Reconstruction of long-lived particles at the ILD

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Motivation

- **Various BSM models predict LLPs**:

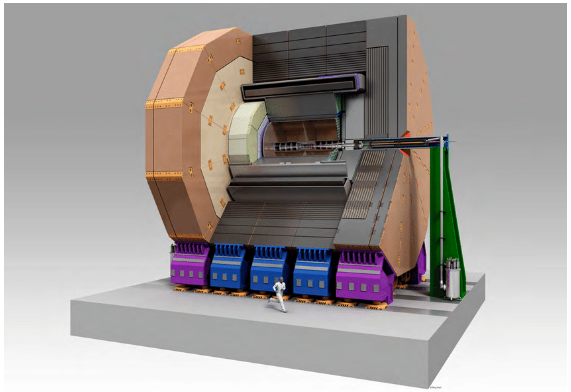
  → SUSY particles, axion-like particles, heavy neutral leptons, dark photons, exotic scalars...

- 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



- Study such challenging signatures from the **experimental perspective**
- Focus on a generic case – two tracks from a displaced vertex
- No other assumptions about the final state, approach **as general as possible**

Vertex finding strategy

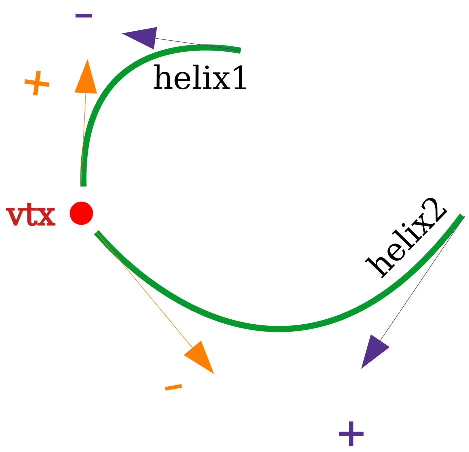
Approach as simple and general as possible:

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

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

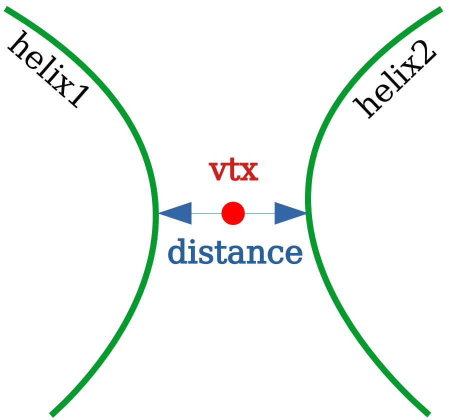
  → consider opposite-charge track pairs only

  → select pair with **closest starting points**



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

  → Require distance < 25 mm

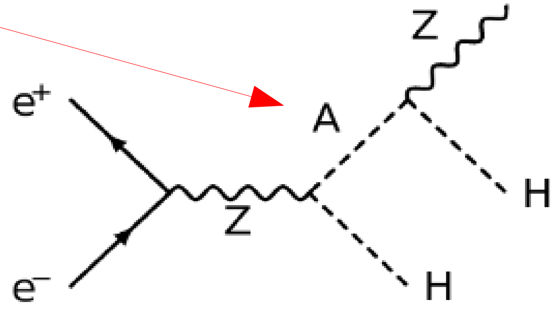


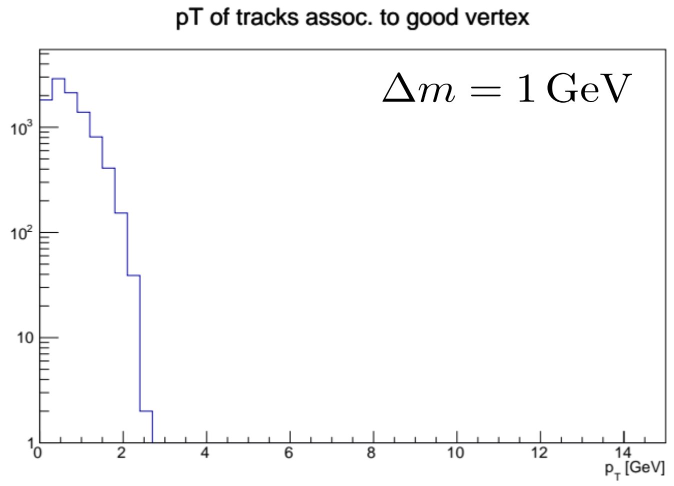
Test signal scenario – heavy scalars

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:

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

Overlay events reduction

$\gamma\gamma \to$ hadrons and seeable e^+e^- pairs occur in each bunch-crossing, and will not only overlay on physical events, but can look like signal on their own

- ~10^{10} bunch-crossings per year at ILC
- kinematics similar to signal

→ expected to give dominant contribution as a separate background

Overlay events reduction

γγ → hadrons and seeable e^+e^- pairs occur in each bunch-crossing, and will not only overlay on physical events, but can look like signal on their own

- ~10^{10} bunch-crossings per year at ILC
- kinematics similar to signal

→ expected to give dominant contribution as a separate background

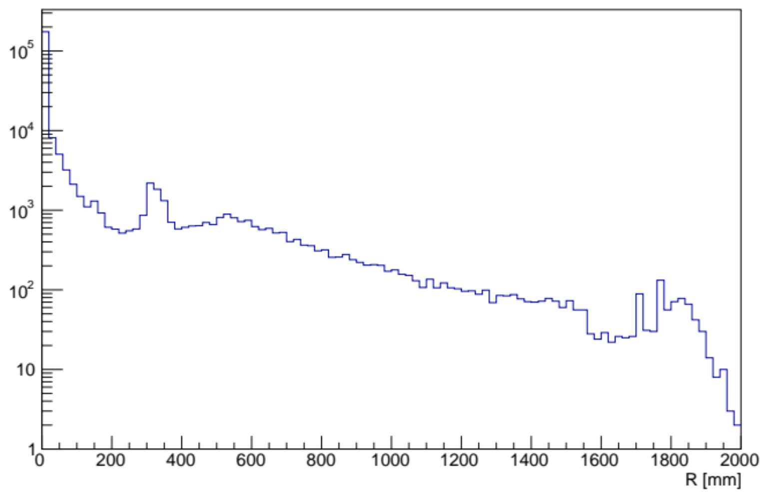
Vertex finding algorithm designed for TPC

