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Overlay reduction in the searches for displaced vertices

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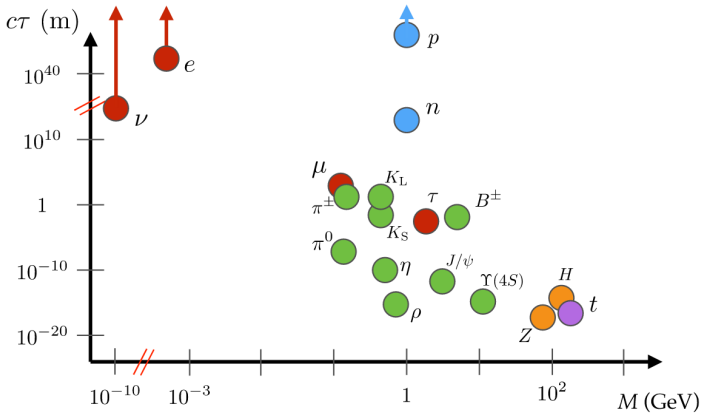
Long-lived particles

- Many particles with macroscopic lifetimes **already in the SM**
- Various BSM models predict LLPs, e.g. SUSY, ALPs, HNLs, dark portals...
- Different possible **exotic signatures**: displaced vertices, tracks/photons not pointing to IP
- Multiple searches at the LHC (see e.g. 1903.04497)
- LHC sensitive to high masses and couplings

  → **e+e- competitive in complementary region**: small masses, couplings and mass splittings
- ILD potentially promising with the TPC



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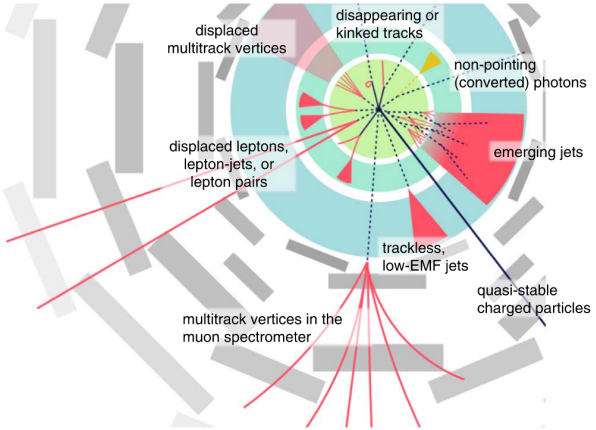


https://indico.cern.ch/event/607314/contributions/2542309

Motivation and goal

- We want to study parameter space regions **complementary to the LHC reach**

→ Soft final states

- Focus on a simple case – two tracks coming from a displaced vertex
- No other assumptions about the final state, approach **as general as possible**

So far:

- Tests of track and hit reco. (see presentations: 30/03/22, 08/12/21), vertex finding and first look at the overlay events (03/08/22)

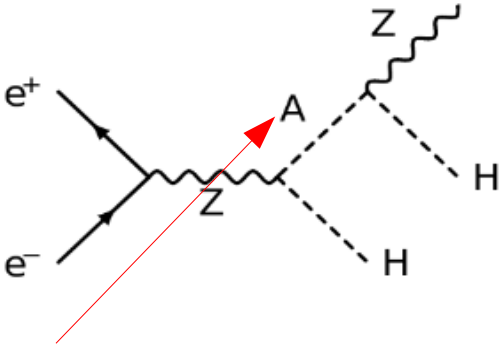
This talk:

- Background due to **overlay** and means of its **reduction**

Test signal scenarios

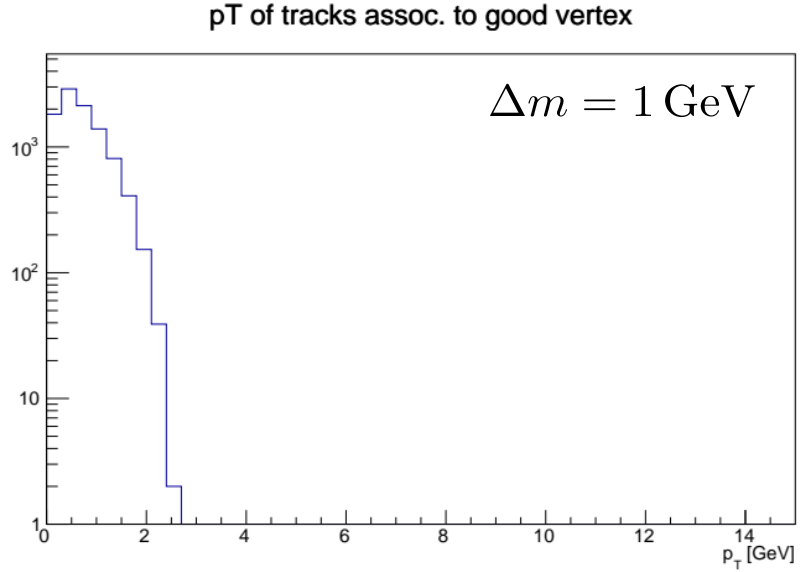
To test desired kinematics (small boost) we considered:

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



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

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



Very compressed spectrum

→ overlay expected to give dominant background contribution due to high ~10^{10} event multiplicity

Vertex finding strategy

Approach based on the V0Finder:

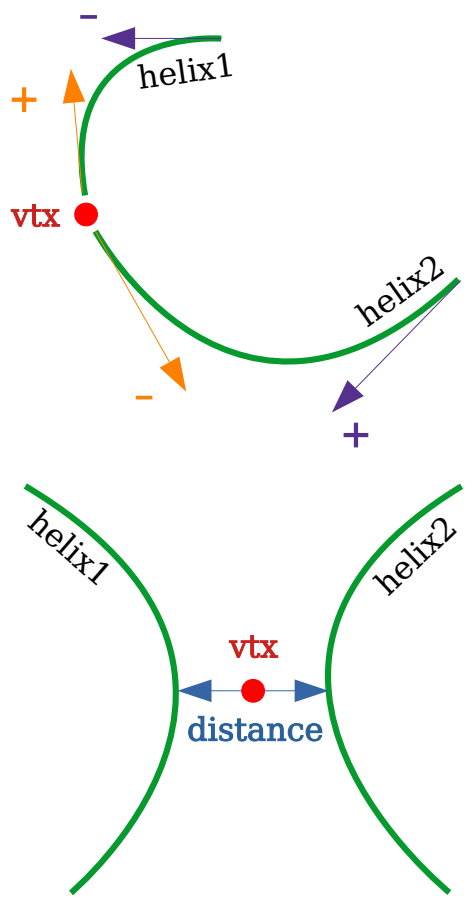
- Consider tracks in pairs
- TPC does not favour any direction, so:

  → fix momentum direction at TrackStates (such that it points into the other track end)

  → take TrackStates in the closest hits considering opposite-charged pairs only

- Calculate distance between helices (*getDistanceToHelix()* method from MarlinUtil)

  → require distance < 25 mm

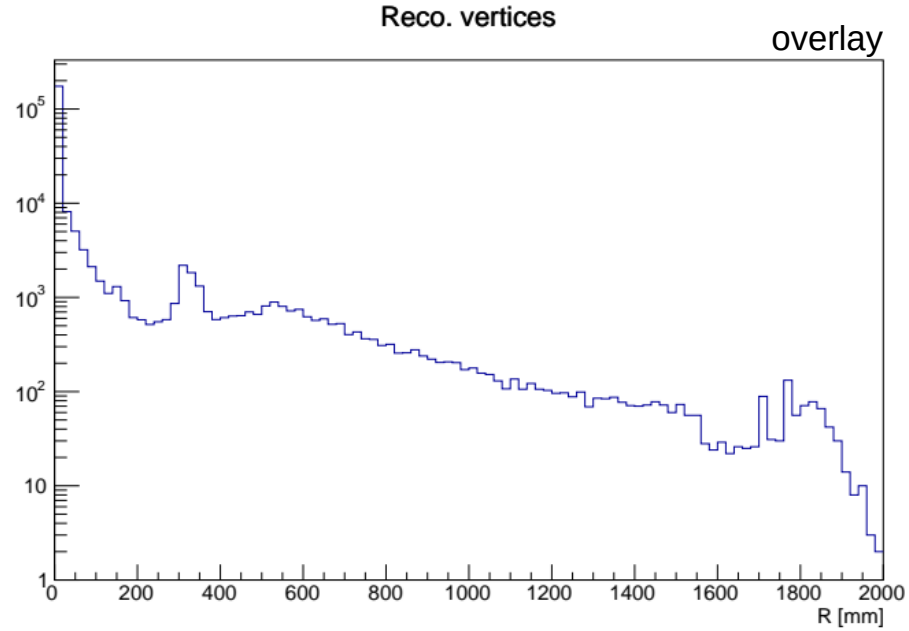


Sources of vertices in overlay events

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

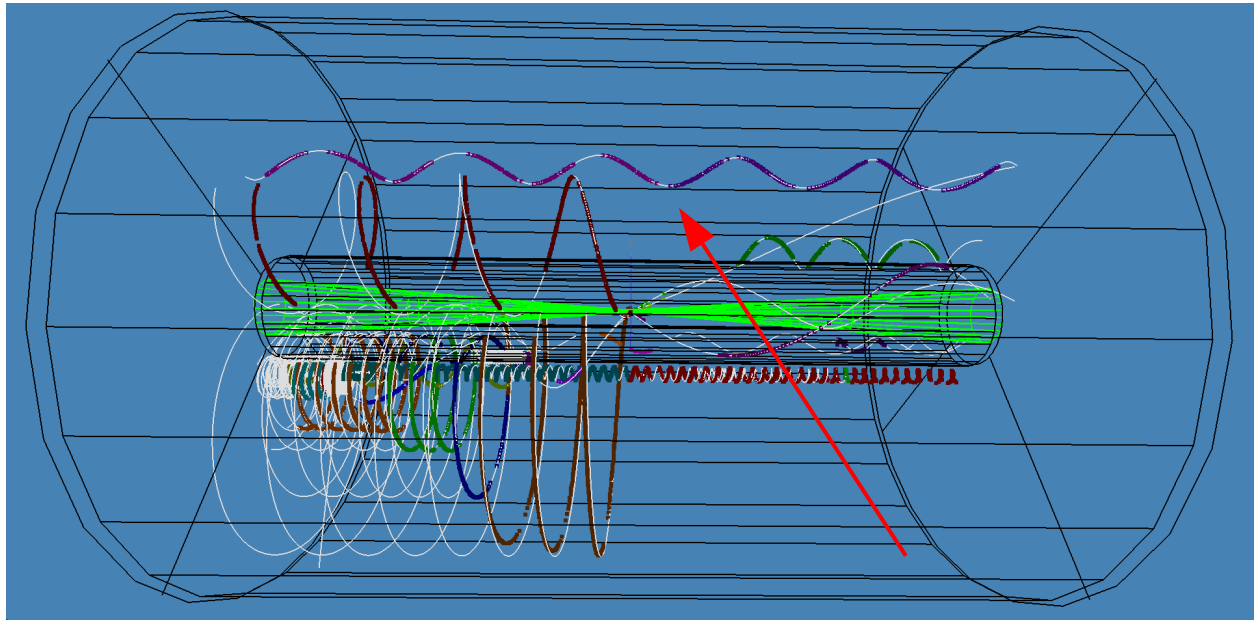
2. Split tracks

