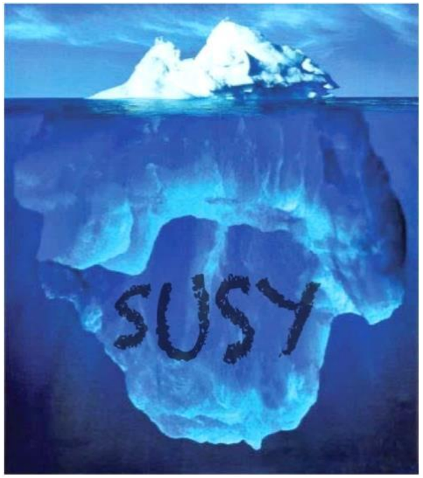
Searches for long-lived particles at the LHC

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 ?
- And what does the future hold ?

Motivation

- Many theories predict long-lived (LL) particles. e.g. In SUSY:
  - RPV: $\tilde{\chi}^0 \rightarrow l^+ l^- \nu$, via virtual $\tilde{l}$,
    where $\tilde{\chi}^0$ is LL because RPV coupling is small.
  - 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 it is very close in mass to $\tilde{\chi}^0$, & $\tilde{q}$ is heavy.
  - Split SUSY: $\tilde{g} \rightarrow g \tilde{\chi}^0$, via loop involving virtual $\tilde{q}$,
    where $\tilde{g}$ is LL because $\tilde{q}$ heavy.



- Why should we care?
  Well for one thing, this can ***hide SUSY*** …

Motivation

How can LL particles hide SUSY ??? Two examples from CMS …

1. Conventional SUSY search for $2\tilde{\chi}_2^0 \rightarrow l^+ l^- \tilde{\chi}_1^0$ (arXiv:1405.7570) requiring dileptons + E_T^{miss}

   If $\tilde{\chi}_1^0$ lifetime is too small, it decays to SM fermions before the calorimeters, so no E_T^{miss}, so limits are invalid!

2. Search for RPV SUSY: $2\tilde{\chi}^0 \rightarrow 2(l^+ l^- \nu)$ (arXiv:1307.7609) requiring 4 leptons from pp collision point.

   If $\tilde{\chi}_1^0$ lifetime is too long, $l^+ l^-$ are displaced from pp collision point, so limits invalid!

Even CMS searches can miss SUSY …

Motivation

- So SUSY might exist after all. We've just been looking in the wrong place!

Motivation

Still don't believe in SUSY? Loads of other theories predict LL particles!



- **The B-L model** (*Southampton + RAL!*)
  - $Z' \to \upsilon_H \overline{\upsilon_H}$ then $\upsilon_H \to l^- W^+$
    where heavy neutrino υ_H is LL, because it only interacts with SM particles because it is slightly mixed with SM neutrino.

- **`Hidden Valley' Models**
  - `Hidden quarks' *Q* do not interact with SM particles, but interact with each other via hidden QCD-like force, to form `hidden mesons'.
  - Hidden quarks interact with a heavy particle (Z', H, SUSY)
  - LHC makes Z', whose decay produces hidden mesons, which are LL, because they decay to SM difermions via a virtual Z'.

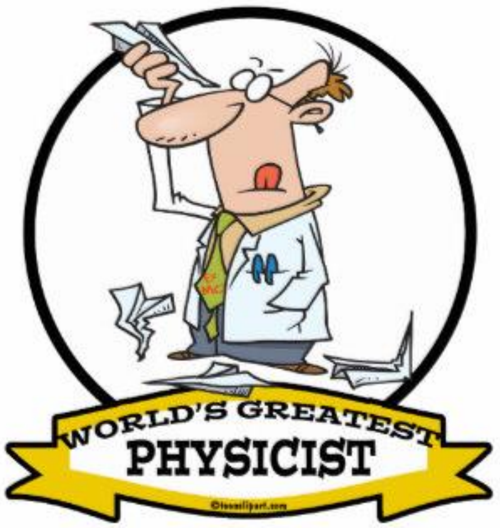
Motivation

So what's the moral???

- If we don't look for LL particles, we may miss a discovery …

- Theoretical physicists are *brilliant* at inventing LL models ! There are loads of them …

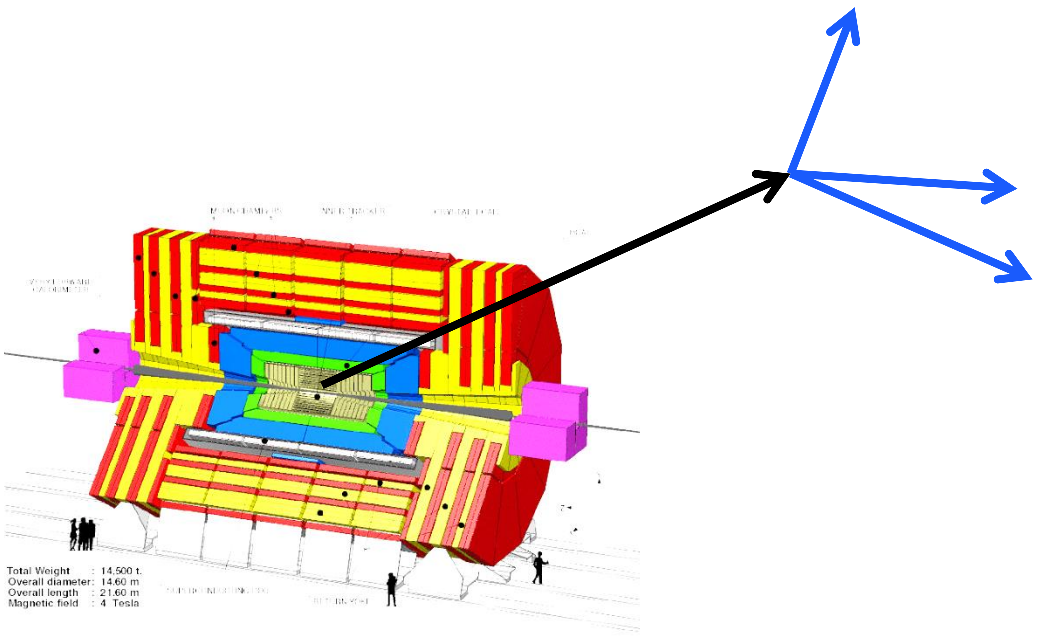
  - **Lesson: Best to do searches that are not specific to only one LL model!**



But LL particle searches are not easy. We shall see that they often require special triggers & event reconstruction …

Very Long-Lived Charged Particles

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



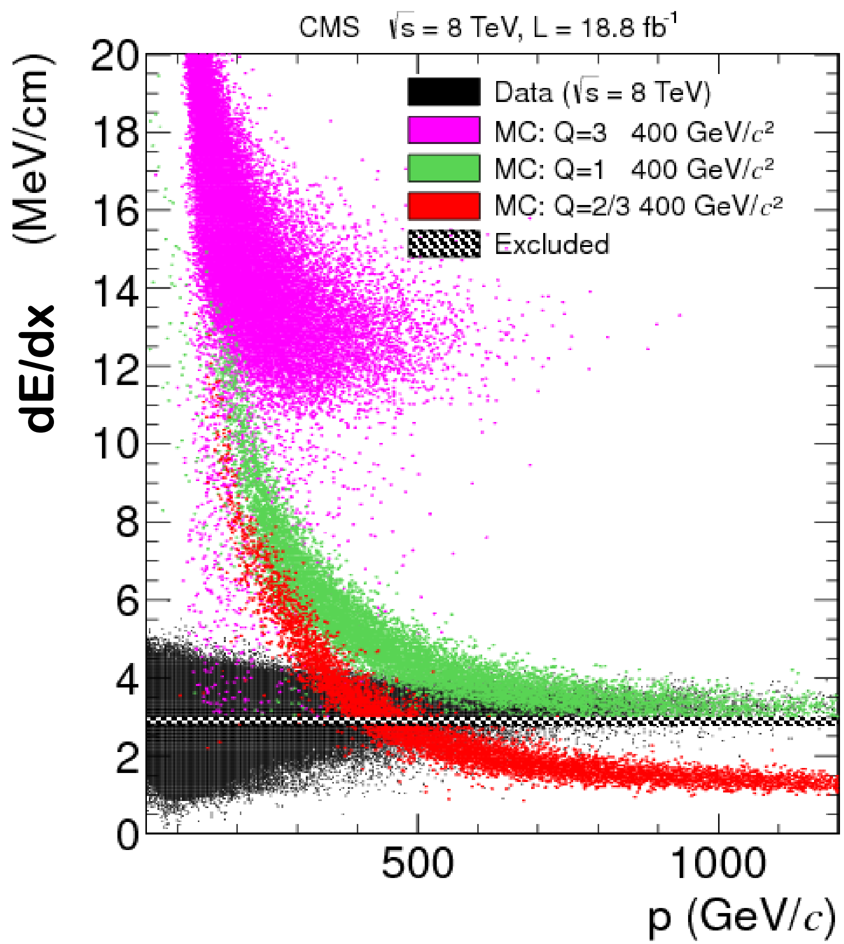
Search for heavy stable charged particles (HSCP) CMS (CERN-PH-EP-2013-073)

The high mass of HSCP means they tend to have low velocity β < 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 + …).

