

Recent results from supersymmetry search combinations with the ATLAS and CMS experiments

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## Expanding the standard SUSY searches

Targeting challenging and rare SUSY signatures

The very first statements on SUSY using the Run 2 data rolled out in 2016

- The quark-induced EWK sector has small cross sections
$\rightarrow$ Emphasis on the strong sector and "standard" SUSY searches
$\rightarrow$ Target final states with multiple SM objects, and large missing energy from undetected SUSY states



## Standard searches



Signal in the tails of kinematic variable that has dimension of mass

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Exploration of stops and the EWK sector relies on the Full Run 2 data

- Update the standard searches: novel analysis techniques
- Explore previously uncovered corners
- Compressed scenarios (small amount of visible energy)
- Sleptons (extremely low cross sections)

Combining the searches: more powerful together $\rightarrow$ Consider various signal scenarios appearing in multiple places


## Standard searches



Signal in the tails of
kinematic variable that has dimension of mass

## Existing and future combinations of searches for stops and EWKinos

## Combinations of searches for stop pairs

Stops: spartners of top quarks


Latest stop combination result is from the CMS Collaboration (2107.10892) - exclude stop masses up to ~1300 GeV!
Target direct stop pair production, with final states of two tops, two b quarks, or tb (mixed topology)
$\rightarrow$ Event categories: 0/1/2 leptons - require MET and jets (use tagging e.g. for b jets)


These SUSY searches can be used to place constraints on (pseudo)scalars that mediate DM production

## Combinations of searches for top pair+DM

A (pseudo)scalar $\phi$ (a) particle mediates the interaction between SM quarks and a DM candidate $X$


Event categories: 0/1/2 leptons - require MET and jets (use tagging e.g. for b jets)
ATLAS: Recent extension of the previous OL final state by adding a low MET category (MET decreased from 250 to 160 GeV )
$\rightarrow$ Combine MET (MET $>250 \mathrm{GeV}$ ) and b-tagged jet triggers
$\rightarrow$ Orthogonality ensured: require MET significance $S<14$ and no large-radius jets


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Combination of OL categories with the 1 L and 2 L categories performed by ATLAS and CMS




## EWKino sector: Go compressed or go home!

LSP: the lightest supersymmetric particle (stable and neutral)
EWKinos (neutralinos and charginos): mass eigenstates formed by the mixing of Winos, Bino, and Higgsinos (spartners of the SM EWK bosons)
Compressed spectra: small mass splitting between the next-to-LSP and the LSP $\rightarrow$ Can be explored in many models, such as with Bino LSP, and Wino NLSP or Slepton NLSP

But.... such scenarios come with a little bit of visible energy
$\rightarrow$ Require e.g. an ISR jet to access the compressed cases
$\rightarrow$ Small number of events (on top of the small XS)
$\rightarrow$ Extremely challenging searches - benefit from combinations!


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$\rightarrow$ Extremely challenging searches - benefit from combinations!
The sleptons could explain the recent results on the muon g-2 anomaly, measured by the Fermilab and BNL experiments



## EWKino combinations: chargino and neutralinos

The latest combination performed by ATLAS (2106.01676) targets production of chargino and neutralino, final states with W and $Z$ boson $\rightarrow$ Wino-like NLSP with Bino-like LSP ( $\tilde{\mathrm{X}}_{1}{ }^{0}$ ) (alternatively Higgsino-triplet)

A 31 search (off- and on-shell Z boson) combined with a previously published 2l search ("compressed"); orthogonality is ensured by requirements on mll and MET, or lepton multiplicity
$\rightarrow$ Results combined where greater exclusion power is expected over the individual results


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The same topologies have been explored by the CMS Collaboration (See back-up and talk by Zachary Flowers!)
$\rightarrow$ Combination is in progress!

| Search | ATLAS | CMS |
| :---: | :---: | :---: |
| $2 \ell$ soft | 1911.12606 | 2111.06296 (incl. 3 3 soft) |
| $3 \ell$ | 2106.01676 | 2106.14246 (incl. 2 $($ SS $)$ and $>3 \ell$ ) |
| Combination? | 2106.01676 | In progress |

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${ }^{*}+(-):$ Positive (negative) product of the two signed neutralino eigenmass parameters $m_{\text {eig }}\left(\tilde{\chi}_{2}^{0}\right) \times m_{\text {eig }}\left(\tilde{\chi}_{1}^{0}\right)$

Beyond the combinations: recent searches

## ATLAS search targeting final states with two leptons, jets, and MET

Recent search from ATLAS targets production of chargino and neutralino with topologies WZ (wino-bino), and ZZ/ZH (GMSB)

## NEW

$\underline{2204.13072}$
Maximal coverage for the models: 13 orthogonal search regions incl. a new SR for off-shell $Z$ boson

