CMS Snapshot of Long Lived Particle Searches

Albert De Roeck
CERN, Geneva, Switzerland

Trieste LLP Workshop
18th October 2017
A tour of the CMS LLP analyses

- Displaced leptons
- Displaced jets
- Displaced photons
- Disappearing tracks
- Stopped particles
- Heavy charged particles

Next analyses in line...
- Towards SMS for LLPs
- Summary/Outlook

Most results still on 8 TeV data

Some new results on 13 TeV data
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts

2016 luminosity > Run-1 luminosity

Preliminary Offline Luminosity

2017
New for the 2017 Run

EYTS 2017: Pixel Detector Upgrade

- 4 layers, 3 disks
  - smaller radius inner layer (3cm)
- New readout chip
  - higher efficiency at high rate & high pile-up (up to 100 PU)
- CO2 cooling and DC-DC powering
  - less material
New for the 2017 Run

- ~95% good channels, losses mainly due to few power & readout groups
- Resolutions in L2-4 & FPix match simulations
- Significant reduction of dynamic inefficiency at high inst. luminosity compared to old detector, with layer 1 closer to beampipe!
A tour of the CMS LLP results…
Displaced Lepton Pairs

- Search for long-lived particles that decay into final states containing two muons or two electrons. Based on the CMS tracker
- Select muons pairs with $p_T > 26$ GeV, electrons with 40/25 GeV. Acceptance for $L_{xy}$ till $\sim 50$ cm
- Models tested: non-Standard Model Higgs and SUSY squark production

Impact parameter significance

$H^0 \rightarrow XX$

$\tilde{q} \rightarrow q\tilde{\chi}^0, \tilde{\chi}^0 \rightarrow \mu^+\mu^-$
Displaced Di-muons with the Muon Chambers

- Search for long-lived particles that decay into final states containing two muons using ONLY the muon system in CMS. Veto on tracker connected muons.
- Allow to extends tracker analysis in $c_\tau$ by an order of magnitude
- Select muons with $p_T > 26$ GeV
- Models tested: non-Standard Model Higgs and SUSY squark production

Collinearity angle

$H^0 \rightarrow XX$

CMS PAS EXO-14-012

$\widetilde{q} \rightarrow q\widetilde{\chi}^0, \widetilde{\chi}^0 \rightarrow \mu^+\mu^-$
Displaced Electron & Muon

EXO-16-022

- Search for long-lived particles that decay into final states containing an electron and muon
- Leptons with transverse impact parameter values between 0.2 mm and 10 cm
- Models tested: SUSY RPV model with stop quarks decaying to an e-mu final states
Light Bosons Decaying to Dimuons

HIG-16-035

Search for new light bosons -> Search for Dark SUSY
Data at 13 TeV  2.8 fb^{-1}. Final state with for 4 muons
Fiducial volume: decay within the pixel system (<9.8 cm)

- \( m(\gamma_D) \): 0.25 – 8.5 GeV
- \( c\tau \): 0 – 100 nm
- \( m(n_1) = 10 \text{ GeV}, m(n_D) = 1 \text{ GeV} \)

Limit on \( \sigma(pp \rightarrow 2\gamma_D + X) \times B^2(\gamma_D \rightarrow 2\mu) \)

exp. back. 0.74 ± 0.34 stat. ± 0.15 syst.
Displaced Jets

- Search for long-lived massive neutral particles decaying to quark-antiquark pairs, leading to displaced jets with $p_T > 60$ GeV
- Range of proper decay length studied: 0.4-200 cm
- Tracker information for displaced vertex (for $L_{xy}$ up to 50 cm)
- Dedicated HLT trigger matching jets tracks to the primary vertex
- Study neutral scalar $H \rightarrow XX$ with $X$ long lived, decaying to 2 jets
Displaced Jets Pairs

Inclusive search for new particles decaying to displaced jets final state. Calorimetric energy measurement. Transverse impact parameter from tracks used as discriminator. Trigger based on total $H_T$ from jets.

