Search for particles predicted by Supersymmetry

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Brandeis University

PIC 2016, Quy Nhon, 17.09.2016
Supersymmetry (SUSY): A symmetry between fermions and bosons

\[ Q|\text{Fermion}\rangle = |\text{Boson}\rangle; \quad Q|\text{Boson}\rangle = |\text{Fermion}\rangle \]

Most obvious consequence: Double the SM particle content

- ’Superpartners’ for every SM degree of freedom (’sparticles’)
- SM fermions: Scalar squarks, sleptons and sneutrinos
- Gauge and Higgs bosons: Fermionic gauginos and higgsinos

→ Note: SUSY requires extended Higgs sector - 2 doublets, 5 massive higgs bosons \((h, H, A, H^\pm)\)
- Partners of EW gauge and Higgs bosons mix into 4 neutralinos and 2 charginos

Experimental data: SUSY must be a broken symmetry

- Apart from spin, unbroken SUSY predicts identical quantum numbers for SM particles and their superpartners
- SUSY breaking allows masses of sparticles to differ from SM partners
- Also introduces wide parameter space: > 100 free parameters!

Why is this interesting for LHC searches?
Why search for SUSY?

Why is SUSY one main branch of LHC new physics searches?

SUSY has compelling theoretical aspects . . .

- Solution to *Hierarchy Problem*
- Potential for *DM Candidate*
- Potential for *B/L violation*
- Mechanism for generating *neutrino masses*

*Note: Some of these mutually exclusive!*

Most important: **Rich spectrum of predicted signatures**

- Drive a wide range of searches
- Guideline to full exploitation of the LHC dataset

Early LHC run 2: The most interesting time for SUSY searches!

- Expect massive improvement of search sensitivity when increasing collider $\sqrt{s}$!

This talk: Attempt at coarse overview of direct searches, highly biased selection!
Supersymmetric particle production at the LHC

Two main production mechanisms of interest

Strong production of squarks and gluinos

- QCD production - high cross-sections
- Sensitivity up to high sparticle masses
- Greatest gain from $\sqrt{s}$ increase
- Jet-rich final states

Electroweak production of gauginos

- Electroweak cross-sections - lower than for QCD production
- Can be dominant in case of decoupled squarks/gluinos
- Final states with leptons and gauge bosons

LHC run 2 (focus of this talk):

First batch of 13 TeV searches targeted strong production, electroweak searches catching up with 2015 + 2016 dataset
LHC search strategies depend on assumed decay chains of produced sparticles

- Cascade decays to SM particles and lighter sparticles
- Nature of cascade determined by initial sparticles, mass spectrum, couplings

Two distinct scenarios, based on R-Parity ($R_p = 1$ for SM, -1 for superpartners):

**R-Parity conservation (RPC)**

- B, L conserved
- Lightest supersymmetric particle (LSP) stable, typically neutralino $\chi_1^0$
- Escapes detection
- Searches based on **Missing transverse energy**

**R-Parity violation (RPV)**

- B or L violated
- Strong constraints through proton lifetime and flavour sector
- Only SM particles in final state
- Requires **dedicated search strategies**

This Talk: Assume zero sparticle lifetime - however, many interesting scenarios with long-lived sparticles
Use simplified models to guide development and interpretation of searches

Bottom-up approach:

- Consider a single production process, typically producing one given pair of sparticles.
- Also fix decay of the sparticles, typically assume 100% BR (manually assigned)
  → Sparticle lifetimes also manually assigned (most common: 'prompt', $\tau = 0$)
- Sparticle masses are usually free and independent parameters to scan over

Useful for searches . . .

- One clearly defined physics signature to look for
- Low-dimensional phase-space for exploration
  → Often just two sparticle masses

. . . but keep in mind when looking at results:

- **Not** a full-fledged physics model!
  → Limits within simplified models give measure of the search sensitivity
  → But are valid only within a strong set of assumptions

Think of an approximate limit on $\sigma \cdot BR$ for one signature occuring within a full-scale model!
Of particular interest: The top squark

**Natural** supersymmetry (solution to hierarchy problem): Top squark expected to be **light**

- Mass expected not far above TeV scale (depending on amount of fine-tuning accepted)
  - In range of LHC experiments?

