Search for Compressed SUSY with the ATLAS Detector

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Joey Reichert

on behalf of the ATLAS Collaboration

University of Pennsylvania

joey@cern.ch

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Introduction

Compressed spectra motivated in many SUSY scenarios

- Higgsino-like LSP motivated by **naturalness** (μ at weak scale)
- Compressed Bino-like LSP with Wino-like NLSP motivated by **DM**
- Anomaly-mediated SUSY breaking models **predict** pure Wino LSP

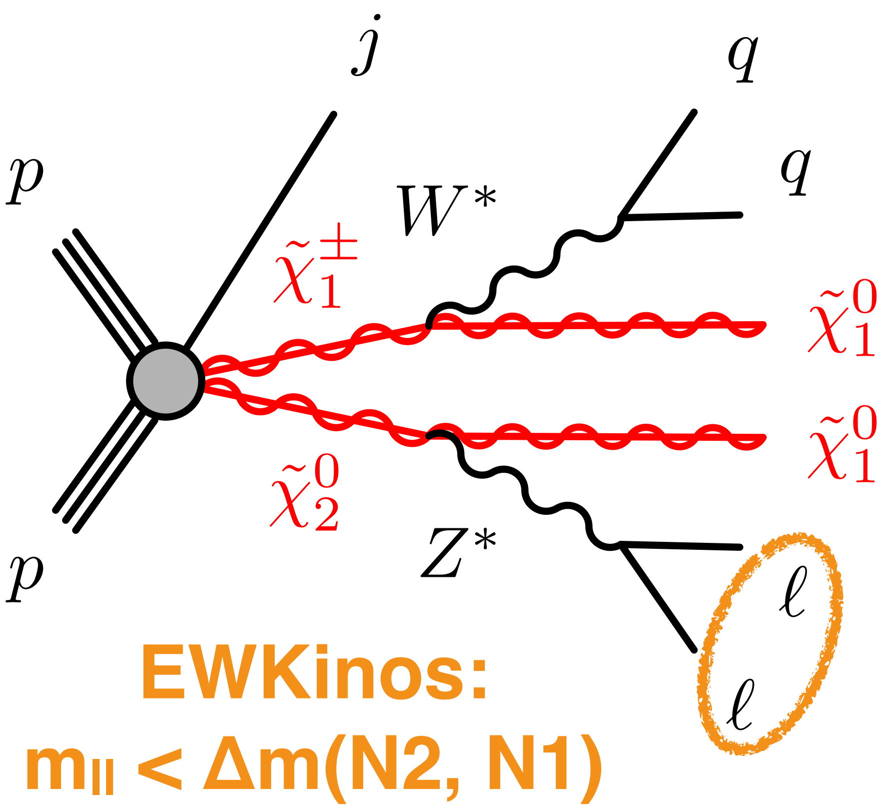
How compressed?

- Pure Higgsino or pure Wino LSP: $\mathcal{O}$(100s MeV) splittings
  - Long lifetimes $\Longrightarrow$ *look for disappearing track*
- "Mostly" Higgsino LSP: $\mathcal{O}$(1-10s GeV) splittings
  - Prompt decays $\Longrightarrow$ *rely on soft leptons with p_T as low as 4 GeV*

Soft leptons and disappearing tracks are challenging signatures!

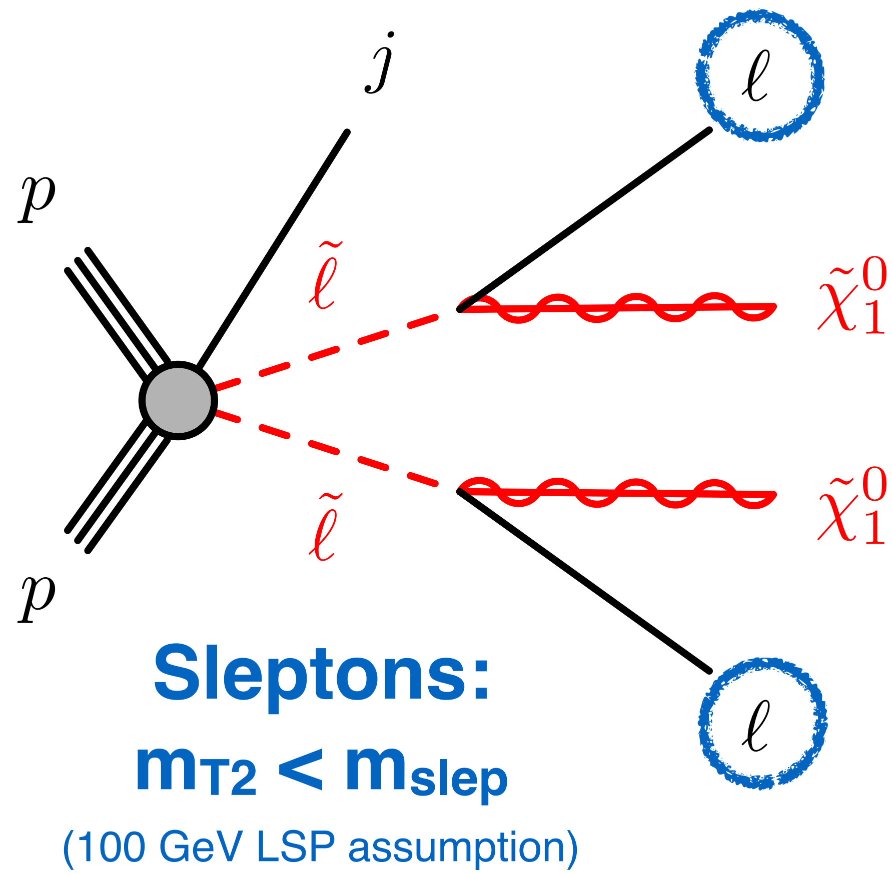
- Use ISR jet + MET topologies to trigger and discriminate against backgrounds

Searches Considered



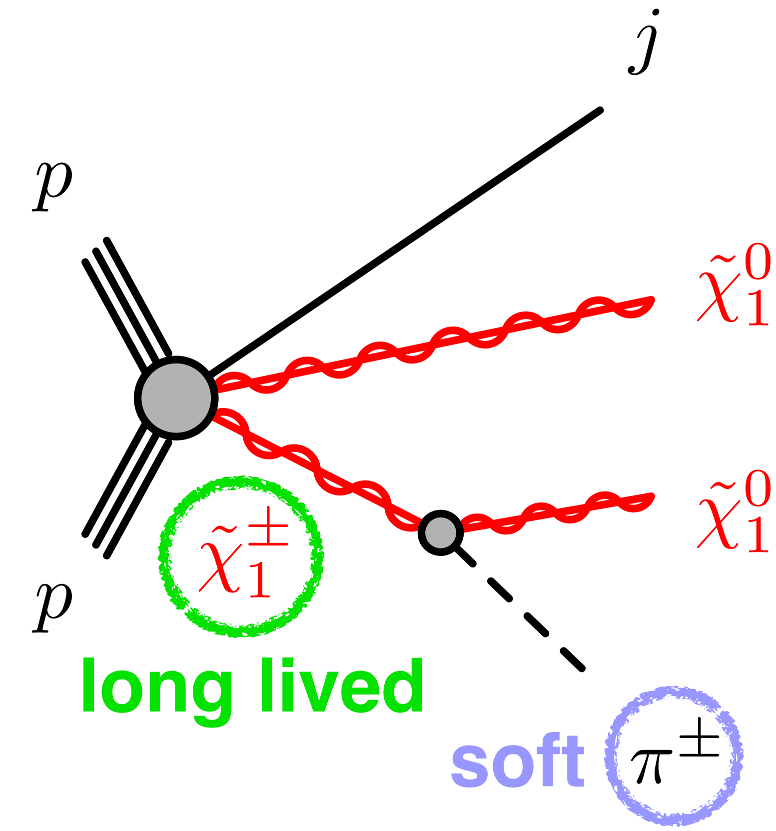
Final state: 2 soft leptons + MET + ISR jet

Interpret as: Higgsino-like LSP or Wino-like NLSP with Bino-like LSP



Final state: 2 soft leptons + MET + ISR jet

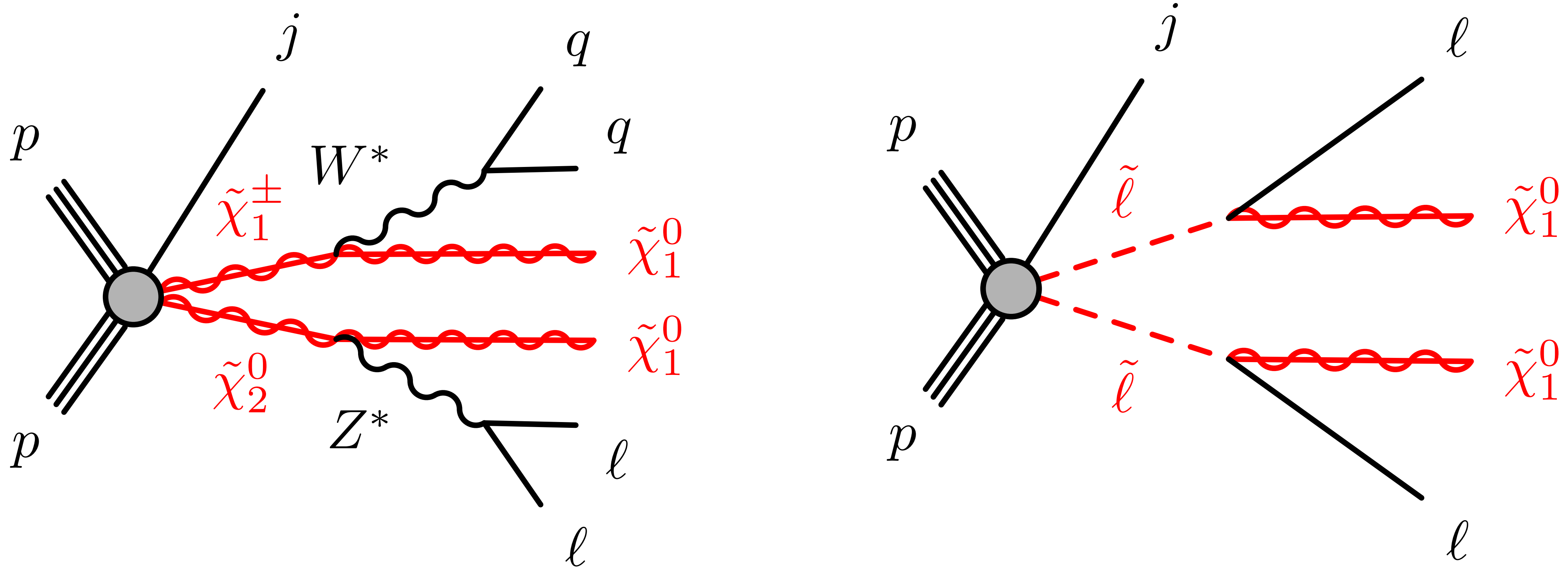
Interpret as: slepton NLSP with Bino-like LSP



Final state: disappearing track + MET + ISR jet

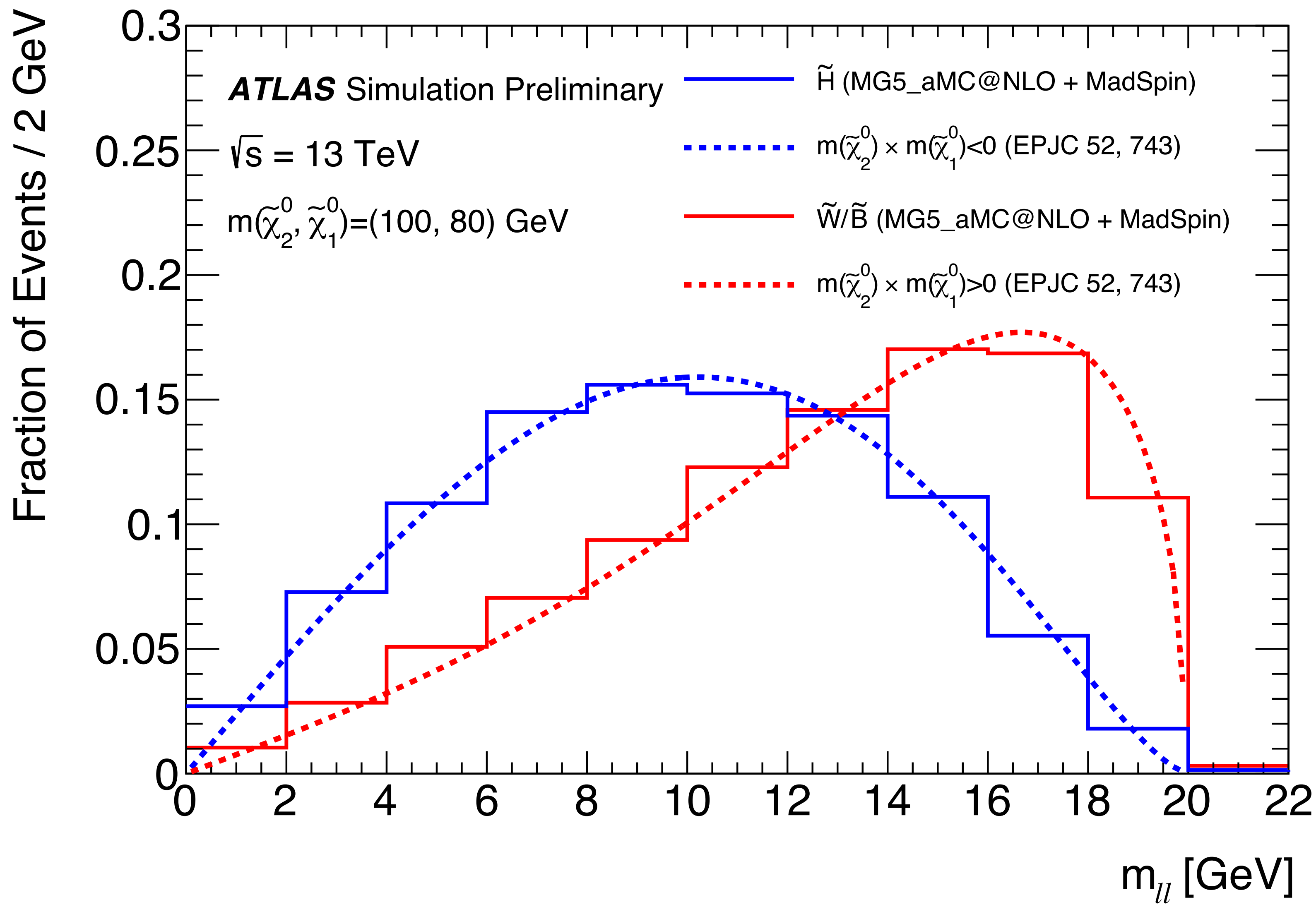
Interpret as: pure Wino LSP or pure Higgsino LSP

2L (soft) search



Compressed scenarios paper (to be submitted):
SUSY-2016-25

EWKino Primary Discriminating Variable



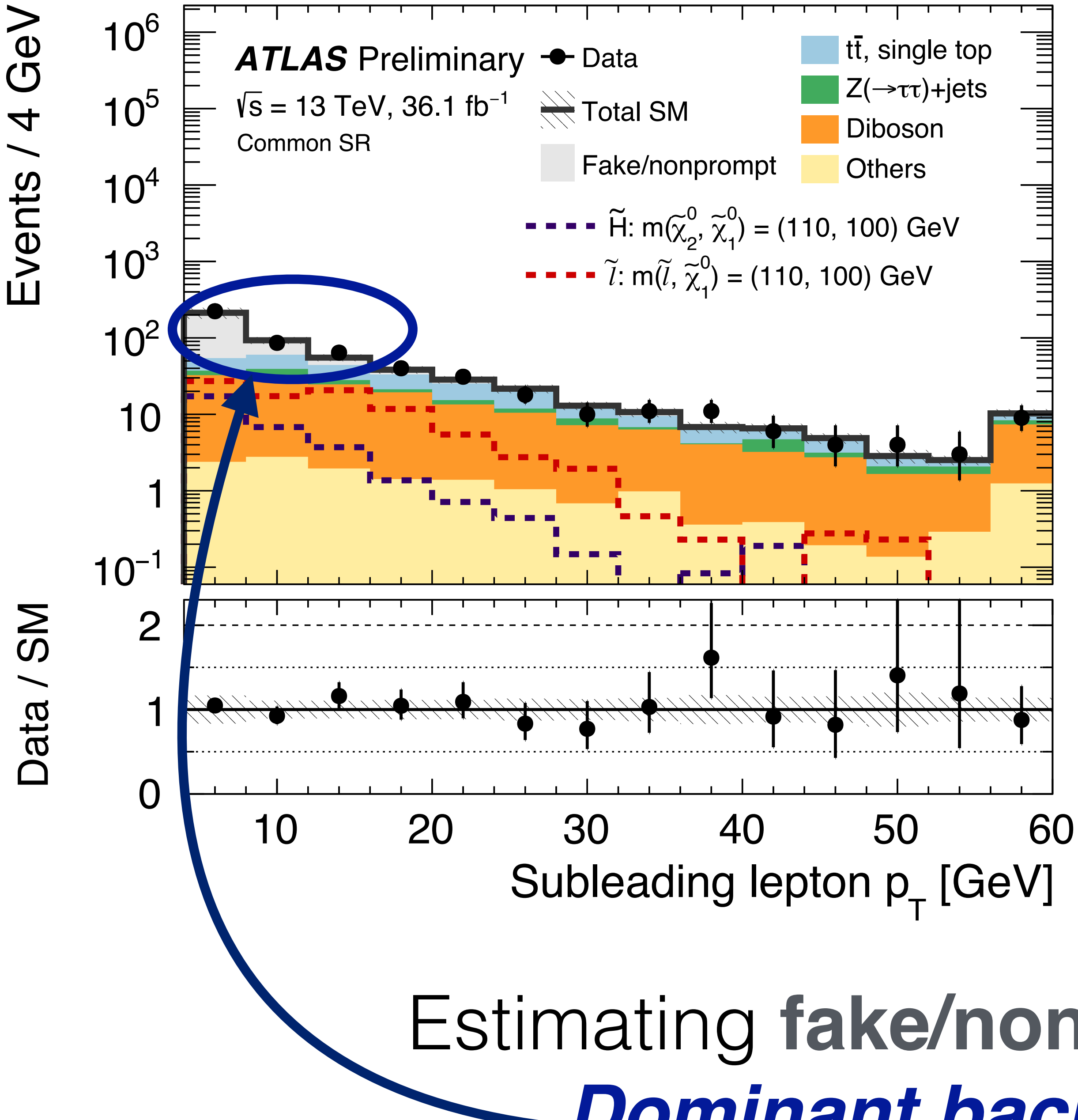
EWKinos: kinematic endpoint at $m_{ll} = \Delta m(N2, N1)$

This is our primary observable for the EWKinos!

