

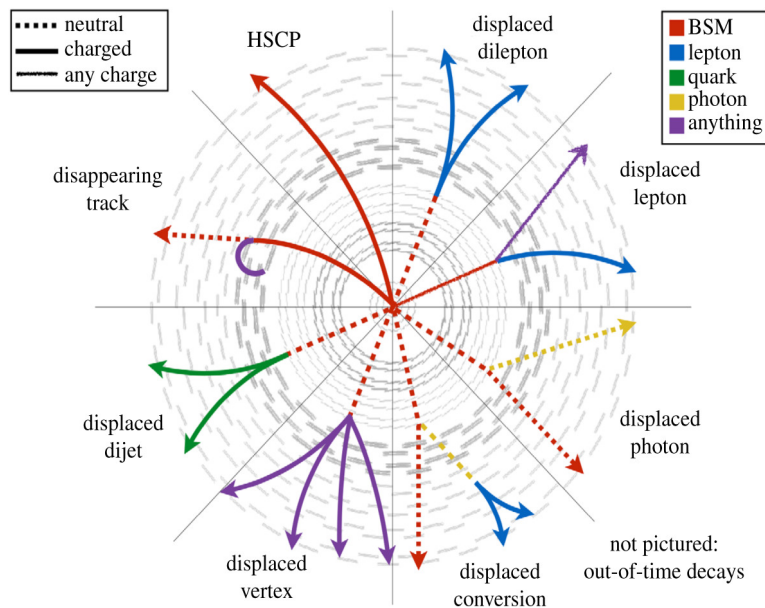
Long-lived particle searches with the ILD experiment

Workshop on the Standard Model and Beyond
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Particles with macroscopic lifetimes naturally appear in numerous BSM models

Three main mechanisms are responsible for that...



		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			✓

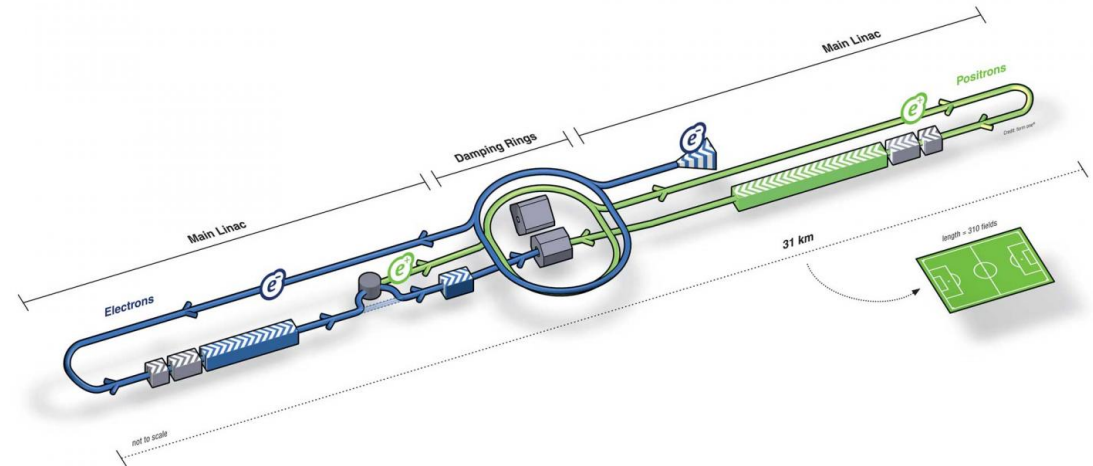
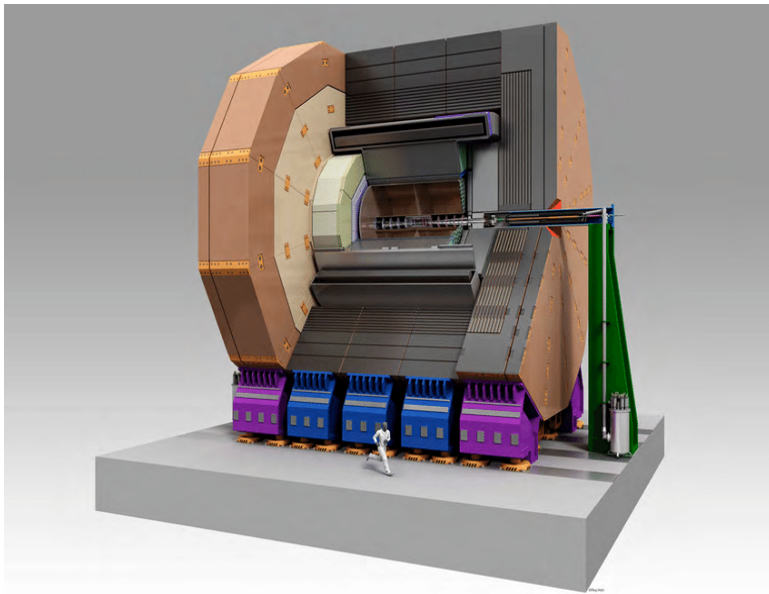
<https://doi.org/10.1098/rsta.2019.0047>

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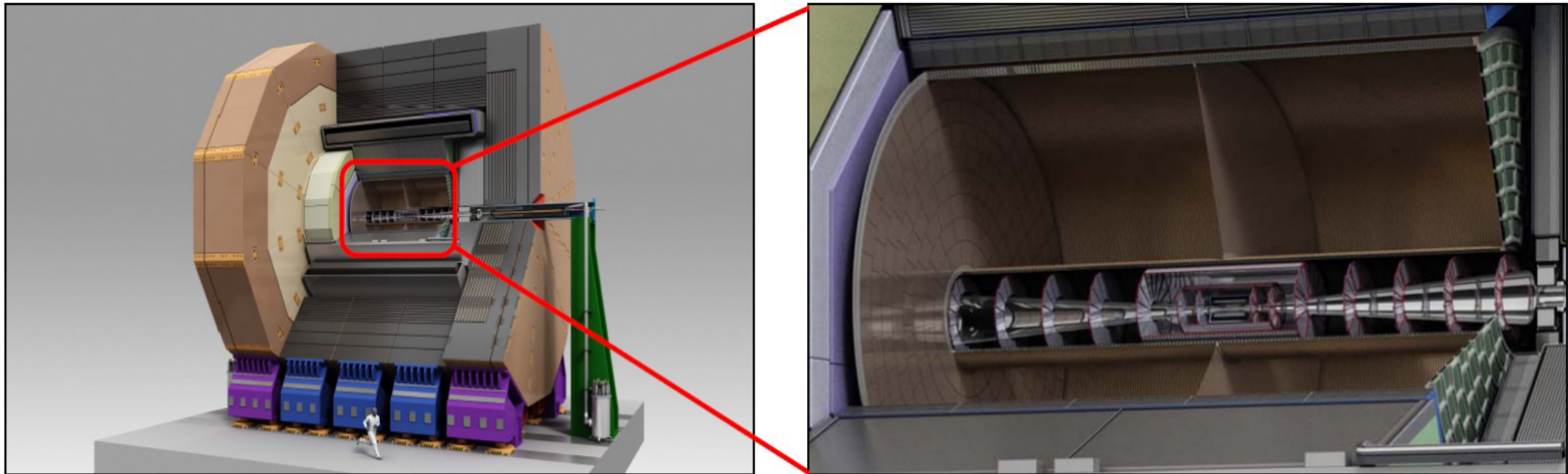
→ ...but they automatically make it challenging for hadron colliders to search for LLPs

