Search for Long-lived Particles at Future Lepton Colliders Using Deep Learning Techniques

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New Physics Beyond the SM - LLPs

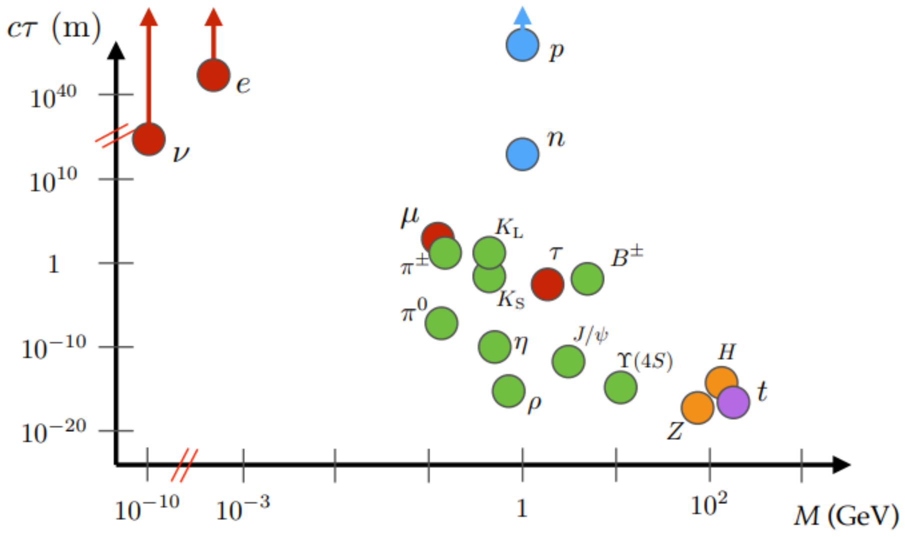
- *Particle lifetimes span a very wide range and long lifetimes can generically appear in the BSM theories.*
- Dedicated searches for long-lived BSM particles are necessary.
- For a comprehensive overview of LLP, please refer to Liang's Talk.

General LLP Topology

- *Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

Signal signature of a long-lived particle:

- Neutral LLP decays are a spectacular signature, and the burst of energy appearing out of nowhere sets it apart from the collision point.



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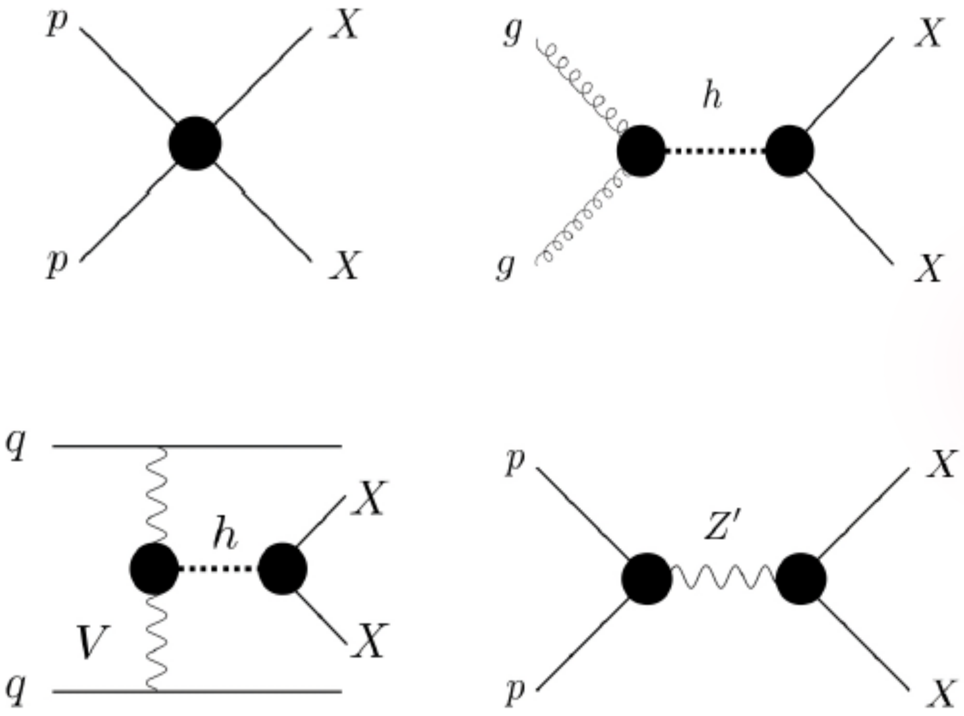
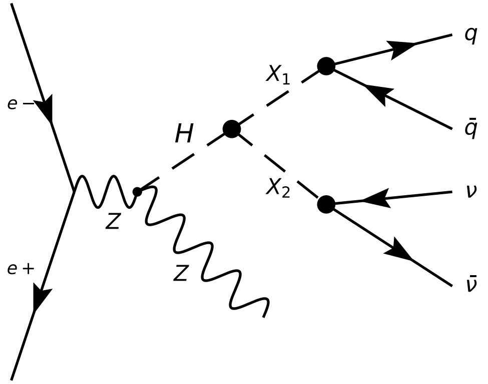
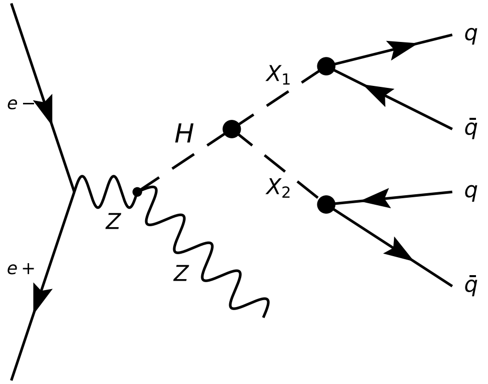
Higgs Portal to BSM