**Simplified RPC SUSY models**: Investigate several final states based on mass hierarchy between top squark and LSP

\[ m(\tilde{t}) - m(\tilde{\chi}^0_1) \]

- Dedicated searches for the different decay modes.
- As for SM top physics: Consider both leptonic and hadronic final states
  - Leptons: Lower trigger thresholds, rarity in SM processes
  - But: Yield limited by SM leptonic BR \((W \rightarrow \ell\nu)\) - tradeoff against statistics
Search for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ using boosted topologies:

- Events with at least 4 jets (2 b-tags), $E_T^{\text{miss}}$ and no leptons
- Recluster AntiKt4 jets into large-R (1.2) jets to reconstruct $t$ and $W$ candidates
- See talk on boosted techniques (Monday afternoon session)
- Main backgrounds include $Z \rightarrow \nu\nu$+jets, $t\bar{t}$, $W \rightarrow \ell\nu$+jets
- Note: Other signal regions based on resolved AntiKt4 jets (not shown here) cover smaller mass splittings

see also CMS-PAS-SUS-16-029, CMS-PAS-SUS-16-030
Complementary channel: one lepton

- Events with at least 2 jets ($\geq 1$ b), $H_T^{\text{Miss}}$ and exactly one lepton
- Separate optimisation for low and high mass splittings
- Main backgrounds: Dileptons with one missed lepton and $W+$jets / $t\bar{t}$ with one lepton (MET tails)

$\rightarrow$ Missed leptons: Data driven using dilepton region
Accessing more compressed spectra - two leptons

ATLAS-CONF-2016-076

- Target 3-body stop decay ($\tilde{t} \rightarrow Wb\tilde{\chi}_1^0$) with dedicated SR
- Leptons: Can use lower $p_T$ thresholds than for jets
- Background suppression via kinematic 'super-razor' variables
- Main backgrounds for 3-body SR: Dibosons, $t\bar{t}$
- Estimation using MC simulation, scaled to data in control regions
Top squark searches - highly compressed scenarios

CMS-PAS-SUS-16-025, see also: CMS-PAS-SUS-16-029

- $m(\tilde{t}) \approx m(\tilde{\chi}_1^0)$: Target 4-body stop decay ($\tilde{t} \rightarrow \ell \nu b \tilde{\chi}_1^0$)
- Leptons can reach very low momenta
- Challenging: Very low lepton $p_T$ thresholds (3.5-5 GeV)
- Trigger using $E_T^{miss}$ and dedicated dimuon+$E_T^{miss}$ triggers
- Main backgrounds: DY $Z^*/\gamma^* \rightarrow \tau\tau$, $t\bar{t}$, $W+$jets (fake leptons)
- Estimation using MC simulation normalised in control regions, fake leptons data driven
Top squark searches - summary

- RPC: Searches target the most likely decay scenarios
- Disclaimer: Summary plots combine different stop decay channels, mass hierarchies and decay scenarios
- Most challenging region: $m(\tilde{t}) \sim m(\tilde{\chi}^0_1)$ - reduced $E_T^{\text{miss}}$, soft cascade particles
  → Reminder: Simplified models
- Also note: Only showed a subset of all the searches - much more to see!

![Graph showing top squark mass spectrum](image)

**CMS Preliminary**
- SUS-16-014, 0-lep ($H_T^{\text{miss}}$), 12.9 fb$^{-1}$
- SUS-16-015, 0-lep ($M_{T\tau}$), 12.9 fb$^{-1}$
- SUS-16-016, 0-lep ($\alpha_T$), 12.9 fb$^{-1}$
- SUS-16-029, 0-lep stop, 12.9 fb$^{-1}$
- SUS-16-030, 0-lep (top tag), 12.9 fb$^{-1}$
- SUS-16-028, 1-lep stop, 12.9 fb$^{-1}$
- Combination 0-lep and 1-lep stop, 12.9 fb$^{-1}$
We covered a lot of RPC scenarios - but could we still miss a stop signal?

