FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

NATIONAL SCIENCE CENTRE POLAND

Long-Lived Particle Searches at a Future Higgs Factory with the ILD experiment

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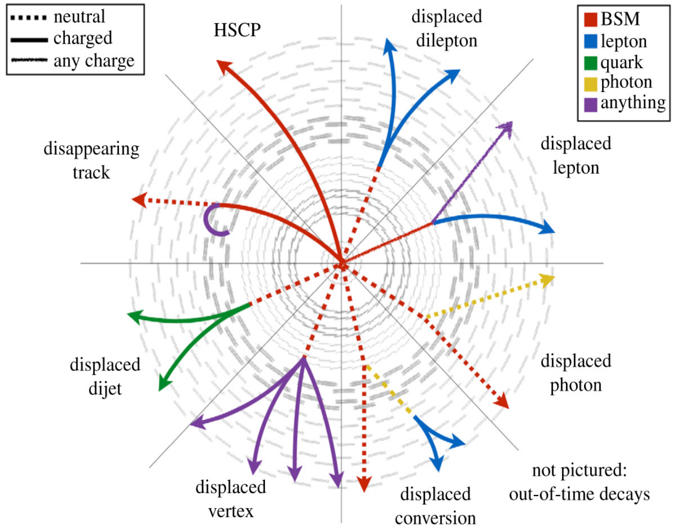
J. Klamka, A.F. Żarnecki
University of Warsaw
jan.klamka@fuw.edu.pl

Long-lived particles (LLPs)

Particles with macroscopic lifetimes naturally appear in numerous BSM models

Three main mechanisms are responsible for that...

	1810.12602	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			✓



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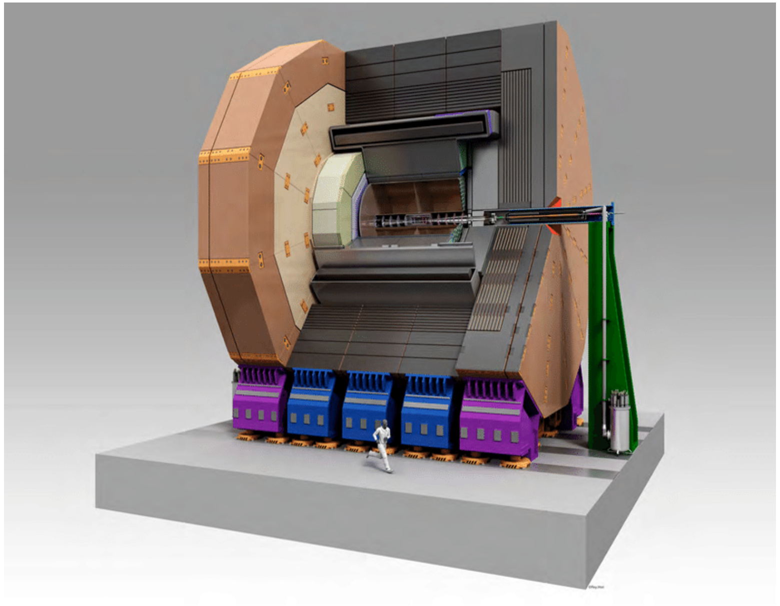
Multiple LLP searches at the LHC, sensitive to high masses and couplings

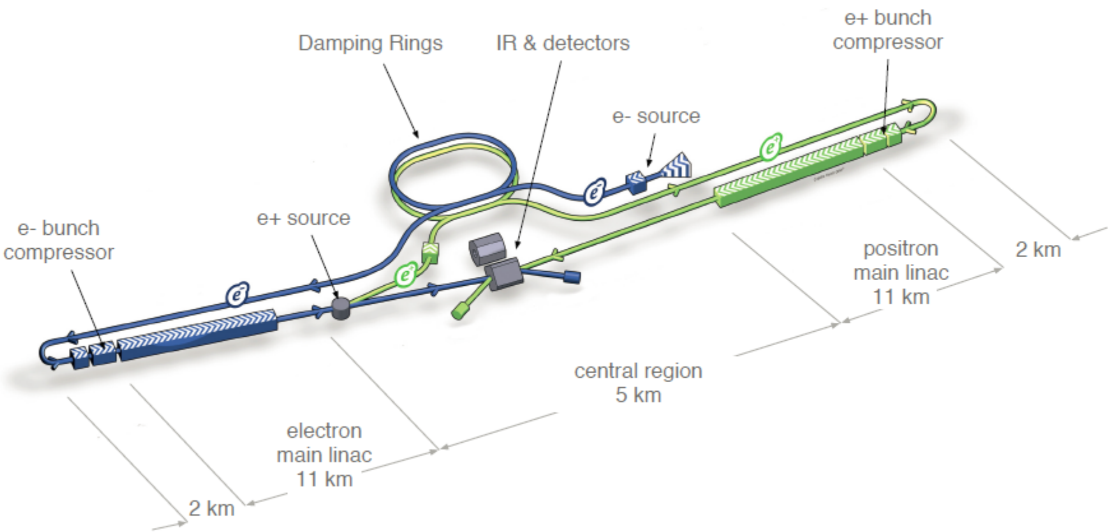
- these properties can make it challenging for hadron colliders
- **complementary regions** could be probed at **e^+e^- colliders** (**small masses, couplings, mass splittings**)

International Large Detector (ILD)

- 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

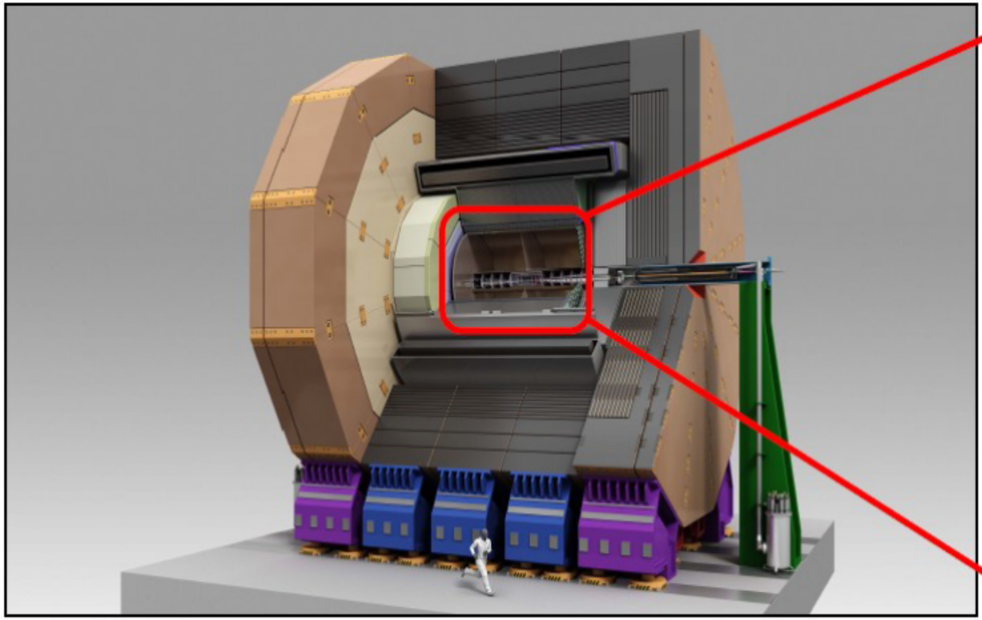
this study

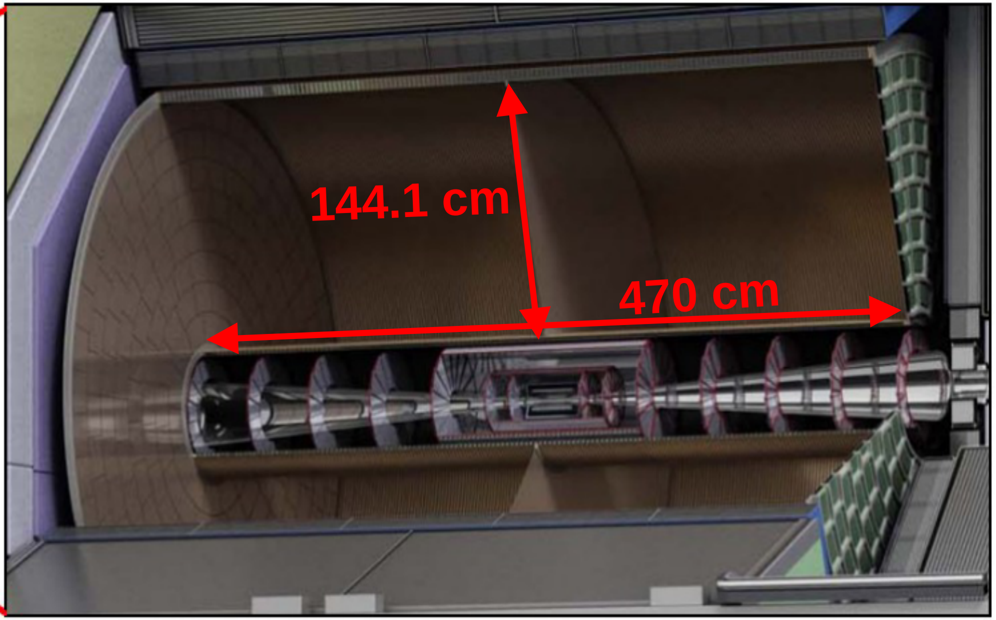




International Large Detector (ILD)

