Search for LLP using Delayed Photons at CMS

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on behalf of the CMS Collaboration

arXiv:1909.06166 (accepted by PRD)

6th Workshop of the LHC LLP Community, Ghent
28 Nov 2019
Unique and challenging signature

- 0, 1 or 2 photons (γ escape detector, or NLSP (˜χ₁) decays to Z/W)
- MET (˜G, missing γ)
- Jets

Final state

Experimental tool

- γ arrival time at ECAL
- MET
- Jets; γ shower shape; γ-vertex (works for ATLAS; not CMS)
CMS ECAL time resolution

- **e/γ timestamp**: resolution weighted average time of all hits in the shower

- **Time resolution for e/γ object**
  - Intrinsic timing resolution in pulse reconstruction (<100ps)
  - Clock jitter of different readout units (~150ps)
  - Beam spot time spread (180-200ps)
  - …
  - Overall resolution: about 300-400ps

\[
\sigma(\Delta t) = \frac{N}{A_{\text{eff}}/\sigma_N} \oplus \sqrt{2C}
\]

\(N_{2016} = 31.6 \pm 1.2 \text{ ns}\)
\(C_{2016} = 0.077 \pm 0.001 \text{ ns}\)
\(N_{2017} = 30.4 \pm 1.2 \text{ ns}\)
\(C_{2017} = 0.095 \pm 0.001 \text{ ns}\)

CMS ECAL Run II timing: [CMS-DP-2019-021](https://cds.cern.ch/record/2726225)
Event selection

- **Trigger:**
  - 2016: diphoton trigger ($p_T > 42/25$ GeV)
  - 2017: dedicated displaced one photon trigger ($p_T > 60$ GeV, cut on $S_{major}$ and $S_{minor}$, HT $> 350$ GeV)
  - > 95% efficient
  - Different triggers result to slightly different event selections between years

**Selection: 2016**

- ≥2 photons: $p_T > 70/40$ GeV, leading $\gamma$ in barrel
- ≥3 jets ($p_T > 30$ GeV)
- Efficiency x acceptance: 10% to 0.15% depending on $c\tau$ (0.1 to 100 m)

**Selection: 2017**

- 2$\gamma$ category: $p_T > 70/40$ GeV, leading $\gamma$ in barrel
- 1$\gamma$ category: $p_T > 70$ GeV in barrel
- ≥3 jets ($p_T > 30$ GeV); HT $> 400$ GeV
- Efficiency x acceptance (1$\gamma$): 10% to 0.65%

**Complementary**

- 1$\gamma$: higher efficiency for large $c\tau$ models
- 2$\gamma$: 10 times less background than 1$\gamma$
Backgrounds

• Non-collisional backgrounds: negligible after offline selection (mainly because of nJets requirement)
  - Conventional backgrounds that are known to have non-zero photon time, like beam halo events, are checked to be small in the negative time region, and negligible when scaled to positive time region

• Collisional backgrounds:
  - From pp collision with high MET and jets, including collisions from satellite bunches spaced ~ 2.5 ns apart
  - Appealing feature: γ time distributions are the same for low MET and high MET events (verified in CRs)
Background estimation

- Purely data-driven ABCD method to perform background estimation and signal extraction

- **Observables**: photon time and MET
  - They are uncorrelated for backgrounds; background in bin C can be constrained by backgrounds in bin A, B and D
  - Bin boundaries X and Y optimized to maximize sensitivity for different signal models

**bin boundaries (X, Y)**

<table>
<thead>
<tr>
<th>(cT) (m)</th>
<th>(\Lambda \leq 300) TeV</th>
<th>(\Lambda &gt; 300) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2016</td>
<td>2017(^\gamma)</td>
</tr>
<tr>
<td>(0, 0.1)</td>
<td>0 , 250</td>
<td>0.5 , 300</td>
</tr>
<tr>
<td>(0.1 , 100)</td>
<td>1.5 , 100</td>
<td>1.5 , 200</td>
</tr>
</tbody>
</table>

\[N_A = Bkg_A + \mu \times Sig_A\]
\[N_B = c_1 \times Bkg_A + \mu \times Sig_B\]
\[N_C = c_1 \times c_2 \times Bkg_A + \mu \times Sig_C\]
\[N_D = c_2 \times Bkg_A + \mu \times Sig_D\]

