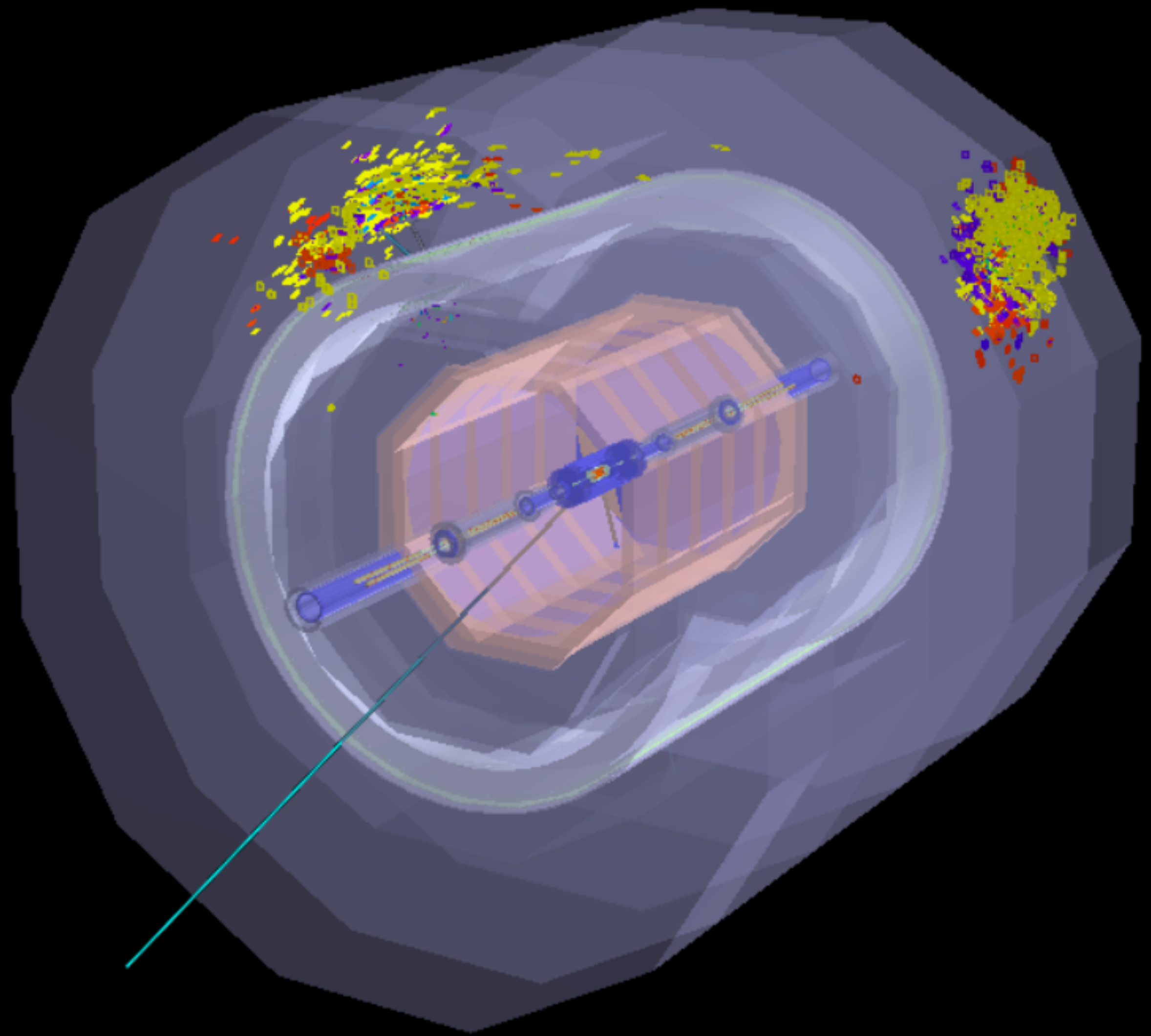
$$e^+e^- \to Zh \to \nu\bar{\nu} + SS1 + SS2 \to \nu\bar{\nu}q\bar{q}q\bar{q}$$



# Long-Lived Particle Search with Lepton Colliders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1 Shanghai Jiao Tong University

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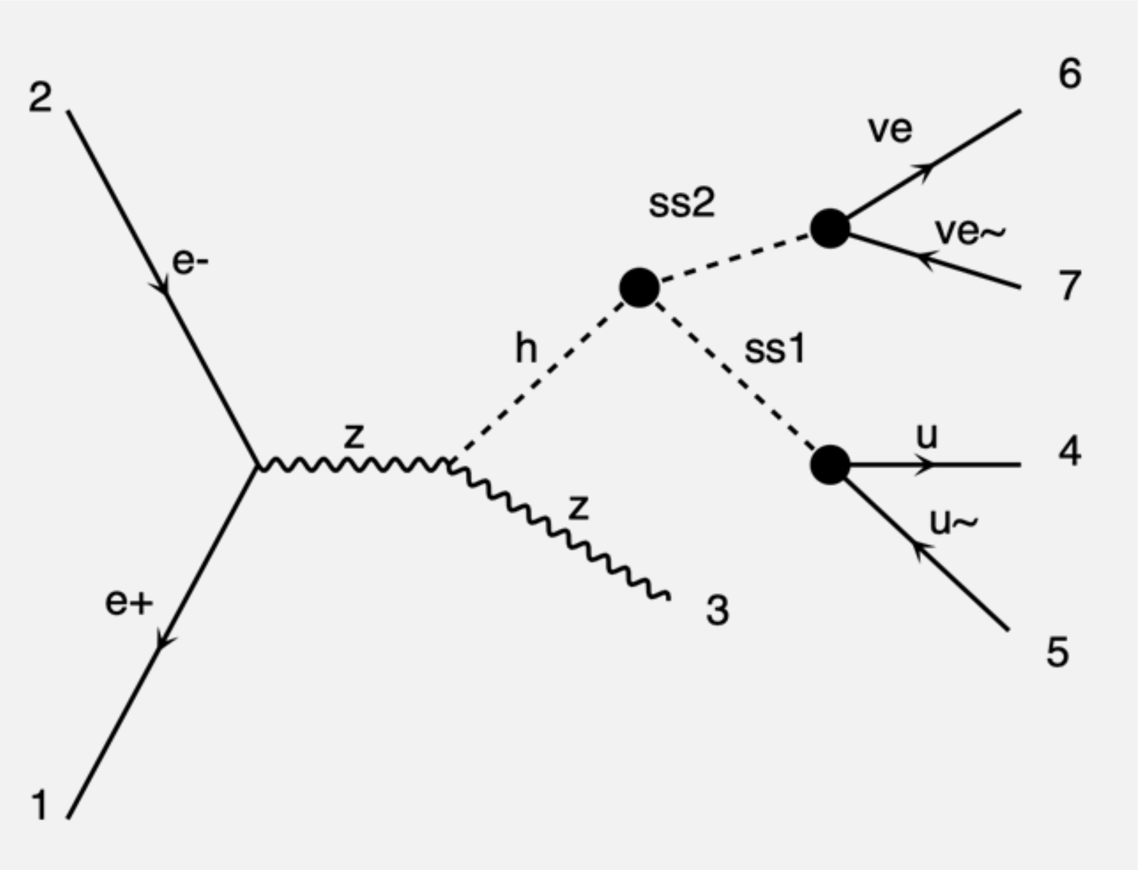
# Outline

## Beyond the Standard Model

- Why LLPs interested
- Search for LLPs at future collider
  - Using time of flight
  - Using energy deposition
- Preliminary results
- Summary