- Multi-purpose detector for an e^+e^- Higgs Factory (HF)
- Example: the International Linear Collider (ILC), with baseline c.m.s. energy 250-500 GeV
- Possible operation at other HF proposals now under study

↑
this study

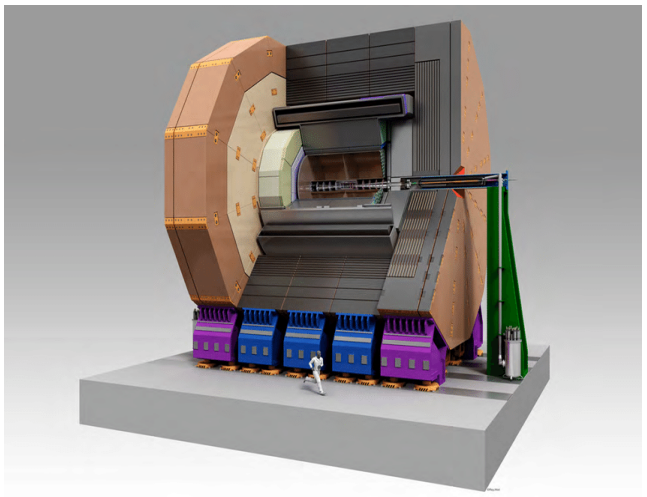
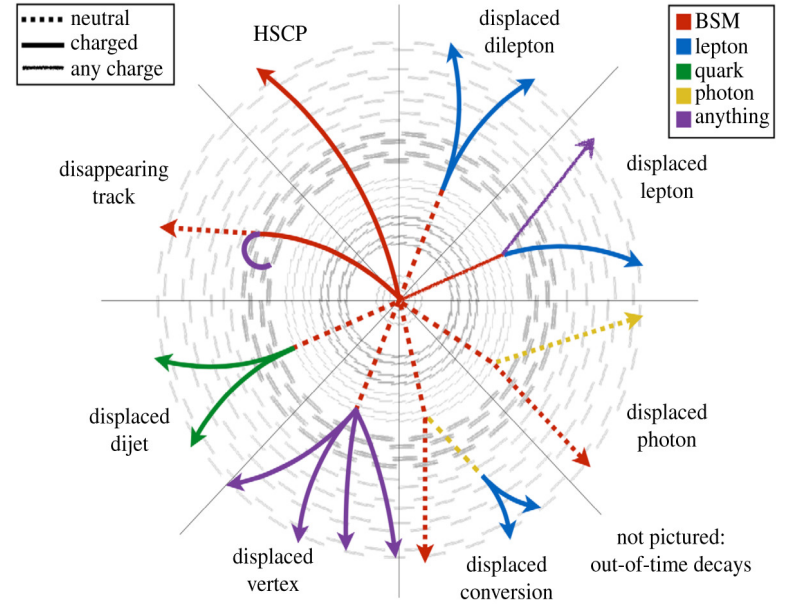


- Nearly 4π angular coverage, optimised for particle flow
- **Time projection chamber (TPC)** as the main tracker allows for continuous tracking and dE/dx PID
- High granularity calorimeter with minimal material in front of it inside 3.5 T solenoid

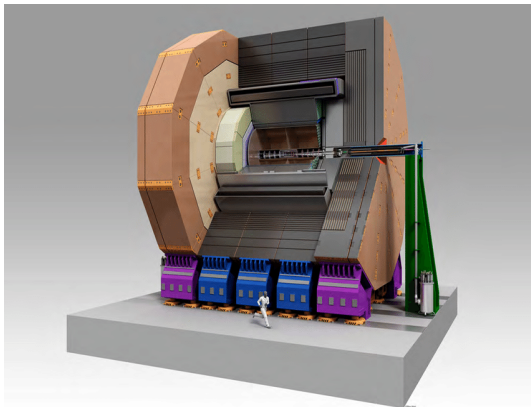
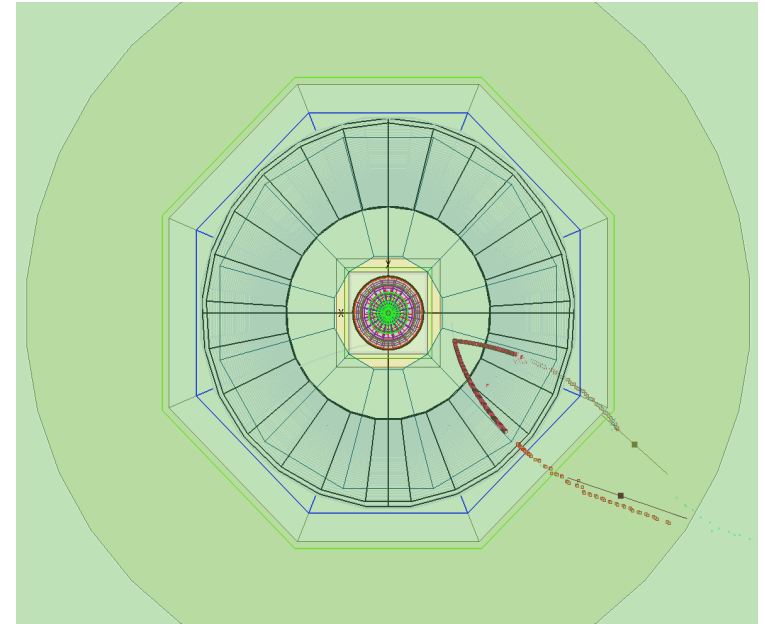


