Opening unexplored frontiers

for new physics at the LHC

Young Theorists Forum @ Durham

10 Jan 2018

Jesse Liu
University of Oxford

Where is the new physics hiding?

What opportunities remain under the search lamppost?

Case study: hunting Higgsinos

Why are MSSM compressed scenarios so challenging?

Surpassing two-decade old LEP limits

How do we detect Higgsino dark matter at hadron colliders?

*Allowed massless particles by consistency between**

RELATIVITY + QUANTUM

0	$\frac{1}{2}$	1	$\frac{3}{2}$	2
Higgs et al.	Matter	Yang-Mills	[Unseen]	Gravity

Highly constrained theory space

for what structure of (sub-Planckian) fundamental physics can look like

Very difficult for new physics to evade principles

underpinning Standard Model & General Relativity

*No-go theorems by *Weinberg* (1968), *Grisaru & Pendleton* (1977). NB 'continuous-spin particles' allowed *Schuster & Toro* [arXiv:1302.1198]

$$S_{\mathrm{SM}} \sim \int \sqrt{-g}\, \mathrm{d}^4x \left[-\frac{1}{4}F^2 + \theta F * F + \mathrm{i}\bar{\psi}\gamma \cdot D\psi + |DH|^2 + \mu^2 H^2 + \lambda H^4 - yH\bar{\psi}\psi \right]$$

Spin 0, $\frac{1}{2}$, 1, 2 states encoded in field representations of Poincaré group

(Spin 2 only dynamical with extra non-renormalisable Einstein–Hilbert kinematic term $\mathscr{L}_{\mathrm{EH}} = M_{\mathrm{Pl}}^2 R/2$, then SM couples to sub-Planckian gravity at leading order via $\sim h_{\mu\nu} T_{\mathrm{SM}}^{\mu\nu}/M_{\mathrm{Pl}}^2$)

Mysteries with masses

(1) Fundamental hierachies & UV sensitivity $\mu^2 \ll M_{\mathrm{Pl}}$ (i.e. 'The hierarchiy problem')
a) Why is weak scale $\sim \mu \ll$ Planck scale M_{Pl}?
b) IR physics should not be severely sensitive to UV dynamics but $\delta\mu^2 \propto M_{\mathrm{UV}}^2$

(2) Parametric hierachies in Yukawa sector yH (e.g. YETI 2018)
EW symmetry breaking: $y_f H \sim m_f \cdot \mathrm{vev}$: Why is $m_{\text{top quark}}/m_{\text{electron}} \sim 10^6$?

$$S_{\mathrm{SM+GR}} \sim \int \sqrt{-g}\, \mathrm{d}^4x \left[\frac{M_{\mathrm{Pl}}^2 R}{2} - \frac{1}{4}F^2 + \theta F * F + i\bar{\psi}\gamma \cdot D\psi + |DH|^2 + \mu^2 H^2 + \lambda H^4 - yH\bar{\psi}\psi \right]$$

Higgsinos make Higgs sector technically natural

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SM fermion masses are technically natural (e.g. 't Hooft 1979)

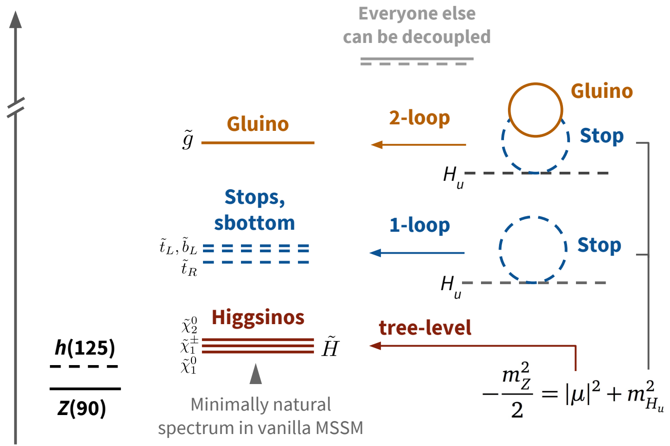
Light mass protected by chiral symmetry – scalars lack such custodial symmetry

Supersymmetry makes mystery (1b) technically natural

Tie Higgs h to Higgsino $\tilde{H}$ fermionic partner with SUSY to keep scalar mass light

$$\underbrace{\tilde{H}}_{\text{protected by chiral symmetry}} \overbrace{\longleftrightarrow}^{\text{SUSY}} \underbrace{h}_{\text{light mass linked to } \tilde{H}}$$

Further elevate naturalness into a guide for SUSY mass scale

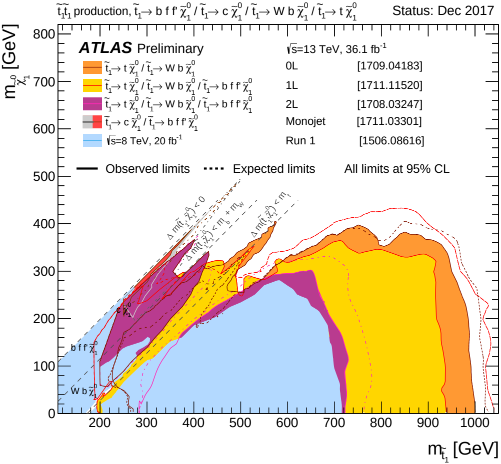


Adapted from Papucci et al [arXiv:1110.6926]

Naturalness desires low fine-tuning between m_Z^2 vs $|\mu|^2 + m_{H_u}^2$

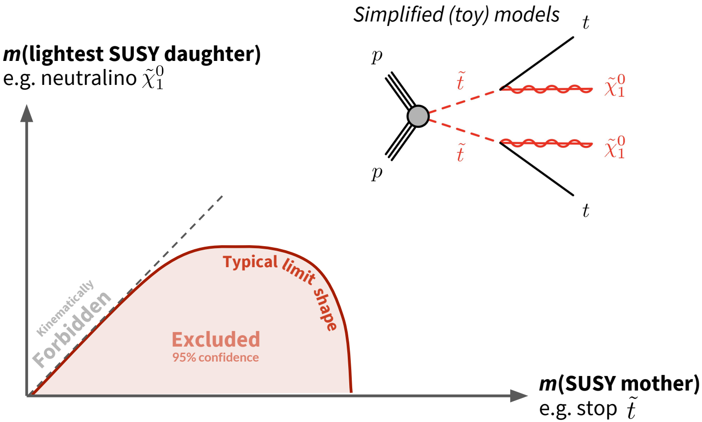
Light gluino & stops keep $m_{H_u}^2$ near weak-scale

