Searches for charginos and neutralinos with the ATLAS detector

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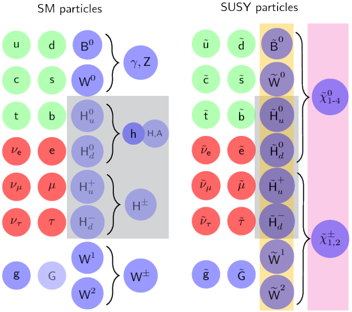
on behalf of the ATLAS Collaboration

SUSY 2021
23-28 August 2021

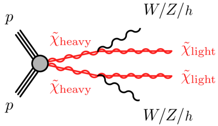
European Research Council
Established by the European Commission

SUSY and simplified models

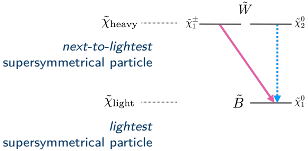
- **Many SM parameters measured with exceptional precision and agreement with theoretical predictions**
- **New physics is out there, why haven't we found it yet?**
  - → nature of DM? hierarchy problem? unification of the forces? flavour anomalies?



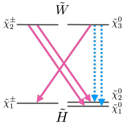
- **SUSY = new (broken) fermion/boson symmetry**
  - → can provide solutions to the open problems
  - → supersymmetric partner for every SM particle
  - → including an **extended Higgs sector**
  - → **chargino/neutralino** eigenstates through mixing of **bino/wino/higgsino** states
- **Focus on simplified models to systematically cover large phase space, but moving to also include more general interpretations**



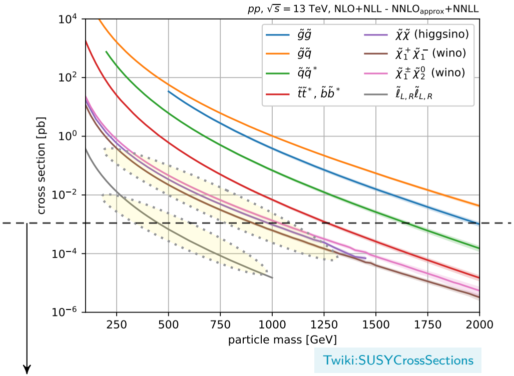
wino NLSP to **bino** LSP scenarios
motivated by DM co-annihilation
(and matching observed DM relic density)



scenarios with light **higgsinos**
motivated by naturalness



(Electroweak) SUSY at the LHC



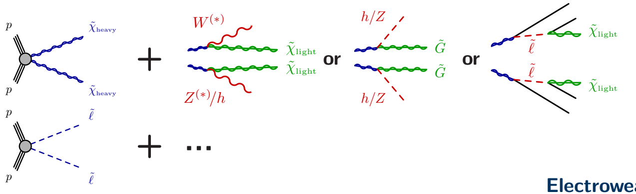
Twiki:SUSYCrossSections

assuming acc*eff $\sim 1\%$
then
expect O(100) events in full Run 2 13 TeV dataset

- **Supersymmetry can provide solutions to the open problems**
- **Stringent limits have been set on strong production of SUSY particles, putting pressure on naturalness**
  - → stop / squark / gluino limits up to 1.3 / 1.85 / 2.2 TeV
  - → electroweak production cross sections smaller
- **Same SUSY motivations remain for electroweak production**
  - → probe lower cross section processes with full Run 2 dataset
  - → naturalness favours light higgsinos

ATLAS searches for electroweak SUSY

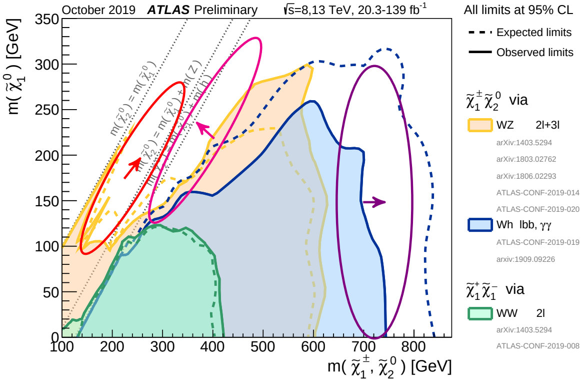
Considering various *production modes*, *intermediate states*, *final states* & *LSP*



Searches continue to evolve

- → push towards kinematic bounds and statistically challenging regions (decreasing cross section)
- → develop searches to cover gaps and target unexplored corners of phase space
- → consider more general models than just the simplified cases
- → further facilitate reinterpretation