LLPs at the Higgs factories

- 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 especially promising with a TPC as the main tracker



- 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 especially promising with a TPC as the main tracker
 - study based on full simulation

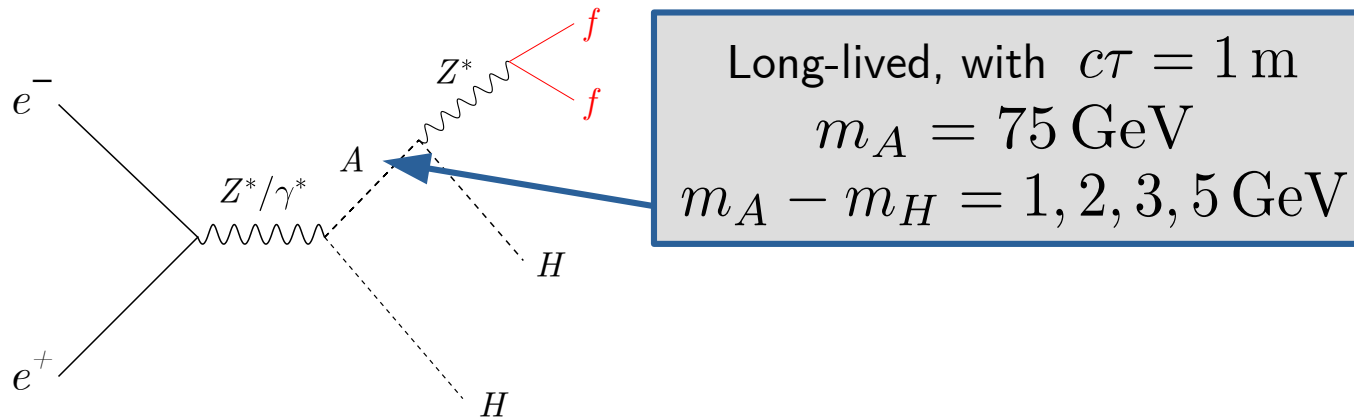


- Study such challenging signatures from the **experimental perspective**
 - experimental/kinematic properties, not points in a model parameter space
- Focus on a generic case – two tracks from a displaced vertex
- No other assumptions about the final state, approach **as general as possible**

As a challenging case (small boost, low-pT final state) we considered:

$$\sqrt{s} = 250 \text{ GeV}$$

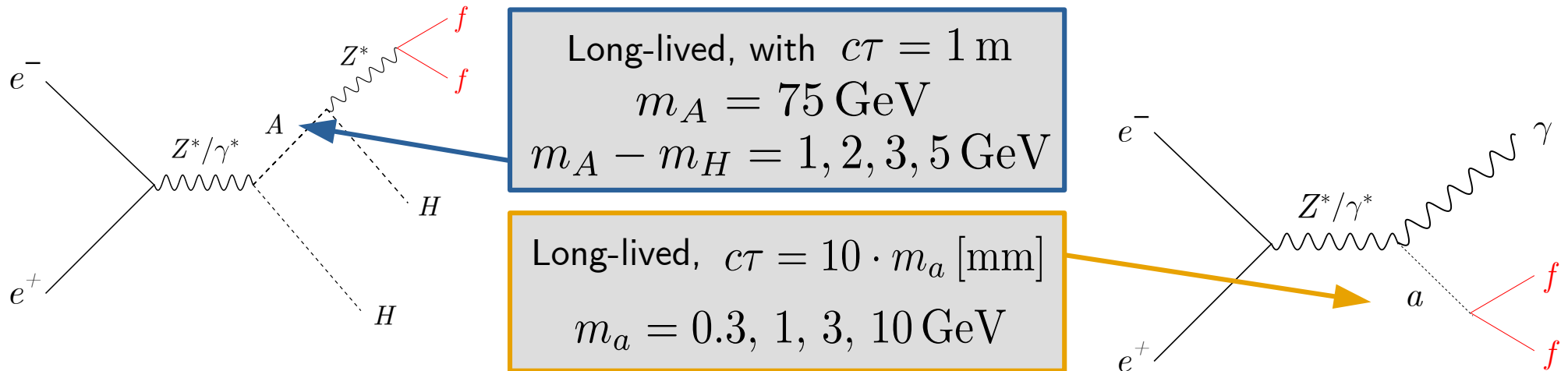
→ heavy scalar LLP (A) and DM (H) pair-production with small mass splitting, $Z^* \rightarrow \mu\mu$



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



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

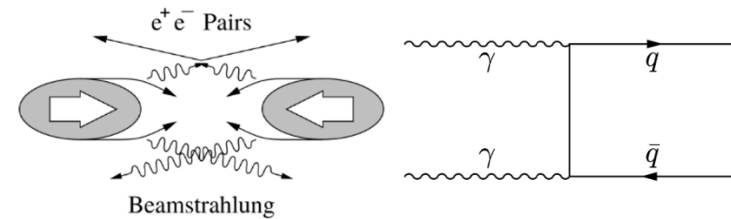
→ light pseudoscalar LLP $a \rightarrow \mu\mu$

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



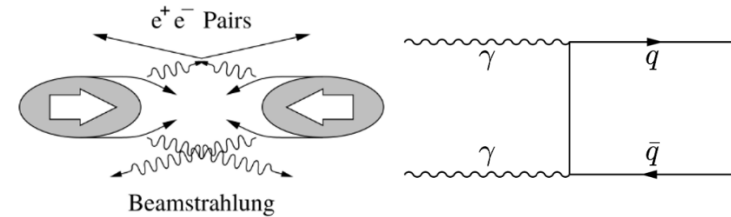
These events are soft, usually important because they **overlay** on physical events