# The lifetime frontier …

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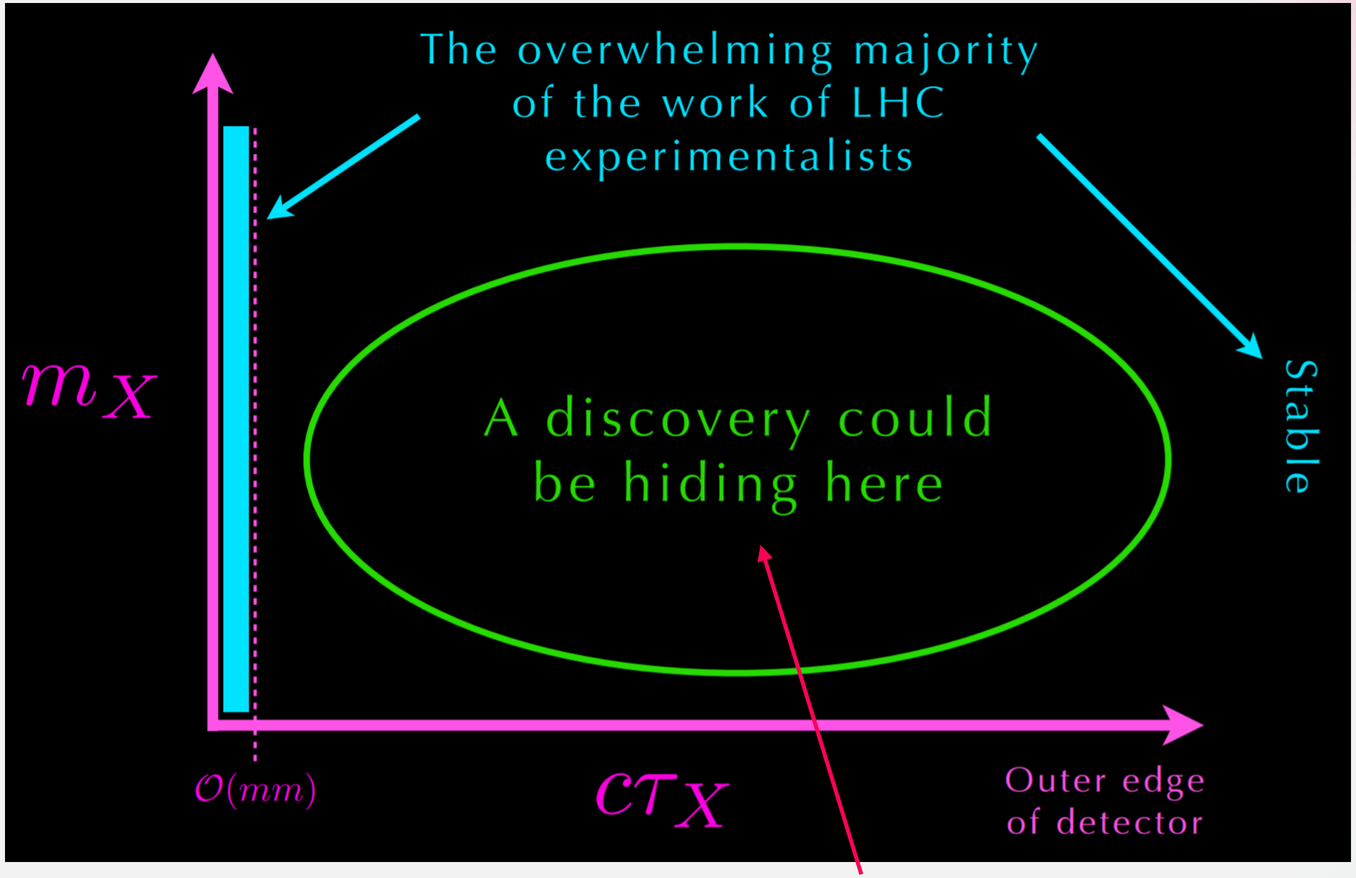
- Large majority of current collider experiment searches and analysis strategies assume the new particle decays promptly.
- Particle lifetimes span a very wide range and long lifetimes can generically appear in the BSM theories.
- Dedicated searches for long-lived BSM particles are necessary.




Long-Lived Particle

# What is a long-lived particle?

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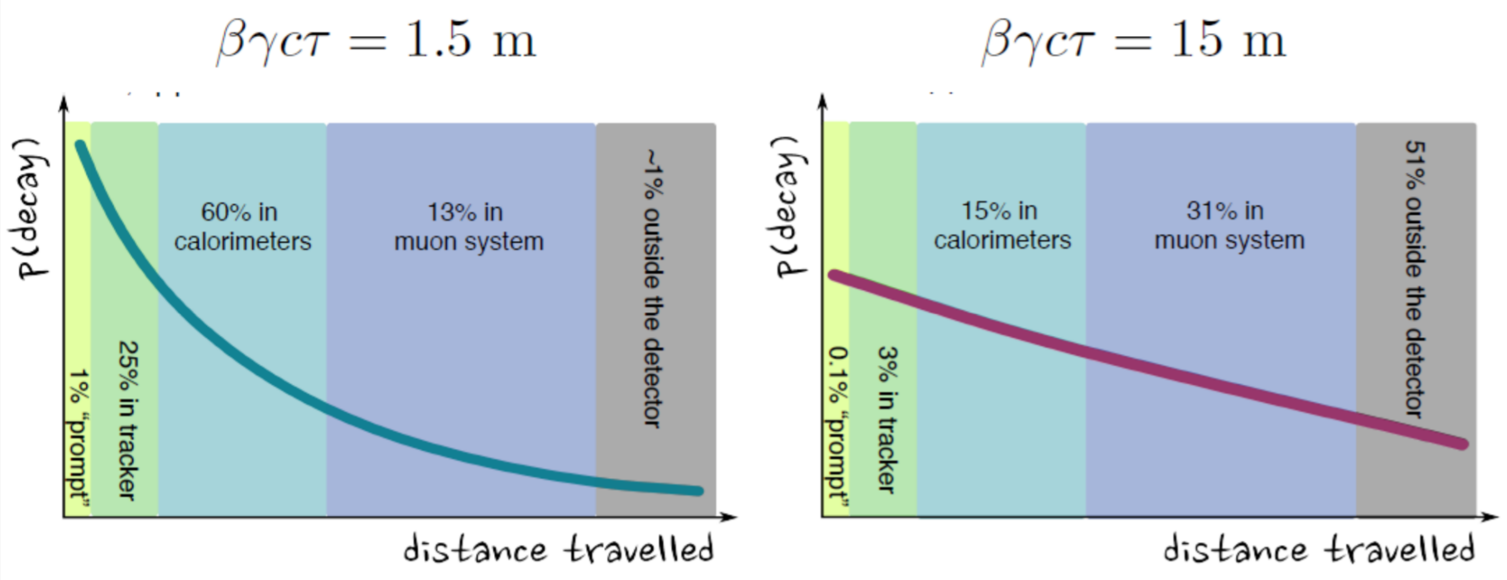
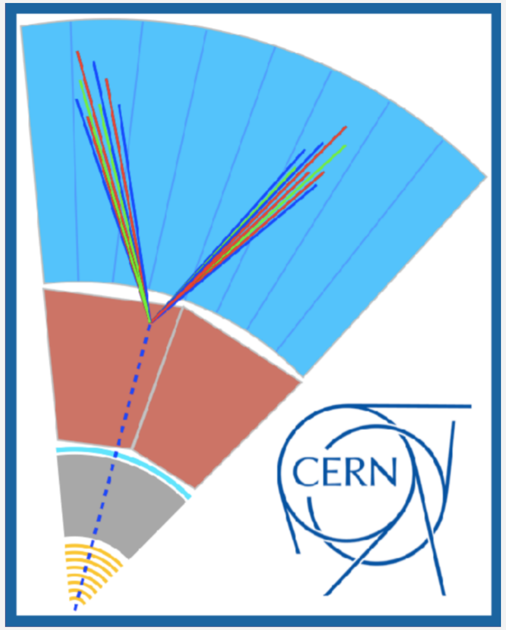
*Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

Signal signature of a long-lived particle:

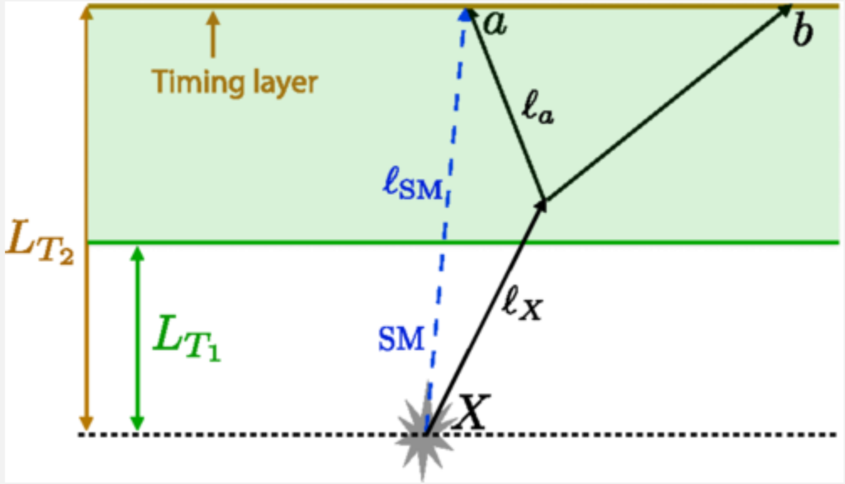
Neutral LLP decays are a spectacular signature, and the burst of energy appearing out of nowhere sets it apart from the collision point.