Require 2 leptons (opposite-sign same-flavour), $1 / 2$ (b)jets, and MET

Mass windows used to target
on-/off-Z boson ( $\left.m_{\|}\right)$, and
W, Z, H bosons (jet system m)
Signal extraction:
MET significance or mll


## ATLAS search targeting final states with two leptons, jets, and MET

Recent search from ATLAS targets production of chargino and neutralino with topologies WZ (wino-bino), and ZZ/ZH (GMSB) $\rightarrow$ Complement the previous search performed by CMS (targeting the same models)
NEW


| Search | WZ | ZZ | ZH |
| :---: | :---: | :---: | :---: |
| ATLAS: $2 \ell+1 / 2 \mathrm{j}(2204.13072)$ | $\checkmark$ | $\checkmark$ | $\checkmark$ |
| CMS: 2 on-Z (2012.08600) | $\checkmark$ | $\checkmark$ | $\checkmark$ |



Wino-Bino interpretation: neutralino (chargino) $\tilde{\chi}_{2}^{0}\left(\tilde{X}_{1}^{+-}\right)$masses excluded up to $\sim 800 \mathrm{GeV}$ GMSB interpretation: neutralino $\tilde{X}_{1}^{0}$ masses excluded up to $\sim 900 \mathrm{GeV}$ (ZZ decay)

## ATLAS search targeting final states with two leptons, and MET

Recent search from ATLAS targets production of charginos with topology WW (semi-compressed spectra near W boson mass)

ATLAS-CONF-2022-006
Require 2 leptons (opposite-sign), MET, and no (b) jets

Main backgrounds SM WW, VZ,
Z+jets, ttbar+top from partially data-driven techniques

Two categories: same- and different flavour pairs
$\rightarrow$ Discriminate signal from background using four BDTs: signal BDT for signal extraction, background BDTs: VV, top, others


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Same search targets direct slepton pair production with a different strategy!



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Require 2 leptons (opposite-sign), MET, and additionally up to 1 jet (ISR) - no b jets

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## ATLAS-CONF-2022-006

 $100 / 110 / 120 / 130 / 140 \rightarrow \infty$
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Require 2 leptons (opposite-sign), MET, and additionally up to 1 jet (ISR) - no b jets

Main backgrounds SM WW, VZ, Z+jets, ttbar+top (Flavour Symmetric Backgrounds, FSB)

Two event categories
Same-flavour. 0/1 jet signal regions
Different-flavour: estimate FSB
Signal extraction using $\mathrm{M}_{\mathrm{T}, 2}$ variable ( $m_{\|}$not meaningful here)
$\rightarrow$ Two binnings for signal extraction: exclusive and inclusive with varying lower bound: 100/110/120/130/140 $\rightarrow \infty$


## Summary of constraints on sleptons



| Search | sleptons |
| :---: | :---: |
| ATLAS: $2 \ell+0 \mathrm{j}$ (ATLAS-CONF-2022-006) | $\checkmark$ |
| CMS: $2 \ell$ non-resonant $(2012.08600)$ | $\checkmark$ |

## Conclusions

The full Run 2 data set allows the exploration of stops and the EWK sector No sign of new physics yet, and the recent results on the muon g-2 anomaly gives hope: all eyes are on the compressed spectra (sleptons, ewkinos)

Combining individual analyses provides multiple opportunities: consider various signal scenarios appearing in multiple places

Both ATLAS and CMS have searched for the production of stop pairs $\rightarrow$ CMS has performed the combination, and both utilised combination to place constraints on (pseudo)scalars that mediate DM production

The latest EWKino Combination results by ATLAS - CMS result is foreseen soon In the meanwhile: new results on EWKinos and sleptons are being published! $\rightarrow$ Searches for SUSY can also inspire new ways to perform SM measurements (see e.g. Fiducial and differential WW cross section measurement by ATLAS)

Combinations of Run 2 searches will define the last words on Run 2 data, and help us to steer the searches for Run 3!



## Thanks for your attention!

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Back-up

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## Event categories: 0/1/2 leptons - require MET and jets (use tagging e.g. for bjets)

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## Event variables

## Definitions of some event variables used commonly by ATLAS and CMS

- MET significance S (ATLAS-CONF-2018-038)
- Is the MET from weakly interacting particles, or a result of mismeasurement, resolutions and inefficiencies? $\rightarrow$ Utilise object-based MET significance based on the total variance in the longitudinal direction along MET (all objects) and the correlation factor of the longitudinal and transverse resolutions of all objects