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

Overlay events background

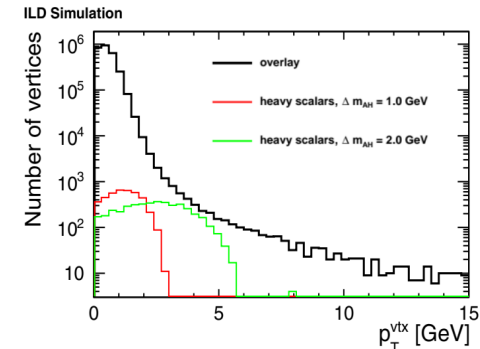
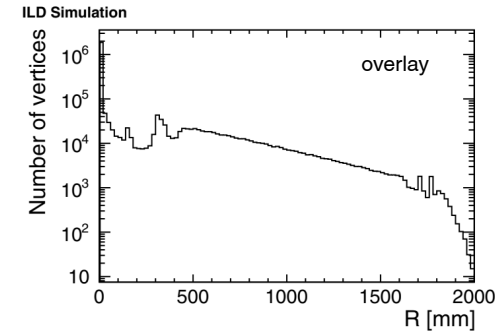
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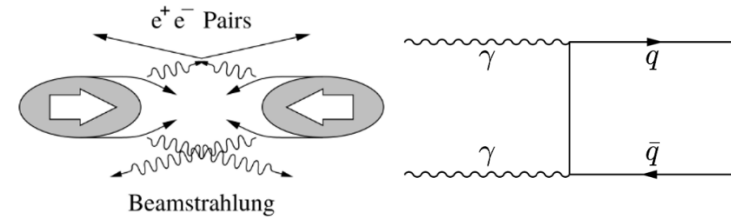
- $\sim 10^{11}$ BXs per year at ILC \rightarrow overwhelming number of overlay events
- Similar kinematics to the signal considered and can be busy
 - \rightarrow many secondary vertices (mostly fake, also V^0 s and photon conversions)
 - \rightarrow significant background



Overlay events background

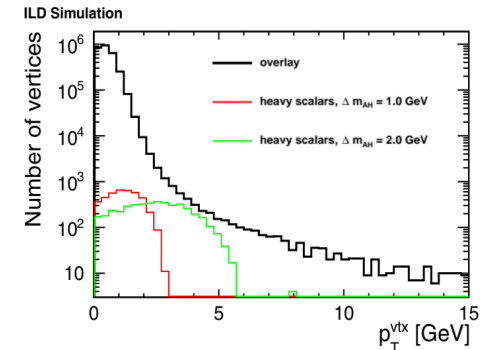
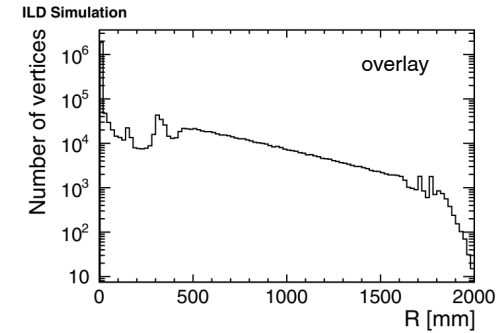
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- Can be suppressed using cuts on the track pair geometry and $p_T > 1.9$ GeV
- Total expected reduction factor at the level of $\sim 10^{-9}$

Background from high- p_T events

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

- Decays of kaons, lambdas, photon conversions
- Secondary tracks from interactions with detector material

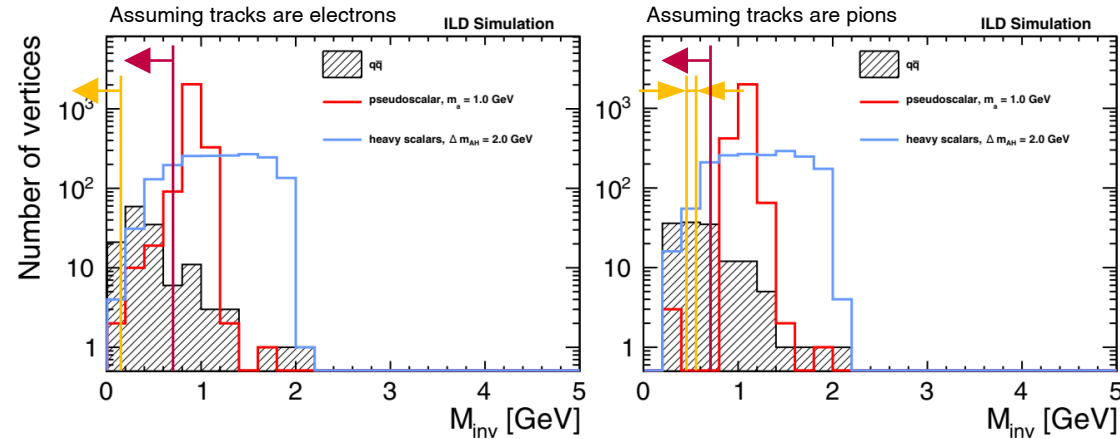
They occur mainly inside jets, so we consider (hard) e^+e^- and $\gamma\gamma$ processes with jets in final state

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:

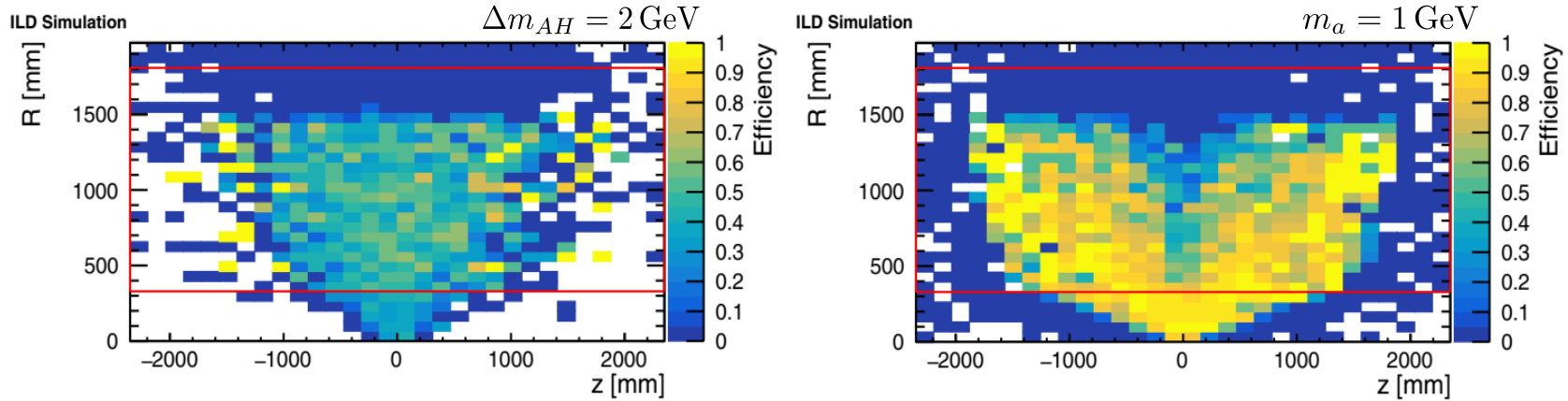
Estimate selection efficiency based on full simulation