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

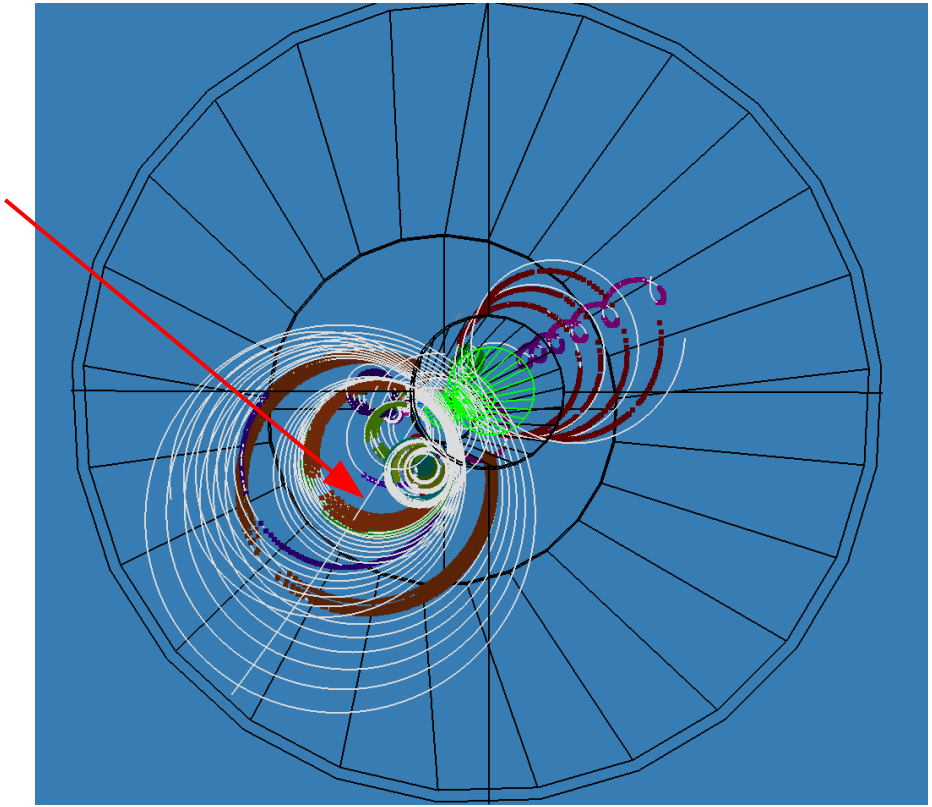
→ Cuts on opening angle $\cos(\alpha) > -0.6$ and tracks' curvatures ratio $|\Omega_1/\Omega_2| < 0.94$ (equiv. to p_T ratio)

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



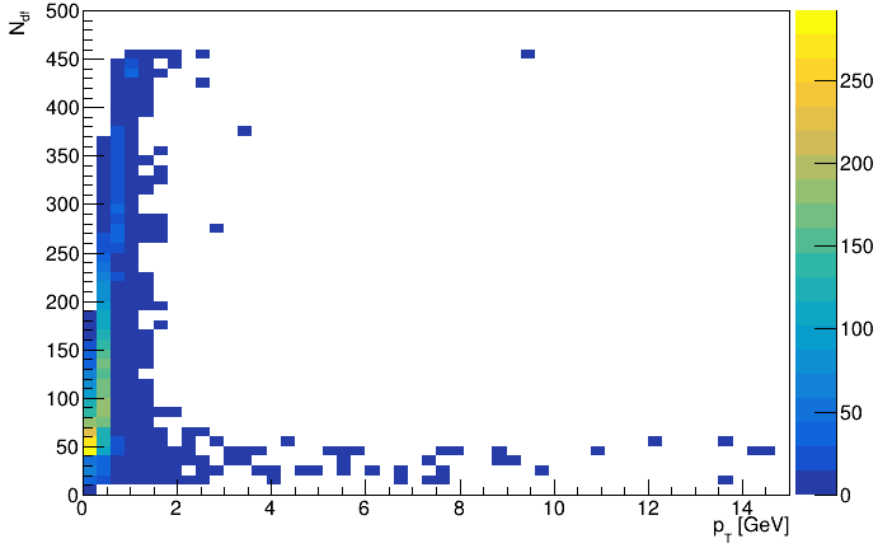
Sources of vertices in overlay events

3. Artificial short high-p_T tracks



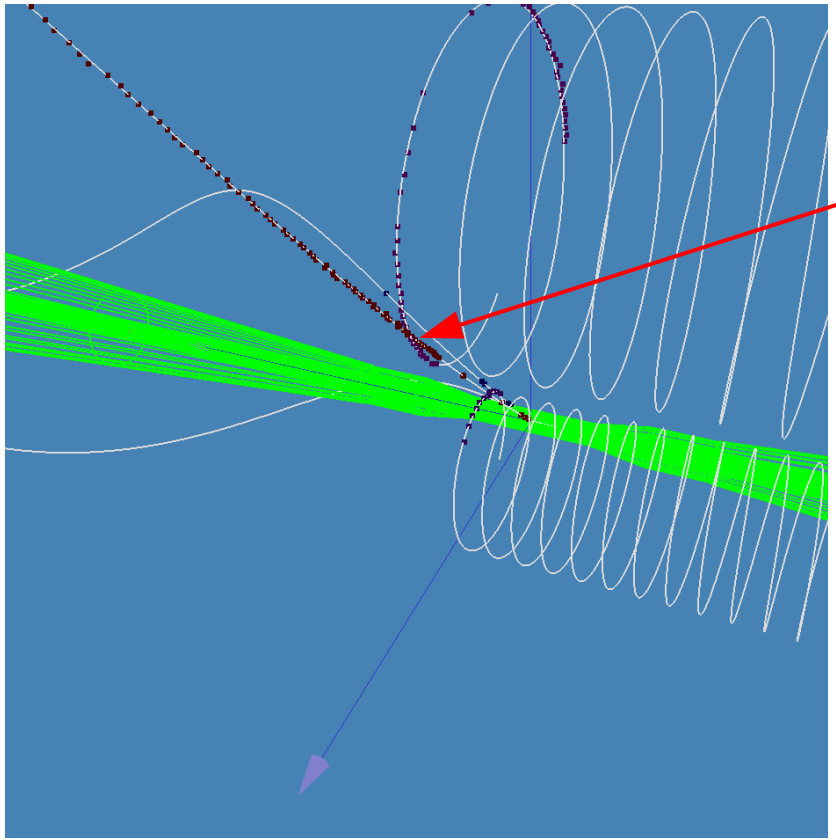
Fraction of hits in a curler can get clustered and formed into a **high-p_T track**

