Long-lived particle searches with the ILD experiment

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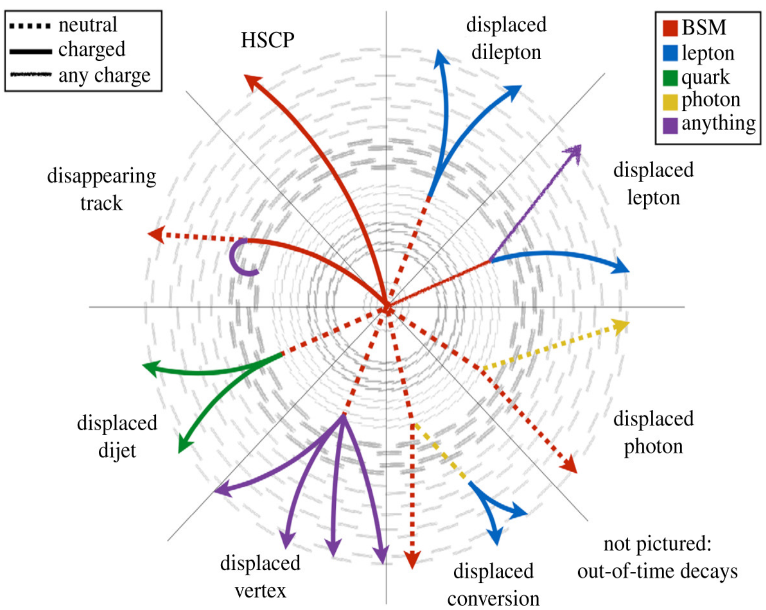
Long-lived particles (LLPs)

Numerous BSM models predict particles with macroscopic lifetimes:

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



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

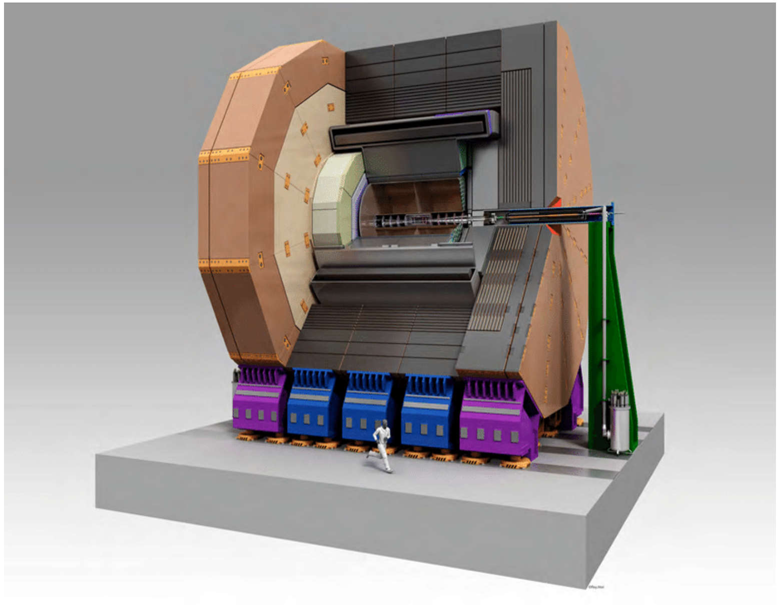
		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

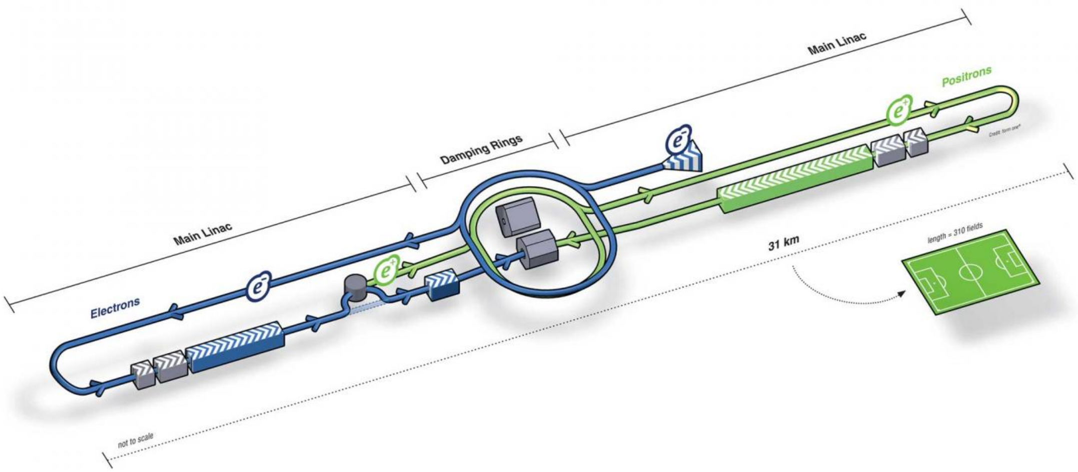
1810.12602

→ their typical properties make it challenging for hadron colliders...

International Large Detector (ILD)

