Searches for long-lived particles and dark matter(ATLAS+CMS)

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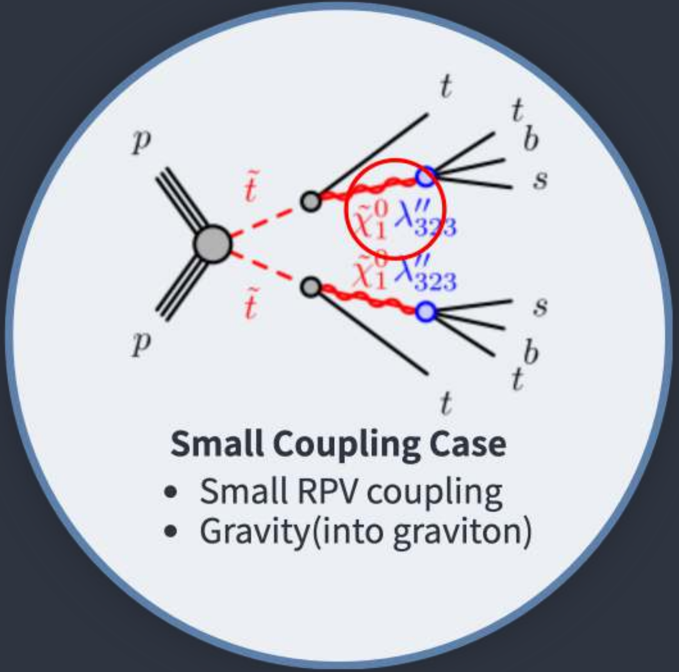
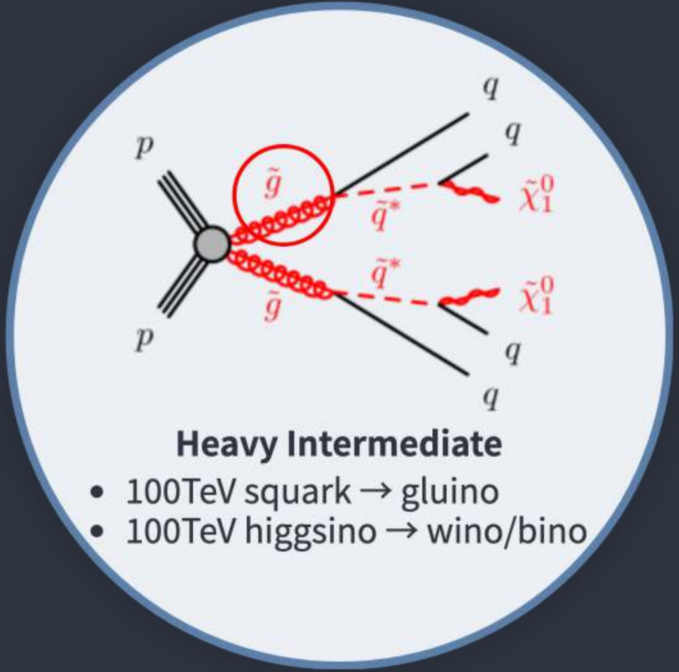
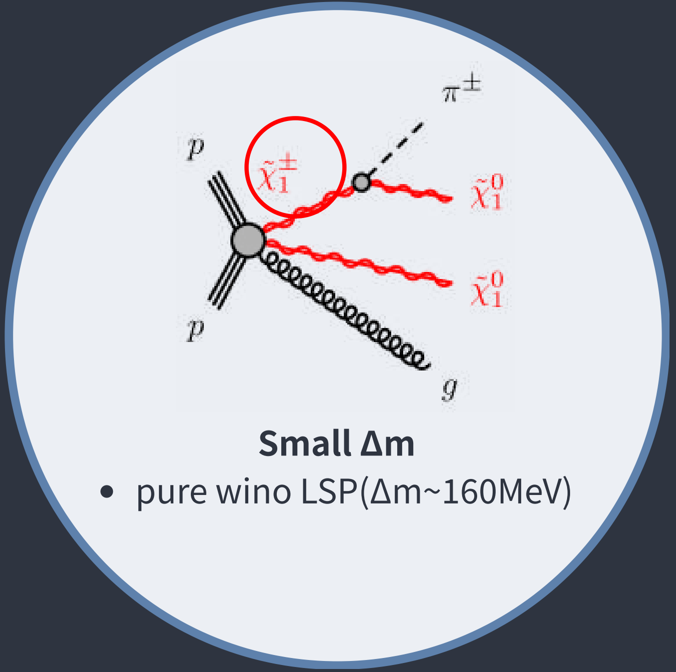
Long-Lived Particles at ATLAS and CMS







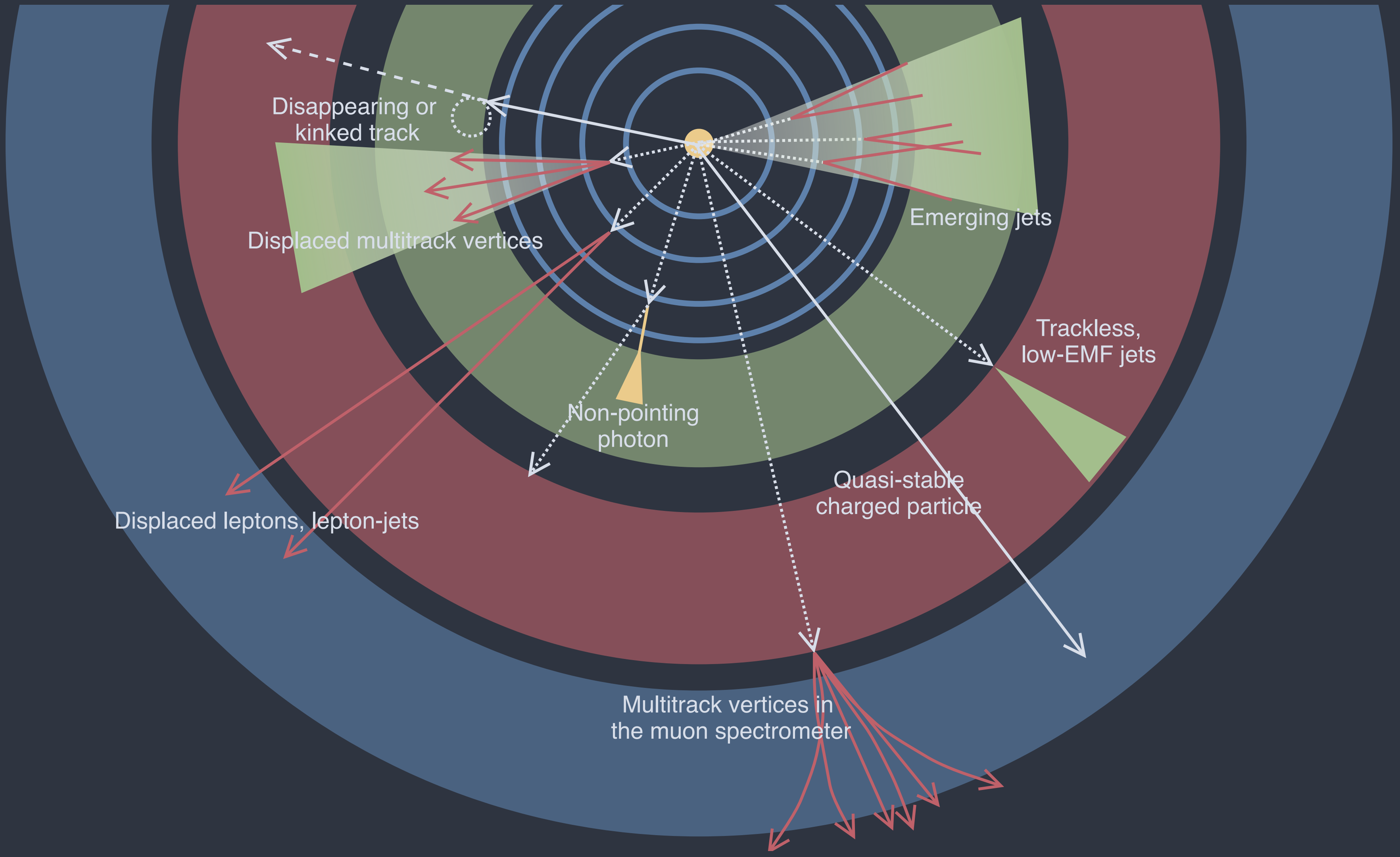
Why Long-Lived Particle(LLP)?

- Dark Matter(DM) should be stable and cold $\longrightarrow$ New particle could be a long-lived!
- Most new physics analysis target prompt decays from signal particles.
- A lot of uncovered phase space due to technical difficulities.

Typical LLP

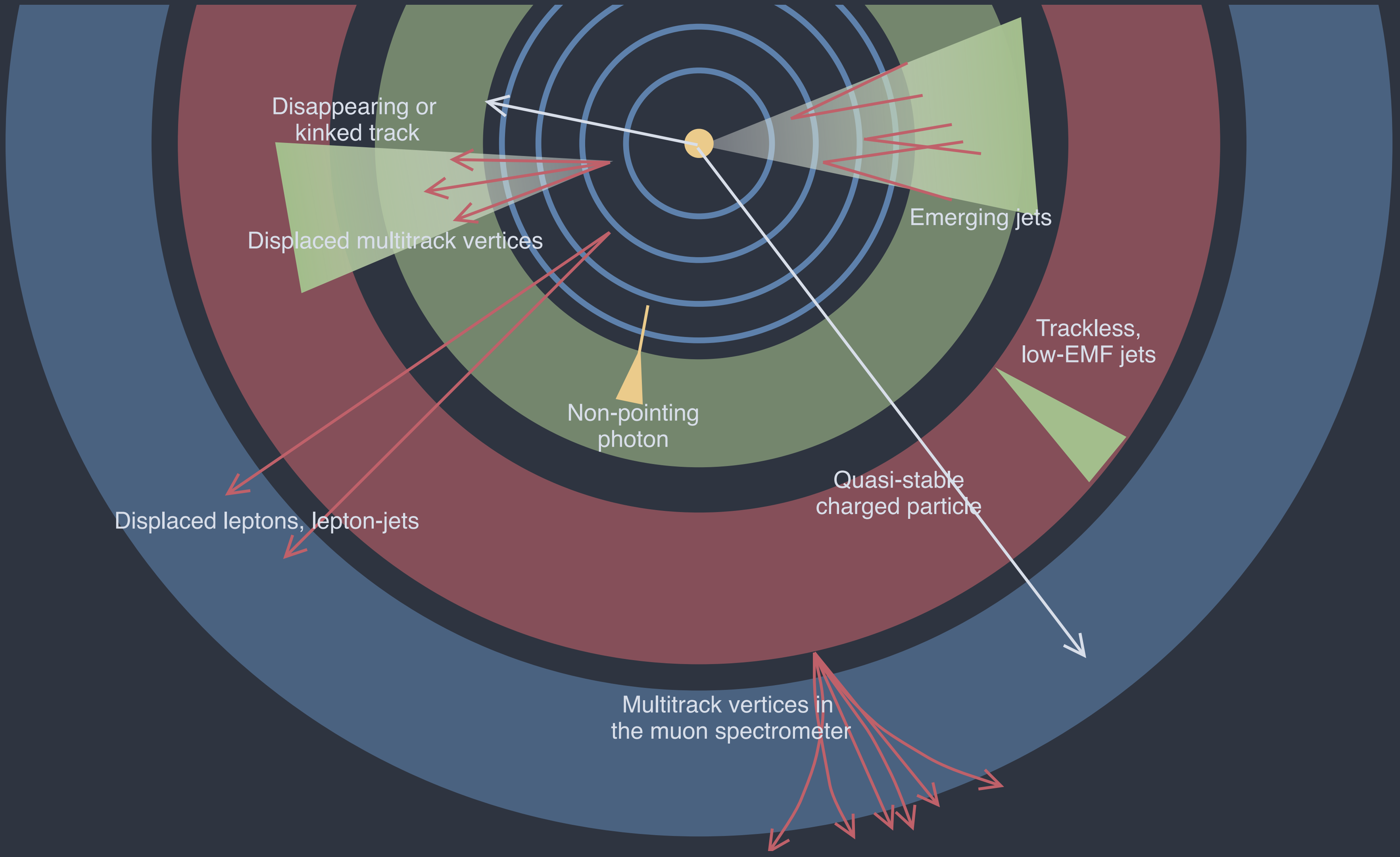
- Small coupling case: Small RPV coupling, gravity
- Heavy intermediate: ~100TeV squark/higgsino
- Small Δm: pure wino LSP

LLP's View in the Detector



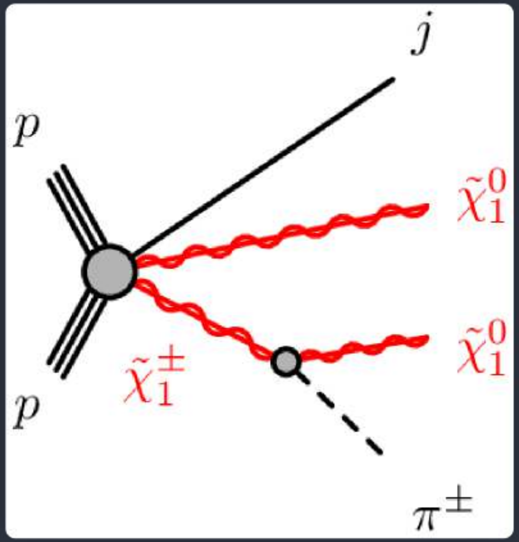
- LLP's view in detector depends on how it produce/decay
- There are many unique signatures.

