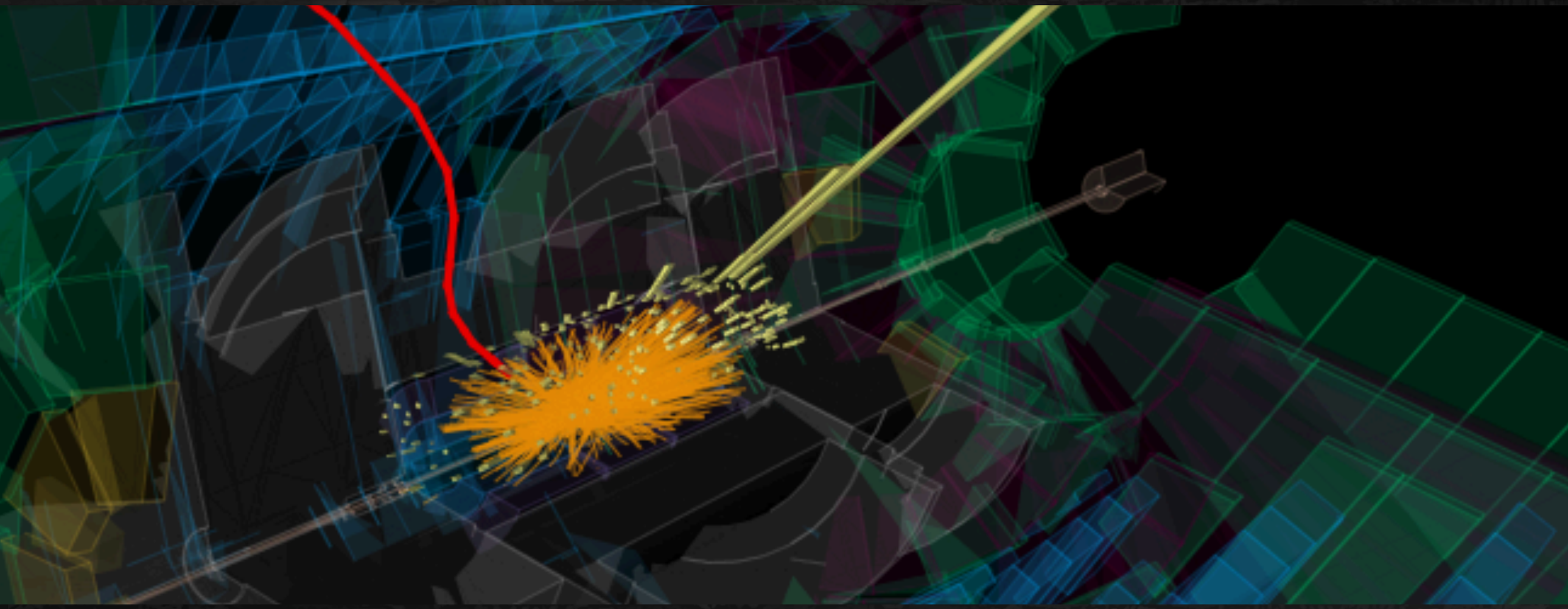
# Searches for Electroweak SUSY and for Long-lived Particles at the LHC




Hide Oide

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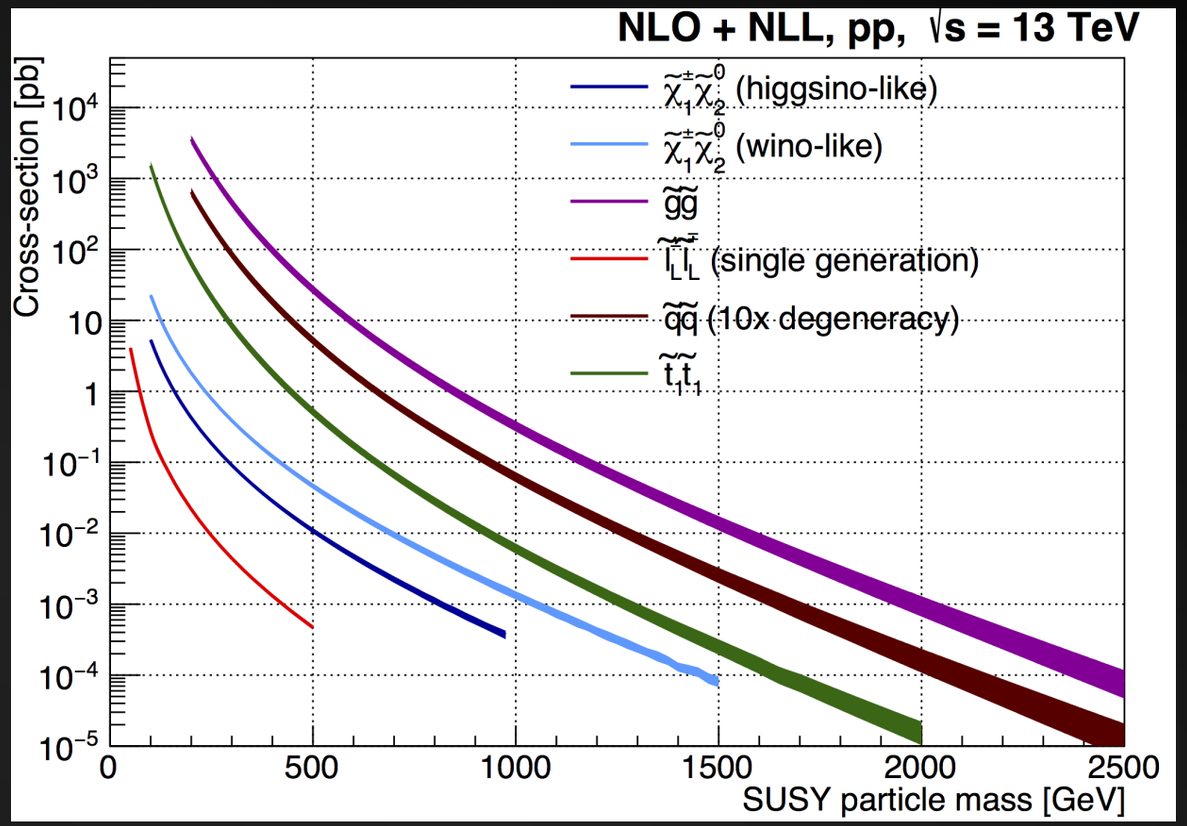
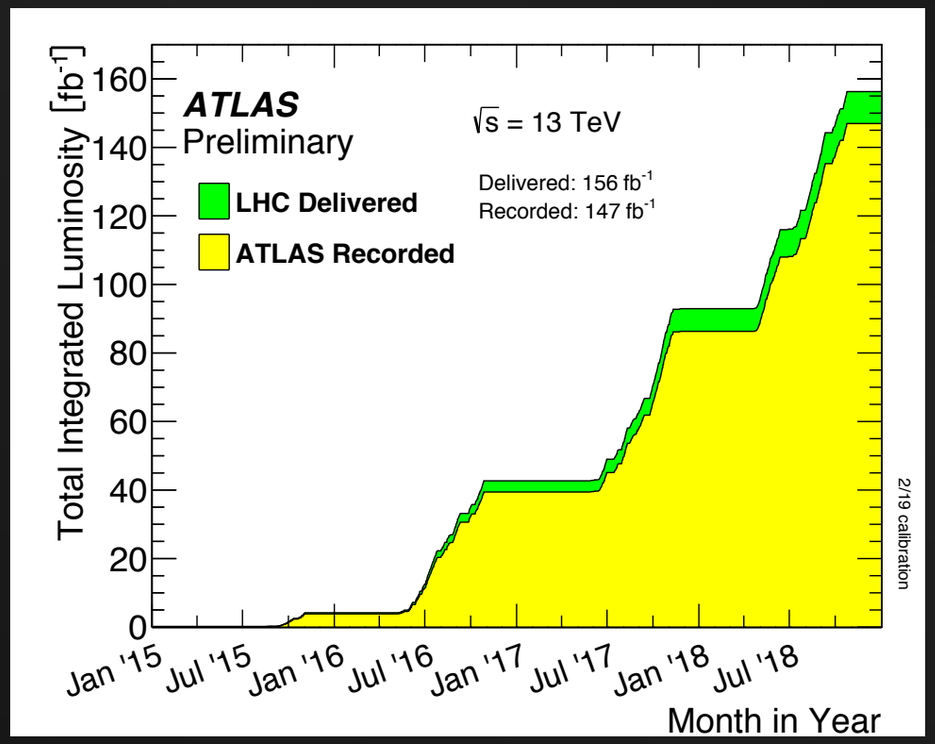
on behalf of the ATLAS and CMS Collaborations

# Introduction

- ★ SUSY: hypothetical **fundamental** space-time symmetry between fermions and bosons.
- ★ Presence of superpartners around the EW scale can mitigate the **hierarchy problem** of the SM.
- ★ SUSY must be broken — how SUSY-breaking happens **hints the physics of the very high-energy scale**.
- ★ If R-parity is exactly conserved, the lightest supersymmetric particle (LSP) can be a dark matter candidate.

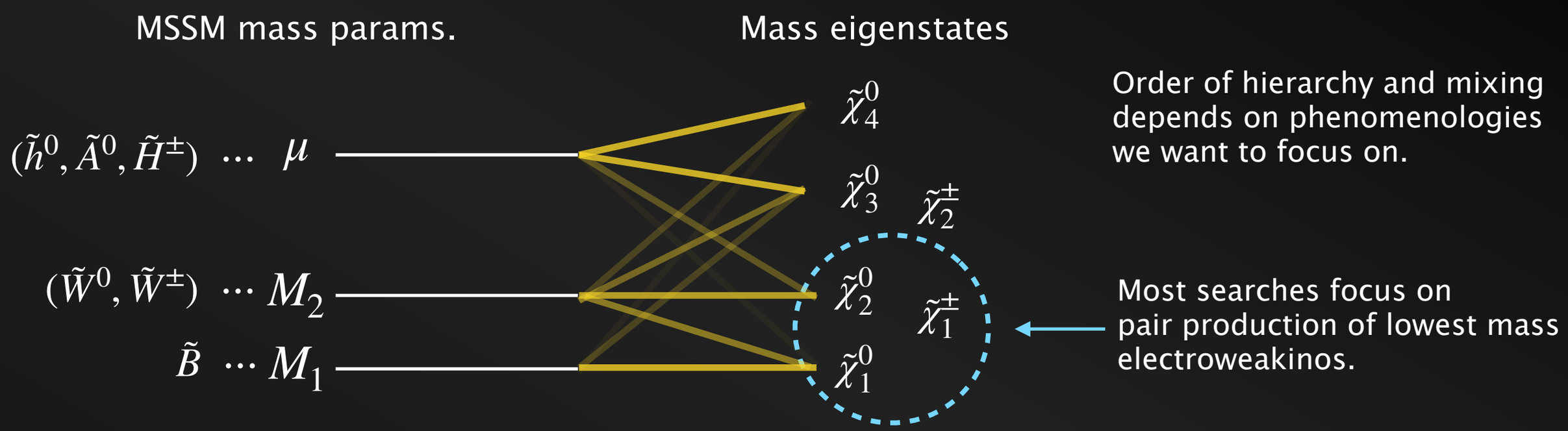



- ★ LHC Run 2 is over!
  — each of CMS and ATLAS collected **~140 fb$^{-1}$**.
- ★ Searches are actively in progress.
- ★ Early full Run 2 results are coming out.




**This talk covers selected recent search results of:**
- Electroweak SUSY production
- Long-lived (SUSY and more…) scenarios

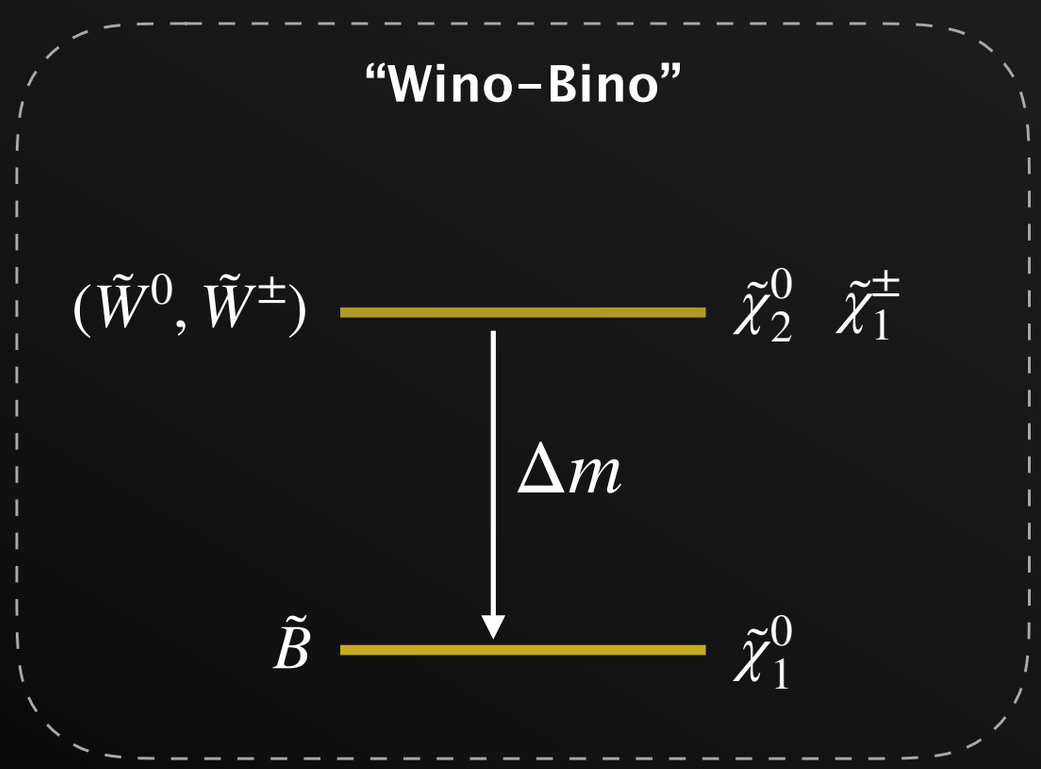
# Electroweak SUSY production searches

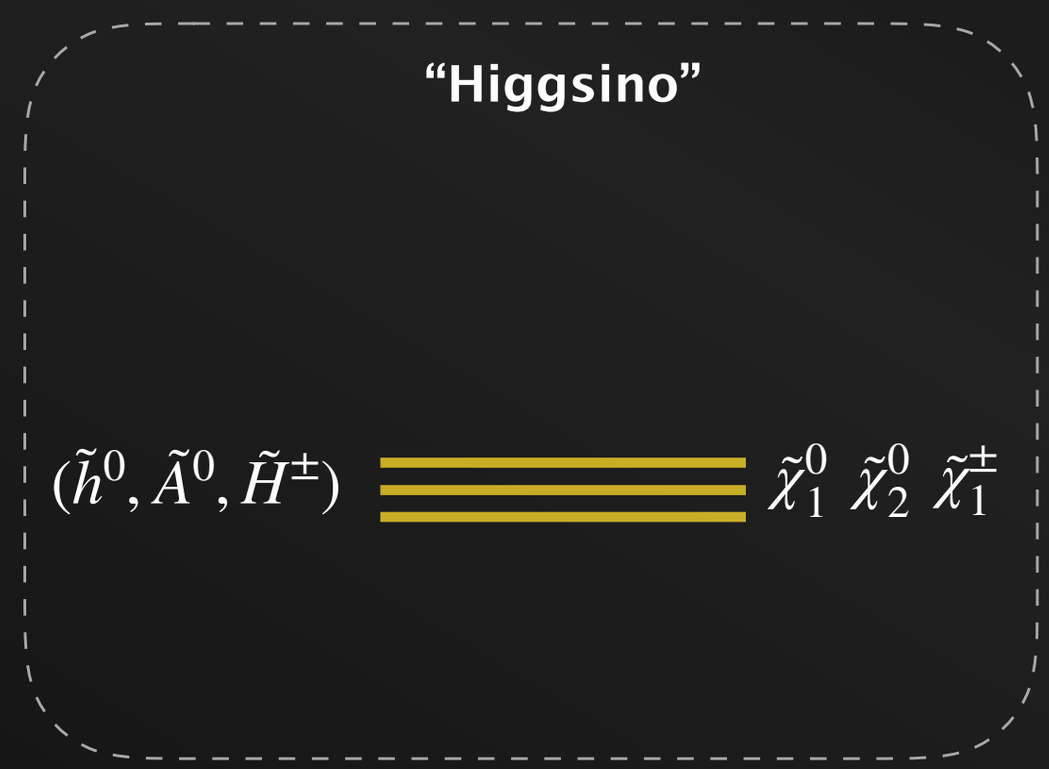



Order of hierarchy and mixing depends on phenomenologies we want to focus on.

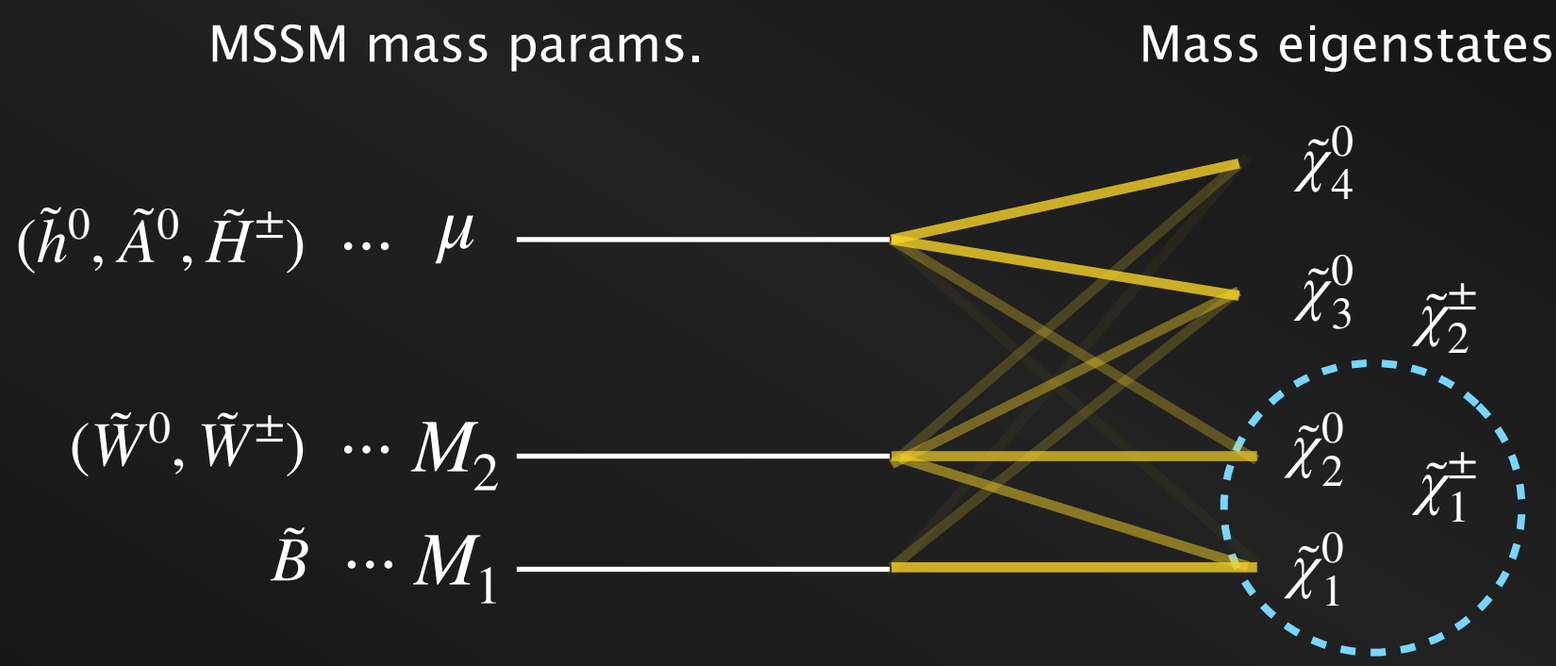
Most searches focus on pair production of lowest mass electroweakinos.

Examples of simplified models



# Electroweak SUSY production searches

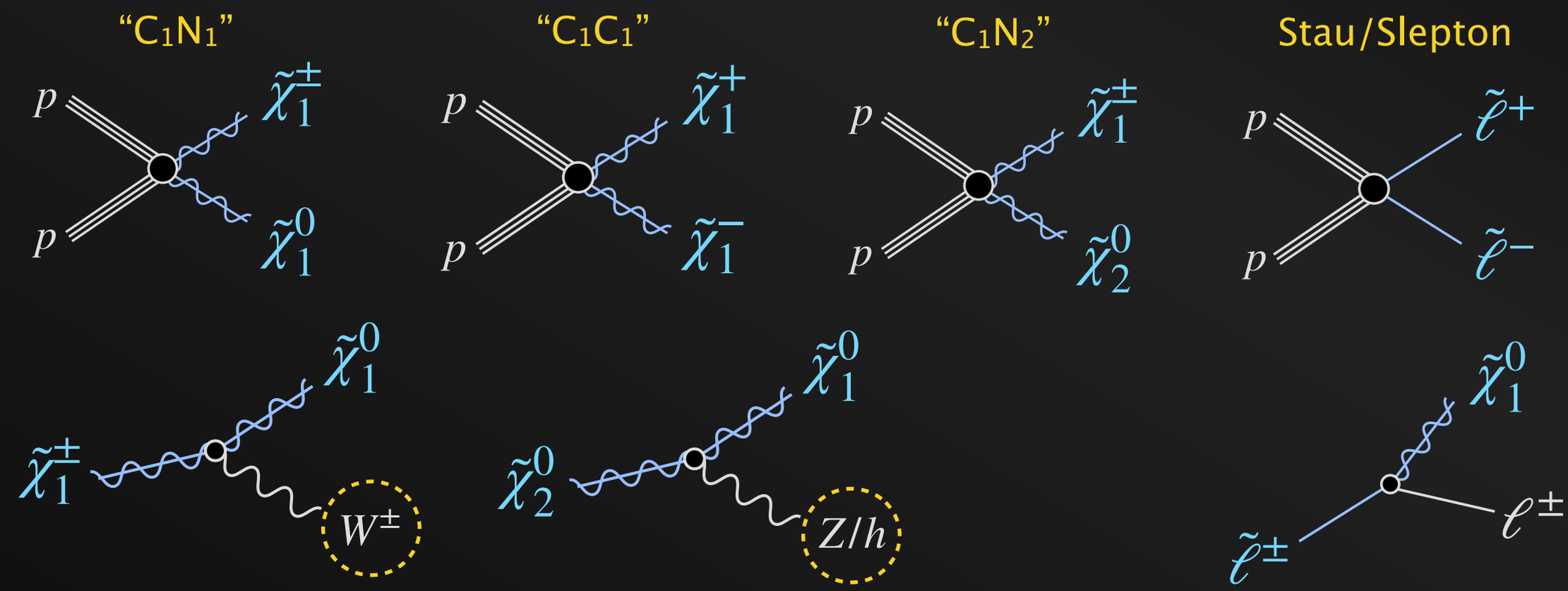



Order of hierarchy and mixing depends on phenomenologies we want to focus on.