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



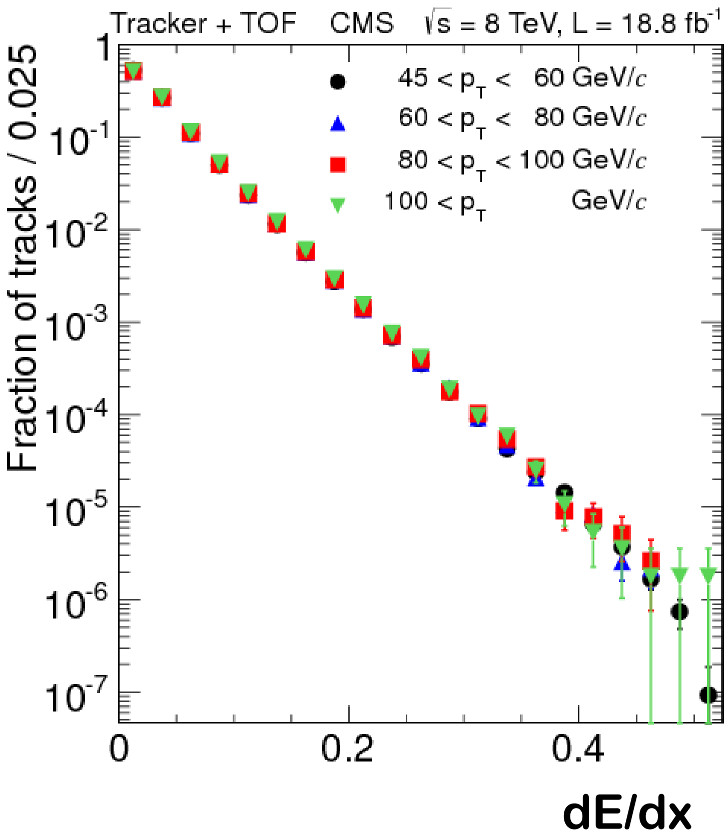
Search for heavy stable charged particles (CMS)
Background estimation

- 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.

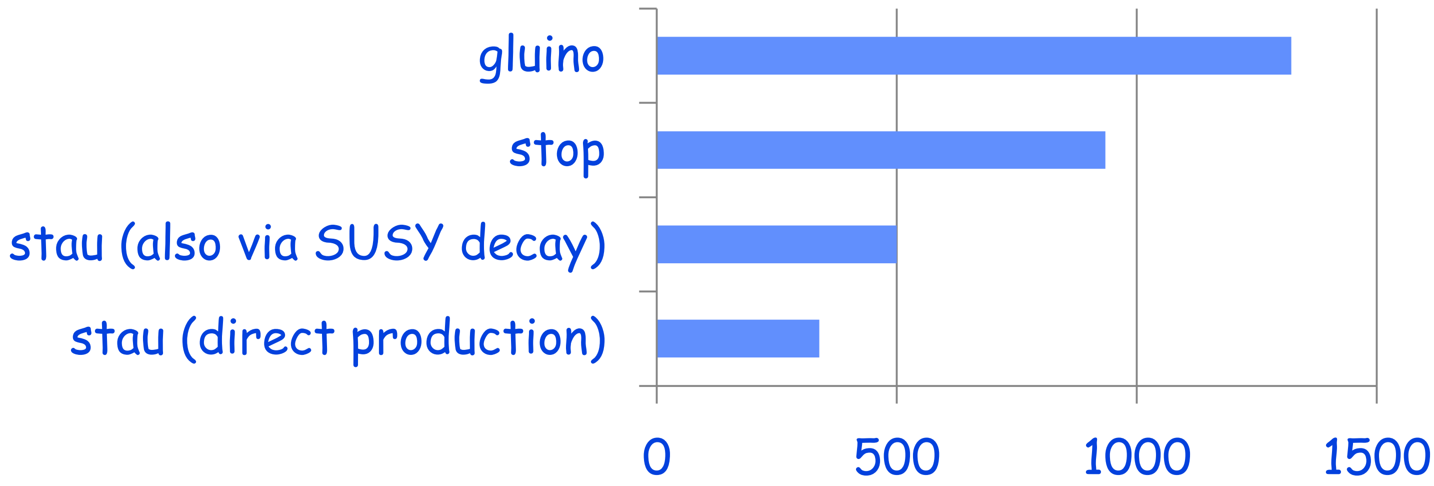
- R-hadrons flip charge as they pass through the CMS detector material.
  A charged R-hadron may be neutral when it reaches the outer detector!

- 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

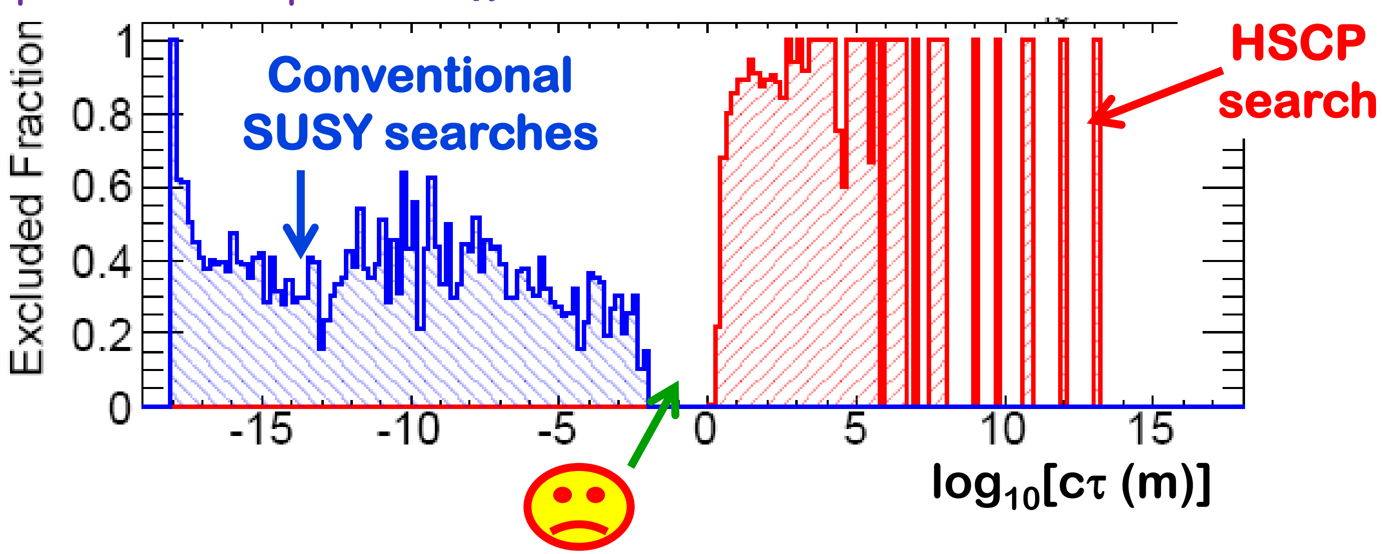
- 95% CL lower mass limits placed:



- 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).

