Update on the LLP searches with the ILD

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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

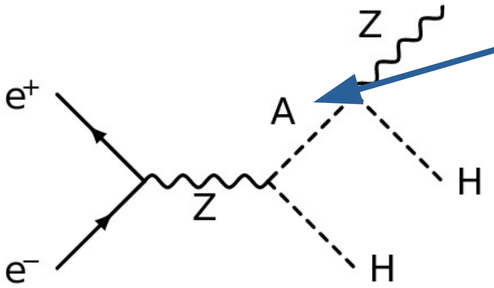
We take:

- **experiment-orientated 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, $Z^* \to \mu\mu$

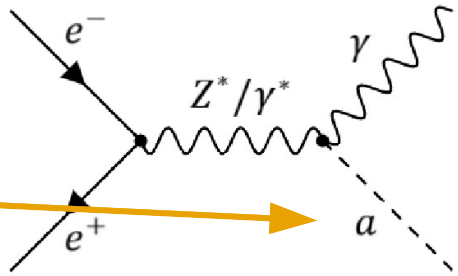


Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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:

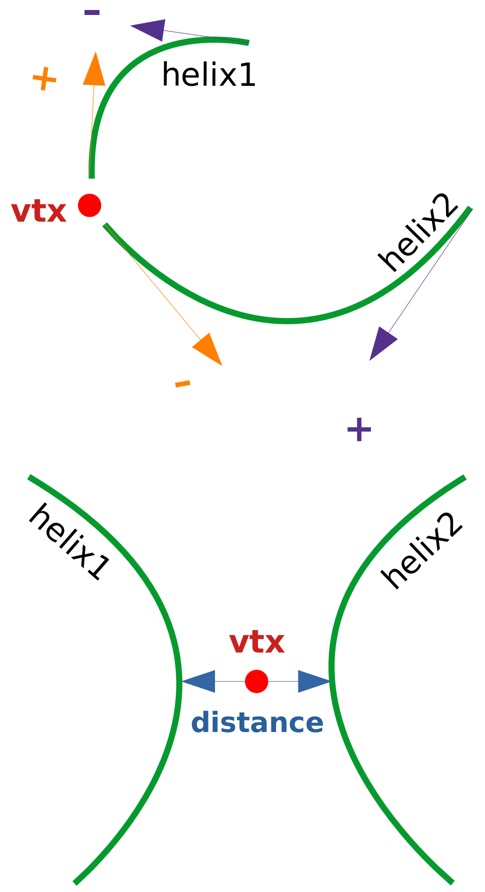
  → use **both track direction** (charge) **hypothesis** for vertex finding

  → 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

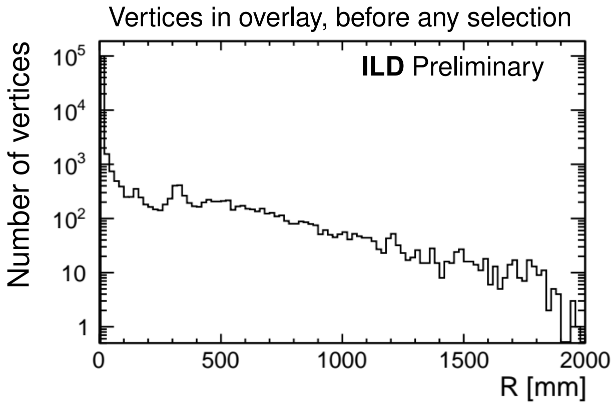


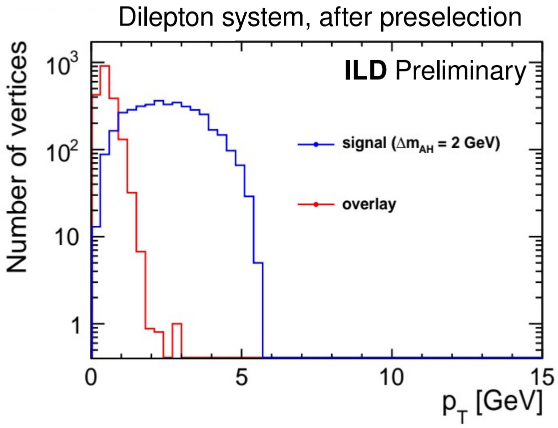
Overlay events as a background

- ~10^{11} bunch-crossings (BXs) per year expected at ILC
- In each BX, **1.05 low-pT hadrons** and **1 seeable e^+e^- pairs** events on average
- Can be busy and have similar kinematics to the signal considered

→ many secondary vertices (mostly fake, also V0s and photon conversions)

→ significant background





- Consider only vertices inside TPC
- Set of "preliminary" cuts to get rid of fakes
- 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**)

Background from physical events

- Consider also hadronic 2-fermion events

  → ~200 pb (~50 pb) total cross section at 250 GeV (500 GeV) and many potential sources of secondary vertices

- We have to re-run tracking (with modified d0 and z0 cuts) on REC samples, so statistics limited

- Some problems on the grid with computing elements (Andre Sailer already informed)

- For now the following results are based on

  → ~100k events at 250 GeV (eLpR)