→ take into account only decays inside its region

Vertices from **split** and **fake tracks**, or random **intersections** → a set of preliminary cuts on:

- tracks opening angle and curvature ratio
- distance from vtx to first track hit, relative to the track length
- number of hits in a track

Vertices in overlay, before preselection



Overlay events – final selection

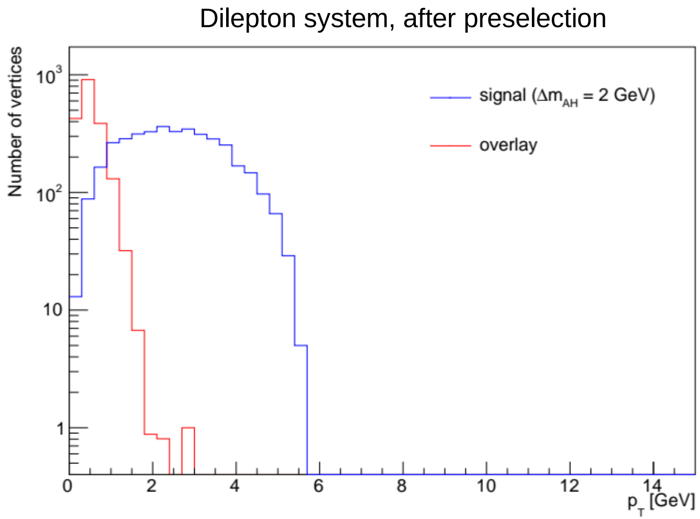
- **~10^{10} events expected per year:** reduction by ~10^{-9} needed
- Limited MC statistics → high uncertainties already at a reduction factor of ~10^{-5}

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

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

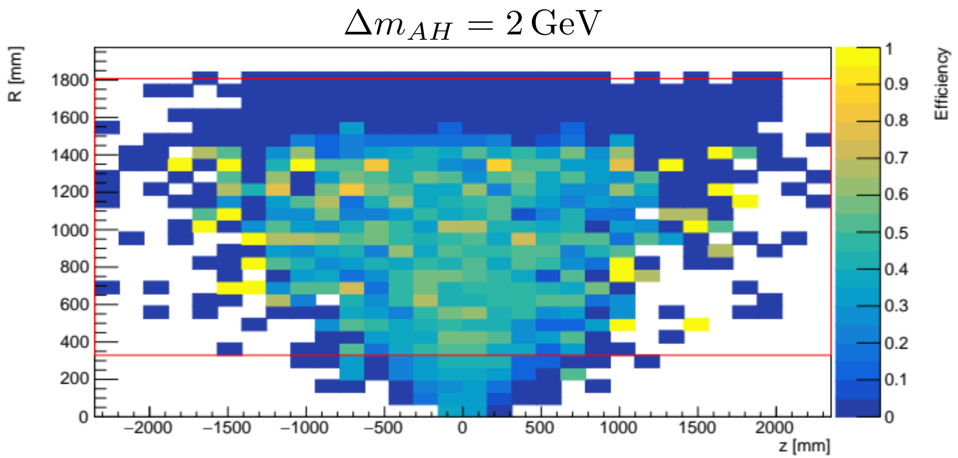
Second variable: combination of **distances between reference points** and centres of helices projections into XY plane **(helix circles)**

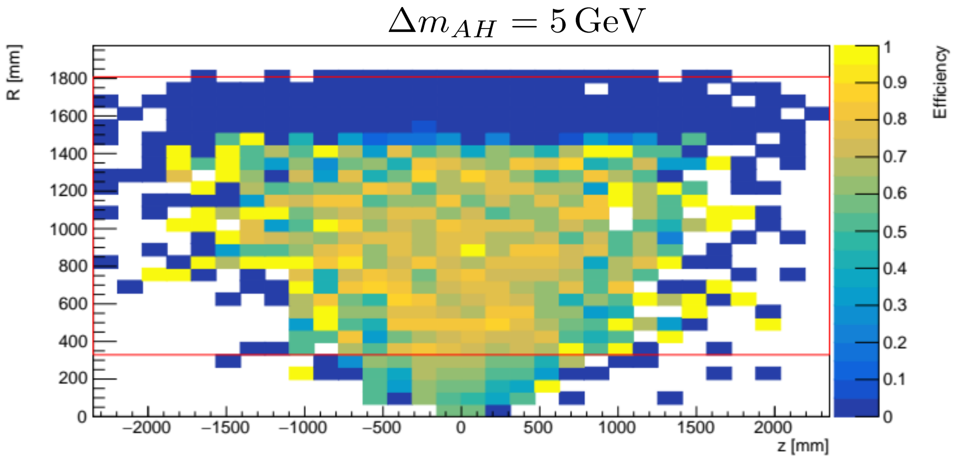
Total expected reduction factor at the level of **~10^{-9}** (**~10^{-10}**) for **γγ → had.** (**e^+e^- pairs**)



Results (IDM signal)

Δm	1 GeV	2 GeV	3 GeV	5 GeV
Tot. eff. (correct / decays within TPC acceptance)	3.9%	37%	52.2%	60.4%
Corectness (correct / all found)	96.4%	97.4%	98.8%	98.6%



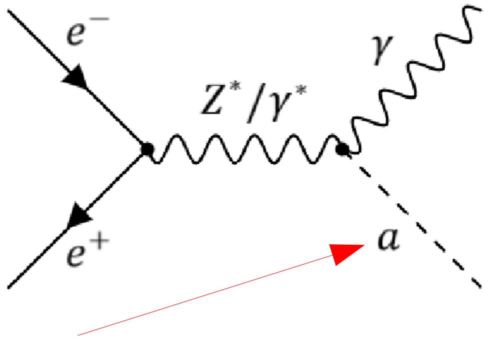


- Consider ”correct” if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality)
- Δm = 1 GeV scenario beyond reach after selection

