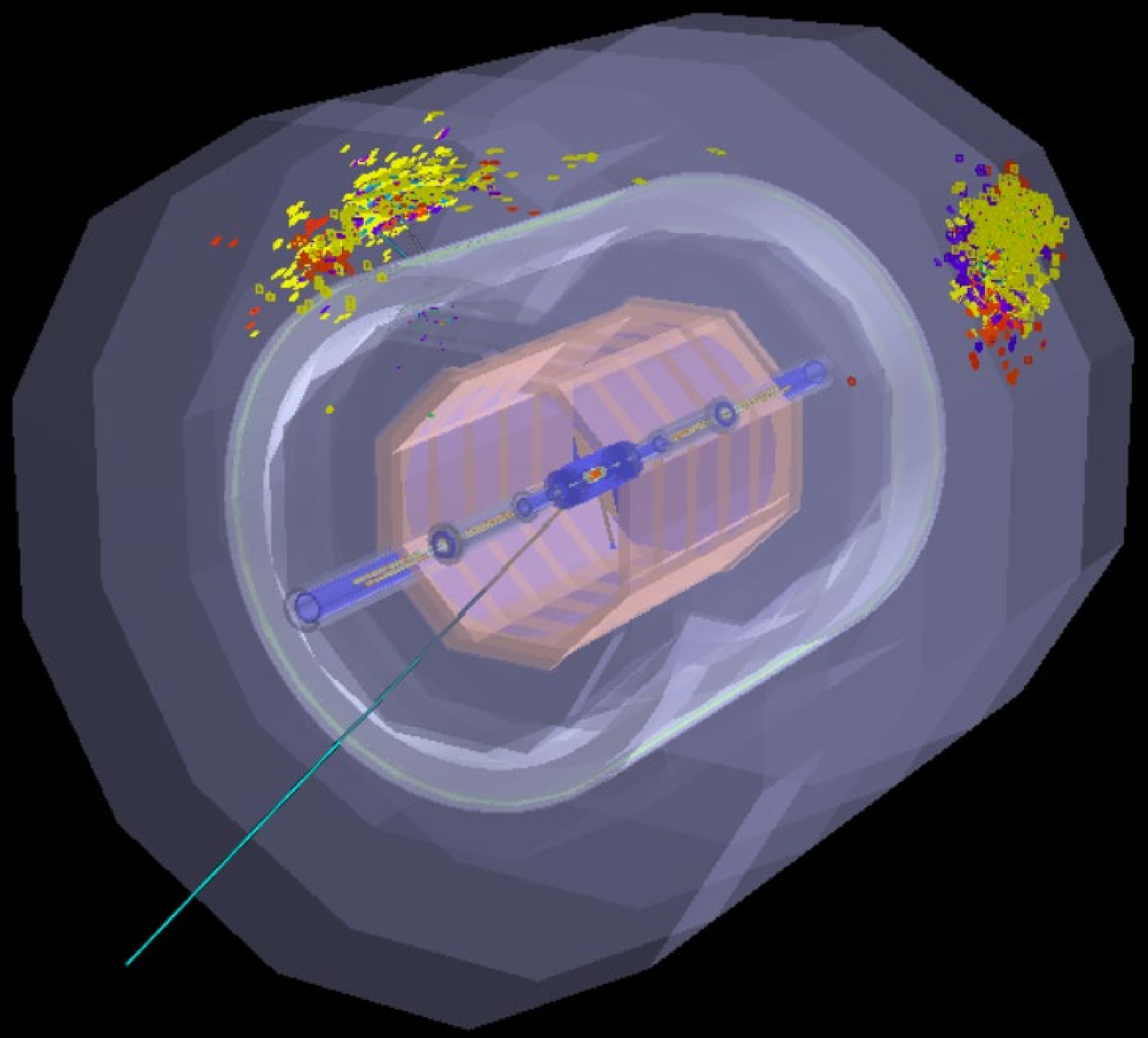
$$e^+e^- \to Zh \to \nu\bar{\nu} + SS1 + SS2 \to \nu\bar{\nu}q\bar{q}q\bar{q}$$



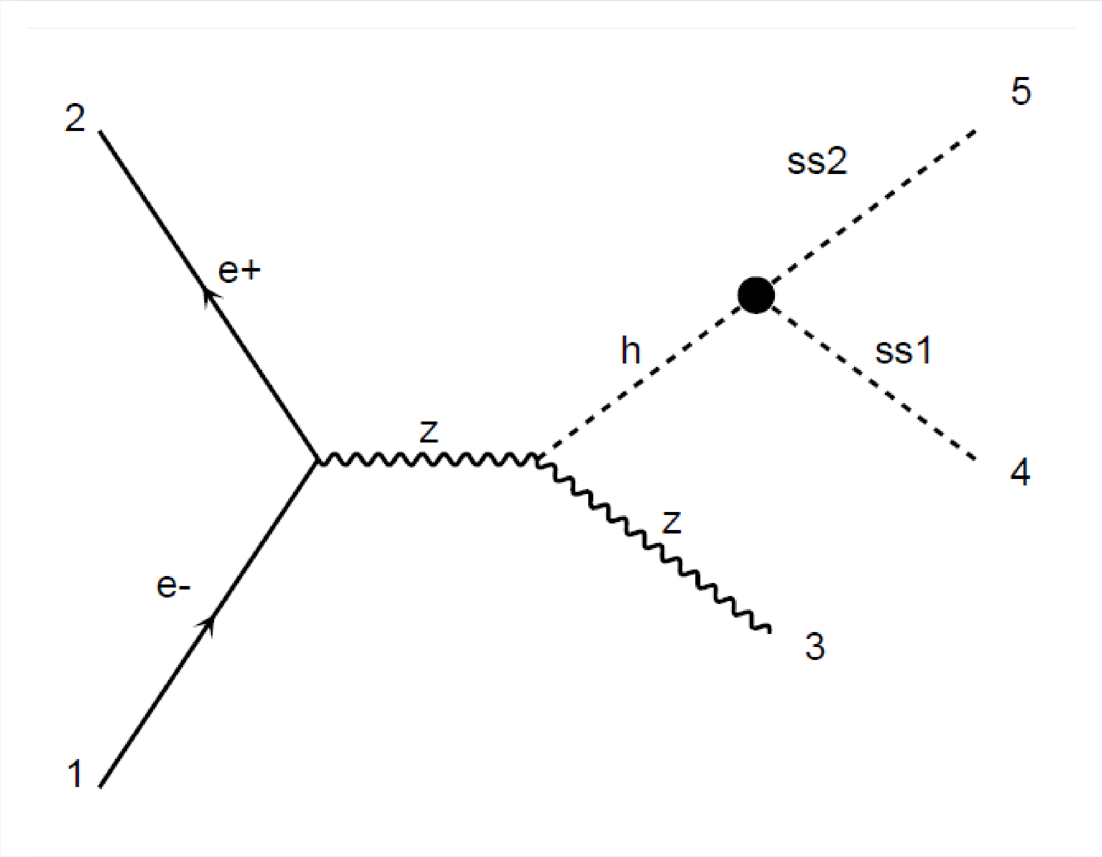
# Long-Lived Particle Search with Lepton Colliders