Use qq efficiency for the remaining processes



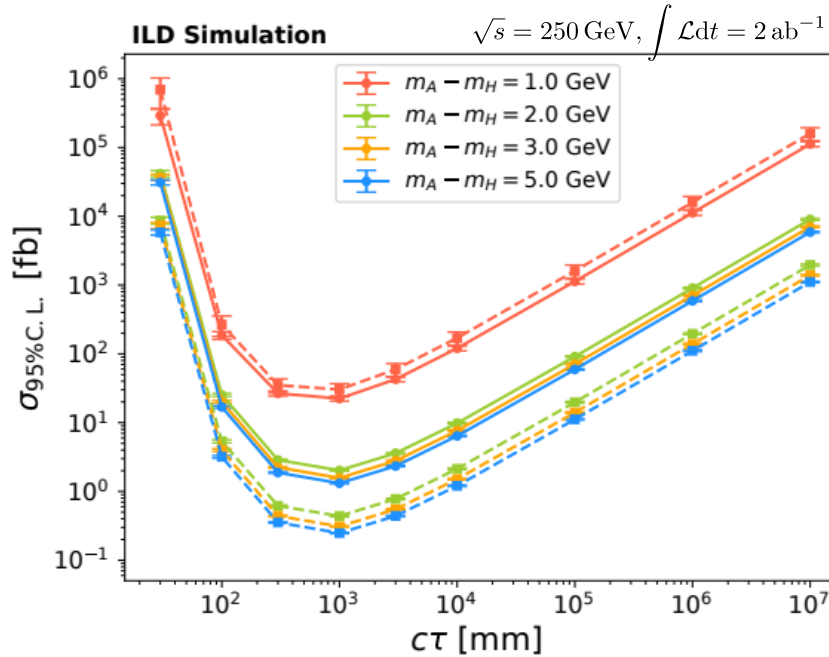
$\text{sgn}(P(e^-), P(e^+))$	(-, +)	(+, -)	(-, -)	(+, +)
channel	σ [fb]			
qq	127,966	70,417	0	0
qqqq	28,660	970	0	0
qq $l\nu$	29,043	261	191	191
$ZZ \rightarrow qqll, qq\nu\nu$	838	467	0	0
$Z\nu_e\nu_e \rightarrow qq\nu_e\nu_e$	454	131	0	0
$Zee \rightarrow qqee$	1,423	1,219	1,156	1,157
process	BB	BW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

Vertex finding results

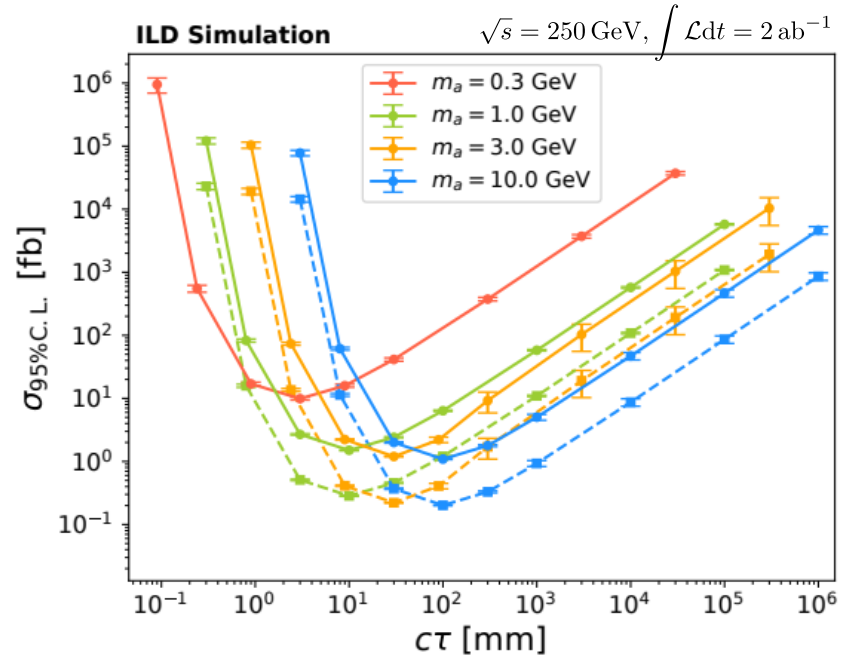


Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

- 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 $\Delta m_{AH} = 1 \text{ GeV}$ and $m_a = 300 \text{ MeV}$ scenarios



