# Search for electroweak supersymmetry with compressed spectra with the ATLAS detector

SUSY 2024 – June 13th, 2024

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On behalf of the ATLAS Collaboration

# Higgsino Refresher

## Why look for higgsinos?

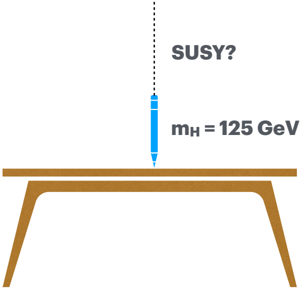
- Appearance of fine-tuning in SM to cancel quadratic divergences in $m_H$
- EWK scale higgsinos: *natural* solution to hierarchy problem
- $\tilde{\chi}_1^0$ is viable DM candidate, provided $R$-parity is conserved and $m(\tilde{\chi}_1^0) \lesssim 1.1$ TeV

## Higgsino LSP phenomenology

- Mass eigenstates: $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0$
- Pure higgsinos: $\boldsymbol{\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx}$ **350 MeV**, driven by radiative corrections
- Additional mixing with $\tilde{W}/\tilde{B}$ can increase this to $\mathcal{O}$**(10 GeV)**

## Why haven't EWK scale higgsinos been ruled out?

- Very low production cross-sections ($\sigma \approx 1.3$ pb for $m(\tilde{H}) = 200$ GeV)
- Very soft decay products $\rightarrow$ difficult to trigger/reconstruct

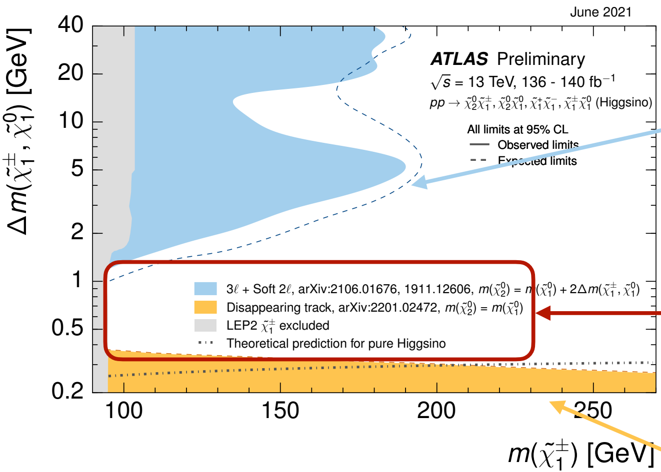


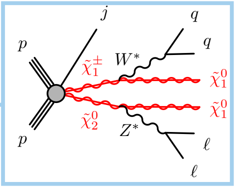

*Analogy from N. Arkani-Hamed*

Minimizing MSSM scalar potential

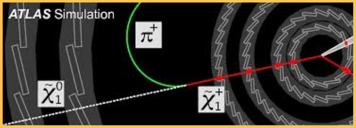
$$-\frac{m_Z^2}{2} \approx |\mu|^2 + m_H^2$$

# Compressed Higgsinos: Where Do We Stand?




**Too compressed for multi-lepton**
**Not compressed enough for disappearing tracks**
***Here be dragons***

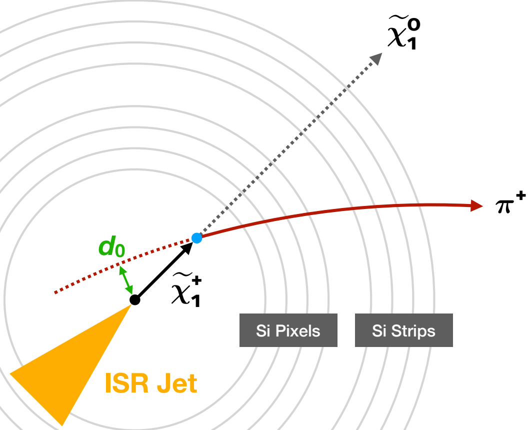



**No sensitivity to 0.4 GeV $\lesssim \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \lesssim$ 1 GeV since LEP!**

**Need new techniques and good ideas**

# New Idea: “Cornering Higgsino” with Soft Displaced Tracks

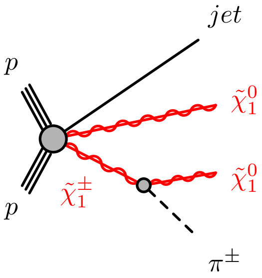
Proposal: “Cornering Higgsino” [arXiv:1910.08065 ]
→ H. Fukuda, N. Nagata, H. Oide, H. Otono, S. Shirai




$\tilde{\chi}_1^\pm$ decays for $0.4\,\text{GeV} \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 1\,\text{GeV}$

