Unravelling SUSY-QCD

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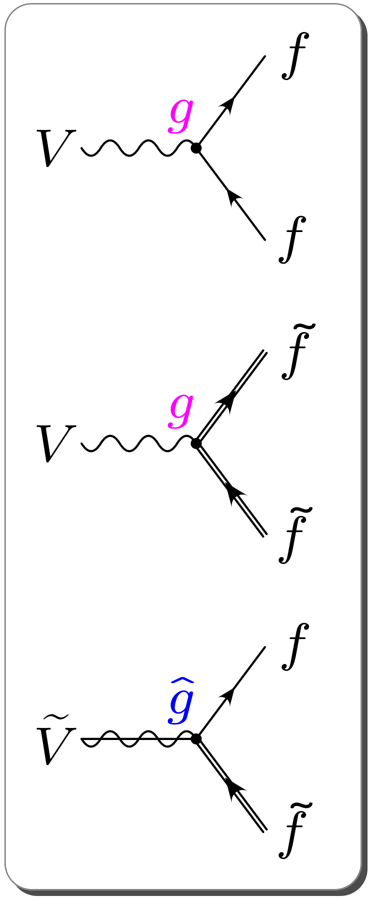
1. Introduction: Gauge and Yukawa couplings
2. SUSY-QCD couplings
3. Phenomenological LHC and ILC analysis
4. First results and conclusion

1. Introduction: Gauge and Yukawa couplings

Fundamental relation in supersymmetry:

Gauge coupling g = Yukawa coupling $\hat{g}$

→ required to resolve hierarchy problem



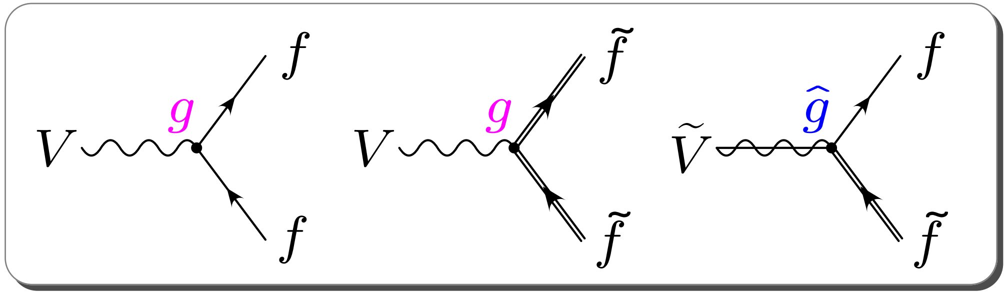
Establish SUSY experimentally:

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

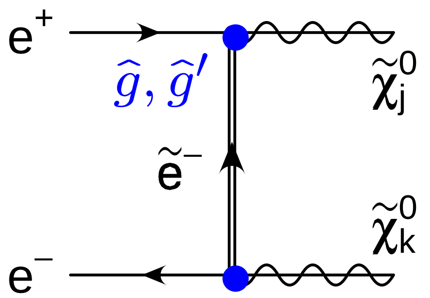
Precision measurements: ideal at high-energy e^+e^- collider

SUSY couplings in the electroweak sector

Electroweak gauge & Yukawa couplings can be probed in



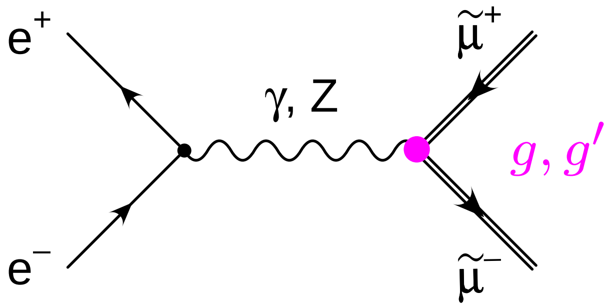
- Neutralino production

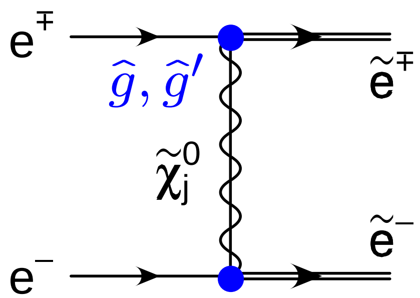


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production

Freitas, v.Manteuffel, Zerwas '03





g' U(1) coupl.

g SU(2) coupl.

