A Search for Beyond the Standard Model Physics Using Final State with Light and Boosted Muon Pairs at CMS Experiment

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Physics at the LHC

- Largest particle accelerator (27km circumference)

- Proton beams circulate in opposite directions (nearly at the speed of light)

- The beams are made to collide at four intersection points, where the most important detectors are placed (ATLAS, CMS, Alice and LHCb)

- The product of these collisions are measured to study properties of known particles and potentially new particles and interactions

A major milestone was accomplished in 2012 with the discovery of a new particle with properties consistent with the predicted SM Higgs boson

Beyond the Higgs boson

- Experimental confirmation whether the newly discovered particle is really the one predicted by the Standard Model (SM), with a detailed analysis of particle properties (e.g. coupling measurements). This task will require a much larger dataset than the current one.
- Could it be that there is more than one Higgs Boson (e.g. SUSY models)?
- What else could be produced at the LHC? Dark matter (DM) particles?

DM astronomical observation

- Galaxies are rotating with such speed that the gravity generated by their observable matter could not possible hold them together.
- Scientist believe there is something giving these galaxies extra mass, generating the gravity they need to stay intact.

Dark matter produces an attractive force (gravity)
Searches for DM

If DM is made up of sub-atomic particles, they can be detected in different ways

- **Direct detection:** low energy recoil (typically a few keV) of nuclei induced by interactions with particles of dark matter, which (in theory) are passing through the Earth (e.g. SNOLAB experiment)

- **Indirect detection:** Search for the product of the self-annihilation or decay of dark matter particles in outer space (e.g. AMANDA, IceCube, ANTARES, AMS experiments)

- **Collider search:** Produced in the laboratory. DM particles will either be created and escape detection (leaving large amount of missing energy), or they could interact weakly with SM particles producing an anomalous event rate
BSM benchmark scenario I (Dark SUSY)

- Postulates a non-SM decay of the Higgs boson in which:
  - The lightest neutralino ($n_1$) is no longer stable and can decay to a dark neutralino and a dark photon ($\gamma_D$)
  - The decay of the dark photon is mediated by very weak interaction with SM (via a kinetic mixing parameter $\varepsilon$)
  - Our model also considers dark photons with non-negligible lifetime (they could travel and decay far from the collision point)

- Dark photons can decay to leptons and hadrons
- In this analysis we explore only the decay to muons (clean signature from the experimental point of view)

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BSM benchmark scenario II (NMSSM)

- The Next to Minimal Supersymmetric Standard Model (NMSSM)
- Extend the Higgs sector (3 CP-even Higgs and 2 CP-odd)
- One of the CP-odd Higgs bosons can be light ($a_1$) and couple to the SM-like ($h_{1,2}$)
- The new light boson ($a_1$) couples weakly to SM particles with the coupling proportional to the fermion mass

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https://cds.cern.ch/record/2232052

$\beta(a_1\to \mu\mu)$

- Probability for a light boson ($a_1$) to decay to muons as a function of the mass of the new light boson

10.1103/PhysRevD.81.075021

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The CMS detector

- 2nd largest detector at the LHC
- Multipurpose particle detector
- Complex systems for triggering and Data Acquisition (DAQ)
- This is a discovery machine (Biggest achievement so far the observation of the Higgs boson)

Muon detection in CMS

**Layout of the CMS muon detector**

- CMS muon system consists of three major subsystems (gas detector technologies)
- Muons pass through the sensitive volume, due to interaction with the medium (ionization) electrons are knocked out from the atoms and via an electric field transported to the readout strips where the signals are converted into position and momentum
- Important muon reconstructed variables are:
  - $P_T =$ muon momentum in the transverse place
  - $\eta =$ pseudo-rapidity (related to the angular position in the $y$-$z$ plane)

**Muon momentum resolution**

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*J. Instrum. 8 (2013) P11002*
Analysis strategy

- Events with four muons
- Muon pairing ("dimuons")
- Define a signal region (region where new physics is most likely to appear)
- Estimate SM contribution in signal region
- Measure the number of events (from collision data) in signal region
- Quantify the agreement between data and SM expectation
- Based on the agreement either claim a discovery or set a limit on the production of these new particles

- **Signal region**: corridor in the 2D invariant mass space where both dimuon masses are compatible
- SM backgrounds are distributed over all the 2D invariant mass space
Monte Carlo signal simulation

- Monte Carlo simulated samples were produced for both Dark-SUSY and NMSSM benchmark scenarios.
- Fully simulated CMS reconstruction.
- Samples were used to optimize event selection, in order to keep a good signal efficiency and reject as much as possible the SM background.
- In addition, samples were used to set limits on particular parameters of both models.
- Variation of parameters were covered as much as possible, the table below summarize the range in mass and lifetime for both benchmark scenarios.