Electroweakino pair production



ATL-PHYS-PUB-2019-044

This talk – Searches in multilepton final states

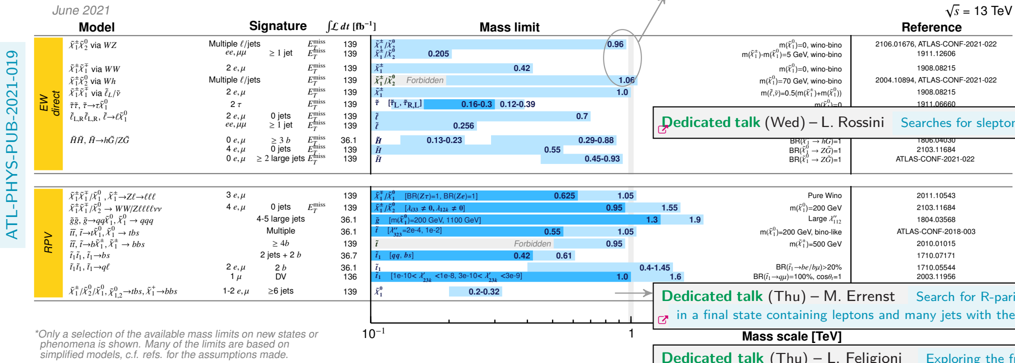
Presenting two ATLAS searches using the 139 fb^{-1} dataset probing novel phase space in different ways

All prompt signatures – fully leptonic – focus on RPC models

- JHEP 07 (2021) 167 — probes chargino–neutralino production in final states with 4 or more leptons
- arxiv:2106.01676 — probes chargino–neutralino production in $3\ell + E_{\perp}^{miss}$ final states

Physics Briefing *on new 3ℓ, all-hadronic, and RPV 1ℓ+multijets results*
The hunt for higgsinos reaches new limits

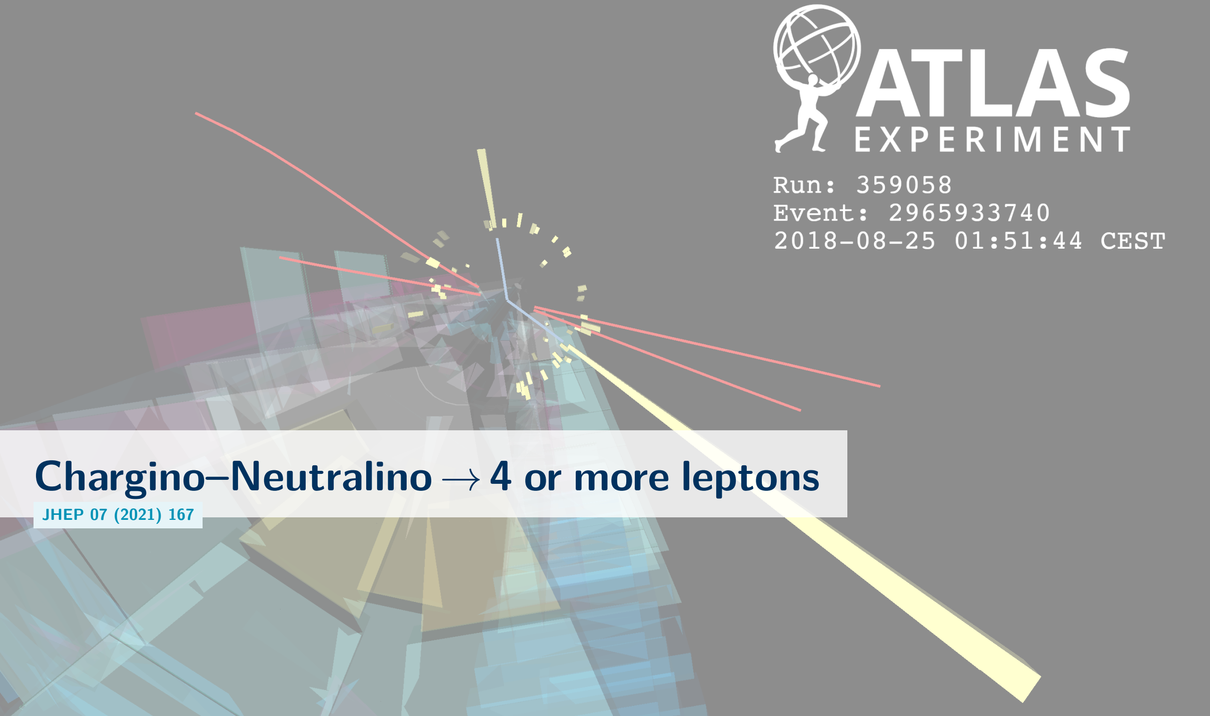
Dedicated talk (Tue) – Y. Okazaki
Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum with the ATLAS detector



Dedicated talk (Wed) – L. Rossini
Searches for sleptons with the ATLAS detector

Dedicated talk (Thu) – M. Errenst
Search for R-parity violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment

Dedicated talk (Thu) – L. Feligioni
Exploring the frontier of R-parity-violating supersymmetry with the ATLAS detector



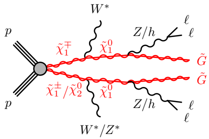
Chargino–Neutralino $\rightarrow$ 4 or more leptons

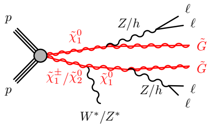
JHEP 07 (2021) 167

$\tilde{\chi}\tilde{\chi} \rightarrow$ 4 or more leptons

- including C1C1 / C1N1 / C1N2 / N1N2 production
- final states with ≥ 4 leptons (including $\leq 2\ \tau_h$)

