Searches for long-lived particles at the LHC

After a few year's of LHC running, both ATLAS & CMS have published several searches for long-lived, exotic particles.

- What motivates these searches ?
- I will summarize *some* of the results from each experiment.
- And ask how well are they exploring the phase space ? Where should we strive to make improvements ?

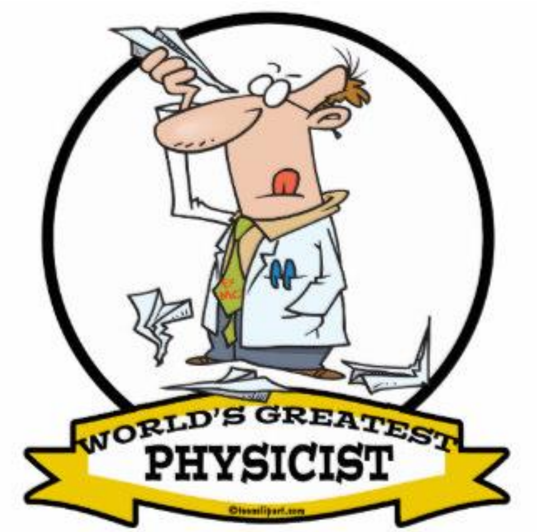
Motivation

- Many theories predict long-lived (LL) particles. e.g. In SUSY:

  - GMSB: $\tilde{\chi}^0 \rightarrow \gamma \, \tilde{G}$ or $\tilde{\tau} \rightarrow \tau \, \tilde{G}$,
    where $\tilde{\chi}^0$ and $\tilde{\tau}$ are LL because $\tilde{G}$ coupling is small.
  - AMSB: $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+$, via virtual $\tilde{q}$,
    where $\tilde{\chi}^+$ is LL because NLSP & very close in mass to $\tilde{\chi}^0$.
  - Split SUSY: $\tilde{g} \rightarrow g \tilde{\chi}^0$, via virtual $\tilde{q}$,
    where $\tilde{g}$ is LL because $\tilde{q}$ heavy.

- Theoretical physicists are *brilliant* at inventing LL models ! ('Hidden Valley' …)

- Lesson: Best to do searches that are not specific to just one model!



Motivation

- Dark matter exists!
  So if one exotic particle with infinite lifetime exists, perhaps others with shorter lifetimes do too?

- The LHC is exploring a large, new energy regime, but no evidence for new physics has been. Why not ?
  Perhaps the new physics *is* being produced, but is hard to see!

  - LL particle searches require dedicated triggers & event reconstruction algorithms.
    Otherwise LL particles are missed!

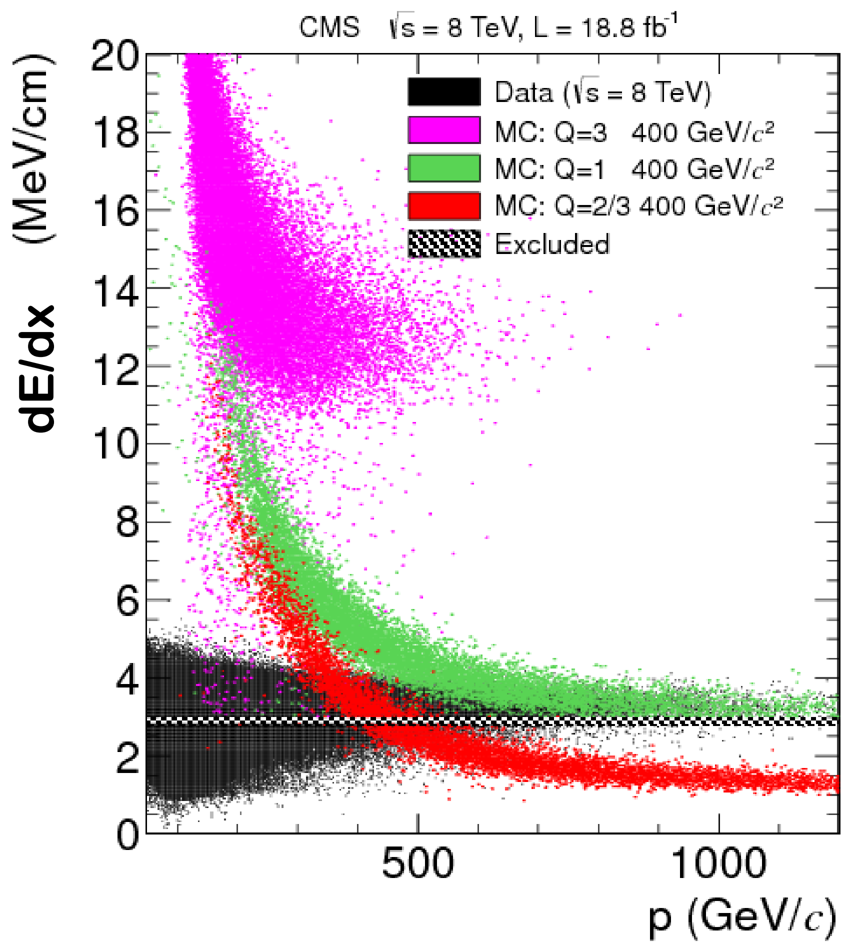
Search for heavy stable charged particles (HSCP) CMS (CERN-PH-EP-2013-073)