- $M_{T, 2}$ variable generalises $M_{T}$ for symmetric event topologies where two identical particles each decay into a visible and invisible product (1502.04358)

$$
\left(M_{\mathrm{T}}^{(i)}\right)^{2}=\left(m^{\mathrm{vis}(i)}\right)^{2}+m_{\mathrm{X}}^{2}+2\left(E_{\mathrm{T}}^{\mathrm{vis}(i)} E_{\mathrm{T}}^{\mathrm{X}(i)}-\vec{p}_{\mathrm{T}}^{\mathrm{vis}(i)} \cdot \vec{p}_{\mathrm{T}}^{\mathrm{X}(i)}\right)
$$

$$
M_{\mathrm{T} 2}\left(m_{\mathrm{X}}\right)=\min _{\vec{p}_{\mathrm{T}}^{\mathrm{X}(1)}+\vec{p}_{\mathrm{T}}^{(2)}=\vec{p}_{\mathrm{T}}^{\text {miss }}}\left[\max \left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)}\right)\right]
$$

A minimization is performed over trial momenta of the undetected particles fulfilling the $p_{T}{ }^{\text {miss }}$ constraint. The unknown mass $m x$ is a free parameter.


The visible parts of each decay chain (leptons) are reconstructed

The invisible parts are unknown! We only reconstruct the total missing transverse energy!

## Input analyses for the CMS EWKino Combination <br> \section*{compressed}



Two categories; 2 or 3 low pT leptons

- 31 category is new (wrt 2016)
- Require an ISR jet
(enhance the MET from LSP)

Aims to reconstruct mass of Z":
$m l l$ serves as proxy for $\Delta m(N 2, N 1)$
$\rightarrow$ Likelihood fit binned in MET ${ }^{(n o w)}$ \& mll


## Targets mass-splittings as low as 5 GeV



## Input analyses for the CMS EWKino Combination

## $\underline{2106.14246}$ "2l (SS) + $\geq 31 "$

Three or four leptons (up to 2 hadronically decaying taus) or two same-sign (SS) light leptons
Leading' lepton pT>30 GeV (31*)

An exhaustive search that considers up to 13 different leptonic final states

2 (SS): light leptons (compressed regions)
3 and 4l: up to 2 hadr. decaying taus in addition to light leptons

Update since 2016 for the 31 category: Parametric signal extraction to target different models with wildly varying kinematics

Parametric Neural Networks using mass-splitting ( $m_{\text {NLSP }}-m_{\text {LSP }}$ ) as a variable
$\rightarrow$ Target each signal model [for the wino-bino model with WZ final state]
$\rightarrow$ Individual background (and signal) distribution for each dM


Around $\sim 50 \mathrm{GeV}$ in $\mathrm{m}_{\text {NLSP }}$ are gained with the use of the parametric neural network

## Machine Learning in CMS stop and multilepton searches

## Parametric Neural Network (NN) is used to learn peculiarities of the signal kinematics depending on SUSY parameters and to provide an optimal performance at ~any signal point

- Parametric NN: introduce a generator-level training variable specific to the signal hypotheses
$\rightarrow$ Parameter in background is randomized to follow the training variable's signal distribution (no discrimination directly from parameter)
$\rightarrow$ The NN learns the correlations of the parameter with other training variables, improving performance
- The NN output is provided for each signal hypotheses (data and background is redistributed!)
- Both stop combination (2107.10892) as well as the multilepton search (2106.14246) utilise parametric NN
- Stop: target top corridor where mass splitting between the top squark and the lightest neutralino is close to top quark mass
- Multilepton: Provide sensitivity even for interpolated mass-splitting values that were not used for training

| Details | Stop combination <br> $(\underline{2107.10892)}$ | Multilepton search (2106.14246) |
| :--- | :--- | :--- |



## ATLAS search targeting final states with two leptons, and MET

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## ATLAS-CONF-2022-006

- Require 2 leptons (opposite-sign), MET, and no (b) jets
- Main backgrounds SM WW, VZ, Z+jets, ttbar+top from partially data-driven techniques
- Two event categories: same- and different flavour pairs (SF and DF)
- Discriminate signal from background using four BDTs
$\rightarrow$ Each event receives four BDT scores: BDT-signal, BDT-VV, BDT-top, and BDT-other (probability for the event to belong to each class)
- Set of training variables optimised through an iterative procedure out of a larger set of variables
$p_{T}^{\ell_{1}}, p_{T}^{\ell_{2}}, E_{\mathrm{T}}^{\mathrm{miss}}, m_{\mathrm{T} 2}, m_{\ell \ell}, \Delta \phi_{\text {boost }}, \Delta \phi_{p_{\mathrm{T}}^{\mathrm{miss}}, \ell_{1}}, \Delta \phi_{p_{\mathrm{T}}^{\text {miss }}, \ell_{2}}, \cos \theta_{\ell \ell}^{*}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ significance

- $\quad$ Signal regions defined by BDT score cuts for BDT-signal