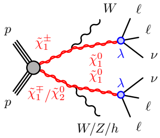
R-parity conserving

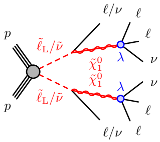


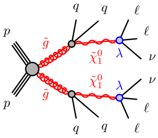


- focus on general gauge mediation (GGM) scenario
- light mass-degenerate higgsino triplet
- nearly massless gravitino LSP
- same-flavour opposite-sign lepton pairs from Z/h decays, additional leptons from W/h decays too soft for detection

R-parity violating







- wino/slepton/gluino NLSP
- $\tilde{\chi}_1^0 \rightarrow \ell^{\pm}\ell^{\mp}\nu$ decays
- focus on τ multiplicity extremes of LL$\bar{\text{E}}$ coupling λ

Dedicated talk – L. Feligioni Exploring the frontier of R-parity-violating supersymmetry with the ATLAS detector

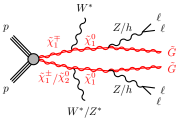
RPC targetting regions

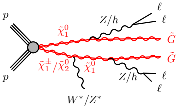
signal regions separated by

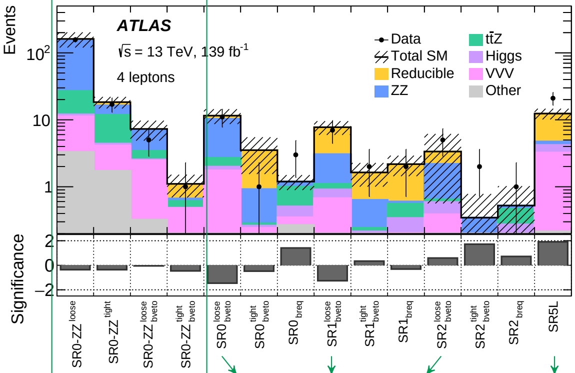
- presence/absence of Z bosons (2Z / 0Z)
- τ_h and b-jet multiplicity
- $E_{\perp}^{\text{miss}}$ and m_{eff}

main backgrounds

- irreducible: ZZ and $t\bar{t}Z$ from MC normalised in CR
- reducible: fake leptons from data-driven measurement