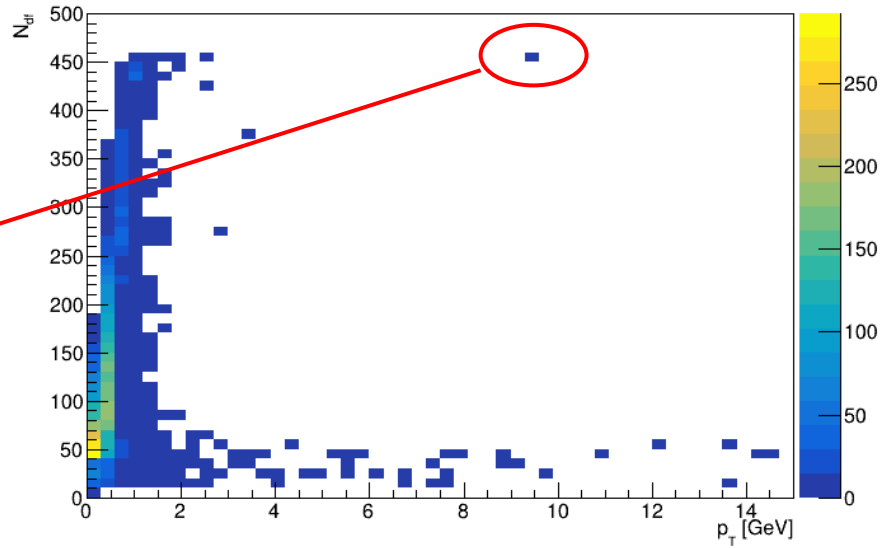
→ Remove vtx candidates with tracks having p_T >1.5 GeV and N_{df} < 70



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

- **~10^{10} events expected** – we need ~10^{-9} selection efficiency
- Available ”only” 500k events → high uncertainties already at the efficiency level of ~10^{-5}

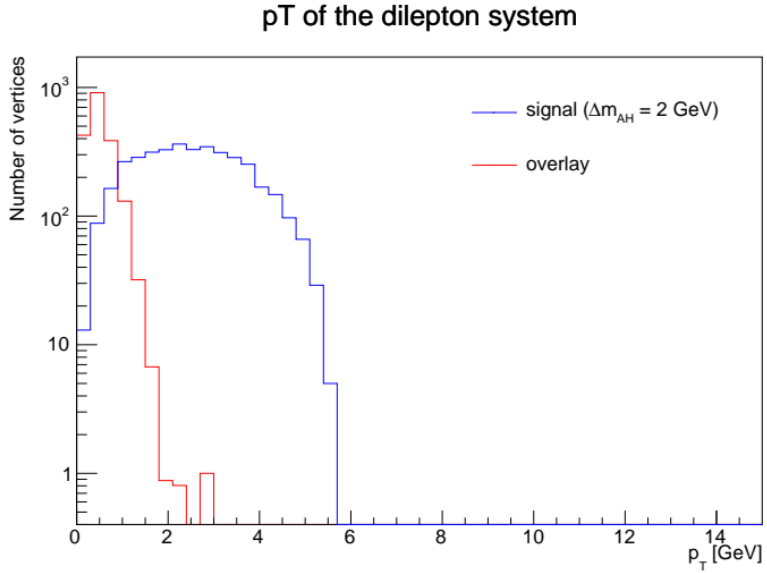
The idea: find independent cuts that **combined** give highest possible efficiency

First (obvious) variable: **p_T**

$p_T > 1.9$ GeV gives signal **eff. ~43%** ($\Delta m = 2$ GeV)
and very strong background suppression

This still removes almost all bg. events

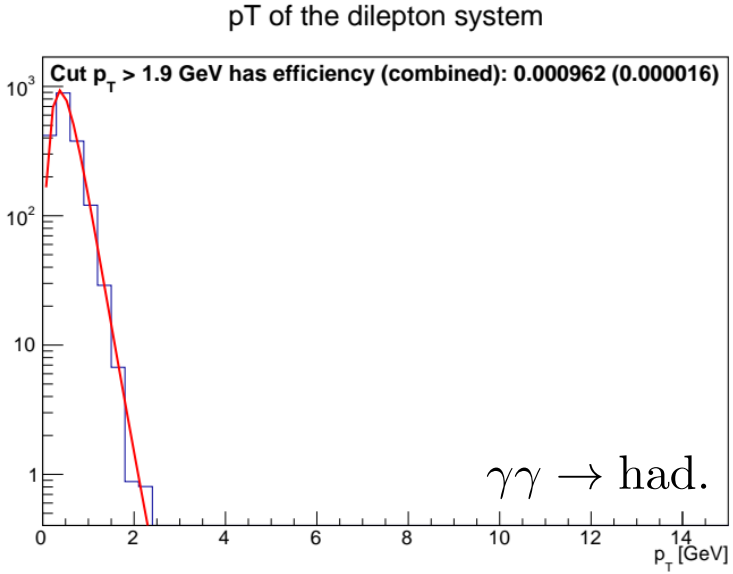
→ Estimate eff. using **fits to distributions**