- 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





Model-independent search for neutral LLPs

Strategy

ILD especially promising with a TPC as the main tracker

→ we want to investigate experimental aspects

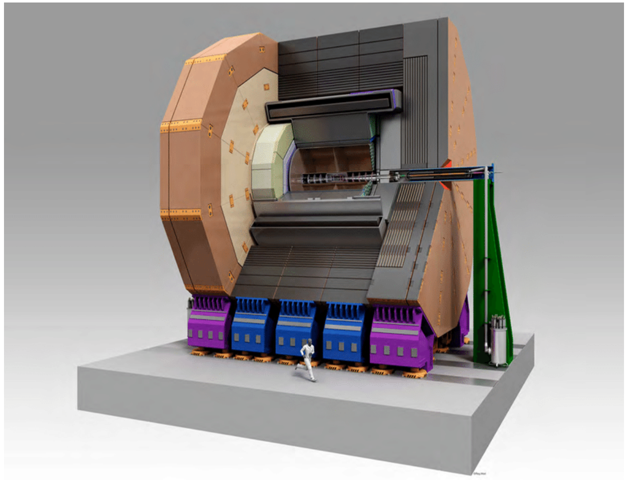
→ study based on full simulation

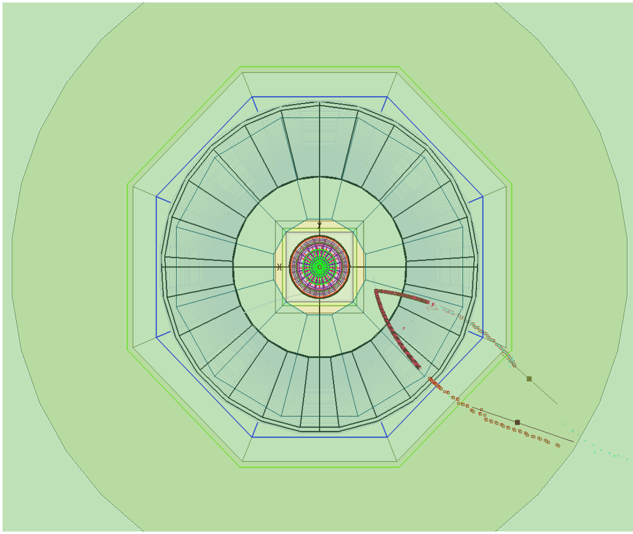
- Study such challenging signatures from the **experimental perspective**

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

- Focus on a generic (and most challenging) case – two tracks from a displaced vertex (DV)

- No other assumptions about the final state, approach **as general as possible**

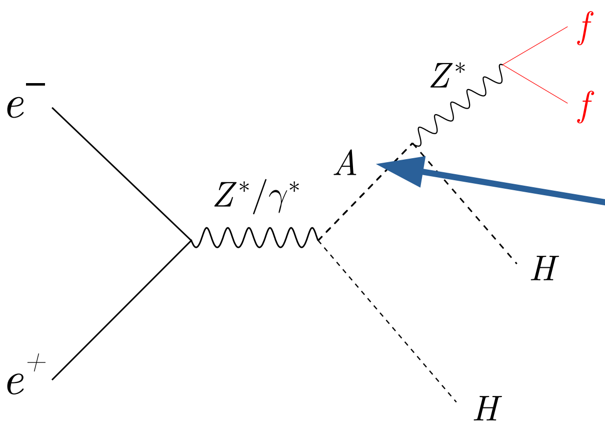




Framework and signatures

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, $\mathrm{Z}^* \rightarrow \mu\mu$



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

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

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

Framework and signatures

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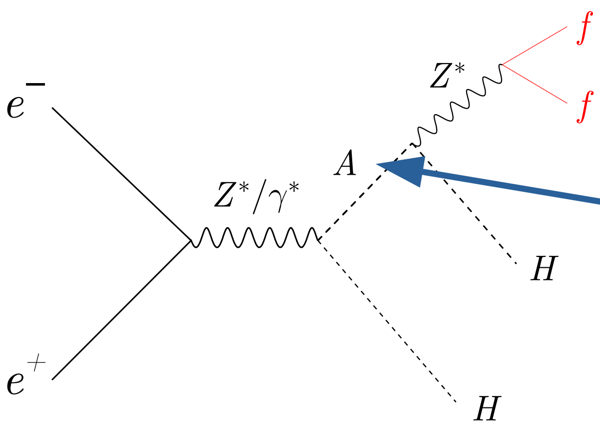


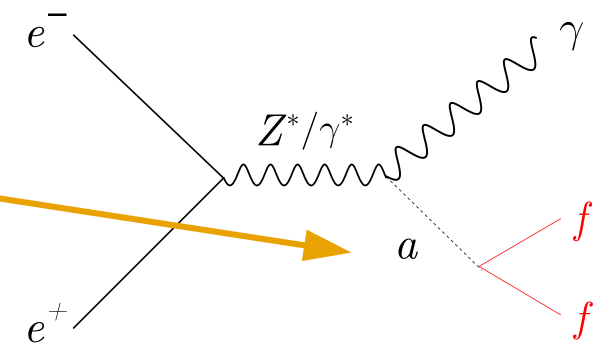
Long-lived, with $c\tau = 1\,\mathrm{m}$

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

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

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)

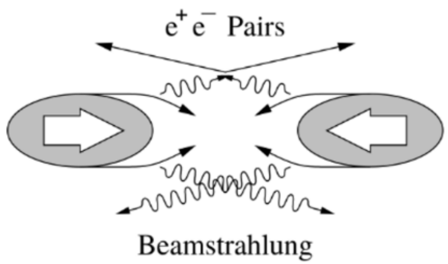
→ light pseudoscalar LLP $a \to \mu\mu$

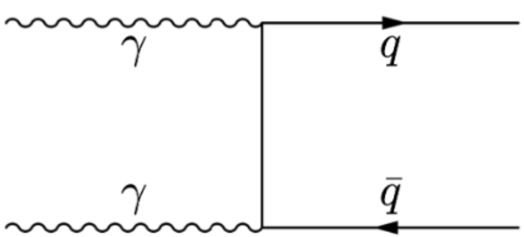
Very simple vertex finding (inside the TPC) based on a distance between track pairs

Overlay events background

At linear e^+e^- colliders beams are strongly focused and radiate photons, so γγ interactions also occur in detector

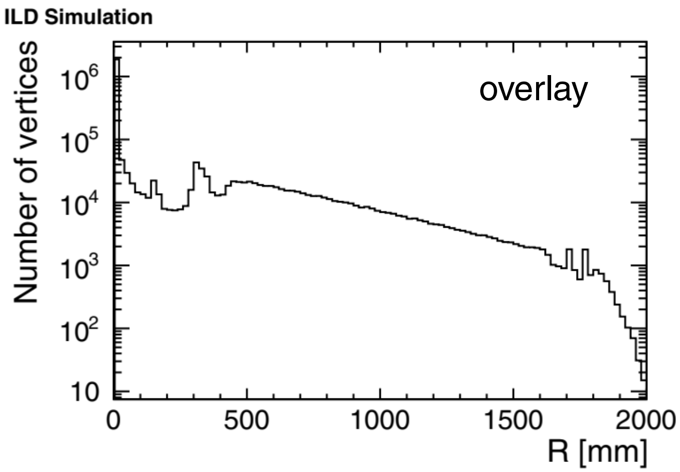
Incoherent e^+e^- pairs

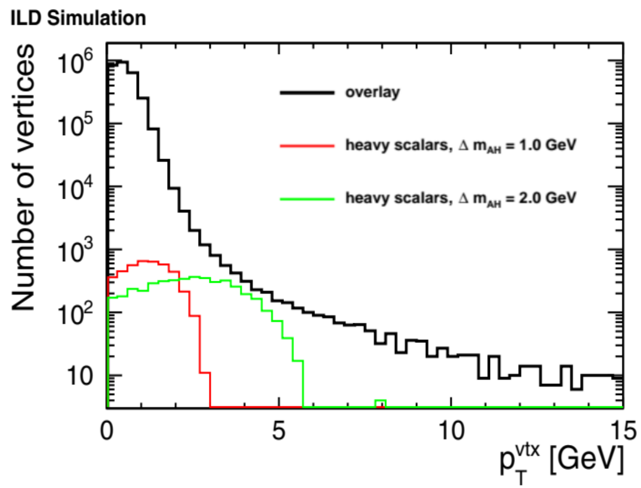




Low-p_T γγ → hadrons

These events are soft, usually important because they **overlay** on physical events... But occur in each bunch crossing (BX) and with ~10^{11} BXs/yr at ILC can also be a source of a standalone background