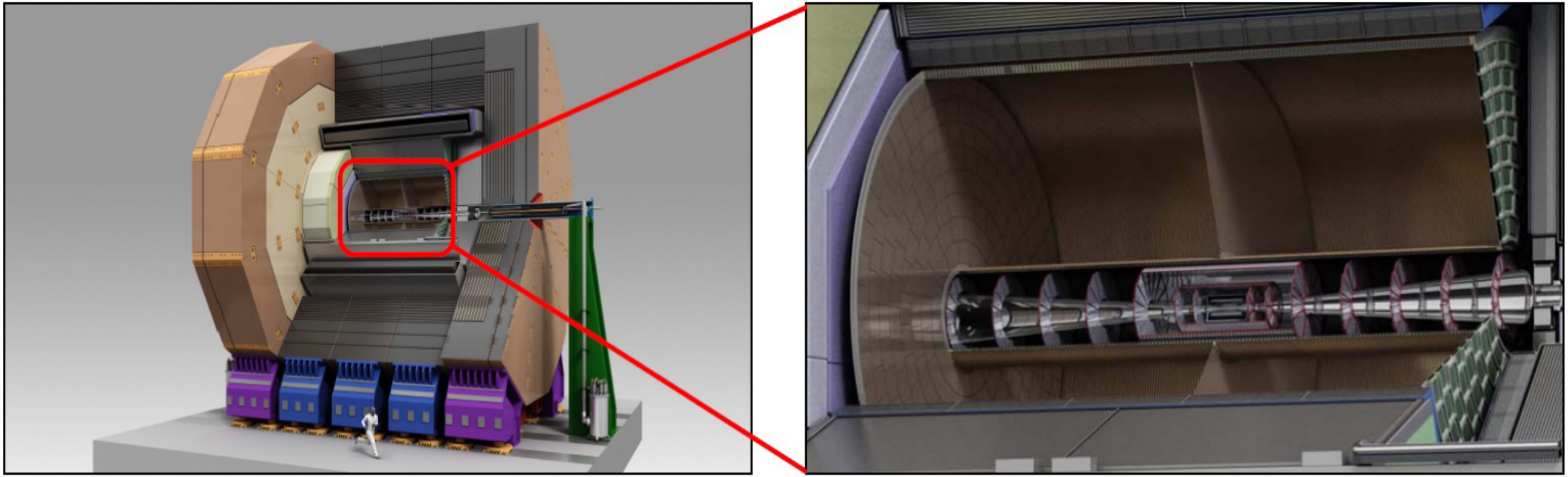
- Originally proposed for the International Linear Collider (ILC)
- Multi-purpose detector for an e^+e^- Higgs factory
- Possible operation at other HF proposals now under study





International Large Detector (ILD)

- Nearly 4π angular coverage, optimised for particle flow
- **Time projection chamber (TPC)** as the 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



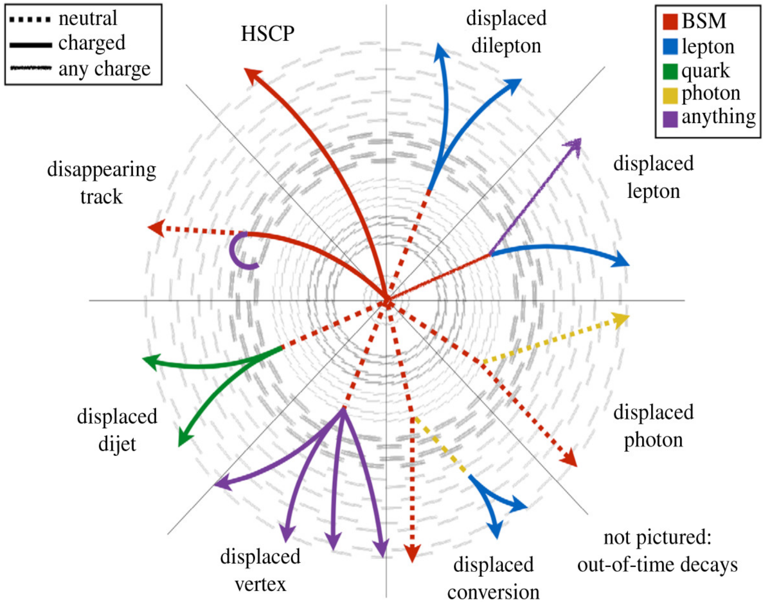
LLPs at the Higgs factories

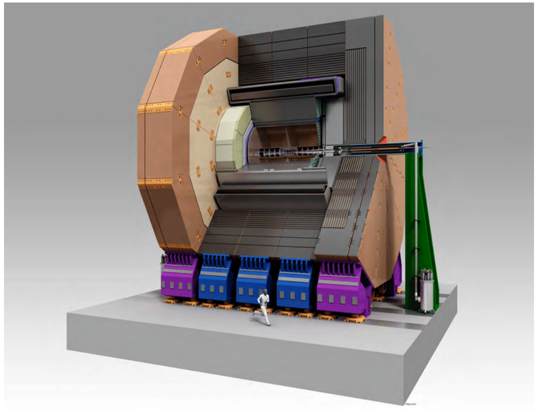
- Multiple LLP searches at the LHC, sensitive to high masses and couplings

  → 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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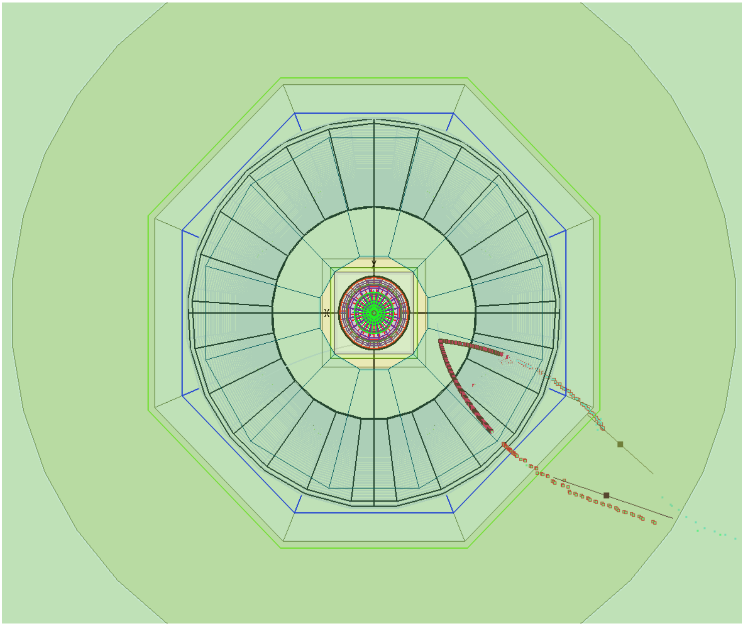
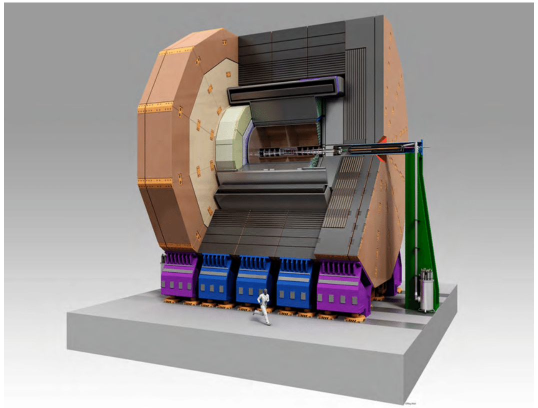