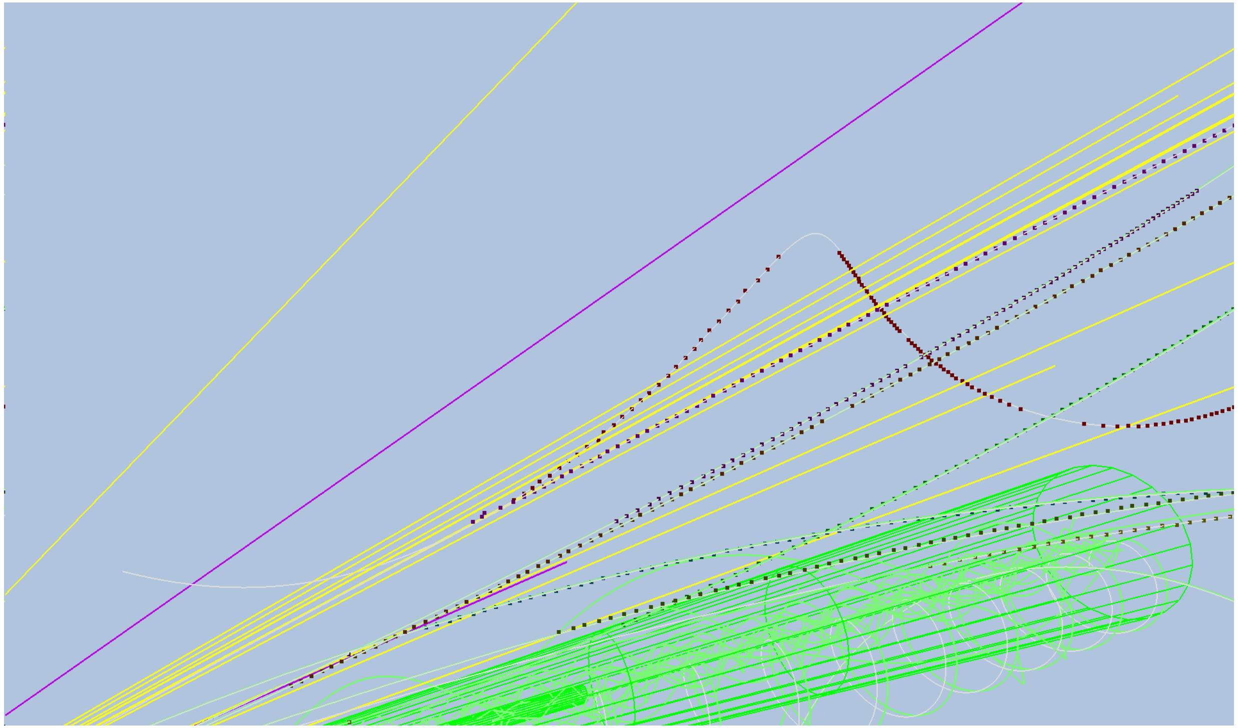
  → ~40k events at 500 GeV (eRpL)

- Assuming that vertex finding is not affected by polarisation

First result: vertices in ~1.5% of qq events after the cuts for overlay reduction!

Displaced vertex sources in qq events

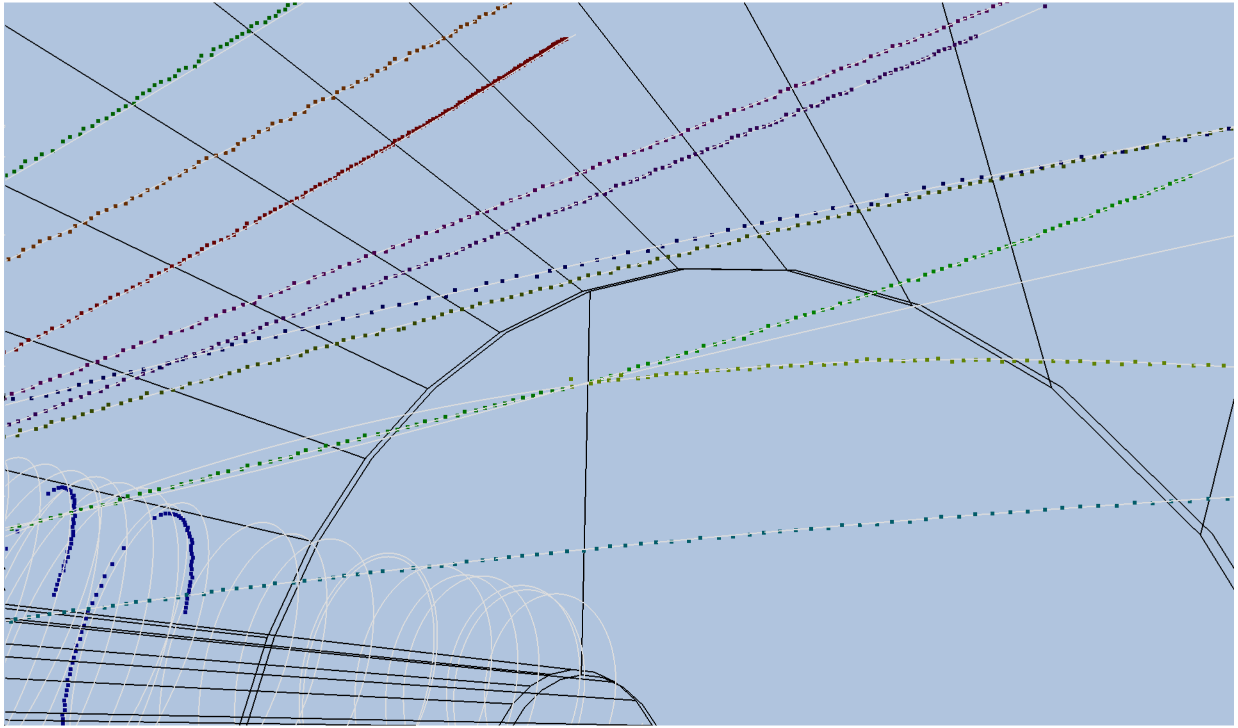
1) **V0 particles** and **photon conversions**