Background from high-p_T events

1. Vertex **quality cuts** + dedicated **overlay selection**
→ ~10^{-10} reduction factor!

2. The following survive overlay selection in the high-p_T SM processes:

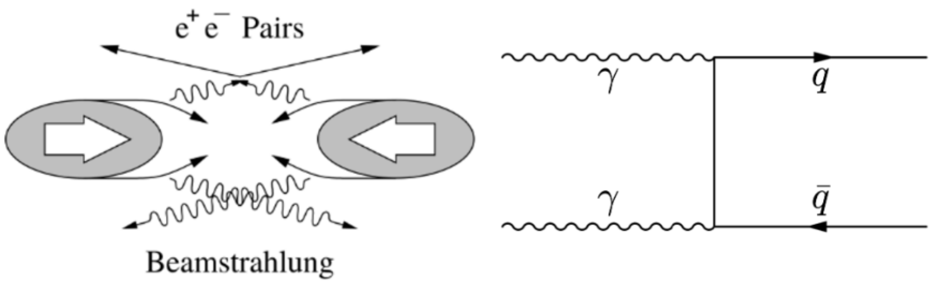
- Decays of kaons, lambdas, photon conversions
- Secondary tracks from interactions with detector material

Backg. sources occur mainly inside jets, so we consider (hard) e^+e^- and γγ 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)

Background samples considered:

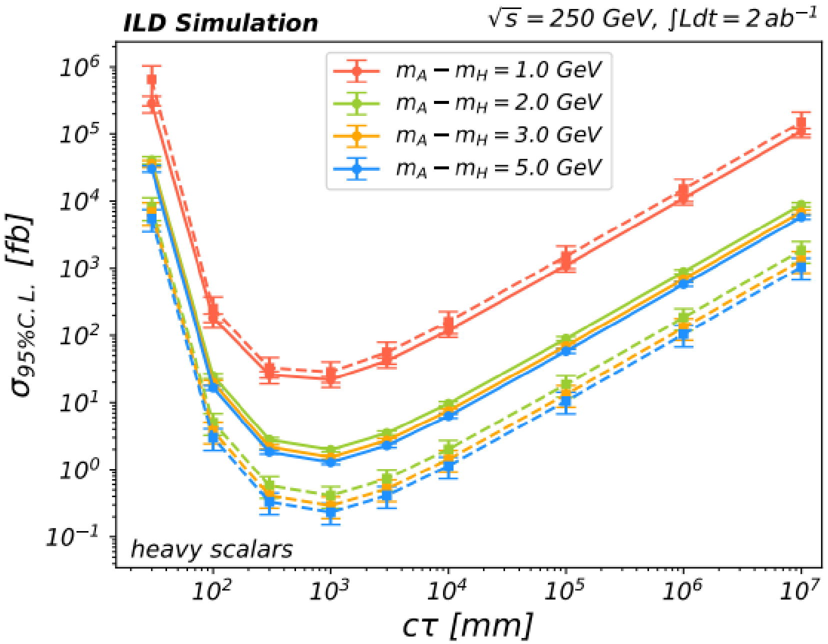
- Beam-induced backgrounds (*overlay events*)

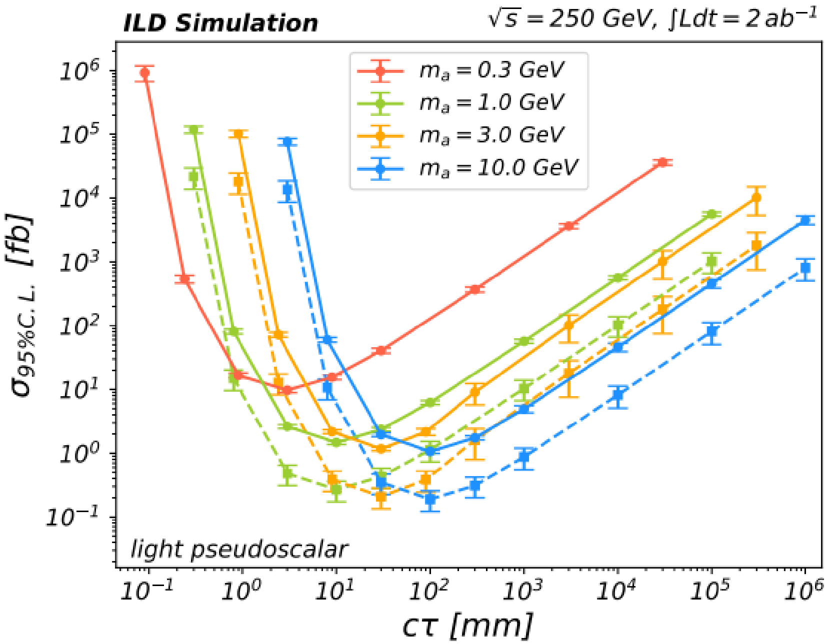


- High-p_T SM processes

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

Cross section limits





- 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

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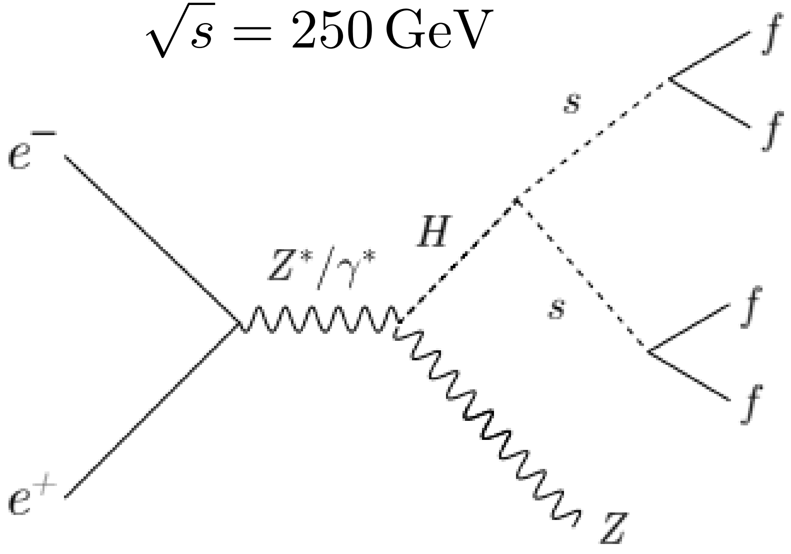
Exotic Higgs decays

Higgs decays to LLPs

Higgsstrahlung with H(125) decay to two long-lived scalars

Long-lived scalar s, using s → μμ decays to simplify the simulation and **Z → νν (invisible)**



Generated scenarios:

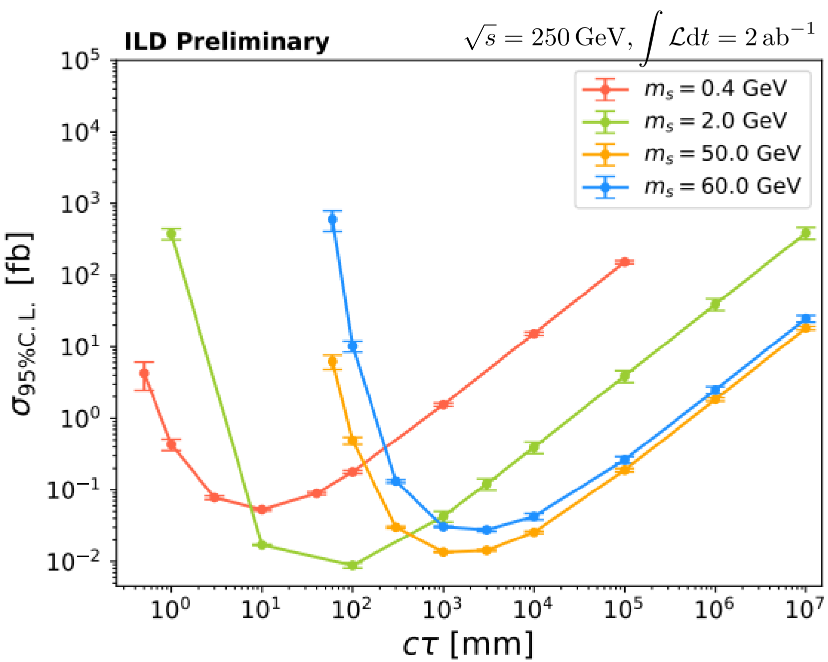
$$m_s = 400\,\mathrm{MeV},\ c\tau = 10\,\mathrm{mm}$$
$$m_s = 2\,\mathrm{GeV},\ c\tau = 10\,\mathrm{mm}$$
$$m_s = 50\,\mathrm{GeV},\ c\tau = 1\,\mathrm{m}$$
$$m_s = 60\,\mathrm{GeV},\ c\tau = 1\,\mathrm{m}$$

