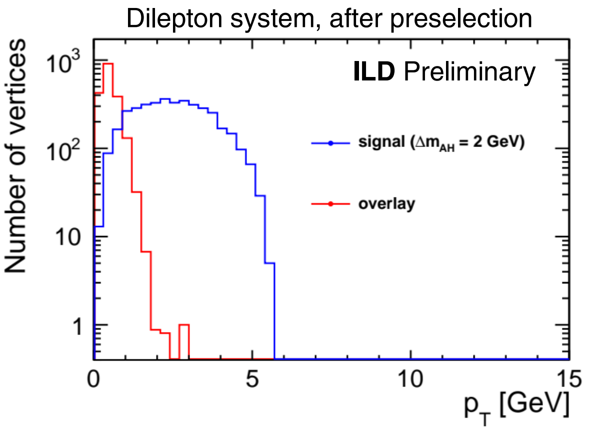
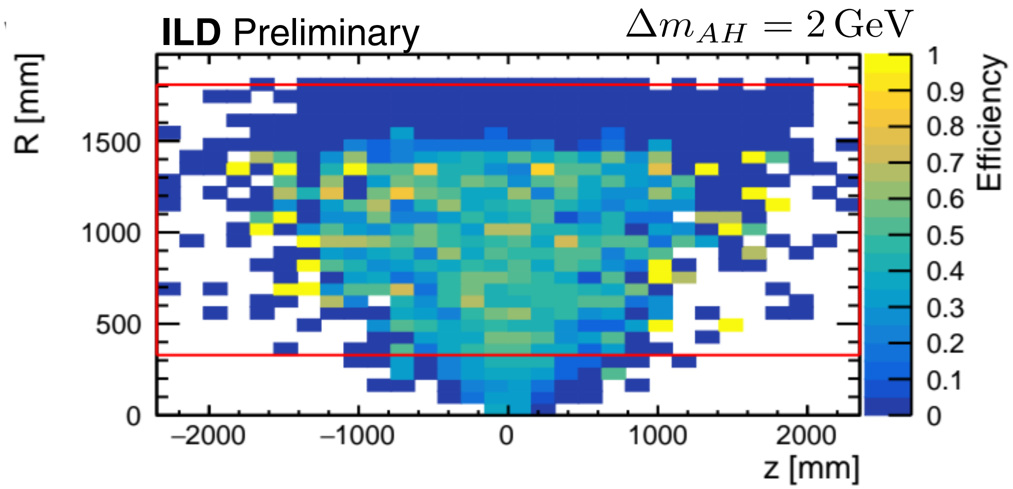


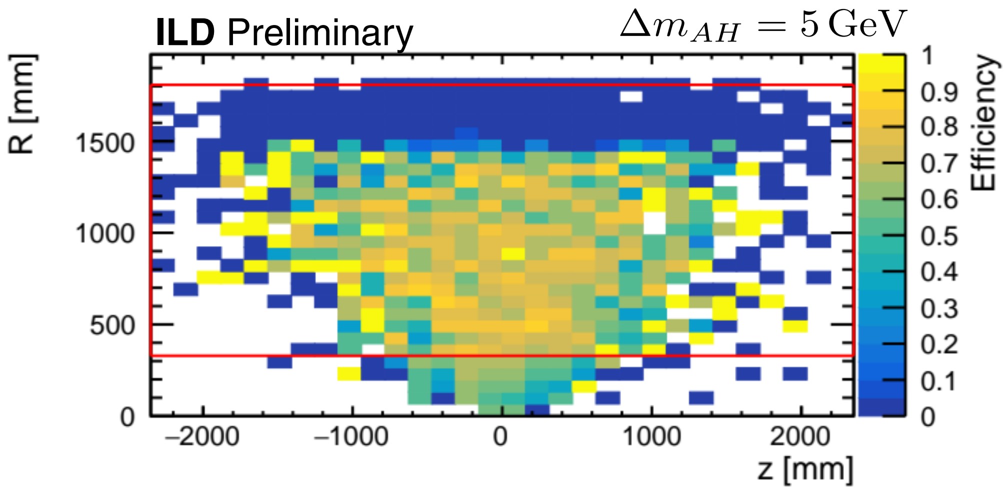


- Can be suppressed using cuts on the p_T and geometry of track pair
- Total expected reduction factor at the level of **~10^{-9}** (**~10^{-10}**) for $\gamma\gamma \to$ **had.** (**e^+e^- pairs**)