→ veto against V0Finder output

Displaced vertex sources in qq events

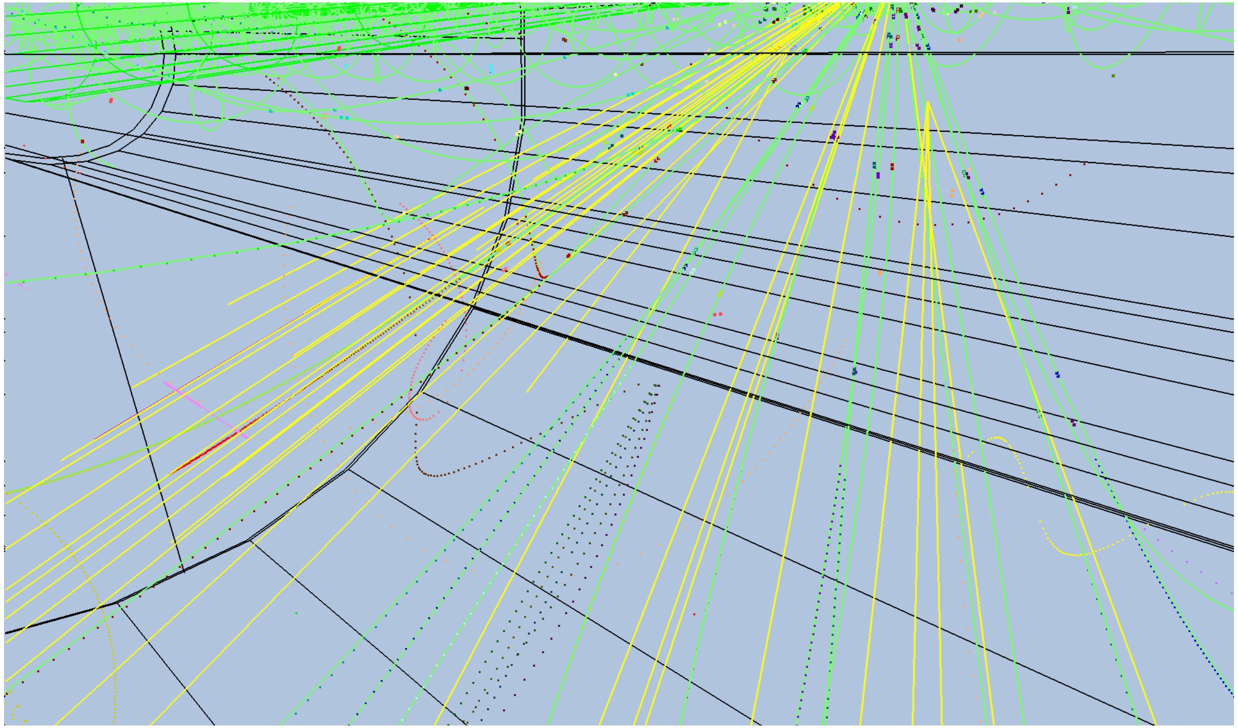
2) Interactions of **charged** particles with detector material



→ reject vertex if there is a track pointing to the IP passing close to the vertex

Displaced vertex sources in qq events

2) Interactions of **neutral** particles with detector material



→ partly irreducible (?), assuming that we want to keep generality (displaced jet signature)
→ for now reject "displaced jets", by requiring no tracks passing close by the vertex

Further background reduction

Described background reduction methods improved the selection efficiency only by an order of magnitude

What remains:

- Not identified V0 particles and photon conversions → further reduction discussed later
- Vertices from secondary interactions of neutral particles (with two tracks coming out)

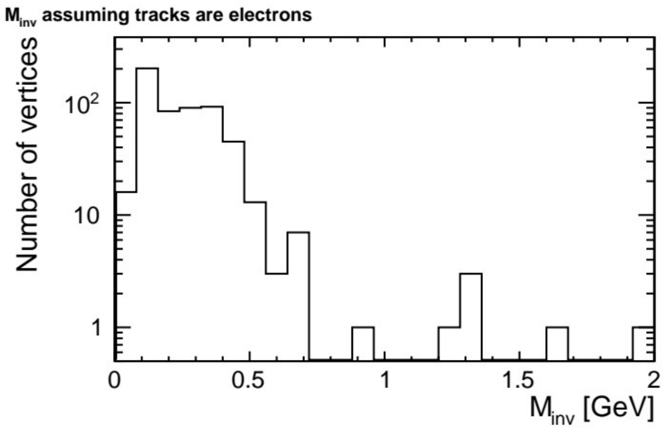
Side remarks:

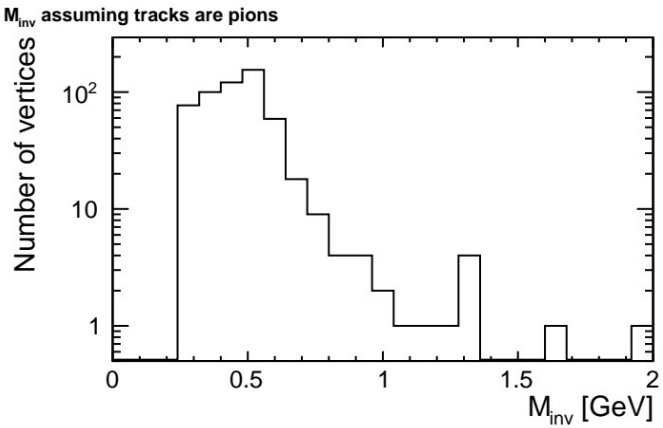
- We can be sensitive also to other topologies (displaced jets, kinked tracks)
- Hard qq events seem to be the dominant background contribution

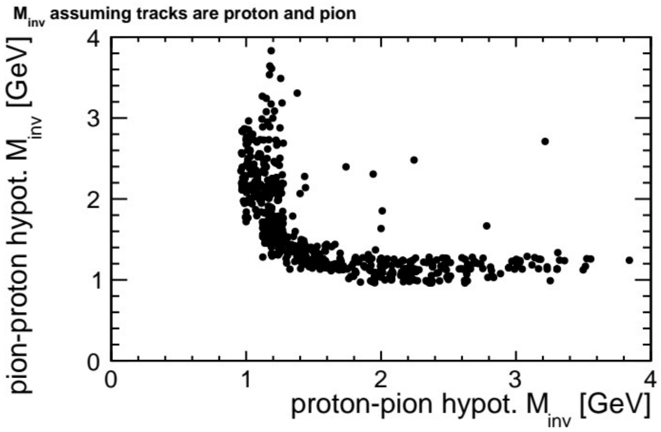
Further background reduction

Despite high V0Finder efficiency, not identified V0s become significant background

- loosen V0Finder selection
- cut on invariant **mass of a track pair** (for different particle hypotheses)







