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.

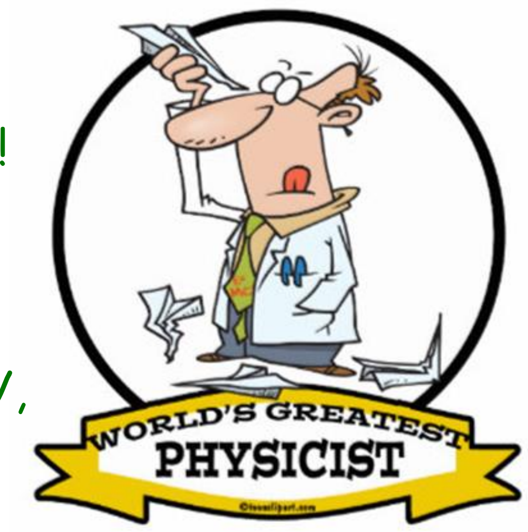
- What motivates these searches ?
- What strengths & weaknesses does the CMS detector have for such searches?
- I will *summarize* the main CMS results (details in later talks) and ask:
  - How well are we exploring the phase space ?
  - Where do we need improvements?
  - Do we have *model-independent* 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)

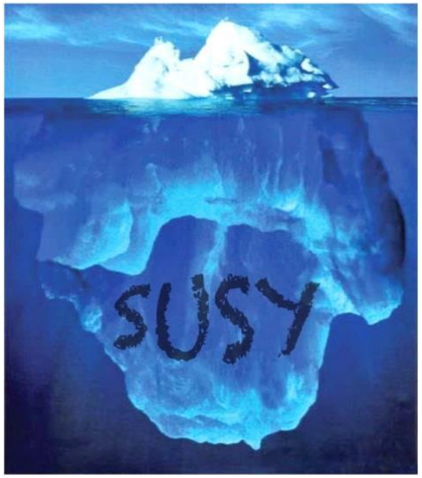


- **Lessons:**
  - LL exotica are well worth looking for.
  - Experimental searches should use simple signatures that are each sensitive to many LL models.
  - Present limits in model-independent way !

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^{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.

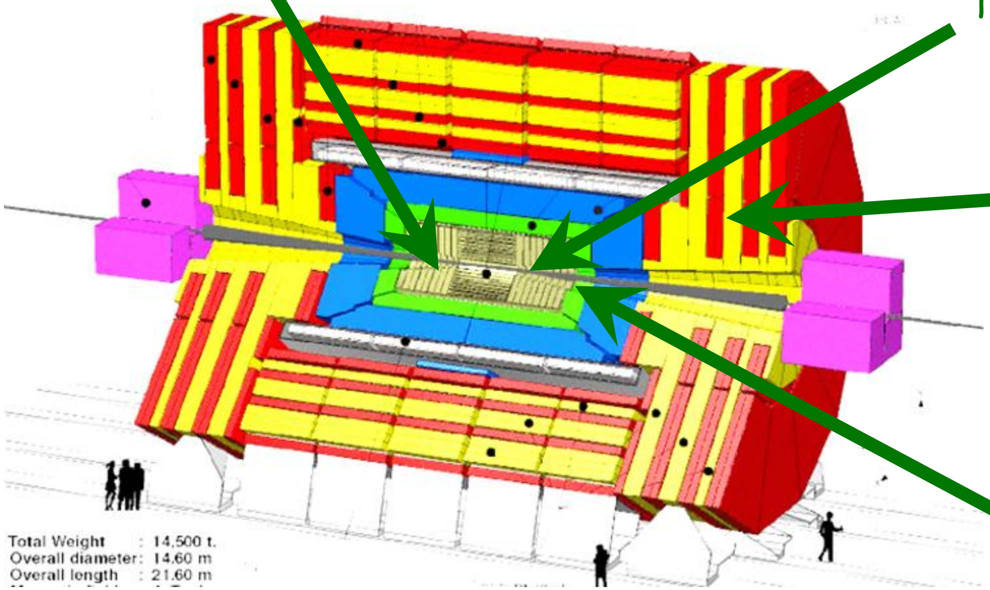


Searching for Long-Lived Particles with the CMS detector

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.



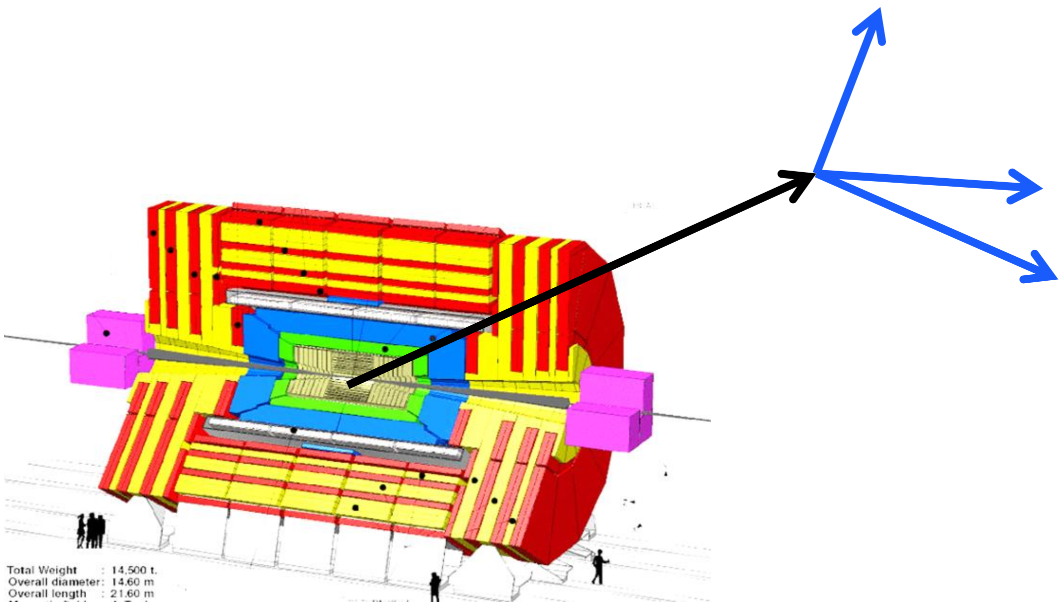
ECAL can find photons from LL particle decay via time-of-flight (TOF) measurement.

ATLAS better at some things:

- Their ECAL is great at finding photons from LL particle decay, as it measures photon *direction*.
- Their muon chambers are surrounded by *air*, not *iron*, so they can track hadrons from LL particle decay inside them, in addition to muons.