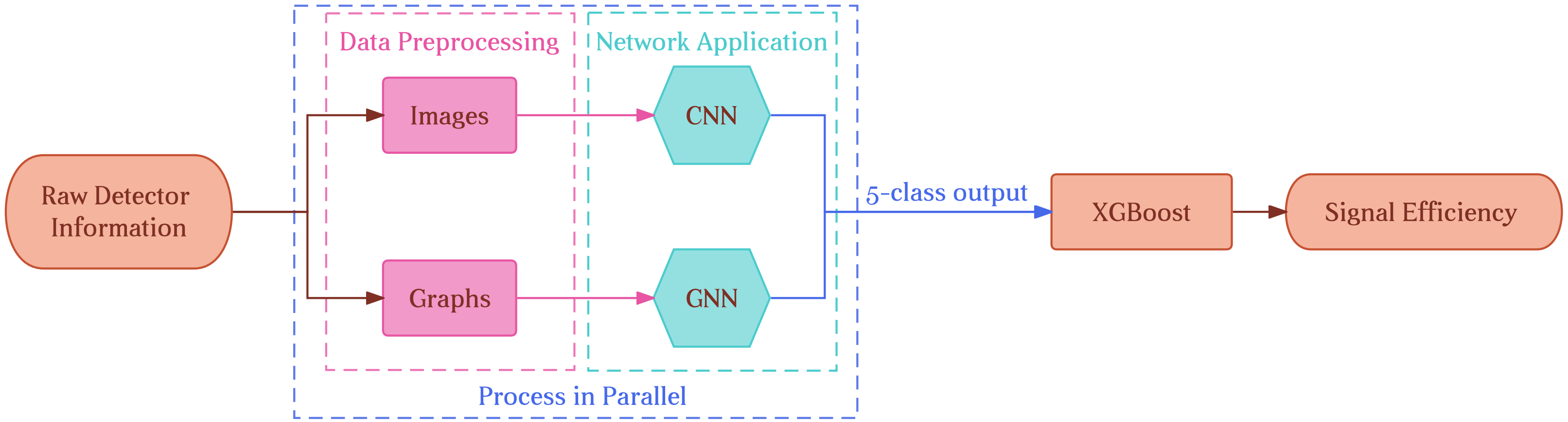
2-jet



4-jet

Analysis Strategy

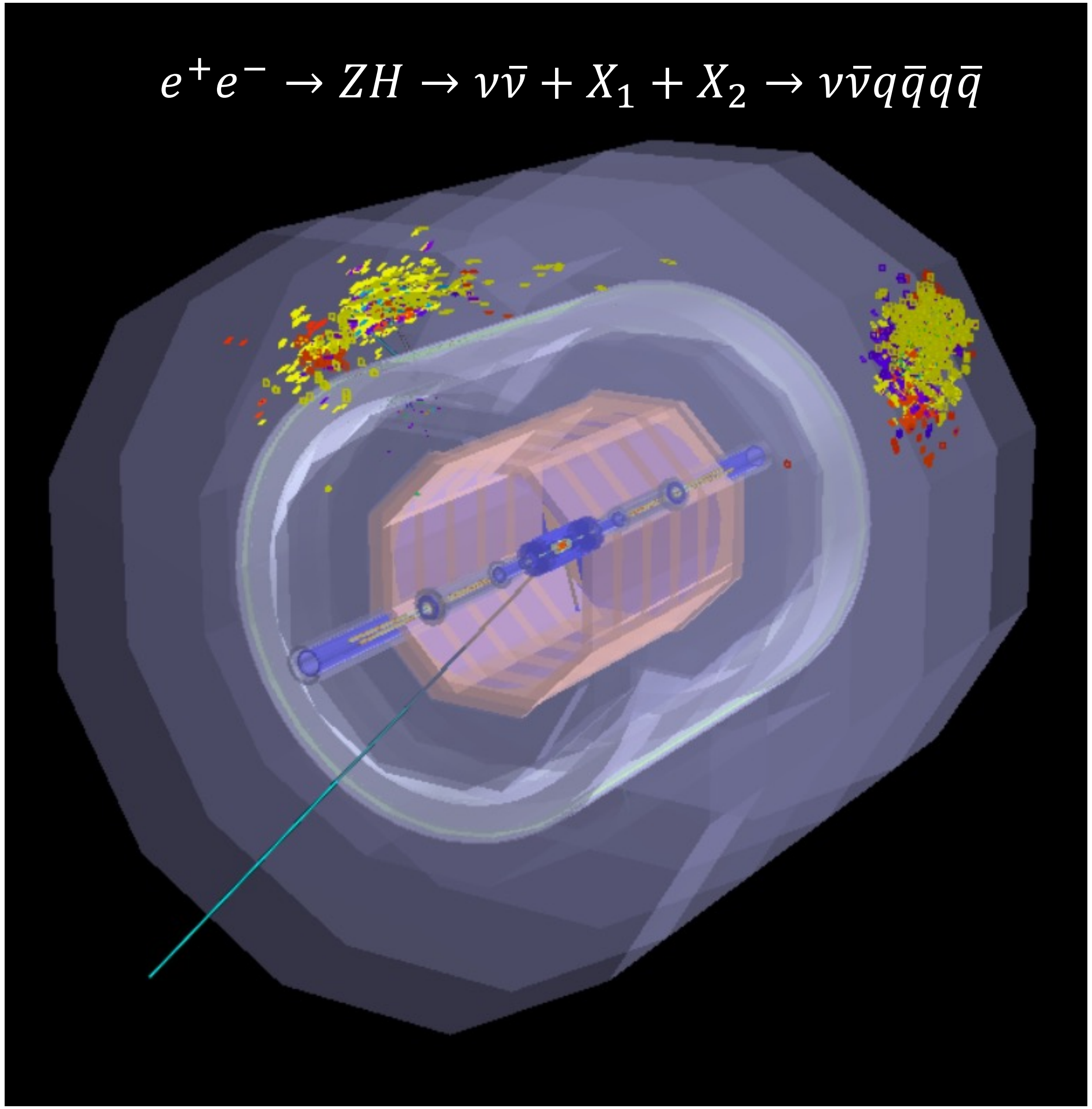
- Traditional selection-based analysis relies on the specific reconstruction and selection algorithm for the limited possible LLP phase space (mass and lifetime).
- **A novel machine learning-based analysis** is introduced, directly **utilizing raw detector response** to classify events with LLPs and SM events.