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)	96.4%	97.4%	98.8%	98.6%

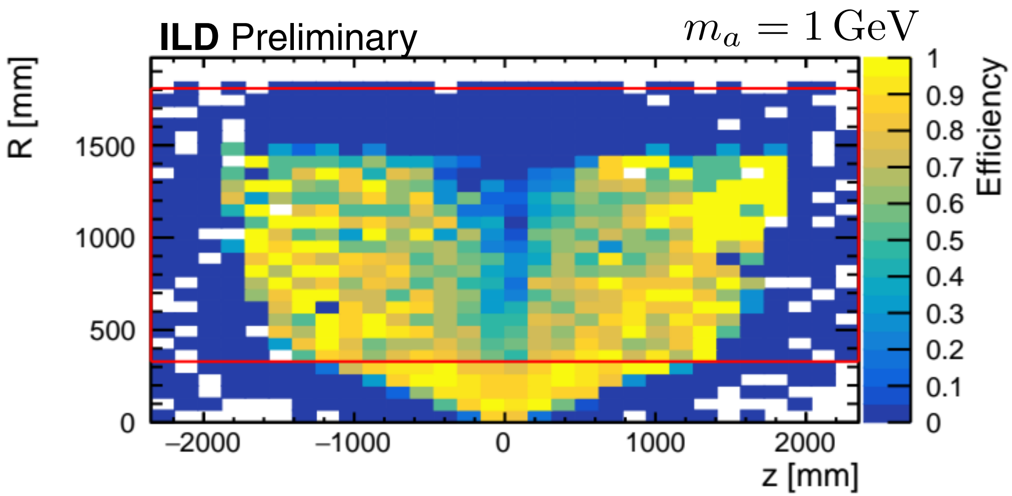


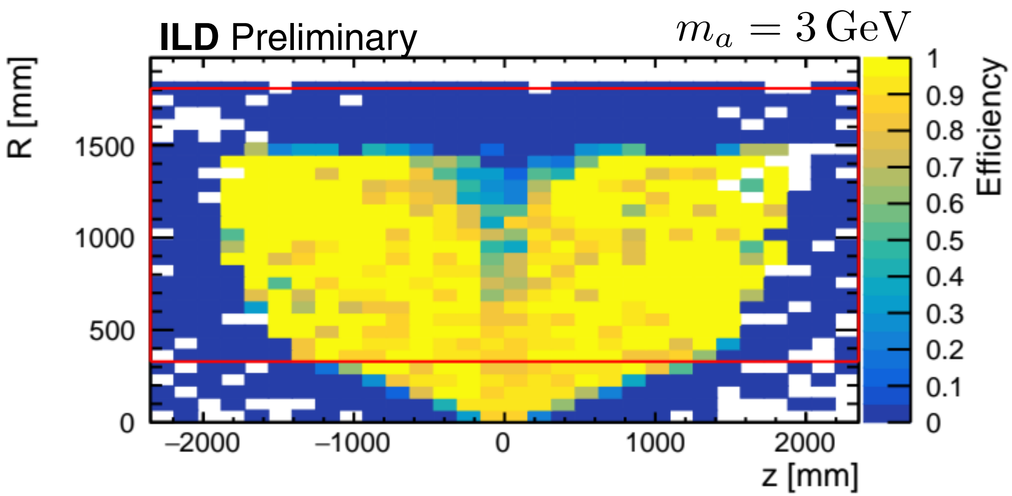


- Consider "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality)
- Δm = 1 GeV scenario needs dedicated approach

Results (ALP signal)

m_a	0.3 GeV	1 GeV	3 GeV	10 GeV
TPC eff. (correct / decays within TPC acceptance)	24%	54%	77%	78%
Accuracy in TPC (correct / all found)	41%	78%	97%	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 ILC,
- 10 yr $\times$ 10^{11} bunch-crossings (BXs)
- 1.05 (1.00) $\gamma\gamma \to$ had. (seeable e^+e^- pairs) events per BX,
- total background rejection of 10^{-9} (10^{-10}) $\to$ ~1150 expected bg. events

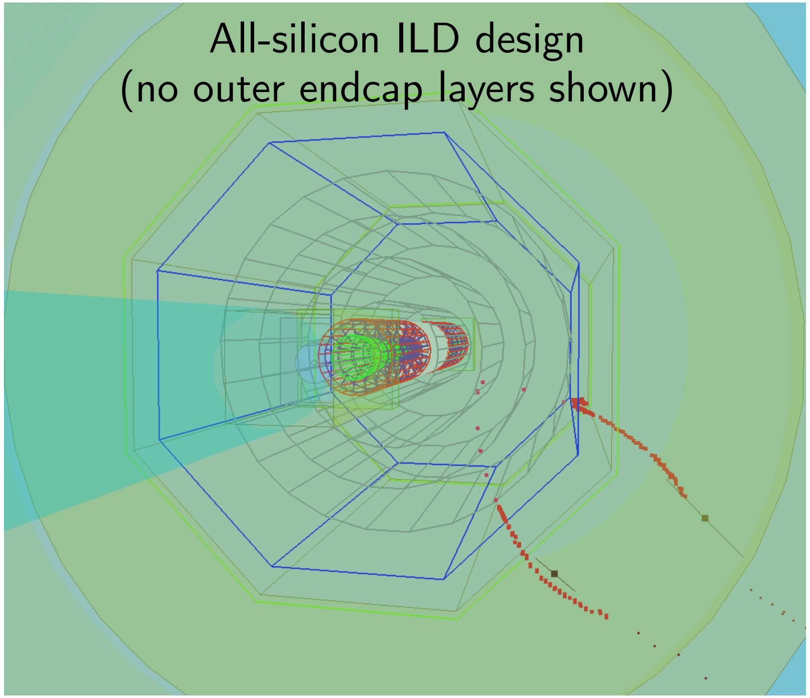
The estimated upper limit for $p_T^{vtx} > 1.9$ GeV:

$$\sigma_{95\%\,\mathrm{C.L.}} \lesssim 0.03\,\mathrm{fb}\;(0.01\,\mathrm{fb\ for}\ 4\,\mathrm{ab}^{-1}\ \mathrm{at}\ 500\,\mathrm{GeV})$$

Alternative all-silicon ILD design

<u>Alternative ILD design</u> implemented for tests

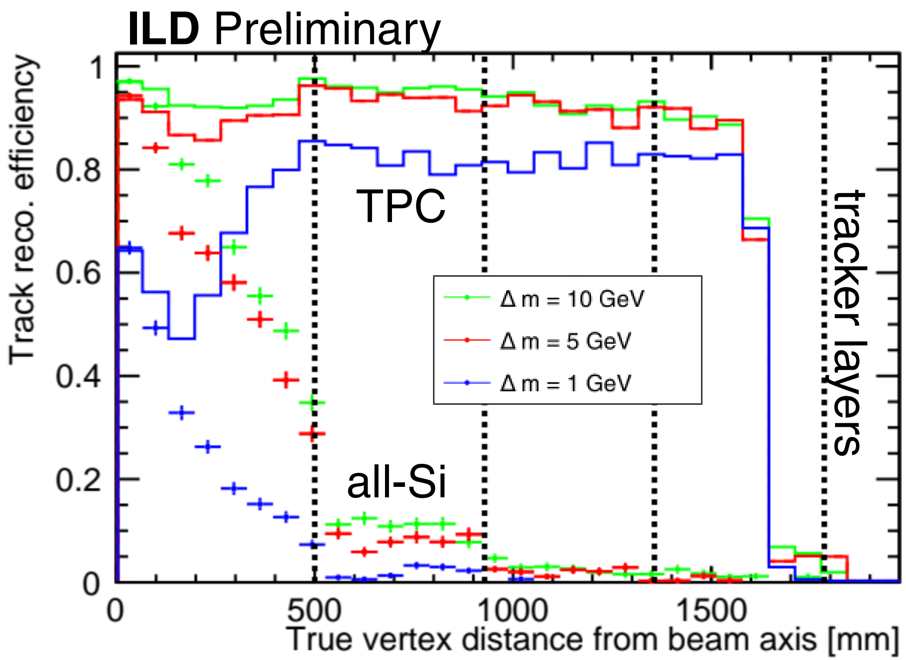
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ Check how the **results** for <u>heavy scalars</u> are influenced by a **change of tracker** design

