Searches for long-lived particles at CMS

After a few year’s of LHC running, CMS has published several searches for long-lived, exotic particles.

- What motivates these searches?

- What strengths & weaknesses does the CMS detector have for such searches?

- I will summarize the main CMS results (details in later talks) and ask:
  - How well are we exploring the phase space?
  - Where do we need improvements?
  - Do we have model-independent results?
Motivation

- Theoretical physicists are brilliant at inventing models with long-lived (LL) particles!

  There are loads of them:

  - e.g. In RPV SUSY, AMSB SUSY, GMSB SUSY, Hidden Valley models ...
    (see theory talks for details)

- Lessons:
  - LL exotica are well worth looking for.
  - Experimental searches should use simple signatures that are each sensitive to many LL models.
  - Present limits in model-independent way!
Motivation

- Long-lived signatures can hide new physics from conventional searches, even if those searches are done by a wonderful experiment like CMS ...

- e.g. In the case of SUSY:
  - If LSP decays to visible particles before calorimeter, then $E_T^{\text{miss}}$ signature used by classic SUSY searches will disappear.
  - CMS has dedicated RPV SUSY searches, but these look from promptly produced leptons etc. from the LSP decay, so will fail if the LSP decay length exceeds a few mm.
Searching for Long-Lived Particles with the CMS detector

Tracker can reconstruct charged particles from LL particle decay up to 50 cm from LHC beam-line.

Heavy, charged particles traversing Tracker can be found via dE/dx measurement.

They are also identified in μ-chambers via time-of-flight (TOF) measurement.

ECAL can find photons from LL particle decay via time-of-flight (TOF) measurement.

ATLAS better at some things:

Ø Their ECAL is great at finding photons from LL particle decay, as it measures photon direction.

Ø Their muon chambers are surrounded by air, not iron, so they can track hadrons from LL particle decay inside them, in addition to muons.
Very Long-Lived Charged Particles

(i.e., which traverse CMS before decaying)
Search for heavy stable charged particles (HSCP) (arXiv:1305.0491)

- HSCP are massive & slow moving.

- There are 3 key selection variables:
  1. Track Pt
  2. $dE/dx$ from Tracker
  3. TOF from $\mu$ chambers

- These 3 variables are statistically uncorrelated for SM particles, which allows the background to be estimated from the data.
  - e.g. $dE/dx$ has little dependence on Pt for relativistic particles.
Search for heavy stable charged particles
Different search strategies for different particles!

- Search for long-lived $\tilde{g}$, $\tilde{t}$ and $\tilde{\tau}$.
  Coloured particles ($\tilde{g}$, $\tilde{t}$) hadronize into R-hadrons with SM q/g.

- R-hadrons flip charge as they pass through the CMS detector material.
  A charged R-hadron may be neutral when it reaches the outer detector!

- Unsure how often $\tilde{g}$ forms neutral hadron with g. Could be 100%!
  If so, track would start neutral (invisible) but may become charged through interaction with detector.

- Therefore do searches using:
  - “tracker + muon chambers” (for $\tilde{\tau}$)
  - “tracker only” (for initially charged R-hadron: $\tilde{t}$, $\tilde{g}$)
  - “muon chambers only” (for initially neutral R-hadron: $\tilde{g}$)
95% CL lower mass limits placed:

- Limits on $\tilde{g}$ & $\tilde{\tau}$ vary by ~100 GeV, depending on R-hadron assumptions.

- CMS also has limits on LL leptons of charge $e/3$ to $8e$. 

![Graph showing mass limits for gluino, stop, stau (also via SUSY decay), and stau (direct production).]
Search for HSCP (arXiv:1502.02522)  
Towards model independent results …

- Publish number of data candidates passing cuts & the expected background.
- Publish selection efficiency vs. Pt, β & η of HSCP.
- If HSCP lifetime is small, multiply this by prob that it transverses CMS before decaying: \( \exp[-M L(\eta) / c \tau P] \).

- Can now estimate efficiency & hence limits for arbitrary HSCP model, if kinematics known at generator-level.

