Long-Lived Particle Search with Lepton Colliders

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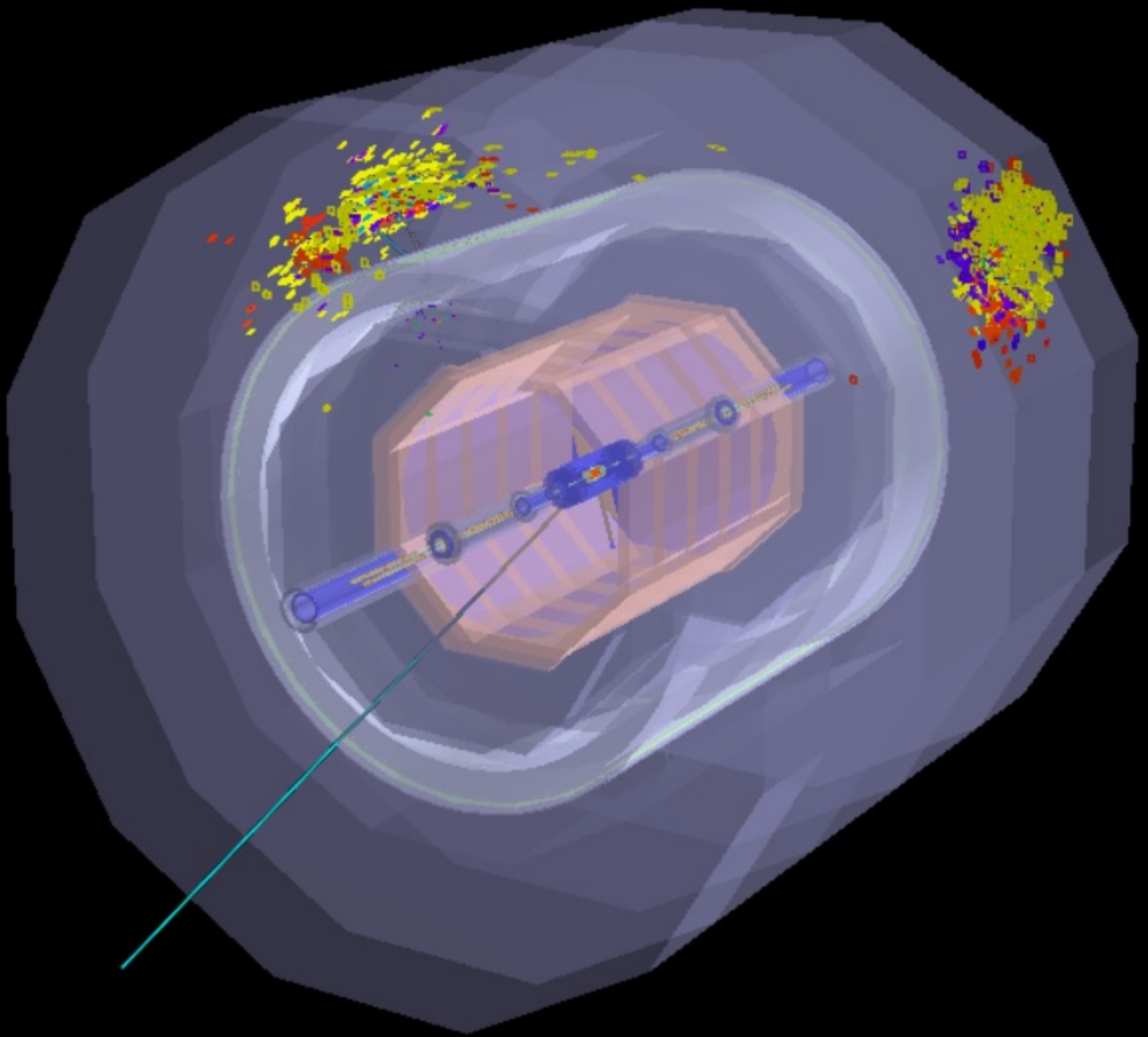
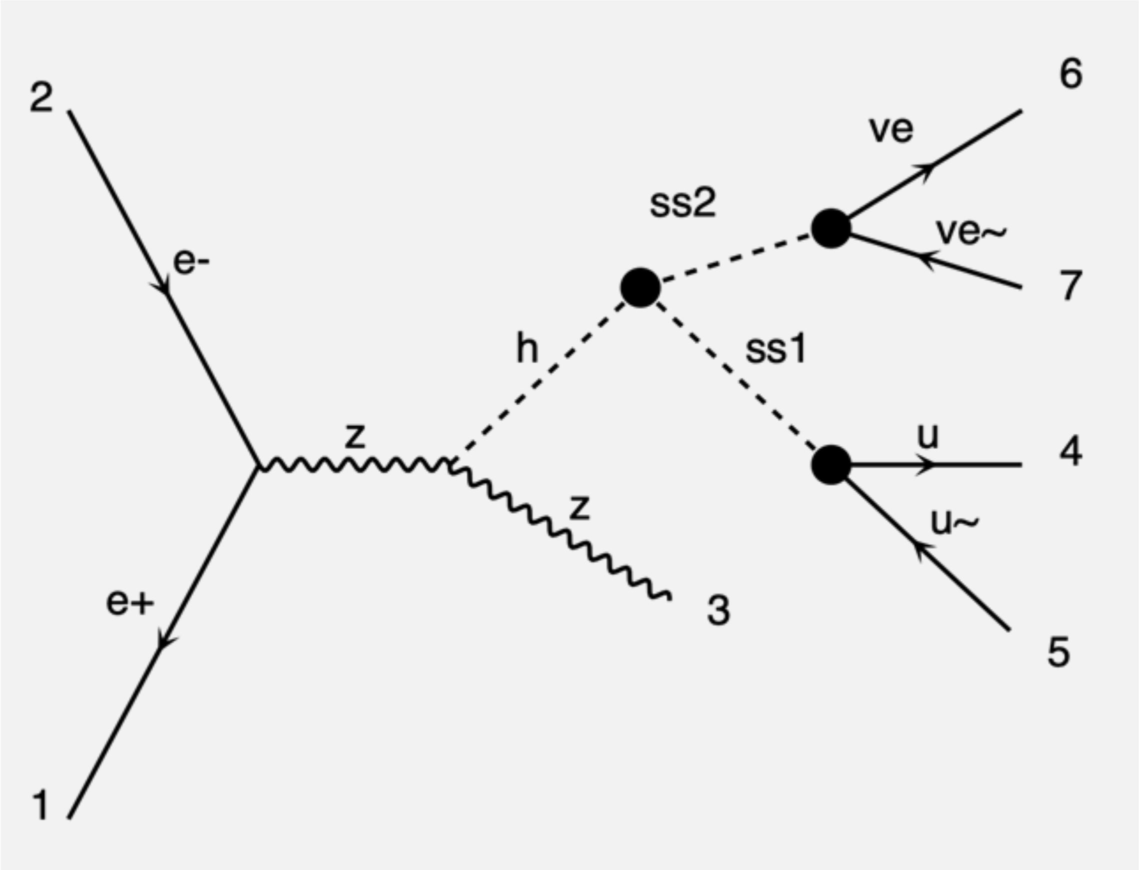
$$e^+e^- \to Zh \to \nu\bar{\nu} + SS1 + SS2 \to \nu\bar{\nu}q\bar{q}q\bar{q}$$