→ reject vertices in m_{V0} +/− 0.05 GeV window and $m_{e+e-} <$ 0.15 GeV

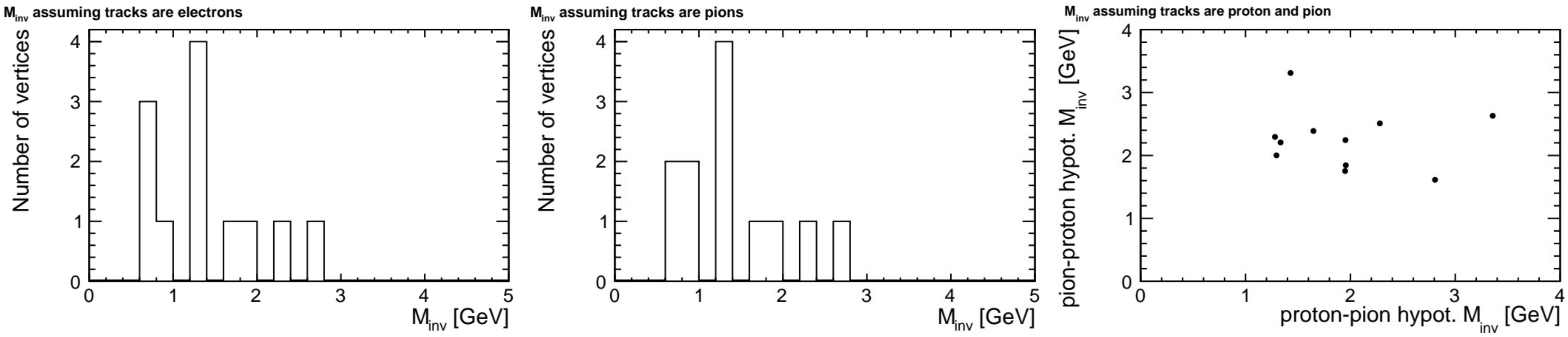
Resulting efficiency: 0.09% (0.1%) for 250 GeV (500 GeV)

Further background reduction

Still remaining (potentially reducible):

- K^0_L semileptonic decays
- Tracks with worse momentum resolution (mostly photon decays)

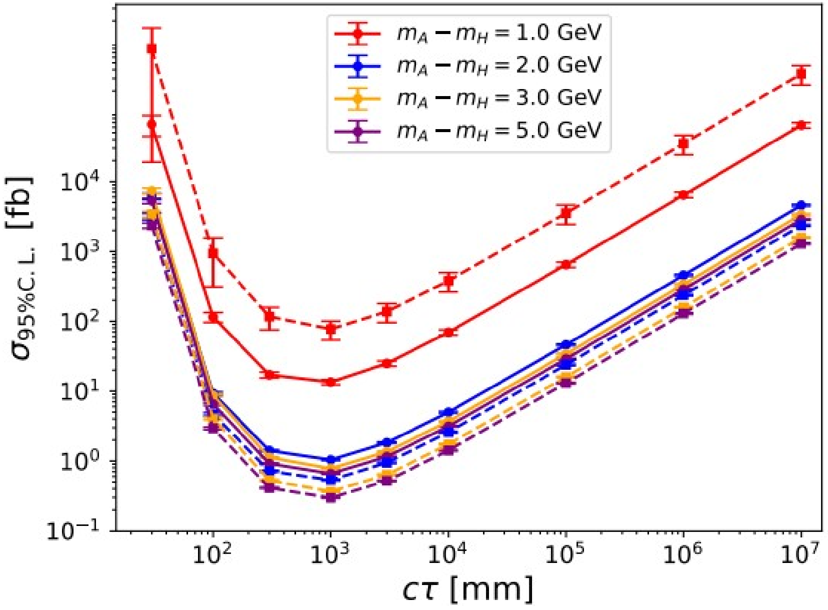
→ alternative **tight** selection, m_Λ +/− 0.02 GeV window, m_{e+e-}, $m_{\pi+\pi-}$ < 0.7 GeV:



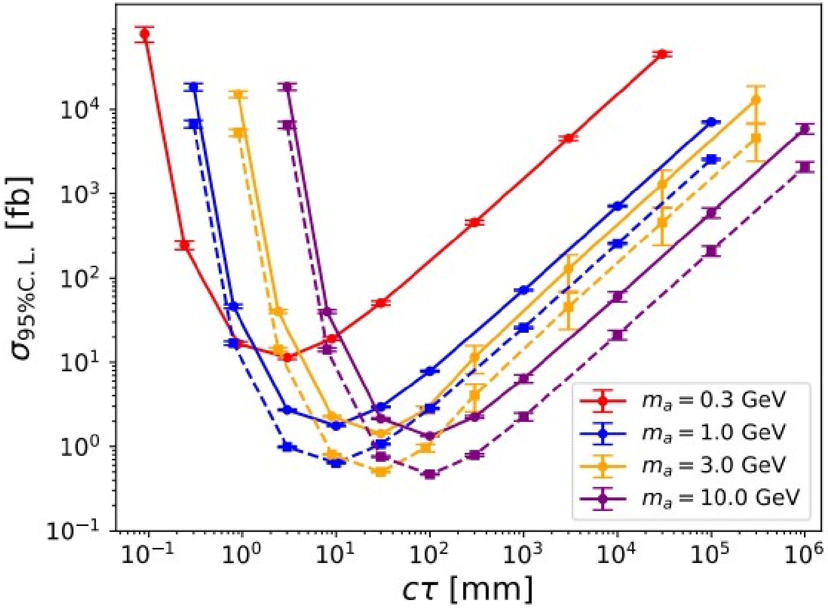
Resulting efficiency: 0.01% (0.02%) for 250 GeV (500 GeV)

Cross section limits

Heavy scalars (IDM), 500 GeV, 4 ab^{-1}



Light pseudoscalar (ALP), 250 GeV, 2 ab^{-1}



- Tight selection: dashed line, loose selection: solid line
- Tighter selection rejects $m_a = 300$ MeV scenario and worsens limit for $\Delta m_{AH} = 1$ GeV, but for the rest of scenarios provides significant improvement