Heavy scalars

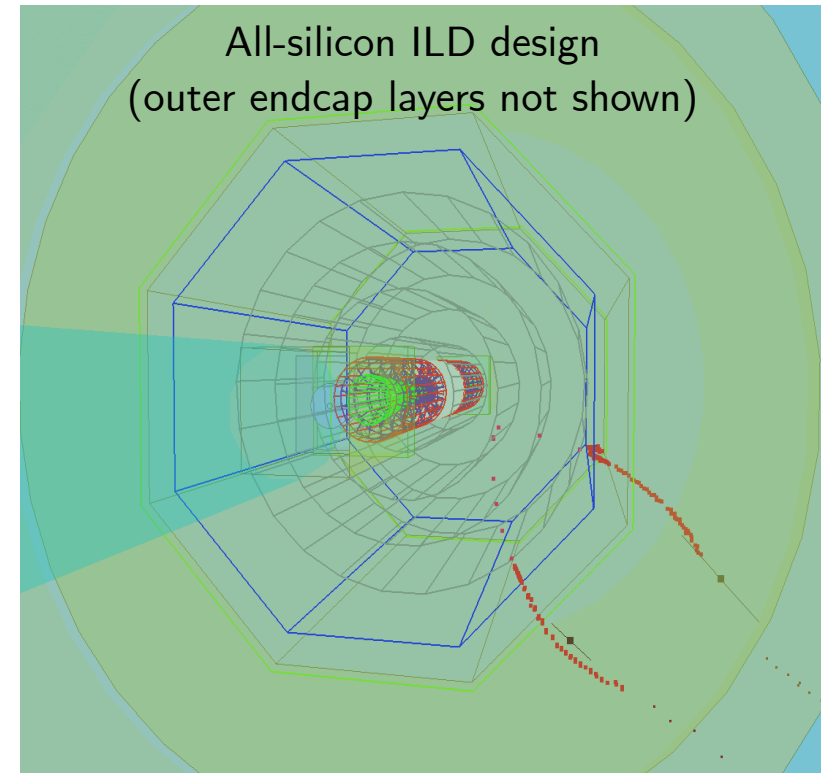


Light pseudoscalar

- Tight selection: dashed line, standard selection: solid line
- A wide range of models with heavy scalars with small mass splittings, or light pseudo scalar particles, can be excluded down to 0.1 fb

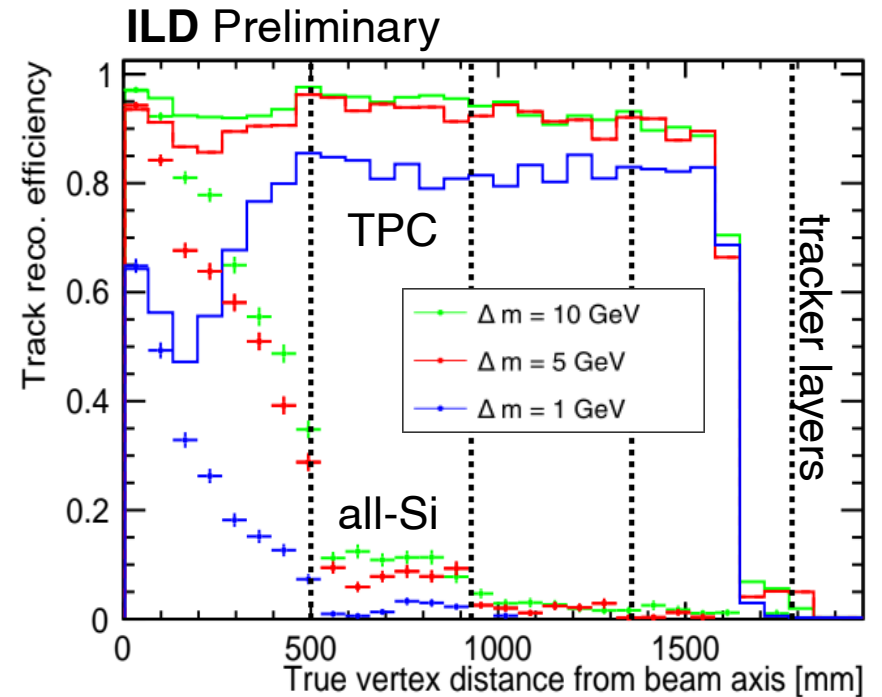
Alternative ILD design implemented for tests

- **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

- 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**

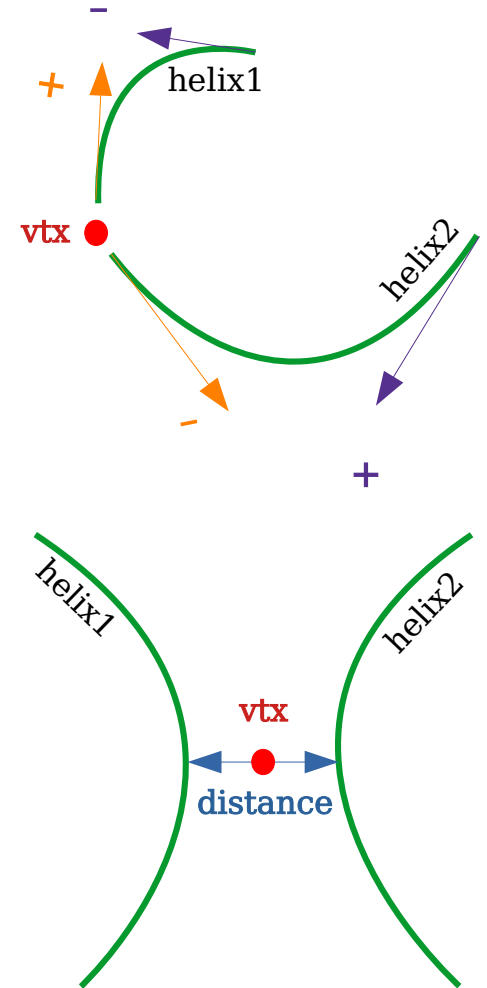


- We study LLPs in parameter space regions complementary to LHC searches
- Inclusive search for with **two tracks** from a **displaced vertex**
 - a simple vertex-finding algorithm developed, with a set of cuts aimed to suppress background from the overlay events and hard SM processes
- For heavy scalars production, with **small mass splittings** between LLP and DM and **low-momenta decay products**, good sensitivity from $\Delta m = 2 \text{ GeV}$
- Reconstruction of **highly boosted**, **light** pseudoscalar decaying into muons performed with the same algorithm and procedure indicates good sensitivity for **masses $\geq 1 \text{ GeV}$**
- 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 a 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

