

Determining the SUSY-QCD Yukawa coupling in a combined LHC/ILC analysis

A. Freitas and P. Skands
University of Zürich / Fermilab

1. Introduction: Gauge and Yukawa couplings
2. SUSY-QCD couplings
3. Phenomenological LHC and ILC analysis
4. First results and conclusion

1. Introduction: Gauge and Yukawa couplings

Fundamental relation in supersymmetry:

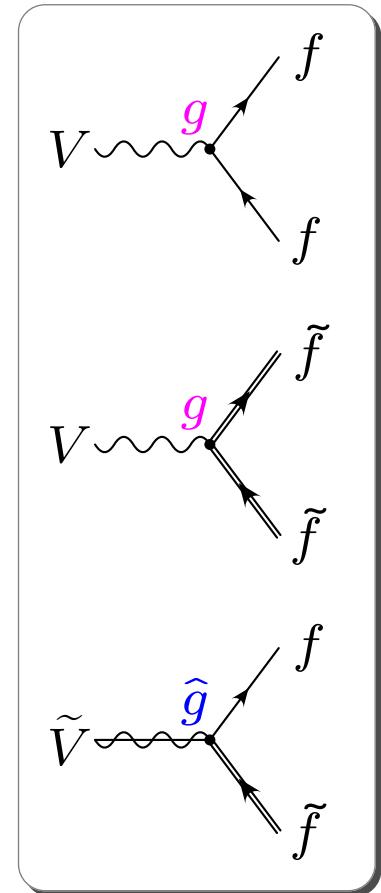
Gauge coupling g = Yukawa coupling \hat{g}

→ required to resolve hierarchy problem

Establish SUSY experimentally:

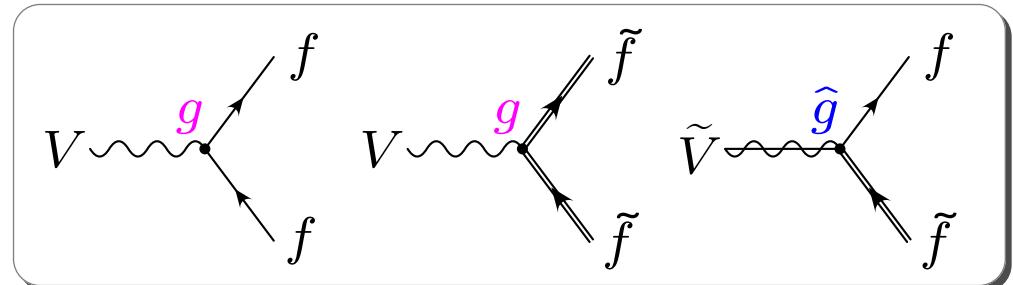
- Find new particles
- Measure their spin, masses, ...
- **Test SUSY coupling relations**
 - compare precise cross-section measurements with theoretical predictions

Precision measurements: ideal at high-energy e^+e^- collider

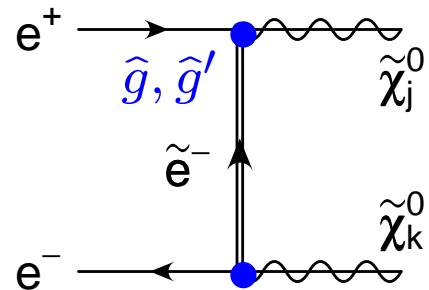


SUSY couplings in the electroweak sector

Electroweak gauge & Yukawa
couplings can be probed in

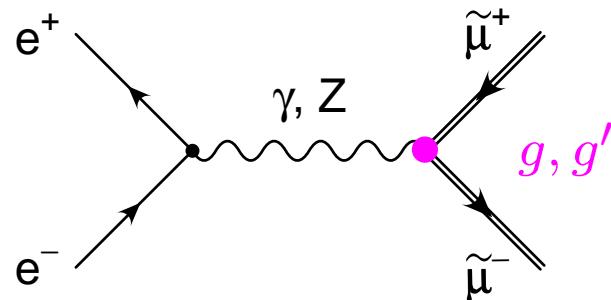


- Neutralino production

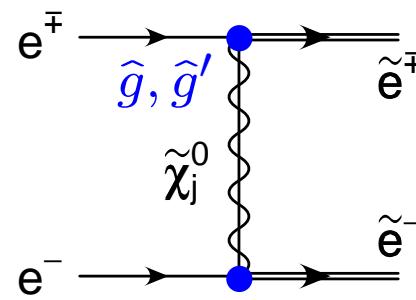


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production



Freitas, v.Manteuffel, Zerwas '03



g' U(1) coupl.

g SU(2) coupl.