Heavy scalars at all-silicon ILD

- <u>Vertex reconstruction</u> driven by **track reconstruction efficiency**
- Performance similar to baseline design (TPC) <u>near the beam axis</u>
- 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

  $\rightarrow$ a simple algorithm developed, with a set of cuts aimed to suppress background from the overlay events

- 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** $\mathbf{\geq 1\ GeV}$
- Estimated 95% CL limit on signal cross section is 0.03 (0.01) fb at 250 (500) GeV ILC

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

  $\rightarrow$ tracking tests for heavy scalars confirm **higher reach of TPC** in LLP searches

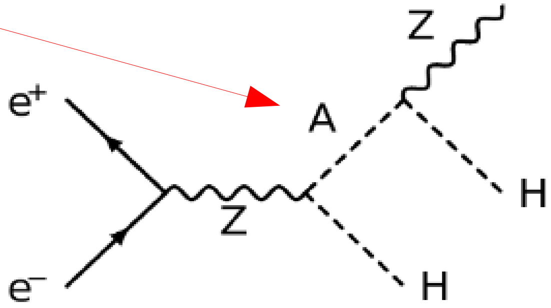
BACKUP

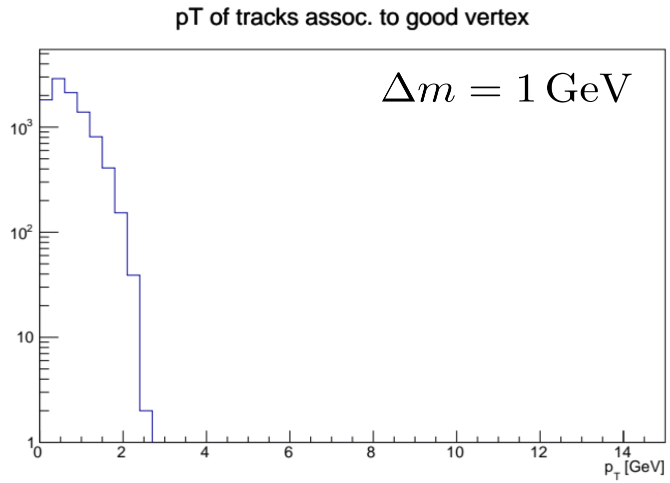
Test signal scenarios

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: $A \rightarrow HZ^*;\ Z^* \rightarrow \mu\mu$ decay used for vertex reconstruction studies

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





Low-pT tracks prevail

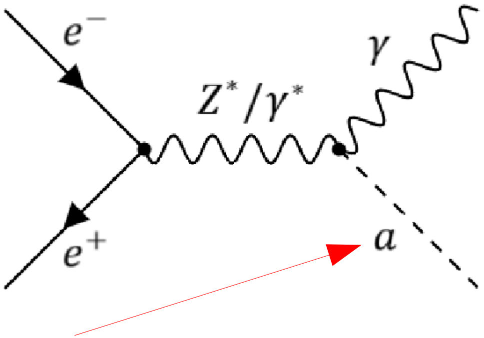
Benchmark scenarios:

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

Test signal scenario – highly boosted light LLPs

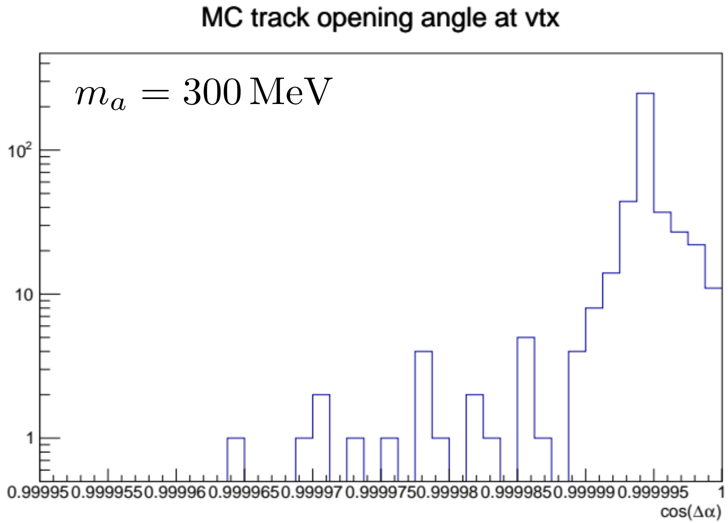
Exactly the opposite extreme scenario (**small LLP mass**, very **high pT**, **collinear tracks**):

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

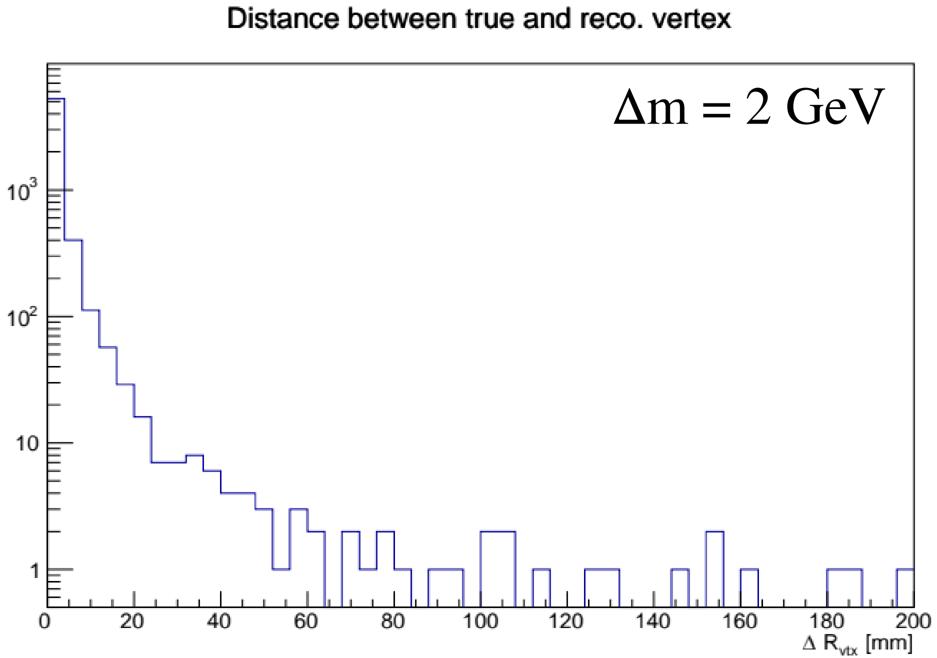
Benchmark scenarios: $m_a = 0.3, 1, 3, 10\,\mathrm{GeV}$