The high mass of HSCP means they tend to have low velocity $\beta < c$, but high Pt. Their low β means:

1. They are highly ionizing (dE/dx). Measure dE/dx using pulse height of silicon tracker hits.

2. They arrive late (compared to relativistic particle) in outer detector. Measure arrival time & hence β using muon chambers (= drift tubes + ...).

$\sigma(1/\beta) \sim 0.065$



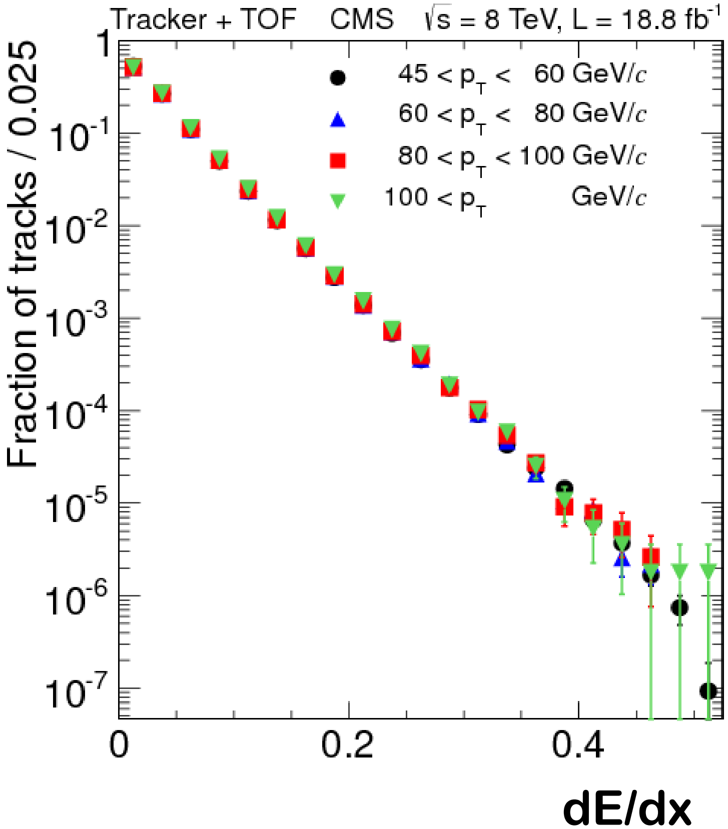
Search for heavy stable charged particles (CMS)
Background estimation

- The 3 key selection variables:
    1. dE/dx
    2. velocity (β)
    3. track Pt

are statistically uncorrelated for SM particles.

e.g. dE/dx has little dependence on Pt for relativistic particles.

- This means the amount of background passing cuts on any 2 (3) variables can be estimated from data.



Search for heavy stable charged particles (CMS)
Different search strategies for different particles!