Outline

Beyond the Standard Model

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



Long-Lived Particle

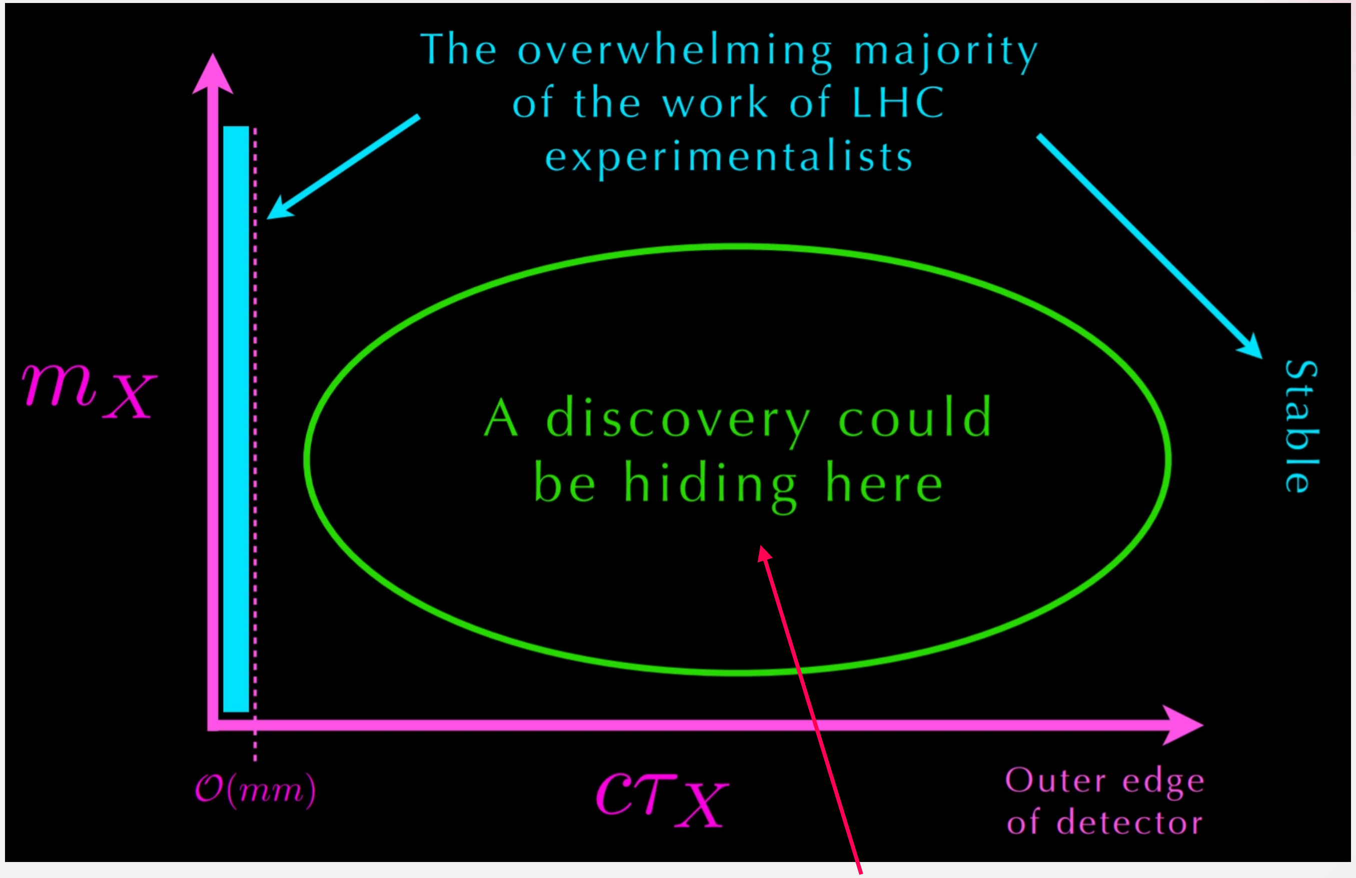
The lifetime frontier …

- Large majority of current collider experiment searches and analysis strategies assume the new particle decays promptly.

- 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.

Sixth workshop of the LHC LLP Community



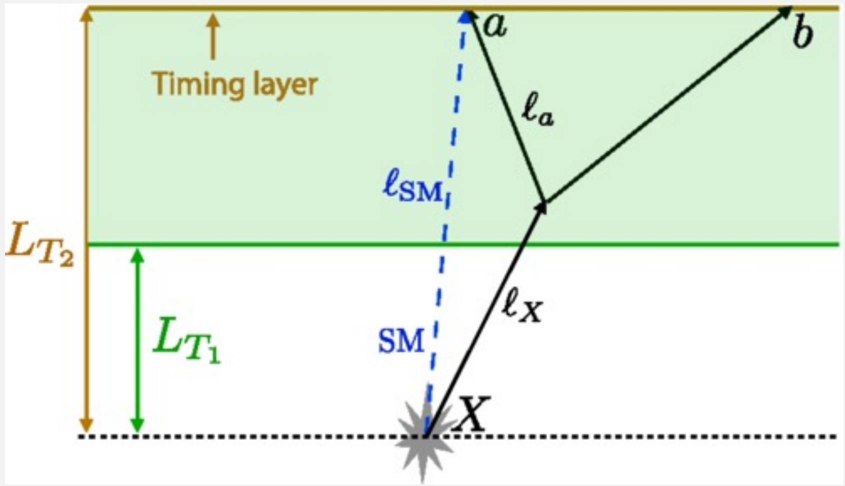
Long-Lived Particle

What is a long-lived particle?