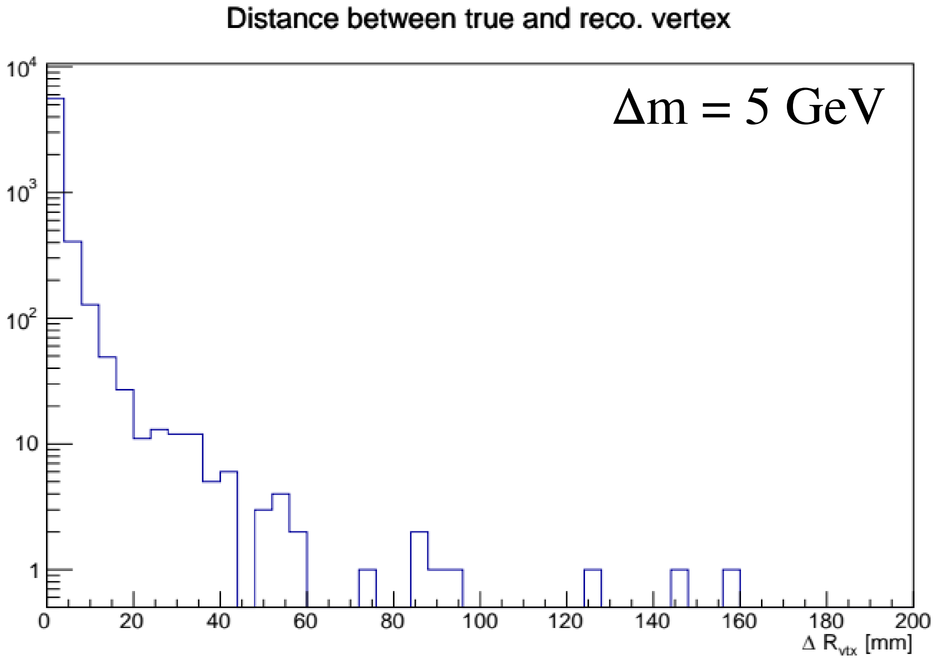


Tracks almost collinear

Distance to the true vertex

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



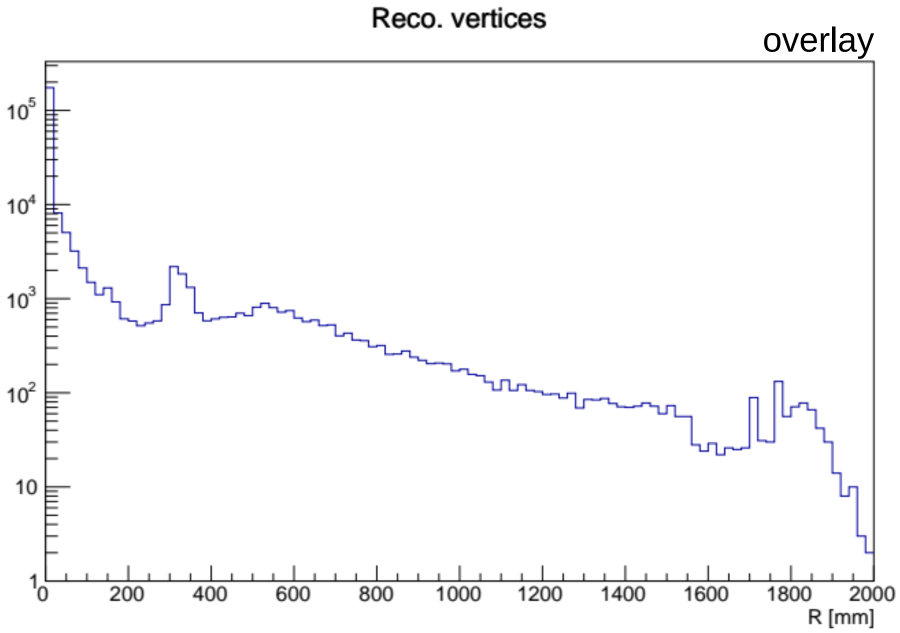


Sources of vertices in overlay events

1. Large number of tracks starting near primary vertex

- Simple „helix distance" approach not accurate enough for numerous soft tracks starting close by in this region of the detector
- Dedicated methods probably needed

