Time-delayed leptons from dark photon in extension Stueckelberg model

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LLPs motivation

• LHC is working hard to search for new particles in BSM
• So far, no evidence of new particles is detected.

➢ If new particles are weakly interacting to SM particles or quasi-stable and travelling far away from primary vertex, they may escape the current detector triggers.

➢ Experimental signatures:
  • Displaced objects
  • Non-pointing/kinked objects
  • Heavy Stable Charged Particles
  • Delayed objects

Heather Russell
Timing detector at CMS phase 2 upgrade (CMS MTD)

- A timing detector is proposed to install in front of ECAL, 1.2 m from beam line.
- Resolution: 30 ps,
- $p_T > 0.7 \text{ GeV}$ (Barrel)
- and $p > 0.7 \text{ GeV}$ (Endcaps)

CMS technical proposal:
https://cds.cern.ch/record/2296612

See Juliette’s talk for more.
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- Using time information to reconstruct 4D vertex.
- **Purpose: reducing pileup** at HL-LHC

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See Juliette’s talk for more.
A possible LLP signal using timing

Estimation delayed time:

\[ LLP \rightarrow a + b \]

\[ \Delta t = \frac{l_{LLP}}{\beta_{LLP}} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}} \]

Signal arrival time

SM bkg ref time

ECAL

Timing layer

ISR

SM

CMS MTD

1.2 m

0.2 m

PV

LLP


J.D Mason arXiv:1905.07772
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Signal arrival
time

SM bkg ref time

Lower bound for delayed time signal:

\[ \Delta t \geq l_{LLP}(\beta_{LLP}^{-1} - 1) \]

Example: \( h \rightarrow LLP + LLP \) with \( m_{LLP} = 50 \text{ GeV} \)

Result in \( \Delta t \approx 3.2 \text{ ns} \)


J.D Mason arXiv:1905.07772
The extension Stueckelberg Model

- In general, one can extend minimal Stueckelberg model by adding $N$ number of abelian gauge $U(1)_X$

\[
\mathcal{L}_{\text{extSt}} = \left( -\frac{1}{4} B_{\mu\nu} B_{\mu\nu} + g_Y B_{\mu} J_{Y}^{\mu} \right) + \sum_{i=1}^{N_V} \left( -\frac{1}{4} C_{\mu\nu\iota} C_{i}^{\mu\nu} + g_i C_{\mu\iota} J_{i}^{\mu} \right) - \frac{1}{2} \sum_{j=1}^{N_S} \left( \partial_{\mu} \sigma_{j} + m_{0j} B_{\mu} + \sum_{i=1}^{N_V} m_{ij} C_{\mu i} \right)^2.
\]

- $N_V$ is number of abelian gauge field
- $N_S$ is number of axion

B. Kors and P. Nath 2005
The extension Stueckelberg Model

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$$-\frac{1}{2} \sum_{j=1}^{N_S} \left( \partial_\mu \sigma_j + m_{0j} B_\mu + \sum_{i=1}^{N_V} m_{ij} C_{\mu i} \right)^2 .$$

- $N_V$ is number of abelian gauge field
- $N_S$ is number of axion

The minimal Stueckelberg model can be realized when $N_V = 1$, $N_S = 1$.

$$\mathcal{L}_{\text{St}} = \left( -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} C_{\mu\nu\iota} C_1^{\mu\nu\iota} + g_Y B_\mu J_Y^\mu + g_{\chi_1} C_{\mu_1} J_{\chi_1}^\mu \right) - \frac{1}{2} \left( \partial_\mu \sigma_1 + m_{01} B_\mu + m_{11} C_{\mu_1} \right)^2$$

- B. Kors and P. Nath 2005
- E. C. G. Stueckelberg 1938
- V. I. Ogievetskii & I. V. Polubarinov 1962
The extension Stueckelberg Model

- The next minimal model is $N_V = 2$ and $N_S = 2$

\[ \mathcal{L}_{St} = -\frac{1}{4} \left( B_{\mu\nu} B^{\mu\nu} + C_{\mu\nu 1} C_{1}^{\mu\nu} + C_{\mu\nu 2} C_{2}^{\mu\nu} \right) + g_Y B_\mu J_1^\mu + g_{X_1} C_{\mu 1} J_1^\mu + g_{X_2} C_{\mu 2} J_1^\mu - \frac{1}{2} \left( \partial_\mu \sigma_1 + m_{01} B_\mu + m_1 C_{\mu 1} \right)^2 - \frac{1}{2} \left( \partial_\mu \sigma_2 + m_{02} B_\mu + m_2 C_{\mu 2} \right)^2. \]