Test signal scenario – highly boosted light LLPs

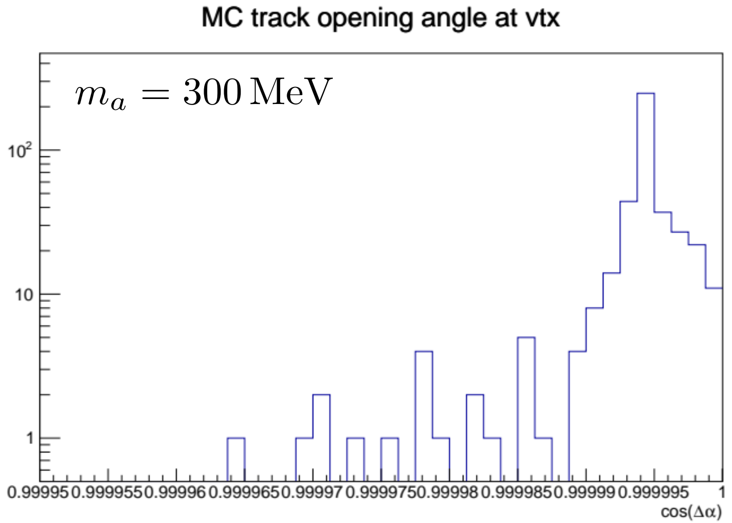
Exactly the opposite extreme scenario (**small LLP mass**, very **high pT**, **collinear tracks**):

- **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 $\rightarrow \mu\mu$ decay used for studies
- Number of decays within acceptance strongly varies between signal scenarios



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

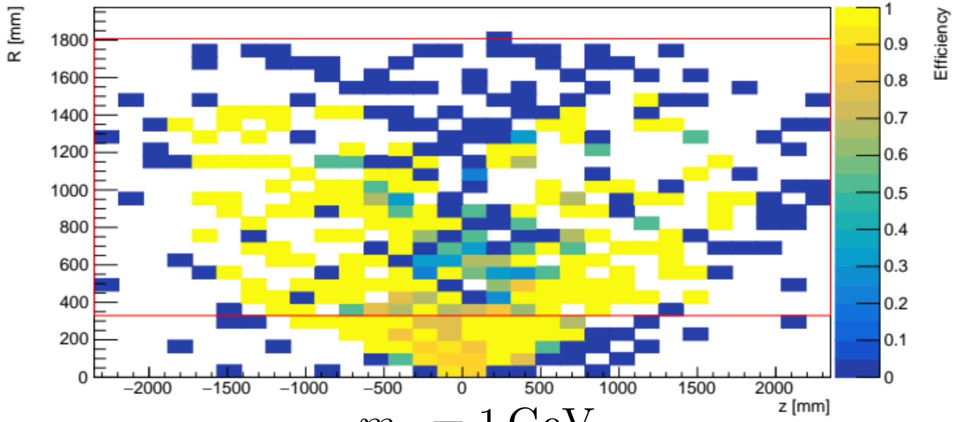
Benchmark scenarios: $m_a = 0.3, 1, 3, 10\,\mathrm{GeV}$



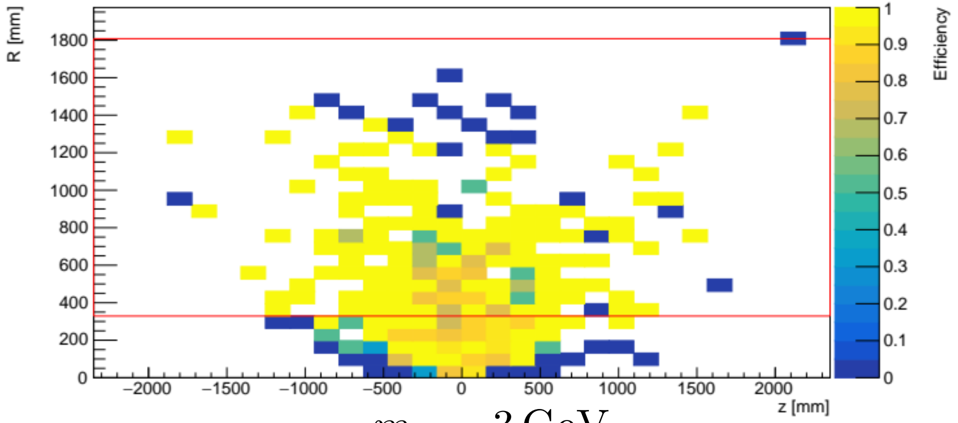
Tracks almost collinear

Results (ALPs signal)

m_a	0.3 GeV	1 GeV	3 GeV	10 GeV
Tot. eff. (correct / decays within acceptance)	31%	68%	86%	87%
Corectness (correct / all found)	53%	86%	95%	97%
TPC eff. (correct / decays within TPC acceptance)	17%	56%	86%	97%
Corectness in TPC (correct / all found)	37%	82%	96%	100%



$m_a = 1\,\text{GeV}$



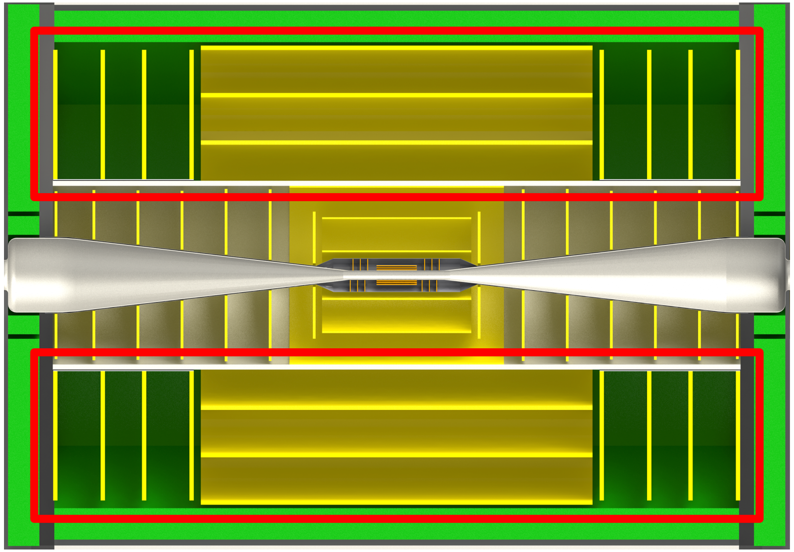
$m_a = 3\,\text{GeV}$

- In the TPC: limited statistics, lower efficiency than for small radii
- **High efficiency** for masses from **1 GeV**

