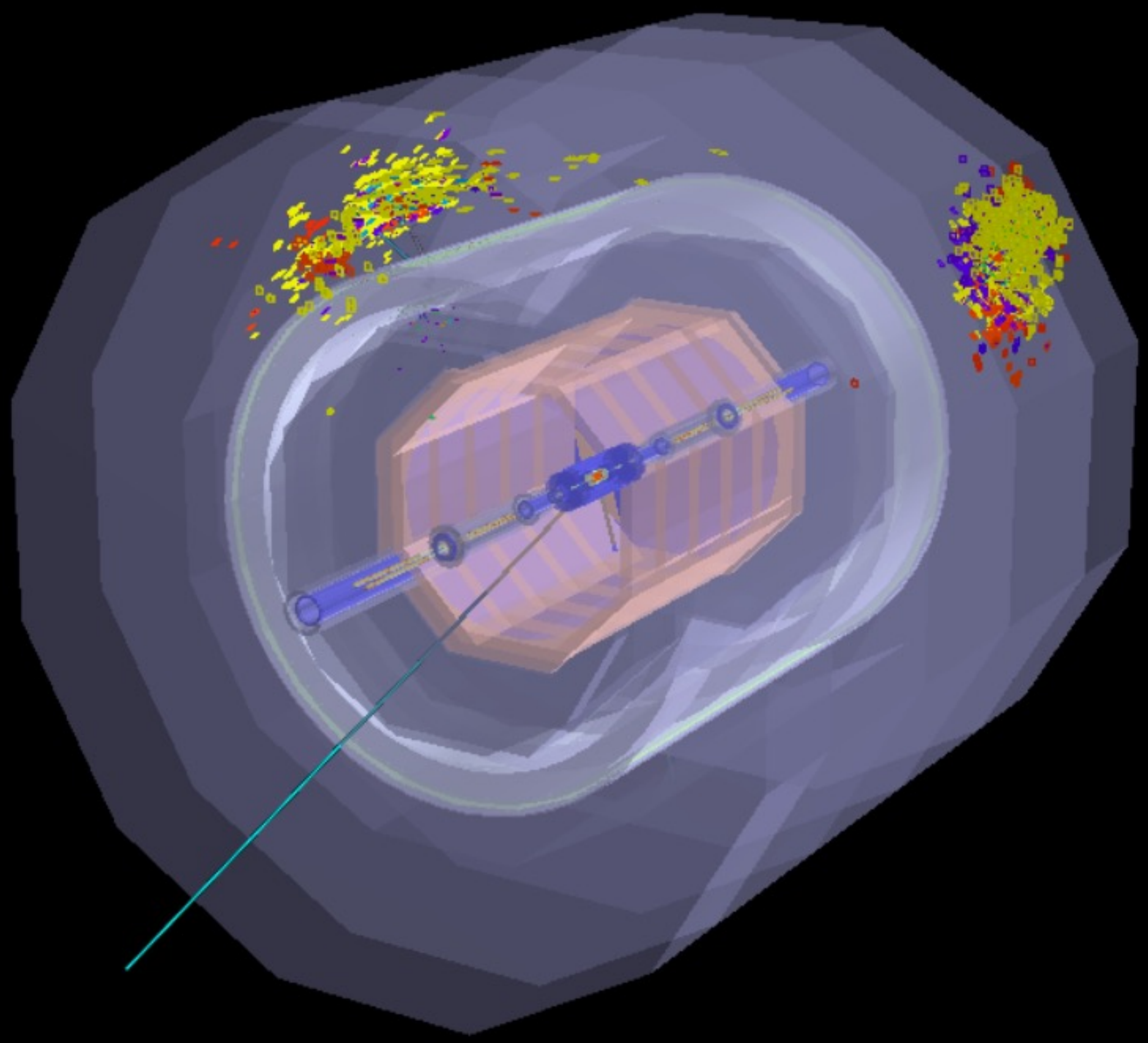


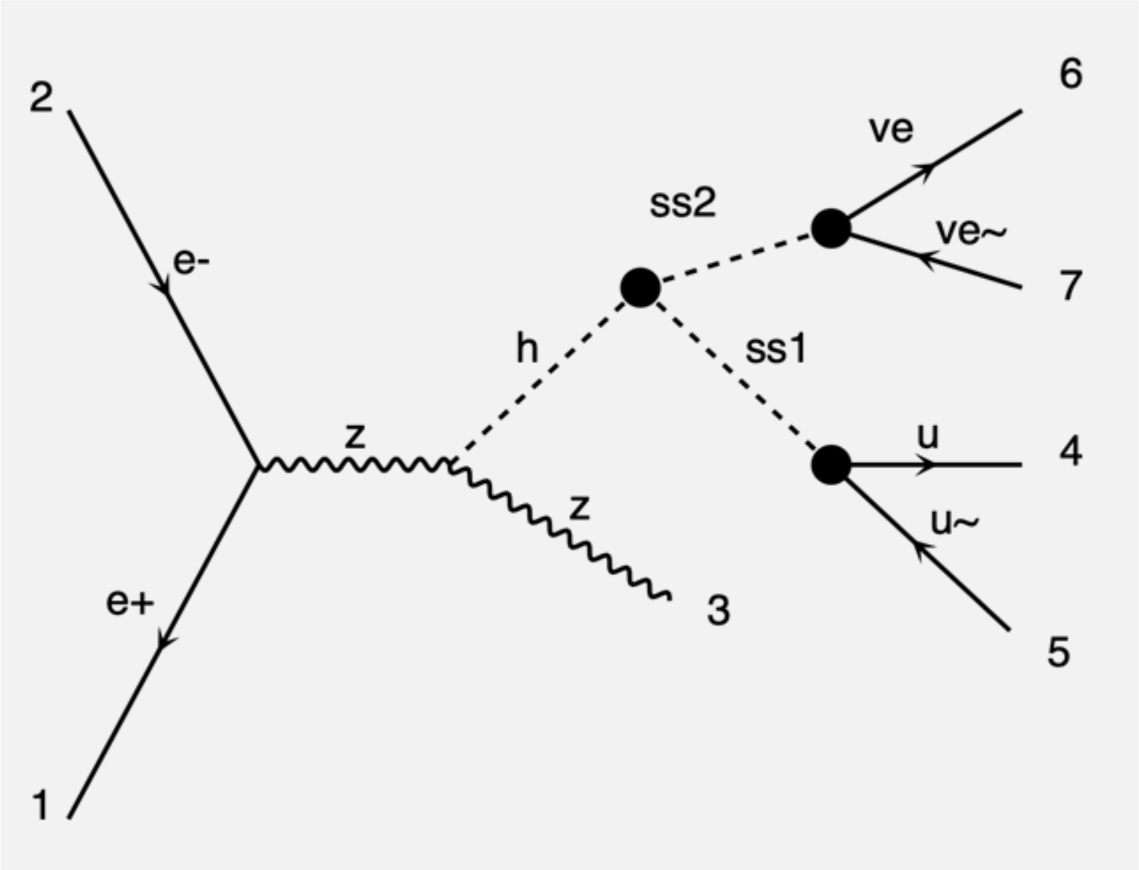
Long-Lived Particle Search with Lepton Colliders

Yulei Zhang[1], Xiang Chen[1], Jifeng Hu[2], Liang Li[1]
1 Shanghai Jiao Tong University
2 South China Normal University

Outline

Beyond the Standard Model

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

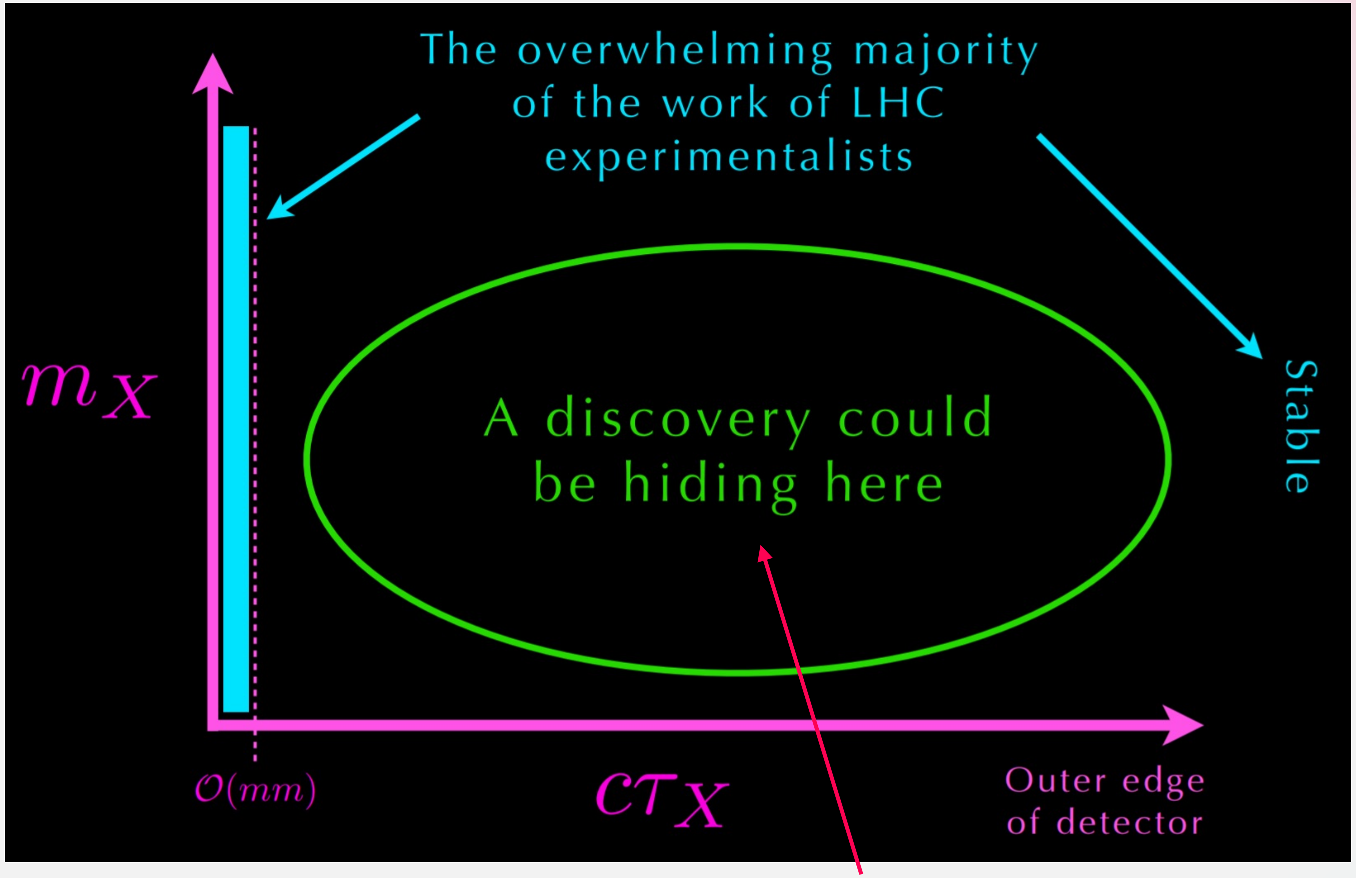


Long-Lived Particle

The lifetime frontier ...

Sixth workshop of the LHC LLP Community

- 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.



Long-Lived Particle

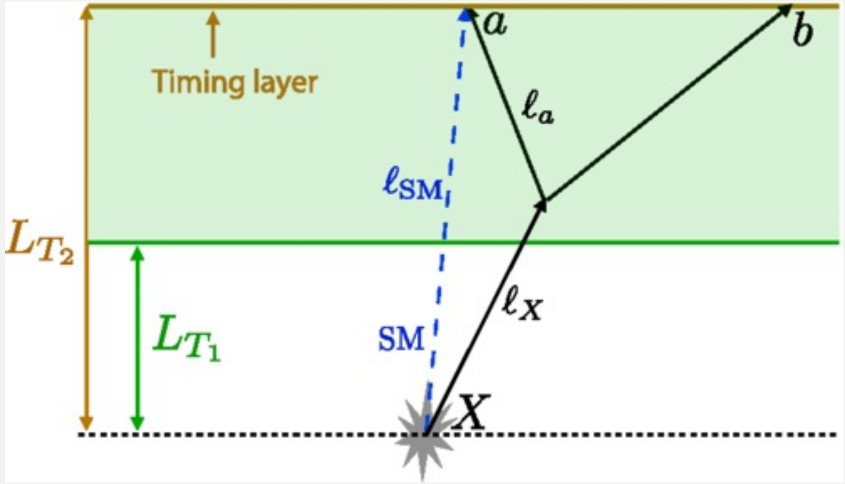
What is a long-lived particle?