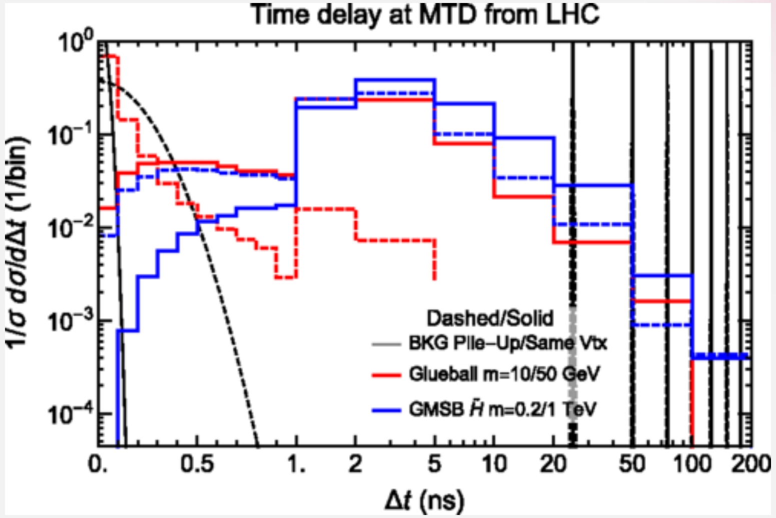


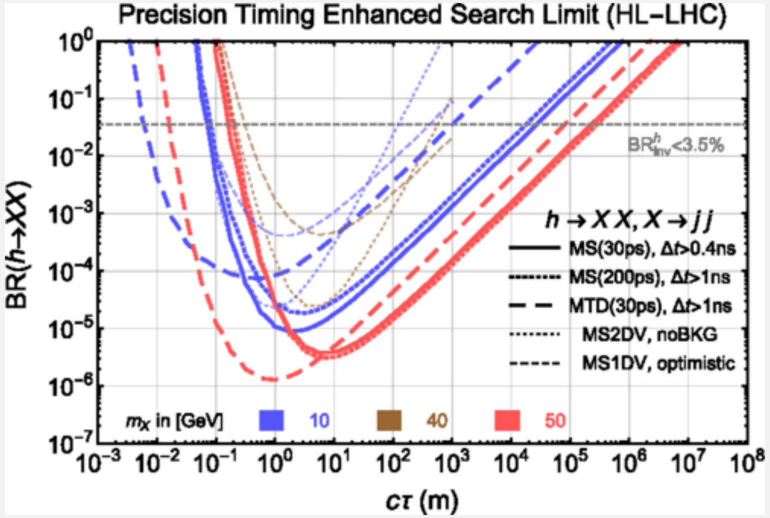

H. Russell, LHC LLP Community workshop, 2017; based on ATLAS geometry



# Enhancing Long-Lived Particles Searches @ LHC with Precision Timing Information



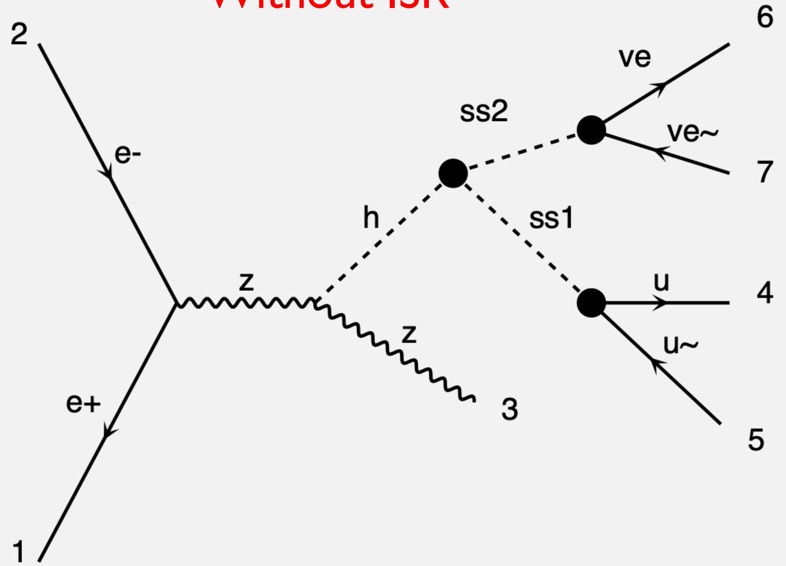

- $\Delta t^i_{\text{delay}} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\text{SM}}}{\beta_{\text{SM}}}, \quad (i = a, b)$
- For SM particles, $\beta_{SM} \sim 1$

Jia Liu, Zhen Liu, and Lian-Tao Wang Phys. Rev. Lett. **122**, 131801 – 2019.04.03

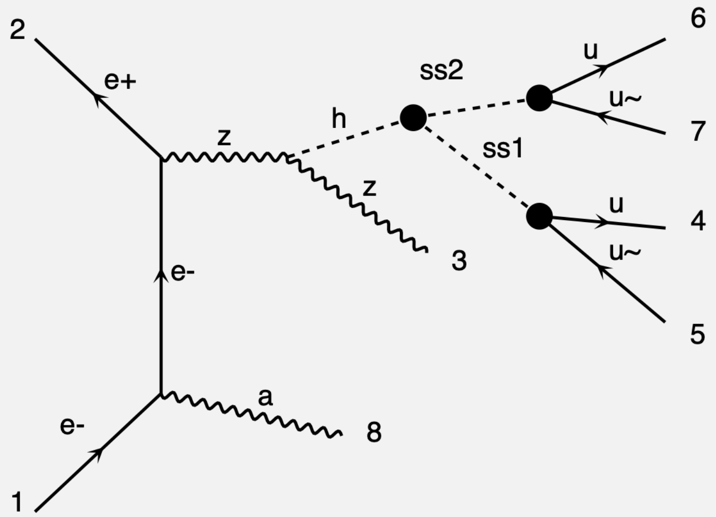
Long-Lived Particle

# LLP Searches at Lepton Colliders (CEPC)

Without ISR



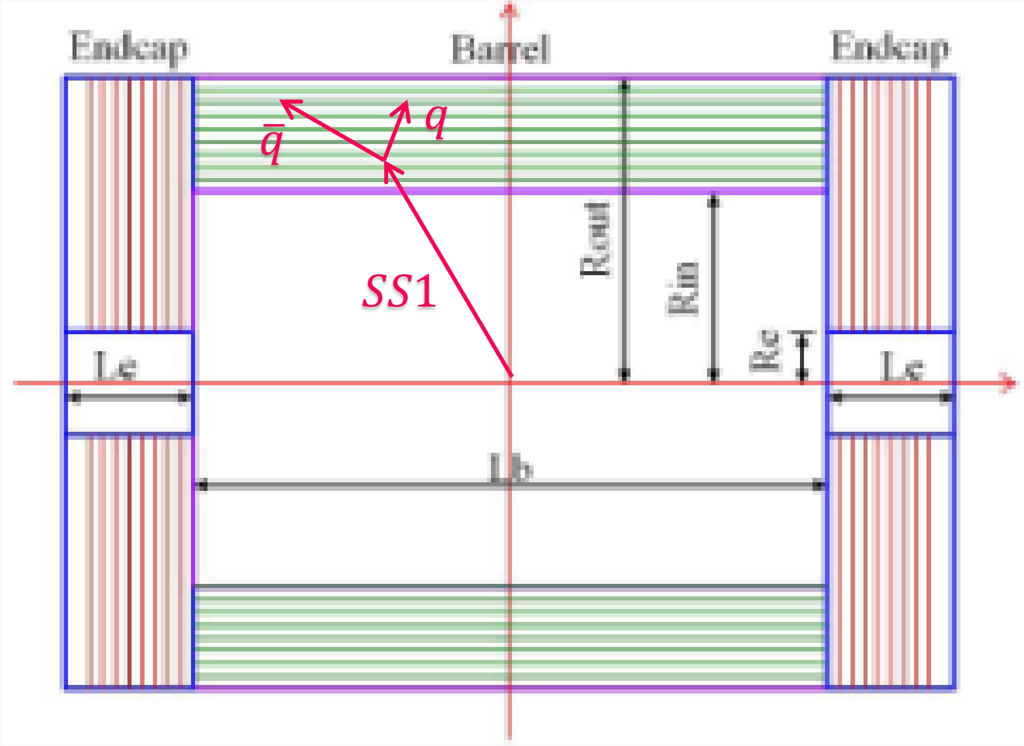

With ISR




- Energy: 250 GeV
- Mass of SS1: 1-50 GeV
- Mass of SS2: 1-50 GeV
- SS1, SS2's lifetime $\tau = R_{\text{out}}/c \;= 6m/c = 20\;ns$ ($R_{\text{out}}$ see next page)
- Focus on $Z \to q\bar{q}$ in this study, Xiang will introduce $Z \to \ell\bar{\ell}$