Yulei Zhang[1], Cen Mo[1], Liang Li[1]
1 Shanghai Jiao Tong University

# Outline

## Beyond the Standard Model

- Why LLPs interesting
- Search for LLPs at future collider
  - Machine Learning
- Preliminary results
- Summary



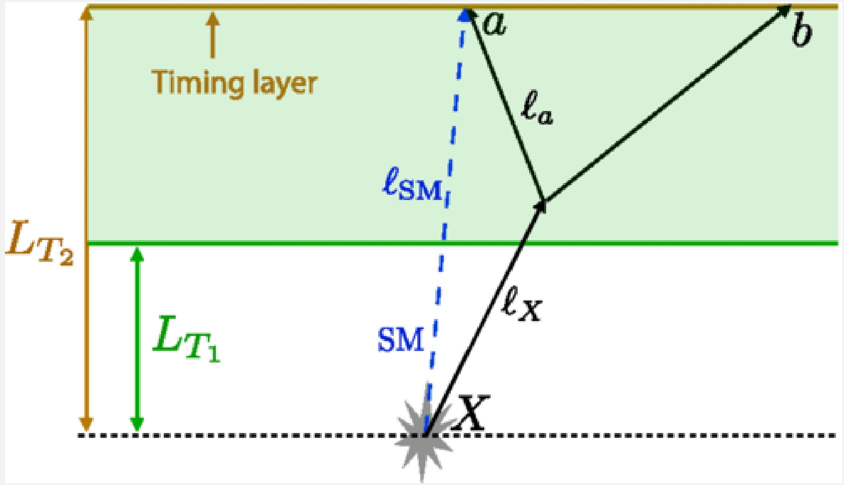

Long-Lived Particle

# What is a long-lived particle?

*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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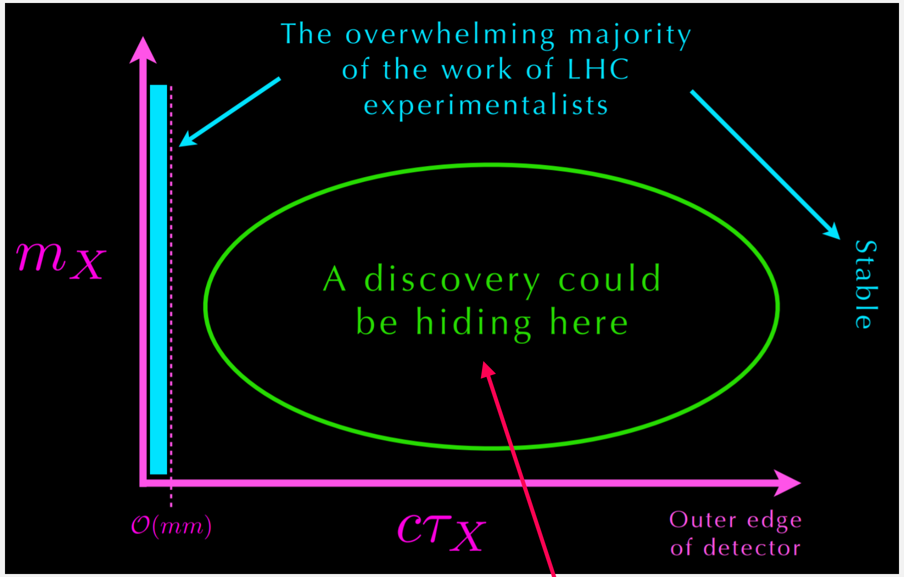
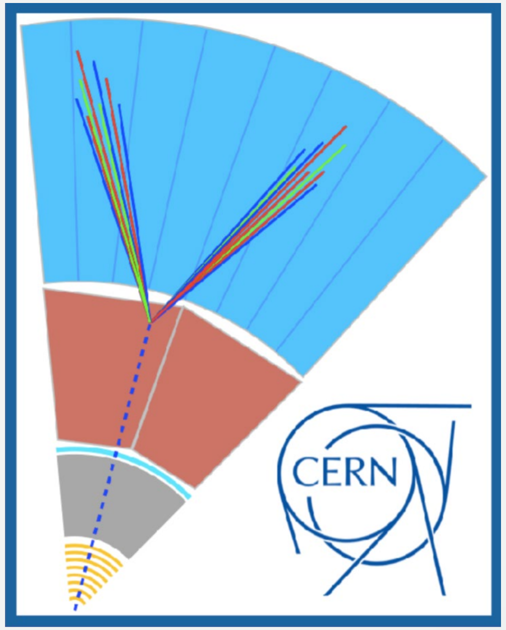
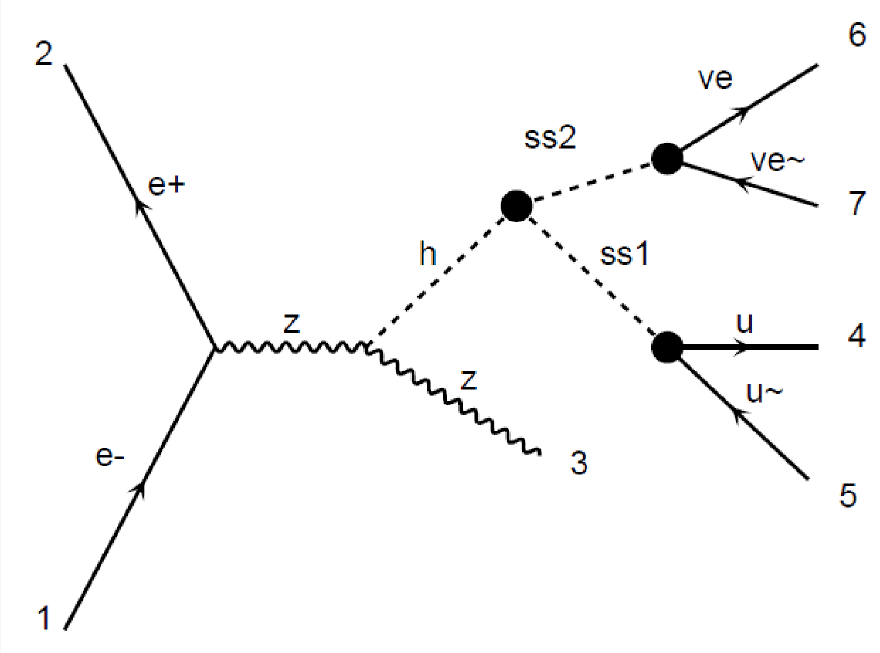