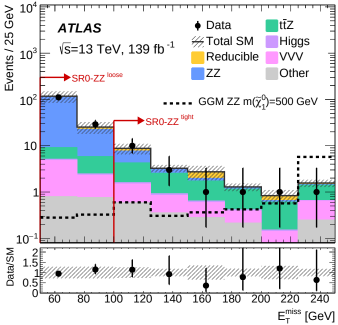


GGM dedicated

Generic BSM regions

Generic $\geq 5\ell$

$E_{\perp}^{\text{miss}}$, b-agnostic, 4L0T



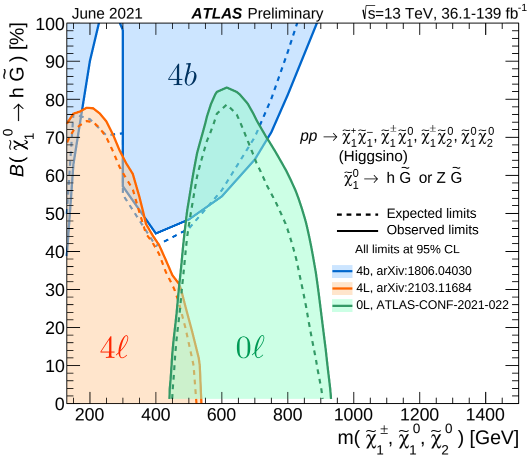
excess follow-up

36fb^{-1} 4ℓ result PRD.98.032009

→ *good agreement with SM now*

RPC targetting regions – results

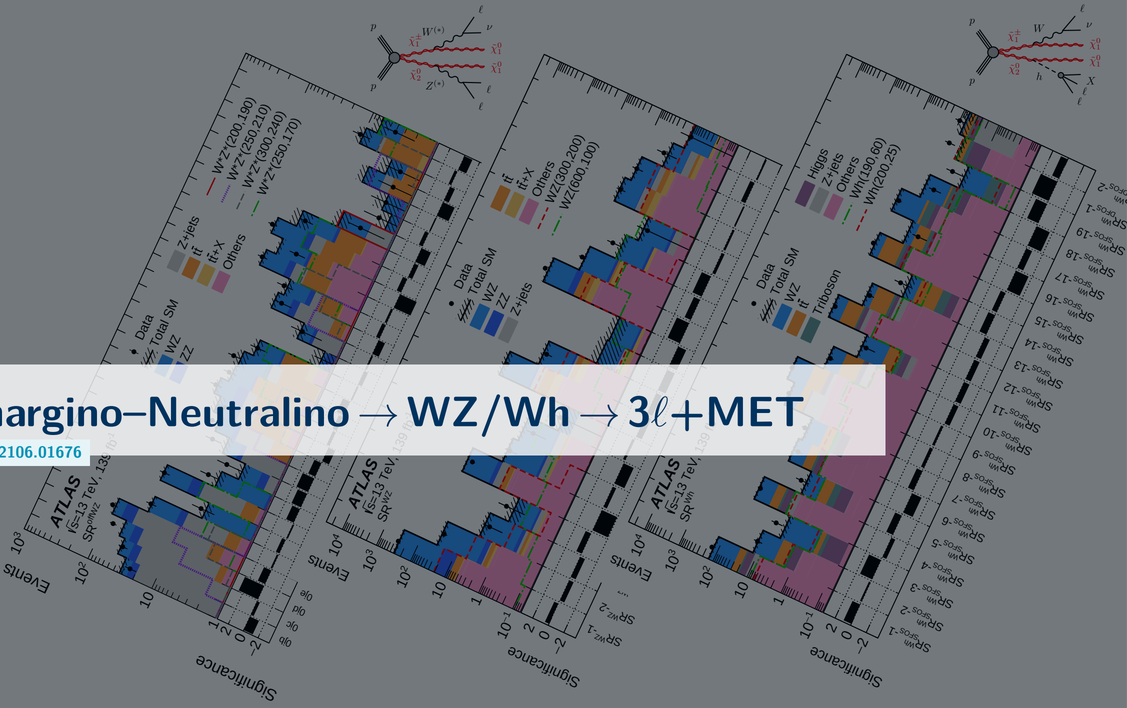
$\tilde{\chi}\tilde{\chi} \rightarrow$ 4 or more leptons



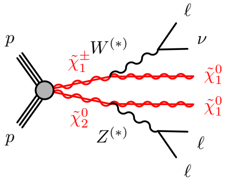
- **better sensitivity** to $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G})$ than to $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h + \tilde{G})$ due to relatively high $Z \rightarrow \ell\ell$ branching ratio
- great complementarity of 4ℓ with $4b$ and 0ℓ results, sensitive respectively at higher $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h + \tilde{G})$ and at higher higgsino mass

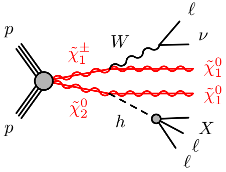
Chargino–Neutralino → WZ/Wh → 3ℓ+MET

arxiv:2106.01676



$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow$ **3**ℓ **+ E$_{\perp}^{\text{miss}}$**

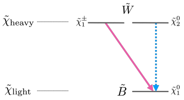




Chargino–Neutralino pair production

- search in $3\ell + \text{E}_{\perp}^{\text{miss}}$ final states
- intermediate WZ (both on-shell or off-shell) or Wh decays ($h \rightarrow WW/ZZ/\tau\tau$)

Two interpretations



1. wino/bino scenario

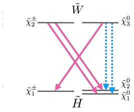
→ used to optimise analysis regions

→ bino-like LSP, degenerate wino-like NLSPs

→ DM co-annihilation motivated

→ slightly higher cross section

→ important for intermediate & higher mass splittings



2. alternative higgsino scenario

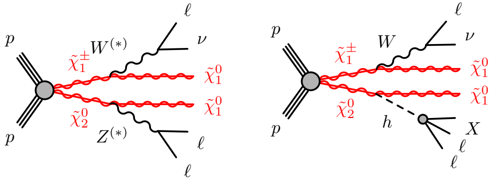
→ nearly degenerate higgsino triplet

→ naturalness motivated

→ smaller cross section

→ important for smaller mass splittings, considered up to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 60$ GeV

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3\ell + E_{\perp}^{\text{miss}}$



Multiple analysis channels

On-shell WZ

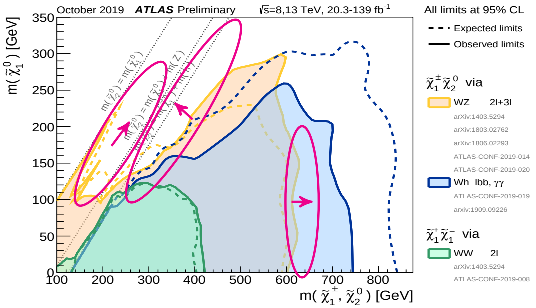
- $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \geq m_Z$
- update $36\,\text{fb}^{-1}$ result arxiv:1803.02762
- extend towards $\Delta m = m_Z$ kinematic bound & towards higher $m(\tilde{\chi}_2^0)$

Off-shell WZ

- $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) < m_Z$
- first 3ℓ result since Run 1 arxiv:1402.7029
- cover Δm gap between on-shell and very compressed phase space arxiv:1911.12606 (soft 2ℓ)

Wh

- first 3ℓ result since Run 1 arxiv:1402.7029



+ Combination of results in WZ channel including new and soft 2ℓ results

Analysis concept

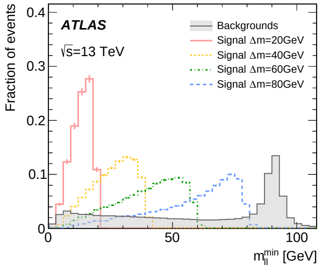
Multibin selection covering varied signal scenarios and masses