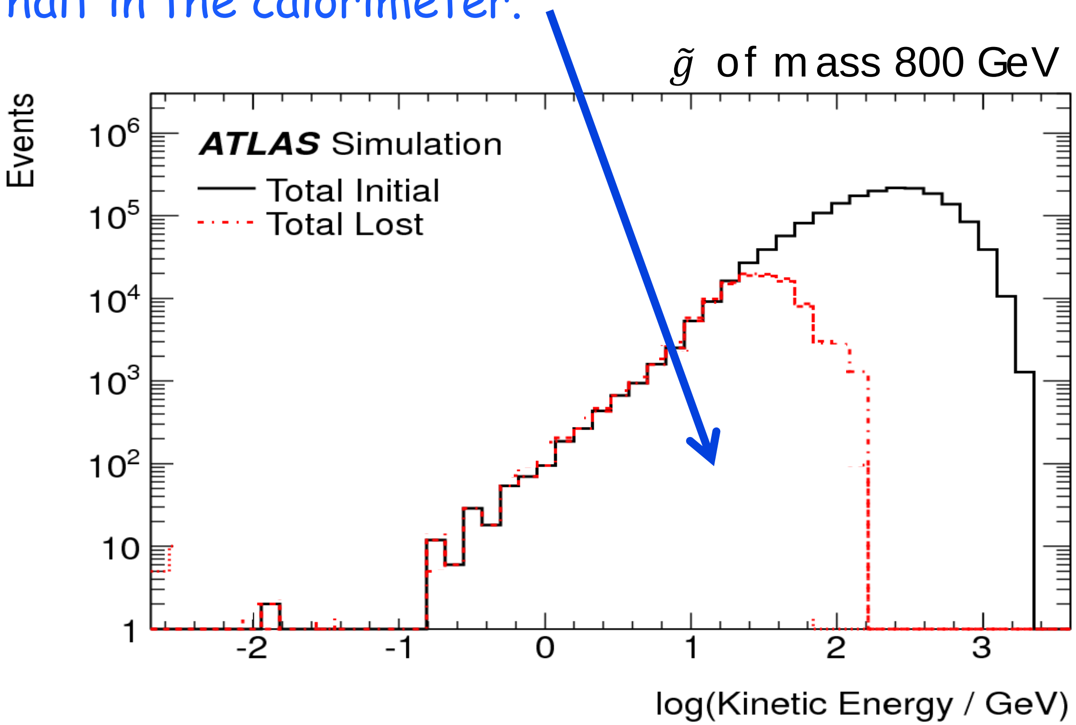
Search for HSCP (CMS-EXO-13-006)
Towards model independent results …

- 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.



Search for stopped R-hadrons (HSCP)
ATLAS (CERN-PH-EP-2013-161)

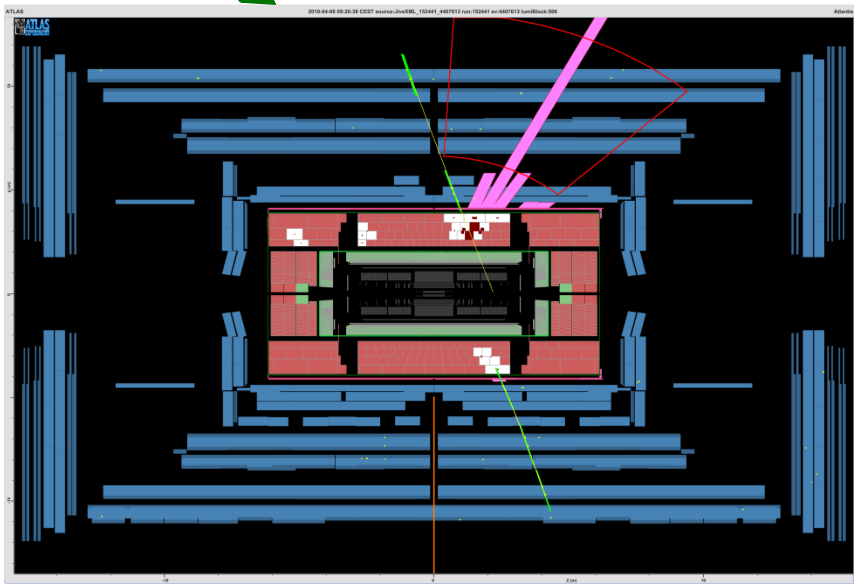
- If R-hadrons are very slowly moving, they lose all their energy through dE/dx, and come to a halt in the calorimeter.

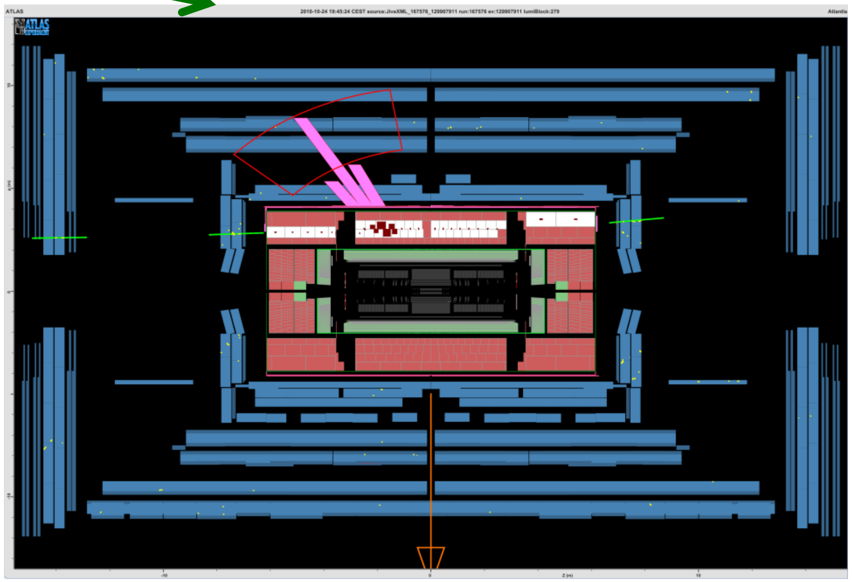


- Search for R-hadrons, produced in LHC collisions, that decay seconds or years later when there is no colliding beam!

Search for stopped R-hadrons (ATLAS)

- R-hadron decay (e.g., $\tilde{g} \rightarrow g\tilde{\chi}^0$) gives energy deposit in calorimeter.
- So require "jet" + E_T^{miss} at least 125 ns after last pp collision.
- Veto events with muons, to avoid background from interacting cosmics or beam-halo muons.





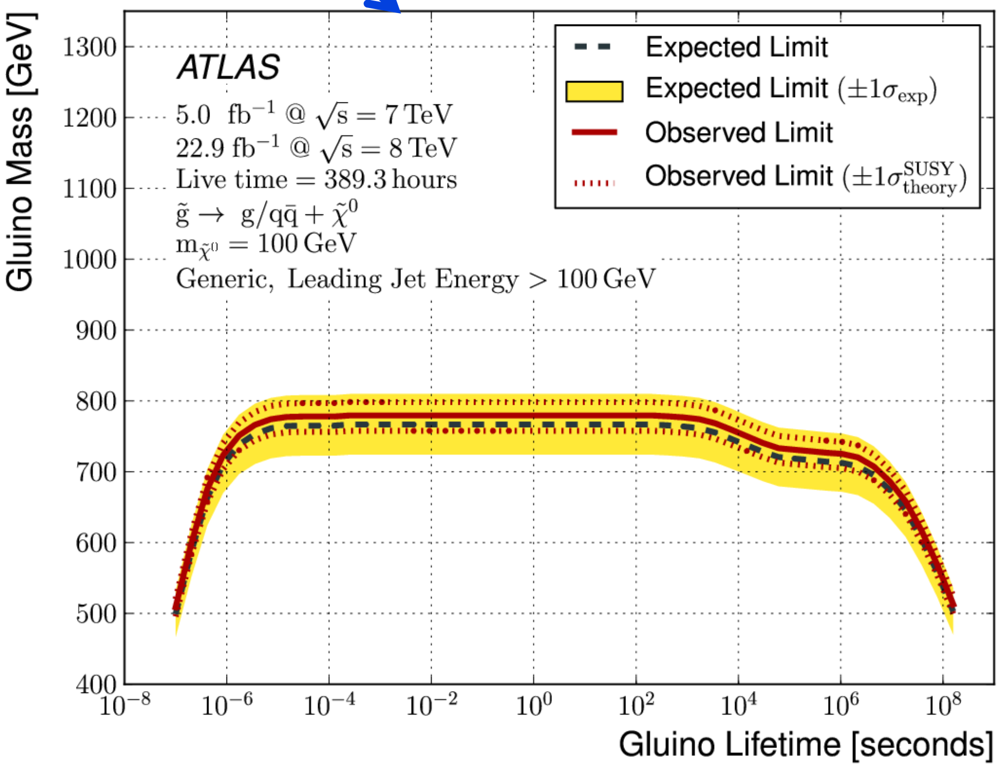
- Cosmic background estimated using data collected before start of LHC data taking!

