

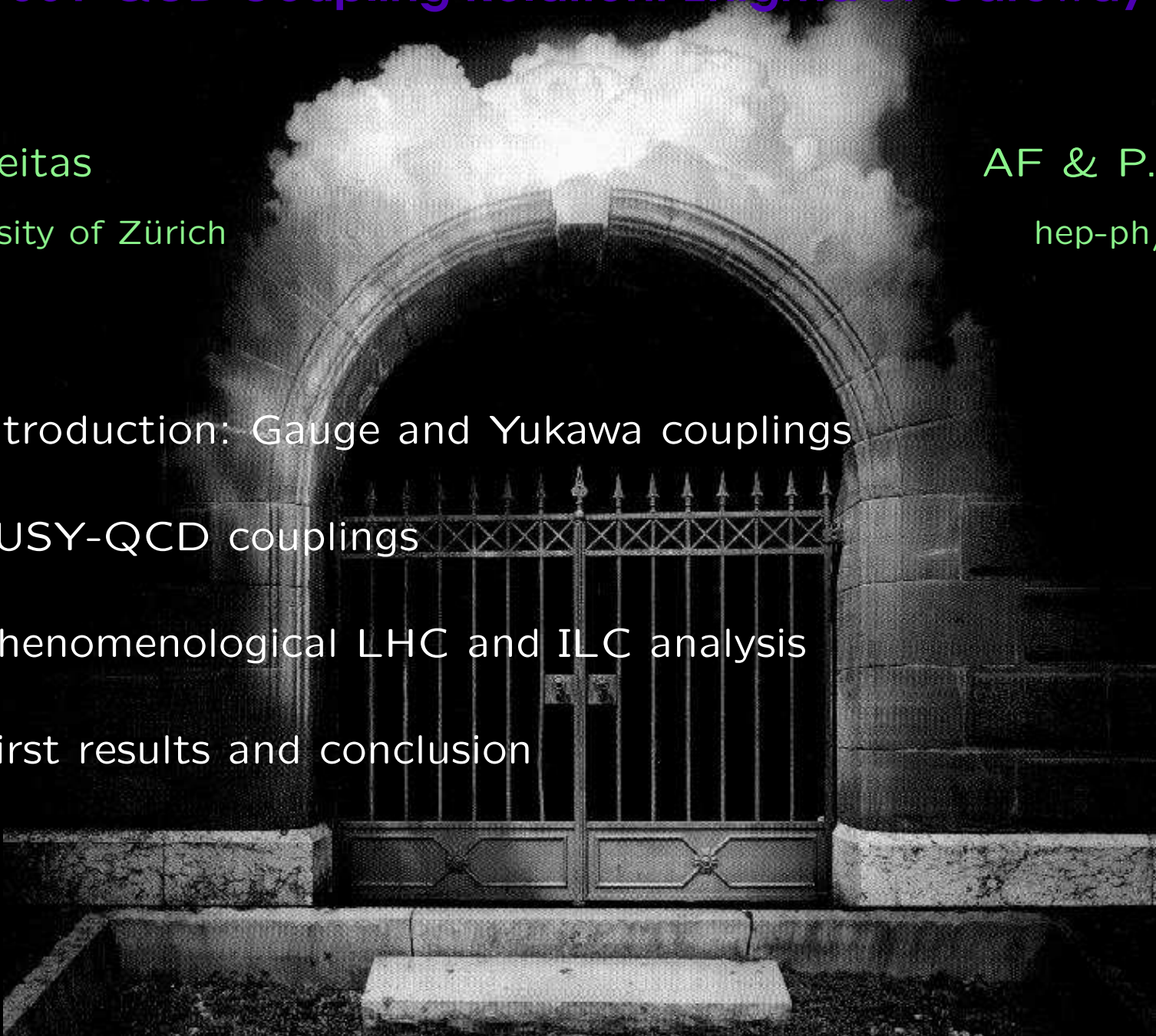
The SUSY-QCD Coupling Relation: Enigma or Gateway?