→ For now take into account only **decays inside the TPC (0.33 < R < 1.8 m)**



1a. V0 particles

- Remove V0s by matching with the V0Finder output

Sources of vertices in overlay events

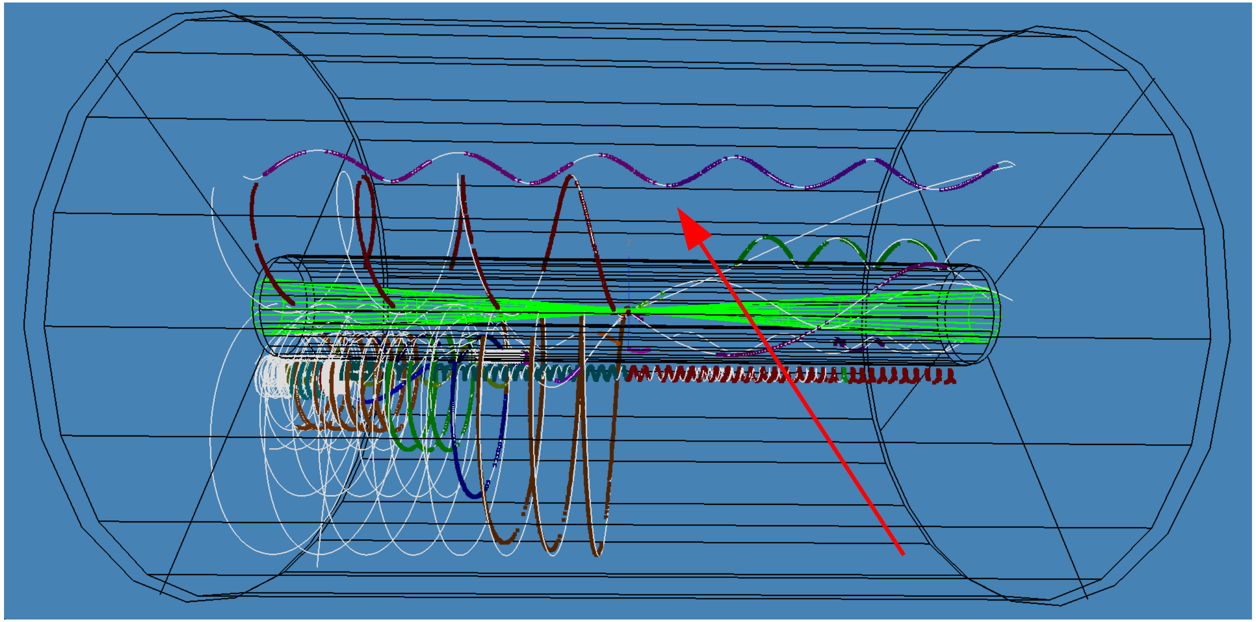
2. Split tracks

Due to missing hits, single track can often be reconstructed as several

Because we consider both possible track directions, a vtx can be found in between

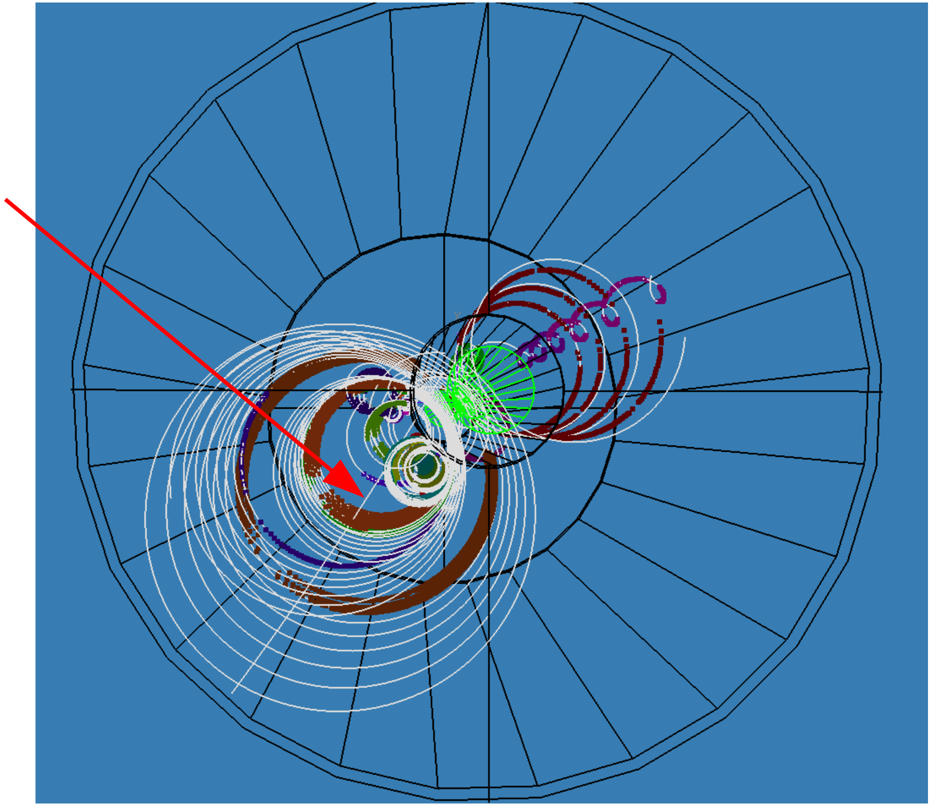
→ Cuts on opening angle $\cos(\alpha) > -0.6$ and tracks' curvatures ratio $|\Omega_1/\Omega_2| < 0.94$ (equiv. to p_T ratio)

→ Additionally require at least one track with Ndf > 40 to remove vertices from short and fractional tracks