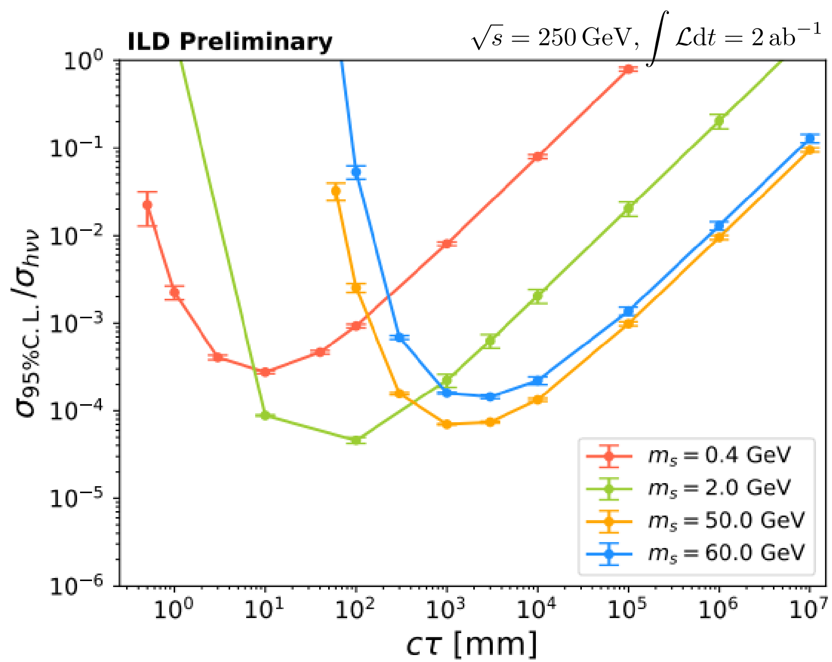
Use the **same analysis procedure**, but further **optimise for this channel** by requiring:

→ no additional prompt tracks with $p_T > 2$ GeV

→ total $p_T^{vtx} > 10$ GeV of tracks forming a vertex (to neglect the overlay)

Higgs decays to LLPs





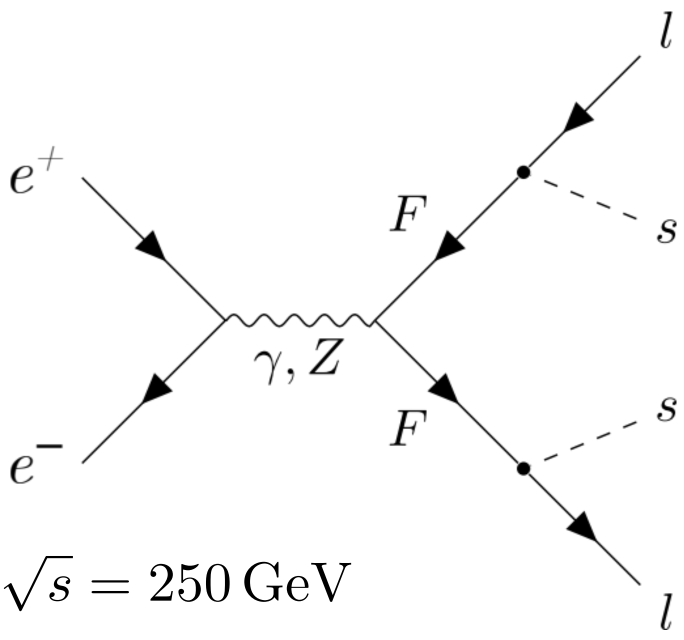
- Current limits: down to 10^{-4} (low masses), down to 10^{-3} in s → bb and 10^{-5} in s → μμ (high masses)
- ILD can improve the current constraints and probe higher lifetimes already @ ILC250 thanks to higher TPC acceptance
- The limits could be further improved by dedicated searches using vertex detector and by more data at higher energy stages

Charged LLPs

Charged LLPs

Many FIMP candidates involve also charged LLPs – can we use the experiences from DV analysis?

→ heavy fermion LLP (F) and DM (s) pair-production $\mathrm{F} \to \ell s \; (\ell = e, \mu)$



$\sqrt{s} = 250\,\mathrm{GeV}$

F long-lived, 6 scenarios:

$m_F = 110\,\mathrm{GeV}(c\tau = 3\,\mathrm{m}),\ 60\,\mathrm{GeV}(c\tau = 1\,\mathrm{m})$

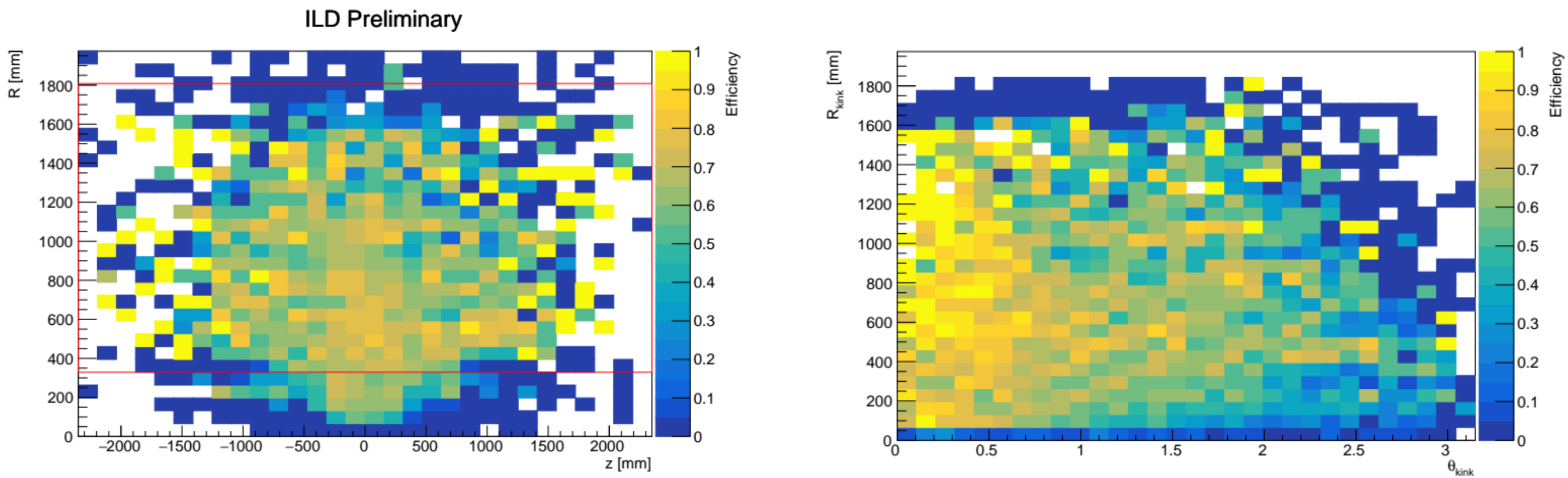
For each m_F: $m_s = 12\,\mathrm{keV},\ m_F/2,\ m_F - 1\,\mathrm{GeV}$

- A range of mass differences considered: small, intermediate, high
- 12 keV mass inspired by the model (1811.05478)

Use KinkFinder to identify kink vertices and use similar strategy as for DVs

Reconstruction and selection

$$m_F = 110\,\text{GeV}, m_s = 109\,\text{GeV scenario}$$



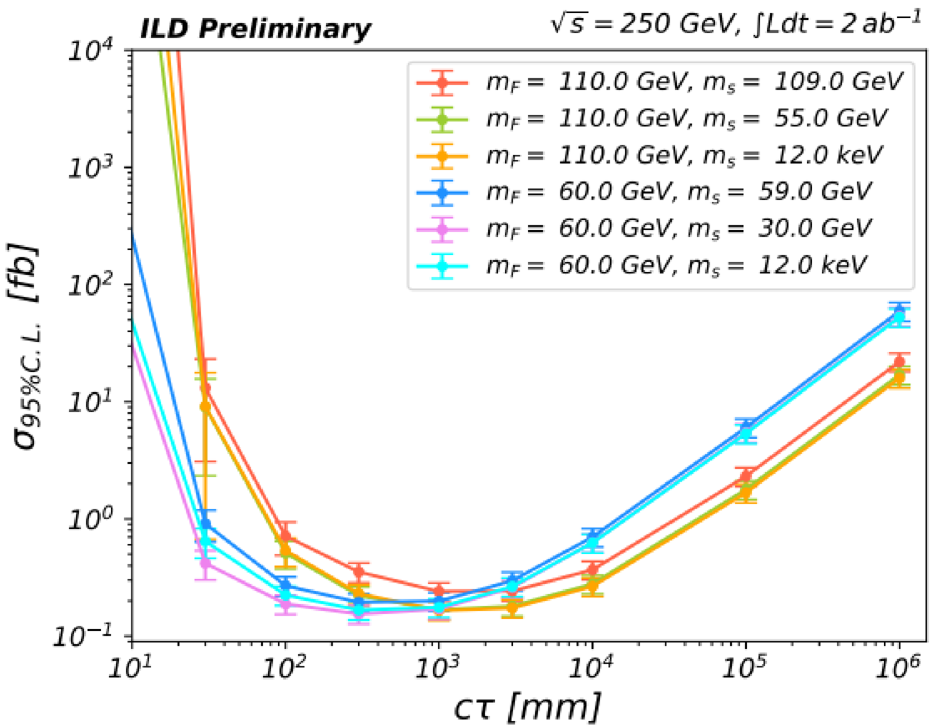
Good kink vertex finding performance, including large angles