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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
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1. Introduction: Gauge and Yukawa couplings

Fundamental relation in supersymmetry:

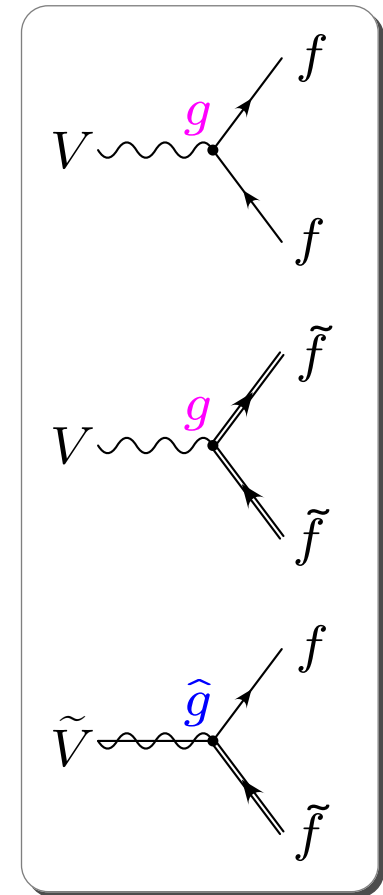
$$\text{Gauge coupling } g = \text{Yukawa coupling } \hat{g}$$

→ required to resolve hierarchy problem

Establish SUSY experimentally:

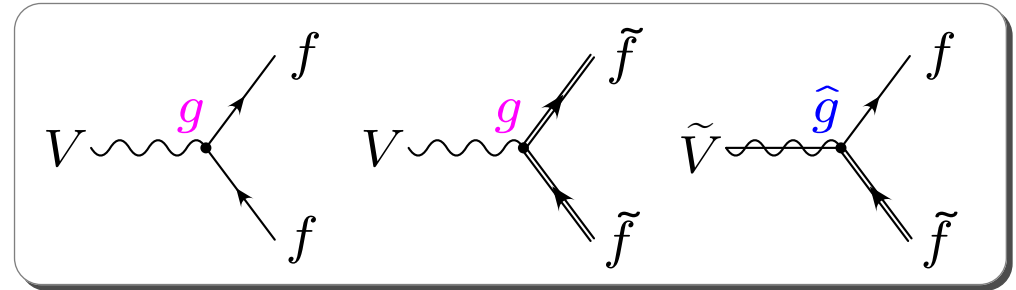
- Find new particles
- Measure their spin, masses, ...
- **Test SUSY coupling relations**
 - compare precise cross-section measurements with theoretical predictions