Long-Lived Particle

# Selection Criteria



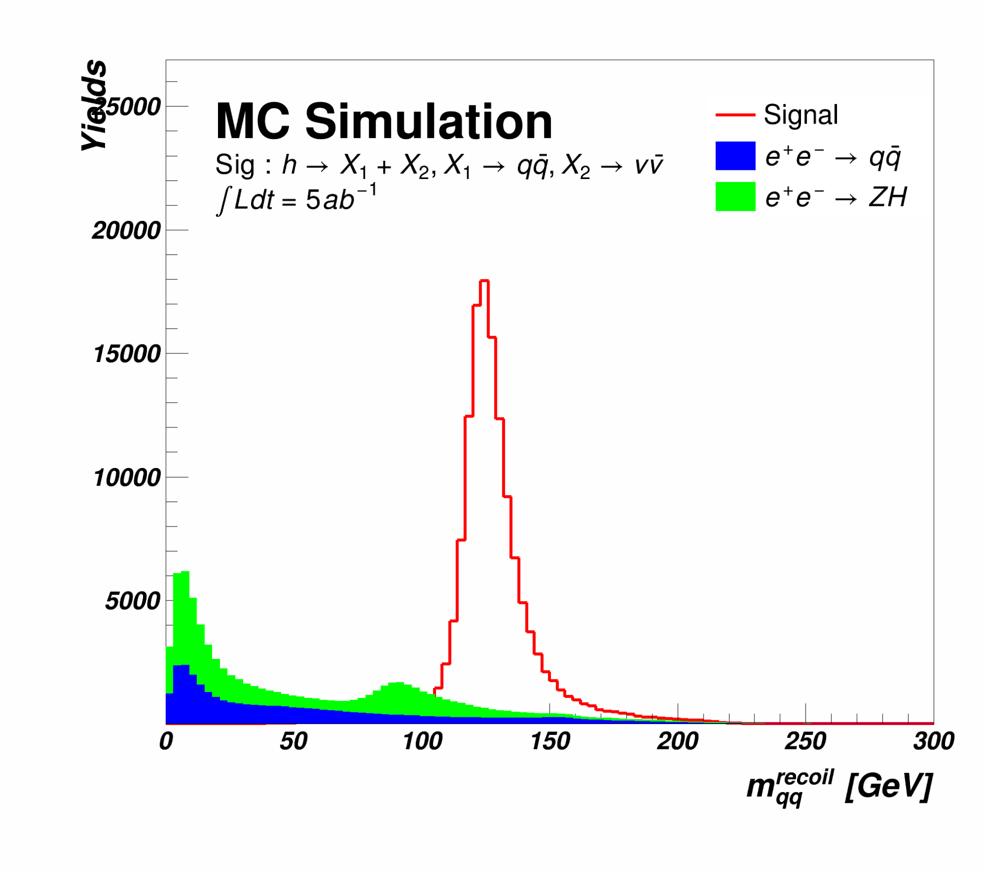

- Muon Detector
  - $R_{\text{in}} \approx 4m$
  - $R_{\text{out}} \approx 6m$
- Select events within Muon detector
  - $\boldsymbol{\Delta t = t_{\text{Hit}} - r_{\text{Hit}}/c}$
- Dominant Background
  - $\boldsymbol{ZH \to \nu\nu bb, \nu\nu jj}$
  - $\boldsymbol{e^+e^- \to qq}$
  - $(\boldsymbol{ZZ \to \nu\nu qq, qqqq})$
- **Full simulation** with CEPC official software

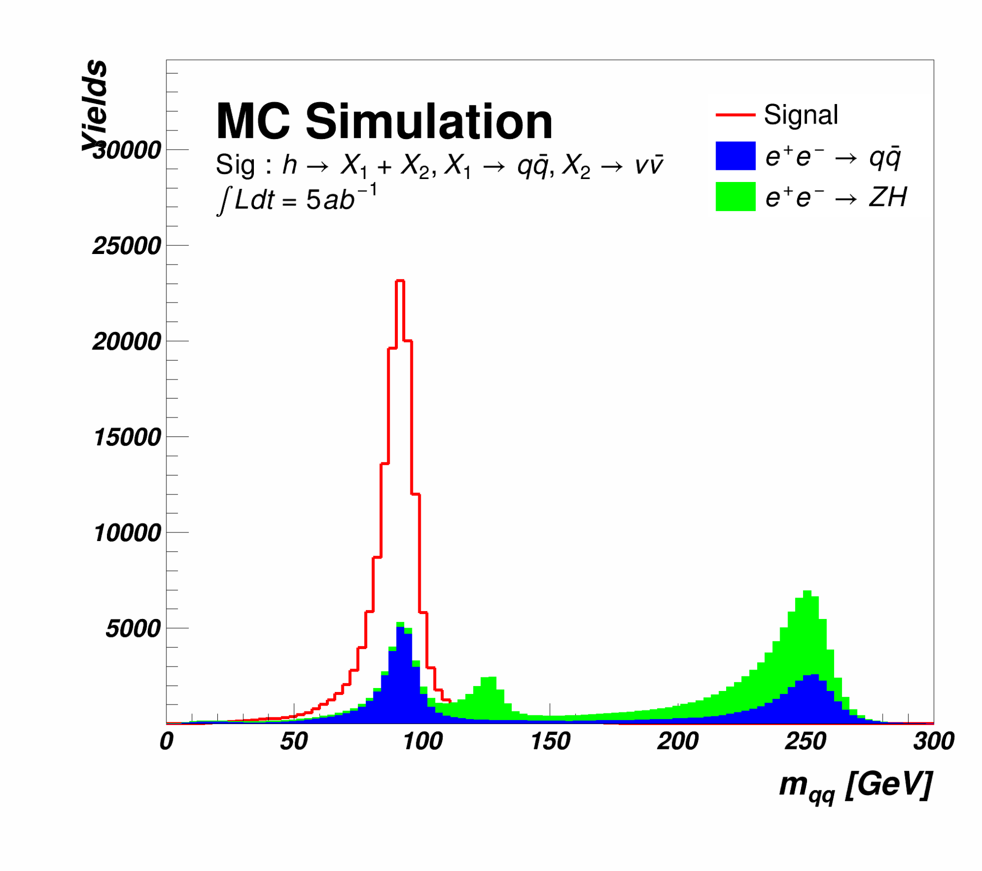
# Event Selection

| | Signal | $e^+e^- \to q\bar{q}$ | $e^+e^- \to Zh$ | Total |
|---|---|---|---|---|
| # of Events in $5ab^{-1}$ | | $2.0\times10^8$ | $1.0\times10^6$ | $2.01\times10^8$ |
| # of Events simulated | $\sim 1.3\times10^6$ | $\sim 1.5\times10^6$ | $\sim 1.37\times10^6$ | $\sim 2.87\times10^6$ |
| Decay in Muon Detector | 137,536 | 1,151,350 | 754,134 | 1,905,484 |
| $\lvert m_{qq} - m_Z \rvert \leq 20$ GeV | 122,055 | 496,499 | 75,157 | 571,656 |
| $\lvert m_{qq}^{rec} - m_h \rvert \leq 20$ GeV | 112,623 | 47,773 | 53,632 | 101,405 |
| $E_{2j} \geq 30$ GeV | 84,240 | 229 | 57 | 286 |
| $\min(\Delta T_{j_1}, \Delta T_{j_2}) > 3$ ns | 81,940 | 146 | 37 | 183 |
| Efficiency | 59.58% | 0.013% | 0.005% | 0.009% |

- $qq$ 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.