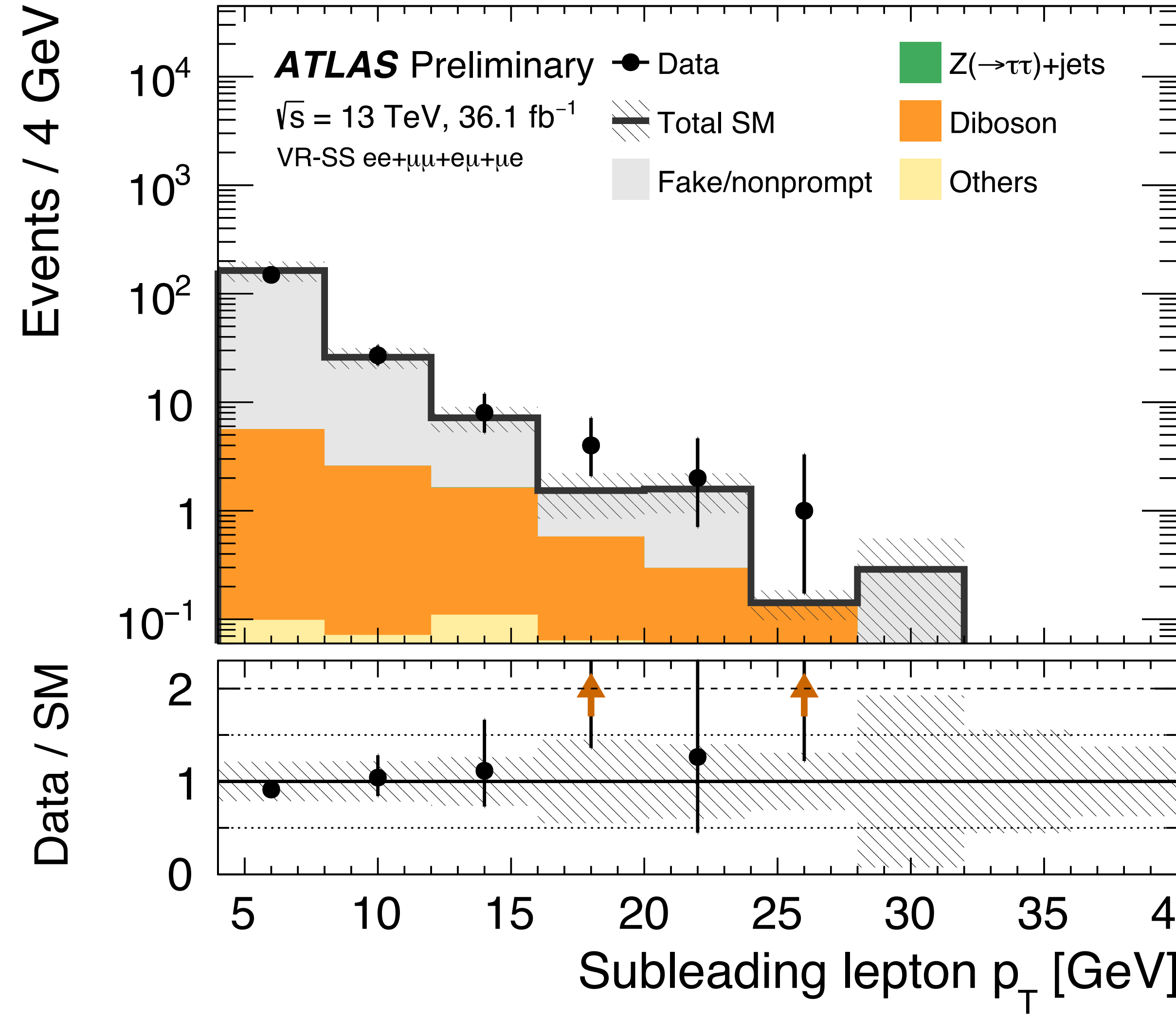
m_{T2} behaves similarly for the slepton final state

Estimating Fake Lepton Backgrounds

Subleading lepton p_T in signal region



Subleading lepton p_T in same-sign events



Estimating **fake/nonprompt** leptons crucial:

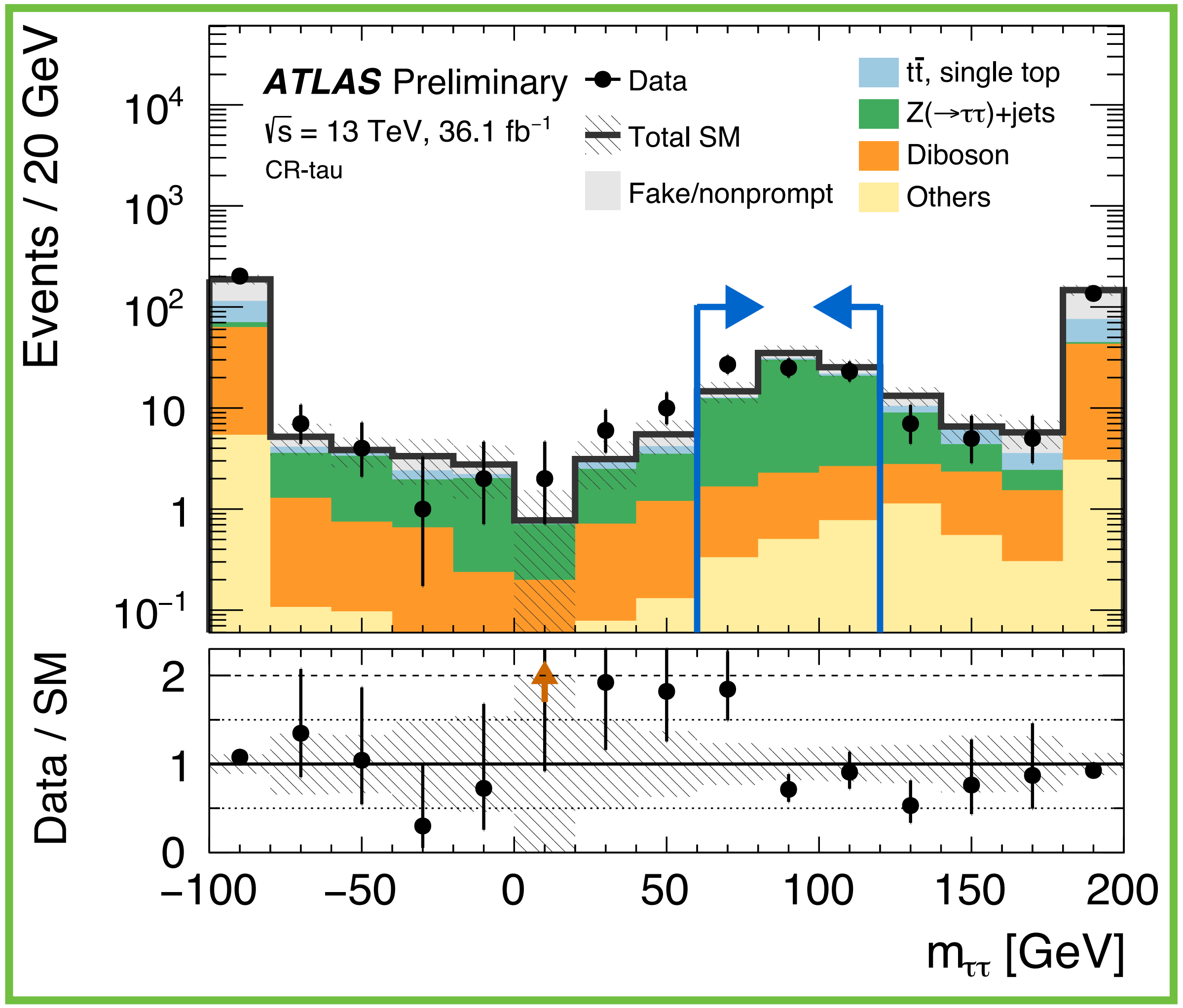
Dominant background at low p_T!

- Estimate using data-driven "Fake Factor" method
- Validate using data in W+jet dominated same-sign region

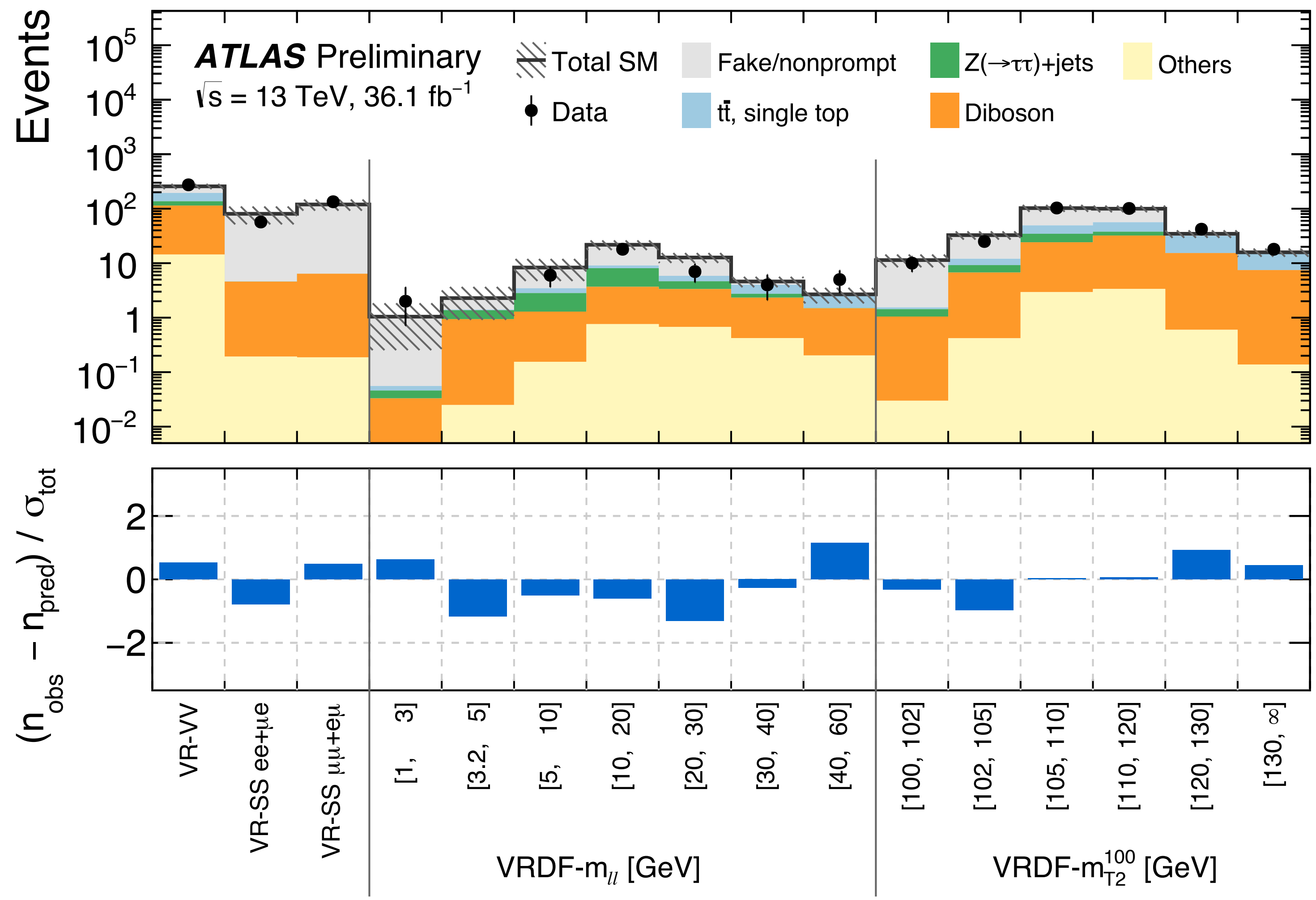
Remaining Background Sources

Use CRs and/or VRs to target each of the remaining backgrounds

$m_{\tau\tau}$ distribution in CR-tau

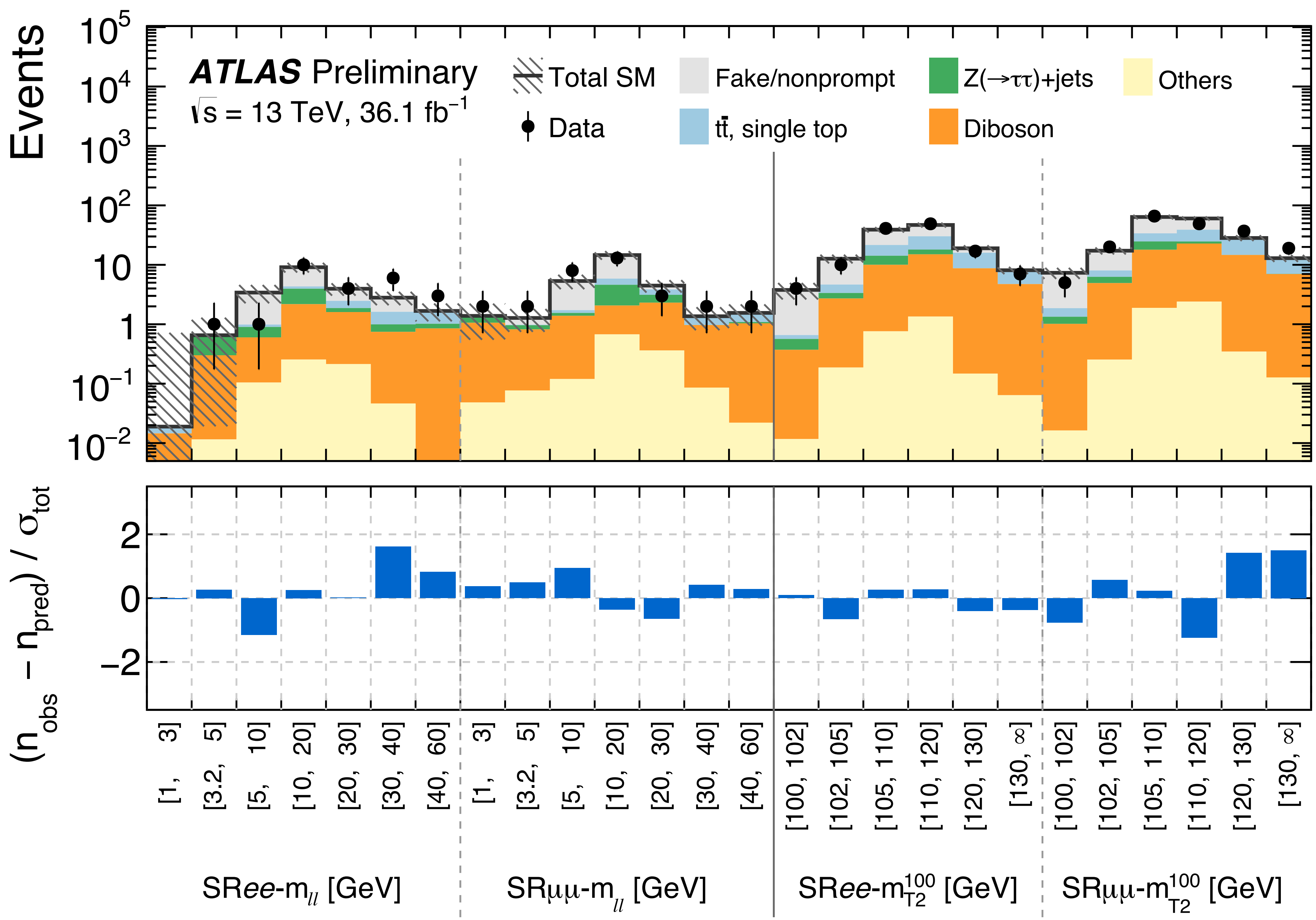


Summary of Validation Regions



- diboson: model with MC down to m_{ll} > 0.5 GeV; validate with events where MET comes from hard leading lepton rather than jet recoil
- $Z\rightarrow\tau\tau$: minimize using ditau mass proxy; use on-Z region for CR
- top: reduce with tight b-jet veto; use ≥1 b-jet region for CR