- Study such challenging signatures from the **experimental perspective**

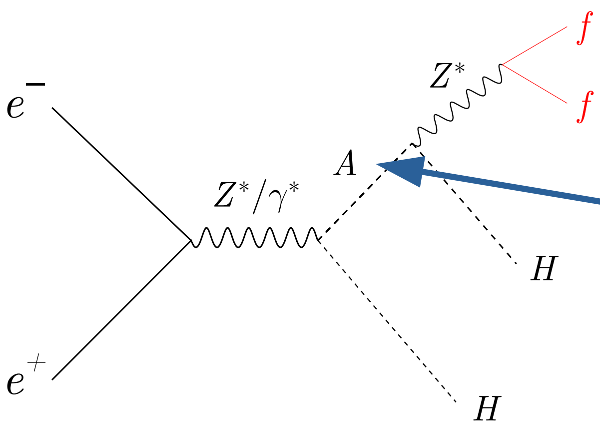
  → experimental/kinematic properties, not points in a model parameter space

- 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:

→ heavy scalar LLP (A) and DM (H) pair-production with small mass splitting, $\mathrm{Z}^* \to \mu\mu$



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

$$m_A = 75\,\mathrm{GeV}$$

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

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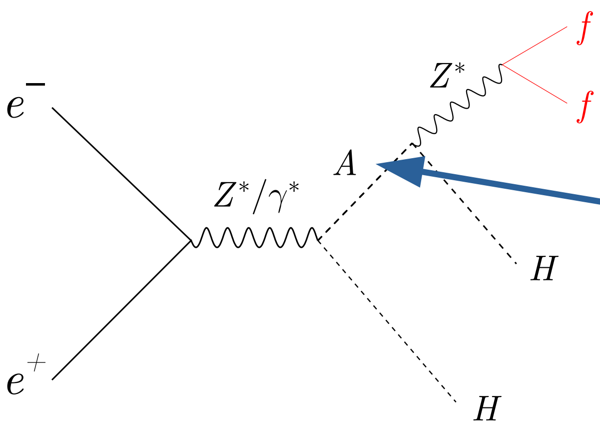

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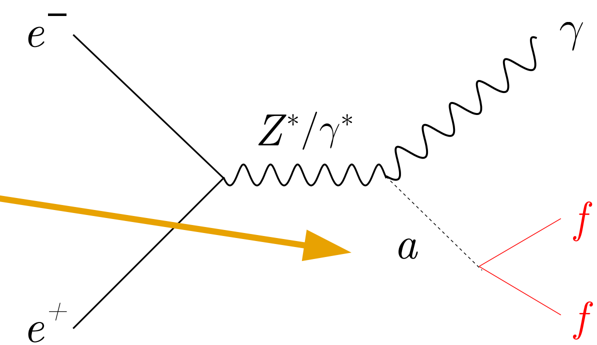
Long-lived, $c\tau = 10 \cdot m_a\,[\mathrm{mm}]$

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



The opposite extreme case, (large boost, high-pT final state)

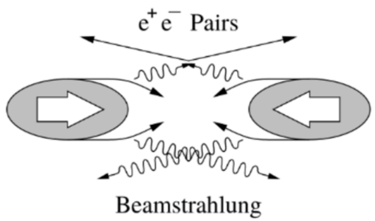
→ light pseudoscalar LLP $a \to \mu\mu$

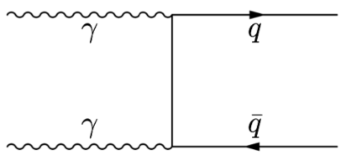
Very simple vertex finding (inside the TPC) based on a distance between track pairs

Overlay events background

At linear e^+e^- colliders beams are strongly focused and radiate photons, so $\gamma\gamma$ interactions also occur in detector. On average, in each bunch-crossing (BXs) at ILC, produced are:

- **1.55 $\gamma\gamma \rightarrow$ low-p_T hadrons** events
- **$O(10^5)$ incoherent e^+e^- pairs**, only a small fraction enters detector





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...but can also look like signal on their own

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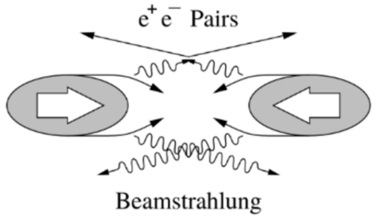

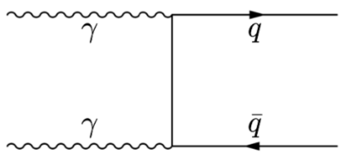

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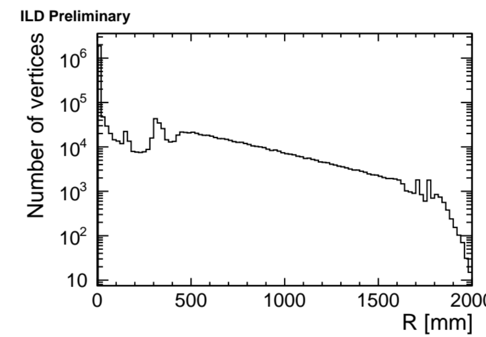
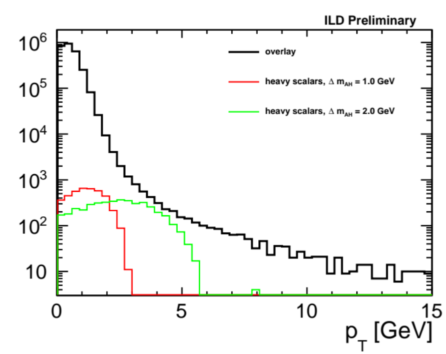
- ~10^{11} BXs per year at ILC → overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy

  → many secondary vertices (mostly fake, also V^0s and photon conversions)

  → significant background





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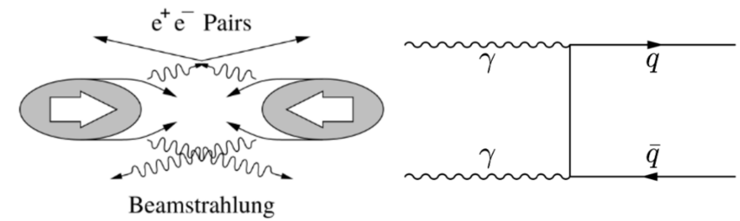

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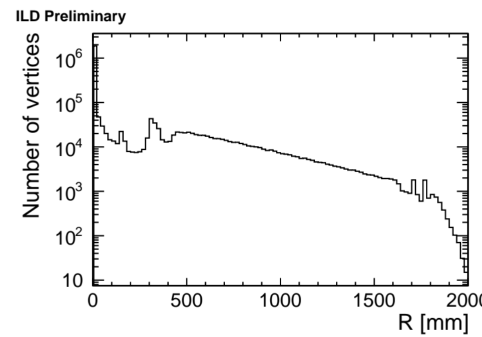

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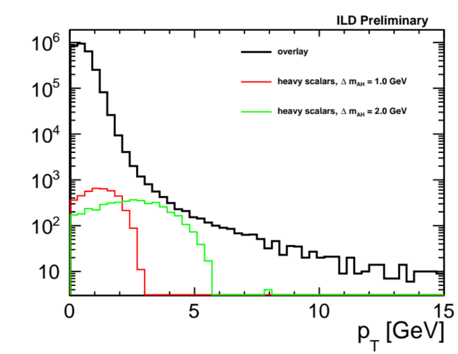


- Can be suppressed using cuts on the p_T and geometry of track pair
- Total expected reduction factor at the level of **~10^{-10}**

Background from physics events

The following survive overlay selection in the hard e^+e^- processes:

- Displaced decays of kaons, lambdas, photons
- Secondary tracks from interactions with detector material

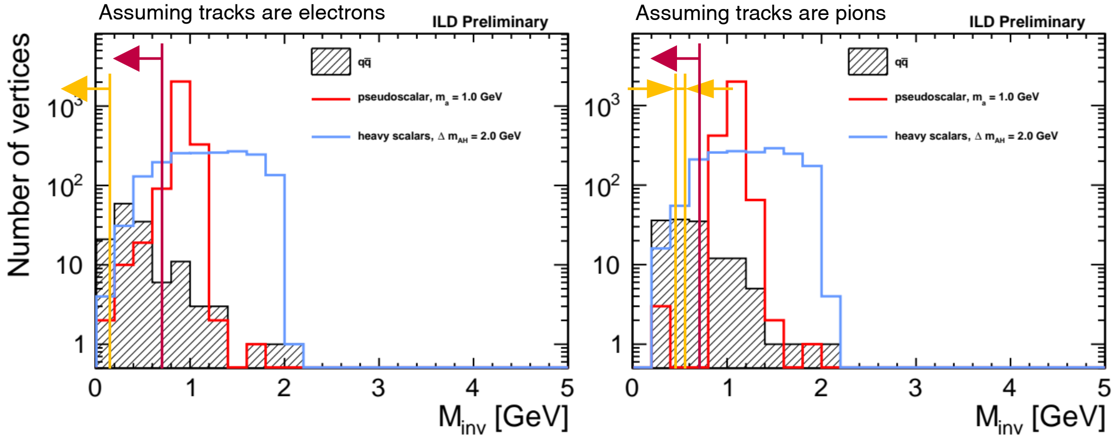
They occur mainly inside jets, so we consider (hard) e^+e^- and $\gamma\gamma$ processes with jets in final state

Additional cuts on invariant mass are applied, with two working points: **standard** and **tight** (tight involving also **isolation** criterium)

Selection eff. depends on number of jets, so:

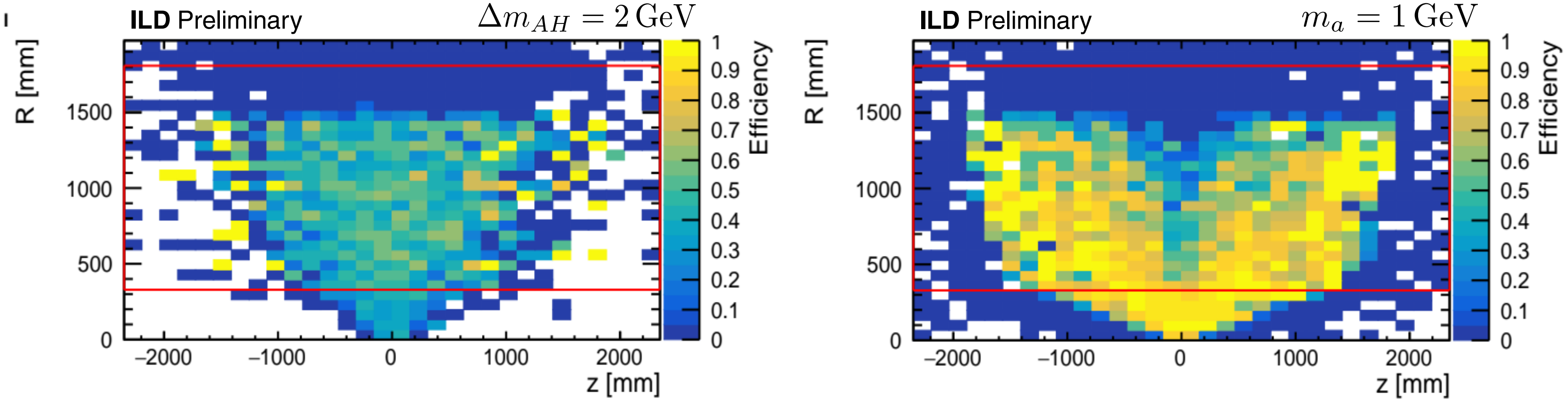
Estimate selection efficiency based on full simulation

