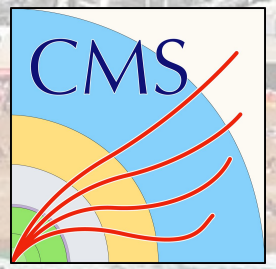
Searches for Supersymmetric Particles

Zubair Bhatti on behalf of **ATLAS** and **CMS**

June 9-13, WIN 2025



Strong and Electroweak Production

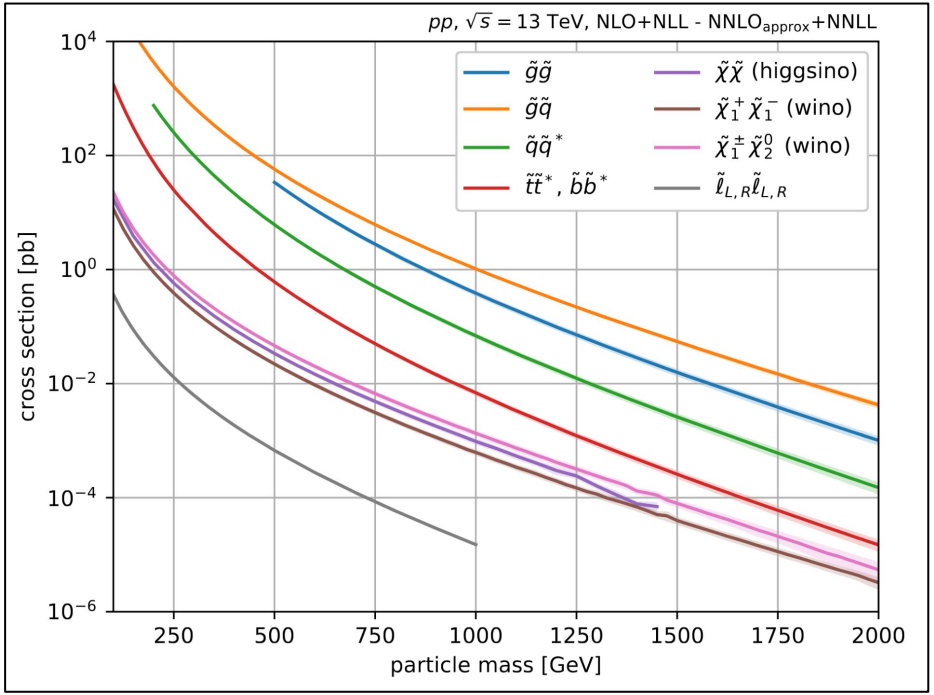
Cross-sections for Strong and EW Production

- Larger for strong production (Squarks, Gluinos)
- Charginos, Neutralinos, Sleptons produced through EWK
- Comparable to rare SM processes (10 million low mass?)

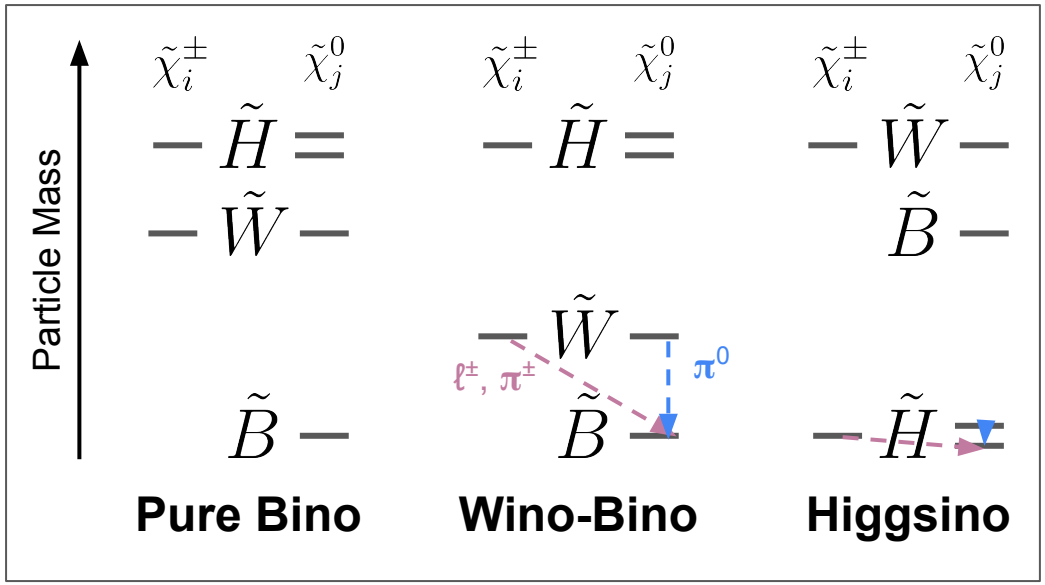
Searches are still covering new parameter space

Some Difficulties

- Mass ordering is unspecified
- Hadron collider is messy for EWK
- Hard to reconstruct O(1) GeV electrons



Electroweakino LSPs and Mass Ordering



Mass eigenstates depend on mixing of superfields

- 4 Neutralinos: $\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$
- 4 Charginos: $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^{\pm}$

LSP ordering & spacing outcomes

- Large p_T leptons or soft leptons
- Soft pions
- Large MET
- Fails trigger or reconstruction

Various Scenarios for LSPs and Mass Spacing

Compressed SUSY

- Mass difference between NLSP and LSP about 1-15 GeV
- Can be for nearly degenerate mass eigenstates

Non-minimal SUSY

- Extra structure for neutrino masses for example

Split SUSY

- Fermionic superpartners (squarks/sleptons) mass >> than scalar sector

R-Parity Violating SUSY

- Allows the LSP to directly to SM for example

Overview

Lepton Searches

1) Search for Z' bosons decaying into charginos in final states with two oppositely charged leptons and missing transverse momentum (**CMS**) [https://cds.cern.ch/record/2929803]
2) Search for displaced leptons in √s = 13 TeV and 13.6 TeV pp collisions with the **ATLAS** detector [https://arxiv.org/abs/2410.16835]
3) Search for cascade decays of charged sleptons and sneutrinos in final states with three leptons and missing transverse momentum in pp collisions at √s =13 TeV with the **ATLAS** detector [https://arxiv.org/abs/2503.13135]

Compressed SUSY EWK Searches

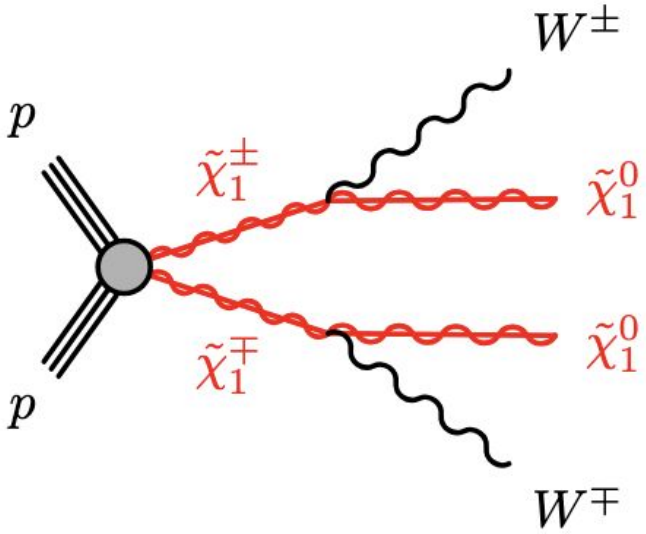
4) Searches for direct slepton production in the compressed-mass corridor in √s =13 TeV pp collisions with the **ATLAS** detector [https://arxiv.org/abs/2503.17186]
5) Search for compressed electroweakinos with low-momentum isolated tracks (**CMS**) [https://cds.cern.ch/record/2929520]
6) Search for new physics with compressed mass spectra in final states with soft leptons and missing transverse energy in proton-proton collisions at √s = 13 TeV (**CMS**) [https://cds.cern.ch/record/2930836]
7) Search for Higgsinos in final states with low-momentum lepton-track pairs at 13 TeV (**CMS**) [https://cds.cern.ch/record/2932111]

Lepton Searches

Lepton Searches

Many well motivated theories predict 2 leptons in the final state

- e.g. Wino-Bino scenario
  - Chargino pair production with W → $\ell\nu$
- Long-lived Charginos
  - picoseconds travel O(100) microns
  - Displaced leptons
- Heavy mother particle to Charginos
  - High p_T leptons and large MET
- 3 Searches discussed: 1 CMS, 2 ATLAS



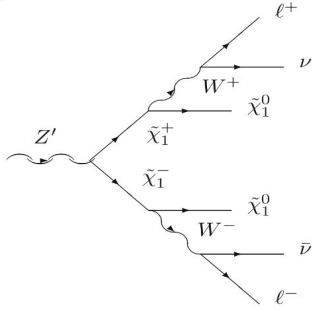
GMSB: Gauge Mediated SUSY Breaking
Higgs Portal: Wino-Bino equivalence for small mixing angle
Leptophobic Z': U(1)' extension leads to Z'

1) Opposite Charge Leptons

Final state has 2 oppositely charged high p_T leptons and large p_T^{miss}

Leptophobic Z' Boson

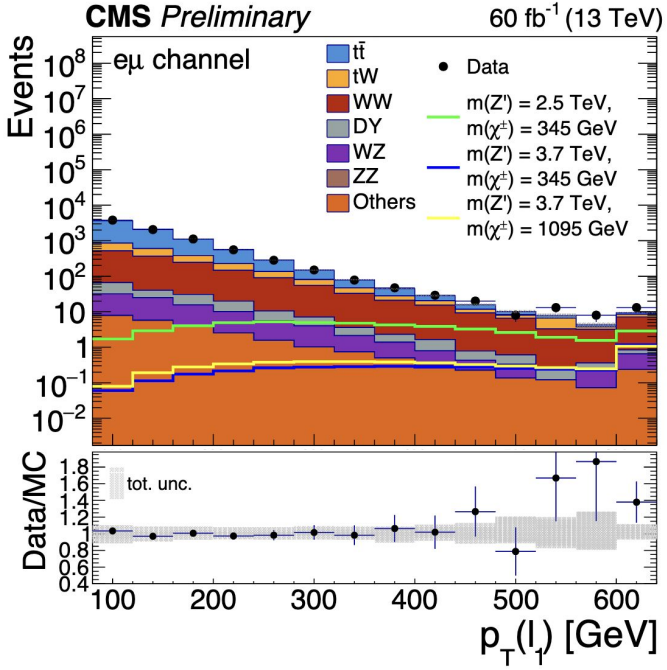
- Avoids leptonic decay constraints
- Enhance cross-section for chargino pair production