[Sixth workshop of the LHC LLP Community]

*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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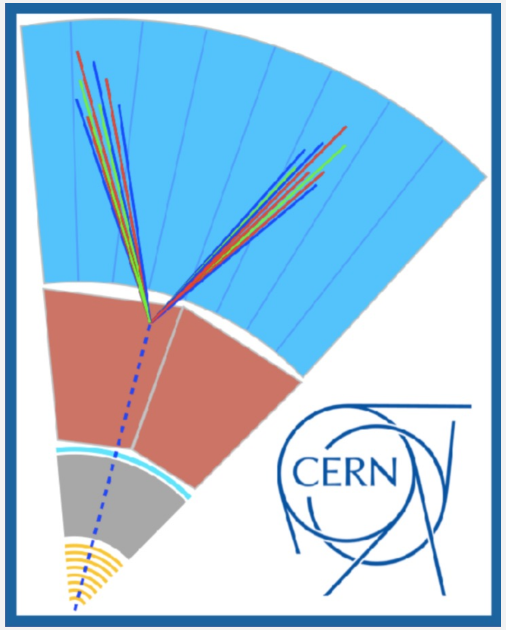
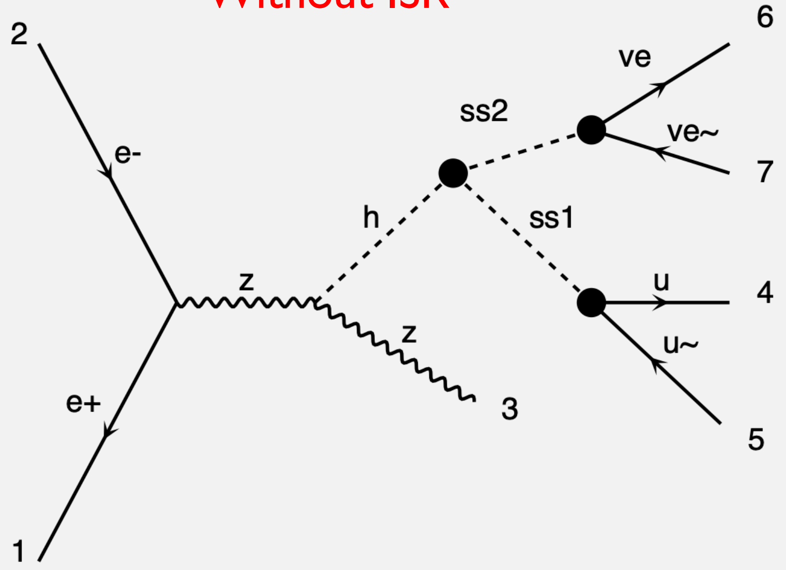
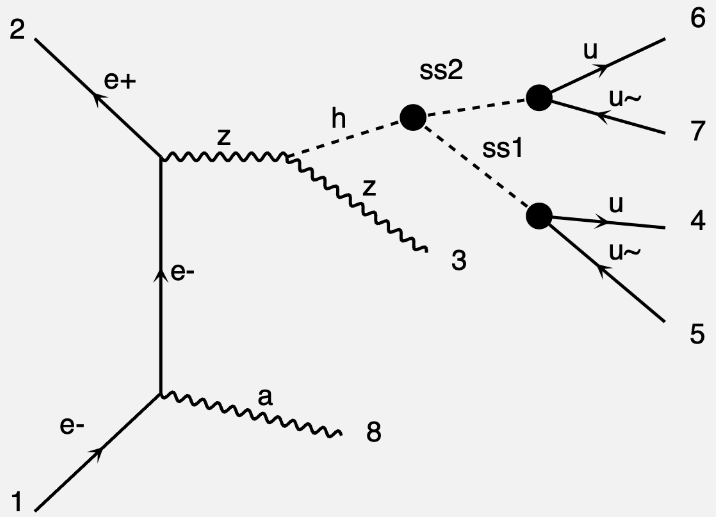


LLP Searches at Lepton Colliders

Without ISR



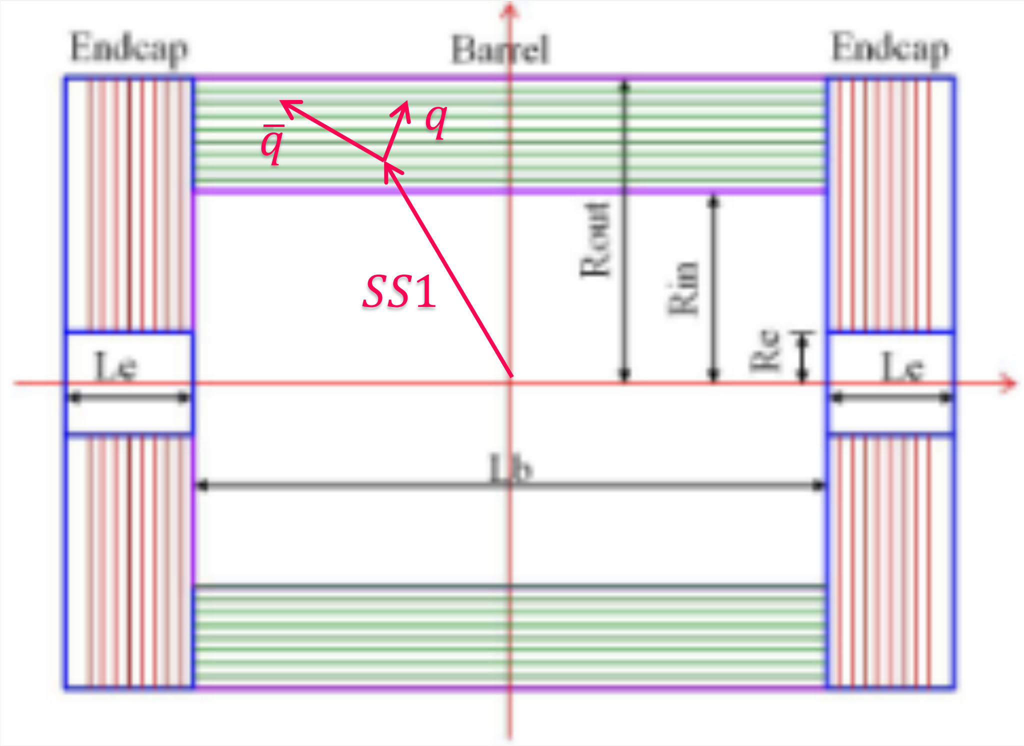
With ISR



- Energy: 240 GeV
- Mass of SS1: 1-50 GeV
- Mass of SS2: 1-50 GeV
- SS1, SS2's lifetime $\tau = R_{out}/c \ = 6m/c = 20\ ns$

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
  - $\boldsymbol{e^+e^- \rightarrow ZH}$
  - $\boldsymbol{e^+e^- \rightarrow qq}$
- **Full simulation** with CEPC official software

First try with traditional reconstruction method
(signal range: 4~6 meters)

Cut-based Analysis

Event Selection ($Z \rightarrow \bar{q}q$)

	Signal: $Z \rightarrow \bar{q}q$	$e^+e^- \rightarrow q\bar{q}$	$e^+e^- \rightarrow Zh$	Total
# of Events in 5.6 ab^{-1}		2.0×10^8	1.0×10^6	2.01×10^8
# of Events simulated	$\sim 1.3\times10^6$	$\sim 0.99\times10^7$	$\sim 1.37\times10^6$	$\sim 2.87\times10^6$
Decay in Muon Detector	134,559	6,516,657	796,596	7,313,253
$\lvert m_{qq} - m_Z \rvert \leq 15$ GeV	113,723	4,013,875	39,631	4,053,506
$\lvert m_{qq}^{rec} - m_h \rvert \leq 15$ GeV	104,942	229,703	26,862	256,565
$0.23 \leq y_{12} \leq 0.72$	93,517	129,546	20,041	149,587
$E_{2j} \geq 30$ GeV	69,468	72	16	88
$\min(\Delta T_{j_1}, \Delta T_{j_2}) > 3$ ns	68,368	50	11	61
Efficiency	50.80%	0.00077%	0.0014%	0.00083%

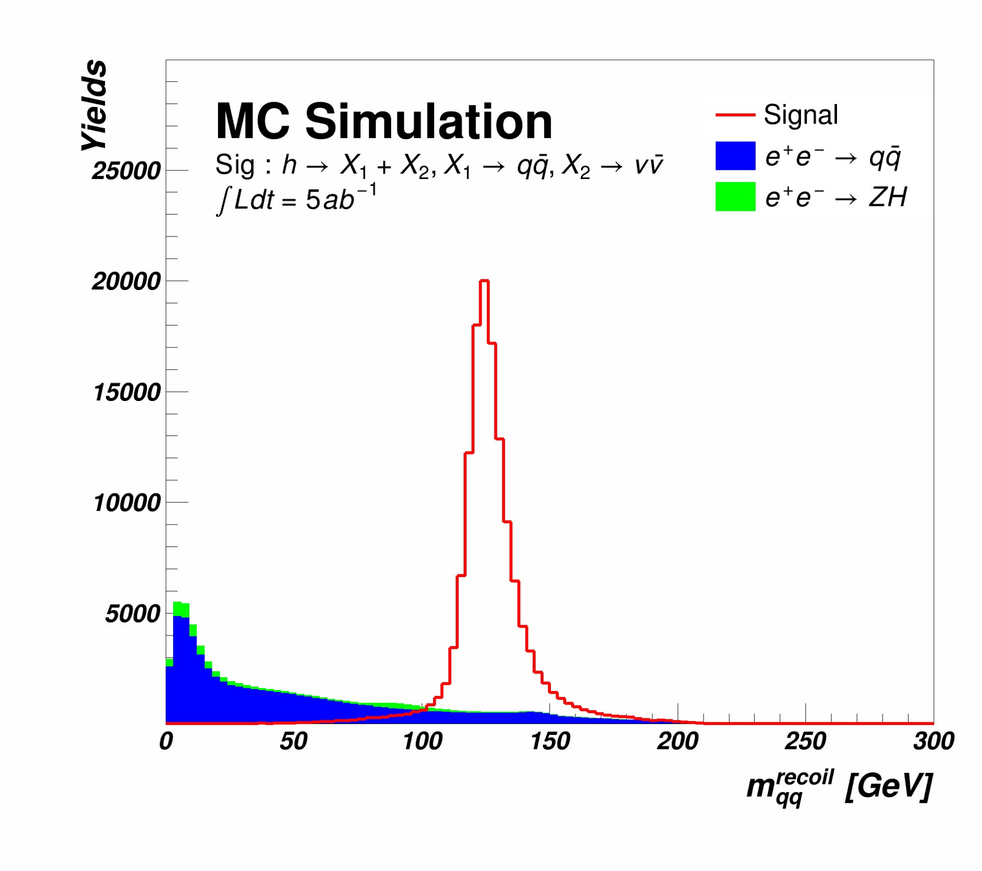
- qq is reconstructed by $e^+e^- - k_T$ algorithm, which represents for the jets from primary vertex
- Using $anti - k_T$ algorithm to cluster hits (j_1 & j_2) in Muon detector.

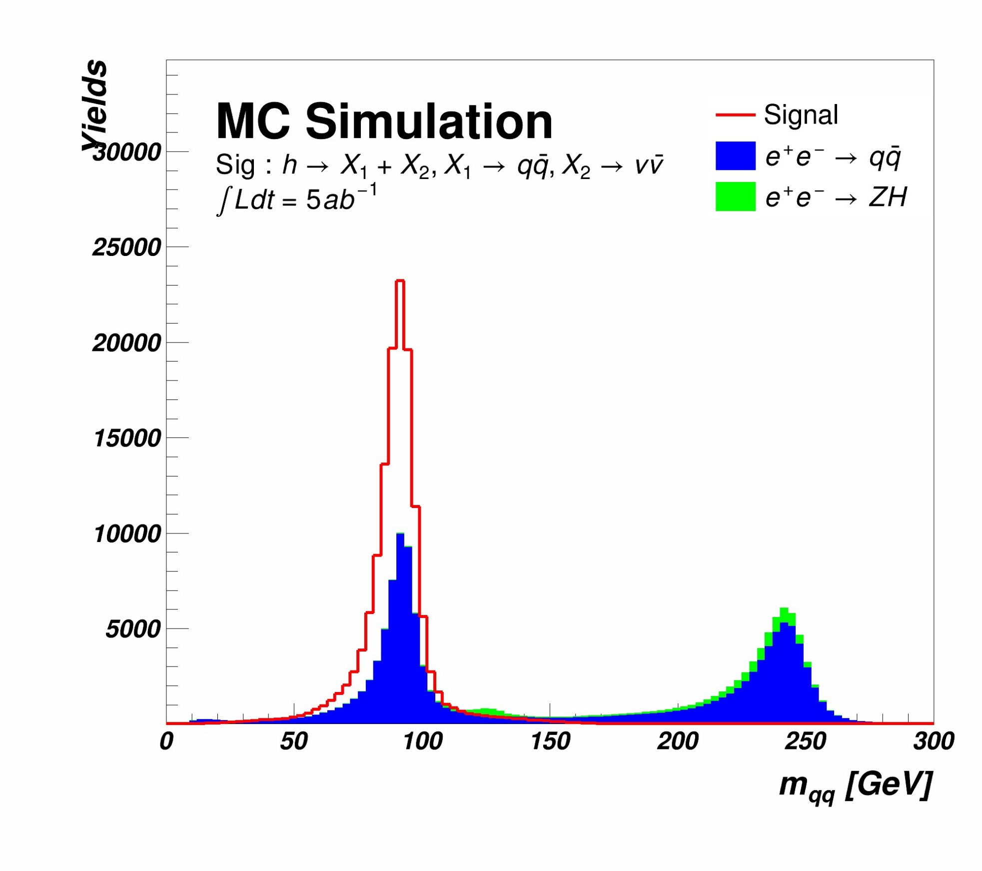
Event Selection ($Z \to \bar{\nu}\nu$)

	Signal: $Z \to \bar{\nu}\nu$	$(e^+e^- \to q\bar{q})^*$	$e^+e^- \to Zh$	Total
# of Events in 5.6 ab^{-1}		2.0×10^8	1.0×10^6	2.01×10^8
# of Events simulated	$\sim 1.0\times10^6$	$\sim 0.99\times10^7$	$\sim 1.37\times10^6$	$\sim 2.87\times10^6$
Decay in Muon Detector	89,757	6,516,657	796,596	7,313,253
$E_{\text{missing}} > 190\ GeV$	89,437	463,421	6,413	469,834
$n_{rec} < 8$	88,103	281,897	3,901	285,798
$E_{2j} \geq 30$ GeV	67,244	0	0	0
$\min(\Delta T_{j_1}, \Delta T_{j_2}) > 3$ ns	66,325	0	0	0
Efficiency	73.89%	–	–	–