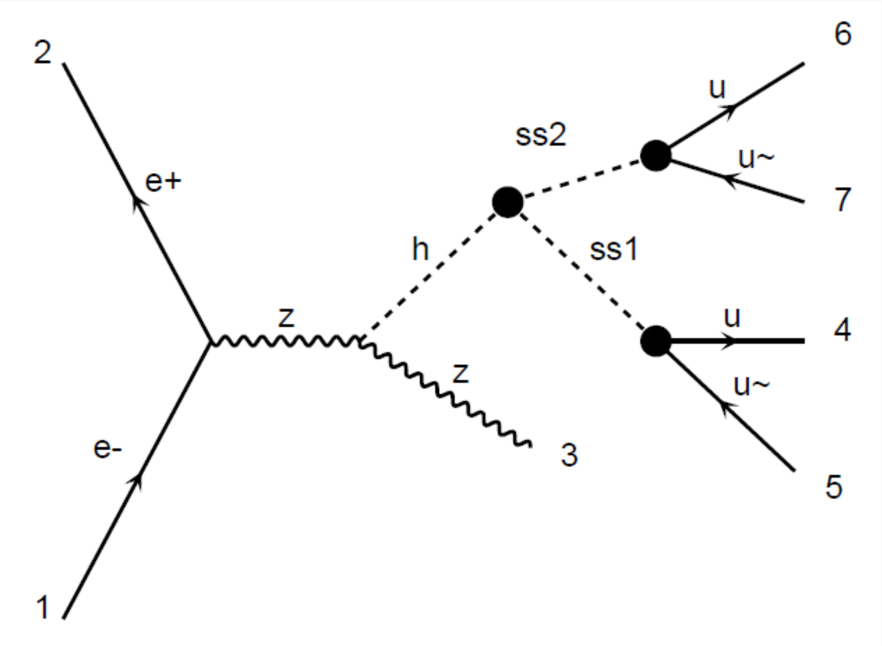
**Long-Lived Particle**

# LLP Searches at Lepton Colliders

2-jet final state




4-jet final state (New)




- Energy: 240 GeV
- Mass of SS1: 0.1-50 GeV
- Mass of SS2: 0.1-50 GeV
- SS1, SS2's lifetime $\tau = R_{\text{out}}/c \ = 6m/c = 20\ ns$

# Basic Setup

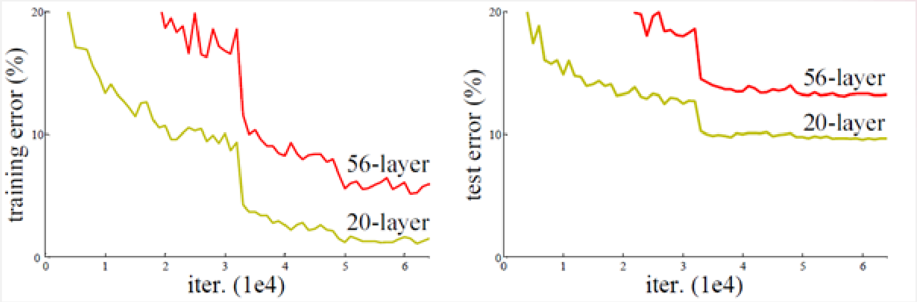
- **Full simulation** with CEPC official software (V4)
- The decay vertex of LLPs: $\mathbf{0 \leq r_{decay} \leq 6\ [m]}$
- Signal sample generated by MadGraph5 and showered by Pythia8
  - Thanks to Zhen LIU, Jia LIU and Xiaoping WANG for providing the long-lived particle model.

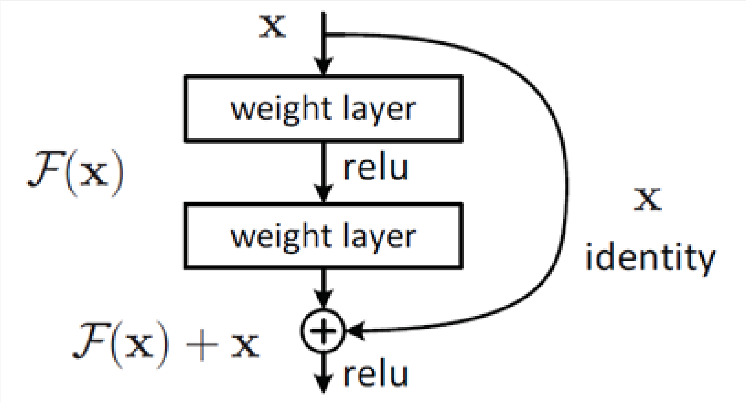
| | # of Events simulated | # of Events in 5.6 $ab^{-1}$ |
|---|---|---|
| Signal: $Z \to \bar{q}q, h \to SS1 + SS2$ (2-jet) | $\sim 1.0 \times 10^6$ | / |
| Signal: $Z \to \bar{\nu}\nu, h \to SS1 + SS2$ (2-jet) | $\sim 1.0 \times 10^6$ | / |
| Signal: $Z \to \bar{q}q, h \to SS1 + SS2$ (4-jet) | $\sim 1.0 \times 10^6$ | / |
| Signal: $Z \to \bar{\nu}\nu, h \to SS1 + SS2$ (4-jet) | $\sim 1.0 \times 10^6$ | / |
| $e^+e^- \to q\bar{q}$ | $(\sim 0.99 \times 10^7)$* | $2.5 \times 10^8$ |
| $e^+e^- \to Zh$ (Standard Model) | $\sim 1.37 \times 10^6$ | $1.0 \times 10^6$ |
| $e^+e^- \to W/Z$ | $\sim 1.3\times 10^7$ | $1.6\times 10^7$ |

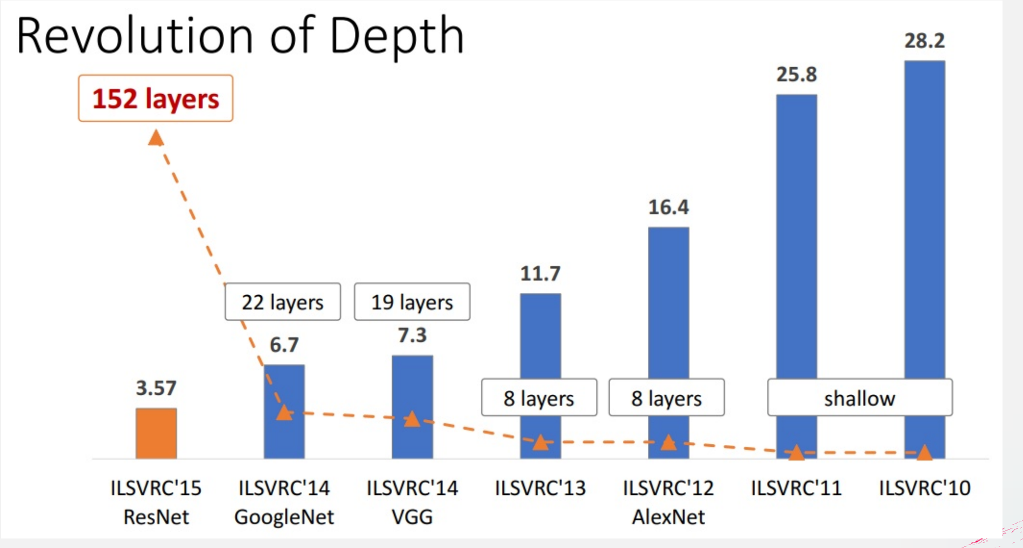
* Due to the limited computing power, $\sim 10^7$ events were simulated so far