Most searches focus on pair production of lowest mass electroweakinos.

**Representative production**

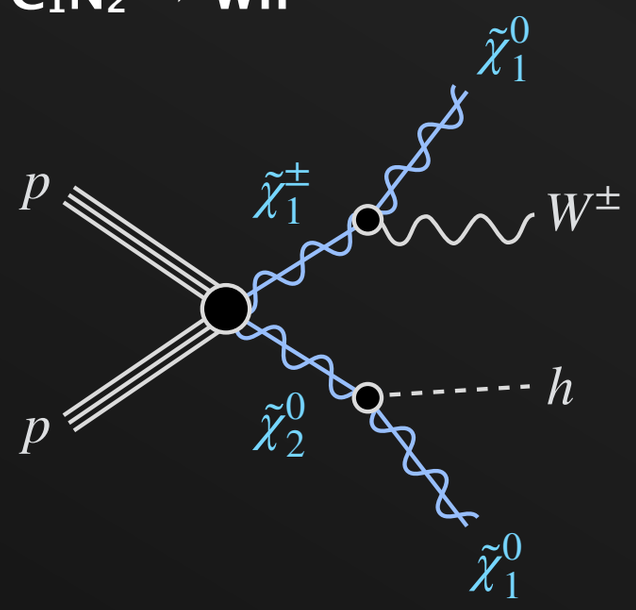
**Decays**



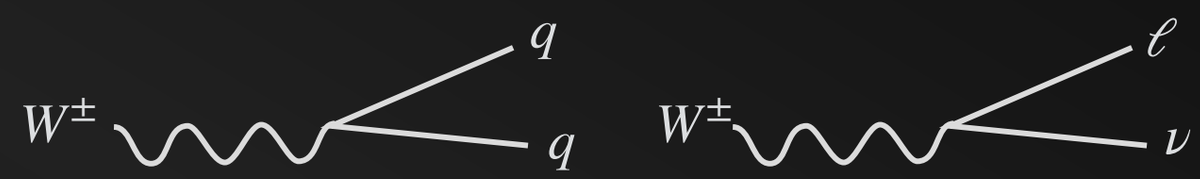

Representative searches: **Wh** (e.g. 1L+bb) or **WW** (e.g. di-lepton) final states.

# $Wh$

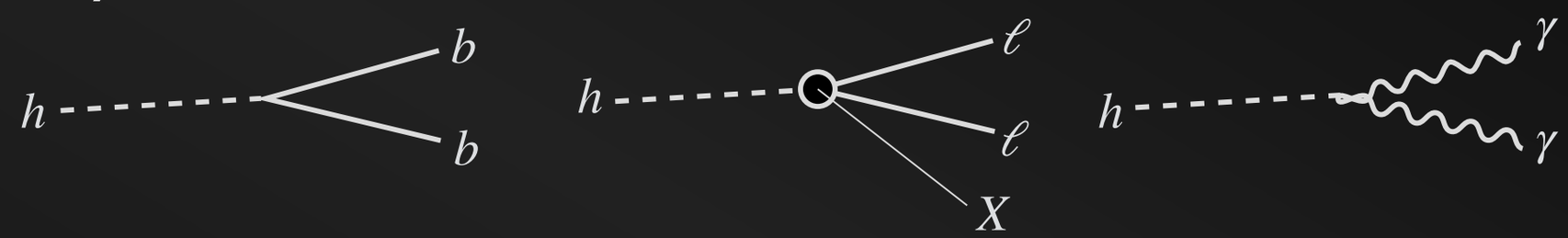
**$C_1N_2 \rightarrow Wh$**




**W decay**




**h decay**




**Key search feature: h(125) mass**

- A large fraction of $C_2 \rightarrow N_1$ decay with higgs emission expected when $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) > m(h)$ and $m(\tilde{h}) > m(\tilde{W})$.
- $C_1$ decay: W(qq) or W(Lν)
- $C_2$ decay: Various higgs decay branches possible e.g. :
  - h(bb)
  - either h(WW), h(ZZ), h(ττ) → 1L+X
  - h(γγ)

- Representative signatures
  - All-hadronic (0L) + 2b
  - Exact 1L + 2b
  - Exact 1L + 2γ
  - Same-sign 2L or 3L

**Complementary sensitivities**

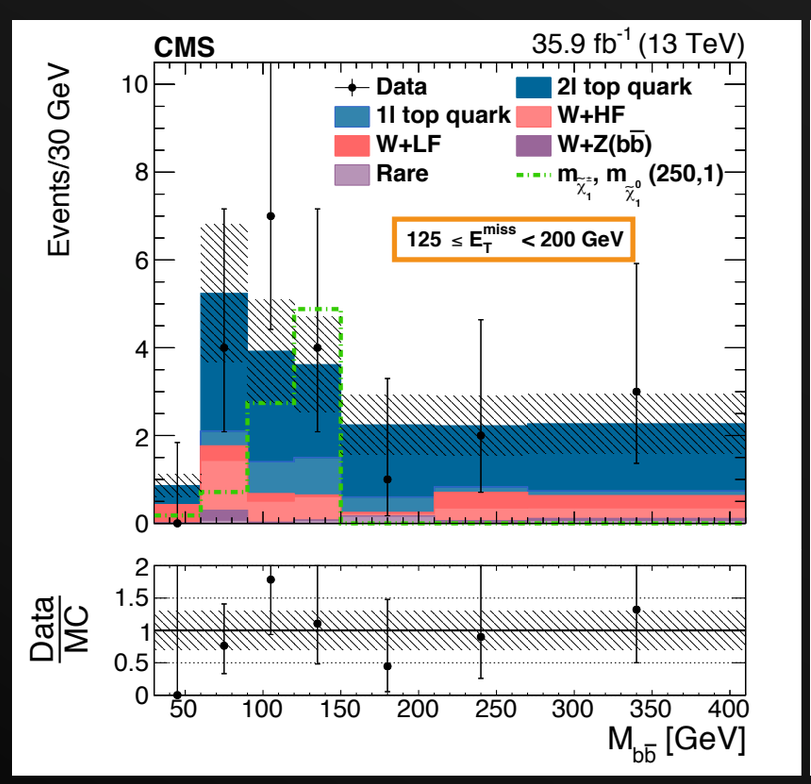
# $Wh$ : $1L + 2b$

CMS-SUS-16-043, 36 fb$^{-1}$

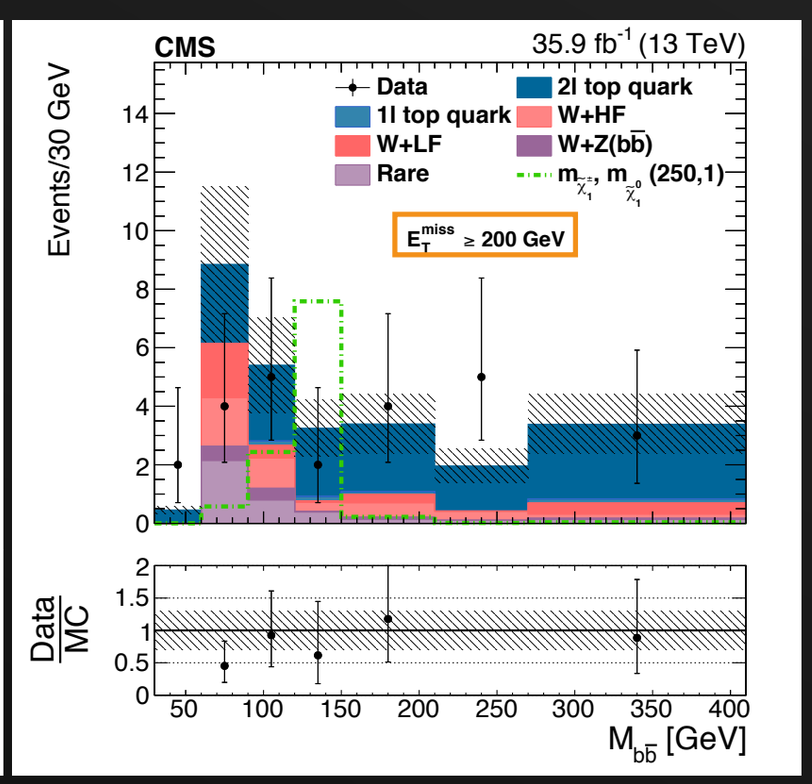
- Lepton-triggered → well-isolated lepton
- Transverse mass $m_T$ > 150 GeV
- Require large contransverse mass $m_{CT}$ > 170 GeV for $t\bar{t}$ rejection.
- h(bb) resonance at 90 GeV < m(bb) < 150 GeV.
- 2 SRs: (1) 125 GeV < MET < 200 GeV and (2) MET > 200 GeV
- No significant excess observed.

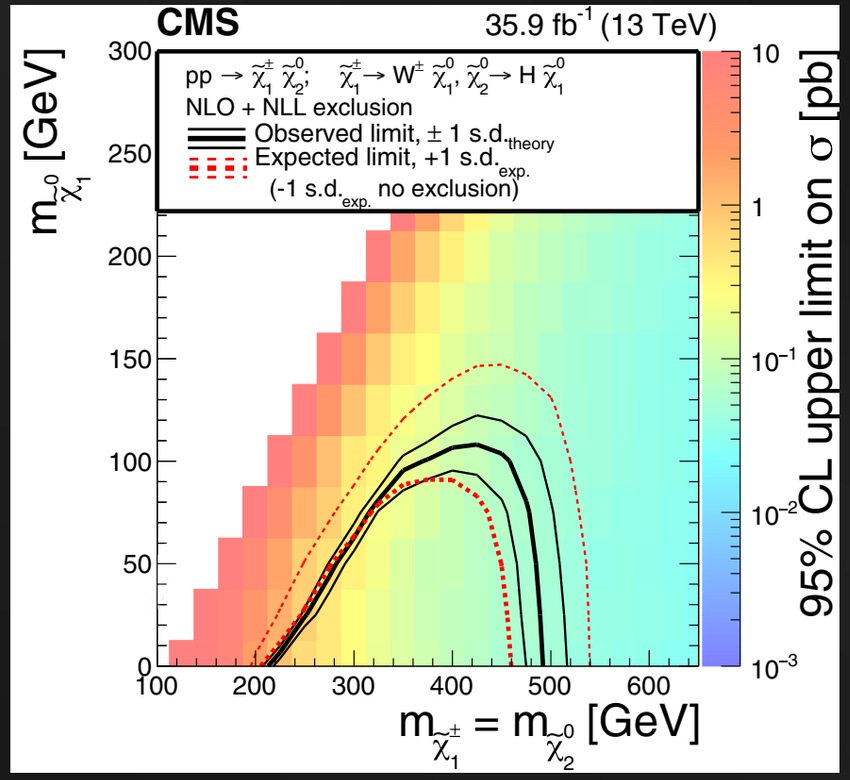
$$m_{CT} = \sqrt{2 p_T^{b_1} p_T^{b_2} \left(1 + \cos \Delta\phi_{bb}\right)}$$

**Low-MET SR**




**High-MET SR**



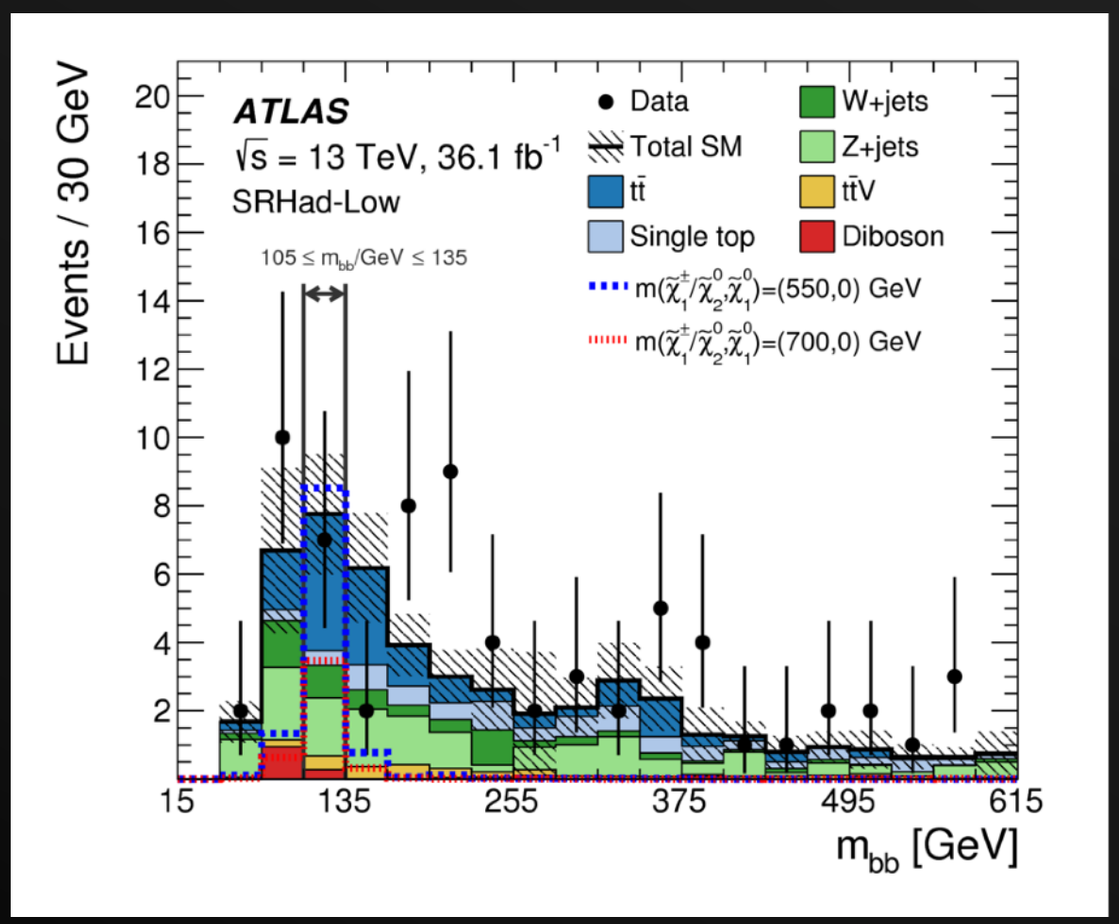

**Excluding $C_1$ 220–490 GeV for massless $N_1$**

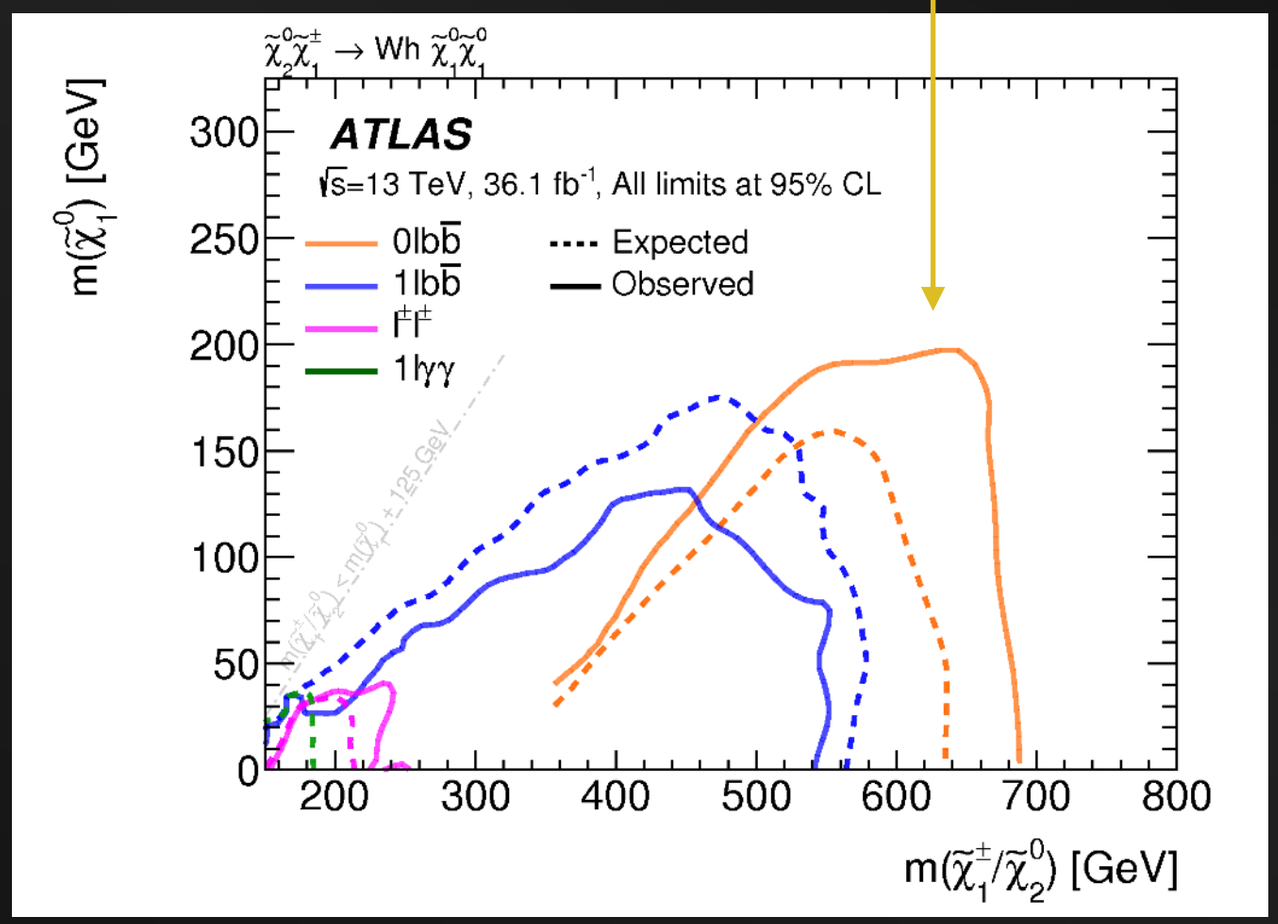
# $Wh$ : 0L + 2b

ATLAS-SUSY-2017-01, (submitted to PRD), 36 fb$^{-1}$

- ★ MET trigger → offline MET > 200–250 GeV required.
- ★ h(bb) resonance at 105 GeV < m(bb) < 135 GeV.
- ★ Require large contransverse mass $m_{\mathrm{CT}}$ for $t\bar{t}$ rejection.
- ★ No excess observed in the signal region.

Sensitive to high-mass end compared to other channels.



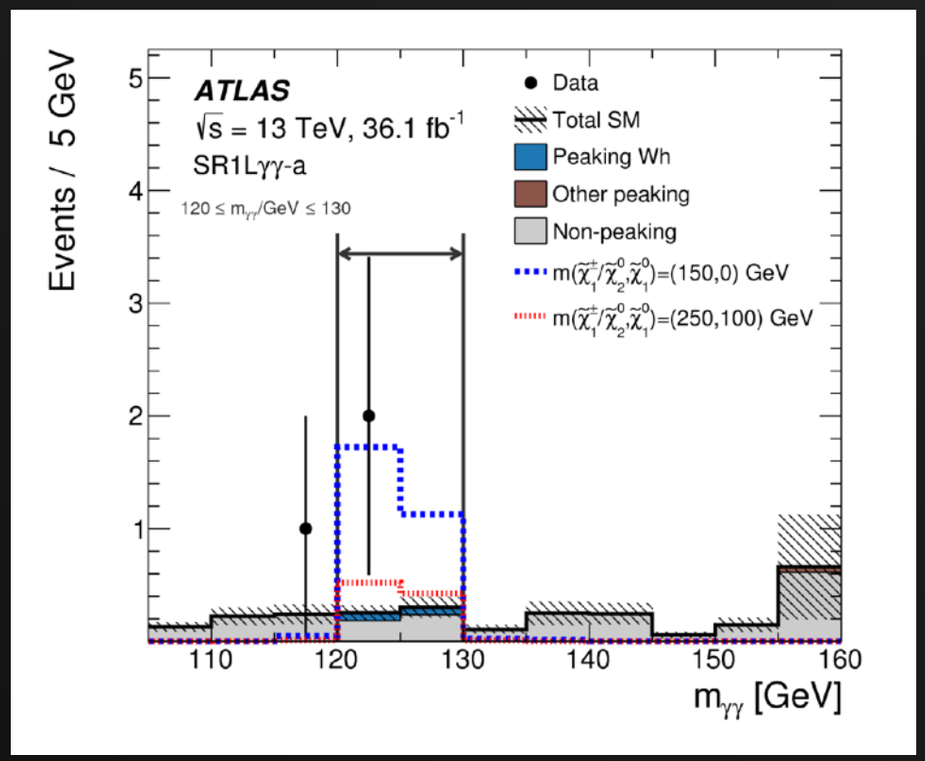



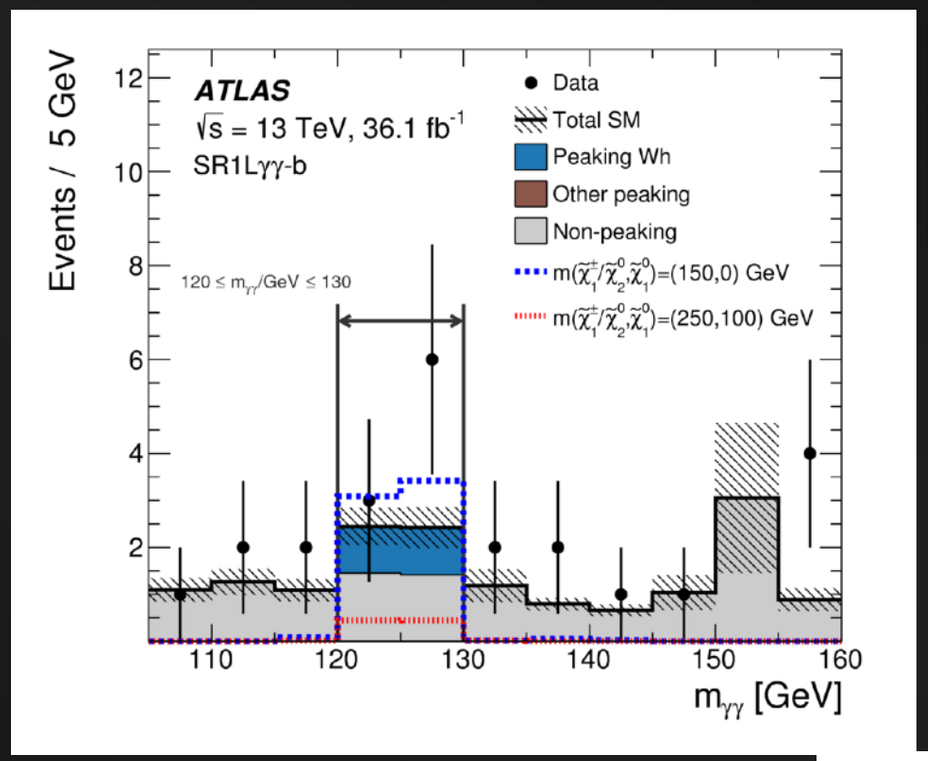

★ Exclusion up to ~690 GeV wino.