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

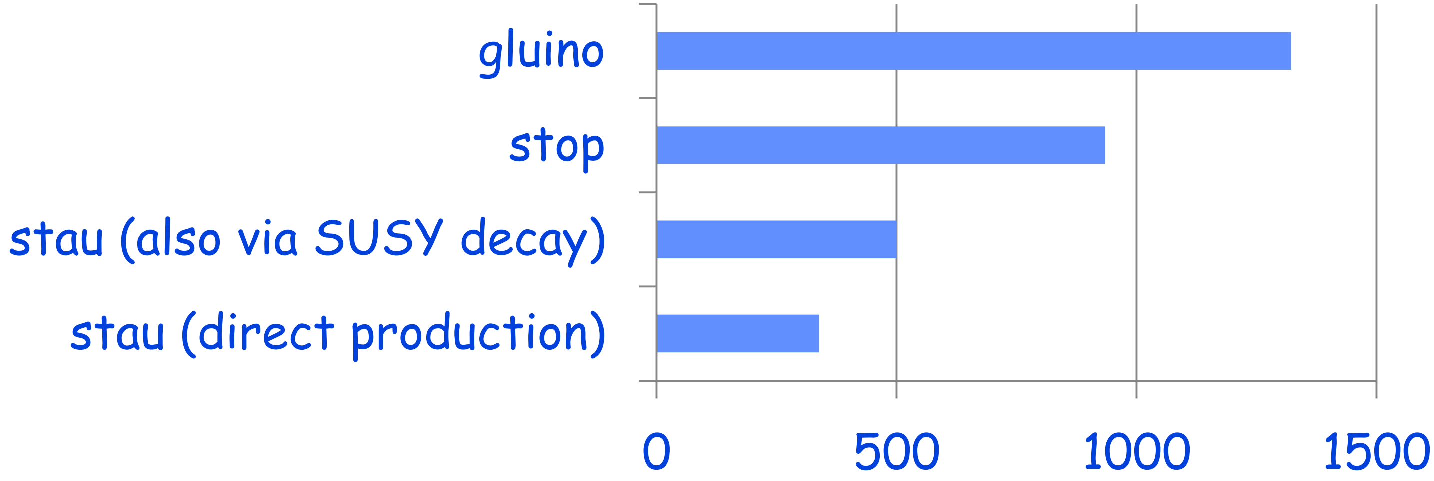
- R-hadrons flip charge as they pass through the CMS detector material.
  A charged R-hadron may be neutral when it reaches the outer detector!

- 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: $\tilde{g}$)

Search for heavy stable charged particles (CMS)
Results

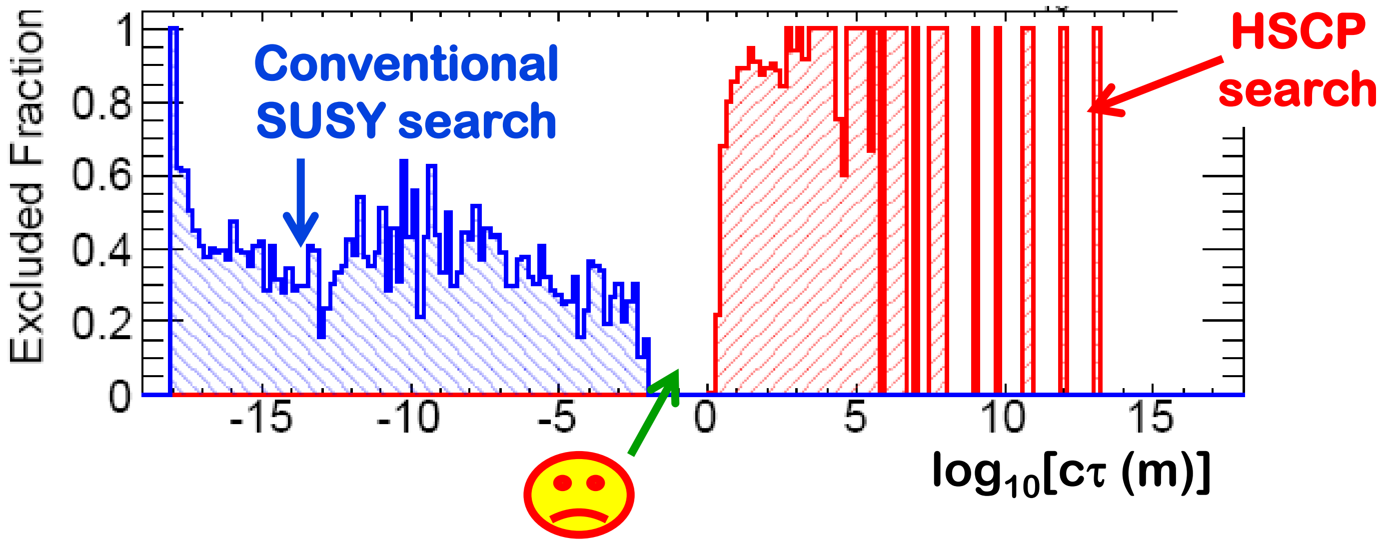
- 95% CL lower mass limits placed:



- Limits on $\tilde{g}$ & $\tilde{t}$ vary by ~100 GeV, depending on R-hadron assumptions.
- CMS also has limits on LL leptons of charge e/3 to 8e.
- ATLAS has a comparable search for LL $\tilde{\tau}$ (ATLAS-CONF-2013-058).

Search for HSCP (CMS-EXO-13-006)
Towards model independent results …

- Publish number of data candidates passing cuts & expected background.
- Publish HSCP 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 & limits for arbitrary HSCP model, if kinematics known at generator-level.
  - E.g. for pMSSM (19 parameter MSSM), plot fraction of excluded parameter space vs. $\tilde{\chi}^{+}$ lifetime.



How to find short-lived HSCP ?

- Conventional SUSY searches cover $c\tau < 1$ mm .
  And HSCP search only covers $c\tau > 1$ m.
  There's a gap in the coverage!

- ***Idea***: HSCP with 1 mm < $c\tau$ < 1 m will decay in the CMS/ATLAS Tracker.

- So search for:
  - Charged tracks that disappear part through the Tracker (ATLAS)
  - Evidence of displaced tracks coming from a LL particle decay. (***Can also detect neutral LL particles !***). – CMS + ATLAS

Disappearing (HSCP) track search
ATLAS (CERN-PH-EP-2013-155)

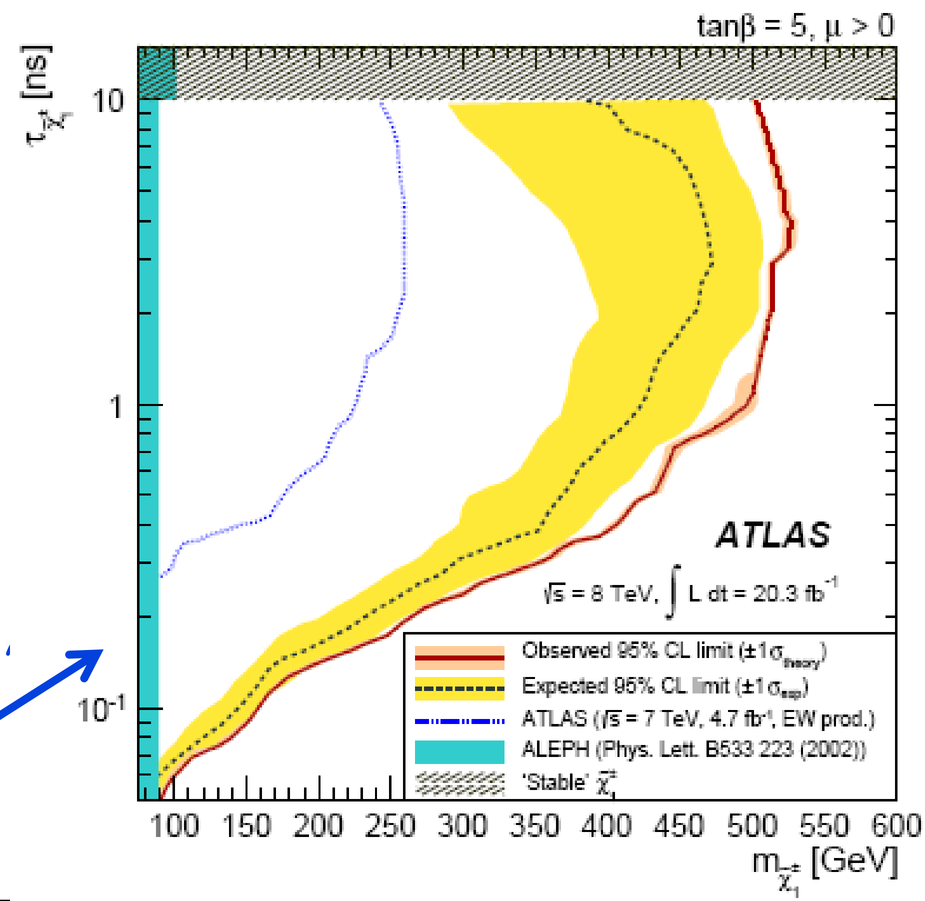
- In AMSB, $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+$, where $\tilde{\chi}^+$ is LL and π^+ very soft, because $\tilde{\chi}^+$ and $\tilde{\chi}^0$ almost mass degenerate.