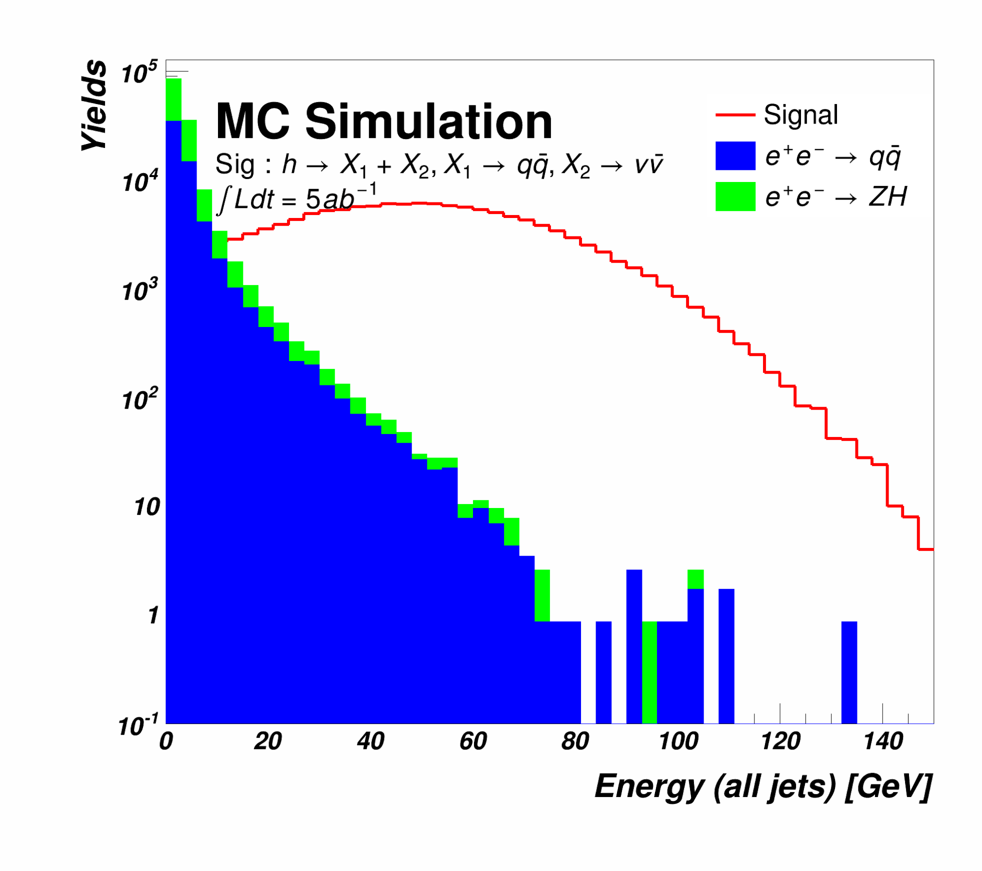
# Time Difference vs. Energy

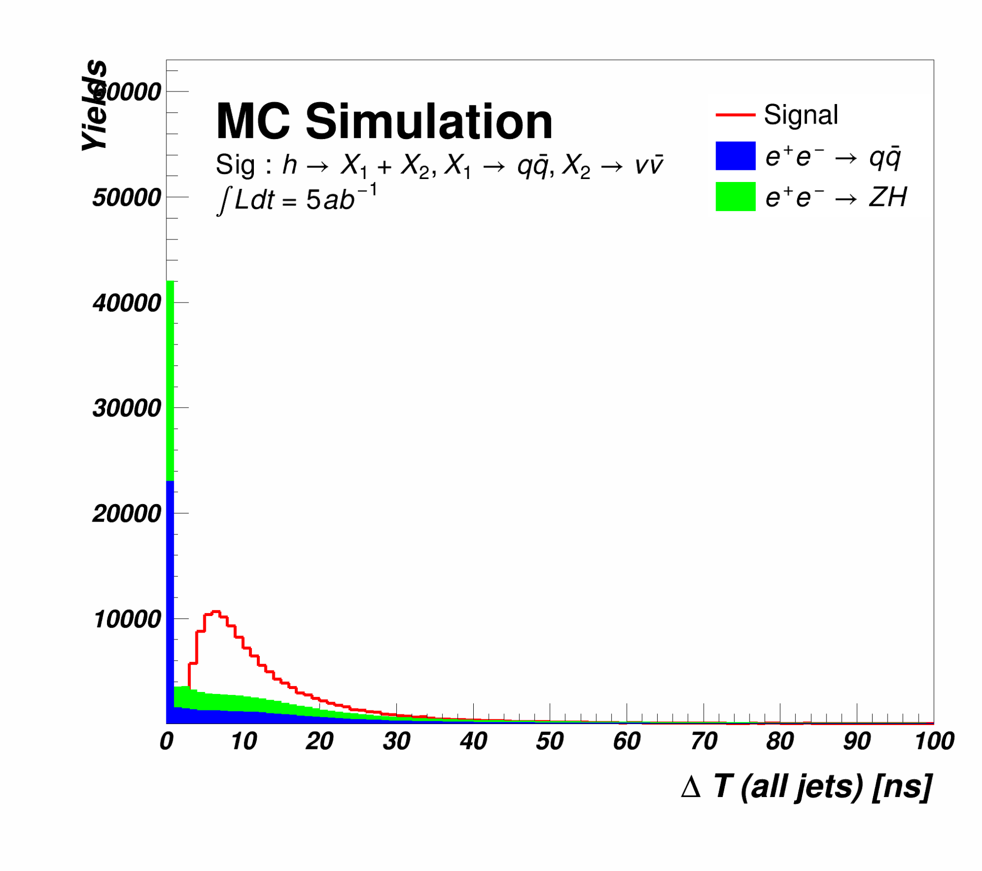



- Background is normalized to the scale of signal.