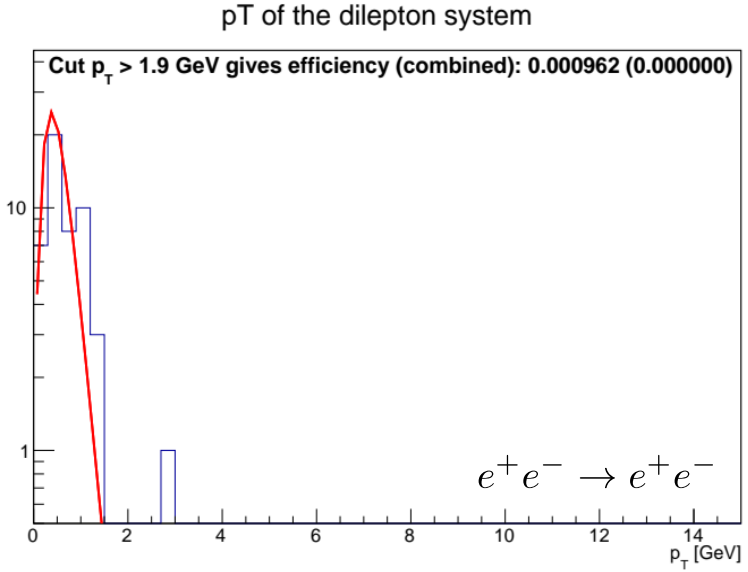


Norm = number of events,
scaled by corresponding Poisson expectation values

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



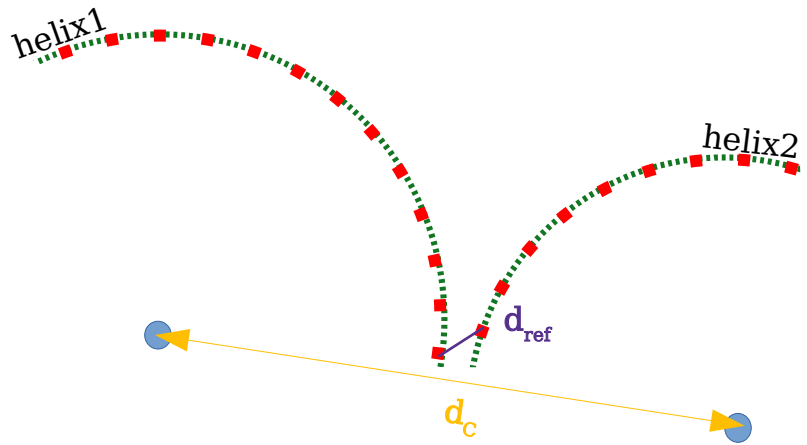


Norm = number of events, scaled by corresponding Poisson expectation values

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

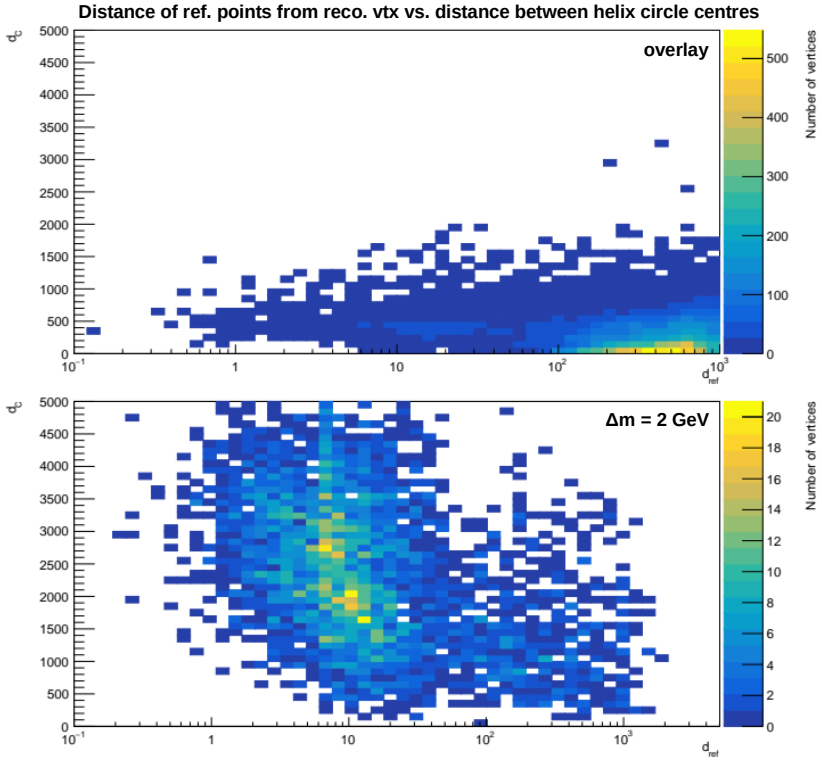
→ either **far reference points** or **close centres of helices**



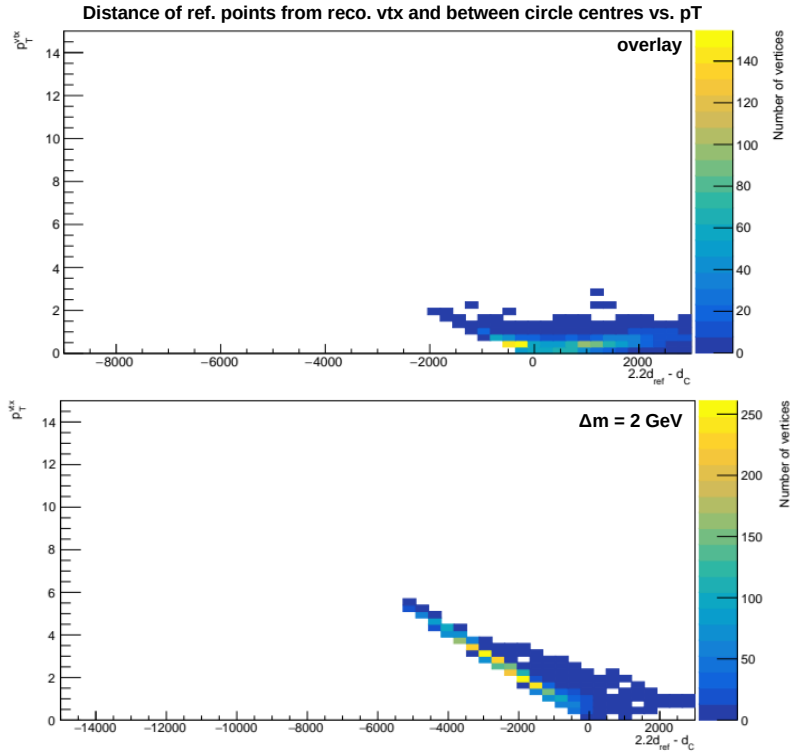
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