- $e^+e^- \to qq$ is scaled by $e^+e^- \to Zh$ process

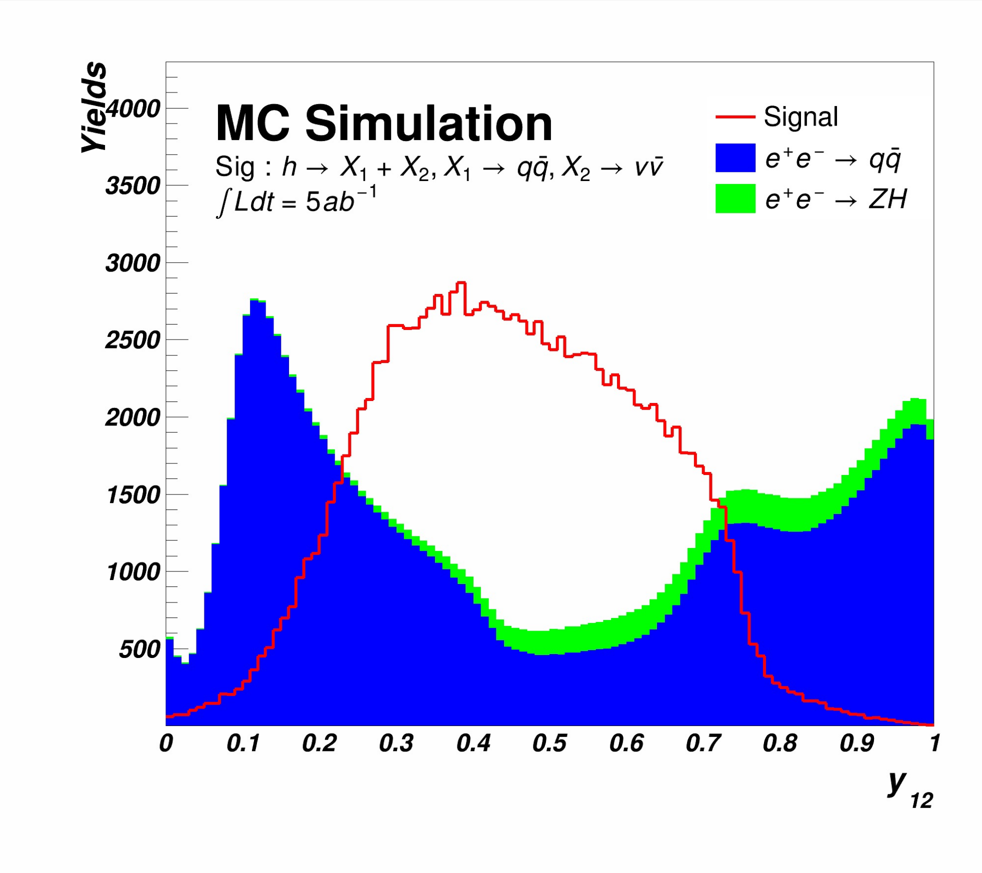
Mass of 2 prompt jets

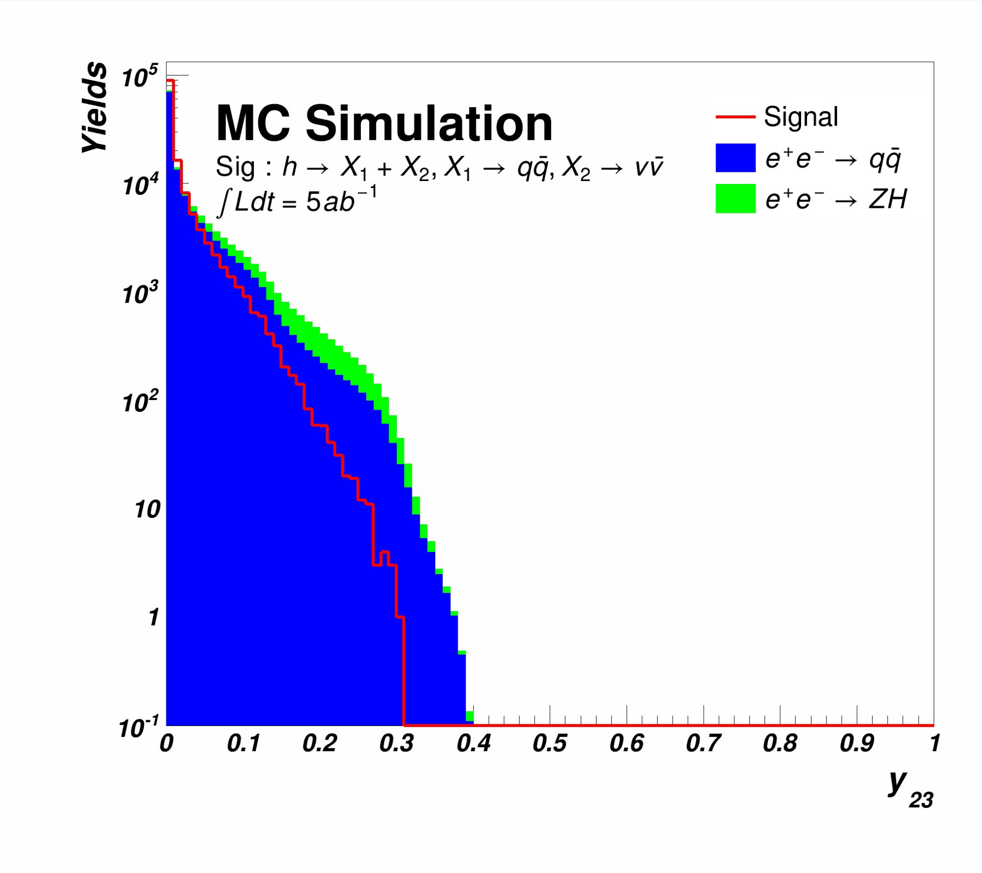




- qq is reconstructed by $e^+e^- - k_T$ algorithm, which represents for the jets from primary vertex
- Background is normalized to the scale of signal.

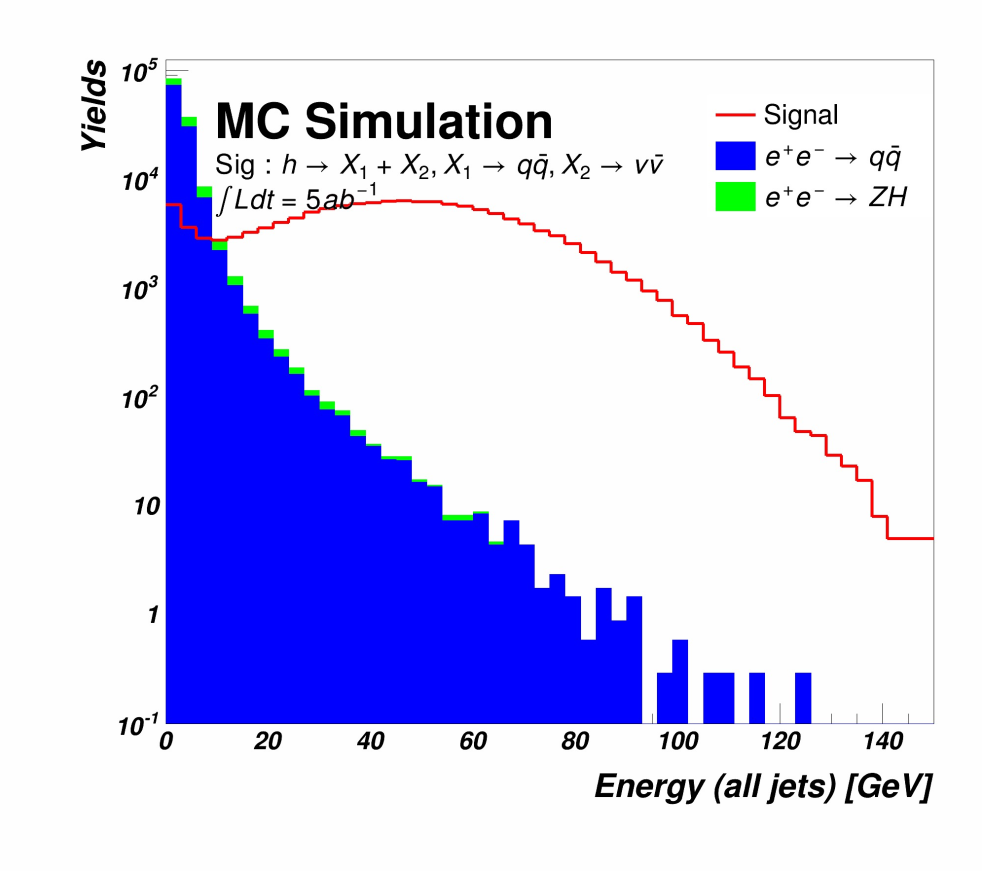
Shower distance

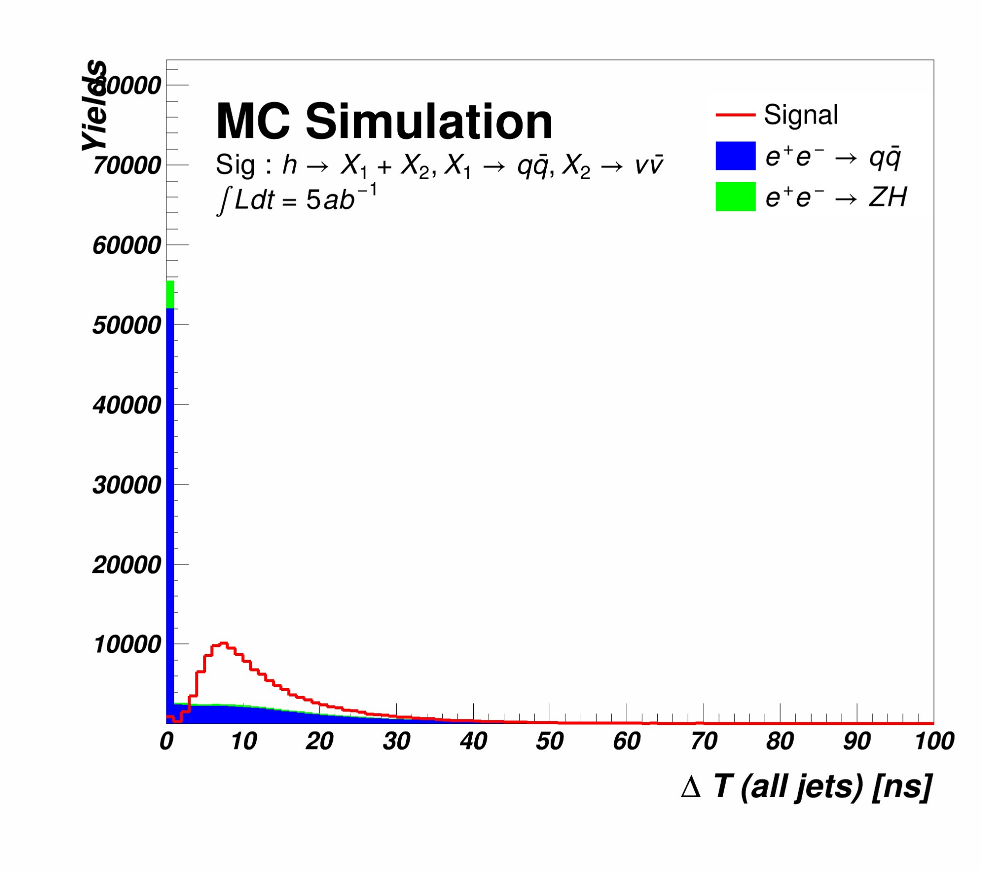




- qq is reconstructed by $e^+e^- - k_T$ algorithm, which represents for the jets from primary vertex
- Background is normalized to the scale of signal.