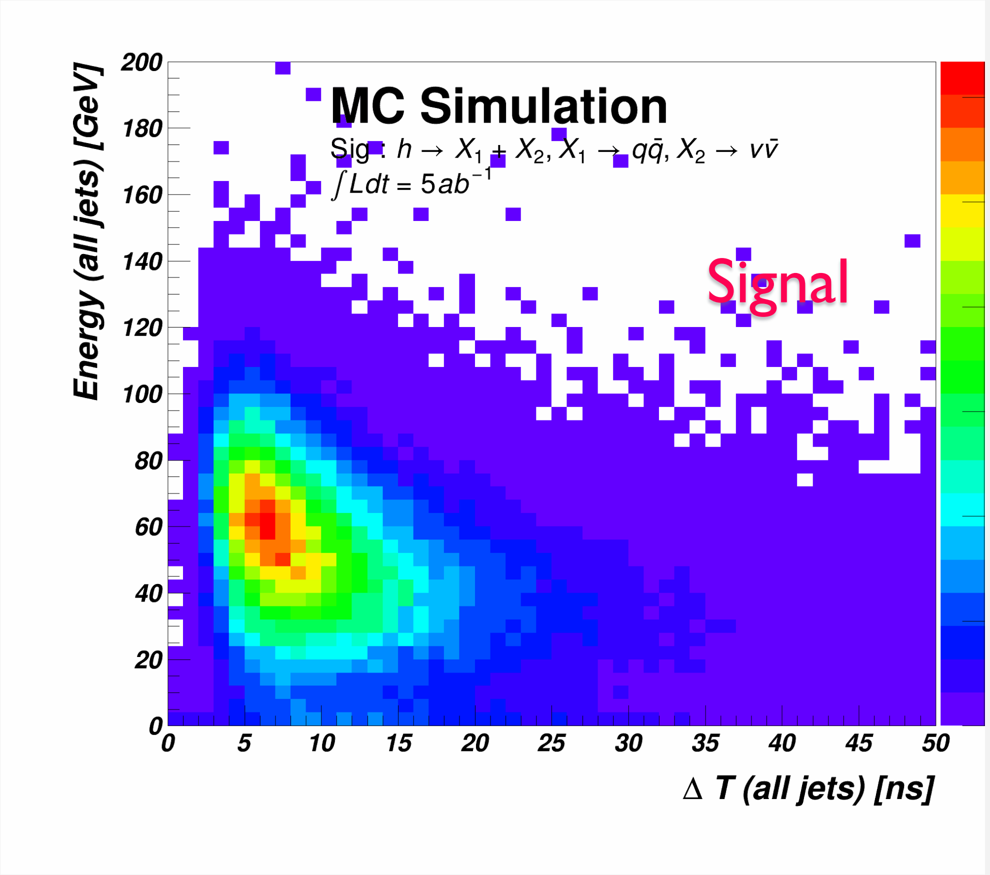
# Time Difference vs. Energy

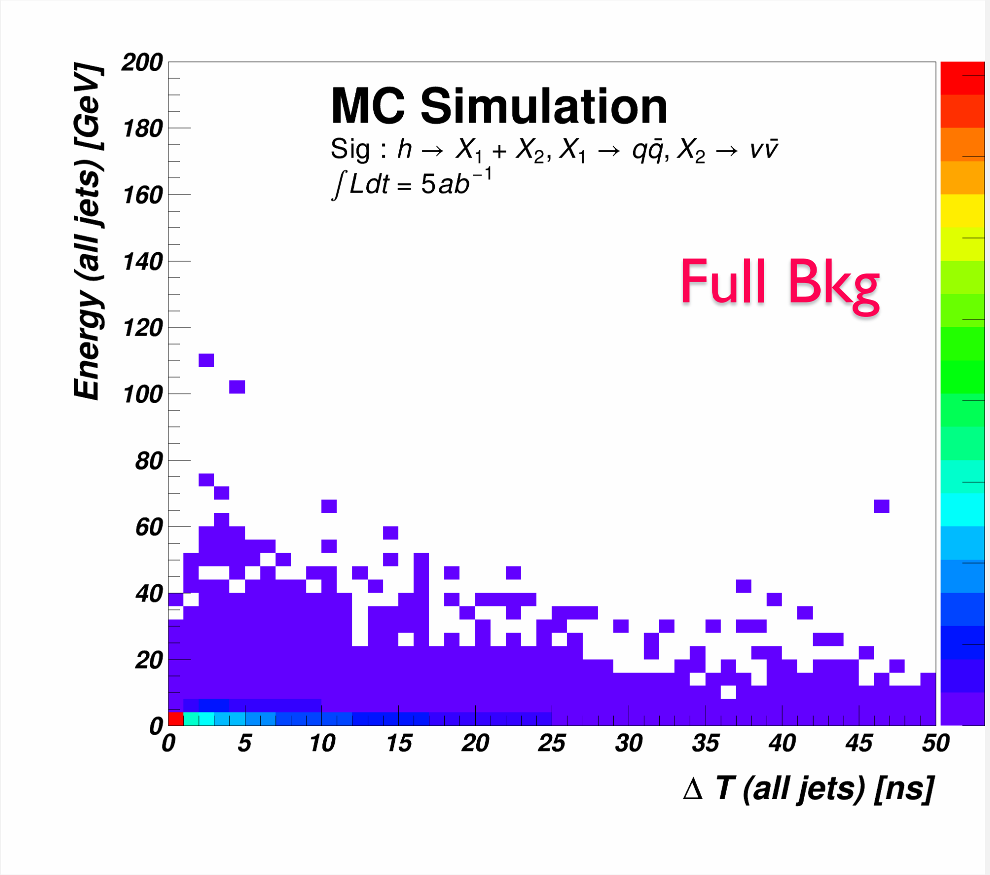



- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

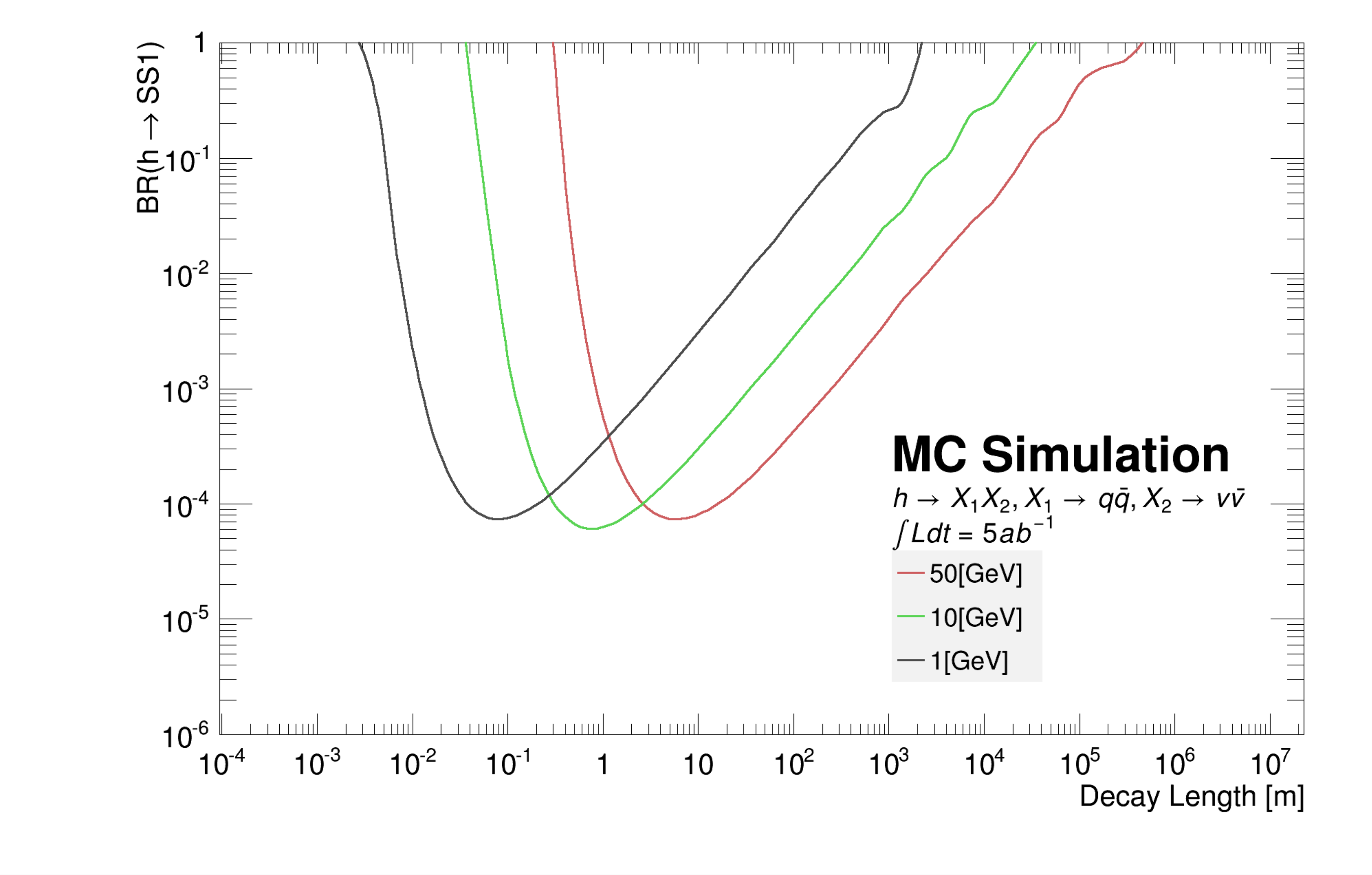
# Time Difference vs. Energy



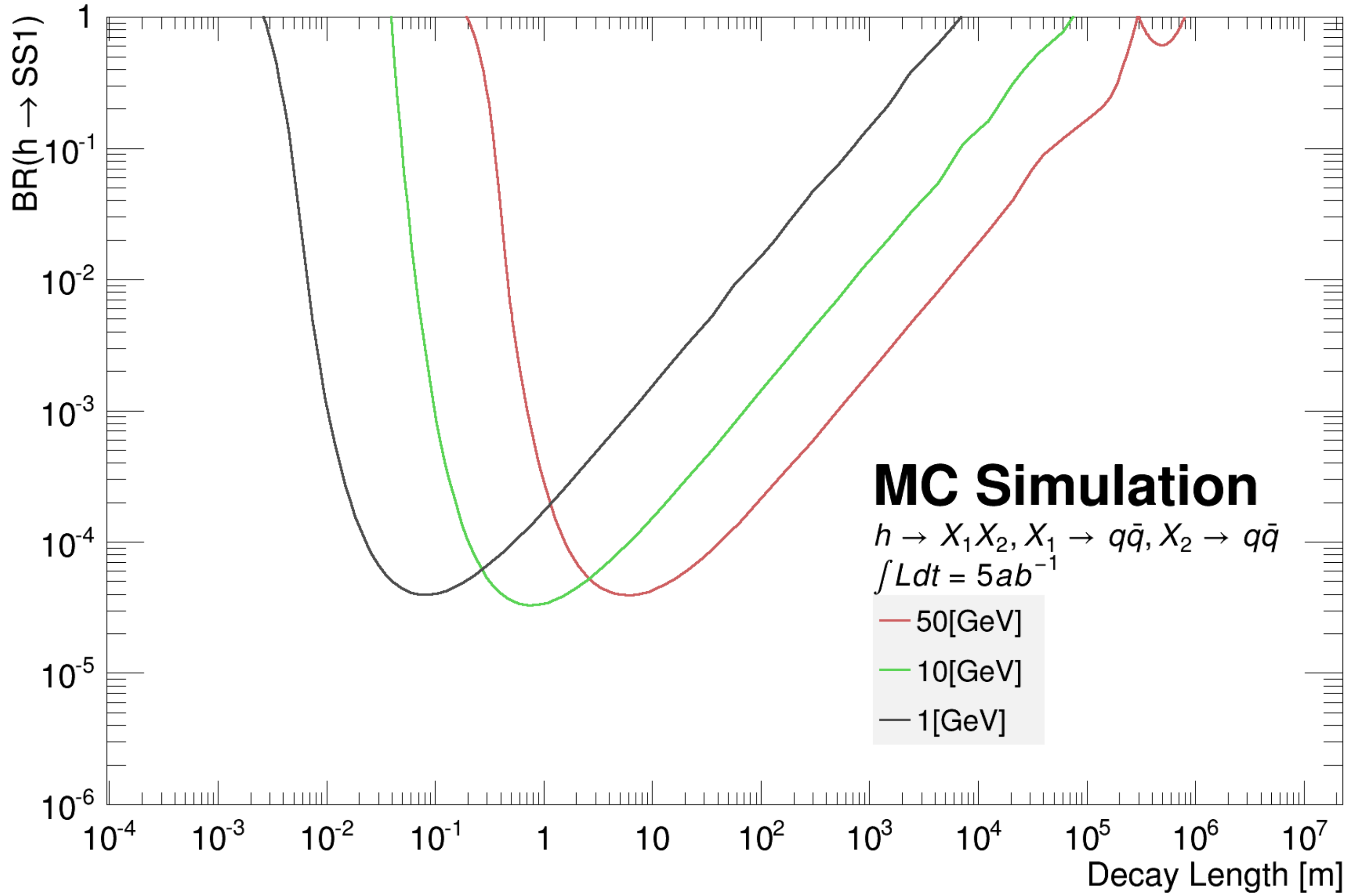




- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

# Sensitivity (2 jets)



# Sensitivity (4 jets)



# Summary

- A preliminary study has been performed on Long-Lived Particle ( $h \to q\bar{q}\nu\bar{\nu}$ and $h \to q\bar{q}q\bar{q}$ ) based on CEPC_V4.
- Time of flight and Energy deposition in Muon detector are the two main variables with good separation power.
- CEPC can provide precise time information.
  - detector time resolution $\sim O(1)\ ns$
- Further optimization on selection and reconstruction and more statistics are necessary for estimate the expected background.