Results: Signal Region Yields

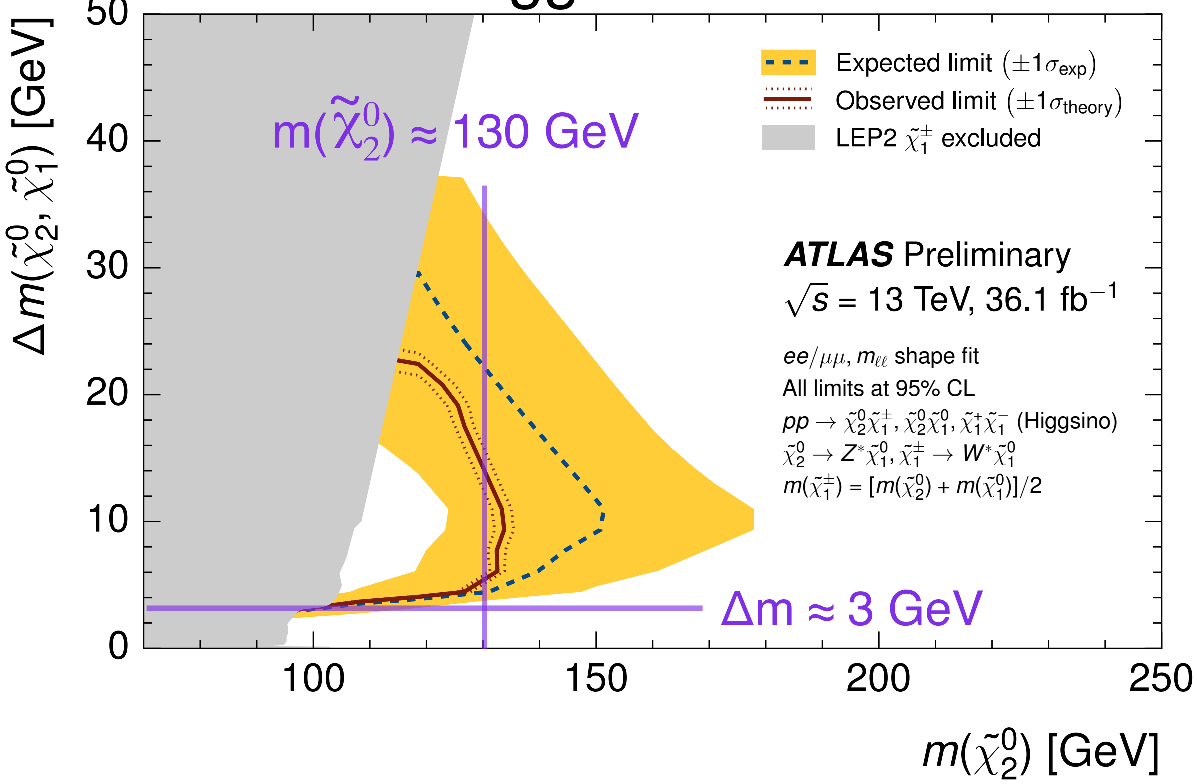


No significant excesses observed:

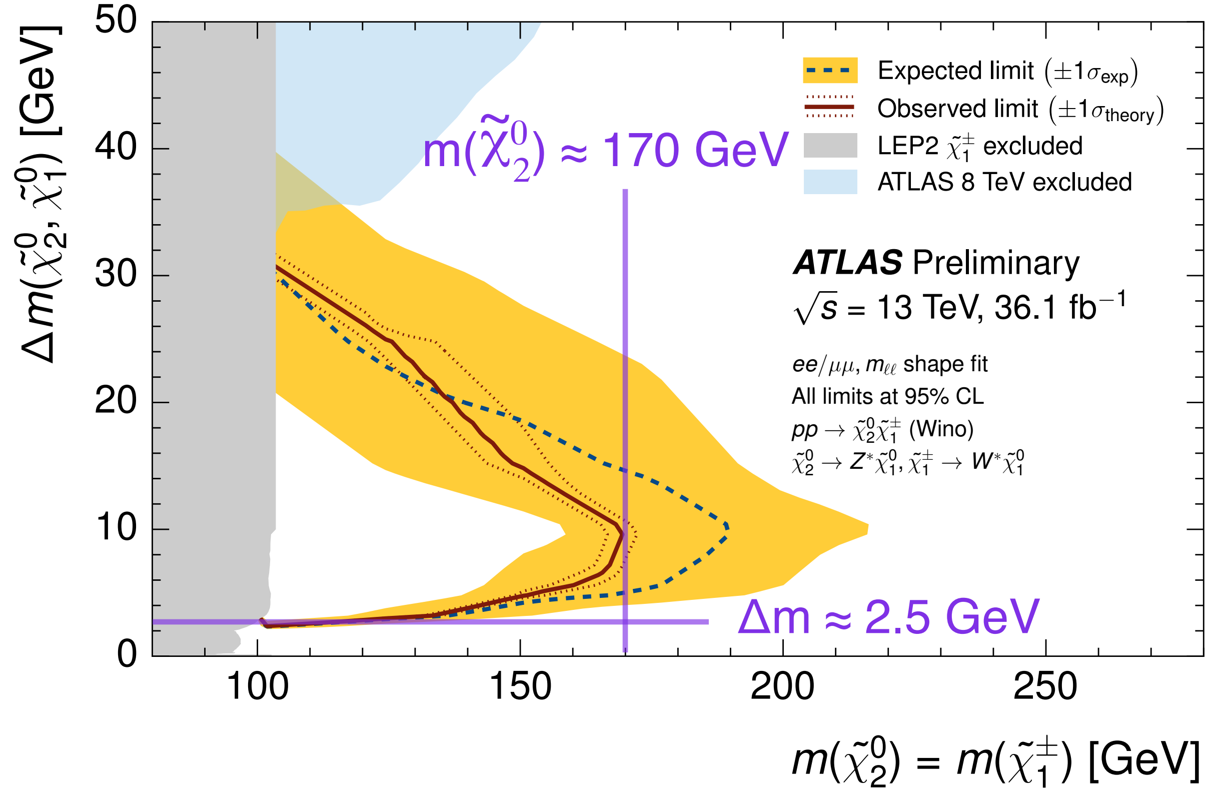
set limits on simplified models

Results: Limits

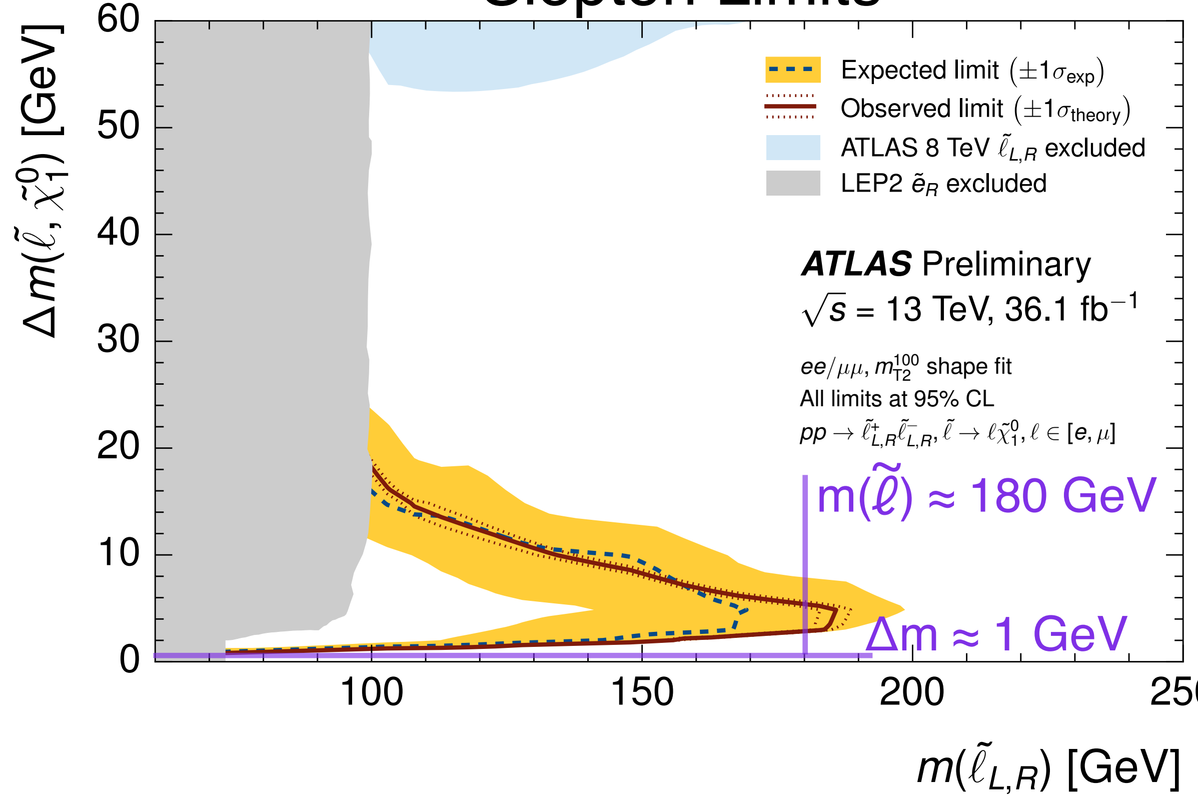
Higgsino Limits



Wino-Bino Limits



Slepton Limits

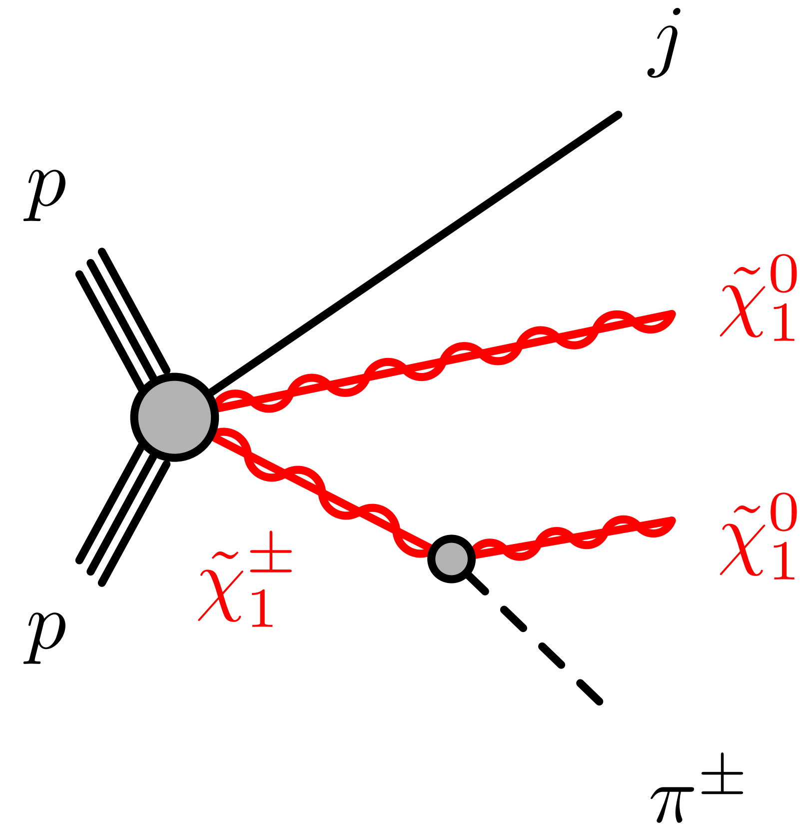


First ATLAS results on direct Higgsino production.
Pushing past the LEP limits!

Probed mass splittings as low as:

- Δm(N2, N1) = 3 GeV for Higgsinos
- Δm(N2, N1) = 2.5 GeV for Wino-Bino
- Δm(slepton, N1) = 1 GeV for sleptons

Disappearing track search



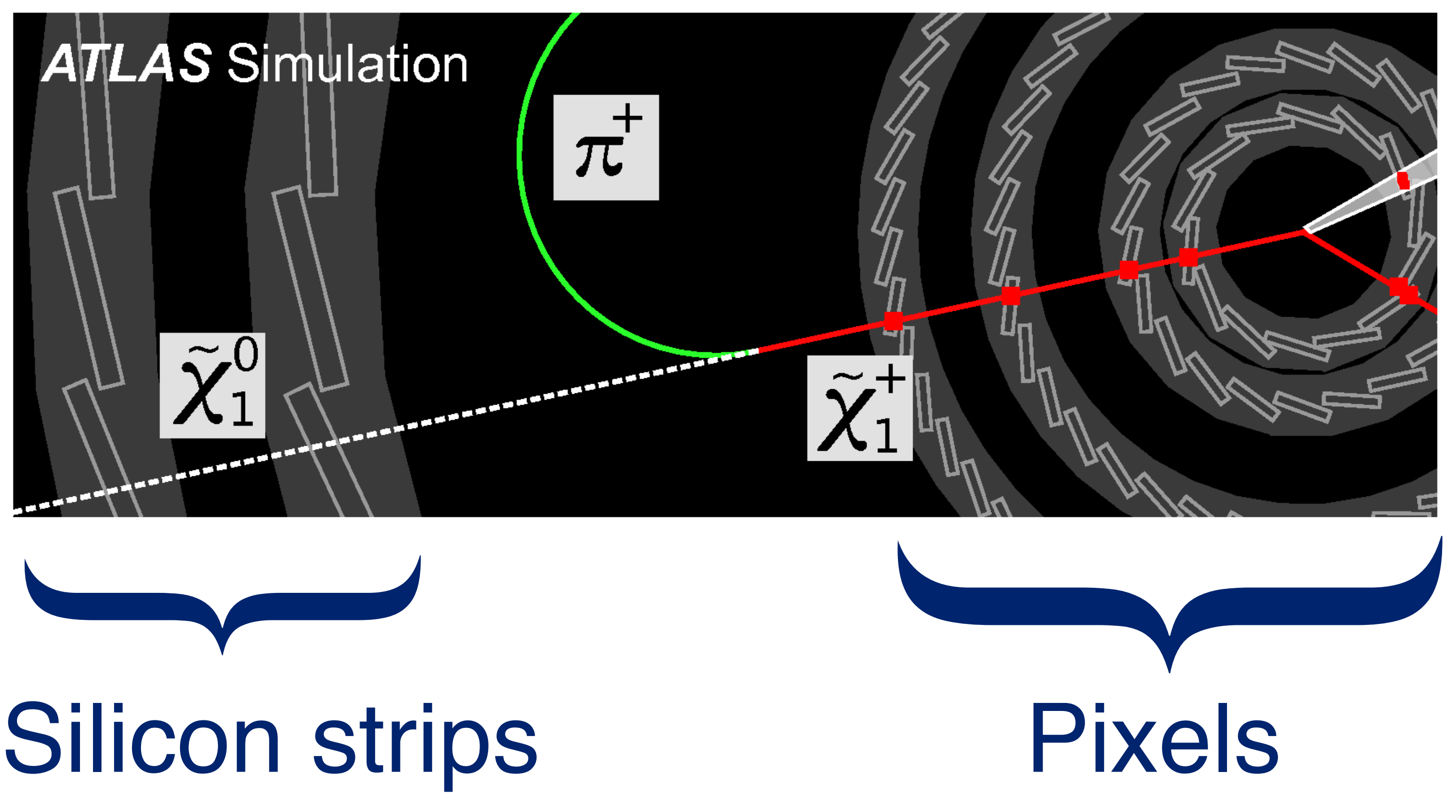
Wino scenario paper:
arXiv:1712.02118

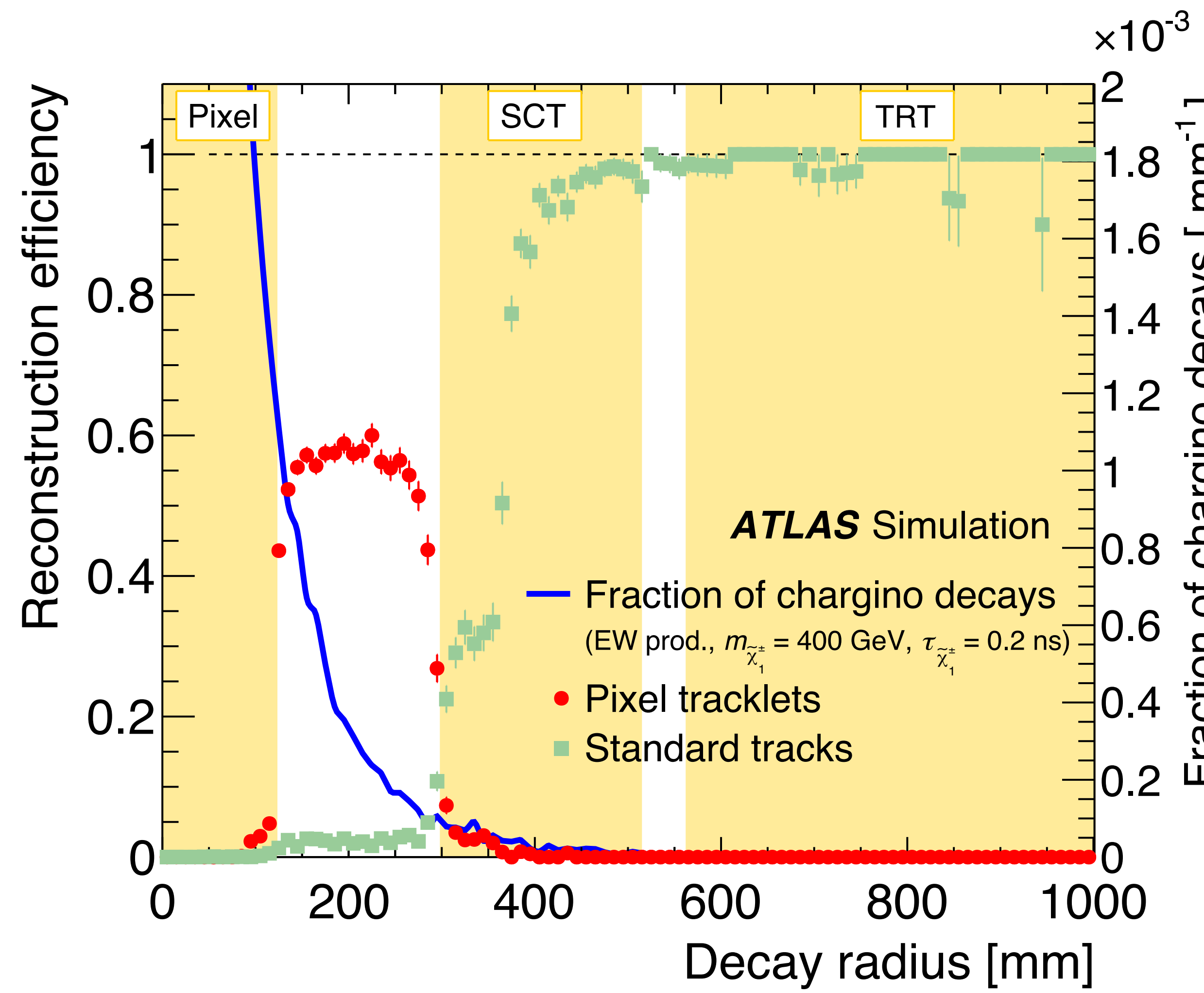
Higgsino reinterpretation:
ATL-PHYS-PUB-2017-019