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

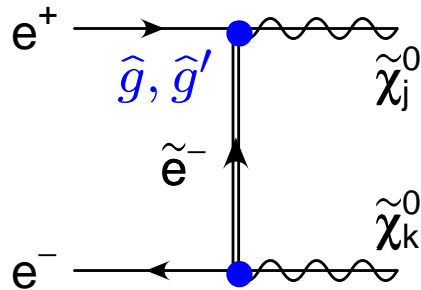


SUSY couplings in the electroweak sector

Electroweak couplings can be probed at % level in

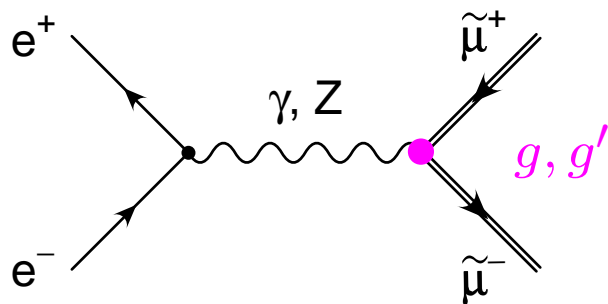


- Neutralino production

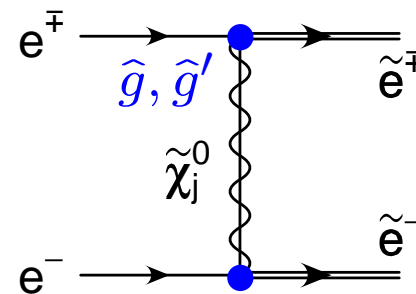


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production



Freitas, v.Manteuffel, Zerwas '03

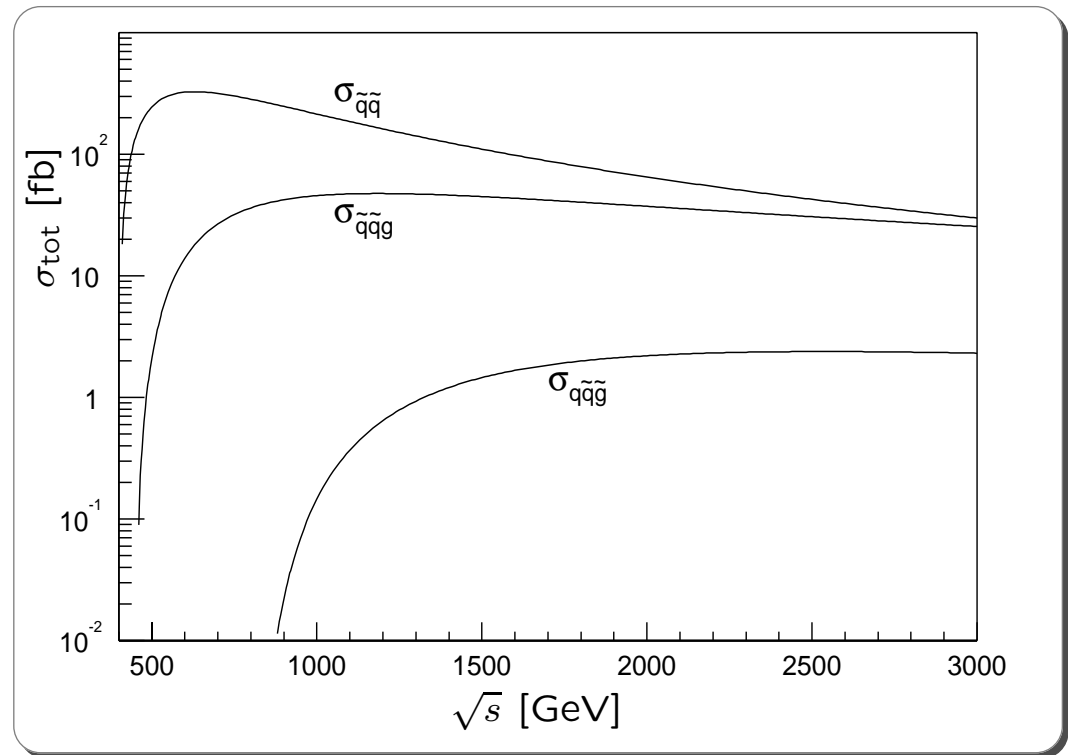
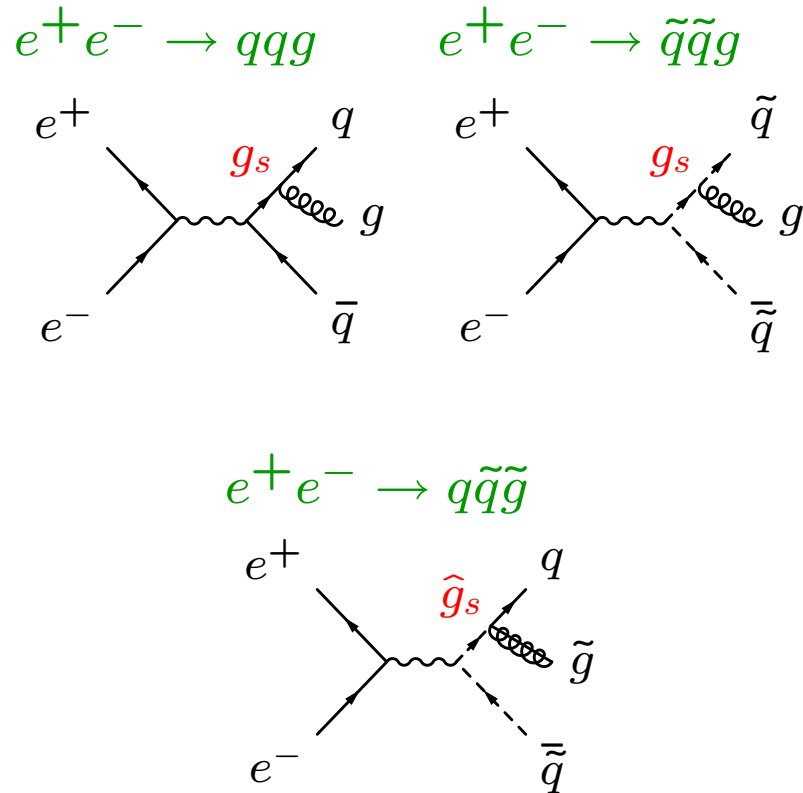