# $Wh: 1L + \gamma\gamma$

ATLAS-SUSY-2017-01, (submitted to PRD), 36 fb$^{-1}$

- ★ h(γγ) narrow peak search.
- ★ SM Wh process as an irreducible peaking background. Estimated from NLO cross section
- ★ Non-peaking contributions are estimated from side-band in 105 GeV < m(γγ) < 160 GeV.

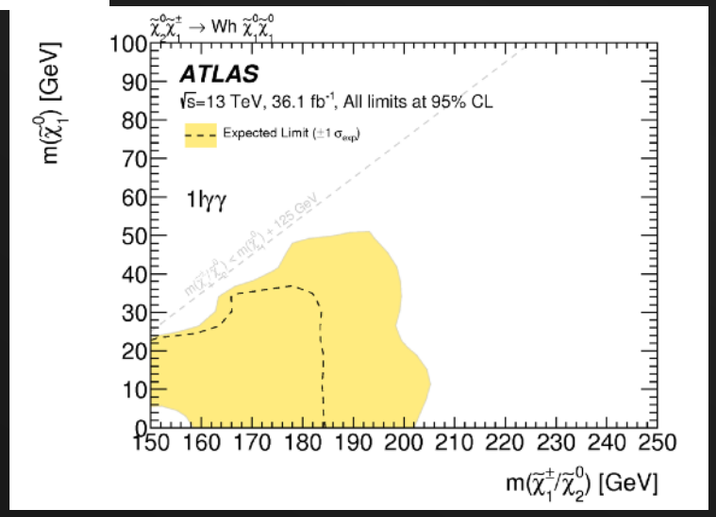



**Mild upper fluctuation observed.**

| SR channels | SR1L$\gamma\gamma$-a | SR1L$\gamma\gamma$-b |
|---|---|---|
| Observed events | 2 | 9 |
| Total bkg events | 0.37 ± 0.22 | 5.3 ± 1.0 |
| $Wh$ background | 0.09 ± 0.01 | 1.8 ± 0.3 |
| Other peaking backgrounds | 0.04 ± 0.01 | 0.19 ± 0.02 |
| Non-peaking background | 0.22 ± 0.22 | 3.3 ± 0.9 |

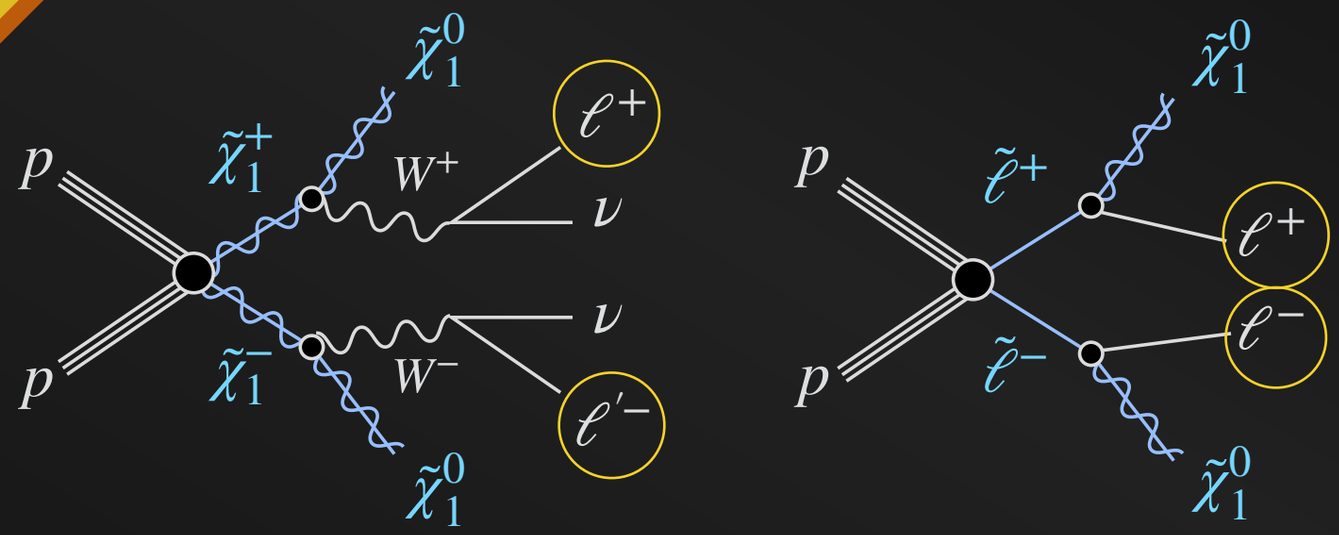
**Discovery $p_0$ values** **0.03 (~1.9σ)** **0.09 (~1.3σ)**

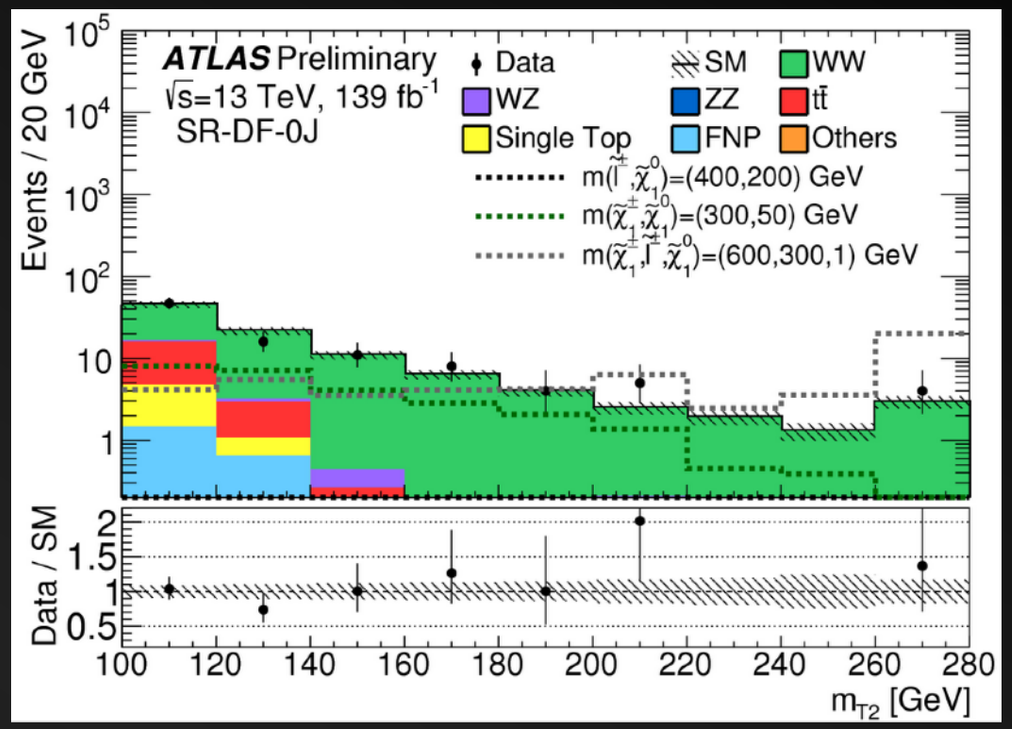


New Full Run2

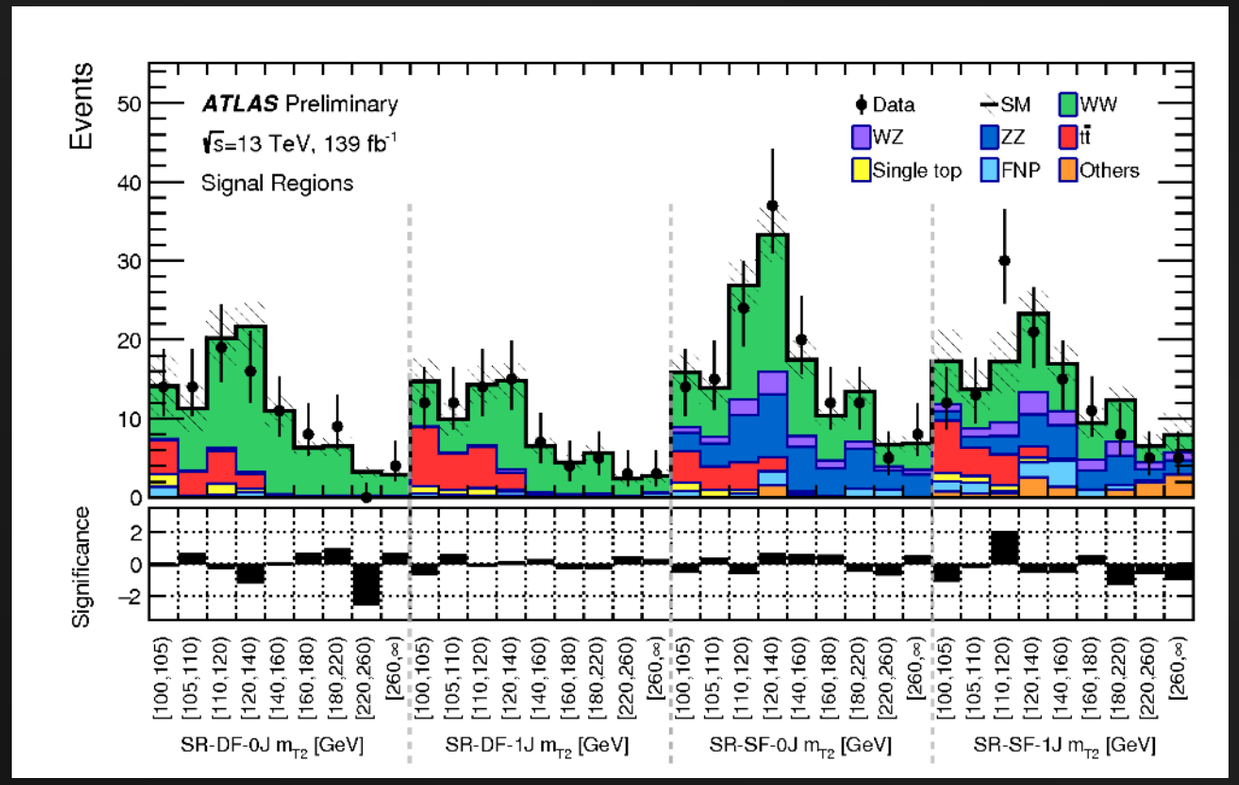
# $WW$, di-lepton + $E_T^{miss}$

ATLAS-CONF-2019-008, 139 fb$^{-1}$




- ★ Opposite-sign di-leptons. Same-flavor (**ee, μμ**; Z-veto) and different-flavour (**eμ**) categories.
- ★ Major backgrounds: **VV** and **tt** (irreducible)
- ★ Di-lepton trigger, both leptons offline $p_T > 25$ GeV
- ★ Di-lepton invariant mass > 25 GeV, $m(Z) \pm 30$ GeV vetoed for SS.
- ★ Allow up to single central light jet (signal region is classified)
- ★ Signal region:
  - ★ $E_T^{miss} > 110$ GeV, $E_T^{miss}$ signif. > 10
  - ★ Stransverse mass $m_{T2} > 100$ GeV
  - ★ SR is binned in $m_{T2}$

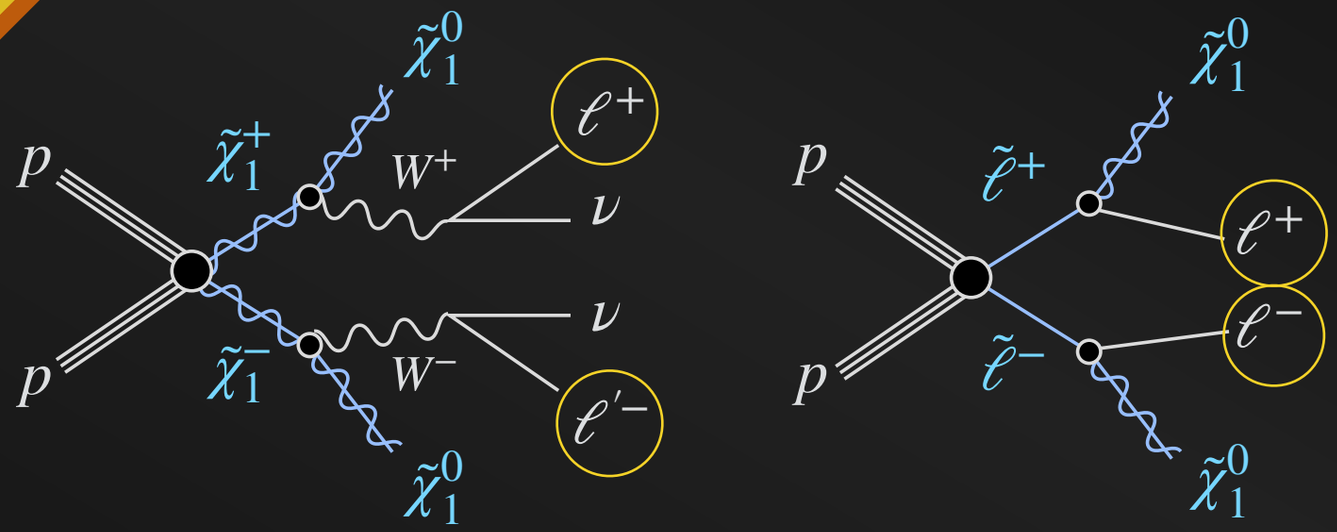


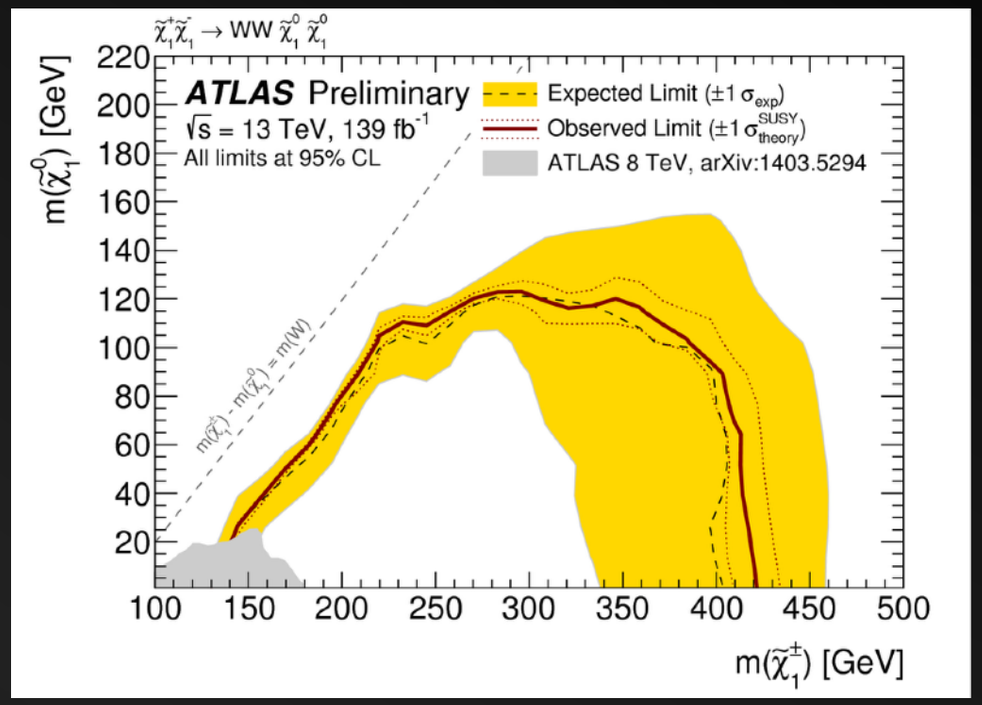

**No significant deviation from the background est.**

New Full Run2

# $WW$, di-lepton + $E_T^{miss}$

ATLAS-CONF-2019-008, 139 fb$^{-1}$




Chargino pair: excluding up to ~420 GeV

- Opposite-sign di-leptons. Same-flavor (**ee, μμ**; Z-veto) and different-flavour (**eμ**) categories.
- Major backgrounds: **VV** and **tt** (irreducible)
- Di-lepton trigger, both leptons offline $p_T > 25$ GeV
- Di-lepton invariant mass > 25 GeV, $m(Z) \pm 30$ GeV vetoed for SS.
- Allow up to single central light jet (signal region is classified)
- Signal region:
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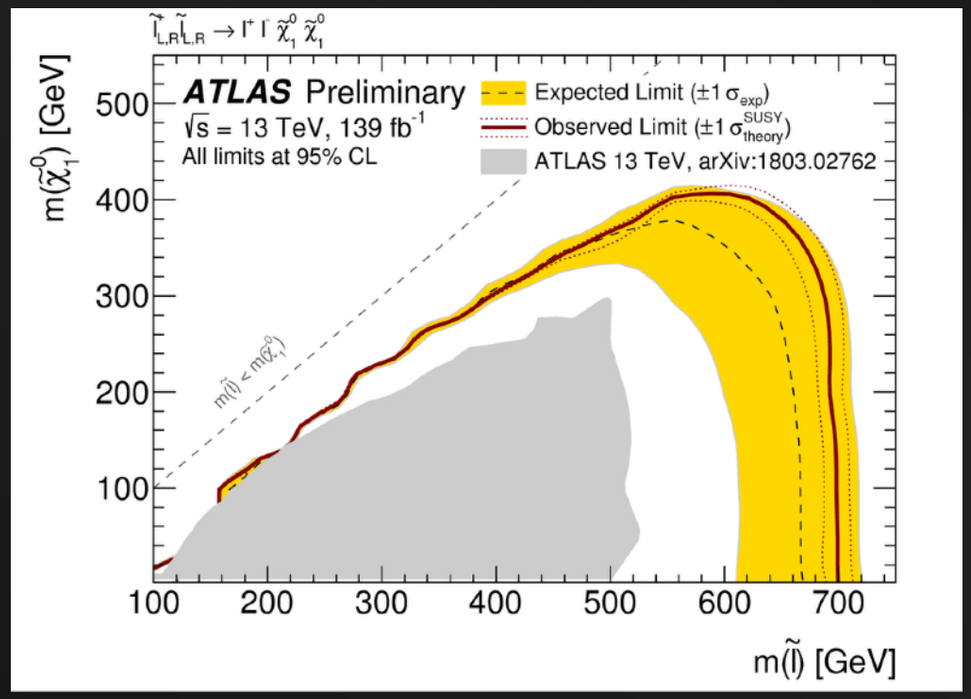
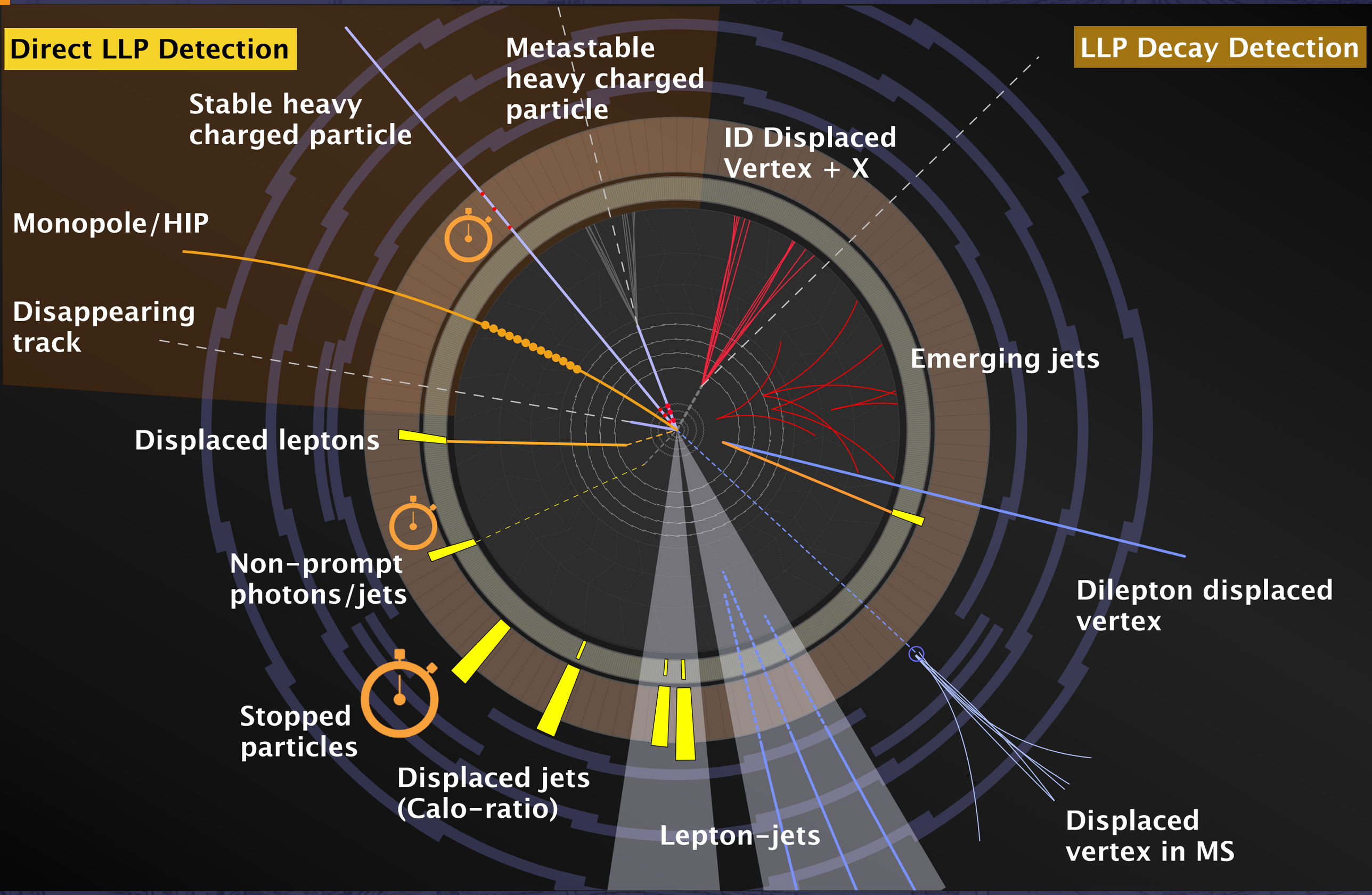