- LLPs are classified into **3 categories** based on the number of detectable LLPs (0/1/2 - DLLPs)
- Possible backgrounds: **2-fermion** and **4-fermion** (SM processes with jets and large cross-section)



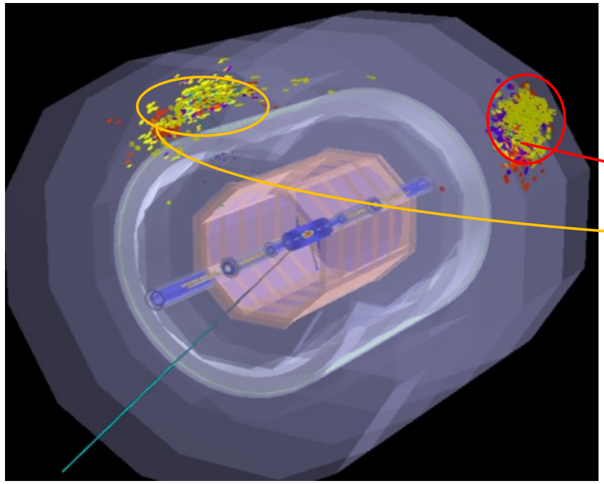
LLPs Search @ CEPC

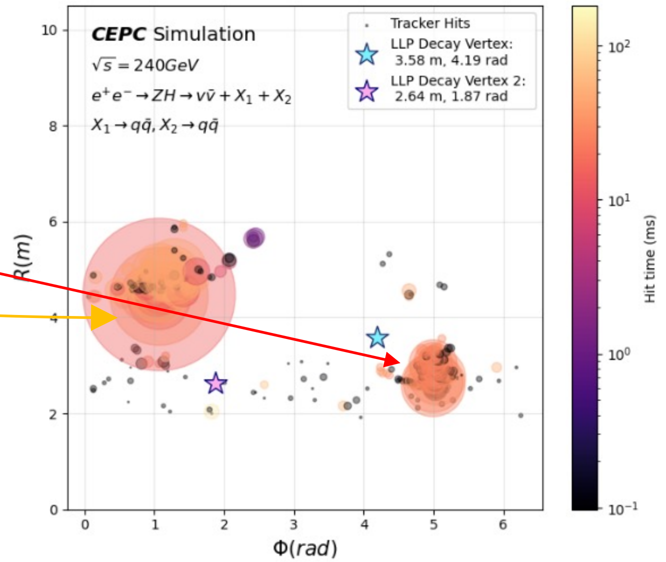
- **Full simulation** with CEPC official software (V4)
- The decay vertex of LLPs: $\mathbf{0 \le r_{decay} \le 6\ [m]}$
- Signal sample generated by MadGraph5 and showered by Pythia8