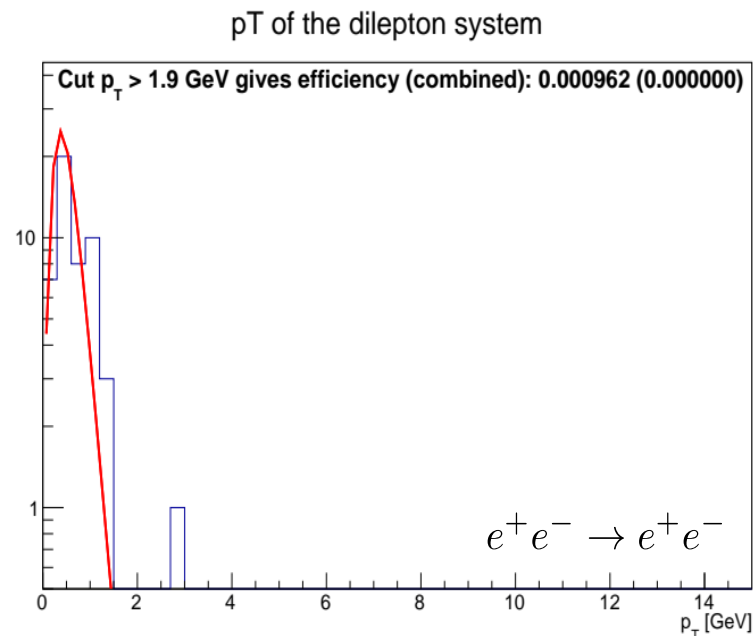
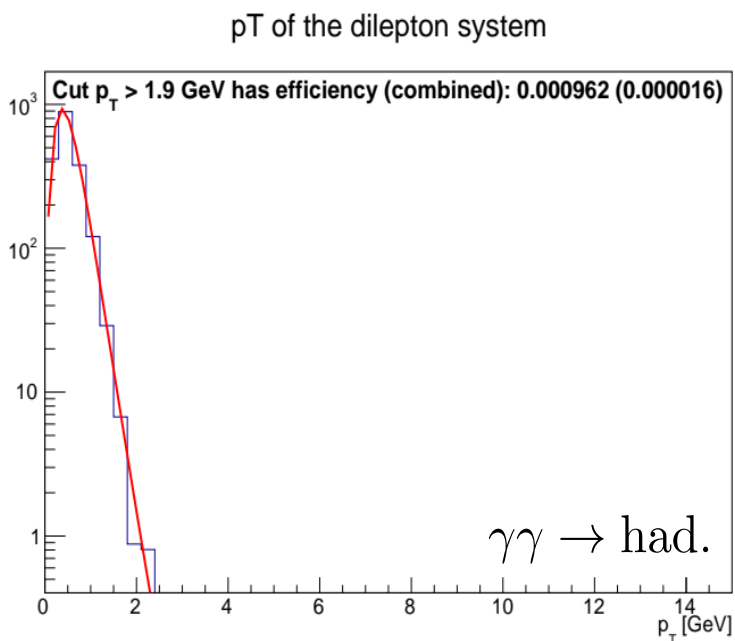
BACKUP

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



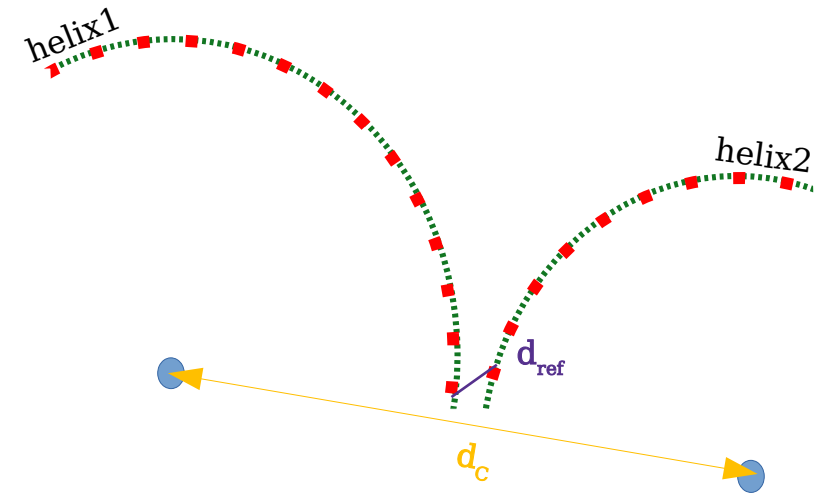
- We consider $\gamma\gamma \rightarrow \text{had.}$ and e^+e^- samples separately
- Estimated background eff. from fitted distributions $\sim 10^{-3}$ ($\sim 10^{-5}$ – 10^{-7} with preselection)
- Very **small statistics** in e^+e^- sample after preselection \rightarrow fit shape from $\gamma\gamma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



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

- 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 background events, still many tracks evade the cuts – e.g. curlers, secondary decays

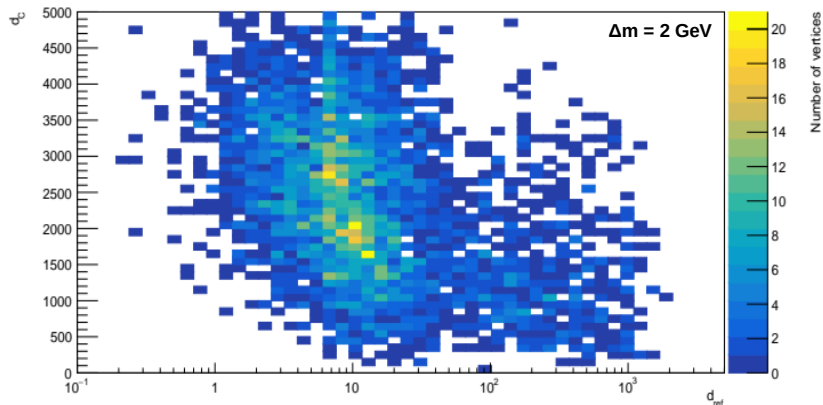
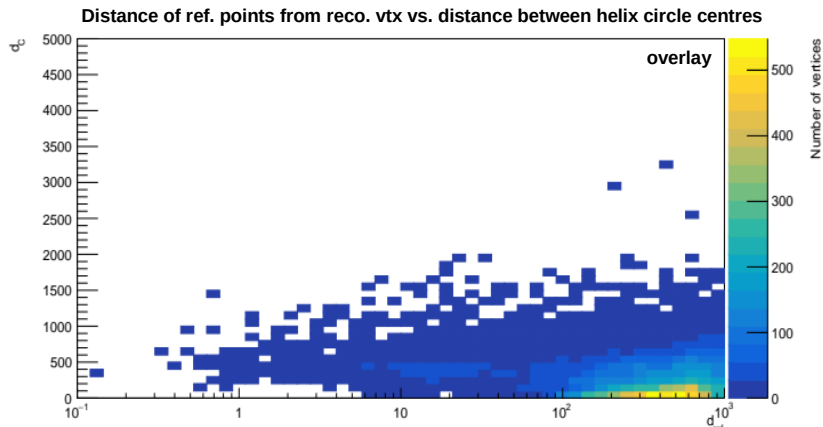
→ either **far reference points** or **close centres of helices**