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

- Offline: also require high Pt, isolated track, with no hits in outer layers of the Tracker.

- Fit track Pt spectrum to signal + background hypothesis,

- Limits for 15 mm < cτ < 3 m



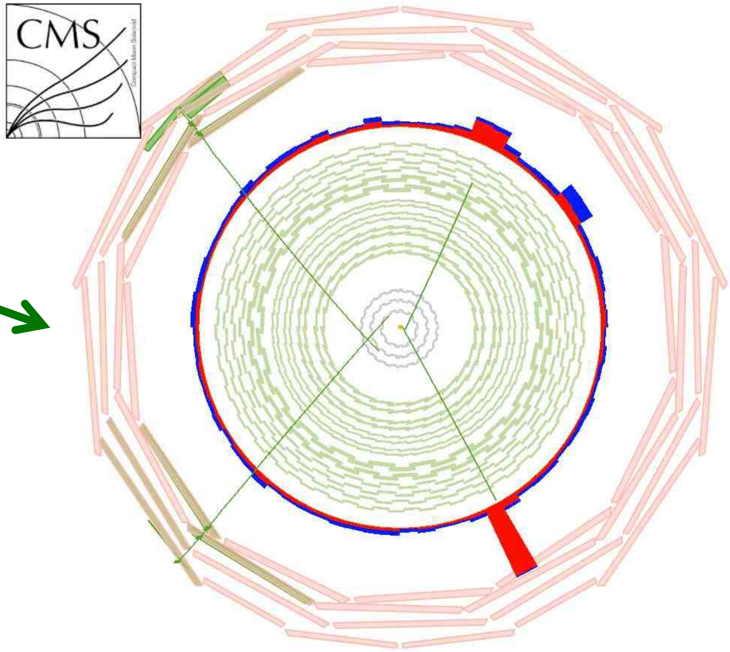
Search for long-lived particles decaying to displaced l^+l^- (CMS-EXO-12-037)

- Goal -- search for charged/neutral LL particle decays to (l^+,l^-,anything).
- Trigger based on ECAL & Muon chamber info only, since reconstructing displaced Tracker tracks in trigger not possible.
- Search for e^+e^- or $\mu^+\mu^-$ that form a displaced track-vertex in the CMS tracker.
- Considered 2 signal models:

Example of

Higgs → 2X → (e+e-)($\mu^+\mu^-$)