- Search for pair produced long-lived decays to four jet final states.
Displaced Photons with Conversions

A search for long-lived neutral particles decaying to photons, using converted Photons. Eg in GMSB models: $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

Evens with two photons with $p_T > 85$ GeV, 2jets and MET > 60 GeV

Sensitive to neutralinos with $c_\tau = 0.4$-$100$ cm

CMS PAS EXO-14-017

Data + background prediction

HEP-PH/0202233
Displaced Photons Using Timing

A search for long-lived neutral particles decaying to photons, using precise Timing in the ECAL. Eg in GMSB models: $\tilde{\chi}^0_1 \rightarrow \gamma + \tilde{G}$

Evens with two photons with $p_T > 65$ GeV, 2jets and MET > 25 GeV

Efficiency for neutralinos with $\tau = 1$-34 nsec

Resolution ~ 270 ps
Disappearing Tracks

Selection:
MET > 100 GeV
Jet with $p_T > 110$ GeV
Track with $p_T > 50$ GeV

arXiv:1411.6006
Disappearing Tracks

arXiv:1411.6006

Results interpreted in AMSB models

AMSB with small mass splitting between chargino and neutralino

[Graph showing CMS results with values for $\tau_{\tilde{\chi}_{1}^\pm}$ vs $m_{\tilde{\chi}_{1}^\pm}$]
Long Lived Particles & The Detector

Split Supersymmetry
- The only light particles are the Higgs and the gauginos
- Gluino can live long: sec, min, years!
- R-hadron formation (eg: gluino+ gluon): slow, heavy particles

Gravitino Dark Matter and GMSB
- In some models/phase space the gravitino is the LSP
  \( \Rightarrow \) NLSP (neutralino, stau lepton) can live ‘long’
  \( \Rightarrow \) non-pointing photons

Hidden Valley models!…
Plethora of possibilities for long lived neutrals

\( \Rightarrow \text{Challenges to the experiments!} \)
Stopped Particles

Look for calorimeter cluster asynchronus with p-p collisions. 281 hours of trigger livetime.

mini-split gluino

\[ q \rightarrow \tilde{q}, \tilde{q}^* \rightarrow 0 \tilde{\chi}_1 \]

Limits on gluino, stop mass for over 13 orders of magnitude!

arXiv:1501.05603

Eg. R-hadrons

Backgrounds: beam halo muons, cosmic rays, HCAL noise.

<table>
<thead>
<tr>
<th>Expected bkgd</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.2 +3.6 -2.5</td>
<td>10</td>
</tr>
</tbody>
</table>
Stopped Long Lived Particles: Hadronic

- Search for long lived particles that stop in the detector & decay into jets ($p_T > 70$ GeV), non-coincident with pp collisions
- 586 hours trigger lifetime in 2016 included in this search.
- Searches for long lived gluinos and stops (R-hadrons) with jets
- 13 events observed in 2016 -> consistent with background

Limits on $M_{\text{stop}} < 744$ GeV and $M_{\text{gluino}} < 1385$ GeV 95% CL for lifetimes from 10 μsec to 1000s
Stopped Long Lived Particles: Muons

- Search for long lived particles that stop in the detector & decay into muons after some time, non-coincident with pp collisions
- 744 hours trigger lifetime in 2015/16 included in this search.
- Searches for long lived gluinos with delayed muons
- No events observed in 2015/16.

Limits on $400<M_{\text{gluino}}<970$ GeV 95%CL for lifetimes from 10 μsec to 1000s
Heavy Stable Ionizing Particles

Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss ($dE/dx$)
- Slower than speed of light ($\beta < 1$) via time of flight measurements with the muon system