ATLAS-CONF-2016-084

- R-Parity violation (RPV): Stop can decay into two SM quarks
  - no $E_T^{\text{miss}}$, no leptons, low jet multiplicity: Eludes RPC searches
- Dedicated search for 'double dijet resonance'
- Main background: SM multijets - data-driven ABCD estimation
- High level of background: Challenging, mass reach reduced compared to RPC scenarios
Inclusive strong production searches

In addition to direct stop production: Wide set of **inclusive searches for strong production**

- Main interest: Gluino pair production
  - Large cross-section if mass accessible
- Decay cascades can provide sensitivity to sparticles not accessible to direct production
- Especially interesting: virtual top/bottom squarks
  - Heavy-flavour-rich final states

Showing only few examples here - much more available!
All-hadronic final states - classical RPC strong production searches

CMS-PAS-SUS-16-014, -015, -016, -030, ATLAS-CONF-2016-078, -052,

- Searches for events with jets, $H_T^{\text{miss}}$ and no leptons
- Decay chains can include intermediate, virtual top/bottom squarks
  → Exploit via b-tagging
- High number of signal regions binned in jet, b-tag multiplicity, $H_T$
  → sensitive to wide range of strong production SUSY scenarios
- Several search variants using various techniques
  Example: CMS, $H_T^{\text{miss}}$ based discrimination

Max Goblirsch (Brandeis)  Search for particles predicted by Supersymmetry  PIC 2016, Quy Nhon, 17.09.2016  15 / 29
All-hadronic final states - classical RPC strong production searches

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Example: ATLAS, multiple b-jets + $E_T^{\text{miss}}$ - using large-R jets for stop-mediated decays
All-hadronic final states - classical RPC strong production searches

CMS-PAS-SUS-16-014, -015, -016, -030, ATLAS-CONF-2016-078, -052,

- Limits demonstrate large mass reach of run-2 strong production searches
- Reduced sensitivity close to diagonal: Typical feature of $E_T^{\text{miss}}$ based RPC Searches

$E_T^{\text{miss}}$ reduced due to high LSP mass, softer jets

- Again: Keep in mind simplified models!
All-hadronic final states - also relevant for RPV SUSY

**ATLAS-CONF-2016-057**

- RPV SUSY: Gluino and neutralino can decay to 3 SM quarks
  - Gluino pair production: 6- or 10-quark final state, no $E_T^{\text{miss}}$!
- Dedicated search using large-radius jets
- Discrimination against SM multijets using centrality and masses of four most energetic large-R jets
- Fully data driven, jet mass template based background estimation

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**Search for particles predicted by Supersymmetry**

- **Events / Bin width [TeV]**
  - **Data**
  - **Prediction**
  - $m_{\tilde{g}} = 1600$ GeV
  - $m_{\tilde{\chi}_1^0} = 650$ GeV
  - $m_{\tilde{\chi}_1^0} = 1200$ GeV

- **ATLAS Preliminary 14.8 fb$^{-1}$ data**

- **Max Goblirsch (Brandeis)**

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**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 14.8 fb$^{-1}$

- **Expected limit ($\pm 1$ $\sigma_{\exp}$)**
- **Observed limit ($\pm 1$ $\sigma_{\text{SUSY}}$)**
- **Run 1 limit**

- All limits at 95% CL
Leptonic signatures: Same-flavour, opposite sign leptons

We can also use **leptons** to probe for strong production signals CMS-PAS-SUS-16-021, see also ATLAS-CONF-2015-082

- Virtual sleptons in the decay chain can lead to same-flavour, opposite sign (SFOS) lepton pairs in the final state
- Interesting: **Kinematic edge** in dilepton invariant mass corresponds to mass splitting in the decay chain
- Look for SFOS lepton pairs in association with jets and $E_T^{\text{miss}}$
- Dominant backgrounds: $Z^*/\gamma^* \rightarrow \ell\ell + \text{jets}$, $t\bar{t}$

→ Estimation via different-flavour dileptons and $\gamma + \text{jets}$ events
Leptonic signatures: Same-sign leptons

**ATLAS-CONF-2016-037**

- Strong production scenarios can also lead to final states with same-sign leptons
- Intermediate sleptons or gauginos, or R-parity violation
- Rare in SM!