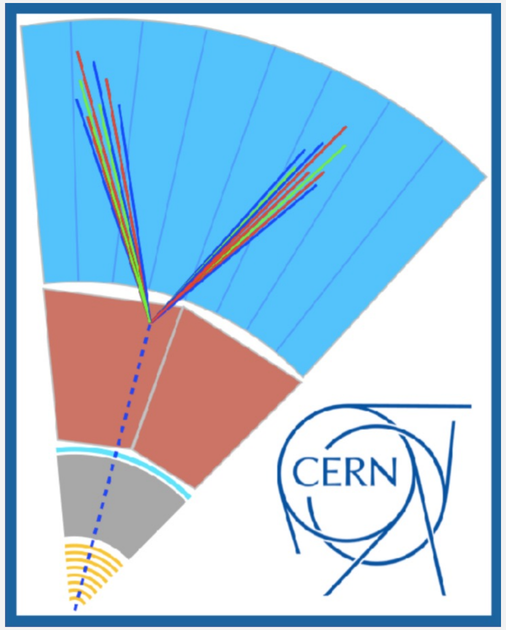
*Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

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.

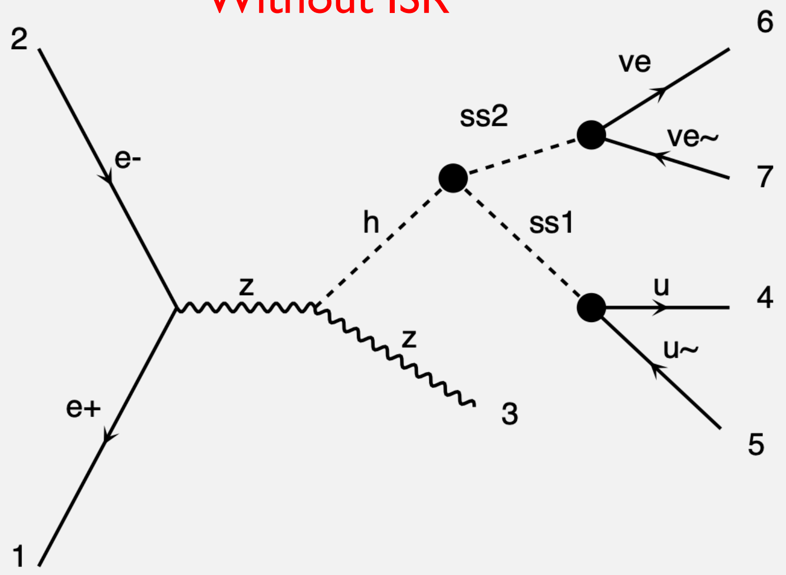


Phys. Rev. Lett. **122**, 131801 – 2019.04.03

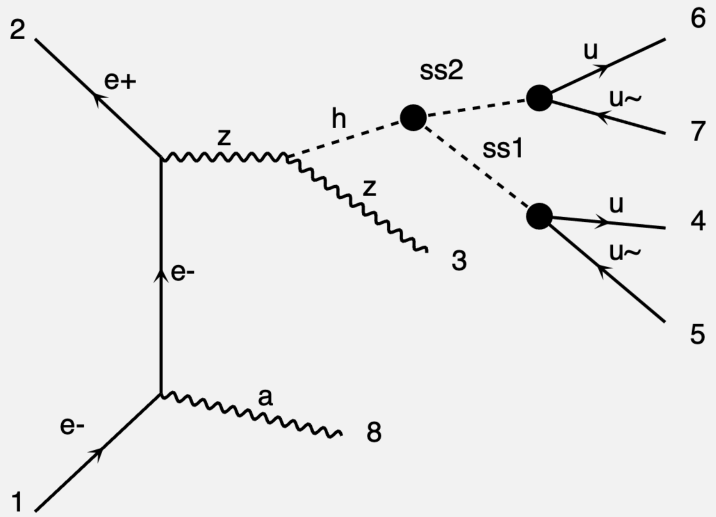


LLP Searches at Lepton Colliders

Without ISR



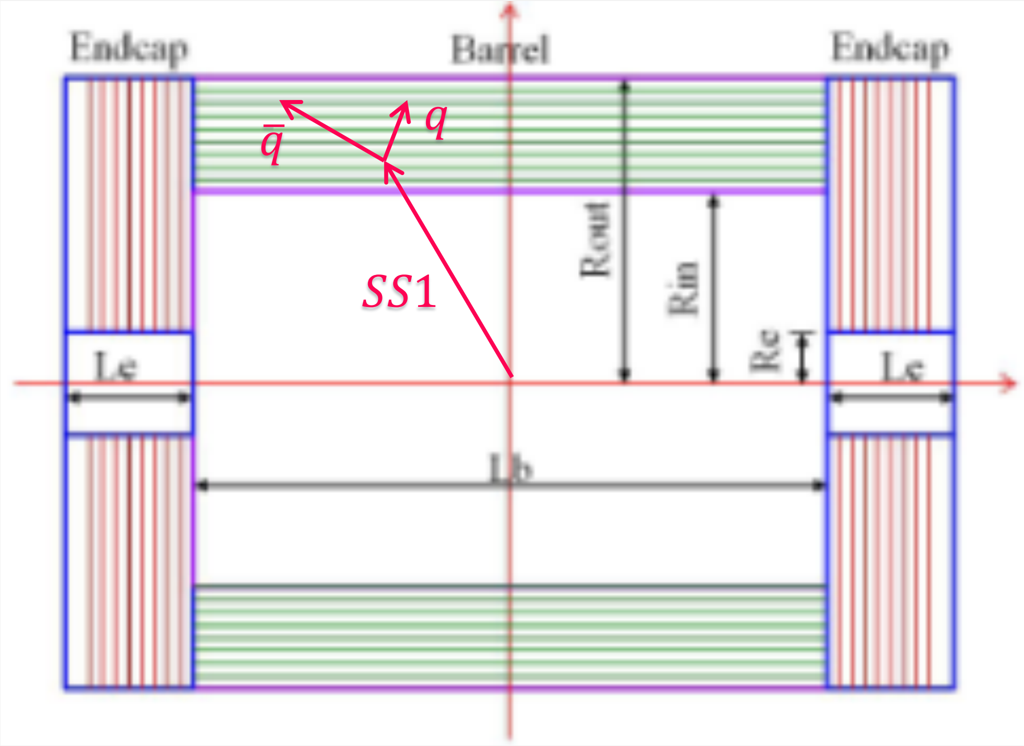
With ISR



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

Long-Lived Particle

Basic Setup



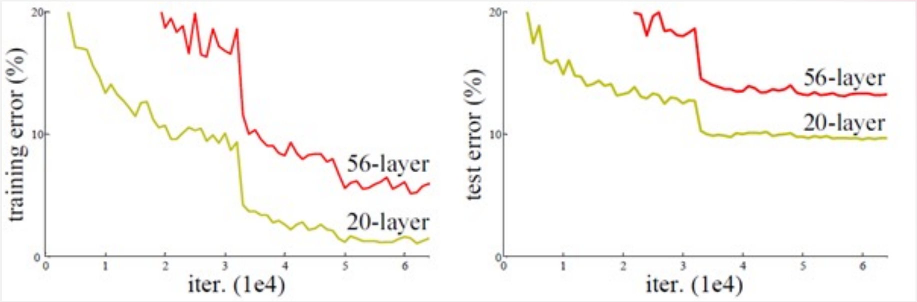
- Muon Detector
  - $R_{\text{in}} \approx 4m$
  - $R_{\text{out}} \approx 6m$
- $\boldsymbol{\Delta t = t_{\text{Hit}} - r_{\text{Hit}}/c}$
- Dominant Background
  - $\boldsymbol{e^+e^- \to ZH}$
  - $\boldsymbol{e^+e^- \to qq}$
- **Full simulation** with CEPC official software