- For example …
  - In AMSB, \( \tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+ \), where \( \tilde{\chi}^+ \) is long-lived, get limits extending down to lifetimes of \( \sim 2 \) ns.
Search for stopped R-hadrons (HSCP)  
(arXiv:1501.05603)

- Slowly moving (< 0.45c) R-hadrons would lose all their energy through dE/dx & come to a halt in the calorimeter.
- They could decay (e.g., $\tilde{g} \rightarrow g \tilde{\chi}^0$) seconds or months later.
- The decay would be seen as energy deposit in calorimeter (require $E_t > 70$ GeV) when no LHC proton bunches are colliding. (The absence of colliding pp bunches can be confirmed by the LHC beam monitors on either side of CMS).

- Main background is from LHC beam-halo muons or cosmic ray muons that emit a bremsstrahlung photon depositing energy in the calorimeters.
  - Reduced by vetoing events in which $\mu$-chambers see evidence for muon.
• 10 events found, compatible with expectation, so limits placed on stopped R-hadrons for huge range of lifetimes ($1\mu s - 1$ year).
• N.B. Right-hand axis of limit plot is model-independent.

- Limits only valid if R-hadron decay deposits significant energy in calorimeter. e.g. For $\tilde{g} \to g\tilde{\chi}^0$, gluino mass must exceed neutralino mass by $> 120$ GeV.
- At face-value, limits weaker than those from HSCP search (which ruled out gluinos of $\sim 1300$ GeV).
Very Long-Lived Neutral Particles?

(i.e., which traverse CMS before decaying)

Only detectable via $E_t^{\text{miss}}$ signatures.
Detecting long-lived, neutral particles via $E_T^{\text{miss}}$ searches.

An example ...

- Monojet searches provide general limits on long-lived, neutral particles.


- The same limits apply to LL neutral particles that decay outside CMS ($R \gtrsim 10$ m).
Look for leptons, jets or photons that do not originate at the pp collision point.
Search for long-lived particles decaying to displaced leptons

• **1st paper** looks for events where a LL particle decays to \((l^+, l^-, \text{anything})\),
  by searching for a single *displaced* \(e^+e^-\) or \(\mu^+\mu^-\) vertex reconstructed in Tracker.

  ➢ Considered 2 signal models:

  1) Higgs \(\rightarrow 2X \rightarrow (e^+e^-)(\mu^+\mu^-)\),
     where \(X\) is LL particle
  2) Long-lived \(\tilde{\chi}^0 \rightarrow e^+e^-\nu / \mu^+\mu^-\nu\)
     produced in \(\tilde{q}\) decay.

• **2nd paper** looks for events with
  one displaced electron + one displaced muon,
  (which are *not* required to form a vertex
  - *good idea* since it broadens range of models we are sensitive to).

  ➢ Considered 1 signal model:

  3) \(2\star(\text{long-lived } \tilde{t}) \rightarrow (b\ e)(b\ \mu)\)
Search for long-lived particles decaying to displaced leptons

Efficiency

- Decent efficiency for Tracker to reconstruct leptons produced up to 50 cm from beam-line, thanks to effort invested in displaced-track reconstruction.

- (2nd paper didn’t fully exploit this, as e\(\mu\) trigger was inefficient for very displaced muons. -- Will fix in future).

RESULT:
- 1\textsuperscript{st} paper sees no candidates.
- 2\textsuperscript{nd} paper sees only a few.
Search for long-lived particles decaying to displaced leptons
Model independent limits from 1st paper

- Define acceptance region where efficiency “high”:
  i.e. Lepton Pt > 26-40 GeV & |η| < 2 & L_{xy} < 50 cm.
- Limits on “σ*BR*acceptance” are ~ independent of model (& even lifetime)!
  - Valid for any model where LL particle decays to (l^+,l^-,anything)!
  - Can be translated to limits on σ*BR if you know the acceptance for your model.

![Graphs showing limits on σ*BR](image)

Ian Tomalin 10/11/2015
Search for events in which a LL particle decays to \((q, \bar{q}, \text{anything})\) by looking for 2 jets whose associated tracks form a single displaced vertex in Tracker.

- Considered 2 signal models:
  1) Higgs \(\rightarrow\) \(2X \rightarrow (q\bar{q})(q\bar{q})\), where \(X\) is LL particle
  2) Long-lived \(\tilde{\chi}^0 \rightarrow q\bar{q}ν\) produced in \(\tilde{q}\) decay.