Determination of Yukawa couplings

SPS1a scenario

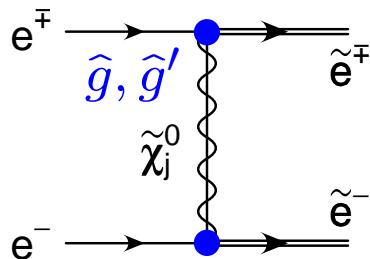
From selectron cross-sections

$$e^+ e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

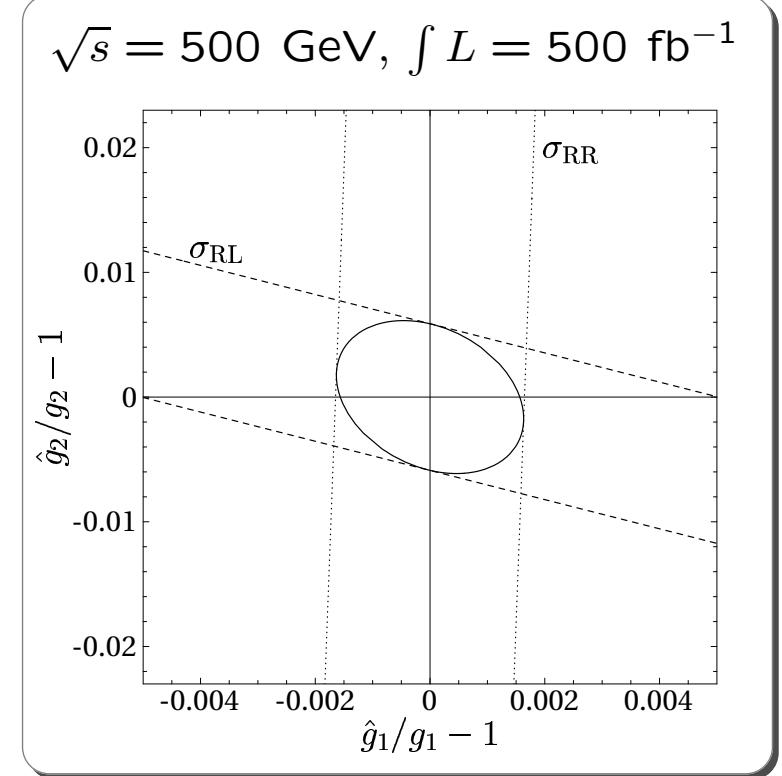
$$e^+ e^- \rightarrow \tilde{e}_R^+ \tilde{e}_L^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_2^0$$

$\tau^+ \tau^- \tilde{\chi}_1^0$

Use polarized beams to disentangle
U(1) and SU(2) couplings



$$\frac{\delta \hat{g}'}{\hat{g}'} \approx 0.2\% \quad \frac{\delta \hat{g}}{\hat{g}} \approx 0.7\%$$

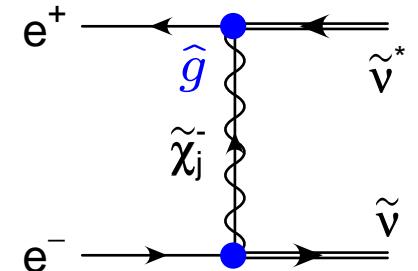


From sneutrino cross-section **only** SU(2) coupling \hat{g}

$$e^+ e^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e^* \rightarrow \nu_e \tilde{\chi}_1^0 e^\pm \tilde{\chi}_1^\mp$$

$\tau^\mp \nu_\tau \tilde{\chi}_1^0$

$$\frac{\delta \hat{g}}{\hat{g}} \approx 5\%$$



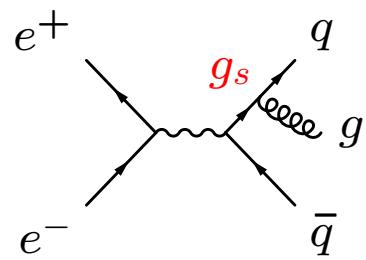
2. Testing SUSY-QCD couplings at a linear collider