Alternative all-silicon ILD design

Alternative ILD design implemented for tests by D. Jeans

- **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

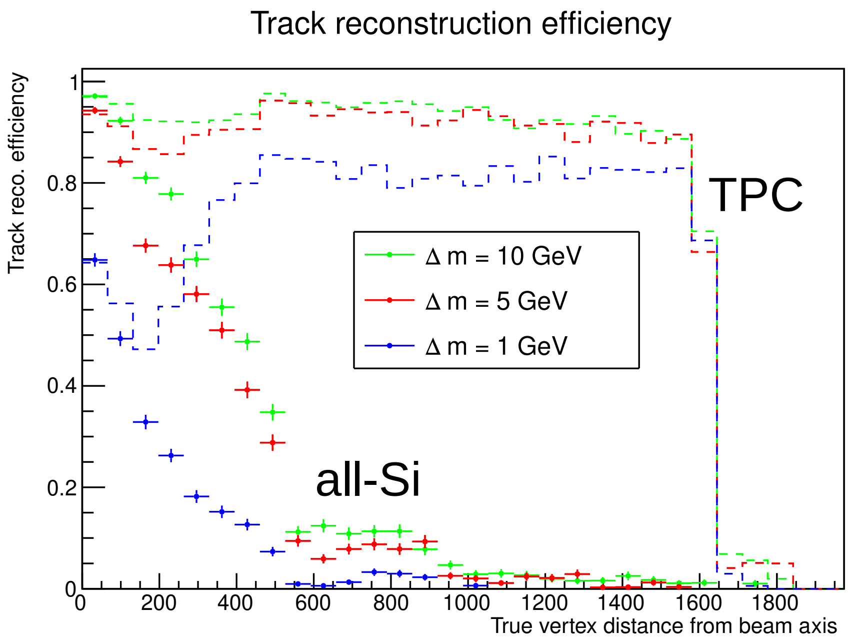


CLICdet tracker region (CLICdp)

→ Check how the **results** for heavy scalars 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

  → 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 **Δm = 2 GeV**
- Reconstruction of **highly boosted**, **light** ALPs decaying into muons performed with the same algorithm and procedure

  → first results indicate good sensitivity for ALP **masses** of **1 GeV** and higher

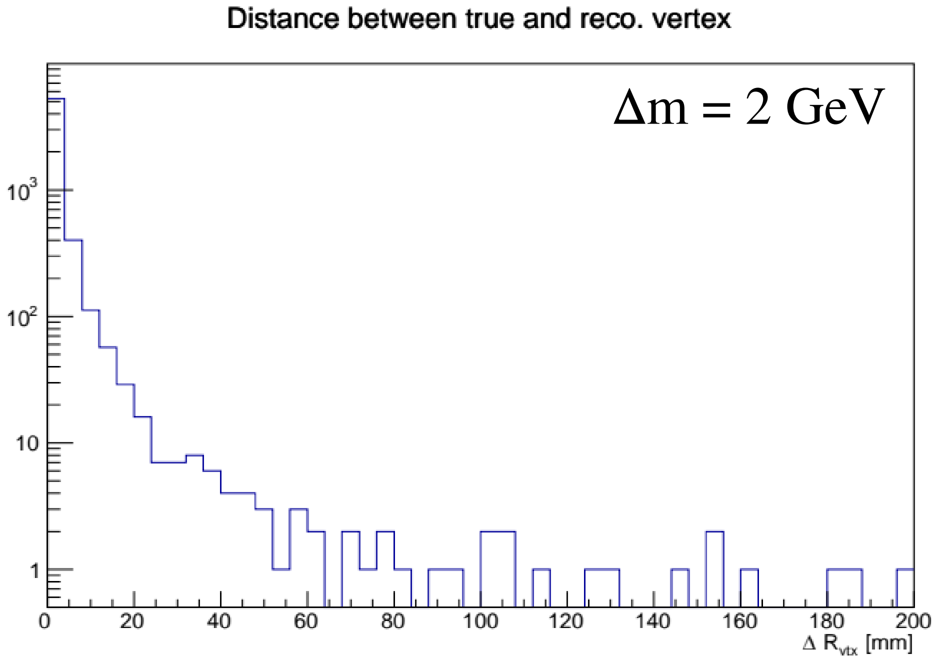
- Alternative ILD design used for comparison between all-silicon tracker and TPC

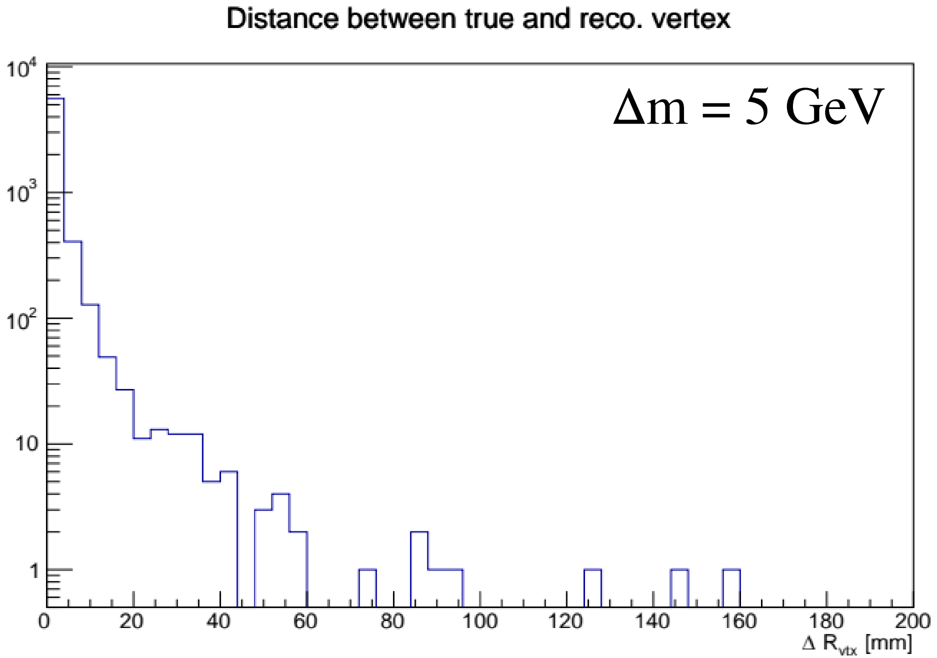
  → tracking tests for heavy scalars confirm **higher reach of TPC** in LLP searches