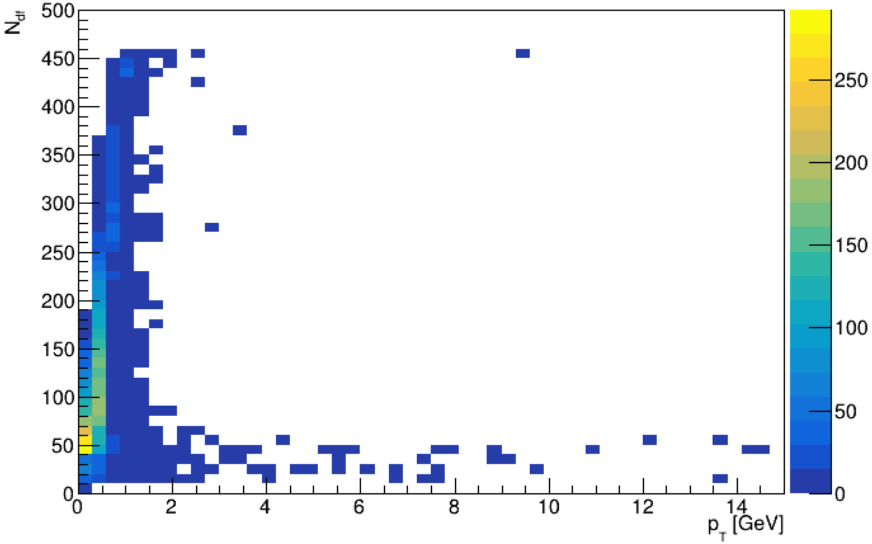
Sources of vertices in overlay events

3. Artificial short high-p_T tracks



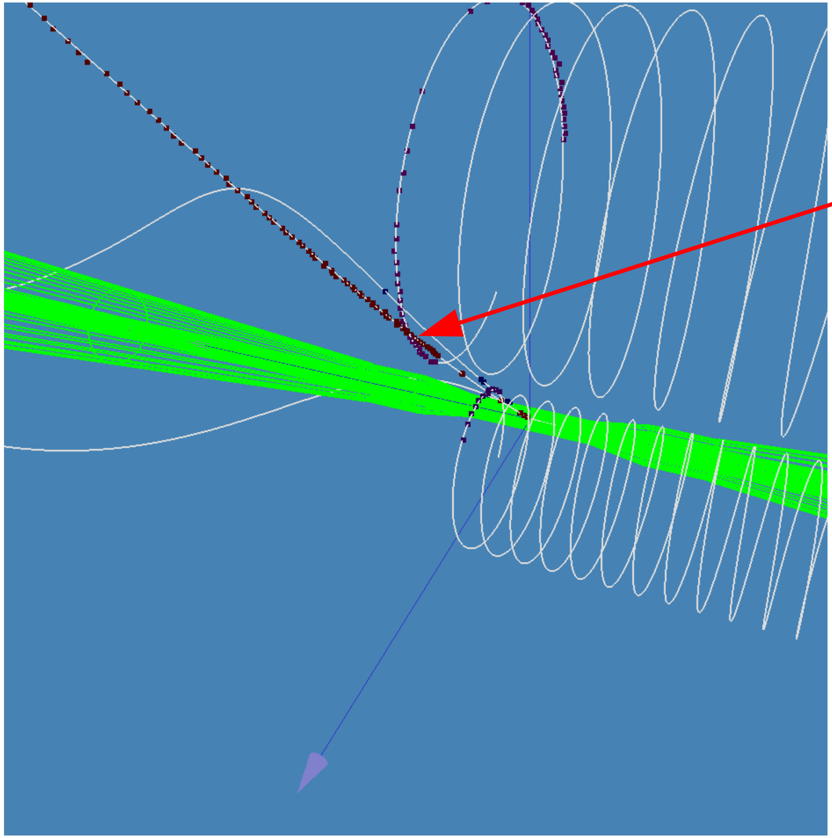
Fraction of hits in a curler can get clustered and formed into a **high-p_T track**

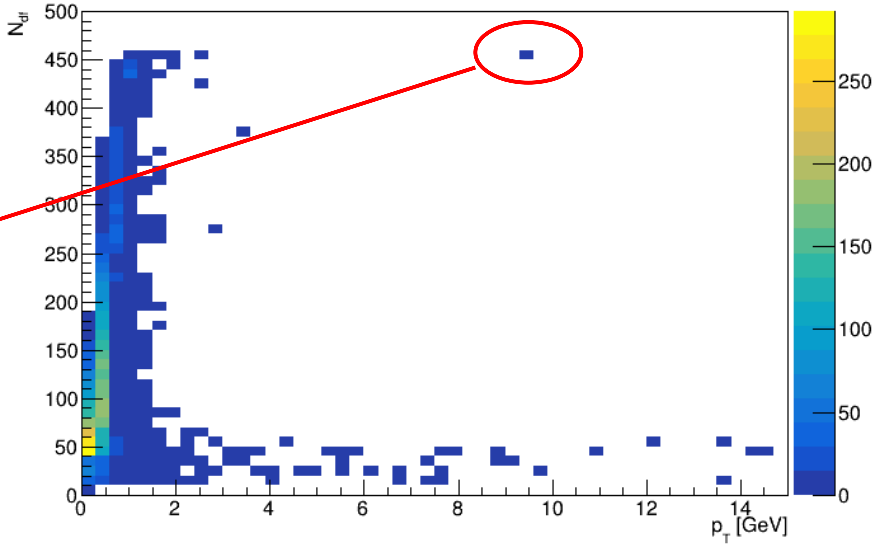
→ Remove vtx candidates with tracks having p_T >1.5 GeV and N_{df} < 70



Sources of vertices in overlay events

4. Intersecting tracks



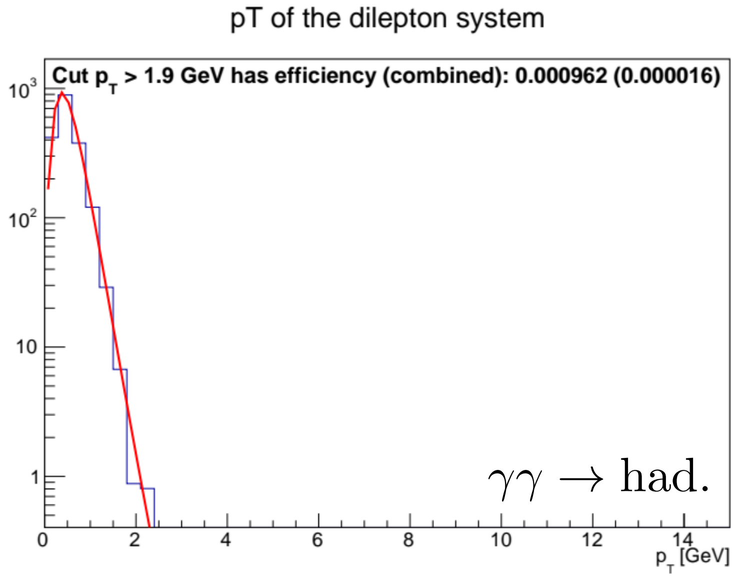


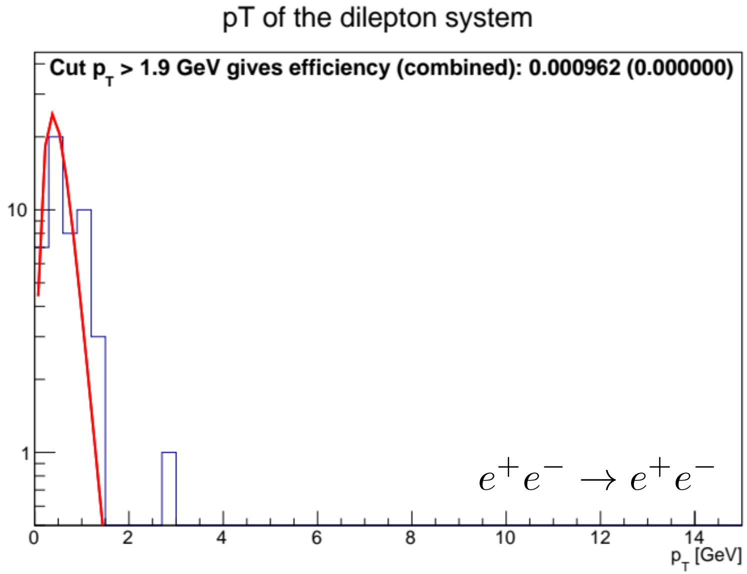
Tracks often randomly cross and intersect
With our (basic) approach vertices are found at the intersections