Initial state at e^+e^- colliders does not contain colored particles

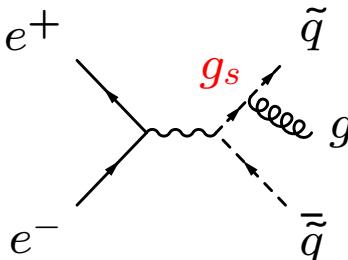
→ Test of SU(3) coupling relations only possible in associated production:

Brandenburg, Maniatis, Weber '02

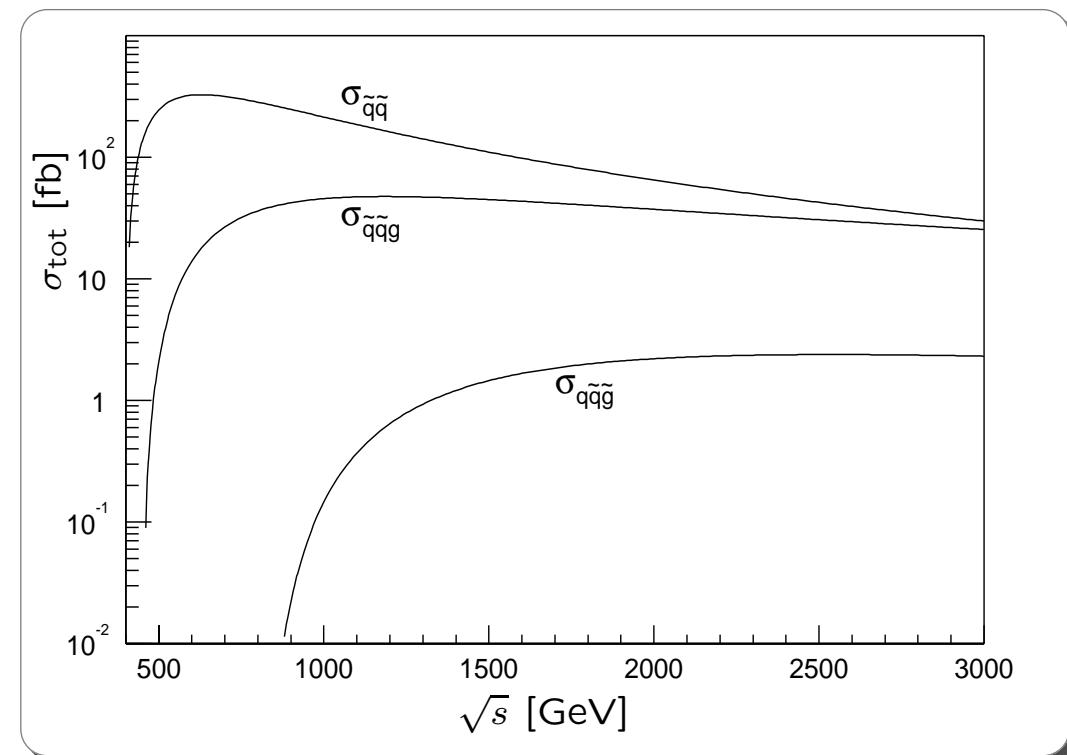
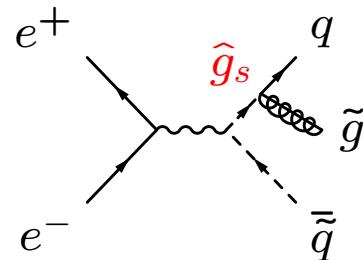
$$e^+e^- \rightarrow qgg$$



$$e^+e^- \rightarrow \tilde{q}\tilde{\bar{q}}g$$



$$e^+e^- \rightarrow q\tilde{q}\tilde{g}$$



Testing SUSY-QCD couplings at a linear collider

Difficult in practice:

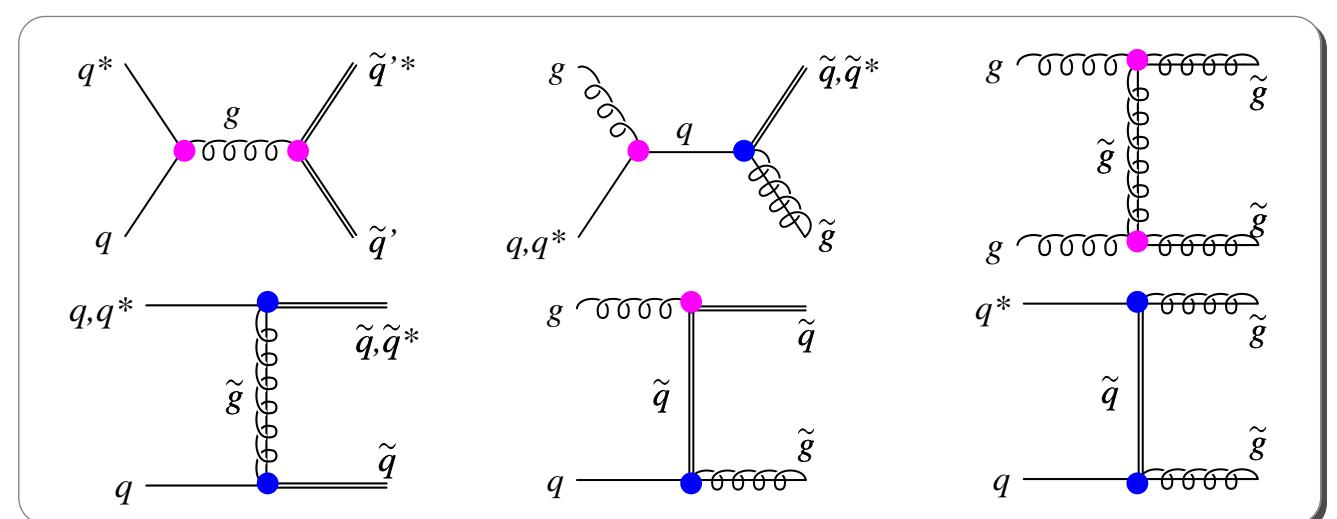
- Need large center-of-mass energy $\mathcal{O}(2 \text{ TeV})$
- Small cross-section for $q\tilde{q}\tilde{g}$ production
 - including BRs the statistics might be too low to separate from background

Alternative: Measure QCD production process at LHC

$$pp \rightarrow \tilde{q}\tilde{q}^{(*)}, \tilde{q}^{(*)}\tilde{g}, \tilde{g}\tilde{g}$$

gauge coupling g_s

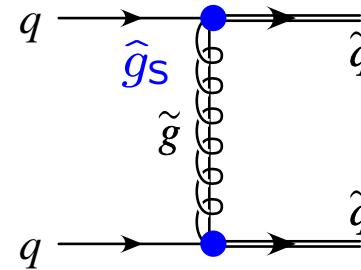
Yukawa coupling \hat{g}_s



Isolating the SUSY-QCD Yukawa coupling at LHC

Production of same-sign squarks:

$$pp \rightarrow \tilde{q}\tilde{q}$$



Tagging of squark charge
through chargino decay chain:

$$\begin{aligned}\tilde{u}_L &\rightarrow d \tilde{\chi}_1^+ \rightarrow d l^+ \nu_l \tilde{\chi}_1^0 \\ \tilde{d}_L &\rightarrow u \tilde{\chi}_1^- \rightarrow u l^- \bar{\nu}_l \tilde{\chi}_1^0\end{aligned}$$

Signature: Two same-sign leptons, two hard jets, missing energy

Main problem: Background from gluinos with $m_{\tilde{g}} > m_{\tilde{q}_L}$ from
 $\tilde{g} \rightarrow q \tilde{q}_L$, especially if q -jet is soft

Assume here that $m_{\tilde{g}} - m_{\tilde{q}_L}$ suffienctly large to cut on extra jet !!

Phenomenological LHC and ILC analysis

Scenario similar to SPS1a, but with larger gluino mass

$M_1 = 99$	$m_L = 197$	$m_{Q1} = 540$	
$M_2 = 193$	$m_R = 136$	$m_{U1} = 522$	
$M_3 = 700$	$\tan \beta = 10$	$m_{D1} = 520$	
$\mu = 352$	$A_\tau = -254$		

→

$m_{\tilde{u}_L} = 537$	$m_{\tilde{\chi}_1^0} = 96$
$m_{\tilde{d}_L} = 543$	$m_{\tilde{\chi}_2^0} = 177$
$m_{\tilde{\tau}_1} = 133$	$m_{\tilde{\chi}_1^\pm} = 176$
$m_{\tilde{g}} = 700$	$m_{\tilde{\chi}_{3,4}^0} \sim 360$