Determination of Yukawa couplings

SPS1a scenario

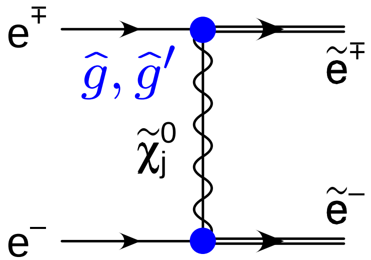
From selectron cross-sections

$$e^+e^- \to \tilde{e}^+_{\mathsf{R}}\tilde{e}^-_{\mathsf{R}} \to e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$$

$$e^+e^- \to \tilde{e}^+_{\mathsf{R}}\tilde{e}^-_{\mathsf{L}} \to e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_2$$

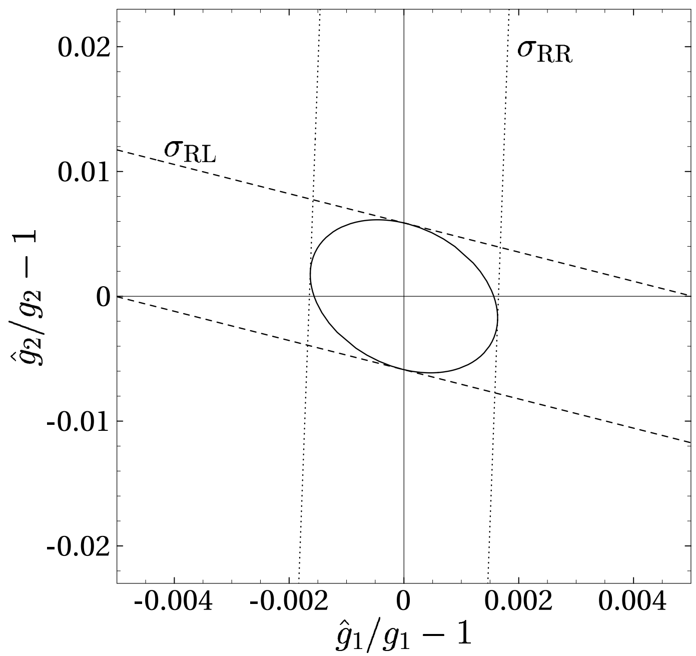
$$\hookrightarrow \tau^+\tau^-\,\tilde{\chi}^0_1$$

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



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

$\sqrt{s} = 500$ GeV, $\int L = 500$ fb^{-1}

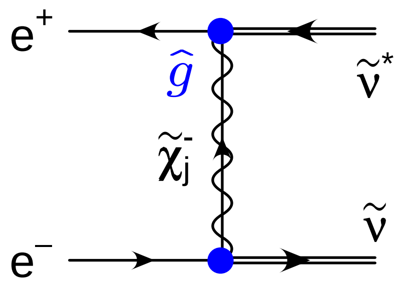


From sneutrino cross-section **only** SU(2) coupling $\hat{g}$

$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}^*_e \to \nu_e\tilde{\chi}^0_1\,e^\pm\tilde{\chi}^\mp_1$$

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

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

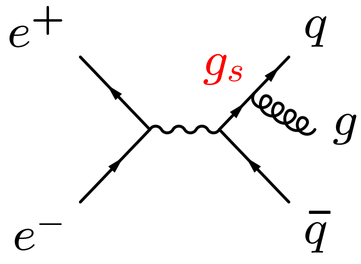


2. Testing SUSY-QCD couplings at a linear collider

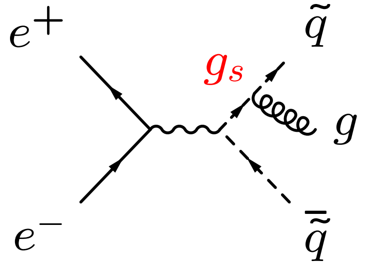
Initial state at e^+e^- colliders does not contain colored particles