→ Cut on the **distance from vtx to first track hit** relative to the **track length**
→ Use φ or z, based on first-last hit distance in z

Final selection – pT

- We consider **$\gamma\gamma \rightarrow$ 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 **$\gamma\gamma \rightarrow$ had.** with floating normalisations



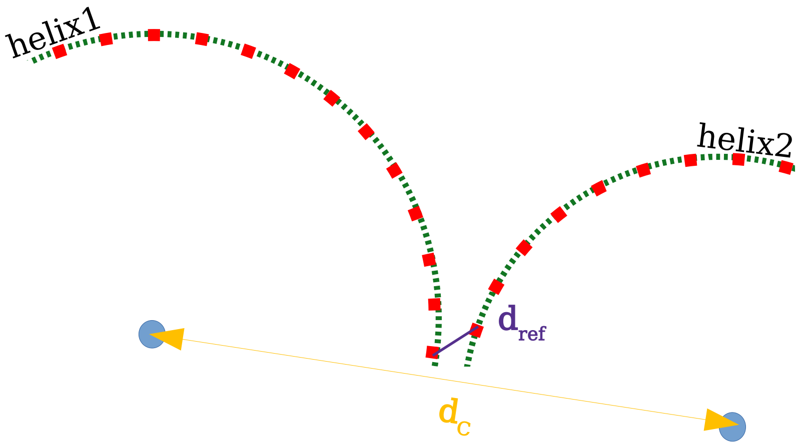


Norm = number of events, scaled by corresponding Poisson expectation values

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

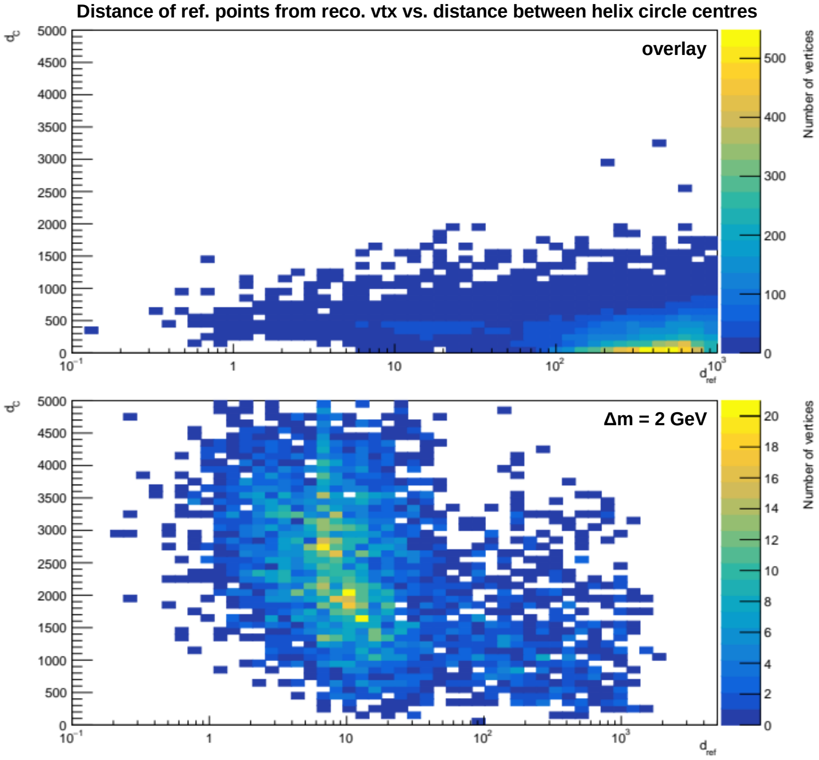
→ either **far reference points** or **close centres of helices**



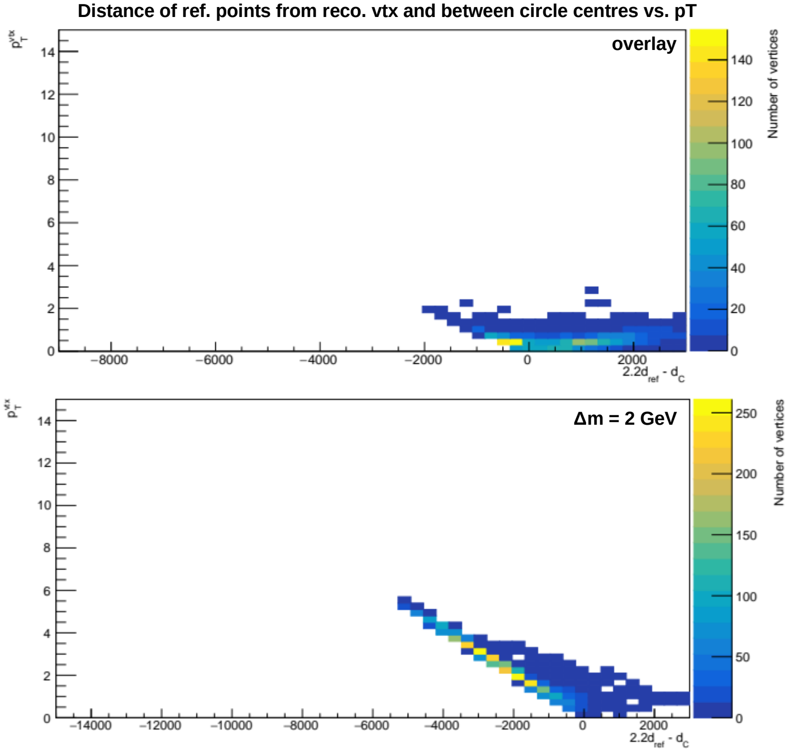
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