BACKUP

Distance to the true vertex

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





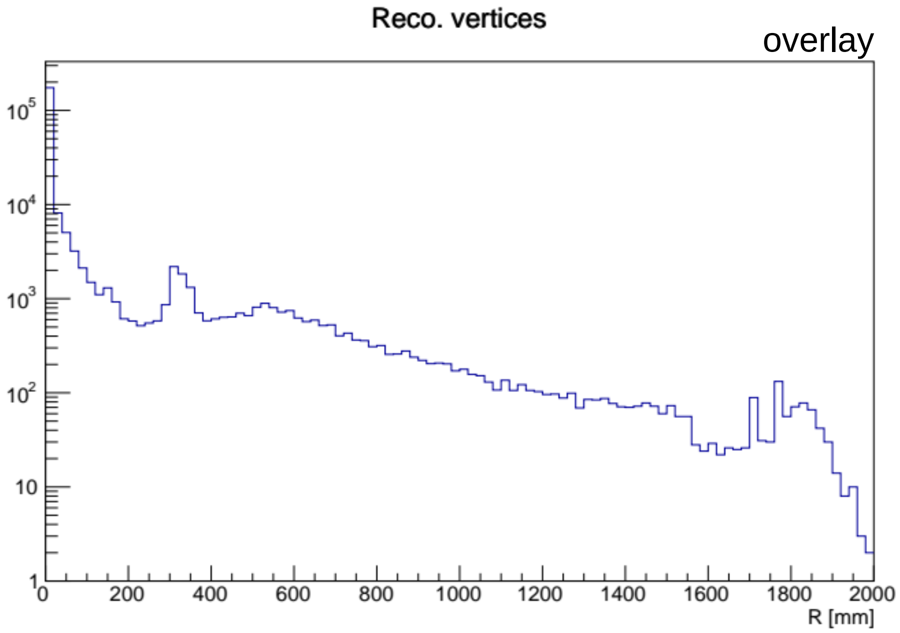
Sources of vertices in overlay events

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

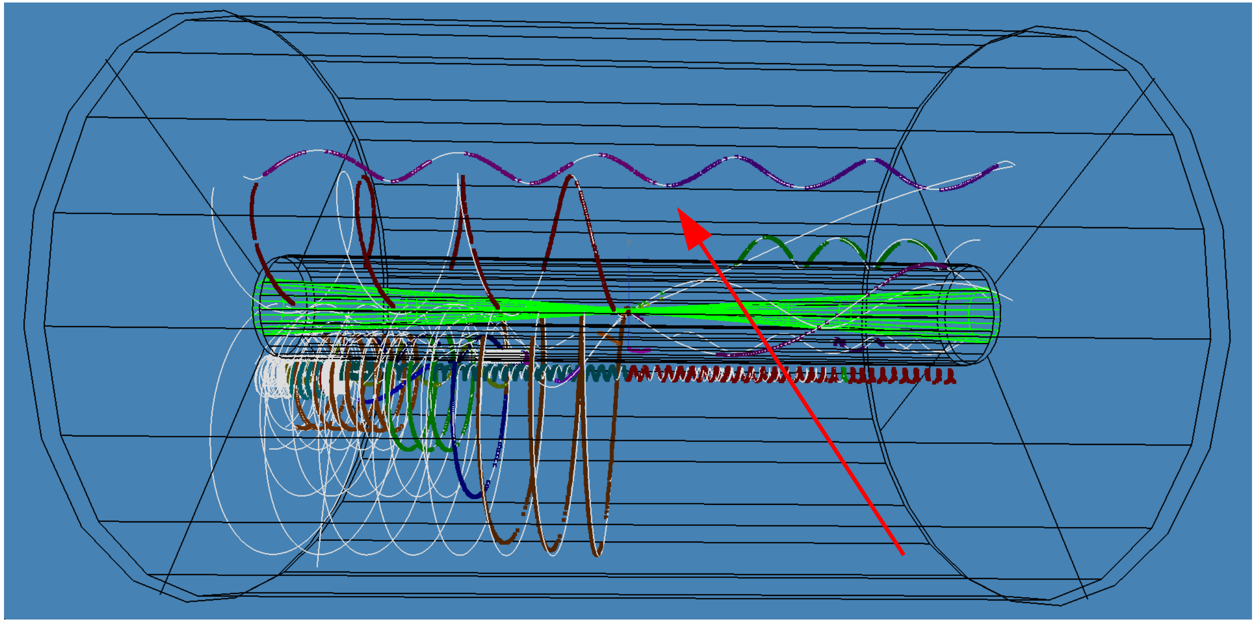
2. Split tracks

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

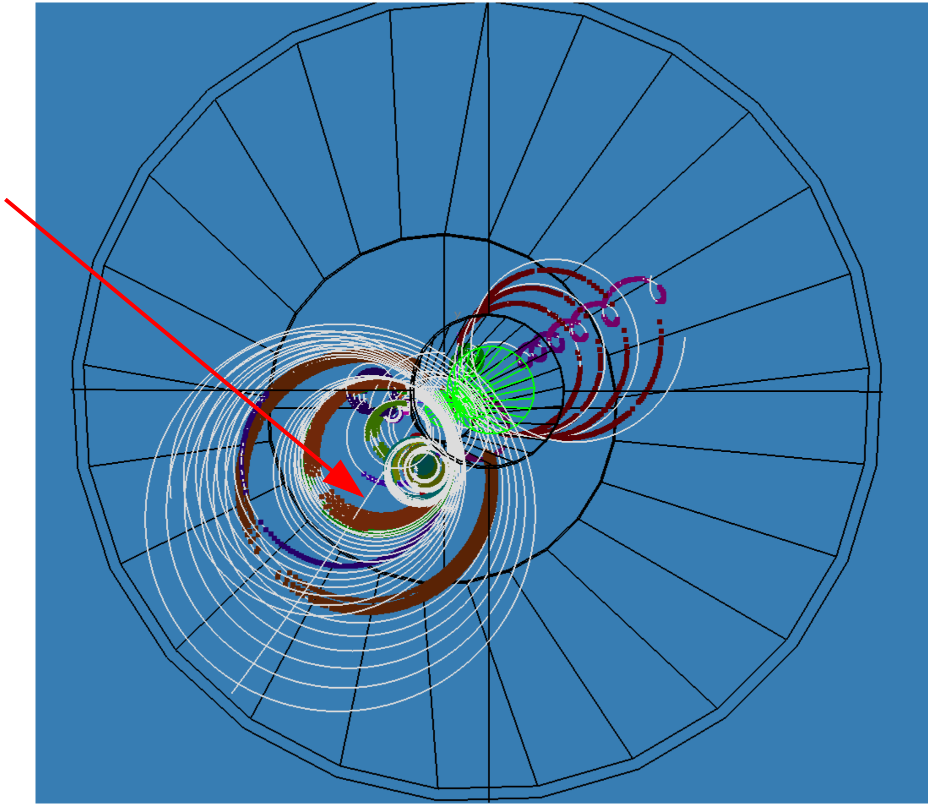
→ Cuts on opening angle $\cos(\alpha) > -0.6$ and tracks' curvatures ratio $|\Omega_1/\Omega_2| < 0.94$ (equiv. to p_T ratio)