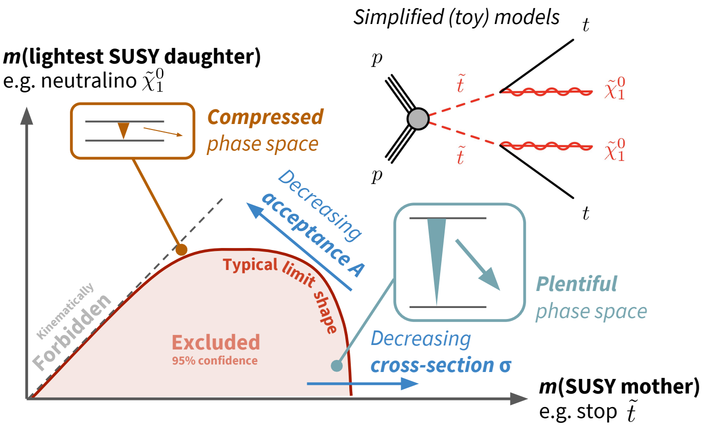
Higgsino μ parameter **probes MSSM naturalness condition at tree-level**



2015–17: formidable efforts to probe **‘diagonal regions’: objects typically soft**

From ATLAS SUSY summary plots


Simplified (toy) models
p
p
$\tilde{t}$
$\tilde{t}$
t
t
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
m(lightest SUSY daughter)
e.g. neutralino $\tilde{\chi}_1^0$
Kinematically
Forbidden
Typical limit shape
Excluded
95% confidence
m(SUSY mother)
e.g. stop $\tilde{t}$



Simplified (toy) models
p
p
$\tilde{t}$
$\tilde{t}$
t
t
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m(lightest SUSY daughter)
e.g. neutralino $\tilde{\chi}_1^0$
Compressed
phase space
Decreasing
acceptance A
Plentiful
phase space
Typical limit shape
Kinematically
Forbidden
Excluded
95% confidence
Decreasing
cross-section σ
m(SUSY mother)
e.g. stop $\tilde{t}$

THE SEARCHLIGHT IS SHIFTING
from spectacular to subtle discoveries

Opportunities & challenges for
soft, rare, quirky signals

Soft stuff
Particle identification
Trigger thresholds

Rare SUSY
Colourless sparticles
Dark sector

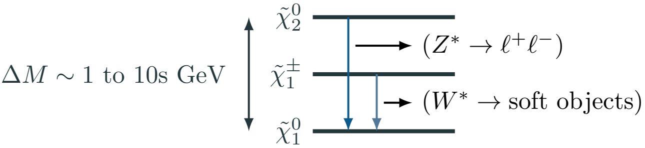
Quirky creatures
Displaced difficulties
Long-lived exotica

Case study
Higgsino

HUNTING HIGGSINOS

A benchmark for probing the soft, rare & long-lived frontiers

Higgsinos are generically compressed electroweak SUSY



Mass splitting governed by electroweak mixing [e.g. arXiv:1704.01577]

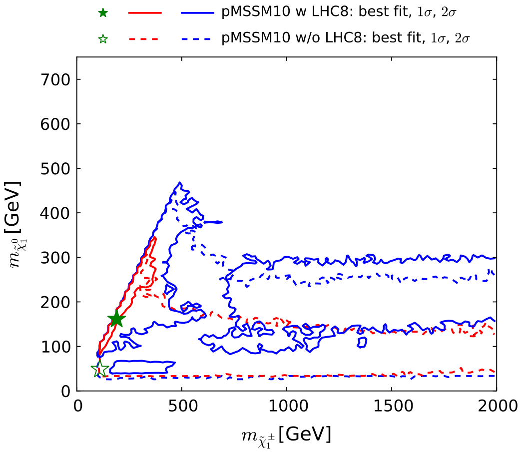
$$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \simeq \frac{m_W^2}{g_2^2}\left(\frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}\right)$$

Like $W^\pm$ and Z boson masses $\sim$ 10% apart due to EW mixing

g_1: $U(1)_Y$ coupling, M_1: mass of **bino** $\widetilde{B}$ (fermionic partner of $U(1)_Y$ boson)
g_2: $SU(2)_L$ coupling, M_2: mass of **winos** $\widetilde{W}$ (fermionic partners of $SU(2)_L$ bosons)

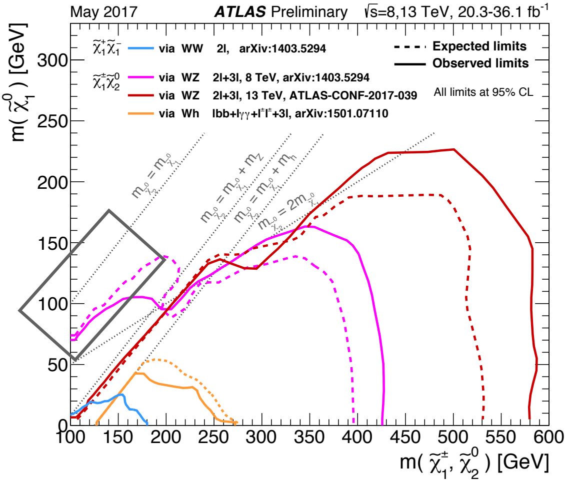
The pMSSM10 after LHC Run 1

K.J. de Vries[a], E.A. Bagnaschi[b], O. Buchmueller[a], R. Cavanaugh[c,d], M. Citron[a], A. De Roeck[e,f], M.J. Dolan[g], J.R. Ellis[h,e], H. Flächer[i], S. Heinemeyer[j], G. Isidori[k], S. Malik[a], J. Marrouche[e], D. Martínez Santos[l], K.A. Olive[m], K. Sakurai[h], G. Weiglein[b]



Green star is best fit to collider & non-collider data in 10-dim parameter space [1504.03260]

Striking gaps in ATLAS sensitivity



$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm (\text{wino}) \to W^{(*)} Z^{(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \text{leptons} + E_T^{\text{miss}}$$

'Smoking-gun' lamppost of high p_T objects is focus of first LHC searches.
Confront the **soft lepton frontier** to open sensitivity to diagonal.