g' U(1) coupl.
 g SU(2) coupl.

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



Testing SUSY-QCD couplings at ILC vs. LHC

Difficult in practice:

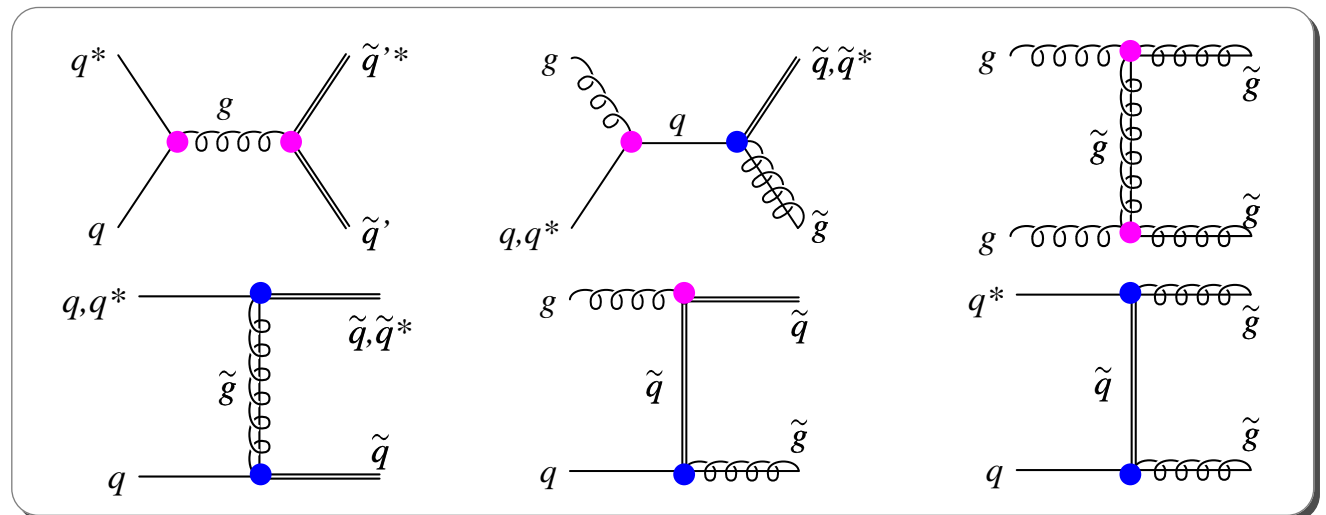
- Need large center-of-mass energy $\mathcal{O}(2 \text{ TeV})$
- Small cross-section for $q\tilde{q}\tilde{g}$ production
 - including BRs the statistics might be too low to separate from background