- Decay length: $c\tau \sim \mathcal{O}(0.1 - 1\,\text{mm})$
  → well within first pixel layer ($\sim 33$ mm for ATLAS)
  but still measurable: $\sigma(d_0) \approx 0.05$ mm for $p_T = 2$ GeV
- $\text{BR}(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm) \approx 90\% - 40\%$

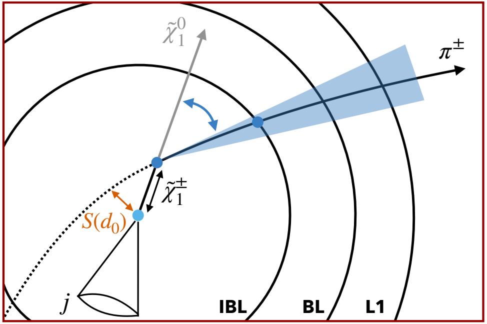
**Mono-jet signature** + **soft, isolated track with significant transverse displacement from PV**: **$S(d_0) = d_0/\sigma(d_0)$**



# Signal Regions

## Event-level Selection

- $E_T^{miss} > 600$ GeV
- Leading jet: $p_T > 250$ GeV, $|\eta| < 2.5$
- $\min[\Delta\phi(\text{any jet}, E_T^{miss})] > 0.4$
- No leptons or photons
- $N_{jets} \leq 4$




**+**

## Track-level Selection

- $p_T \in [2\text{ GeV}, 5\text{ GeV}]$, $|\eta| < 1.5$
- $|d_0| < 10$ mm, $|z_0 \sin\theta| < 3$ mm
- $\Delta\phi(\text{track}, E_T^{miss}) < 0.4$
- No other track with $p_T > 1$ GeV within $\Delta R = 0.4$
- Not matched to $K_S^0$ or $\Lambda^0$ decay vertex
- `TightPrimary` WP + $N_{hits}^{IBL} > 0$
- $S(d_0) > 8$

**Monojet signature + soft, isolated, displaced track**

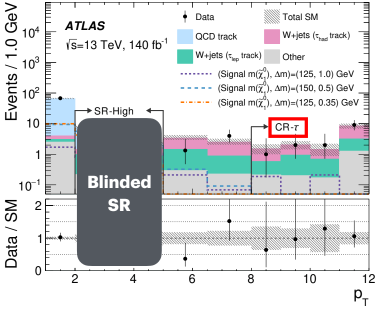
**SR-Low: $S(d_0) \in [8, 20]$**
**SR-High: $S(d_0) > 20$**

[arXiv:2401.14046]

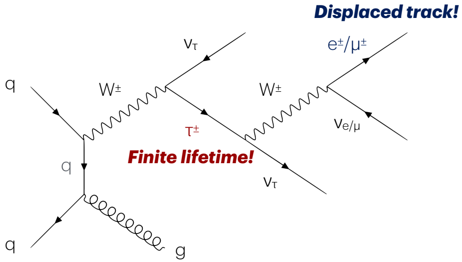
# Standard Model Backgrounds

## Dominant backgrounds

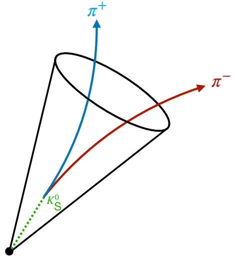
- "**QCD tracks**": $W(\to \ell\nu)/Z(\to \nu\nu)$ + jets events where track from long-lived hadron decays, pileup, underlying event is tagged as signal candidate track
  - Fully data-driven estimate via ABCD method in $E_{\mathrm{T}}^{\text{miss, lep. inv.}}$ vs. $S(d_0)$ plane
  - Transfer factors computed in $1\mu$ regions, applied in $0\ell$ regions
- "**$\tau$ tracks**": $W(\to \tau\nu)$ + jets events where soft pion/lepton from $\tau$ decay is tagged as signal candidate track
  - Semi-data-driven estimate
  - MC samples normalized to data in $\tau$ track enriched CRs at higher track $p_{\mathrm{T}}$: 8 GeV $< p_{\mathrm{T}}^{\text{track}} <$ 20 GeV




τ track bkg.