Tracklets

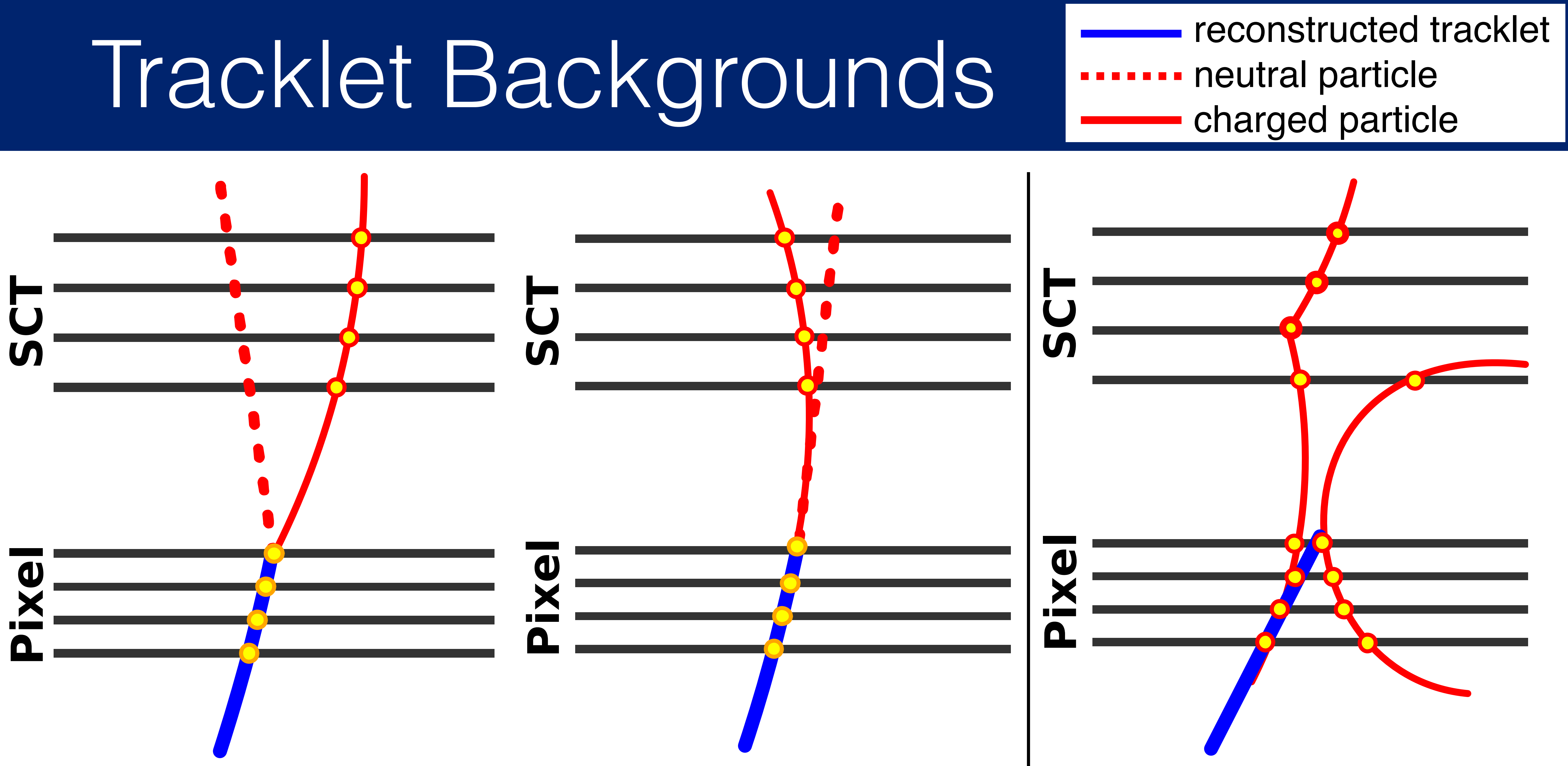
Long lived chargino can leave hits in the tracker before decay

- Look for “tracklet” with hits in ATLAS pixel layers (R < 12 cm) but none in silicon strips (R > 30 cm)
- Sensitive to lifetimes between 10 ps - 10 ns (optimal for 1 ns)
- Note: innermost pixel layer new for Run 2, and allows for the use of such short tracklets!





Tracklet Backgrounds

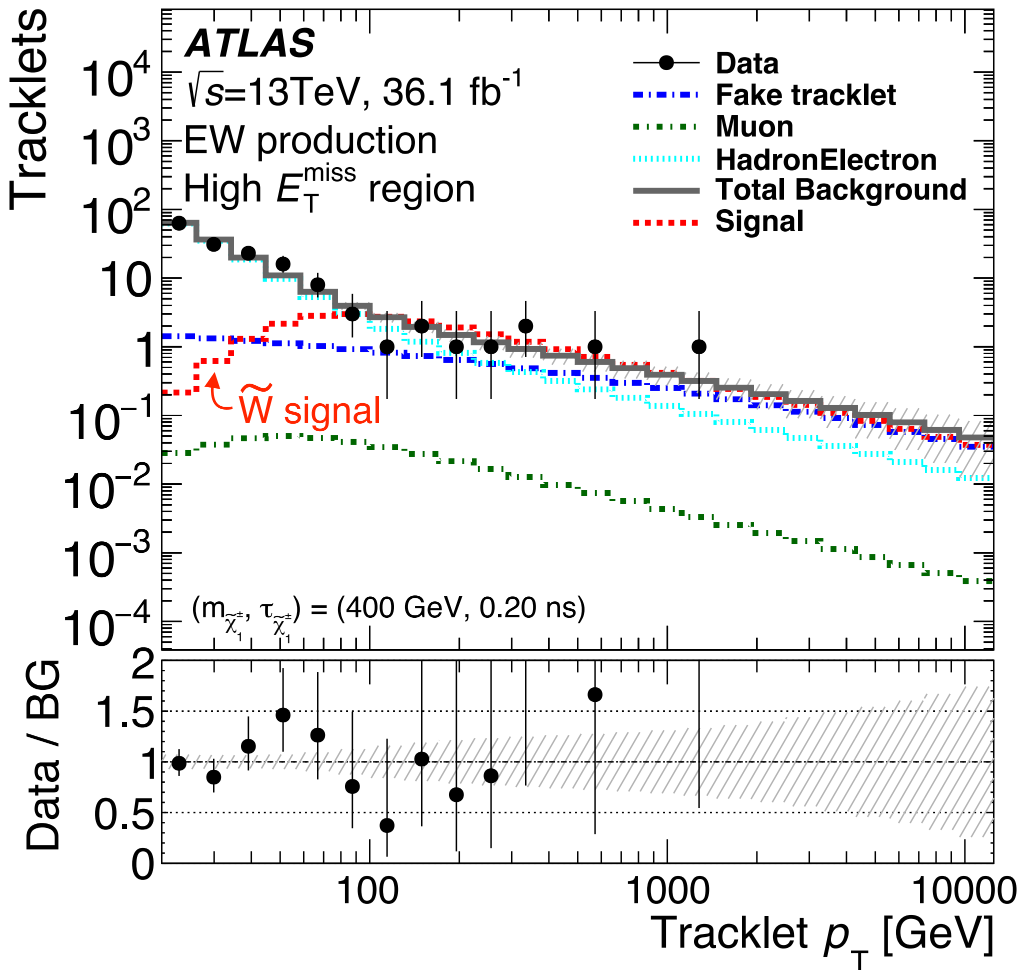


Hadron with hard scattering or lepton emits photon:
pixel and SCT tracks not associated

Random combination:
hits from nearby particles
fake tracklet

Suppress backgrounds with isolation, impact parameter requirements, and by dropping low quality hits (e.g. hit position far from tracklet)

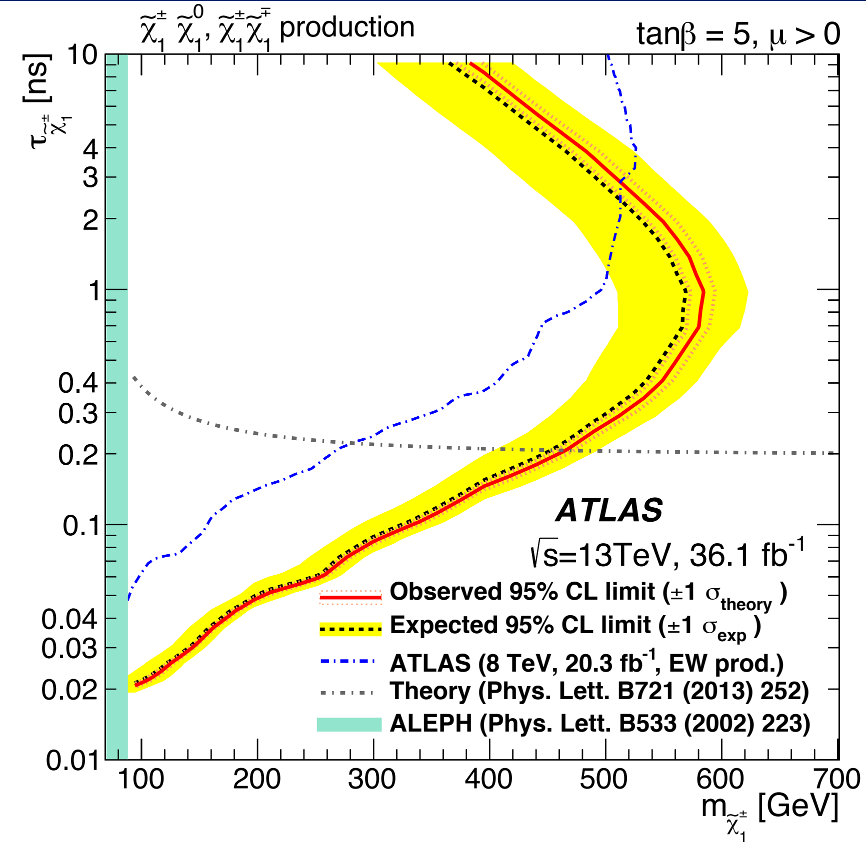
Disappearing Track Results



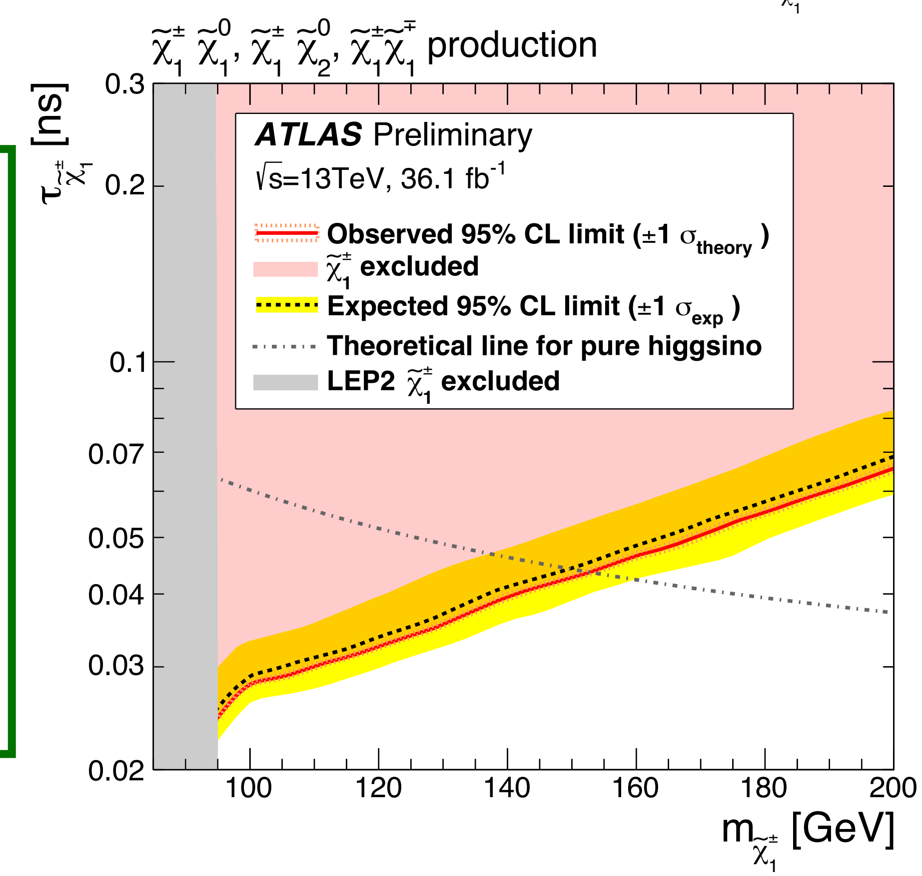
Backgrounds live at low tracklet p_T, so $p_T > 100$ GeV used for signal region.