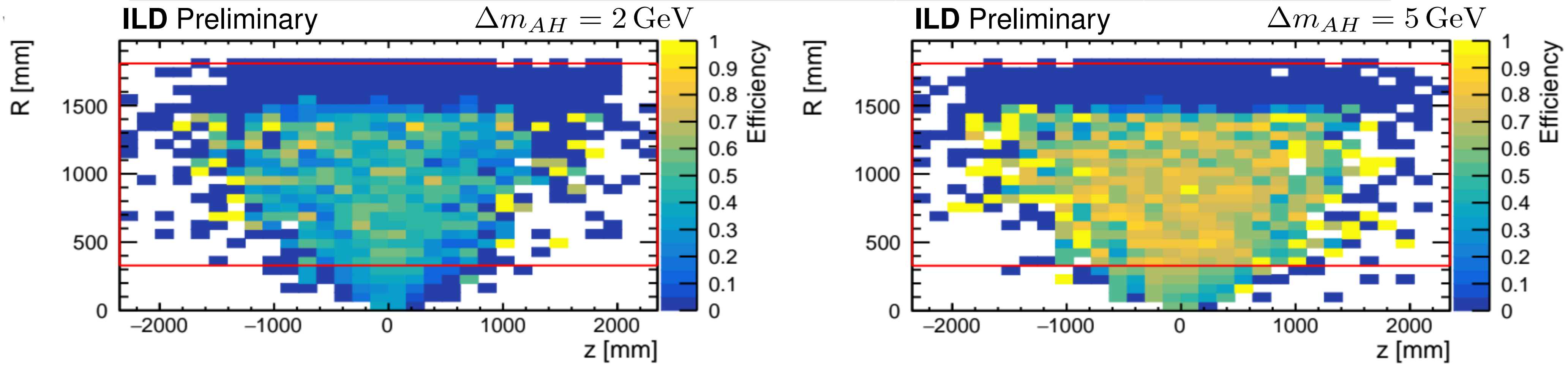
Summary

- 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
- We study the impact of the **2-fermion hadronic** physical events → dominant background
- Additional selection imposed, including loose and tight sets of cuts on the track pair invariant mass
- New selection results in 95% CL limits on signal **cross section** at the order of **0.1-10 fb** for a wide range of scenarios, with $c\tau$ between 1 mm and 100 m
- Open questions: more improvement needed? Are any other SM channels significant?

BACKUP

Results (heavy scalar signal)

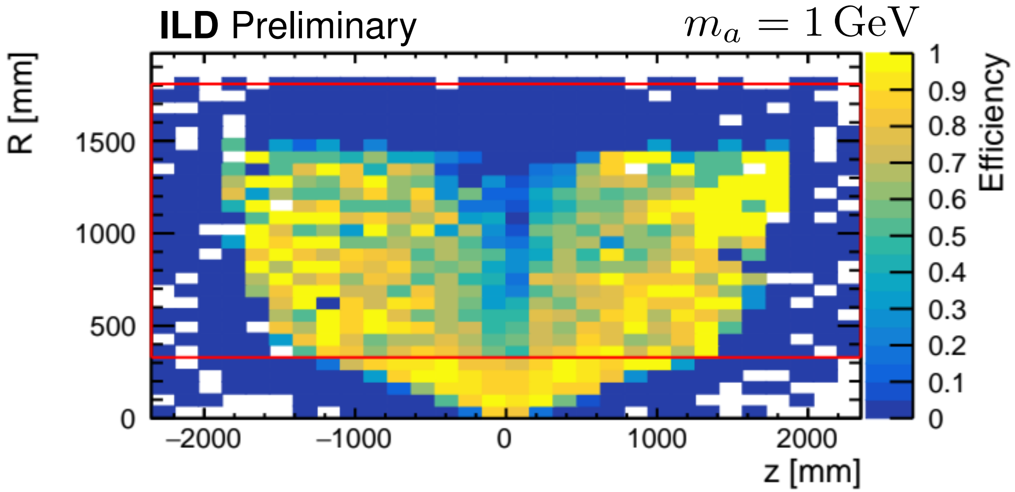
Δm	1 GeV	2 GeV	3 GeV	5 GeV
TPC eff. (correct / decays within TPC acceptance)	3.9%	37%	52.2%	60.4%
Accuracy in TPC (correct / all found)	99.1%	99.5%	99.5%	99.7%

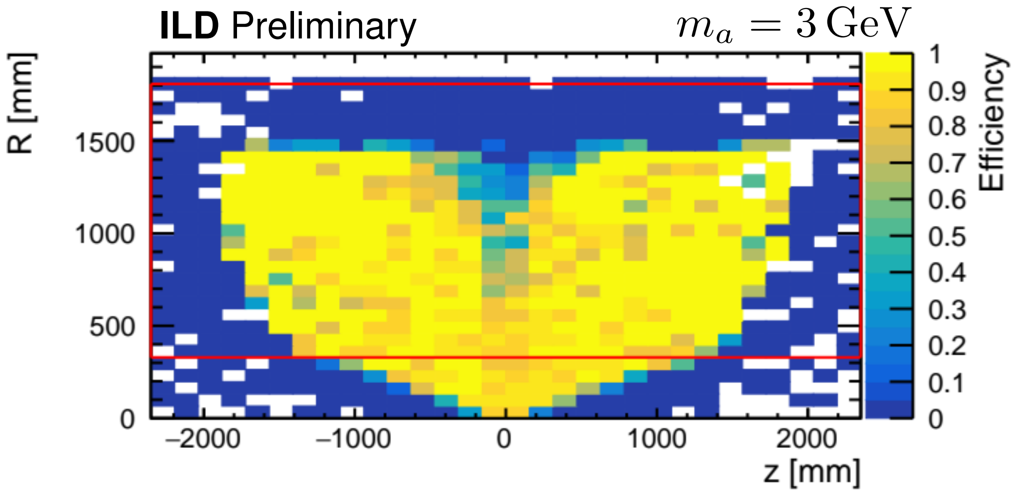


- Consider "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality)
- Δm = 1 GeV scenario needs dedicated approach

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 and qq events as the 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,
- Same selection eff. for different beam polarisations, qq total production cross sections of **198.382 pb** (**49.268 pb**) for **250 GeV** (**500 GeV**)
- **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: $N_{sig} = 1.64 \cdot \sqrt{N_{bg}}/\epsilon_{sel}$

Reweighting events

- For different lifetimes, **τ'**, reweight the events by ratio of exponential PDFs:

  w = P(t, τ')/P(t, τ_0) (with τ_0 used to **generate the samples**; for τ' = τ_0, w = 1)