Search for stopped R-hadrons (ATLAS)

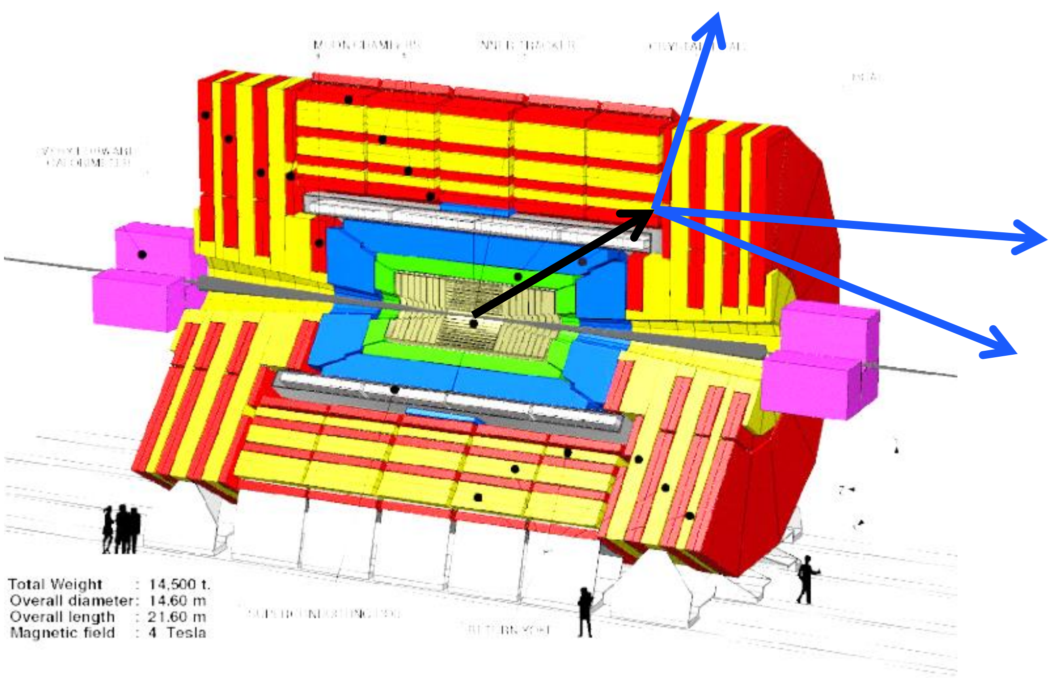
- No events found, so limit on gluino mass > 750 GeV for gluino lifetime of 1μs – 1 year.

- Rarely competitive with HSCP search, but *very cute …*

- Similar analysis from CMS (arXiv:1207.0106)



Long-Lived Particles that decay within the detector volume



How to find LL particles that decay inside the detector volume ?

- Search for:
  - Charged tracks that disappear part through the Tracker (ATLAS)
  - Evidence of displaced tracks or photons coming from a LL particle decay (CMS + ATLAS)

Disappearing (HSCP) track search
ATLAS (arXiv:1310.3675)

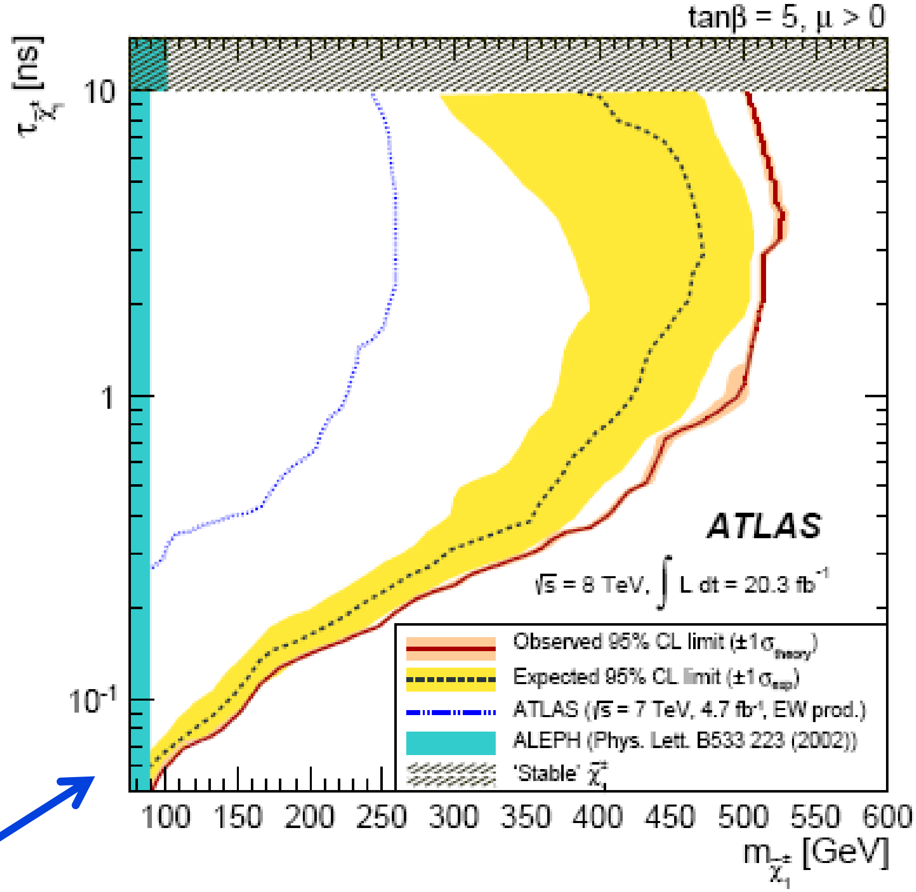
- In AMSB, $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+$, where $\tilde{\chi}^+$ is LL and π^+ very soft, because $\tilde{\chi}^+$ and $\tilde{\chi}^0$ almost mass degenerate.

- 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 (background Pt spectrum = Pt spectrum of all tracks)

- Limits for 15 mm < cτ < 3 m



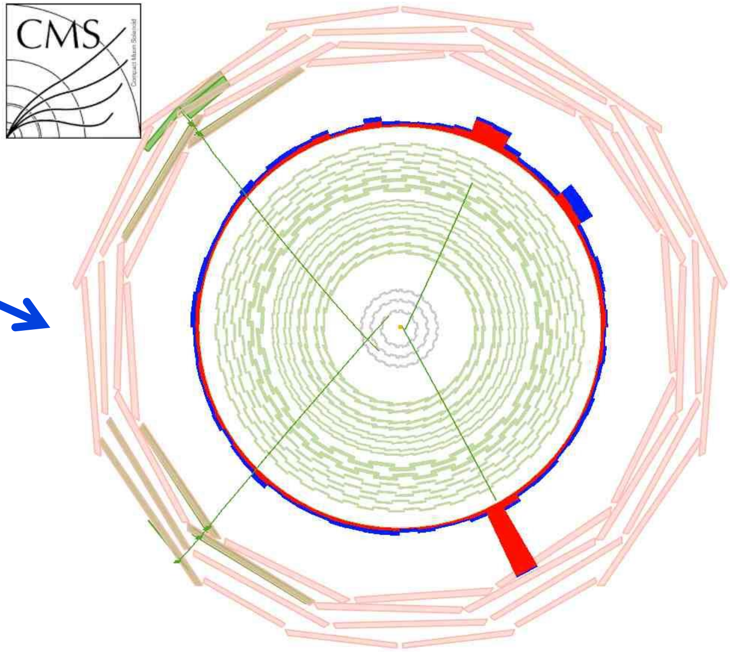
Search for long-lived particles decaying to displaced l^+l^- (CMS-EXO-12-037)