Use qq efficiency for the remaining processes



sgn(P(e^-), P(e^+))	(−, +)	(+, −)	(−, −)	(+, +)
channel		σ [fb]		
qq	127,966	70,417	0	0
qqqq	28,660	970	0	0
qq$\ell\nu$	29,043	261	191	191
ZZ $\to$ qq$\ell\ell$, qq$\nu\nu$	838	467	0	0
Z$\nu_e\nu_e$ $\to$ qq$\nu_e\nu_e$	454	131	0	0
Zee $\to$ qqee	1,423	1,219	1,156	1,157
process	BB	BW	WB	WW
hard $\gamma^{B/W}\gamma^{B/W}$	42,150	90,338	90,120	71,506

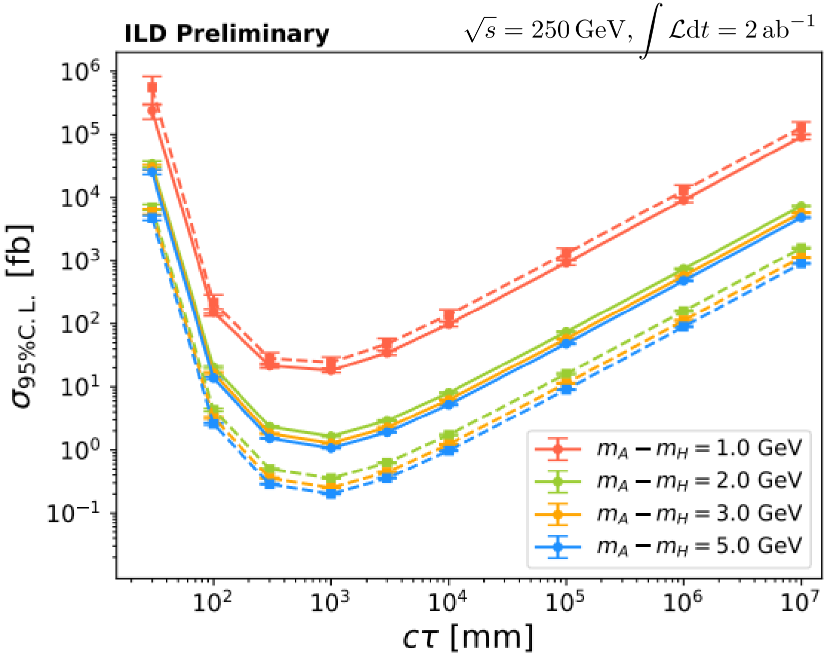
Vertex finding results



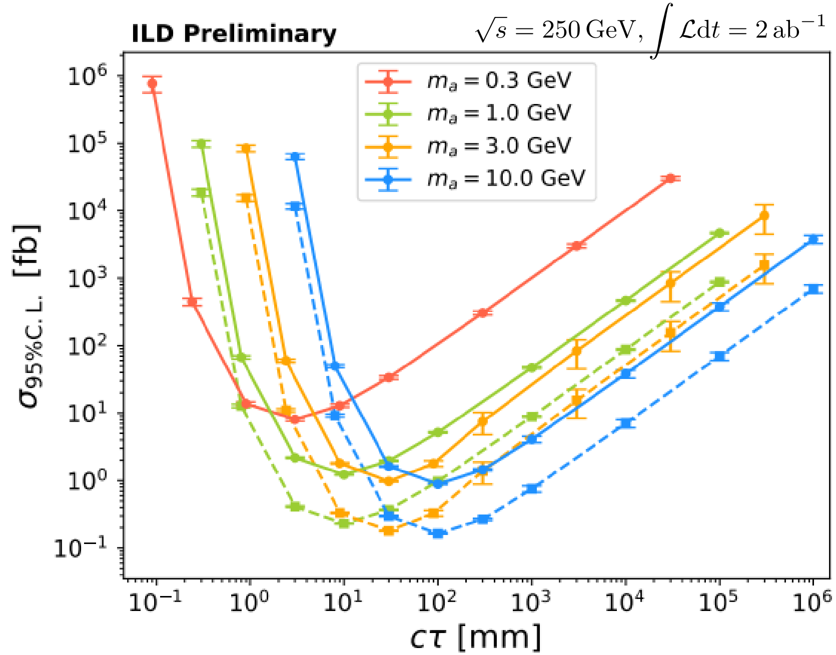
Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

- Efficiency = (correct / decays within TPC acceptance), "correct" if distance to the true vtx < 30 mm
- **Signal selection** depends strongly on the **mass splitting** (Z* virtuality) and **mass** of *a* (final state boost)
- A dedicated approach could enhance sensitivity for Δm_{AH} = 1 GeV and m_a = 300 MeV scenarios