Time Difference vs. Energy

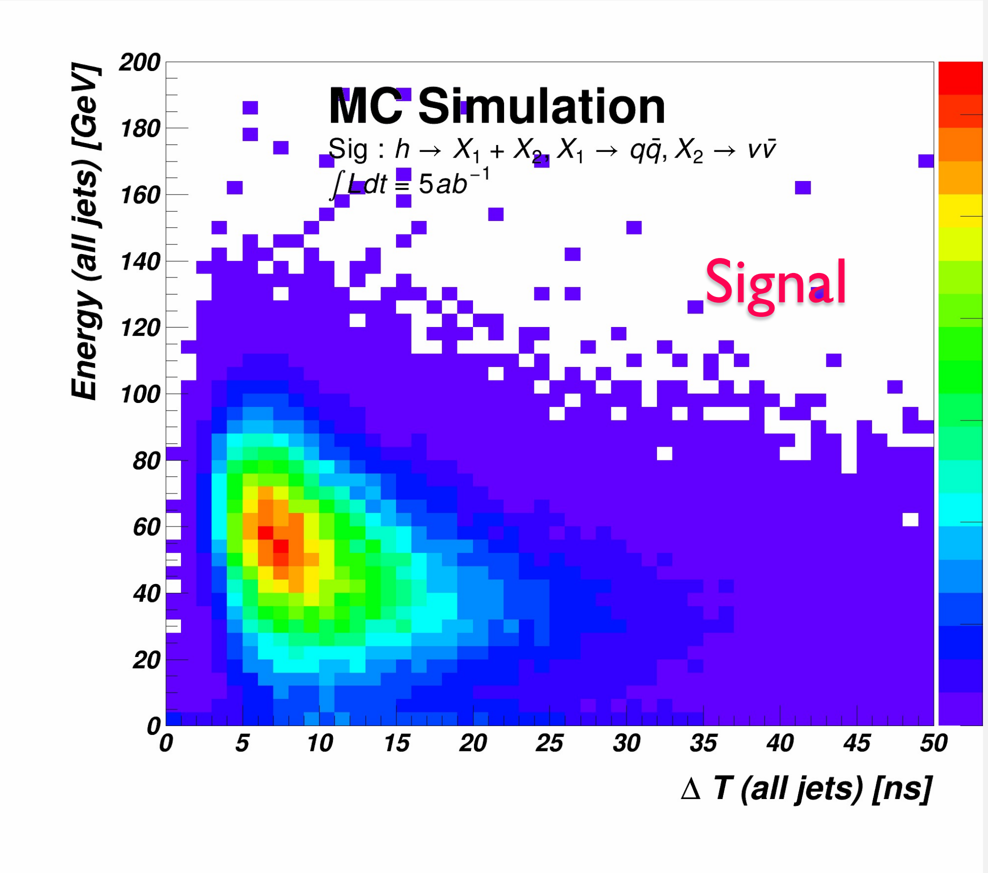


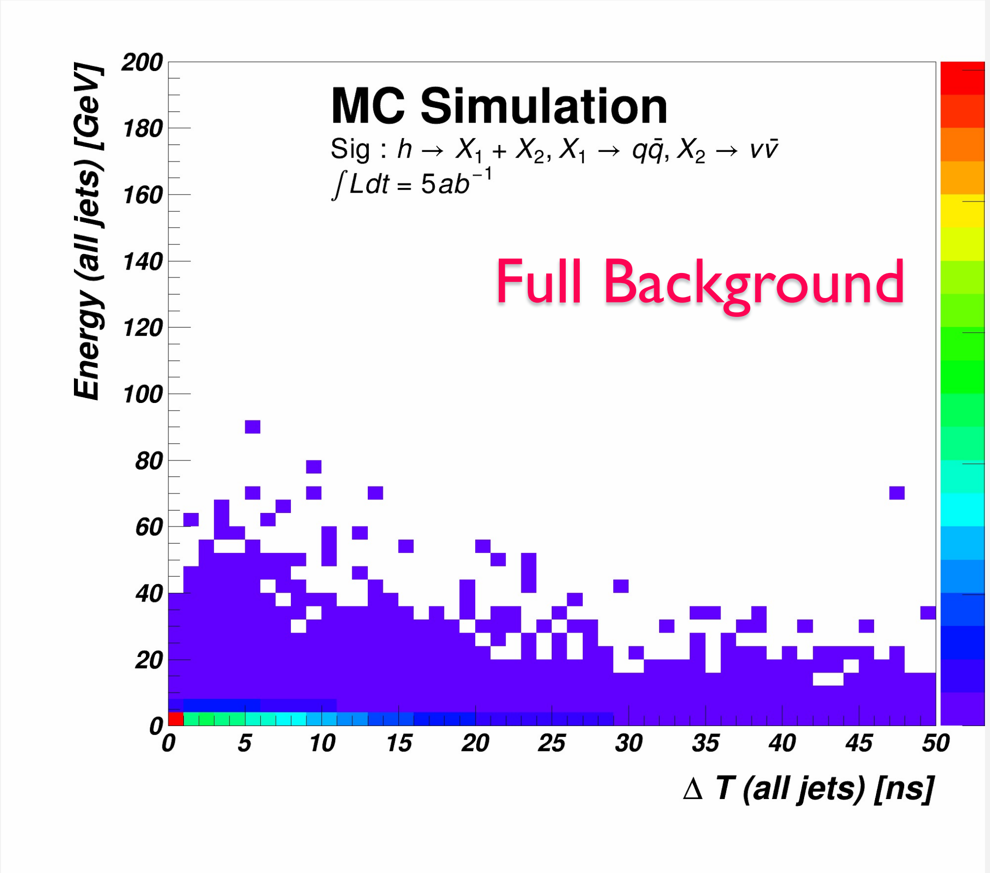


- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

Long-Lived Particle

Time Difference vs. Energy





- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

Estimation of comic ray

- Energetic muon goes in muon detector ($E > 30$ GeV)
- Muon travels with certain angle ($\theta > 60°$)
- $n_{CR} = (\Phi_{\mu} \times A_{\text{CEPC}} \times T_{\text{CEPC}} \times 2\pi) \times \sigma_P \left(\frac{dE}{dx} \geq 12.5GeV\right) \times \sigma_{\theta} = 0.02$

The overall distribution function as a function of both the energy and the zenith angle then can be written as

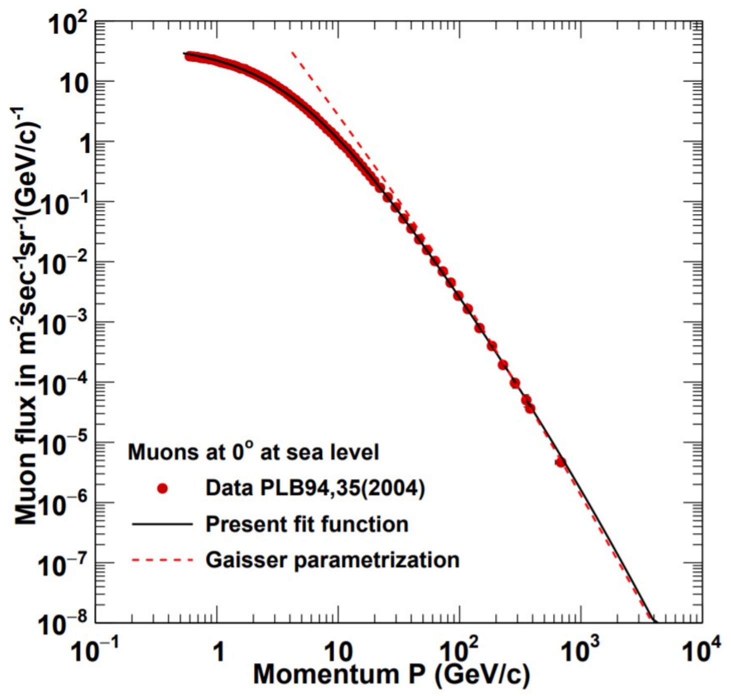
$$I(E,\theta) = I_0\, N\, (E_0 + E)^{-n} \left(1 + \frac{E}{\epsilon}\right)^{-1} D(\theta)^{-(n-1)}. \quad (10)$$

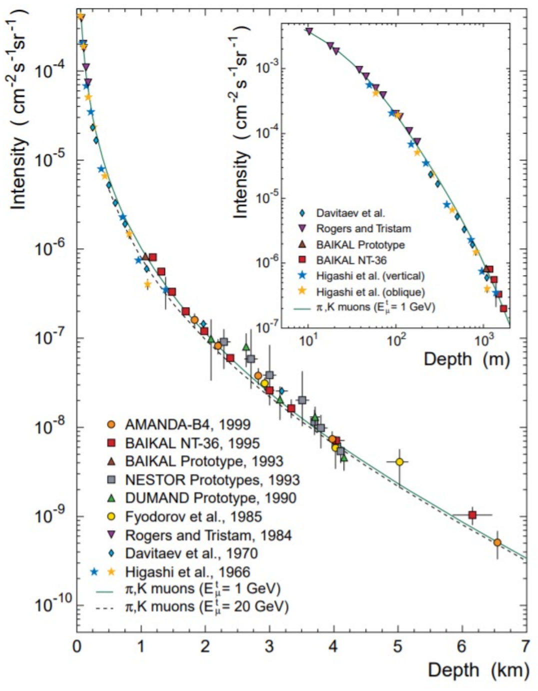
Here, the function $D(\theta)$ is given by Eq 7. If the Earth is assumed to be flat then $D(\theta) = 1/\cos\theta$ which on putting in Eq. 9 leads to

$$\Phi(\theta) = I_0 \cos^{n-1}\theta. \quad (11)$$

$$\frac{dN_{\mu}}{dEd\Omega} \approx 1400 E_{\mu}^{-2.7}/(\text{m}^2\text{sGeVsr}) \left(\frac{1}{1 + \frac{1.1 E \cos\theta}{\epsilon_{\pi}}} + \frac{0.054}{1 + \frac{1.1 E \cos\theta}{\epsilon_{K}}} \right), \quad (12)$$

https://arxiv.org/pdf/1606.06907.pdf





Expected Limits

	Signal	Total Background	Expected Limits
$e^+e^- \to Zh \to (Z:\bar{q}q)\bar{q}q\bar{\nu}\nu$	43,176	511	9.5×10^{-4}
$e^+e^- \to Zh \to (Z:\bar{\nu}\nu)\bar{q}q\bar{\nu}\nu$	17,680	$\sim$0.02 (CR)	5.1×10^{-4}

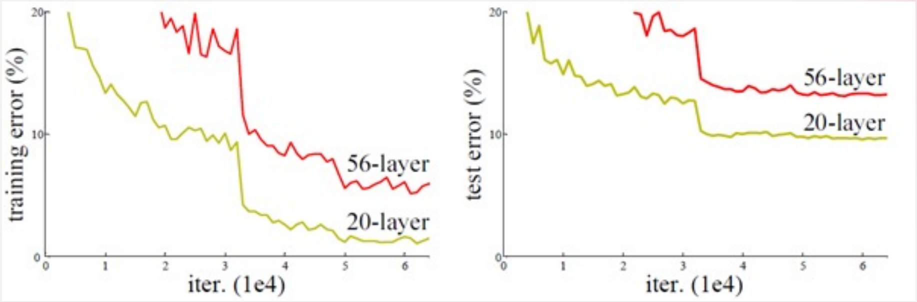
- Limits are the minimal branching ratio of Higgs decaying to LLPs (the smaller the better).
- Cosmic Ray(CR) veto efficiency is calculated by the filter that the time difference of two clusters on the outermost cell must be less than 2.4 meters. (signal inefficiency~ 2.1%)
- Signal Yield: $n_s = \mathcal{L}\times\sigma(e^+e^-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

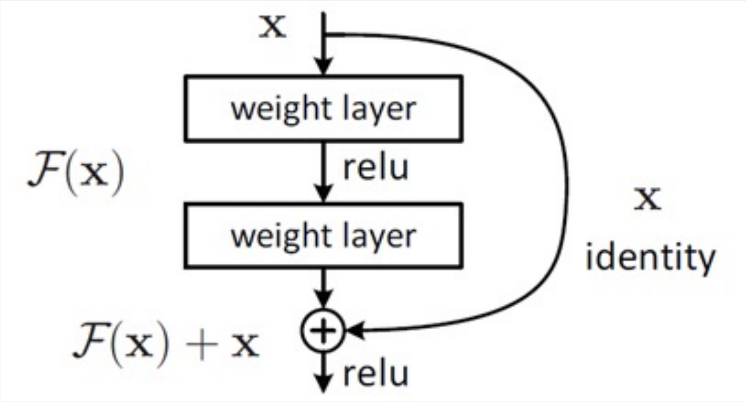
How about those LLPs within Calorimeters?
(signal range: extend to 1~6 meters)

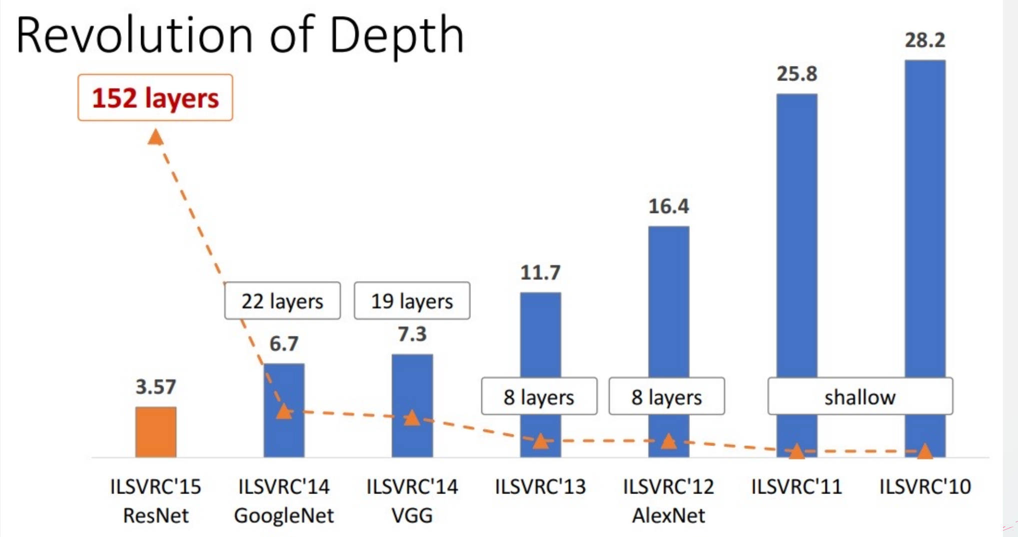
ML based Analysis

Deep Residual Network, ResNet

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



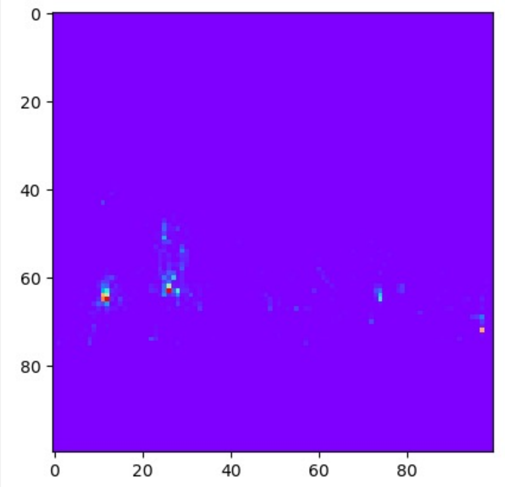




Configuration

- 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.
  - 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:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$