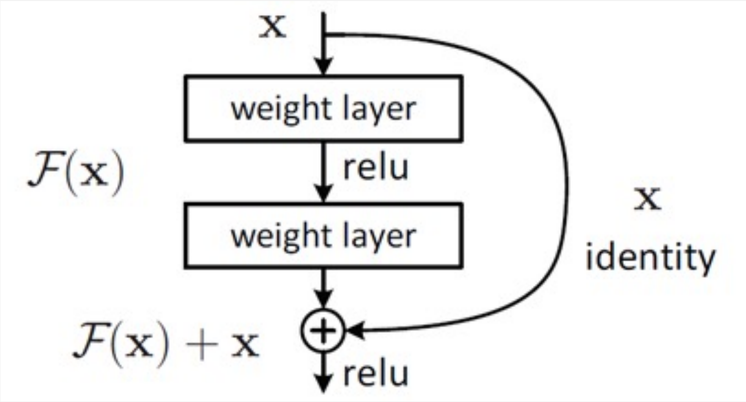
Signal range: LLPs decay within 0~6 meters

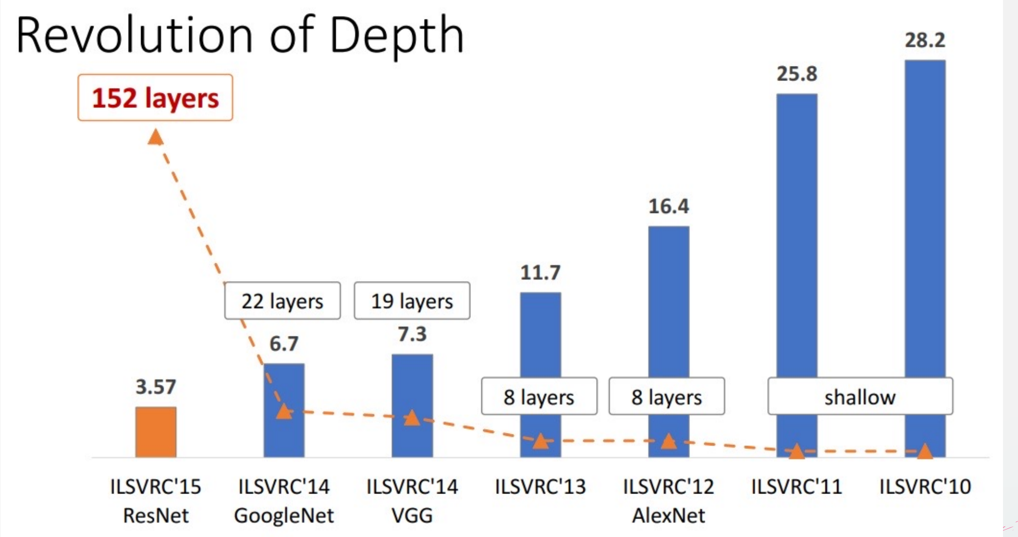
ML based Analysis

Deep Residual Network, ResNet

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



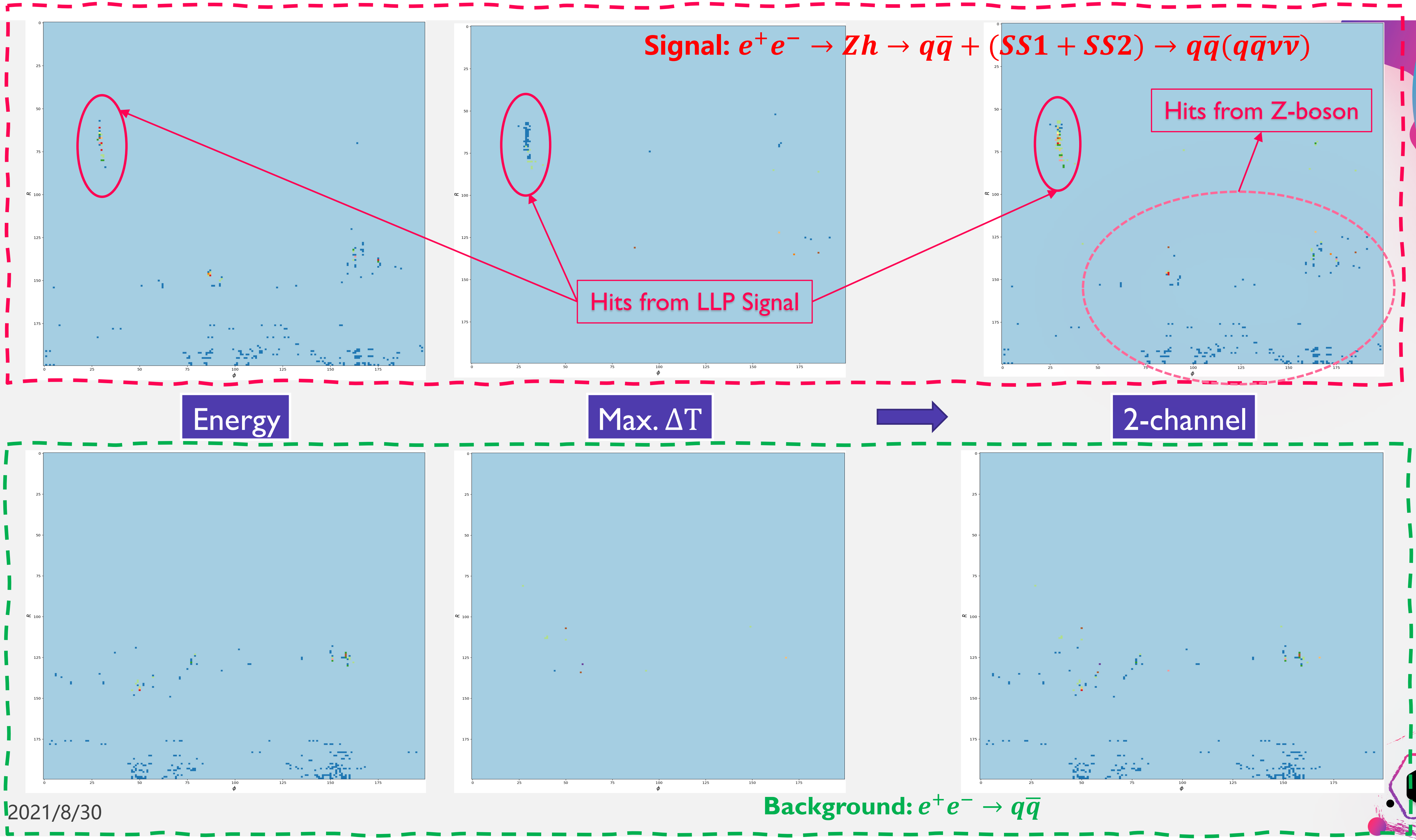




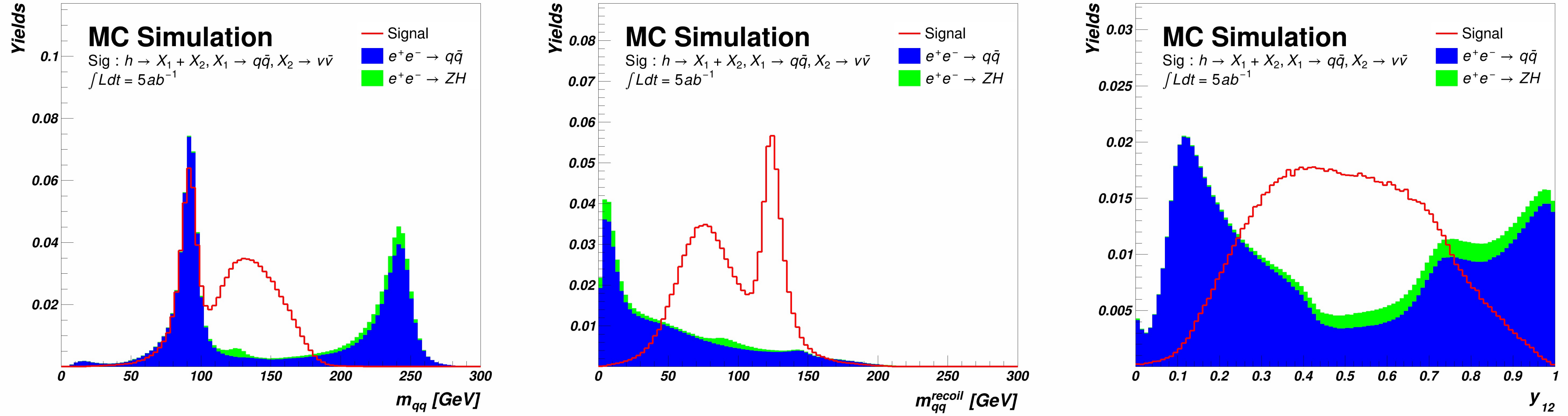
Long-Lived Particle

Configuration

- Mapping the raw detector information to a 2D image
- Input Format: image with resolution of $(\mathrm{R}, \phi) = 200\times200$ and 1 to 3 channel(s)
  - $R_i = i\times\Delta R_i$, R starts from 0 m to 8 m.