- 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:

  1) Higgs → 2X → (e+e-)($\mu^+\mu^-$), where X is LL particle

  2) Long-lived $\tilde{\chi}^0 \rightarrow l^+ l^- \upsilon$ (R-parity violating SUSY)

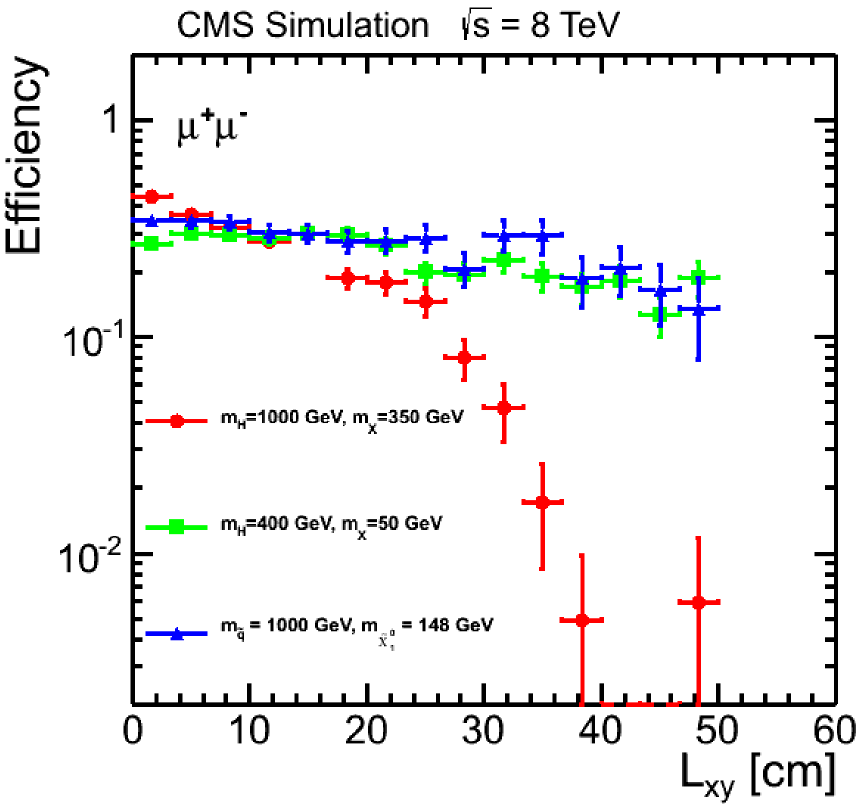


Search for long-lived particles decaying to displaced l^+l^- (CMS)
Efficiency

- 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).

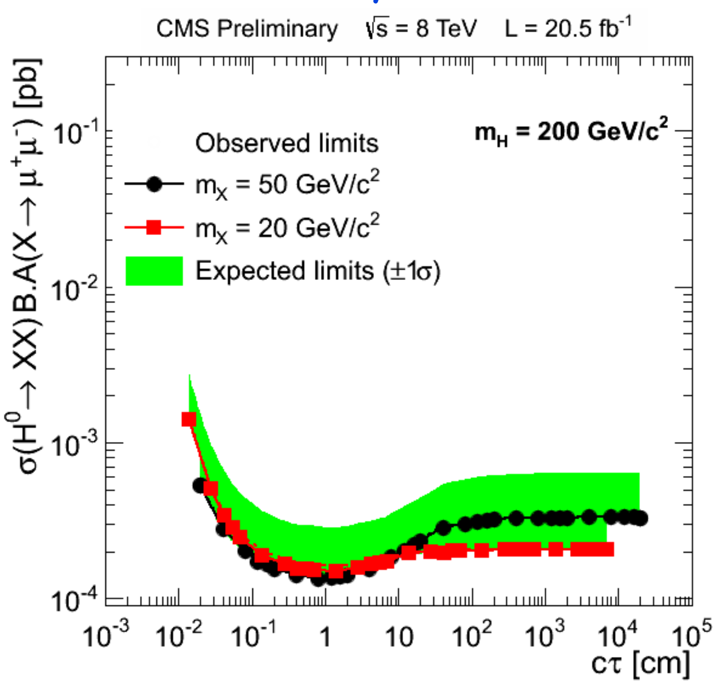
- Tracking efficiency for displaced isolated leptons measured using cosmic rays.

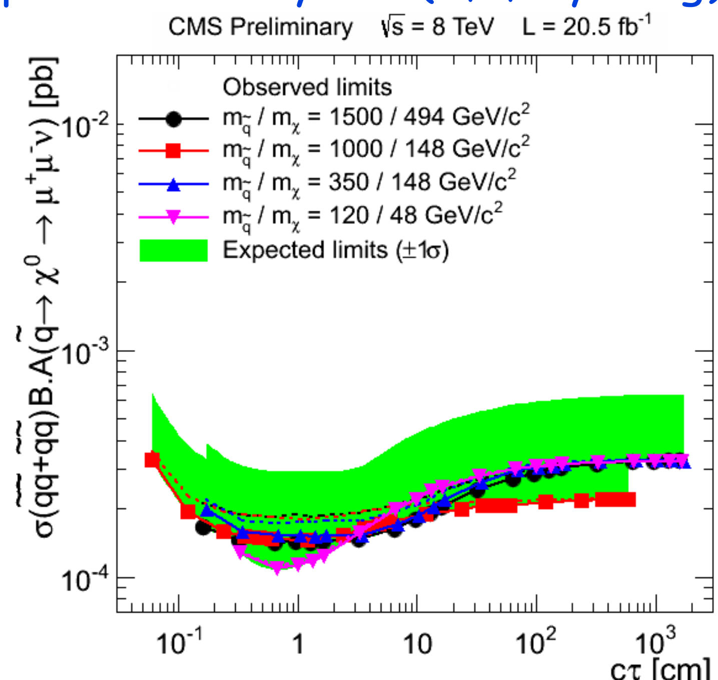
- No candidates pass cuts in data.



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)!



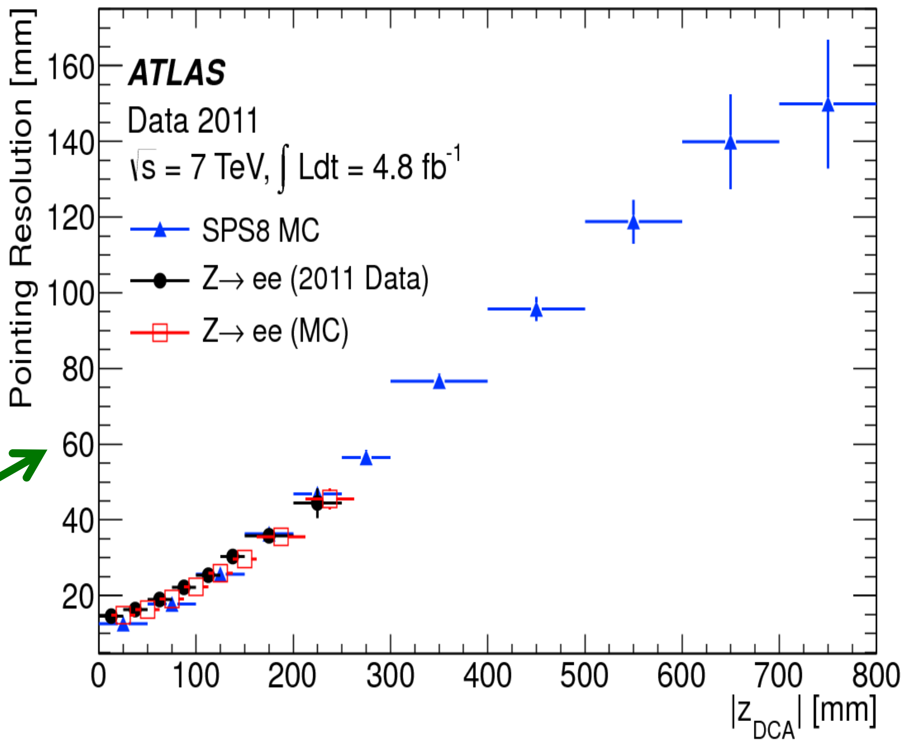


Search for long-lived particles decaying to displaced photons ATLAS (CERN-PH-EP-2013-049)

- 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.

