# Associated Production of Squarks and Gauginos at 100 TeV

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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 $\rightarrow$ 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?**

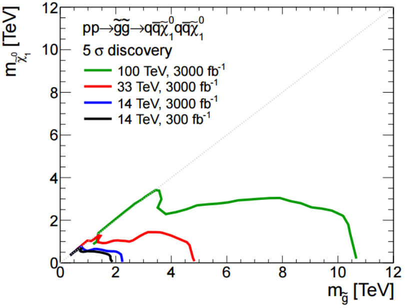
# Discovery Prospects at a 100 TeV Proton Collider

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

Higher CM energies ⇒ considerably better reach than LHC-14

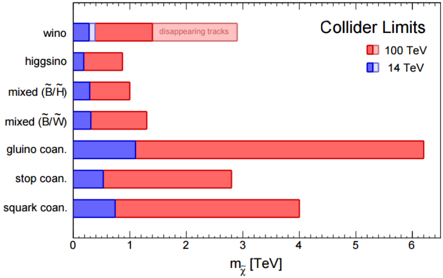
**See plenary talk by Lian-tao**

Gluino pair prod.




Cohen et. al arxiv:1311.6480

Neutralino DM pair prod.



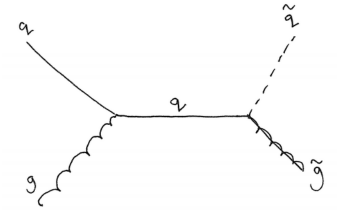

Low and Wang arxiv:1404.0682

# Squark-Gaugino Associated Production at $\sqrt{s} = 100$ TeV

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

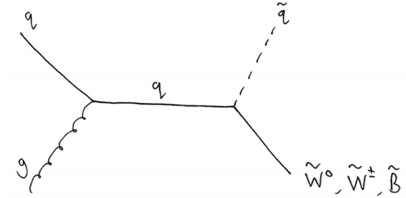
Our work instead considers squark-gaugino associated production

Squark-gluino:




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

Squark-wino/bino:




$\sigma \sim \mathcal{O}(\alpha_s \alpha_W)$

Will focus on spectra with **heavy squarks** and **light gauginos**

# Why Associated Production?

**Spectra w/ mass hierarchies**

- Certain SUSY theories predict "mini-split" spectra, where

$$M_{\mathrm{Gaugino}} \lesssim 10 \times m_{\mathrm{sfermion}} \Rightarrow \sigma(pp \to \tilde{g}\tilde{q}) \gg \sigma(pp \to \tilde{q}\tilde{q})$$

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**Strong vs Weak EW-ino Production**

- $pp \to \tilde{W}\tilde{W}$: $\sigma \sim \mathcal{O}(\alpha_W{}^2)$ **vs** $pp \to \tilde{W}\tilde{q}$: $\sigma \sim \mathcal{O}(\alpha_W \alpha_s)$
- Hard jet from $\tilde{q} \to q\tilde{W}$ helps with $S/\sqrt{B}$

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**Gluino-Neutralino Co-Annihilation Region**

- If $\tilde{g}$ and $\chi^0$-LSP nearly degenerate, $\chi^0$ can be DM!

  (see e.g. Ellis, Luo, Olive arXiV:1503.07142)

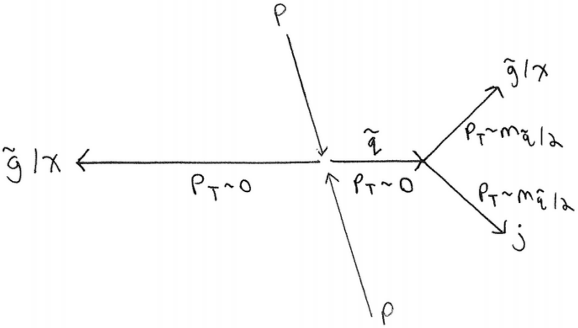
- $\tilde{g}\tilde{g} \to$ ISR/FSR jet + MET vs. $\tilde{q}\tilde{g} \to$ hard jet + MET.
  If $\tilde{q}$ - $\tilde{g}$ mass splitting is sizeable, latter much easier to see

# II. Anatomy of Squark-Gaugino Production

# Kinematics of Heavy Squark Associated Production

I will focus on spectra with **heavy squarks** and **light gauginos**

Cartoon of associated production event:

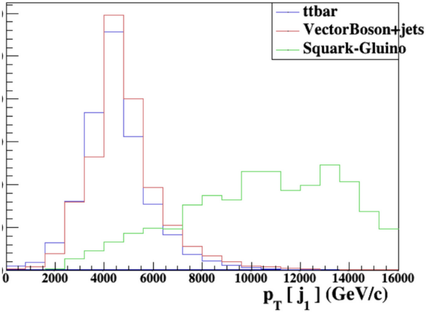



High $p_T$ final state particles arise as boosted squark decay products, with $p_T \sim m_{\tilde{q}}/2$