No excesses observed: Place limits on pure Wino and pure Higgsino scenarios

Pure Wino LSP with 0.2 ns lifetime (Δm = 160 MeV) excluded up to 460 GeV

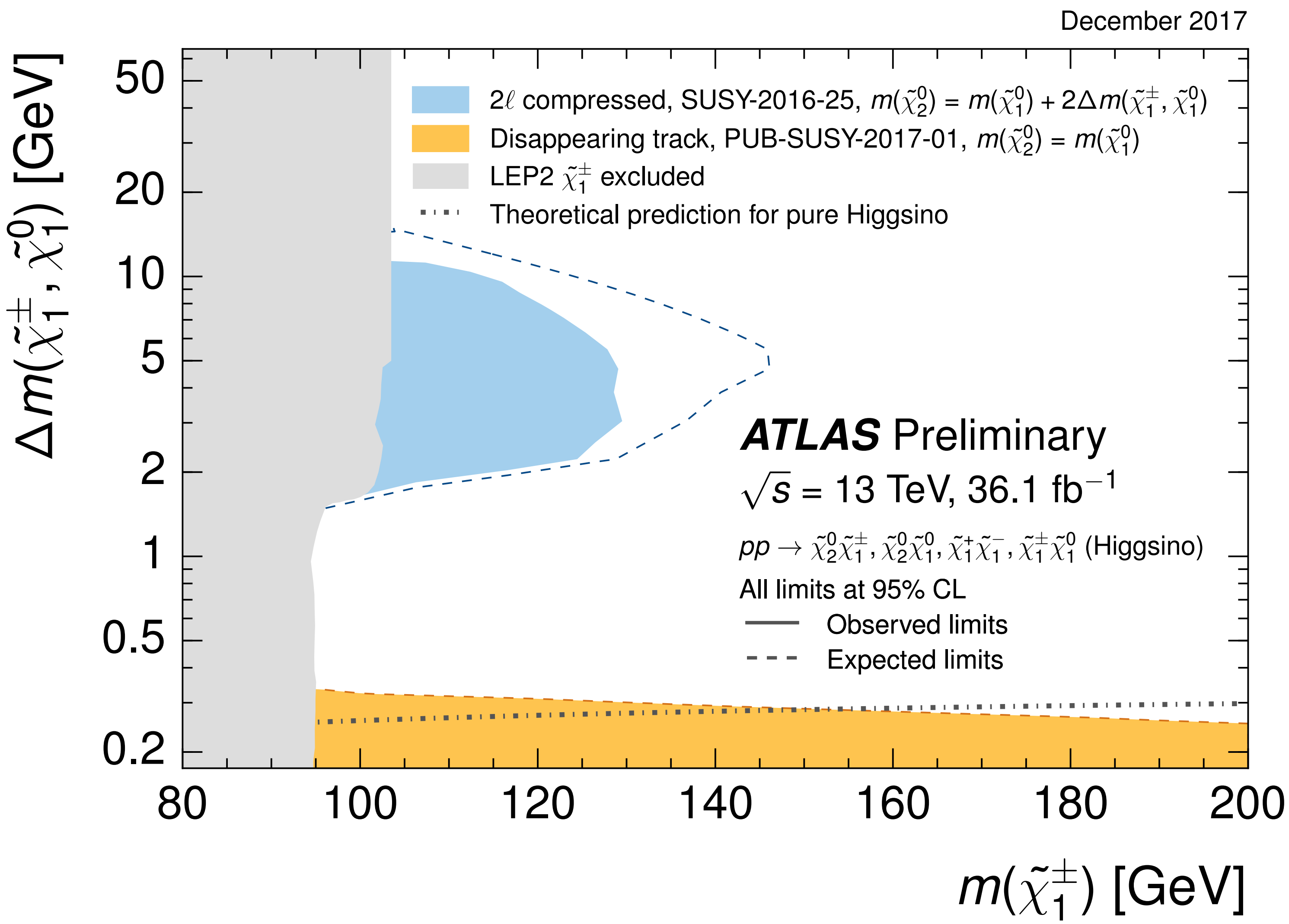


Pure Higgsino LSP with 0.05 ns lifetime (Δm = 275 MeV) excluded up to 152 GeV

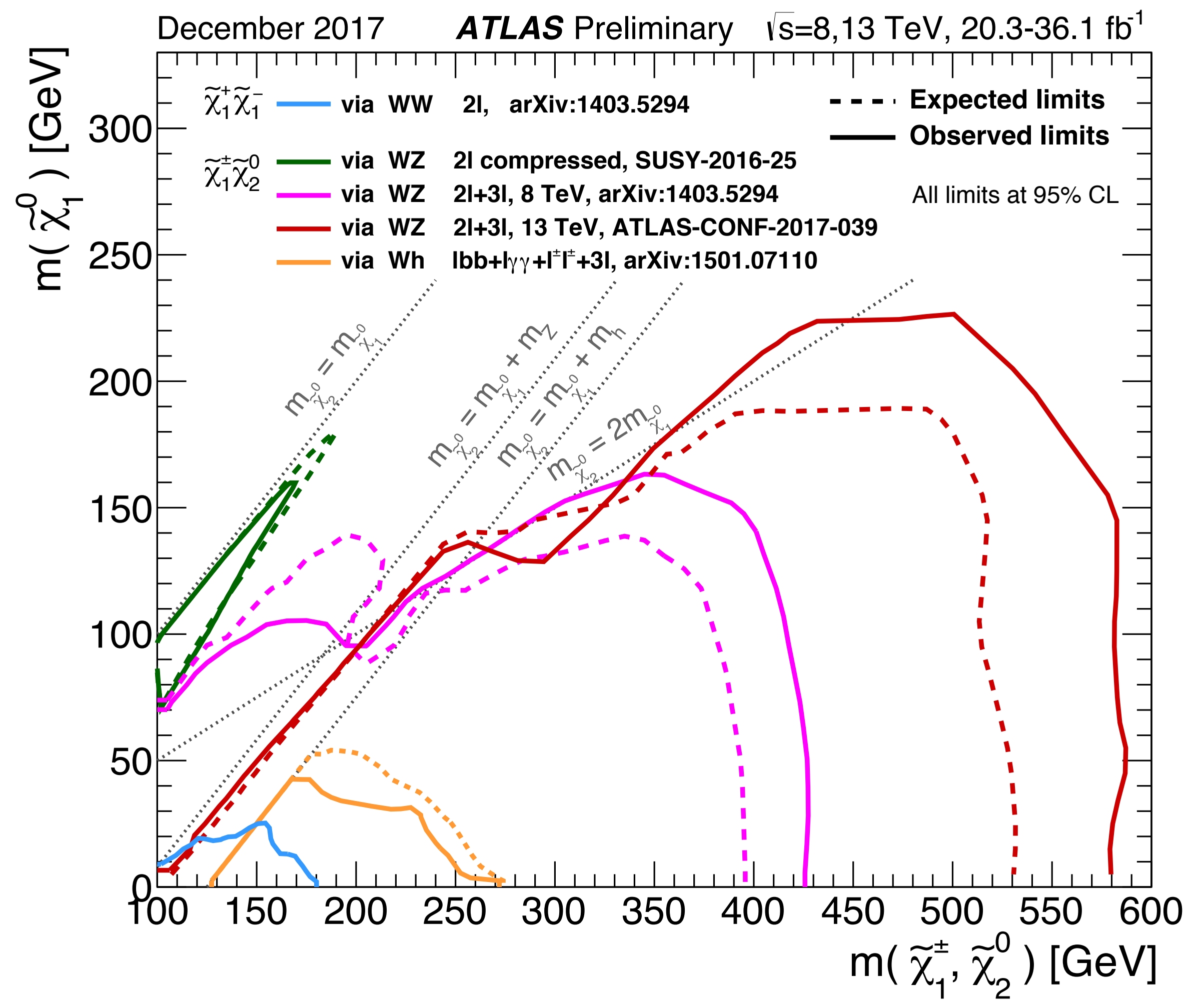


Summary

Combined limits on direct Higgsino production



Combined limits on Wino-Bino production

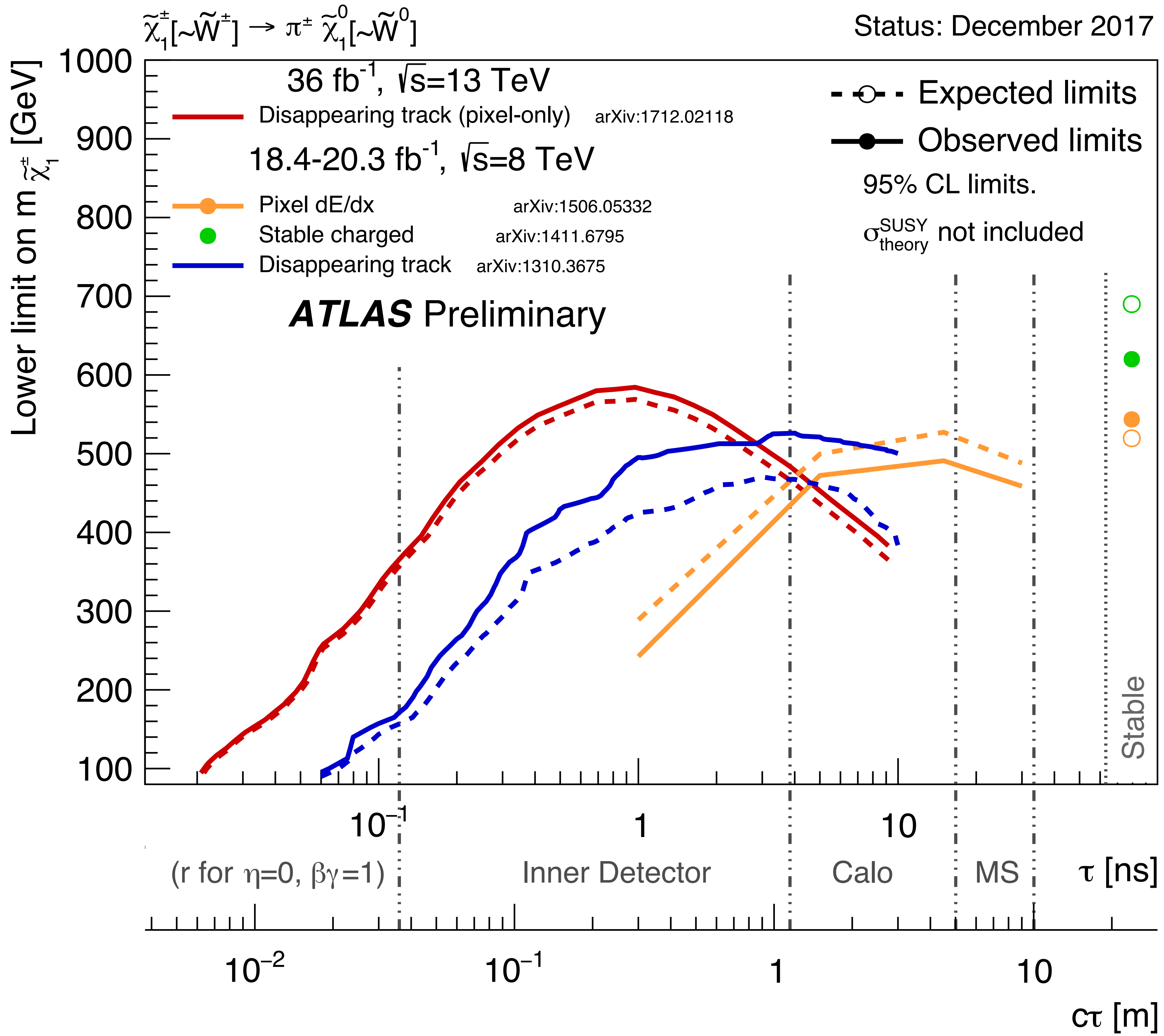


Compressed SUSY searches well-motivated by naturalness and dark matter constraints

- No signs of SUSY yet—exclusion starting to push beyond LEP limits from over a decade ago!

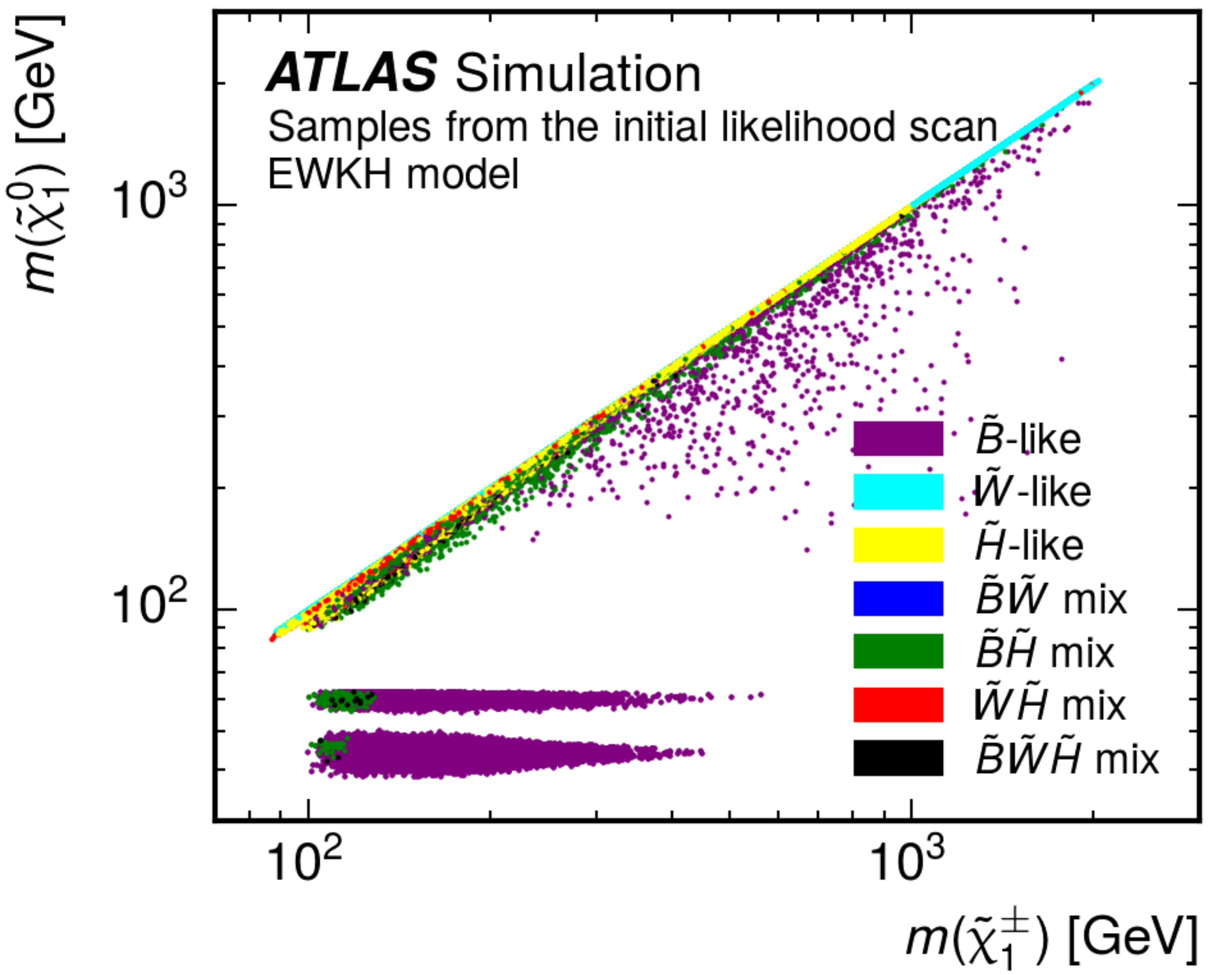
Backup

Pure Wino LSP Summary

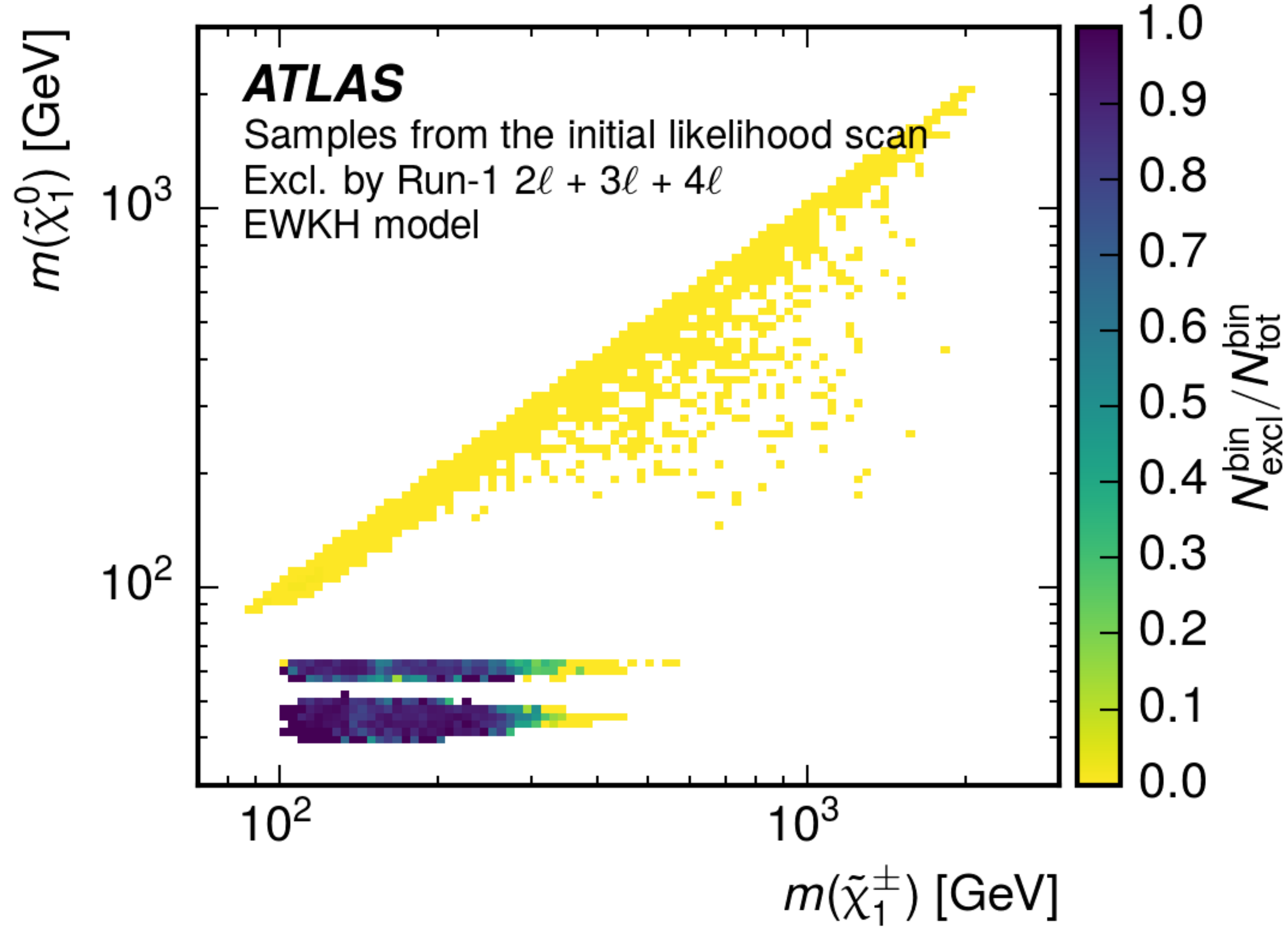


Theoretical Motivation: pMSSM

5-parameter pMSSM scan from ATLAS Run 1 Dark Matter Summary Paper



Composition of lightest neutralino



Fraction of points excluded per bin in Run 1

Higgsino LSPs tend to fall along the diagonal, which has evaded searches so far

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“Mostly” Higgsino mass splittings

Case 1: Heavy bino

$M_1 >> M_2 > \mu$

$$\left|m_{\chi_2^0}\right| - \left|m_{\chi_1^0}\right| \approx \frac{m_W^2 \left(\pm|\mu|\, s_{2\beta} + M_2\right)}{\left(M_2^2 - |\mu|^2\right)}$$

Case 2: Heavy wino

$M_2 >> M_1 > \mu$

$$\left|m_{\chi_2^0}\right| - \left|m_{\chi_1^0}\right| \approx \frac{m_W^2 t_{\theta_W}^2 \left(\pm|\mu|\, s_{2\beta} + M_1\right)}{\left(M_1^2 - |\mu|^2\right)}$$

$$\Longrightarrow \quad \Delta m(N2, N1) \approx \frac{(m_W)^2}{\min(M_1, M_2)}$$