Theorists very active in this area recently

Nearly Degenerate Gauginos and Dark Matter at the LHC

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[c] *Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*

[d] *Department of Physics, Princeton University, Princeton, NJ 08540, USA*

1004.4902

Hunting Quasi-Degenerate Higgsinos

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[2] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540*

[3] *Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA*

1401.1235

M_{T2} to the Rescue – Searching for Sleptons in Compressed Spectra at the LHC

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Yandong Liu

Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

1412.0618

Cornering electroweakinos at the LHC

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[c] *School of Physics, Korea Institute for Advanced Study, Seoul 130-722, Korea*

[d] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, 60637*

1307.5952

Monojet plus soft dilepton signal from light higgsino pair production at LHC14

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[1] *Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA*

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1409.7058

A boost for the EW SUSY hunt: monojet-like search for compressed sleptons at LHC14 with 100 fb^{-1}

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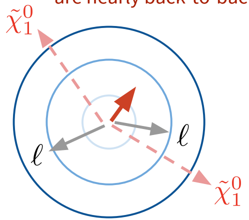
[b] *United States Air Force Institute of Technology, Wright-Patterson Air Force Base, OH 45433, USA*

1501.02511

EXISTING PROBES

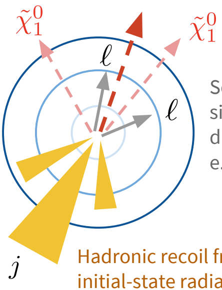
Low missing E_T as LSPs are nearly back-to-back



Leptons too soft to pass lepton triggers

OUR STRATEGY

Trigger on missing E_T by boosting LSPs



Soft dileptons allow signal-background discrimination e.g. m(ll), mT2

Hadronic recoil from initial-state radiation (ISR)

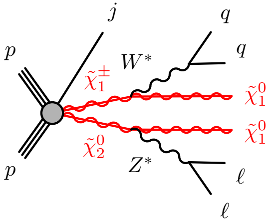
ATLAS 1712.08119 [ATLAS-SUSY-2016-25]

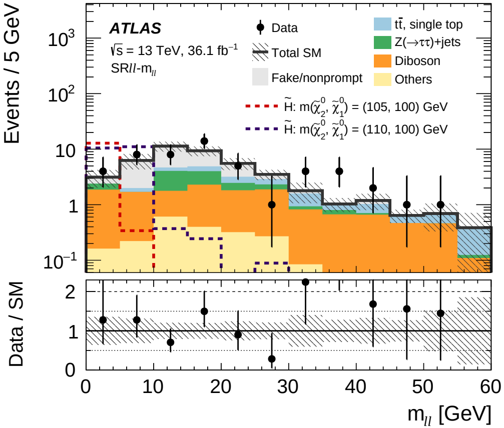
Trigger on E_T^{miss}, offline $E_T^{\text{miss}} > 200$ GeV, perform compressed sleptons search too

CMS 1801.01846 [CMS-SUS-16-048]

Also $2\mu + E_T^{\text{miss}}$ triggers, offline $E_T^{\text{miss}} > 125$ GeV, perform compressed stop search too

Signals localised at low $m_{\ell\ell}$: bump-hunt SUSY style!

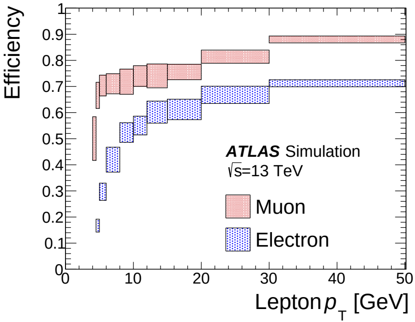




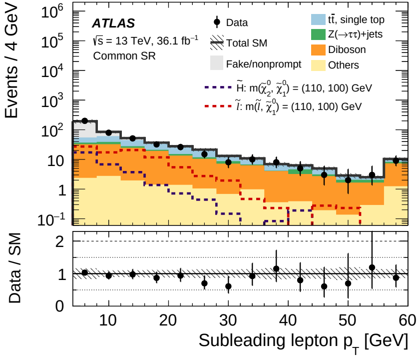
Sensitivity driven by $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ (same-flavour opposite-sign)

Signal kinematic endpoint: $m_{\ell\ell} < \Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ gives dramatic background discrimination

New for 2017: soft lepton frontier at ATLAS extended down to 4 GeV



How well we reconstruct leptons from signals



Lepton with lower transverse momentum

Confronting experimental limitations of soft lepton reconstruction crucial for sensitivity

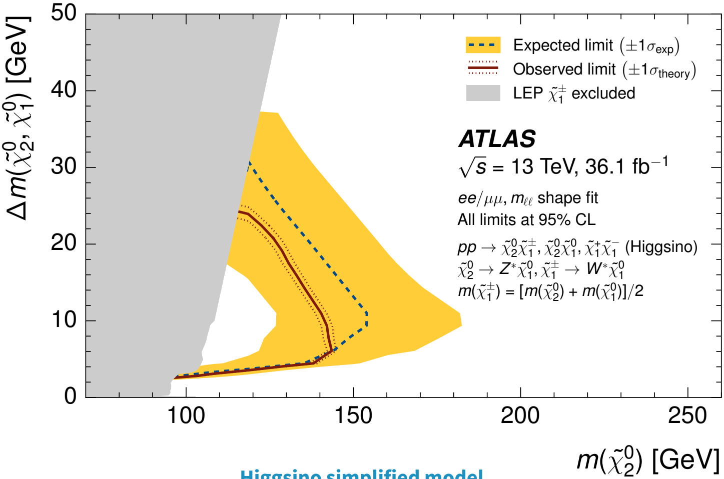
Fun fact: a muon loses 3 GeV of energy before reaching the ATLAS muon spectrometer

Soft lepton regime dominated by challenging fake/nonprompt lepton* backgrounds

*These include misidentified jets, photon conversions, semi-leptonic decays of *B*-hadrons, pileup

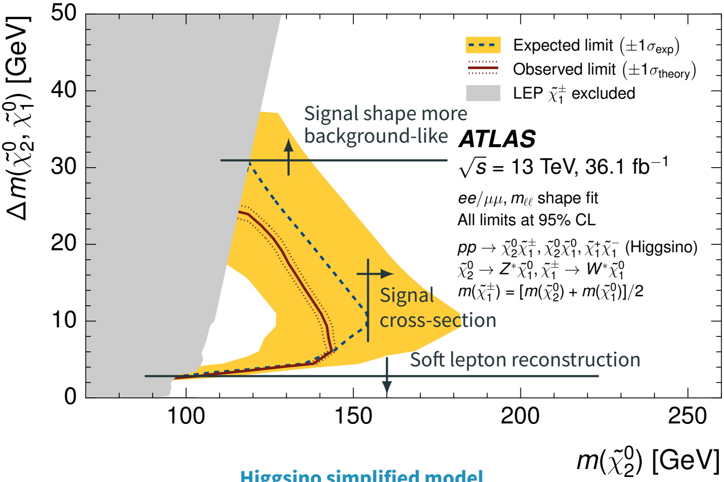
LHC HIGGSINO SENSITIVITY

A hadron collider extends nearly 20 year old LEP limits



Higgsino simplified model

Down to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim 3$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 140$ GeV.