event, where X is LL particle



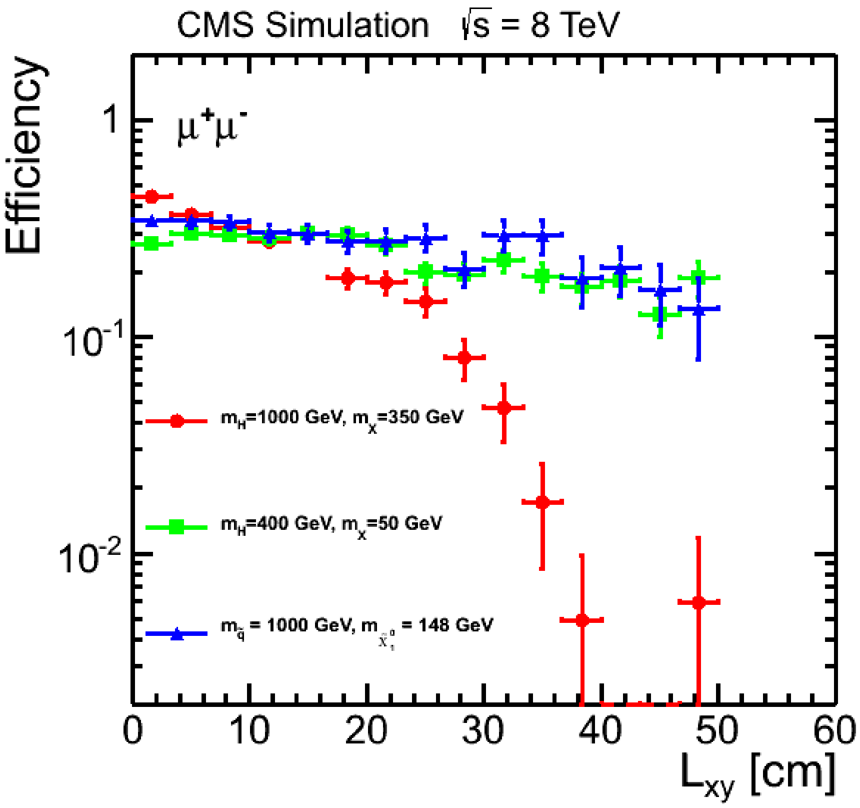
Also studied
long-lived $\tilde{\chi}^0 \rightarrow l^+ l^- \nu$
(R-parity violating SUSY)

Search for long-lived particles decaying to displaced l^+l^- (CMS)
Efficiency

- Decent efficiency to reconstruct LL particles in both signal models up to 50 cm from beam-line.
  (Thanks to effort invested in displaced-track reconstruction).

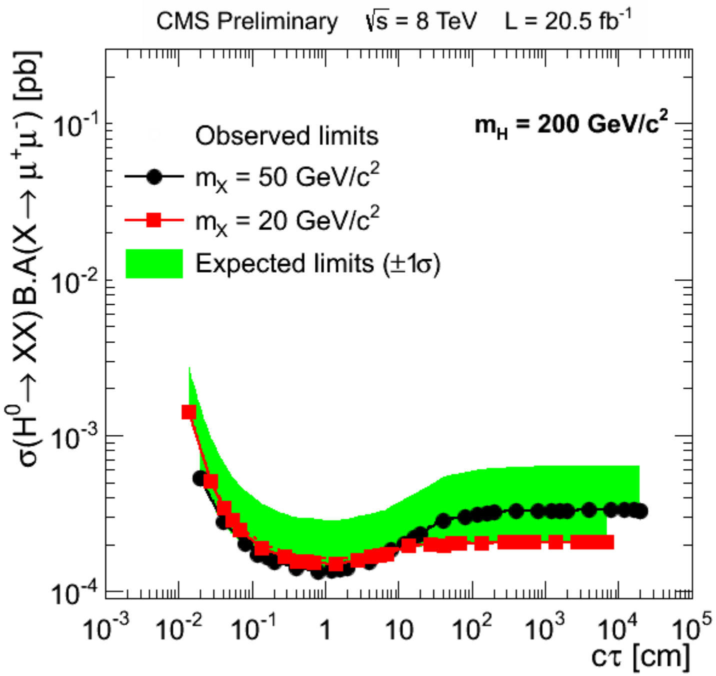
- Tracking efficiency for displaced isolated leptons measured using cosmic rays.