- Main difficulty is triggering on these events.
  - Required 2 jets of \(E_t > 60\) GeV with few associated prompt tracks. (N.B. Hard to reconstruct displaced tracks fast enough for use in trigger)
  - Also required \(HT > 300\) GeV (total transverse energy in event) makes analysis insensitive to 125 GeV Higgs decays.
  - Threshold could be reduced in future by triggering on other particles produced in association with LL particle. (But increases model-dependence).
Search for long-lived particles decaying to displaced jets

- Only 2 events passed selection, consistent with expectation, so quote limits.

- Found no (simple) model-independent way of presenting limits. (Difficulty is HT > 300 GeV requirement, which makes limits dependent on what both LL particles in event do).

- Nonetheless, results can be translated to powerful limits on other models (e.g. Brock Tweedie - arXiv:1503.05923)
Search for long-lived particles decaying to displaced photons
(2 papers: https://cds.cern.ch/record/2063495/ + https://cds.cern.ch/record/2019862/)

- In GMSB SUSY: long-lived $\tilde{\chi}^0 \rightarrow \gamma \tilde{G}$.
- 1st paper uses ECAL timing resolution (~0.37 ns) to detect late arrival of $\gamma$ at ECAL (due to indirect path & due to non-relativistic $\tilde{\chi}^0$).
- 2nd paper profits from large amount of material in tracker (!) to reconstruct $\gamma$ conversion & hence show that $\gamma$ trajectory doesn’t originate at beam-line.
- Both require $E_{\text{miss}} > 60$ GeV (due to $\tilde{G}$).
Search for long-lived particles decaying to displaced photons

ECAL timing measurement in 1\textsuperscript{st} paper

- ECAL time measurement for simulated GMSB SUSY signal significantly different to data distribution.

- Non-gaussian tails in data due to bremsstrahlung photons from LHC beam-halo or cosmic muons + ECAL detector effects.
Search for long-lived particles decaying to displaced photons

Results

- **1st paper** gets limits for $\tau > 3$ ns, as lower lifetimes do not give sufficiently delayed $\gamma$ for ECAL timing measurement to be significant.
- **2nd paper** extends limits to lower $\tau$ due to precise measurement of $\gamma$ trajectory obtained from conversions.

- **ATLAS** limits stronger due its ECAL’s ability to reconstruct $\gamma$ direction.

- Limits only presented for one specific SUSY benchmarks (SPS8).
- **Would be good to find model-independent way of presenting them.**

![Graph showing limits for neutralino mass vs. SUSY $\wedge$ (TeV) and Neutralino lifetime (ns)]
Long-Lived Particles that decay within the detector volume to invisible particles (!)

Possible if the long-lived particle is charged ...
In AMSB, $\tilde{\chi}^+ \to \tilde{\chi}^0 \pi^+$, where the $\tilde{\chi}^+$ and $\tilde{\chi}^0$ are almost mass degenerate. The $\tilde{\chi}^+$ is long-lived. Let us assume it decays somewhere inside the Tracker. The $\pi^+$ is very soft & usually undetectable.

- Trigger using ISR jet + missing Et (from $\tilde{\chi}^0$), since can’t trigger on $\pi^+$.

- Offline: $\tilde{\chi}^+$ seen as track with no hits in outer layers of the Tracker. But there are loads of such tracks, due to nuclear interactions!

- Rescued by additional cuts, requiring track to:
  - Have Pt > 50 GeV.
  - Be isolated.
  - Deposit < 10 GeV in calorimeter.
  - Not be identified e, $\mu$ or $\tau$. 
Disappearing (HSCP) track search (arXiv:1411.6066)

- After all cuts, only 2 tracks survive. Both have normal dE/dx in Tracker, so are not heavy, exotic particles.
- Expected background mainly $\tau \to$ hadron, $e$ or $\mu$ from $W \to l \nu$ events.
- Good limits (although not yet presented in model-independent way ...)
- These limits extend to lower lifetime those from HSCP search (slide 9).
Conclusions

- CMS searches for LL particles are usually based on simple signatures that are sensitive to a wide range of models.
  - Massive, stable charged particles.
  - Displaced leptons, jets or photons.
  - Disappearing tracks

- Several of these searches attempt to present limits in a model-independent way.
  - Good to know if theorists think we succeeded !??

- Analysis & trigger techniques still maturing, with significant improvements from year to year, so expect great things to come!
BACKUP SLIDES