Higgsino simplified model

Down to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim 3$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 140$ GeV.

Recall particle lifetime inversely related to phase space.

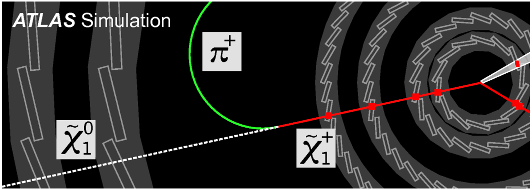
Pure Higgsino (ultra-compressed) limit, chargino becomes long–lived

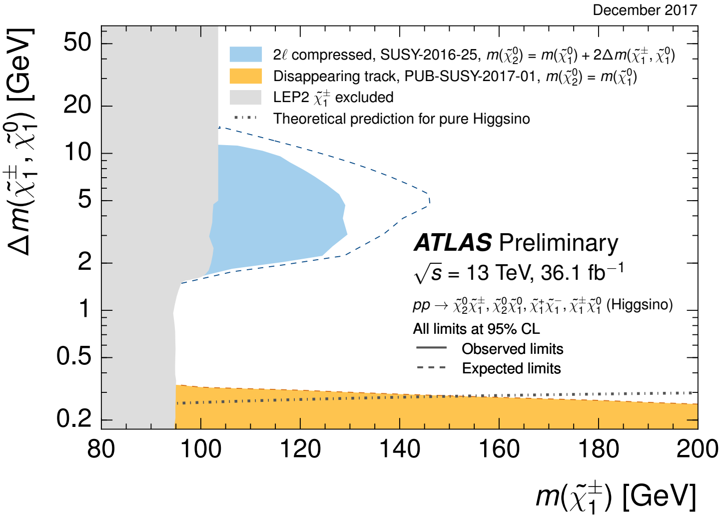
$$c\tau \sim \frac{0.7\ \text{cm}}{\left(\frac{\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}{340\ \text{MeV}}\right)^3 \sqrt{1 - \left(\frac{m_\pi}{\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}\right)^2}}$$

From Fukuda, Nagata, Otono, Shirai [arXiv:1703.09675], ATL-PHYS-PUB-2017-019

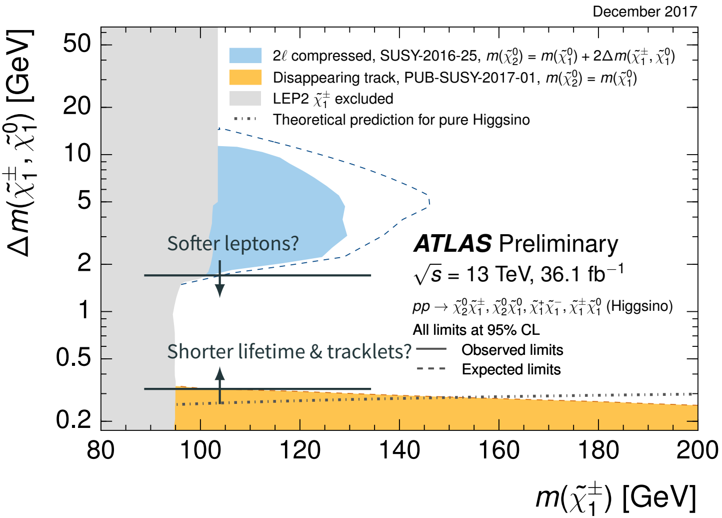
Signature: partial 'disappearing' track

(Trigger on $E_{\mathrm{T}}^{\mathrm{miss}}$ from ISR)





Sub-100 GeV Higgsinos in $0.3 \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 2$ GeV regime remain viable!



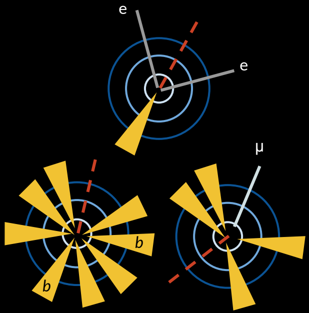
Need new techniques to overcome limiting factors in sensitivity

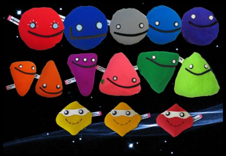
REFLECTIVE EPILOGUE

Being PhD students amidst confusion in fundamental physics

Expectation: a new golden age of striking discoveries + robust measurement

Signature storm → particle zoo → underlying theory





$$\mathscr{L}(old) + \mathscr{L}(new)$$

Supersymmetry?
Dark matter?
Extra dimensions?
Hidden gauge sectors?
Exciting exotica?

What is the structure of new physics data?

Use simplified models to organise kinematics & structures in data as **detector-independent signatures**.

E.g. Alwall, Schuster, Toro [arXiv:0810.3921]

How do we measure mass, spin, coupling?

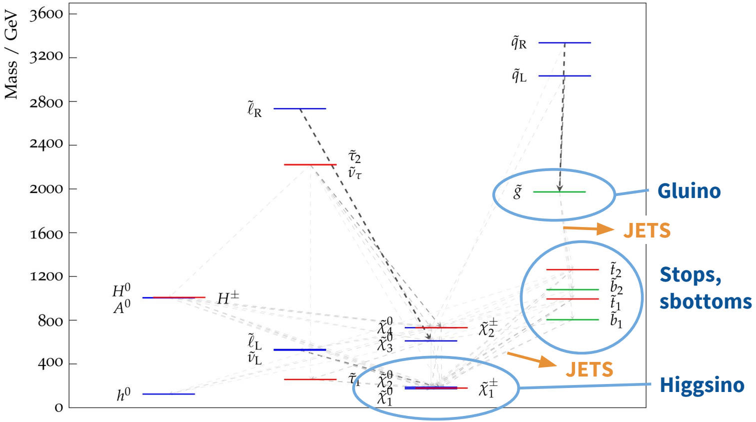
Timing, tracking, flavour, angles, endpoints, proxies like mT, mT2 **to perform spectroscopy**.

E.g. Barr, Gripaios, Lester [arXiv:0711.4008]

Which underlying theory is it?

Two distinct theories can give the same signature: study how to **lift signature degeneracies**.