3 Channels: ee, $\mu\mu$, eμ

NN trained to discriminate Signal and SM Backgrounds

- Top Backgrounds: tt, tW, WW
- Top discriminants: $p_T(\ell)$, $m_{\ell\ell}$, p_T^{miss} , M_T, and M_{T2}

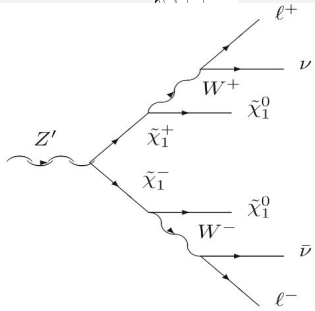


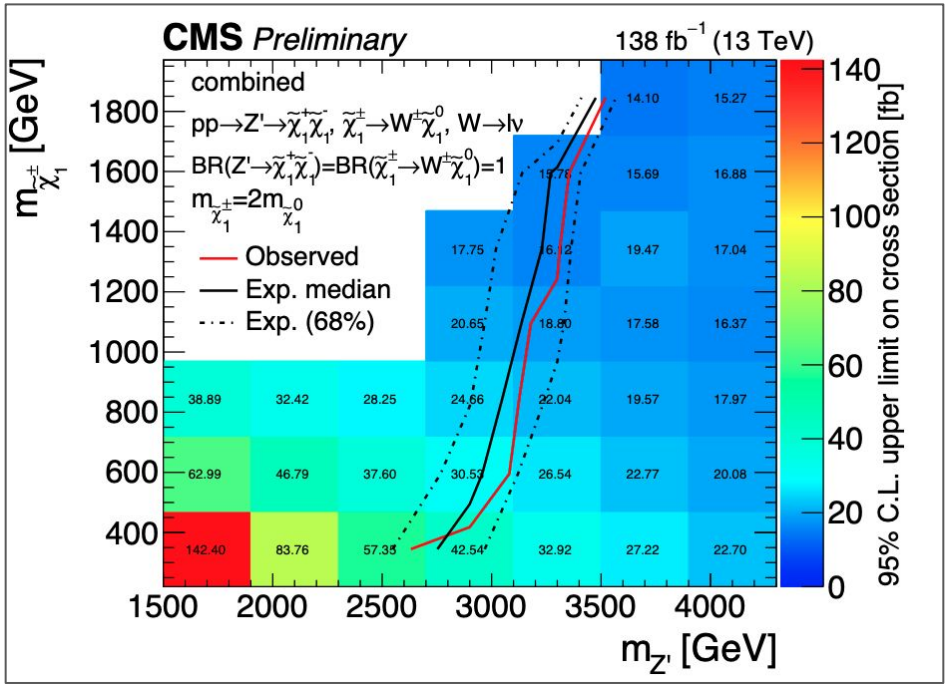
$$M_T(\ell\ell) = \sqrt{2p_T^{miss}p_T(\ell\ell)(1-\cos(\Delta\phi(\vec{\ell\ell},\vec{p}_T^{miss})))}$$

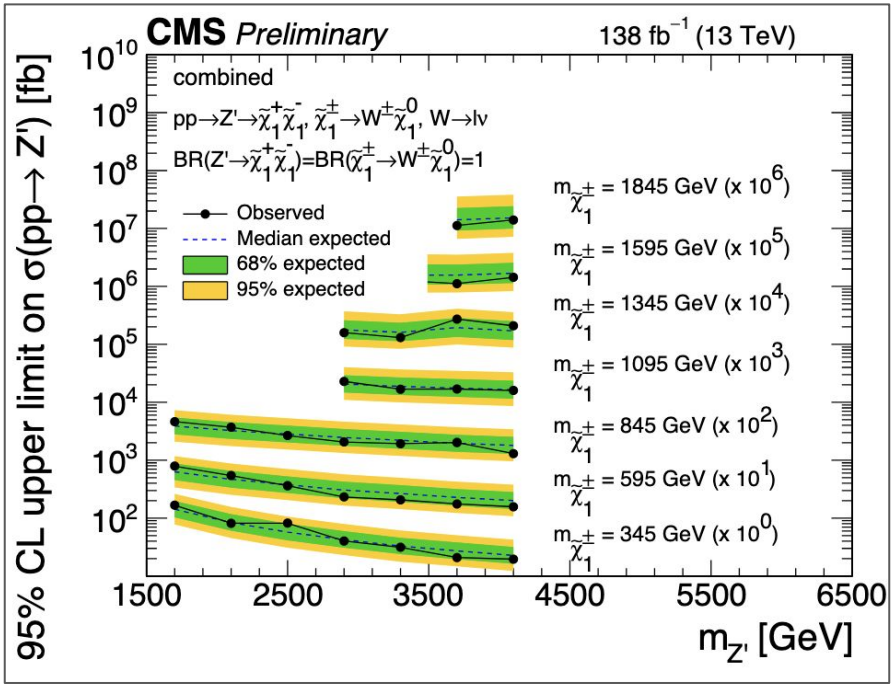
$$M_{T2}(\ell_1,\ell_2) = \min_{\vec{p}_T^{miss(1)}+\vec{p}_T^{miss(2)}=\vec{p}_T^{miss}} [\max(M_T(\ell_1),M_T(\ell_2))]$$

1) Opposite Charge Leptons

- 2-3σ excess in $\mu\mu$ channel
- Parameter Space:
  - Z' mass and Chargino Mass
  - Neutralino mass = ½ Chargino mass



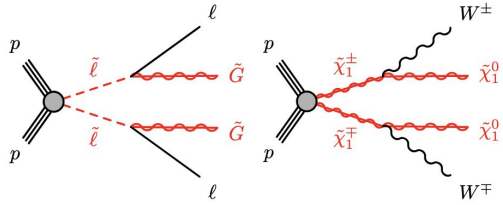




2) Displaced Lepton Pairs

submitted to Phys. Rev. D.

Final state has **displaced** electrons or muons

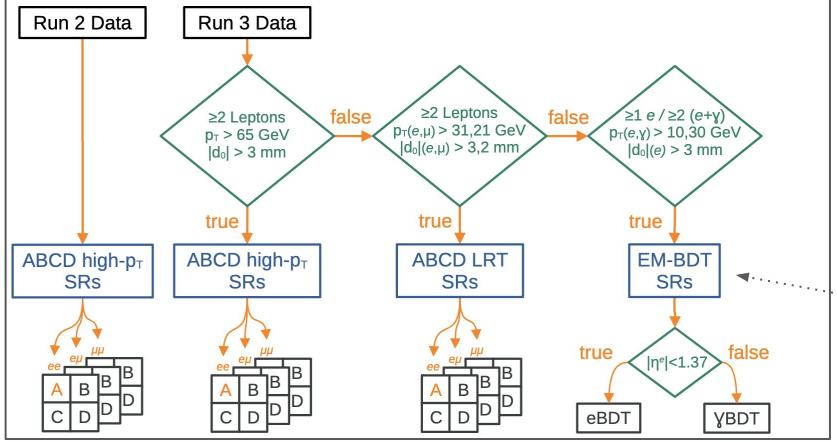


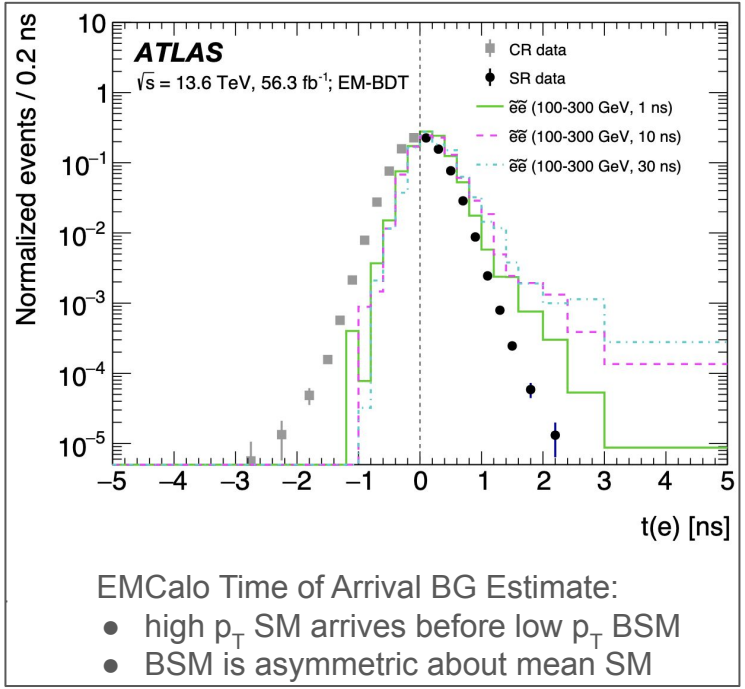
- GMSB has **long lived** selectrons, smuons, stau (left)
- Wino-Bino like Higgs Portal has **long lived** charginos (right)

First Search with Run 3 Data!