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



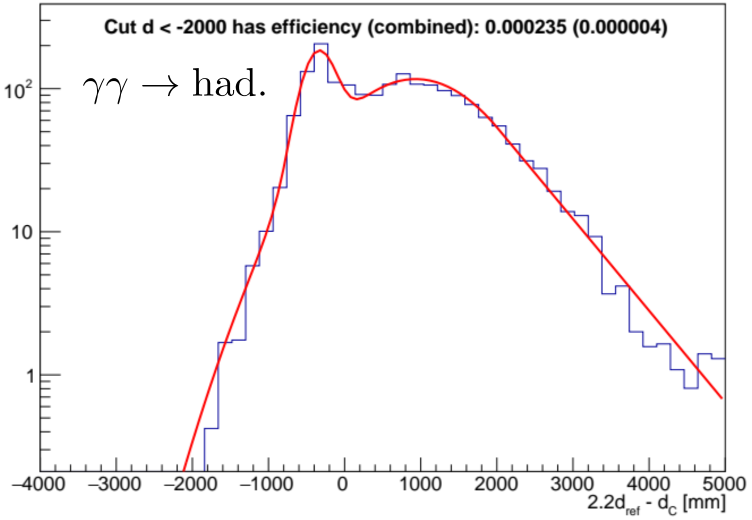
Warp and check correlation with p_T

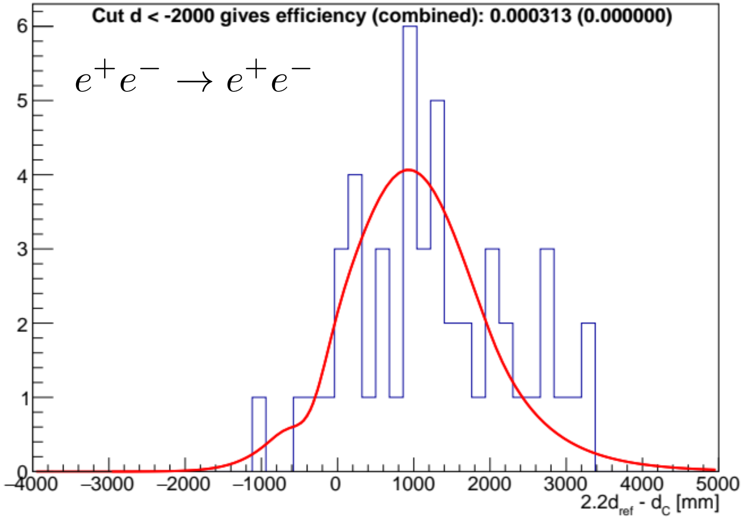


- Small correlation for the background
- Signal strongly correlated

Final selection – second variable

- Same approach as for the pT
- For $2.2d_{ref} - d_C < -2000$ mm, **signal eff. ~37%** (Δm = 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

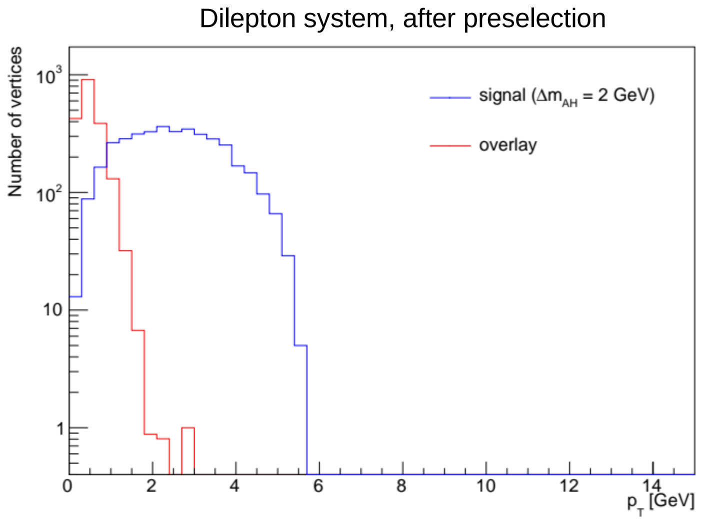
Overlay events – final selection

- **~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**)

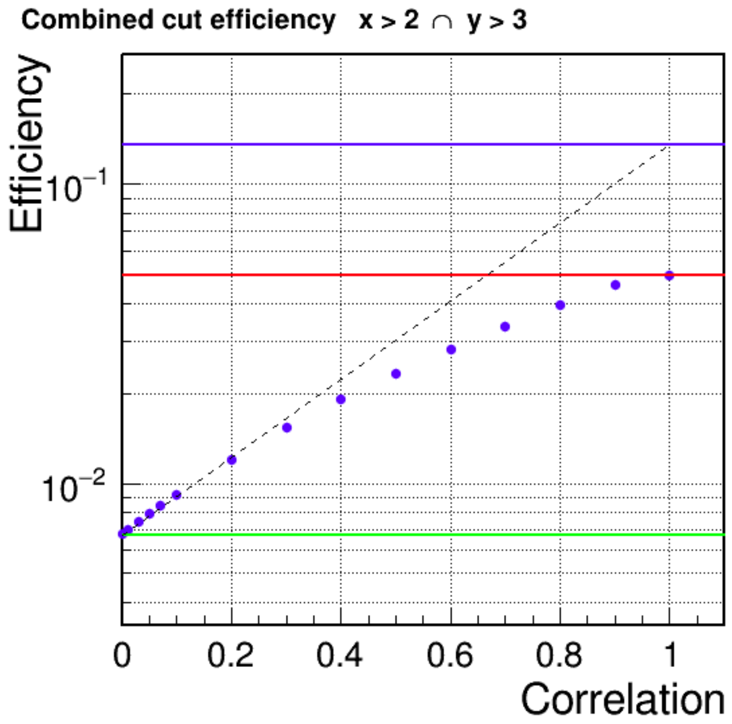
Selection assuming correlations

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



Collinear tracks in TPC

- Impossible to distinguish the tracks close to the production vertex
- Tracking often assigns first hit of the second track far from vertex (small influence on reco. momentum)
- In vtx reco. we take two closest hits – here it can be the two last hits!

→ Still find a vertex – if it's closer to the other pair of hits, take TrackStates in this other pair