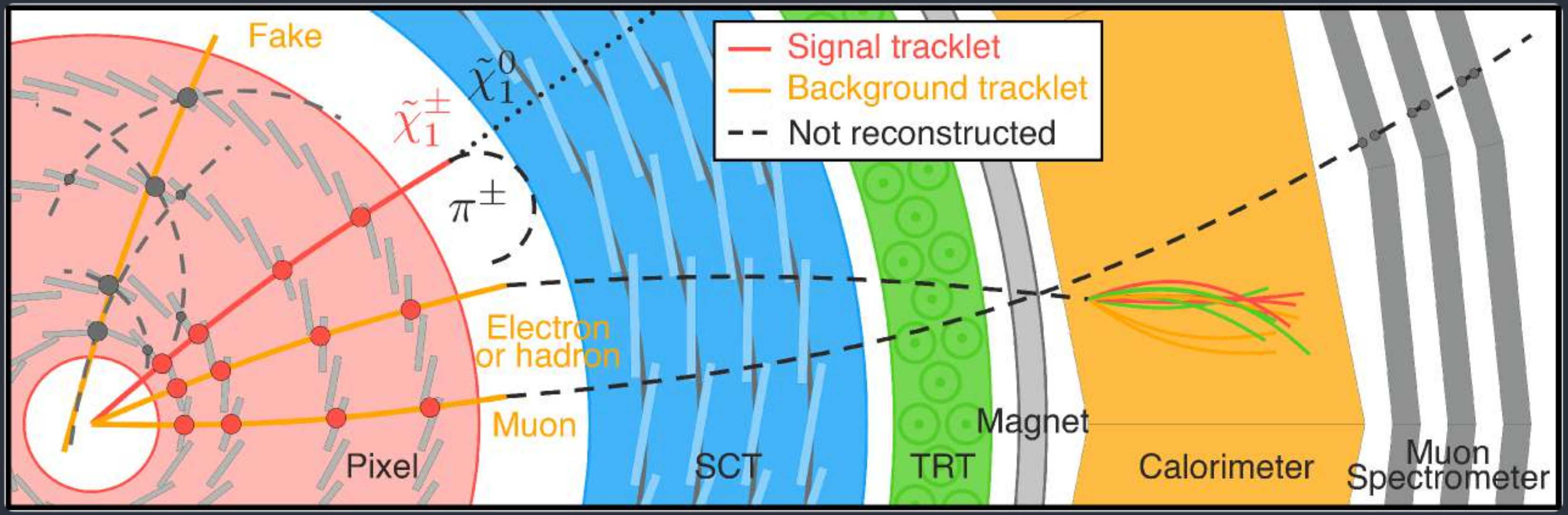
LLP's View in the Detector



- LLP's view in detector depends on how it produce/decay
- There are many unique signatures.

Disappearing Track @ATLAS

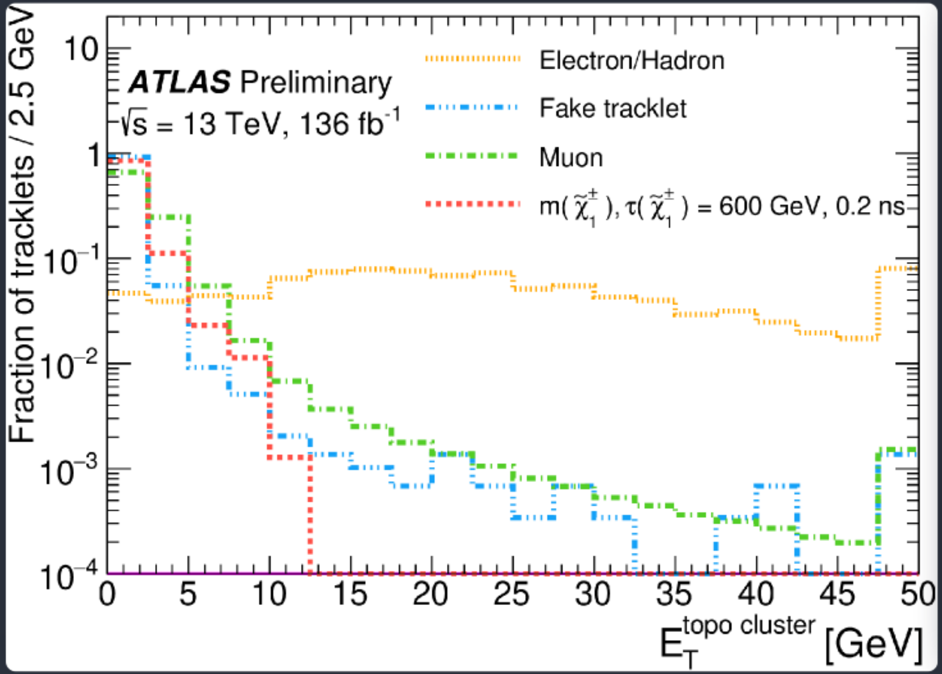


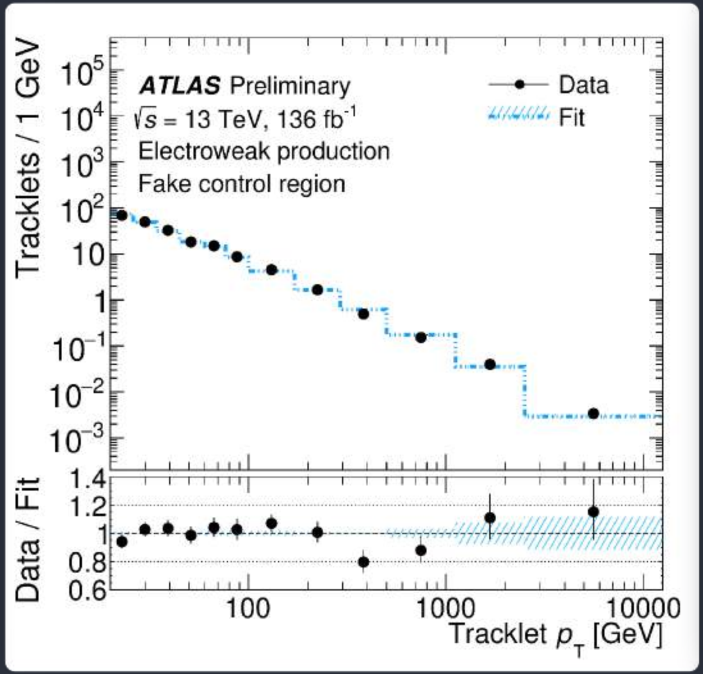


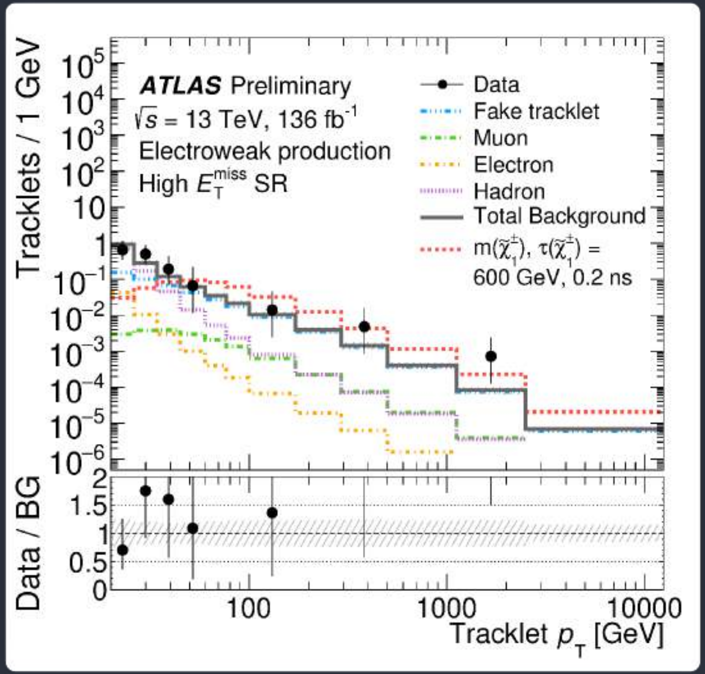
ATLAS Disappearing Track (ATLAS-CONF-2021-015) with full Run2 data

- If LSP is purely wino, wino is a candidate of DM, and $\Delta m(\tilde{\chi}_0, \tilde{\chi}_1) \sim 160$MeV $\rightarrow$ chargino would be a LLP!
- ATLAS searches a signature of a short track, which is called as ***tracklet***, with large missing transverse energy($E_{\mathrm{T}}^{\mathrm{miss}}$).
  - Tracklet: decay inside of inner detector(between Pixel and SCT), requiring four Pixel hits.
- Background: Estimate from completey data-driven way using control regions that dominate each background components.
  - *Electron/hadron* : electron/hadron that kinked before SCT, tend to have more calorimeter activities $\rightarrow$ ***calorimeter veto*** is newly developed!
  - *Muon* : Muon track without SCT and MS track, or cannot associate into MS track.
  - *Fake* : Randomly connected hits from different tracks, which are low enough to not reconstruct as a standard track.