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



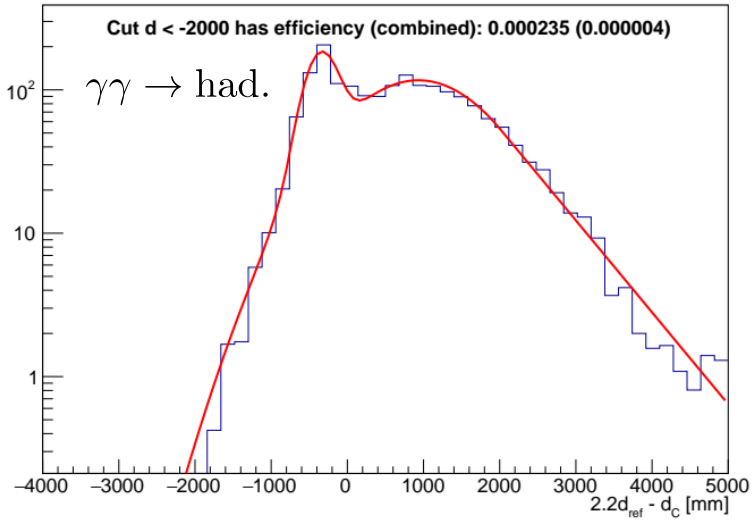
Warp and check correlation with p_T

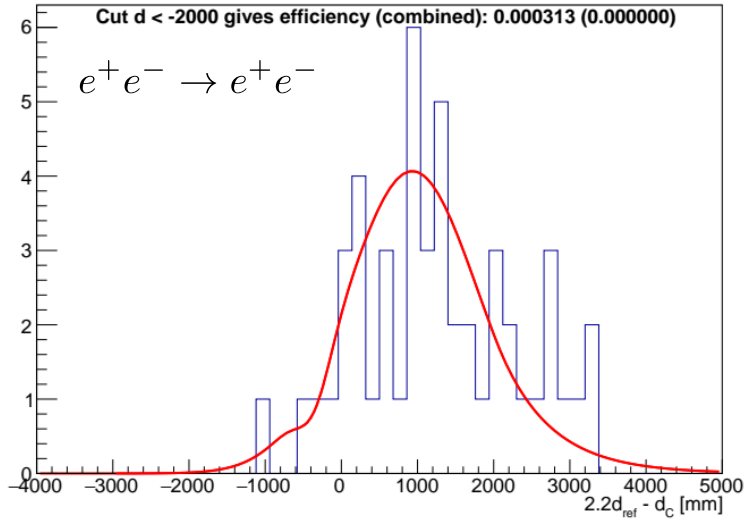


- Small correlation for the background
- Signal strongly correlated

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 **γγ → had.** (**e^+e^- pairs**)



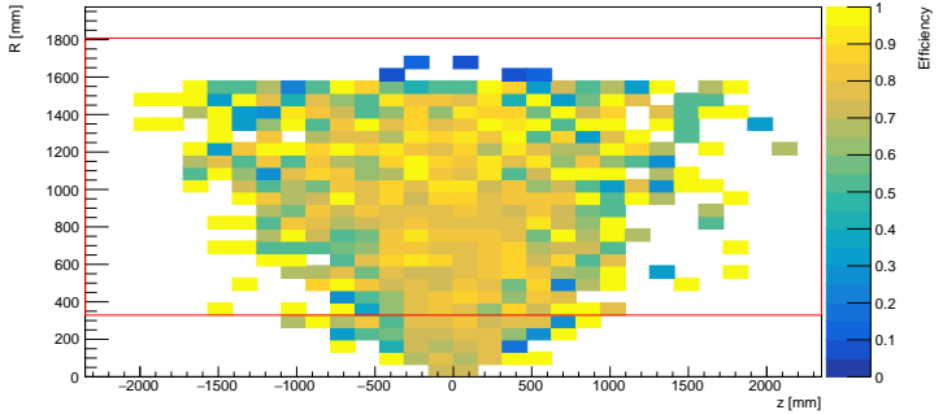


Norm = number of events, scaled by corresponding Poisson expectation values

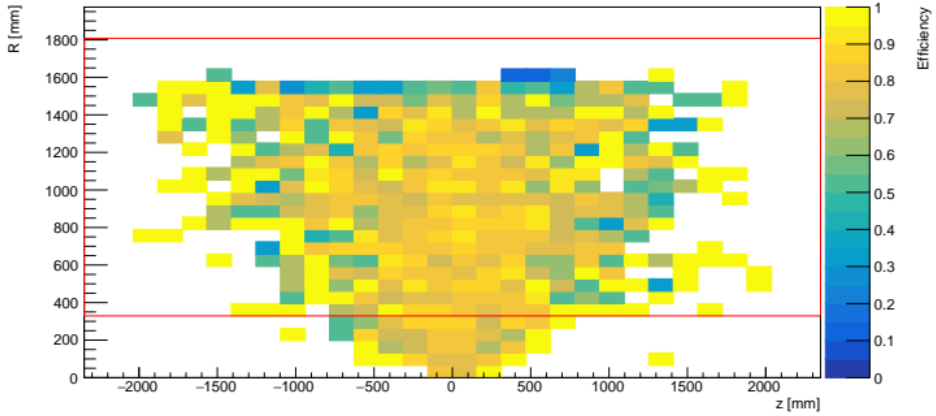
Results (signal)

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%

$\Delta m_{AH} = 2\,\mathrm{GeV}$



$\Delta m_{AH} = 5\,\mathrm{GeV}$



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

Summary

- Events with **displaced vertices**, **small mass splitting** and **low-momenta products** studied
- Simple algorithm for the vertex finding developed

  → designed for **vertices inside TPC**, we limit ourselves to its region
- Consider overlay as the primary source of background

  → A set of preliminary cuts established
- → **Final selection** based on two (almost) **”orthogonal” variables**

  → Efficiency estimations performed on continous distributions to reduce uncertainties

  → Achieved total efficiency of the order of **~10^{-9}** (**~10^{-10}**) for **$\gamma\gamma \rightarrow$ had.** (**e^+e^- pairs**) events
- Signal selection efficiency > 35% for the test scenarios, for mass splitting above 2 GeV
- Specific physics scenario can provide additional constraints on the signal