ATLAS RPV signal region (shown here):

- Require $\geq 6$ jets and 2 same-sign / 3 leptons
- Main backgrounds: $t\bar{t}V$, Fake leptons
- No $E_T^{\text{miss}}$ for RPV signal: Final discrimination using effective mass

Many other signal regions, also targeting RPC ($E_T^{\text{miss}}$-based)

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See also: CMS-PAS-SUS-16-020

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Lepton-based electroweak searches

Final state leptons are an essential tool when searching for **gaugino pair production**

- EW cross-sections lower than for strong production
- But: SM background in lepton-rich topologies also much lower
- Leptons can come from intermediate gauge / Higgs bosons or virtual sleptons/sneutrinos
  - Intermediate gauge bosons: More challenging - SM leptonic W/Z BR
- Of particular importance: Hadronic $\tau$ decays - $H \rightarrow \tau\tau$ and higgsinos
Chargino pairs - two-lepton final states

ATLAS-CONF-2016-093, ATLAS-CONF-2016-096

Virtual sleptons and sneutrinos enhance the leptonic BR in chargino production

- Does not rely on leptonic W/Z BR
- Search for events with 2 leptons and $E_T^{miss}$
- Jet veto to suppress backgrounds

![Diagram](image.png)

<table>
<thead>
<tr>
<th>Events</th>
<th>Data / MC</th>
<th>ATLAS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\chi}^0_1 \to \nu l$</td>
<td>Data</td>
<td>Other</td>
</tr>
<tr>
<td>$\bar{\chi}^0_1 \to \nu l$</td>
<td>VV</td>
<td>Reducible</td>
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<tr>
<td>$\bar{\chi}^0_1 \to \nu l$</td>
<td>Top Quark</td>
<td>Bkg. Uncert.</td>
</tr>
<tr>
<td>$(m_{\bar{\chi}^0_1}, m_{\bar{\chi}^0_1}) = (500, 0)$ GeV</td>
<td>Data</td>
<td>MC</td>
</tr>
</tbody>
</table>

![Graph](graph.png)

$\int Ldt = 13.3 fb^{-1}$, $\sqrt{s} = 13$ TeV

$\bar{\chi}^+_1 \bar{\chi}^-_1 \to 2 \times \nu l (\bar{l}l) \to 2 \times \nu l \bar{\chi}^0_1$

$m_{\bar{\chi}^+_1} = (m_{\bar{\chi}^+_1} + m_{\bar{\chi}^-_1})/2$
Chargino pairs - two-lepton final states

Light staus: Tau-rich final states of particular interest

- Lower purity than light leptons: particularly challenging
- Search for events with $2 \tau_{\text{had}}$ and $E_T^{\text{miss}}$
- b-jet veto to suppress backgrounds

ATLAS-CONF-2016-093, ATLAS-CONF-2016-096

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 14.8 fb$^{-1}$

Events / 30 GeV

Data

ATLAS Preliminary

SR-C1C1

$\tilde{\chi}_i^\pm \to 2 \tau \nu$ (103.5 GeV)

All limits at 95% CL

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Search for particles predicted by Supersymmetry

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Chargino pairs - compressed scenarios

CMS-PAS-SUS-16-025

Very small gaugino mass splittings: Leptons become very soft

- CMS soft lepton pair + $E_T^{\text{miss}}$ search (see earlier): Also target $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1 \rightarrow Z^* (\rightarrow \ell\ell) \ W^* \tilde{\chi}^0_1 \tilde{\chi}^0_1$