  - Other backgrounds like pileup, cosmic rays are negligible in our case.
- To do…
  - Reconstruction from $Z \to \ell^{\pm}\ell^{\mp}$ process
  - Reconstruction of the displacement vertex ( SS1 and SS2 decay vertex)

# Thanks

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# Backup

# Challenges of searching for BSM LLPs

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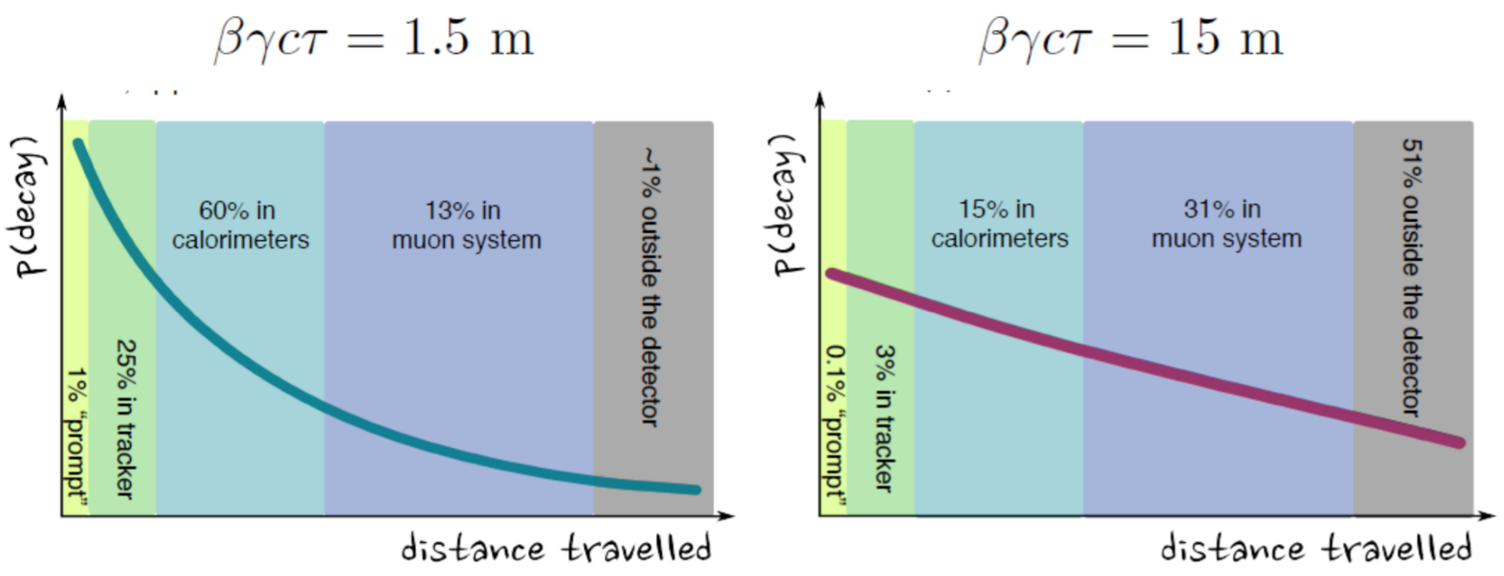
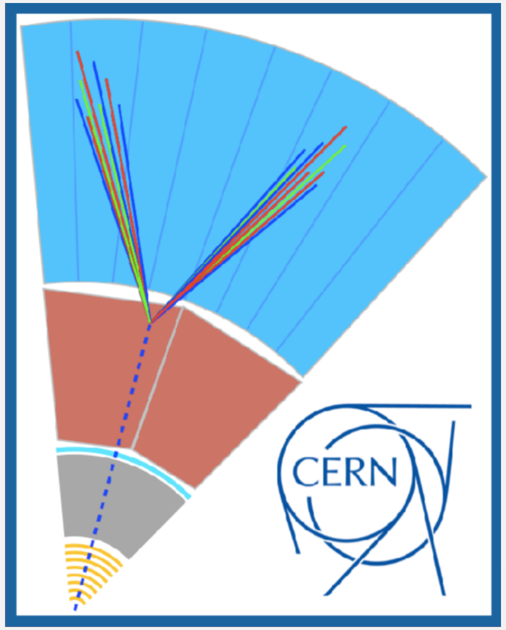
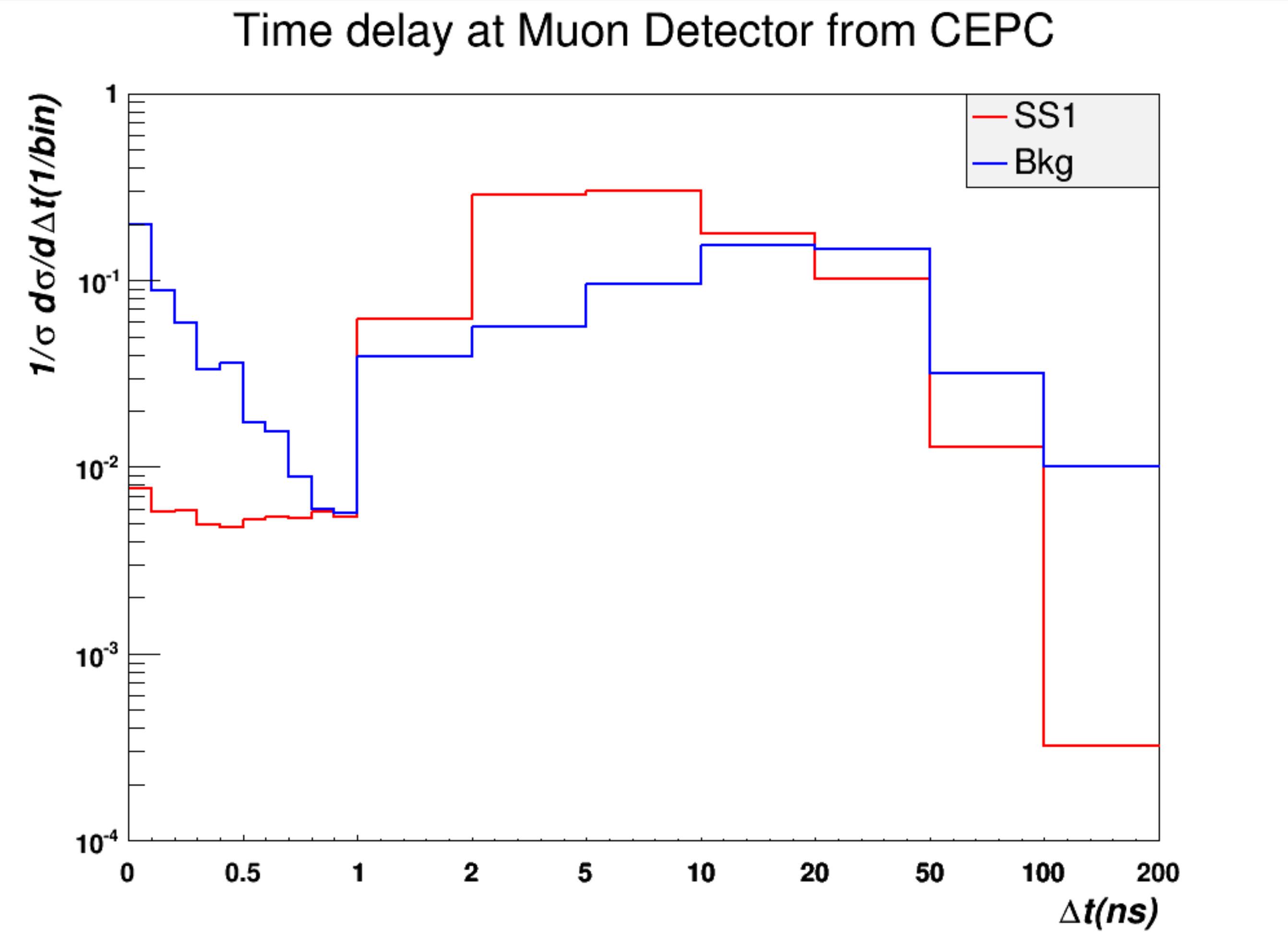
- Final states:
  - Limited by how well the experiments can reconstruct final state objects
- Displacement:
  - High displacement helps to discriminate against SM backgrouds
  - High displacement searches are also limited by the physical size of the detector
  - **Need very good vertexing and tracking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