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:

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

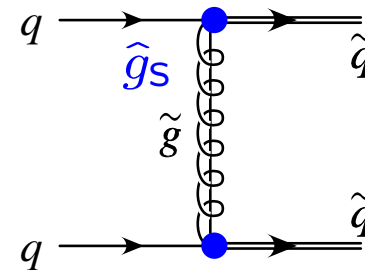
Tagging of squark charge
through chargino decay chain:

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

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 $m_{\tilde{g}} - m_{\tilde{q}_L}$ sufficiently large to cut on extra jet !!



Phenomenological LHC and ILC analysis

Scenario similar to [SPS1a](#), but with larger gluino mass

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

→

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

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
- $\tilde{q}\tilde{q}$ 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

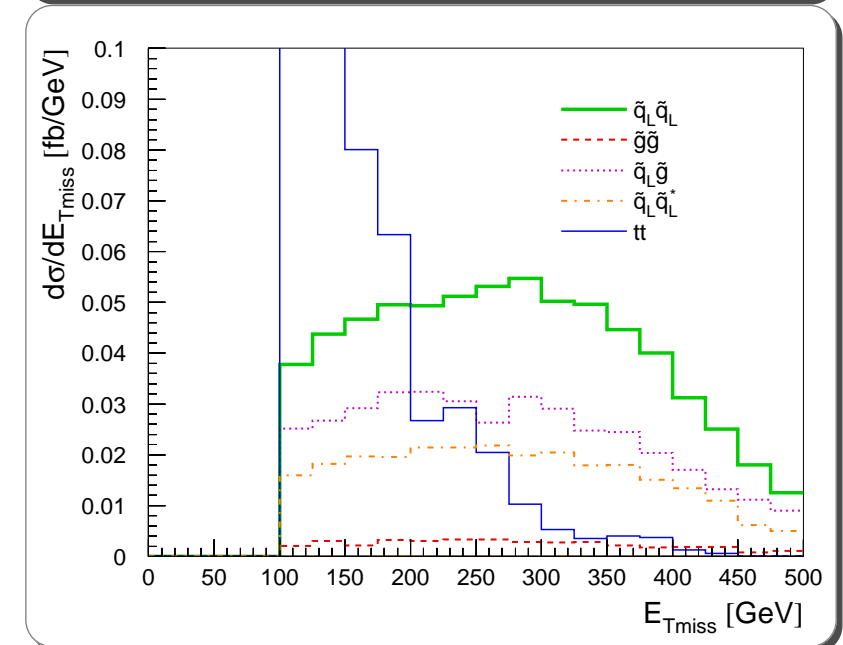
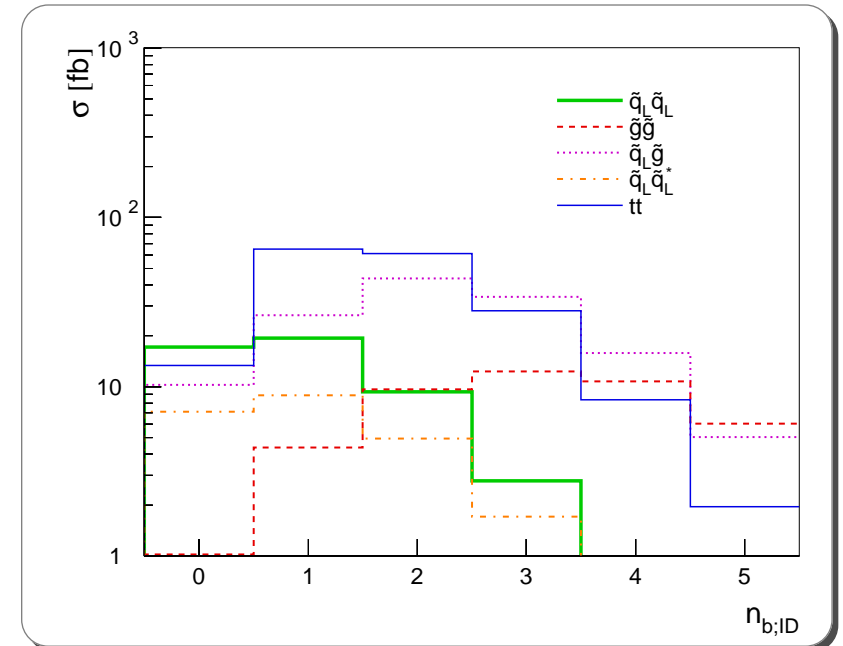
2. b-tagging to reduce $t\bar{t}$