Interesting decay chain:

$$\tilde{u}_L \xrightarrow{65\%} u \tilde{\chi}_1^+ \xrightarrow{100\%} u \tau^+ \nu_\tau \tilde{\chi}_1^0 \xrightarrow{35\%} u l^+ + \cancel{E}, \quad l = e, \mu$$

LHC backgrounds:

$t\bar{t}$ veto on b tag, cut on \cancel{E}

W^+W^+jj cut on \cancel{E}

$\tilde{g}\tilde{g}$ veto on additional hard jets

$\tilde{q}\tilde{g}$ veto on additional hard jets

Selection of signal at LHC

Selection of same-sign squark signal

1. Preselection

at least 2 jets with $p_{T,j} > 100$ GeV

2 same-sign leptons with $p_{T,l} > 7$ GeV

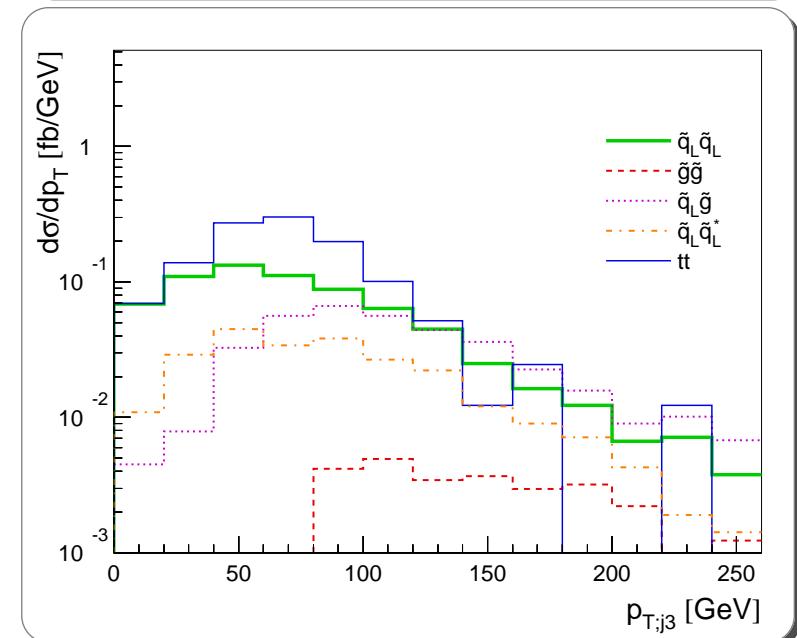
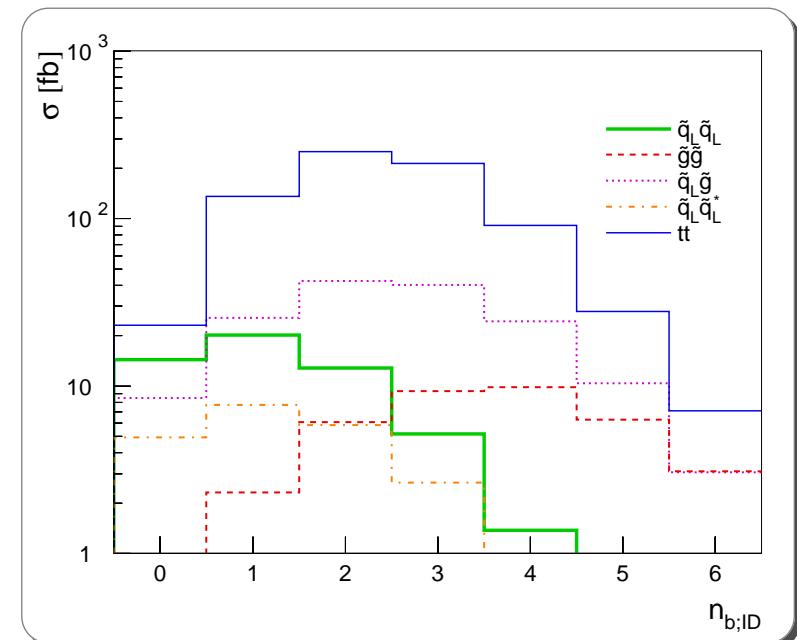
2. b-tagging to reduce $t\bar{t}$

efficiency 90%, u, d mistag 25%

ATLAS TDR '99

3. $p_{T,j3} < 75$ GeV to reduce \tilde{g} background

4. $p_{T,j1} > 200$ GeV to cut SM background



Selection of signal at LHC

5. $E_T > 150$ GeV to cut SM background

Remaining cross-sections:

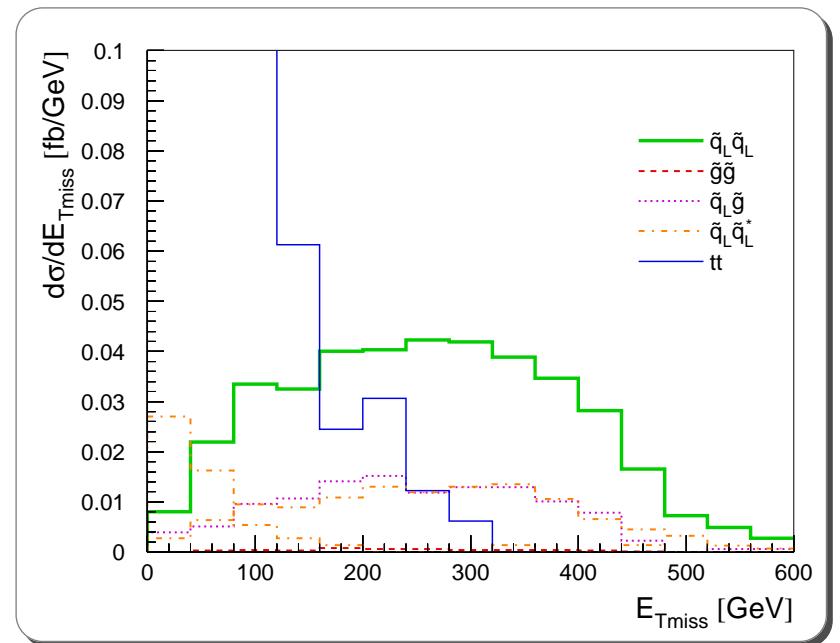
$\tilde{q}_L \tilde{q}_L$ 5.6 fb

$\tilde{q}_L \tilde{q}_L^*$ 1.6 fb $S/B = 1.6$

$\tilde{q}_L \tilde{g}$ 1.2 fb with 100 fb^{-1} :

$\tilde{g} \tilde{g}$ 0.04 fb $\Delta_{\text{stat}} = 5.4\%$

SM 0.6 fb



Alternative cut strategy: Minimize background

$p_{T,j3} < 50$ GeV,

only positive leptons since signal is uu dominated

$\tilde{q}_L \tilde{q}_L$ 2.4 fb $\tilde{g} \tilde{g}$ 0.001 fb $S/B = 2.5$

$\tilde{q}_L \tilde{q}_L^*$ 0.5 fb

$\tilde{q}_L \tilde{g}$ 0.3 fb SM 0.2 fb $\Delta_{\text{stat}} = 7.7\%$

Input from linear collider

Branching ratios in LHC decay chain:

$$\tilde{u}_L \rightarrow d \tilde{\chi}_1^+, \tilde{d}_L \rightarrow u \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tau^+ \nu_\tau$$

BRs of squarks can be studied in $\tilde{q}\tilde{q}^*$ production at e^+e^- collider

→ Need $\sqrt{s} > 1$ TeV in our scenario

→ Assume $\sqrt{s} = 1.5$ TeV $|P(e^+)| = 50\%, |P(e^-)| = 80\%$

Identify different decay products of squarks by characteristic signature:

$$\tilde{\chi}_1^+ \rightarrow \tau^+ \nu_\tau \tilde{\chi}_1^0 \quad (100\%)$$

$$\tilde{\chi}_2^+ \rightarrow Z \tilde{\chi}_1^+ \rightarrow Z \tau^+ \nu_\tau \tilde{\chi}_1^0 \quad (24\%)$$

Assume 80% τ ID eff.
for hadronic decay
(BR = 65%)

$$\tilde{\chi}_2^0 \rightarrow \tau\tau \tilde{\chi}_1^0 \quad (100\%)$$

$$\tilde{\chi}_{3,4}^0 \rightarrow W^\pm \tilde{\chi}_1^\mp \rightarrow W^\pm \tau^\mp \nu_\tau \tilde{\chi}_1^0 \quad (59\%, 52\%)$$

Generate samples of squark signal and dominant SM background

Use **c**-tagging (eff. 40%, purity 90%) to differentiate u- and d-squarks

Input from linear collider

Need also information about BRs of charginos and neutralinos.