4 equations
4 unknowns (Bkg\(_A\), c\(_1\), c\(_2\), \(\mu\)
Photon time and MET

**Graphs:***
- **Left Graph:** Photon time and MET for Event / GeV.
  - **Title:** CMS
  - **Data:** [\(t_\gamma < 1.0\) ns] (Scaled \(\times 0.011\))
  - **Legend:**
    - Red: Data [\(t_\gamma < 1.0\) ns]
    - Blue: Data [\(t_\gamma \geq 1.0\) ns]
    - Dashed: GMSB \(\Lambda: 200\) TeV
    - Dotted: GMSB \(\Lambda: 200\) TeV
  - **X-axis:** \(p_T^{\text{miss}}\) (GeV)
  - **Y-axis:** Event / GeV

- **Right Graph:** Photon time and MET for Event / ns.
  - **Title:** CMS
  - **Data:** [\(p_T^{\text{miss}} < 100\) GeV] (Scaled \(\times 0.039\))
  - **Legend:**
    - Red: Data [\(p_T^{\text{miss}} < 100\) GeV]
    - Blue: Data [\(p_T^{\text{miss}} \geq 100\) GeV]
    - Dashed: GMSB \(\Lambda: 200\) TeV
    - Dotted: GMSB \(\Lambda: 200\) TeV
  - **X-axis:** \(t_\gamma\) (ns)
  - **Y-axis:** Event / ns

**Text:**
- **Diagram Descriptions:**
  - **Left Diagram:** MET in small and large photon time slices.
  - **Right Diagram:** Photon time in low and high MET slices.

**Figure 3:** The Photon time and MET for CMS.

- **Table 2:** The entries in each bin are normalized by the bin width. The horizontal bars on data indicate the last bin in each plot includes overflow events.
- **Signal and Background:** The background yields in bins B, D, and C are calculated as given bin boundary by the number of events with CRs with negligible signal yield, defined by requiring that in enriched regions, we estimate the background yields using only the observed yield in data for CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield, defined by requiring that CRs with negligible signal yield.
Systematic uncertainties

- The dominant uncertainty comes from the background estimation
- A closure test is performed to validate the MET-time uncorrelated assumption, and assign uncertainties
  - Define two control regions: $\gamma$+jets CR (invert nJets cut); QCD CR (invert isolation on leading photon)
  - Count observed events in bin C: $N_C$
  - Calculate predicted events in bin C: $N_{C\text{predict}} = N_B \times N_D / N_A$
  - Compare $N_C$ with $N_{C\text{predict}}$, and assign systematics uncertainty on bin C background estimation based on this difference

- For ABCD binning corresponds to $c\tau \leq 0.1 m$: less than 4%
- For larger $c\tau$: assign 90% (limited by statistics of CR yields in bin C)
### Table 4: Observed number of events ($N_{\text{data}}^{\text{obs}}$) and predicted background yields from the background-only fit ($N_{\text{post-fit}}^{\text{bkg}}$) in bins A, B, C, and D in data for the 2016 category and for the different $t_{\gamma}$ and $p_{\text{T}}^{\text{miss}}$ bin boundaries summarized in Table 2. In addition, the predicted post-fit yields from the background-only fit not including bin C ($N_{\text{post-fit}}^{\text{bkg(no C)}}$) are provided as a test of the closure. Uncertainties in the $N_{\text{post-fit}}^{\text{bkg}}$ and $N_{\text{post-fit}}^{\text{bkg(no C)}}$ values are the sums in quadrature of the statistical and systematic components, with the former being dominant.