# Kinematic Variables for Background Discrimination

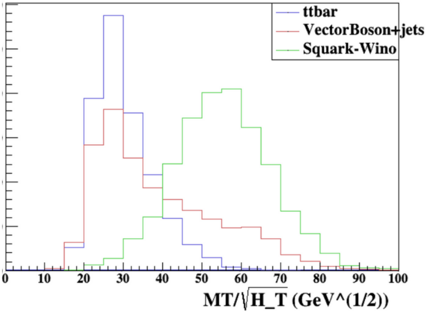
Distributions below for events with $\not{E}_T > 2$ TeV

Squark-gluino: Leading jet $p_T$




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

Squark-wino/bino: $\not{E}_T/\sqrt{H_T}$




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

Both spectra give $\mathcal{O}(0.1)$ fb associated production xsecs

# Methodology for Estimating Reach

Estimate reach by taking points in the $(M_{\tilde{q}}, M_{\mathrm{Gaugino}})$ 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

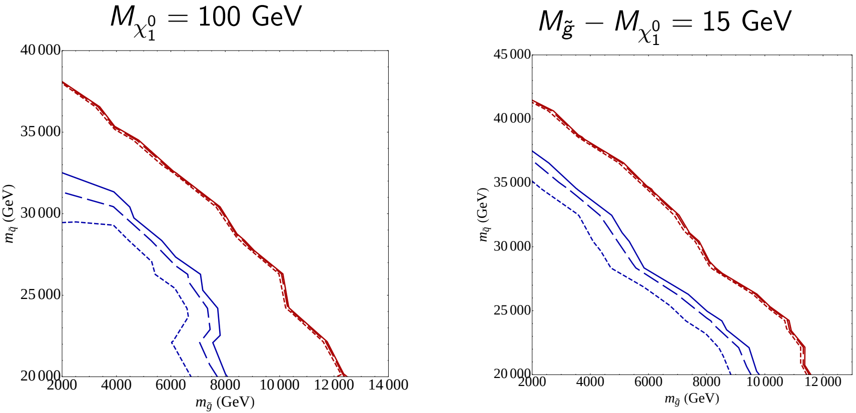
See backup slide for simulation details and description of baseline cuts

# III. Projected Reaches at $\sqrt{s} = 100$ TeV

# Projected Reach: Squark-Gluino Production

Projected reach at $\sqrt{s} = 100$ TeV, 3 ab$^{-1}$

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




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

Excluded for $M_{\tilde{q}} \lesssim 28$ TeV! (RH Plot)

# Projected Reach: Squark-Wino/Bino LSP Production

Projected reach at $\sqrt{s} = 100$ TeV, 3 ab$^{-1}$

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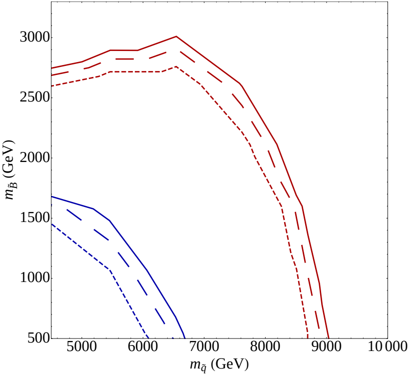
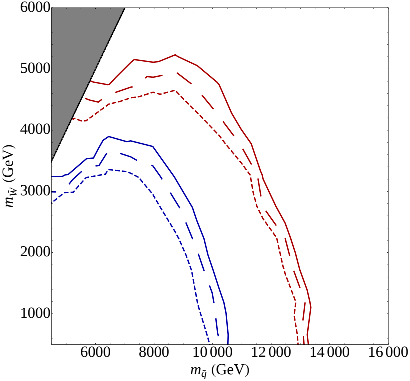
Squark-Bino Production




Squark-Wino Production



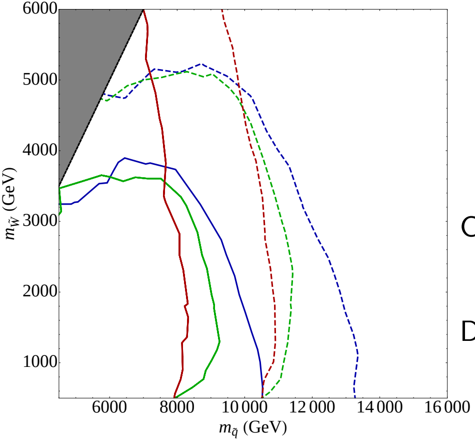

Compare to 1.2 TeV reach in Wino pair production via VBF

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**: $M_{\mathrm{Wino}} - M_{\mathrm{LSP}} = 200$ GeV
- **Red**: $M_{\mathrm{LSP}} = 100$ 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

# Summary

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

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- 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!

# Backup Slide

Simulation Details:

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

  1308.1636
- 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

  1309.1057

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, $\Delta\phi(j_{1,2}, \not{E}_T) > 0.5$