E.g. Arkani-Hamed, Kane, Thaler, Wang [hep-ph/0512190]


Mass / GeV
3600
3200
2800
2400
2000
1600
1200
800
400
0
$\tilde{q}_R$
$\tilde{q}_L$
$\tilde{\ell}_R$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{g}$
Gluino
JETS
H^0
A^0
$H^\pm$
$\tilde{t}_2$
$\tilde{b}_2$
$\tilde{t}_1$
$\tilde{b}_1$
Stops, sbottoms
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{\ell}_L$
$\tilde{\nu}_L$
JETS
$\tilde{\tau}_1$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
Higgsino
h^0

Reality: despair?

A GOLDEN AGE FOR NEW IDEAS

Actually, striking opportunities for critical reflection & fruitful innovation

How can experimentalists open uncharted sensitivity?

Use detector beyond original design goals e.g. soft lepton frontier, new triggers

Explore exotic signatures at lifetime frontier [LLP workshops]

What is the nature of dark matter?

Dark sector potentially rich & vast beyond vanilla WIMP paradigm

Sub-GeV thermal relics? Sub-MeV ultra-light particles? Table-top frontier? [e.g. 1707.04591]

Why is naturalness not a robust guide for new physics?

Critically re-examine long-standing theoretical assumptions

E.g. Cosmological relaxation? [1504.07551] Nnaturalness? [1607.06821]

Gratitude

Bucharest

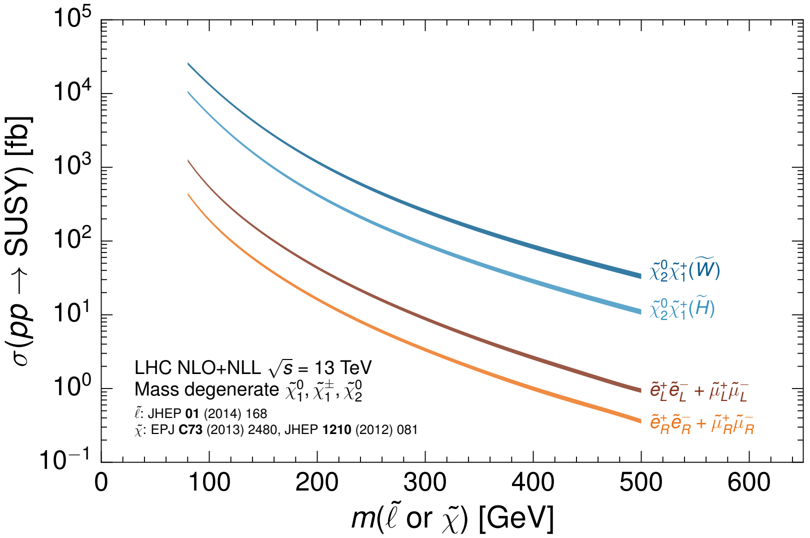
Geneva

Thanks to excellent leadership and collaboration of international analysis team from British Columbia, Cambridge, Harvard, Milano, Oklahoma, Santa Cruz, UPenn, Urbana–Champaign, Valencia, Würzburg et al across 9 time zones

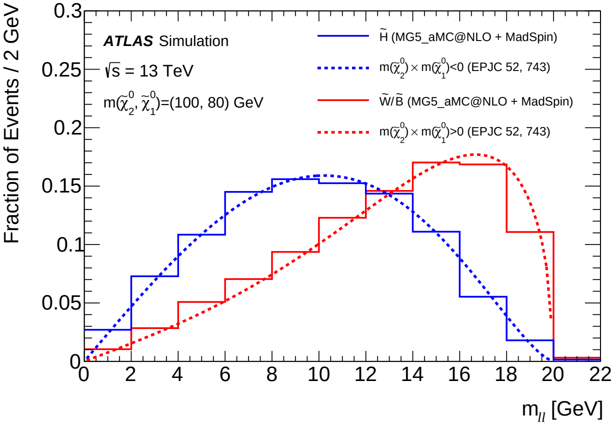
Thanks to CERN, ATLAS Experiment, STFC, Oxford for support & hospitality

EXTRAS

LHC cross-sections for wino, Higgsino, slepton production



Higgsino vs wino–bino dilepton invariant mass shape



LHC can probe *composition* of electroweakinos i.e. underlying SUSY parameters

$m_{\ell\ell}$ shape differs for Higgsino $\tilde{H}$ vs wino–bino $\tilde{W}/\tilde{B}$ scenarios.

Using MadSpin to model $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ decays to match predicted shape.

Background estimation strategy: schematic overview

Prediction
Mix of data & MC methods

Fake Factor
Data-driven method

CR-top
N(b-jets) ≥ 1
ttbar, tW
MC normalisation

CR-tau
60 < m($\tau\tau$) < 120 GeV
MC normalisation

Monte Carlo only

Monte Carlo only

Signal region
Same flavour leptons

≥ 1 lepton fake/non-prompt
> 50% at low lepton pT
E.g. W+jets

Top quark
2L ttbar & tW missed b-jet

Z → $\tau\tau$
2L decays

Diboson
WW 2L
WZ missed 3rd lepton

Others
E.g. $Z \rightarrow ee/\mu\mu$, Higgs

Validation
Check background modelling

VR-SS
MET/HT(lep) > 5.
Same sign leptons.
Fakes purity > 90%.

VR-VV
MET/HT(lep) < 3.
Diboson purity ~40%.

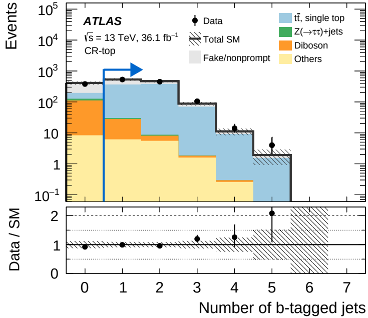
VR-DF
Different flavour leptons.

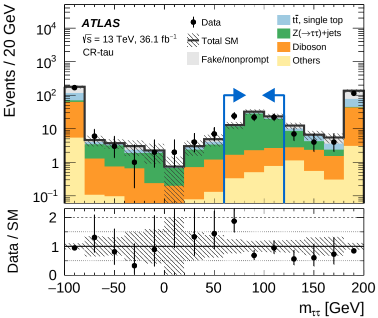
Exactly the same kinematic regimes as SRs.

Global check of background modelling.

Irreducible: 2 real & prompt leptons and MET from neutrinos
Reducible: ≥ 1 or more fake/non-prompt lepton(s), instrumental MET (negligible)

List of MC samples in backup p**??**, more details of strategy in backup p**??**.





CR-top

$\mu_{\text{top}} = 0.97 \pm 0.09$ for $t\bar{t}$, Single top

CR-tau

$\mu_{Z\to\tau\tau} = 0.77 \pm 0.14$ for $Z \to \tau\tau$

Region	Leptons	$E_{\text{T}}^{\text{miss}}/H_{\text{T}}^{\text{lep}}$		Additional requirements
CR-top	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	> 5	For SR orthogonality	≥ 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

Background-only fit to CR-top & CR-tau (each single-bins).

