Long-Lived Particle Search with Lepton Colliders

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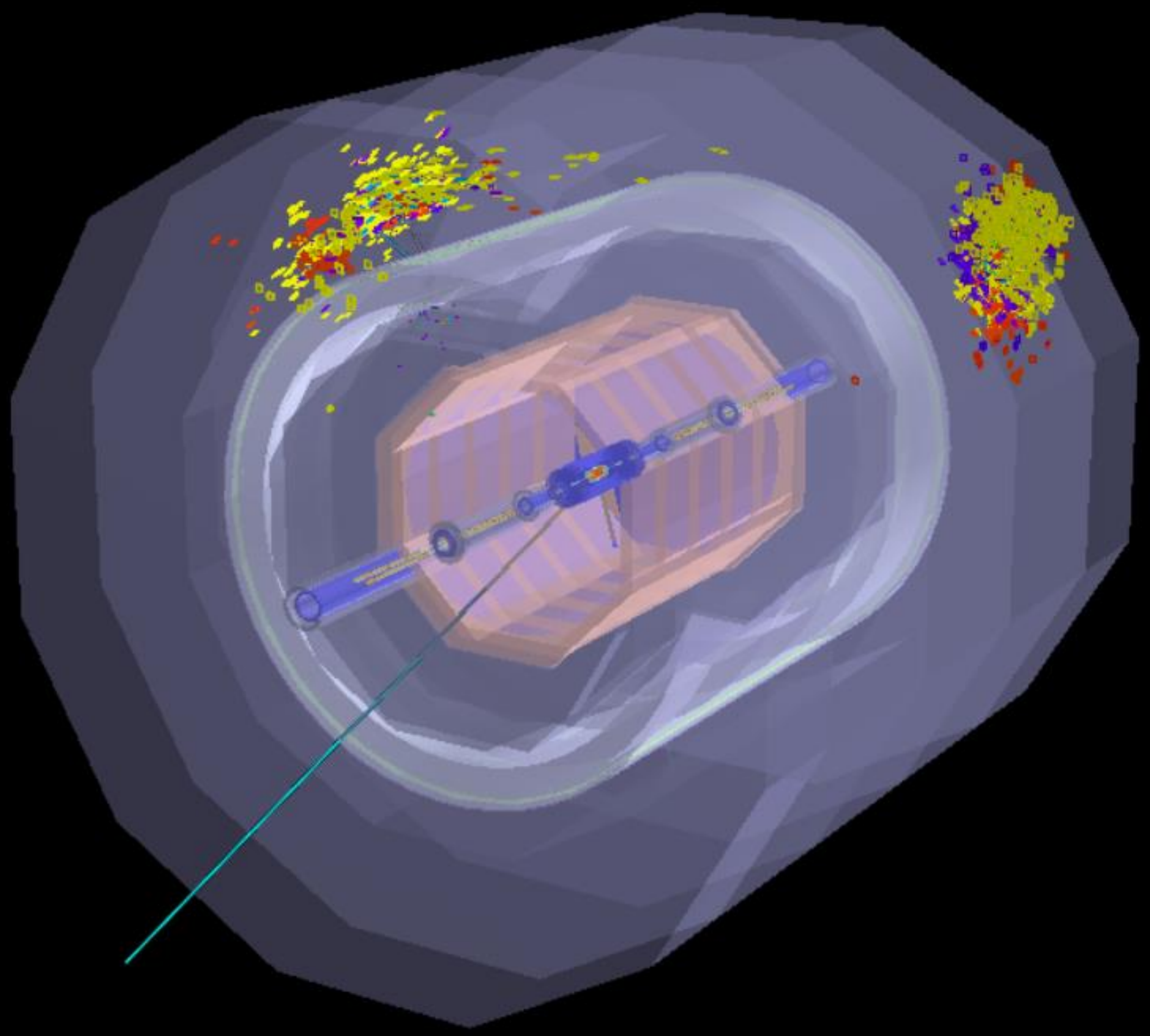
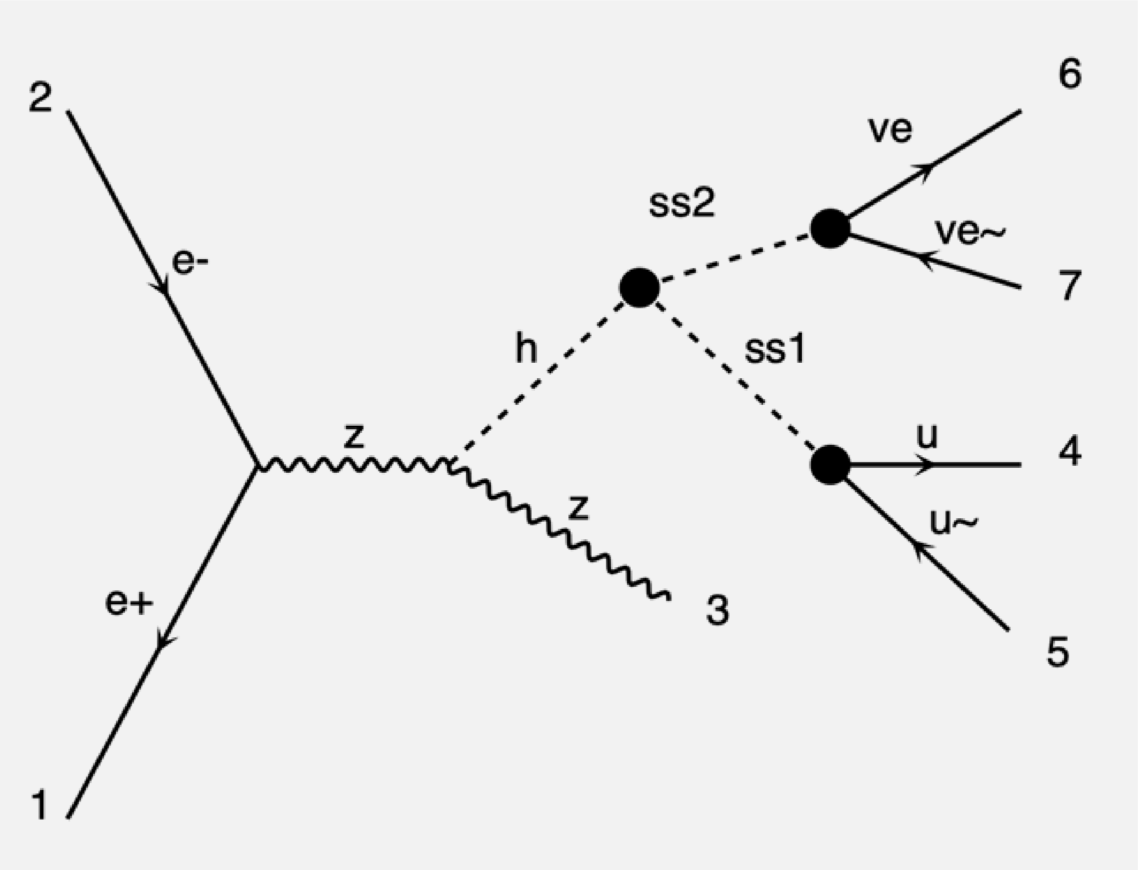
$$e^+e^- \rightarrow Zh \rightarrow \nu\bar{\nu} + SS1 + SS2 \rightarrow \nu\bar{\nu}q\bar{q}q\bar{q}$$



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.

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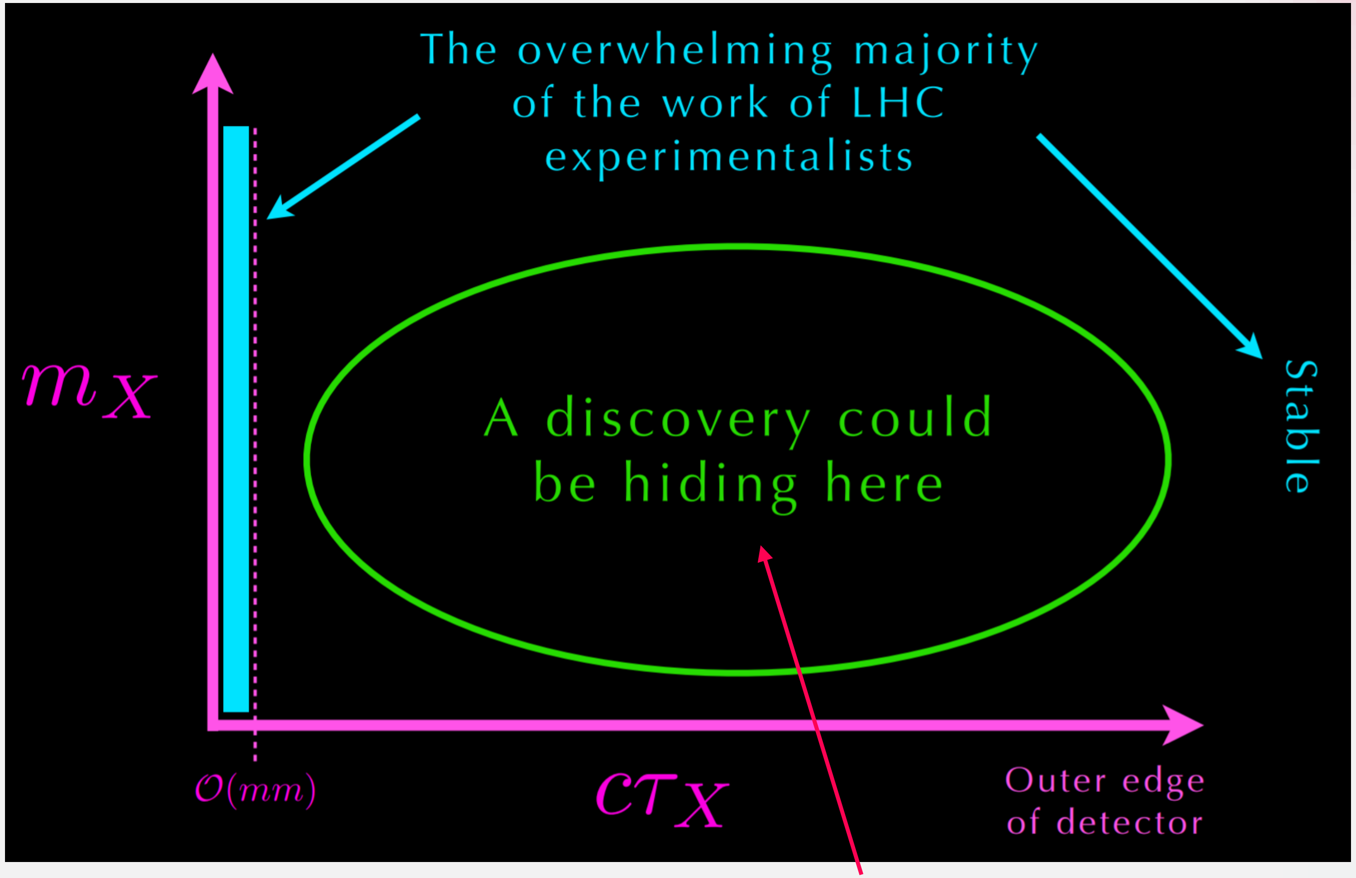

Long-Lived Particle

What is a long-lived particle?

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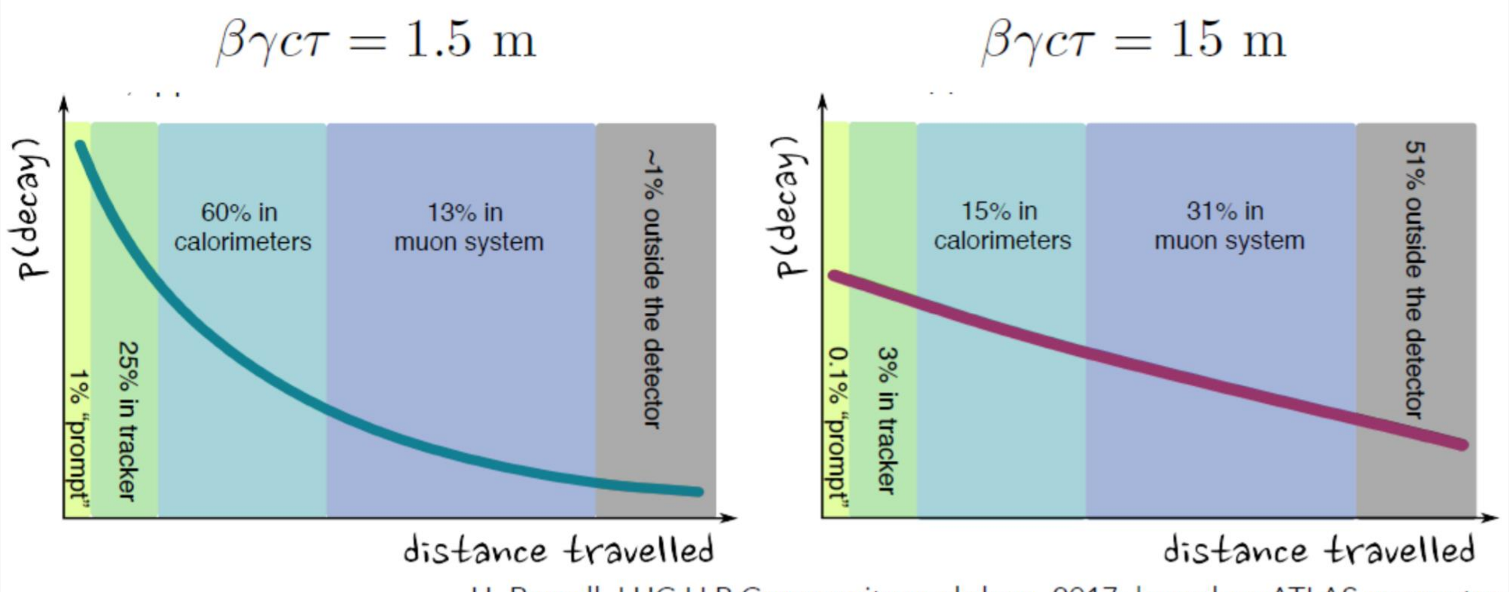
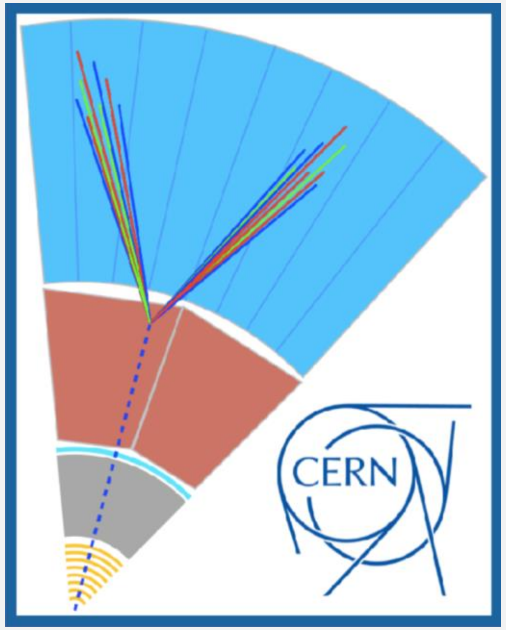
*Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

Signal signature of a long-lived particle:

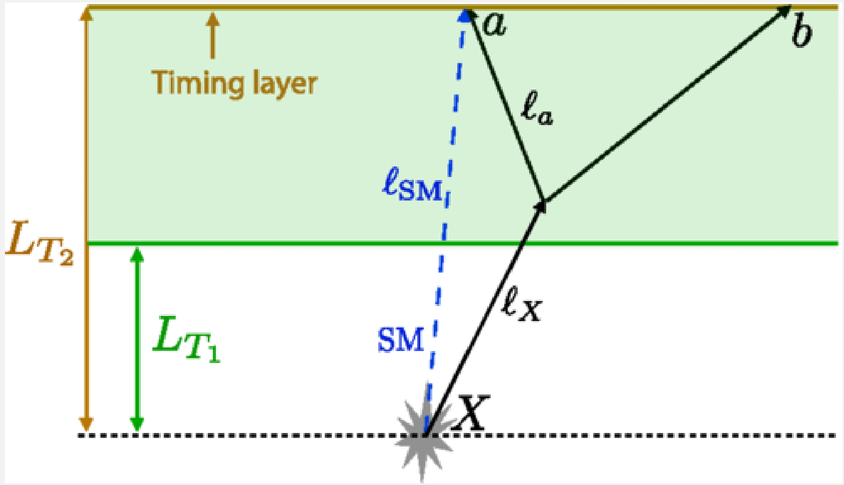
Neutral LLP decays are a spectacular signature, and the burst of energy appearing out of nowhere sets it apart from the collision point.



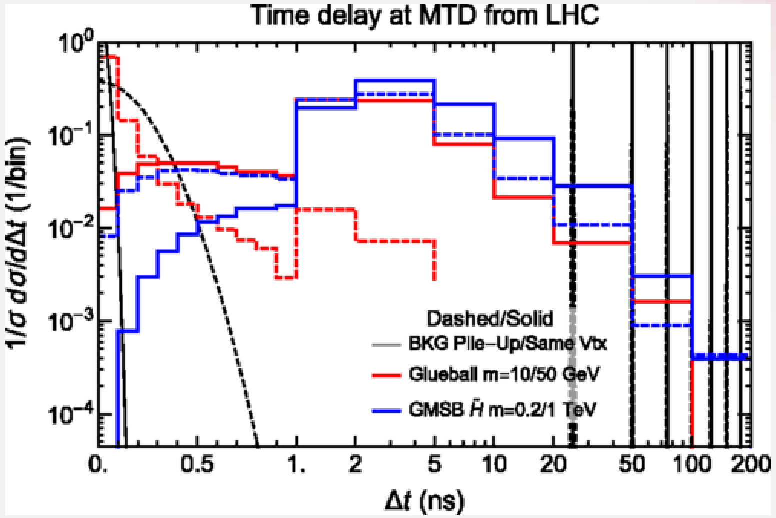
H. Russell, LHC LLP Community workshop, 2017; based on ATLAS geometry

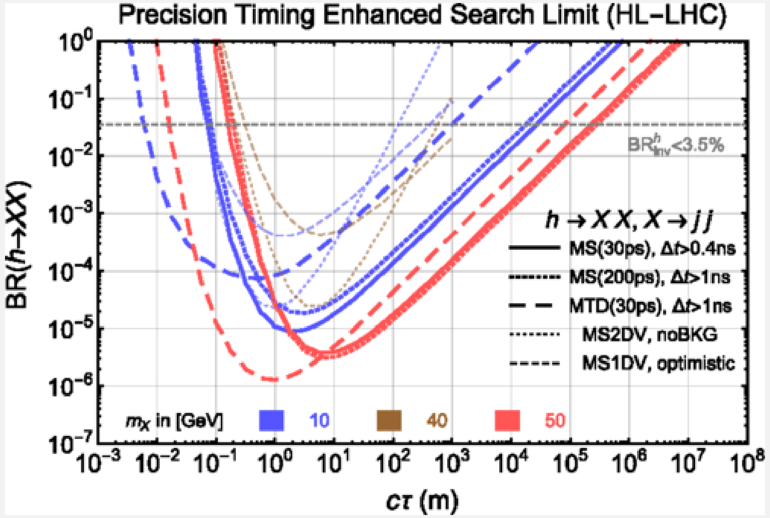


Enhancing Long-Lived Particles Searches @ LHC with Precision Timing Information



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

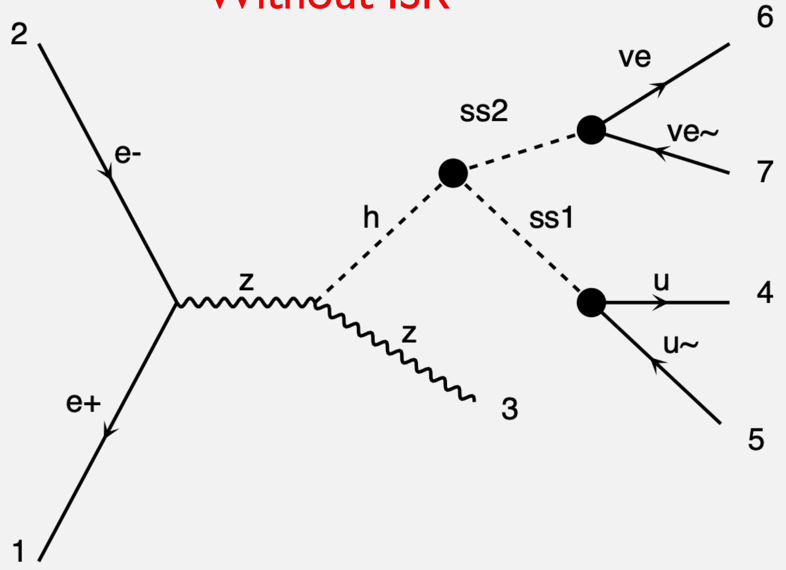




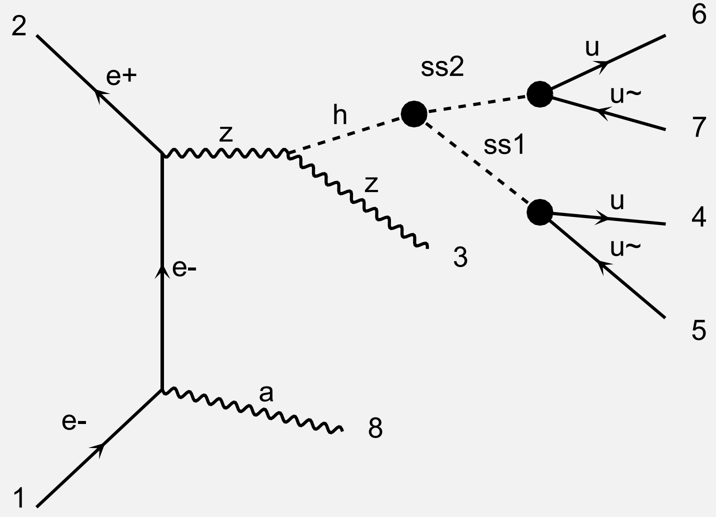
Jia Liu, Zhen Liu, and Lian-Tao Wang Phys. Rev. Lett. **122**, 131801 – 2019.04.03

LLP Searches at Lepton Colliders (CEPC)

Without ISR



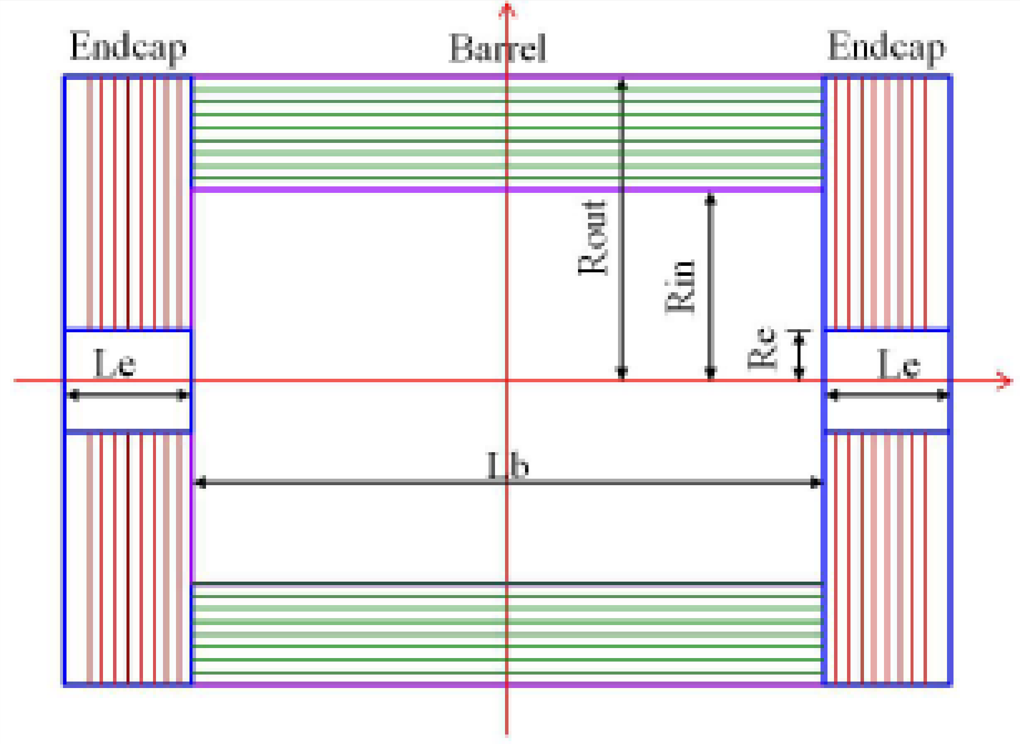
With ISR



- 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_{out} see next page)

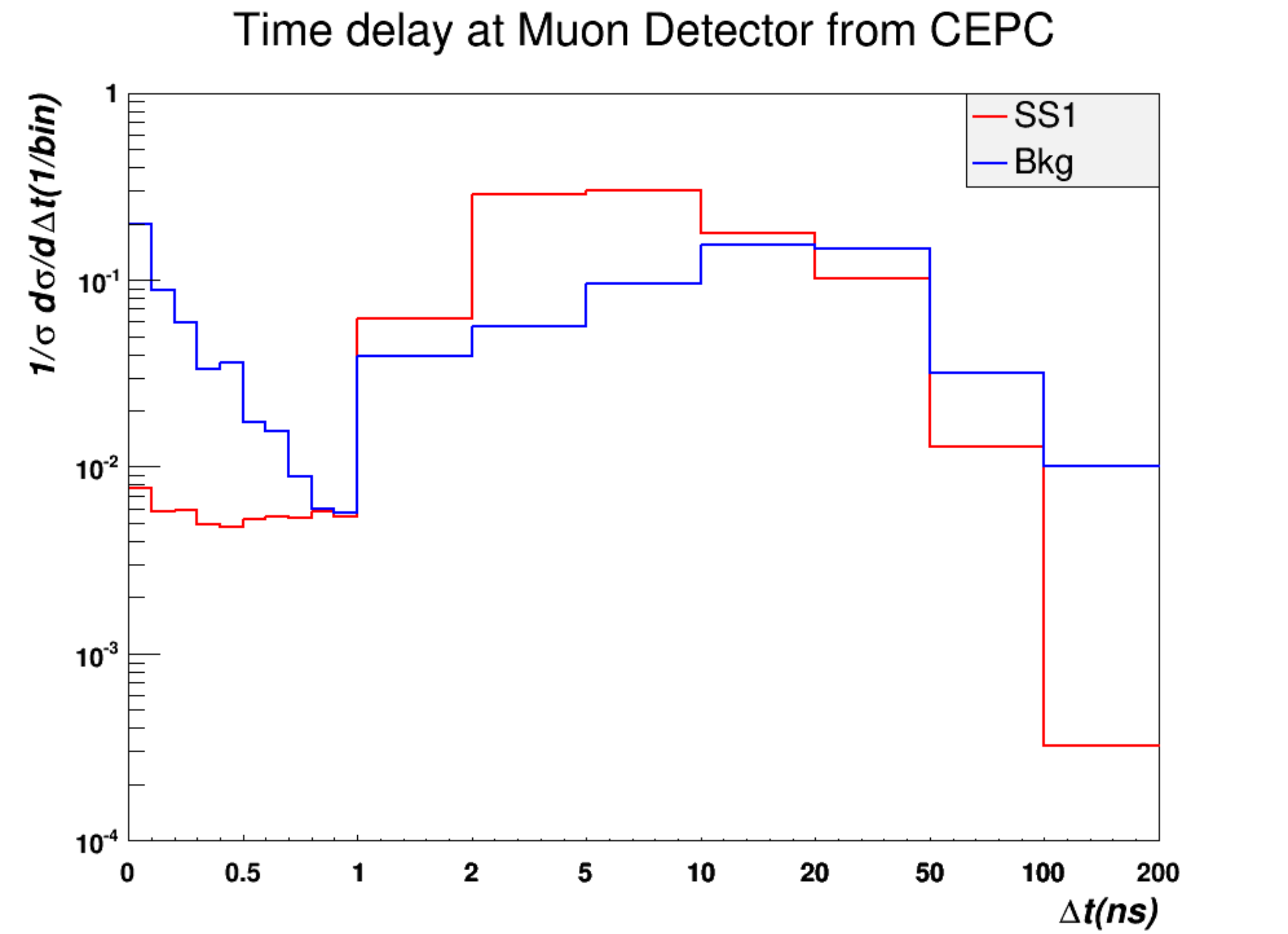
Long-Lived Particle

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

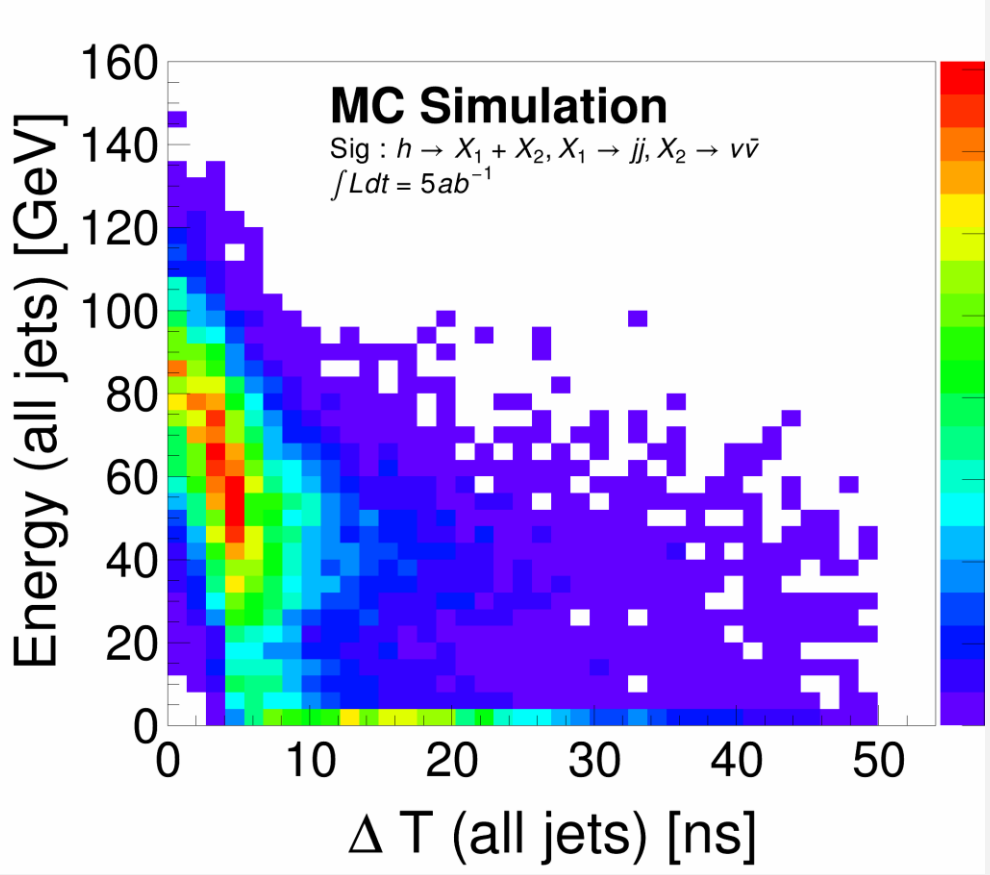
Time Difference (Normalized)

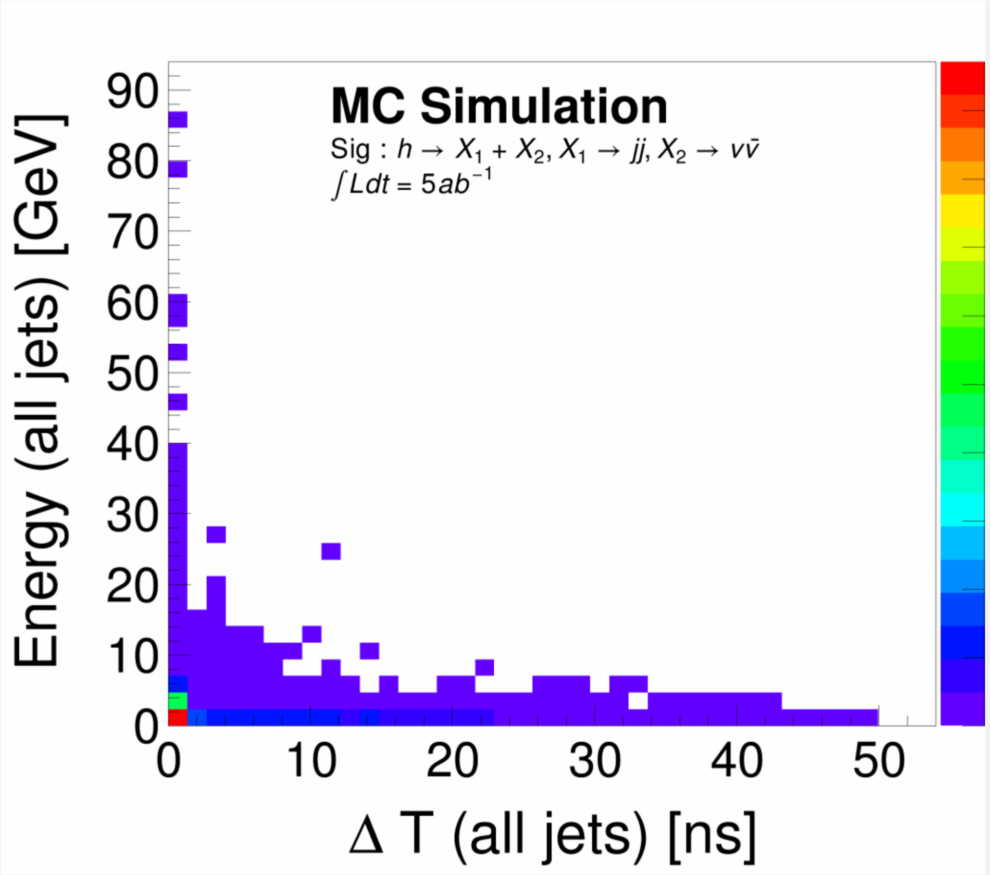


$$\Delta t = t_{\mathrm{Hit}} - r_{\mathrm{Hit}}/c$$

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

Time Difference vs. Energy

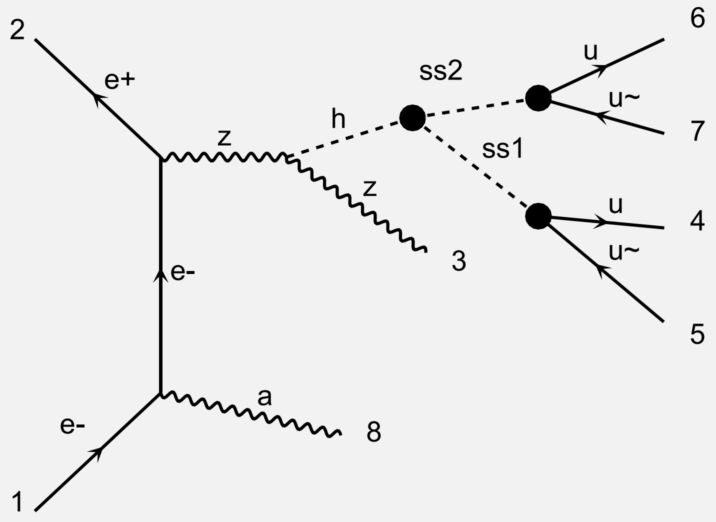




- Only count the energy in Muon detector

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

Long-Lived Particle

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

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 ($q\bar{q}$)

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

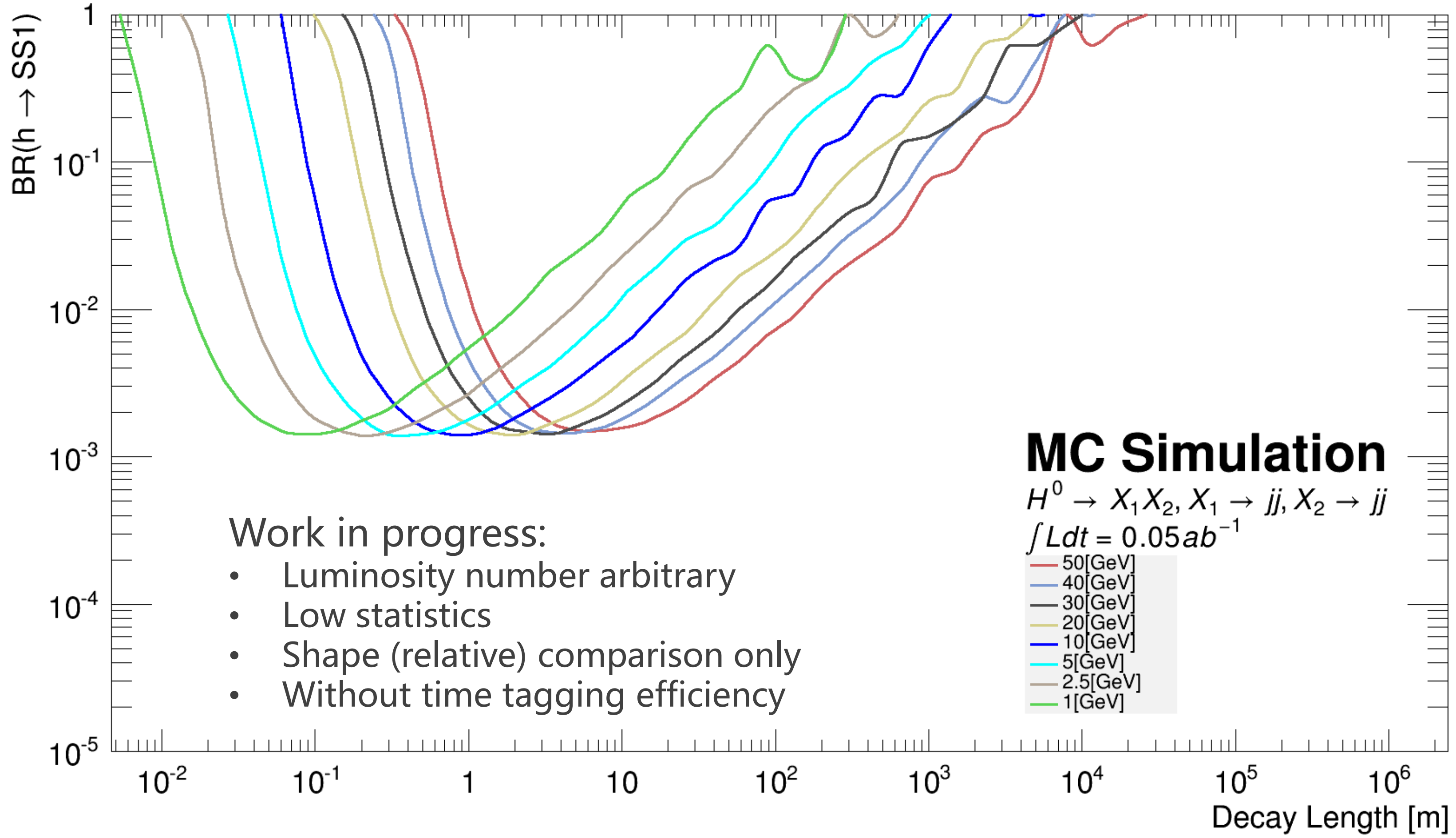
- In $Z \rightarrow q\bar{q}, h \rightarrow q\bar{q}\nu\bar{\nu}$ samples, require γ selected from the constituents of jets.
- Efficiency of Reconstructing a γ from jet: $\epsilon_{rec} \geq 99\%$
- Efficiency of Reconstructing a γ from jet with MC truth link: $\epsilon_{rec}^{MC} = 86\%$
- Efficiency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

	$\boldsymbol{\epsilon_{rec}^{Z}}$	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%**

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

Long-Lived Particle

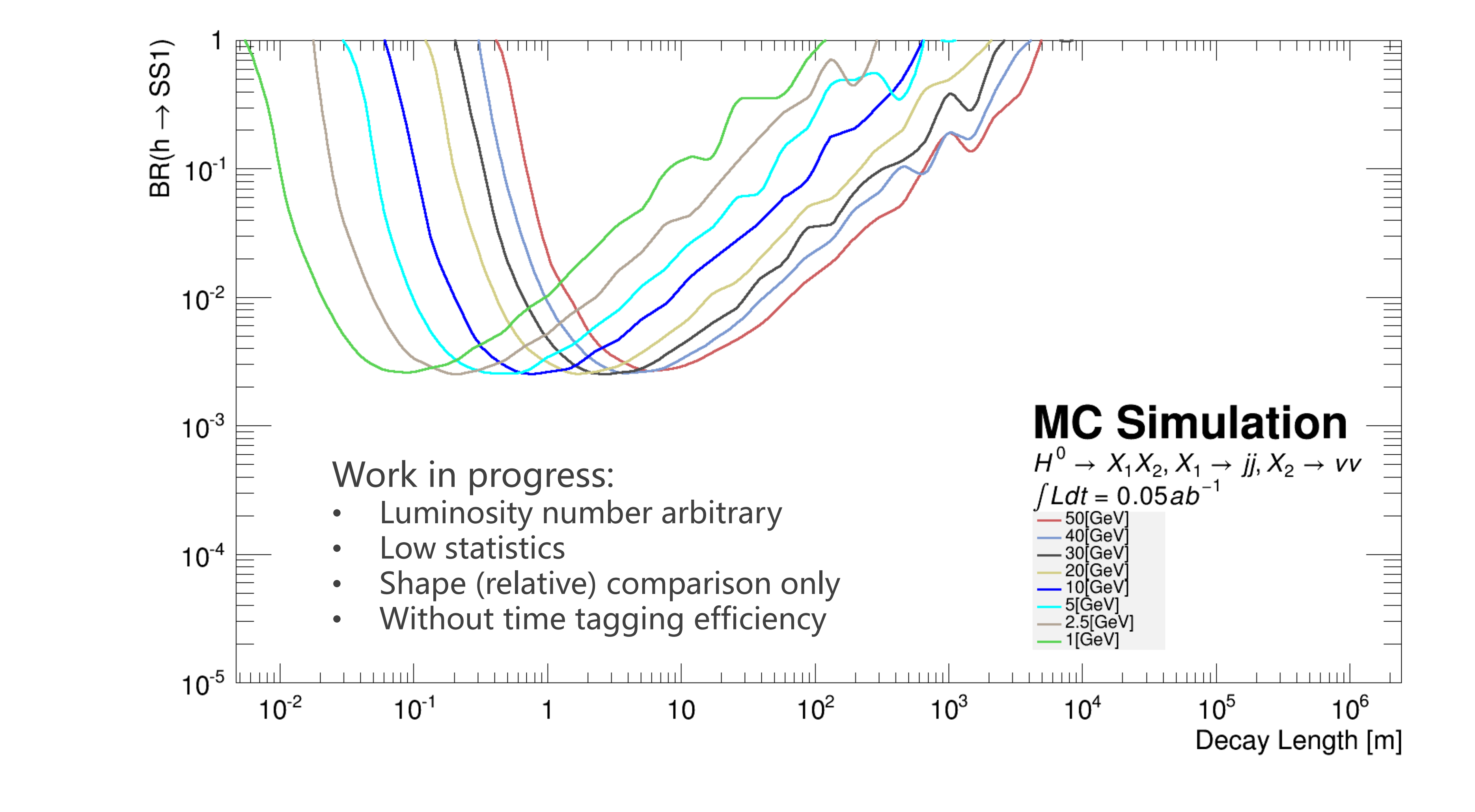
Sensitivity (4 jets)



Work in progress:

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

Sensitivity (2 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.
- γ is a good candidate for time stamp.
  - $\Delta t = t_{\mathrm{Hit}} - r_{\mathrm{Hit}}/c$ ~ detector time resolution
  - ISR\FSR γ $\boldsymbol{\epsilon_{rec}^{\gamma} = 5.10\%}$
  - $\pi^0 \to \gamma\gamma$ in jets $\boldsymbol{\epsilon_{rec}^{\gamma} = 55.32\%}$
- Expected background is 2 without further optimization on selection and reconstruction.
  - Other backgrounds like pileup, cosmic rays are negligible in our case.
- To do…
  - Time tagging 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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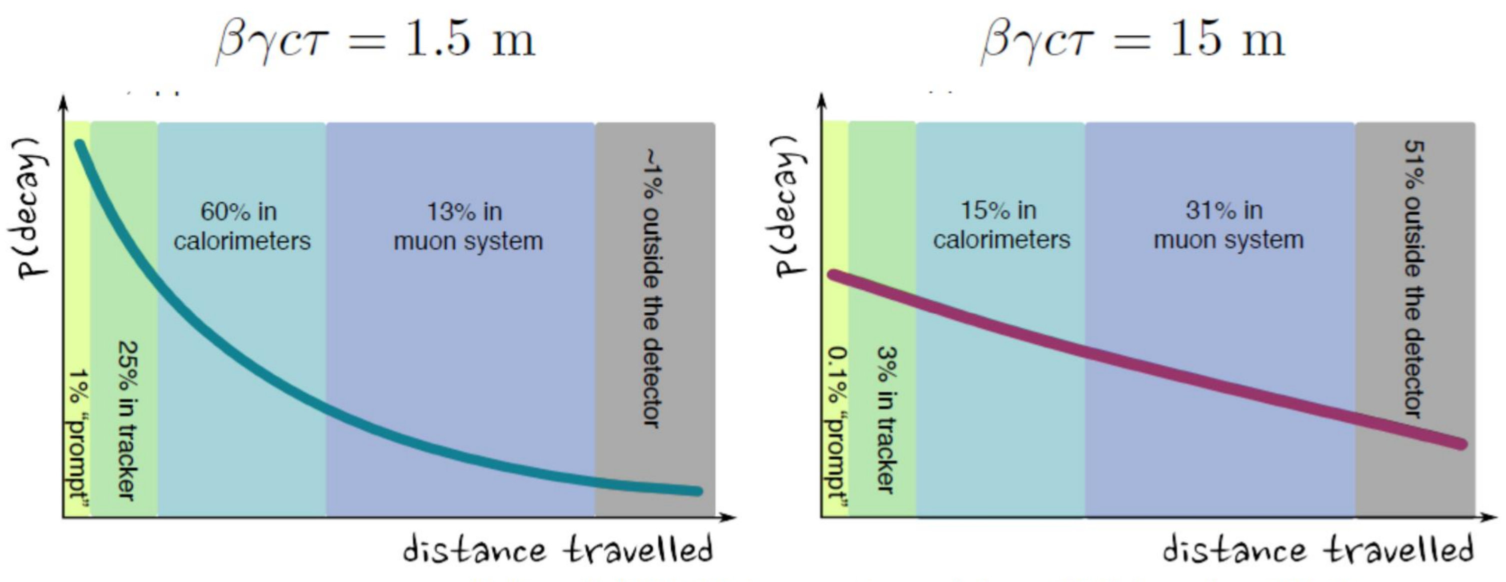
- Final states:
  - Limited by how well the experiments can reconstruct final state objects
- Displacement:
  - High displacement helps to discriminate against SM backgrouds
  - High displacement searches are also limited by the physical size of the detector
  - **Need very good vertexing and tracking techniques to reconstruct displaced vertex**