So if e.g. M_1 or M_2 is O(1-2 TeV), then Δm(N2, N1) ≈ 3-6 GeV

arXiv:1401.1235

Pure Higgsino lifetimes

$$c\tau[\text{mm}] \sim 7 \times \left[\left(\frac{\Delta m \left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^{0} \right)}{340\,\text{MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m \left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^{0} \right)^2}} \right]^{-1}$$

Example lifetimes:

μ = 100 GeV $\Longrightarrow$ Δm = 257 MeV, so cτ = 19.3 mm

μ = 1 TeV $\Longrightarrow$ Δm = 355 MeV, so cτ = 6.7 mm

2L + MET + ISR jet signal samples

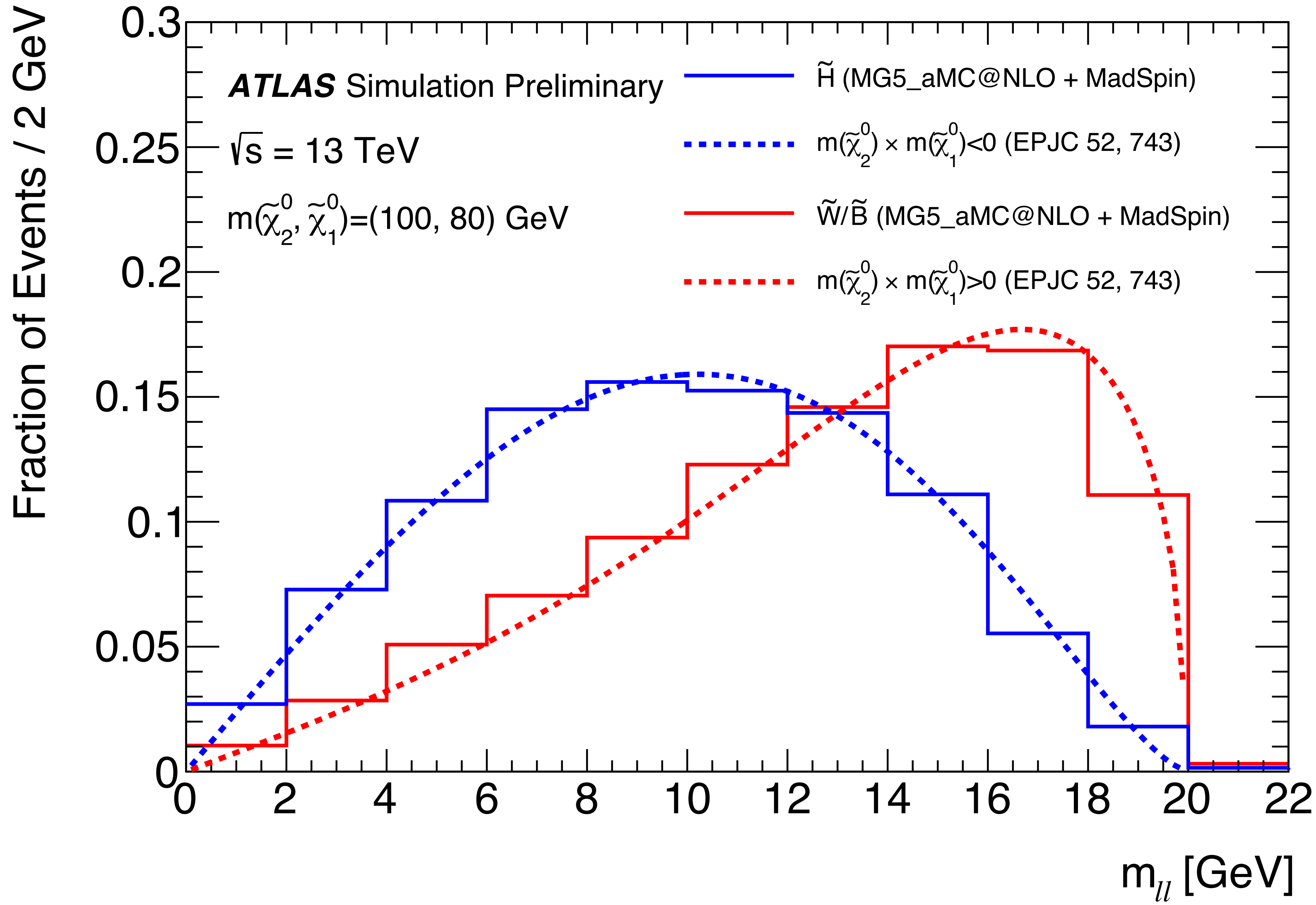
For Higgsino-like LSP, Wino-Bino, and slepton samples:

- Generated at LO using MG5_aMC@NLO with up to two extra partons and showered with Pythia8
- Resummino at NLL+NLO used to compute the cross-sections

Specific for EWKino samples:

- MadSpin used to model the off-shell W*/Z* decays properly
- Lepton BRs vary with Δm(N2, N1) when Z* becomes too light to decay to e.g. ττ or bb pairs; calculated using SUSY-HIT

Higgsino vs. Wino-Bino Differences

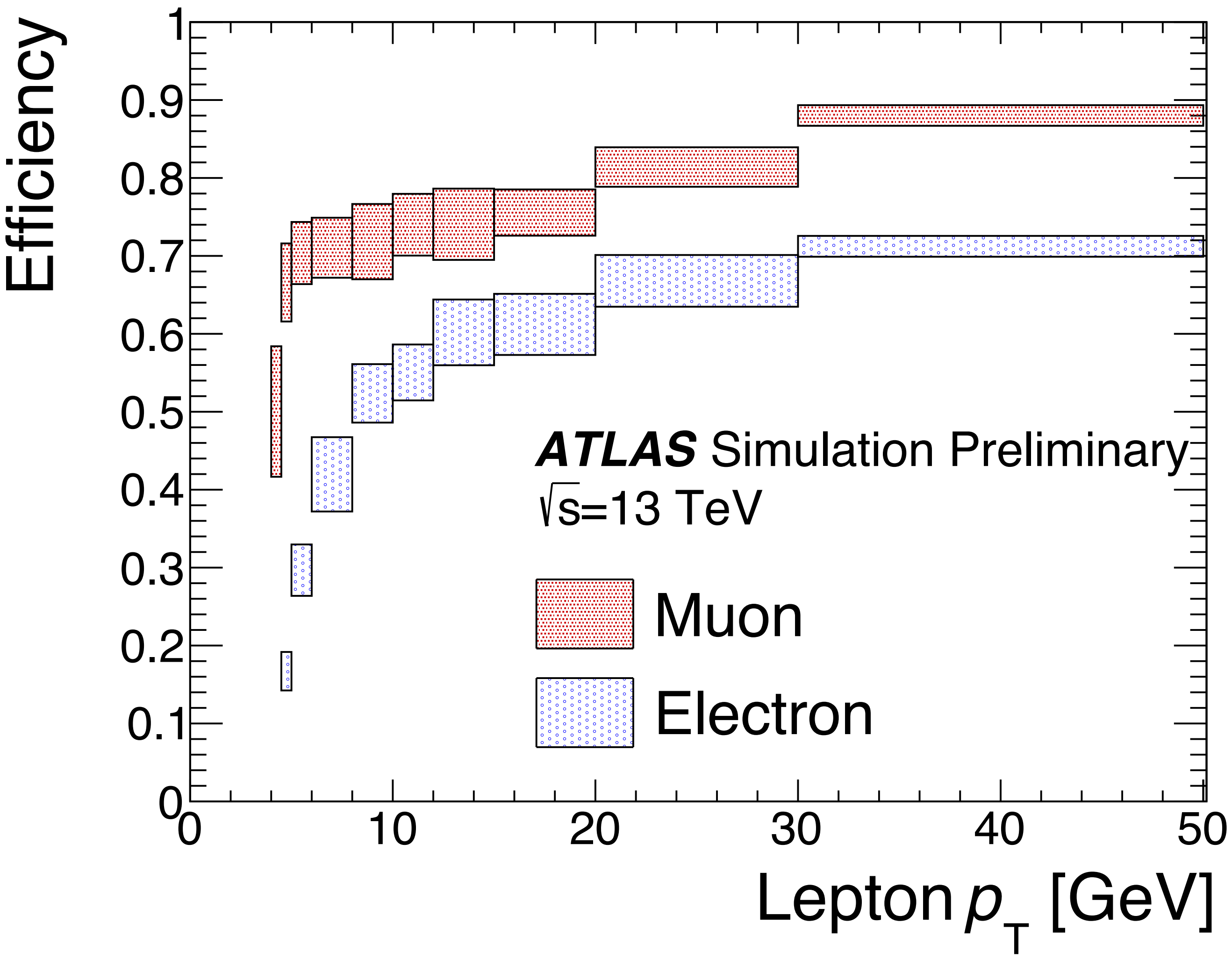


Simulation compared with the theoretical lineshape for the Higgsino and Wino-Bino m_{ll} distributions. Additionally:

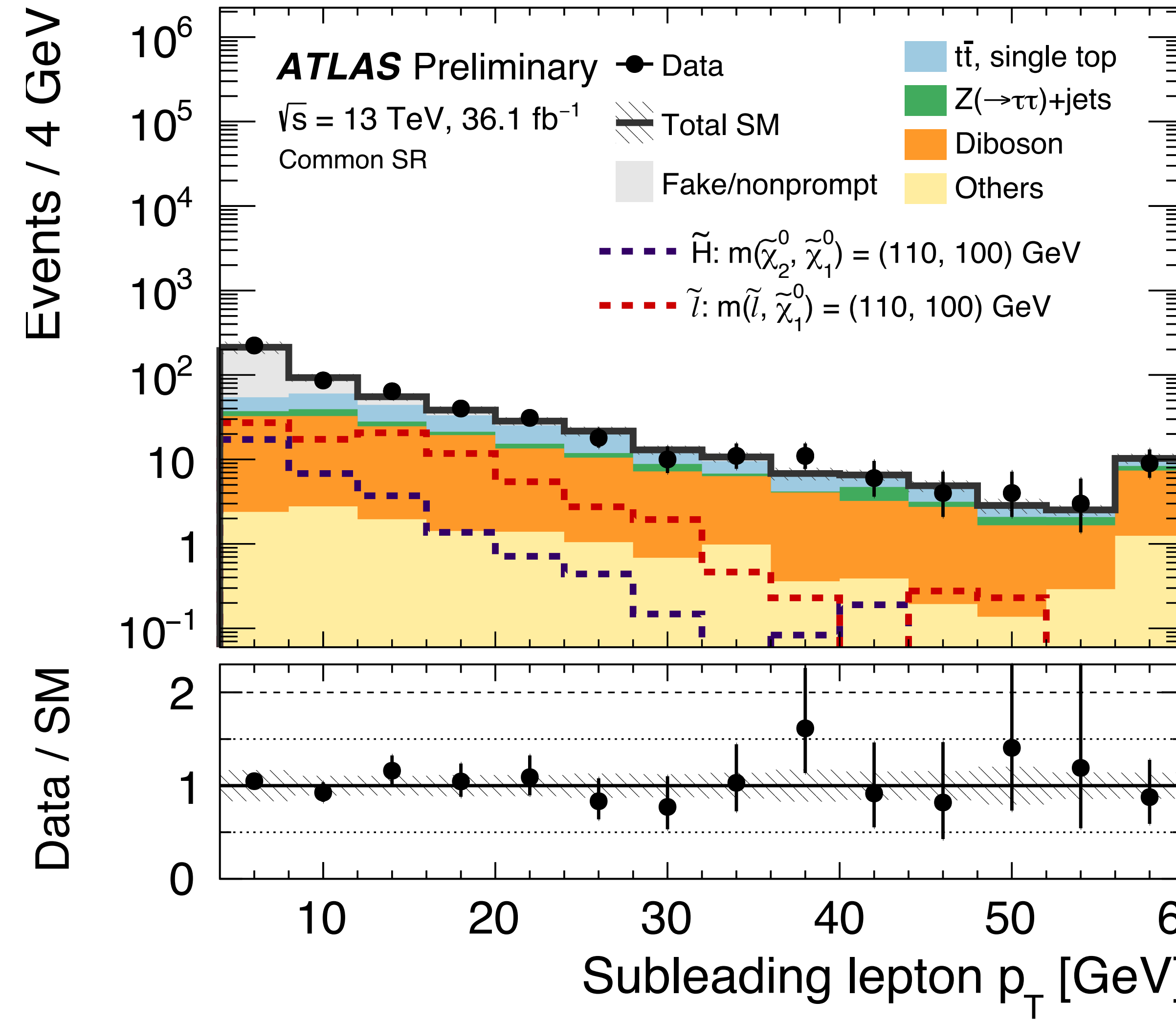
- Wino-Bino production has ~4x larger cross-section
- Mass degenerate C1 and N2 in Wino-Bino scenario, while m(C1) = [m(N2) + m(N1)]/2 for Higgsino scenario

Low p_T Leptons

Lepton reco+ID+isolation efficiency



Subleading lepton p_T in signal region



Reconstructing and identifying soft leptons **critical** for this search!

Rejecting (and estimating) fake/nonprompt leptons also crucial.
Dominant background at low p_T!

2L + MET + ISR jet: event selection

Variable	Common requirement	
Number of leptons	$= 2$	
Lepton charge and flavor	e^+e^- or $\mu^+\mu^-$	
Leading lepton $p_T^{\ell_1}$	> 5 (5) GeV for electron (muon)	
Subleading lepton $p_T^{\ell_2}$	> 4.5 (4) GeV for electron (muon)	
$\Delta R_{\ell\ell}$	> 0.05	
$m_{\ell\ell}$	$\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV	
E_T^{miss}	> 200 GeV	
Number of jets	≥ 1	
Leading jet p_T	> 100 GeV	
$\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$	> 2.0	
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{\text{miss}}))$	> 0.4	
Number of b-tagged jets	$= 0$	
$m_{\tau\tau}$	< 0 or > 160 GeV	
	Electroweakino SRs	**Slepton SRs**
$\Delta R_{\ell\ell}$	< 2	
$m_T^{\ell_1}$	< 70 GeV	
$E_T^{\text{miss}}/H_T^{\text{lep}}$	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$
Binned in	$m_{\ell\ell}$	m_{T2}^{100}

Reduce low (and high) mass resonances

LSP recoils off of jet (E_T^{miss} through $\min(\Delta\phi)$ requirements)

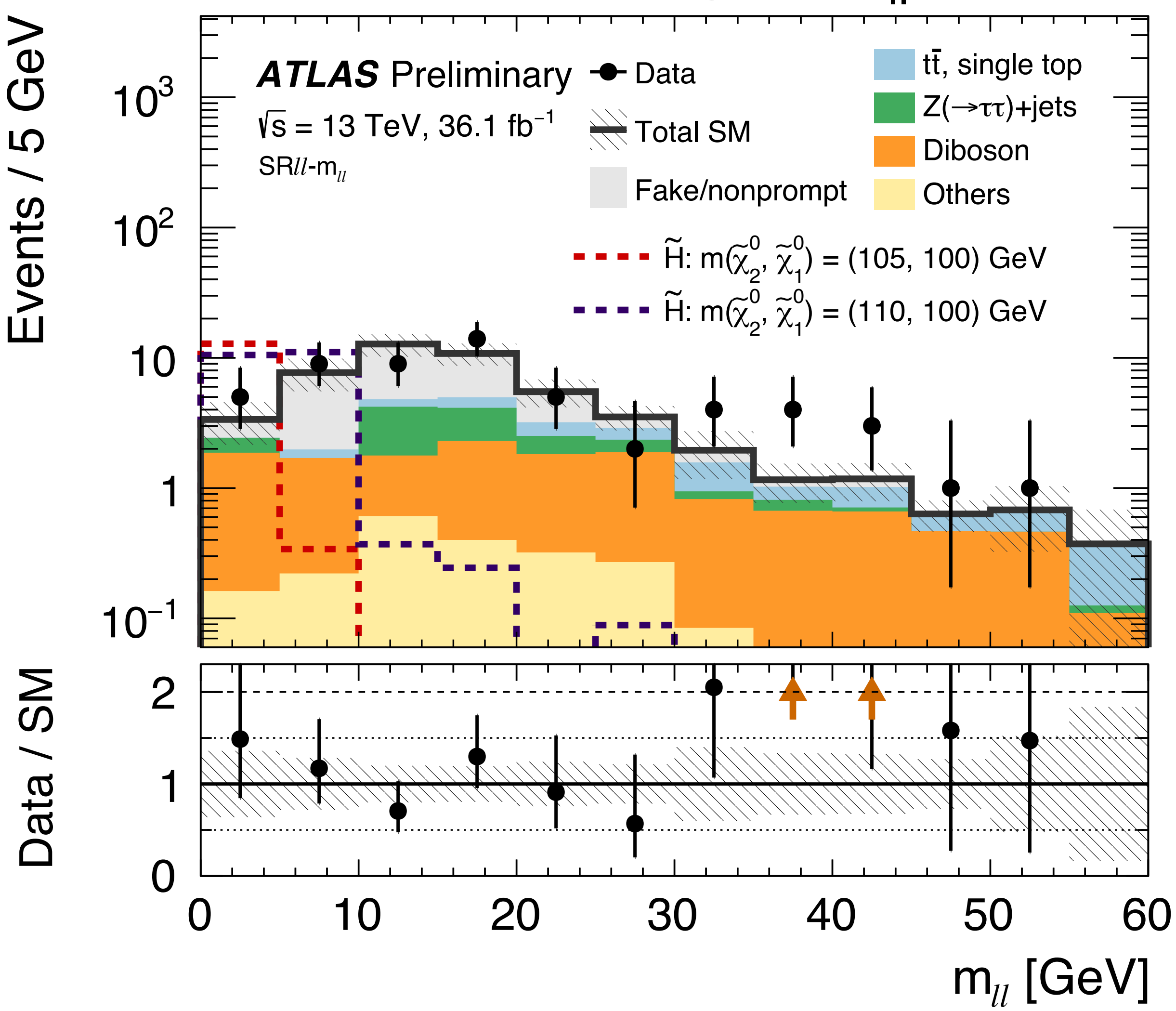
Leptons from Higgsino decay tend to be nearby ($\Delta R_{\ell\ell} < 2$)