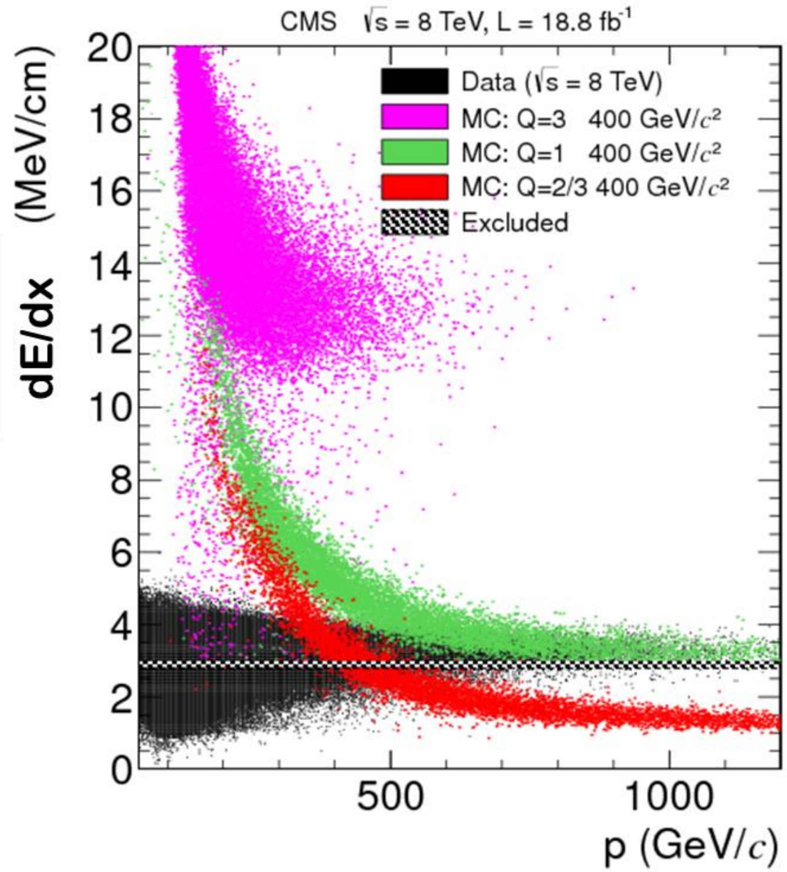
Very Long-Lived Charged Particles

(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 μ 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.

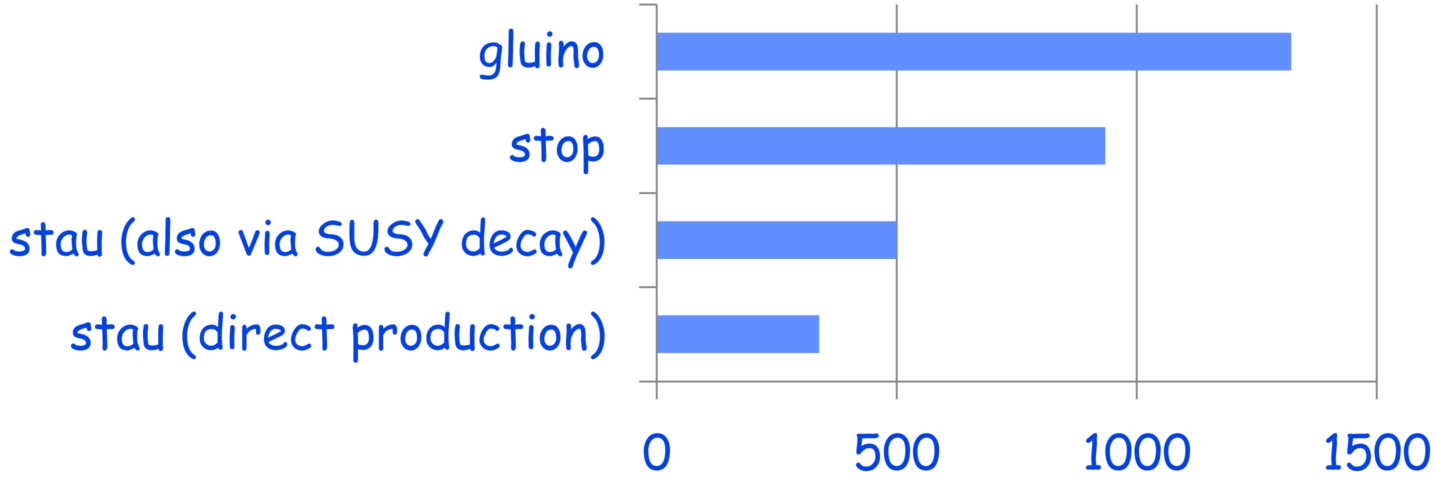
- R-hadrons flip charge as they pass through the CMS detector material.
  A charged R-hadron may be neutral when it reaches the outer detector!

- 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: $\tilde{g}$)

Search for heavy stable charged particles
Results

- 95% CL lower mass limits placed:

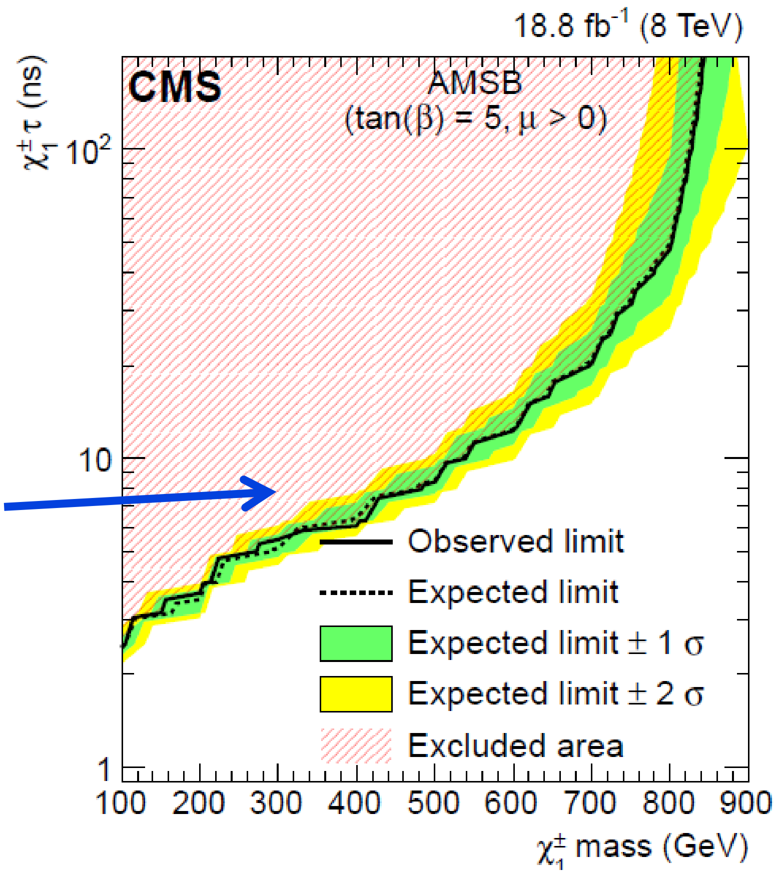


- Limits on $\tilde{g}$ & $\tilde{t}$ vary by ~100 GeV, depending on R-hadron assumptions.
- CMS also has limits on LL leptons of charge e/3 to 8e.