New technique to obtain absolute BRs:

Measure near threshold: unique signal of monoenergetic particles from two-body decays

$\tilde{\chi}_2^0 \tilde{\chi}_3^0$ threshold , $\mathcal{L} = 50 \text{ fb}^{-1}$: $\text{BR}[\tilde{\chi}_3^0 \rightarrow W^\pm \tilde{\chi}_1^\mp] = (59 \pm 6.5) \%$

$\tilde{\chi}_3^0 \tilde{\chi}_4^0$ threshold , $\mathcal{L} = 50 \text{ fb}^{-1}$: $\text{BR}[\tilde{\chi}_4^0 \rightarrow W^\pm \tilde{\chi}_1^\mp] = (52 \pm 2.5) \%$

$\tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$ threshold, $\mathcal{L} = 50 \text{ fb}^{-1}$: $\text{BR}[\tilde{\chi}_2^+ \rightarrow Z \tilde{\chi}_1^-] = (24 \pm 1.3) \%$

Together with squark production at $\sqrt{s} = 1.5 \text{ TeV}$ and $\mathcal{L} = 500 \text{ fb}^{-1}$:

$\tilde{u}_L \rightarrow u \tilde{\chi}_1^0$	$0.9 \pm 0.5 \%$	$\tilde{d}_L \rightarrow d \tilde{\chi}_1^0$	$1.9 \pm 0.8 \%$
$u \tilde{\chi}_2^0$	$29.0 \pm 3.0 \%$	$d \tilde{\chi}_2^0$	$28.3 \pm 4.8 \%$
$u \tilde{\chi}_3^0$	$< 1 \%$	$d \tilde{\chi}_3^0$	$< 0.2 \%$
$u \tilde{\chi}_4^0$	$< 1 \%$	$d \tilde{\chi}_4^0$	$1.9 \pm 0.8 \%$
$d \tilde{\chi}_1^+$	$67.7 \pm 3.2 \%$	$u \tilde{\chi}_1^-$	$63.9 \pm 5.2 \%$
$d \tilde{\chi}_2^+$	1.4 ± 0.7	$u \tilde{\chi}_2^-$	$4.0 \pm 1.4 \%$

Results

Combination of errors:

$$\sigma[\tilde{q}_L \tilde{q}_L] \propto \hat{g}_S^4$$

	$\sigma[\tilde{q}_L \tilde{q}_L]$	\hat{g}_S/g_S
LHC signal statistics	5.4%	1.3%
SUSY-QCD Yukawa coupling in $\tilde{q}_L \tilde{g}$ background	5%	1.2%
PDF uncertainty (estimate)	$\sim 10\%$	2.4%
NNLO corrections*	8%	2.0%
Squark mass $\Delta m = 10$ GeV	6%	1.5%
$\text{BR}[\tilde{q}_L \rightarrow q' \tilde{\chi}_1^\pm]$	8.2%	2.0%
	18.0%	4.2%

* NLO corrections available [Beenakker, Höpker, Plehn, Zerwas '96](#)

Conclusions

- Hunt for SUSY involves the test of SUSY coupling relations:
Fundamental identity
 $gauge\ coupling = Yukawa\ coupling$
- Can be tested to $\lesssim 1\%$ in electroweak sector at future linear collider
- Using a combination of LHC and ILC measurements, the strong SUSY coupling identity can be tested to the level of $\sim 4\%$



Results

Combination of errors:

$$\sigma[\tilde{q}_L \tilde{q}_L] \propto \hat{g}_S^4$$

	$\sigma[\tilde{q}_L \tilde{q}_L]$	\hat{g}_S/g_S
LHC signal statistics	5.4%	1.3%
SUSY-QCD Yukawa coupling in $\tilde{q}_L \tilde{g}$ background	5%	1.2%
PDF uncertainty (estimate)	$\sim 10\%$	2.4%
NNLO corrections*	8%	2.0%
Squark mass $\Delta m = 10$ GeV	6%	1.5%
$\text{BR}[\tilde{q}_L \rightarrow q' \tilde{\chi}_1^\pm]$	8.2%	2.0%
	18.0%	4.2%

* NLO corrections available Beenakker, Höpker, Plehn, Zerwas '96