Parameter range in the Monte Carlo simulation for NMSSM and Dark-SUSY

<table>
<thead>
<tr>
<th>Benchmark Scenario</th>
<th>Light boson mass [GeV]</th>
<th>Lifetime (ct) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMSSM</td>
<td>0.5 – 3.55</td>
<td>0</td>
</tr>
<tr>
<td>Dark SUSY</td>
<td>0.25 – 9.0</td>
<td>0 - 100</td>
</tr>
</tbody>
</table>
Event selection

- Tri-muon trigger with $(15,5,5) \, P_T$ thresholds
- Four reconstructed muons with $P_T > 8$ GeV (at least one with $P_T > 17$ GeV)
- Pairing of oppositely charged muons with consistent vertex and invariant mass $< 9$ GeV (dimuons)

Consistent vertex between dimuons

Isolated dimuons

CMS (Unpublished) 20.7 fb$^{-1}$ (8TeV)
Model independent analysis

After applying the complete event selection on simulated benchmark scenarios the results are as follow:

### Dark-SUSY

<table>
<thead>
<tr>
<th>$m_h$ [GeV/$c^2$]</th>
<th>125</th>
<th>125</th>
<th>125</th>
<th>125</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\gamma 0}$ [GeV/$c^2$]</td>
<td>0.25</td>
<td>0.7</td>
<td>1.5</td>
<td>8.5</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}^{MC}$</td>
<td>0.00631 ± 0.00021</td>
<td>0.01733 ± 0.00042</td>
<td>0.03325 ± 0.00056</td>
<td>0.13099 ± 0.00137</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$</td>
<td>0.00982 ± 0.00026</td>
<td>0.02710 ± 0.00053</td>
<td>0.05096 ± 0.00070</td>
<td>0.20032 ± 0.00175</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}^{MC} / \alpha_{\text{gen}}$</td>
<td>0.64232 ± 0.01258</td>
<td>0.63956 ± 0.00919</td>
<td>0.65242 ± 0.00637</td>
<td>0.65393 ± 0.00380</td>
</tr>
</tbody>
</table>

### NMSSM

<table>
<thead>
<tr>
<th>$m_{h_1}$ [GeV/$c^2$]</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{a}_1}$ [GeV/$c^2$]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}^{MC}$</td>
<td>0.0944 ± 0.0000</td>
<td>0.1130 ± 0.0003</td>
<td>0.12815 ± 0.0004</td>
<td>0.1488 ± 0.0005</td>
<td>0.1768 ± 0.0000</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$</td>
<td>0.1415 ± 0.0005</td>
<td>0.1685 ± 0.0000</td>
<td>0.19389 ± 0.0003</td>
<td>0.2282 ± 0.0005</td>
<td>0.2760 ± 0.0003</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}^{MC} / \alpha_{\text{gen}}$</td>
<td>0.6669 ± 0.0028</td>
<td>0.6706 ± 0.0026</td>
<td>0.66097 ± 0.0024</td>
<td>0.6520 ± 0.0023</td>
<td>0.6405 ± 0.0021</td>
</tr>
</tbody>
</table>

The ratio $\epsilon/\alpha$ remains flat despite the variations in the parameter of the models for both NMSSM and Dark-SUSY.

This has the implication that our analysis is model independent, meaning our results can be re-interpreted in a new physics model that predict similar topology and final state.
SM backgrounds

Three are the SM processes that can mimic our signal topology, they are listed below in order of relevance:

- **QCD pp->bb->4mu**: Contribution is dominated by events in which both b-quarks decay to pair of muons (via double semi-leptonic decay) or resonances (e.g. omegha, rho, phi, J/psi). Contribution estimated directly from data
  
  \[
  \text{Estimate} = 0.68 \pm 0.34
  \]

- **Prompt pp->2J/psi->4mu**: Consists of two production mechanisms, “Single” and “Double” parton scattering. Contribution estimated using data and Monte Carlo simulation
  
  \[
  \text{Estimate} = 0.064 \pm 0.020
  \]

- **EWK pp->4mu**: Smallest contribution from SM, estimated directly from Monte Carlo simulation. Contribution was found to be negligible

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Results

- Total SM contribution:
  - QCD $pp\rightarrow bb\rightarrow 4\mu +$ QCD $pp\rightarrow 2J/\psi\rightarrow 4\mu = 0.74 \pm 0.15$
  - Consistent with one observed event in data (yellow triangle in 2D plot)

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Model independent Limit

$$\sigma(pp \rightarrow 2a + X) \times B^2(a \rightarrow 2\mu) \times \alpha_{gen} \leq \frac{N(m_{\mu\mu})}{L \times r}.$$  

\[ \leq 1.7 \text{ fb} \]

- Where:
  - $N(m_{\mu\mu}) = 95\%$ C.L on the number of signal events
  - $L = $ Total luminosity (2.8fb$^{-1}$)
  - $r = \varepsilon/\alpha$ ratio (average among the variations in the Dark-SUSY model)
Interpretation (new light bosons)

