CMS Long-Lived Particle Searches at the HL-LHC

Juliette Alimena, on behalf of the CMS Collaboration


October 31, 2017
Long-Lived Particle Searches

- neutral
- charged
- any charge

- displaced vertex
- HSCP
- disappearing track
- displaced photon
- displaced jet
- displaced dilepton
- displaced lepton

Not pictured: Stopped HSCP

J. Antonelli

October 31, 2017

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Direct Searches

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Heavy Stable Charged Particles: Tracker Upgrade (I)

- **HSCPs:** New, heavy particles could propagate through the detector before decaying
  - Could look like heavy, highly-ionizing, slow-moving muons

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**Phase-2 Inner Tracker (Pixels):**

- dE/dx measurement from analogue Time over Threshold readout
- Similar to dE/dx measurements from current pixels and strips

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14 TeV, 200 PU

**dE/dx discriminator shows large separation between signal and background**
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- $dE/dx$ measurement from analogue Time over Threshold readout
- Similar to $dE/dx$ measurements from current pixels and strips

**Phase-2 Outer Tracker (Strips):**
- Readout is binary, cannot provide full $dE/dx$ discriminator
- Original Phase-2 strips planned with no $dE/dx$ at all

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With no $dE/dx$ information at all, HSCP stau Phase-2 limit projection is worse than with the Phase 1 detector!
Heavy Stable Charged Particles: Tracker Upgrade (I)

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**Phase-2 Inner Tracker (Pixels):**
- $dE/dx$ measurement from analogue Time over Threshold readout (currently set to 4 bits resolution)
- Similar to $dE/dx$ measurements from current pixels and strips

**Phase-2 Outer Tracker (Strips):**
- Readout is binary, cannot provide full $dE/dx$ discriminator
- **However,** implemented dedicated hit-over-threshold bit ("HIP flag"), currently set to $1.4 \times$ MIP charge

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**dE/dx discriminator shows large separation between signal and background**

**Number of clusters with HIP flag set shows good discrimination between signal and background**

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Heavy Stable Charged Particles: Tracker Upgrade (II)

Impact on the HSCP analysis of the Phase-2 inner tracker dE/dx discriminator and outer tracker HIP flag:

HIP flag is critical to restore tracker sensitivity to HSCPs in Phase 2
Heavy Stable Charged Particles: 
RPC Trigger Upgrade (I)

- HSCPs could look like heavy, highly-ionizing, slow-moving muons
- RPC upgrade (RPC Link Board System) will provide ~1.5 ns time of flight resolution to each RPC station
- RPC-HSCP trigger algorithm: linear fit to time at each RPC hit as a function of its distance from the IP

See poster by G. Sanchez for more details

Upgraded RPC Link Board System will allow us to trigger, at the correct BX, HSCPs with velocities as low as $\beta \sim 0.25$
Impact on the HSCP analysis of the Phase-2 RPC trigger:

**HSCP Mass Resolution:**
Resolution from Phase-2 RPC trigger is comparable to Resolution from Run 2 offline TOF measurement (from DTs and CSCs)

**HSCP Reconstruction Efficiency:**
As a function of $|\eta|$ and $\beta$
With the Phase-2 RPC trigger, we can increase the reconstruction efficiency for low $\beta$, as compared to Run 2

**Stau, 1599 GeV**

Phase-2 with RPC Trigger
Full $p_T$ range

Run 2 with Online Selection
$120 < p_T < 200$ GeV
Indirect Searches

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- any charge

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Not pictured: Stopped HSCP
Long-Lived Dark Z Bosons (I):
Muon Trigger Upgrade

• Long-lived dark Z boson in dark SUSY:
  \[ H \rightarrow Z_d Z_d + X \]

• Decay signature: four displaced muons

Need a suite of displaced muon triggers to cover the range of possible signatures:

**High momentum muon signatures:**
- Decays of heavy particles
- Can use single muon trigger
  - Significant fraction of acceptance in the barrel region

**Low momentum muon signatures:**
- Decays of relatively light particle
- Will require a dimuon trigger with low enough thresholds
  - Endcap region becomes very important
Long-Lived Dark Z Bosons (II):
Muon Trigger Upgrade

• As part of the Phase-2 muon system upgrade, new Gas Electron Multiplication (GEM) detectors will be installed:
  – GE1/1, GE2/1: Improve muon triggering in $1.6 |\eta| < 2.4$ (2.15 for GE1/1)
  – ME0: Improve muon ID and triggering up to $|\eta| \sim 2.8$
  – GEMs can handle high Phase-2 rate in forward region better than current CMS CSCs and RPCs
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• Can use the measurement of the muon direction within a single station to discriminate high $p_T$ displaced muons from low $p_T$ prompt muons
Long-Lived Dark Z Bosons (II): Muon Trigger Upgrade

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- Can use the measurement of the muon direction within a single station to discriminate high p_T displaced muons from low p_T prompt muons

- Measurement of muon direction in new GE1/1 and existing CSC ME1/1 chambers → efficient rejection of mismeasured muons that dominate the L1 rate
Long-Lived Dark Z Bosons (III): Muon Trigger Upgrade

