Associated Production of Squarks and Gauginos at 100 TeV

Bob Zheng

Based on 1506.02644 with Sebastian Ellis

Michigan Center for Theoretical Physics

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I. Motivation
Where is SUSY?

Several ways to interpret null LHC results:

- **Optimist**: SUSY will be found at LHC-13/14, just wait for enough data!

- **Pessimist**: Natural SUSY is disfavored → nature probably not SUSY

- **Somewhere in the middle** (this talk): SUSY manifest in nature, but out of LHC reach?

**If LHC can't reach SUSY, maybe future colliders can?**
Squark-Gaugino Associated Production at $\sqrt{s} = 100$ TeV

**Focus of this talk:** future p-p collider, $\sqrt{s} = 100$ TeV

Previous studies focused on SUSY pair production channels, e.g. $pp \rightarrow \tilde{q}\tilde{q}$, $pp \rightarrow \tilde{g}\tilde{g}$, $pp \rightarrow \tilde{\chi}^\pm/0\tilde{\chi}^\pm/0$

Our work focuses instead on squark-gaugino associated production

**Squark-gluino:**

$\sigma \sim \mathcal{O}(\alpha_s^2)$

**Squark-wino/bino:**

$\sigma \sim \mathcal{O}(\alpha_s \alpha_W)$
Why Associated Production?

**Spectra w/ mass hierarchies**

- Certain SUSY theories predict “mini-split” spectra, where

\[ M_{\tilde{G}} \lesssim 10 \times m_{\tilde{s}} \Rightarrow \sigma(pp \rightarrow \tilde{g}\tilde{q}) \gg \sigma(pp \rightarrow \tilde{q}\tilde{q}) \]
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\[ M_{\text{Gaugino}} \lesssim 10 \times m_{\text{sfermion}} \Rightarrow \sigma(pp \rightarrow \tilde{g}\tilde{q}) \gg \sigma(pp \rightarrow \tilde{q}\tilde{q}) \]

Electroweak vs Strong Production Cross Sections

- Pair production: \( pp \rightarrow \tilde{W}^+\tilde{W}^-, \sigma \sim O(\alpha_W^2) \)
- Associated production: \( pp \rightarrow \tilde{W}\tilde{q}, \sigma \sim O(\alpha_W\alpha_s) \)
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**Electroweak vs Strong Production Cross Sections**
- Pair production: \( pp \rightarrow \tilde{W}^+\tilde{W}^-, \sigma \sim \mathcal{O}(\alpha_W^2) \)
- Associated production: \( pp \rightarrow \tilde{W}\tilde{q}, \sigma \sim \mathcal{O}(\alpha_W\alpha_s) \)

**Gluino-Neutralino Co-Annihilation Region**
- If \( M_{\tilde{g}} - M_{\chi^0} \ll M_{\chi^0}, \chi^0 \) can be DM provided \( M_{\chi} \lesssim 8 \text{ TeV} \) (see e.g. Ellis, Luo, Olive arXiv:1503.07142)
- Collider signal:
  \( \tilde{g}\tilde{g} \rightarrow \text{ISR/FSR jet} + \not{E}_T \text{ vs. } \tilde{q}\tilde{g} \rightarrow \text{hard jet} + \not{E}_T \).
II. Anatomy of Squark-Gaugino Production
I will focus on spectra with heavy squarks and light gauginos

Cartoon of associated production event:

High $p_T$ final state particles arise as boosted squark decay products, with $p_T \sim m_{\tilde{q}}/2$
Kinematic Variables for Background Discrimination

Distributions below for events with $\slashed{E}_T > 2$ TeV

**Squark-gluino: Leading jet $p_T$**

$M_{\tilde{g}} = 4$ TeV, $M_{\tilde{q}} = 26$ TeV

**Squark-wino/bino: $\slashed{E}_T / \sqrt{H_T}$**

$M_{\tilde{\nu}} = 2$ TeV, $M_{\tilde{q}} = 9$ TeV

Both spectra give $\mathcal{O}(0.1)$ fb associated production xsecs
Estimate reach by taking points in the \((M_{\tilde{q}}, M_{\text{Gaugino}})\) plane and:

1. Impose a set of spectrum-independent “basline” cuts

2. Squark-Gluino: Scan over \(\not\!E_T\) and leading jet \(p_T\) cuts
   Squark-Wino/Bino: Scan over \(\not\!E_T\) and \(\not\!E_T/\sqrt{H_T}\) cuts
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Results presented in context of simplified models:

- **Squark-Gluino**: Gluino, Bino, 1st+2nd gen squarks
- **Squark-Wino/Bino**: Wino, Bino, 1st+2nd gen squarks

See backup slide for simulation details and description of baseline cuts
III. Projected Reaches at $\sqrt{s} = 100$ TeV
Projected reach at $\sqrt{s} = 100$ TeV, 3 ab$^{-1}$

**Red:** 95% CL  **Blue:** 5 $\sigma$

$M_{\chi_1^0} = 100$ GeV

Gluino-neutralino co-annihilation region: $M_{\tilde{g}} \lesssim 8$ TeV.

Excluded for $M_{\tilde{q}} \lesssim 28$ TeV! (RH Plot)
Projected reach at $\sqrt{s} = 100$ TeV, 3 ab$^{-1}$

**Red**: 95% CL  
**Blue**: 5 $\sigma$

**Squark-Bino Production**

Compare to 1.2 TeV reach in Wino pair production via VBF

Berlin, Lin, Low, Wang 1502.05044
Projected Reach: Squark-Wino NLSP Production

Search strategy is robust even for NLSP Wino!

**Dashed**: 95% CL. **Solid**: 5 \( \sigma \)

- **Blue**: Wino LSP
- **Green**: \( M_{\text{Wino}} - M_{\text{LSP}} = 200 \text{ GeV} \)
- **Red**: \( M_{\text{LSP}} = 100 \text{ GeV} \)

Compare: Wino NLSP pair prod.

- 5\( \sigma \) reach: 1-3 TeV Wino.

Depends on Wino BR to \( h/W/Z \)

Gori, Jung, Wang, Wells 1410.6287
Squark-gluino:

- At $\sqrt{s} = 100$ TeV w/ 3 ab$^{-1}$, can discover 32 (25) TeV squarks for 2 (10) TeV gluino masses

- Can exclude gluino-neutralino co-ann. for $< 28$ TeV squarks
Summary

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Squark-Wino/Bino:

- Can discover Wino (Bino) masses up to 3 (1.5) TeV for $\lesssim 8$ (6) TeV squark masses

- Stronger reach in Wino mass compared to Wino pair production if $m_{\tilde{q}} \lesssim 10$ TeV
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Ass. prod. at $\sqrt{s} = 100$ TeV can probe $\mathcal{O}(10)$ TeV squark masses. Comparable to bounds from low-energy flavor observables!
Simulation Details:

- Used backgrounds generated by the Snowmass collab. for a 100 TeV collider, neglecting pile-up effects

- Signal events generated with Madgraph 5, hadronization/showering via Pythia 6, detector effects simulated with Delphes-3

- Used Snowmass detector framework for 100 TeV p-p Collider

Baseline Cuts:

- Squark-gluino: $H_T > 10$ TeV, $\not\! E_T / \sqrt{H_T} > 20$ GeV$^{1/2}$, 8 jets with $p_T > 50(150)$

- Squark-Wino/Bino: $p_T(j_1) > 2$ TeV, $\not\! E_T > 3$ TeV, $\Delta \phi(j_{1,2}, \not\! E_T) > 0.5$