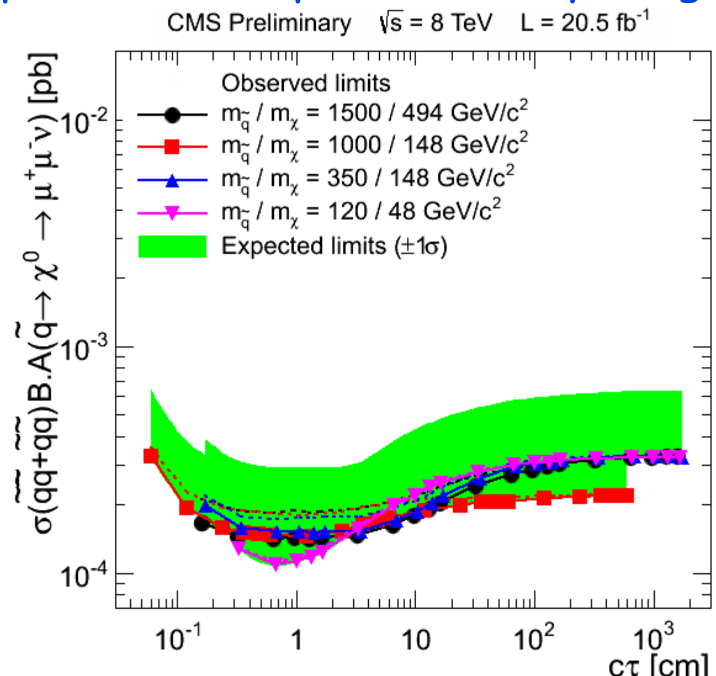
- No candidates pass cuts in data.



Long-lived particles decaying to displaced l^+l^- (CMS) → Model independent results

- Define acceptance region where efficiency "high":
  i.e. Lepton Pt > 26-40 GeV & $|\eta| < 2$ & $L_{xy} < 50$ cm.
- Non-trivial limits for 0.1 mm < $c\tau$ < 100 m
- Limits on "σ*BR*acceptance" approximately independent of model (& even lifetime) !
  - i.e. Valid for any model where LL particle decays to (l^+,l^-,anything)!



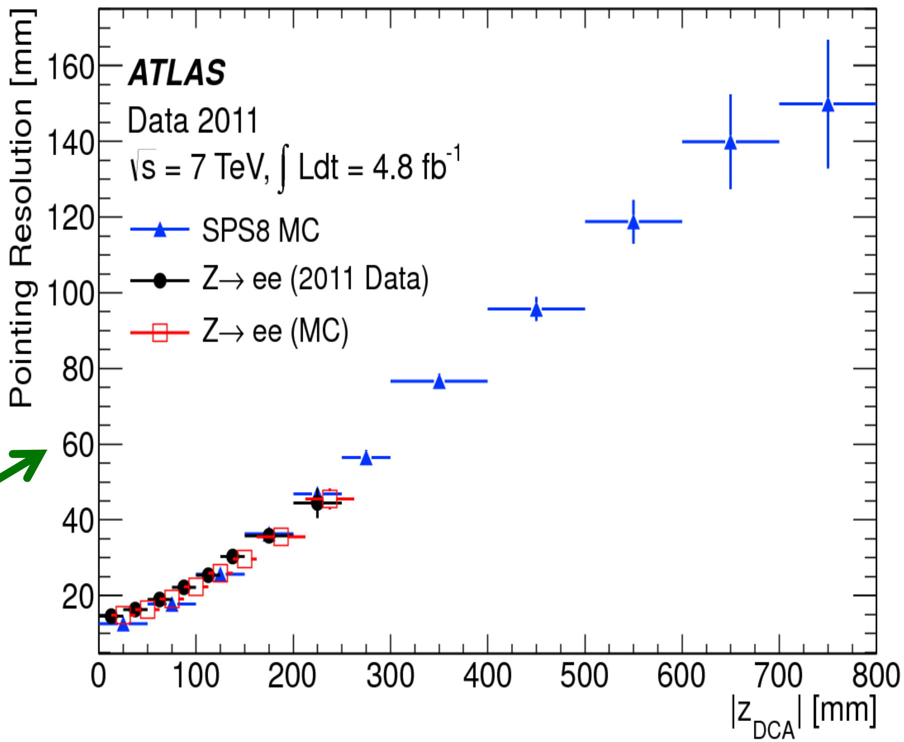


Search for long-lived particles decaying to displaced photons ATLAS (CERN-PH-EP-2013-049)

- In GMSB SUSY: long-lived $\tilde{\chi}^0 \rightarrow \gamma \, \tilde{G}$.
- Expect 2 $\tilde{\chi}^0$ per event, so trigger requires 2 photons.
- Offline, also require missing Et from $\tilde{G}$.

- Profit from depth-segmented ECAL, to measure photon flight direction!
- Hence estimate z_0 impact parameter of photon.
- z_0 should be small for background & large for signal.