- L1 muon candidates will be loosely matched to L1 Track trigger candidates
- L1 Track trigger will not be able to reconstruct displaced tracks
- **However**, besides muon direction measurement within a station (previous slide), have another handle for displaced muons:
  - Can veto event if L1Mu matched to L1 track, since tracker tracks would not be reconstructed for displaced muons

**Barrel Displaced Muon Trigger**

![Trigger rate](chart1.png)

![Trigger efficiency](chart2.png)

*Rate under control, trigger efficiency high even for displaced muons*
Long-Lived Dark Z Bosons (IV): Muon Trigger Upgrade

Endcap Displaced Muon Trigger

GEM detectors key to keep rate under control, trigger efficiency high even for displaced muons

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Long-Lived Smuons (I): Muon System Upgrades

• Long-lived smuon in GMSB: $q\bar{q} \rightarrow \tilde{\mu}\tilde{\mu}, \tilde{\mu} \rightarrow \mu \tilde{G}$
• Decay signature: two displaced muons + MET
• Decay length: 10 mm to 1 m
• Low production cross section ($\sim 10^{-2}$ fb for 1 TeV smuon)

**Displaced StandAlone Muons:** Dedicated muon reconstruction algorithm using only hits in the muon system and no constraints to the IP

Improved muon reconstruction efficiency using **Displaced StandAlone Muons**, compared to standard muon-only reconstruction (**StandAlone Muons**)
Long-Lived Smuons (II): Muon System Upgrades

Backgrounds:
- QCD: Heavy quarks with non-prompt decays produce displaced muons
- $tt$: Leptonic decay of top quarks
- DY: Prompt muons that are poorly reconstructed as displaced
- Cosmic muons, beam halo, pileup are removed by selection criteria ($p_T > 30$ GeV)

Scenario Assumptions:
- Phase-1 Scenario:
  - Phase-1 CMS detector
  - PU200, 300 fb\(^{-1}\)
  - 60% trigger efficiency benchmark
  - Phase-1 analysis systematic uncertainties
- Phase-2 Scenario:
  - Phase-1 CMS detector + forward muon detectors
  - PU200, 3000 fb\(^{-1}\)
  - 90% trigger efficiency benchmark
  - Reduced systematic uncertainties

Analysis is sensitive only with the HL-LHC
Long-Lived Neutralinos: MIP Timing Detector (MTD)

- Long-lived neutralinos in GMSB
- Generator-level study with PYTHIA8
  - Smear tracks, vertices, electron momentum (see backup for resolution assumptions)
- Plots shown for $M(\tilde{t}) = 1$ TeV, $M(\tilde{\chi}_1^0) = 700$ GeV

Reconstructed Mass of Neutralino:
Assume 30 ps timing resolution of MTD
Can use to distinguish signal from background

Events are required to have a displaced secondary vertex with 3σ significance in both space and time:

Simulation Preliminary
Long-Lived Neutralinos with Mass Difference: MTD

- Long-lived neutralinos with small mass difference
- Similar generator-level study as previous slide
- Plots shown for $M(\tilde{\chi}^\pm) = M(\tilde{\chi}_2^0) = 400$ GeV, $M(\tilde{\chi}_1^0) = 390$ GeV

Reconstructed $E_{e^+e^-}$

$E = \Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$

Assume 30 ps timing resolution of MTD

Events are required to have a displaced secondary vertex with 3σ significance in both space and time:

- Phase-2 hermetic timing layer is crucial to assign times to vertices
- With this timing information, can reconstruct LLP time-of-flight and mass
Summary

• The High-Luminosity LHC will be a time of exciting physics potential and many experimental challenges
• The CMS Phase-2 upgrades will address these challenges and increase the physics potential
• CMS exotic long-lived particles searches will benefit from the upgraded detectors mentioned here, as well as the other upgrades → stay tuned!
Backup
Sources

• The Phase-2 Upgrade of the CMS Tracker, CMS-TDR-17-001-001, https://cds.cern.ch/record/2267042
• The phase-2 upgrade of the CMS muon detector, CMS-TDR-17-003-002, https://cds.cern.ch/record/2279132
• Estimated Sensitivity for New Particle Searches at the HL-LHC, CMS-PAS-FTR-16-005, https://cds.cern.ch/record/2274436
• Enhanced scope of a Phase 2 CMS detector for the study of exotic physics signatures at the HL-LHC, CMS-PAS-EXO-14-007, https://cds.cern.ch/record/2206863
Phase-2 RPC HSCP Trigger Algorithm

- Muon produced at BX=0 hit
- Muon produced at BX=+1 hit
- HSCP produced at BX=0 hit
- HSCP produced at BX=-1 hit

- BX=+1
- BX=0
- BX=-1

- 25 ns
- 12.5 ns
- 0 ns
- -12.5 ns
- -25 ns

- $d$, RPC hit Distance to the Vertex [cm]
Long-Lived Neutralinos

• Generator-level study with PYTHIA8

**Smearing**

- Track resolution: 10$\mu$m and 30$\mu$m in transverse and longitudinal impact parameter (JINST 9 P10009, 2014) → use 30$\mu$m for simplicity
- PV resolution: 10-12um in each of three dimensions (JINST 9 P10009, 2014)
- Electron momentum resolution is 2%
- Timing resolution for tracks is 30 ps