$\rightarrow$ Test of SU(3) coupling relations only possible in associated production: Brandenburg, Maniatis, Weber '02

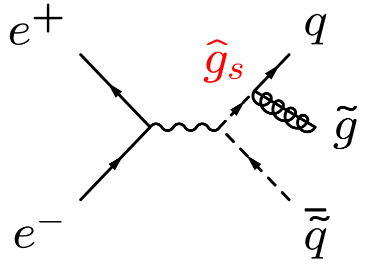
$e^+e^- \rightarrow qqg$

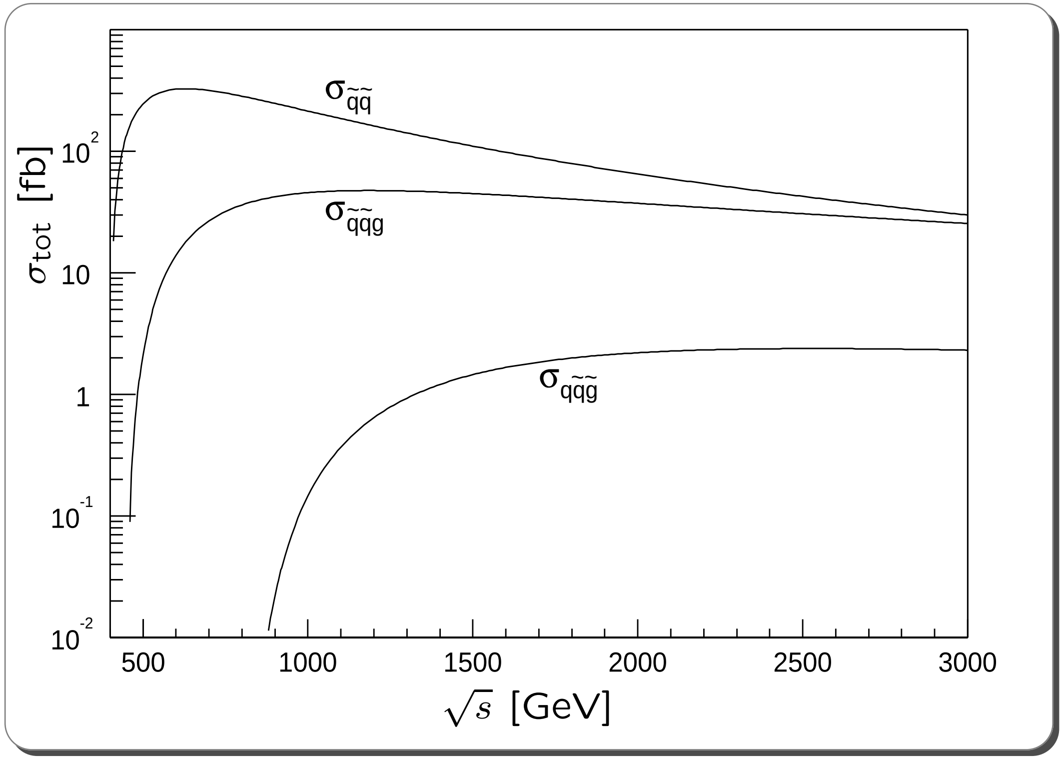


$e^+e^- \rightarrow \tilde{q}\tilde{q}g$



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





Testing SUSY-QCD couplings at ILC vs. LHC

Difficult in practice:

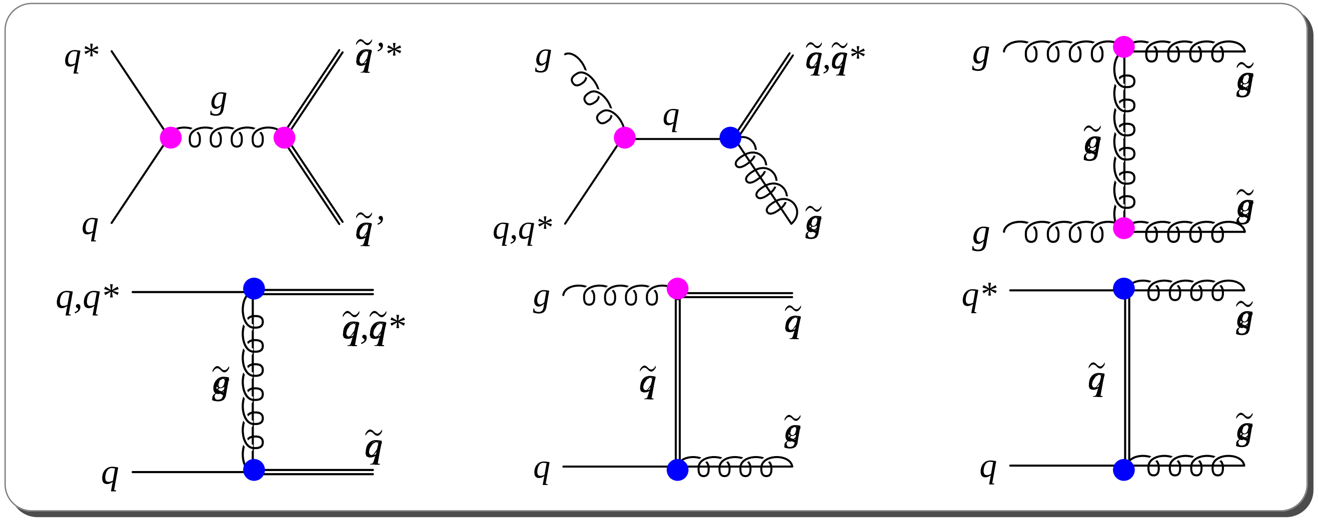
- Need large center-of-mass energy $\mathcal{O}(2\text{ TeV})$
- Small cross-section for $q\tilde{q}\tilde{g}$ production
  $\longrightarrow$ including BRs the statistics might be too low to separate from background

Alternative: Measure QCD production process at LHC

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

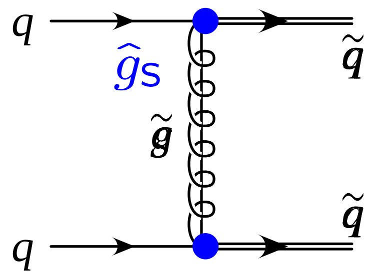
gauge coupling g_s

Yukawa coupling $\hat{g}_s$



Isolating the SUSY-QCD Yukawa coupling at LHC

Production of same-sign squarks:
$pp \longrightarrow \tilde{q}\tilde{q}$



Tagging of squark charge
through chargino decay chain:
$\tilde{u}_L \longrightarrow d\,\tilde{\chi}_1^+ \longrightarrow d\,l^+\,\nu_l\,\tilde{\chi}_1^0$
$\tilde{d}_L \longrightarrow u\,\tilde{\chi}_1^- \longrightarrow u\,l^-\,\bar{\nu}_l\,\tilde{\chi}_1^0$

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

Main problem: Background from gluinos with $m_{\tilde{g}} > m_{\tilde{q}_L}$ from $\tilde{g} \longrightarrow q\,\tilde{q}_L$, 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

$M_1 = 99$	$m_{\mathsf{L}} = 197$	$m_{\mathsf{Q}1} = 540$
$M_2 = 193$	$m_{\mathsf{R}} = 136$	$m_{\mathsf{U}1} = 522$
$M_3 = 700$	$\tan\beta = 10$	$m_{\mathsf{D}1} = 520$
$\mu = 352$	$A_\tau = -254$	

$\longrightarrow$

$m_{\tilde{u}_{\mathsf{L}}} = 537$	$m_{\tilde{\chi}^0_1} = 96$
$m_{\tilde{d}_{\mathsf{L}}} = 543$	$m_{\tilde{\chi}^0_2} = 177$
$m_{\tilde{\tau}_1} = 133$	$m_{\tilde{\chi}^\pm_1} = 176$
$m_{\tilde{g}} = 700$	$m_{\tilde{\chi}^0_{3,4}} \sim 360$

Interesting decay chain:

$$\tilde{u}_{\mathsf{L}} \xrightarrow{65\%} u\,\tilde{\chi}^+_1 \xrightarrow{100\%} u\,\tau^+\,\nu_\tau\,\tilde{\chi}^0_1 \xrightarrow{35\%} u\,l^+ + \not{E}, \qquad l = e,\,\mu$$

LHC backgrounds:

$t\bar{t}$	veto on b tag, cut on $\not{E}$
W^+W^+jj	cut on $\not{E}$
$\tilde{g}\tilde{g}$	veto on additional hard jets
$\tilde{q}\tilde{g}$	veto on additional hard jets

Selection of signal at LHC

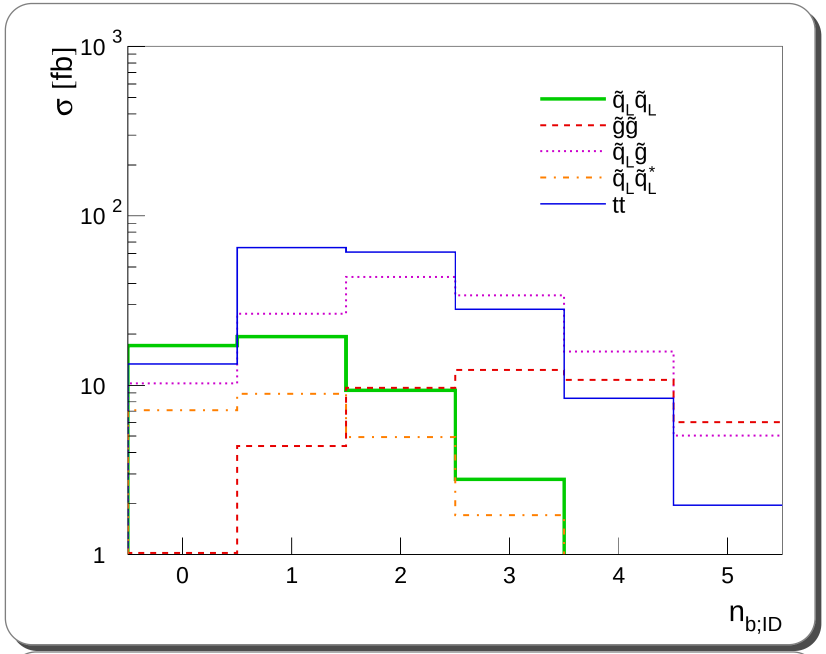
Selection of same-sign squark signal

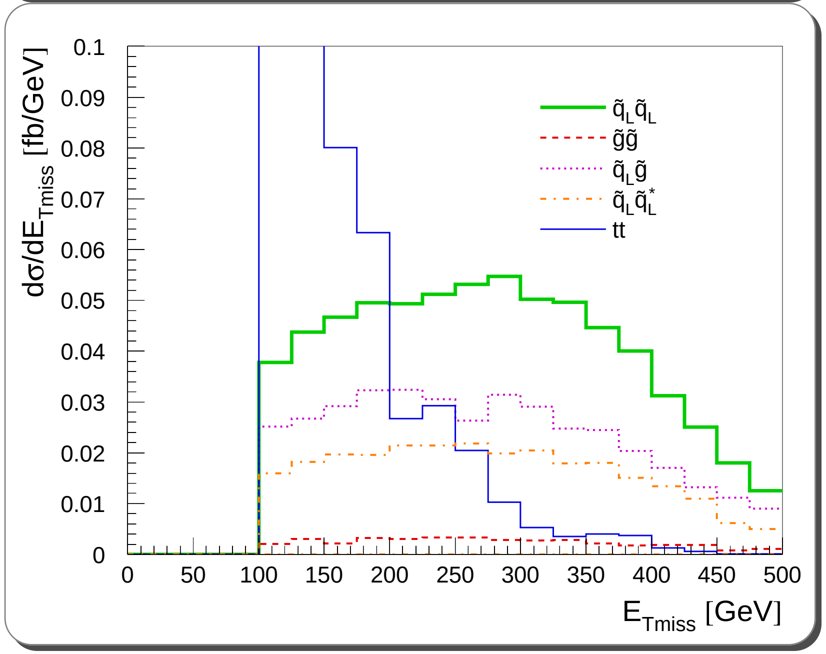
1. Preselection
   at least 2 jets with $p_{T,j} > 100$ GeV
   2 same-sign leptons with $p_{T,l} > 7$ GeV

2. b-tagging to reduce $t\bar{t}$
   efficiecy 90%, u, d mistag 25%
   ATLAS TDR '99

3. $\not{E} > 150$ GeV to cut SM background

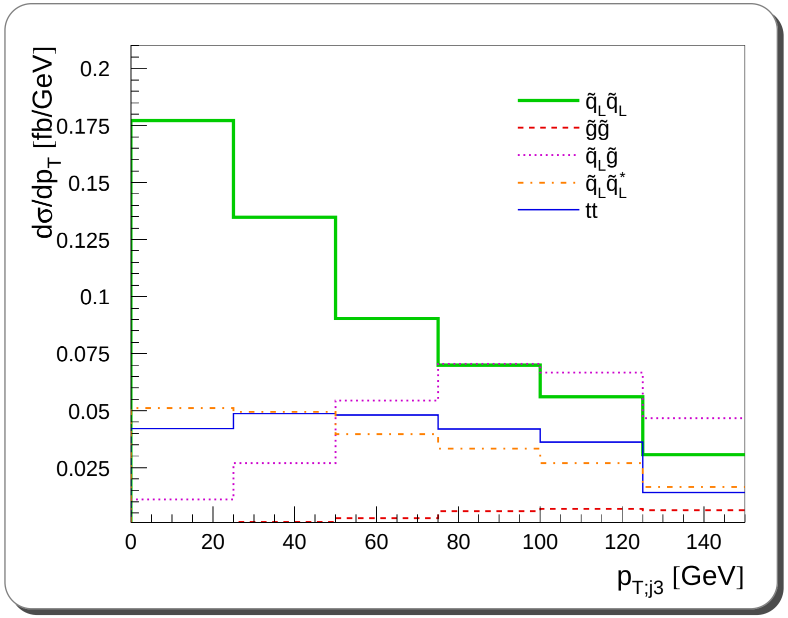
4. $p_{T,j1} > 200$ GeV to cut SM background





Selection of signal at LHC

5. $p_{\mathrm{T,j3}} < 50$ GeV to reduce $\tilde{g}$ background



Remaining cross-sections:

$\tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{L}}$	6.9 fb
$\tilde{q}_{\mathrm{L}}\tilde{q}^*_{\mathrm{L}}$	2.3 fb
$\tilde{q}_{\mathrm{L}}\tilde{g}$	0.8 fb
$\tilde{g}\tilde{g}$	0.03 fb
SM	1.6 fb

S/B = 1.45

with 100 fb^{-1}:

$\Delta_{\mathrm{stat}} = 4.9\%$

Alternative cut strategy: Minimize background

Only positive leptons since signal is uu dominated

$\tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{L}}$	4.8 fb	$\tilde{g}\tilde{g}$	0.01 fb
$\tilde{q}_{\mathrm{L}}\tilde{q}^*_{\mathrm{L}}$	1.4 fb		
$\tilde{q}_{\mathrm{L}}\tilde{g}$	0.5 fb	SM	1.1 fb