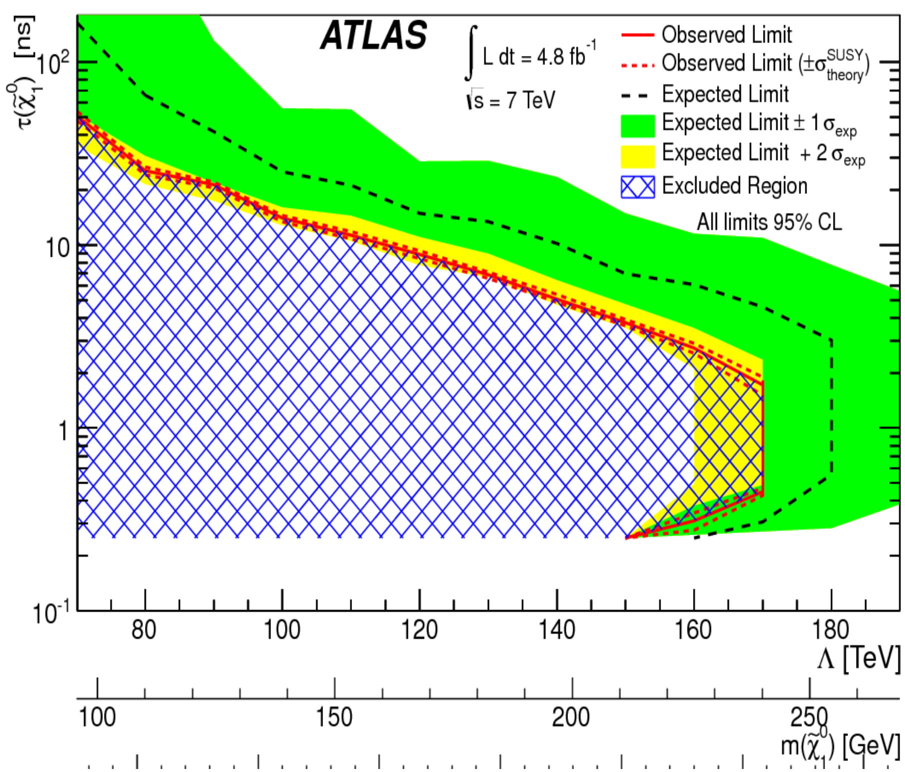
- z_0 resolution measured using Z→e+e-.
- Z→e+e- also used to estimate prompt γ background.



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

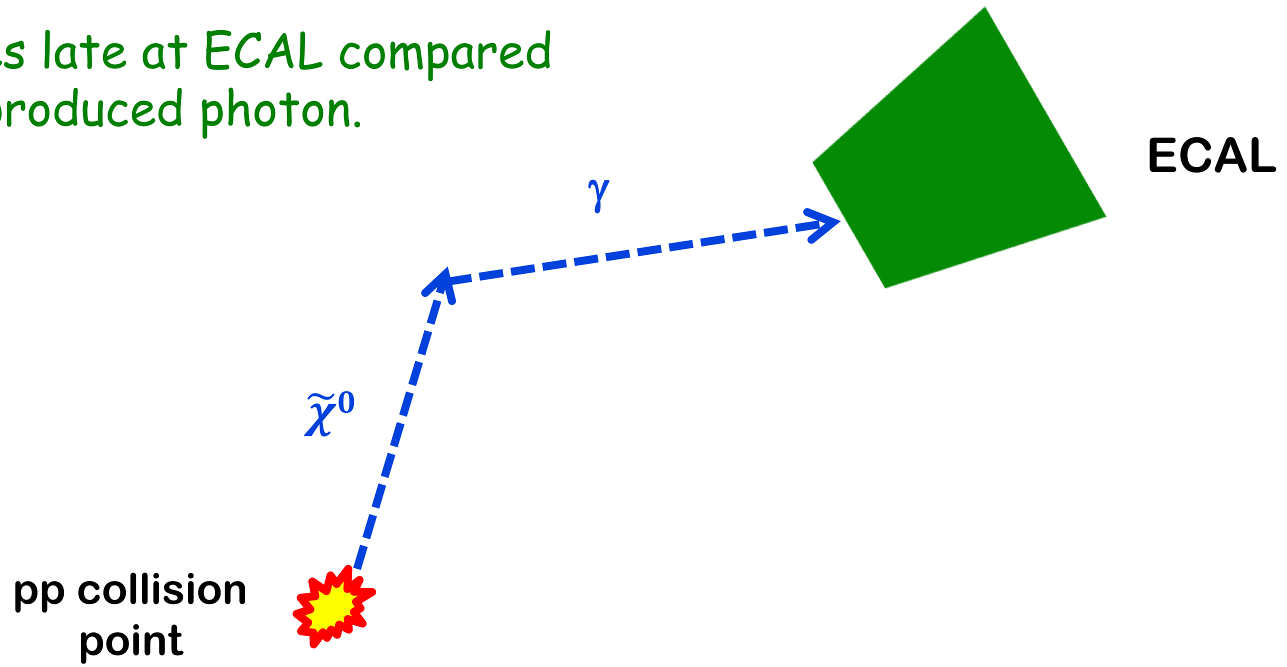
- Fit to photon z_0 impact parameter distribution gives limits in plane of $\tilde{\chi}^0$ lifetime vs. mass, assuming SPS8 SUSY parameters.
- Together, CMS & ATLAS have limits for $c\tau$ < 30 m.

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



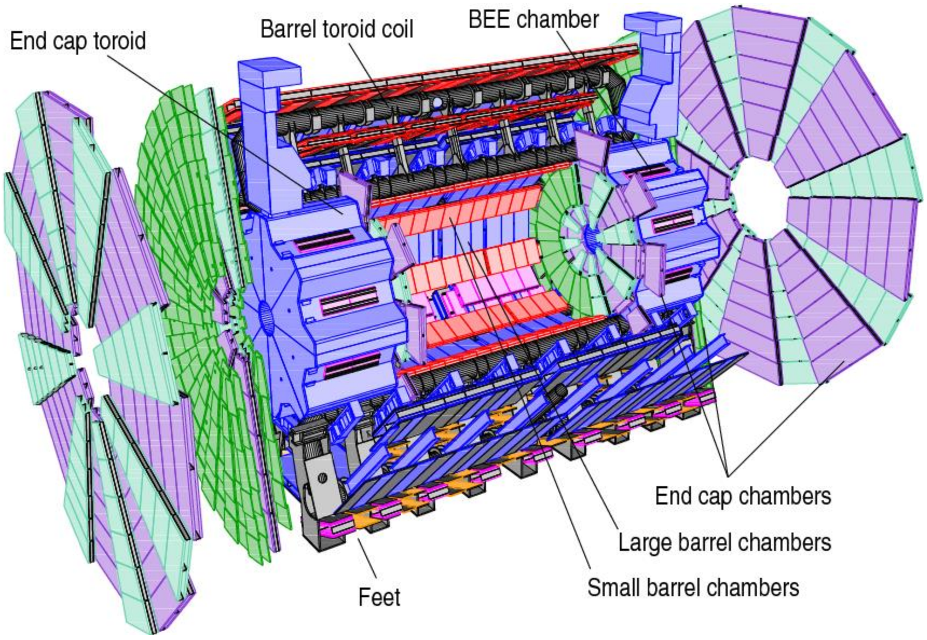
Search for long-lived particles decaying to displaced photons (CMS)

- The CMS ECAL is not depth segmented, so can't reconstruct the γ flight direction.
- But it does have a timing resolution of ~150ps, which it uses to identify long-lived $\tilde{\chi}^0 \rightarrow \gamma \tilde{G}$.
- Photon arrives late at ECAL compared to promptly produced photon.