- Large d_0 tracking for displaced tracks with low p_T

Disjoint EM-BDT and ABCD Analyses



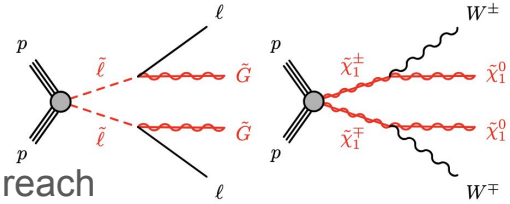


EMCalo Time of Arrival BG Estimate:

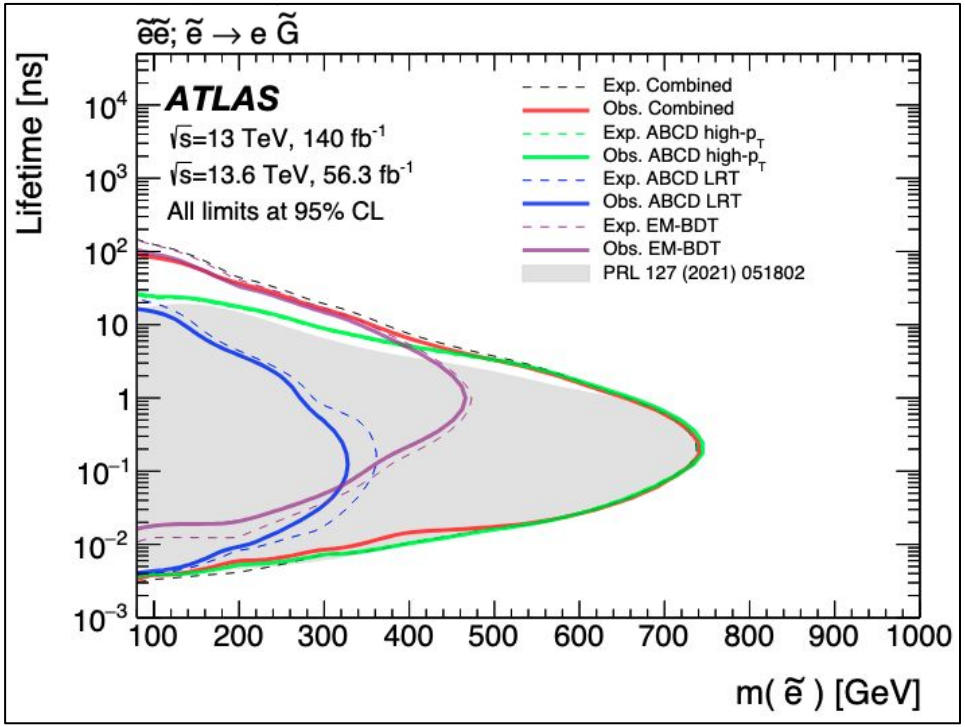
- high p_T SM arrives before low p_T BSM
- BSM is asymmetric about mean SM

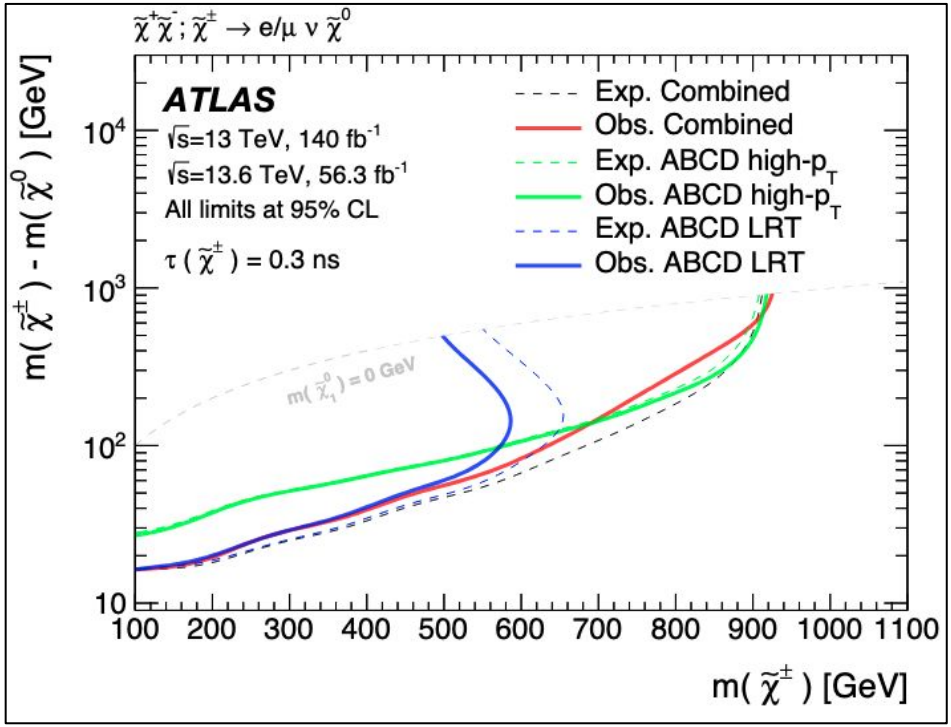
2) Displaced Lepton Pairs

- 2.2σ excess in SRee-LRT
- Complementary analyses have different advantages
  - GMSB (left): EM-BDT for lifetime, ABCD high p_T for mass
  - Wino-Bino (right): ABCD LRT for mass splitting, ABCD high p_T for mass reach



CMS Analogue

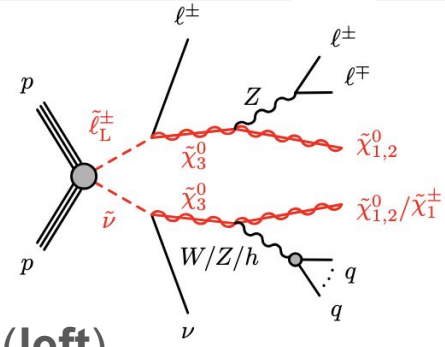




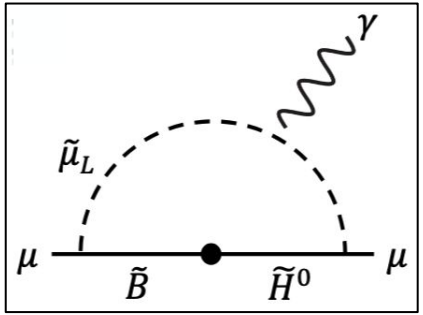
3) Slepton Production with Decay via Bino into Higgsino

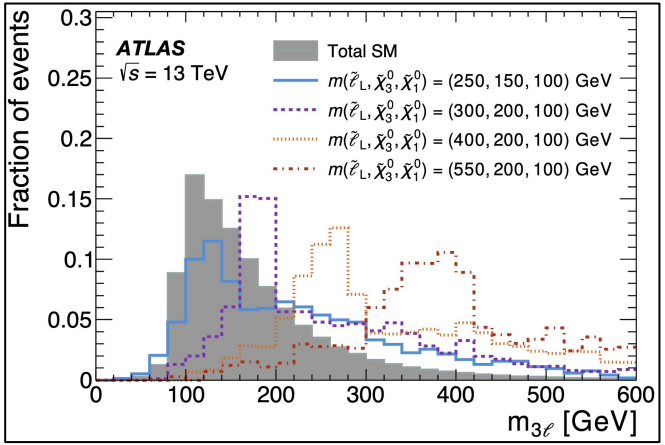
submitted to Phys. Rev. D.

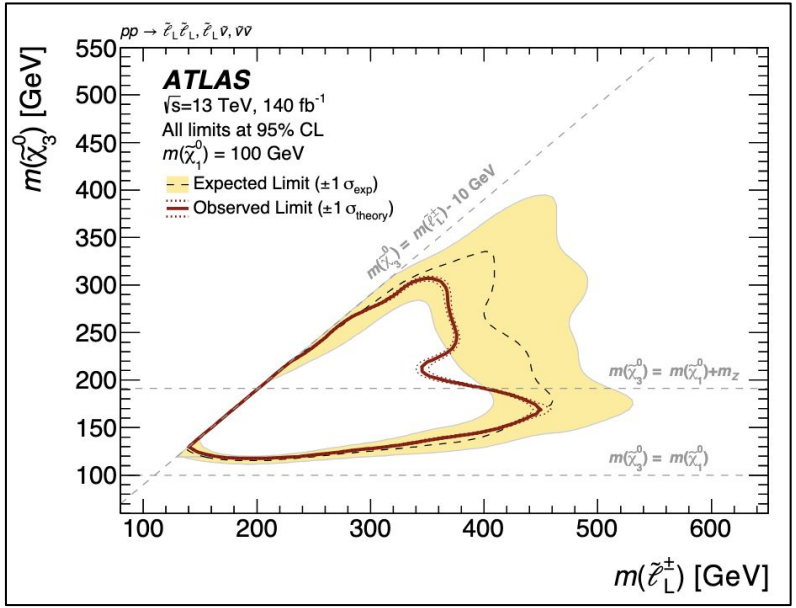
Final state has three leptons and MET



- Slepton-Bino-Higgsino Scenario
  - Pure Bino and mass-degenerate Higgsino
  - Less simplified Model
- Loops from Bino-Higgsino add to anomalous magnetic moment (**left**)
- Higher $m_{3\ell}$ predicted (**middle**)
- Maximum 1.8σ excess seen (**right**)





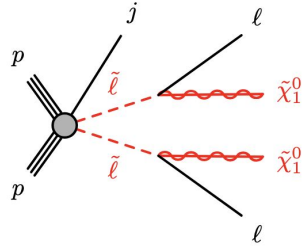


Compressed EWK Searches

4) Compressed Sleptons

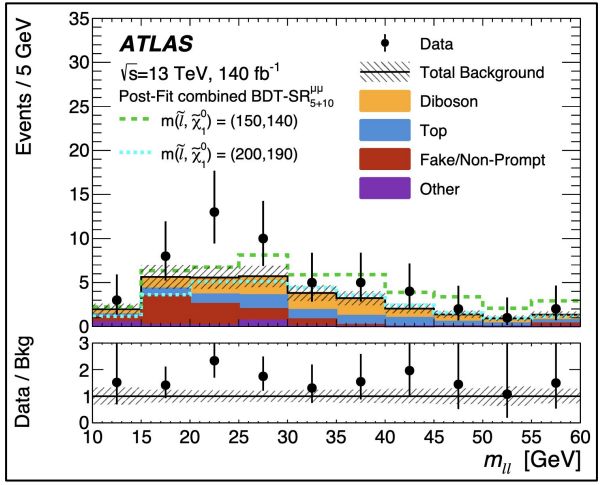
submitted to JHEP

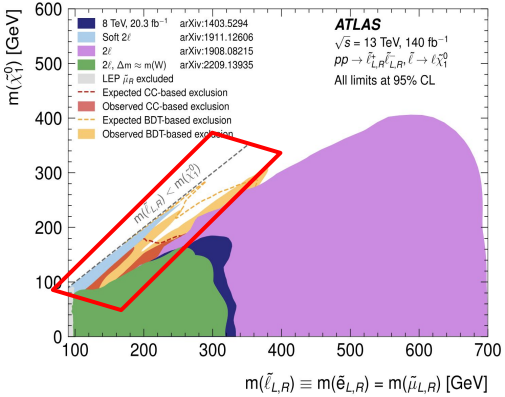
Large p_T jet, MET from ISR jet, and 2 same-flavour opposite-sign leptons

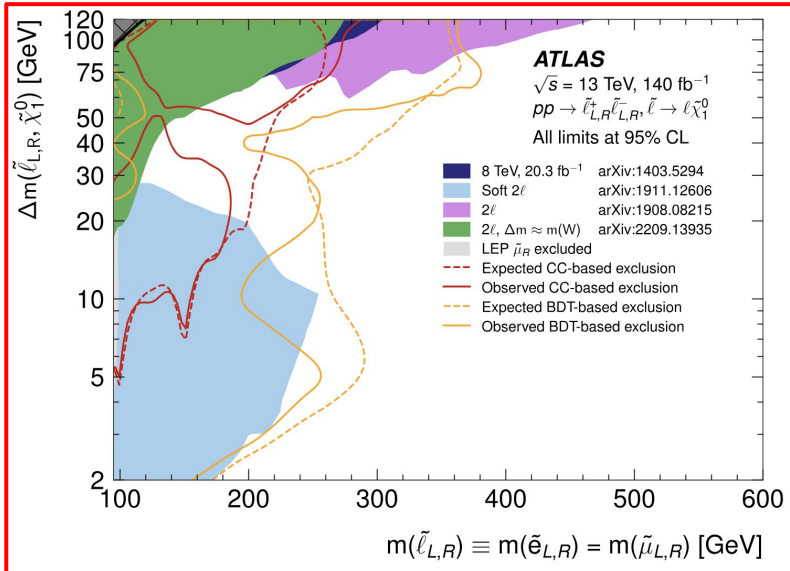


- Slepton-Bino **Compressed** Scenario
  - 4 fold degeneracy (**right**) and 2-fold investigated
- Trigger on MET instead of leptons
  - Diboson backgrounds dominate (**left**)
- Disjoint Cut-and-Count and BDT analyses
- Up to 2.4σ excess seen

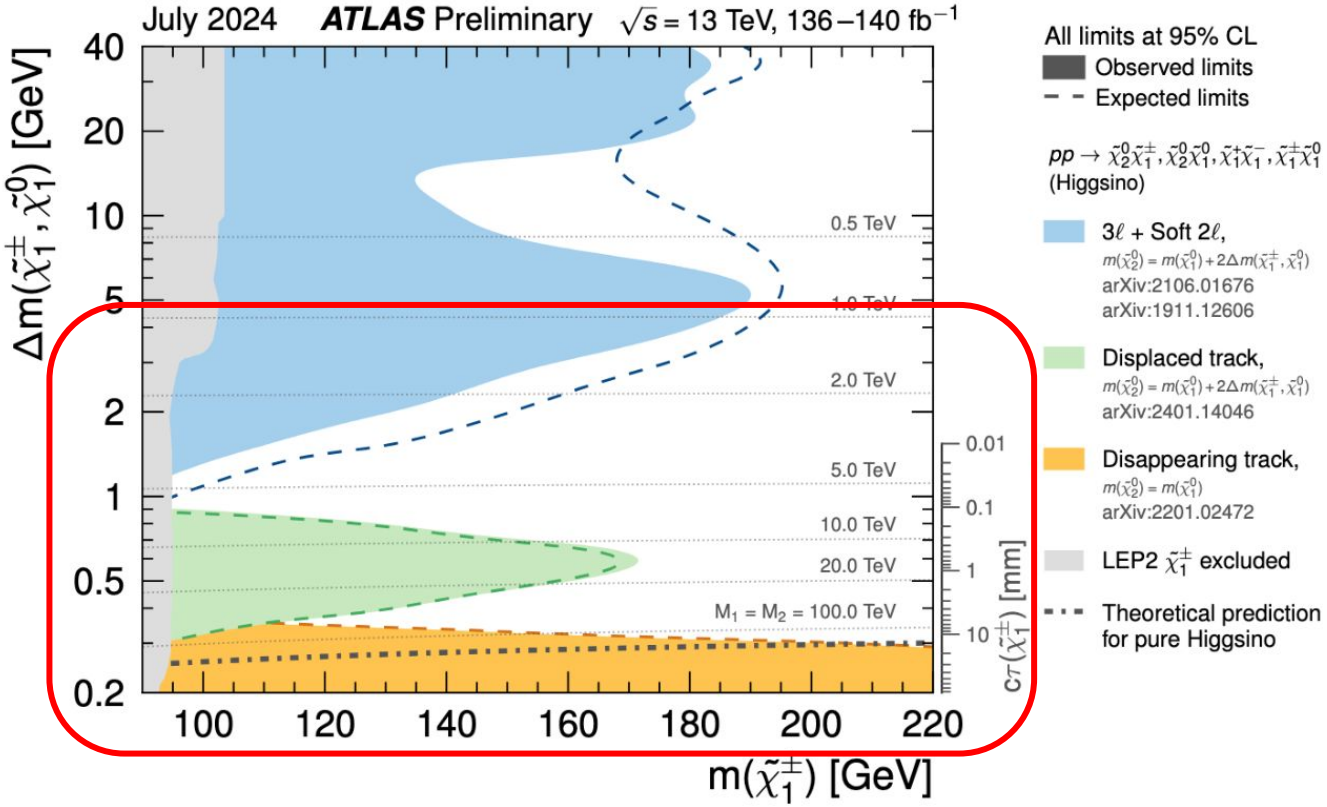
CMS Analogue







Higgsino Compressed Results from ATLAS and CMS

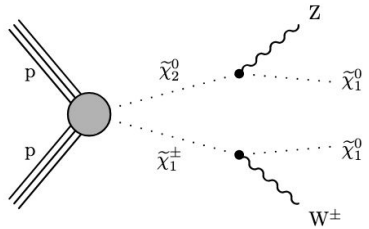


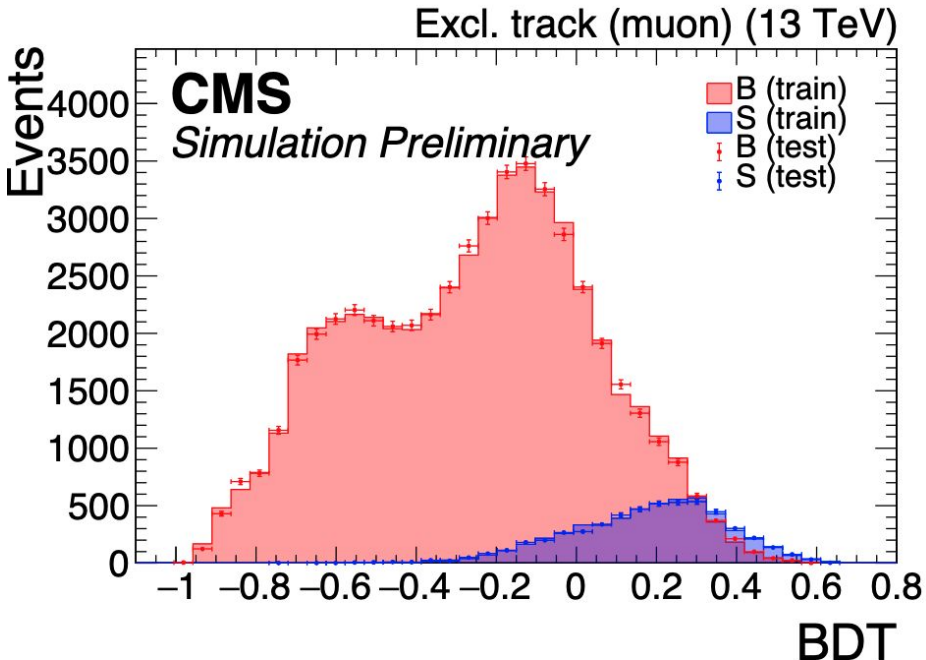
- 3 CMS Searches to compare Compressed Higgsino with ATLAS

5) Soft Leptons and Isolated Track

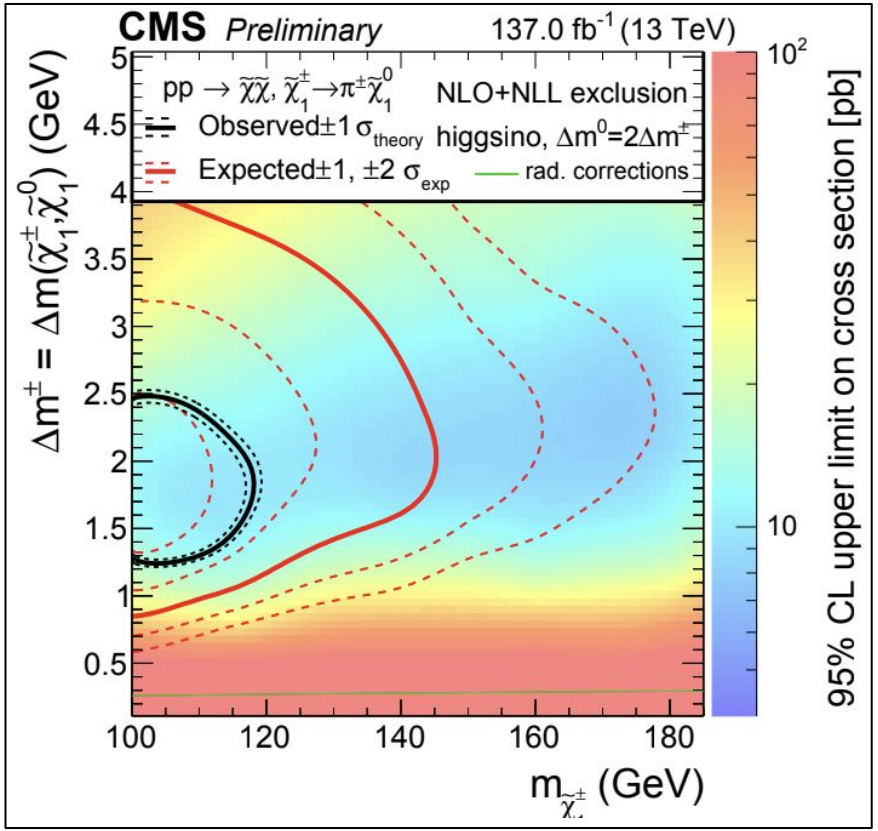
Large p_T^{miss}, 2 muons or lepton and isolated track

- Higgsino LSP Scenario
  - **0.5 - 5.0 GeV** Mass Splitting
  - Isolated track for low p_T leptons
  - Small lepton opening angles
- BDTs score events as signal-like
  - Takes ΔR, Δη and p_T for example
  - >0.6 score defines SR
- 5 Categories
  - Dimuon
  - Muon and isolated track (right)
  - Electron and isolated track
  - **×2 for tracker upgrades**





5) Soft Leptons and Isolated Track



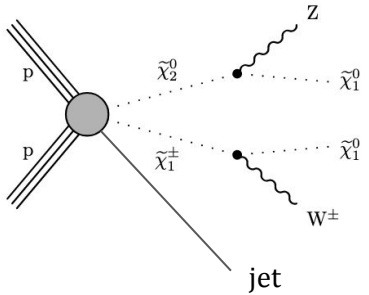
Up to 3σ local excess seen

Parameter Space:

- Chargino Mass
- Mass splitting between 1st Chargino and Neutralino
- $m(\tilde{\chi}_2^0) = 2m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$

6) Soft Leptons and MET

≥ 2 low p_T electrons or muons and MET

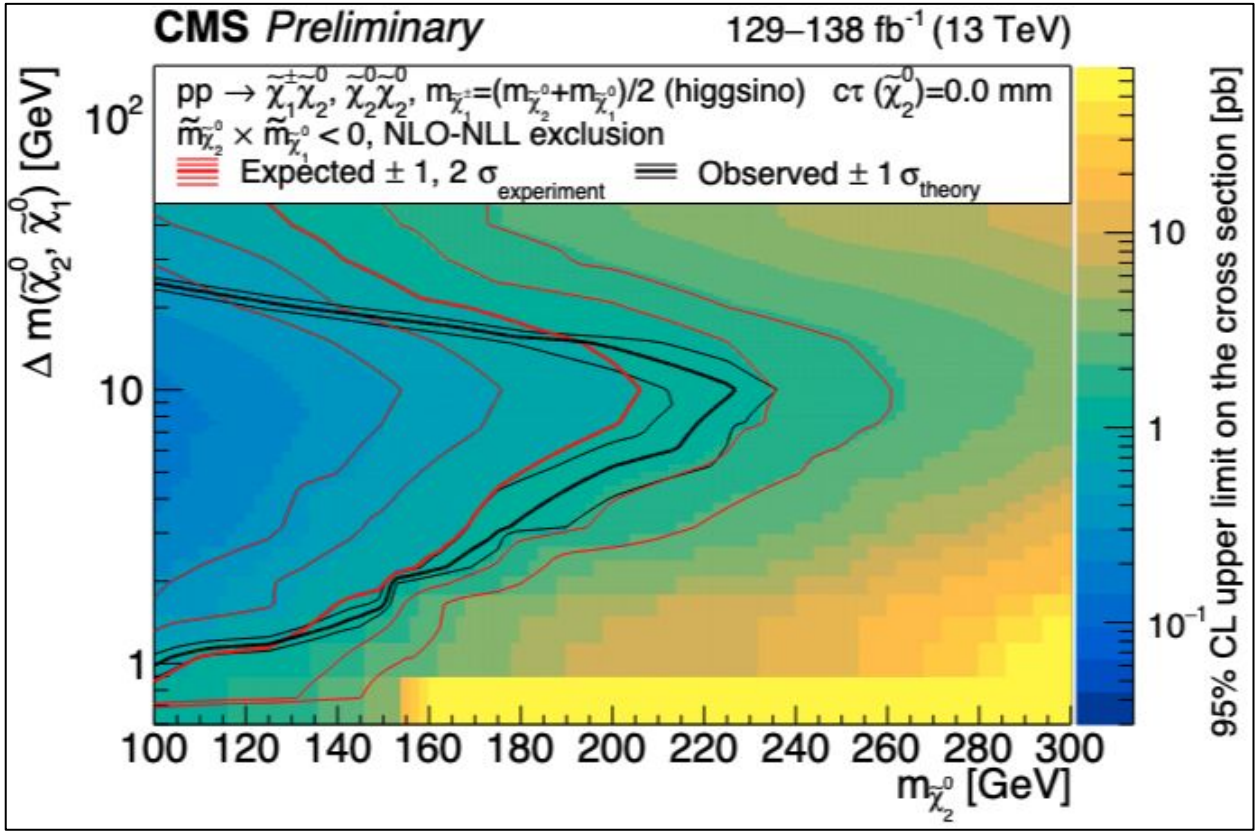


- Higgsino Scenarios (Wino-Bino not discussed)
  - **.6 GeV to 50 GeV** mass splitting
  - Isolated same flavor electrons
  - Initial State Radiation jets (p_T^{miss})

- Utilizes low p_T lepton reconstruction
  - Applied for 1-3 GeV electrons
  - Compliments particle flow (> 2 GeV)
  - BDTs trained on low p_T electrons

- Dimuon, dielectron, trilepton SRs

6) Soft Leptons and MET



First coverage of gap since LEP

Parameter Space:

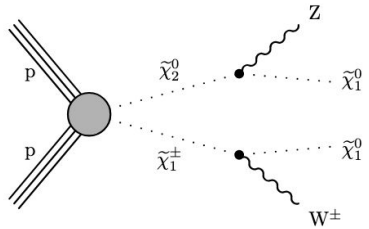
- Chargino Mass
- Mass splitting between 1st Chargino and Neutralino
- $m(\tilde{\chi}_2^0) = 2m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$

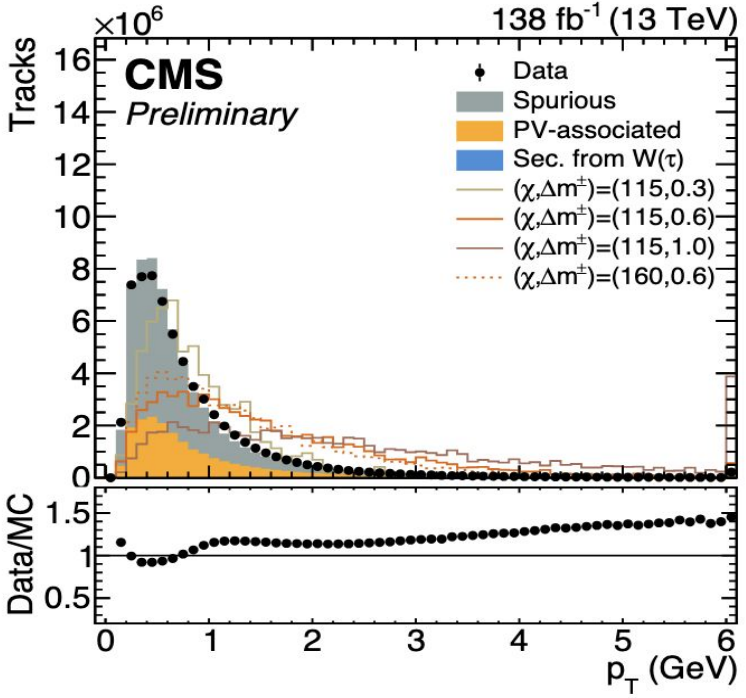
7) Isolated Soft Tracks and MET

Low momentum, isolated track and large MET

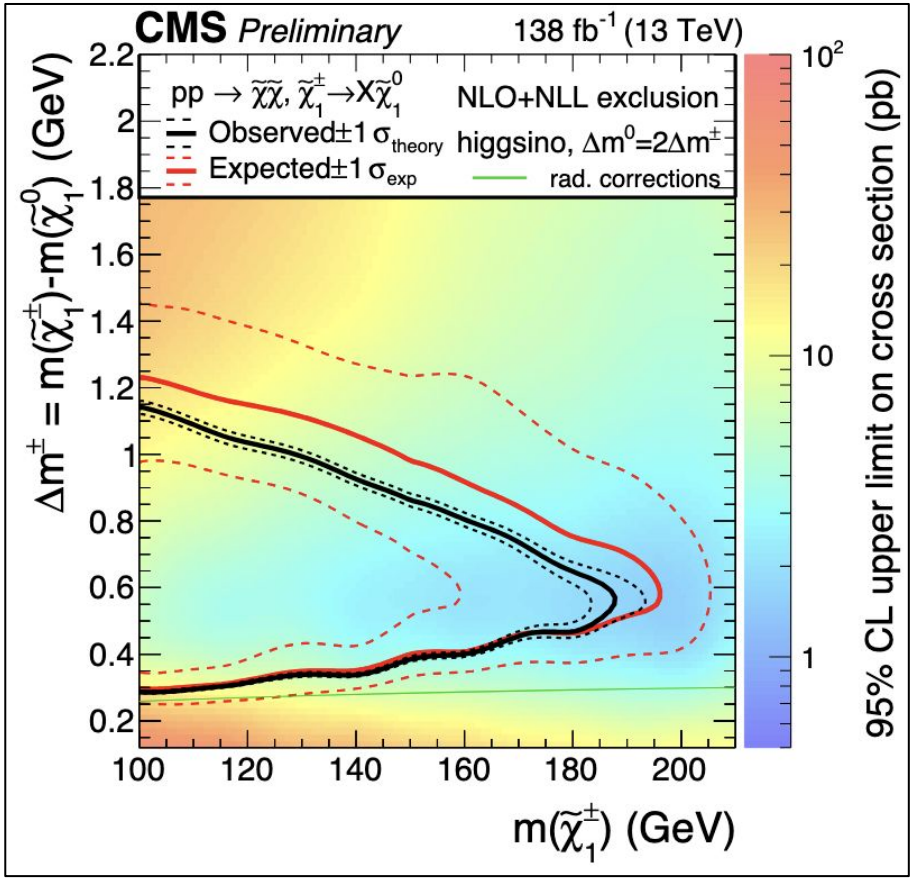
- Higgsino LSP Scenario
  - **0.3 - 1.0 GeV** Mass Splitting
  - Soft pions dominate
  - Displaced pion tracks

- NN estimates how signal-like are tracks
  - Trained on track and event features
  - p_T is a key feature (right)
    - Peaks around mass splitting





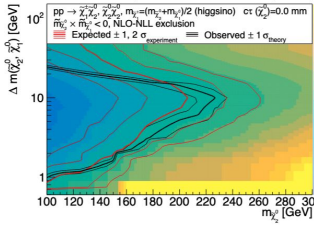
7) Isolated Soft Tracks and MET

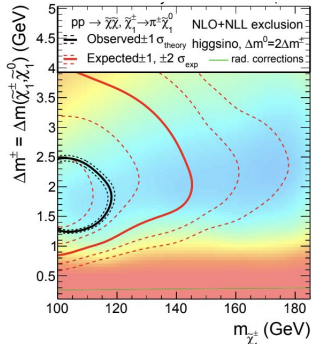


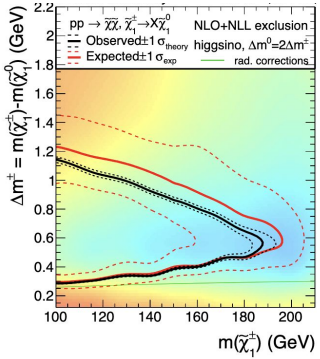
Parameter Space:

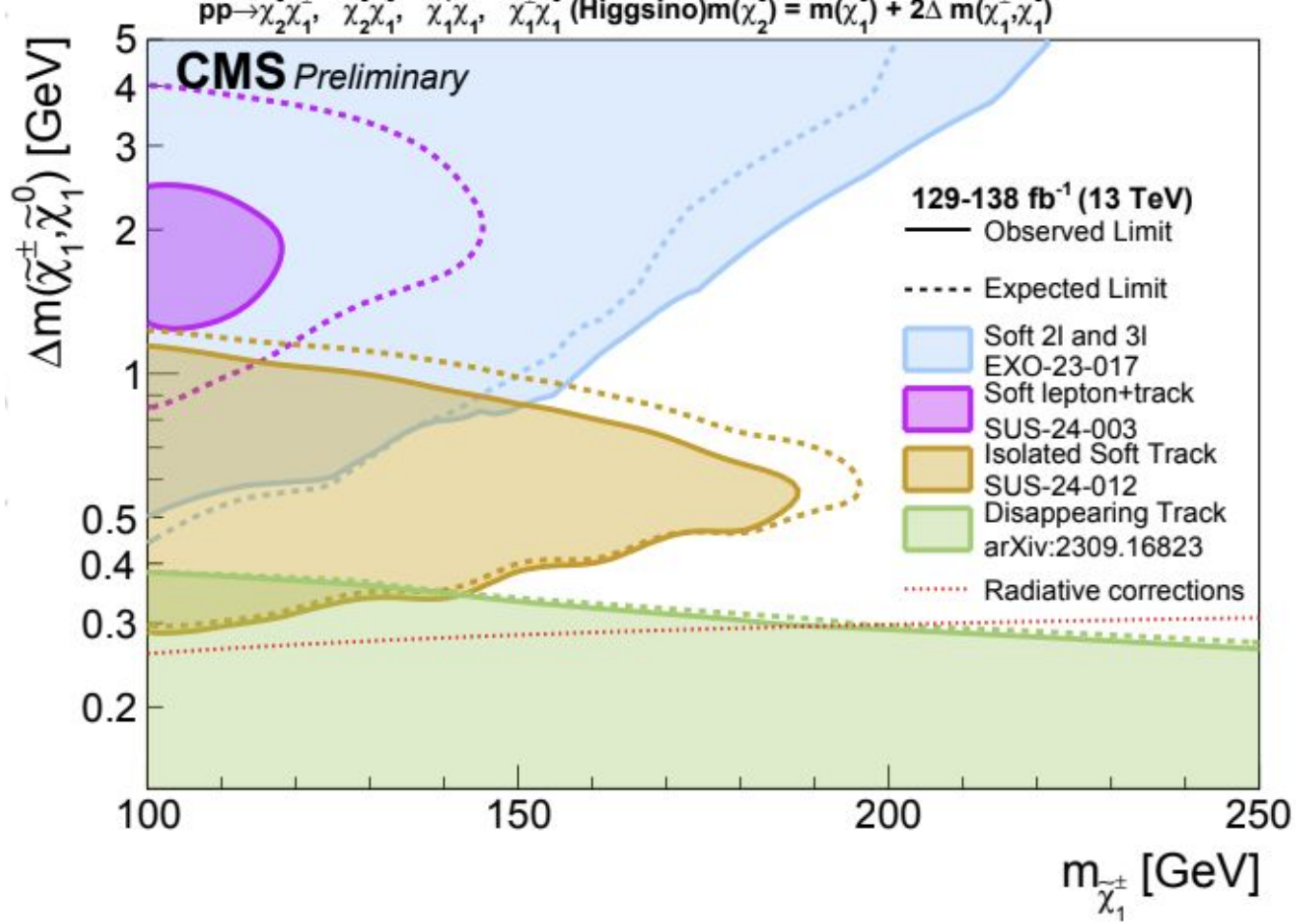
- Chargino Mass
- Mass splitting between 1st Chargino and Neutralino
- $m(\tilde{\chi}_2^0) = 2m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$

Putting It All Together…





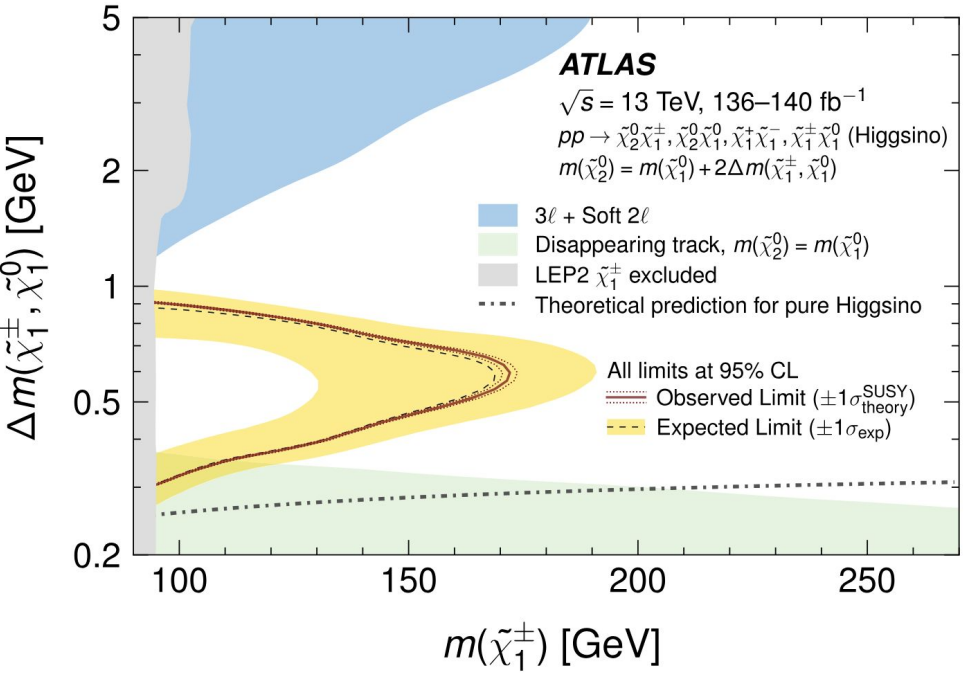


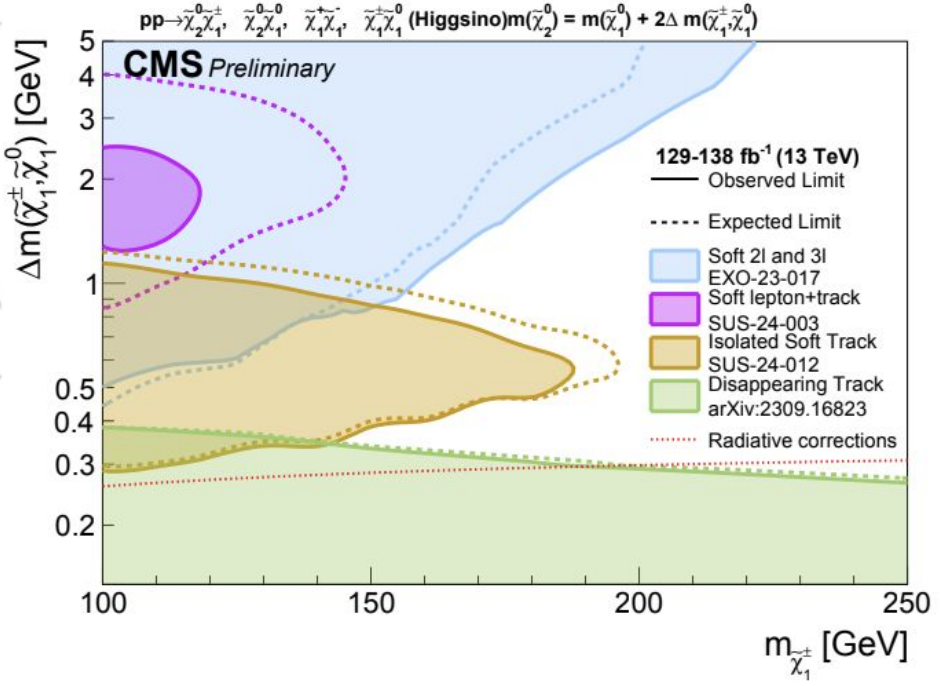


Comparing Compressed SUSY Performance with ATLAS

Just beginning to exclude Higgs mass Charginos!

Compressed EWK Production possibilities are shrinking





2024 Results from ATLAS Low-p_T Mildly Displaced Tracks Search

Much much more…

Charm+MET Searches

- Search for supersymmetry in final states with missing transverse momentum and charm-tagged jets using 139 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector
  - https://doi.org/10.1007/JHEP02(2025)193
- Reinterpretation of searches for flavour-violating supersymmetry into flavour-violating dark matter models using 139 fb^{-1} of ATLAS Run 2 data
  - https://cds.cern.ch/record/2927712