Cross section limits



Heavy scalars



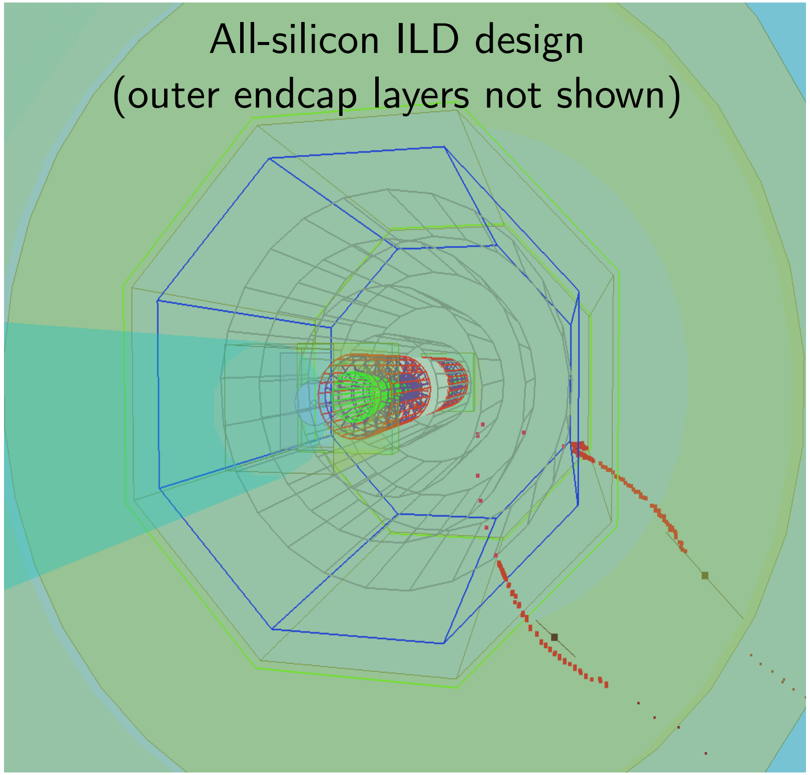
Light pseudoscalar

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

Alternative all-silicon ILD design

Alternative ILD design implemented for tests

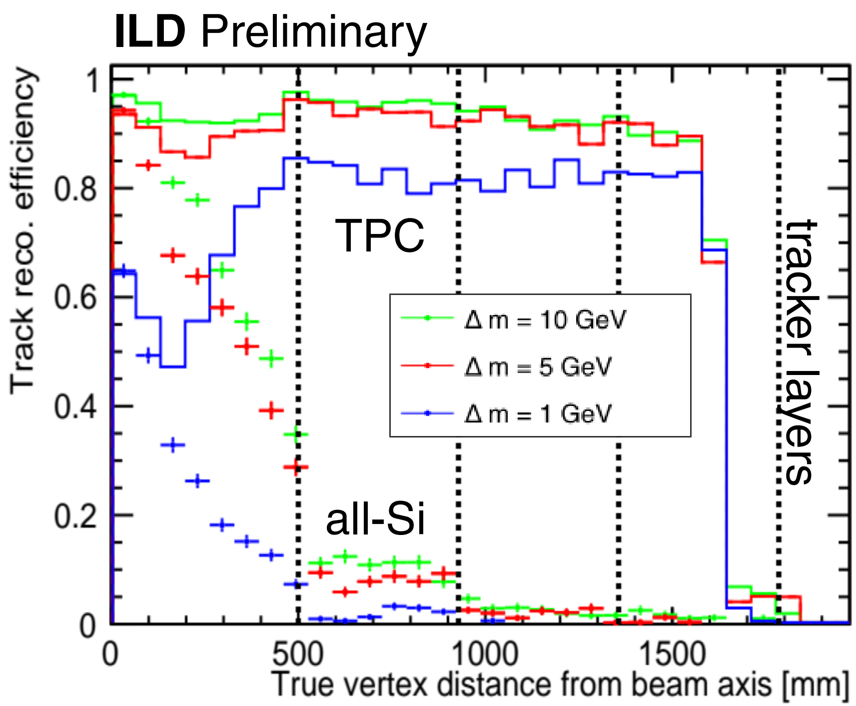
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ 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
- Inclusive search for with **two tracks** from a **displaced vertex**

  → a simple vertex-finding algorithm developed, with a set of cuts aimed to suppress background from the overlay events and hard SM processes

- 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** pseudoscalar decaying into muons performed with the same algorithm and procedure indicates good sensitivity for **masses** $\geq$ **1 GeV**
- Estimated 95% CL limits on signal cross section indicate ILD's high reach for a wide range of lifetimes (0.003-10 m, depending on scenario)

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

  → tracking tests for heavy scalars confirm **TPC can improve the reach** in LLP searches

BACKUP

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:

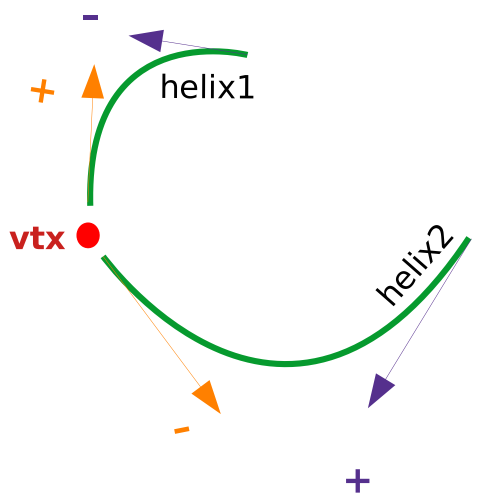
  → use **both track direction** (charge) **hypothesis** for vertex finding

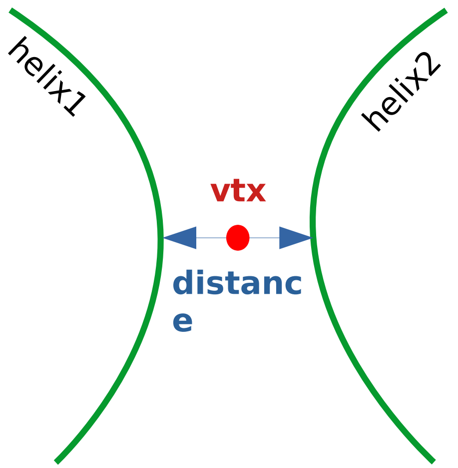
  → consider opposite-charge track pairs only