- → $3\ell + E_{\perp}^{miss}$ with ≥ 1 opposite-sign same-flavour pair
- → jet-veto and jet-inclusive selections
- → further binning in $E_{\perp}^{miss}$, m_{T}, and $m_{\ell\ell}^{min}$

Background estimation

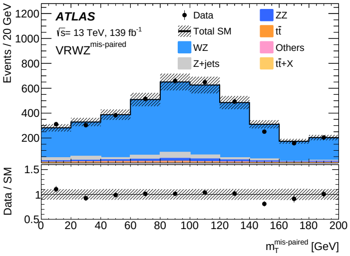
- irreducible: **WZ** (MC with normalisation in CR), **$t\bar{t}$** (MC)
- reducible: **Z+jets fake/non-prompt** (data-driven estimation)

$m_{\ell\ell}^{min}$ edge in off-shell selection



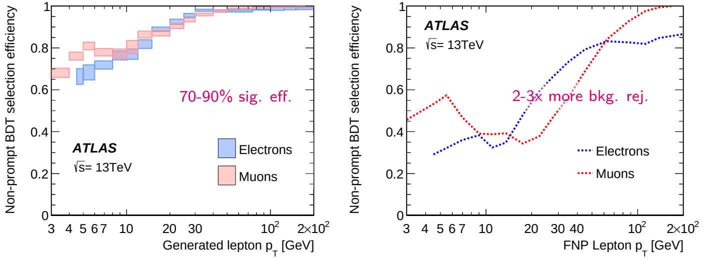
on-shell WZ m_{T} shape validation

in DFOS mis-paired events



BDT-based 3rd lepton isolation in off-shell WZ selection

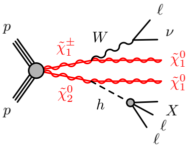
for fake/non-prompt lepton background reduction

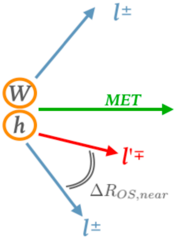


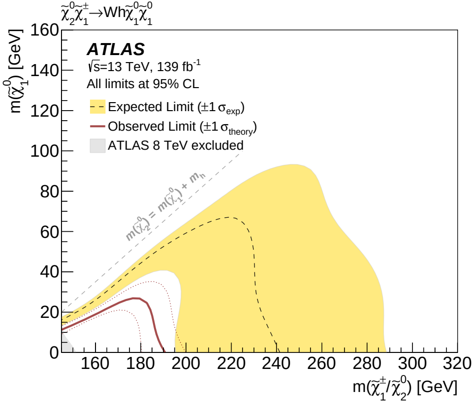
Results – intermediate Wh

$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair production in wino/bino scenario

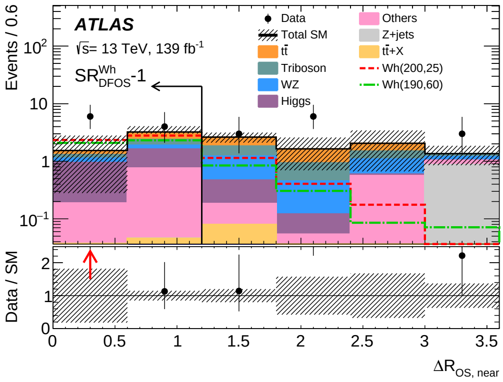
- 19 SFOS regions + 2 extra DFOS regions important for sensitivity
  $\rightarrow$ slight excesses translate to exclusion contour
- first 3ℓ result for Wh since Run 1
- expected sensitivity improved by 90 GeV in $m(\tilde{\chi}_2^0)$





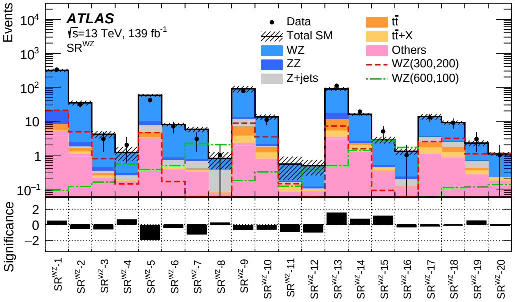


3ℓ **Wh** DFOS region



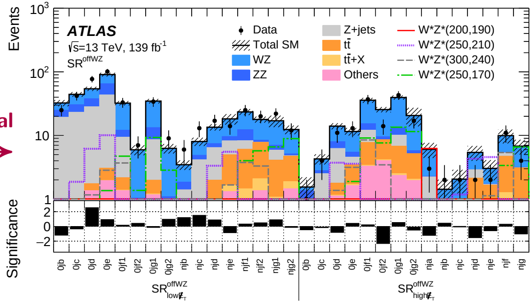
Results – intermediate WZ

3ℓ **on-shell** SRs



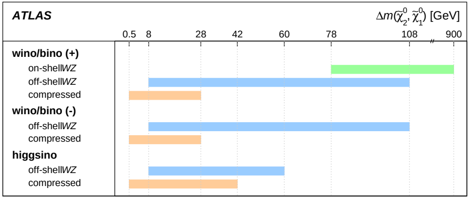
fully orthogonal

3ℓ **off-shell** SRs



+ Combine results in WZ channel where sensitivity overlaps

- new on-shell + off-shell SRs and results of previous **soft 2ℓ search**



+ Excess follow-up 3ℓ recursive jigsaw reconstruction technique result

- 36fb^{-1} result arxiv:1806.02293
- *good agreement with SM expectation in full Run 2 dataset*