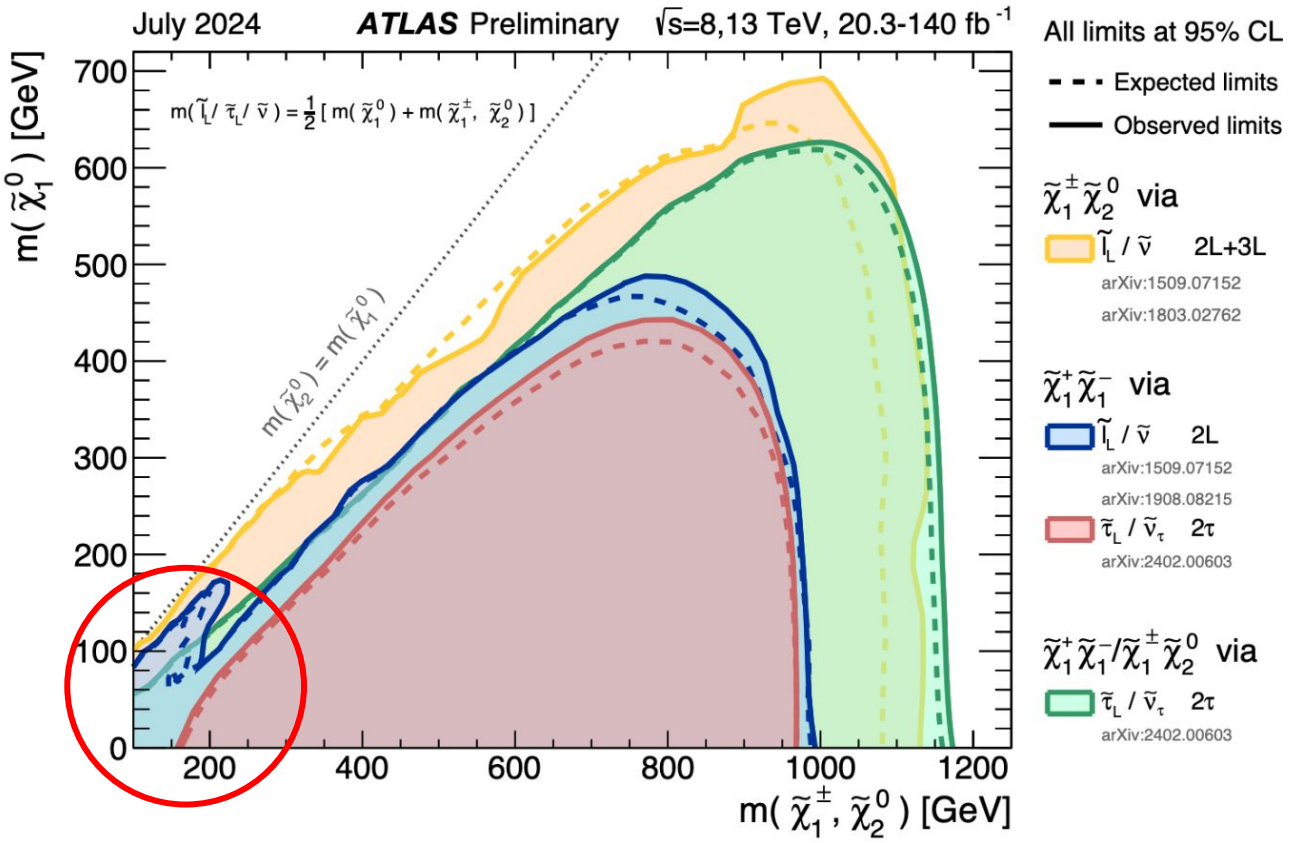
dE/dx Ionization Loss Searches

- Search for long-lived charged particles using large specific ionisation loss and time of flight in 140 fb^{-1} of pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector
  - https://arxiv.org/abs/2502.06694
- Limits on long-lived chargino production using large specific ionisation and low-β in 140 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV using the ATLAS experiment
  - https://cds.cern.ch/record/2899235

ATLAS Public Results **CMS Public Results**

Backup

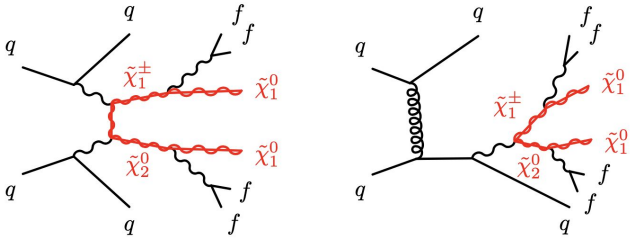
Wino-Bino Limits from ATLAS



- 1 ATLAS Search covering compressed Wino-Bino with VBF

Vector Boson Fusion and MET

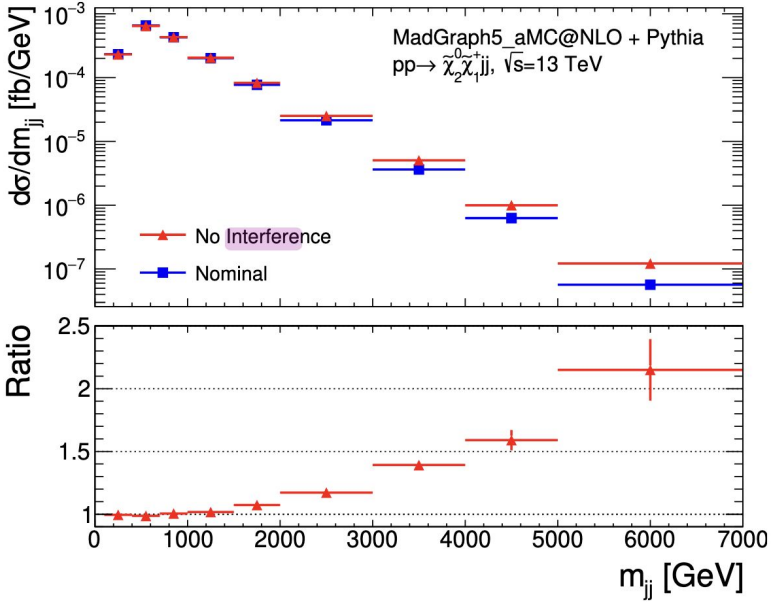
≥ 2 jets with large pseudorapidity gap, large MET, 0 leptons



- Wino-Bino Scenario
  - O(1) pb production but unique signature
  - Enhance EWK sensitivity with hadronic activity
  - t- and s-channel modes
  - Strict 0 lepton from low mass split

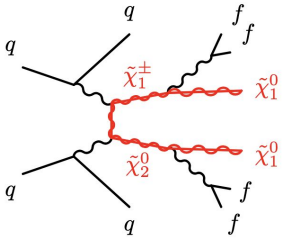
- BDT scores event as signal-like
  - Jet η gap and subleading jet p_T dominate

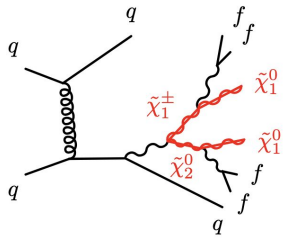
- Interference in s-channel (**right**)
  - Partons exchange W, Z, γ, gluons
  - Identical final state

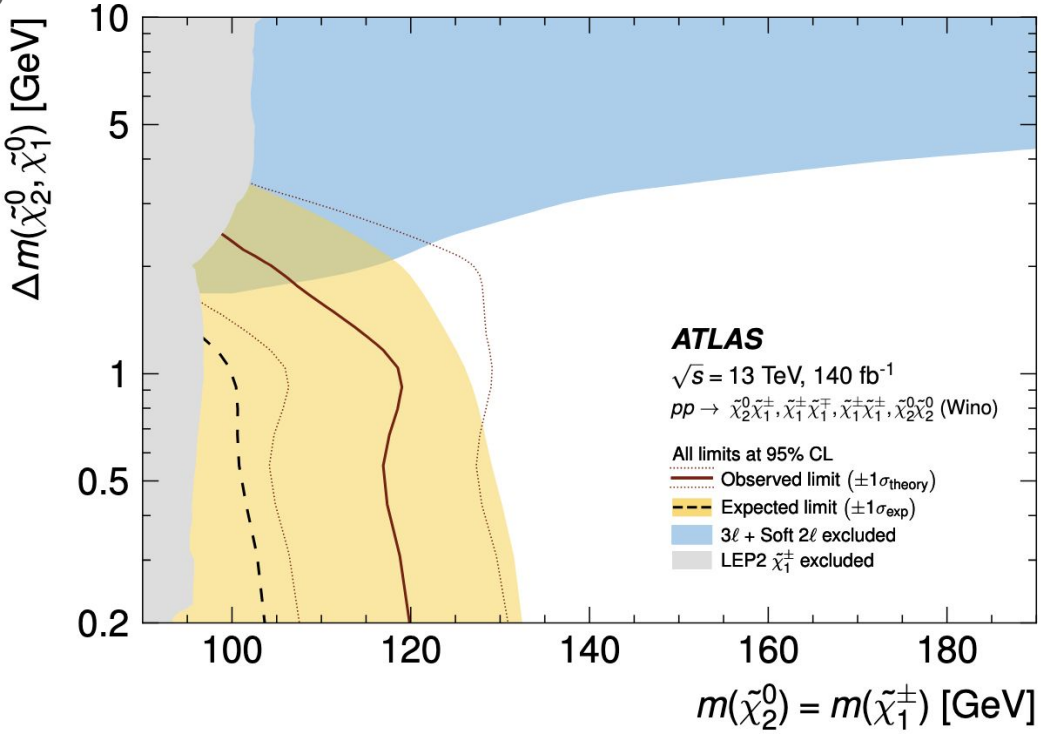


Vector Boson Fusion and MET

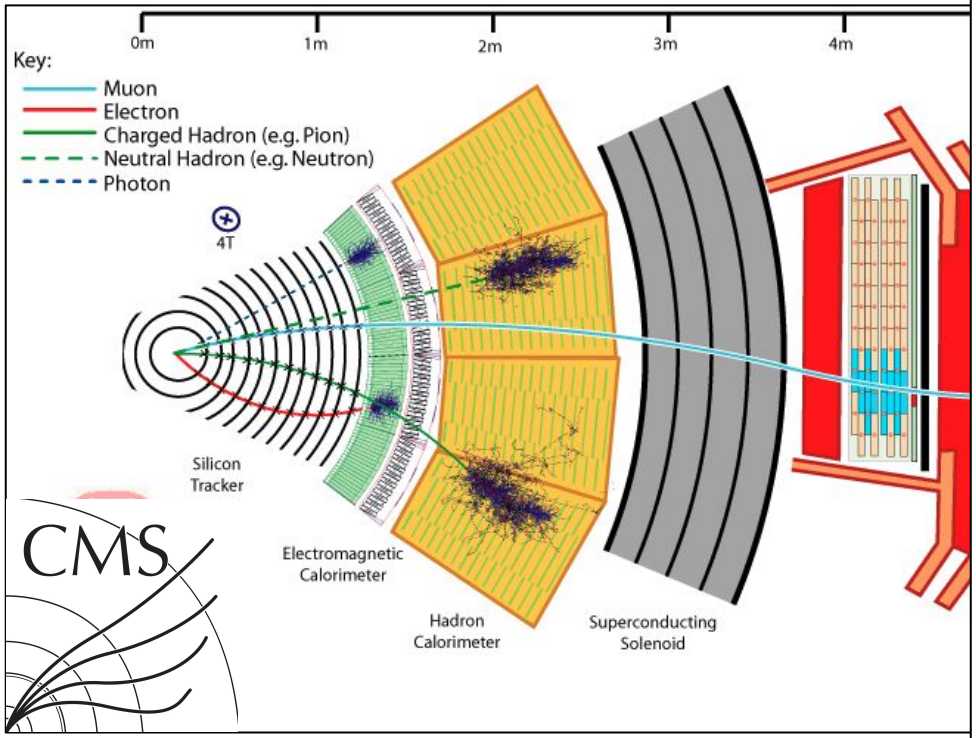
- Largest excess is <1σ in ≥3 jets region
- Parameter Space:
  - Mass splitting of Neutralinos
  - Mass of Chargino (degenerate with NLSP Neutralino)
- Improves on LEP by 25 GeV at hadron collider