Slepton pair: excluding up to ~680 GeV

# LLP Search Classes

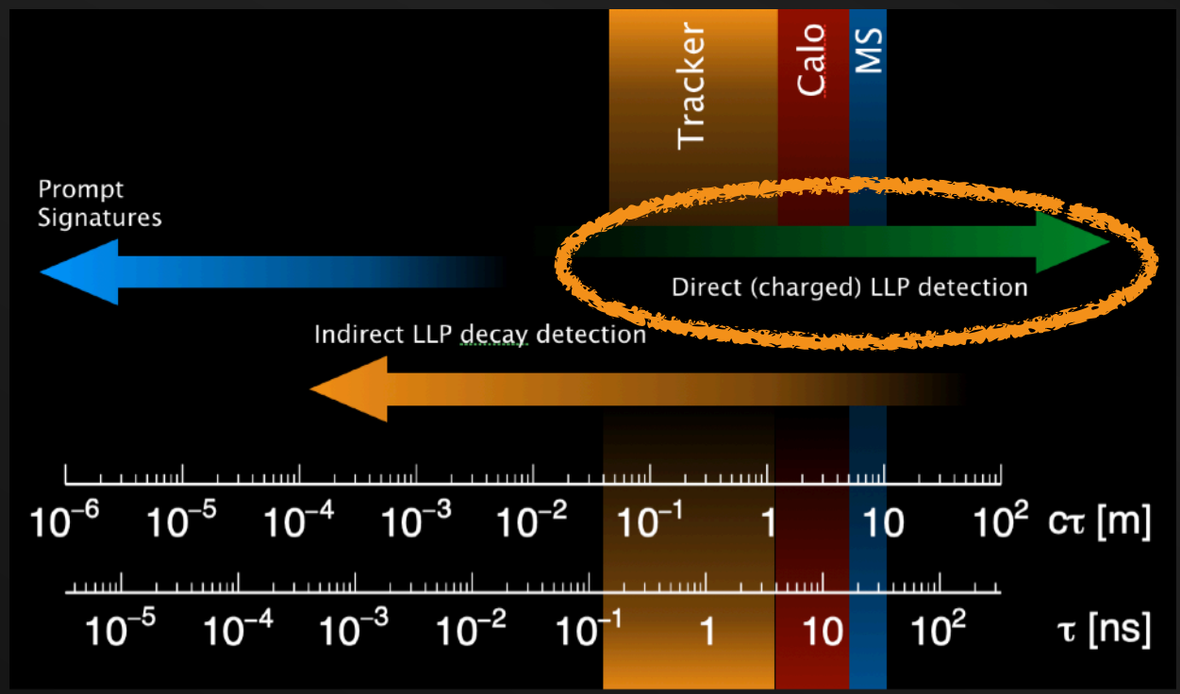


# LLP Search Classes

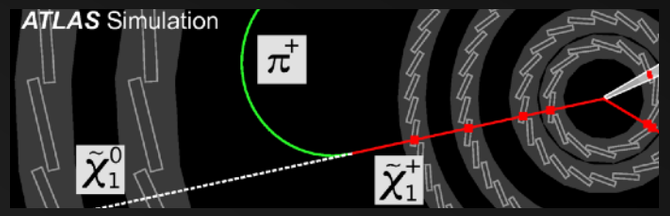
| Ref. Code | | Analysis | $\mathscr{L}$ [fb$^{-1}$] |
|---|---|---|---|
| SUSY-2016-06 | JHEP 06 (2018) 022 | Disappearing track | 36 |
| SUSY-2016-31 | Accepted by PRD | NEW Stable and meta-stable massive charged particles | 36 |
| SUSY-2016-32 | Phys. Lett. B 788 (2019) 96 | Stable massive charged particles (dE/dx + ToF) | 32 |
| EXOT-2017-13 | Phys. Rev. D 99 (2019) 052003 | Multi-charged particle searches | 36 |
| SUSY-2016-08 | Phys. Rev. D 97 (2018) 052012 | Displaced vertex + MET | 33 |
| CONF-2019-006 | — | NEW Displaced vertex + muon | **136** |
| EXOT-2017-25 | Submitted to EPJC | NEW Displaced jets (Calorimeter) | 36 |
| EXOT-2017-24 | Accepted by PRL | NEW Displaced jet (Calorimeter) + Z | 36 |
| EXOT-2017-05 | Phys. Rev. D 99 (2019) 052005 | NEW Displaced jets (Muon Spectrometer) | 36 |
| EXOT-2017-03 | Phys. Rev. D 99 (2019) 012001 | Non-collimated muons | 36 |
| HIGG-2017-05 | JHEP 10 (2018) 031 | h(125) → aa, $a_{(LLP)}$ → bb | 36 |
| CONF-2016-042 | — | Displaced lepton-jets | 3.4 |
| EXO-16-044 | JHEP 08 (2018) 016 | Disappearing track | 35.7 |
| SUS-19-005 | — | NEW Disappearing track | **137** |
| EXO-15-010 | PRD 94 (2016) 112004 | Stable massive charged particles (dE/dx+ToF) | 2.5 |
| EXO-17-018 | PRD 98 (2018) 092011 | Displaced vertex + jets | 38.5 |
| EXO-16-003 | PLB 780 (2018) 432 | Inclusive displaced jets | 2.6 |
| PAS-EXO-16-022 | — | Displaced leptons | 2.6 |
| PAS-EXO-19-001 | — | NEW Delayed jets | **137** |
| EXO-16-004 | JHEP 08 (2018) 130 | Stopped particles | 39 |

# Direct detection of massive charged particles

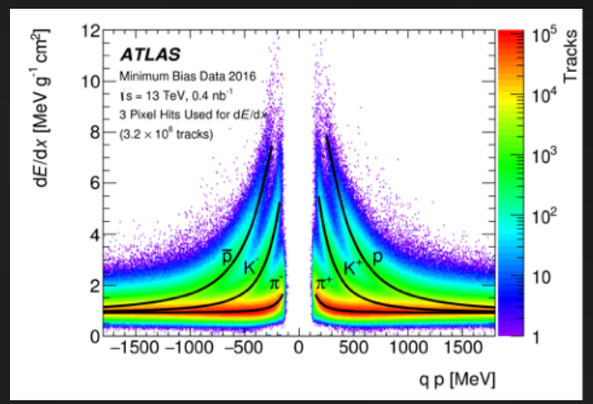
**Lifetime coverage >O(0.1 ns) up to stable. Observables depending on lifeime**



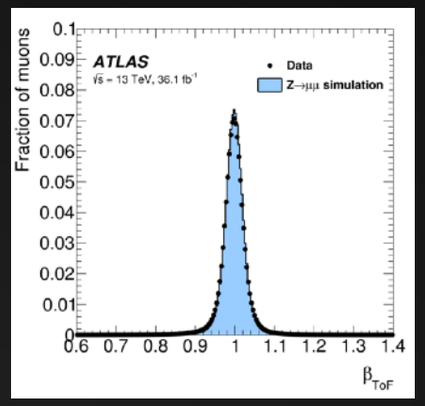

**Short (disappearing) track**

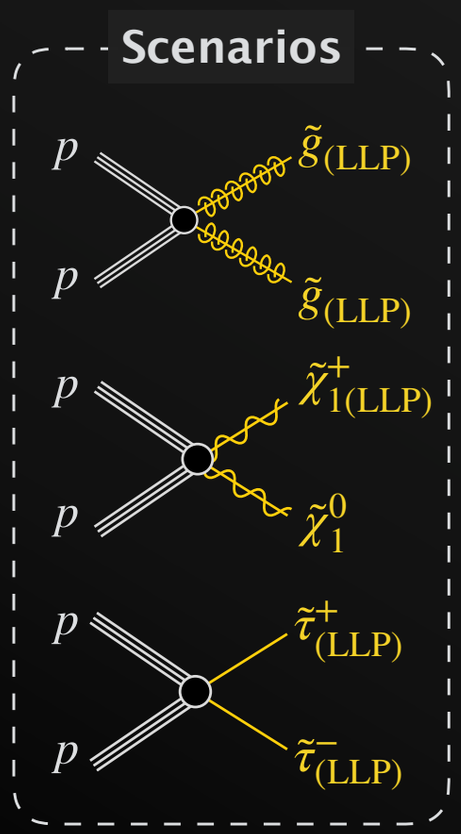



**pixel dE/dx**




**Calo or MS timing**

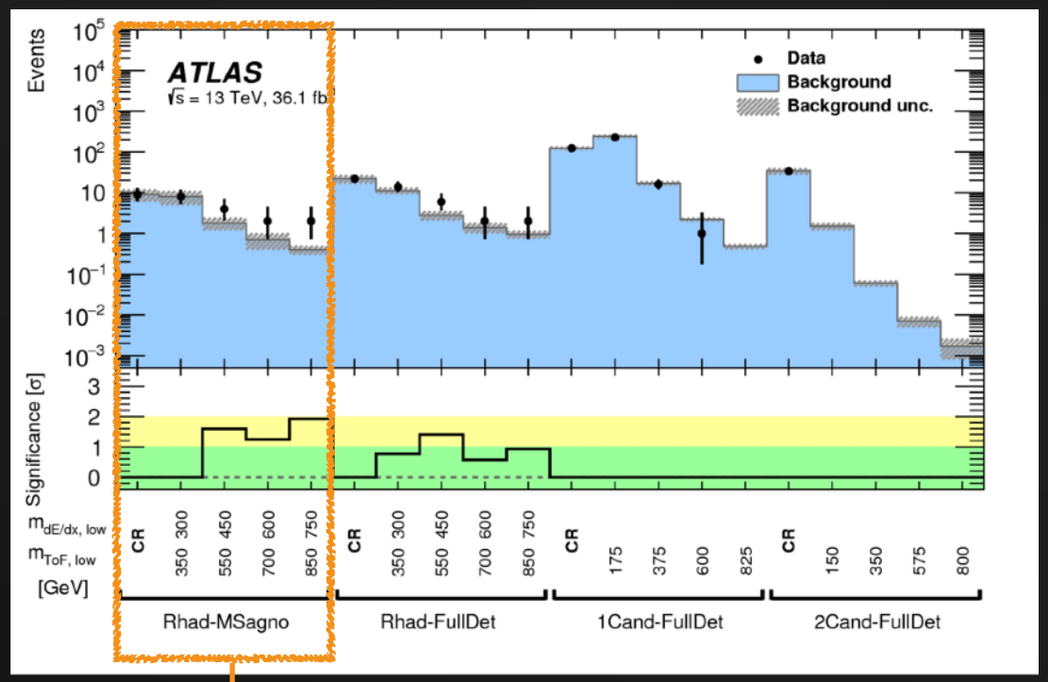


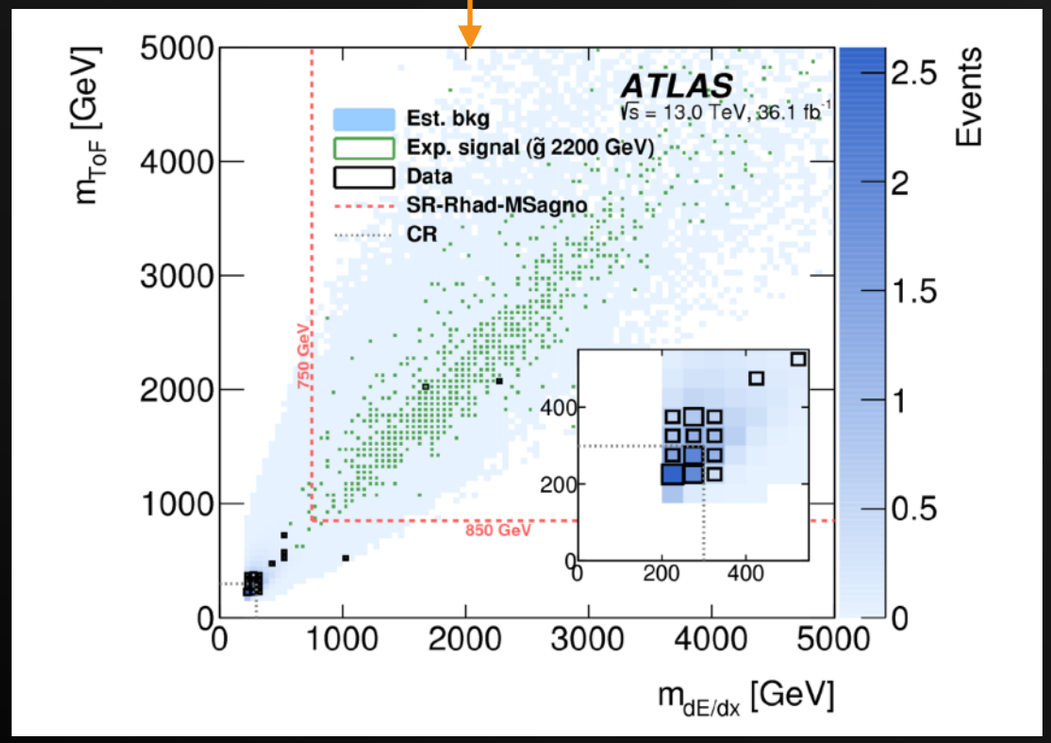




| LLP Observable | Short Track | dE/dx | | | dE/dx & ToF | | ToF | |
|---|---|---|---|---|---|---|---|---|
| Target Lifetime | < 3 ns | < 50 ns | | Stable | Stable | | Stable | |
| Detector | Inner Detector | Inner Detector | | Inner&Muon Trackers | ID+Calo | Full Detector | 1 track Full Det. | 2 track Full Det. |
| Main Target Interpretations | $\tilde{\chi}_1^\pm$ | $\tilde{g}$ $\tilde{t}$ $\tilde{b}$ (R-hadron) | | | | | $\tilde{\chi}_1^\pm$ $\tilde{\tau}^\pm$ | |

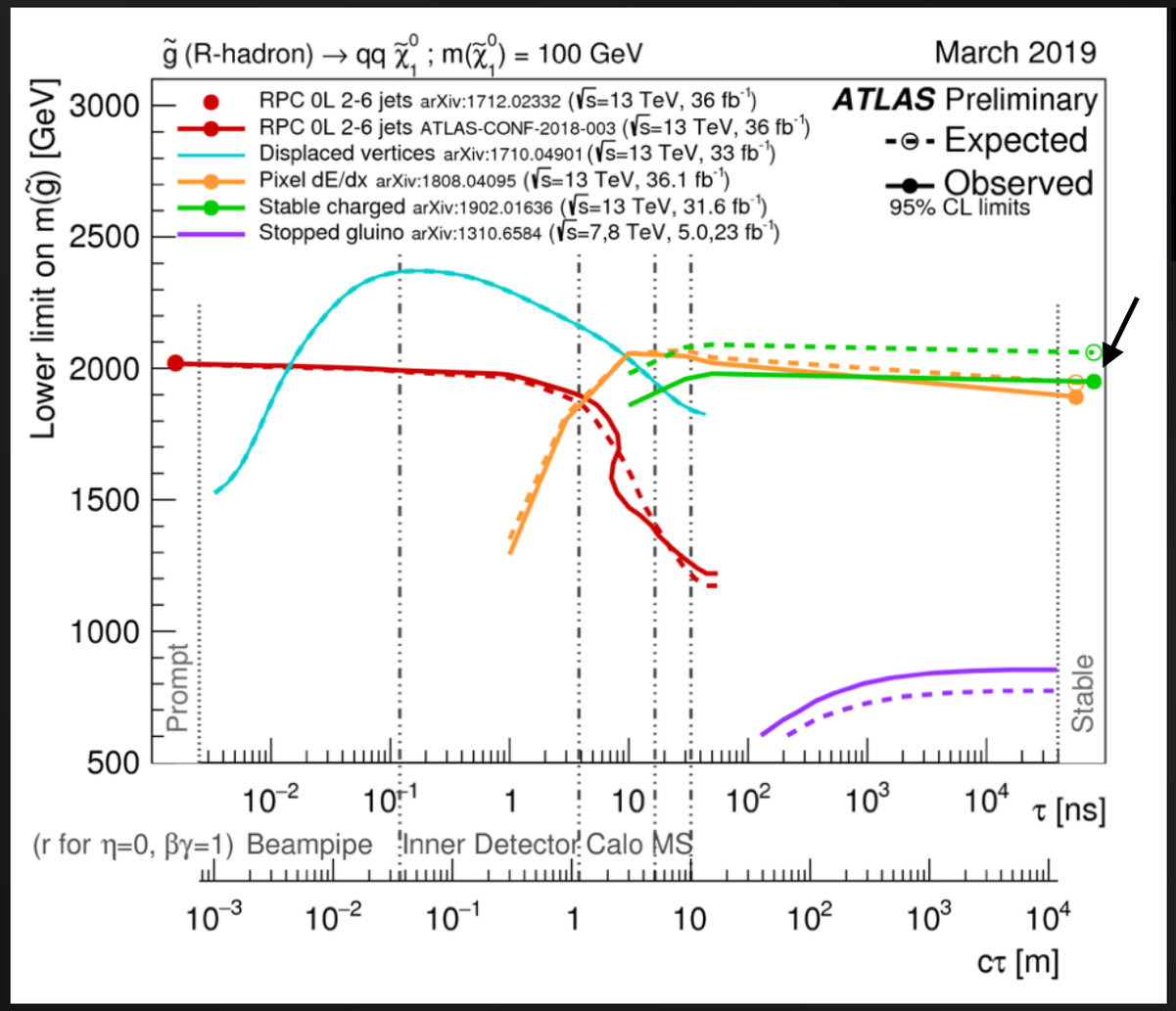
# Direct detection of massive charged particles

**ATLAS-SUSY-2016-032, submitted to PRD, 36fb$^{-1}$**




- ★ Recent update for stable charged particle search using ToF (and dE/dx) for 2015+2016 dataset.
- ★ Various strong limits interpretations for R-hadron, charginos or sleptons depending on signal topologies.