  - ϕ starts from $-\pi$ to π
  - Energy is the sum of both Tracker hits and Calorimeter hits.
  - Time is the maximum ΔT $(E > 0.1\ GeV)$ within (R, ϕ) pixel
- Model: ResNet18 (Classification), ResNet50 (Vertex Finding)
- **Binary Cross Entropy Loss:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$

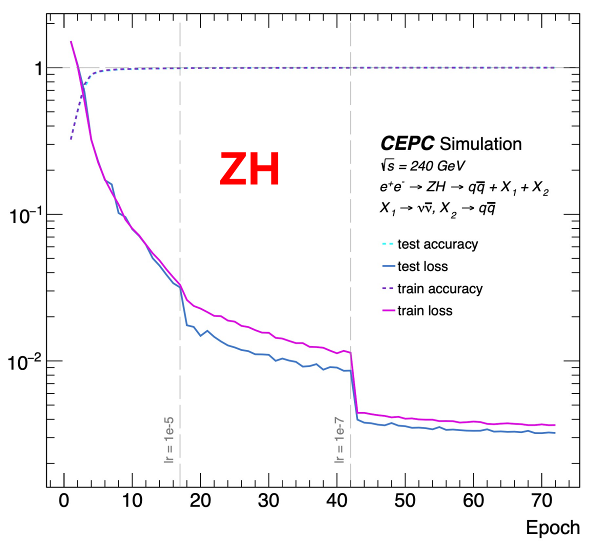

Signal: $e^+e^- \rightarrow Zh \rightarrow q\bar{q} + (SS1 + SS2) \rightarrow q\bar{q}(q\bar{q}\nu\bar{\nu})$
Hits from Z-boson
Hits from LLP Signal
Energy
Max. ΔT
2-channel
Background: $e^+e^- \rightarrow q\bar{q}$

