pMSSM scans in ATLAS

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on behalf of the ATLAS Collaboration

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Even minimal SUSY extension to the SM — the MSSM — has 120 parameters at low scales that encode our ignorance of how SUSY is broken: → intractable to probe directly, need to cut dimensions.

Most common approaches for probing SUSY:

1. UV-inspired **concrete models**: e.g. mSUGRA/CMSSM, GMSB:
   - low dimensionality, easy interpretability as a full theory
   - rigid relationships of parameters not necessarily realistic

2. **simplified models**: very reduced, accessible spectrum
   - focus on decay chains to which LHC is sensitive, easier to reinterpret.
   - not a full SUSY model. Reinterpretation of single analysis may suffer from small factors (BR ≪ 1)
Motivation

Intermediate approach: systematic reinterpretations of existing analyses w.r.t low-medium sized parameter sub-spaces of MSSM

- re-use existing measurements, analysis procedures (selections, background estimates, statistical evaluation)
- full SUSY models without high-scale theory assumption

Challenges to solve:

- How to sample parameter space
- How to decide which points to run through expensive simulation
- How to interpret/combine results of individual analyses

This talk: two parameter scans of (a subspace of ) the pMSSM.
MSSM fully generic low-scale parametrization. experimentally motivated assumptions can cut number of parameters significantly:

- R-parity conservation
- lightest neutralino as LSP
- degenerate 1st and 2nd generation sparticles
- no new CP violation
- minimal flavor violation
- simplified Yukawa couplings

gives 19-D **phenomenological MSSM (pMSSM)** as a basis for reinterpretation campaigns:

- 3rd gen trilinear couplings: $A_{e,\mu,\tau}$
- $\tan\beta$
- higgsino mass parameter: $\mu$
- pseudo-scalar Higgs mass: $m_A$
- wino/bino/gluino mass: $M_{1,2,3}$
- squark/slepton soft masses (10)
pMSSM-19 scan

arXiv:1508.06608
To study ATLAS Impact on full pMSSM, comprehensive reinterpretation campaign was conducted at end of Run-1:

- 22 analyses
- 200 signal regions

Plan:

1. scan pMSSM space
2. find points that are not excluded by other constraints, yet accessible to ATLAS.
3. generate samples and obtain new exclusion limits for each analysis using original analysis code
4. determine overall status of points based on all analysis results
A cartesian grid in 19-D is not possible (*curse of dimensionality*), so we need to **sample the parameter space** statistically.

Sampled from uniform distributions in the 19 parameters with ranges chosen w.r.t existing exclusions and LHC reach

With this initial sampling, point are subjected to existing experimental constraints

**precision electroweak and flavor observables:**
- e.g. $\rho$-parameter, $(g-2)_\mu$, $\text{BR}(B_s \rightarrow \mu\mu)$

**dark matter:**
- LSP relic abundance (Planck)
- direct detection cross-section limits (LUX, COUPP, XENON100)

**collider results:**
- $Z$ inv. width, sparticle mass lower bounds (LEP)
- Higgs mass constraint (ATLAS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min value</th>
<th>Max value</th>
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<tbody>
<tr>
<td>$m_{L_1} (= m_{L_2})$</td>
<td>90 GeV</td>
<td>4 TeV</td>
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<tr>
<td>$m_{\tilde{e}<em>1} (= m</em>{\tilde{e}_2})$</td>
<td>90 GeV</td>
<td>4 TeV</td>
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<tr>
<td>$m_{L_3}$</td>
<td>90 GeV</td>
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<td>$m_{\tilde{e}_3}$</td>
<td>90 GeV</td>
<td>4 TeV</td>
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<tr>
<td>$m_{\tilde{Q}<em>1} (= m</em>{\tilde{Q}_2})$</td>
<td>200 GeV</td>
<td>4 TeV</td>
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<td>$m_{\tilde{t}<em>1} (= m</em>{\tilde{t}_2})$</td>
<td>200 GeV</td>
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<td>$m_{\tilde{d}<em>1} (= m</em>{\tilde{d}_2})$</td>
<td>200 GeV</td>
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<td>$m_{\tilde{Q}_3}$</td>
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<td>$M_3$</td>
<td>200 GeV</td>
<td>4 TeV</td>
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<td>$</td>
<td>A_{t_1}</td>
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<td>$</td>
<td>A_{b_1}</td>
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<tr>
<td>$</td>
<td>A_{t_2}</td>
<td>$</td>
</tr>
<tr>
<td>$M_A$</td>
<td>100 GeV</td>
<td>4 TeV</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>1</td>
<td>60</td>
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Since full simulation is very CPU intensive, points compatible with constraints go through sequence of processing steps to decide whether simulation is necessary:

1. points with too low cross-section considered not excluded
2. Madgraph+Pythia MC sample generation for remaining points
3. Truth-level analysis of points to categorize into 3 groups based on SR acceptance:
   a) excluded: $N_{\text{sig}} \gg N_{95}$ limit for at least one SR
   b) insensitive: $N_{\text{sig}} < N_{95}$ points counted as not excluded
   c) viable: $N_{\text{sig}} \sim N_{95}$. points eligible for further processing using full detector simulation. Total number of viable points: $\sim 45k$

For points in group c), fully simulated and reconstructed samples are passed through original analysis code + statistical evaluation to obtain exclusion status (CL$_s$ value)
SR with strongest limit defines overall result for parameter point. **no statistical combination of SR.**

Result Presentation as **exclusion fraction maps** in 2-D projections superimposed with relevant simplified model limit contours.