S/B = 1.6

$\Delta_{\mathrm{stat}} = 5.8\%$

Input from linear collider

Branching ratios in LHC decay chain:
$\tilde{u}_L \to d\,\tilde{\chi}_1^+,\ \tilde{d}_L \to u\,\tilde{\chi}_1^-,\ \tilde{\chi}_1^+ \to \tau^+\nu_\tau$

BRs of squarks can be studied in $\tilde{q}\tilde{q}^*$ production at e^+e^- collider
$\to$ Need $\sqrt{s} > 1$ TeV in our scenario
$\to$ Assume $\sqrt{s} = 1.5$ TeV $|P(e^+)| = 50\%$, $|P(e^-)| = 80\%$

Identify different decay products of squarks by characteristic signature:

$\tilde{\chi}_1^+ \to \tau^+\nu_\tau\tilde{\chi}_1^0$	(100%)
$\tilde{\chi}_2^+ \to Z\tilde{\chi}_1^+ \to Z\,\tau^+\nu_\tau\,\tilde{\chi}_1^0$	(24%)
$\tilde{\chi}_2^0 \to \tau\tau\,\tilde{\chi}_1^0$	(100%)
$\tilde{\chi}_{3,4}^0 \to W^\pm\tilde{\chi}_1^\mp \to W^\pm\,\tau^\mp\nu_\tau\tilde{\chi}_1^0$	(59%,52%)

Assume 80% $\boldsymbol{\tau}$ ID eff.
for hadronic decay
(BR = 65%)

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 paricles from two-body decays

$\tilde{\chi}^0_2\tilde{\chi}^0_3$ threshold , $\mathcal{L} = 50$ fb^{-1}: BR$[\tilde{\chi}^0_3 \to W^\pm \tilde{\chi}^\mp_1] = (59 \pm 6.5)$ %
$\tilde{\chi}^0_3\tilde{\chi}^0_4$ threshold , $\mathcal{L} = 50$ fb^{-1}: BR$[\tilde{\chi}^0_4 \to W^\pm \tilde{\chi}^\mp_1] = (52 \pm 2.5)$ %
$\tilde{\chi}^\pm_2\tilde{\chi}^\mp_2$ threshold, $\mathcal{L} = 50$ fb^{-1}: BR$[\tilde{\chi}^+_2 \to Z\,\tilde{\chi}^\mp_1] = (24 \pm 1.3)$ %

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

$\tilde{u}_L \to$	$u\tilde{\chi}^0_1$	0.9 ± 0.5 %	$\tilde{d}_L \to$	$d\tilde{\chi}^0_1$	1.9 ± 0.8 %
	$u\tilde{\chi}^0_2$	29.0 ± 3.0 %		$d\tilde{\chi}^0_2$	28.3 ± 4.8 %
	$u\tilde{\chi}^0_3$	< 1 %		$d\tilde{\chi}^0_3$	< 0.2 %
	$u\tilde{\chi}^0_4$	< 1 %		$d\tilde{\chi}^0_4$	1.9 ± 0.8 %
	$d\tilde{\chi}^+_1$	67.7 ± 3.2 %		$u\tilde{\chi}^-_1$	63.9 ± 5.2 %
	$d\tilde{\chi}^+_2$	1.4 ± 0.7		$u\tilde{\chi}^-_2$	4.0 ± 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	4.9%	1.3%
SUSY-QCD Yukawa coupling in $\tilde{q}_L \tilde{g}$ background	2.4%	1.2%
PDF uncertainty (estimate)	$\sim$ 10%	2.4%
NNLO corrections*	8%	2.0%
Squark mass $\Delta m = 10$ GeV	6%	1.5%
BR$[\tilde{q}_L \to q' \tilde{\chi}_1^{\pm}]$	8.2%	2.0%
	17.3%	4.1%

* 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 $\lesssim \mathbf{1\%}$ 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 $\sim \mathbf{4\%}$