Process	# of Events simulated
Signal: $Z \to \bar{q}q, H \to X_1 + X_2$ (2-jet)	$\sim 1.0\times10^6$
Signal: $Z \to \bar{\nu}\nu, H \to X_1 + X_2$ (2-jet)	$\sim 1.0\times10^6$
Signal: $Z \to \bar{q}q, H \to X_1 + X_2$ (4-jet)	$\sim 1.0\times10^6$
Signal: $Z \to \bar{\nu}\nu, H \to X_1 + X_2$ (4-jet)	$\sim 1.0\times10^6$
$e^+e^- \to q\bar{q}$	$\sim 0.99\times10^7$
$e^+e^- \to ZH$ (Standard Model)	$\sim 1.37\times10^6$
$e^+e^- \to W/Z$	$\sim 1.3\times10^7$



Convert Events to Images





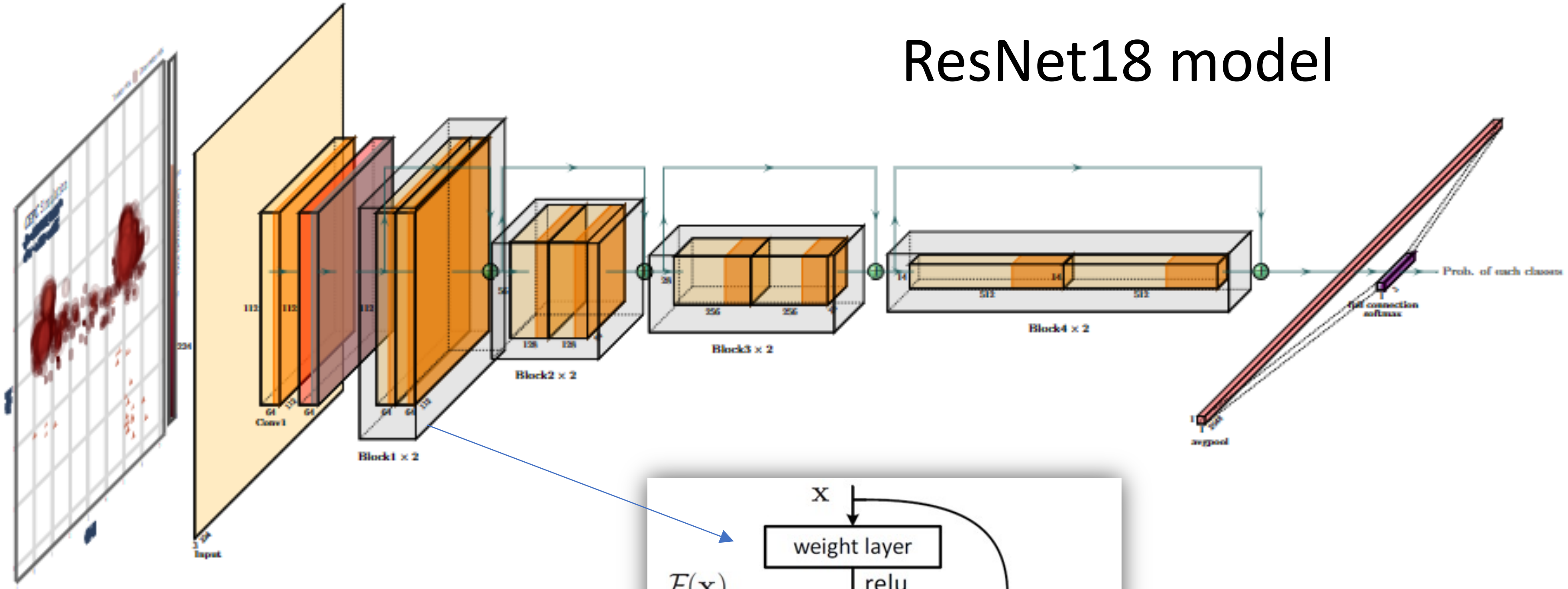
Images received by neural network.

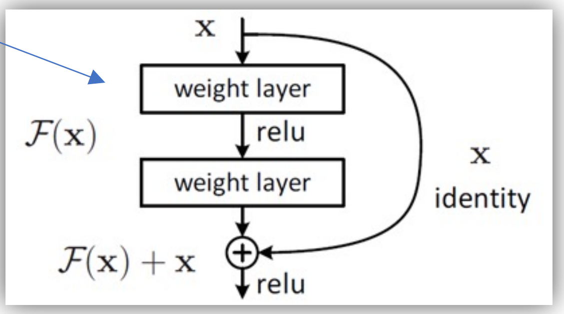
- **Time difference**: $\Delta t = t_{hit} - \frac{R}{c}$ is represented by the color of circle: light color represents large Δt.
- **Energy deposition** is illustrated as the size of circle: bigger circle represents more energy.

Raw detector information → a 2D image in a size of $(\mathrm{R}, \phi) = 200 \times 200$ and 2 channels.