# Deep Residual Network, ResNet

- Firstly, appeared in the ILSVRC 2015 classification challenges (ImageNet Large Scale Visual Recognition Challenge)
- ResNet18, ResNet50, ResNet101…



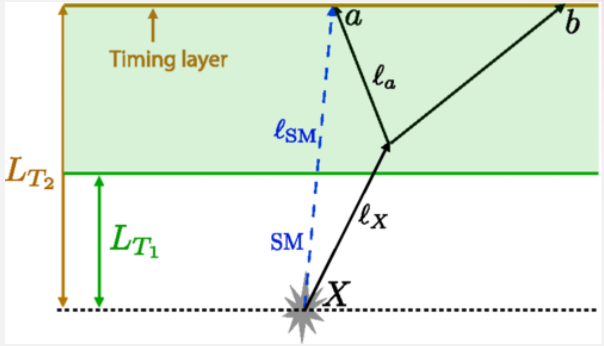






Long-Lived Particle

# Configuration

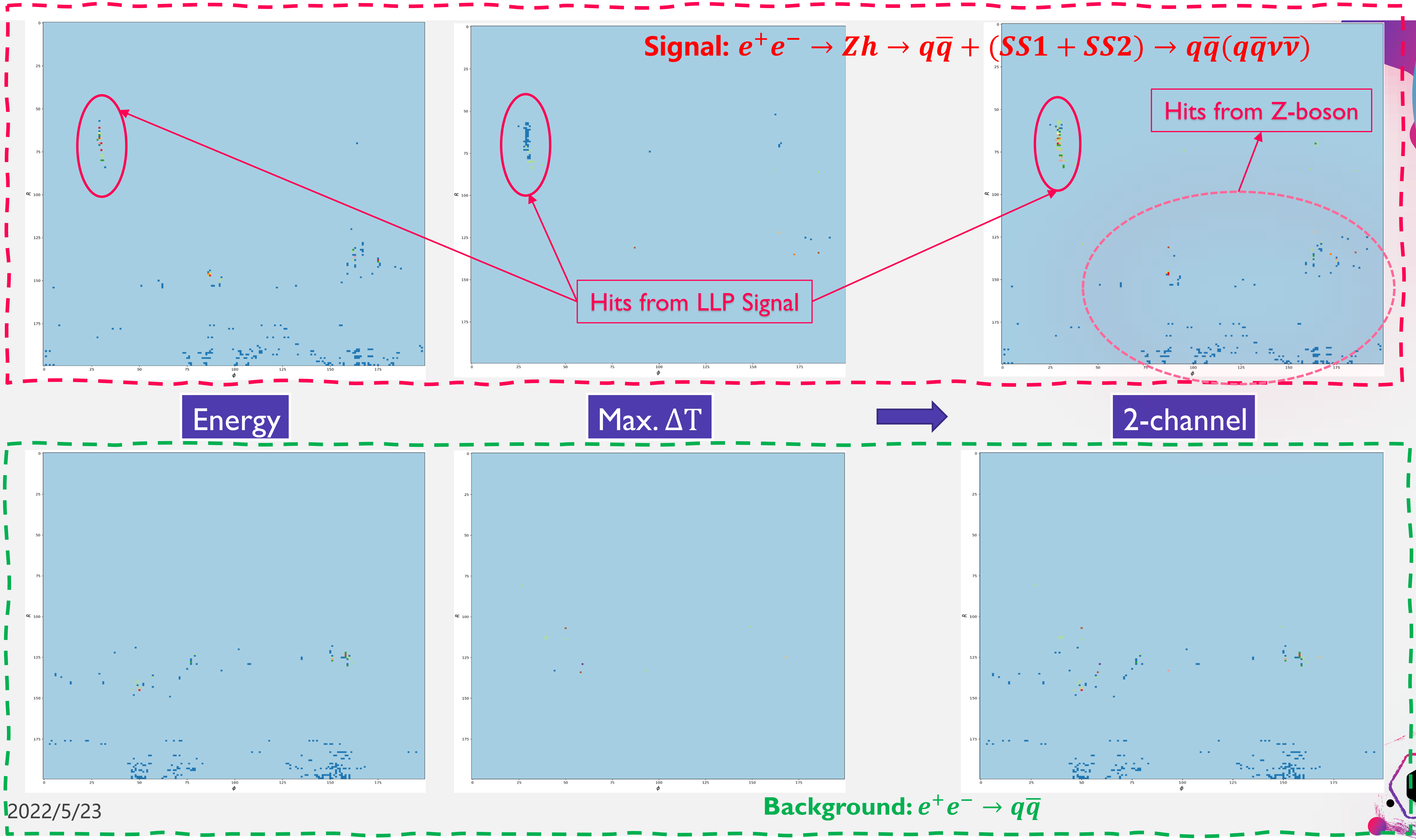



$\Delta t = t_{\mathrm{Hit}} - r_{\mathrm{Hit}}/c$

- Mapping the **raw detector information** to a 2D image
- Input Format: image with resolution of $(\mathrm{R}, \phi) = 200 \times 200$ and 1 to 3 channel(s)
  - $R_i = i \times \Delta R_i$, R starts from 0 m to 8 m.
  - $\phi$ starts from $-\pi$ to $\pi$
  - Energy is the sum of both Tracker hits and Calorimeter hits.
  - Time is the maximum $\Delta T$ $(E > 0.1\ GeV)$ within $(\mathrm{R}, \phi)$ pixel
- Model: ResNet18 (Multi-Class Classification), ResNet50 (Vertex Finding)
- **Cross Entropy Loss:** $loss = -[\omega_0 * y_0 \log(x_0) + \omega_1 * y_1 \log(x_1) + \omega_2 * y_2 \log(x_2)]$