Next, for the selection:

- Reject random intersections, split tracks, interactions with outer TPC walls
- Apply criteria on impact parameters of parent and daughter tracks, and their momenta

Background from di-lepton production included in addition to hadronic events

Cross section limits



- Weak dependence on the mass splitting
- Sensitivity at the level of 0.1-1 fb in range of cτ between 30 mm to 70 m, depending on mass

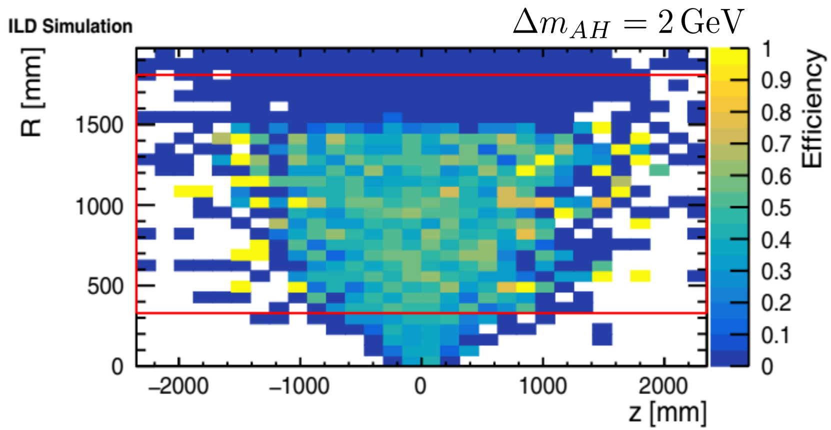
Summary

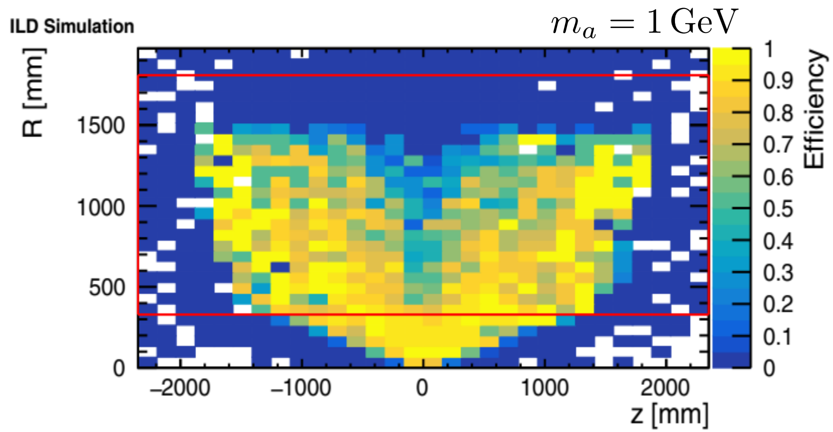
- ILD has a good potential to study long-lived particles, considering the model-independent approach and extreme signatures tested
- TPC plays the key role by enhancing the acceptance, allowing to probe very high lifetimes
- Additional selection utilizing features of a given signature can greatly improve sensitivity
- Presented expected limits on SM-like Higgs decays to LLPs would improve current constraints by order of magnitude or probe longer lifetimes
- ILD shows great prospects also for studies of charged LLPs using kinked track signature

Thank you!

BACKUP

Vertex finding results





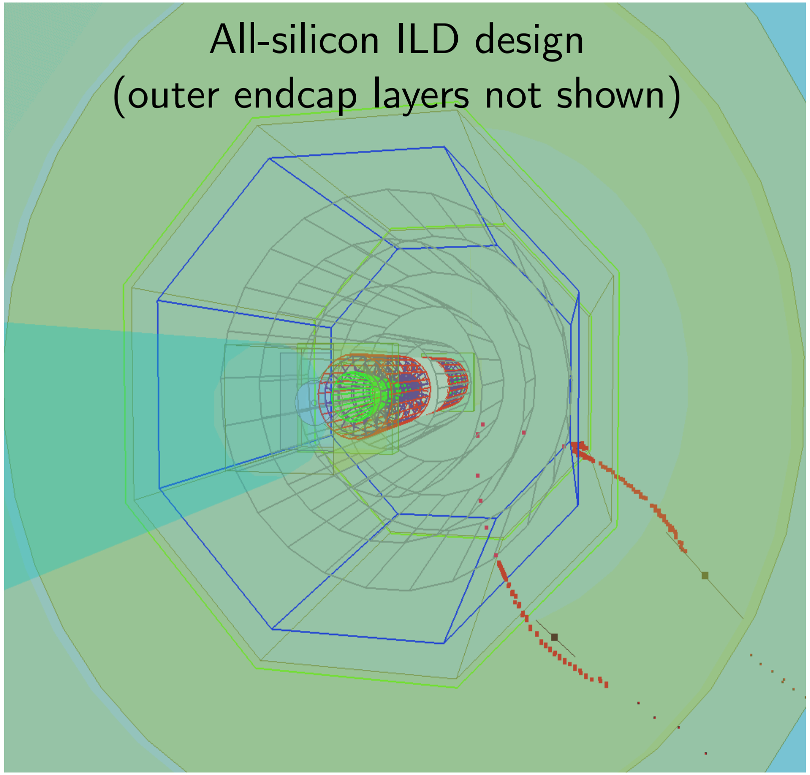
Δm_{AH} [GeV]	1	2	3	5
Efficiency (standard) [%]	3	33.2	43.4	51.1
Efficiency (tight) [%]	0.4	28.3	40.7	50.2
m_a [GeV]	0.3	1	3	10
Efficiency (standard) [%]	7.4	48.4	61.7	65.8
Efficiency (tight) [%]	–	47.3	61.7	65.8

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

Alternative all-silicon ILD design

Alternative ILD design implemented for tests

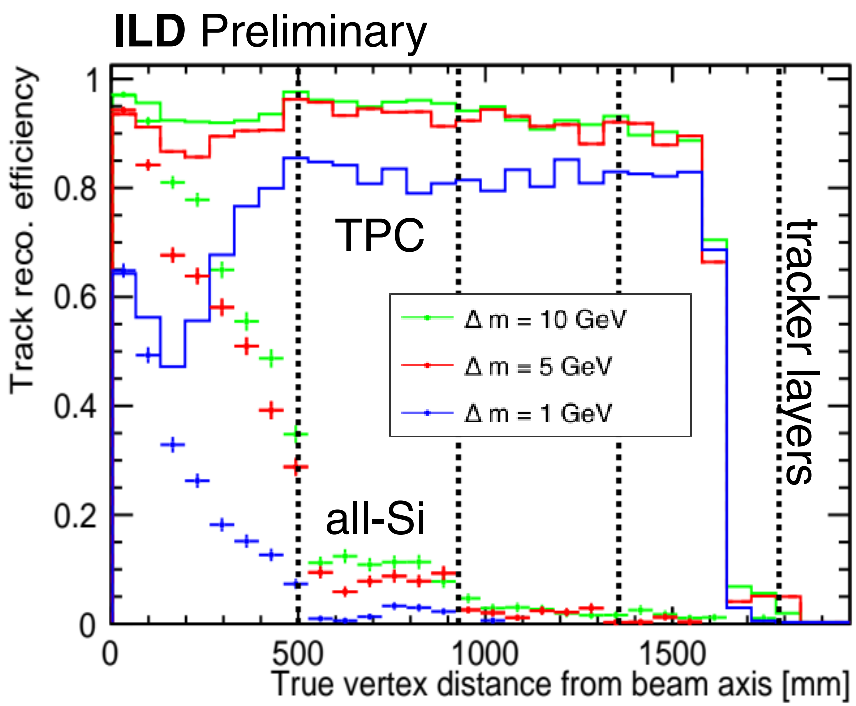
- **TPC replaced** by the **silicon Outer Tracker**, modified from the CLICdet
- One **barrel layer** added and **endcap layers spacing** increased w.r.t. CLICdet
- **Conformal tracking** algorithm (designed for CLICdet) used for reconstruction at all-silicon ILD



→ 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**



Vertex finding strategy

Approach as simple and general as possible:

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

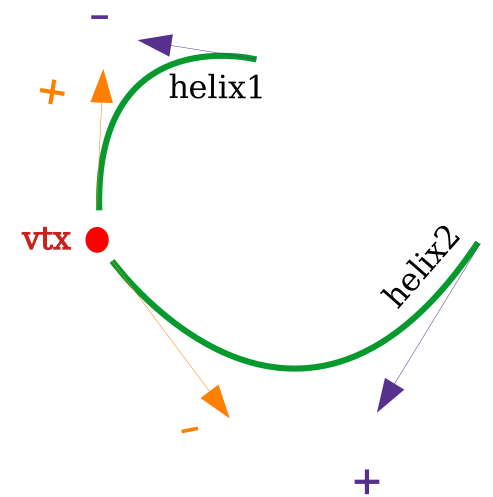
  → use **both track direction** (charge) **hypothesis** for vertex finding

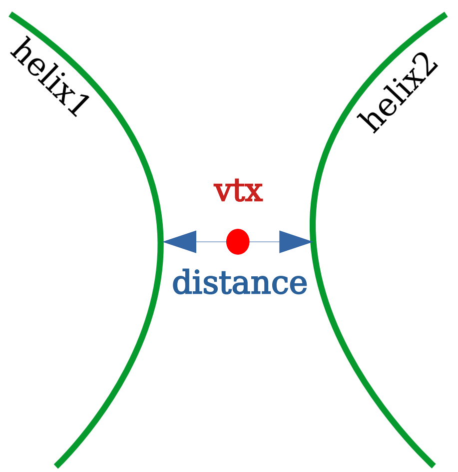
  → consider opposite-charge track pairs only

  → select pair with **closest starting points**

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

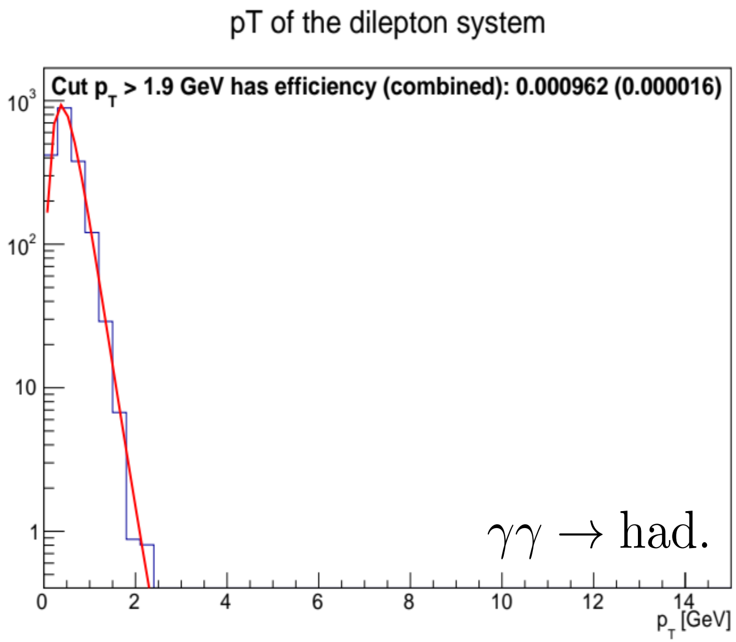
  → Require distance < 25 mm

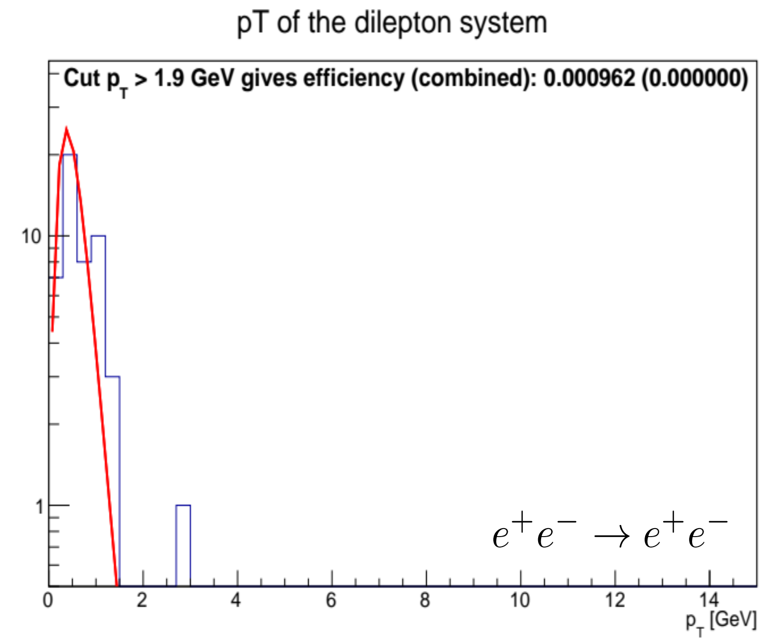




Final selection – pT

- 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



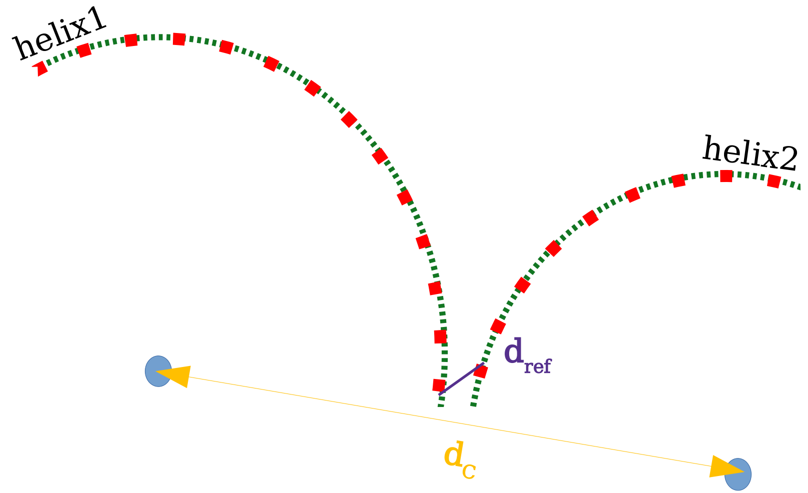


Norm = number of events, scaled by corresponding Poisson expectation values

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

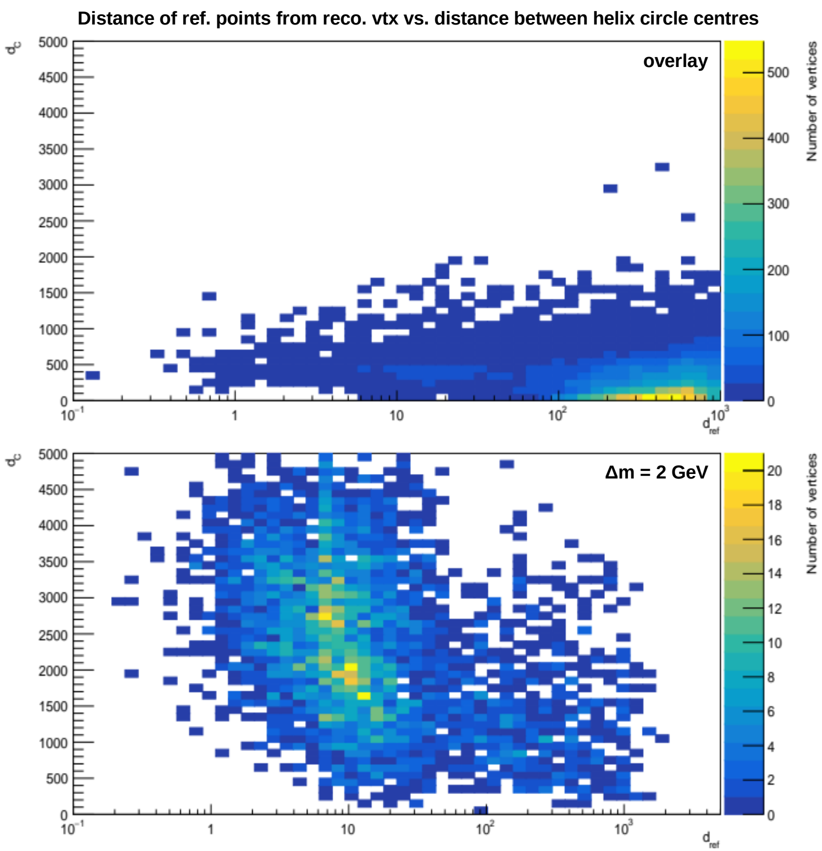
→ either **far reference points** or **close centres of helices**



