




Long-Lived Particle Search with Lepton Colliders

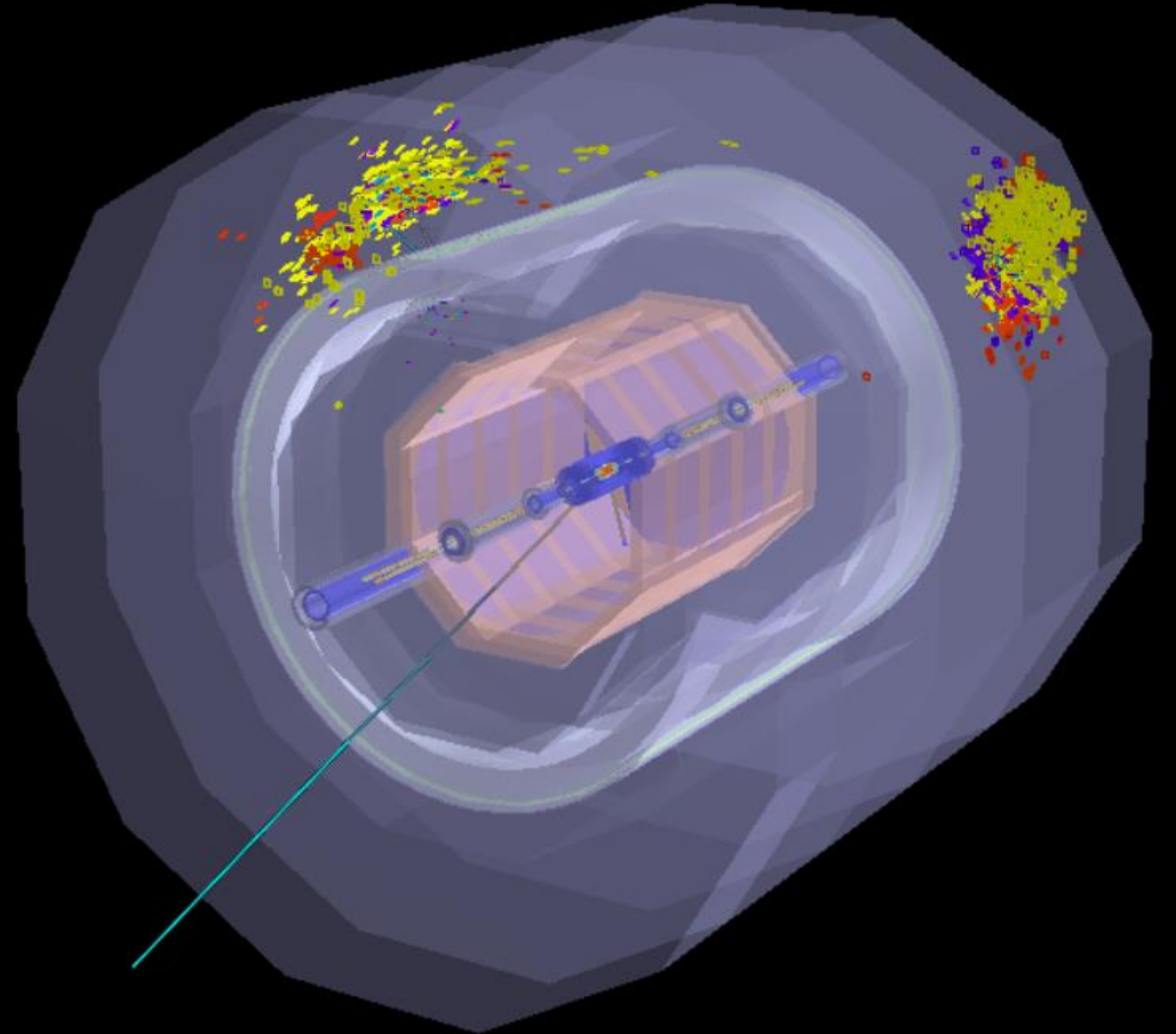
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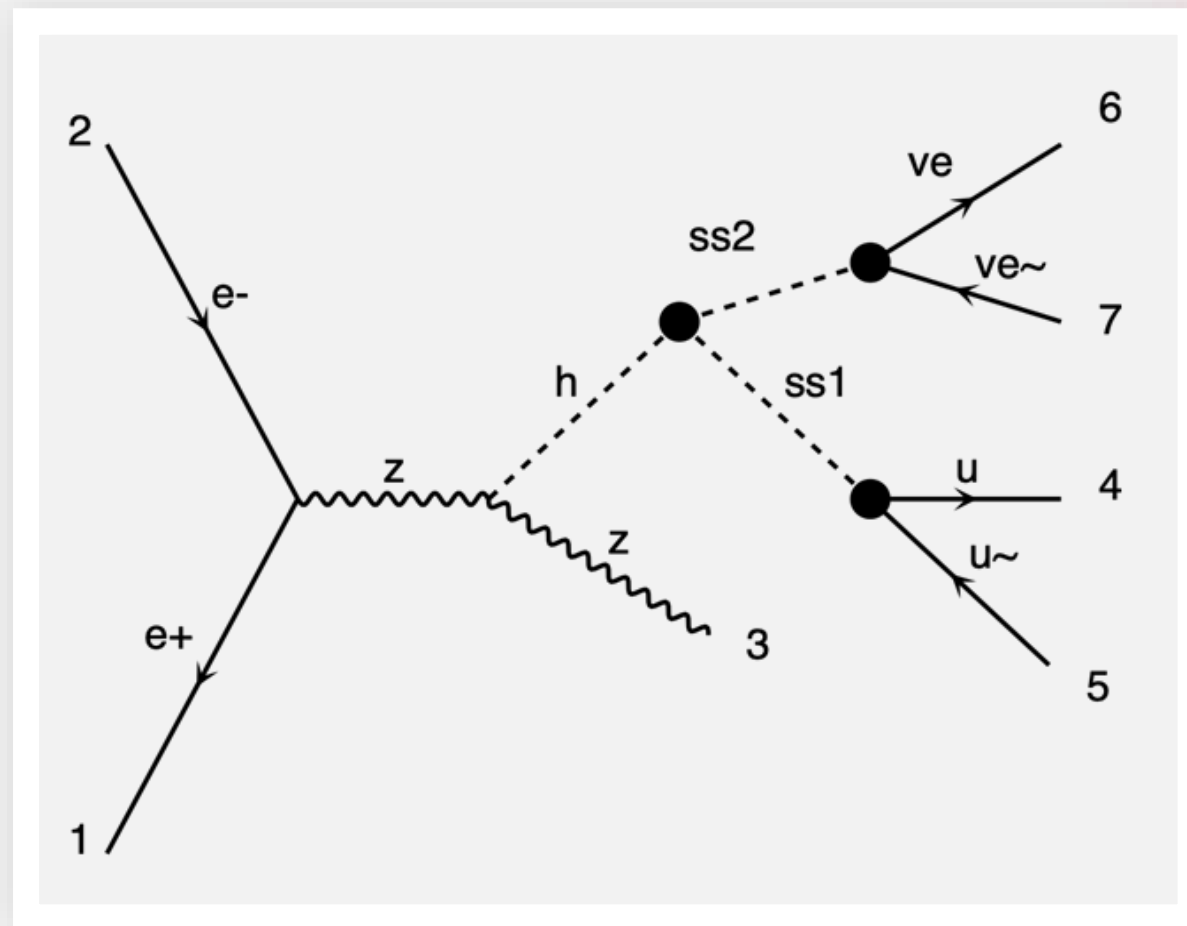
$$e^+e^- \rightarrow Zh \rightarrow \nu\bar{\nu} + SS1 + SS2 \rightarrow \nu\bar{\nu}q\bar{q}q\bar{q}$$