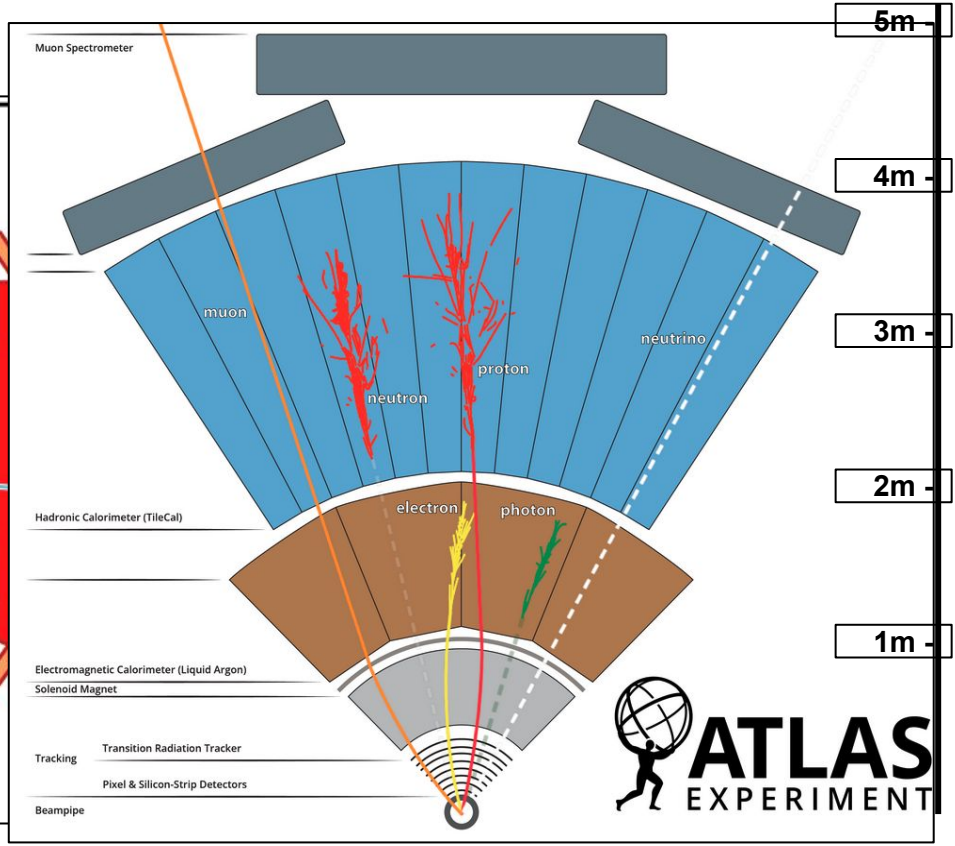




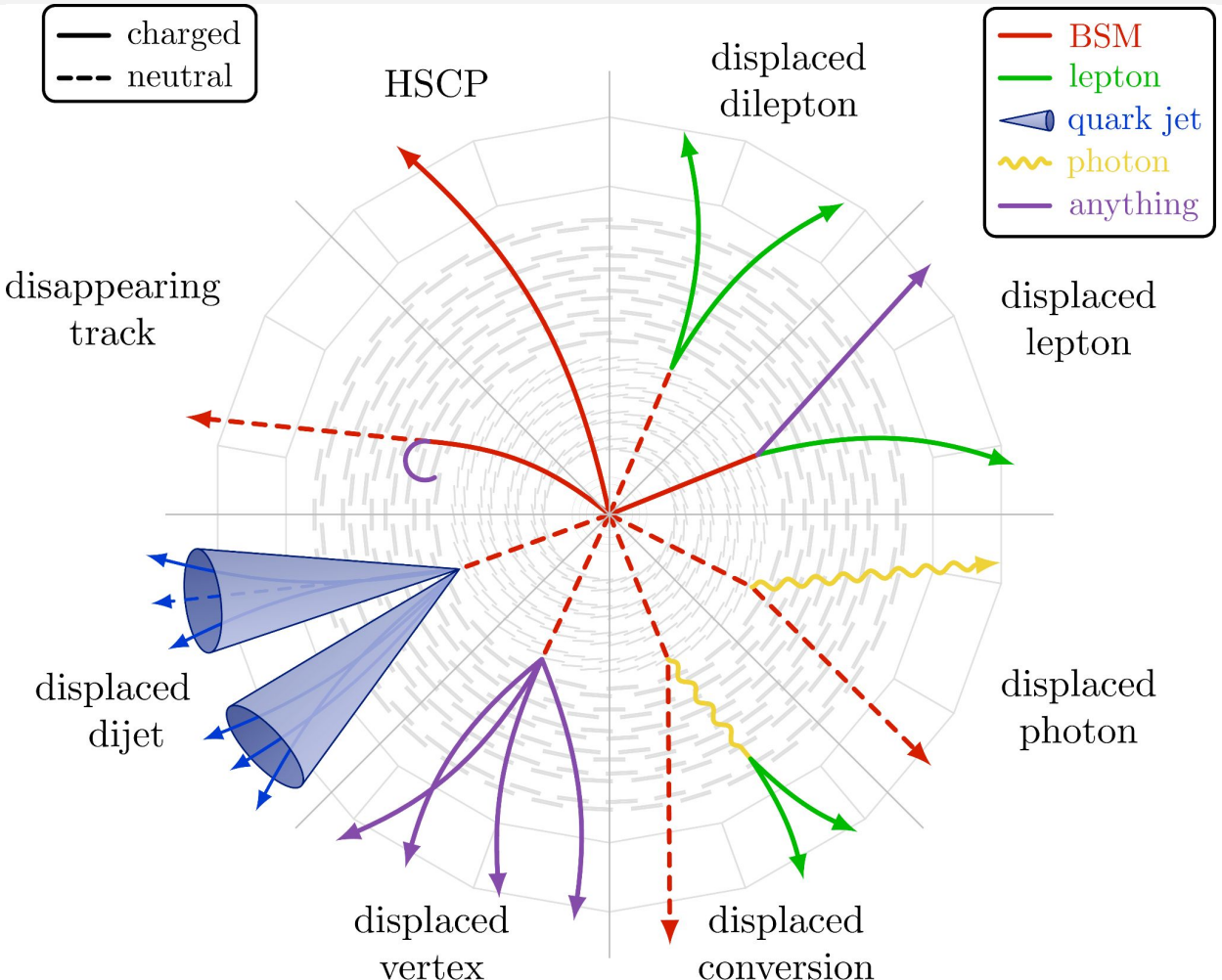


CMS vs ATLAS Detectors





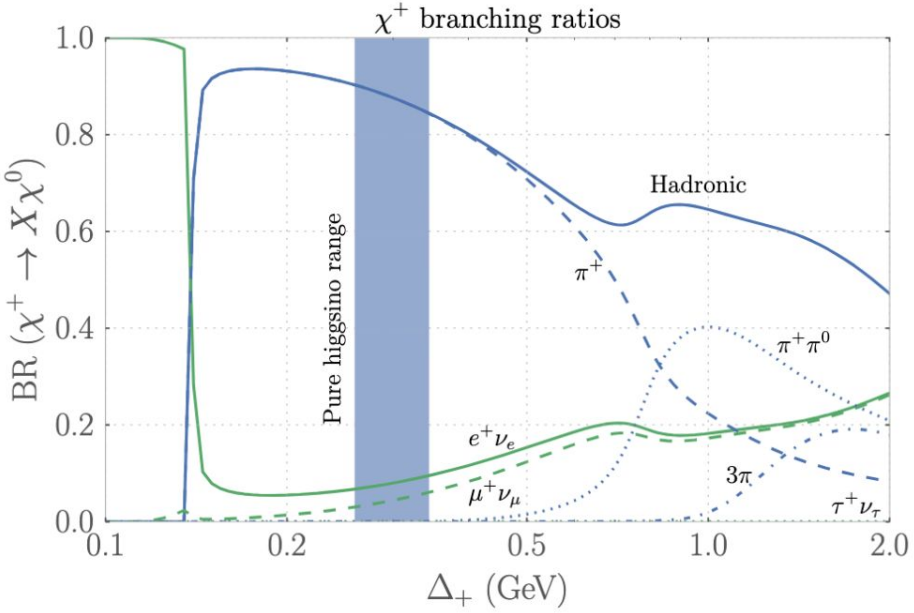
CMS LLP Signatures

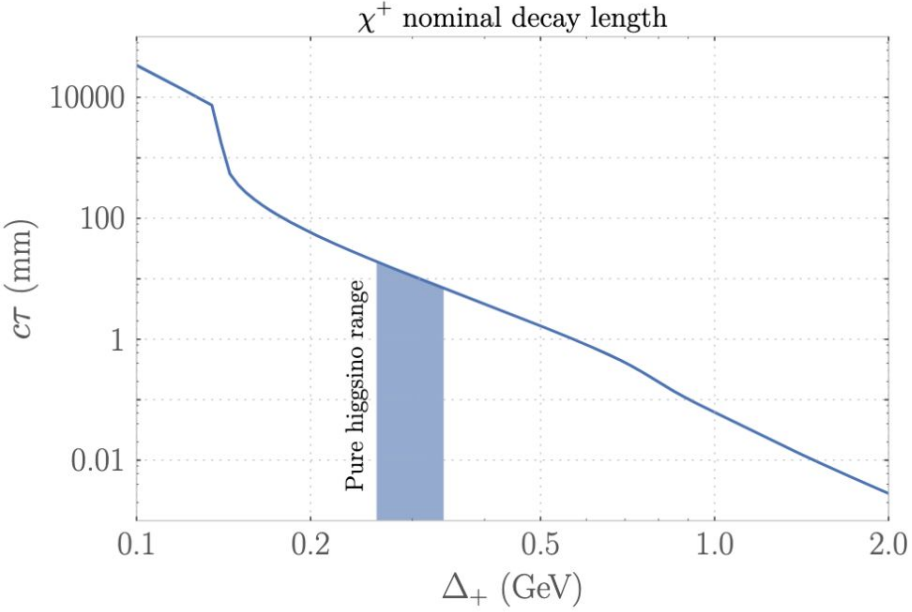


Izaak Neutelings via tikz.net

Partial Chargino Widths

Range of mass splitting with neutralino





Closing the window for compressed Dark Sectors with disappearing charged tracks, R. Mahbubani, P. Schwaller, J. Zurita, JHEP06(2017)119