  → select pair with **closest starting points**

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

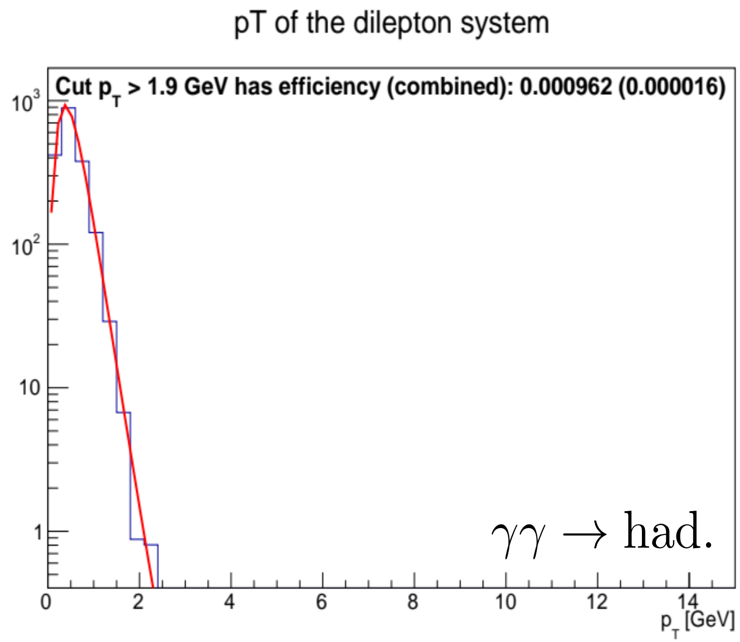
  → Require distance < 25 mm

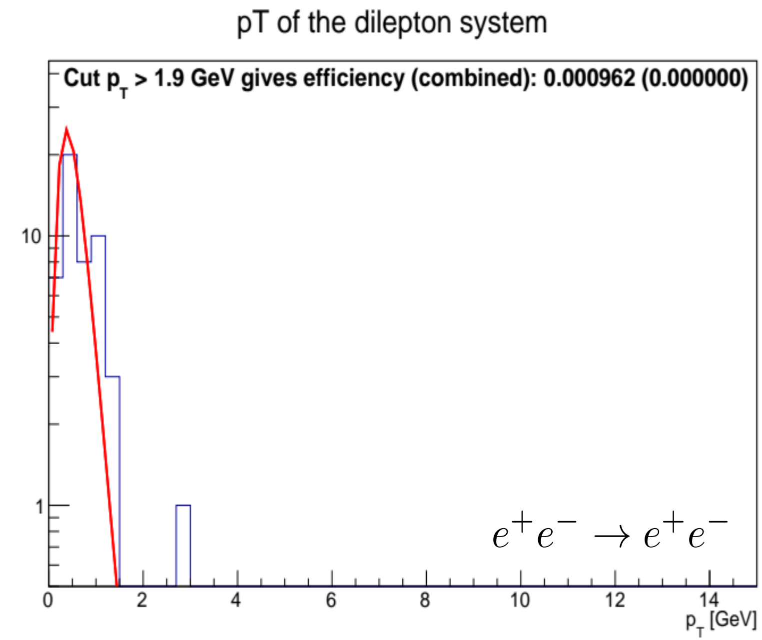




Final selection – pT

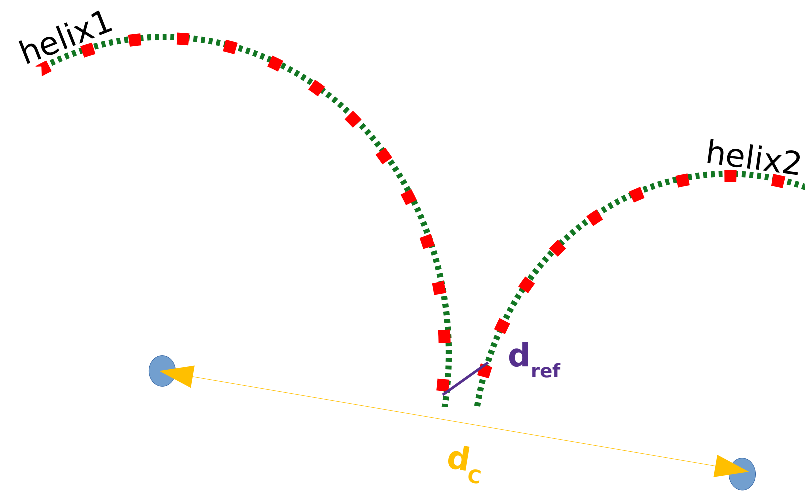
- We consider **γγ → had.** and **e^+e^- samples** separately
- Estimated background eff. from fitted distributions ~10^{-3} (**~10^{-5}–10^{-7}** with preselection)
- Very **small statistics** in **e^+e^- sample** after preselection → fit shape from **γγ → had.** with floating normalisations





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

Final selection – other variables



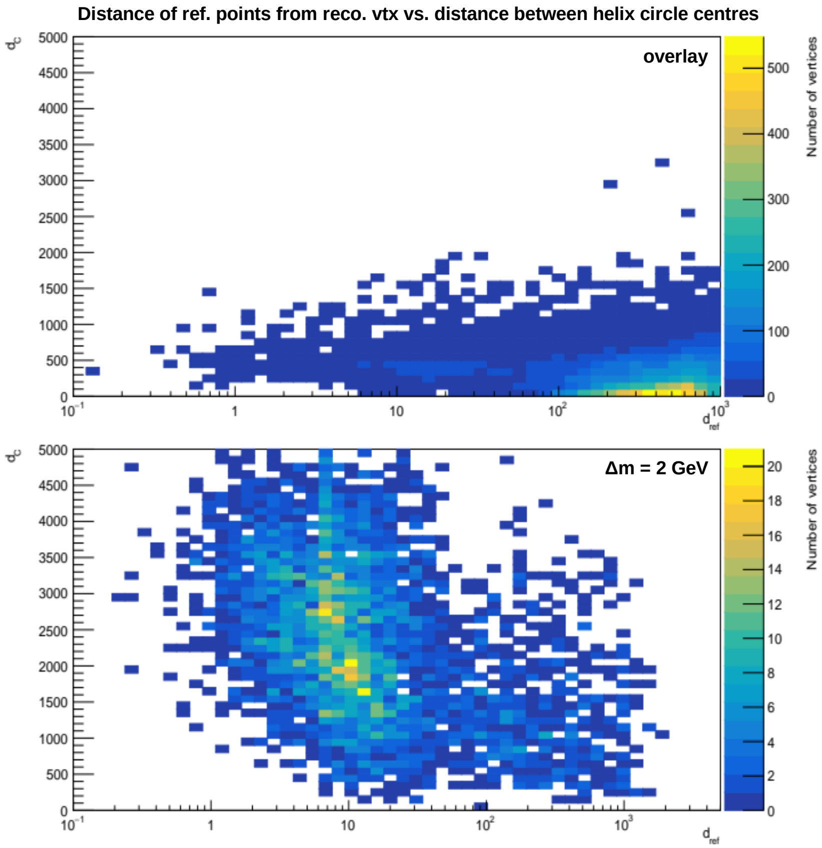
- At least one more (independent) variable needed to achieve the assumed reduction
- We expect that **signal** tracks should come out of a single point → **reference points should be close**
- In busier backgound events, still many tracks evade the cuts – e.g. curlers, secondary decays