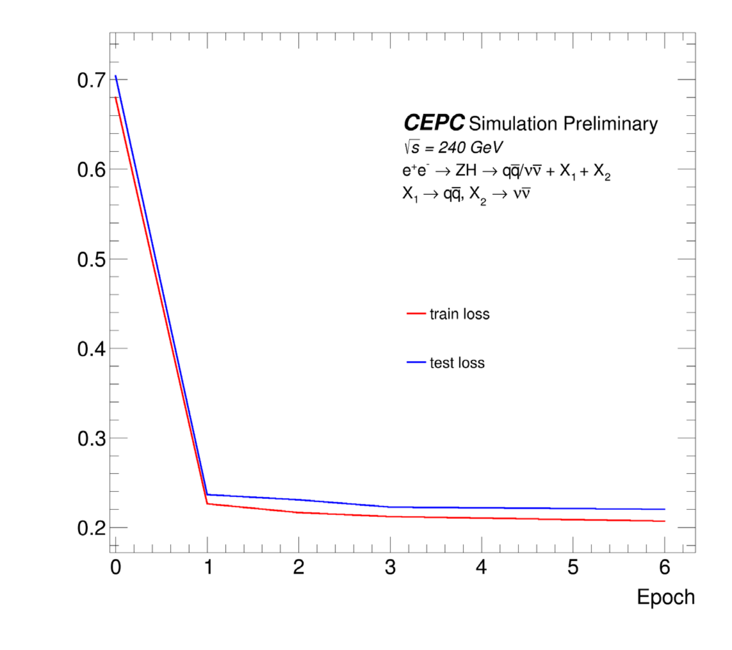
| Class 0: 2-fermion bkg | Class 1: 4-fermion bkg | Class 2: LLP Signal |
|---|---|---|
| $\omega_0 = 0.5$ | $\omega_1 = 0.25$ | $\omega_2 = 0.25$ |

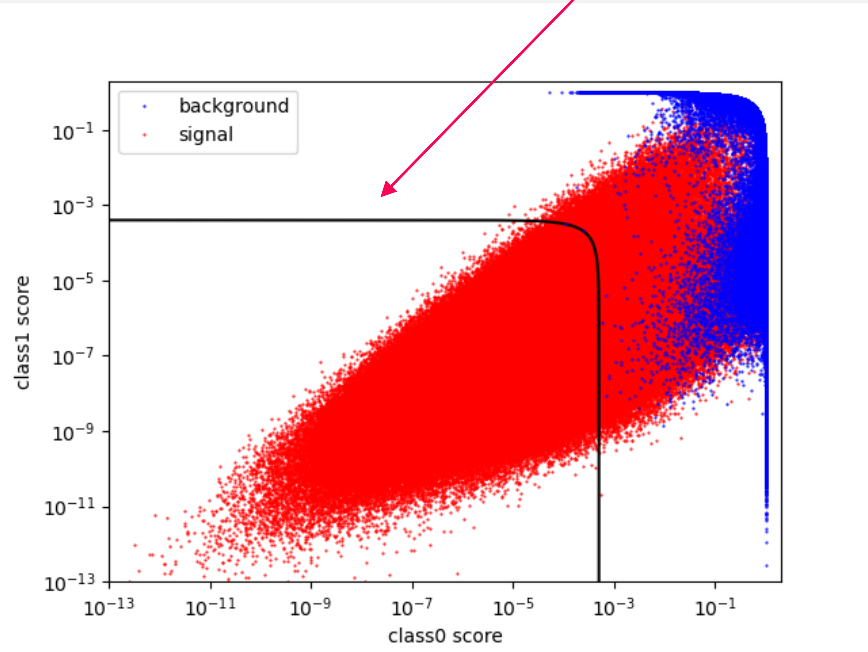
Long-Lived Particle


Signal: $e^+e^- \rightarrow Zh \rightarrow q\bar{q} + (SS1 + SS2) \rightarrow q\bar{q}(q\bar{q}\nu\bar{\nu})$
Hits from Z-boson
Hits from LLP Signal
Energy
Max. ΔT
2-channel
Background: $e^+e^- \rightarrow q\bar{q}$

# Training on LLP 2-jet

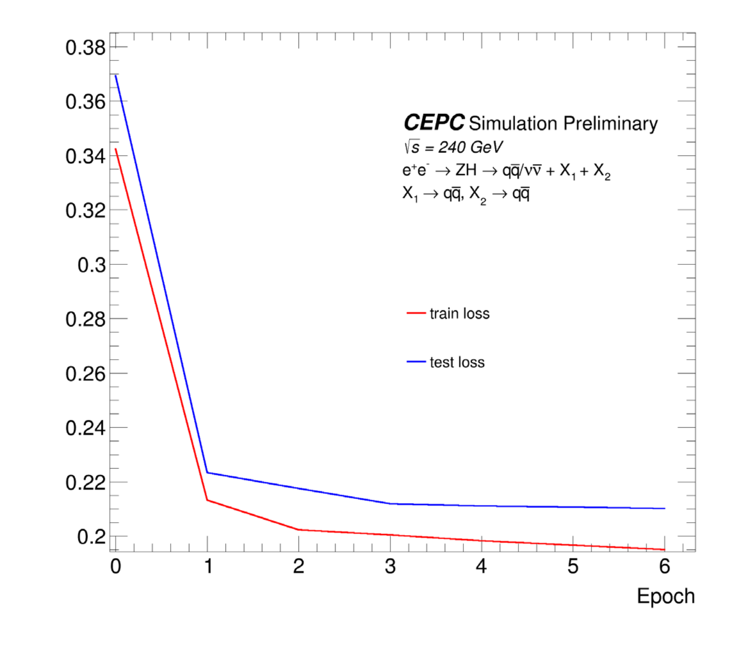
Optimized Cut on network's outputs



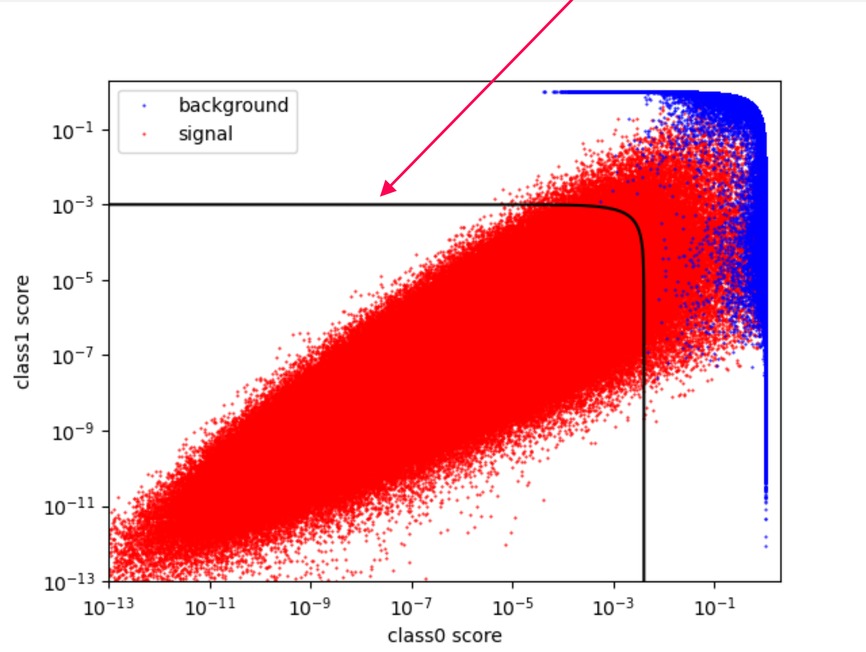




| | Passed Event | Total Event | $\epsilon$ |
|---|---|---|---|
| Signal: $Z \to \bar{q}q, h \to SS1 + SS2$ (2-jet) | 308,274 | 424,100 | 72.69% |
| Signal: $Z \to \bar{\nu}\nu, h \to SS1 + SS2$ (2-jet) | 325,550 | 449,160 | 72.47% |
| Class 0: 2-fermion background | 0 | 7,665,900 | 0.00% |
| Class 1: 4-fermion background | 0 | 13,033,405 | 0.00% |