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

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

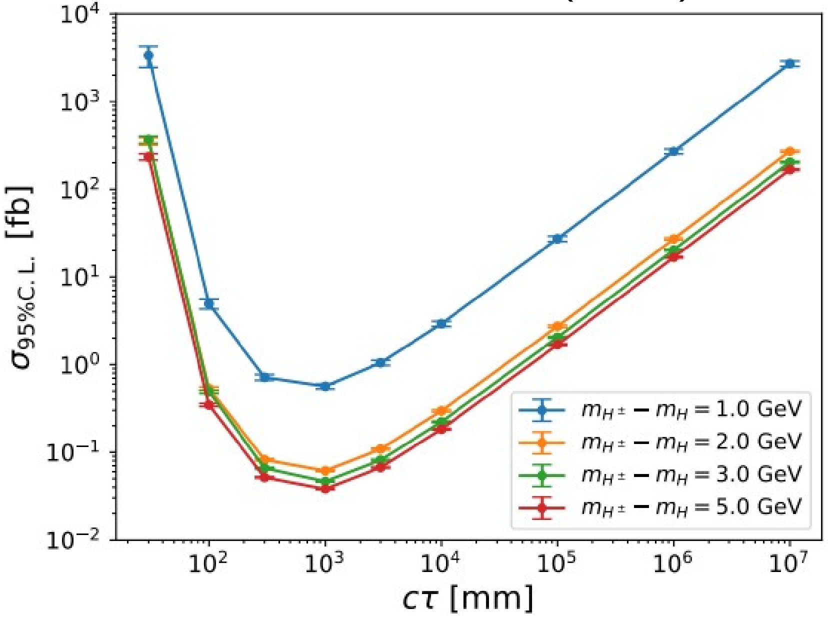
  → **N_{all} = Σw/w_{max}** where **w_{max} = tot. probability that LLP decays before L_{max}**

  → **N_{pass} = Σw** for events passing selection in TPC

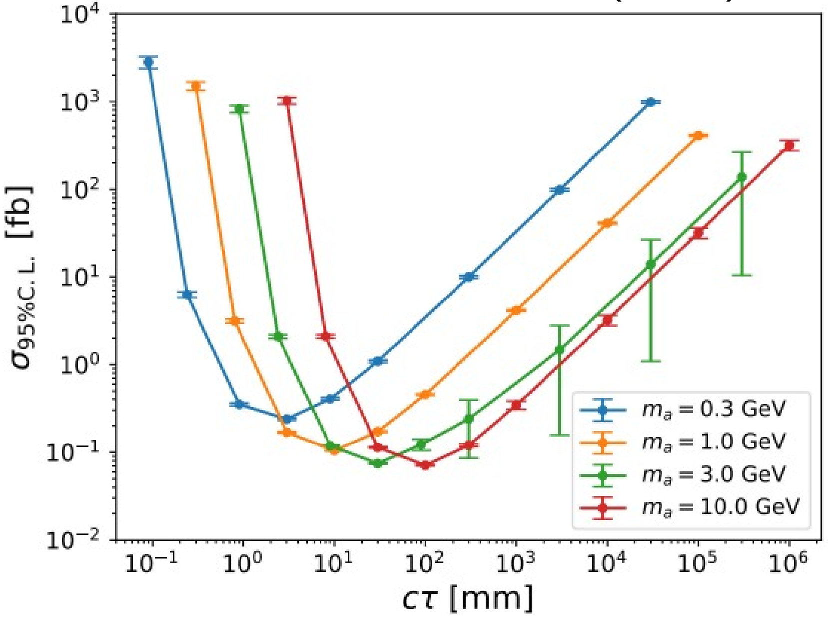
Now with $\epsilon_{sel} = N_{pass}/N_{all}$, $N_{sig} = 1.64 \cdot \sqrt{N_{bg}}/\epsilon_{sel}$

Cross section limits (old)

Heavy scalars (IDM)



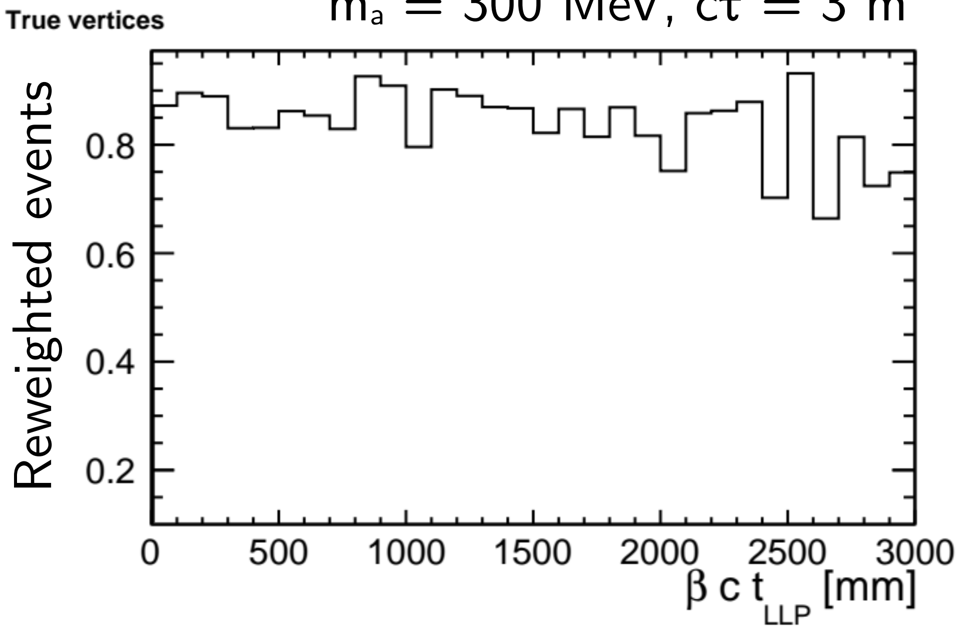
Light pseudoscalar (ALP)