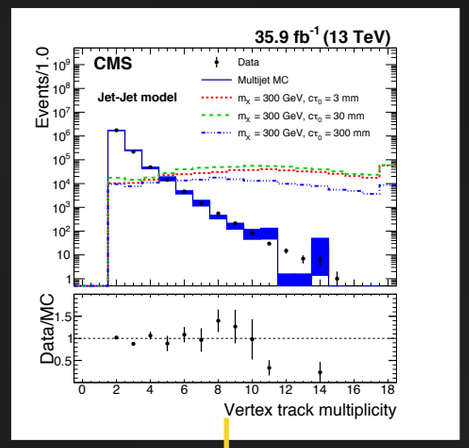

**Stable R-hadron lifetime excluded up to ~2 TeV.**
**Overall quite complementary searches.**

# Displaced vertices with jets

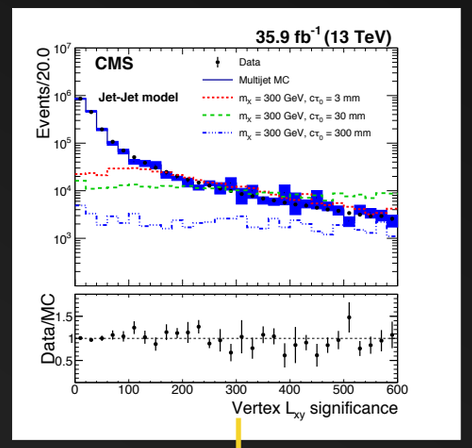
CMS-EXO-18-007, 36fb$^{-1}$


- ★ An inclusive search for displaced jets w/ displaced vertex.
- ★ CMS approach: define displacement likelihood

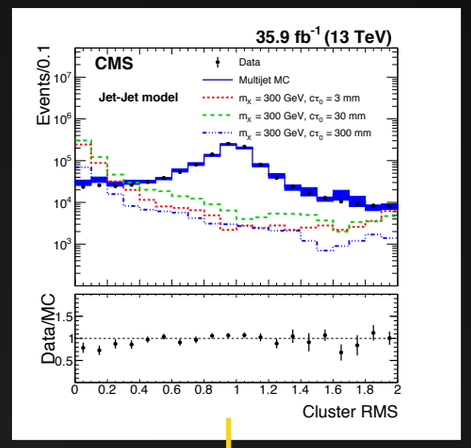
**$N_{track}$**



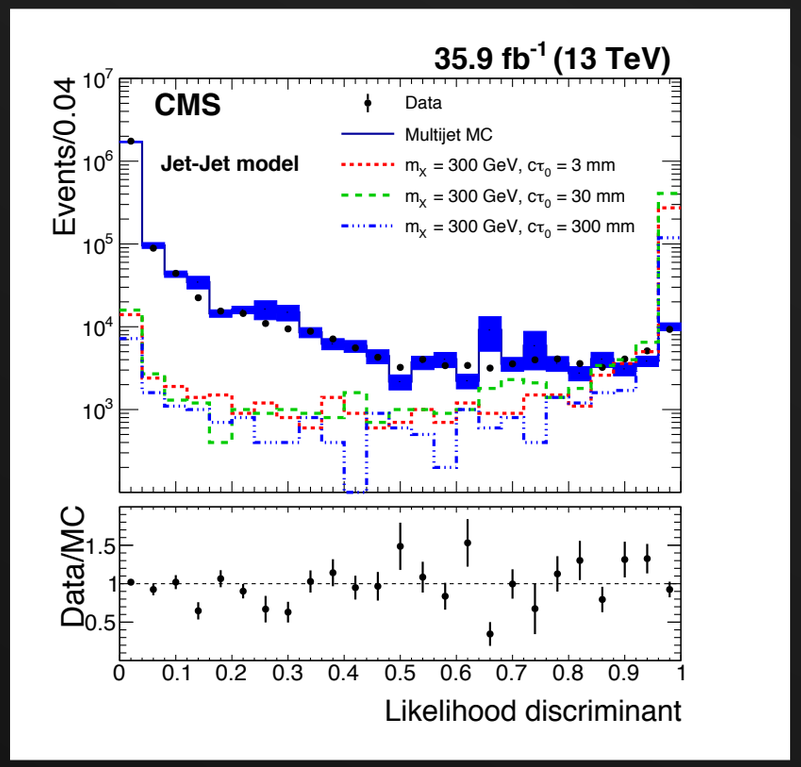

**Displacement signif.**




**Track collimation**




**Combined**



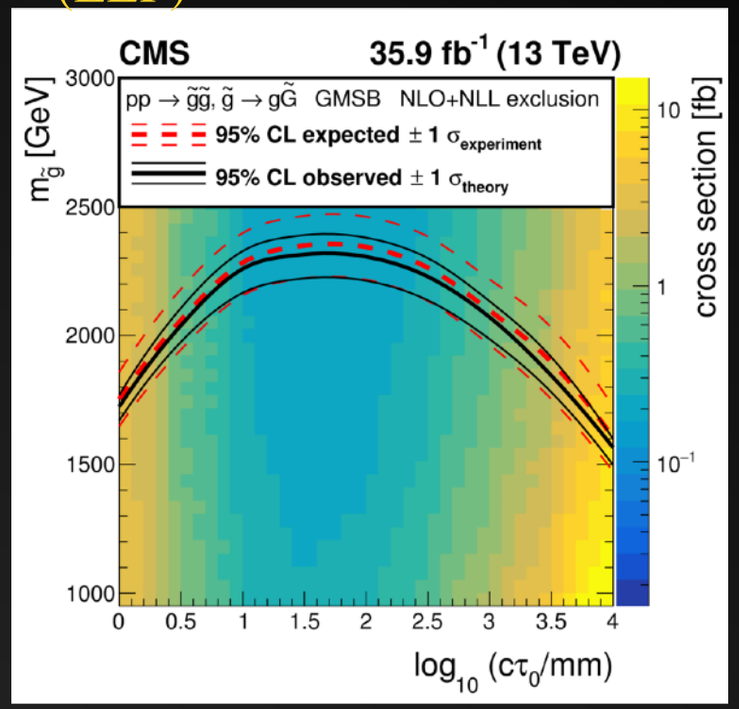
# Displaced vertices with jets

CMS-EXO-18-007, 36fb$^{-1}$

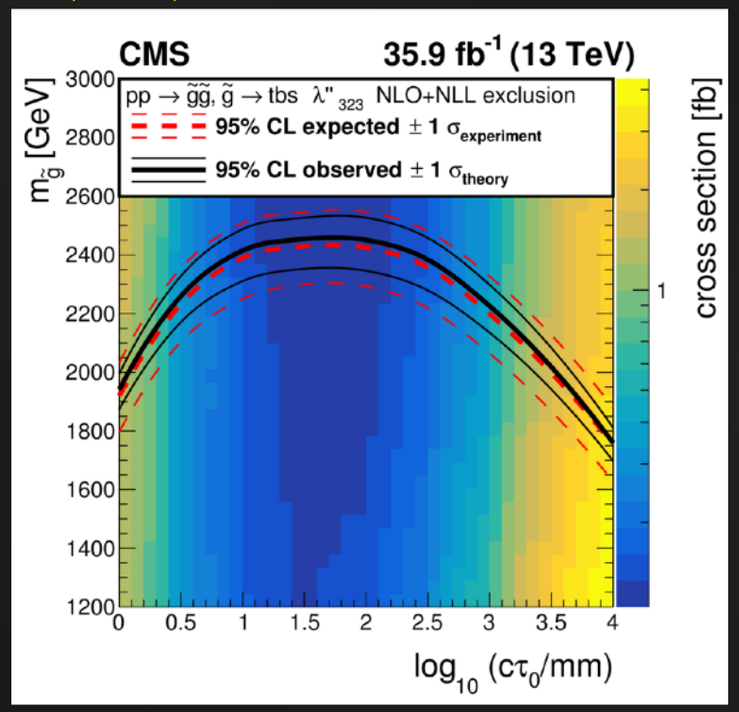
- Dedicated displaced jet HLT:
  - $H_T$ > 350 GeV, ≥2 **displaced jets** w/ $p_T$ > 40 GeV and |η| < 2.0
    (*) displaced jets: associating ≤2 prompt tracks, ≥1 displaced tracks
  - Offline $H_T$ > 400 GeV
- Jet-seeded displaced vertex reconstruction
  - Seed tracks: associated to a di-jet pair,
    IP signif. > 5 or $|d_0|$ > 0.5 mm
  - Vertex mass > 4 GeV and pT > 8 GeV
  - Track's second largest IP signif. > 15
- Charged energy fraction of the di-jet associated with the most compatible primary vertices (sort of displaced version of "jet-vertex fraction").
- Displaced jet likelihood score > 0.9993

| Selection on $H_T$ | Number of dijets | Expected | Observed |
|---|---|---|---|
| $400 < H_T < 450$ GeV | 1 | $0.42 \pm 0.14$ (stat) $\pm 0.01$ (syst) | 0 |
| $450 < H_T < 550$ GeV | 1 | $0.23 \pm 0.08$ (stat) $\pm 0.07$ (syst) | 0 |
| $H_T > 550$ GeV | 1 | $0.19 \pm 0.07$ (stat) $\pm 0.05$ (syst) | 1 |
| — | >1 | $0.16 \pm 0.11$ (stat) $\pm 0.06$ (syst) | 0 |

$\tilde{g}_{(\mathrm{LLP})} \to g\tilde{G}$




$\tilde{g}_{(\mathrm{LLP})} \to tbs$



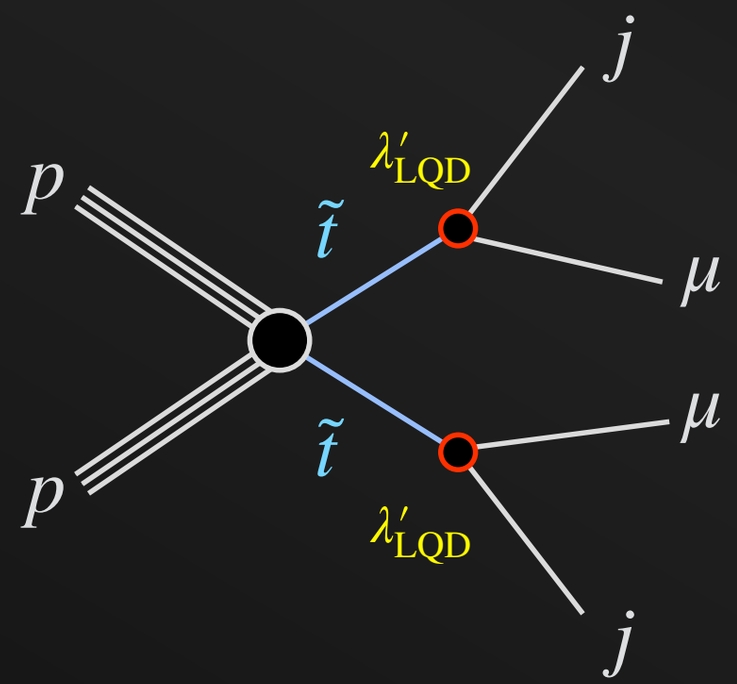

**Observed events in the SRs are consistent with data-driven estimated QCD background yields.**
**Excluded ~2.3 TeV GMSB $\tilde{g}_{(\mathrm{LLP})} \to g\tilde{G}$**
**~2.4 TeV RPV (UDD) $\tilde{g}_{(\mathrm{LLP})} \to tbs$**

New Full Run2

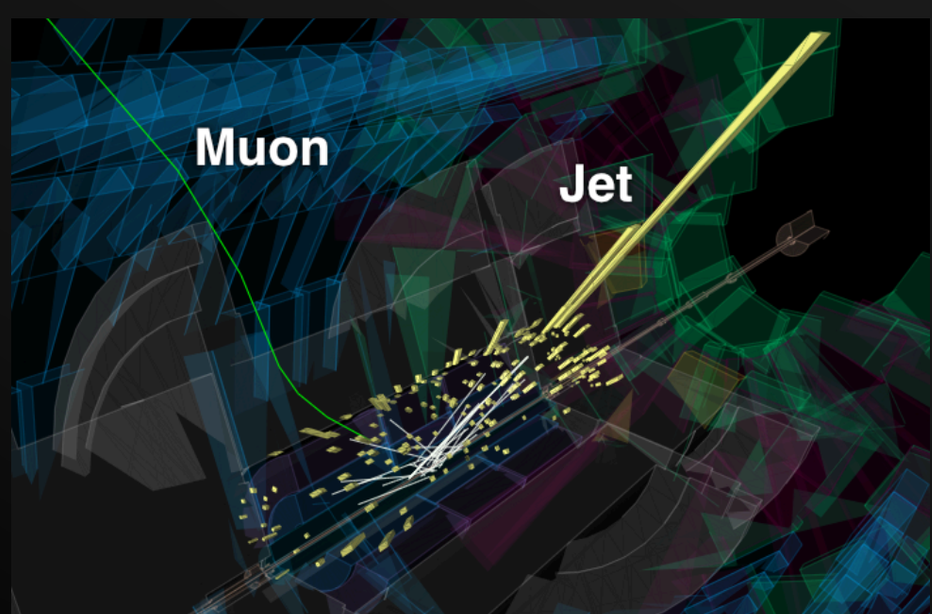
# Displaced vertices with muons

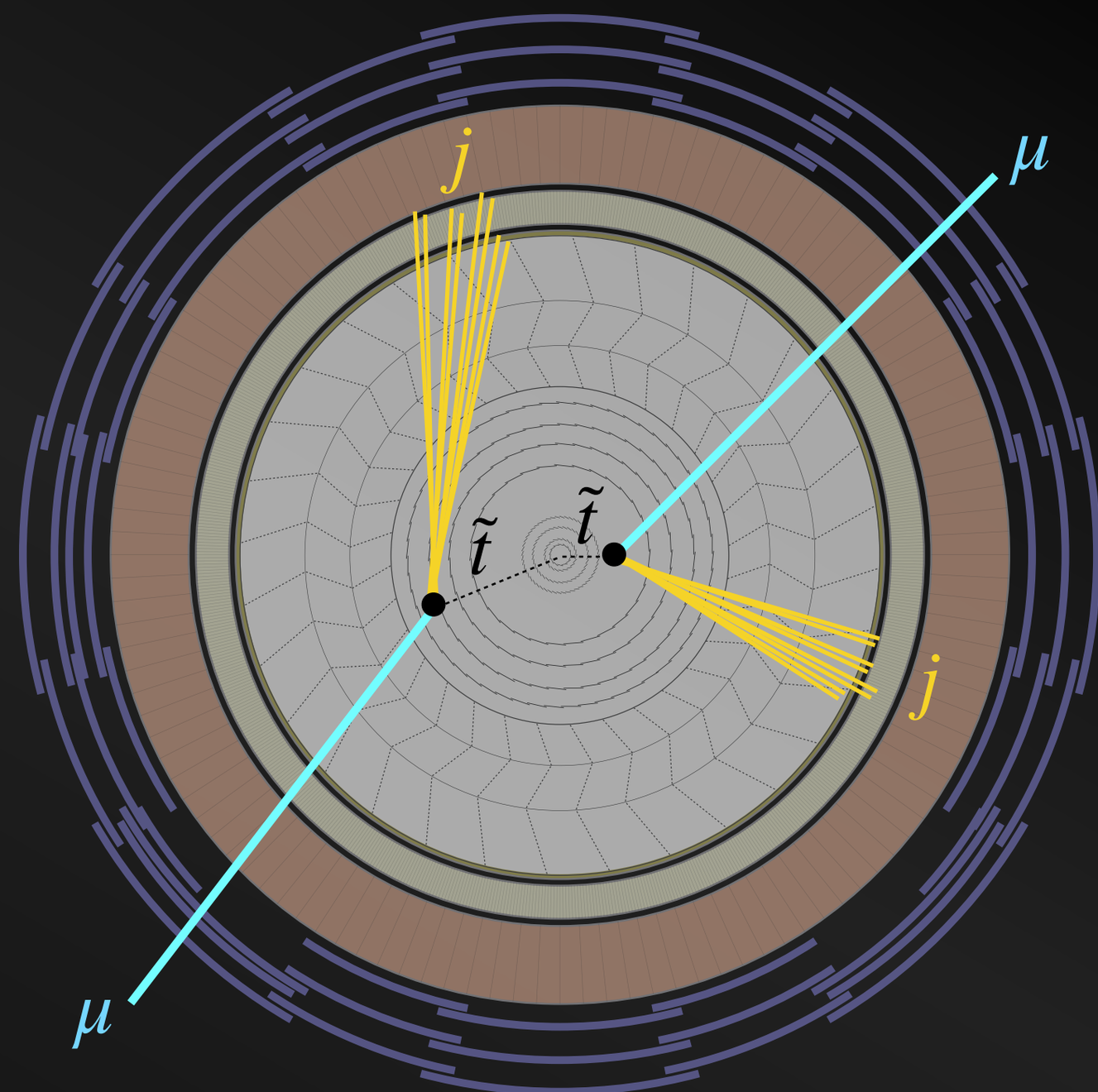
ATLAS-CONF-2019-006, 136fb$^{-1}$

**Benchmark model:**
**A tiny RPV coupling would make stop alive for O(1ns)**




$$\tau(\tilde{t}) \sim \left(\frac{500\ \mathrm{GeV}}{m(\tilde{t})}\right)\left(\frac{10^{-7}}{\lambda'_{23k}}\right)^2\left(\frac{0.12}{\cos^2\theta_t}\right)\times 10^{-3}\ \mathrm{ns}$$



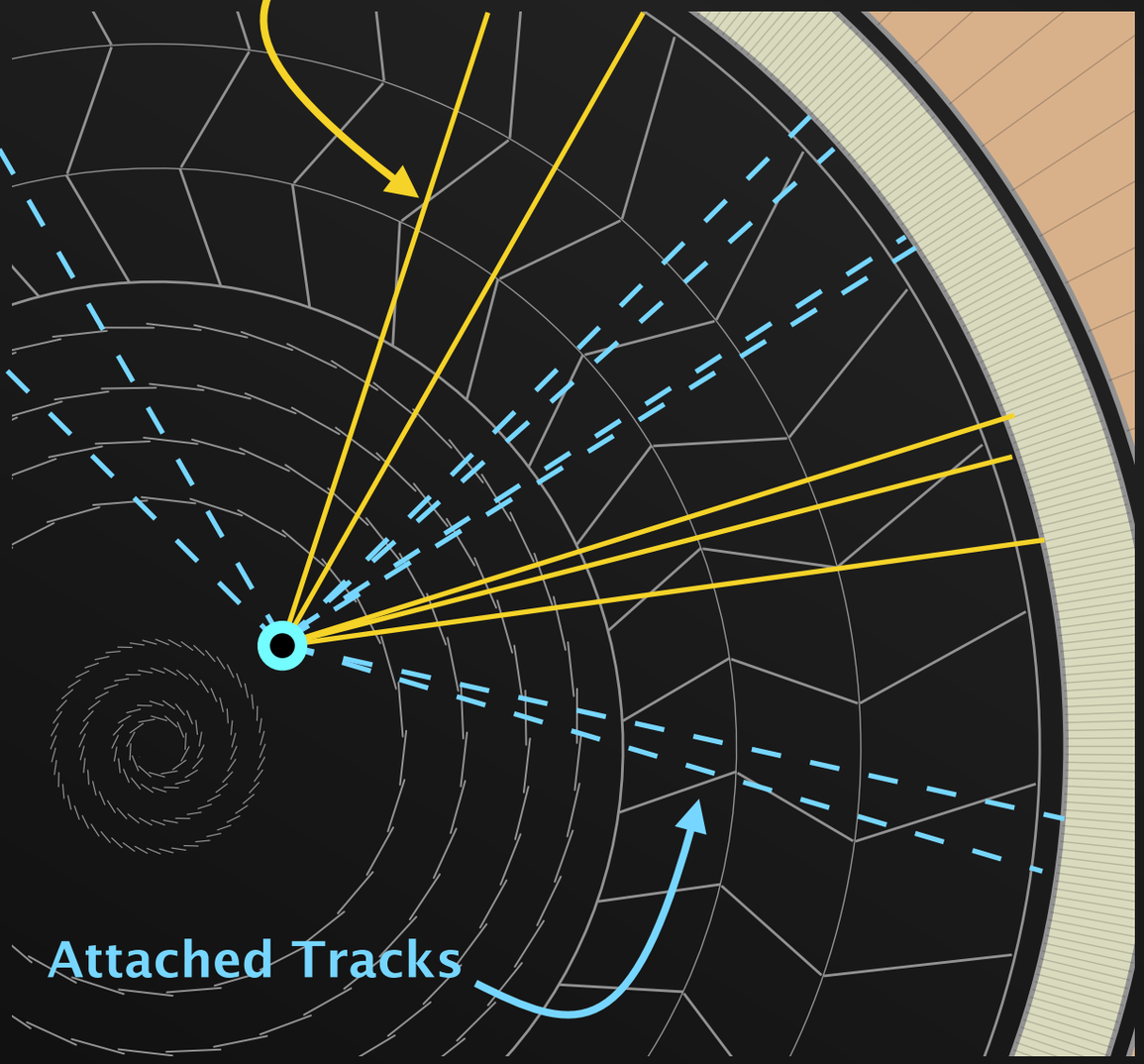

**Signal DV: r > 4 mm, ≥3 tracks, $m_{vis}$ > 20 GeV and isolated non-prompt muon (decent cosmic ray veto)**

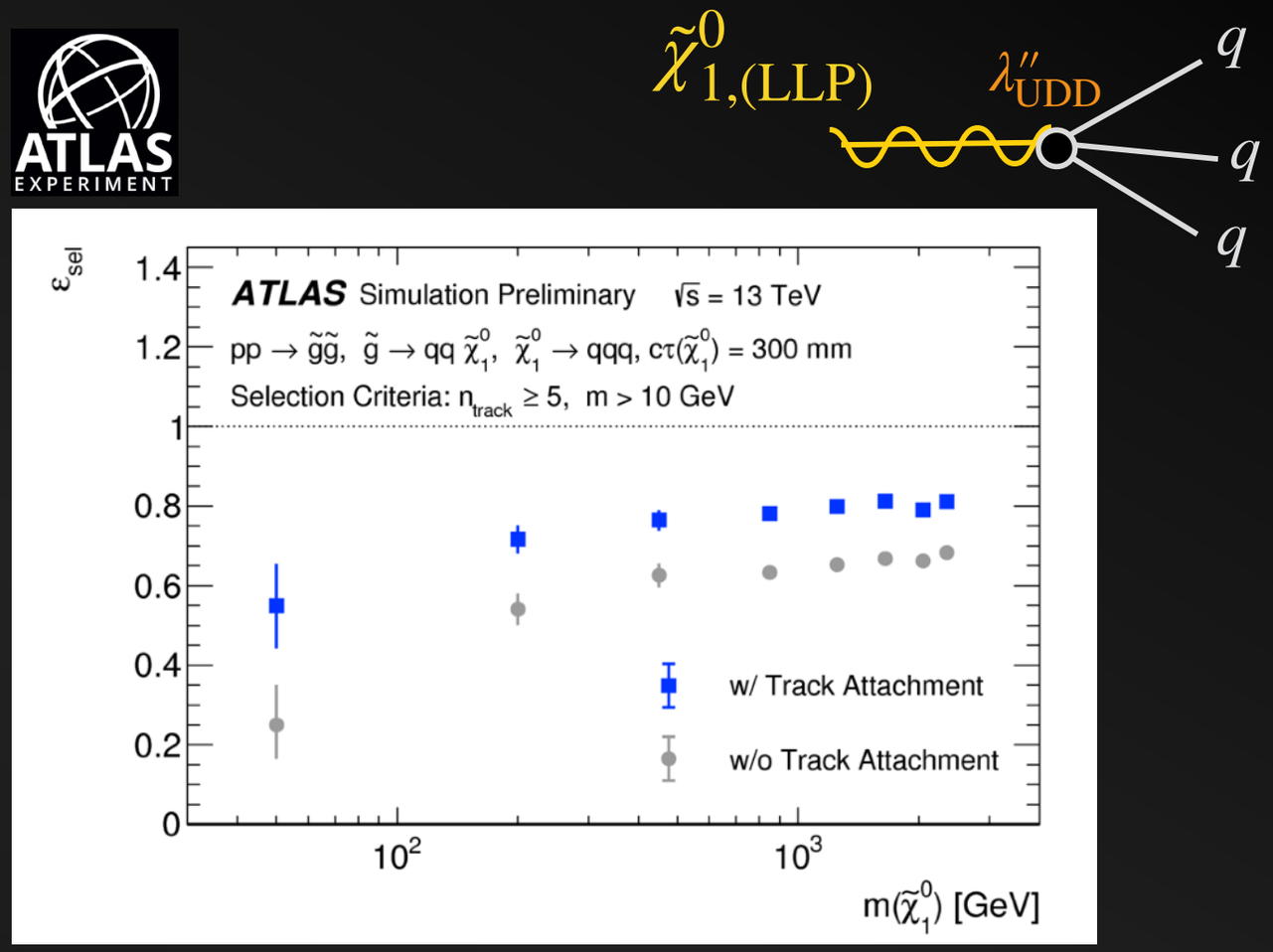
**Resembling BGs: cosmic, b-jets, instrumental fakes**