# Training on LLP 4-jet

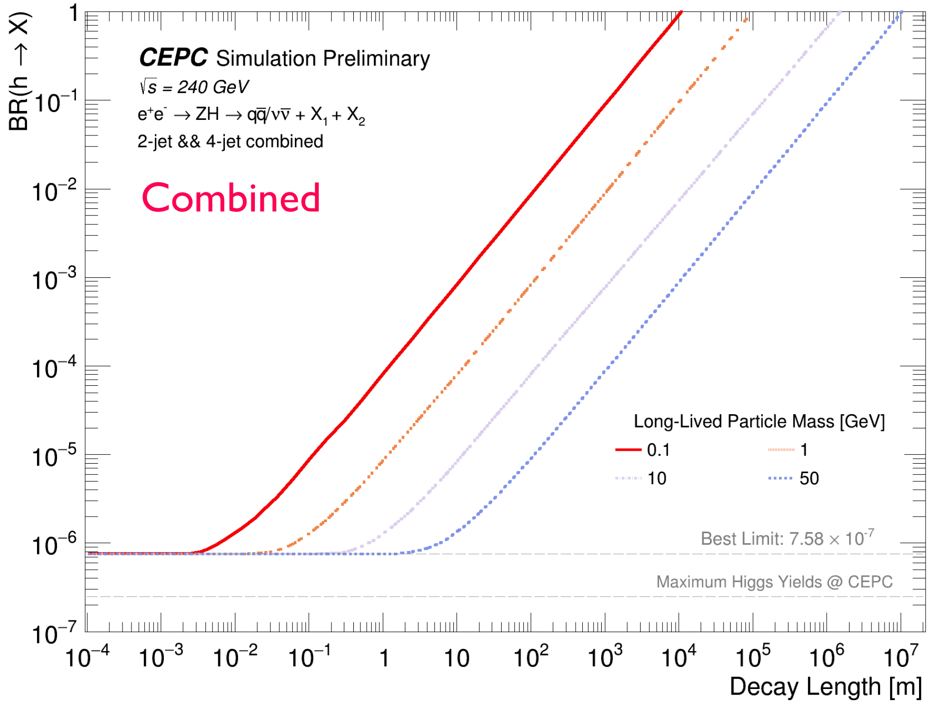



Optimized Cut on network's outputs

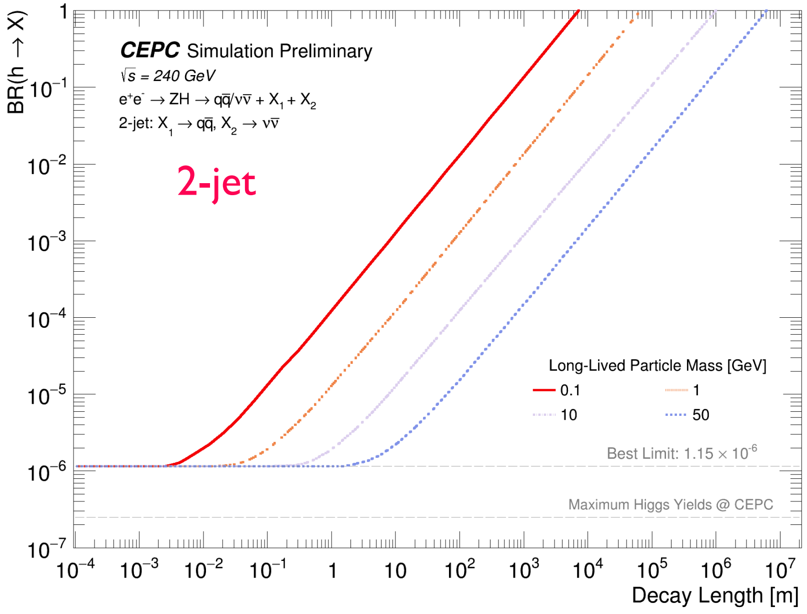


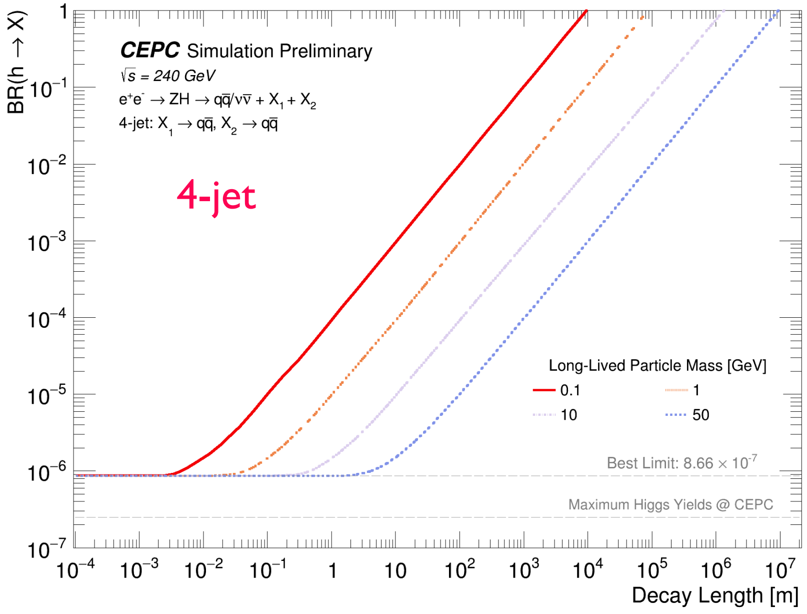

| | Passed Event | Total Event | $\epsilon$ |
|---|---|---|---|
| Signal: $Z \to \bar{q}q, h \to SS1 + SS2$ (4-jet) | 398,846 | 415,780 | 95.93% |
| Signal: $Z \to \bar{\nu}\nu, h \to SS1 + SS2$ (4-jet) | 427,262 | 434,710 | 98.29% |
| Class 0: 2-fermion background | 0 | 7,665,900 | 0.00% |
| Class 1: 4-fermion background | 0 | 13,033,405 | 0.00% |