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

Final selection – second variable

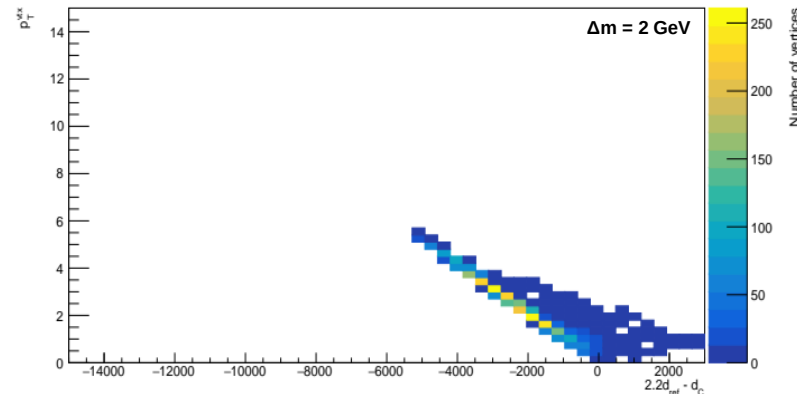
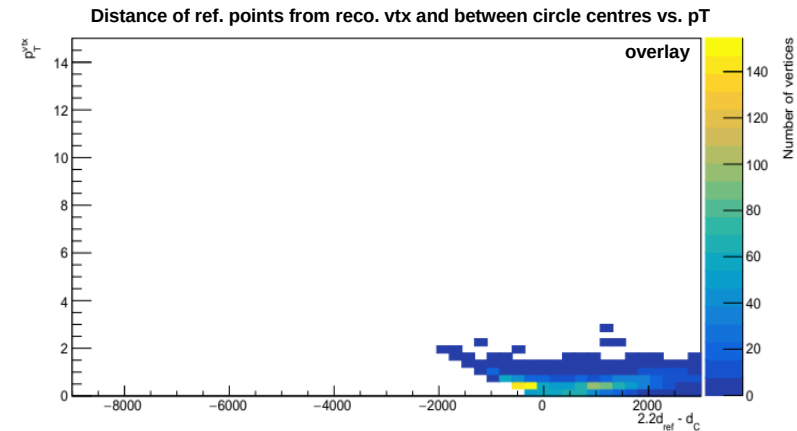
- New variable(s) should be uncorrelated with p_T to make the cuts independent
- $2.2d_{ref} - d_C$ good for optimal signal-background separation → use it to look for correlation



Warp and check correlation with p_T

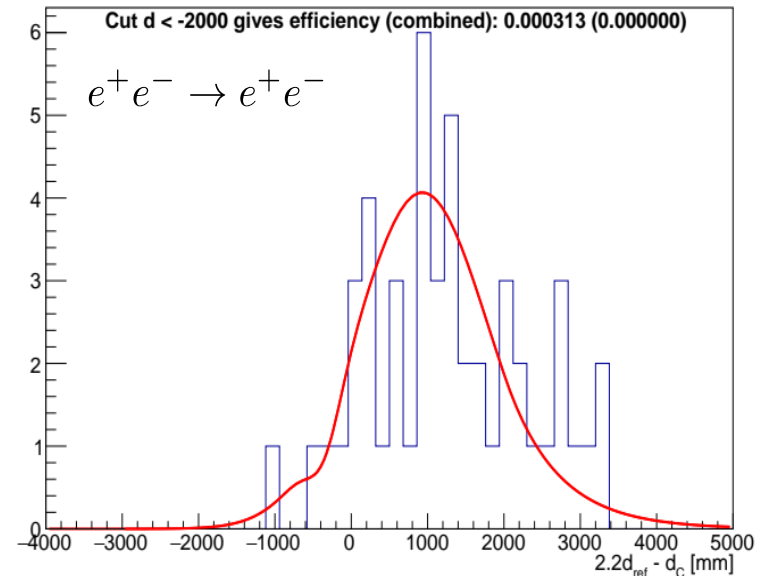
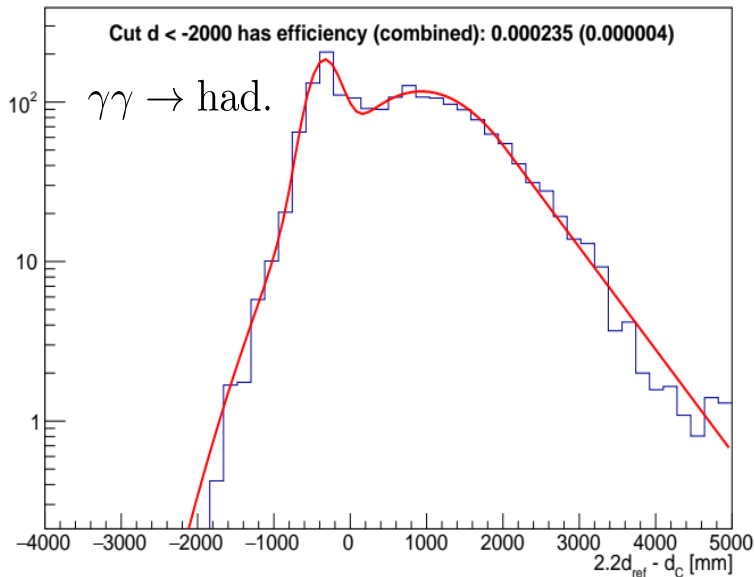


- Small correlation for the background
- Signal strongly correlated



Final selection – second variable

- Same approach as for the p_T
- For $2.2d_{\text{ref}} - d_C < -2000$ mm, **signal eff. $\sim 37\%$** ($\Delta m = 2$ GeV)
- Estimated background eff. from fitted distributions $\sim 10^{-4}$ ($\sim 10^{-6}$ – 10^{-7} with preselection)
- Total expected efficiency at the level of **$\sim 10^{-9}$** ($\sim 10^{-10}$) for **$\gamma\gamma \rightarrow \text{had.}$** (e^+e^- pairs)



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

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

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

For cuts on \mathbf{p}_T and $2.2\mathbf{d}_{\text{ref}} - \mathbf{d}_C$ (slide 5), assuming **30% correlation**, for $\gamma\gamma \rightarrow \text{had. (e}^+e^- \text{ pairs)}$ 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

Combined cut efficiency $x > 2 \cap y > 3$