Search for long-lived particles decaying to $b\bar{b}$ in the ATLAS muon spectrometer (arXiv:1203.1303)

- ATLAS muon spectrometer lies at 4 < r < 10 metres from beam-line. Sensitive layers are separated by *air,* (unlike CMS, which uses steel).
- Search for **Higgs → 2X → 2($b\bar{b}$)** , where LL X boson decays inside muon spectrometer. (CMS can't do this).
- Special tracking used to reconstruct charged hadrons from $b\bar{b}$ fragmentation in muon spectrometer.
- Require 2 reconstructed X decay vertices per event.

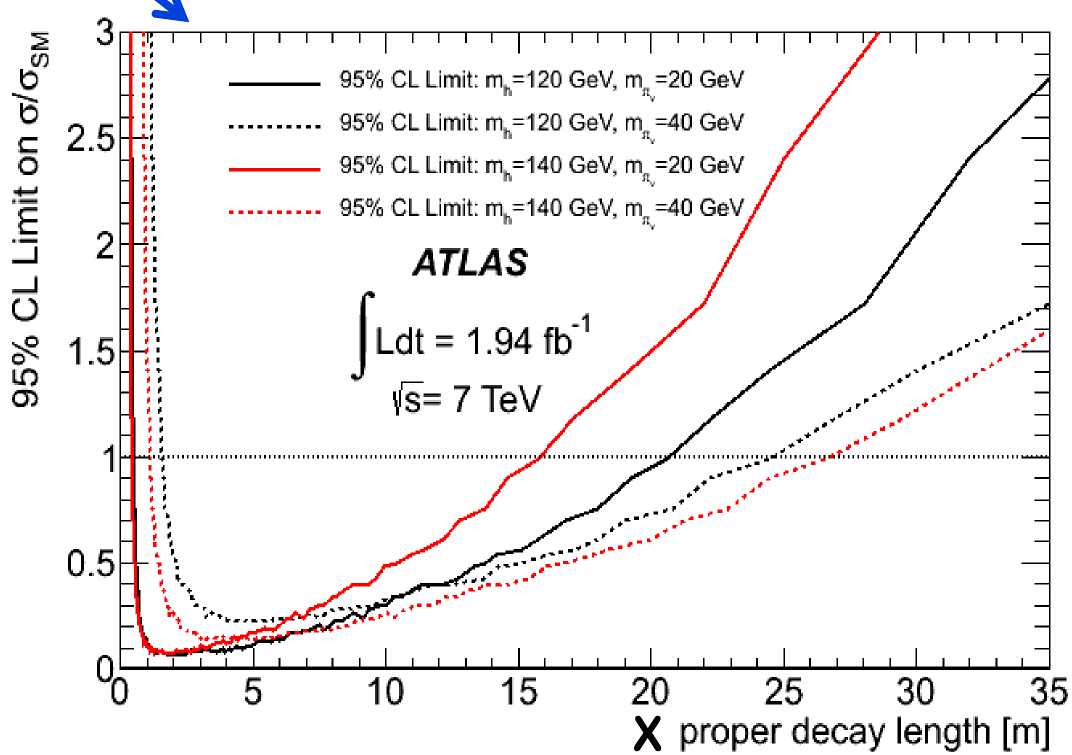


Search for long-lived particles decaying to $b\bar{b}$ in the ATLAS muon spectrometer

- No events found.
- Non-trivial limits (below SM Higgs cross section) for $1 \lesssim c\tau \lesssim 20$ m, assuming 120 GeV Higgs mass & 100% BR.

- N.B. Peak sensitivity at longer decay lengths than Tracker-based searches.

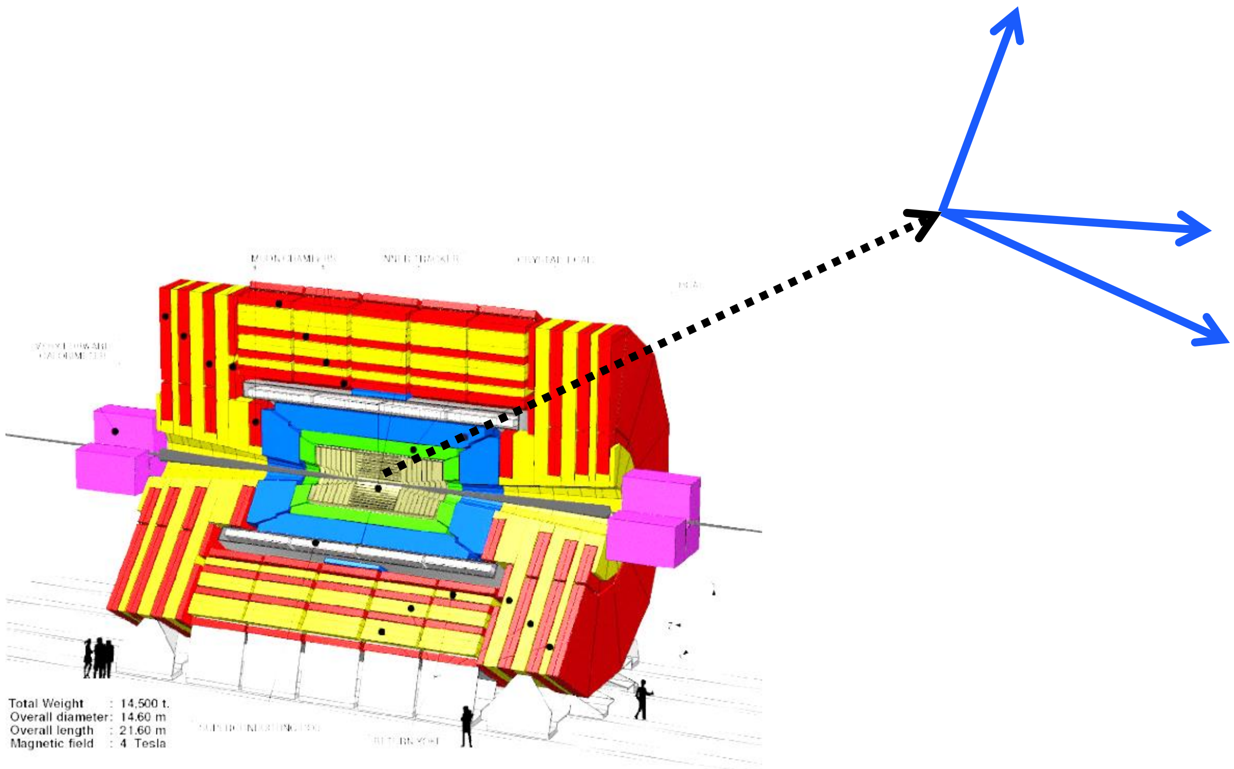
- *ATLAS uses same technique to search for "dark photons"→ $\mu^+\mu^-$ (arXiv:1409.0746)*



Other displaced particle searches

- LL particles decaying within the detector volume can decay to many different final states. Several other searches, like those presented here, have been done to find these:
  - CMS arXiv:1304.6310: long-lived $\tilde{\chi}^0 \rightarrow \gamma\, \tilde{G}$ using *ECAL timing* to detect displaced photon.
  - CMS-EXO-12-038: Higgs → 2 LL particle → 2 $(q\bar{q})$ via *displaced* jets identified usingTracker.
  - CMS arXiv:1409.4789: Events with a displaced e + displaced μ identified using Tracker.
  - ATLAS-CONF-2013-092: long-lived $\tilde{\chi}^0 \rightarrow \mu\, q\bar{q}$ identified using Tracker

What did we miss???



Do conventional searches tell us about LL particles ?

- What about *neutral* particles that are so *long-lived* that they have little chance of decaying inside detector?
- What about LL particles that are so *short-lived* that they have little chance of decaying to significantly displaced fermions?

Conventional searches can help answer these questions …

e.g. SUSY searches assume that the LSP is stable & everything else decays instantly. But their limits remain valid if the LSP usually decays outside the detector ($R \gtrsim 10$ m) & everything else decays at $R \lesssim 1$ mm.

