SUSY searches in ATLAS and CMS

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Supersymmetry

- **What it is?**
  - global symmetry between fermions & bosons

- **Why is it attractive?**
  - Higgs: predicts a below-135-GeV Higgs scalar
    - may be SM-like
    - completely solves hierarchy problem
  - **unification** of gauge couplings at a single scale
  - dark matter candidate

![Diagram of Supersymmetry](image-url)
SUSY searches strategy

Strong-production channels
• copious production at hadron colliders
• MET-based generic channels

Third-generation sparticles
• naturalness $\Rightarrow$ mass of $O(<\text{TeV})$
• lighter than other squarks

Electroweak production
• coloured spartners too heavy
• direct gaugino/slepton production
• relevant for dark matter searches

RPC or RPV
• RPV $\Rightarrow$ more leptons/jets and less MET
• RPV $\Rightarrow$ prompt or delayed LSP decay

Interpretations in other BSM scenarios (including dark matter)

(Meta)stable sparticles
• suppressed (effective) coupling
• lack of phase space, e.g. mass degeneracies
• may induce non-trivial signals in detectors

Strong production channels

SUSY searches strategy
Interpretation

• Sparticle masses from SUSY breaking not fixed by theory ⇒ huge parameter space to explore

• How to test that at LHC?

1. Top-down approach
   ▫ SUSY breaking mechanism → different models
   ▫ GUT scale unification → few free parameters

2. Bottom-up approach
   ▫ Phenomenological models (pMSSM, ...)
     • fix mass hierarchy, mass scales and other assumptions
     • scan remaining parameters
   ▫ Simplified topologies
     • specific decay chain
     • easy to interpret results in terms of other models
Typical SUSY search

- **Signal region (SR)**
  - may be single-bin (“cut & count”) or multi-bin
  - optimised for best discovery in targeted production/decay mode
  - to cover different mass hierarchies → few SRs for each final state

- **Data-driven background estimate**
  - **irreducible backgrounds** estimated using control region (CR) data as a constraint and Monte Carlo to extrapolate from CR to SR
  - **reducible background** (fake/non-isolated leptons, MET from jet mis-measurement) from data
  - validation regions (VR) to check background estimate method and CR→SR variable modelling

- **Likelihood fit of data in SRs and CRs**
  - hypothesis testing of signal models → 95% CL cross-section upper limits
  - background versus data → model-independent upper limits at 95% CL in visible cross-section
Large Hadron Collider at CERN

- Run 1: 2010 – 2012
  - proton-proton $\sqrt{s} = 7 – 8$ TeV
- Run 2: 2015 – 2018
  - proton-proton $\sqrt{s} = 13$ TeV
- Spectacular LHC performance!
Production of 1st and 2nd generation squarks and gluinos with subsequent cascade decay to lighter sparticles
Squarks & gluinos: 0L + jets + MET

- Events with no isolated lepton (e/μ) in the final state relying on high MET and hadronic activity
- Various strategies:
  a) multi-bin SRs: shape of jet-related variables, e.g. \( m_{\text{eff}} = \sum_{\text{jets}} p_T^j \)
  b) Boosted Decision Tree (BDT) trained against SM
  c) split events into two pseudojets and compute \( MT_2(j_1; j_2) \)
  d) use \( \text{MHT} = \left\| - \sum_{\text{jets}} p_T^j \right\| \)
0L + jets + MET interpretation

Combined production of $q\tilde{q}$, $g\tilde{g}$ and $\tilde{q}\tilde{g}$

3rd generation: interpretations also for $t\bar{t}$ and $b\bar{b}$ and for $g$-mediated $t\bar{b}$ production
**Same-sign 2 leptons & 3 leptons**

Targets leptonic decay signals (including $R$-parity violation*)

- limited SM (irreducible) same-sign lepton backgrounds
- reducible detector backgrounds non negligible: fake/non-prompt leptons, electron charge flip, ... → estimated from data