efficiency 90%, u, d mistag 25%

ATLAS TDR '99

3. $\cancel{E} > 150$ GeV to cut SM background

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

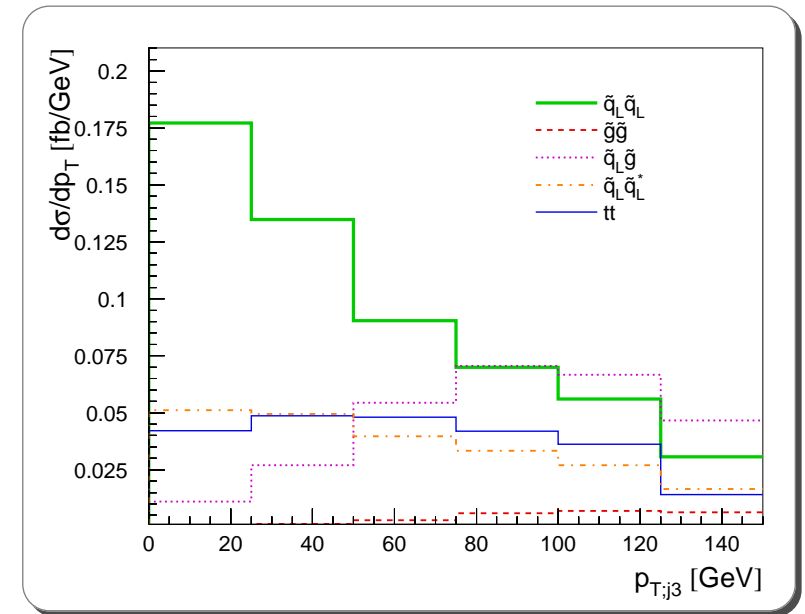


Selection of signal at LHC

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

Remaining cross-sections:

$\tilde{q}_L \tilde{q}_L$	6.9 fb	$S/B = 1.45$ with 100 fb^{-1} : $\Delta_{\text{stat}} = 4.9\%$
$\tilde{q}_L \tilde{q}_L^*$	2.3 fb	
$\tilde{q}_L \tilde{g}$	0.8 fb	
$\tilde{g}\tilde{g}$	0.03 fb	
SM	1.6 fb	



Alternative cut strategy: Minimize background

Only positive leptons since signal is uu dominated

$\tilde{q}_L \tilde{q}_L$	4.8 fb	$\tilde{g}\tilde{g}$	0.01 fb	$S/B = 1.6$ $\Delta_{\text{stat}} = 5.8\%$
$\tilde{q}_L \tilde{q}_L^*$	1.4 fb			
$\tilde{q}_L \tilde{g}$	0.5 fb	SM	1.1 fb	

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:

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

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

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

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

Assume 80% τ 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 particles from two-body decays

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

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

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

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	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%
$\text{BR}[\tilde{q}_L \rightarrow q' \tilde{\chi}_1^\pm]$	8.2%	2.0%
	17.3%	4.1%

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

Conclusions

- Quest 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 $\sim 4\%$