→ First search at such low splittings since LEP

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Chargino-neutralino final states - three-lepton searches

CMS-PAS-SUS-16-024

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production: Final states with 3 leptons (W+Z / W+H / slepton-mediated) accessible

- Either require or veto same-flavour, opposite sign lepton pairs
- Include hadronic tau decays - interesting for final states with $H \rightarrow \tau\tau$
- Main backgrounds: Dibosons, fakes (esp. $\tau$ regions)
- Highest sensitivity: Slepton-mediated decays

See also: CMS-PAS-SUS-16-025, ATLAS-CONF-2016-096
Chargino-neutralino final states - three-lepton searches

CMS-PAS-SUS-16-024

$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ production: Final states with 3 leptons ($W+Z$, $W+H$, slepton-mediated) accessible

- More challenging: Decoupled sleptons
- Decays via gauge or Higgs bosons
- Easier case: $WZ$ final state

$\rightarrow$ suppression via $BR(Z \to \ell\ell) \times BR(W \to \ell\nu)$

- Note: Realistic model would include both $WZ$ and $WH$ modes

$\tilde{\chi}_1^0$ production: Final states with 3 leptons ($W+Z$, $W+H$, slepton-mediated) accessible

$\rightarrow$ suppression via $BR(Z \to \ell\ell) \times BR(W \to \ell\nu)$

Note: Realistic model would include both $WZ$ and $WH$ modes

See also: CMS-PAS-SUS-16-025, ATLAS-CONF-2016-096

CMS Preliminary 12.9 fb$^{-1}$ (13 TeV)

95% CL upper limit on cross section [pb]
Chargino-neutralino final states - three-lepton searches

CMS-PAS-SUS-16-024

\( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) production: Final states with 3 leptons (\( W+Z / W+H / \) slepton-mediated) accessible

- Hardest case: WH final state
  - suppression via \( \mathcal{BR}(H \rightarrow \tau\tau) \times \mathcal{BR}(W \rightarrow \ell\nu) \)
- Added complication: Reduced purity for \( \tau \) leptons
- Note: Realistic model would include both \( WZ \) and \( WH \) modes

<table>
<thead>
<tr>
<th>( m_{\tilde{\chi}_1^\pm} ) [GeV]</th>
<th>( m_{\tilde{\chi}_2^0} ) [GeV]</th>
<th>Lower limit on cross section [pb]</th>
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<td>10^{-5}</td>
</tr>
<tr>
<td>250</td>
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</table>

Events

Data/pred.

Signal region

2l same-sign

- Observed ± 1 \( \sigma_{\text{theory}} \)
- Expected ± 1 \( \sigma_{\text{experiment}} \)

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Lepton-based signatures - increasing the multiplicity even more

ATLAS-CONF-2016-075

’LLE’ RPV couplings can lead to final states with **at least** 4 charged leptons

- Look for events with at least 4 charged leptons
- Non-resonant signal: strong background suppression via $Z$-veto
- Dominant backgrounds: $t\bar{t}Z$, $t\bar{t}$ (fakes), ZZ
- Estimation via MC (Data-driven for fakes)
- Final discriminant: **Effective mass**

**Effective mass**

![Effective mass plot](image)
Supersymmetry is a key provider of new physics scenarios for the LHC

- Predicts wide range of physics signatures
- Guideline to an exhaustive search program
- Framework of **simplified models** used for experimental exploration

Searches often limited by production cross-sections - strong gain from $E_{\text{cm}}$ increase

- LHC run 2: Largest leap in sensitivity for decades to come!

  Analysis of 13 TeV LHC data ramping up

- Strong production searches mostly updated to early $\sqrt{s} = 13$ TeV dataset
- Electroweak and RPV searches catching up, first results arriving
- Reminder: This talk is only an overview, several interesting aspects not covered, including . . .

- Long-lived particle signatures
- Gauge-mediated SUSY breaking

**Interesting times ahead! Stay tuned!**