# Exclusion Limit

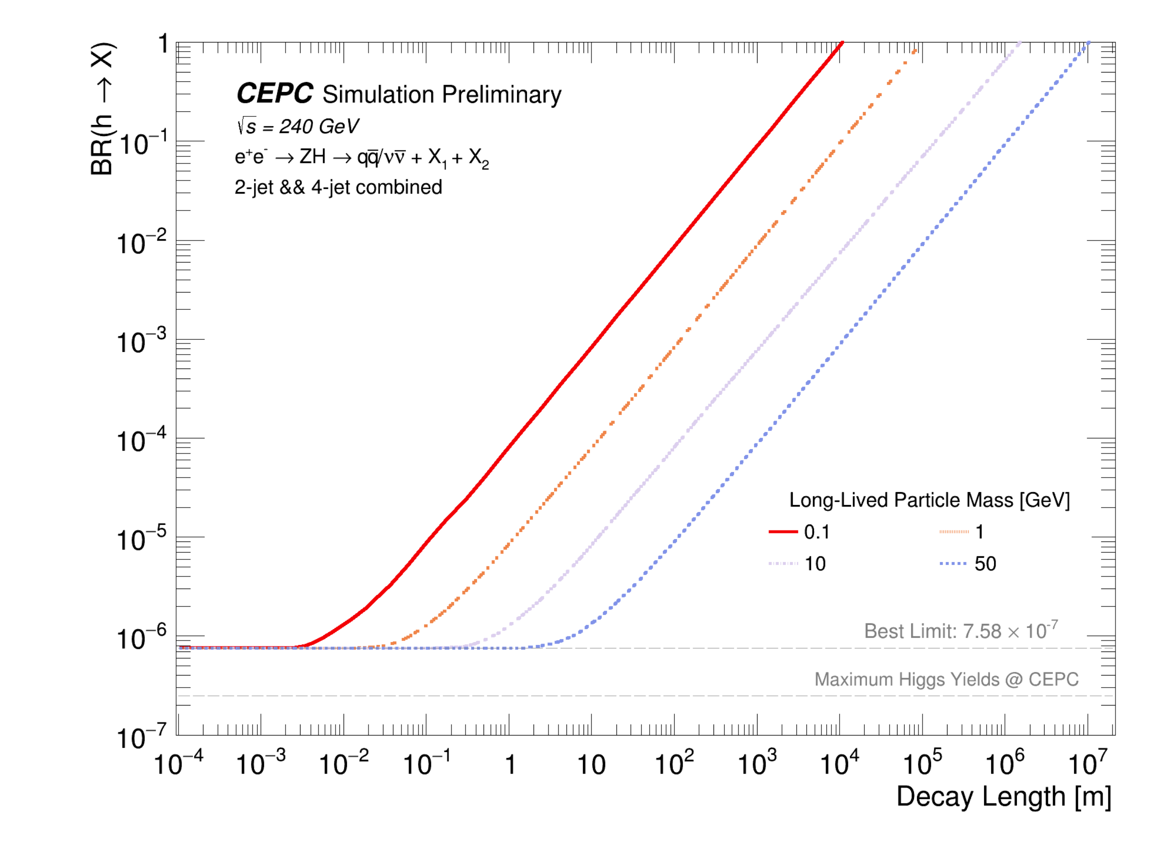



| Channel | 95% CL upper limit on BR $(h \rightarrow XX)$ |
| --- | --- |
| 2-jet | $1.15 \times 10^{-6}$ |
| 4-jet | $8.66 \times 10 - 7$ |
| Combined | $7.58 \times 10^{-7}$ |

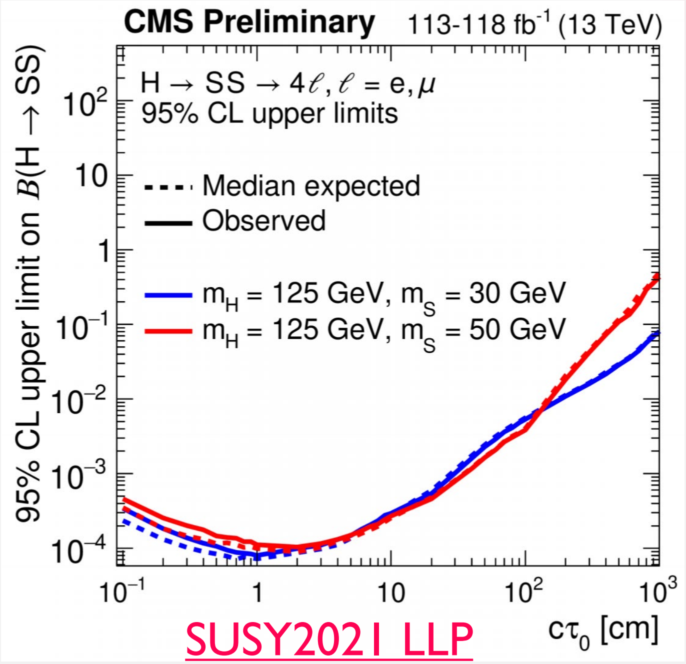


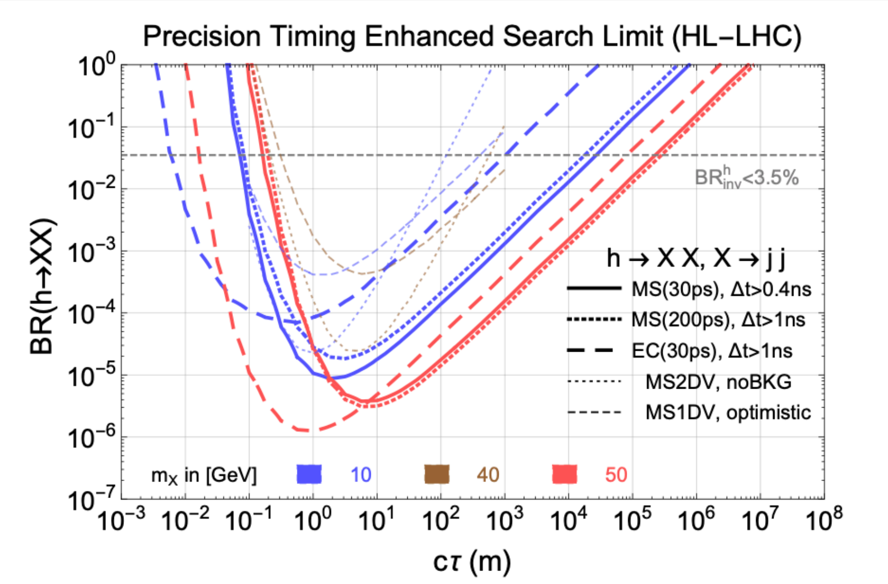
# Sensitivity (other exp.)