Outline

Beyond the Standard Model

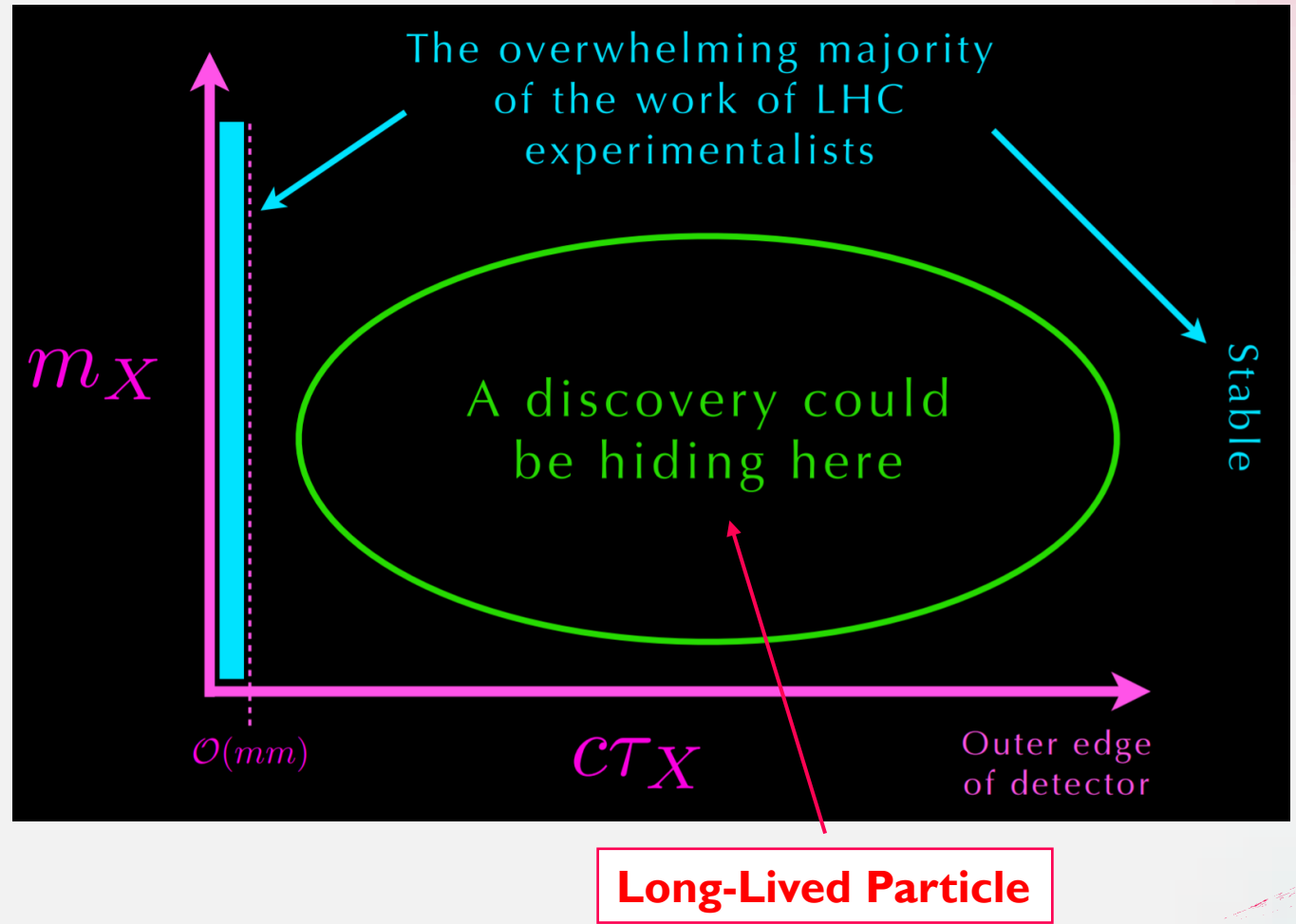
- Why LLPs interested
- Search for LLPs at future collider
 - Using time of flight
 - Using energy deposition
- Preliminary results
- Summary



The lifetime frontier ...

- 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

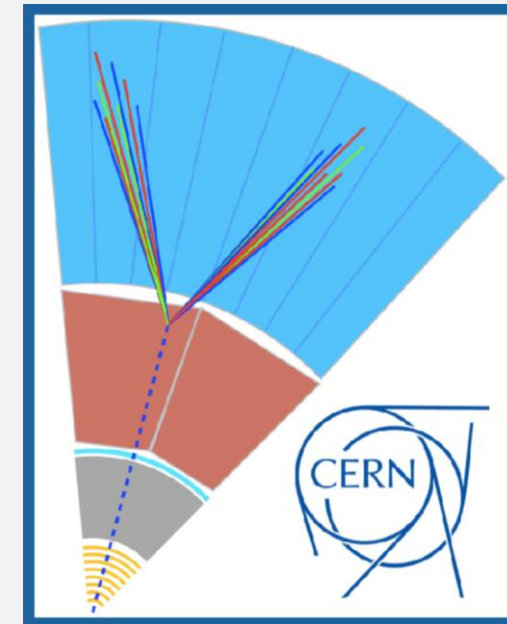
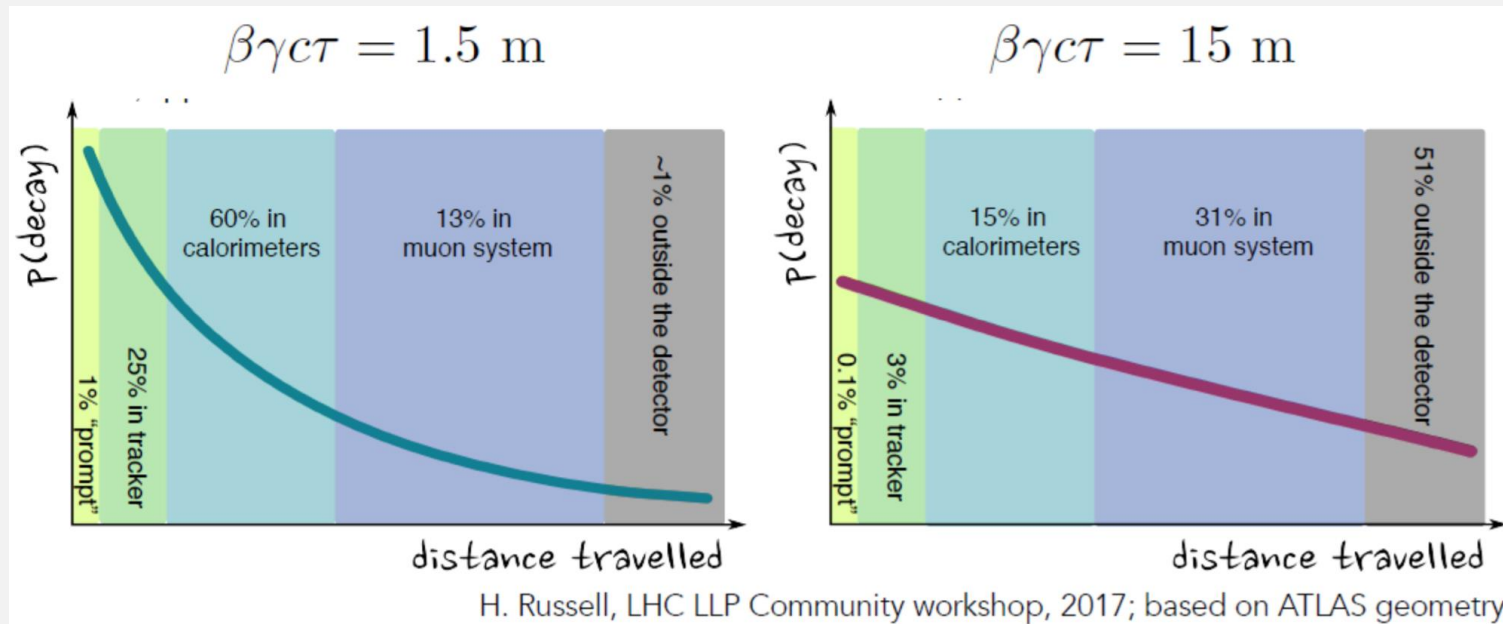