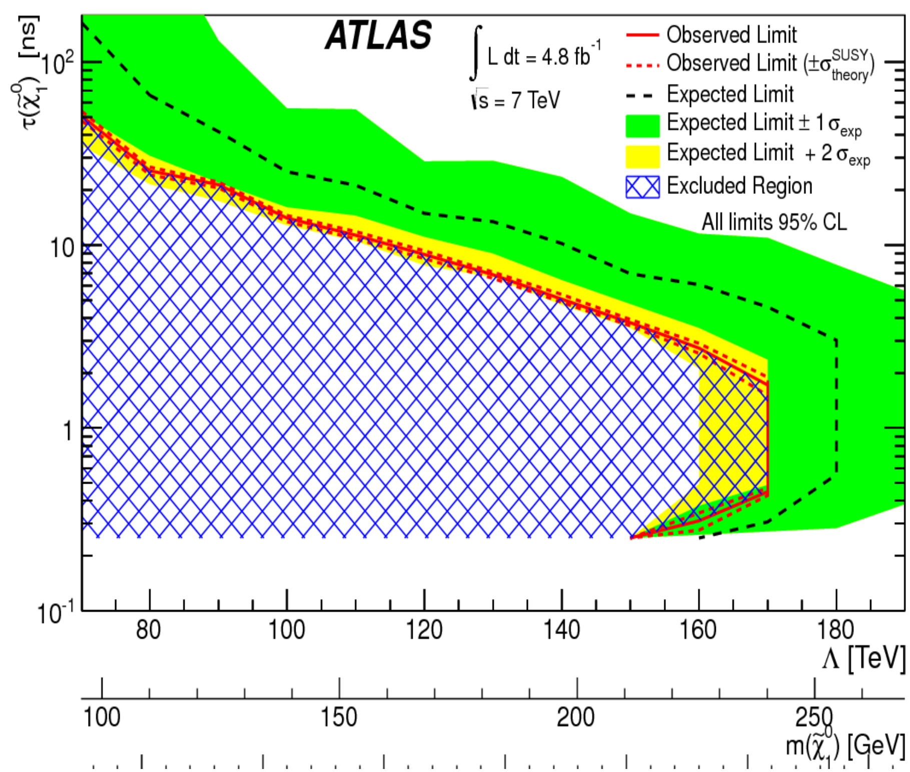
- z_0 resolution measured using Z→e+e-. Good enough to be useful!



Search for long-lived particles decaying to displaced photons (ATLAS)

- Fit to photon z_0 impact parameter distribution gives limits in plane of $\tilde{\chi}^0$ lifetime vs. mass, assuming SPS8 SUSY parameters.
- Together, CMS & ATLAS have limits for $c\tau$ < 30 m.

- N.B. These searches sensitive to *any model* giving displaced photons!
- So presenting limits in a more model-independent way would be welcome …



Other displaced track searches

- Similar to CMS displaced dilepton search, but searches for displaced track vertices found in tracker with different final states.
  - CMS-EXO-12-038: Higgs → 2 LL particle → 2 ($q\bar{q}$)
  - ATLAS-CONF-2013-092: long-lived $\tilde{\chi}^0 \rightarrow \mu\, q\bar{q}$
  - ATLAS (CERN-PH-EP-2012-241): Higgs → 2 LL particle → 2($\mu^+\mu^-$"ν")

- One cute search (ATLAS CERN-PH-EP-2011-228) profits from the air-core muon chambers to search for LL particles decaying in the muon chambers to $b\bar{b}$.

  (Sensitive to decay lengths of several metres, unlike the Tracker-based searches).

Conclusions

- Both ATLAS & CMS have published several searches for LL particles.
- Signature-based searches, with limits applicable to a wide range of models, are starting to appear.

- *Charged* LL particles can be explored over all lifetime ranges from essentially prompt decays to stable. However, if they decay within the detector, not all possible decay channels studied yet …
- *Neutral* LL particle decays can be sometimes be reconstructed if they occur within ATLAS/CMS volume.
  - Decays outside this, may be found by "dark matter" searches.
  - Decays with $c\tau$ < 1mm, may be found by conventional, promptly-decaying-particle searches.