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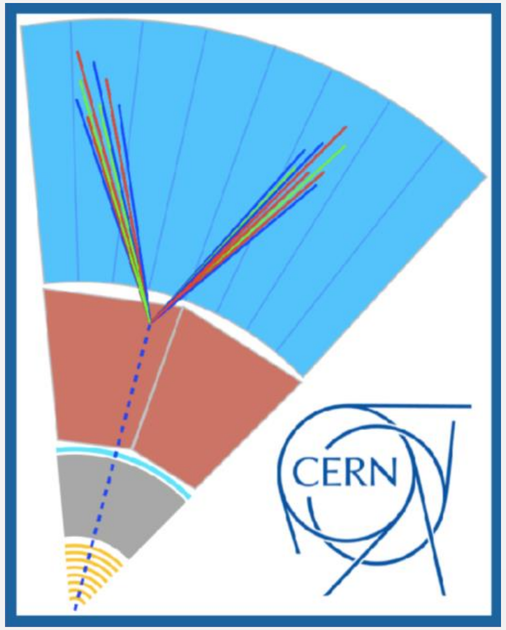
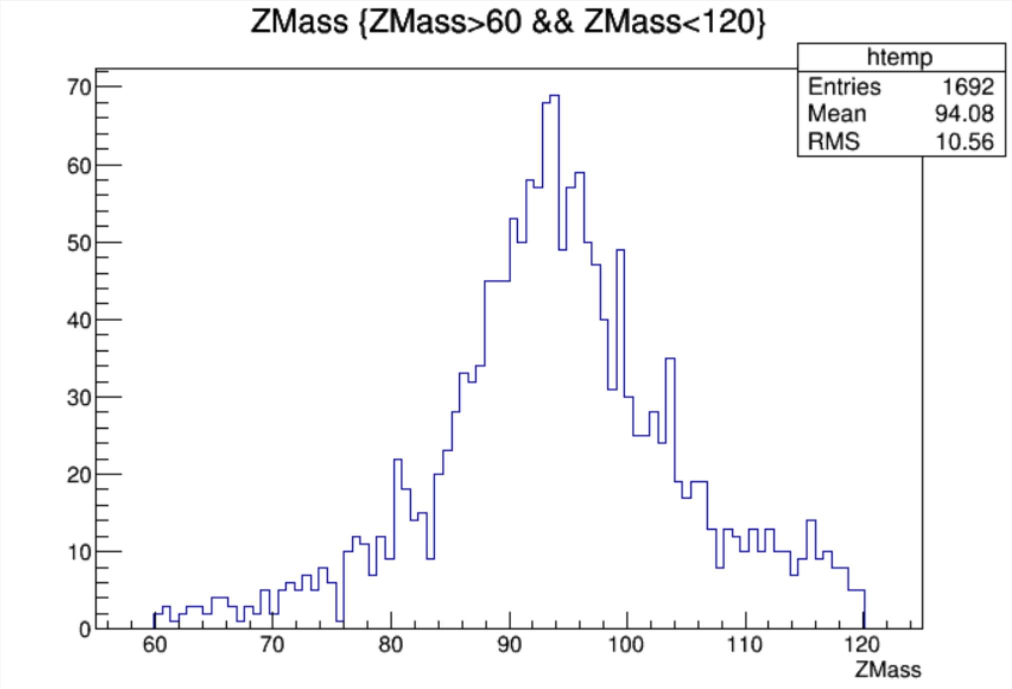
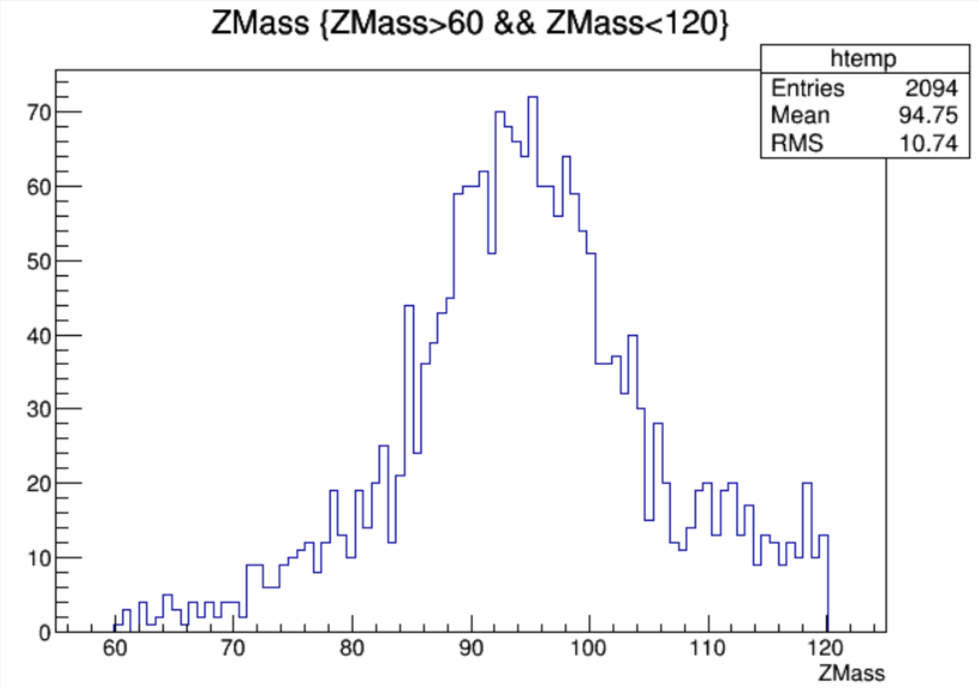


Z Mass



2 jets



4 jets