Search for HSCP (arXiv:1502.02522)
Towards model independent results …

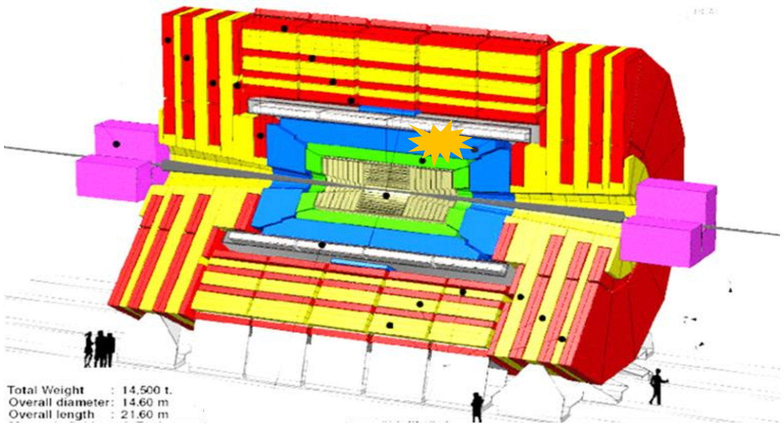
- Publish number of data candidates passing cuts & the expected background.
- Publish selection efficiency vs. Pt, β & η of HSCP.
- If HSCP lifetime is small, multiply this by prob that it transverses CMS before decaying: $\exp[-M\, L(\eta) / c\, \tau\, P]$.

- 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 ~2 ns.



Search for stopped R-hadrons (HSCP) (arXiv:1501.05603)

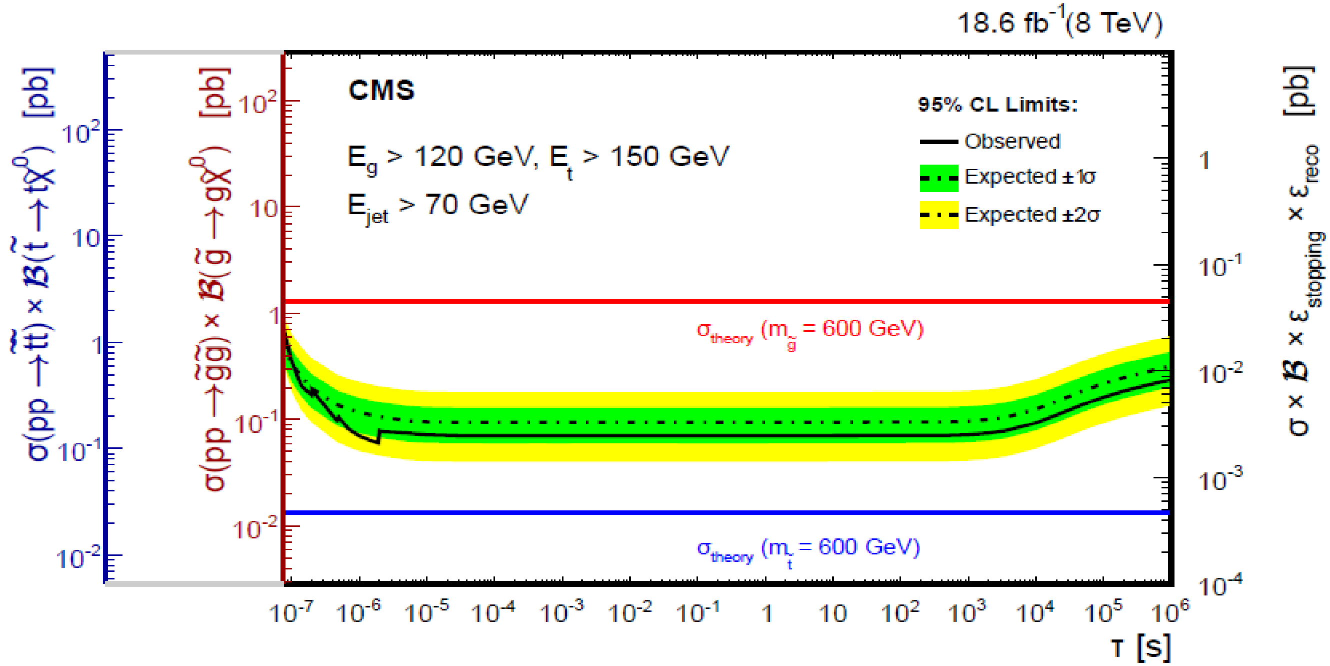
- Slowly moving (< 0.45c) R-hadrons would lose all their energy through dE/dx & come to a halt in the calorimeter.
- They could decay (e.g., $\tilde{g} \to g\tilde{\chi}^0$) seconds or months later.
- The decay would be seen as energy deposit in calorimeter (require Et > 70 GeV) when no LHC proton bunches 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 μ-chambers see evidence for muon.

Search for stopped R-hadrons
Results

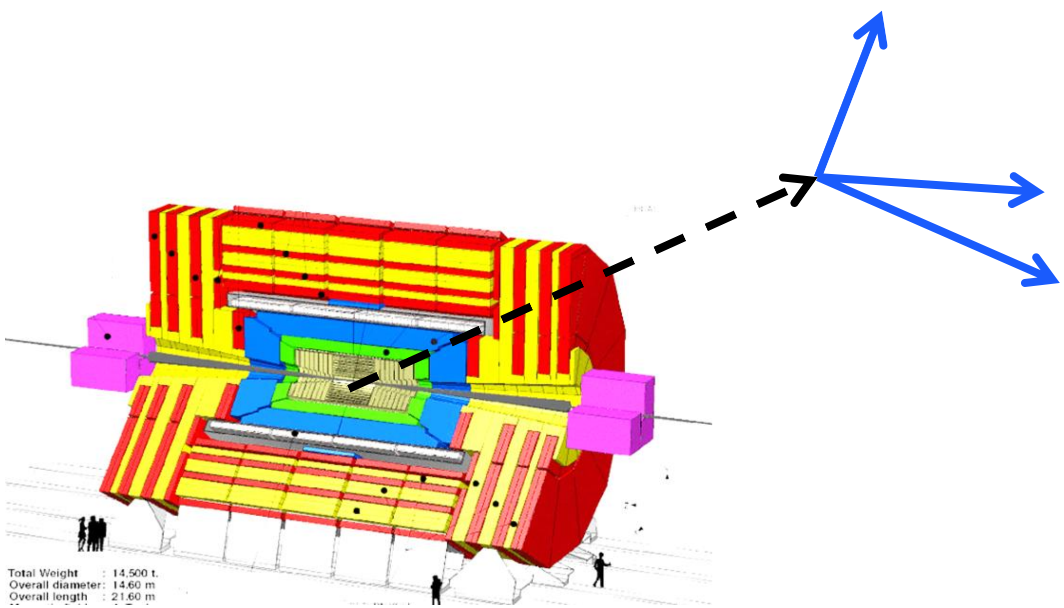
- 10 events found, compatible with expectation, so limits placed on stopped R-hadrons for huge range of lifetimes (1μs – 1 year).
- N.B. Right-hand axis of limit plot is model-independent.



- 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 ~1300 GeV).

Very Long-Lived Neutral Particles?