Our search (4mu) for light bosons (NMSSM) is sensitive up to $m(a1)=3.5\text{GeV}$ due to the reduction in Branching ratio, after that other processes become dominant.
As opposite to NMSSM in Dark SUSY scenario we can extend the mass range (as the Branching ratio stay flat up to 9 GeV)
Summary and perspectives

• No evidence of physics beyond SM found in signal region (for preliminary results at 13 TeV)
• Limits extracted in a model independent fashion and as a function of NMSSM and Dark SUSY models
• Results can be re-interpreted for another model with similar topology
• Our analysis is sensitive for the production of new light bosons (NMSSM) with a mass up to 3.5 GeV, in case of Dark SUSY scenario our analysis was improved increasing the mass range (up to 9 GeV) and extending the sensitivity for detection of particles with intermediate to large lifetime
• Analysis update with 2016 dataset (10 times more luminosity) is undergoing and results will be presented to the experimental collaboration soon.
Backup slides
## Analysis uncertainties

**CMS-PAS-HIG-16-035 (2016)**  
[https://cds.cern.ch/record/2232052](https://cds.cern.ch/record/2232052)

<table>
<thead>
<tr>
<th>Source of uncertainties</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.7</td>
</tr>
<tr>
<td>Muon trigger</td>
<td>3</td>
</tr>
<tr>
<td>Muon ID</td>
<td>1 (per $\mu$) × 4</td>
</tr>
<tr>
<td>Muon tracking</td>
<td>0.2 (per $\mu$) × 4</td>
</tr>
<tr>
<td>Di-muon isolation</td>
<td>1 (per di-$\mu$) × 2</td>
</tr>
<tr>
<td>Overlapping in Tracker</td>
<td>1.2 (per di-$\mu$) × 2</td>
</tr>
<tr>
<td>Overlapping in Muon System</td>
<td>1.3 (per di-$\mu$) × 2</td>
</tr>
<tr>
<td>Pile-up</td>
<td>1.6</td>
</tr>
<tr>
<td>Dimuons mass consistency</td>
<td>1.5</td>
</tr>
<tr>
<td>NNLO Higgs $p_T$ re-weighting</td>
<td>2.0</td>
</tr>
<tr>
<td>PDF+$\alpha_s$</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.1</strong></td>
</tr>
</tbody>
</table>
NMSSM limit as a function of the mass of the Higgs boson (NMSSM)

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Conversion lifetime to kinetic mixing parameter

- Starting the Dark photon lifetime and the total decay width relation

\[
\tau_{\gamma D} = \frac{\hbar}{\Gamma_{\gamma D\text{Total}}} = \frac{1}{\Gamma_{\gamma D\rightarrow e^+e^-} + \Gamma_{\gamma D\rightarrow \mu^+\mu^-} + \Gamma_{\gamma D\rightarrow \text{hadrons}}}
\]

\[
\tau_{\gamma D}(\epsilon, m_{\gamma D}) = \frac{1}{\epsilon^2} \times f(m_{\gamma D}),
\]

\[
c\tau_{\gamma D}(\epsilon, m_{\gamma D})[\text{mm}] = \frac{c[\text{mm/s}] \times \hbar[\text{GeV} \cdot \text{s}]}{\epsilon^2} \times f(m_{\gamma D})[\text{GeV}^{-1}],
\]

\[
c\tau_{\gamma D}(\epsilon, m_{\gamma D})[\text{mm}] = \frac{1.97 \cdot 10^{-13}[\text{GeV} \cdot \text{mm}]}{\epsilon^2} \times f(m_{\gamma D})[\text{GeV}^{-1}],
\]
QCD pp→bb→4μ

- Starting with a control sample in data enriched with bb events (1 dimuon + 1 “orphan”)
- Modeling of the invariant mass spectrum (Gaussian and Crystal ball distributions for the resonances) and Bernstein polynomial for the Bulk shape
- Independent shapes combined to get obtained a 2D model that is used to normalize contribution in signal region

\[
\text{Estimate} = \frac{0.15}{0.86} \times (4 \pm \sqrt{4}) = 0.68 \pm 0.34
\]

Fraction of events inside/outside signal corridor in control sample

Events outside signal corridor (normal selection)

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QCD pp->2J/ψ and EWK

QCD pp->2J/ψ

• Starting with a control sample in data enriched with events with double J/ψ’s
• Cleaning of the data by applying invariant mass cut consistent with J/ψ mass value
• Separation of prompt and non-prompt J/ψ production using isolation variable as discriminant
• Once a clean sample of double J/ψ’s is obtained the ration DATA/MC is used to correct the estimation in signal region

\[ \text{Estimate} = 0.064 \pm 0.020 \]

EWK to 4 muons

• Estimated purely from Monte Carlo simulation
• This is the smallest contribution among the SM backgrounds
• Contribution found to be negligible