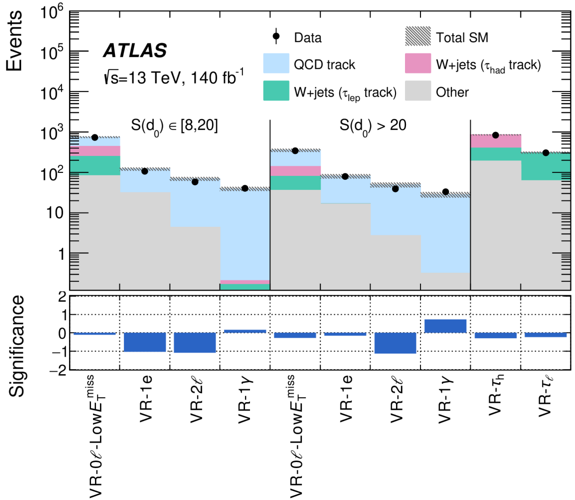

QCD track bkg.



# Validation Regions

**Well-modeled SM backgrounds in VRs**

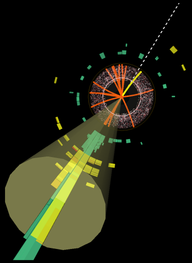
- Low-$E_T^{miss}$ VRs: shift $E_T^{miss}$ to [300 GeV, 400 GeV] $\rightarrow$ similar bkg. composition as SRs
- $1e$, $2\ell$, $1\gamma$ VRs: QCD track bkg.
- $\tau_{lep/had}$ VRs: shift track $p_T$ to [5 GeV, 8 GeV]

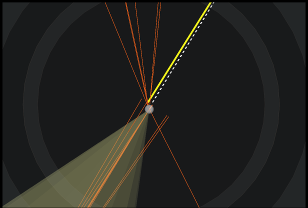


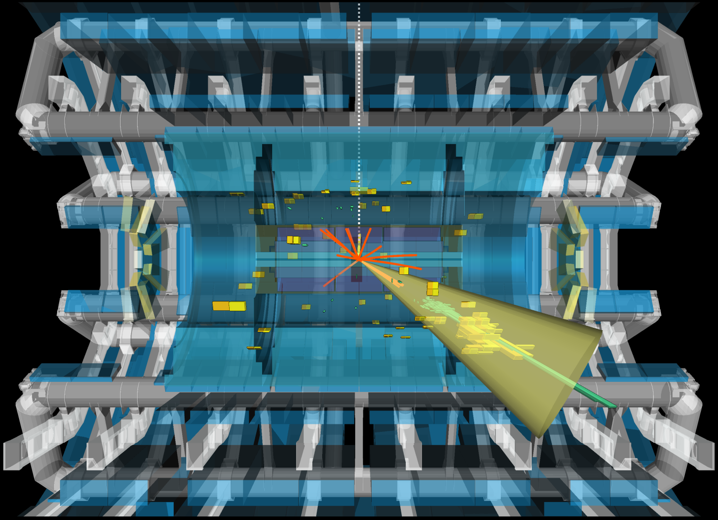

$\rightarrow$ Time to unblind!

ATLAS EXPERIMENT

Run: 349309
Event: 1342904905
2018-05-01 16:21:51 CEST







SR = SR-High

$E_T^{miss}$ = 1001 GeV

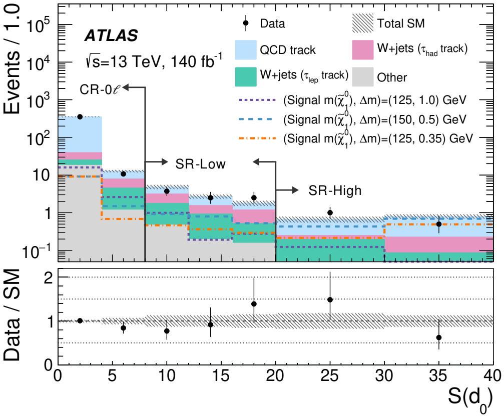
$p_T(j)$ = 1009 GeV

$p_T$(track) = 3.3 GeV

$S(d_0)$ = 38.3

## Unblinded Results

- **Observed data** in excellent agreement with **SM prediction** → **no SUSY**
- Set limits on **visible cross-section of generic BSM physics** and higgsino masses in simplified model