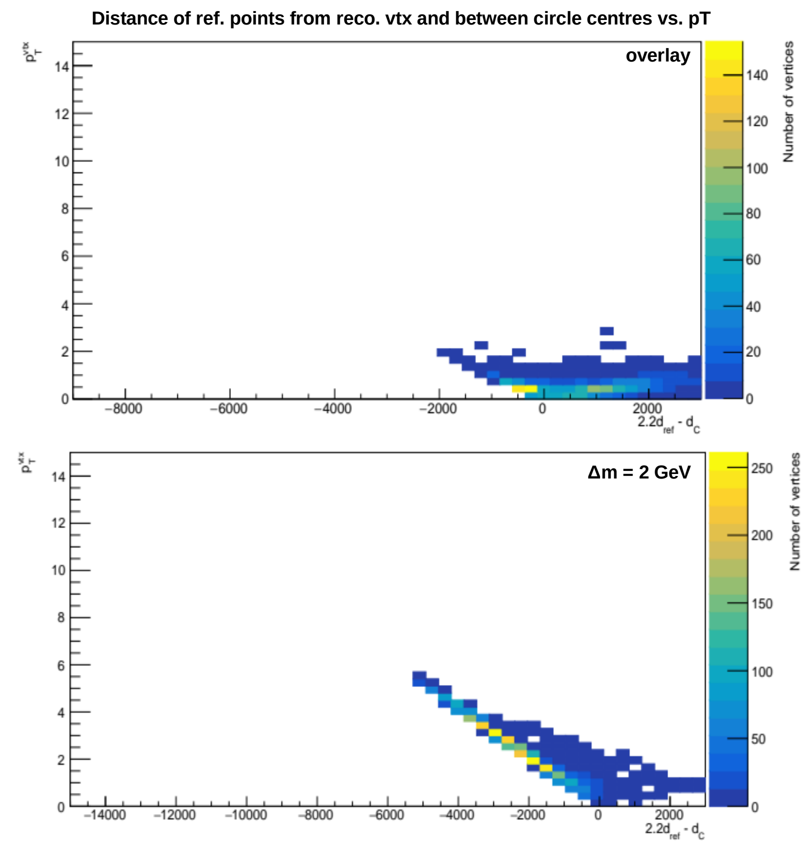
- $\mathbf{d_{ref}}$ – distance between reference points (TrackStates / first hits)
- $\mathbf{d_C}$ – distance between centres of helices projections into XY plane

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



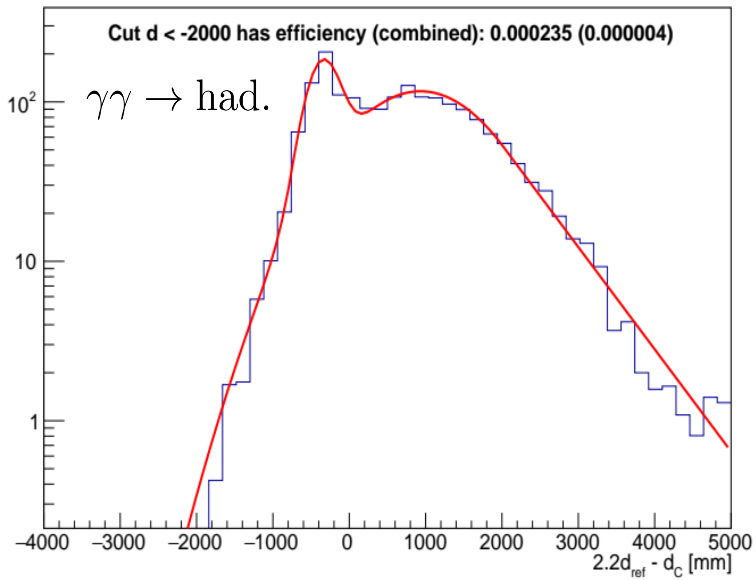
Warp and check correlation with p_T

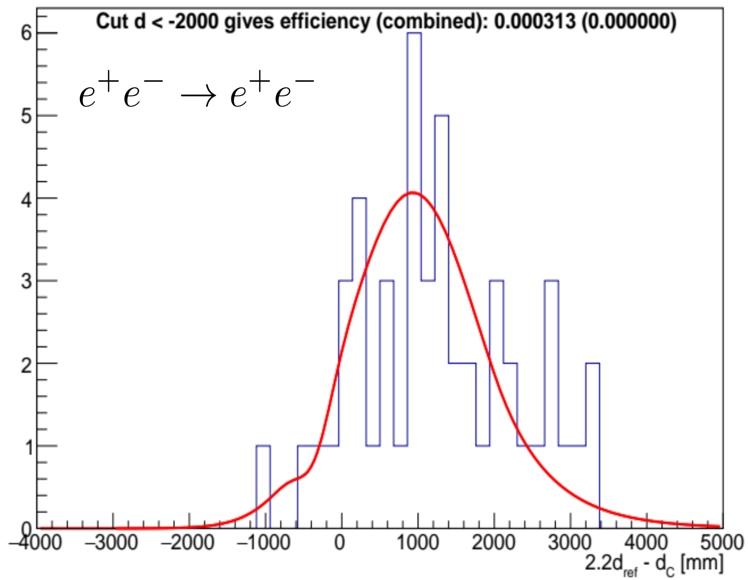


- Small correlation for the background
- Signal strongly correlated

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 **$\gamma\gamma \rightarrow$ had.** (**e^+e^- pairs**)



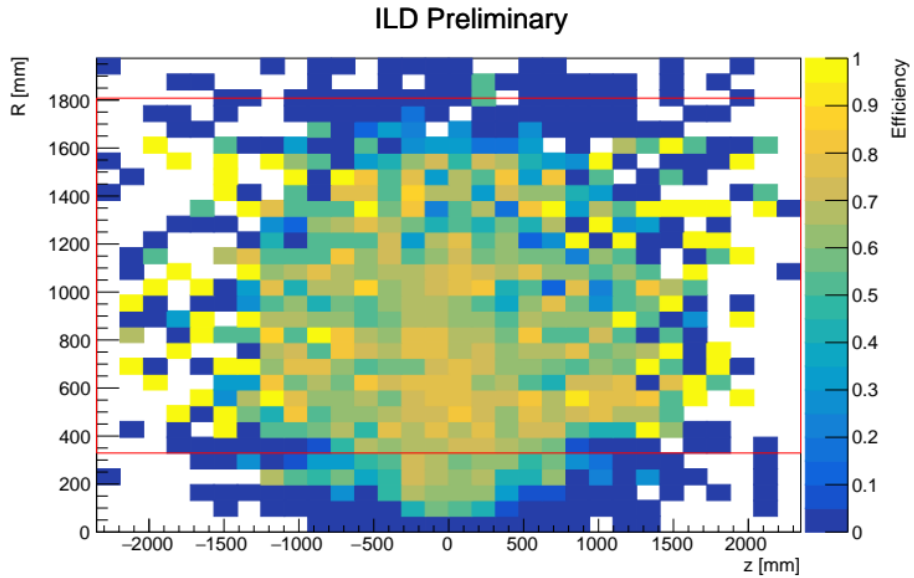


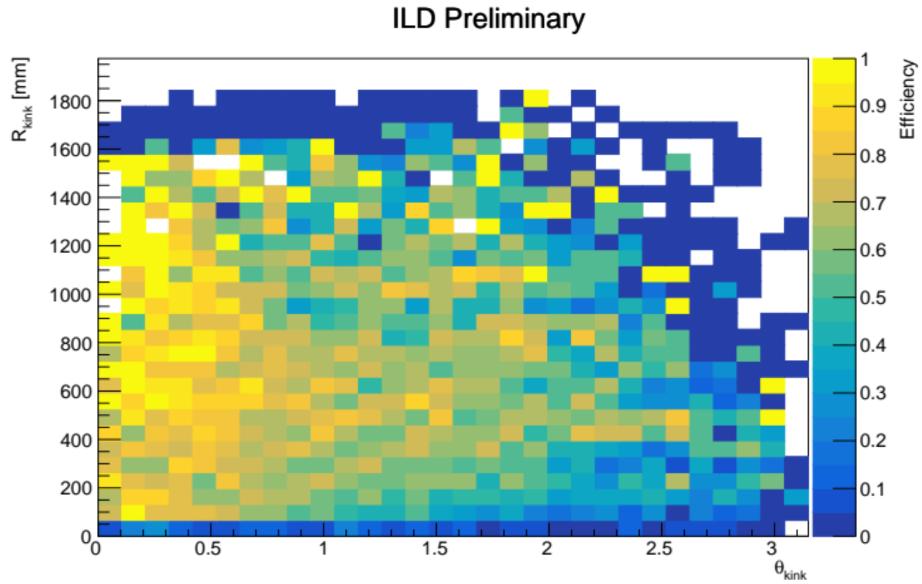
Norm = number of events, scaled by corresponding Poisson expectation values