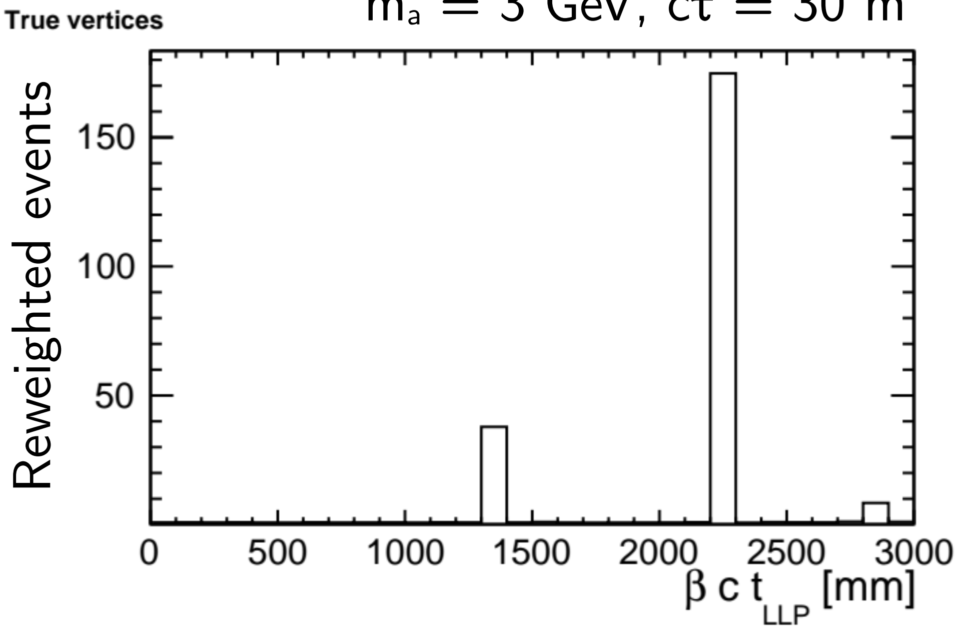
- Good sensitivity, even for high lifetimes
- Limits still conservative due to the model-independent approach (not using e.g. invariant mass or missing energy)