<table>
<thead>
<tr>
<th>Bin boundary $[t_{\gamma}$ (ns), $p_{\text{T}}^{\text{miss}}$ (GeV)]</th>
<th>2016 category</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>(0, 250)</td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>16 139</td>
<td>41</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>$16 130 \pm 110$</td>
<td>$47.5 \pm 4.8$</td>
<td>$55.6 \pm 5.6$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg(no C)}}$</td>
<td>$16 140 \pm 110$</td>
<td>$41.0 \pm 6.5$</td>
<td>$47.8 \pm 7.7$</td>
</tr>
<tr>
<td>(1.5, 100)</td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>33 760</td>
<td>1302</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>$33 760 \pm 160$</td>
<td>$1303 \pm 37$</td>
<td>$0.29 \pm 0.28$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg(no C)}}$</td>
<td>$33 760 \pm 160$</td>
<td>$1302 \pm 37$</td>
<td>$0.19 \pm 0.21$</td>
</tr>
<tr>
<td>(1.5, 150)</td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>34 595</td>
<td>467</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>$34 600 \pm 170$</td>
<td>$467 \pm 22$</td>
<td>$0.08 \pm 0.08$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg(no C)}}$</td>
<td>$34 600 \pm 170$</td>
<td>$467 \pm 22$</td>
<td>$0.08 \pm 0.09$</td>
</tr>
</tbody>
</table>

- $N_{\text{post-fit}}^{\text{bkg}}$: predicted background yields from the background-only fit
- $N_{\text{post-fit}}^{\text{bkg(no C)}}$: background-only fit when masking bin C

No excess over SM background. Will set upper limits on the signal cross sections.
Upper limits

- Extended the previous limits
  - One order of magnitude in neutralino $\tau$
  - About 100 GeV in neutralino mass

- Most sensitive $\tau$: about 1 m (ECAL radius)
Categories comparison

- $\gamma$ and $\gamma\gamma$ categories are complementary
- $\gamma$: for larger $c\tau$
- $\gamma\gamma$: for smaller $c\tau$

![Graphs showing observed and expected cross sections with maximum likelihood projections for $\gamma$ and $\gamma\gamma$.]
Towards Phase-2

- With upgraded ECAL
  - ECAL time resolution reduced to 30 ps (vs. current 100 ps intrinsic + 150 ps clock jitter)
  - Limited by beam spot time spread (180 ps)
- With Mip Timing Detector (MTD)
  - Can measure the primary vertex time with up to 30 ps resolution (eliminates the 180 ps spread)
  - Can also measure arrival time for converted photons
- Significant extended reach for low $c\tau$ models

See details in: CMS-TDR-020
Out-of-time (OOT) photon reconstruction:

- To reject spikes, CMS has a time cut on photons (~ 3 ns) in the standard reconstruction.
- We had to go back to RAW data to save those OOT photons…
- (Non-standard object reconstruction, potential challenge for other LLP searches)

When one of the signal photons is produced outside ECAL and deposits energy in outer detector (HCAL, muon system), it will **look like an isolated noise**

- Hits in HCAL, nothing in ECAL
- (up to 10% of) our photon signals will be killed by the filters designed to kill such isolated noise
- This is a potential issue for other LLP searches as well
Summary

- A search for LLP using delayed photon using photon arrival time at ECAL and MET is presented.

- Extended the previous best limits by one order of magnitude of proper decay length and about 100 GeV of mass of the NLSP.

- Limitations:
  - For small $c\tau$: limited by ECAL time resolution - will be significantly improved in Phase-2.
  - For large $c\tau$: limited by ECAL geometry acceptance.
BACK UP
Photon time and MET (2017)

- **CMS**
  - **2017\(\gamma\)**
  - **Data** [\(t_\gamma < 1.0\) ns]
  - (Scaled \(\times 0.012\))
  - **Data** [\(t_\gamma \geq 1.0\) ns]
  - **GMSB** \(\Lambda : 200\) TeV
  - **cr: 2 m** [\(t_\gamma \geq 1.0\) ns]

- **CMS**
  - **2017\(\gamma\gamma\)**
  - **Data** [\(p_{miss}^T < 100\) GeV]
  - (Scaled \(\times 0.011\))
  - **Data** [\(p_{miss}^T \geq 100\) GeV]
  - **GMSB** \(\Lambda : 200\) TeV
  - **cr: 2 m** [\(p_{miss}^T \geq 100\) GeV]