Reconstruction of kink vertices

$R_{kink} > 60$ mm (VTX last layer), $\Delta r_{TPC} > 30$ mm between tracks for kinks in TPC

$$m_F = 110\,\text{GeV}, m_s = 109\,\text{GeV scenario}$$



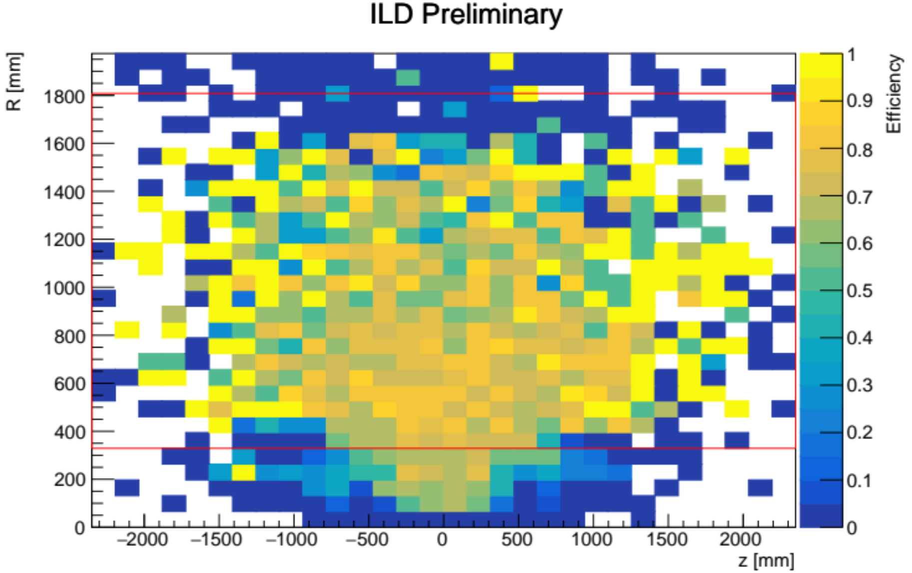


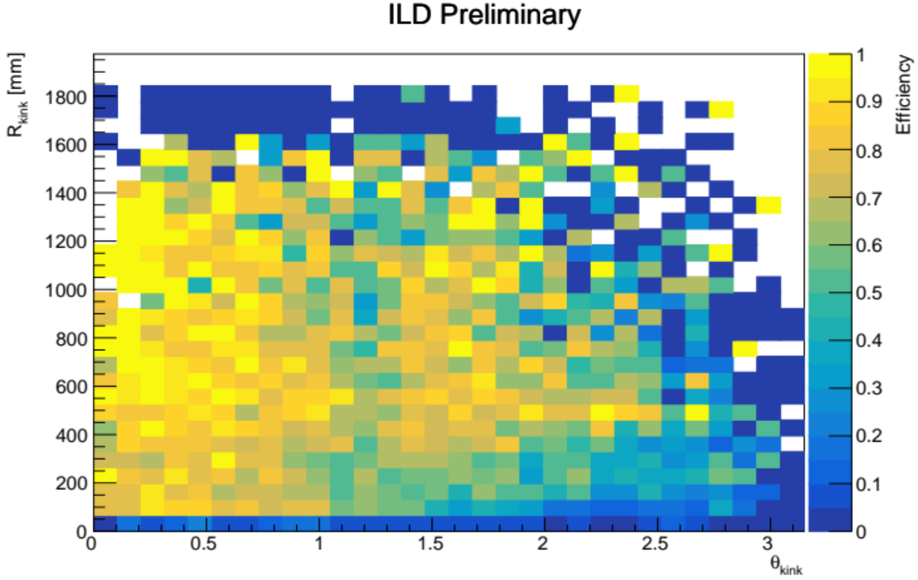
- Good kink vertex finding performance

Reconstruction of kink vertices

$R_{kink} > 60$ mm (VTX last layer), $\Delta r_{TPC} > 30$ mm between tracks for kinks in TPC

$$m_F = 110\,\text{GeV}, m_s = 12\,\text{keV scenario}$$





- Good kink vertex finding performance
- Preliminary results on sensitivity promising, but backgrounds need to be better understood

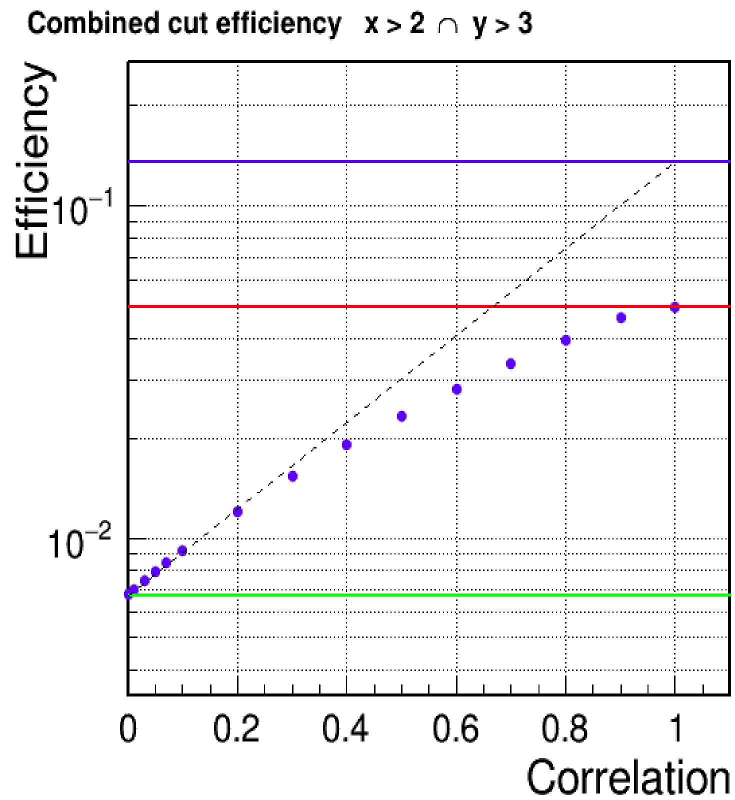
Selection assuming correlations

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

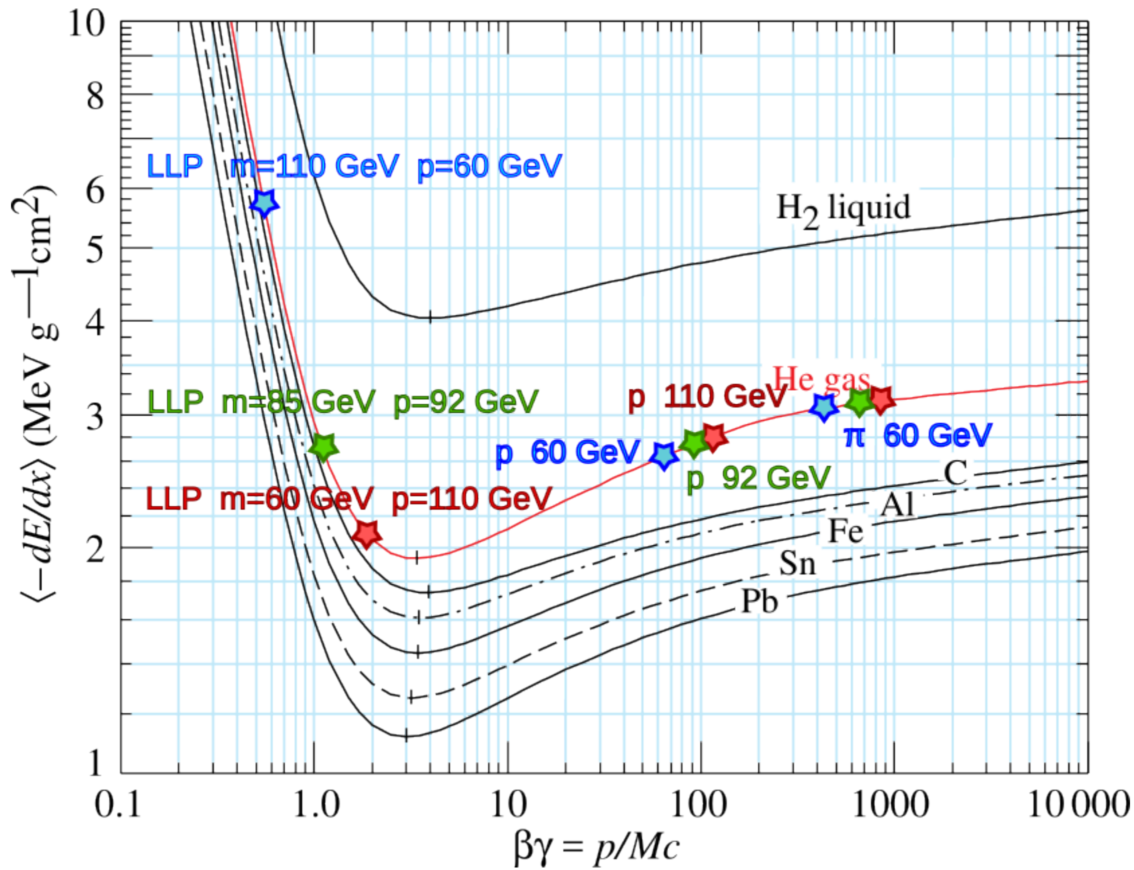
$$\epsilon_{xy} = \epsilon_y^{(1-r)} \epsilon_x, \ \epsilon_x > \epsilon_y$$

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



Bethe-Bloch for charged LLPs



Most points close to the minimum → hard to distinguish from SM LLPs