Disappearing Track @ATLAS

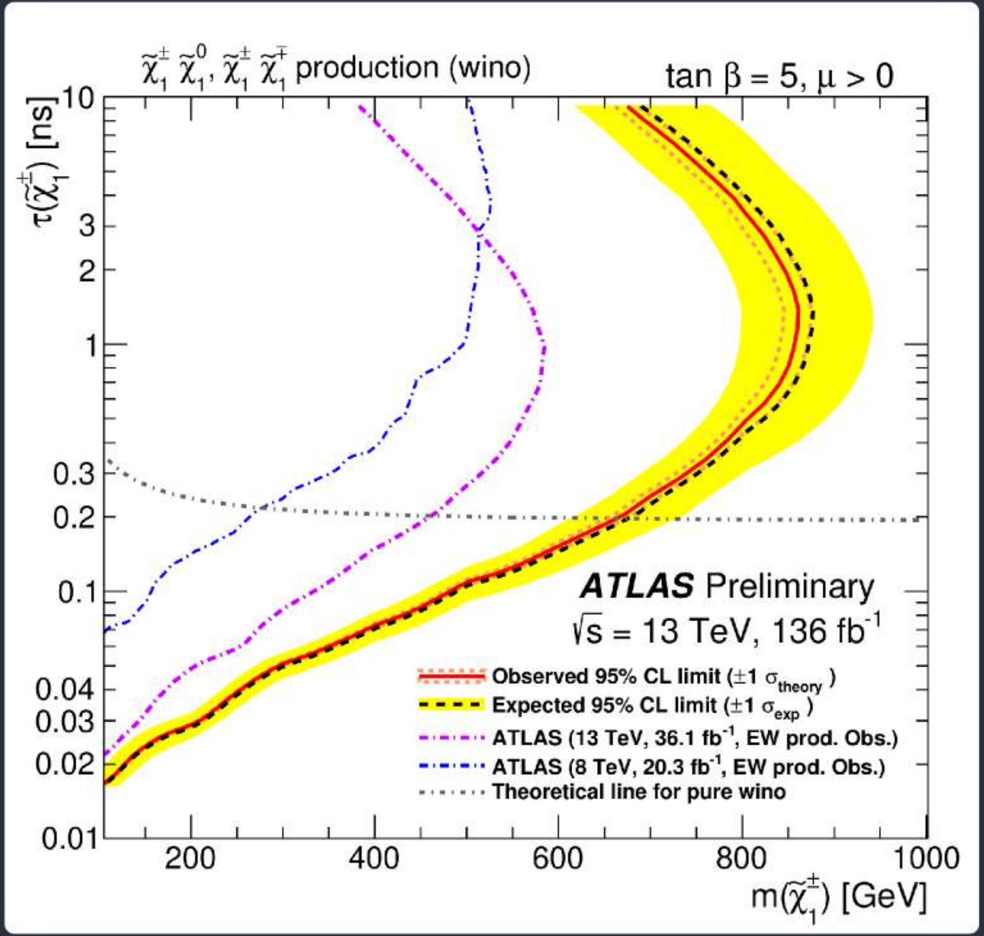


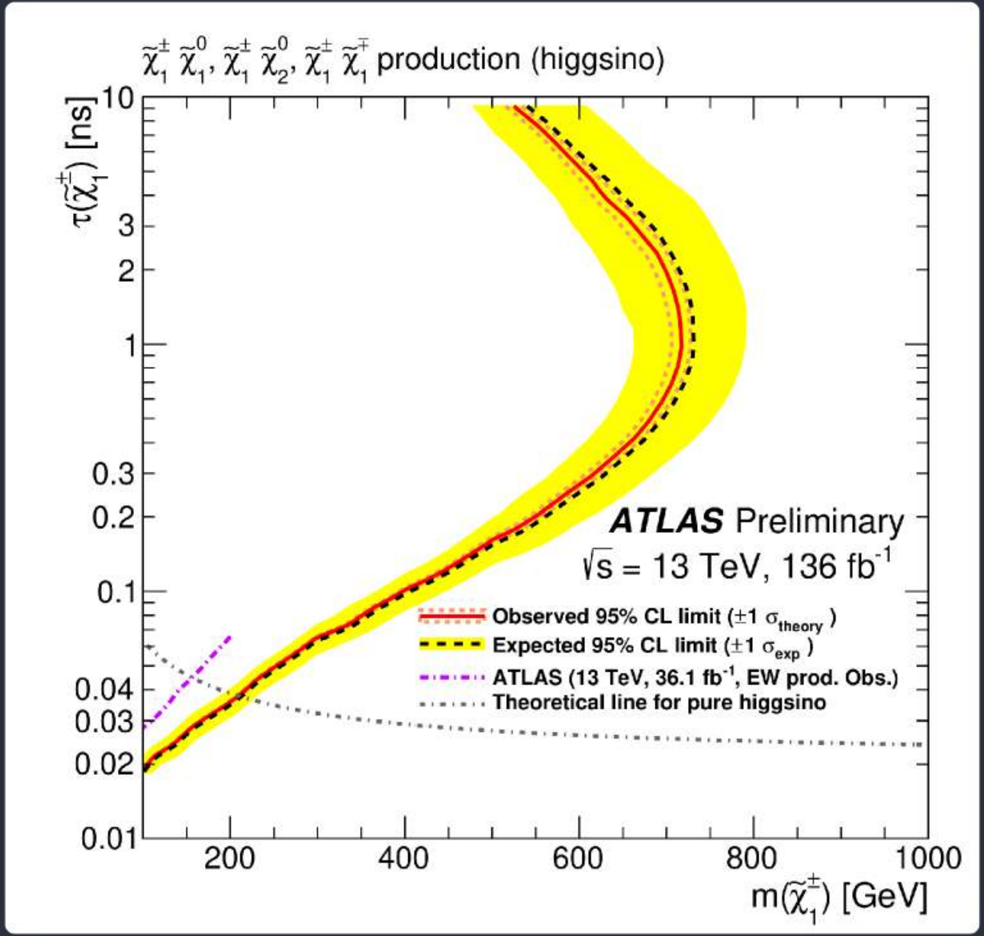




- **Calorimeter activity** : Electron/Hadron tends to have significant activity, the signal has less. Veto events with $E_T^{\text{topo cluster}} > 5$ GeV
- **Fake events estimation** : Unbinned fit to fake data at the fake CR simultaneously with signal region fit.
- Data/Background comparison:
  - There is no significant excess compared with observed data
  - At high p_T tail, the fake background is the dominant process.

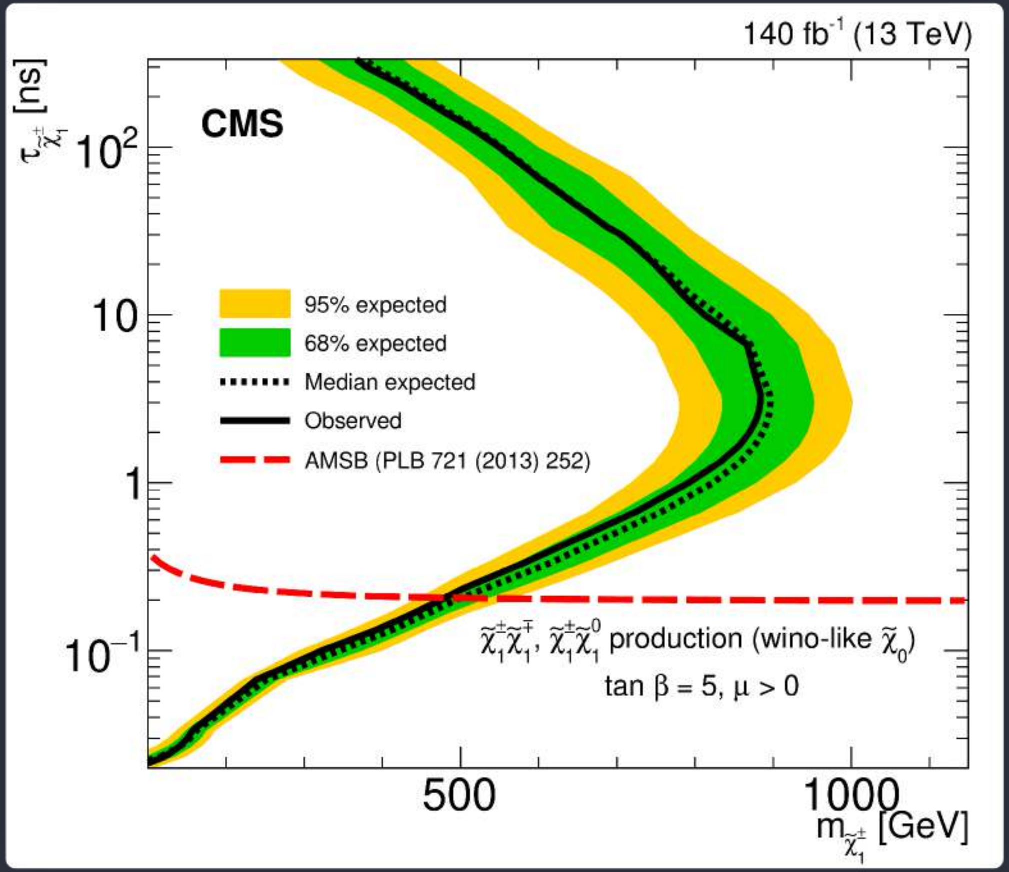
Disappearing Track @ATLAS

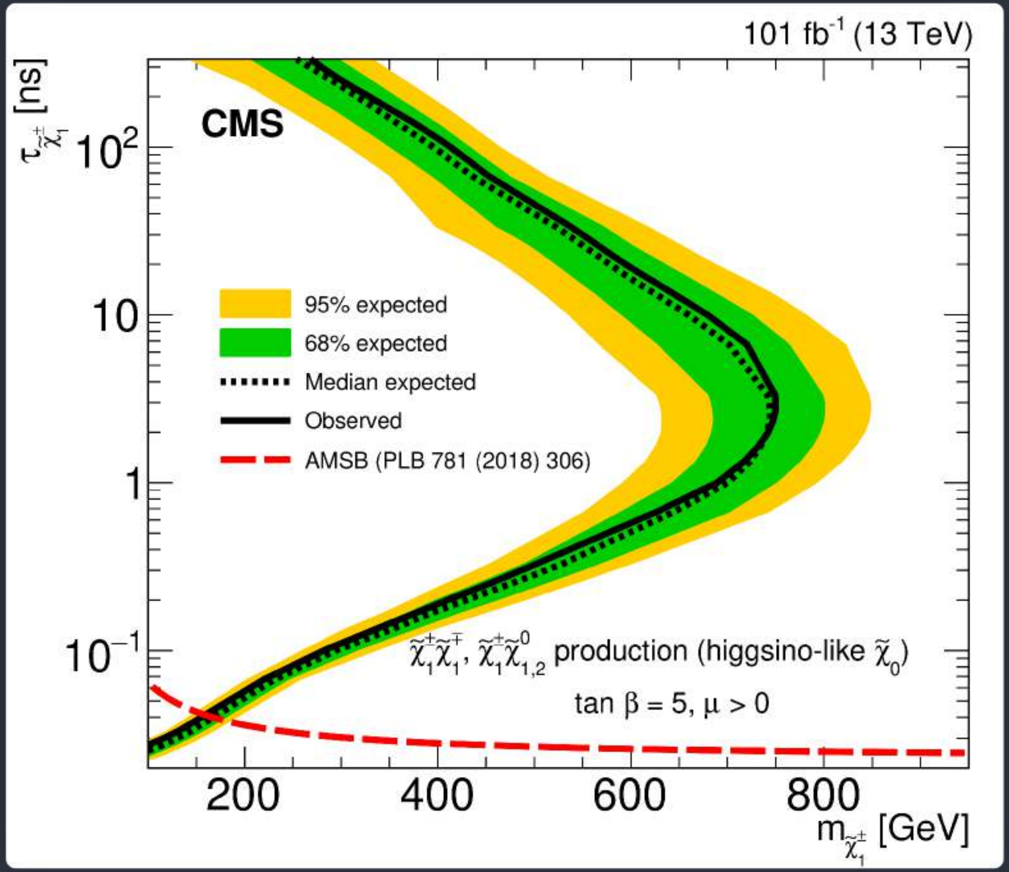




- Limits on pure wino production(left) and pure higgsino production(right)
  - Significant imporvement from early Run2 result ($36.1\mathrm{fb}^{-1}$), Int. luminosity and calorimeter veto play important role.
  - Pure wino : exclude $m_{\tilde{\chi}_1^{\pm}} < 660$ GeV @Theory line
  - Pure higgsino : exclude < $m_{\tilde{\chi}_1^{\pm}} < 21$ GeV @Theory line