CNN Architecture

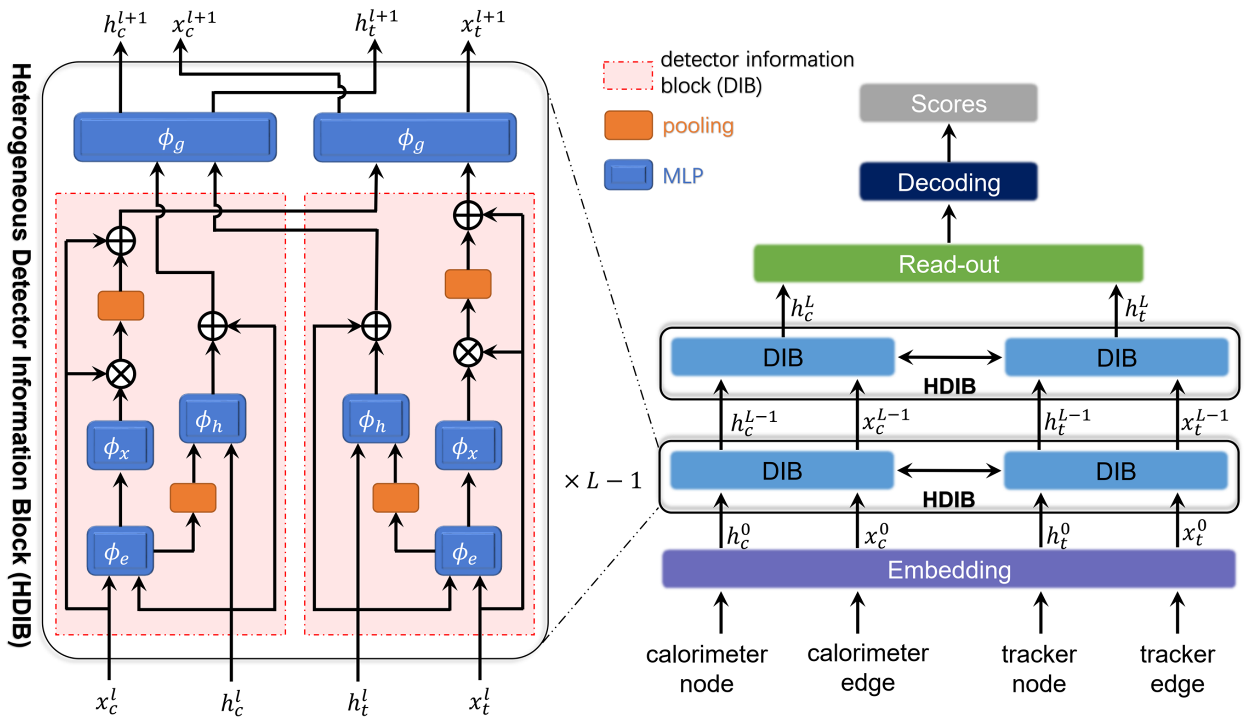
ResNet18 model





Heterogeneous Graphs

Features	Variable	Definition
calorimeter type node i	$\lvert x_i^\mu \rvert$	the space-time interval
	$\lvert p_i^\mu \rvert$	the invariant mass
	N_i	the number of hits
	η_i	$\frac{1}{2}\ln\frac{1+\frac{p_z}{p}}{1-\frac{p_z}{p}}$
	ϕ_i	$\arctan\frac{p_y}{p_x}$
	R_i	$\sqrt{\eta^2+\phi^2}$
calorimeter type edge between node i and j	$x_i^\mu x_{j\mu}$, $p_i^\mu p_{j\mu}$, $x_i^\mu p_{j\mu}$, $p_i^\mu x_{j\mu}$ $\lvert x_i^\mu - x_j^\mu\rvert$, $\lvert p_i^\mu - p_j^\mu\rvert$, $\eta_i-\eta_j$, $\phi_i-\phi_j$, R_i-R_j	
tracker type node i	$\lvert r \rvert$	euclidean distance
	N_i	the number of hits
	η_i	$\frac{1}{2}\ln\frac{1+\frac{z}{r}}{1-\frac{z}{r}}$
	ϕ_i	$\arctan\frac{y}{x}$
	R_i	$\sqrt{\eta^2+\phi^2}$
tracker type edge between node i and j	$\lvert r_i - r_j\rvert$, $r_i r_j$, $\eta_i-\eta_j$, $\phi_i-\phi_j$, R_i-R_j	