**Time of flight**

\[ \frac{1}{\beta} = 1 + \frac{c\delta t}{L} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Analysis</th>
<th>Mass Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluino $f = 0.1$</td>
<td>tracker-only</td>
<td>$M &gt; 1850(1850)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 1810(1810)$ GeV</td>
</tr>
<tr>
<td>Gluino $f = 0.1$ CS</td>
<td>tracker-only</td>
<td>$M &gt; 1840(1840)$ GeV</td>
</tr>
<tr>
<td>Gluino $f = 0.5$</td>
<td>tracker-only</td>
<td>$M &gt; 1760(1760)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 1720(1720)$ GeV</td>
</tr>
<tr>
<td>Gluino $f = 0.5$ CS</td>
<td>tracker-only</td>
<td>$M &gt; 1800(1800)$ GeV</td>
</tr>
<tr>
<td>Stop</td>
<td>tracker-only</td>
<td>$M &gt; 1250(1250)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 1200(1200)$ GeV</td>
</tr>
<tr>
<td>Stop CS</td>
<td>tracker-only</td>
<td>$M &gt; 1220(1220)$ GeV</td>
</tr>
<tr>
<td>GMSB Stau</td>
<td>tracker-only</td>
<td>$M &gt; 660(660)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 660(660)$ GeV</td>
</tr>
<tr>
<td>Pair Prod. Stau</td>
<td>tracker-only</td>
<td>$M &gt; 170(170)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 360(360)$ GeV</td>
</tr>
<tr>
<td>DY $Q = 1e$</td>
<td>tracker-only</td>
<td>$M &gt; 720(720)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 730(730)$ GeV</td>
</tr>
<tr>
<td>DY $Q = 2e$</td>
<td>tracker-only</td>
<td>$M &gt; 670(750)$ GeV</td>
</tr>
<tr>
<td></td>
<td>tracker+TOF</td>
<td>$M &gt; 890(890)$ GeV</td>
</tr>
</tbody>
</table>
Particles with Fractional Charge

Search for long-lived particles with fractional charge

- Backgrounds
  - Cosmics: estimate from $d_{xy}$ sidebands
  - Collisions: using $Z \rightarrow \mu \mu$ data, fit $N_{\text{hits}}$ with low $dE/dx$

- Assume lepton-like spin=1/2 particle masses

Exclude: $Q = e/3$: $m > 140$ GeV

$Q = 2e/3$: $m > 310$ GeV

arXiv:1210.2311

Study for 7 TeV data
Re-interpretation of Results

Constraints on the pMSSM and AMSB model from the search for long-lived charged particles (HSCPs)

Constrained pMSSM

-3 ≤ $M_1, M_2$ ≤ 3 TeV
0 ≤ $M_3$ ≤ 3 TeV
-3 ≤ $\mu$ ≤ 3 TeV
0 ≤ $m_A$ ≤ 3 TeV
2 ≤ $\tan \beta$ ≤ 60
0 ≤ $\tilde{Q}_{1,2,3}$ ≤ 3 TeV
0 ≤ $\tilde{U}_{1,2,3}$ ≤ 3 TeV
0 ≤ $\tilde{D}_{1,2,3}$ ≤ 3 TeV
0 ≤ $\tilde{L}_{1,2,3}$ ≤ 3 TeV
0 ≤ $\tilde{E}_{1,2,3}$ ≤ 3 TeV
-7 ≤ $A_t, A_b, A_\tau$ ≤ 7 TeV

-> The HSCP limits allow to exclude:
- pMSSM: ~ 95% of subspace with chargino lifetime > 10 ns
- AMSB: charginos with lifetime > 100 ns and mass < 800 GeV

arXiv:1502.02522
Long-lived program for DM and SUSY

Extension of MET + X and SUSY searches adding long-lived final state: Production of MC based on: arXiv:1704.06515

• Stage 1: Produce a set of long-lived signatures to benchmark where our prompt searches “break”!
  – Revert to a large and well understood portfolio of simplified models that are already in use by the experiments, in SUSY and Dark Matter analyses!
  – Started production with the obvious final states like displaced pairs of jets + MET but eventually will cover more signatures.
  – This might reveal potential holes in our search program, which in turn will inform new dedicated searches.

• Stage 2: Develop dedicated searches with LL objects.
  – Large area of parameter space and new signatures to cover.
  – Various different displaced signatures are possible and are also well motivated.
Upcoming new Analyses

- Emerging jets
- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced lepton Jets
- Displaced photons
- Dark photons
- Monopoles
- HNL Searches
- Tracks with kinks
- Heavy Stable Charged Particles
- Strongly Interaction Massive Particles
- Stopped particles
- pMSSM maps with LLP decay and disappearing tracks
- … (others…new ideas… )
Summary

- Clearly and increased interest in LLP searches within CMS, more groups joining in.
- More channels on roadmap than what has been covered so far. Synergies with Higgs and SUSY studies
- Tendency to move to more model independent analyses, where possible
- Continuing studies for better triggers for LLP channels
- Strong interest to present results via simplified models to have a common “language” with TH community
- New pixel detector available as of the 2017 data run.
- Phase-2 upgrade will allow some additional phase space coverage (see talks later this meeting)
- White paper is timely eg for the new groups that join and for defining common ATLAS/CMS/TH strategy