Reduce W+jets (fake leptons) ($m_T^{\ell_1} < 70$ GeV)

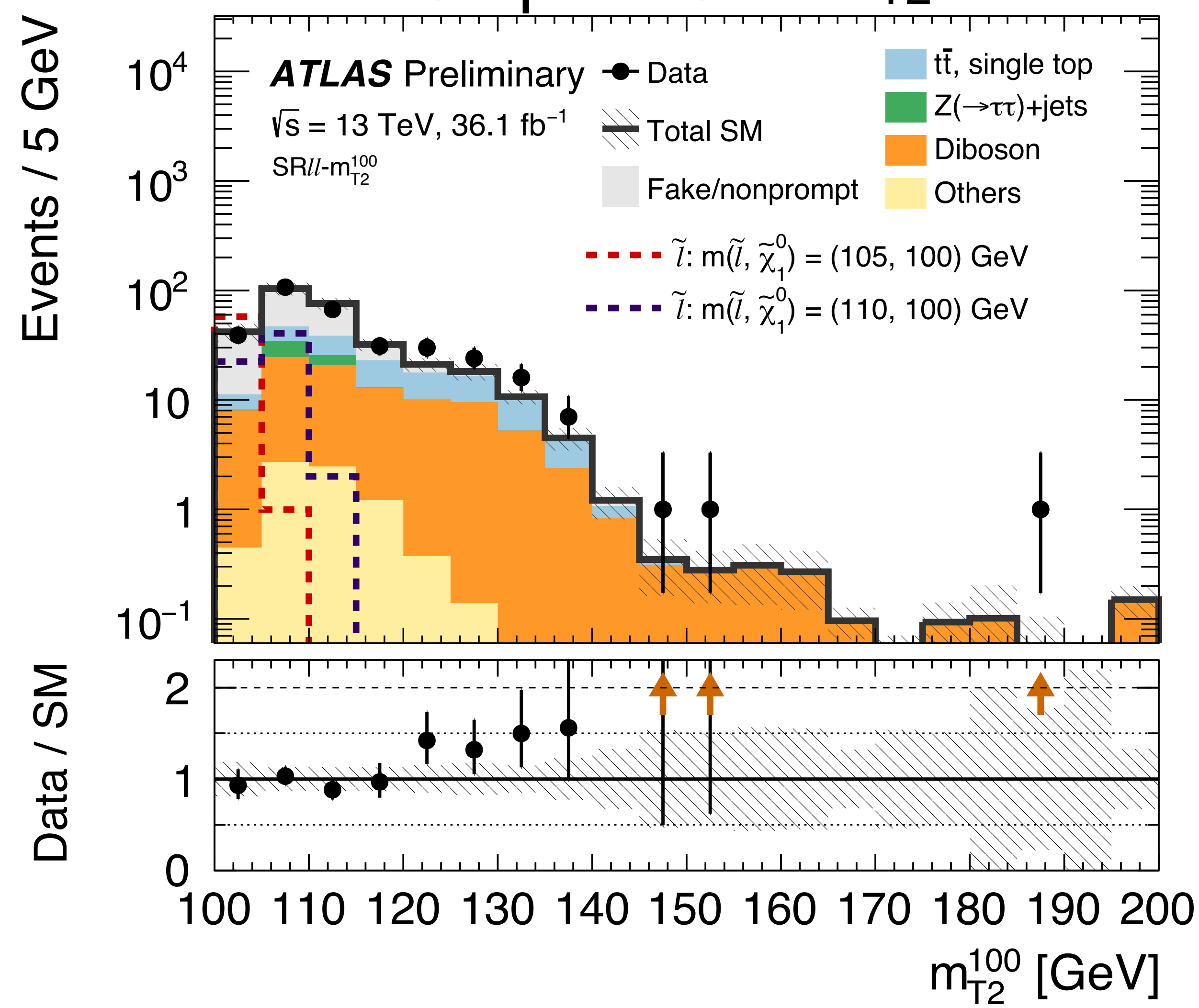
Suppress backgrounds with high pT leptons ($E_T^{\text{miss}}/H_T^{\text{lep}}$)

Primary Discriminating Variables

EWKino SR: m_{ll}



Slepton SR: m_{T2}

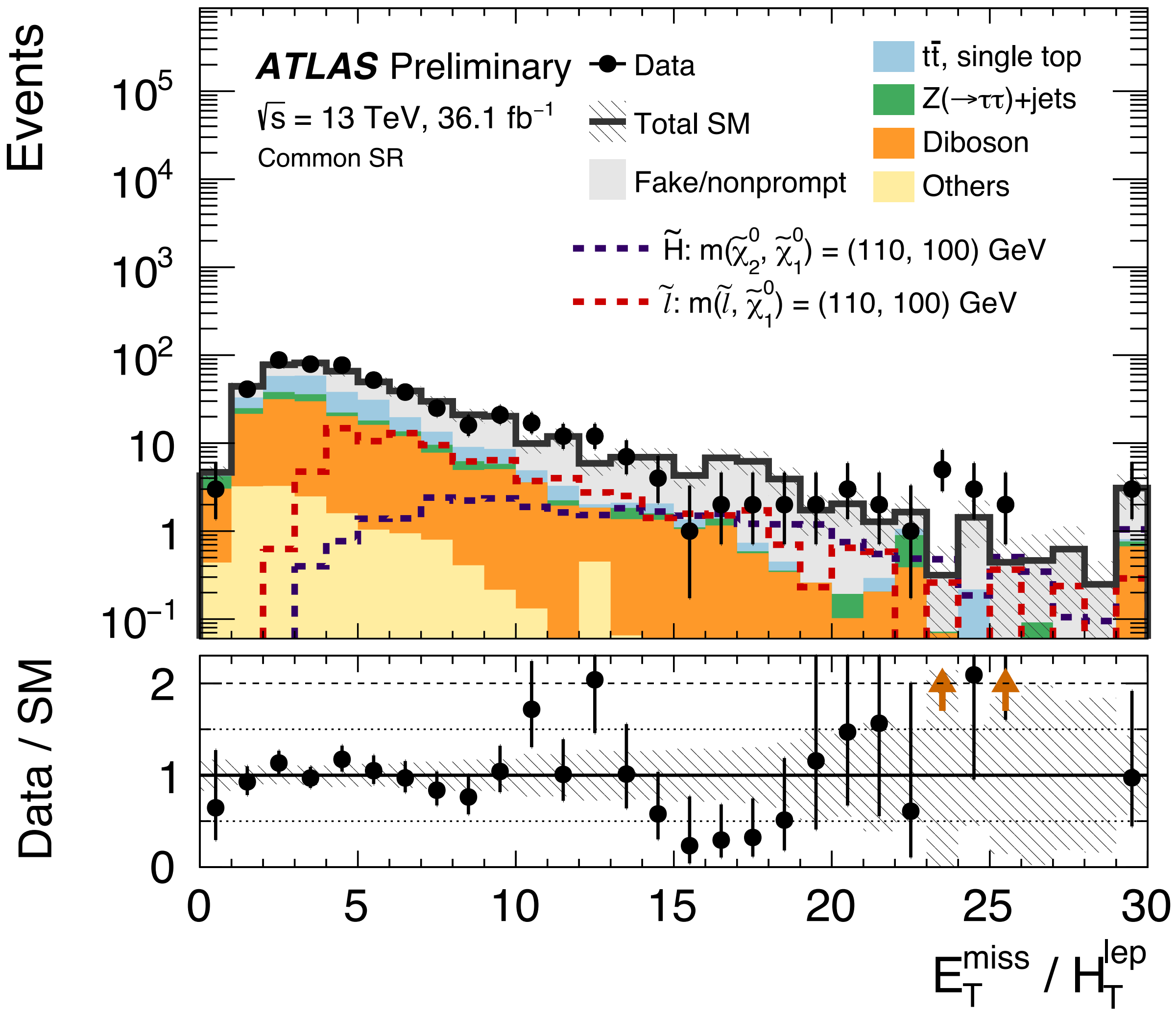


EWKinos: kinematic endpoint at $m_{ll} = \Delta m(N2, N1)$
Sleptons: kinematic endpoint at m_{T2} = m(slepton)

These are our primary observables!

Additional Example Discriminating Variables

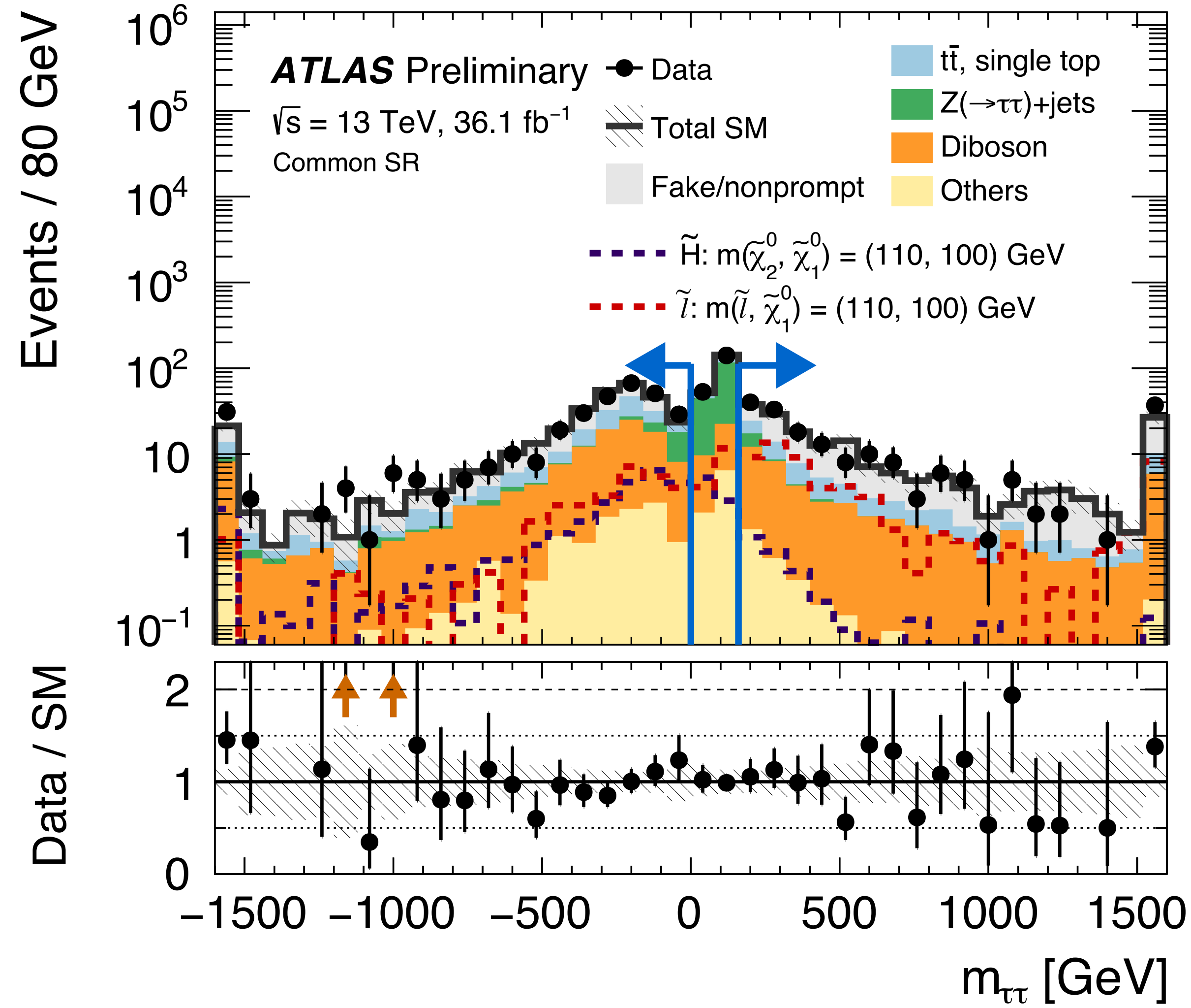
MET/H_T^{Lep}



Ratio of MET and the lepton pT scalar sum.

Ensures that the MET comes from the jet recoil, rather than hard leptons.