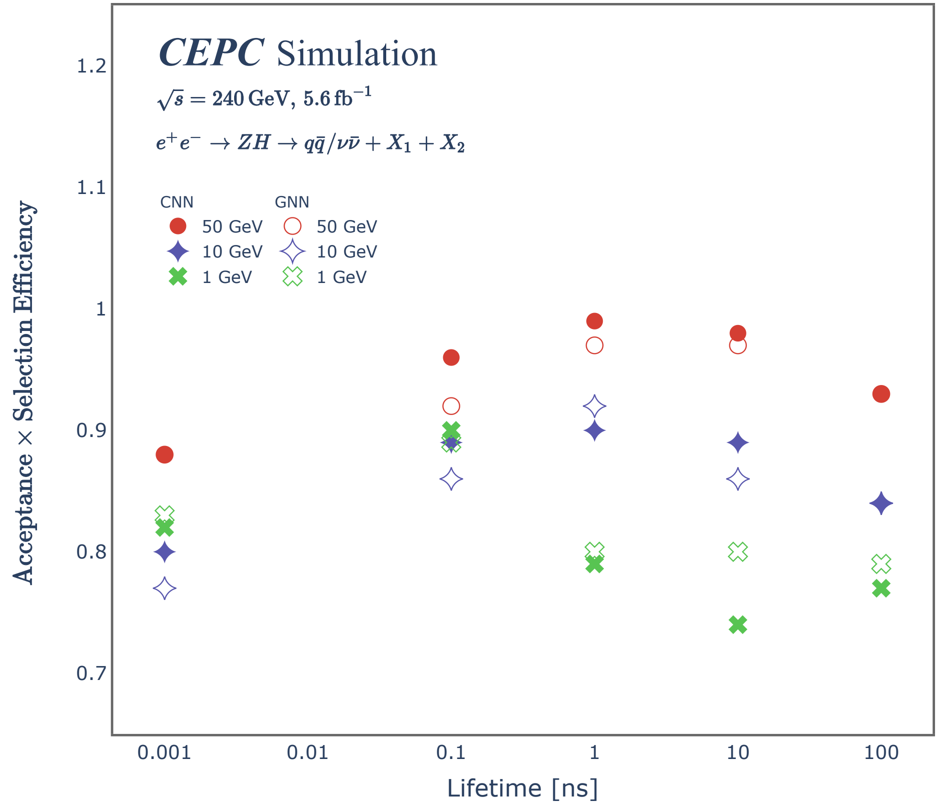
- Features of nodes: calorimeter-type and tracker-type.
- Features of edges: interaction between neighbor nodes.

ML-based Analysis Results

- Both CNN and GNN achieve **high signal efficiencies**.
- The performance is consistent across different LLP mass and lifetime considerations.
- Best efficiency (50 GeV, 1 ns): **0.99**
- With full range of CEPC detector, LLPs with different masses and lifetimes manifest high Acceptance × Efficiency

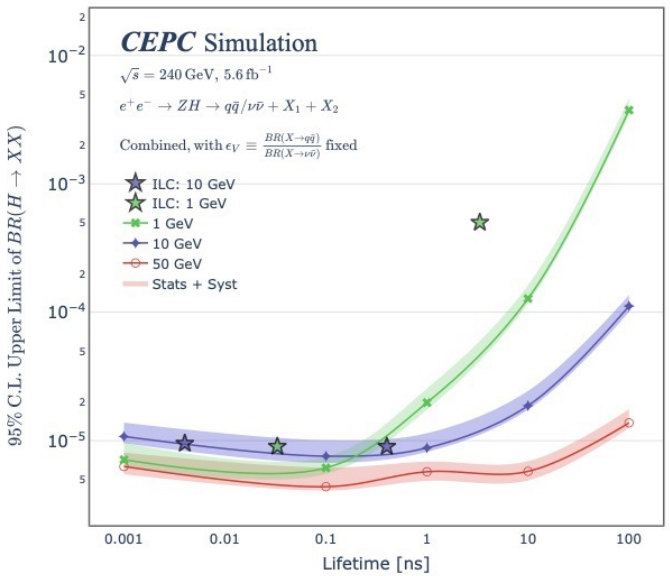
Approach	Efficiency	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
CNN	1	0.82	0.90	0.79	0.74	0.77
	10	0.80	0.89	0.90	0.89	0.84
	50	0.88	0.96	0.99	0.98	0.93
GNN	1	0.83	0.89	0.80	0.80	0.79
	10	0.77	0.86	0.92	0.86	0.84
	50	0.88	0.92	0.97	0.97	0.93

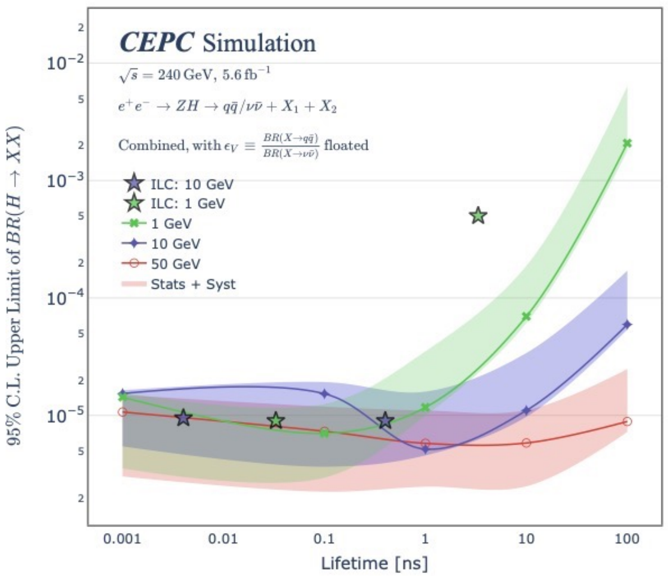
Signal efficiency with background-free condition