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



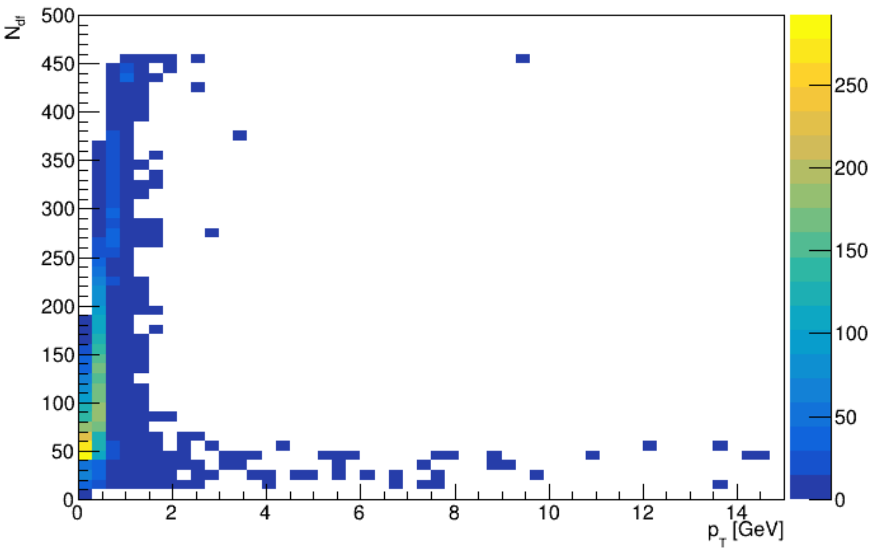
Sources of vertices in overlay events

3. Artificial short high-p_T tracks



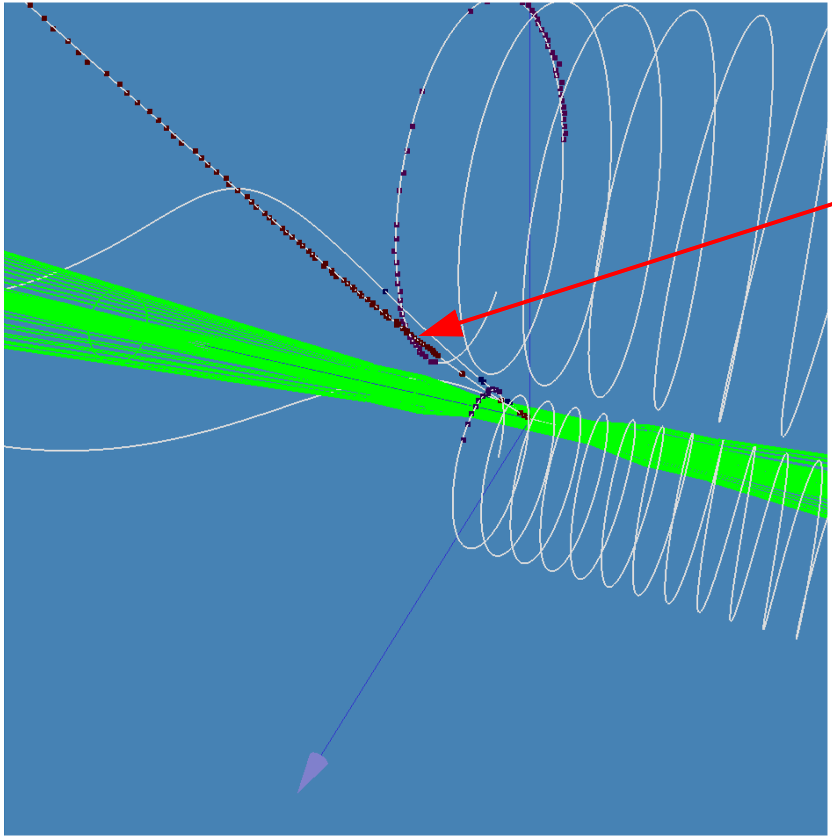
Fraction of hits in a curler can get clustered and formed into a **high-p_T track**

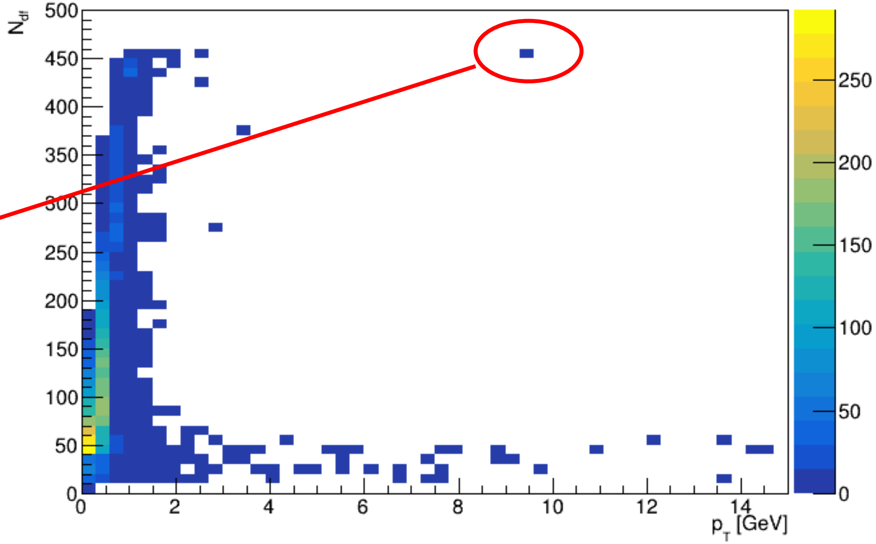
→ Remove vtx candidates with tracks having p_T >1.5 GeV and N_{df} < 70