* Discussed in detail in “$R$-parity violation”
Strong production - summary

ATLAS Preliminary

- $\tilde{g} \to \tilde{q} \tilde{q}$, 0 lep. [1712.02332]
- $\tilde{g} \to \tilde{b}\tilde{b}$, $\geq 3$ b-jets [CONF-2018-041]
- $\tilde{g} \to \tilde{t}\tilde{t}$, $\geq 3$ b-jets + $\geq 2$ lep. SS [CONF-2018-041, 1706.03731]
- $\tilde{g} \to \tilde{q}WZ$ or $\tilde{q}ZZ$, 0 lep. + 1 lep. [1712.02332, 1708.08232]
- $\tilde{g} \to \tilde{q}WZ$, $\geq 7$-11 jets + 1 lep. + $\geq 2$ lep. SS [1708.02794, 1708.08232, CONF-2019-015]
- $\tilde{g} \to \tilde{q}(ll, vv)\tilde{\chi}_1^0$ or $\tilde{q}(ll, vv)\tilde{\chi}_2^0$ via $\tilde{\chi}_1^0 \to \tilde{\chi}_0^0 \gamma$ or $\tilde{\chi}_1^0 \to \tilde{\chi}_0^0 \tau^\pm \nu_{\tau}$ [1805.11381, 1706.03731]
- $\tilde{g} \to \tilde{q}(ll, vv)\tilde{\chi}_1^0$ via $\tilde{\chi}_1^0 \to \tilde{\chi}_0^0 \gamma$ [1808.06358]
- $\tilde{g} \to \tilde{q}(ll, vv)\tilde{\chi}_2^0$ via $\tilde{\chi}_1^0 \to \tilde{\chi}_0^0 \gamma$ [1802.03158]

All limits at 95% CL

- 100% branching ratios are assumed
- Exclusion curves not necessarily directly comparable
  - different sparticle mass hierarchies
  - different simplified decay scenarios

ATL-PHYS-PUB-2019-022
3rd generation quarks

- Inspired by naturalness arguments
- Focuses on stop and sbottom production
Stop in 1-lepton channel

- Selection: $1 \ell$ (e/\mu), $\geq 2$ jets, large MET, large $M_T$, $\geq 1$ (soft) b-jet
- New techniques to address specific regions: neural networks, modified topness variable, ...

$$t_{\text{mod}} = \ln(\min S), \quad S = \frac{(m_W^2 - (p_\nu + p_\ell)^2)^2}{a_W^4} + \frac{(m_t^2 - (p_b + p_W)^2)^2}{a_t^4}$$

39 SRs for top-categories (merged, resolved, un-tagged) or inclusive
Sbottom decay to Higgs

- $h \rightarrow b \bar{b}$ decay leads to multi-$b$-jets final signature
- Depending on mass splittings, $b$-jets from sbottom may have different kinematics from ones from $h$

- lepton veto
- many (≥ 3 or 4) $b$-jets
Stop production

Overlaid contours belong to different:
- stop decay channels
- sparticle mass hierarchies
- simplified decay scenarios

Charm tagging

m(stop) $\leq$ m(top) + m($\tilde{\chi}_1^0$)

Stop 2 lepton

Stop 0 lepton

Stop 1 lepton

ATL-PHYS-PUB-2019-022
Electroweak production

- Involves \textit{neutralino, chargino, slepton} direct production
- Results also interpreted in the context of \textit{dark matter}
Chargino/neutralino with \( h \rightarrow \gamma\gamma \)

- Targetting
  - wino-like \( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \)
  - higgsino-like \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \) in GMSB with \( \tilde{G} \) LSP

- Selection: \( \geq 2\gamma \), \( H \rightarrow \gamma\gamma \) tag, 1 e/\( \mu \) OR \( e^+e^-/\mu^+\mu^- \) pair close to \( m(Z) \) OR \( \geq 1 \) jet
# 2 leptons + 0 jets

- **Signature**: $2\ell$ opposite-sign, 0/1 jet, $b$-jet veto (to reject $t\bar{t}$)

- **Analysis** uses object-based missing transverse momentum significance
  - significantly reduces MET background, particularly in 1-jet events

- **Binned SRs** in transverse mass $m_{T2}$ to exploit shape differences between signal and background

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<table>
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<th>arXiv:1908.08215</th>
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**Big improvement** w.r.t. Run 1 limits excluding up to 400 GeV in $\tilde{\chi}_1^\pm$ mass

- **ATLAS**
  - $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
  - All limits at 95% CL
  - ATLAS 8 TeV, arXiv:1403.5294

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Compressed scenarios

- Light higgsinos: compressed mass spectrum, i.e. \( m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) \ll m(W/Z) \) ⇒ very low-\( p_T \) leptons (~5 GeV)
- Trigger: ISR jet or MET
- Gaugino production via vector boson fusion considered recently
Compressed scenarios with staus

- First SUSY search in events with one soft tau
  + one energetic ISR jet and large MET
- Signal models: co-annihilation between (nearly mass degenerates) $\tilde{\tau}$ and $\tilde{\chi}_1^0 \rightarrow$ generates “correct” dark matter relic density

Upper limits set on the $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\tau}$ production cross sections
⇒ lower mass limit of 290 GeV on the mass of the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$
⇒ most stringent to date
Electroweak production - summary