Disappearing Track @CMS

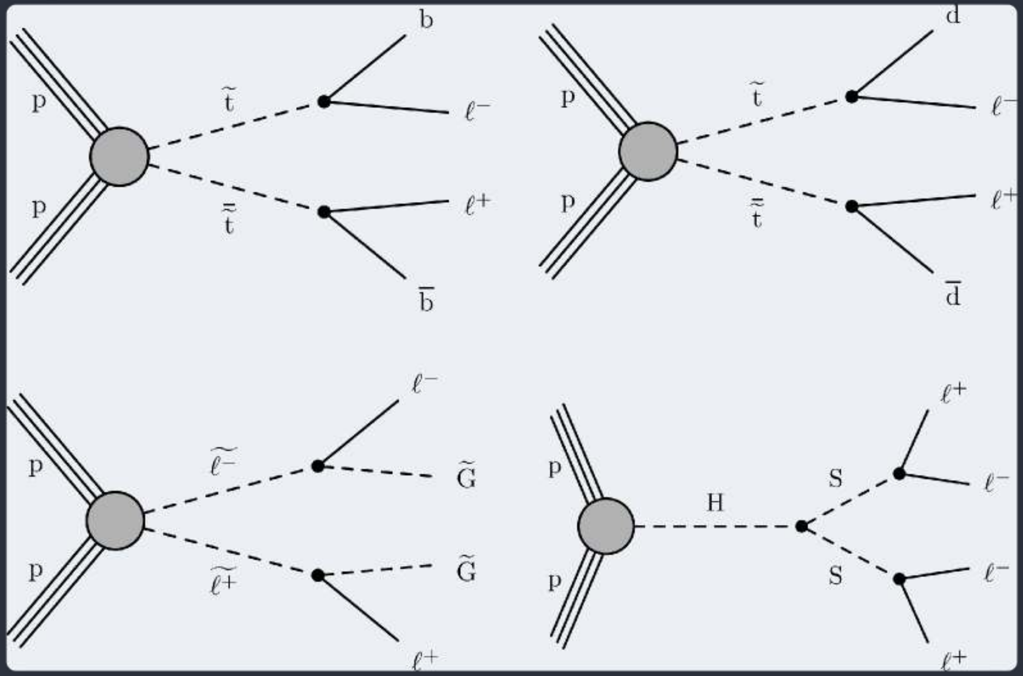




CMS Disappearing Track: EXO-19-010 with full Run2 data

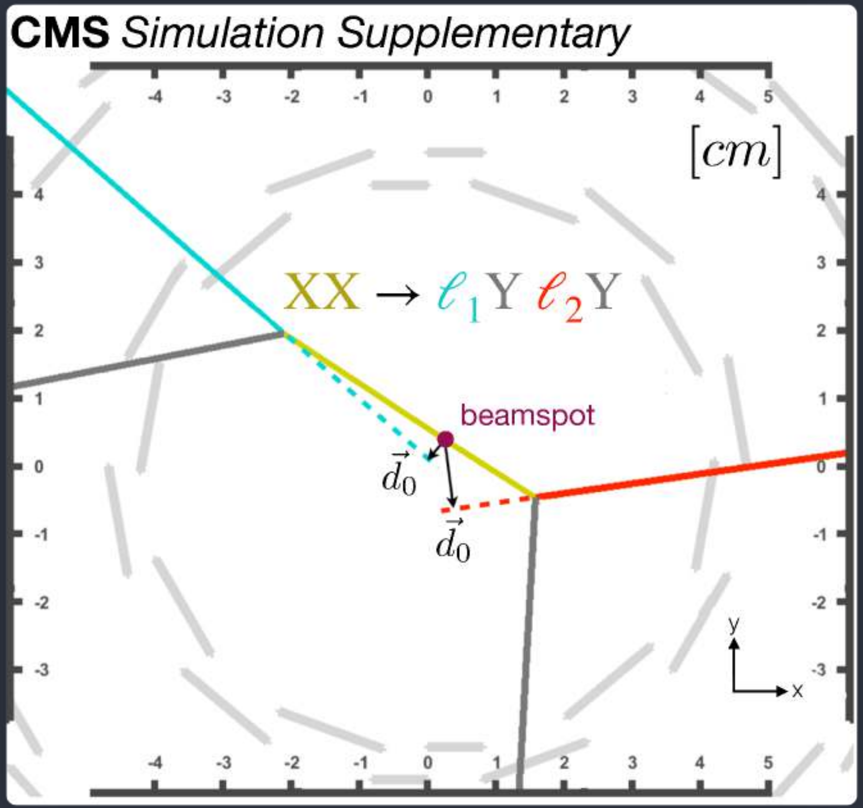
- Similar analysis with ATLAS disappearing track,
- Pure wino(left) : exclude $m_{\tilde{\chi}_1^{\pm}} < 474$ GeV @$\tau_{\tilde{\chi}_1^{\pm}} = 0.2$ nsec
- Pure higgsino(right) : exclude $m_{\tilde{\chi}_1^{\pm}} < 175$ GeV, @$\tau_{\tilde{\chi}_1^{\pm}} = 0.05$ nsec

LLP to Leptons with Large Impact Parameter @CMS



LLP to Leptons w/ Large d_0 (EXO-18-003) with full Run2 data

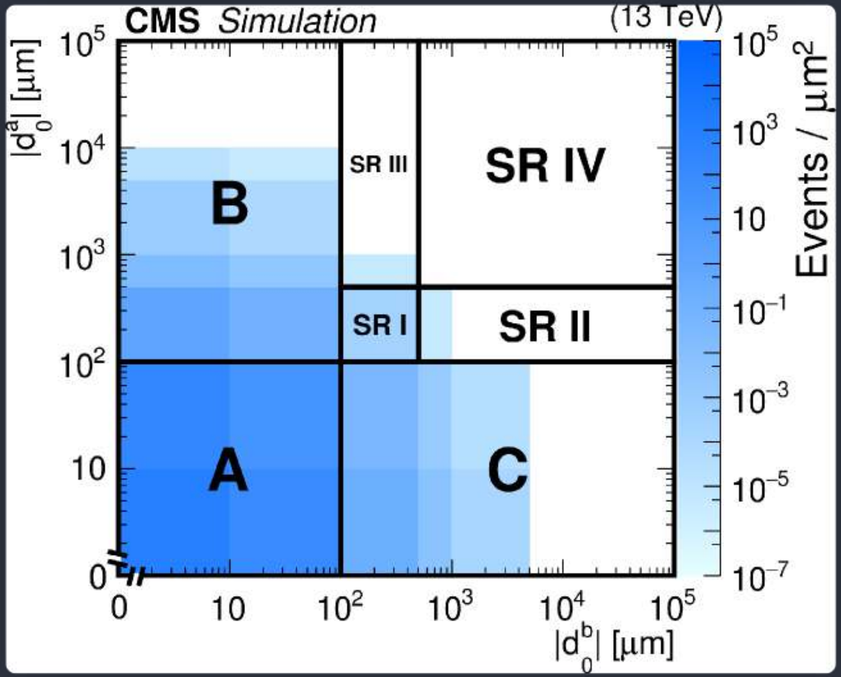
- LLP : Stop, slepton, or other scalar decay into leptons and jets
- Leptons : Select $ee, e\mu$ and $\mu\mu$ channel with $d_0 > 100\mu$m
- Cosmic muon veto: timing information and vertex information are used.

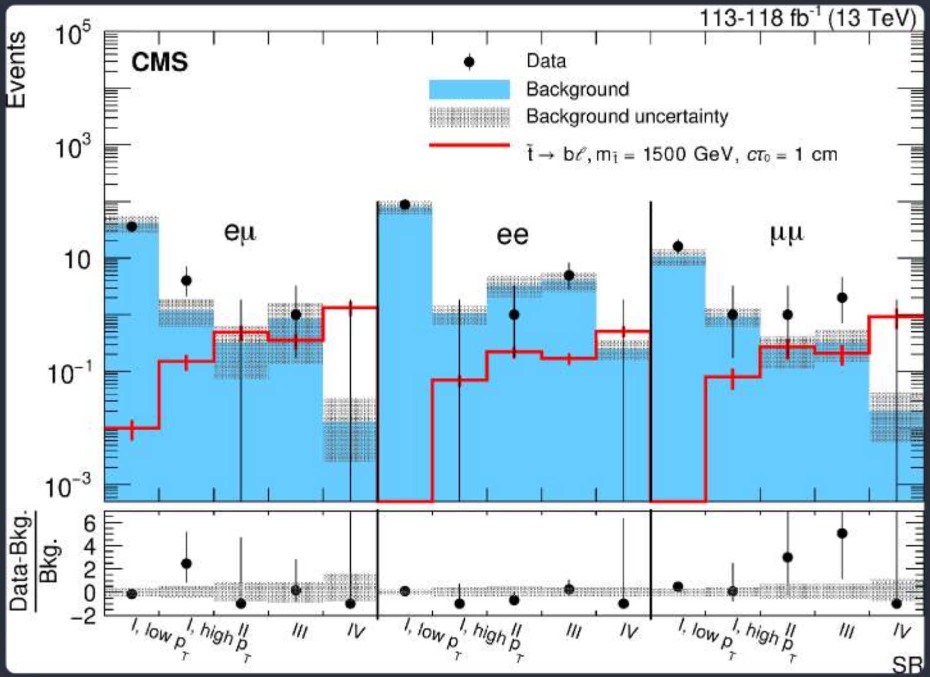


Event Display(Simulation)

- Diagram of a generic signal event, from a transverse view of the interaction point.
- The black arrows show the lepton d_0 vectors.

LLP to Leptons with Large Impact Parameter @CMS

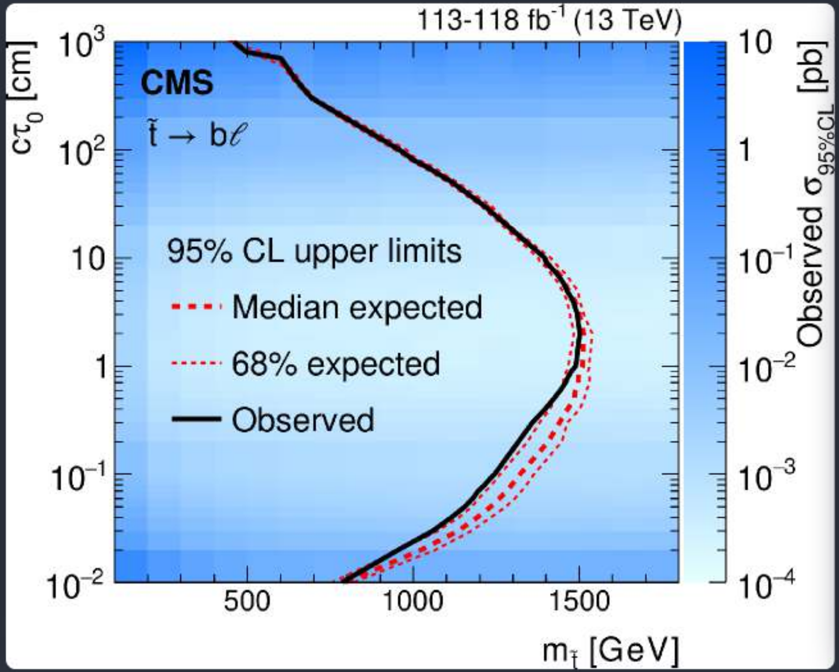


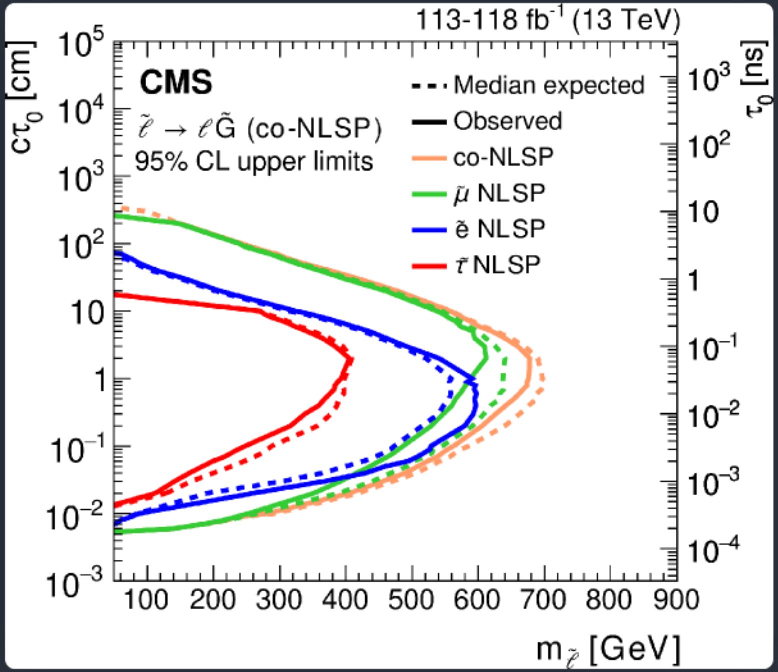


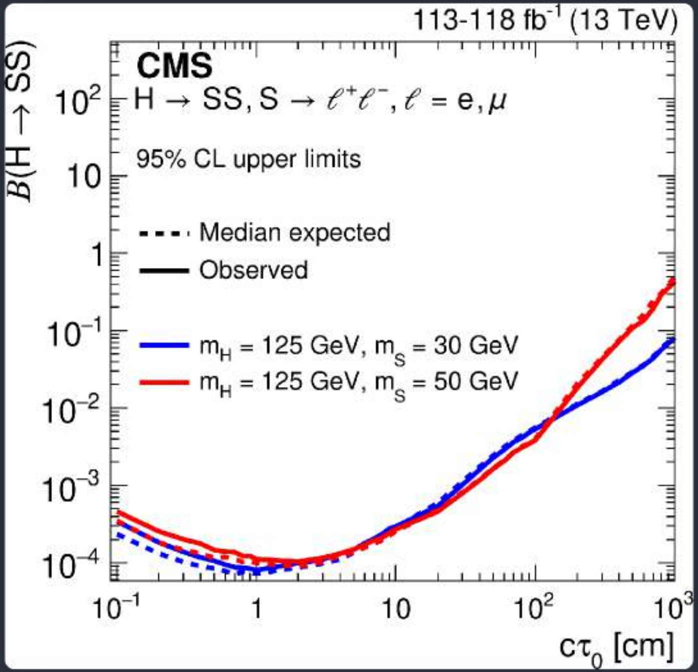
- Four signal region(SR)s : categorize events with each lepton's $d_0 = 100\mu\text{m}, 500\mu\text{m}, 10\text{cm}$
- Background : Estimate by ABCD method(data driven)

- data agree well with expectation within uncertainties.
- No significant excess in all SRs...