This derives normalisation factors $\mu_{\text{top}}, \mu_{Z\to\tau\tau}$ respectively.

Highlight ATLAS $2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ + ISR search

	Variable	Common requirement
Select 2 soft SFOS leptons	Number of leptons	$= 2$
	Lepton charge and flavour	e^+e^- or $\mu^+\mu^-$
	Leading lepton $p_{\mathrm{T}}^{\ell_1}$	> 5 (5) GeV for electron (muon)
	Subleading lepton $p_{\mathrm{T}}^{\ell_2}$	> 4.5 (4) GeV for electron (muon)
Conversions/fake muons	$\Delta R_{\ell\ell}$	> 0.05
Drell-Yan resonances	$m_{\ell\ell}$	$\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV
Select ISR topology	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV
	Leading jet $p_{\mathrm{T}}^{j_1}$	> 100 GeV
	$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	> 2.0
Mis-measured jets	$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4
Top quarks	Number of b-jets	$= 0$
$Z \to \tau\tau$	$m_{\tau\tau}$	< 0 or > 160 GeV

Same-flavour opposite sign (SFOS) signature

Higgsino sensitivity dominated by $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0(Z^* \to \ell^+\ell^-)$.

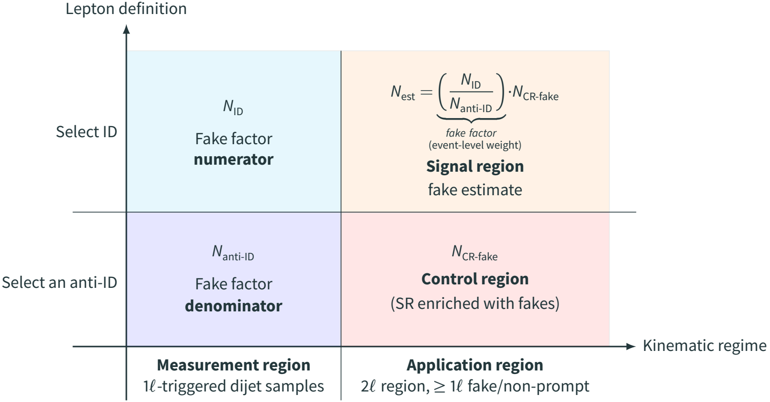
Select ISR topology

$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV, $p_{\mathrm{T}}^{j_1} > 100$ GeV, $\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 2.0$.

Suppress backgrounds

Other common requirements reduce various backgrounds labelled above.

Schematic of data-driven *Fake Factor* method



Numerator (denominator) intuition: given fake leptons, fraction that **pass (fail)** signal requirements.

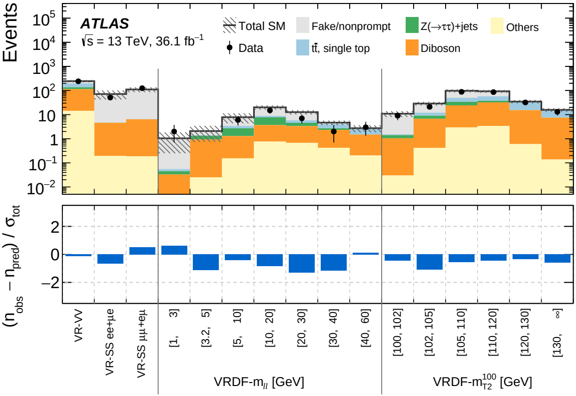
ID Electrons: *Tight* identification, *GradientLoose* isolation.
ID Muons: *Medium* identification, *FixedCutTightTrackOnly* isolation.

ID leptons: same as signal leptons | **Anti-ID leptons**: invert ≥ 1 ID requirements.

Bin in p_{T} for e & μ, bin in $N_{\text{b-jet}}$ only for μ fake factors.

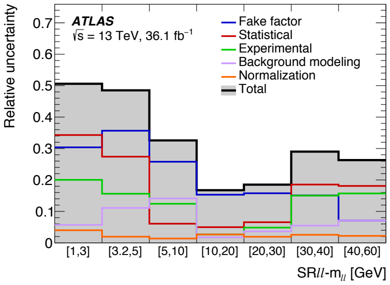
Fake Factor developed in H to WW analysis. Studied fake composition in MC (mostly heavy flavour), optimised object definitions.

Summary of background estimation validation

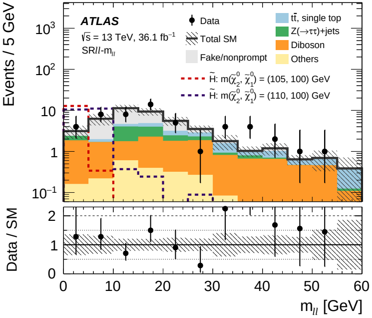


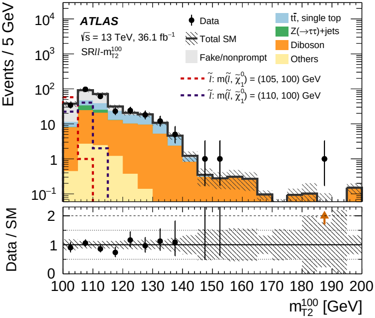
Region	Leptons	E_T^{miss}/H_T^{lep}	Additional requirements
CR-top	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	> 5	≥ 1 b-tagged jet(s)
CR-tau	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$\in [4, 8]$	$m_{\tau\tau} \in [60, 120]$ GeV
VR-VV	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$,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