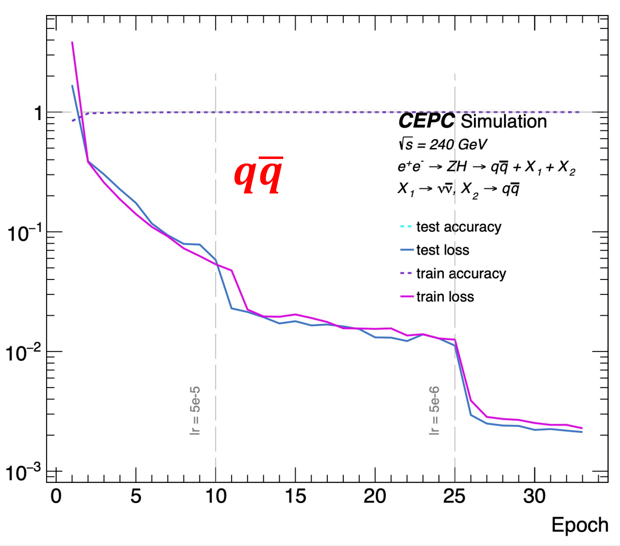
Preselection

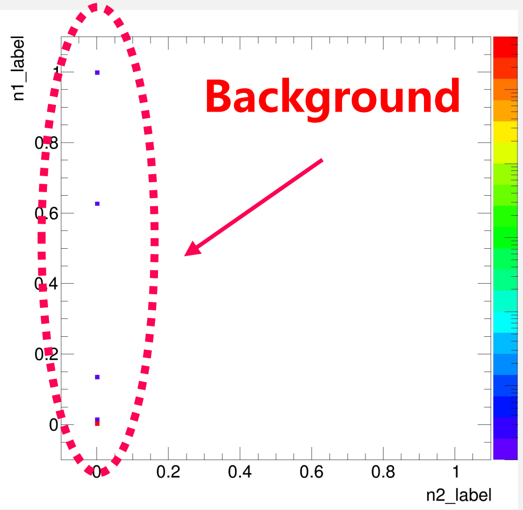


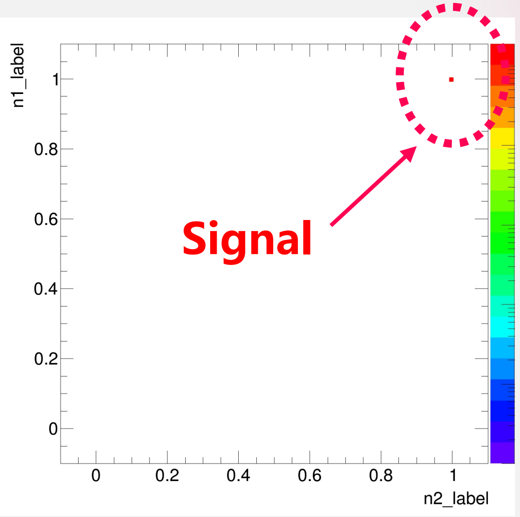
	Signal	ZH	eeqq
Raw Entries	0.5×10^6	0.93×10^6	0.99×10^7
$50 < m_{qq} < 180$ && $35 < m_{\text{recoil}} < 175$ && $0.25 \le y_{12} \le 0.72$	3.8×10^5	182,844	848,529
Efficiency	72.41%	19.66%	8.57%

ResNet18 (2 channel: $E, \Delta T$)









	$n_1 = 1$ & $n_2 = 1$	ϵ	Weight
Signal	377742	99.99%	×1
ZH	0	0.00%	×1
qq	0	0.00%	×25

Long-Lived Particle

ML-based and Cut-based comparison ($Z \to \bar{\nu}\nu$)

	Signal: $Z \to \bar{\nu}\nu$	$e^+e^- \to q\bar{q}$	$e^+e^- \to Zh$	**Total**
# of Events in 5.6 ab^{-1}		2.5×10^8	1.0×10^6	2.01×10^8
# of Events simulated	$\sim 1.0\times10^6$	$(\sim 0.99\times10^7)^*$	$\sim 1.37\times10^6$	$\sim 2.87\times10^6$
$\mathrm{E}_{\mathrm{missing}} > 190\ GeV$ && $n_{rec} < 8$	88,077	290	3,361	3,651
$ML\ score > 0.95$	87,050	0	0	0
Efficiency (ML-based)	**98.83%**	–	–	–
$E_{2j} \geq 30\ \mathrm{GeV}$ && $\min(\Delta T_{j_1}, \Delta T_{j_2}) > 3\ \mathrm{ns}$	66,325	0	0	0
Efficiency (Cut-based)	**73.89%**			

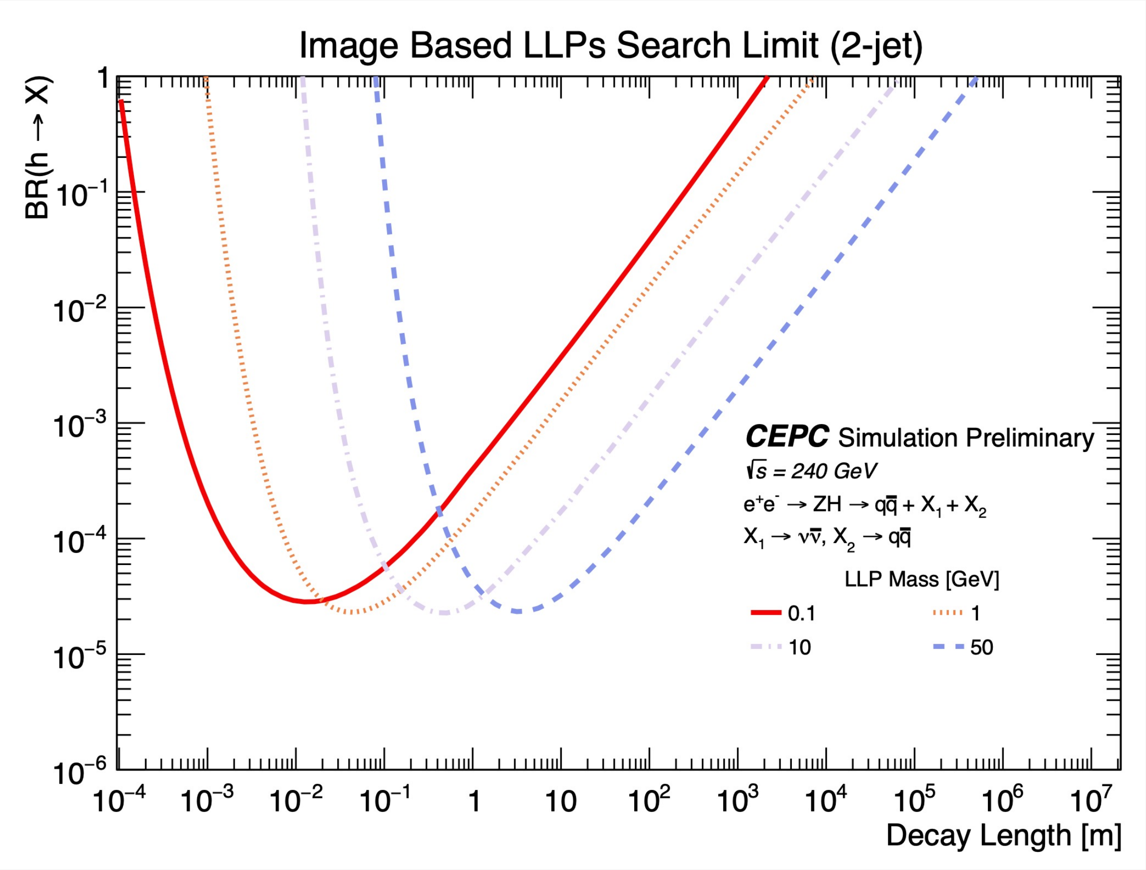
* Due to the limited computing power, $\sim10^7$ events were simulated so far