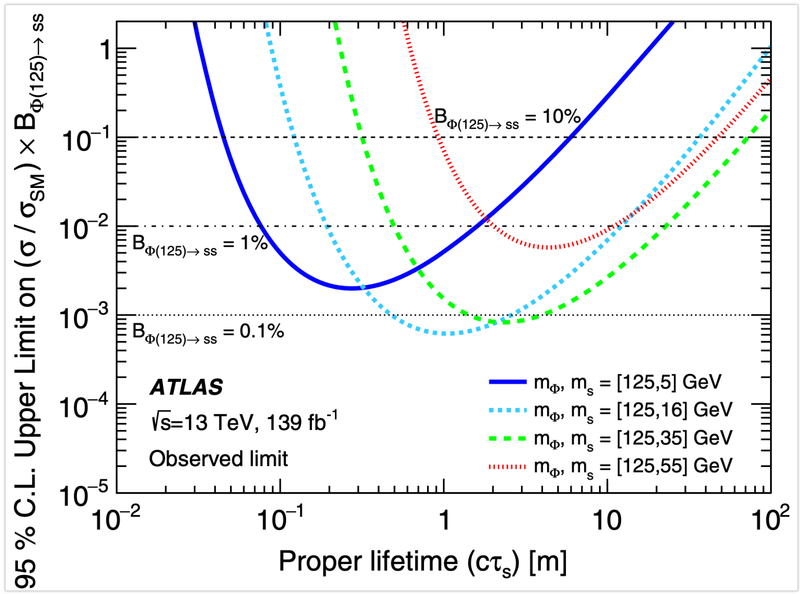
Exclusion Limit

- Best expected limit of 4×10^{-6} has been achieved.
- **Outperforming** the current limit from ATLAS and CMS by **two order of magnitude**.
- *Comparable performance* with ILC's when $\tau_{LLP} < 1$ ns
- **An order of magnitude better** than the ILC's when $\tau_{LLP} > 1$ ns

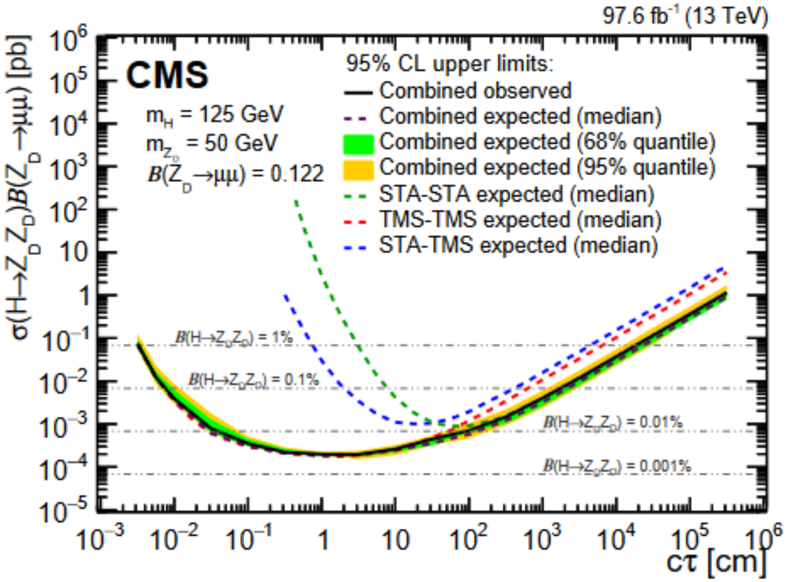




ILC baseline
arXiv:2203.08347



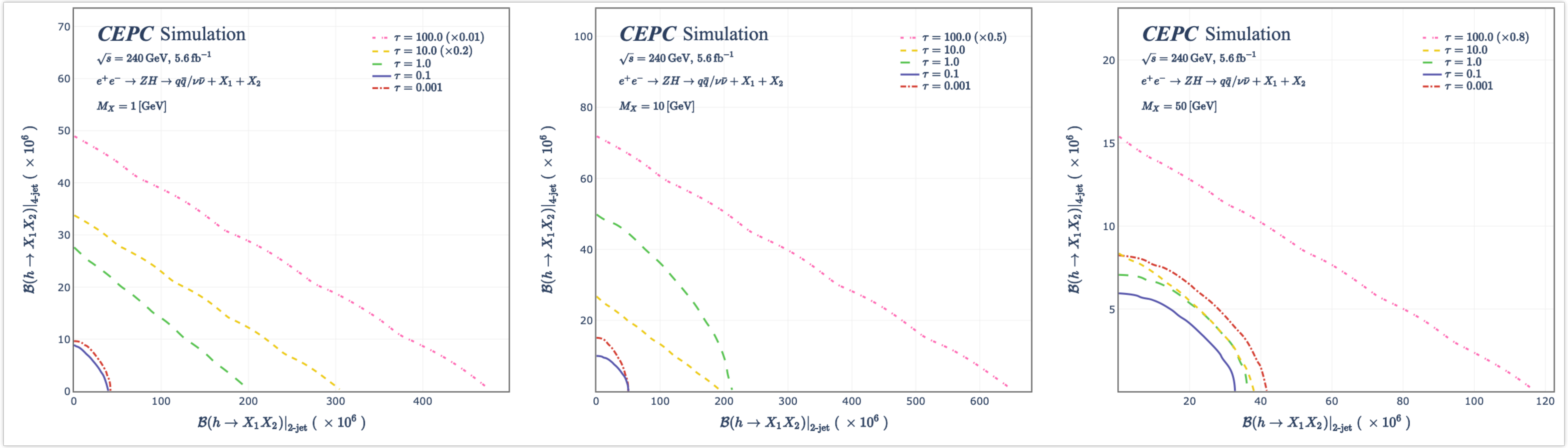
ATLAS [link]