What is a long-lived particle?

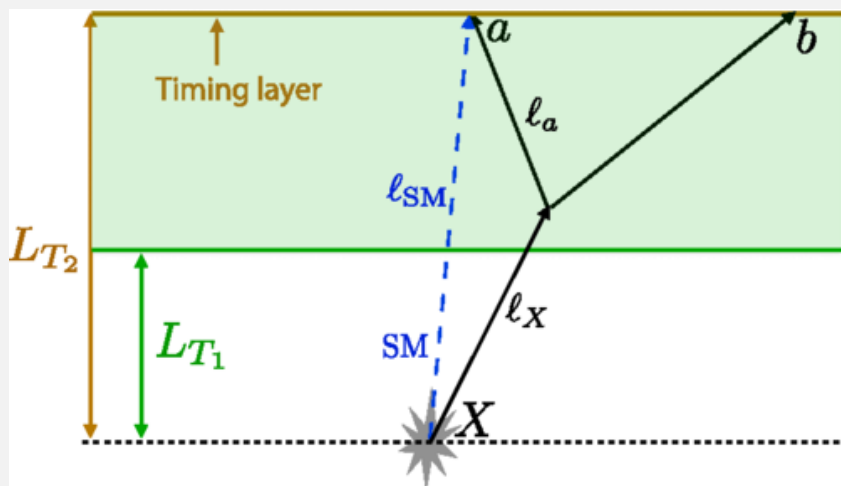
Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP

Signal signature of a long-lived particle:

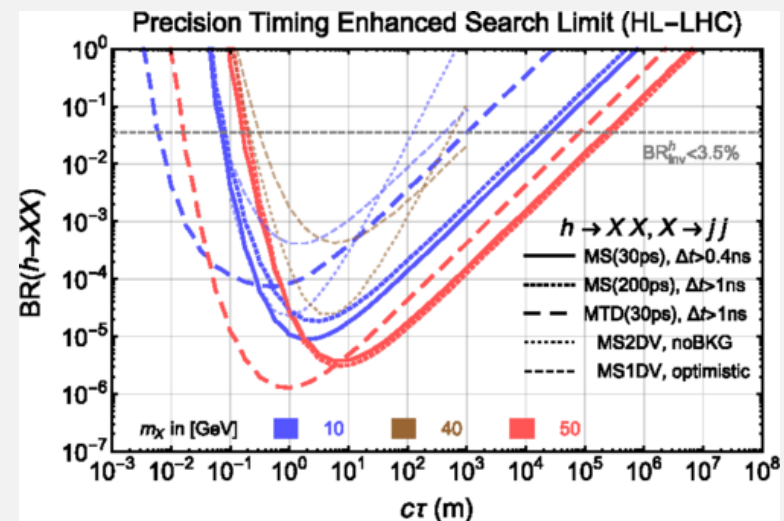
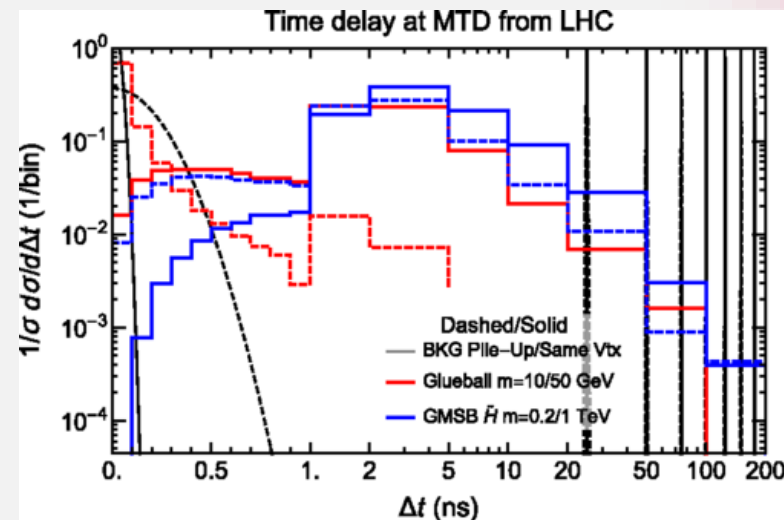
Neutral LLP decays are a spectacular signature, and the **burst of energy** appearing out of nowhere sets it apart from the collision point.



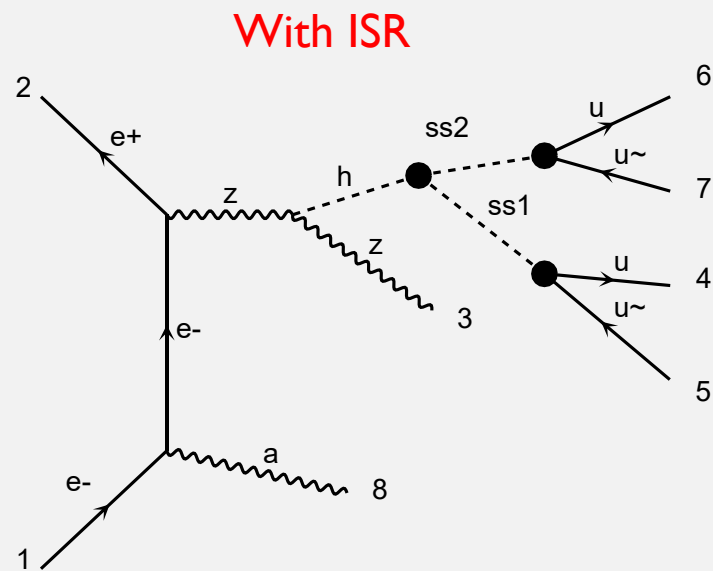
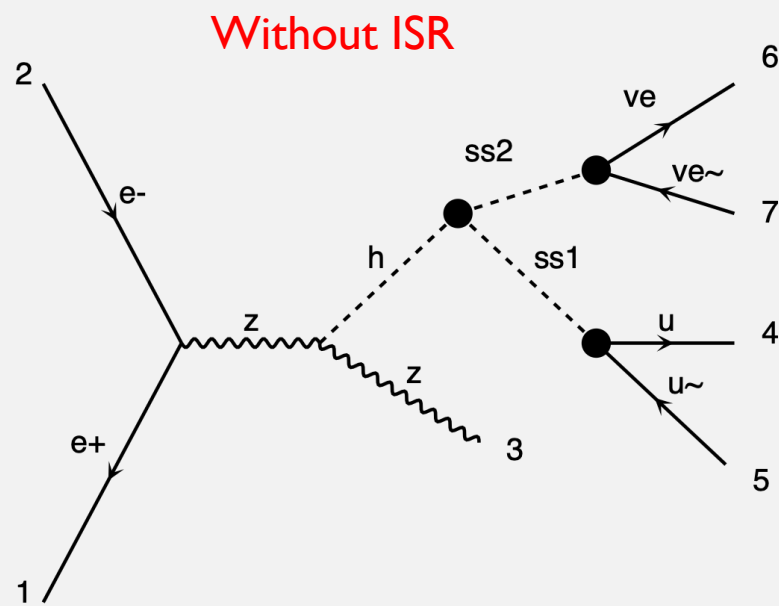
Enhancing Long-Lived Particles Searches @ LHC with Precision Timing Information



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

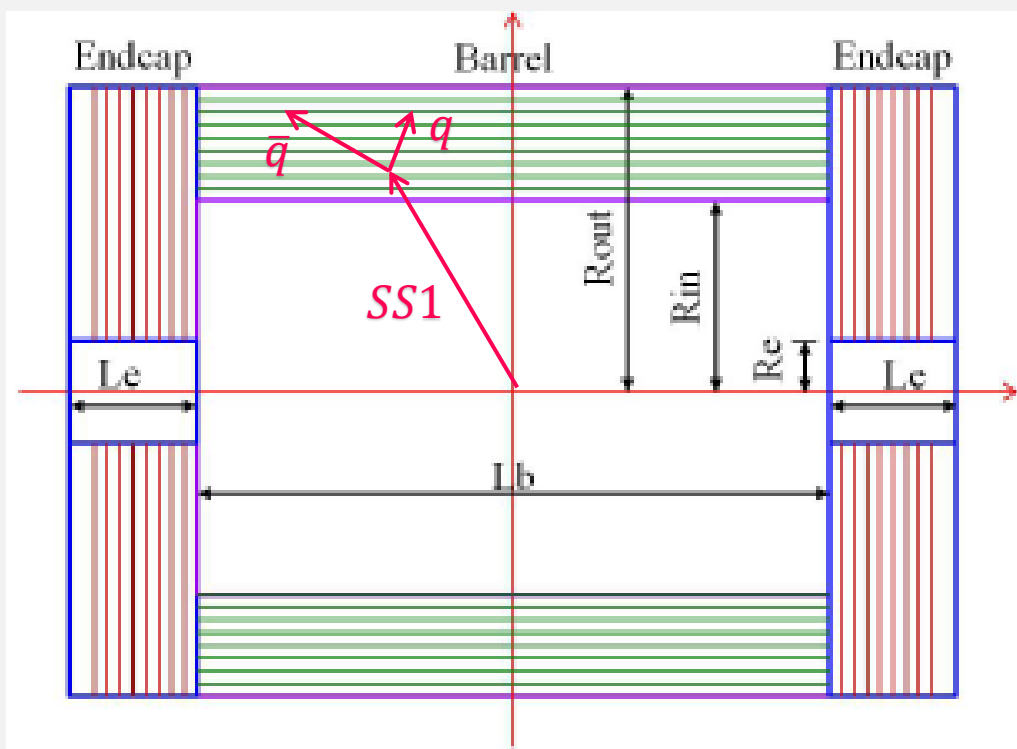


LLP Searches at Lepton Colliders (CEPC)



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

Selection Criteria



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

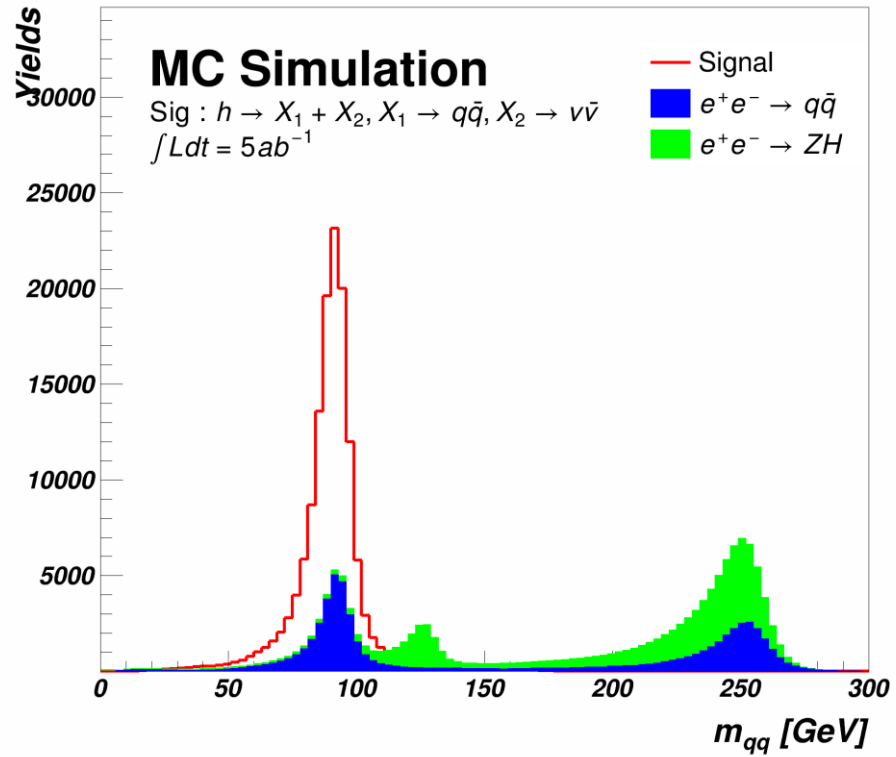
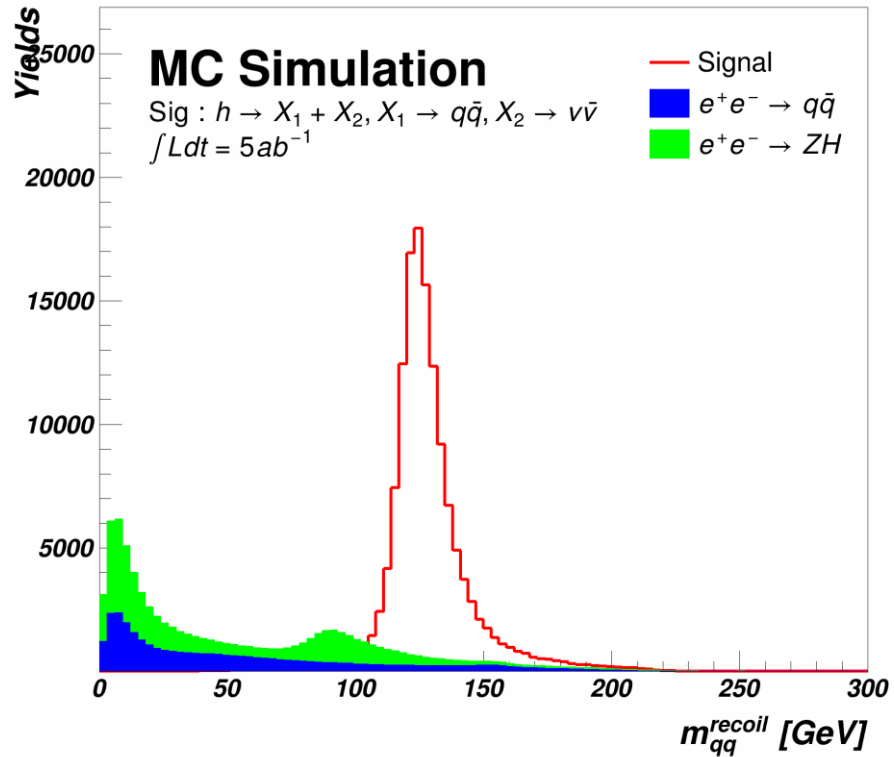
Event Selection

	Signal	$e^+e^- \rightarrow q\bar{q}$	$e^+e^- \rightarrow Zh$	Total
# of Events in 5 ab^{-1}		2.0×10^8	1.0×10^6	2.01×10^8
# of Events simulated	$\sim 1.3 \times 10^6$	$\sim 1.5 \times 10^6$	$\sim 1.37 \times 10^6$	$\sim 2.87 \times 10^6$
Decay in Muon Detector	137,536	1,151,350	754,134	1,905,484
$ m_{qq} - m_Z \leq 20\text{ GeV}$	122,055	496,499	75,157	571,656
$ m_{qq}^{rec} - m_h \leq 20\text{ GeV}$	112,623	47,773	53,632	101,405
$E_{2j} \geq 30\text{ GeV}$	84,240	229	57	286
$\min(\Delta T_{j_1}, \Delta T_{j_2}) > 3\text{ ns}$	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.

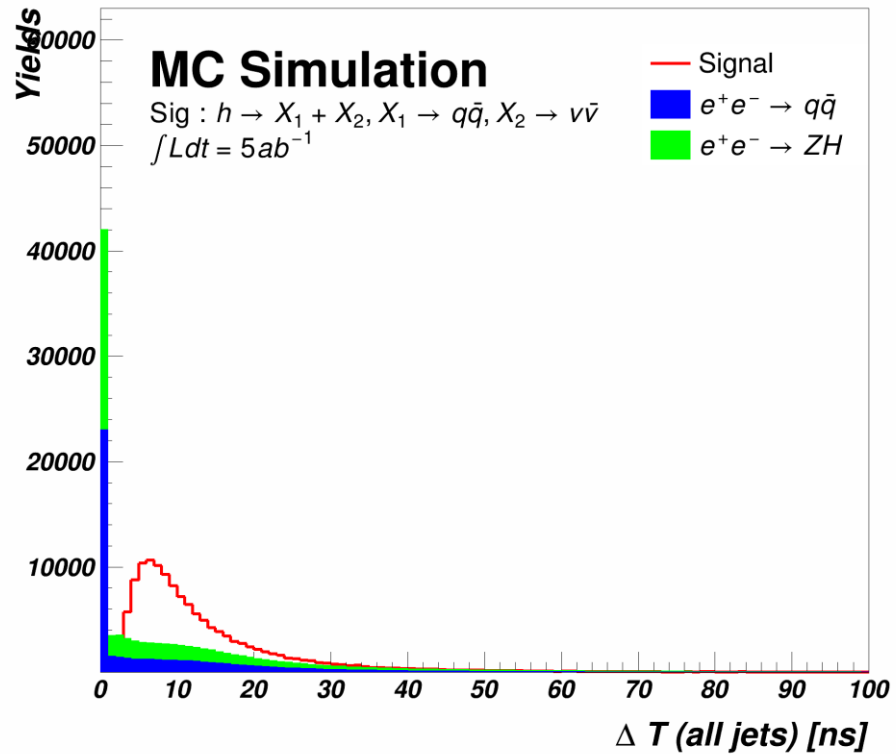
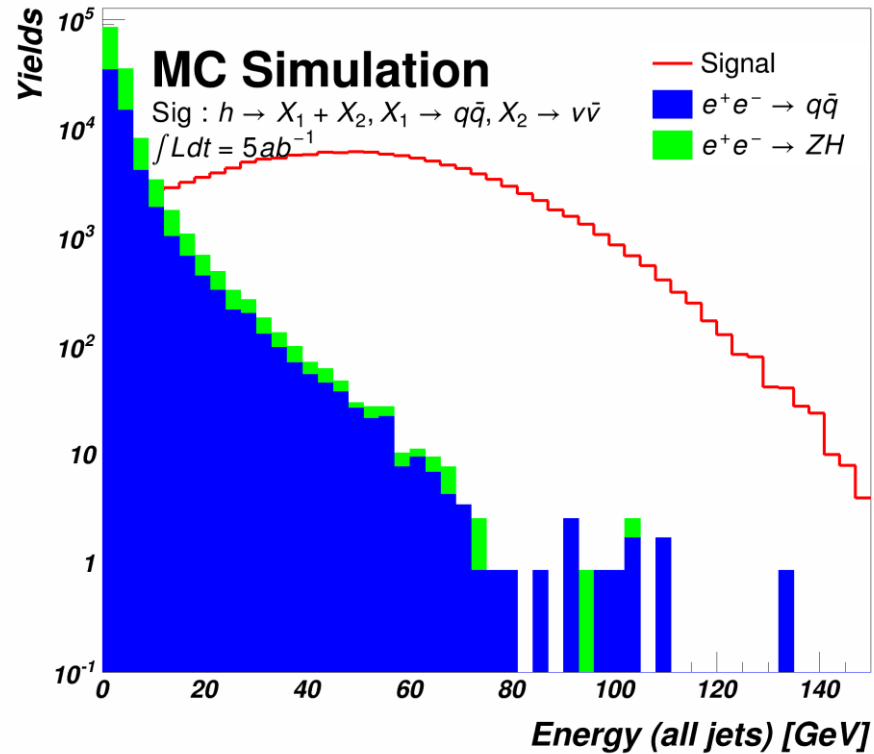


Mass of 2 prompt jets



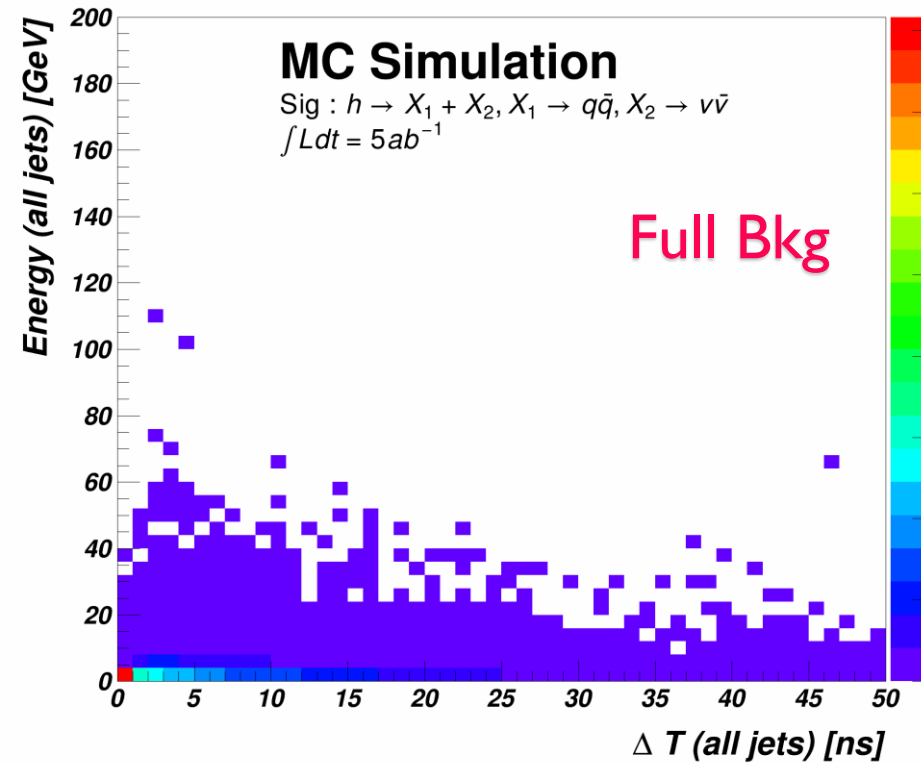
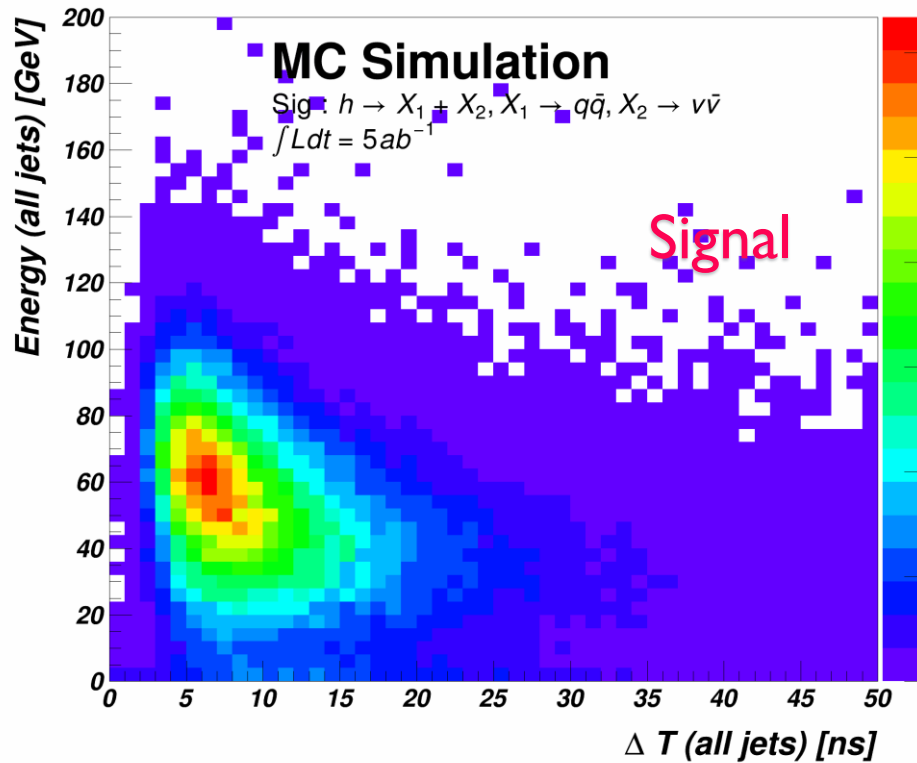
- qq is reconstructed by $e^+e^- - k_T$ algorithm, which represents for the jets from primary vertex
- Background is normalized to the scale of signal.

Time Difference vs. Energy



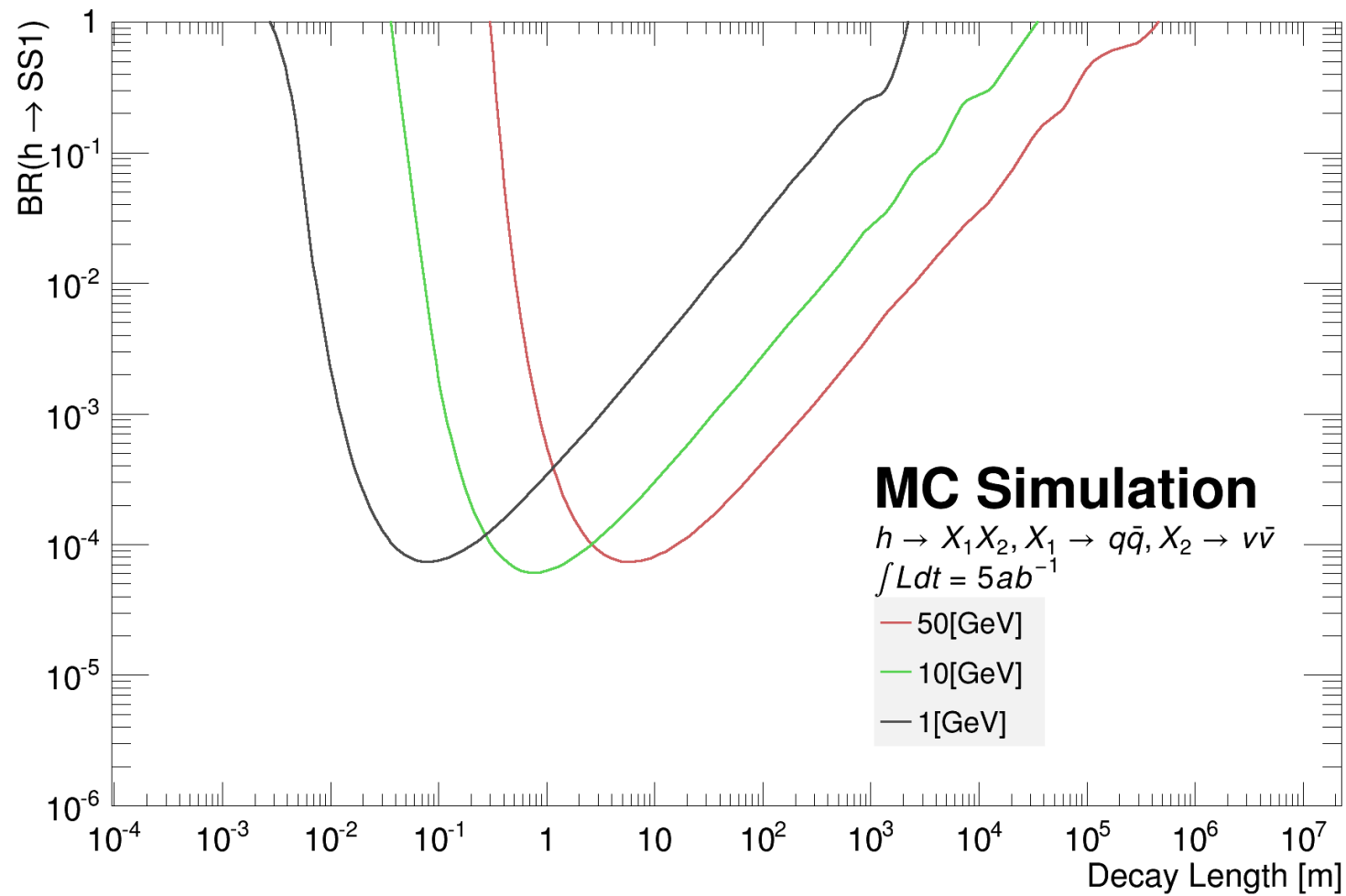
- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