- CMS SUSY search for $\tilde{\chi}^+ \to l^+ \upsilon\, \tilde{\chi}^0$ (arXiv:1405.7570) constrains short-lived $\tilde{\chi}^+$ ($R \lesssim 1$ mm) & long-lived $\tilde{\chi}^0$ ($R \gtrsim 10$ m).
- Combined CMS SUSY results constrain pMSSM points in which $\tilde{\chi}^+$ has $c\tau < 1$ cm (CMS-PAS-SUS-13-020).
  - (You saw this in model-independent HSCP study).

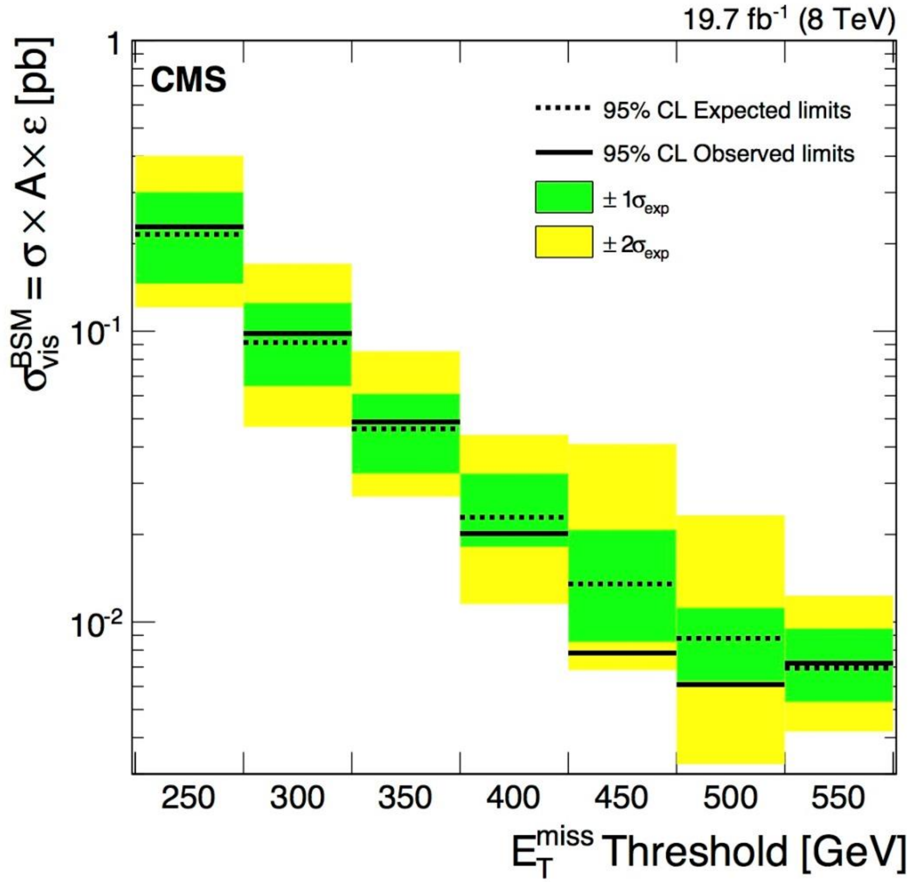
Do conventional searches tell us about LL particles ?

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

- The CMS monojet search (arXiv:1408.3583) explicitly limits pair production of dark matter particles accompanied by ISR jet.

- The same limits apply to LL neutral particles that decay outside CMS ($R \gtrsim 10$ m).

Model-independent monojet limits



What does the future hold???

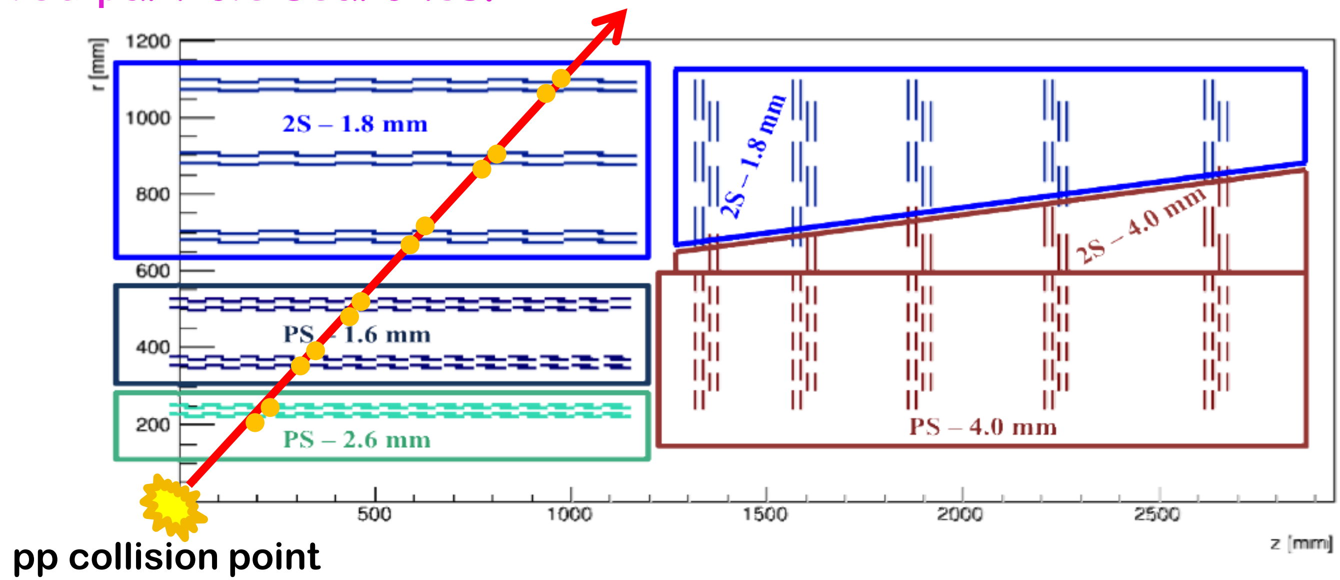
Long-Lived Particle Searches at HL-LHC (≥ 2025)

- HL-LHC gives 300/fb/year at $\sqrt{s} = 14$ TeV
- Useful if LL particle has low cross section (e.g. possible in hidden valley models) or long lifetime (so that only small chance it decays within detector volume).
- Many LL particle searches are background free, so cross section sensitivity may scale as 1/Lumi.

- But how will the proposed "phase 2" upgraded LHC detectors change this? Let's look at CMS …

Phase 2 CMS detector
& implications for long-lived particle searches

- The core of the CMS detector is the Tracker, which is also crucial to long-lived particle searches.



- It consists of closely spaced pairs of layers. The readout electronics looks for pairs of hits in these consistent with a high Pt track coming from the beam-line.
- This allows the tracks to be reconstructed very fast for use in the L1 trigger. This keeps trigger rates down, despite the high luminosity.

Phase 2 CMS detector
& implications for long-lived particle searches

- Unfortunately, the L1 trigger will only reconstructs tracks produced near the pp collision point. It will not find displaced fermions from LL particle decay.
  - Therefore, it will be difficult to keep low Pt trigger thresholds for this signal.

- The Phase 2 Tracker has "binary" readout of the hits produced by charged particles. Therefore, unlike the current tracker (which has "analogue" readout), it will not record the hit pulse height, needed to reconstruct a particle's dE/dx.
  - But dE/dx info is important to the HSCP search …

Phase 2 CMS detector
& implications for long-lived particle searches

But some things should improve …

- L1 triggering on muons using the muon chambers will be dramatically improved due to, e.g. addition GEM detectors in the forward region. This should keep Pt thresholds low.

- The ECAL electronics will be replaced, offering the chance to improve on its current 150 ps timing resolution, which should benefit searches like $\tilde{\chi}^0 \rightarrow \gamma \, \tilde{G}$.

Nonetheless, work is needed if CMS is to remain effective at long-lived particle searches in 2025 …


Conclusions

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.

- LL particles that traverse the detector before decaying are found by dedicated HSCP searches (if charged), or monojet searches if neutral.
- LL particles that decay within the detector can be found via disappearing track or displaced fermion signatures.
- LL particles decaying within 1mm of P.V. can be found by conventional searches.

- Lots of design work on Phase 2 detectors needed if we are still to do such searches in 2025+!

BACKUP SLIDES

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!

Short-Lived Particles

(i.e., $c\tau$ < 1mm)