BACKUP

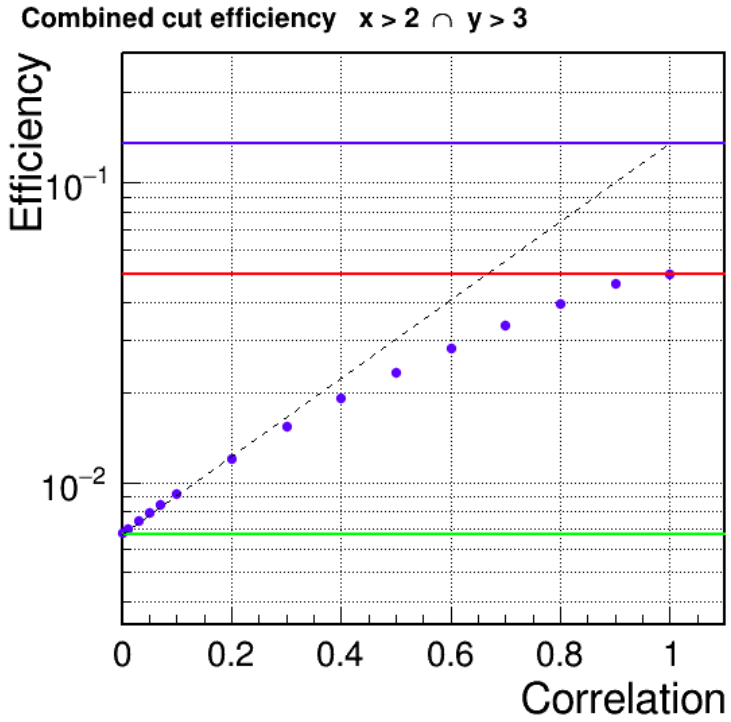
Selection assuming correlations

For small correlations r between x and y, total selection efficiency can be described as

$$\epsilon_{xy} = \epsilon_y^{(1-r)} \epsilon_x, \; \epsilon_x > \epsilon_y$$

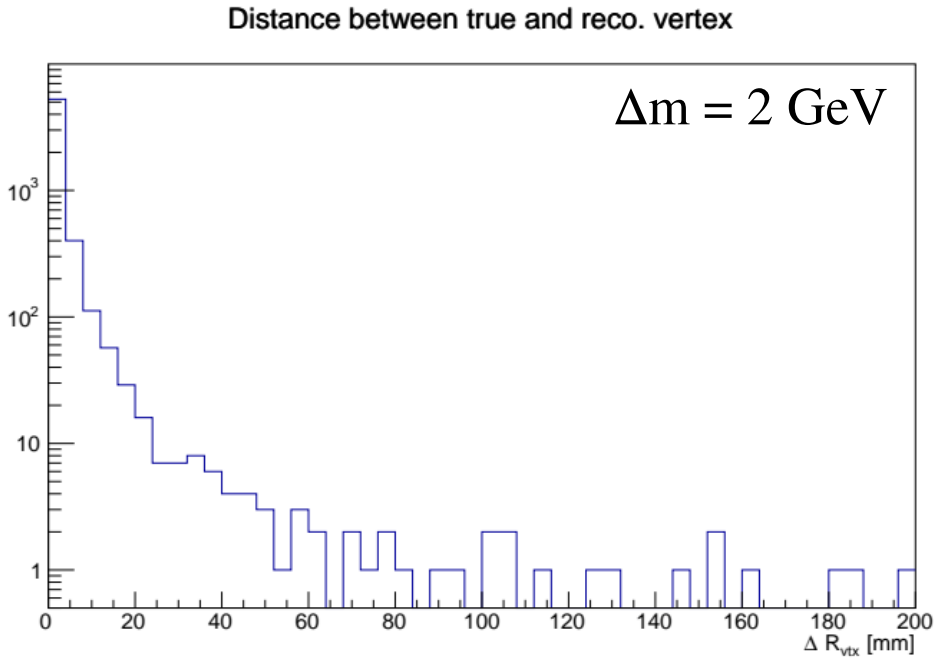
For cuts on $\mathbf{p_T}$ and $\mathbf{2.2d_{ref} - d_C}$ (slides 10-14), assuming **30% correlation**, for γγ → had. (e^+e^- pairs) that gives:

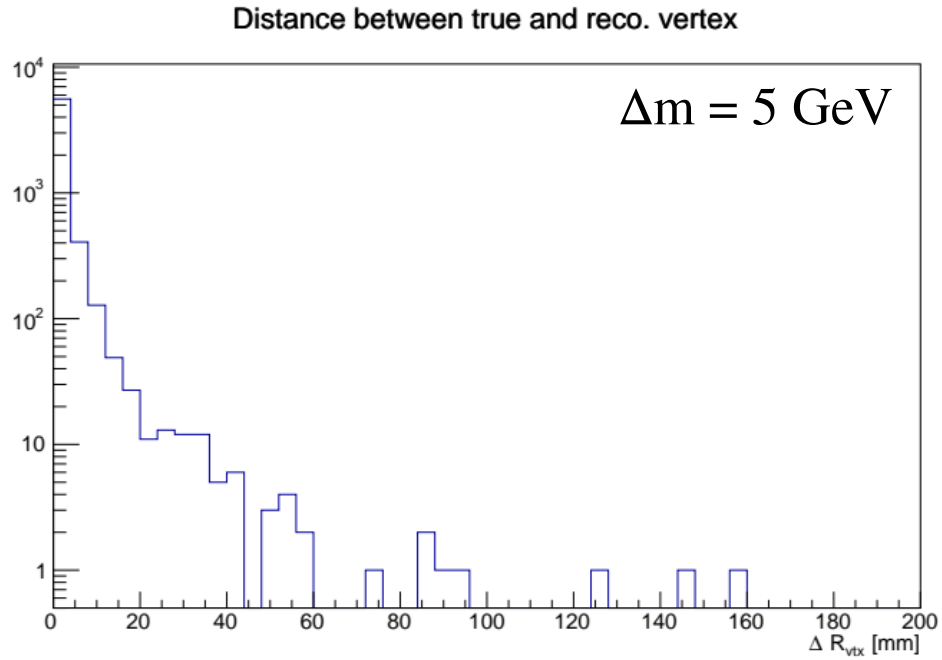
- $2.8 \cdot 10^{-6}$ ($3.4 \cdot 10^{-6}$)
- $4.6 \cdot 10^{-8}$ ($1.7 \cdot 10^{-9}$) ← combined with preselection