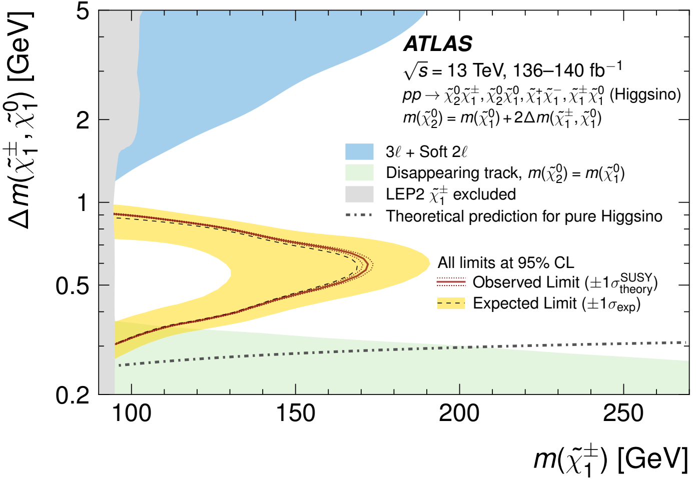

| | SR-Low | SR-High |
|---|---|---|
| Observed data | 35 | 15 |
| SM prediction | $37 \pm 4$ | $14.8 \pm 2.0$ |
| QCD track | $14.0 \pm 1.7$ | $10.0 \pm 1.6$ |
| $W(\to \tau_\ell \nu)$+jets | $9.6 \pm 1.6$ | $2.0 \pm 0.6$ |
| $W(\to \tau_h \nu)$+jets | $10.6 \pm 2.0$ | $1.9 \pm 0.8$ |
| Others | $3.2 \pm 0.7$ | $0.8 \pm 0.4$ |
| $\langle \epsilon\sigma \rangle^{95}_{\text{obs}}$ [fb] | 0.10 | 0.07 |
| $S^{95}_{\text{obs}}$ | 13.5 | 9.9 |
| $S^{95}_{\text{exp}}$ | $15.1^{+6.3}_{-4.2}$ | $9.6^{+4.4}_{-2.8}$ |

# Higgsino Simplified Model Limits

First LHC limits on higgsinos with
$0.4\,\text{GeV} \lesssim \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \lesssim 1\,\text{GeV}$

Probing this regime for first time since LEP2

Low-mass higgsinos/naturalness under increasing scrutiny at LHC.
But complementary techniques are crucial!



# Summary/Outlook

**New ATLAS search for compressed higgsinos with Run 2 data** [arXiv:2401.14046]

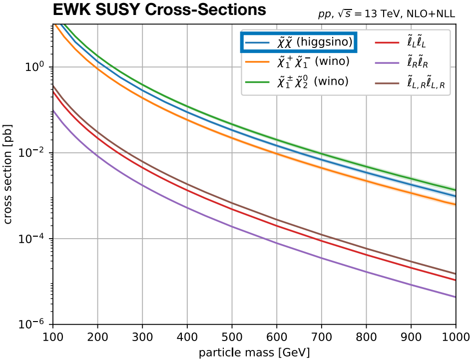
- Hard ISR jet + large $E_T^{miss}$ + soft, displaced, isolated track
- Bridging the sensitivity gap between soft di-lepton and disappearing track searches
- First limits since LEP2 on higgsinos with 0.4 GeV $\lesssim \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \lesssim$ 1 GeV
  - Peak sensitivity: $m(\tilde{\chi}_1^{\pm}) < 170$ GeV for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 0.6$ GeV

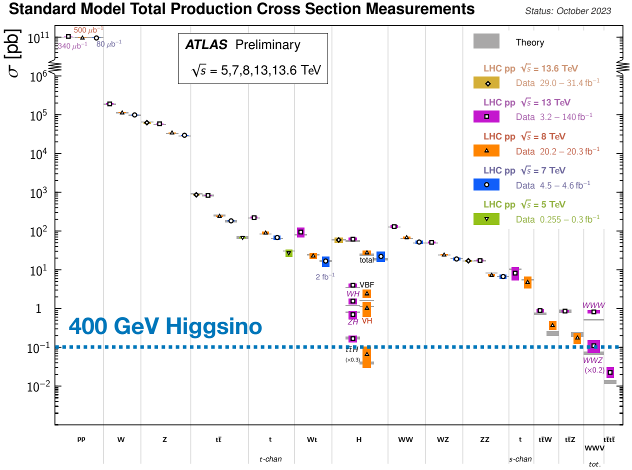
**Outlook**

- Significant constraints on low-mass higgsinos from LHC Run 2, but far from ruled out!
  - Natural solution to hierarchy problem could still be just around the corner
- Exploring the full $\Delta m$ space requires complimentary techniques and new ideas
- Simplest model of higgsino DM at 1.1 TeV still far over the horizon, but let's keep pushing!