Sources of vertices in overlay events

4. Intersecting tracks



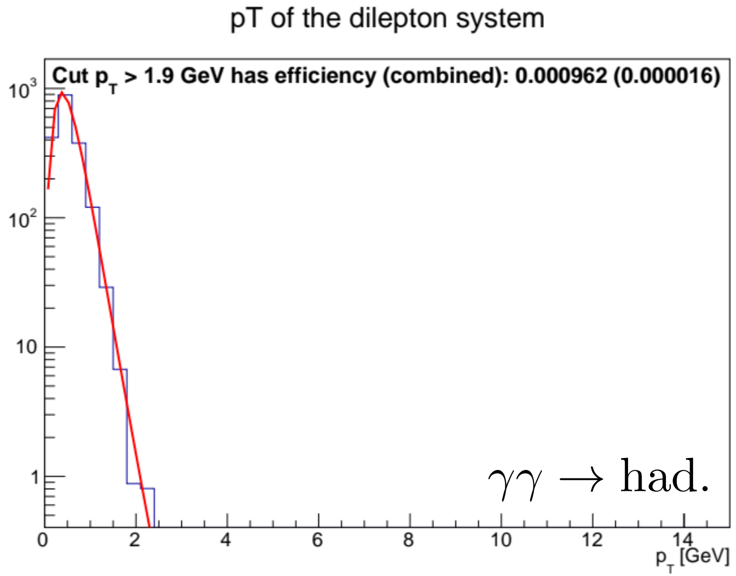


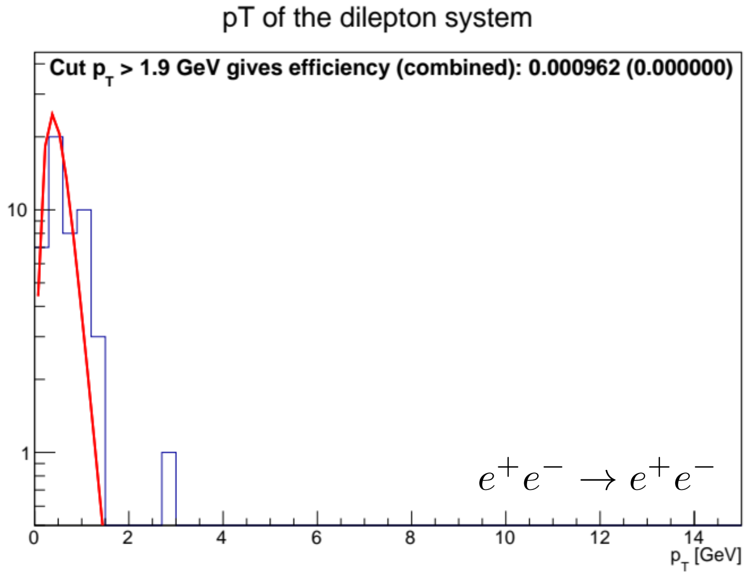
Tracks often randomly cross and intersect
With our (basic) approach vertices are found at the intersections

→ 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 $\gamma\gamma \to$ **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 $\gamma\gamma \to$ **had.** with floating normalisations



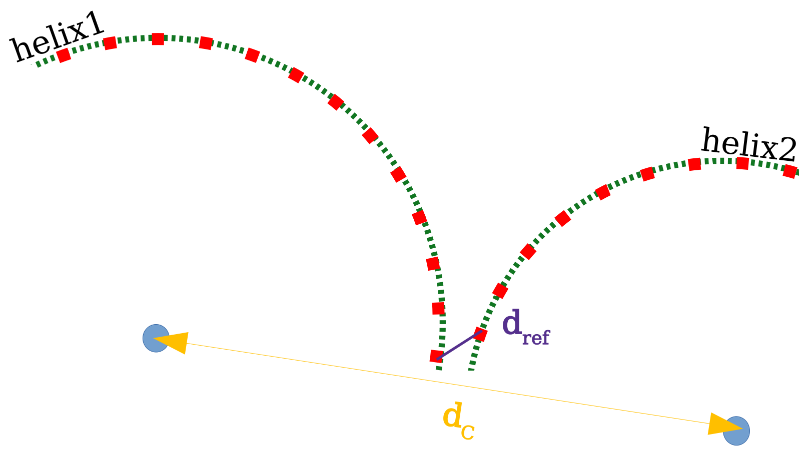


Norm = number of events, scaled by corresponding Poisson expectation values

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

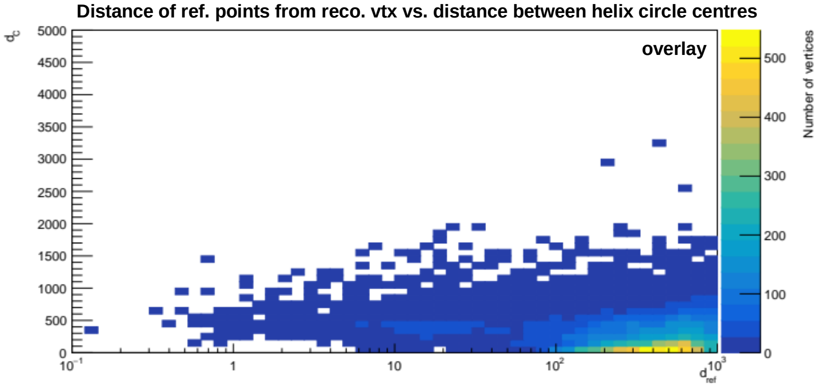
→ either **far reference points** or **close centres of helices**