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

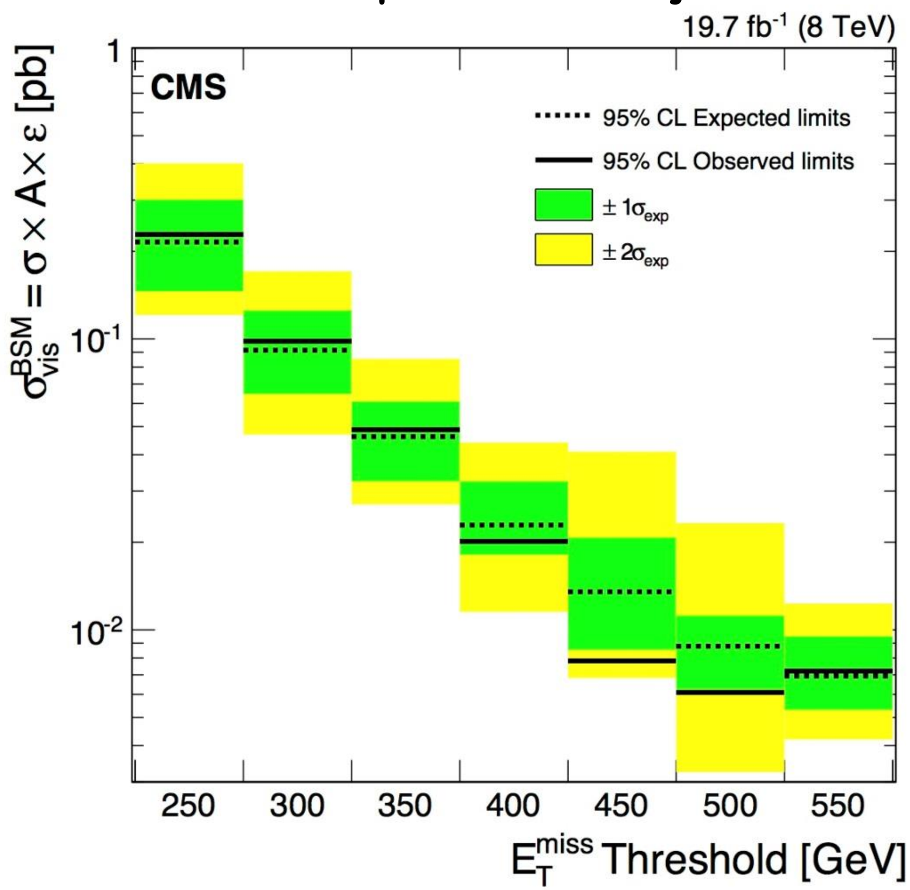


Only detectable via E_t^{miss} signatures.

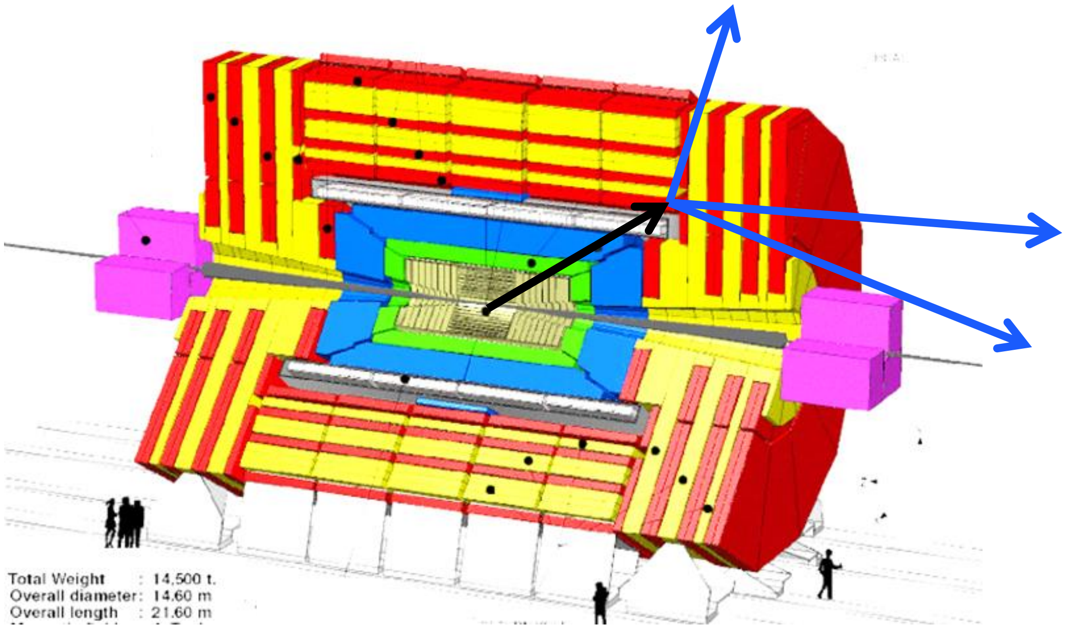
Detecting long-lived, neutral particles via E_t^{miss} searches.
An example …

- Monojet searches provide 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



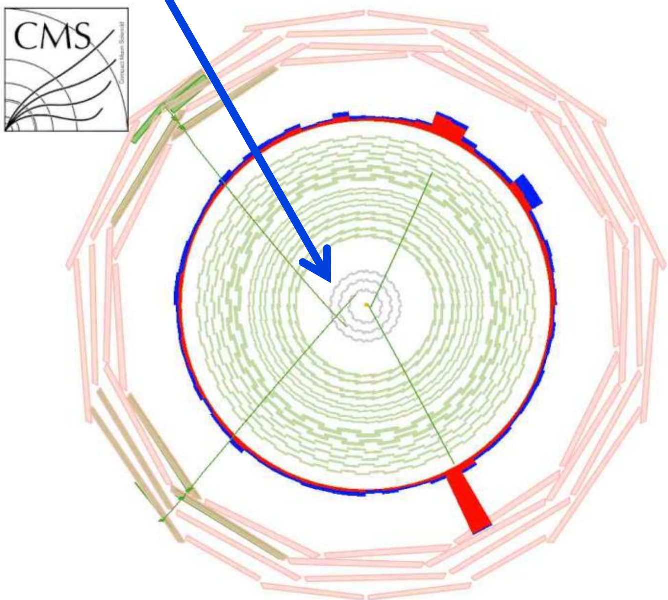
Long-Lived Particles that decay within the detector volume



Look for leptons, jets or photons that do not originate at the pp collision point.

Search for long-lived particles decaying to displaced leptons (two papers: arXiv:1411.6977 + arXiv:1409.4789)

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



  - Considered 2 signal models:

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

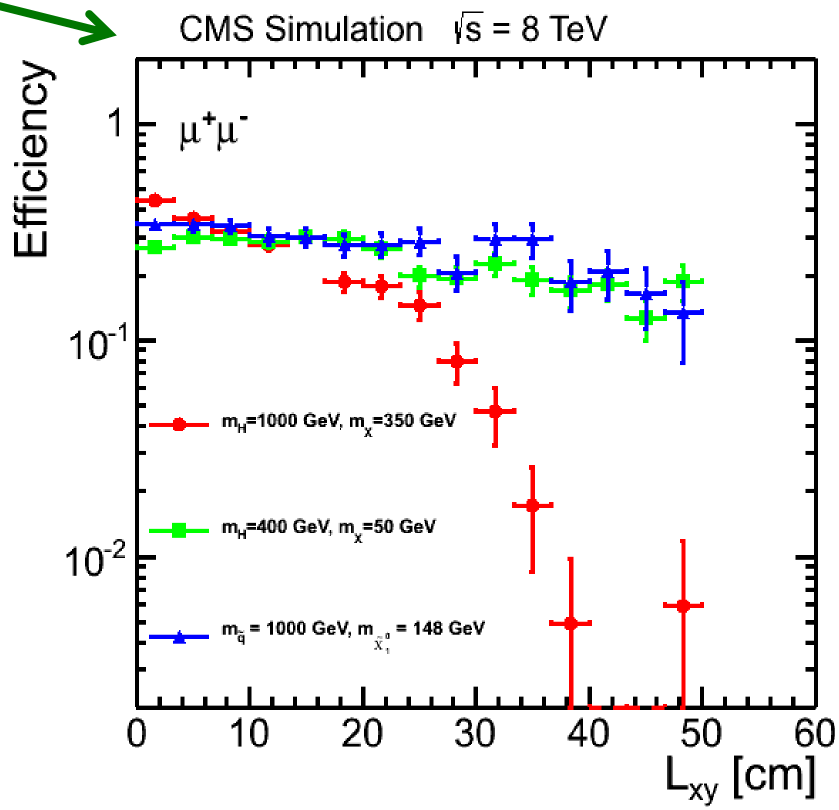
- **2nd paper** looks for events with one displaced electron + one displaced muon, (which are ***not*** required to form a vertex - ***good idea*** since it broadens range of models we are sensitive to).