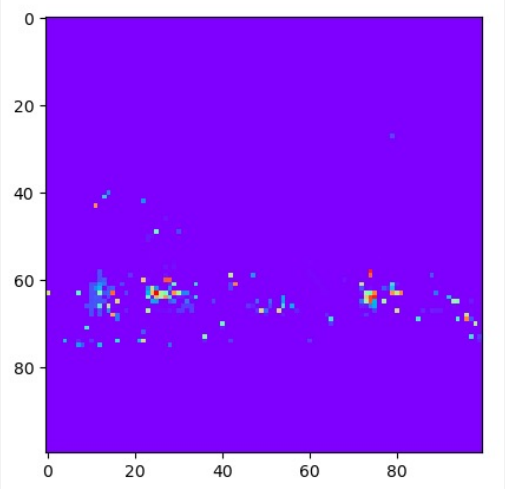
Input Image



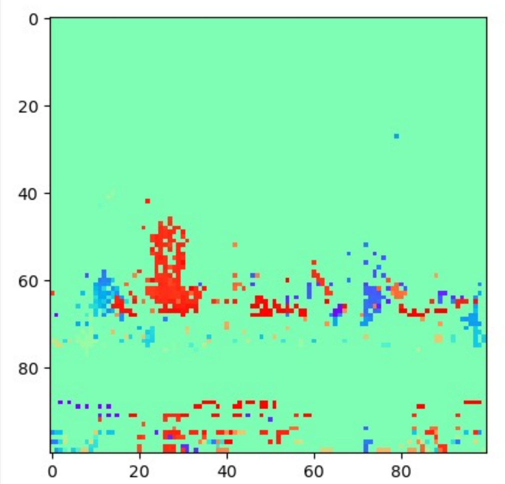
Energy

↓

1-channel Grey

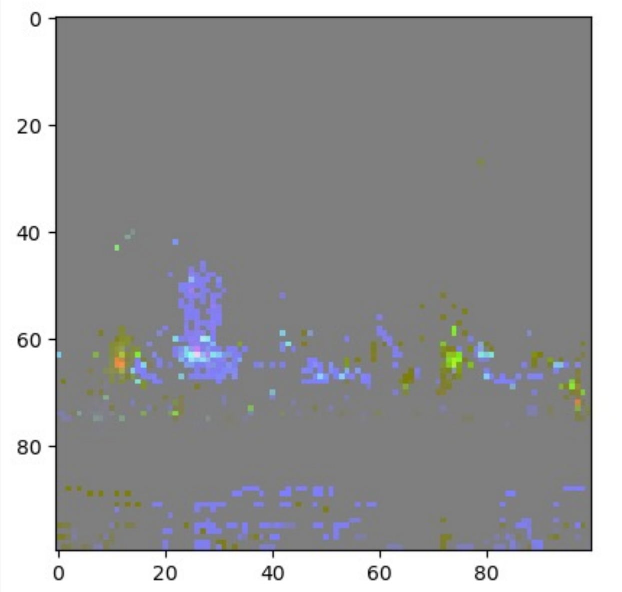


Max. ΔT



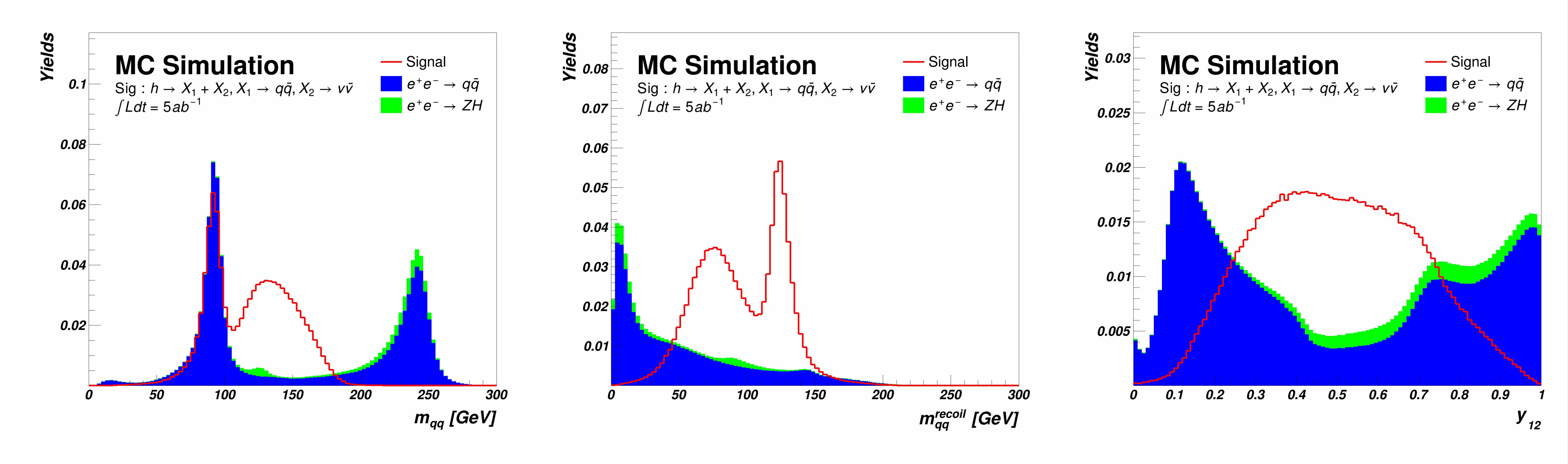
$\cos(\theta)$ of Max. E

→



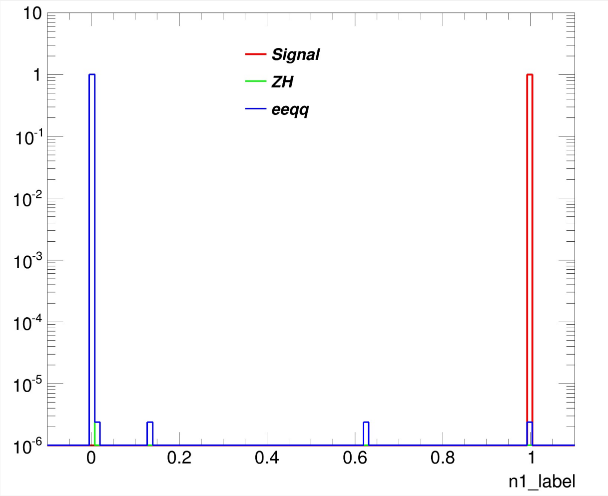
3-channel RGB

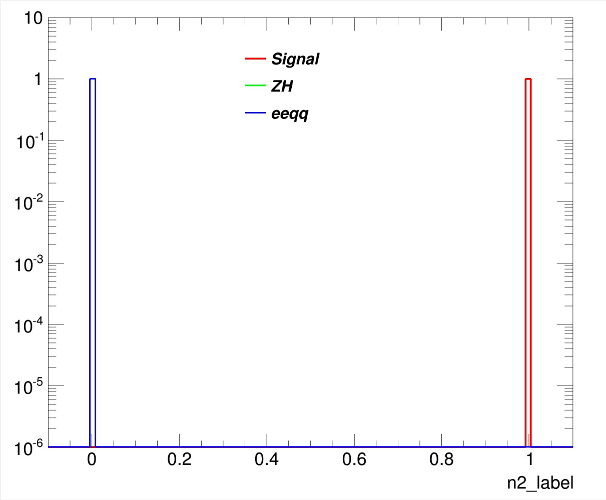
Preselection

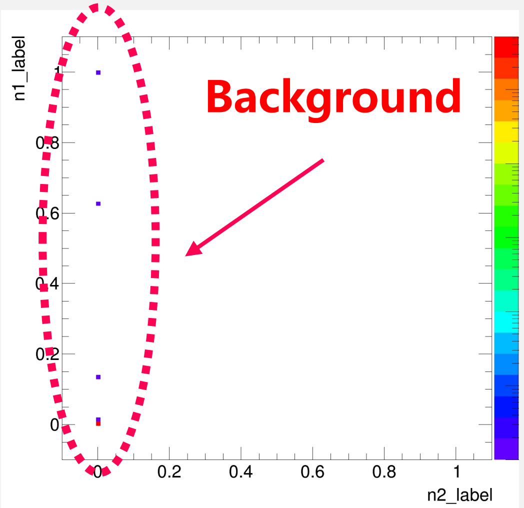


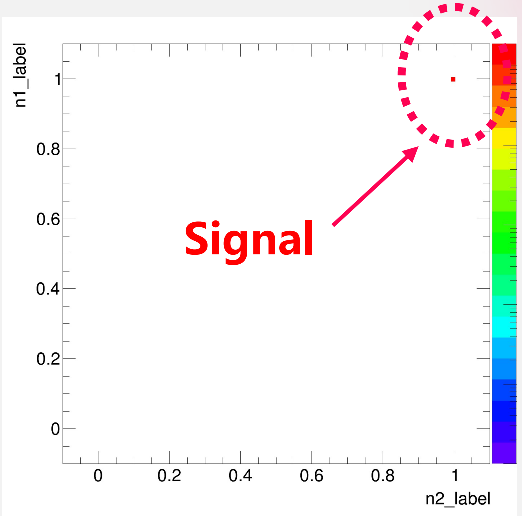
	Signal	ZH	eeqq
Raw Entries	0.5×10^6	0.93×10^6	0.99×10^7
$50 < m_{qq} < 180$ && $35 < m_{\text{recoil}} < 175$ && $0.25 \le y_{12} \le 0.72$	3.8×10^5	182,844	848,529
Efficiency	72.41%	19.66%	8.57%

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









	$n_1 = 1 \,\&\, n_2 = 1$	ϵ	Weight
Signal	377742	99.99%	$\times 1$
ZH	0	0.00%	$\times 1$
eeqq	0	0.00%	$\times 25$

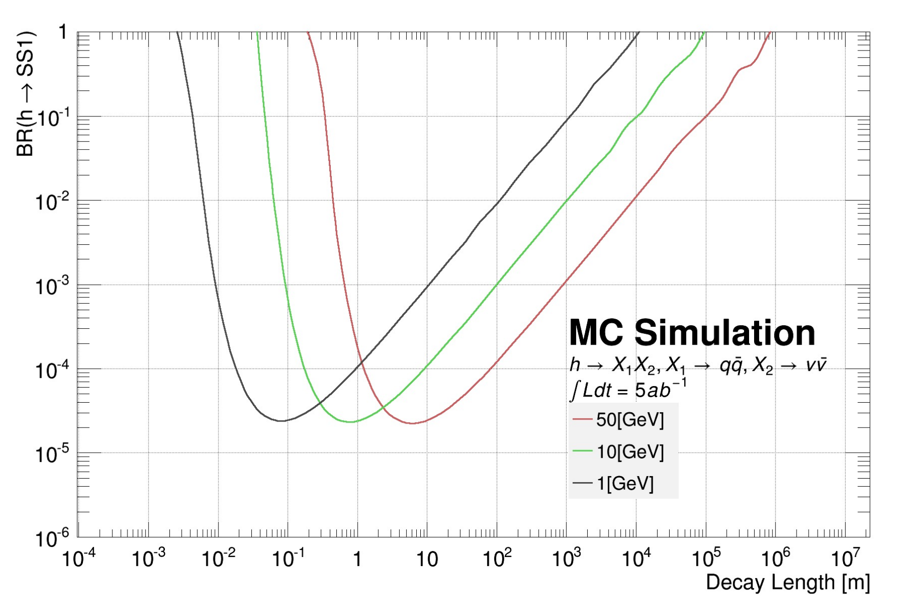
- Due to the limited computing power, it's hard to simulate all $e^+e^- \to q\bar{q}$ samples ($\sim 2.5\times 10^8$)
  - Available samples on lxslc7@ihep $\sim 1.0\times 10^7$

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}
$e^+e^- \to Zh \to (Z{:}\bar{v}v)\bar{q}q\bar{v}v$	92,367	0.02 (CR)	9.8×10^{-5}
Combined limit: 1.9×10^{-5}			

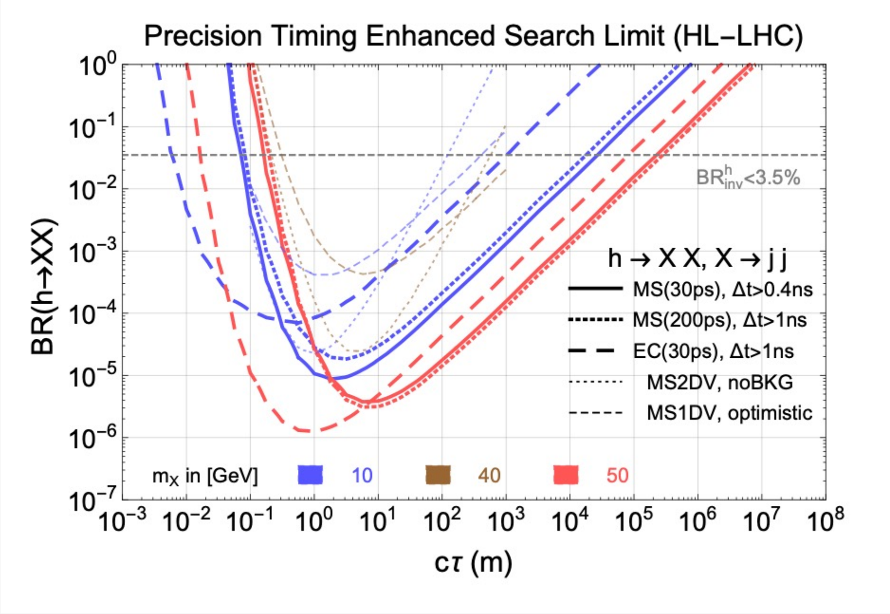
- Limits are the minimal branching ratio of Higgs decaying to LLPs (the smaller the better).
- Cosmic Ray(CR) veto efficiency is calculated by the filter that the time difference of two clusters on the outermost cell must be less than 2.4 meters. (signal inefficiency~ 2.1%)
- Signal Yield: $n_s = \mathcal{L}\times\sigma(e^+e^-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