- Results based on $5.6\ \mathrm{ab}^{-1}$ and projected to $20\ \mathrm{ab}^{-1}$
- Good sensitivity for low LLP mass (as low as 0.1 GeV)




SUSY2021 LLP

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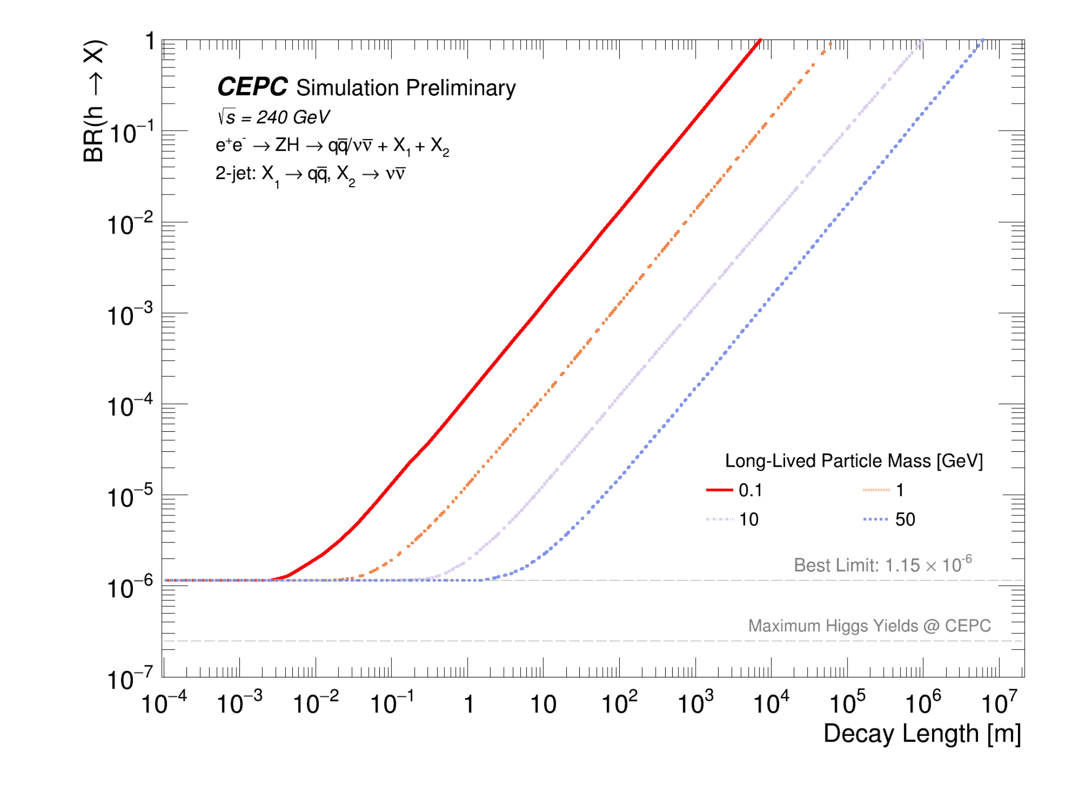
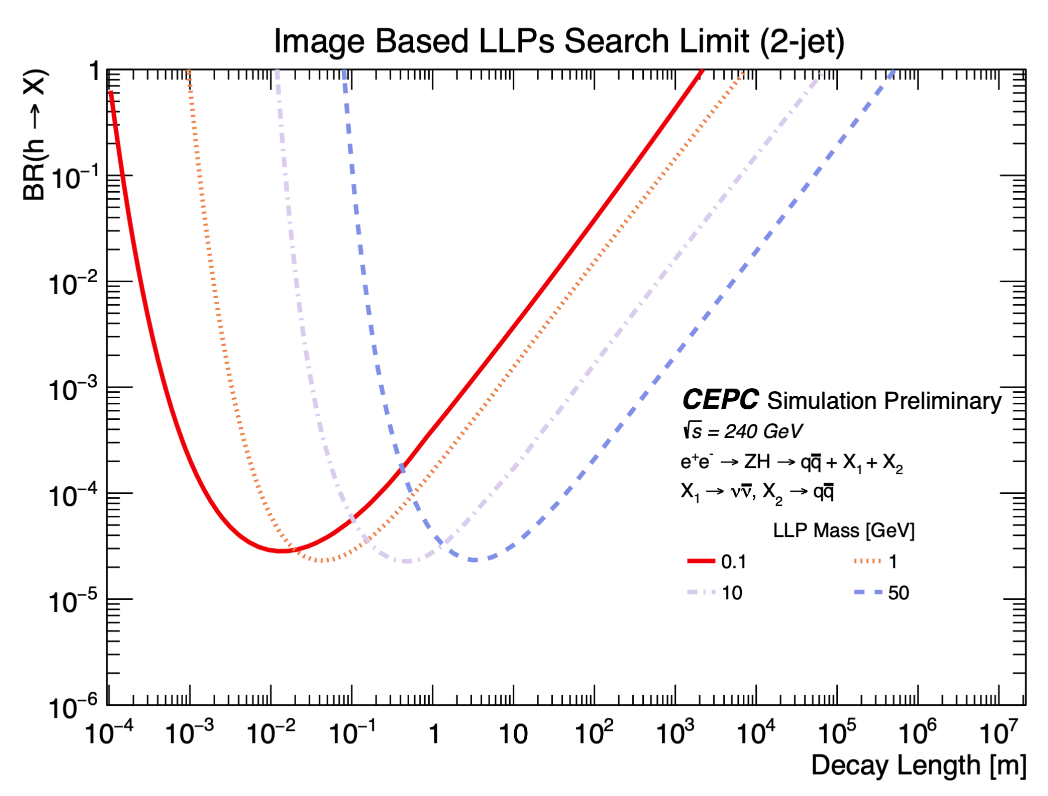
# Sensitivity (compared with previous 2-jet analysis)




- Previous best limit: $\sim 1 \times 10^{-5}$ $(5.6\ \mathrm{ab}^{-1})$, Current best limit: $\sim 1 \times 10^{-6}$ $(20\ \mathrm{ab}^{-1})$
- Main improvement on geometry acceptance: $\boldsymbol{r}_{\mathbf{decay}}$ from [1,6] to (0,6]

Long-Lived Particle

# Summary

- Long-Lived Particle (2-jet and 4-jet final states) study done with future lepton collider
  - current results based on CEPC_v4 geometry setup
- First attempt to apply AI image recognition techniques to raw detector hits
  - Very good sensitivity reached ($> 10^{-7}$) with (expected) $4 \times 10^6$ Higgs statistics compared to current LHC limits ($\sim 10^{-4}$, expected HL-LHC limits of $> 10^{-6}$).
  - Other ML possibilities: vertex finding, momentum finding…
- Future improvement on geometry acceptance: extra detectors
- Paper submission in preparation (Snowmass summer meeting)

# Thanks

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