Distance to the true vertex

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

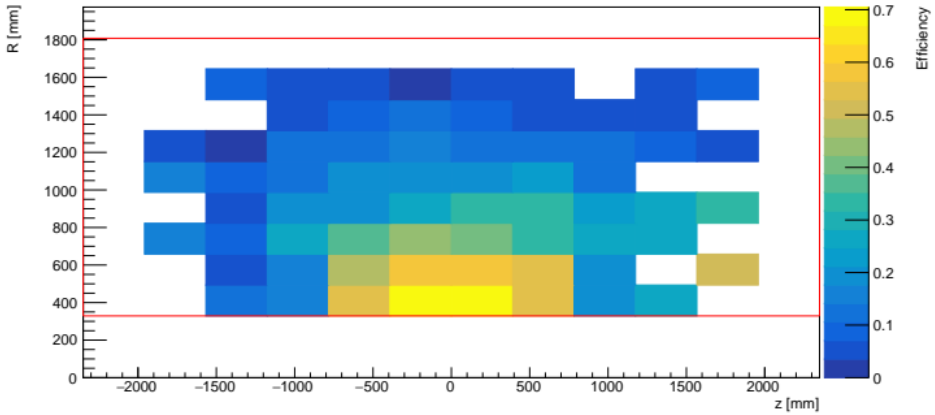




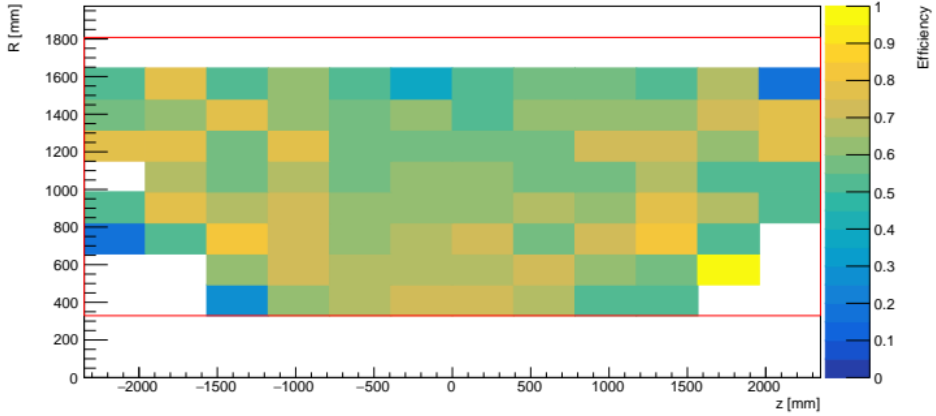
First limitations

Tracking efficiency strongly suppressed by default cuts d0, z0 < 500 mm in the *FullLDCTracking_MarlinTrk* processor → simply remove (or loosen) the cut

Position of a LLP decay vertex



Position of a LLP decay vertex



$\Delta m_{AH} = 1\,\mathrm{GeV}$

Missing hits problem

Virtual volumes in the TPC

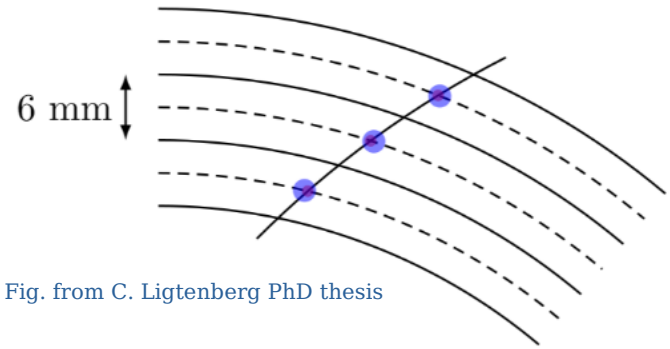
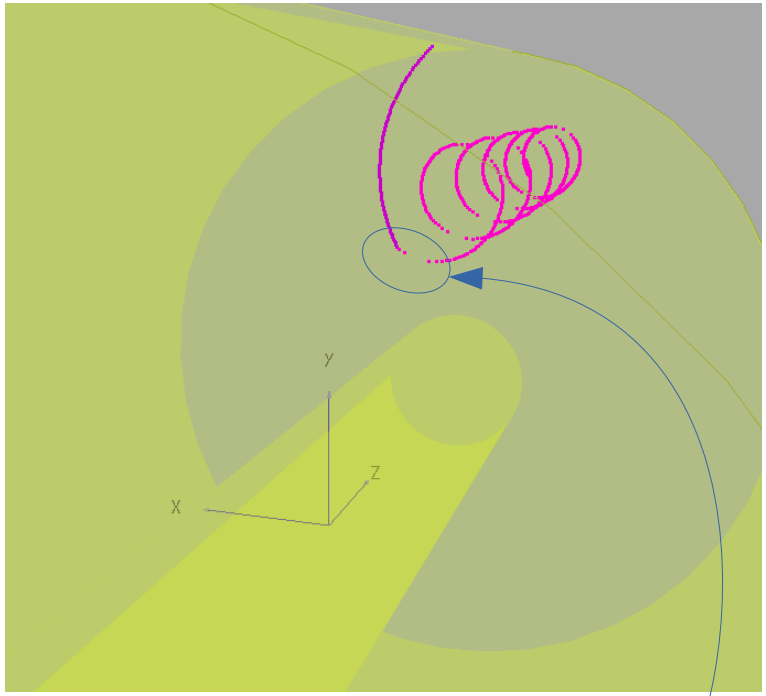


Fig. from C. Ligtenberg PhD thesis

Particle travelling alongside the boundaries generates no hits

TPC SimTrackerHits



Long distance between first hit and true vertex leads to wrong track parameters!

Tracking efficiency

Take only LLP decays inside the TPC

Track state in the first or the last hit (for now take one closer to the true vertex)

In matching to MC require:

- Angular separation < 0.2 between true and reco. direction
- Good charge sign

Total efficiency:

$$\sim 75\% \ (\Delta m_{AH} = 1\,\mathrm{GeV})$$
$$\sim 85\% \ (\Delta m_{AH} = 5\,\mathrm{GeV})$$