# Backup

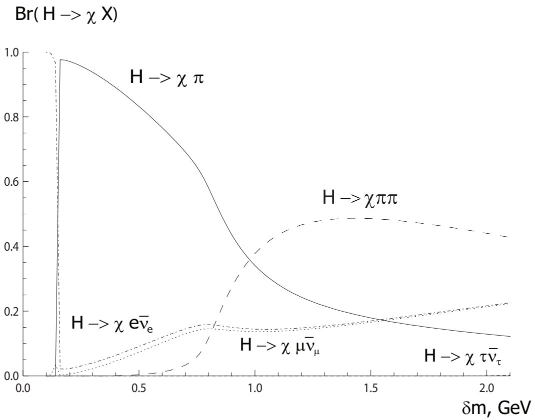
**Higgsino production cross-sections** are at the level of the **rarest SM processes** observed at the LHC



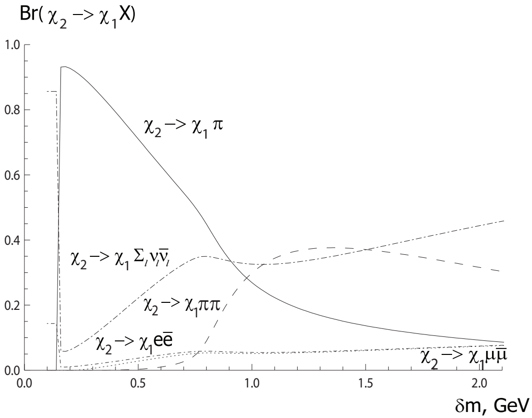



Int. J. Mod. Phys. A **24**, 6051 (2009)

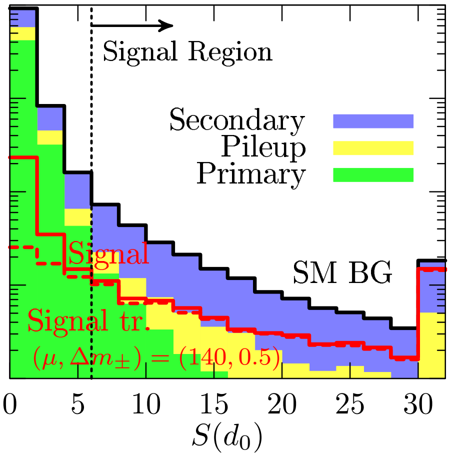
## $\tilde{\chi}_1^\pm$ Branching Ratios

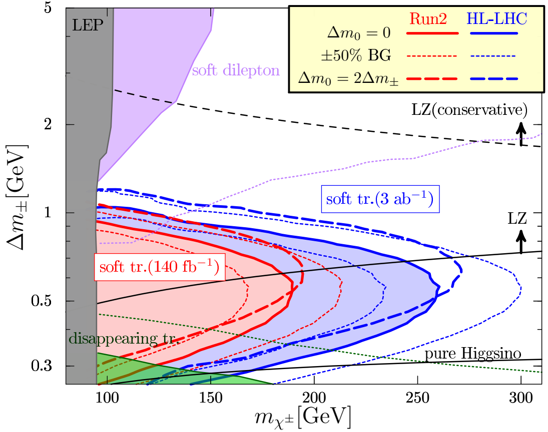



## $\tilde{\chi}_2^0$ Branching Ratios



[arXiv:1910.08065 ]



# Full Signal Region Selection

## Monojet-like selections

| Variable | Requirement |
|---|---|
| Trigger | $E_T^{miss}$ trigger |
| Leading jet $p_T$ [GeV] | > 250 |
| Leading jet working point | *Tight* |
| ① Leading jet $\|\eta\|$ | < 2.4 |
| Leading jet cleaning working point | *Tight* |
| $E_T^{miss}$ [GeV] | > 300 |
| Number of leptons | = 0 |
| Number of jets | $\leq 4$ |
| $\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{miss}))$ | > 0.4 |

+

## Track selections

| Variable | Requirement |
|---|---|
| Track quality | *Tight Primary* |
| ② $N_{IBL}$ | > 0 |
| ③ $p_T$ [GeV] | [1:5] |
| $\eta$ | < 1.5 |
| $d_0$ [mm] | < 10 |
| $\|\Delta z_0 \sin\theta\|$ [mm] | < 3 |
| ④ $\|\Delta\phi(p_T^{track}, E_T^{miss})\|$ | < 0.4 |
| ⑤ Track-based isolation | No tracks with $p_T > 1$ GeV within a $\Delta R < 0.4$ cone |
| Secondary vertex veto | Veto tracks assigned to secondary vertex by `InDetV0FinderTool` |
| ⑥ Leading $S(d_0)$ selection | Select track with largest $S(d_0)$ |