- **Neutralino, chargino, slepton** direct production
- **Final states (+MET):**
  - multileptons
  - hadronic taus
  - (di-)bosons $\rightarrow$ b-jets, photons

Sensitive to details of scenario considered, e.g. nature of gaugino (bino, wino, higgsino)

Intense effort to cover compressed-spectra region
$R$-parity violation

talk by Stephen F. King for connection between neutrino masses and RPV SUSY
**R-parity violation**

\[ W_{RP} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u + \chi''_{ijk} \hat{U}^C_i \hat{D}_j^C \hat{D}_k^C \]

- **L-number violation**
- **Bilinear terms**
- **B-number violation**

**In broken R-parity**
- LSP is *not* stable
- LSP may be charged and/or carry colour
- MET may be small \( \rightarrow \) "standard" SUSY searches *may miss* RPV signal
- **multi-lepton** and/or **multi-jet** inclusive final states
- **resonant LSP reconstruction** \( \rightarrow \) impossible in RPC SUSY
- LSP may be long-lived \( \rightarrow \) **displaced vertices**

**R-parity conservation** hinted but *not required* by proton stability

**R-parity conservation/violation** largely define final states of SUSY events

\[ R = (-1)^{3(B-L)+2s} \]

\[ R = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for superpartners} \end{cases} \]

Extensive search program for RPV SUSY in both ATLAS and CMS, also inclusive searches with RPV interpretations
Prompt* $ R$-parity violation

Many more RPV decays considered

Reinterpreting RPC & RPV analyses in varying RPV coupling

- rich phenomenology offers full coverage
- nice complementarity between RPC and RPV searches

* More on delayed LSP decays in “Long-lived particles”
• For dedicated reviews, see:
  • LHC-LLP Community, *arXiv:1903.04497*

- talk by Herbi Dreiner on long-lived neutralinos in RPV on Thursday afternoon
- talk by Haifa Rejeb Sfar on CMS searches for long-lived particles on Thursday afternoon
- talk by Audrey Kvam on ATLAS search for displaced hadronic jets on Tuesday Sep 10th
Long-lived particles

- Long-lived decays of spartners possible in several frameworks, including
  - nearly conserved symmetry
    - long-lived gluinos or squarks that hadronise before decaying → R-hadrons in Split SUSY
  - low coupling between the particle and the final state
    - weak RPV couplings or gravitational (GMSB)
  - mass degeneracy between the particle and the final state
    - chargino and neutralino wino in AMSB
    - stau and neutralino in coannihilation scenarios
- Depending on the lifetime, different detection techniques involving various objects: tracks, photons, leptons, displaced vertices, ...

(1) Slow, large dE/dx
    ~ 1000 mm
(2) Slow, stopped
    ~ 100 mm
(3) Disappearing track
(4) Kinked track
    ~ 10 mm
(5) displaced track

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Displaced dilepton decays

- Search for displaced $e^+e^-$, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ vertices in the inner detector
- Analysis designed to be model-independent
  - interpreted for RPV models with $\lambda$ coupling
  - also motivated by GMSB

- Sensitivity in $c\tau$ depends on $\tilde{q}/\tilde{\chi}_1^0$ mass splitting (controls boost)
- Higher efficiency for large $m(\tilde{\chi}_1^0)$

\[ m(\tilde{q}) = 700 \text{ GeV} \]
\[ m(\tilde{q}) = 1.6 \text{ TeV} \]

[Graphs and diagrams showing ATLAS upper limits on cross-section vs. $c\tau$, for different masses and couplings.]
Delayed jets

- Search for LLPs decaying to hadronic jets
  - shower would arrive late at the ECAL
  - targeting decays beyond the acceptance of the tracker
- First search to use ECAL timing to tag delayed jets
- Extensive quality selections to remove hardware or cavern backgrounds
- Limits placed on long-lived $\tilde{g}$ production in the context of a GMSB model

arXiv:1906.06441
R-hadrons & long-lived charginos

Results on R-hadrons
Split SUSY with metastable $\tilde{g} \rightarrow g/qq \tilde{\chi}_1^0$

Summary on disappearing track
Long lived chargino, $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$
Long-lived particles – summary

Including R-parity violation

Overview of CMS long-lived particle searches

Conclusions & outlook

• ATLAS and CMS have developed a vast program to search for supersymmetry
  ▫ many new results have just been released with the full Run 2 dataset
  ▫ no significant excess seen so far
• Improved search methods and new reconstruction techniques have de possible the exploration of kinematic regions previously inaccessible
• More searches and updates keep coming with the full Run-2 dataset and beyond
• Stay tuned for upcoming results!

More results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS