Long Lived Particle Search with timing information at the HL-LHC

Dong Woo Kang
(Yonsei U.)

Based on arXiv:1903.05825
Collaborated with Seong Chan Park (Yonsei U.), Zachary Flowers, Quinn Meier, Christopher Rogan (University of Kansas)
LLP searches @ collider

- Missing transverse energy
- Displaced vertices
- Non-pointing events (Large impact parameter)
- Disappearing tracks
- Initial state radiation
LLP searches @ collider

- Missing transverse energy
- Displaced vertices
- Non-pointing events (Large impact parameter)
- Disappearing tracks
- Initial state radiation

What else?
Timing detector @ HL-LHC

ATLAS
- High-Granularity Timing Detector at the endcap region
- ~30 ps resolution
- Coverage $2.4 < |\eta| < 4.0$

CMS
- Minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
- ~30 ps resolution for charged tracks
- Coverage $|\eta| < 3.0$
We can measure *displaced vertex* +

We can measure *time of flight (ToF)*

↓

We can measure $\beta$ of *long-lived particle* !!!
Neutral LLP search example

$p p \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 ZZ$
$\rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 l^+ l^- l^+ l^-$

It is impossible to fully reconstruct the system by conventional method. Why?

# of unknowns > # of knowns

4 momenta = 16
2 momenta = 8
$p_T^{miss} = 2$
2 displaced vertices = 4

How can we solve this kind of system?
Sol1: Reconstruction without timing

$\textbf{LLP} : \text{Long-lived particle}$

$\textbf{V} : \text{Visible SM particle}$

$\textbf{I} : \text{Invisible particle}$

$\# \text{ of unknowns} = \# \text{ of knowns} + \# \text{ of constraints}$

$p_{\text{LLP}_a}, p_{\text{LLP}_b}, p_{I_a}, p_{I_b}$

$P_{V_a}, P_{V_b}$

$p_{\text{miss}}$  = 8

$|\hat{r}_a|, |\hat{r}_b|$  = 4

Sol1: 2 assumptions

$M_{\text{LLP}_a} = M_{\text{LLP}_b}, M_{I_a} = M_{I_b}$

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Sol2: Reconstruction with timing

\[ \# \text{ of unknowns} = \# \text{ of knowns} + \# \text{ of new inputs} \]

\[ P_{LLP_a}, P_{LLP_b}, P_{I_a}, P_{I_b}, P_{V_a}, P_{V_b} = 16 \]

\[ p_T^{\text{miss}}, \hat{r}_a, \hat{r}_b = 2, 4 \]

Sol2: 2 timing information

\[ T_a, T_b \]

LLP : Long-lived particle
V : Visible SM particle
I : Invisible particle
Sol1: Reconstruction without timing

- 6 d.o.f become two 3-momenta
  - \( \hat{r}_a, \hat{r}_b \) 4 d.o.f
  - \( p_T^{\text{miss}} \) 2 d.o.f

3-momenta of LLPs

\[
p_a = \frac{\hat{r}_b \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} \hat{r}_a
\]

\[
p_b = \frac{\hat{r}_a \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\hat{r}_a \times \hat{r}_b \cdot \hat{k}} \hat{r}_b
\]

3-momenta of invisible particles

\[
p_{I_a} = p_a - p_{V_a}
\]

\[
p_{I_b} = p_b - p_{V_b}
\]

4-momentum conservation

\[
m_a^2 = m_{I_a}^2 + m_{V_a}^2 + 2E_{V_a} \sqrt{m_{I_a}^2 + |p_{I_a}|^2 - 2p_{V_a} \cdot p_{I_a}}
\]

\[
m_b^2 = m_{I_b}^2 + m_{V_b}^2 + 2E_{V_b} \sqrt{m_{I_b}^2 + |p_{I_b}|^2 - 2p_{V_b} \cdot p_{I_b}}
\]

We can find 1 or 2 positive mass pairs with 2 assumptions

\[
m_a = m_b, \ m_{I_a} = m_{I_b}
\]

[M. Park and Y. Zhao, 1110.1403]
[G. Cottin, 1801.09671]
6 d.o.f become two 3-momenta
- $\hat{r}_a, \hat{r}_b$: 4 d.o.f
- $p_T^{\text{miss}}$: 2 d.o.f