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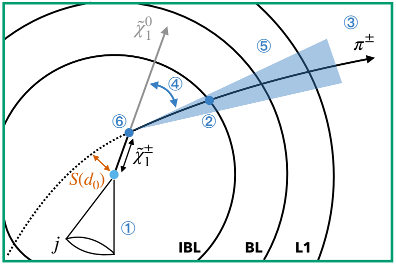
## Optimisation

$$E_T^{miss} > 600 \text{ GeV}$$

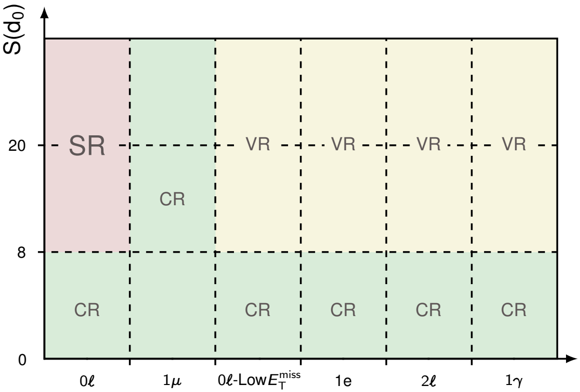
$$8 < S(d_0) < 20 \;||\; S(d_0) > 20$$

$$2 < p_T^{track}/\text{GeV} < 5$$

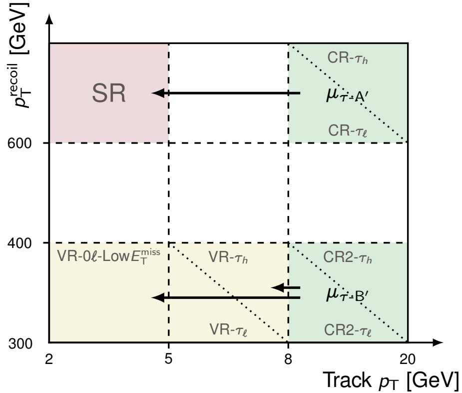
- Figures courtesy of A. Sala
- SRs binned in $S(d_0)$, sensitive to different $\Delta m$
  - **SR-low**: $S(d_0) \in [8, 20]$
  - **SR-high**: $S(d_0) > 20$



QCD track background estimation




τ track background estimation

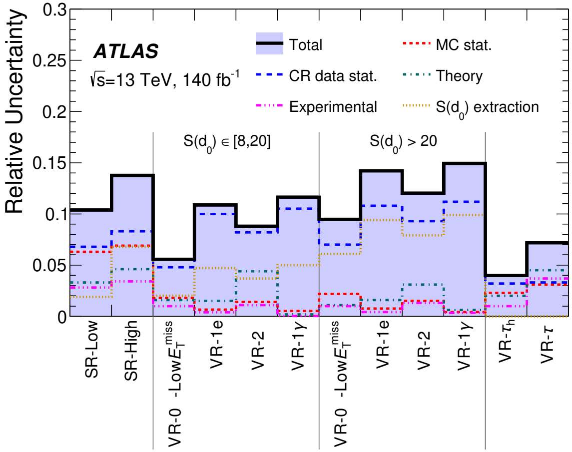


# SM Background Uncertainties

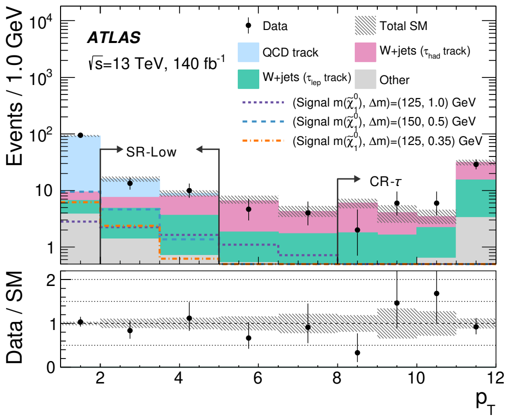
Relative uncertainties on SM backgrounds

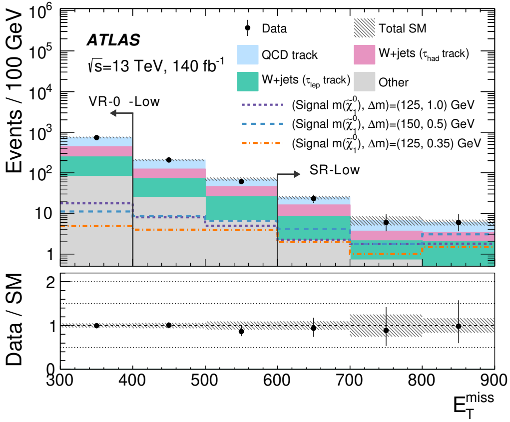
- Data statistics in $W(\rightarrow \tau\nu)$ + jets CRs
- MC sample statistics for non-QCD track backgrounds
- Theoretical modeling
- $S(d_0)$ shape extraction from CR-1$\mu$
- Lepton, jet, $E_T^{miss}$ reconstruction

Largest uncertainties from limited statistics
$\rightarrow$ expect improvements including Run 3 data