Sensitivity

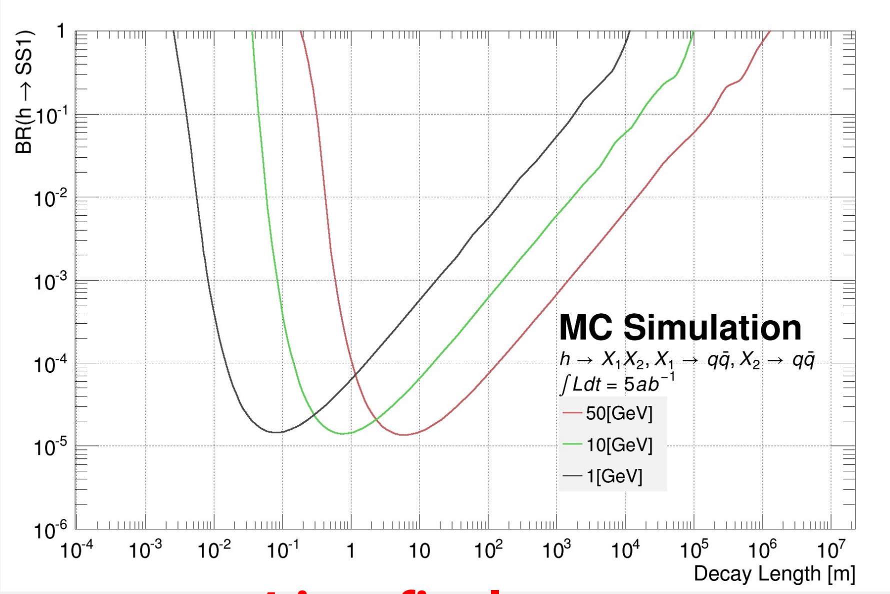


2 jets final state

- **HL-LHC: > 1×10⁸ Higgs**
- **CEPC: ~1×10⁶ Higgs**

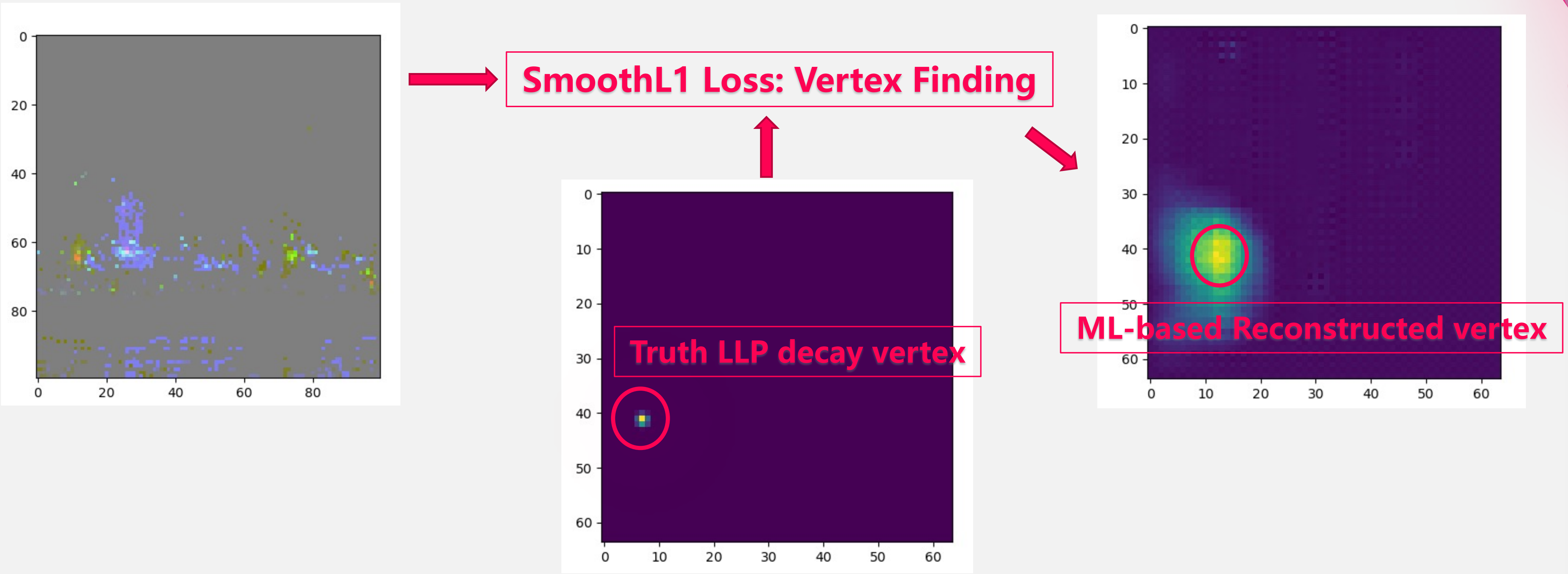


Phys. Rev. Lett. **122**, 131801 – 2019.04.03



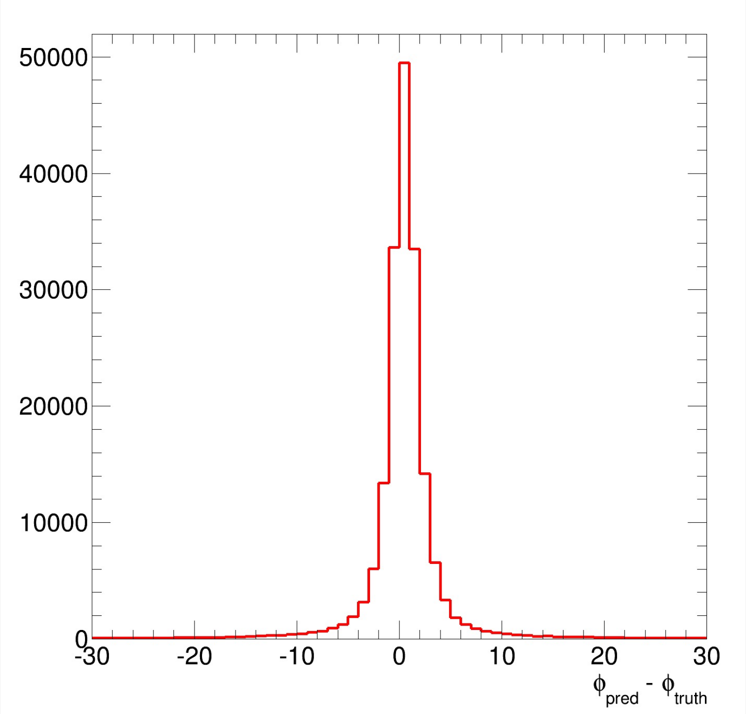
4 jets final state

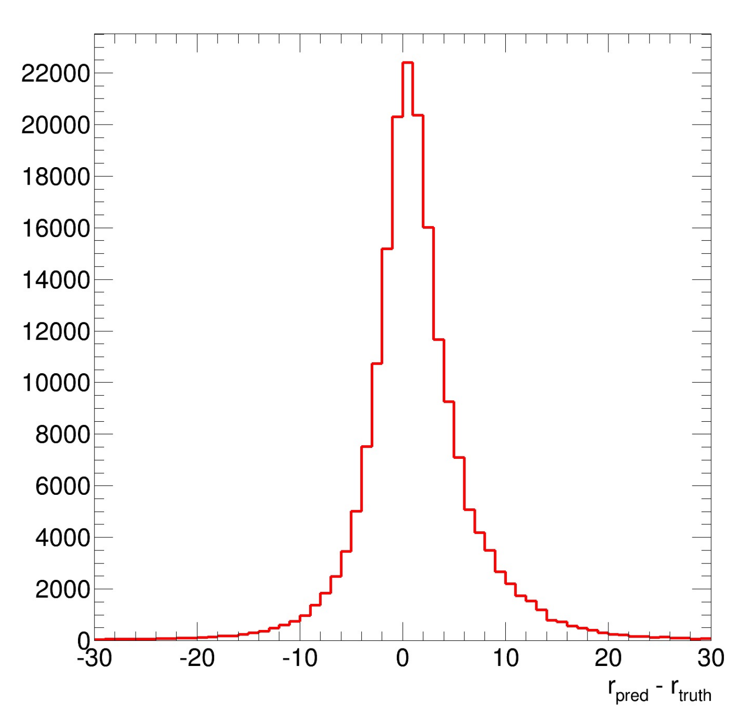
Preliminary Study: Vertex Finding With ML

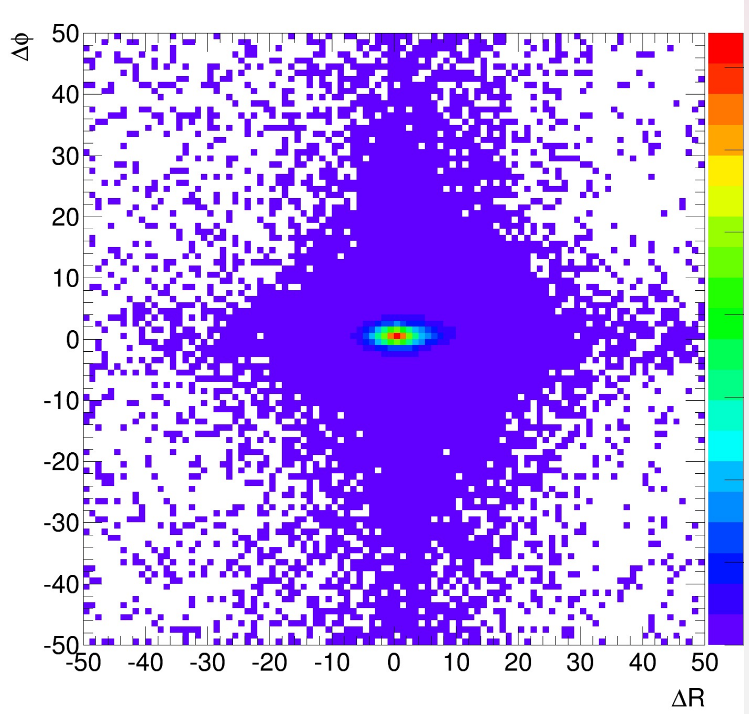


Smooth L1 Loss: $loss(x,y) = \frac{1}{n}\sum_{i=1}^{n}\begin{cases} 0.5\times\left(y_i - f(x_i)\right)^2, & \text{if } |y_i - f(x_i)| < 1 \\ |y_i - f(x_i)| - 0.5, & \text{otherwise} \end{cases}$

Preliminary Study: Vertex Finding Results







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

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

Long-Lived Particle

Summary

- A preliminary study has been performed on Long-Lived Particle ($h \rightarrow q\bar{q}\nu\bar{\nu}$ and $h \rightarrow q\bar{q}q\bar{q}$) based on CEPC_V4.
- Time of flight and Energy deposition in Muon detector are the two main variables with good separation power.
- Preliminary study using deep ML techniques done:
  - results looks very promising
  - improve training on vertex finding and explore other possibilities with ML

Thanks

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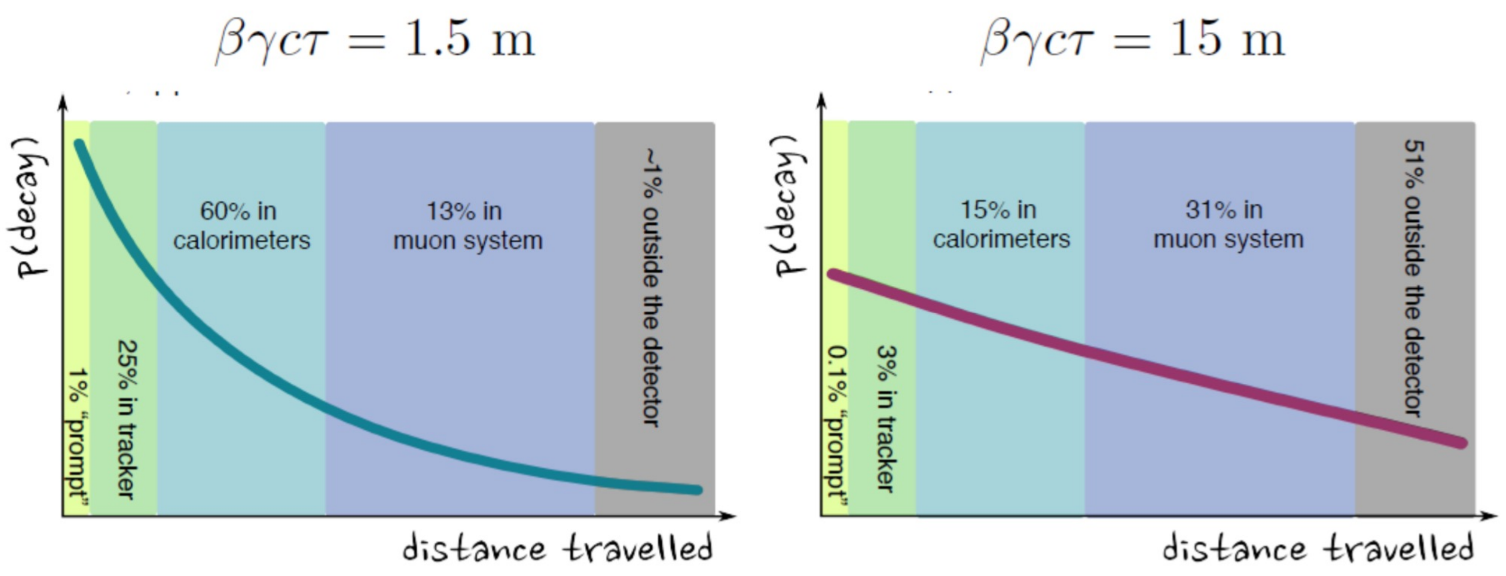
Backup