Time Difference vs. Energy

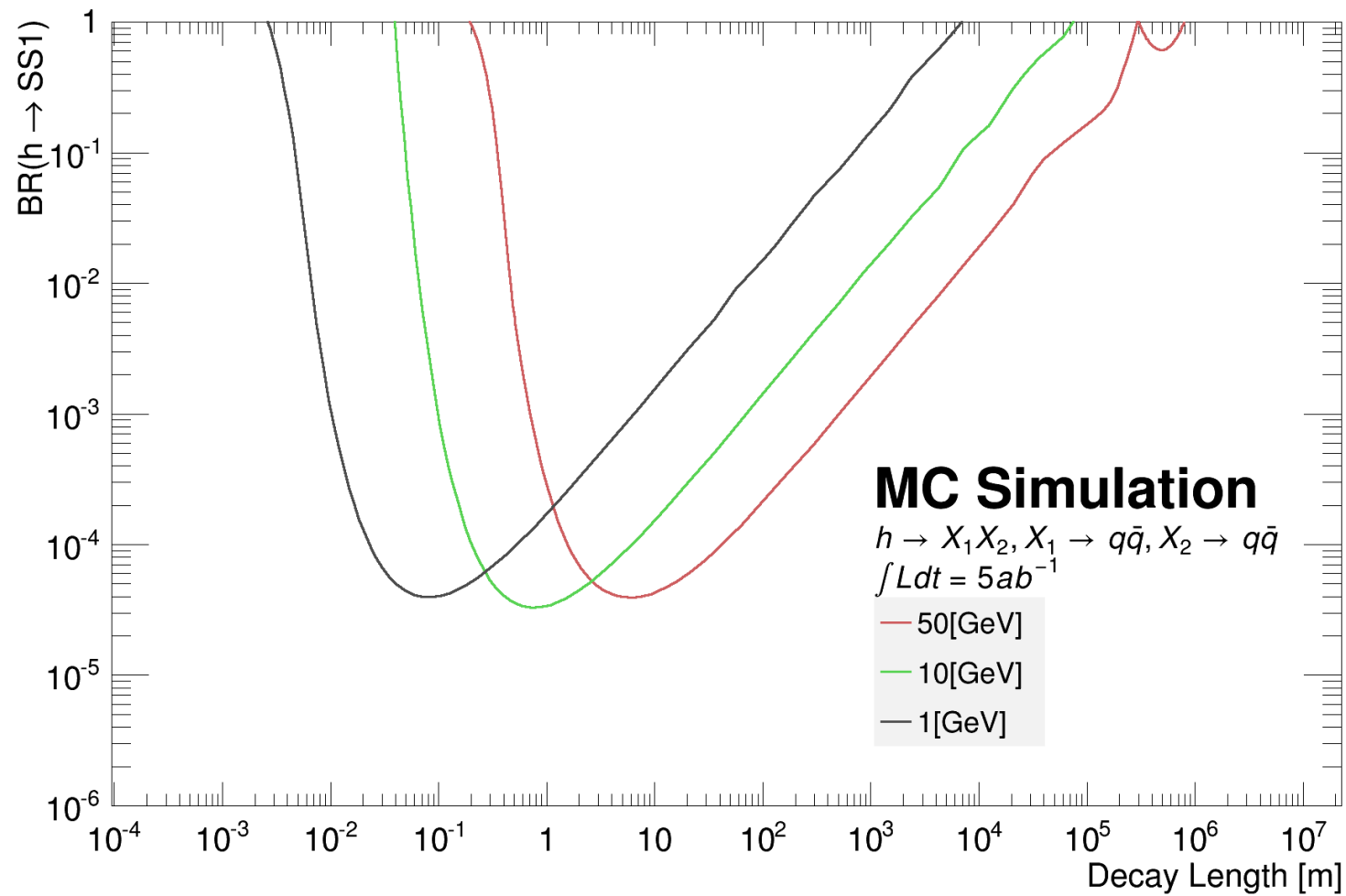


- Background is normalized to the scale of signal.
- Only count the energy in Muon detector

Sensitivity (2 jets)



Sensitivity (4 jets)



Summary

- A preliminary study has been performed on Long-Lived Particle ($h \rightarrow q\bar{q}\nu\bar{\nu}$ 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.
- CEPC can provide precise time information.
 - detector time resolution $\sim O(1) \text{ ns}$
- Further optimization on selection and reconstruction and more statistics are necessary for estimating the expected background.
 - Other backgrounds like pileup, cosmic rays are negligible in our case.
- To do...
 - Contribution from $Z \rightarrow \ell^\pm \ell^\mp$ process



Thanks

Yulei Zhang

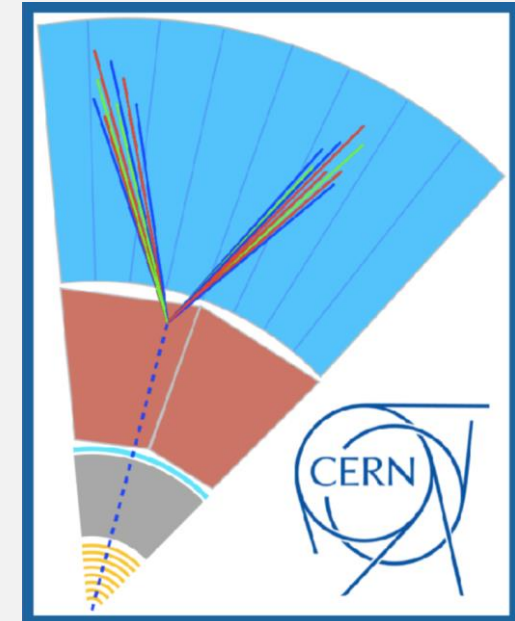
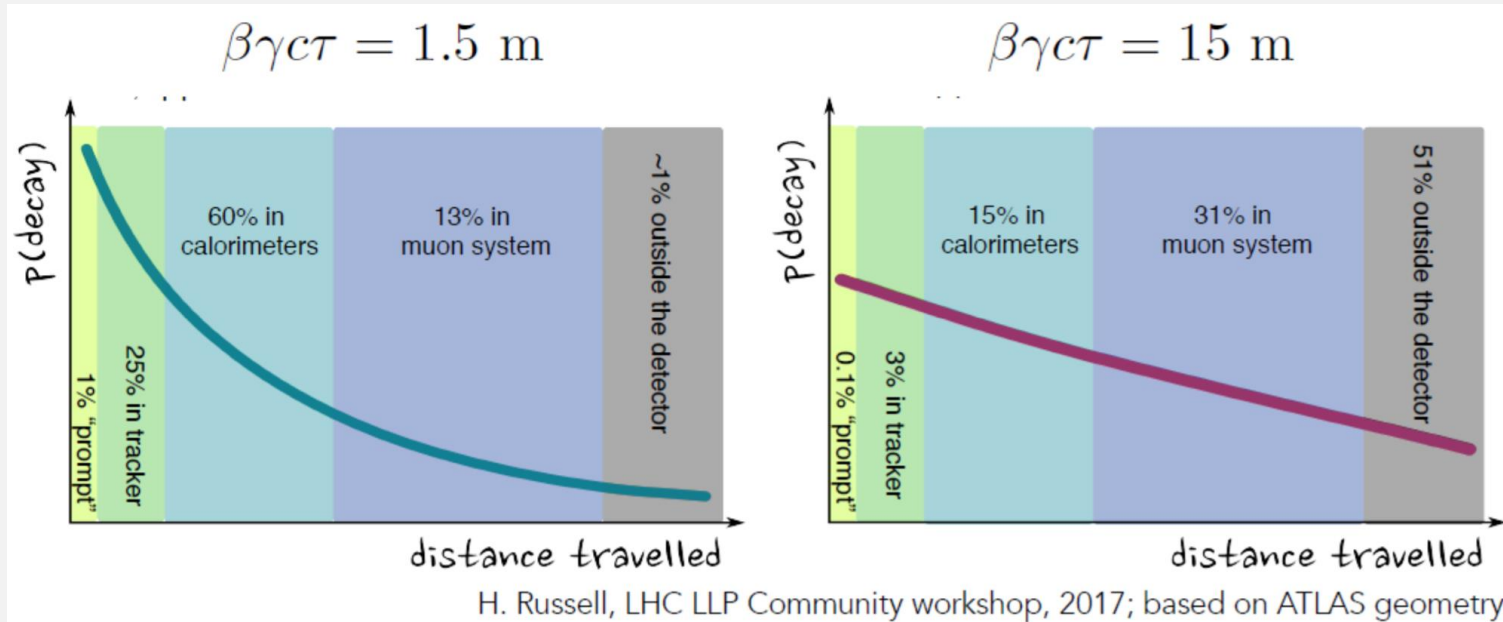
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Backup