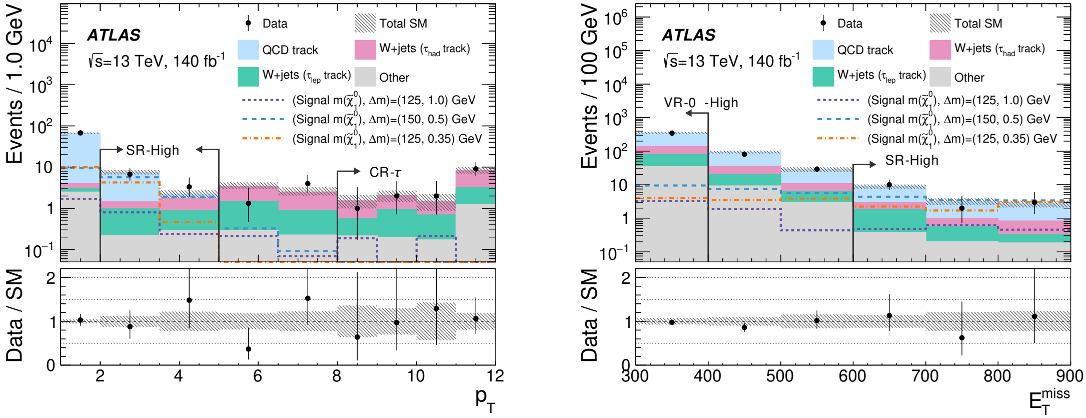


# Signal Region Kinematics: SR-Low



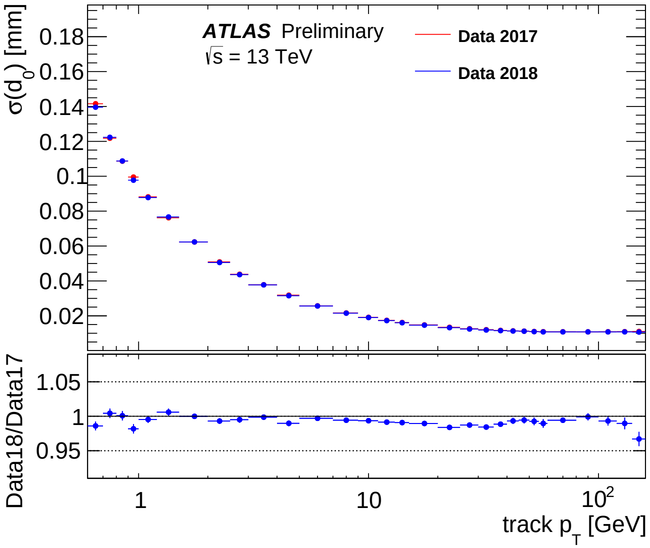
# Signal Region Kinematics: SR-High



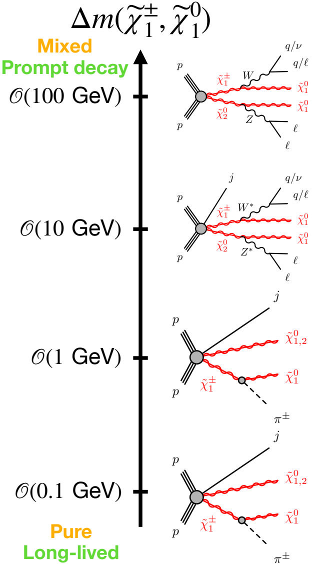
# ATLAS Track $d_0$ Resolution

IDTR-2018-008

- Measured for `TightPrimary` tracks in di-jet events
- $\sigma(d_0) \approx 0.05$ mm for $p_T$(track) = 2 GeV



# ATLAS Higgsino Strategy




**On-shell boson decays —> hard leptons/jets +** $E_{\mathrm{T}}^{miss}$

**Not phenomenologically viable**

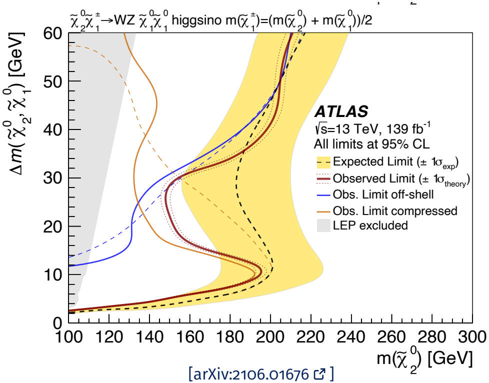
**Off-shell boson decays —> ISR jet + soft leptons +** $E_{\mathrm{T}}^{miss}$