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



# Time Difference (Normalized)

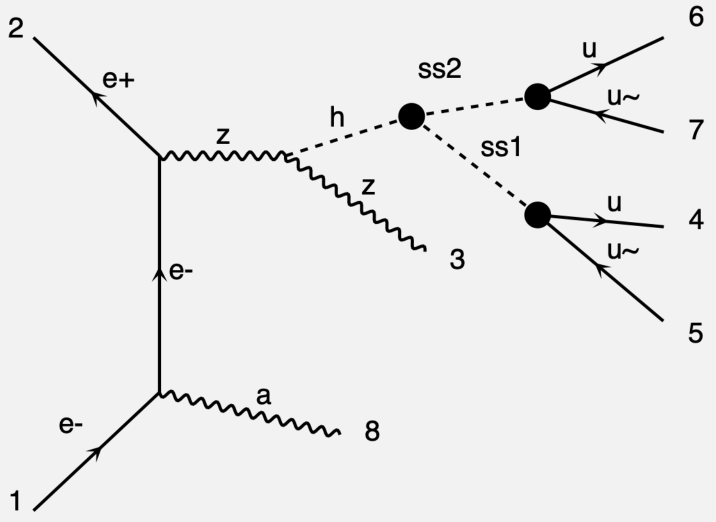



$$\Delta t = t_{\mathrm{Hit}} - r_{\mathrm{Hit}}/c$$

- 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 $\gamma$ 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*

# Discussion on ISR $\gamma$

- Current ISR $\gamma$ selection:
  - Isolated$(\Delta R > 0.3)$ $\gamma$ 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 $\gamma$.
  - Relatively low ISR $\gamma$ efficiency for $Z \to q\bar{q}$ (due to jet background)

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

# $\gamma$ from prompt process ( $q\bar{q}$ )

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

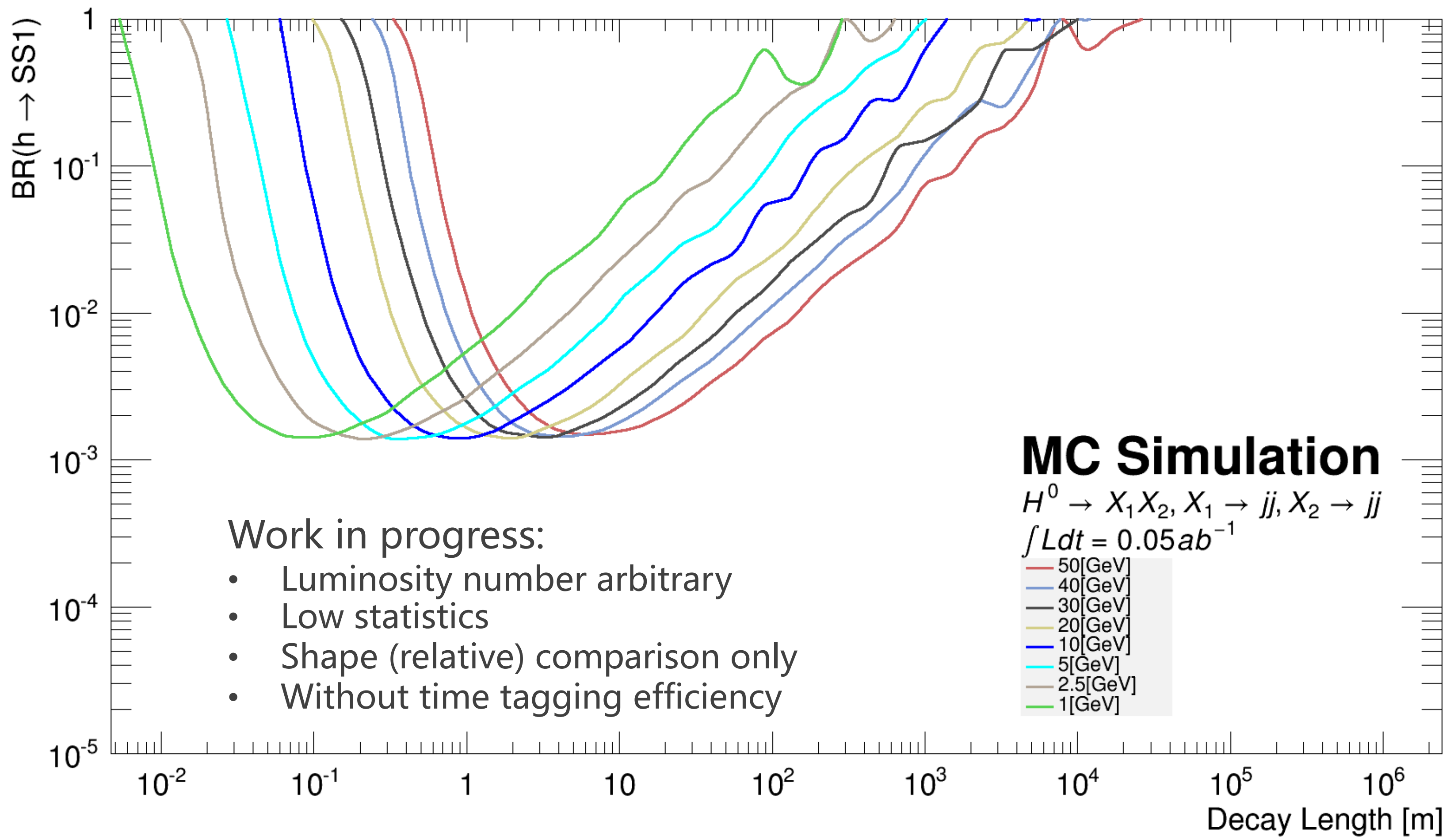
- In $Z \rightarrow q\bar{q}, h \rightarrow q\bar{q}\nu\bar{\nu}$ samples, require $\gamma$ selected from the constituents of jets.
- Efficiency of Reconstructing a $\gamma$ from jet: $\epsilon_{rec} \geq 99\%$
- Efficiency of Reconstructing a $\gamma$ from jet with MC truth link: $\epsilon_{rec}^{MC}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

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

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

Long-Lived Particle

# Sensitivity (4 jets)




Work in progress:

- Luminosity number arbitrary
- Low statistics
- Shape (relative) comparison only
- Without time tagging efficiency

Long-Lived Particle