New Full Run2

# Displaced vertices with muons

ATLAS-CONF-2019-006, 136fb$^{-1}$




ATL-PHYS-PUB-2019-013

**For DV+μ: around 20-30% of the signal efficiency recovery.**

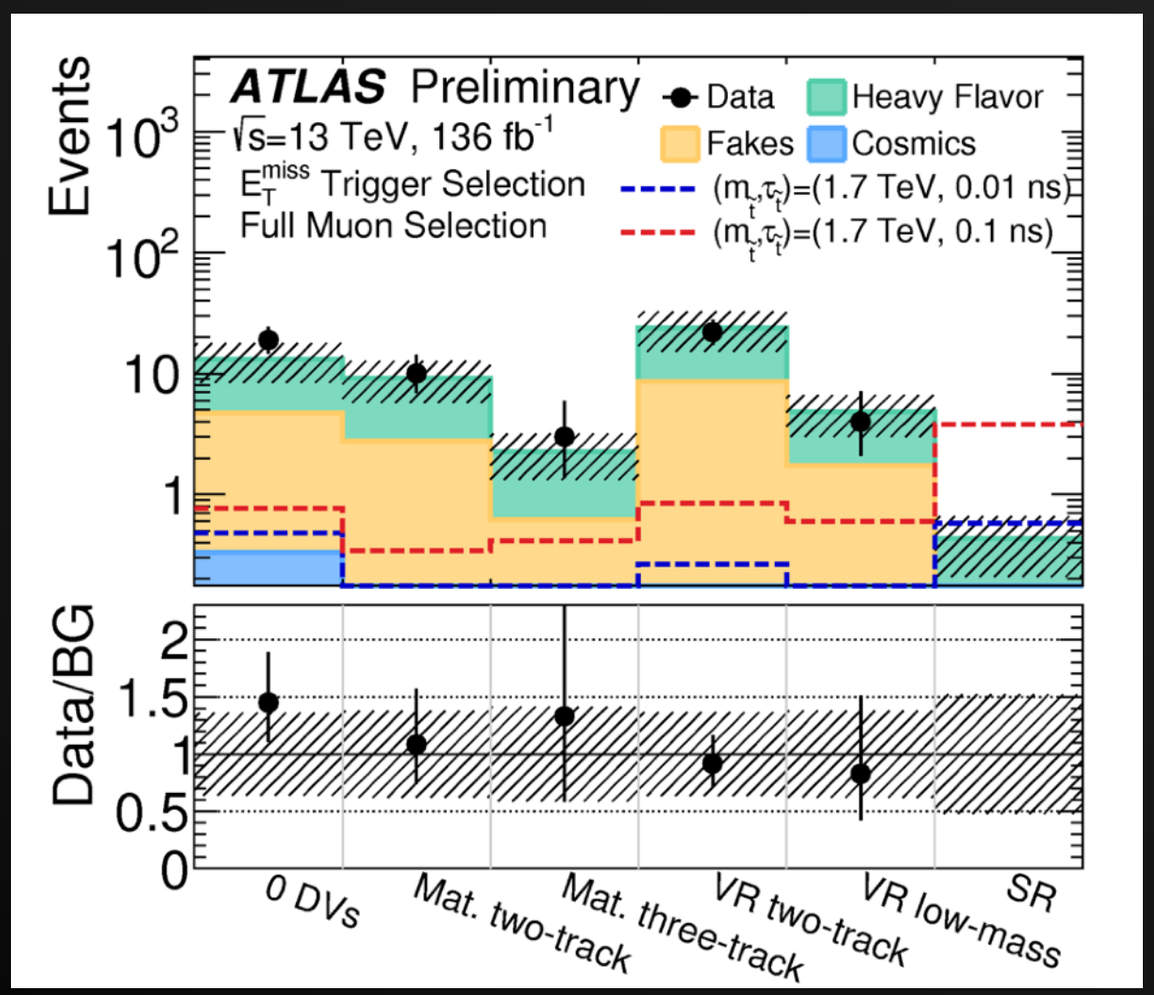
★ For full Run-2 DV analyses: a significant improvement in the vertex reconstruction algorithm in enriching vertex properties of multiplicity and mass.

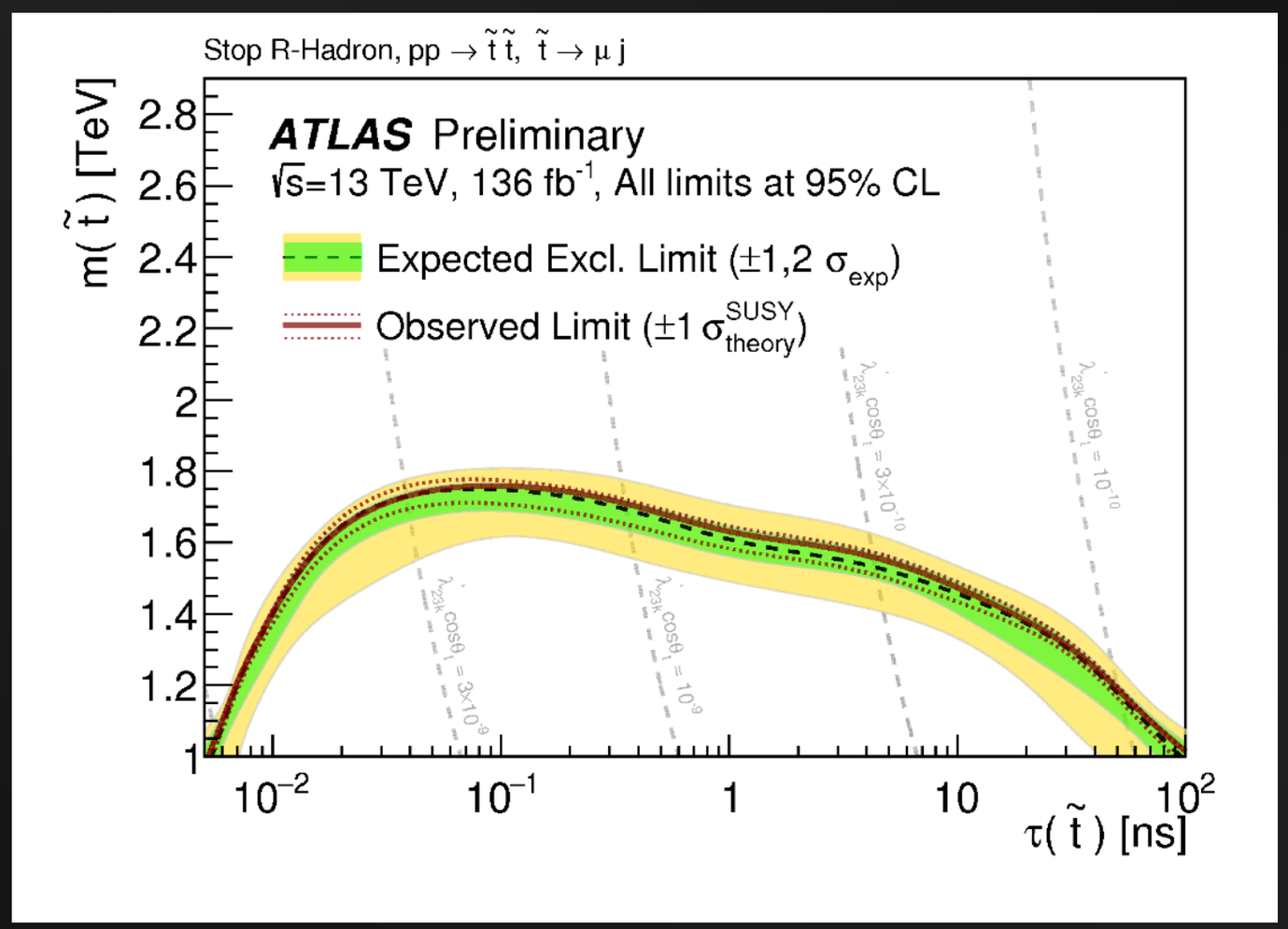
New Full Run2

# Displaced vertices with muons

ATLAS-CONF-2019-006, 136fb$^{-1}$

- ★ MET or displaced muon trigger; exclusive 2 SRs. Cosmic ray veto + hadronic interaction veto.
- ★ Robust data-driven background estimation for 3 exclusive categories (transfer factor from CR to SR for each of cosmic, heavy-flavor, fake Bkg components)
- ★ SR yields are consistent with background estimation.
- ★ Excluding stop mass up to **1.75 TeV** around ~0.1 ns lifetime.

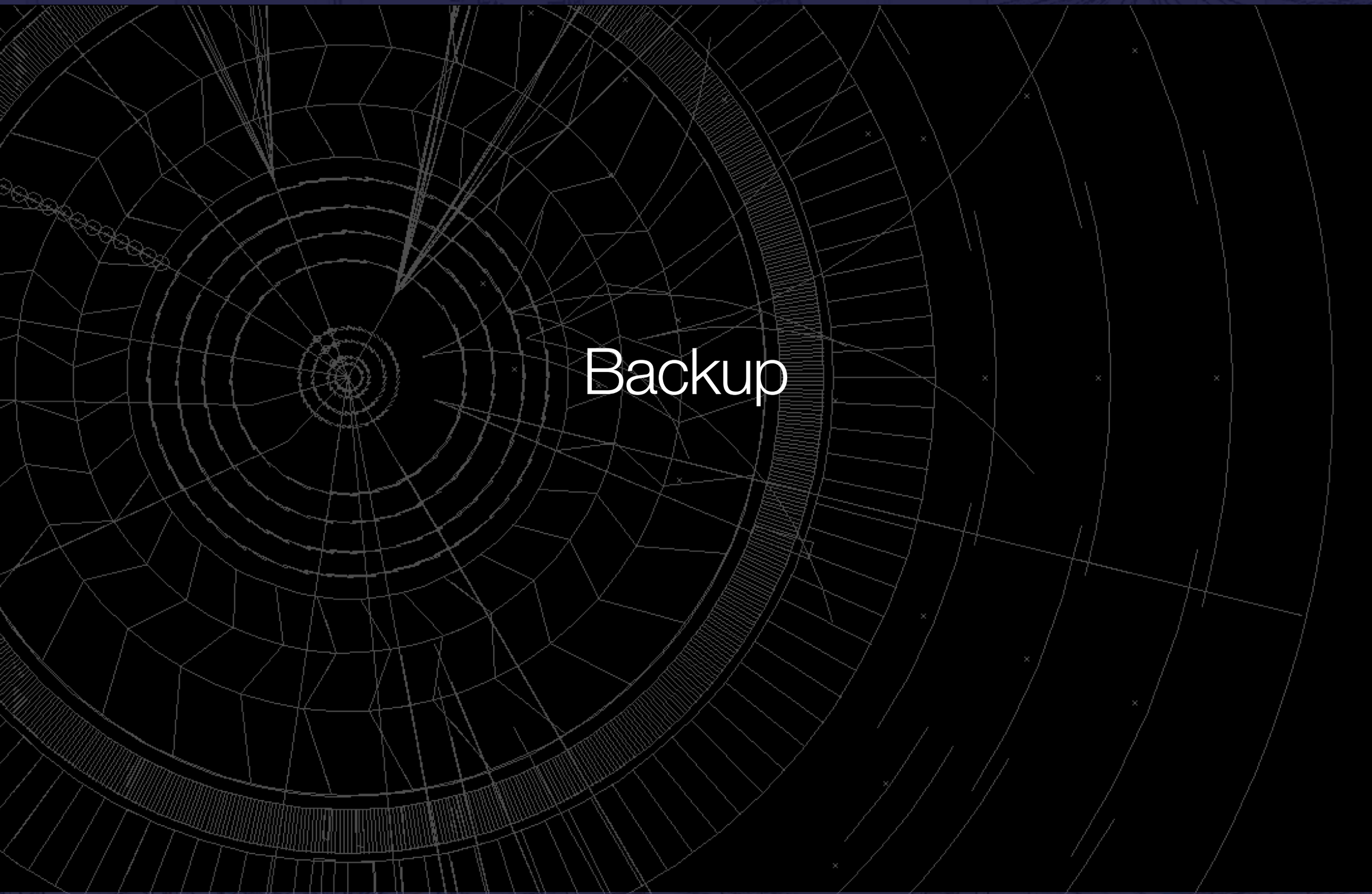


# Summary

- CMS and ATLAS have been performing wide-range SUSY searches.
  - Today I focused on most-recent results.
- Quite strong limits have been set so far, including R-parity-violating or long-lived scenarios (incl. other BSM scenarios).
- Unfortunately, no SUSY/BSM discovery so far…
- Early preliminary full Run-2 dataset results were presented, with new ideas or techniques.
- More of full dataset analyses expected to come…

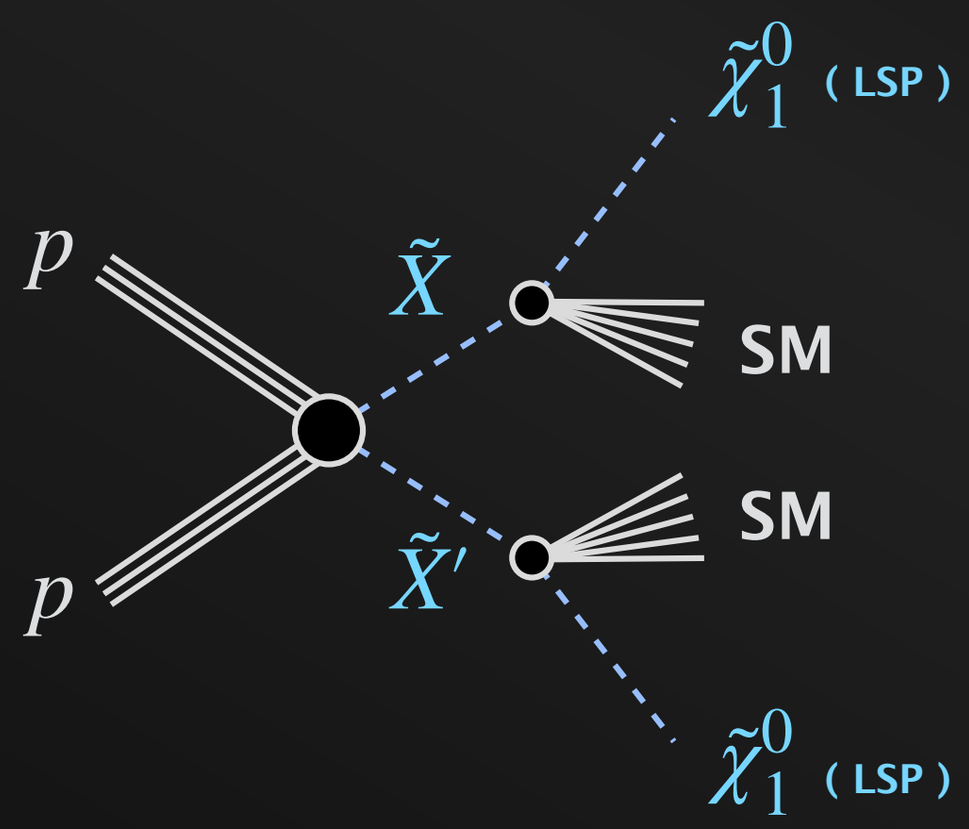
**Stay Tuned!**



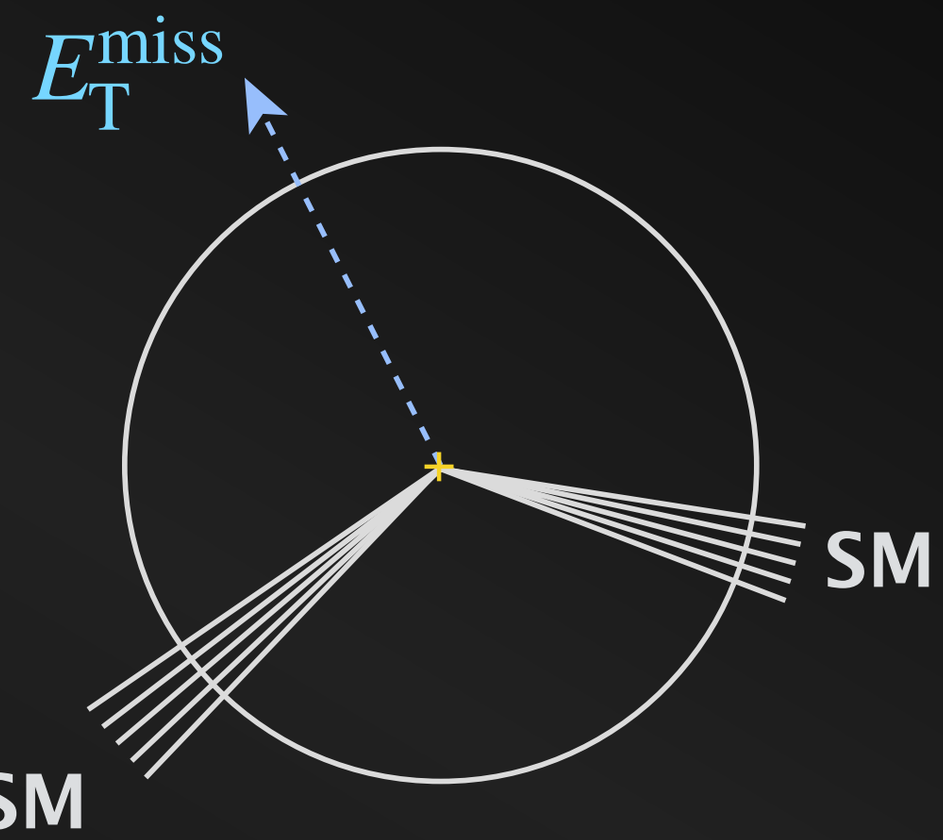
# Backup

# SUSY searches in LHC

— Simplified Production Diagram —



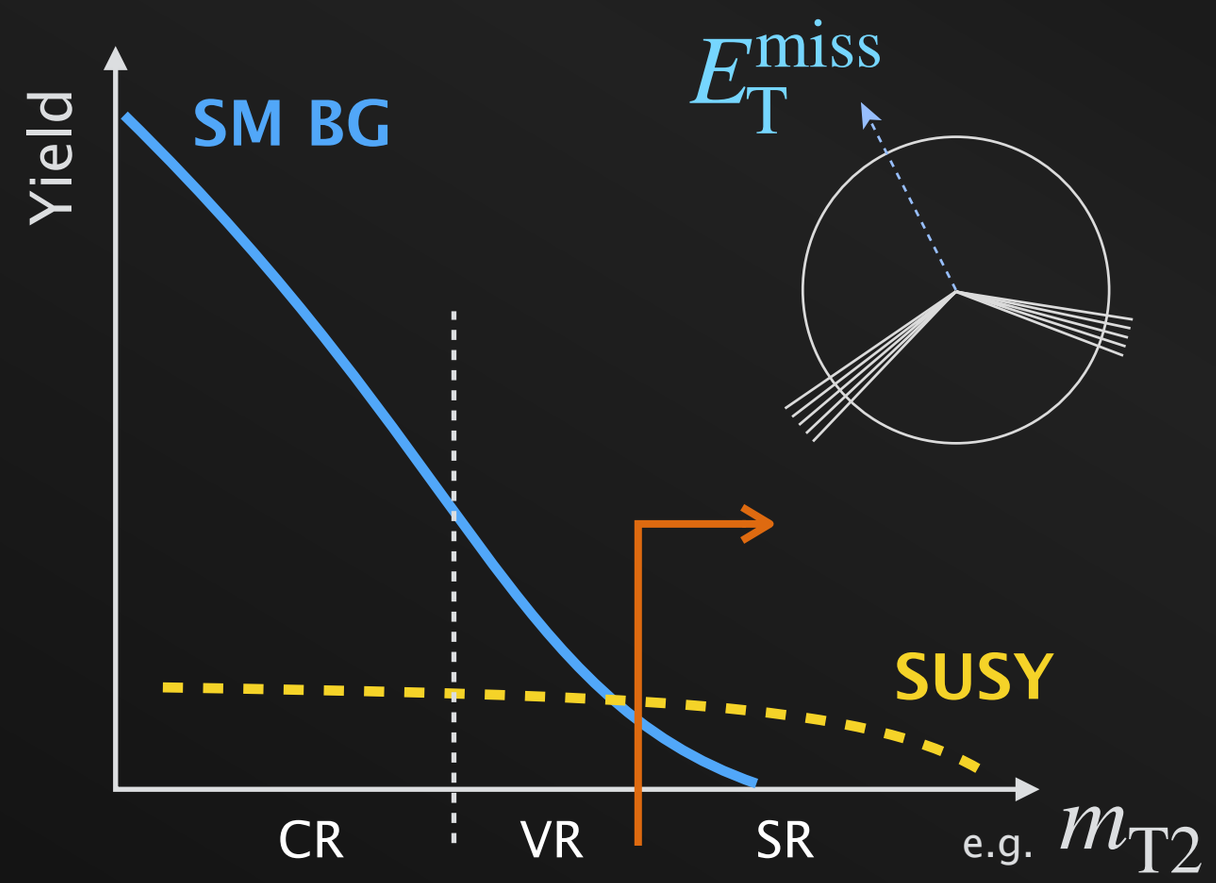

— Simplified Event Topology —



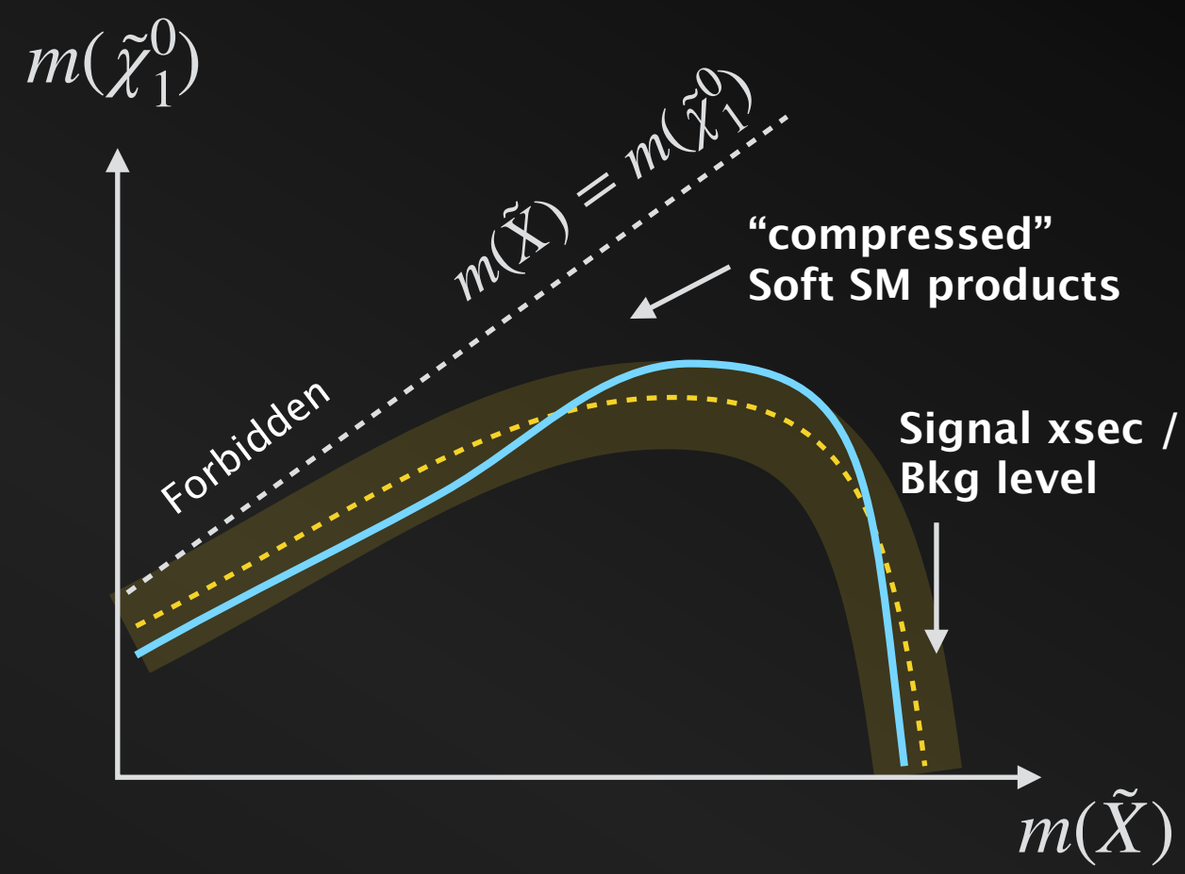

- ★ Usual to assume $R$-parity is conserved: a **pair-production** of sparticles results in final states with **2x LSPs**, yielding a **significant** $E_{\mathrm{T}}^{\mathrm{miss}}$.
- ★ Can suppose versatile sparticle mass spectra: branch search analyses depending on the characteristic of the visible (SM) final-state objects.
- ★ On top of general/comprehensive searches, dedicated searches for specifically interesting phenomenological scenarios.

# SUSY searches in LHC

— Typical Analysis Scheme —




— Typical Sensitivity Limit —




- ★ Most classically, select/optimize the signal regions where the SM backgrounds deplete while a good SUSY acceptance is ensured.
- ★ Estimate the background yields using various control regions.
  - ★ Validate the BG estimation of each enriched sub-component in the vicinity of signal regions (VRs).
- ★ Unblinding SRs after validating the BG estimation.
  - ★ Exclusion limits are drawn if no significant excess is observed.

# The *R*-parity violation

R-parity-violating (RPV) superpotential

- ★ No fundamental reasons to prohibit RPV from QFT — if R-parity conserves, it's **accidental**.
- ★ Large constraints from low-energy limits e.g. proton decay at Super KamiokaNDE.

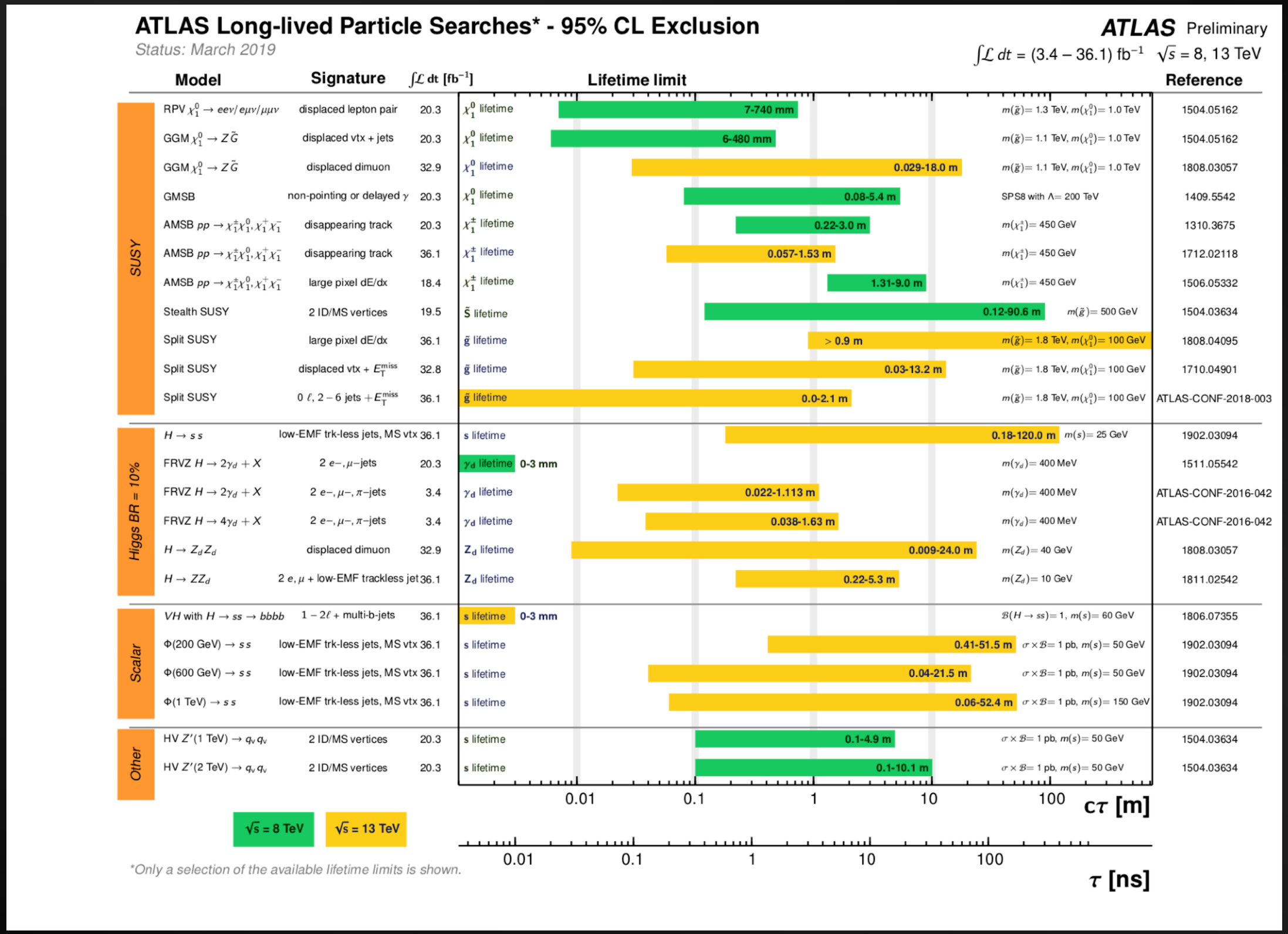
$$\mathcal{W}_{\mathrm{RPV}} = \underbrace{\mu_i l_i h_u}_{\text{bilinear}} + \underbrace{\lambda_{ijk} l_i l_j \bar{e}_k}_{\text{LLE}} + \underbrace{\lambda'_{ijk} l_i q_j \bar{d}_k}_{\text{LQD}} + \underbrace{\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}_{\text{UDD}}$$

- ★ Different topologies compared to R-parity-conserving (e.g. not always $E_{\mathrm{T}}^{\mathrm{miss}}$ ).
- ★ In LHC searches, usually assume only a specific RPV term and search for it.
- ★ Some signatures are similar to lepto-quark pair production or RPC-SUSY scenarios.

# Long-lived cases

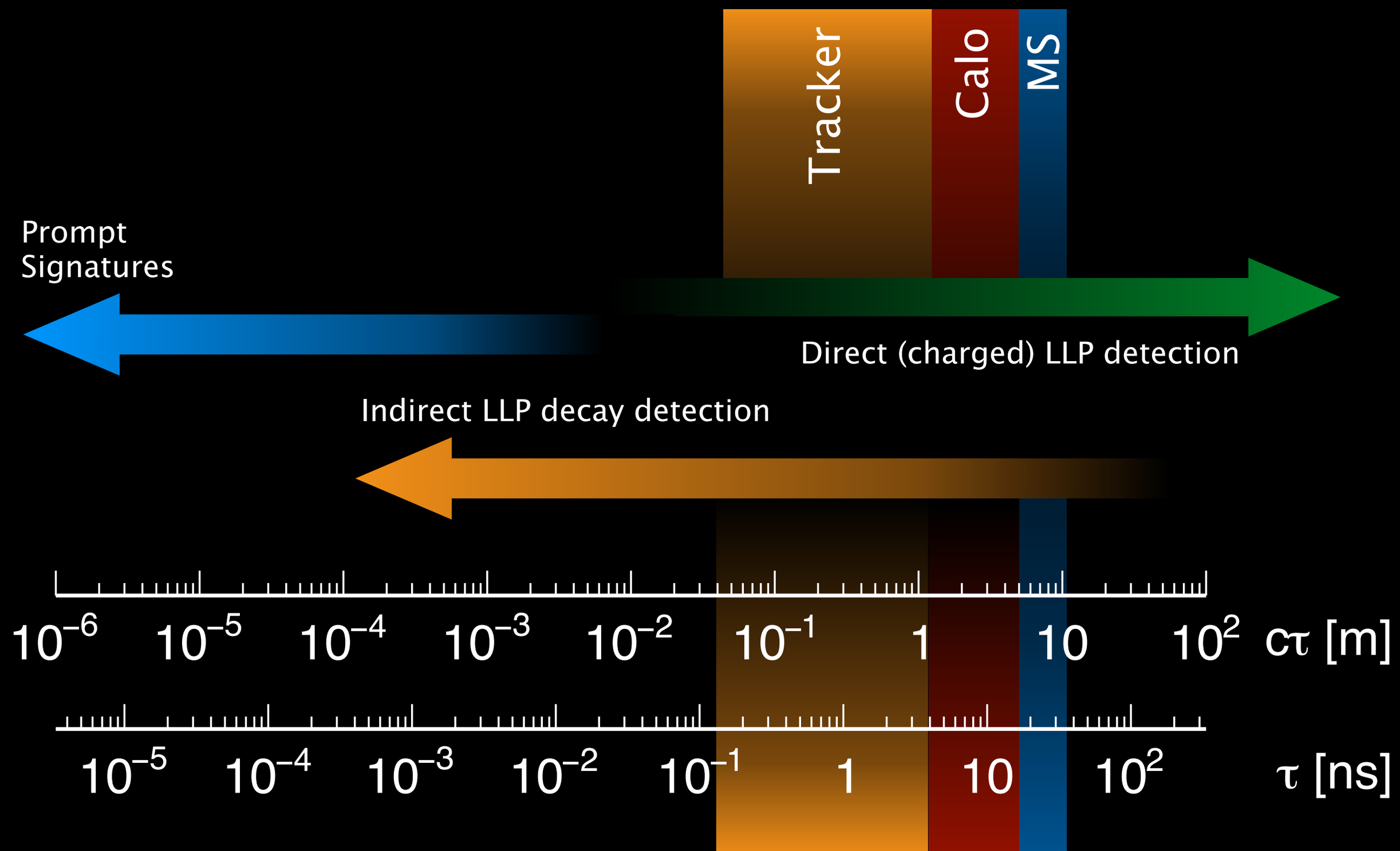
- Many BSM scenarios have a possibility of creating a BSM particle with a macroscopic or stable lifetime (i.e. very narrow decay width) in the LHC.
- Given that comprehensive searches are demanded, the importance of long-lived particle searches have been highlighted in recent years.
- Pros:
  - A unique probe to super-compressed or small coupling BSM scenarios.
  - In many cases, zero or small SM backgrounds can be achieved; can expect extension of search sensitivity as luminosity gains.
- Cons:
  - The LHC experiment program isn't primarily designed/optimized to perform long-lived scenarios. Sensitivity is largely determined by the geometry.
  - Often dedicated techniques are needed, and cares are needed in understanding of reconstruction and specialized data flow.
  - Backgrounds are often instrumental, cosmic ray: hard to predict using common MC simulations. Need to know your instruments, and in many cases data-driven background estimation is required.

# Lifetime summary



# Geometry and lifetime

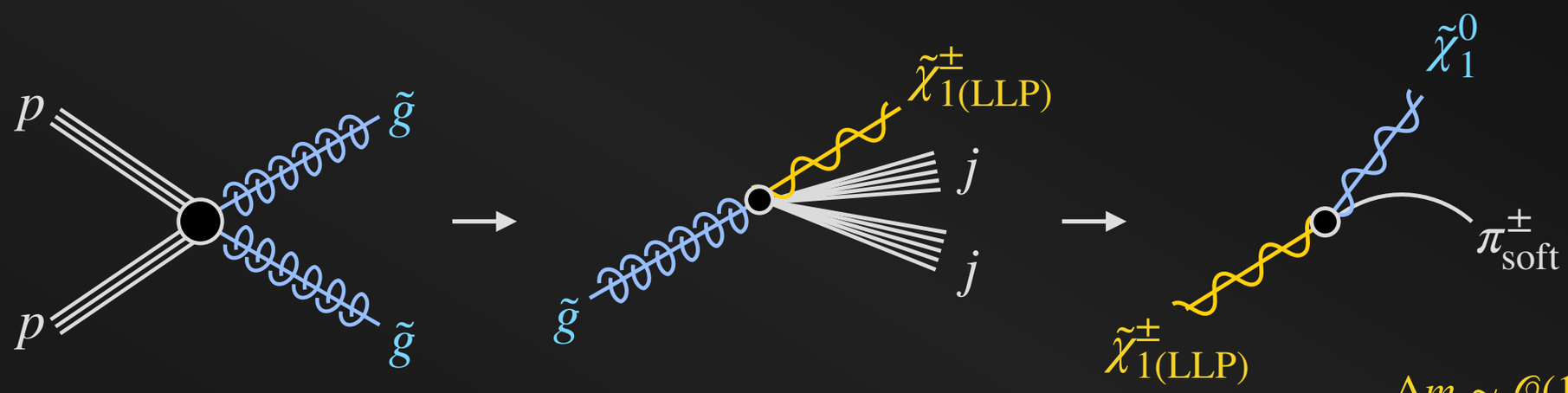
LLP searches complete what we can do with the collider experiments.

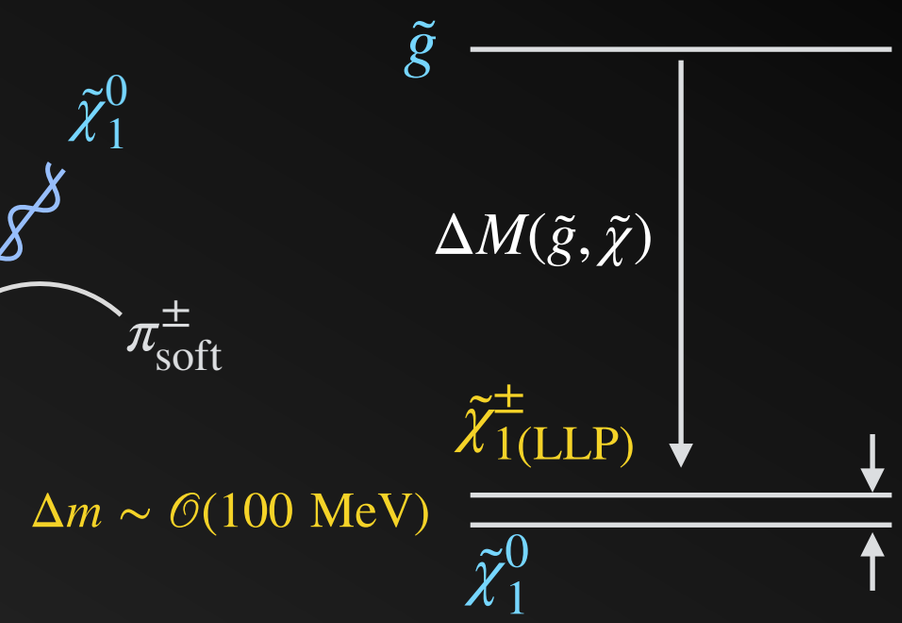


New Full Run2

# Disappearing track: a highly-compressed spectrum

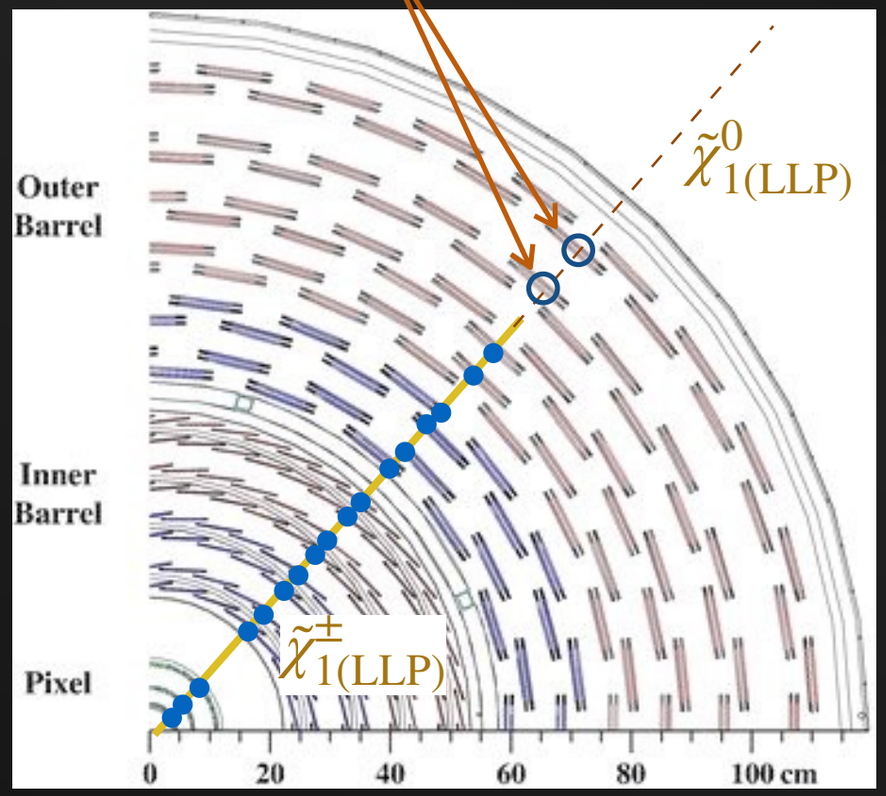
**CMS-SUS-19-005-PAS, 137 fb$^{-1}$**




- ★ A specific SUSY scenario (pure wino) like AMSB.
  - ★ $C_1$–$N_1$ masses splitting arises only by dynamical loop running correction (~150 MeV)
- ★ Long-lived $C_1$ production via strong interaction.
- ★ Long-lived $C_1$ decays to almost degenerated $N_1$, emitting a soft pion which is hard to be visible in the reconstruction.
- ★ Signature in CMS: isolated high-$p_T$ track with no presence of hits in the outermost 2 layers. (short track) — further classified by track length.

**Require no hits in the outermost 2 layers**

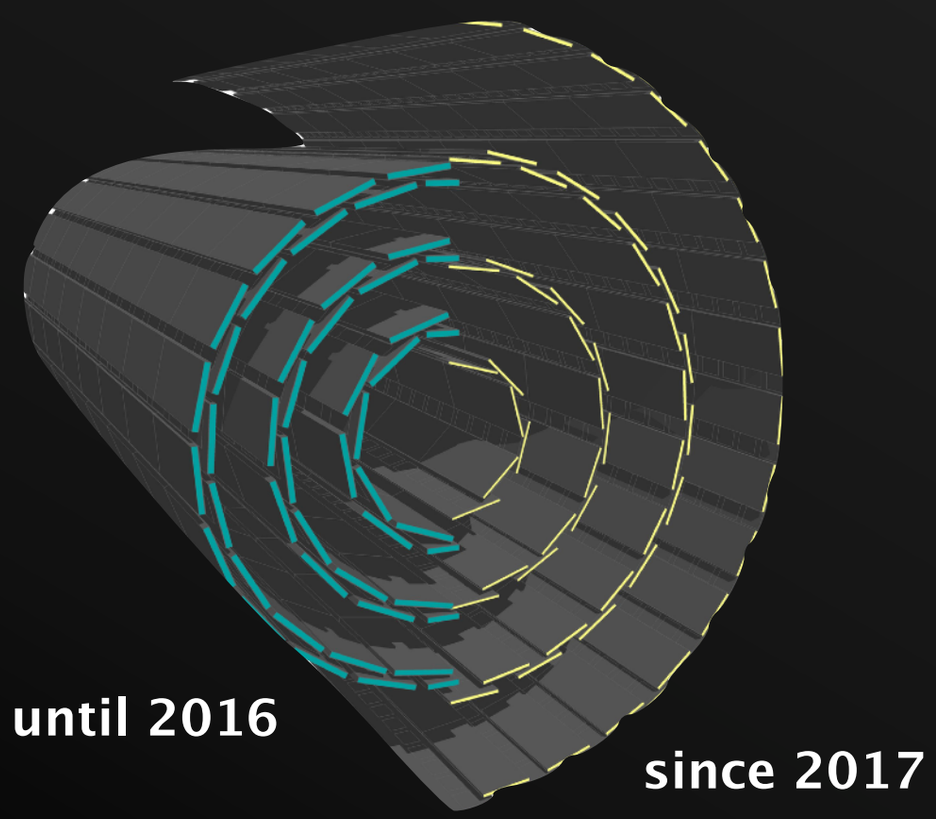


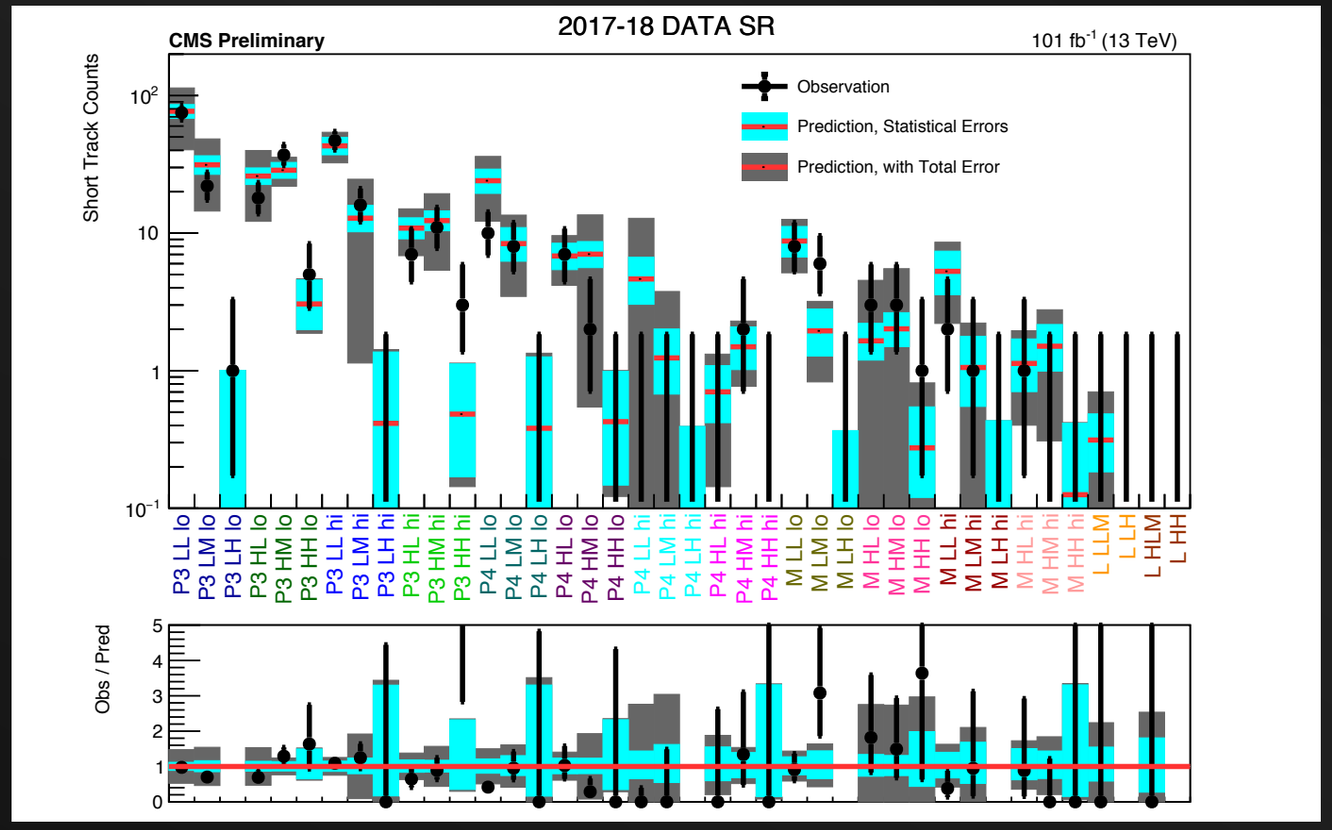
New Full Run2

# Disappearing track: a highly-compressed spectrum

**CMS-SUS-19-005-PAS, 137 fb$^{-1}$**

- Trigger: mixture of $H_T$, MET, $H_T^{miss}$ and jet $p_T$.
- Backgrounds: fake (combinatoric), charged hadrons, leptons.
  - Transfer factor for each component estimated mostly pure data-driven, for longer track case, assisted by MC simulation.
- Signal region defined separately for 2016 and 2017+2018 (pixel detector upgrade in between)



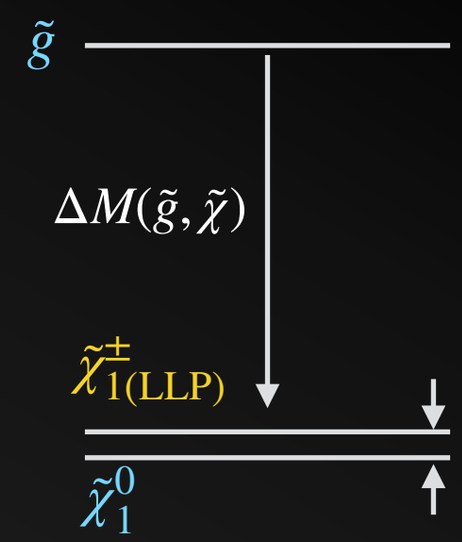




**No significant excess observed in multiple SRs**

New Full Run2

# Disappearing track: a highly-compressed spectrum

**CMS-SUS-19-005-PAS, 137 fb$^{-1}$**

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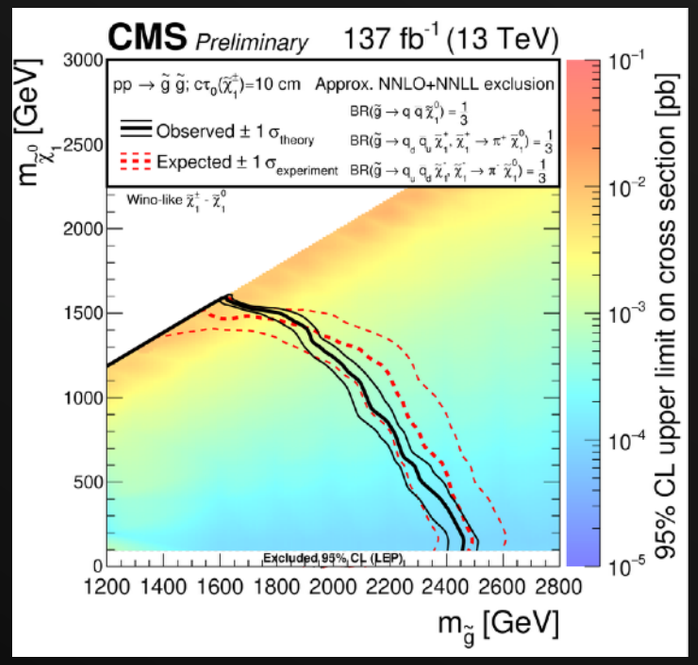
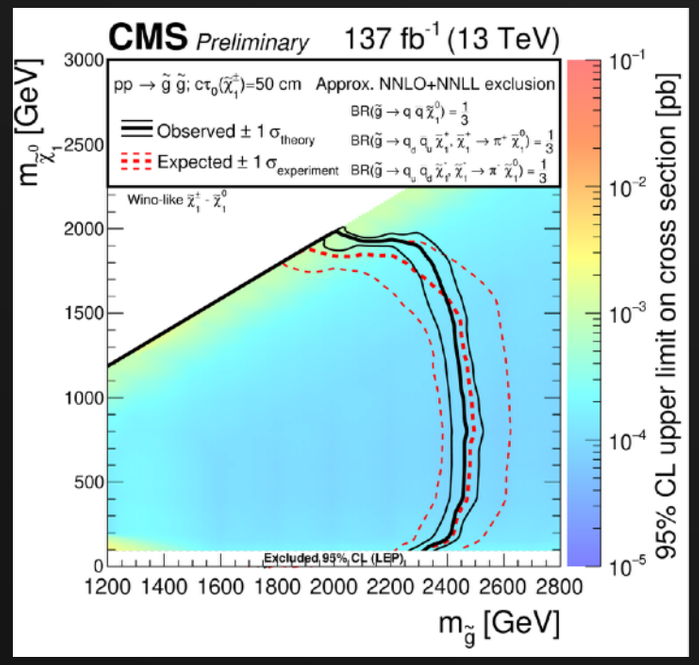
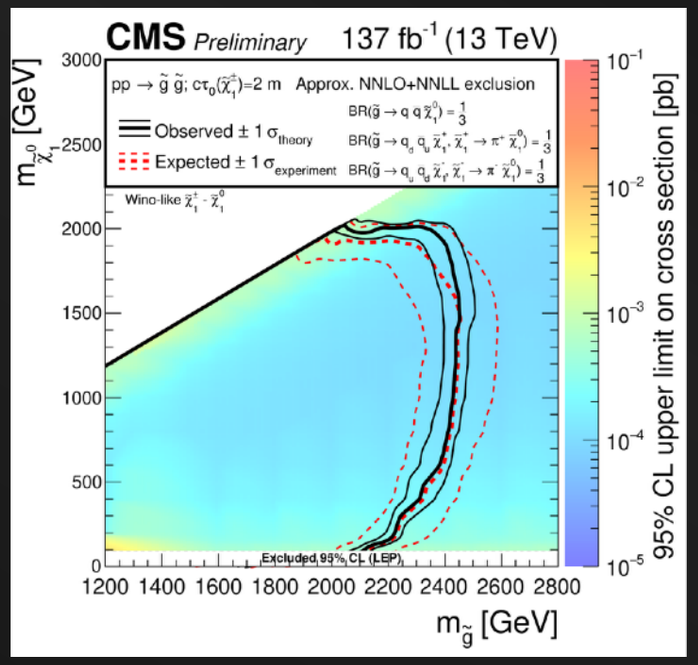



10 cm




50 cm



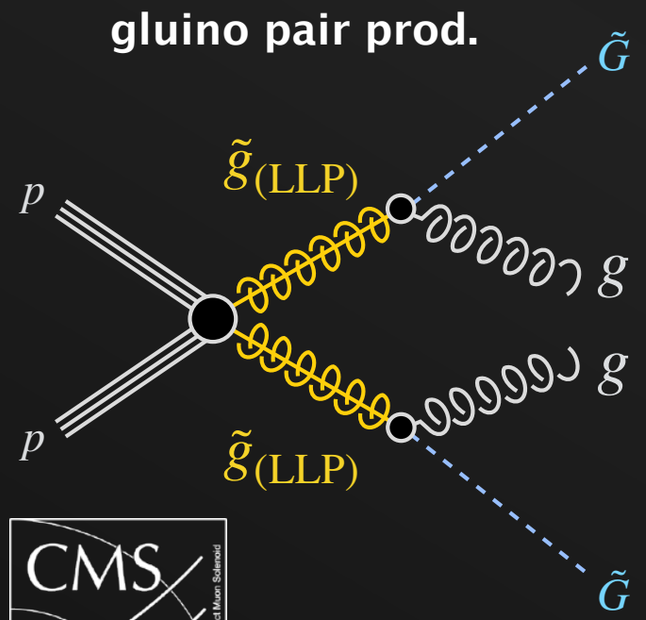

200 cm

**Excluding gluino mass up to 2.46 TeV at the most sensitive lifetime (50 cm)**

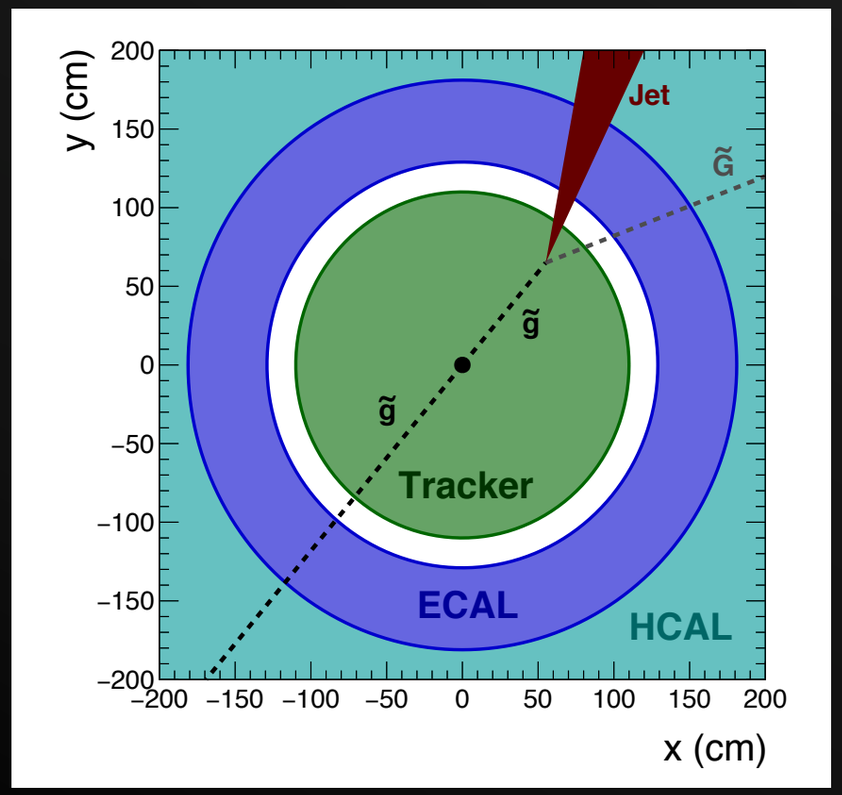
New Full Run2

# Delayed jet

**Benchmark: GMSB gluino pair prod.**



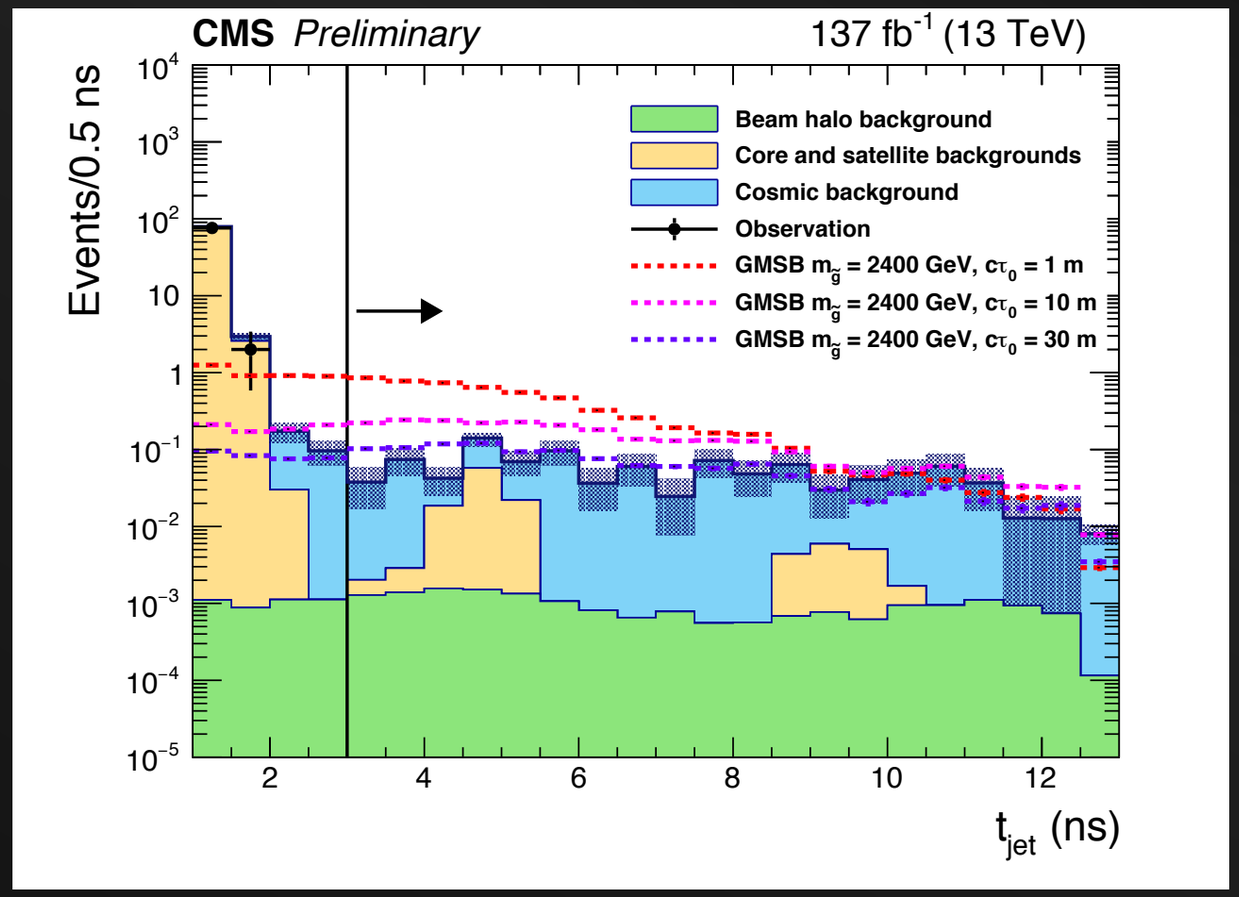

- Assume a BSM particle yields a displaced jet before reaching the calorimeter.
- A heavy BSM long-lived particle flies with significantly small β.
- The total flight path length can be longer than prompt jets due to presence of kinks.
- A displaced jet may arrive later than prompt jets.
  - e.g. a β=0.5 gluino decaying at the outer surface of the CMS tracker at |η| = 0: Δt ~ 4 ns.
  - CMS ECal timing resolution: down to ~0.2 ns.
  - Ecal timing: median of the each cell timing comprising the jet, after cleaning |t| > 20 ns clusters.

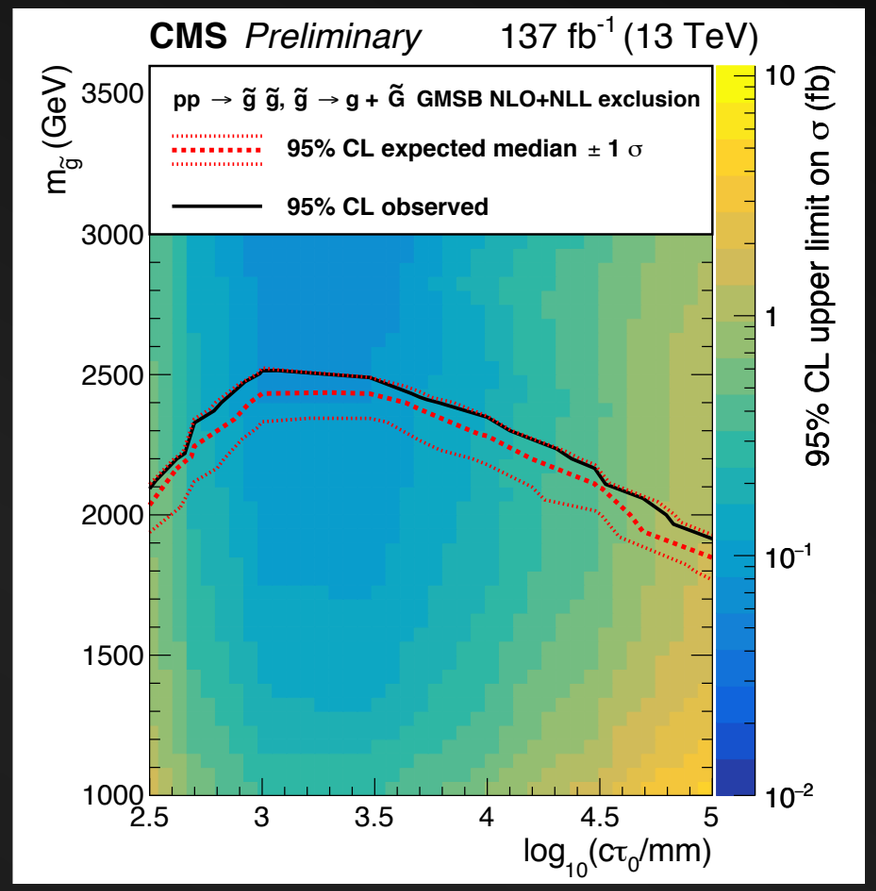



- Various backgrounds
  - Timing resolution tail
  - Electronic noises
  - Direct APD hits (skipping scintillation ~ 11 ns)
  - In/Out-time pileup
  - Satellite bunches (at ±5 ns)
  - Beam halo, or “non-collision backgrounds”
  - Cosmic muon hits

New Full Run2

# Delayed jet




- ★ Background estimation for 3 different categories (cosmic, core/satellite collision, non-collision backgrounds)
- ★ No events observed in the delayed signal region.
- ★ Limit to gluino mass up to ~2.5 TeV. (most sensitive for around 1000 mm/c lifetime )