Additional sensitivity vs simplified model from disappearing track searches instead of prompt searches. Less sensitivity with full models, due to deviation from assumptions (massive neutralino, etc). Simplified model assumes massless LSP degenerate quarks.
Impact on Dark Matter observables:

- Full pMSSM scan — Results

ATLAS
Before ATLAS Run 1

ATLAS
After ATLAS Run 1
EWKH-5 scan
(to appear)
Model Overview

pMSSM scan investigated full 19D space with strong constraints on colored particle production. Now, a more tailored 5D pMSSM sub-space scan to assess ATLAS impact on electroweak production and DM observables.

Model parameters

1. Bino mass $M_1$
2. Wino mass $M_2$
3. Higgs mixing $\mu$
4. $\tan \beta$
5. Pseudo-scalar Higgs mass

{ fixes electroweakino sector }

{ fixes Higgs sector }

all other parameters set such as to decouple sfermions, squarks, gluinos.
Sampling Strategy:

For initial sampling of viable parameter points, the space sampled using a posterior distribution obtained from a nested bayesian sampling using a joint likelihood that incorporates existing experimental constraints:

\[ \ln L_{\text{joint}} = \ln L_{\text{EW}} + \ln L_{\text{B}} + \ln L_{\Omega \chi h^2} + \ln L_{\text{DD}} + \ln L_{\text{Higgs}} + \ln L_{\text{LEP} - \chi_1^\pm} \]

Constraints:

Higgs mass constraint from ATLAS measurement

B-physics : combinations on B measurements from HFAG and \( B_s \to \mu\mu \) BR results from CMS, LHCb

LEP precision measurements of electroweak observables
DM Relic Density: Neutralino is allowed to be subdominant component of DM. Total DM relic density is constrained by Planck data.

\[ \Omega_{\text{DM}} h^2 = 0.1186 \pm 0.0031 \text{(exp.)} \pm 0.012 \text{(th.)} \]

\[ \mathcal{L}_{\Omega_x h^2} = \mathcal{L}_0 \int_{\Omega_x h^2 / \sigma_{\text{Planck}}}^{\infty} e^{-\frac{1}{2}(x-r_x)^2} x^{-1} dx \]

DM Direct Detection experiments: limits from XENON100 and LUX in neutralino mass - cross-section plane

<table>
<thead>
<tr>
<th>Limit (95% CL)</th>
<th>( \tau ) (theor.)</th>
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<tbody>
<tr>
<td>( m_\chi ) vs. ( \sigma^{SI}_{\chi N} )</td>
<td>XENON100 2012 limits (224.6 \times 34 \text{ kg days})</td>
</tr>
<tr>
<td>( m_\chi ) vs. ( \sigma^{SD}_{\tilde{\chi}_1^0-p} )</td>
<td>XENON100 2012 limits (224.6 \times 34 \text{ kg days})</td>
</tr>
<tr>
<td>( m_\chi ) vs. ( \sigma^{SI}_{\chi N} )</td>
<td>LUX 2013 limits (118 \times 85.3 \text{ kg days})</td>
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</table>

LEP chargino lower bound: \( m_{\chi^\pm} \geq 91.4 \text{ GeV} \)
Sampling Strategy

using initial sampling of ~570k points, profile likelihood maps are constructed to categorize points into three groups:

1. **Excluded:** outside of 95% confidence region in likelihood scan (~98k points)

2. **Unreachable:** no sensitivity due to low cross-section ($\sigma<0.25$fb from Prospino, ~146k points)

3. **Viable:** sufficient cross-section to be reachable. ~327k points for which full Madgraph+Pythia samples have been produced to assess ATLAS impact.
Set of four ATLAS SUSY searches designed for electroweak production are used to assess impact:

The Analyses:

• **2-lepton**: opposite sign 2 $e/\mu$ + $mT_2$ (stransverse mass) in 7 signal regions  \[1403.5294\]

• **2-tau**: opposite sign, hadronically decaying taus + $mT_2$ in four signal regions  \[1407.0350\]

• **3-lepton**: $2(e/\mu) + \tau_{\text{had}} \parallel 1(e/\mu)$ +2$\tau_{\text{had}}$ final states in 24 signal regions  \[1402.7029\]

• **4-lepton**: $(4(e/\mu) \parallel 3(e/\mu) + \tau_{\text{had}} \parallel 2(e/\mu) + 2\tau_{\text{had}}) + \text{MET} \ [1405.5086]$

Running all samples for viable parameter points through full detector simulation and analysis to extract CLs values — as in pMSSM-19 — computationally unfeasible.

Instead, a small sample of 500 points is used to calibrate CLs values to generator yields.
reconstructed event yields in signal regions — from which we extract CL$_s$ — related to truth yields by reconstruction efficiency that is assumed to be model-independent.

\[ CL_s \leftrightarrow N_{\text{reco}} = \epsilon N_{\text{truth}} \]

- Calibration function shape CL$_s(N_{\text{reco}}(\epsilon))$ extracted using test yields parametrized by efficiency.
- Fit is performed on 500 fully simulated models for each signal region (bin). SR where efficiency uncertainty < 20% retained
- With calibration we can then extract CL$_s$ values for all ~327k models and assess ATLAS impact
As in pMSSM-19, no stat. combination of analyses. Most sensitive SR (i.e. smallest CLs) used to either exclude or retain point post-ATLAS.

Presentation as 1-D and 2-D exclusion fraction maps for both model parameters, particle masses and dark matter observables Z/h-funnels largely excluded. Compressed spectra still viable.
• medium-dimensional pMSSM scans provide powerful way to reinterpret existing searches in context of full UV-agnostic SUSY models

• Two scans performed using Run-1 analyses: full 19-D pMSSM, 5-D electroweak production subspace (EWKH)

• care needs to be taken in choosing sampling strategy and for which points full detector simulation is worthwhile (e.g. based on expected sensitivity, existing experimental constraints)

• efforts under way to streamline these reinterpretation campaigns for Run-2 within the collaboration