LLP to Leptons with Large Impact Parameter @CMS

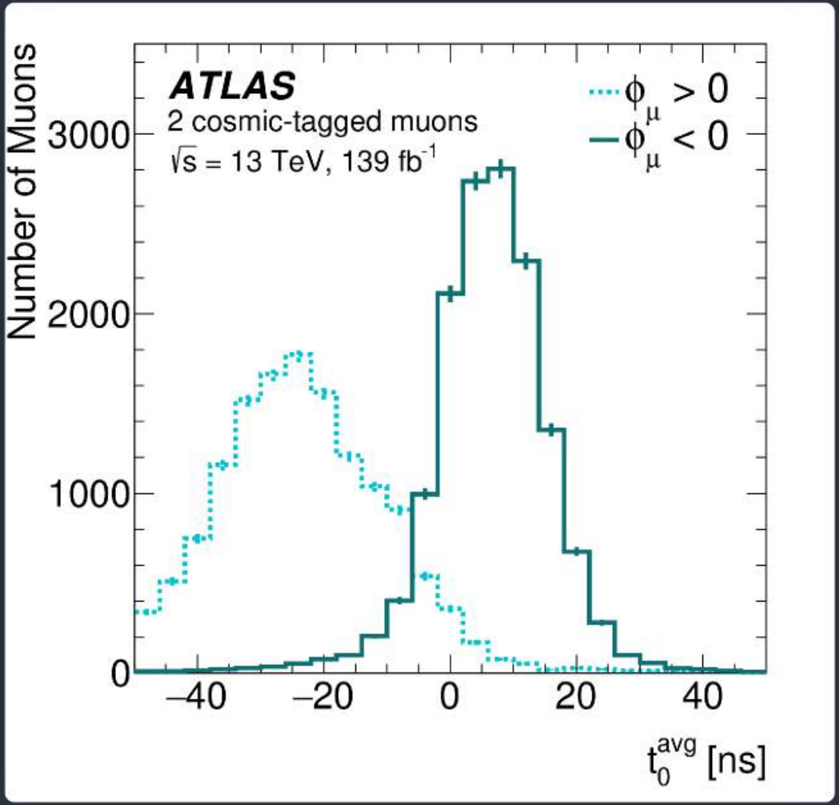


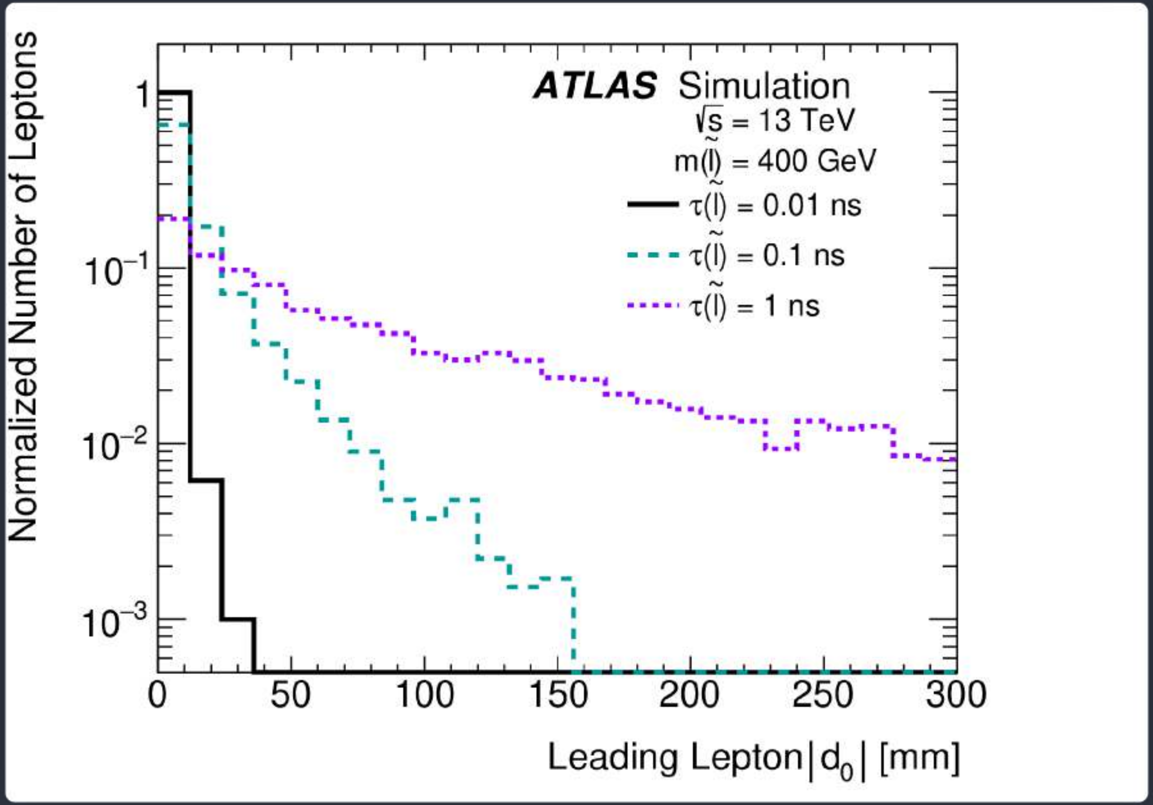




- Limits on three signal scenarios :
  - $\tilde{t} \to \mathrm{b}\ell$: Exclude about $m_{\tilde{t}} \sim 1.5$ TeV and $c\tau_0 \sim 1.0$cm
  - $\tilde{\ell} \to \ell\tilde{G}$: Three case, which slepton is NLSP, in co-NLSP case $m_{\tilde{\ell}} \sim 700$ GeV and $c\tau_0 \sim 1$cm
  - $H \to S$: Test two mass hypothesis with $m_S = 30, 50$ GeV with $m_H = 125$GeV on a branching fraction v.s. $c\tau_0$ plane.

Displaced Leptons @ATLAS

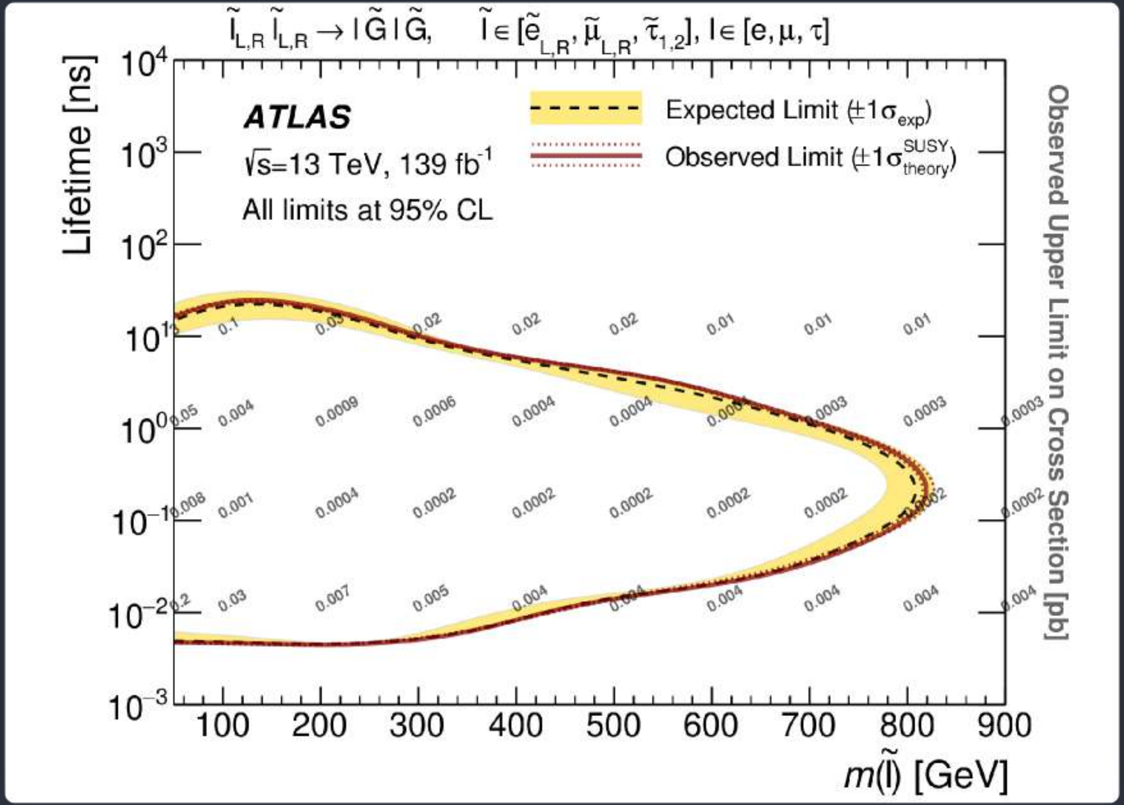


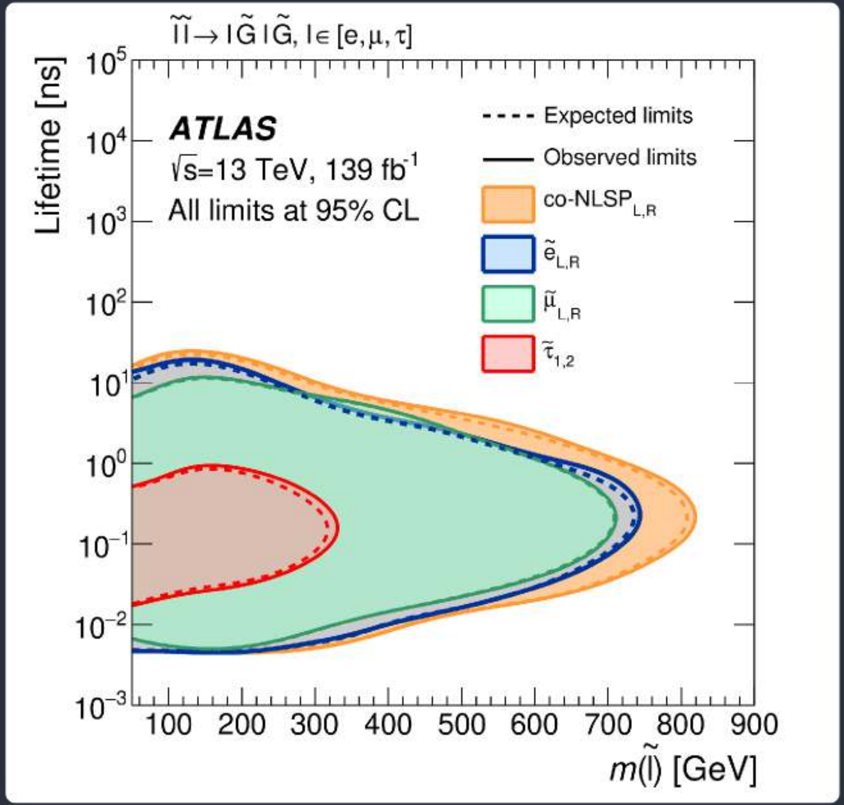


Displaced leptons (SUSY-2018-14) with full Run2 data

- Similar result from ATLAS, Cosmic muon veto using timing information
- Leading lepton d_0 has siginificant dependency against signal lifetime.

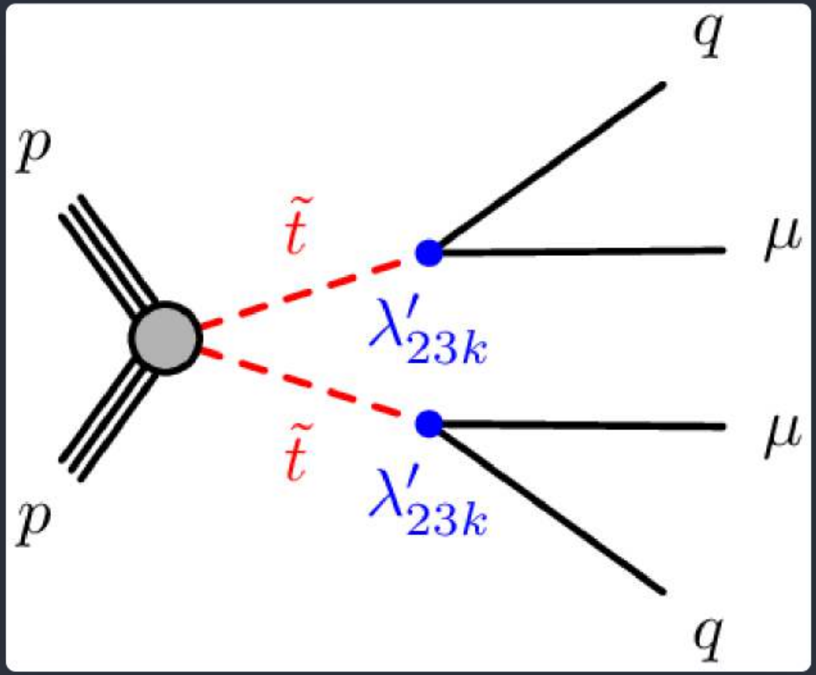
Displaced Leptons @ATLAS

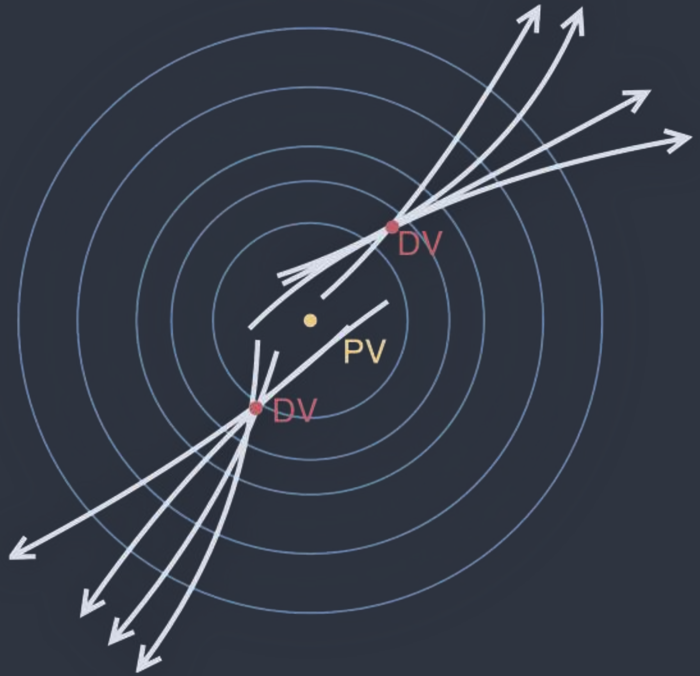


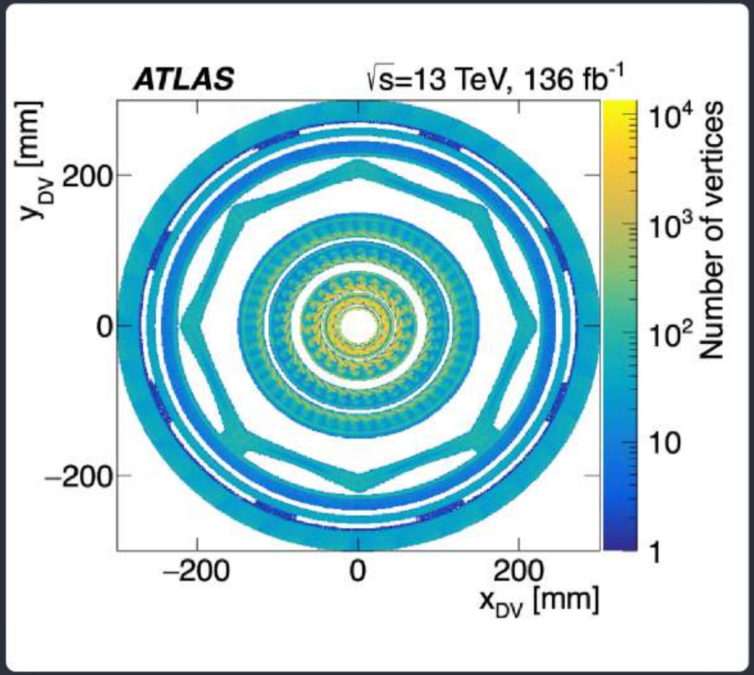


- Exclusion limit looks slightly better compared with CMS's result for $\tilde{e}, \tilde{\mu}$ case.
- $\tilde{\tau}$ behind about 100GeV
- co-NLSP limit is better than CMS's one.

Displaced Vertex @ATLAS



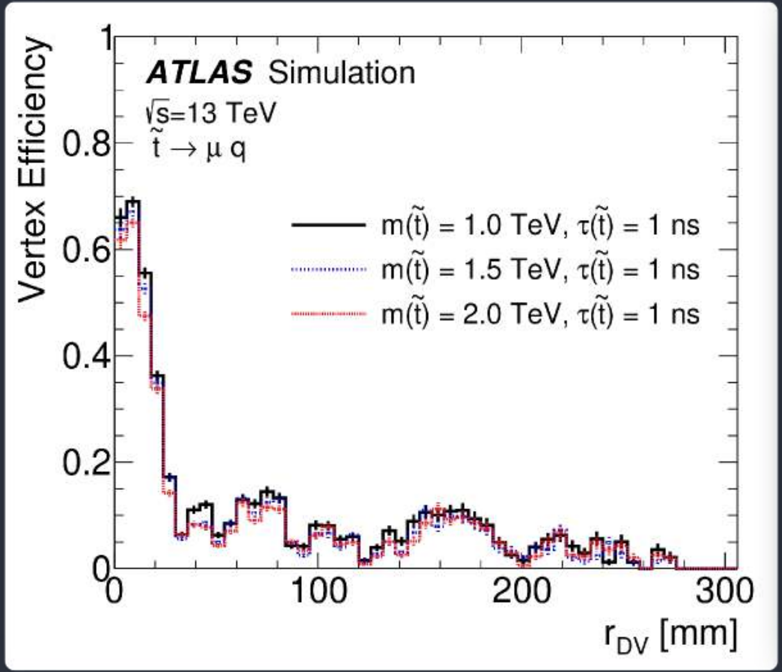


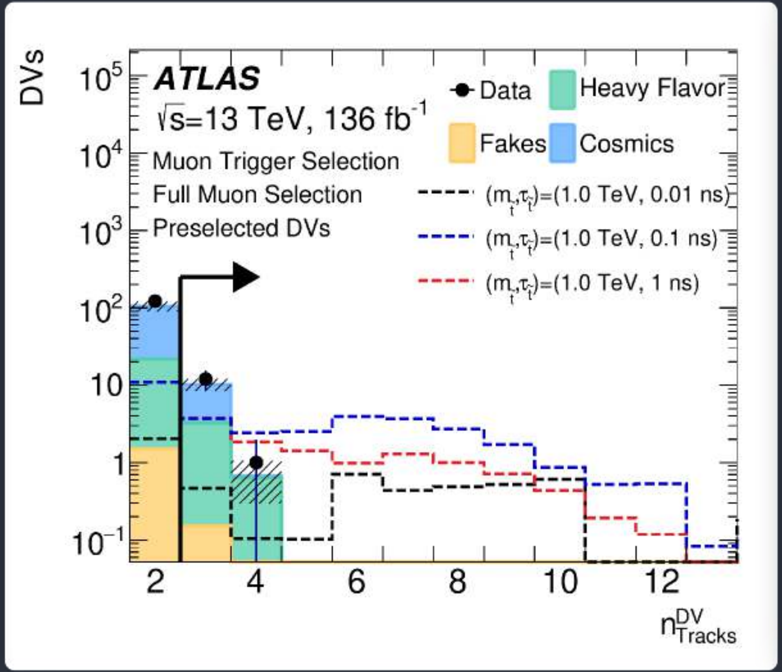


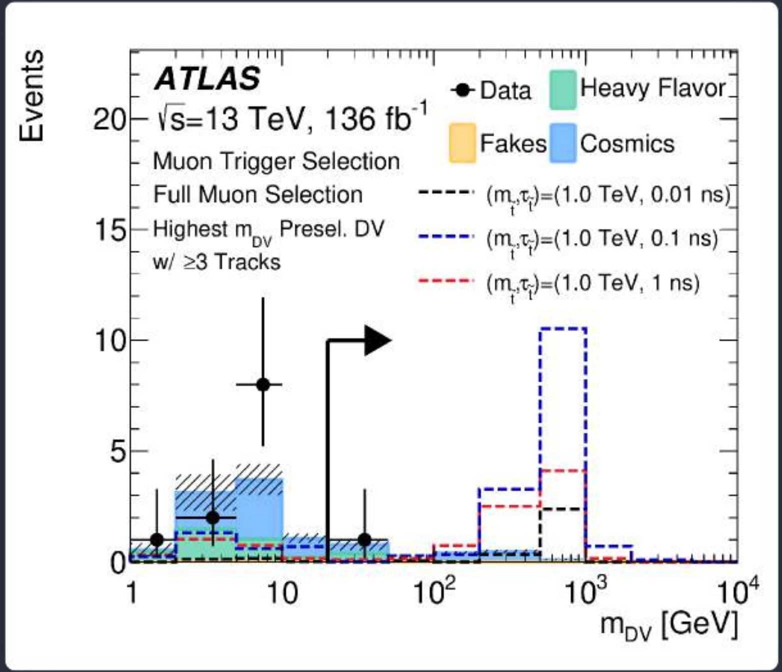
Displaced vertex (SUSY-2018-33) @ATLAS with full Run2 data

- Displaced vertex(DV) : secondary vertex reconstructed with large-d_0 tracks
- Signal : $\tilde{t} \to \mu + R$-hadron
- Material vetor : Veto reconstructed DV around ATLAS detector material $\to$ suppress
- Trigger : $E_{\mathrm{T}}^{\mathrm{miss}}$ or muon trigger

Displaced Vertex @ATLAS

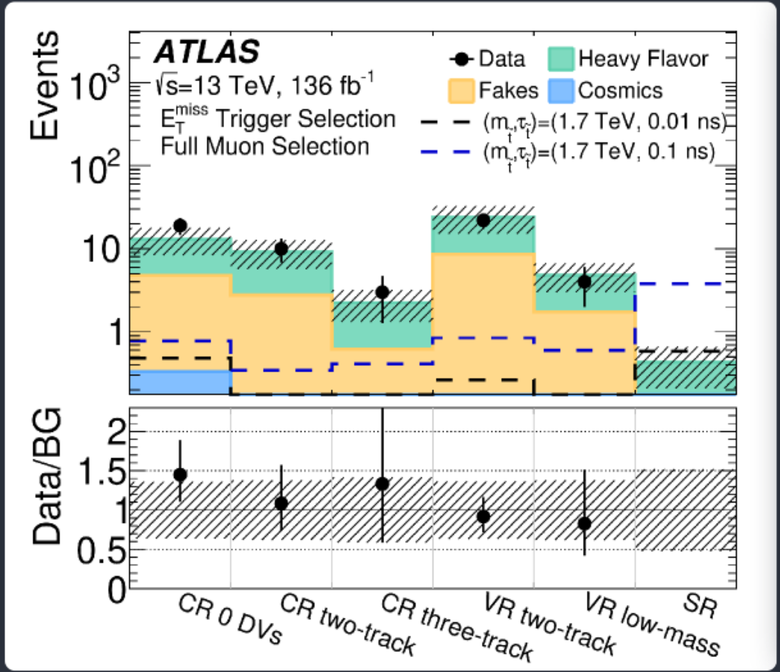


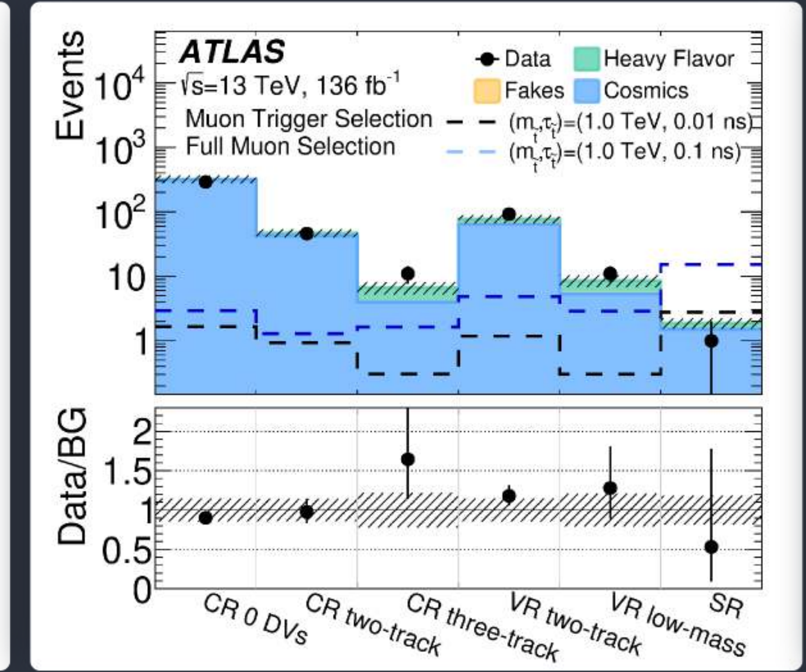


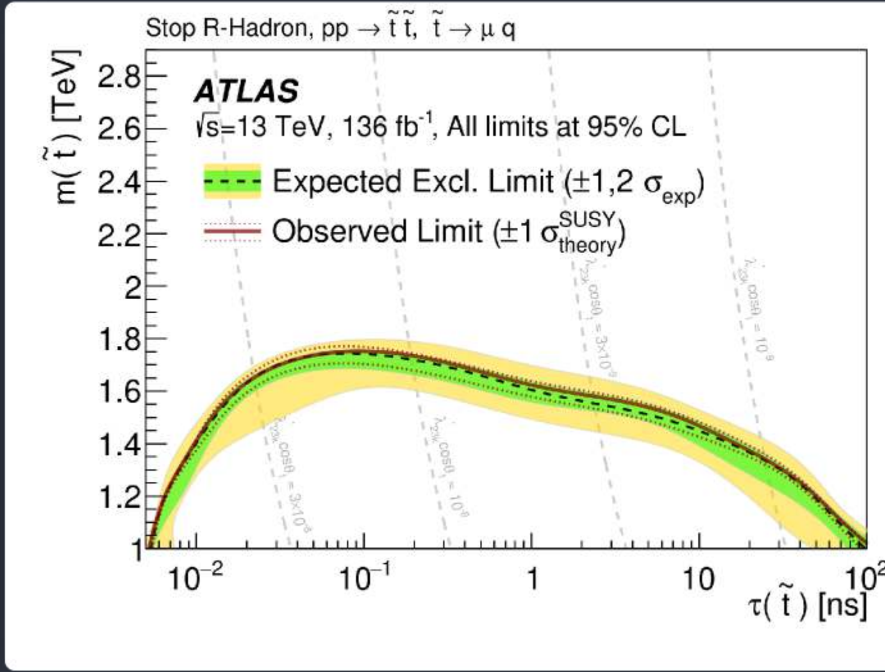


- Signal vertex efficiency: No clear dependency as a function of mass of signal
- Require two reconstructed DVs and invariant mass of DV $m_{\mathrm{DV}} > 20$ GeV
- Same criteria for $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger category.

Displaced Vertex @ATLAS

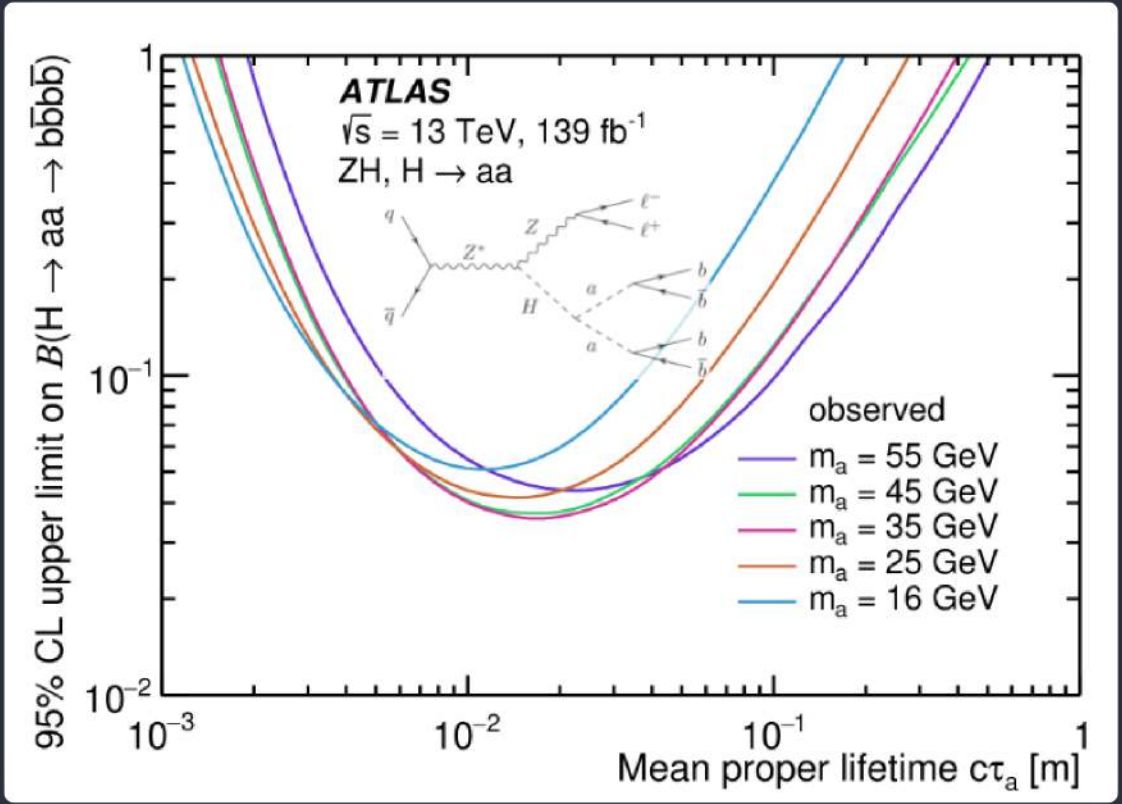


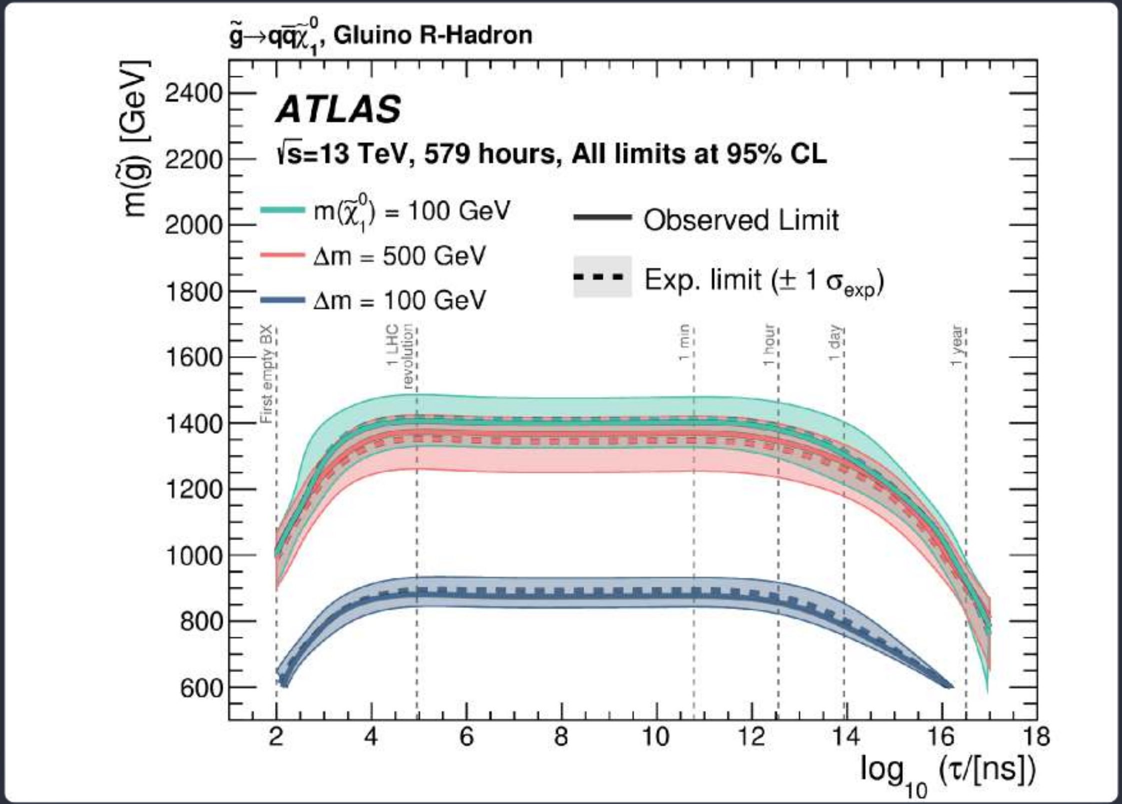




- Events are validated and controlled by using validation regions and control regions.
- No excess are observed → Exclusson limit on $\tau_{\tilde{t}} - m_{\tilde{t}}$ plane.

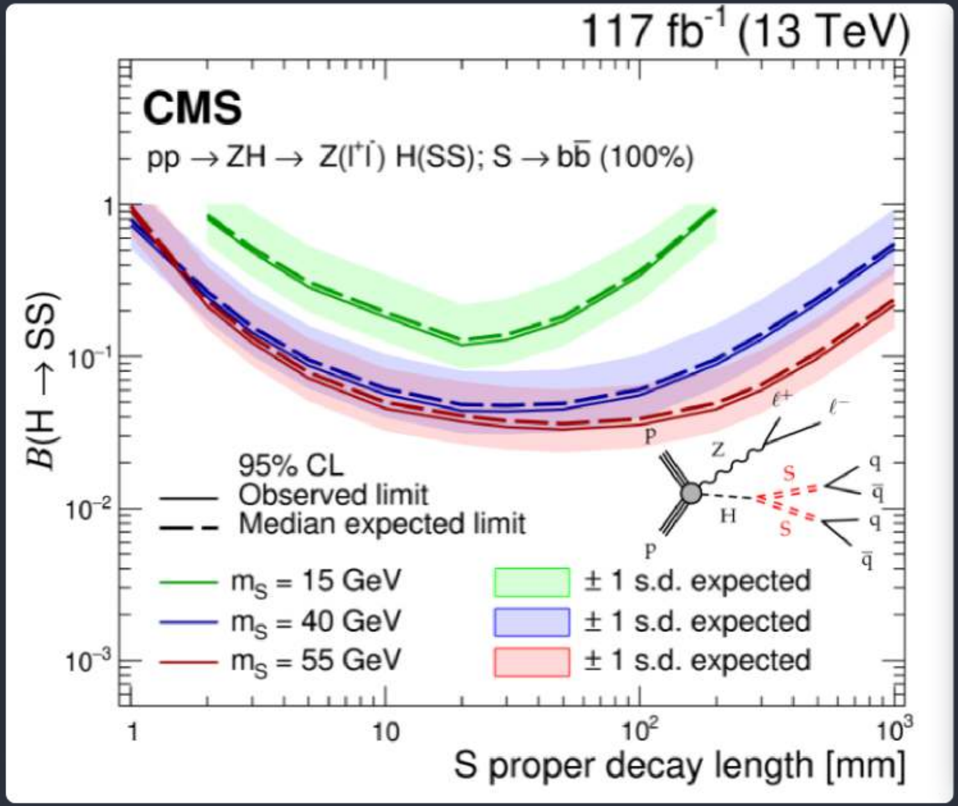
Other Results from ATLAS

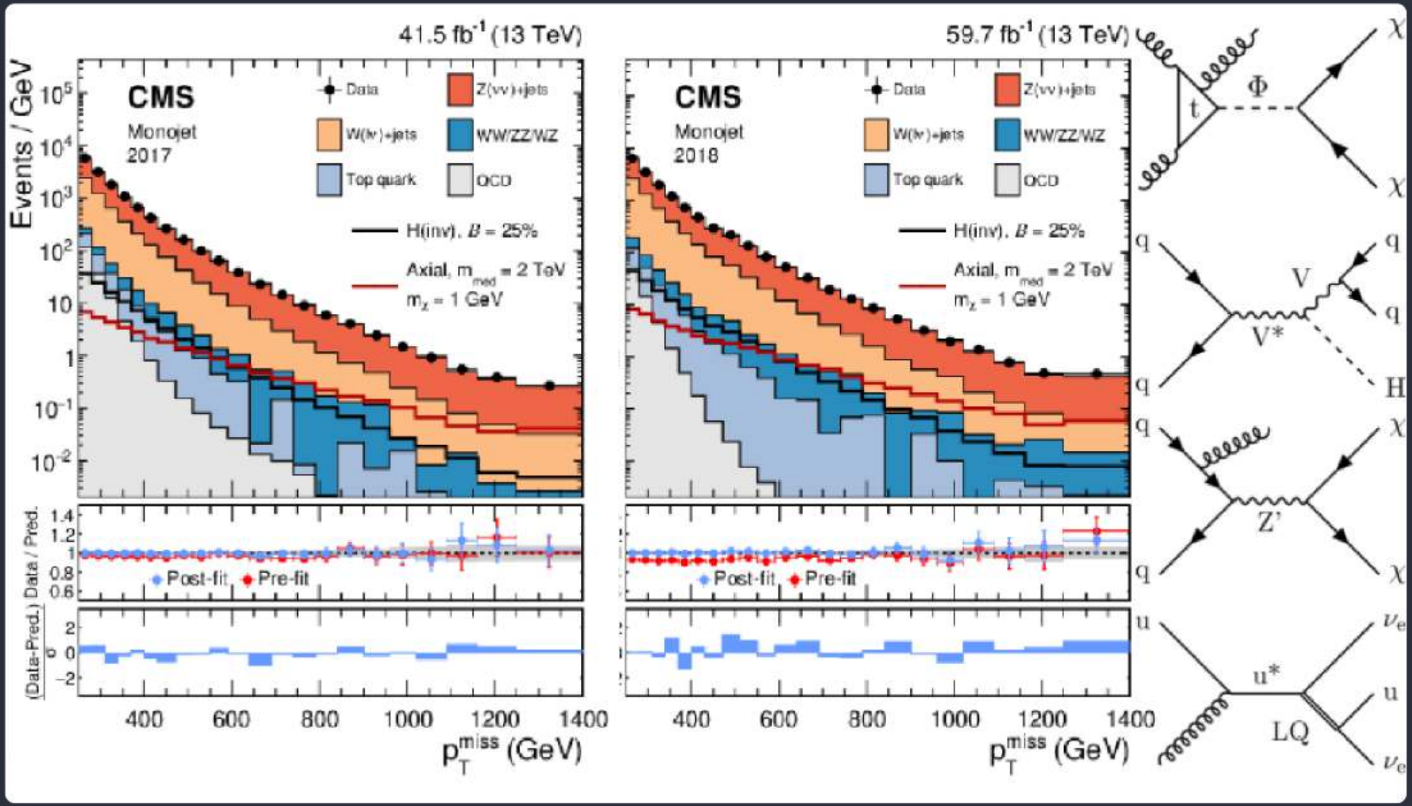




- $VH \to aa \to 4b + \ell\ell$: long-lived Higgs to 4 b-jets as displaced jet
  - Reconstruct two displaced vertices at the inner detector.
  - Tag $Z \to \ell\ell$ to reduce huge background
  - Data-driven background estimation, γ+jet events are used.
  - Discriminate background using b-tagging score from DV.
  - No significant excess, limit on BR as a function of proper lifetime $c\tau_a$ [m]
- Stopped LLP: Gluino R-hadron not pointing interaction point (pp)
  - LLP stopped at detector and decay into jets, which have muon track not pointing IP.
  - Select events within empty bunch-crossing.
  - Background is a cosmic muon event, and beam-induced backgrounds (BIB).
  - No data excess, limit with several $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ as a function of $\tau(\tilde{g})$.

Other Results from CMS





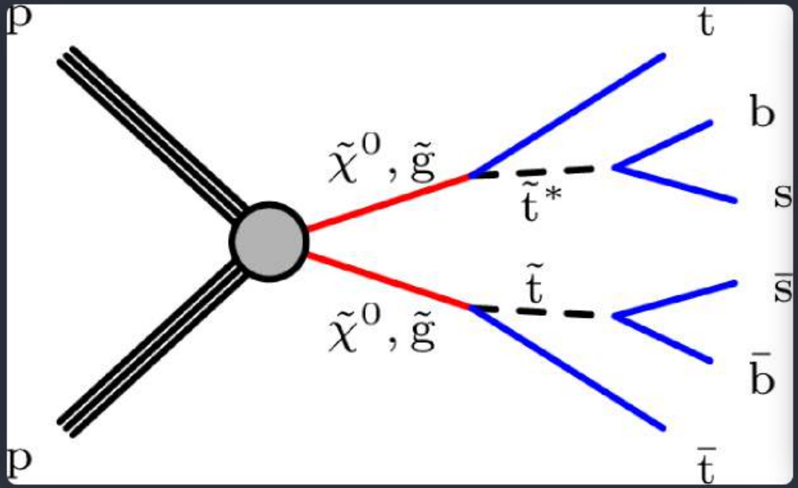
- $VH \to aa \to 4b/4d + \ell\ell$: long-lived Higgs to 4 d/b-jets as displaced jet
  - Similar results from CMS, also with including $s \to dd$ decay.
  - Using $\hat{\mathrm{IP}}^{\mathrm{2D}}_{\mathrm{sig}}$, a significance of impact parameter of DV.
  - No significant excess, limit on BR as a function of proper decay length[mm].
- Mono-jet: Higgs invisible,colorless spin-0/1 mediator, single LQ production.
  - DM search with high p_{T} jets and large $E_{\mathrm{T}}^{\mathrm{miss}} \to$ Mono-jet
  - Machine learning technique to suppress background events.
  - A joint maximum likelihood fit is done along all SRs and CRs simulteniously to extract a amount of signal.
  - Good agreement with prediction, limit for several BSM models.

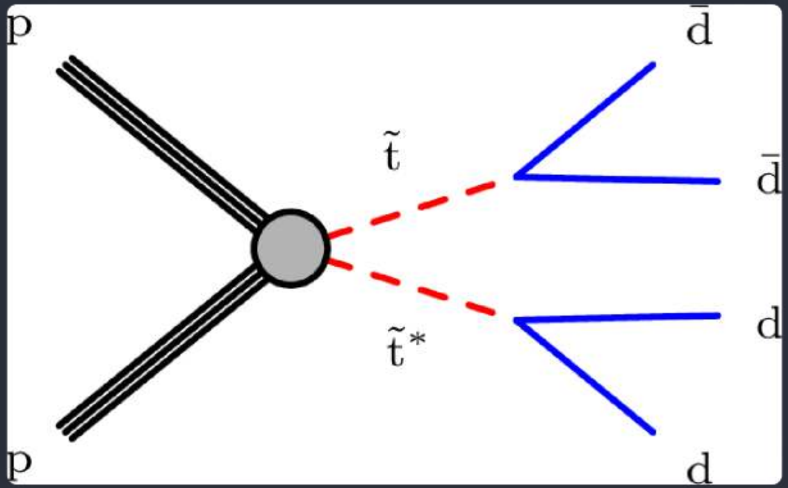
Summary

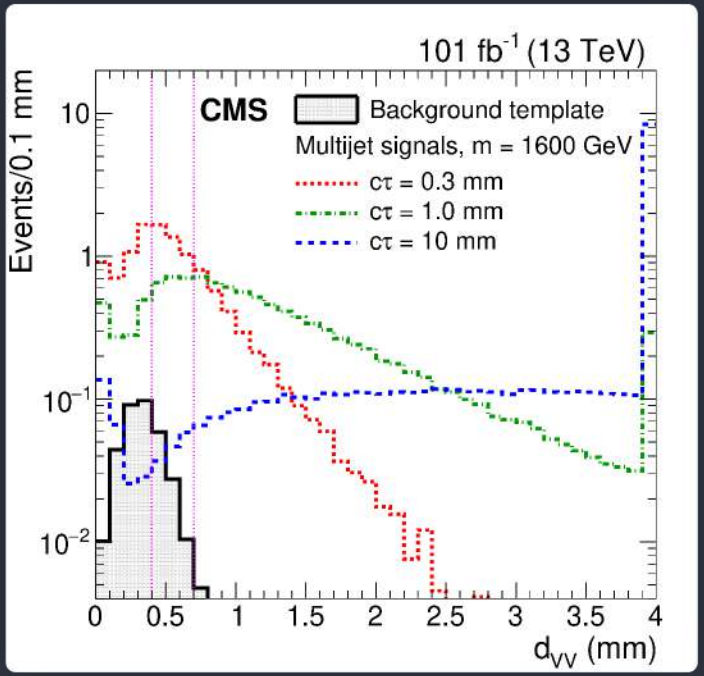
- ATLAS and CMS search long-live particles with various event signatures.
- There are a lot of important techniques, which are newly developed.
    - Short track reconstruction
    - Large d_0 tracking
    - Dislpaced vertex/jet reconstruction
- There is still much room for improvements by using a machine learning technique!

Backup

Displaced Vertex @CMS



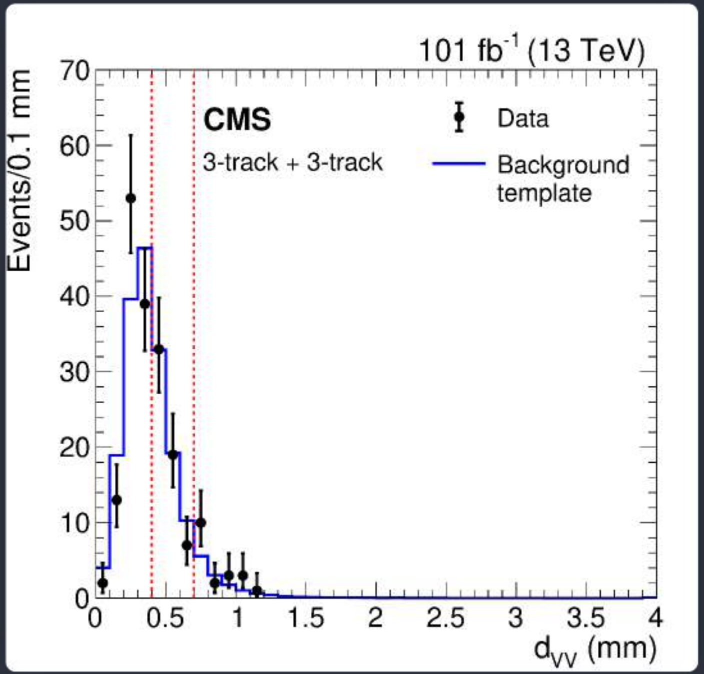


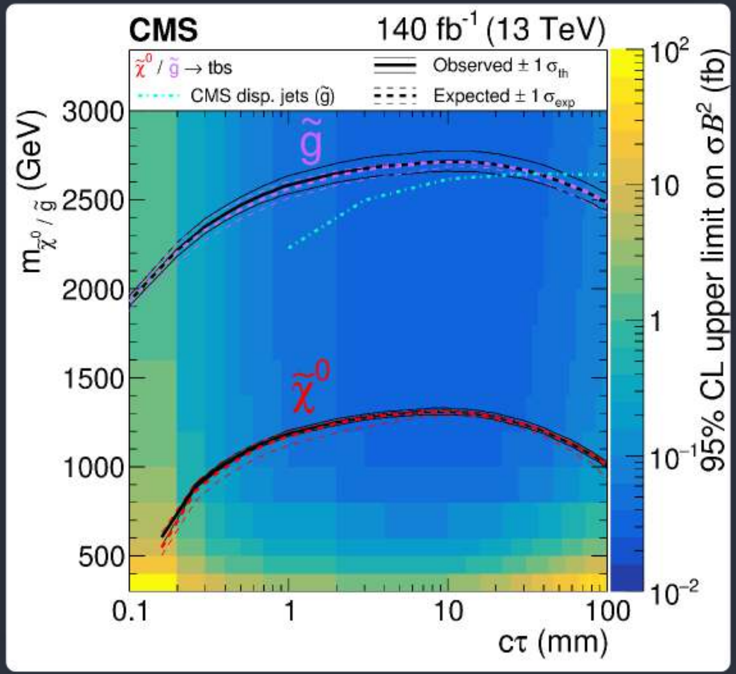


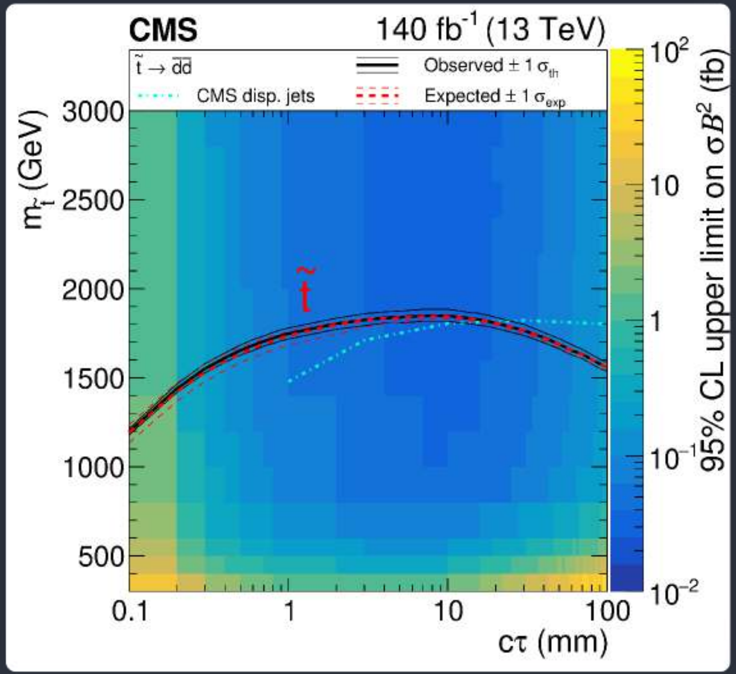
LLP jets with displaced vertex (EXO-10-013) @CMS with full Run2 data

- Similar, but not exactly same analysis as ATLAS.
- Signal : Two signal are considered:
  - Multijet signal : Long-lived neutralinos($\tilde{\chi}_0$) or gluino($\tilde{g}$) decay into $\tilde{t}^* + t$
  - Dijet signal : stop $\tilde{t} \rightarrow d\bar{d}$
- d_{VV} : distance betwee two DVs

Displaced Vertex @CMS







- Using d_{VV} as final discriminant, count #of events within two vertical dashed lines.
- No significant excess