Reweighted events

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

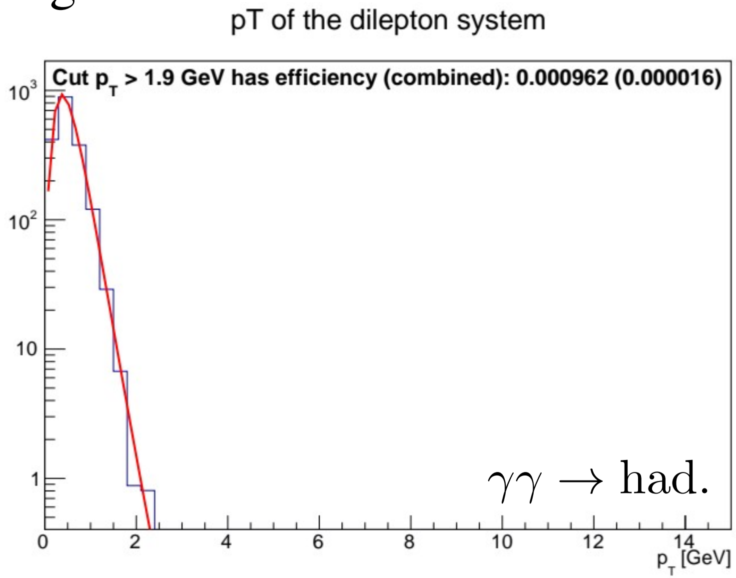


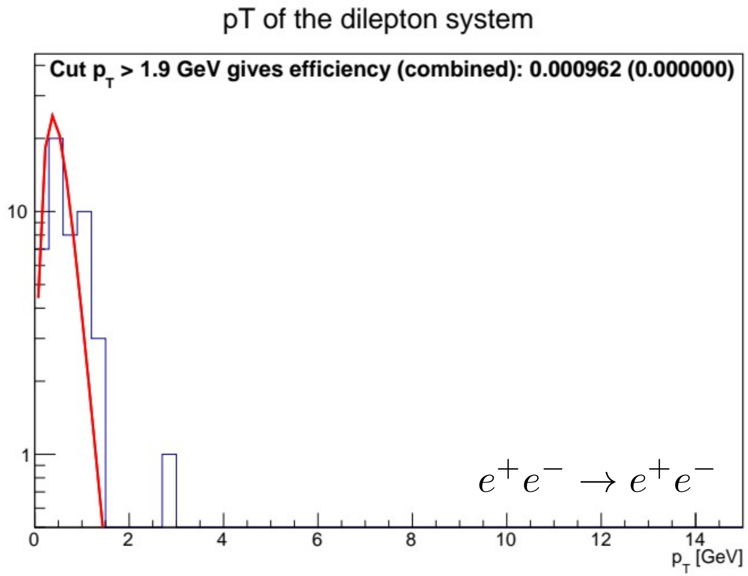
$m_a = 3$ GeV, $c\tau = 30$ m



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



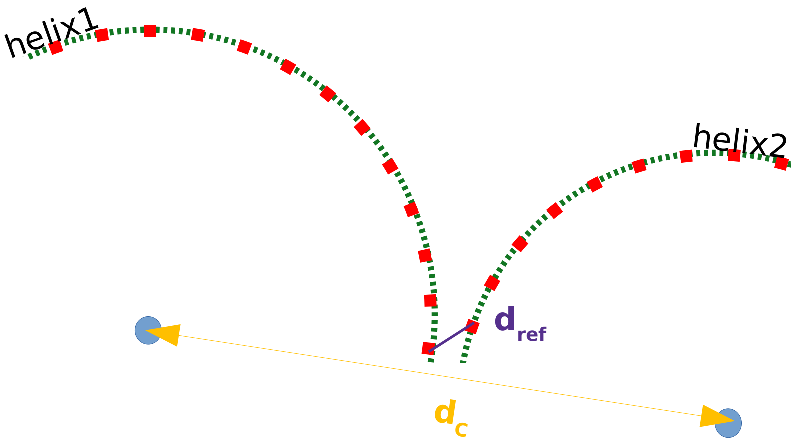


Norm = number of events, scaled by corresponding Poisson expectation values

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

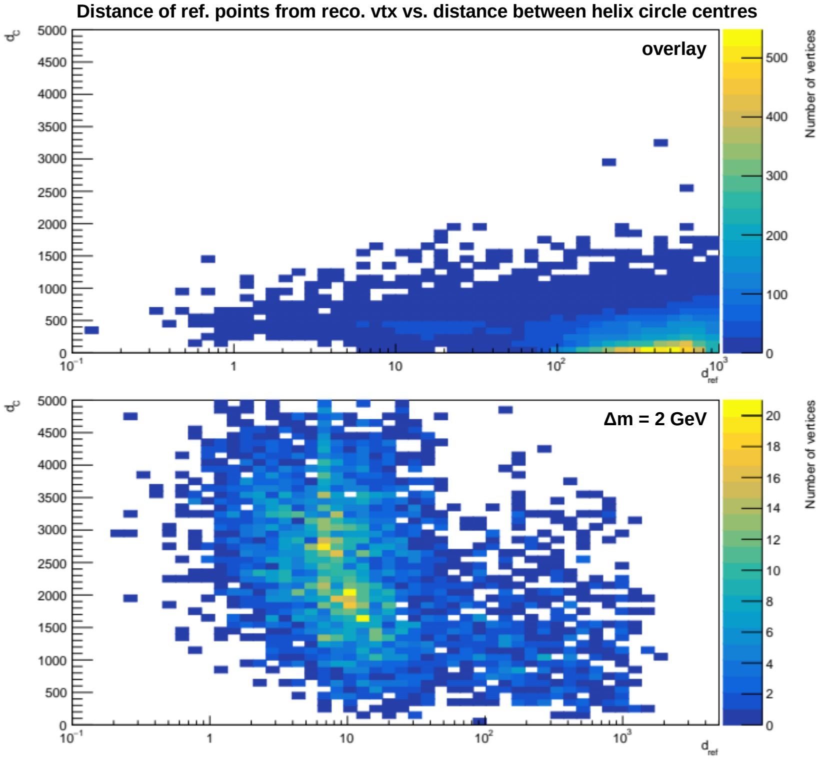
→ either **far reference points** or **close centres of helices**



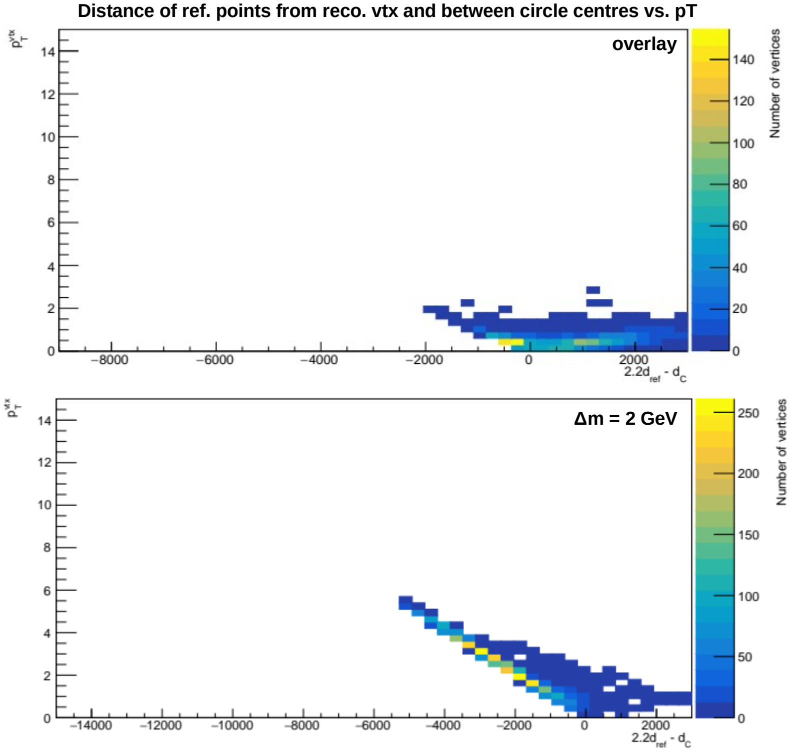
- **d_{ref}** – distance between reference points (TrackStates / first hits)
- **d_C** – distance between centres of helices projections into XY plane

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



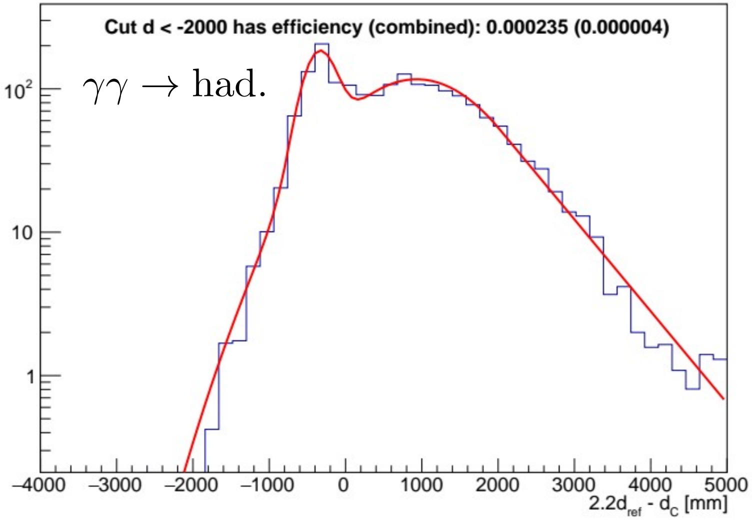
Warp and check correlation with p_T

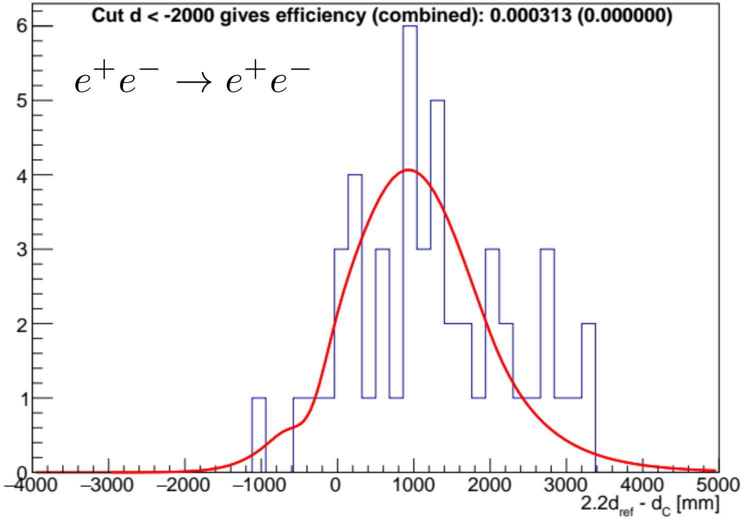


- Small correlation for the background
- Signal strongly correlated

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 $\mathbf{2.2d_{ref} - d_C}$, 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