Results – WZ – wino/bino scenario

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with intermediate WZ

- **improved exclusion** → by ~150 GeV in $m(\tilde{\chi}_2^0)$ in $\Delta m = m_Z$ region
  → by 40 GeV towards higher $m(\tilde{\chi}_2^0)$
  → down to $\Delta m = 7$ GeV and up to $m(\tilde{\chi}_2^0) = 310$ GeV covering the gap between the bulk and very compressed region

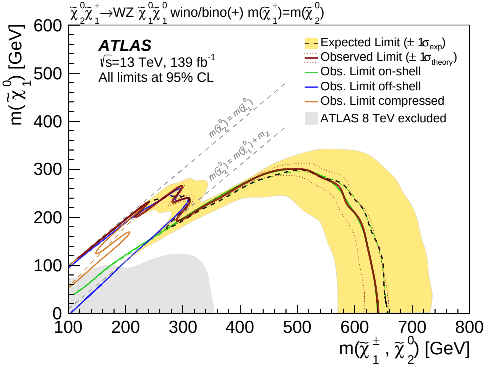
3ℓ on-shell

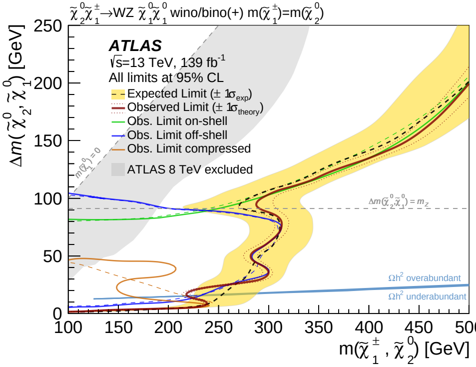
3ℓ off-shell

soft 2ℓ

- showing observed DM relic density interpretation following arxiv:1804.05238
- **combination** with previous soft 2ℓ result arxiv:1911.12606

  improves exclusion → from 240 to 280 GeV near $\Delta m = m_Z$
  → from 210 to 240 GeV around $\Delta m = 10 - 15$ GeV





Results – WZ – higgsino scenario

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with intermediate WZ

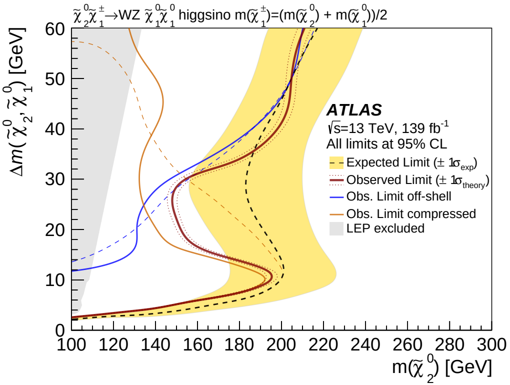
- alternative scenarios targeted with **off-shell WZ** search category
- subtly different kinematics and lower cross section

- improved exclusion from 120 to 200 GeV in $m(\tilde{\chi}_2^0)$ GeV for intermediate mass splittings

- combination with previous soft 2ℓ result arxiv:1911.12606
- mild excess around $\Delta m = 25$ GeV, mostly from soft 2ℓ result, still visible in combined result

3ℓ **off-shell**

soft 2ℓ



Summary

Several new and updated ATLAS results in the search for electroweak SUSY

- Explored the full Run 2 dataset with a wide range of analysis techniques
- No significant deviations observed and setting stronger exclusion limits

Searches discussed today probe various well-motivated and challenging corners of phase space

- Complementary sensitivity in $\tilde{\chi}_1^0 \rightarrow Z/h + \tilde{G}$ plane from 4ℓ, $4b$, and 0ℓ results
- Covering gaps in sensitivity for chargino–neutralino pair production with targeted 3ℓ searches and combination of results, improving limits for Δm near m_{Z} by 150 GeV and for intermediate $\Delta m < m_{\mathrm{Z}}$ by up to 310 GeV in $m(\tilde{\chi}_2^0)$
- More new results in dedicated talks (see p.5)

Continue with exciting search program in Run 3

- Dataset will keep growing beyond Run 2
- Still more phase space to cover
- Search strategies and analysis techniques continue to evolve

Additional slides

Search strategy

Analyses may use varying techniques for signal/background separation

- **cut & count analysis**: use simple selection on kinematic variables
- **shape analysis**: use multi-bin fit

Signal regions (SRs) are built optimising discovery/exclusion power

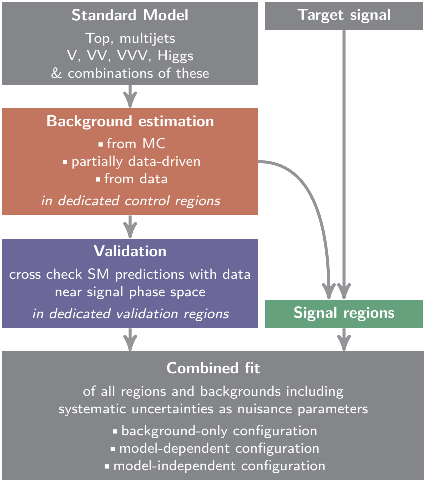
- target specific signatures and maximise S/B
- range from simple selection, to building complex variables, to employing e.g. machine-learning techniques

Background estimation

- Reducible/irreducible: different/same final state as signal
- estimation from MC / partially data-driven / from data
- often normalisation to data in dedicated control regions (CRs)

Validation regions (VRs)

- typically defined close to SR phase space to validate background estimation



Lepton reconstruction and identification performance

Improvements for leptons at very low transverse momentum open up opportunities for searches

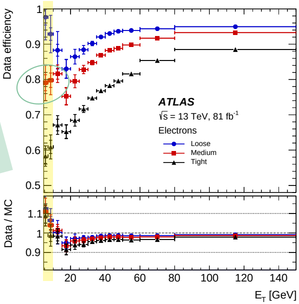
Lowest reach:

electrons: 4.5 GeV

muons: 3.0 GeV

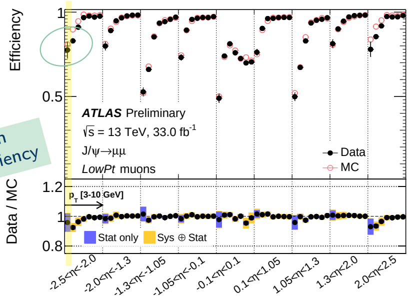
→ 80% efficiency

electron ID efficiency



arxiv:1908.00005

muon ID efficiency



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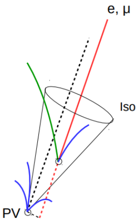
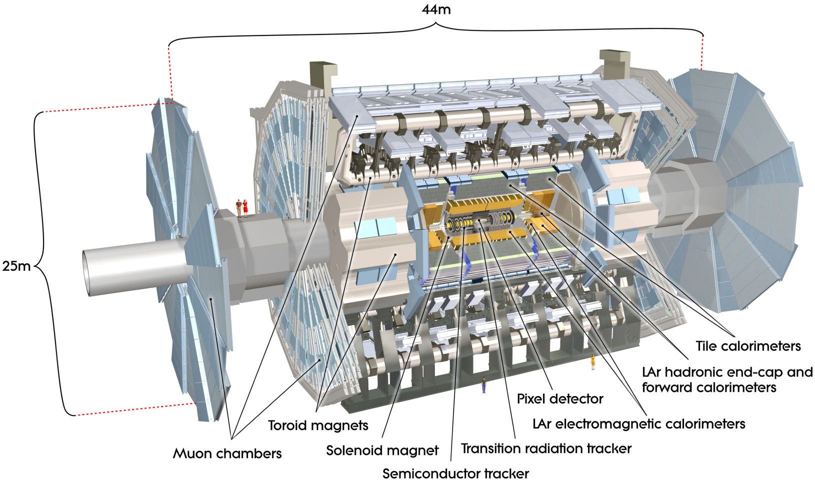


New techniques for lepton isolation assist fake/non-prompt lepton background reduction

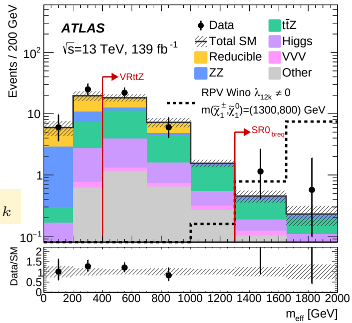
- BDT-based isolation using lepton isolation, lepton and track quantities, and b-jet likeness in cone around lepton
- optimised for use down to the lowest lepton transverse momenta
- performance example from 3ℓ analysis:
  2-3x background reduction while retaining 70-90% efficiency for real leptons

ATLAS detector

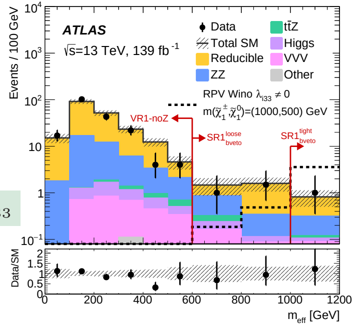


RPV targetting regions

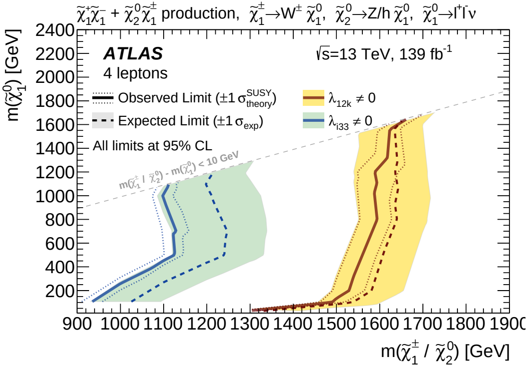
- **4L0T** (λ_{12k} (k=1,2)) and **3L1T/2L2T** (λ_{i33} (i=1,2)) regions
- selection using **Z-veto** and separating by **b-multiplicity**
  - general SRs & VRs with moderate m_{eff} threshold
  - specific λ_{ijk} targetting SRs at very high m_{eff}
- dominant backgrounds: **ZZ** and **$t\bar{t}Z$**, as well as **fake leptons**
- considering $\mathcal{B}(\tilde{\chi}_1^0 \to \ell\ell\nu) = 100\%$
- showing **wino NSLP scenario**, additional results for slepton/gluino NLSP

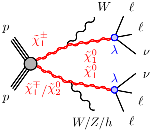


λ_{12k}



λ_{i33}



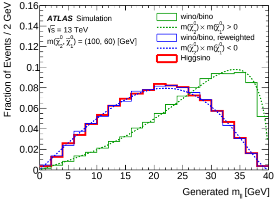


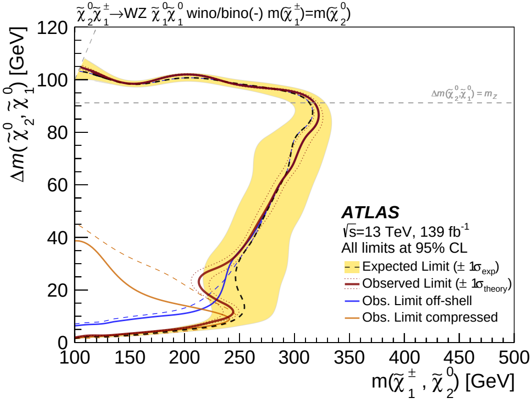
Results – WZ – wino/bino alternative interpretation

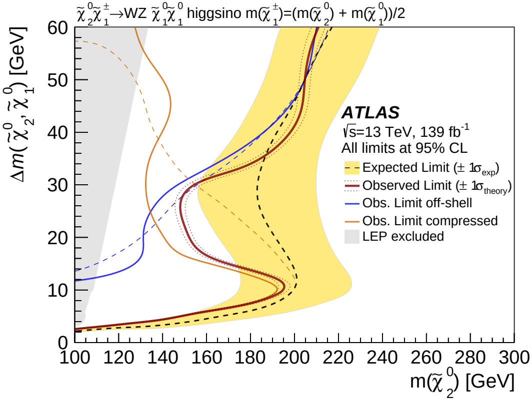
$\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$ pair production with intermediate WZ and 3ℓ+$E_{\perp}^{miss}$ final state

Also combined with soft 2ℓ result

- alternative scenarios targeted with off-shell WZ search category
- wino/bino ($-$) kinematics reweighted from wino/bino ($+$), similar to higgsino kinematics

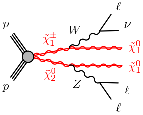




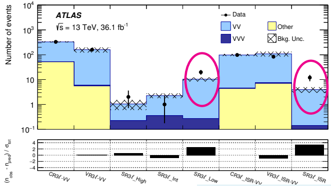


Excess follow-up: Recursive Jigsaw Reconstruction technique

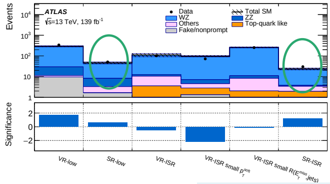
$\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$ pair production with on-shell intermediate W/Z decays, and 3ℓ + final state



- RJR technique: arxiv:1607.08307 , arxiv:1705.10733
- Two excesses in $2/3\ell$ 36 fb^{-1} result: SR3ℓ-Low (2.1σ) and SR3ℓ-ISR (3.0σ)
  - → RJR technique to boost back to the rest frames of the parent particles
  - → discriminating variables can be defined using object/frame momenta
- Earlier follow-up analysis with 139 fb^{-1} emulated RJR analysis
  - → Translation of RJR variables to lab frame variables
  - → Able to reproduce 36 fb^{-1} result
  - → No significant excesses using full 139 fb^{-1} dataset
- New result repeating original analysis with 139 fb^{-1} dataset
  - → No changes to original analysis
  - → Good agreement with emulated RJR result
  - → No significant excesses using full 139 fb^{-1} dataset



$2/3\ell$ RJR (36 fb^{-1}), arxiv:1806.02293



3ℓ emulated RJR (139 fb^{-1}), arxiv:1912.08479

Region	SR3ℓ-Low	SR3ℓ-ISR
Observed	53	25
Fitted SM	49 ± 14	17 ± 4
Diboson	47 ± 14	16 ± 4
FNP leptons	1.36 ± 0.29	0.83 ± 0.27
Triboson	0.40 ± 0.14	0.14 ± 0.06
Others	0.052 ± 0.029	0.41 ± 0.21

3ℓ RJR (139 fb^{-1}), arxiv:2106.01676