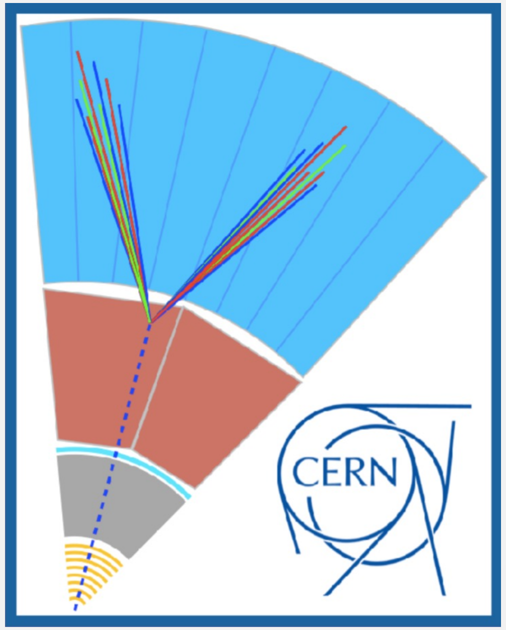
Challenges of searching for BSM LLPs

Sixth workshop of the LHC LLP Community

- Final states:
  - Limited by how well the experiments can reconstruct final state objects
- Displacement:
  - High displacement helps to discriminate against SM backgrouds
  - High displacement searches are also limited by the physical size of the detector
  - **Need very good vertexing and tracking techniques to reconstruct displaced vertex**

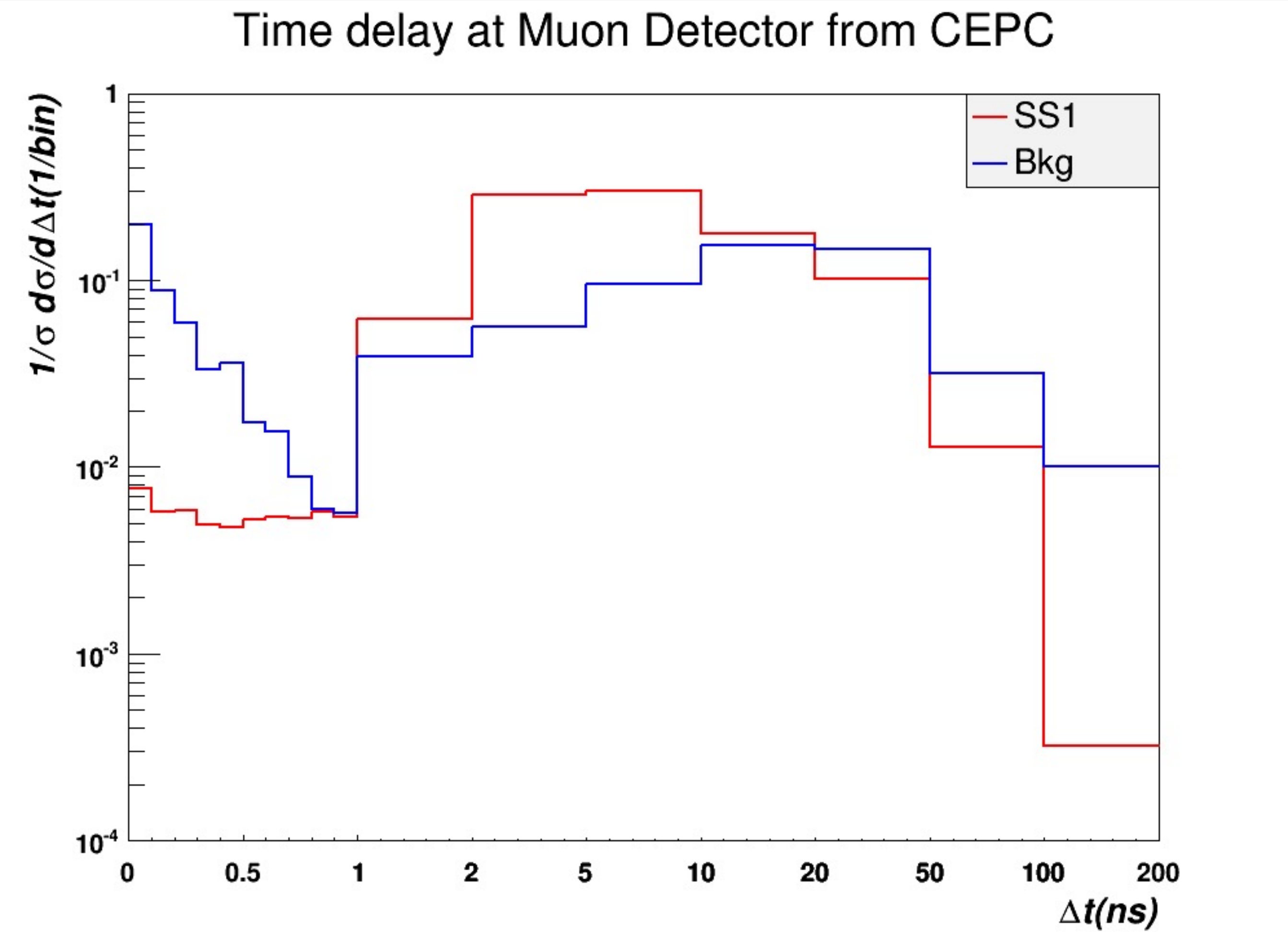


H. Russell, LHC LLP Community workshop, 2017; based on ATLAS geometry



Long-Lived Particle

Time Difference (Normalized)

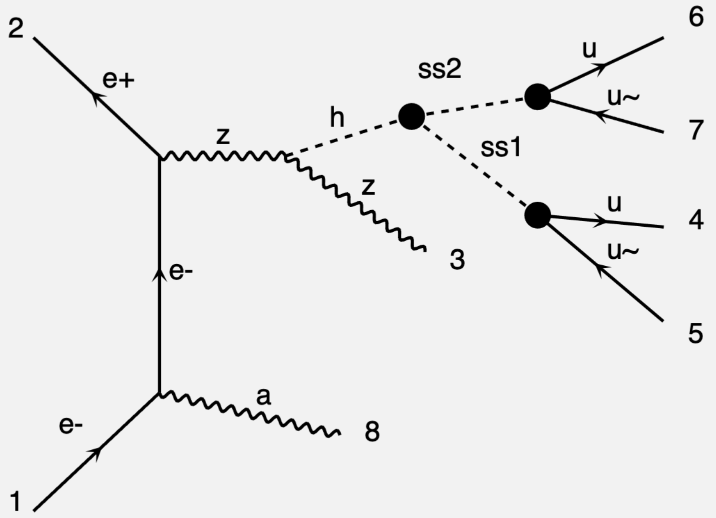


$$\Delta t = t_{\mathrm{Hit}} - r_{\mathrm{Hit}}/c$$

- Using FastJet Algorithm to cluster hits in Muon detector.
- Determine hit point by select $\min_{t}(\mathrm{j1}, \mathrm{j2})$

Time Stamp Tagging

- Initial State Radiation Photon (ISR)
  - Isolated photon from primary vertex
  - Precise time information from ECAL hits.
  - Production cut: $|\eta| \leq 3.0$ && $E \geq 0.1\ GeV$
  - $h \to q\bar{q}q\bar{q}$ (4 jets), apply to $Z \to \ell^{\pm}\ell^{\mp}$ & $Z \to \bar{\nu}_{\ell}\nu_{\ell}$
  - $h \to q\bar{q}\nu\nu$ (2 jets), apply to $Z \to inclusive$



	$h \to 4j$	$h \to 4j$ with ISR (no cut)	$h \to 4j$ with ISR (with cut)
$\sigma/\sigma_{h\to 4j}$	1.0000	0.8329	0.1569

The cross section ratio is calculated by MadGraph5

Reconstructed ISR γ Efficiency

Higgs decay mode	Z decay mode	$\sigma/\sigma_{h\to 4j,\, Z\to \text{inclusive}}$	$\epsilon_{\gamma_{\text{ISR}}}$
4 jets: $SS1 \to q\bar{q}$ $SS2 \to q\bar{q}$	inclusive	1.000	$\epsilon^{\gamma}_{\text{inclusive}} = 28.40\%$
	$q\bar{q}$	0.658	11.10%
	$\ell^{\pm}\ell^{\mp}(\ell = e, \mu)$	0.066	82.20%
	$\nu\bar{\nu}$	0.196	79.95%
2 jets: $SS1 \to q\bar{q}$ $SS2 \to \nu\bar{\nu}$	inclusive	0.386	$\epsilon^{\gamma}_{\text{inclusive}} = 29.61\%$
	$q\bar{q}$	0.266	10.79%
	$\ell^{\pm}\ell^{\mp}(\ell = e, \mu)$	0.026	81.99%
	$\nu\bar{\nu}$	0.080	80.33%
$\epsilon^{\gamma}_{\text{total}} = 39.83\%$			
$\epsilon^{\gamma}_{\text{final}} = \mathbf{32.53\%}$ (excluding 6 jets final state)			

The cross section ratio is calculated by MadGraph5

Long-Lived Particle

Discussion on ISR γ

- Current ISR γ selection:
  - Isolated$(\Delta R > 0.3)$ γ with maximum $\cos(\theta)$ or E
  - No big difference using $\cos(\theta)$ or E

- $\epsilon_{Z\to\ell^\pm\ell^\mp} \geq \epsilon_{Z\to\nu\bar{\nu}} \gg \epsilon_{Z\to q\bar{q}}$
  - The reason why leptonic decay has the best efficiency is because of FSR γ.
  - Relatively low ISR γ efficiency for $Z \to q\bar{q}$ (due to jet background)

- Other options for tagging:
  - γ from other prompt process ($q\bar{q}$)

γ from prompt process ($q\bar{q}$)

- $\pi^0 \to \gamma\gamma$
- In MC, over 99.3% jets have a large amount of π^0 → Plenty of γ as time stamp.

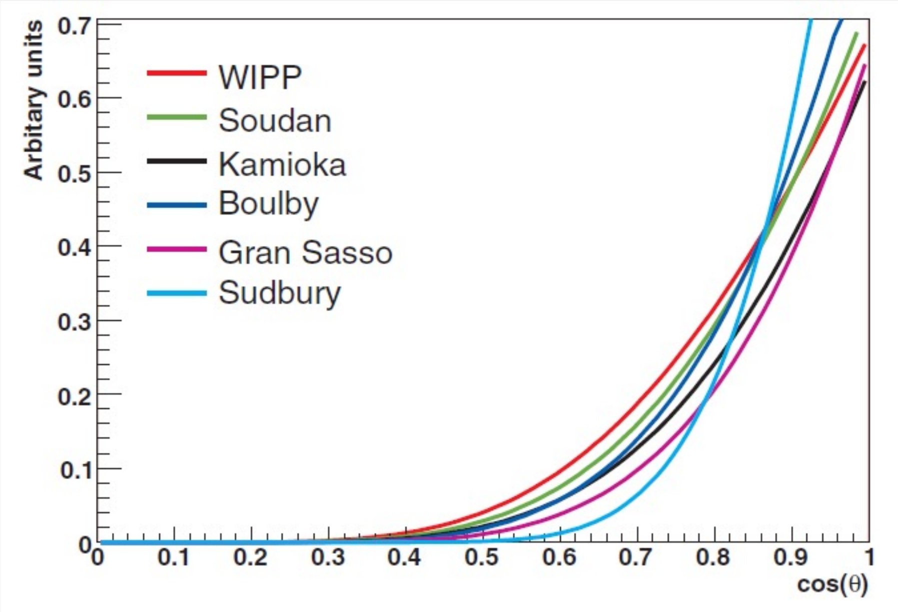
- In $Z \to q\bar{q}, h \to q\bar{q}\nu\bar{\nu}$ samples, require γ selected from the constituents of jets.
- Efficiency of Reconstructing a γ from jet: $\epsilon_{rec} \geq 99\%$
- Efficiency of Reconstructing a γ from jet with MC truth link: $\epsilon_{rec}^{MC} = 86\%$
- Efficiency of acceptance cuts: $\epsilon_{accept} = 95.2\%$
- Final efficiency for $Z \to q\bar{q}$: $\epsilon_{\text{final}}^{\gamma} = 86\% \times 95.2\% = 81.94\%$ (much larger than ISR)

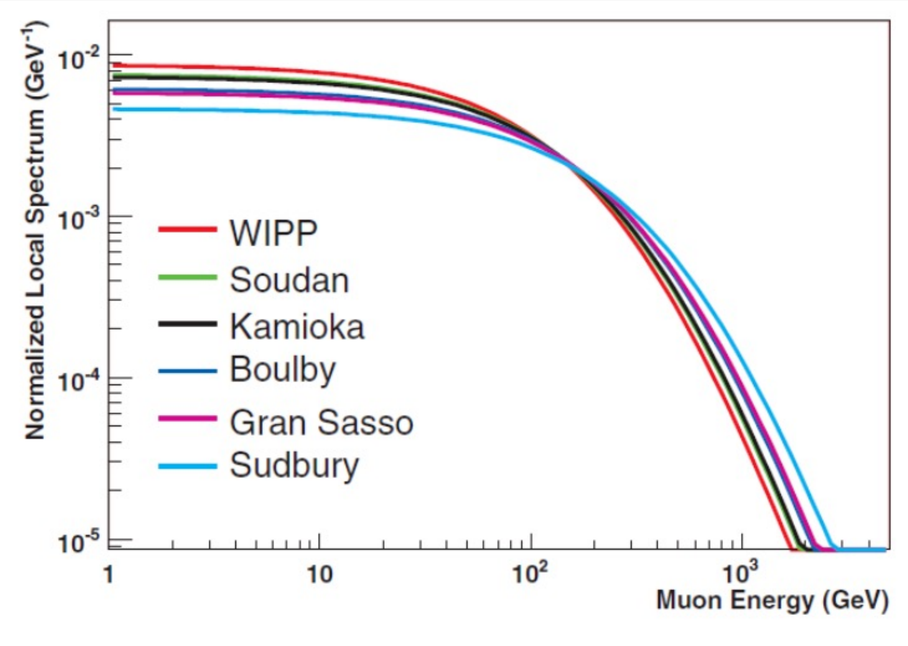
	$\boldsymbol{\epsilon_{rec}^{Z}}$	ϵ_{rec}^{MC}	ϵ_{accept}	$\epsilon_{Z\to q\bar{q}}^{\gamma}$
4 jets:	64.93%	85.21%	96.18%	**53.21%**
2 jets:	93.17%	86.07%	95.20%	**76.34%**