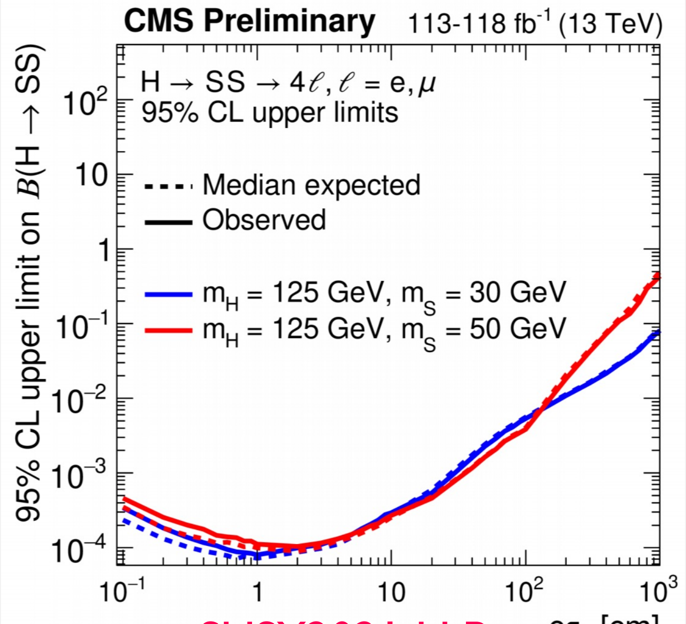
Expected Limits

	Signal	Total Background	Expected Limits
$e^+e^- \to Zh \to (Z{:}\,\bar{q}q)\bar{q}q\bar{v}v$	373308	0.02 (CR)	2.4×10^{-5}
$e^+e^- \to Zh \to (Z{:}\,\bar{v}v)\bar{q}q\bar{v}v$	87,050	0.02 (CR)	9.8×10^{-5}
Combined limit: $\mathbf{1.9\times10^{-5}}$			

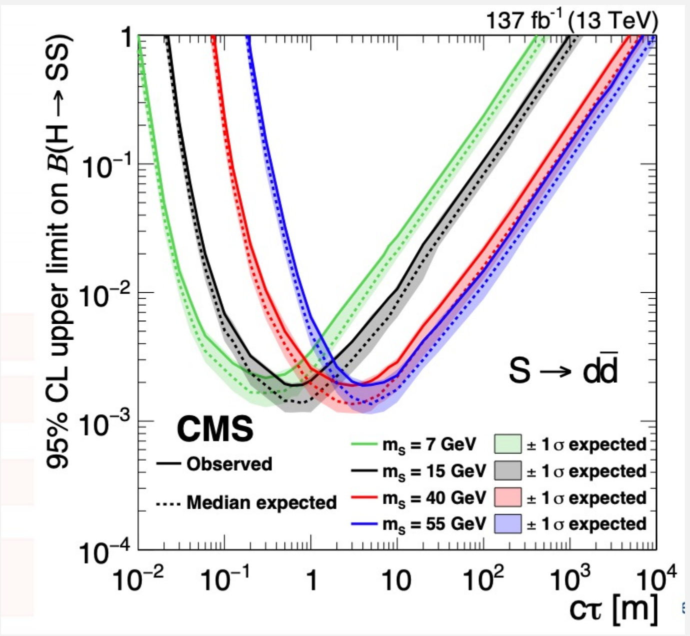
- Limits are the minimal branching ratio of Higgs decaying to LLPs (the smaller the better).
- Cosmic Ray(CR) veto efficiency is calculated by the filter that the time difference of two clusters on the outermost cell must be less than 2.4 meters. (signal inefficiency~ 2.1%)
- Signal Yield: $n_s = \mathcal{L}\times\sigma(e^+e^- \to Zh)\times\sigma(Z \to qq,\bar{v}v)\times\epsilon_{sig}\times\epsilon_{CR}$

Sensitivity





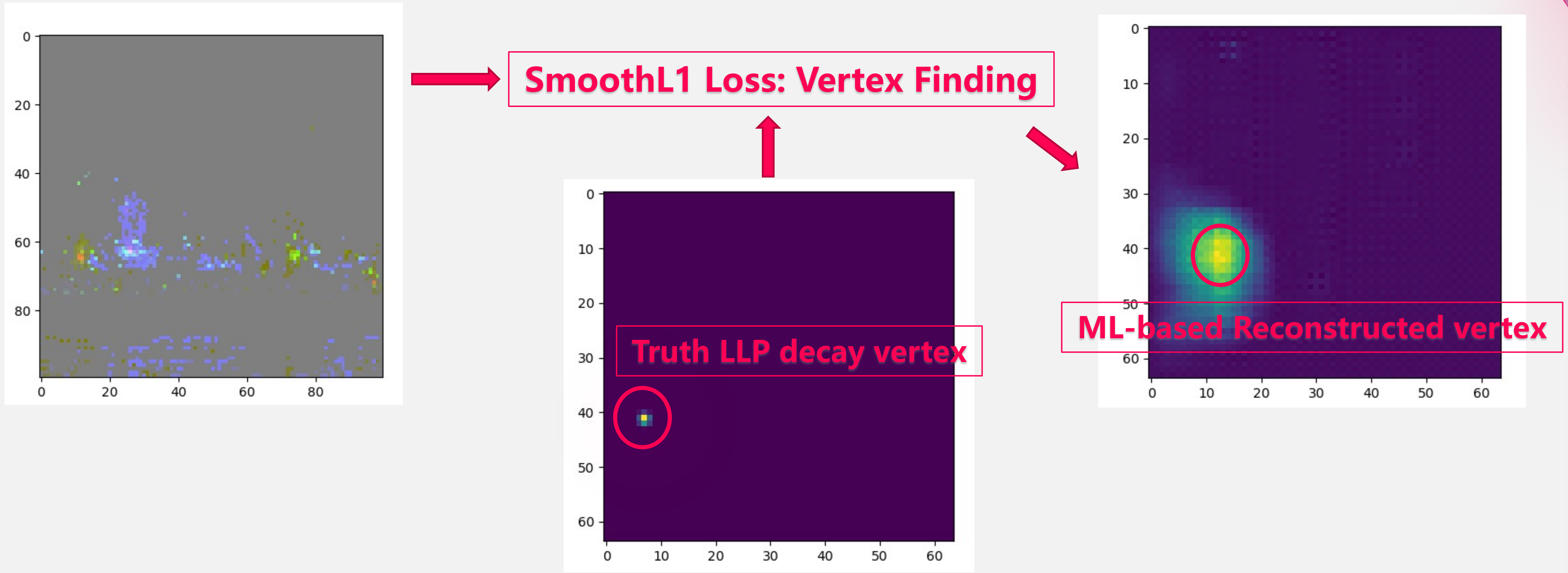
SUSY2021 LLP



- Best branching ratio exclusion limit at decay length around a few meters: $BR(h \to XX) > \sim 10^{-5}$ for most LLP masses
- Good sensitivity for low LLP mass (as low as 0.1 GeV)