- Where $J_1^\mu = \bar{\chi} Y^\mu \chi$
- $\chi$ is fermionic dark matter
- $Z_1$ has feeble coupling to SM particles and could be a LLP

\[ m_{Z_2} \gg m_{Z_1} \]

\[ \epsilon_2 \gg \epsilon_1 \]
Current constraints

- We obtain the upper limit on $\epsilon_2$ from $Z$ mass shifted

$$|\epsilon_2| \lesssim 0.036 \sqrt{1 - (M_Z/m_2)^2}$$

- Constraint from di-lepton search at ATLAS is weaker than $Z$ mass shifted
Time-delayed leptons from Dark Photon

- The production of Dark matters is proportional to $\epsilon^2$.
- Dark matter radiated off Dark Photon.
- Dark photon decays into SM leptons or jets which may arrive timing detector late.
Production of DM at LHC

- $Z$ boson exchange is dominant channel when $m_\chi < 2 m_Z$.
- $\sigma(pp \to \chi \bar{\chi} j) \sim O(100 \text{ fb})$ at LHC 13 TeV
Dark Radiation

The differential probability for a collinear splitting:

\[
\frac{\alpha Z_1}{2\pi} \frac{dz}{z} \frac{dt}{t} P_{\chi \to \chi Z_1}(z, t)
\]

- \( t = \) the virtuality of the incoming dark matter particle
- \( z = \frac{E_{\chi_{\text{in}}}}{E_{\chi_{\text{out}}}} \)
- The splitting function is

\[
P_{\chi \to \chi Z_1}(z, t) = \frac{1 + z^2}{1 - z} - \frac{2(m_{\chi}^2 + m_{Z_1}^2)}{t}
\]


M. Kim, H.S. Lee, M. Park and M. Zhang (2016)
Dark photon decay and lifetime

\[ c\tau_{Z_1} \approx \mathcal{O}(m) \times \left( \frac{10^{-7}}{\epsilon_1} \right)^2 \left( \frac{3 \text{ GeV}}{m_{Z_1}} \right) \]
Background

Same hard interaction (SV)

- ISR jet
- Jets
- Faked Photon
- Faked photon or leptons

- Time of arrival mis-measurement due to timing resolution: 30 ps

Pile up (PU)

- ISR jet
- Trackless jet
- Faked photon or leptons

- Time of arrival mis-measurement due to the spread of the proton bunch: 190 ps
Background

Same hard interaction (SV)

- Time of arrival mis-measurement due to timing resolution: 30 ps
- Estimation number of this BG:

\[ N_{SV} = \sigma_\gamma \mathcal{L} + \sigma_j \mathcal{L} f_\gamma \approx 2 \times 10^{11} \]

Pile up (PU)

- Time of arrival mis-measurement due to the spread of the proton bunch: 190 ps
- Estimation number of this BG:

\[ N_{PU} = \sigma_j \mathcal{L} f_j f_\gamma (n_{PU} \sigma_j / \sigma_{inc}) \approx 1 \times 10^7 \]
Background

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- Other BGs come from cosmic ray, core and satellite bunch and beam halo. See Juliette’s talk.

\[ \text{arXiv:1906.06441} \]
Results

• After timing cut $\Delta t > 1$ ns, the number of BG: $N_{SV} \approx 0$ and $N_{PU} \approx 0.7$.

• Higher transverse momentum of lepton, result in smaller number signal time-delayed.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>BP</th>
<th>bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{T,j} &gt; 30$ GeV &amp; $</td>
<td>\eta(j)</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$0.2 m &lt; L_{T}^{Z1} \leq 1.17 m$</td>
<td>28267.3</td>
<td>−</td>
</tr>
<tr>
<td>$z_{Z1} \leq 3.04 m$</td>
<td>19744.2</td>
<td>−</td>
</tr>
<tr>
<td>$p_{T,\ell} &gt; 0.7 \ (2.0 \ (3.0)$ GeV</td>
<td>17922.82 \ (12845.32 \ (9715.45)</td>
<td>−</td>
</tr>
<tr>
<td>$\Delta t &gt; 1$ ns</td>
<td>2207.82 \ (431.96 \ (47.99)</td>
<td>SV: 0; PU: 0.7</td>
</tr>
</tbody>
</table>
Results

CMS MTD, $p_{T,l} > 0.7 \text{ GeV}, \Delta t > 1\text{ns}$

$ct_0 = 1\text{m}, m_2 = 700\text{GeV}, \alpha_D = 0.18, \varepsilon_2 = 0.01$

$p_{rel}$ preliminary
Results

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$c\tau_0 = 1\text{m}, m_2 = 700\text{GeV}, \alpha_D = 0.18, \varepsilon_2 = 0.01$

$m_{Z_1} = 2m_\chi$

$L = 3ab^{-1}$
Conclusion

• The timing information is a promised direction searching for LLP.
• Dark photon in extension Stueckelberg Model weakly interact with SM and can be a LLP.
• With low $p_T$ threshold and good timing resolution at CMS MTD, one can search for the time-delayed LLP signal from Dark photon.
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Thank You