**Slightly long-lived chargino —> ISR jet + soft pion +** $E_{\mathrm{T}}^{miss}$

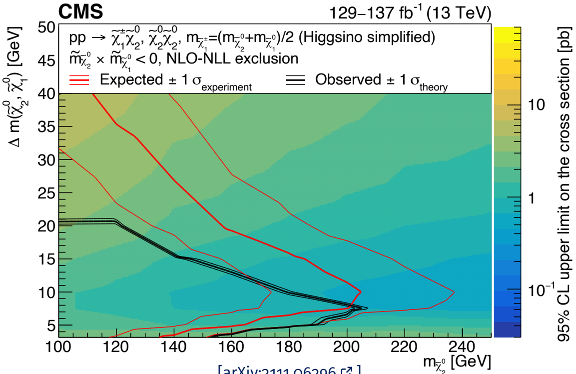
**Long-lived chargino —> ISR jet + disappearing track +** $E_{\mathrm{T}}^{miss}$

# Soft Lepton Search Results

- Higgsino mass limits using combination of $2\ell$ and $3\ell$ searches
- Similar mass reach: $m(\widetilde{\chi}_2^0)$ excluded below $\sim$ 200 GeV for $\Delta m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0) \approx 7 - 10$ GeV in simplified model
- Mild excess seen by both experiments for $\Delta m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0) \sim 20$ GeV

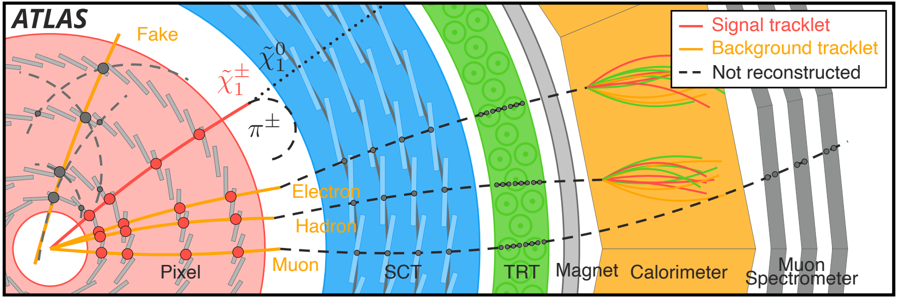



[arXiv:2106.01676]




[arXiv:2111.06296]

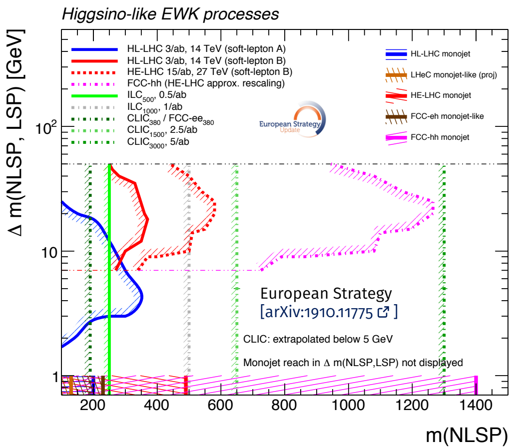
# Disappearing Track Searches

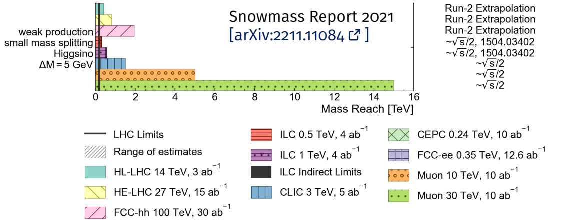


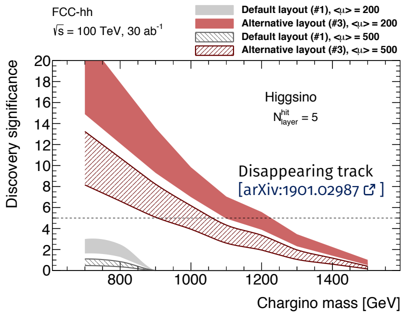

## Disappearing Track Signature for pure Higgsinos

- Pure higgsinos: $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 280 - 350$ MeV $\rightarrow$ **$c\tau \approx 7 - 14$ mm**
- Charginos can be detected in first layers of tracker before decaying to invisible $\tilde{\chi}_1^0$ and very soft pion (not reconstructed) $\rightarrow$ **charged track that "disappears" in tracker volume ("tracklet")**
- Backgrounds:
  - Random hits in Si detector mimicking tracklet
  - Charged lepton/hadron track with large kink due to material interaction/bremsstrahlung

# Long Term Projections




**1.1 TeV higgsinos not a guarantee even at highest-energy *pp* colliders**

**Robust coverage from lepton colliders, but limited by $\sqrt{s}/2$**

**Remains an important benchmark for planning future of collider physics**