Breakdown of systematics in SRs



Electroweakino and slepton SRs

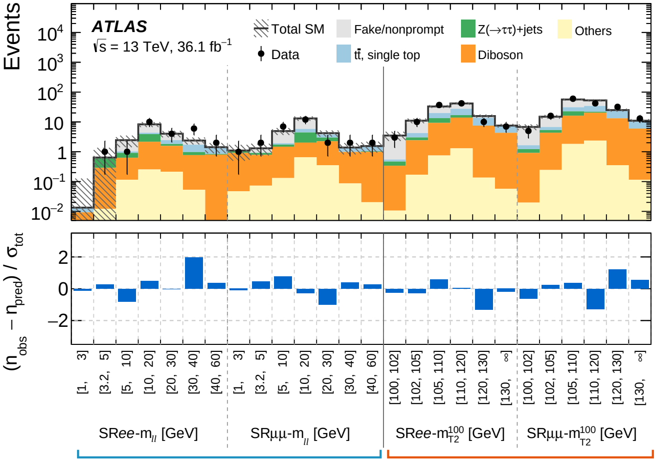




Variable	Common requirement	
Number of leptons	= 2	
Lepton charge and flavour	e^+e^- or $\mu^+\mu^-$	
Leading lepton $p_T^{\ell_1}$	> 5 (5) GeV for electron (muon)	
Subleading lepton $p_T^{\ell_2}$	> 4.5 (4) GeV for electron (muon)	
$\Delta R_{\ell\ell}$	> 0.05	
$m_{\ell\ell}$	∈ [1, 60] GeV excluding [3.0, 3.2] GeV	
E_T^{miss}	> 200 GeV	
Leading jet $p_T^{j_1}$	> 100 GeV	
$\Delta\phi(j_1, \mathbf{p}_T^{miss})$	> 2.0	
min($\Delta\phi$(any jet, $\mathbf{p}_T^{miss}$))	> 0.4	
Number of b-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^{miss}/H_T^{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}

		Electroweakino SRs						
Exclusive	SRee-$m_{\ell\ell}$, SR$\mu\mu$-$m_{\ell\ell}$	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
Inclusive	SR$\ell\ell$-$m_{\ell\ell}$	[1, 3]	[1, 5]	[1, 10]	[1, 20]	[1, 30]	[1, 40]	[1, 60]
		Slepton SRs						
Exclusive	SRee-m_{T2}^{100}, SR$\mu\mu$-m_{T2}^{100}		[100, 102]	[102, 105]	[105, 110]	[110, 120]	[120, 130]	[130, ∞]
Inclusive	SR$\ell\ell$-m_{T2}^{100}		[100, 102]	[100, 105]	[100, 110]	[100, 120]	[100, 130]	[100, ∞]

Exclusive bins for shape fit

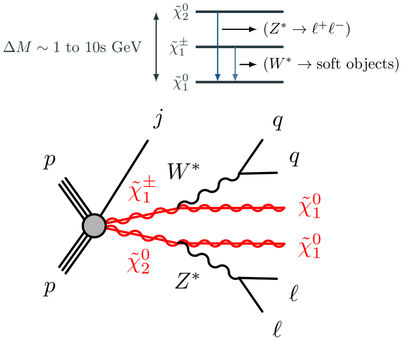


Electroweakinos use $m_{\ell\ell}$ SRs

Sleptons use m_{T2}^{100} SRs

Make bins orthogonal, split by $ee/\mu\mu$ to statistically combine, improving exclusion.

Showing fit with $\mu_{signal} = 0$.



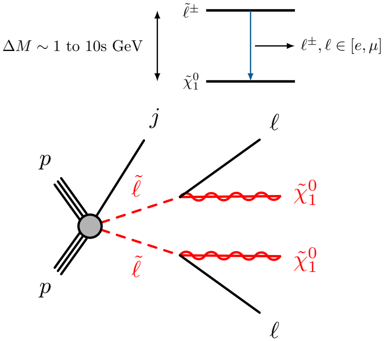
Electroweakinos

Target $\ell^+\ell^-$ from **same** leg

Bump in **dilepton invariant mass** $m_{\ell\ell}$

Higgsino: $m(\tilde{\chi}_1^\pm) = [m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2$

Sensitivity driven by $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



Sleptons

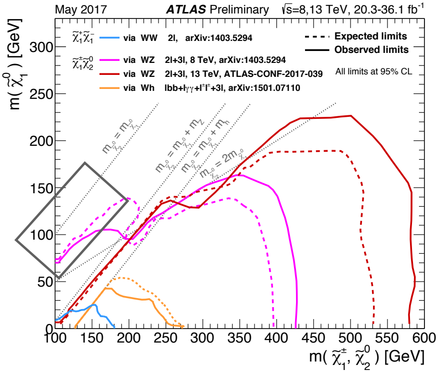
Target $\ell^+\ell^-$ from **different** legs

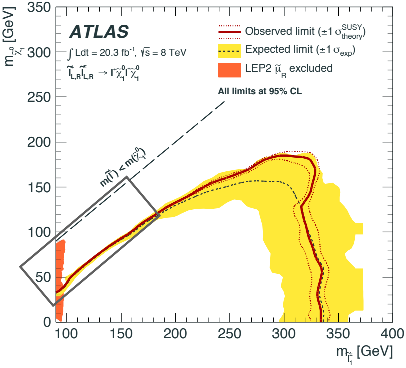
Bump in **stransverse mass** m_{T2}

$m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$

$\sigma \times \mathrm{BR}_{2\ell}$ similar to electroweakinos

Striking gaps in ATLAS sensitivity





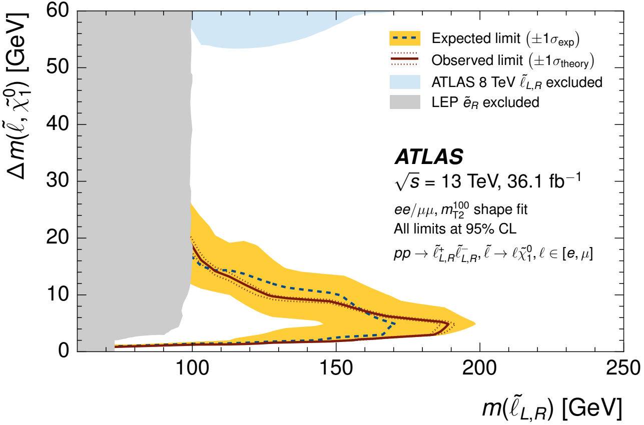
Wino $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to W^{(*)} Z^{(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \lesssim 40$ GeV

Sleptons $\tilde{\ell}^+ \tilde{\ell}^- \to \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim 60$ GeV

First LHC probe of sleptons in $\Delta M \lesssim 55$ GeV gap

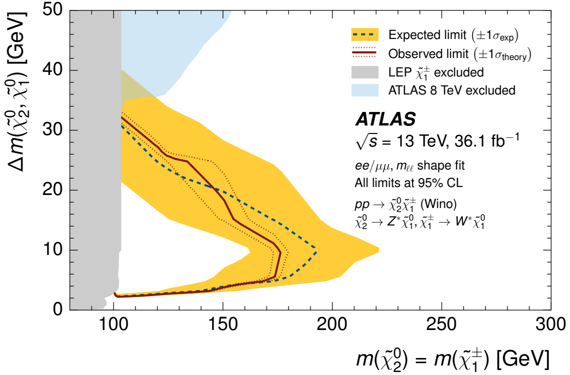


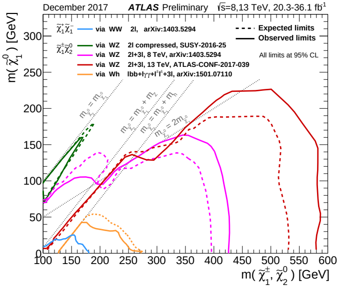
Slepton simplified model

Down to $\Delta M \sim 1$ GeV | Up to $m(\tilde{\ell}) \sim 180$ GeV.