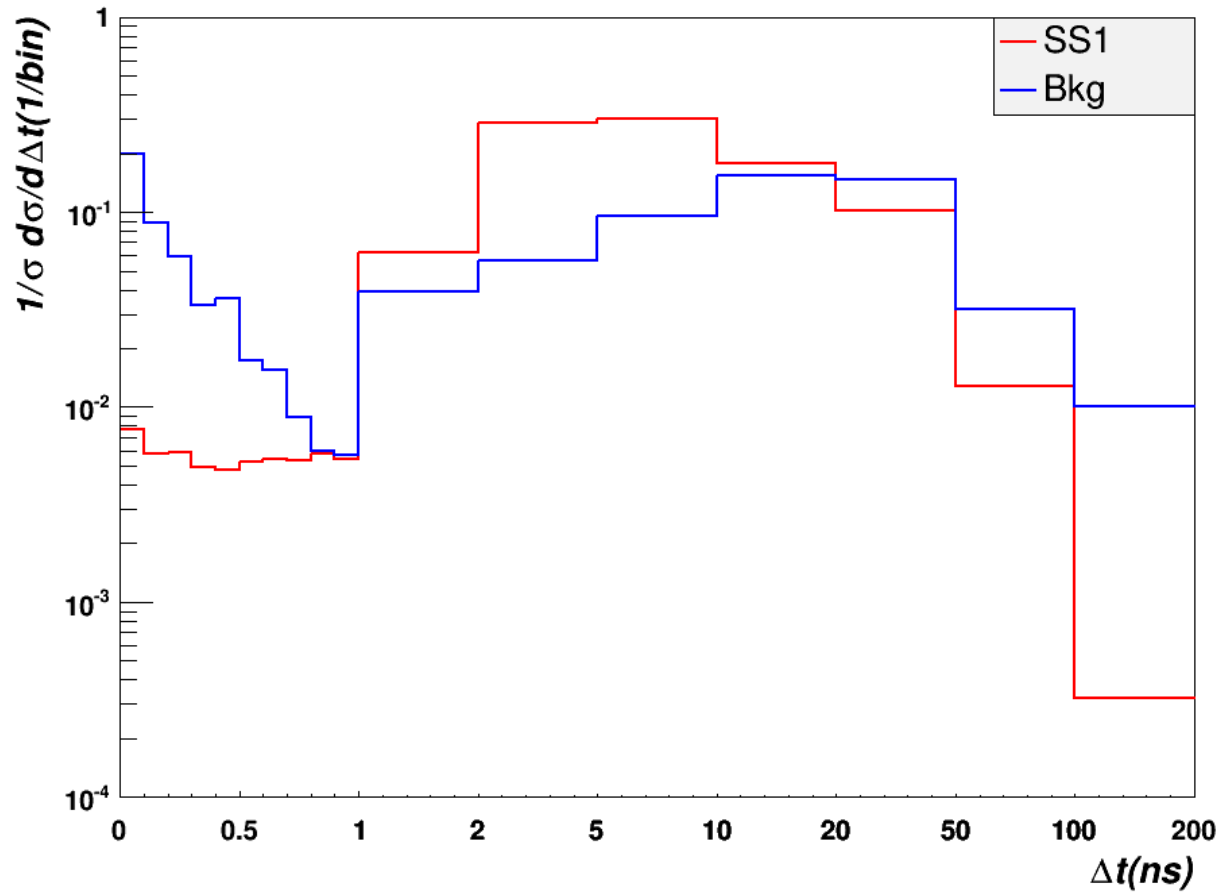
Challenges of searching for BSM LLPs

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



Time Difference (Normalized)

Time delay at Muon Detector from CEPC

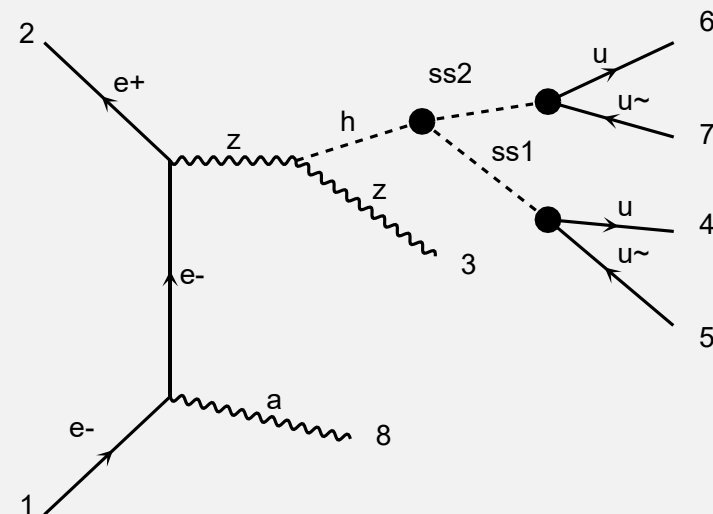


$$\Delta t = t_{\text{Hit}} - r_{\text{Hit}}/c$$

- Using FastJet Algorithm to cluster hits in Muon detector.
- Determine hit point by select $\min_t(j1, j2)$

Time Stamp Tagging

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



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

The cross section ratio is calculated by MadGraph5

Reconstructed ISR γ Efficiency

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

The cross section ratio is calculated by MadGraph5

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

γ from prompt process ($q\bar{q}$)

- $\pi^0 \rightarrow \gamma\gamma$
- In MC, over **99.3% jets** have a large amount of $\pi^0 \rightarrow$ Plenty of γ as time stamp.
- In $Z \rightarrow q\bar{q}, h \rightarrow q\bar{q}\nu\bar{\nu}$ 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 $Z \rightarrow q\bar{q}$: $\epsilon_{final}^\gamma = 86\% \times 95.2\% = \mathbf{81.94\%}$ (much larger than ISR)

	ϵ_{rec}^Z	ϵ_{rec}^{MC}	ϵ_{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%

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



Sensitivity (4 jets)