  - Considered 1 signal model:

    3) 2*(long-lived $\tilde{t}$)→ (b e)(b μ)

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.



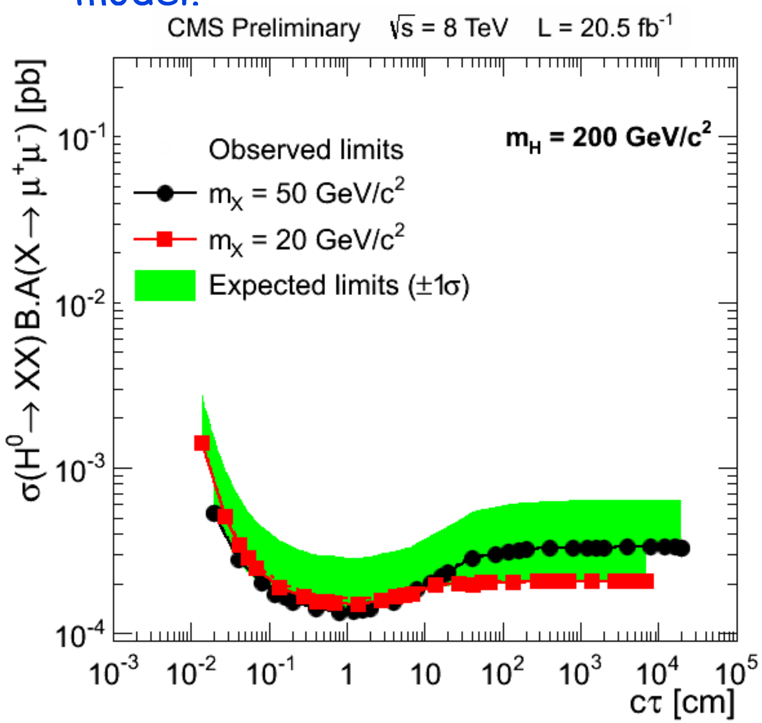
- (2nd paper didn't fully exploit this, as eμ trigger was inefficient for very displaced muons.
  -- Will fix in future).

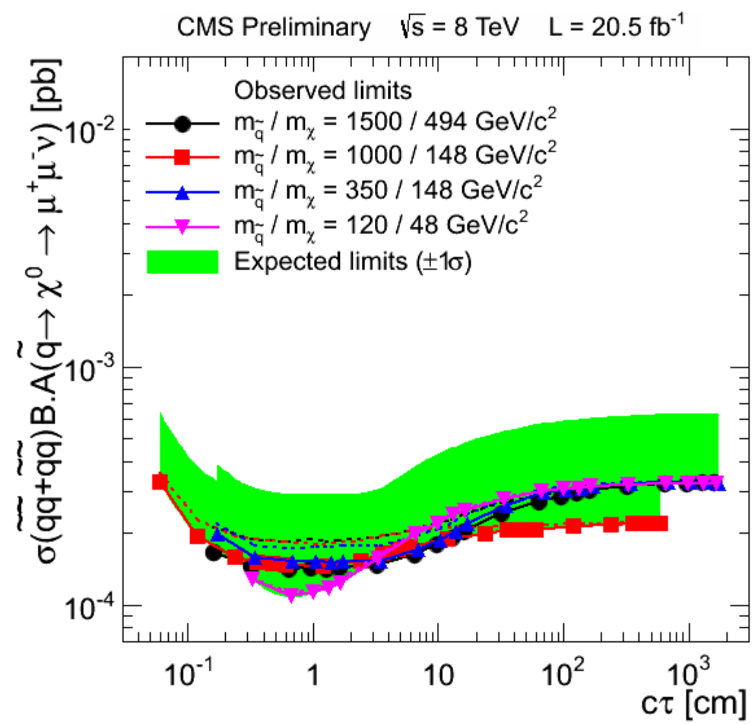
RESULT:

- 1st paper sees no candidates.
- 2nd paper sees only a few.

Search for long-lived particles decaying to displaced leptons
Model independent limits from 1st paper

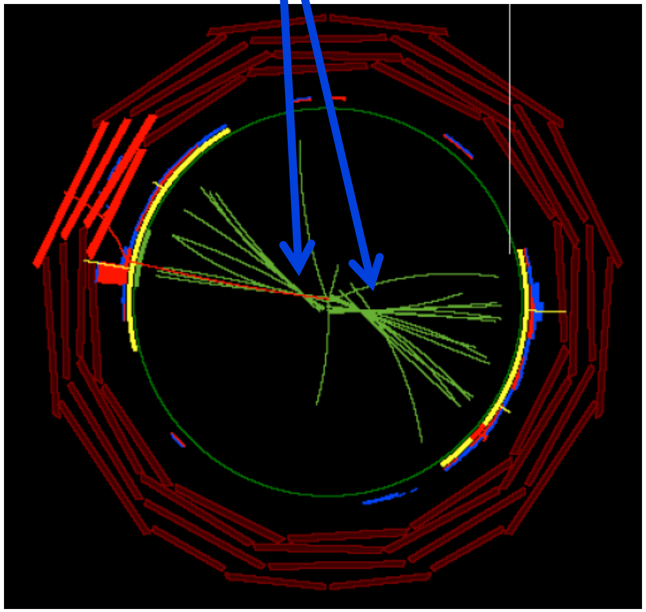
- Define acceptance region where efficiency "high":
  i.e. Lepton Pt > 26-40 GeV & $|\eta| < 2$ & $L_{xy} < 50$ cm.
- Limits on "σ*BR*acceptance" are ~ independent of model (& even lifetime) !
  - Valid for any model where LL particle decays to (l^+,l^-,anything)!
  - Can be translated to limits on σ*BR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





Search for long-lived particles decaying to displaced jets (arXiv:1411.6530)

- Search for events in which a LL particle decays to ($q, \bar{q}$, anything) by looking for 2 jets whose associated tracks form a single *displaced vertex* in Tracker.