2 years after being asked, realised Barr–Scoville [1501.02511] strategy using data! :)

Moderately compressed gap $20 \lesssim m(\tilde{\ell}) - m(\tilde{\chi}_1^0) \lesssim 60$ GeV challenging due to e.g. WW.





Zoom into diagonal.

Wino–bino simplified model

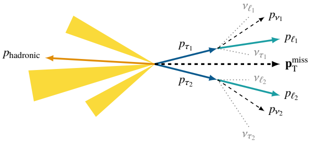
Down to $\Delta M \sim 2.5$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 170$ GeV.

Priority in 2018: close gap at $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) \approx 30$ GeV.

Simplified models motivated by 3 compressed spectra scenarios

Simplified models considered	Higgsino LSP	Slepton / Bino LSP	Wino / Bino LSP
Use in this analysis	Optimisation & interpretation	Optimisation & interpretation	Interpretation
Compression	Radiative/mixing	Accidental	Accidental
SM splitting analogy	W/Z bosons ~10% apart	Charm quark & tau lepton mass ~30% apart	Charm quark & tau lepton mass ~30% apart
Desirable feature	Weak scale naturalness[§]	Resolve $(g\text{-}2)_\mu$ tension[%]	Favoured by global fits[**]
LSP as dark matter	'Well-tempered' mixing[£]	Bino saturates relic density via coannihilation[^]	Bino saturates relic density via coannihilation[^]
E.g. cross-sections[#]	$m(\tilde{\chi}^0_2, \tilde{\chi}^\pm_1)$ = (110, 105) GeV $\sigma(pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1)$ = 4.3 pb	$m(\tilde{\ell}_{L,R})$ = 110 GeV $\sigma(pp \to \tilde{\ell}_{L,R}\tilde{\ell}_{L,R})$ = 0.55 pb	$m(\tilde{\chi}^0_2 = \tilde{\chi}^\pm_1)$ = 110 GeV $\sigma(pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1)$ = 16 pb

E.g. arXiv: [§]1110.6926, [%]1505.05896, **1504.0326, [£]hep-ph/0601041 [^]1508.06608, [#]Resummino NLO+NLL 1304.0790



$$m_{\tau\tau} = \mathrm{sign}(m_{\tau\tau}^2)\sqrt{|m_{\tau\tau}^2|} \tag{1}$$

The construction assumes the τ leptons decay products are nearly collinear.

$p_{\tau_i} = p_{\ell_i} + p_{\nu_i}$. Then the τ momentum is a rescaling of the observable lepton momenta p_{ℓ_i}

$$p_{\tau_i} = (1+\xi_i)p_{\ell_i} \equiv f_i p_{\ell_i}, \tag{7}$$

where $f_i \equiv 1 + \xi_i$. To solve for the two unknown scalars ξ_i, one constrains the neutrino momenta using the missing transverse momentum [1] as Ref. [46] prescribes

$$\mathbf{p}_\mathrm{T}^\mathrm{miss} = \xi_1 \mathbf{p}_\mathrm{T}^{\ell_1} + \xi_2 \mathbf{p}_\mathrm{T}^{\ell_2}. \tag{8}$$

Equation (8) assumes the lepton–invisible colinearity limit $p_{\nu_i} \simeq \xi_i p_{\ell_i}$ and comprises two independent constraints in the transverse plane for the two unknown scalars ξ_i. This is solved by performing 2×2 matrix inversion in for example the x-y transverse plane

$$\begin{pmatrix}\xi_1 \\ \xi_2\end{pmatrix} = \frac{1}{p_x^{\ell_1} p_y^{\ell_2} - p_x^{\ell_2} p_y^{\ell_1}} \begin{pmatrix} p_x^\mathrm{miss} p_y^{\ell_2} - p_x^{\ell_2} p_y^\mathrm{miss} \\ p_y^\mathrm{miss} p_x^{\ell_1} - p_x^\mathrm{miss} p_y^{\ell_1}\end{pmatrix}. \tag{9}$$

Assuming highly boosted taus such that $m_{\tau_i}^2 \simeq 0$, the di-tau invariant mass squared is then given by

$$m_{\tau\tau}^2 = (p_{\tau_1} + p_{\tau_2})^2 \simeq 2 p_{\ell_1} \cdot p_{\ell_2} (1+\xi_1)(1+\xi_2). \tag{10}$$

$m_{\tau\tau}^2$ can go negative when $f_i \equiv 1 + \xi_i < 0$. This happens when one of the leptons is anti-aligned with $\mathbf{p}_\mathrm{T}^\mathrm{miss}$ and $E_\mathrm{T}^\mathrm{miss} > |\mathbf{p}_\mathrm{T}^{\ell_i}|$, such that the rescaling has to invert the direction to approximate the tau-momentum.

In slepton-pair production (Figure 1(b)), the event topology can be used to infer the slepton mass given the LSP mass. The stransverse mass [37, 38] is defined by

$$m_{\mathrm{T2}}^{m_\chi}\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right) = \min_{\mathbf{q}_{\mathrm{T}}}\left(\max\left[m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{q}_{\mathrm{T}}, m_\chi\right), m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}}, m_\chi\right)\right]\right),$$

where the transverse vector $\mathbf{q}_{\mathrm{T}}$ is chosen to minimize the larger of the two transverse masses, defined by

$$m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}, \mathbf{q}_{\mathrm{T}}, m_\chi\right) = \sqrt{m_\ell^2 + m_\chi^2 + 2\left(\sqrt{p_{\mathrm{T}}^2 + m_\ell^2}\sqrt{q_{\mathrm{T}}^2 + m_\chi^2} - \mathbf{p}_{\mathrm{T}} \cdot \mathbf{q}_{\mathrm{T}}\right)}.$$

The values of $m_{\mathrm{T2}}^{m_\chi}$ are bounded by the slepton mass from above when the hypothesis invisible mass m_χ is set to the LSP mass. The stransverse mass m_{T2}^{100} with $m_\chi = 100$ GeV is used to define the binning of the slepton SRs as further described below. The value of 100 GeV is chosen based on the expected LSP masses of the slepton signals targeted by this analysis.