$\boldsymbol{\epsilon_{rec}^{Z}}$: $60\ \text{GeV} \leq M_{q\bar{q}}^{Z} \leq 120\ \text{GeV}$

Estimation of comic ray

- **Top right plot:** angle distribution of cosmic muon. About 99% of muon is smaller than 60 degree
- **Bottom right plot:** histogram of cosmic muon energy distribution. A rough estimation is made that only 0.09% of muon is over 30GeV





Long-Lived Particle

Estimation of comic ray

- $< \frac{dE}{dx} > \sim \frac{30\ GeV}{2.4\ m} \sim 12.5\ GeV/m$ in muon detector
- $\sigma\left(\frac{dE}{dx} \geq 12.5GeV\right) \sim 1\times10^{-9}$
- $n_{CR} = (5\times10^{-5}\times6.1\times10^{6}\times1200^{2}\times2\pi)\times(1\times10^{-9})\times(8.6\times10^{-3}) = 0.0236$

The overall distribution function as a function of both the energy and the zenith angle then can be written as

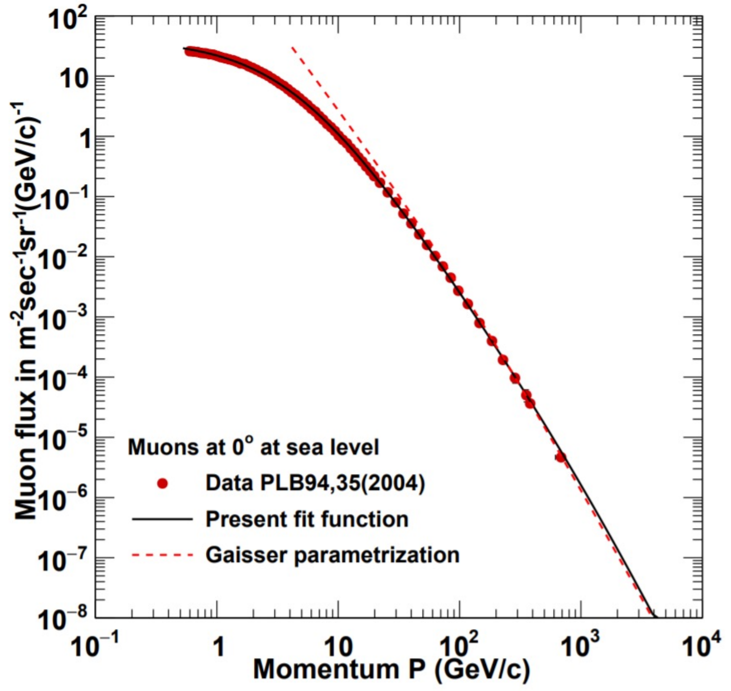
$$I(E,\theta) = I_0\, N\, (E_0 + E)^{-n} \left(1 + \frac{E}{\epsilon}\right)^{-1} D(\theta)^{-(n-1)}. \qquad (10)$$

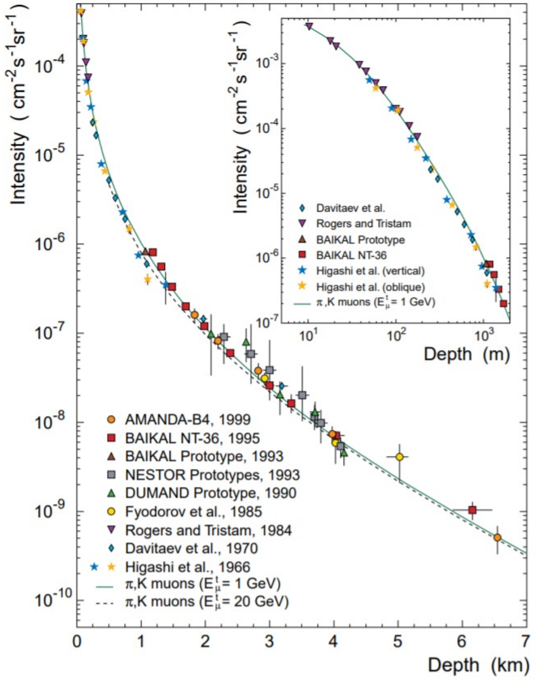
Here, the function $D(\theta)$ is given by Eq 7. If the Earth is assumed to be flat then $D(\theta) = 1/\cos\theta$ which on putting in Eq. 9 leads to

$$\Phi(\theta) = I_0 \cos^{n-1}\theta. \qquad (11)$$

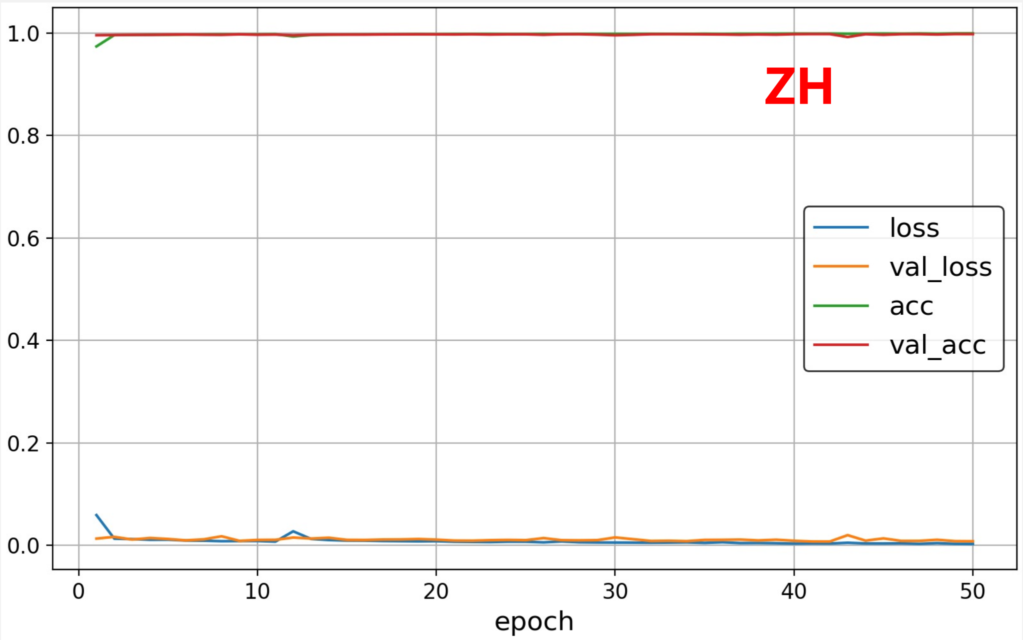
$$\frac{dN_\mu}{dE d\Omega} \approx 1400 E_\mu^{-2.7}/(\mathrm{m^2 s GeV sr}) \left(\frac{1}{1 + \frac{1.1 E\cos\theta}{\epsilon_\pi}} + \frac{0.054}{1 + \frac{1.1 E\cos\theta}{\epsilon_K}} \right), \qquad (12)$$

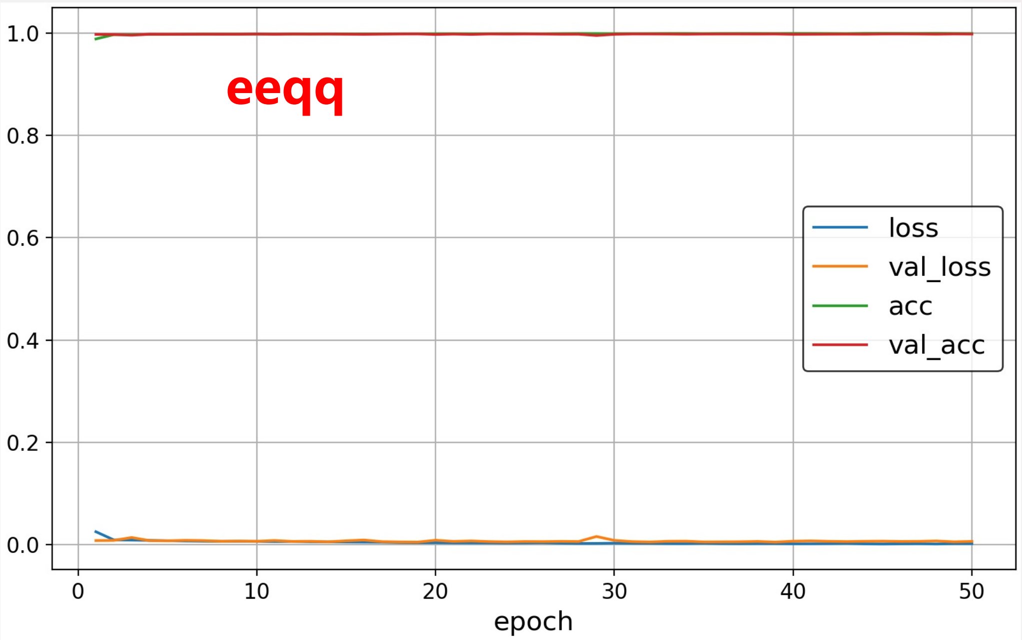
https://arxiv.org/pdf/1606.06907.pdf





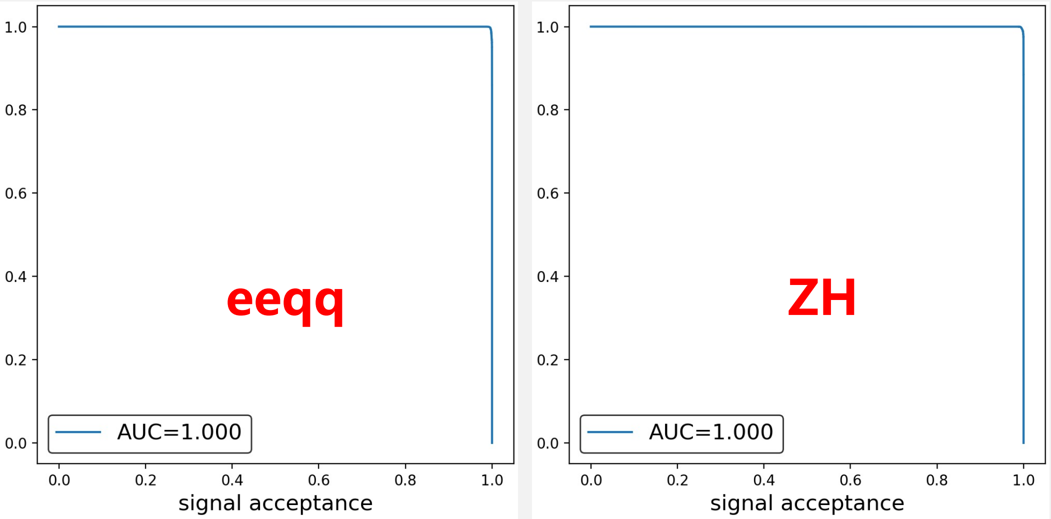
ResNet18 (1 channel: E)

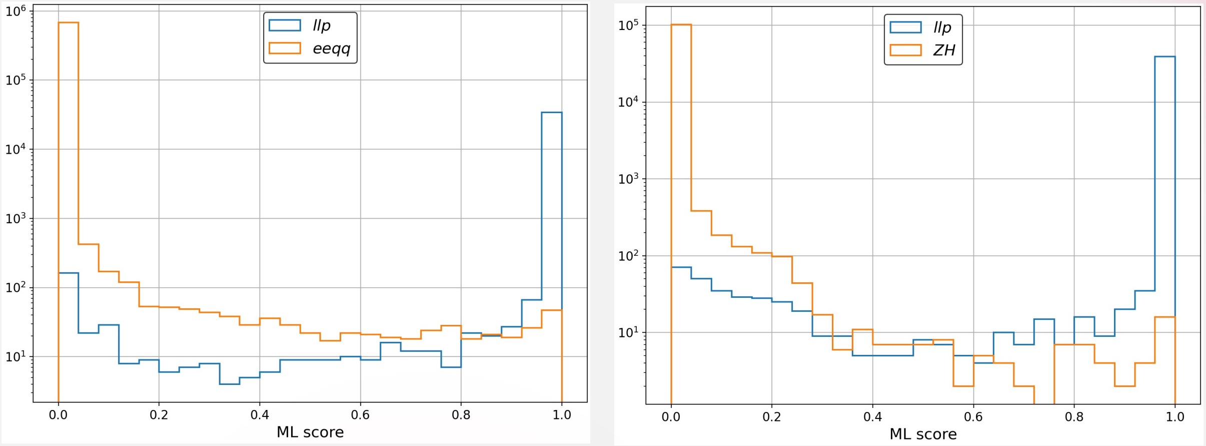




	Loss	Accuracy	Test Loss	Test Accuracy
ZH	0.002477	0.999239	0.007901	0.997773
eeqq	0.001880	0.999309	0.006324	0.998264

ResNet18 (1 channel: E)





	0.99	ϵ	0.999	ϵ	0.9995	ϵ	0.9999	ϵ
Signal	39056	98.63%	38330	96.79%	37878	95.65%	8223	20.77%
ZH	4	0.004%	0	0.000%	0	0.000%	0	0.000%
Signal	34103	98.00%	33216	95.45%	31917	91.72%	15869	45.60%
eeqq	21	0.003%	6	0.001%	5	0.001%	0	0.000%

- Combined ZH and eeqq ML_score can cut all the backgrounds.