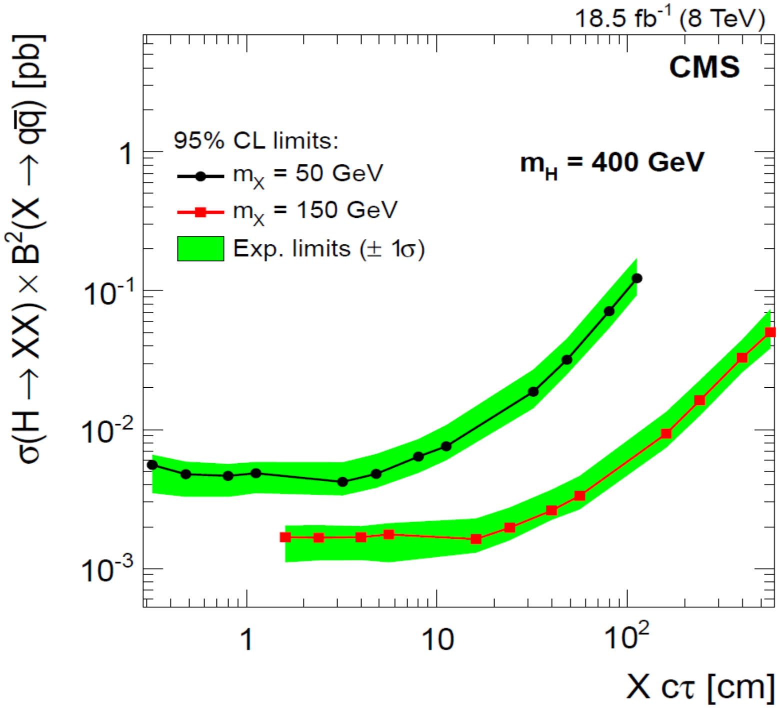
  - Considered 2 signal models:

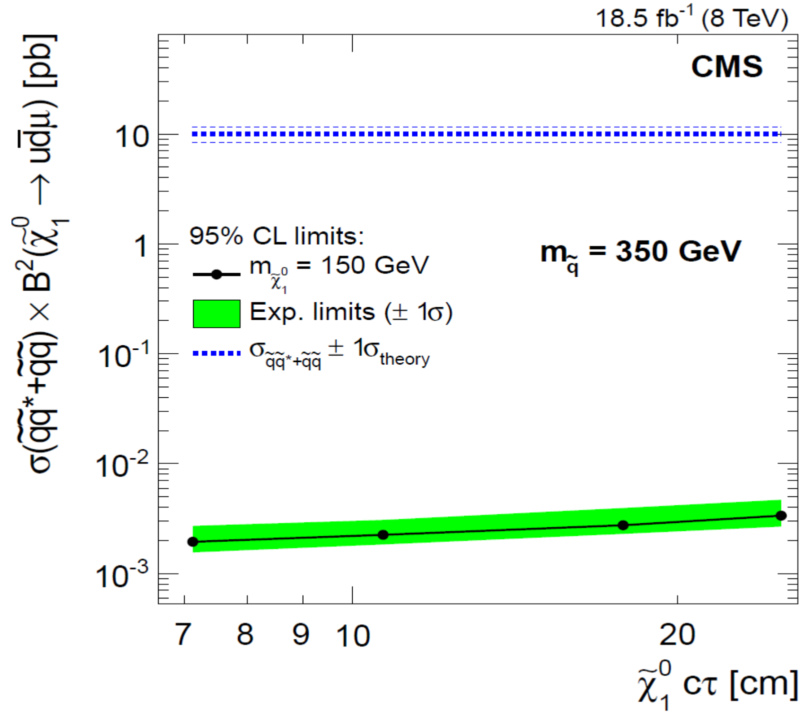
    1) Higgs → 2X → $(q\bar{q})(q\bar{q})$, where X is LL particle
    2) Long-lived $\tilde{\chi}^0$ → $q\bar{q}\nu$ produced in $\tilde{q}$ decay.

- Main difficulty is **triggering** on these events.
  - Required 2 jets of Et > 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.

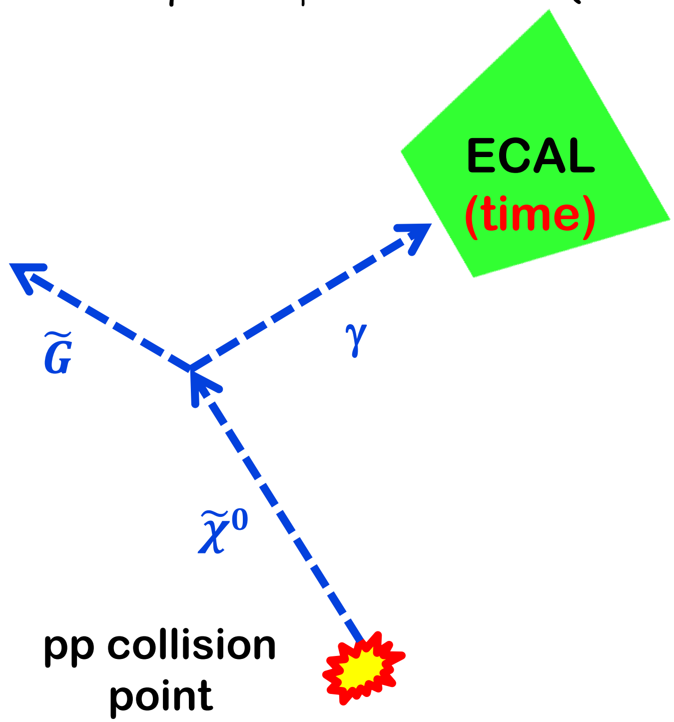


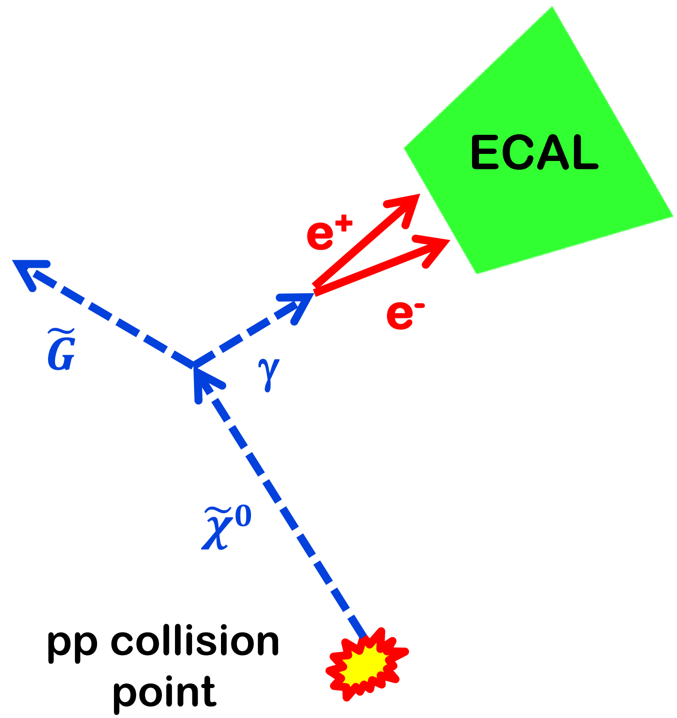


- Found no (simple) model-independent way of presenting limits. (Difficulty is HT > 300 GeV requirement, which makes limits dependent on what *both* LL particles in event do).
- Nonetheless, results can be translated to powerful limits on other models (e.g. Brock Tweedie - arXiv:1503.05923)

Search for long-lived particles decaying to displaced photons
(2 papers: https://cds.cern.ch/record/2063495/ + https://cds.cern.ch/record/2019862/)