CMS sensitivity
arXiv: 2205.08582

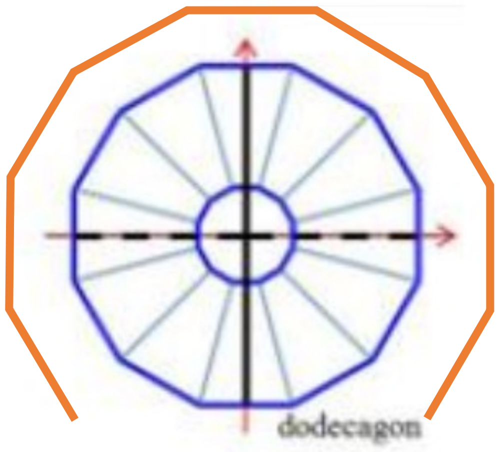
2D Limit Scan

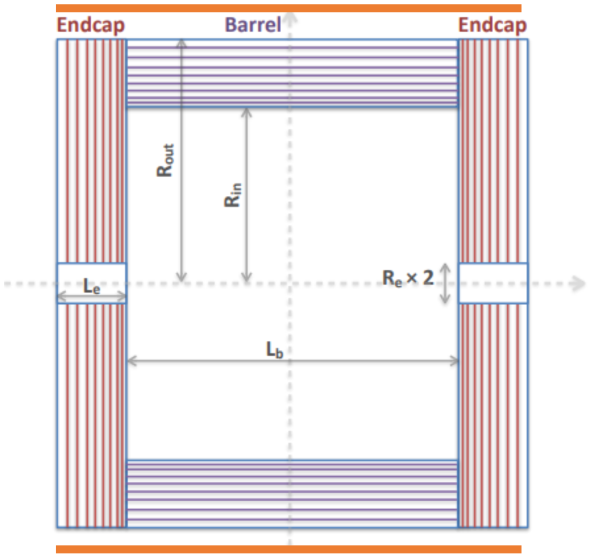
- The 2D scan on $(\mathcal{B}(h \to XX)|_{2-\text{jet}}, \ \mathcal{B}(h \to XX)|_{4-\text{jet}})$ for the 95% CL upper limits.
- Better exclusion results for high-mass region (50 GeV) and low-mass region with short lifetime (< 1 ns).



External Detector Design

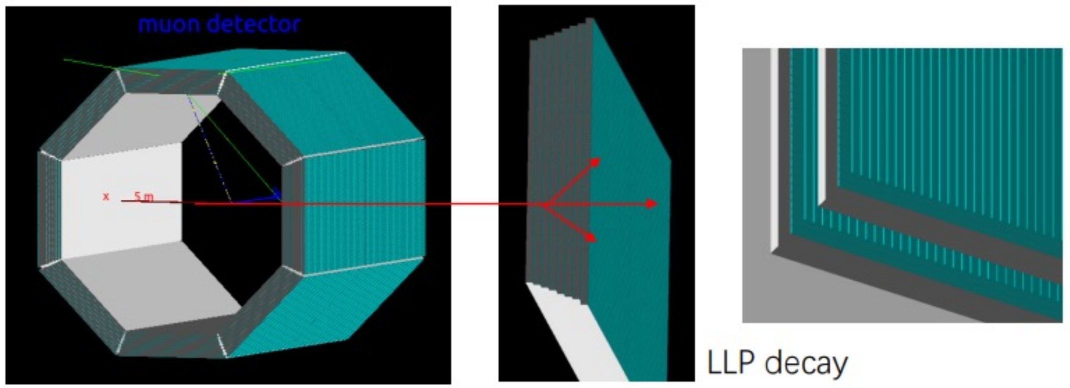
- Outside muon detector to track LLPs
- Same detector structure in [Xiaolong's report]
  - scintillator strip + WLS fiber +SiPM
- geometry acceptance $\epsilon_{\text{geo}} \approx 0.65$





-	Gain	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
Ext. Detector	1	1	1	3.2	11.6	16.2
	10	1	1	1	3.3	11.8
	50	1	1	1	1.1	3.6

an external detector covering distance of 100 meters



Summary

- Investigated a ML-based solution of searching for Long-Lived Particles (2-jet and 4-jet final states) @ CEPC.
  - current results are based on CEPC_v4 geometry setup
  - Can easily adapt to other geometry settings or other lepton collider settings
- First attempt only using raw detector information
  - **Good sensitivity** reached ($\sim 10^{-6}$) with (expected) 1×10^{6} Higgs statistics.
  - The performance of different neural networks (CNN, GNN) are consistent and comparable.
- An external detector outside the baseline CEPC detector can benefit the LLP sensitivity.
  - **An order of magnitude ($\sim$16)** improvement for low mass (≤ 1 GeV) and long lifetime (> 100 ns) LLPs
- Paper to be submitted soon.