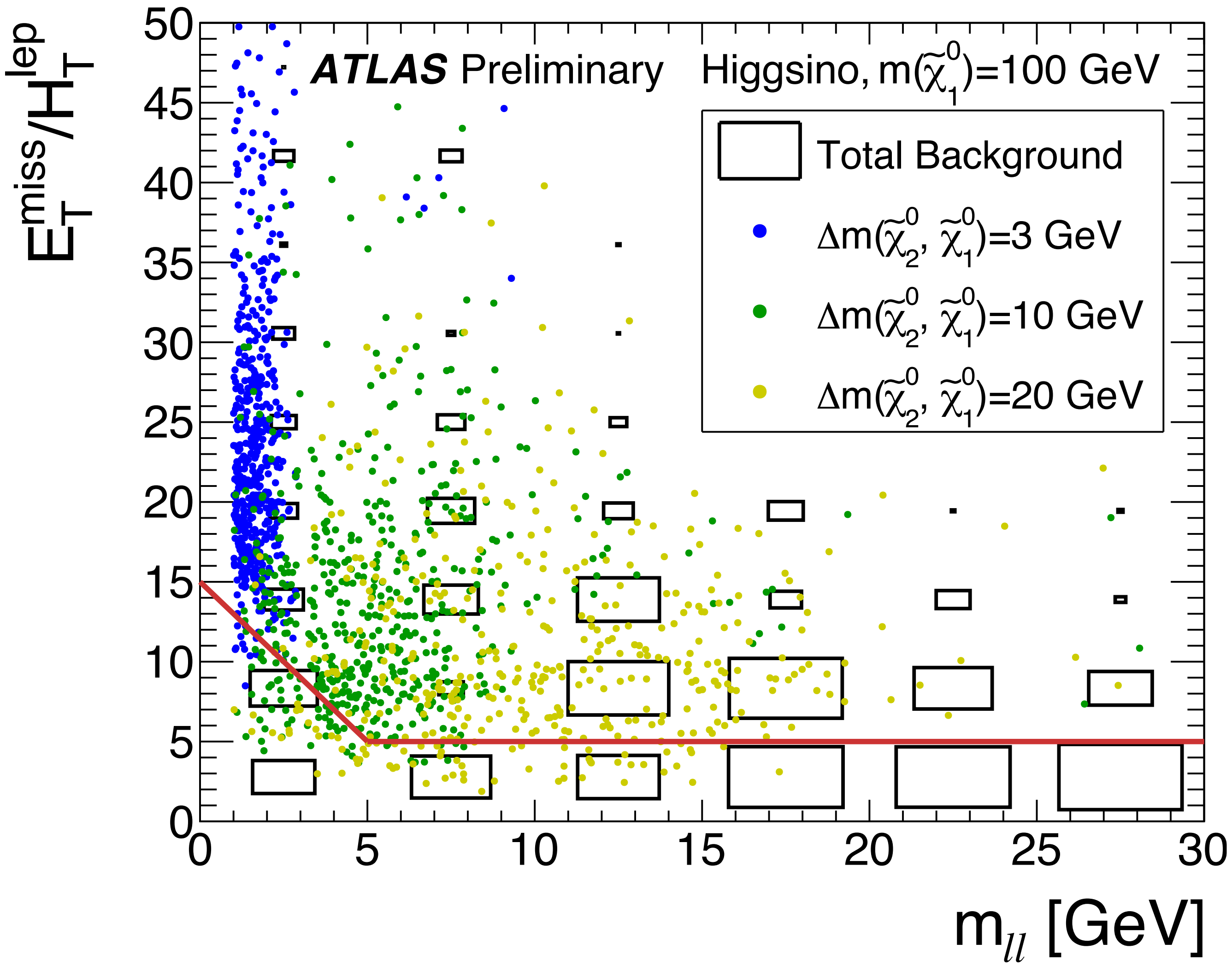
$m_{\tau\tau}$



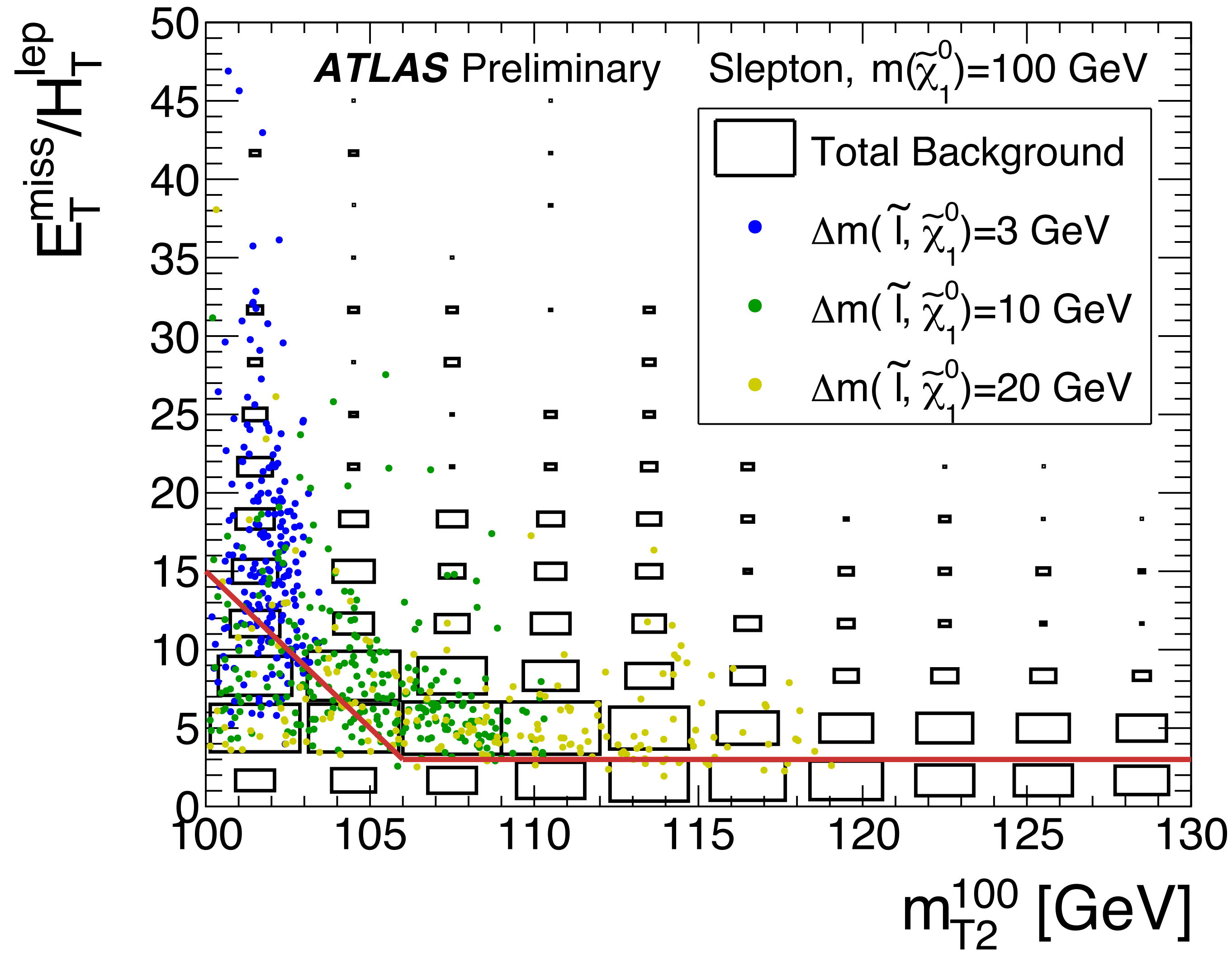
Use MET and the visible leptons to reconstruct tau kinematics, and obtain a proxy for the di-tau mass.

MET/H_T^{Lep} for EWKino vs. Sleptons

EWKino Signal Region



Slepton Signal Region



Anything below the red line is rejected.

Events with low MET/H_T^{Lep} are typically background.
For small mass splittings, the selection is tightened to improve rejection.

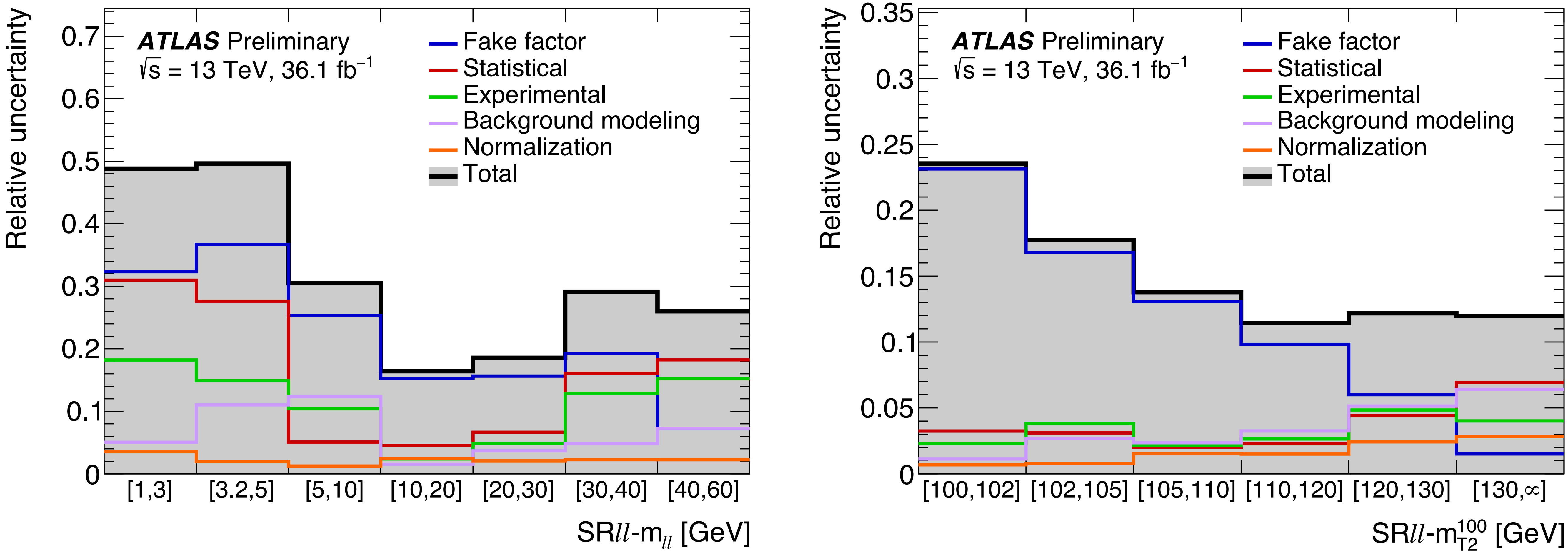
CR and VR Definitions

CRs and VRs defined are identical to the common event selection except for the quantities noted.

Also use eμ events to enhance CR statistics.

Region	Leptons	E_T^{miss}/H_T^{lep}	Additional requirements
CR-top	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	> 5	≥ 1 b-tagged jet(s)
CR-tau	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$\in [4, 8]$	$m_{\tau\tau} \in [60, 120]$ GeV
VR-VV	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	< 3	
VR-SS	$e^\pm e^\pm$, $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, $\mu^\pm e^\pm$	> 5	
VRDF-$m_{\ell\ell}$	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$	$\Delta R_{\ell\ell} < 2$, $m_T^{\ell_1} < 70$ GeV
VRDF-m_{T2}^{100}	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$	

2L + MET + ISR jet: uncertainties



Uncertainties in the EWKino and slepton SR—typically dominated by uncertainties on the fake lepton estimate

Disappearing track signal samples

- Generated at LO using MG5_aMC@NLO with up to two extra partons
- Chargino decay simulated in GEANT4 to precisely simulate the detector response

For pure Wino samples:

- Prospino2 at NLO used to compute the EWK cross-sections

For pure Higgsino samples:

- Resummino at NLO+NLL used to compute the cross-sections

Disappearing track event selection

Selection requirement	Electroweak channel	
	Observed	Expected signal
Trigger	434 559 704	1276 (0.20)
Jet cleaning	288 498 579	1181 (0.19)
Lepton veto	275 243 946	1178 (0.19)
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jet requirements	2 697 917	579.1 (0.092)
Isolation and p_{T} requirement	464 524	104.2 (0.017)
Geometrical $\lvert\eta\rvert$ acceptance	339 602	83.6 (0.013)
Quality requirement	6134	29.6 (0.0047)
Disappearance condition	154	24.1 (0.0038)

For Wino signal point:
$(m_{\tilde{\chi}_1^{\pm}}, \tau_{\tilde{\chi}_1^{\pm}}) = (400\ \mathrm{GeV}, 0.2\ \mathrm{ns})$

MET and jet requirements:

- MET > 140 GeV
- at least one jet with p_{T} > 140 GeV
- Δϕ > 1.0 between MET and up to four leading jets with p_{T} > 50 GeV

Isolation and p_{T} requirements:

- ΔR > 0.4 between tracklet and any jet with p_{T} > 50 GeV or MS track
- $p_{\mathrm{T}}^{\mathrm{cone40}}/p_{\mathrm{T}} < 0.04$
- Candidate tracklet must be highest p_{T} track or tracklet in event, and have p_{T} > 50 GeV

Quality requirement:

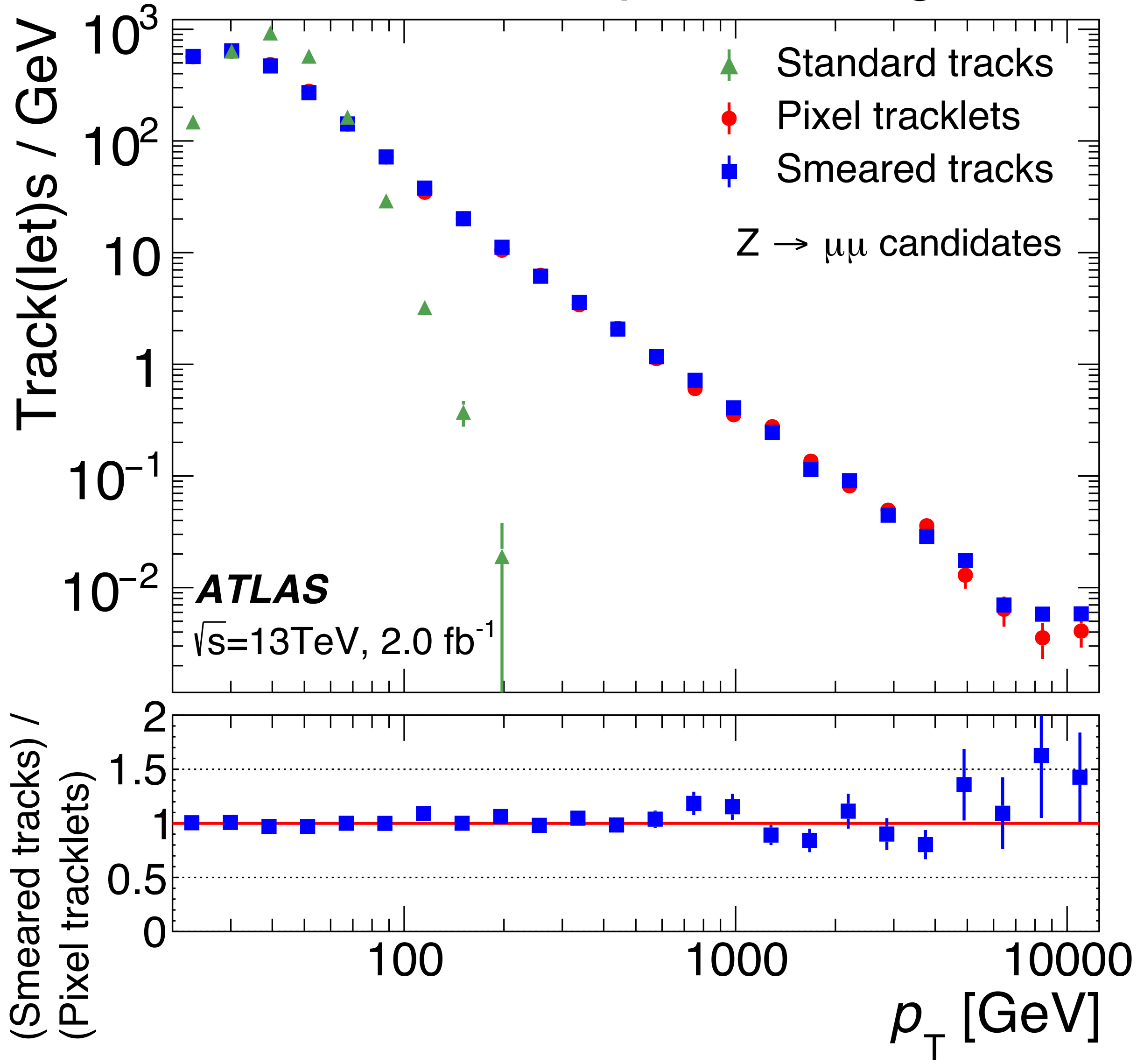
- Hits on all four pixel layers; zero holes
- Zero "low quality" hits
- $|d_0|/\sigma(d_0) < 2$, $|z_0 \sin(\theta)| < 0.5$ mm
- Fit χ^2 probability > 10%

Disappearance condition: zero SCT hits associated to tracklet

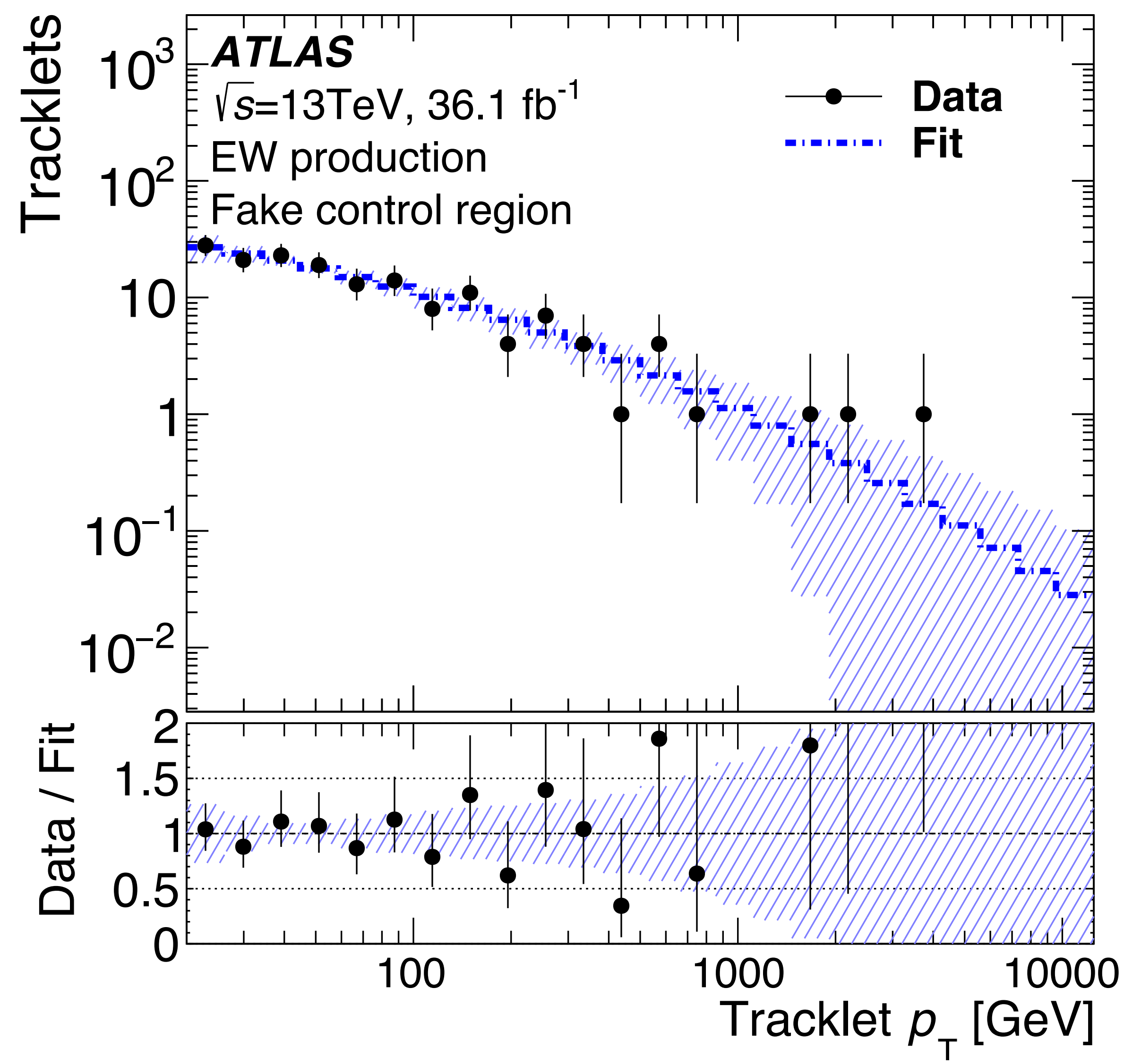
Geometrical Iηl acceptance: 0.1 < |η| < 1.9

Disappearing Track Background Estimation

Validation of p_T smearing



Fake tracklet control region



Hadrons/leptons: data-driven templates using standard tracks with p_T smearing to match tracklet resolution; normalized to account for e.g. differences between lepton and tracklet reconstruction

Fake tracklets: relax $|d_0|/\sigma_{d_0}$ and MET; fit analytically

Disappearing track: SR yields and uncertainties

SR yields

Number of observed events		
	9	
Number of expected events		
Hadron+electron background	6.1	$\pm$ 0.6
Muon background	0.15	$\pm$ 0.09
Fake background	5.5	$\pm$ 3.3
Total background	11.8	$\pm$ 3.1
Number of expected signal events		
for the higgsino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (\mathbf{160\,GeV, 0.05\ ns})$		
	10.3	$\pm$ 2.1
Number of expected signal events		
for the wino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (\mathbf{400\,GeV, 0.2\ ns})$		
	13.5	$\pm$ 2.1

Uncertainties

Relative uncertainties [%]	Electroweak channel	Strong channel
MC statistical uncertainty	6.6	6.5
ISR/FSR	7.6	0.2
Jet energy scale and resolution	2.0	0.7
Trigger efficiency	0.2	<0.1
Pile-up modelling	11	
Tracklet efficiency	6.9	
Luminosity	3.2	
Sub-total	17	15
Cross-section	6.4	28
Total	18	32