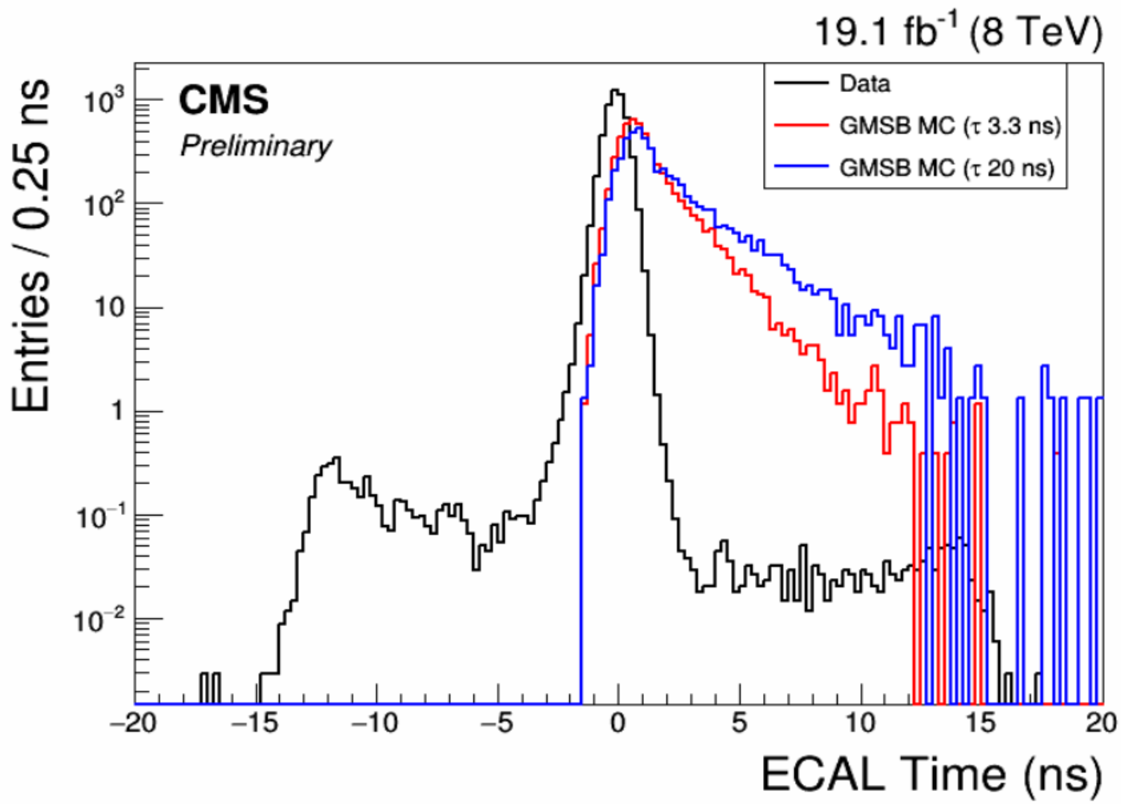
- In GMSB SUSY: long-lived $\tilde{\chi}^0 \rightarrow \gamma\,\tilde{G}$.
- **1st paper** uses ECAL timing resolution (~0.37 ns) to detect late arrival of γ at ECAL (due to indirect path & due to non-relativistic $\tilde{\chi}^0$)
- **2nd paper** profits from large amount of material in tracker (!)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





Search for long-lived particles decaying to displaced photons
ECAL timing measurement in 1st paper

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



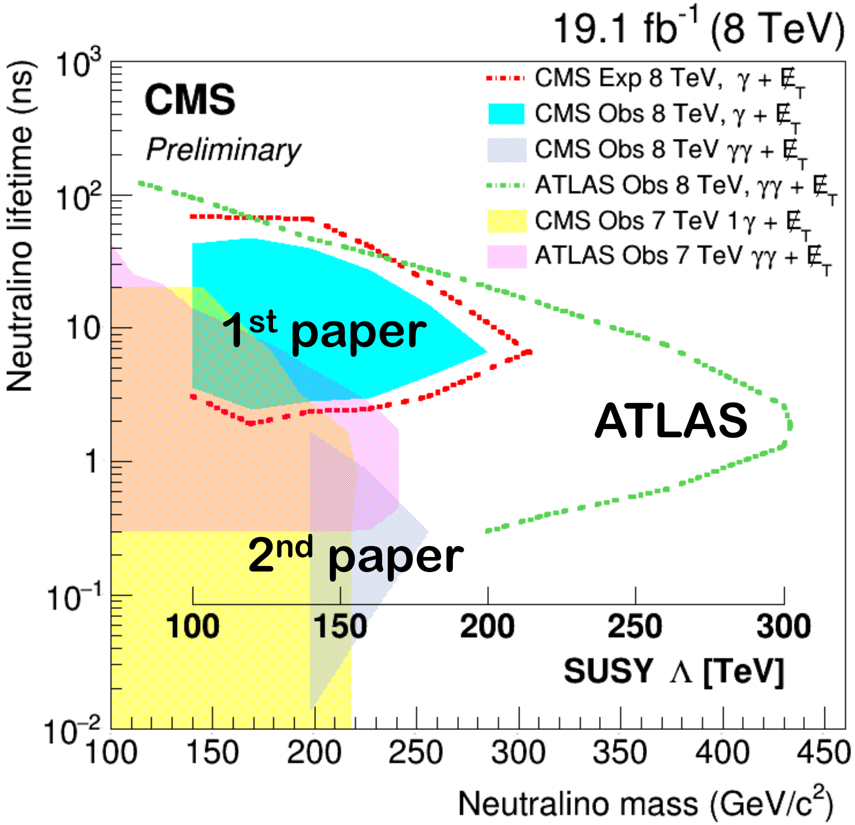
- Non-gaussian tails in data due to bremsstrahlung photons from LHC beam-halo or cosmic muons + ECAL detector effects.

Search for long-lived particles decaying to displaced photons
Results

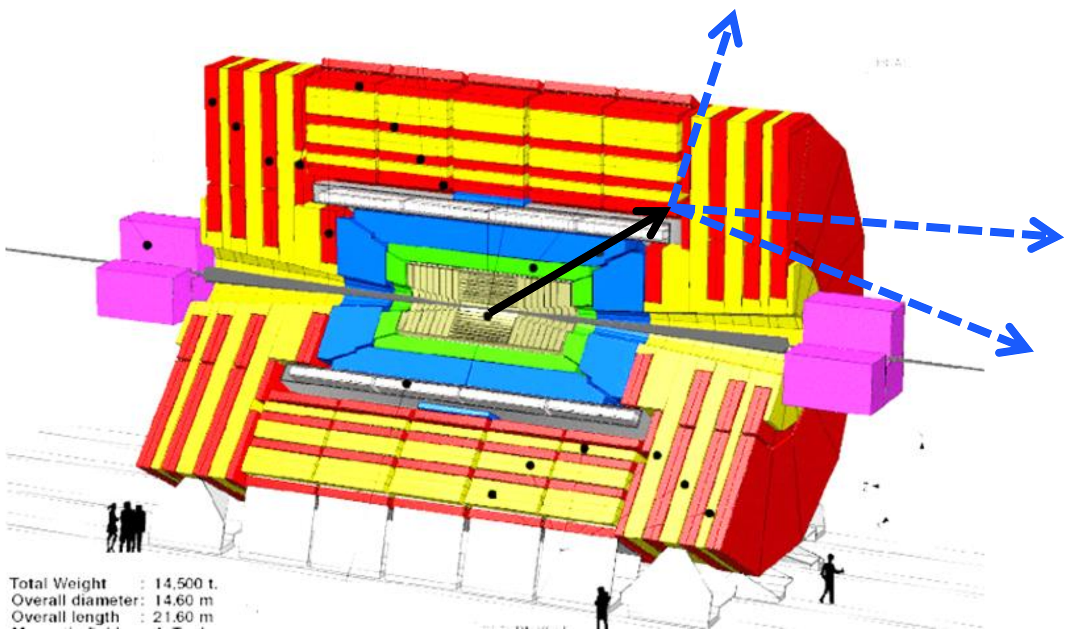
- 1^{st} paper gets limits for $\tau > 3$ ns, as lower lifetimes do not give sufficiently delayed γ for ECAL timing measurement to be significant.
- 2^{nd} paper extends limits to lower τ due to precise measurement of γ trajectory obtained from conversions.