- **Event / GeV**
  - **Event / ns**

- **Figure 4**: The \(p_{miss}^T\) (left) and \(t_\gamma\) (right) distributions for the 2017 \(\gamma\) and 2017 \(\gamma\gamma\) event selections shown for data and a representative signal benchmark (GMSB: \(\Lambda = 200\) TeV, \(c_\tau = 2\) m). The \(p_{miss}^T\) distribution for data is separated into events with \(t_\gamma \geq 1.0\) ns (blue, darker) and \(t_\gamma < 1.0\) ns (red, lighter), scaled to match the total number of events with \(t_\gamma \geq 1.0\) ns. Signal (black, dotted) is shown only for events with \(t_\gamma \geq 1.0\) ns. The \(t_\gamma\) distribution for data is separated into events with \(p_{miss}^T > 100\) GeV (blue, darker) and \(p_{miss}^T < 100\) GeV (red, lighter), scaled to match the total number of events with \(p_{miss}^T > 100\) GeV. Signal (black, dotted) is shown only for events with \(p_{miss}^T > 100\) GeV. The entries in each bin are normalized by the bin width. The horizontal bars on data indicate the bin boundaries. The last bin in each plot includes overflow events.
## Result of fit (2017)

<table>
<thead>
<tr>
<th>Bin boundary $[t_\gamma\text{ (ns)}, p_T^{miss}\text{ (GeV)}]$</th>
<th>2017$\gamma$ category</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0.5, 300)$</td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>458372</td>
<td>281</td>
<td>41</td>
<td>67655</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>458370 ± 660</td>
<td>281 ± 15</td>
<td>41.4 ± 2.4</td>
<td>67660 ± 280</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>460369 ± 660</td>
<td>281 ± 16</td>
<td>41.5 ± 2.7</td>
<td>67660 ± 280</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>524652</td>
<td>1364</td>
<td>1</td>
<td>332</td>
</tr>
<tr>
<td>$(1.5, 200)$</td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>524650 ± 710</td>
<td>1364 ± 36</td>
<td>0.9 ± 0.8</td>
<td>330 ± 20</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>524650 ± 700</td>
<td>1364 ± 35</td>
<td>0.9 ± 1.0</td>
<td>330 ± 20</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>525694</td>
<td>322</td>
<td>0</td>
<td>333</td>
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<tr>
<td>$(1.5, 300)$</td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>525690 ± 700</td>
<td>322 ± 17</td>
<td>0.19 ± 0.21</td>
<td>330 ± 20</td>
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<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>525690 ± 700</td>
<td>322 ± 17</td>
<td>0.20 ± 0.24</td>
<td>330 ± 20</td>
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<tr>
<td>$(0.5, 150)$</td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>21640</td>
<td>362</td>
<td>56</td>
<td>3201</td>
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<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>21640 ± 140</td>
<td>362 ± 17</td>
<td>54.0 ± 3.0</td>
<td>3200 ± 60</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>21640 ± 140</td>
<td>362 ± 18</td>
<td>53.6 ± 3.3</td>
<td>3200 ± 60</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>21863</td>
<td>139</td>
<td>24</td>
<td>3233</td>
</tr>
<tr>
<td>$(0.5, 200)$</td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>21860 ± 140</td>
<td>142 ± 11</td>
<td>21.1 ± 1.7</td>
<td>3240 ± 60</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>21860 ± 140</td>
<td>139 ± 11</td>
<td>20.6 ± 1.8</td>
<td>3230 ± 60</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>24824</td>
<td>418</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>$(1.5, 150)$</td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>24820 ± 150</td>
<td>420 ± 20</td>
<td>0.25 ± 0.28</td>
<td>16.7 ± 4.4</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>24820 ± 150</td>
<td>420 ± 20</td>
<td>0.29 ± 0.36</td>
<td>17.0 ± 4.4</td>
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<tr>
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<td>$N_{\text{data}}^{\text{obs}}$</td>
<td>25079</td>
<td>163</td>
<td>0</td>
<td>17</td>
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<tr>
<td>$(1.5, 200)$</td>
<td>$N_{\text{post-fit}}^{\text{bkg}}$</td>
<td>25080 ± 150</td>
<td>163 ± 12</td>
<td>0.11 ± 0.12</td>
<td>16.9 ± 4.4</td>
</tr>
<tr>
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<td>$N_{\text{post-fit}}^{\text{bkg (no C)}}$</td>
<td>25080 ± 150</td>
<td>163 ± 12</td>
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