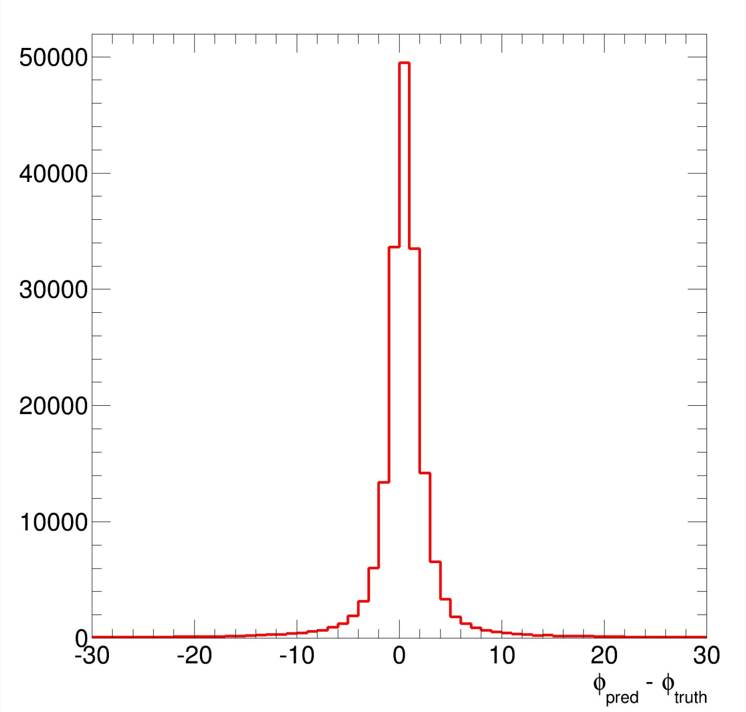
Long-Lived Particle

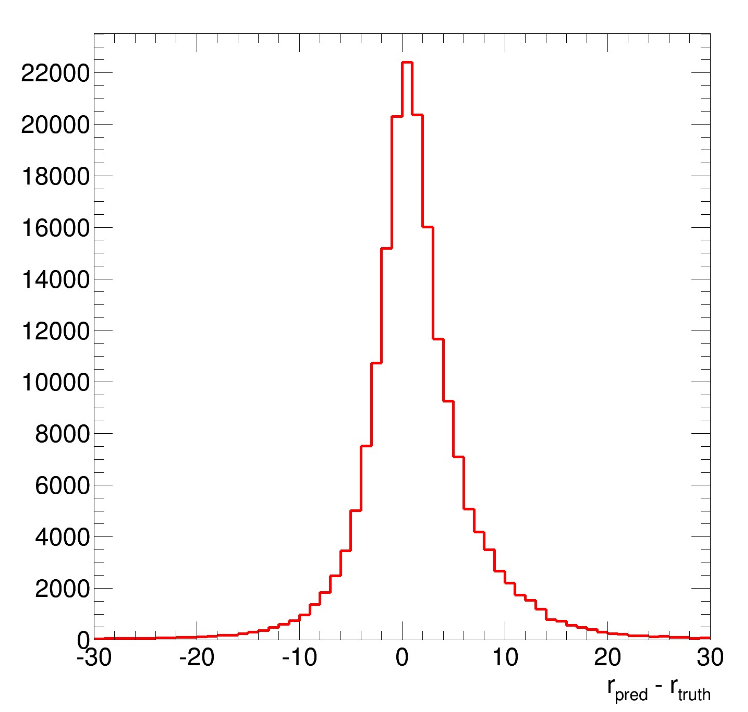
Preliminary Study: Vertex Finding With ML

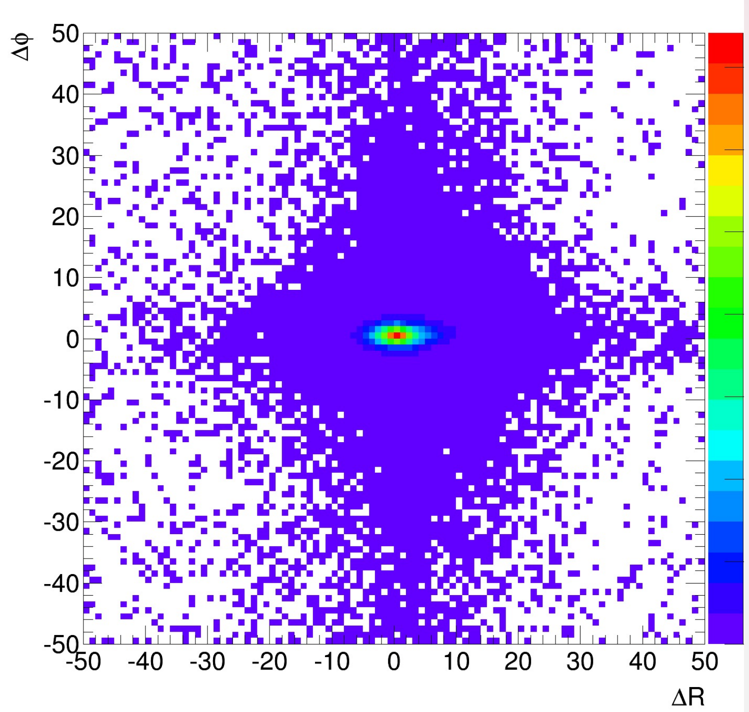


Smooth L1 Loss: $loss(x,y) = \frac{1}{n}\sum_{i=1}^{n}\begin{cases}0.5\times\left(y_i - f(x_i)\right)^2, & \text{if } |y_i - f(x_i)| < 1\\ |y_i - f(x_i)| - 0.5, & \text{otherwise}\end{cases}$

Preliminary Study: Vertex Finding Results







$$\Delta \mathrm{R} = \mathrm{R}_{\mathrm{pred}} - \mathrm{R}_{\mathrm{truth}} \quad \Delta\phi = \phi_{\mathrm{pred}} - \phi_{\mathrm{truth}}$$

- **pixel size: 7.1cm**
- **Initial result looks very promising**

Summary

- Long-Lived Particle ($h \to q\bar{q}\nu\bar{\nu}$) study done with future lepton collider
  - current results based on CEPC_v4 geometry setup
- For background-free channel (both for ML-based and cut-based), $\boldsymbol{ZH \to \bar{\nu}\nu + SS_1 + SS_2}$, ML can increase signal efficiency from 73.9% to 98.8%.
- Working on exploring other possibilities with ML: e.g., vertex finding
- First attempt to apply AI image recognition techniques to raw detector hits
  - Very good sensitivity reached $(\sim 10^{-5})$ with (expected) 10^6 Higgs statistics compared to current LHC limits $(\sim 10^{-4})$.

Thanks

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