- ATLAS limits stronger due its ECAL's ability to reconstruct γ direction.

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



Long-Lived Particles that decay within the detector volume *to invisible particles* (!)



Possible if the long-lived particle is *charged* …

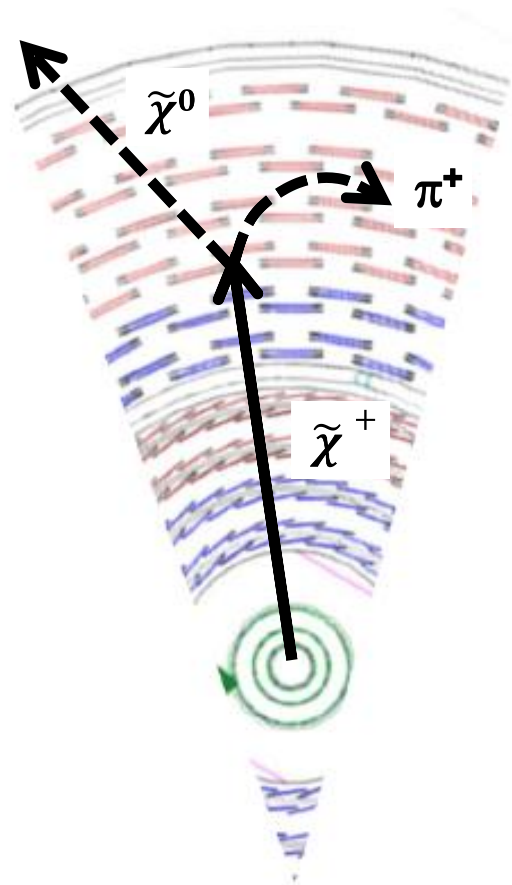
Disappearing (HSCP) track search (arXiv:1411.6066)

- In AMSB, $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+$, 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 π^+ is very soft & usually undetectable.

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

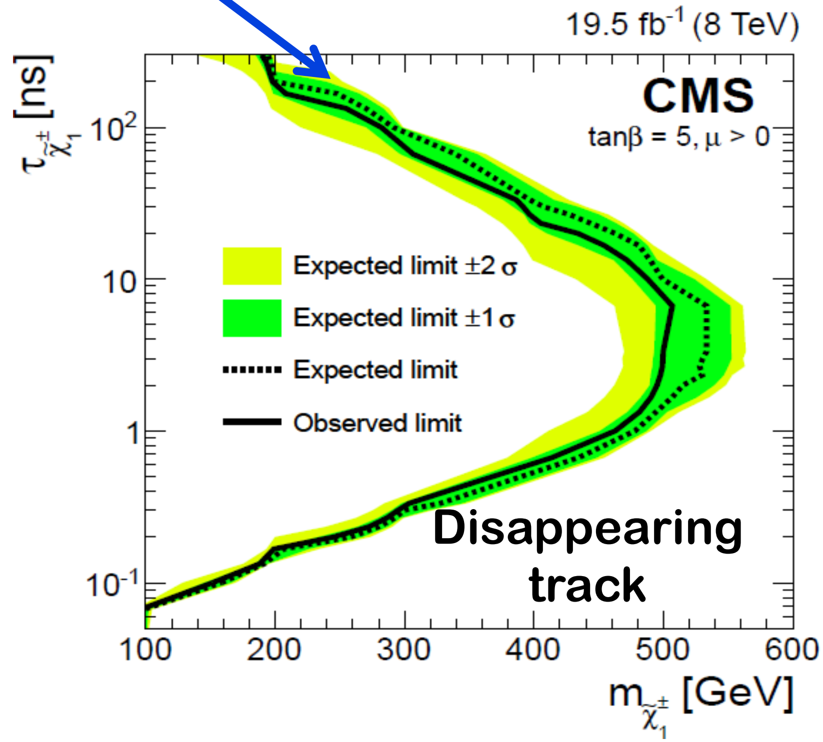
- Offline: $\tilde{\chi}^+$ seen as track with no hits in outer layers of the Tracker. But there are *loads* of such tracks, due to nuclear interactions!

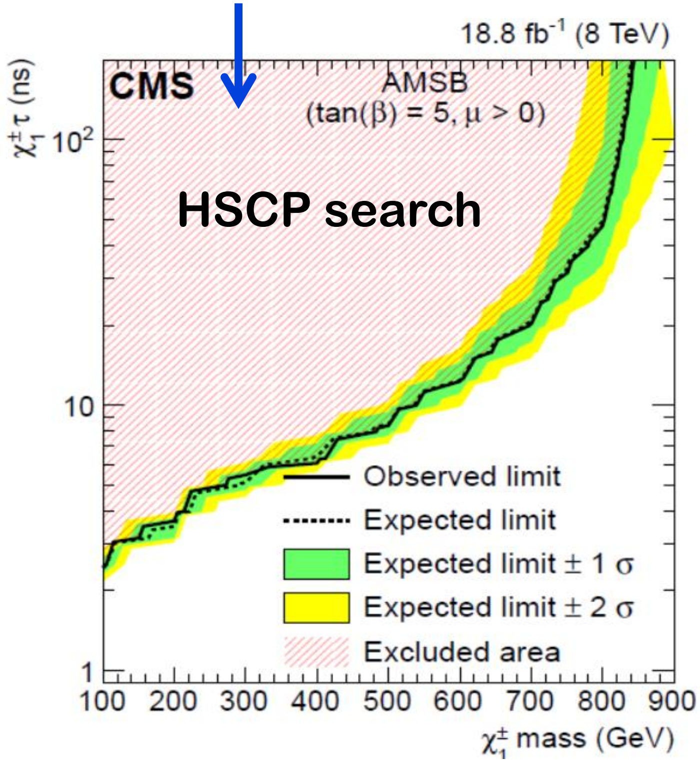
- Rescued by additional cuts, requiring track to:
  - Have Pt > 50 GeV.
  - Be isolated.
  - Deposit < 10 GeV in calorimeter.
  - Not be identified e, μ or τ.



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 $\tau \rightarrow$ hadron, e or μ from W $\rightarrow$ l ν events.
- Good limits (although not yet presented in model-independent way …)
- *These* limits extend to lower lifetime *those* from HSCP search (slide 9).






Conclusions

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