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

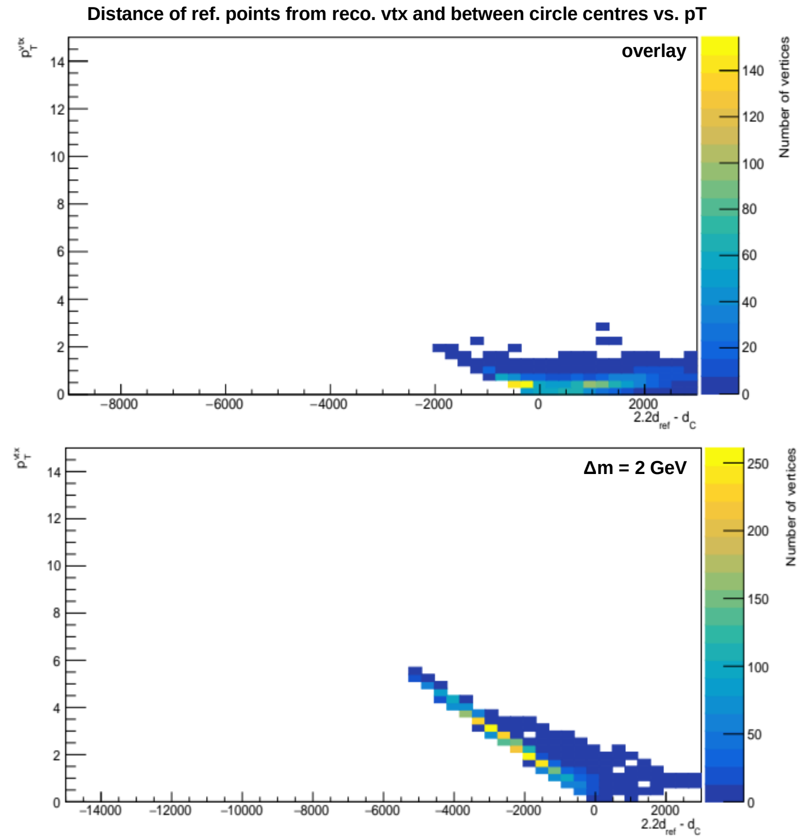
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

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



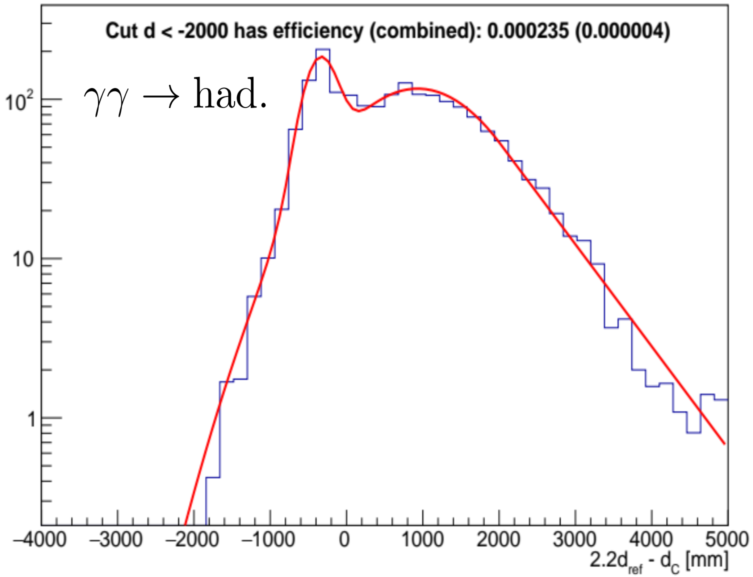
Warp and check correlation with p_T

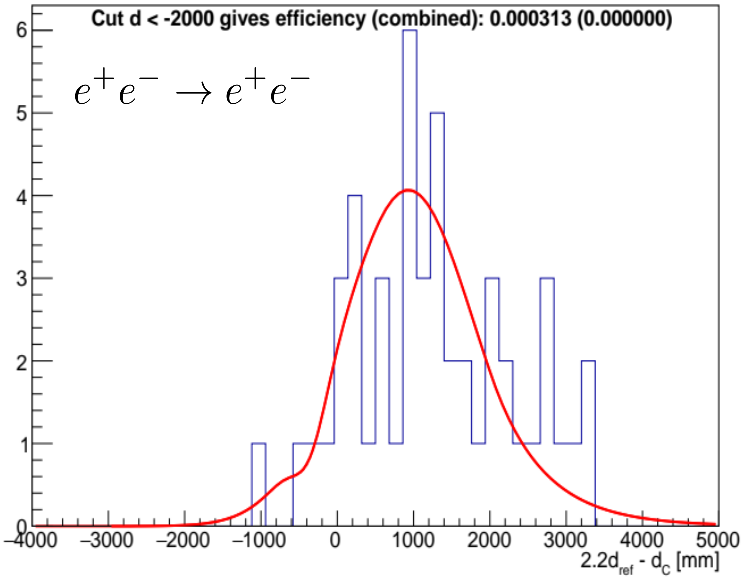


- Small correlation for the background
- Signal strongly correlated

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**)





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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