Search for long-lived particles using delayed photons in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Figure 1: Example Feynman diagrams for SUSY processes that result in diphoton (left) and single photon (middle and right) final states via squark (upper) and gluino (lower) pair-production at the LHC.
The search of LLPs is based on pp collision data recorded by the CMS detector at √s = 13 TeV corresponding to an integrated luminosity of 35.9/fb in 2016 and 41.5/fb in 2017.

### 2016 and 2017γγ data sets

- Diphoton trigger is selected
  - $p_T > 42 \text{ GeV}$ for leading photons
  - $p_T > 25 \text{ GeV}$ for subleading photons.

### 2017γ data set

- HLC algorithm is used to select events with a single photon;
  - photon $p_T$ is required to exceed 60 GeV.
  - scalar $p_T$ sum of all jets is required to exceed 350 GeV.
Event reconstruction

- The particle-flow (PF) algorithm is used;
- $|\eta| < 2.5$;
- photon candidates that share the same energy cluster as an identified electron associated with the primary vertex and photons matched geometrically to charged-particle tracks are vetoed;
- out-of-time (OOT) photons in which signals are delayed by more than 3 ns;
- Jets clustered with anti-$k_T$ algorithm with a distance parameter $0.4$, $p_T > 30$ GeV and $|\eta| < 3.0$;
- the negative vector $p_T$ is the sum of all candidates PF in an event and defined as $\vec{p}_T^{\text{miss}}$ corrected for OOT photons
Event selection

- $|\eta| < 1.444$ and $p_T$ larger than 70 GeV are selected;
- We require, at least events to have three or more jets with $p_T$ larger than 30 GeV;
- For the 2016 data set we require a second photon with $p_T$ larger than 40 GeV;
- For 2017$\gamma$ category we require events with no subleading photon or events where the subleading photon does not pass the photon identification criteria;
- For 2017$\gamma\gamma$ we require events to have a subleading photon satisfying the photon identification criteria;
Signal extraction and background estimation

- Bin A: low $p_T^{\text{miss}}$ and low $t_\gamma$ -> High background;
- Bin B: high $p_T^{\text{miss}}$ and low $t_\gamma$ -> Signals with short lifetimes;
- Bin C: high $p_T^{\text{miss}}$ and high $t_\gamma$ -> Signal with long lifetimes;
- Bin D: low $p_T^{\text{miss}}$ and high $t_\gamma$;

- ABCD method -> Background yield in the signal enriched bin C: $N_C = (N_D N_B)/N_A$;
- ABCD modified method -> The background yields in bins B, D, and C are calculated as $N_A r_{B/A}$, $N_A r_{D/A}$, and $N_A r_{B/A} r_{D/A}$, respectively.

Gregor Kasieczka, Benjamin Nachman, Matthew D. Schwartz, and David Shih Phys. Rev. D 103, 035021
Results

A. M. Sirunyan et al. (CMS Collaboration), Phys. Rev. D 100, 112003
A search for long-lived particles that decay to a photon and a weakly interacting particle has been presented in proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment; The search is performed using a combination of the 2016 and 2017 data sets, corresponding to a total integrated luminosity of 77.4/fb; The SPS8 benchmark model was used to interpreter the results in the context of supersymmetry with gauge-mediated supersymmetry breaking; Both single-photon and diphoton event samples are used for the search; For neutralino proper decay lengths of 0.1, 1, 10, and 100 m, masses up to about 320, 525, 360, and 215 GeV are excluded at 95% confidence level, respectively.
Thanks for the attention
Backup slide
Photon time reconstruction

\[ t_{\text{ECAL}} = \frac{\sum_i t^i_{\text{ECAL}}}{\sum_i \frac{1}{\sigma_i^2}}, \]

\[ \sigma_i^2 = \left( \frac{N}{A_i / \sigma_{N_i}} \right)^2 + C^2, \]

- \( t^i_{\text{ECAL}} \) is the timestamp of the signal pulse in crystal \( i \);
- \( \sigma_i \) is the time resolution of the signal pulse on the crystal \( i \);
- \( N \) and \( C \) are constants fitted from a dedicated measurement of the time resolution of the crystal sensors.

A. M. Sirunyan et al. (CMS Collaboration), Phys. Rev. D 100, 112003
Time Calibration

- \( Z \rightarrow e^+ e^- \);  
  - Electrons are reconstructed as photons;  
  - for each photon candidates the \( t \) ECAL is estimated as a function of the photon energy;  
  - the time response mean is adjusted to zero for both data and simulation;  
  - the timestamps in the simulated events are smeared by an additional Gaussian-distributed random variable;  
  - the calibrated photon arrival time is denoted as \( t_\gamma \).
Systematic uncertainties

Table 3: Summary of systematic uncertainties in the analysis. Also included are notes on whether each source affects signal yields (Sig) or background (Bkg) estimates, to which bins each uncertainty applies, and how the correlations of the uncertainties between the different data sets are treated. We assign different values for the uncertainty in the closure of the background prediction for short and long lifetime signal models. The column labeled 2017 includes both the $2017\gamma$ and $2017\gamma\gamma$ categories.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Sig/Bkg</th>
<th>Bins</th>
<th>2016</th>
<th>2017</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>2.5%</td>
<td>2.3%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>1%</td>
<td>2%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>1%</td>
<td>1%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>1.5%</td>
<td>2%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>1.5%</td>
<td>1.5%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Photon time bias</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>1.5%</td>
<td>1%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Photon time resolution</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>0.5%</td>
<td>0.5%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>2%</td>
<td>&lt;1%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Photon identification</td>
<td>Sig</td>
<td>A,B,C,D</td>
<td>2%</td>
<td>3%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Closure in bin C ($c\tau \leq 0.1$ m)</td>
<td>Bkg</td>
<td>C</td>
<td>2%</td>
<td>3.5%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Closure in bin C ($c\tau &gt; 0.1$ m)</td>
<td>Bkg</td>
<td>C</td>
<td>90%</td>
<td>90%</td>
<td>Correlated</td>
</tr>
</tbody>
</table>