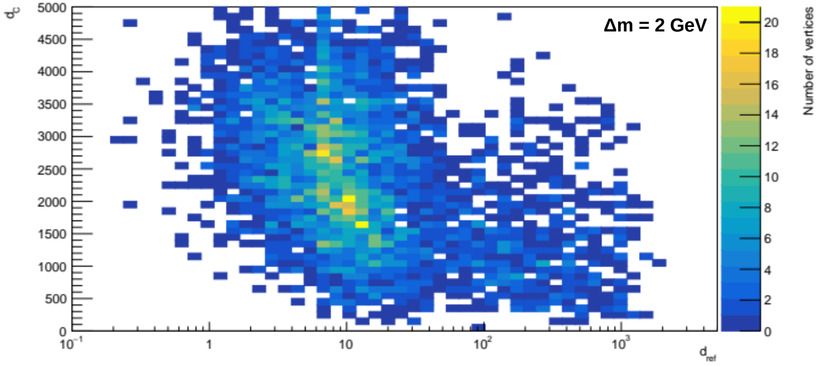


- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

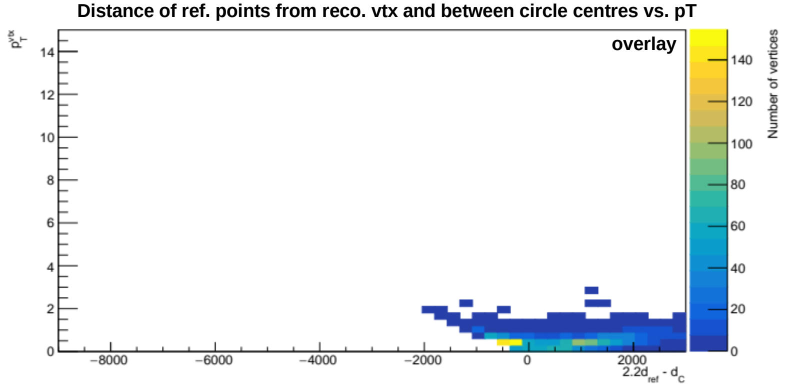
Final selection – second variable

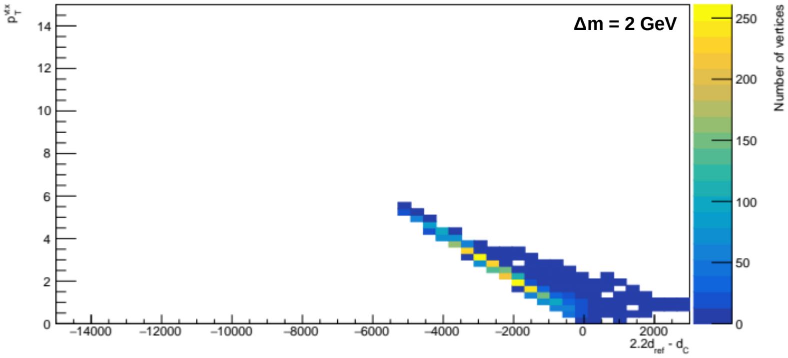
- New variable(s) should be uncorrelated with pT to make the cuts independent
- $2.2d_{ref} – d_C$ good for optimal signal-background separation → use it to look for correlation





Warp and check correlation with p_T

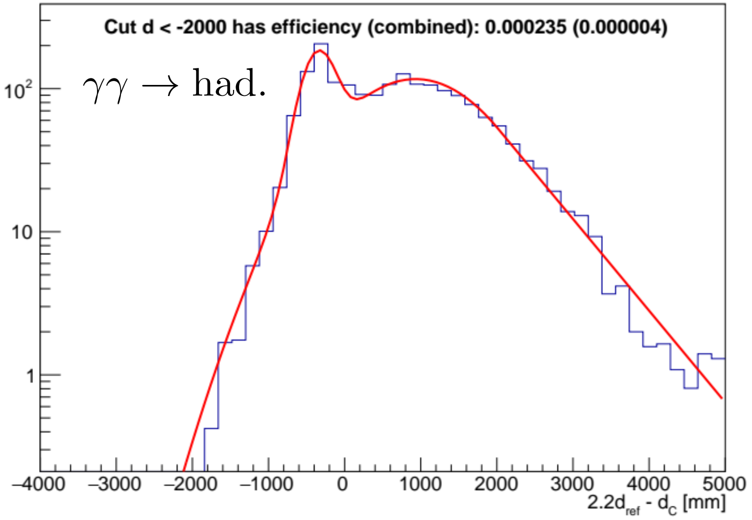


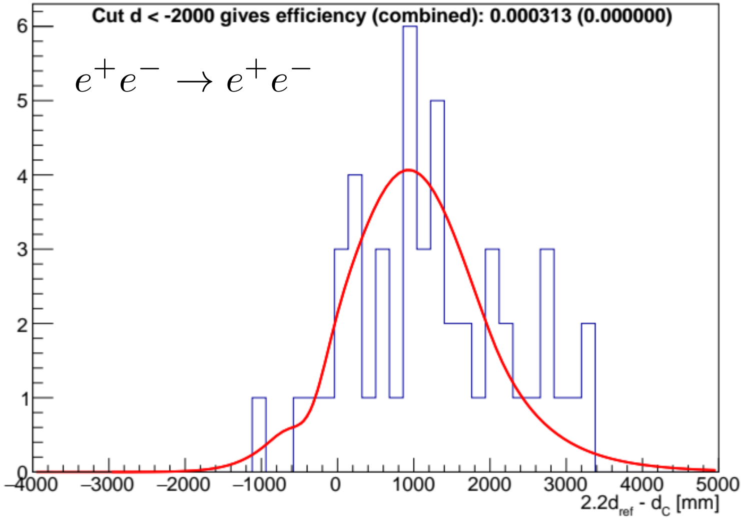


- Small correlation for the background
- Signal strongly correlated

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

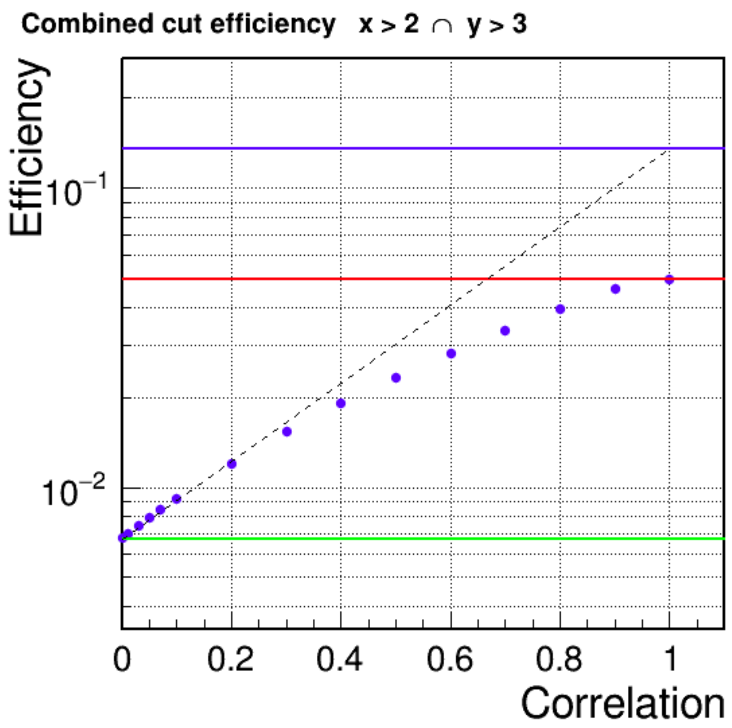
Selection assuming correlations

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