3-momenta of LLPs
$$p_a = \frac{\beta_b \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_b \times \beta_a \cdot \hat{k}} \beta_a$$
$$p_b = \frac{\beta_a \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_a \times \beta_b \cdot \hat{k}} \beta_b$$

3-momenta of invisible particles
$$p_{I_a} = p_a - p_{V_a}$$
$$p_{I_b} = p_b - p_{V_b}$$

2 Timing information
- $\beta_a = \hat{r}_a / T_a$, $\beta_b = \hat{r}_b / T_b$

We can find unique mass pairs without assumptions
Case 1: $LLP_a = LLP_b$, $I_a = I_b$
MC result: Sol1

\[ M_{LLP_a} = M_{LLP_b} = 400 \text{ GeV} \]
\[ M_{I_a} = M_{I_b} = 200 \text{ GeV} \]

<table>
<thead>
<tr>
<th></th>
<th>( m_{LLP_a} )</th>
<th>( m_{LLP_b} )</th>
<th>( m_{I_a} )</th>
<th>( m_{I_b} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 w/o timing</td>
<td>397.6 ± 1.2</td>
<td>397.6 ± 1.2</td>
<td>206.0 ± 1.5</td>
<td>206.0 ± 1.5</td>
</tr>
</tbody>
</table>

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MC result: Sol2

Without assuming $L_{LLP_a} = L_{LLP_a}$

Without assuming $I_a = I_b$

<table>
<thead>
<tr>
<th>Case</th>
<th>$m_{LLP_a}$</th>
<th>$m_{LLP_b}$</th>
<th>$m_{I_a}$</th>
<th>$m_{I_b}$</th>
</tr>
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</tr>
<tr>
<td>timing</td>
<td>400.91 ± 0.35</td>
<td>400.77 ± 0.35</td>
<td>201.53 ± 0.49</td>
<td>201.53 ± 0.49</td>
</tr>
</tbody>
</table>

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MC result: Sol1 vs Sol2

\[ P_P : 400 \text{ GeV} \]
\[ I_I : 200 \text{ GeV} \]
Case2: $LLP_a \neq LLP_b, I_a \neq I_b$
**MC result: Sol2**

\[ M_{LLP_a} : 300 \text{ GeV}, \quad M_{LLP_b} : 600 \text{ GeV} \]
\[ M_{Ia} : 100 \text{ GeV}, \quad M_{Ib} : 300 \text{ GeV} \]

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<th>Case</th>
<th>( m_{LLP_a} )</th>
<th>( m_{LLP_b} )</th>
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<td>2019-08-20</td>
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\[ \text{Case2: w/o timing: } - \quad - \quad - \quad - \quad - \quad - \]

\[ \text{Timing: } 307.25 \pm 0.38 \quad 612.18 \pm 0.72 \quad 118.54 \pm 0.89 \quad 319.1 \pm 1.1 \]

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MC result: Sol2

$M_{LLPa} : 300$ GeV, $M_{LLPb} : 600$ GeV
$M_{Ia} : 100$ GeV, $M_{Ia} : 300$ GeV
We can reconstruct the entire event including the LLP decay angle, which can be used to remove poorly-measured events.
Using timing information at HL-LHC we can measure the $\beta$ of the long-lived particles.

- We can fully reconstruct the LLP events even if they decay to visible and invisible particles.
- Timing reconstruction method will flash the LLP searches at HL-LHC.
Primary vertex uncertainty

Time stamping

For heavy ion collision, there is no Pile-up.

- All tracks come from the same vertex.
- → No uncertainty in primary vertex position.
Timing detector resolution
Monte Carlo Simulation

- Event simulation with MG5_aMC+Pythia8
- Smearing
  - Position 12 $\mu$m
  - Momentum 2%
  - Timing 30ps
- Case1: $LLP_a = LLP_b$, $I_a = I_b$
  
  \[
  M_{LLP_a} = M_{LLP_b} = 400 \text{ GeV} \\
  M_{I_a} = M_{I_b} = 200 \text{ GeV}
  \]
- Case2: $LLP_a \neq LLP_b$, $I_a \neq I_b$
  
  \[
  M_{LLP_a} : 300 \text{ GeV}, \quad M_{LLP_b} : 600 \text{ GeV} \\
  M_{I_a} : 100 \text{ GeV}, \quad M_{I_a} : 300 \text{ GeV}
  \]