Probing the SUSY-QCD coupling identity at LHC

A. Freitas

University of Zürich

with P. Skands

hep-ph/0606121

with P. Skands, M. Spira and P. Zerwas

hep-ph/0703160

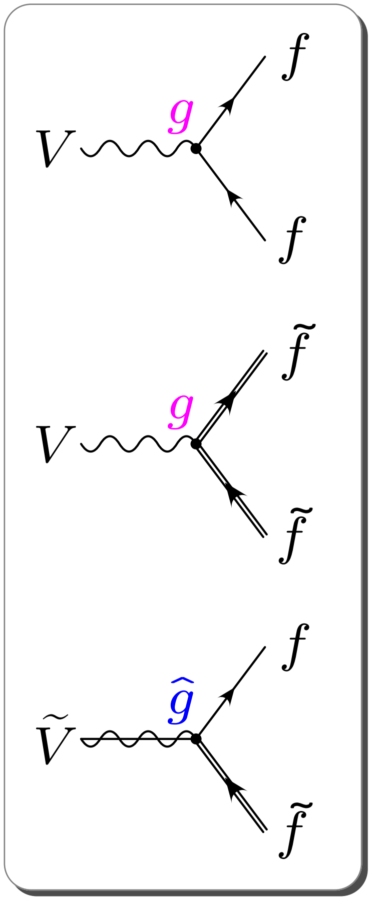
1. Introduction: Supersymmetry, gauge and Yukawa couplings
2. Some comments about ILC
3. Phenomenological analysis for LHC
4. Results for three cases:
    - Maximal model assumptions
    - Medium assumptions
    - (Almost) no assumptions

Supersymmetric couplings

Fundamental relation in supersymmetry:

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

→ not broken by SUSY breaking
required to resolve hierarchy problem

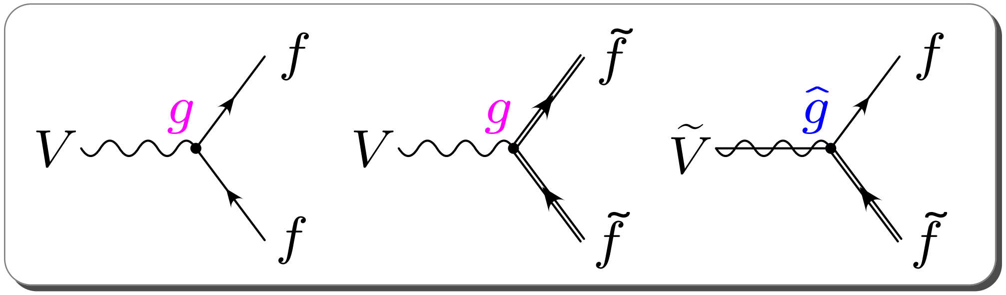


Establish SUSY experimentally:

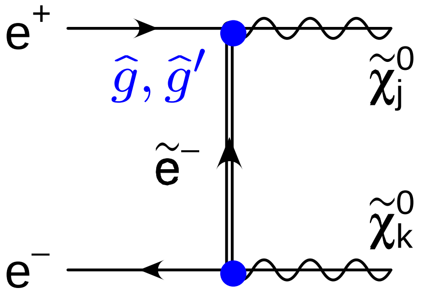
- Find new particles
- Measure their spin, masses, ...
- **Test SUSY coupling relations**
  → compare precise cross-section measurements with theoretical predictions

SUSY couplings in the electroweak sector

Electroweak couplings
can be probed at **%** level in



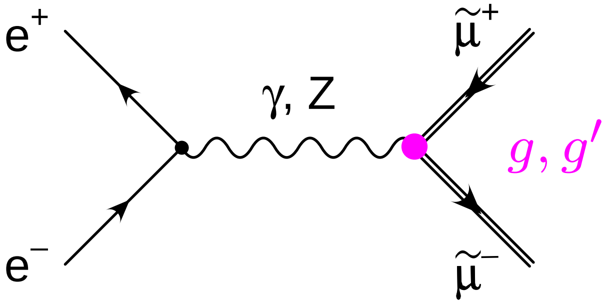
- Neutralino production

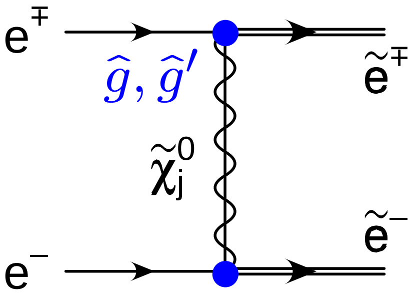


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production

Freitas, v.Manteuffel, Zerwas '03





g' U(1) coupl.

g SU(2) coupl.

Testing SUSY-QCD couplings at ILC vs. LHC

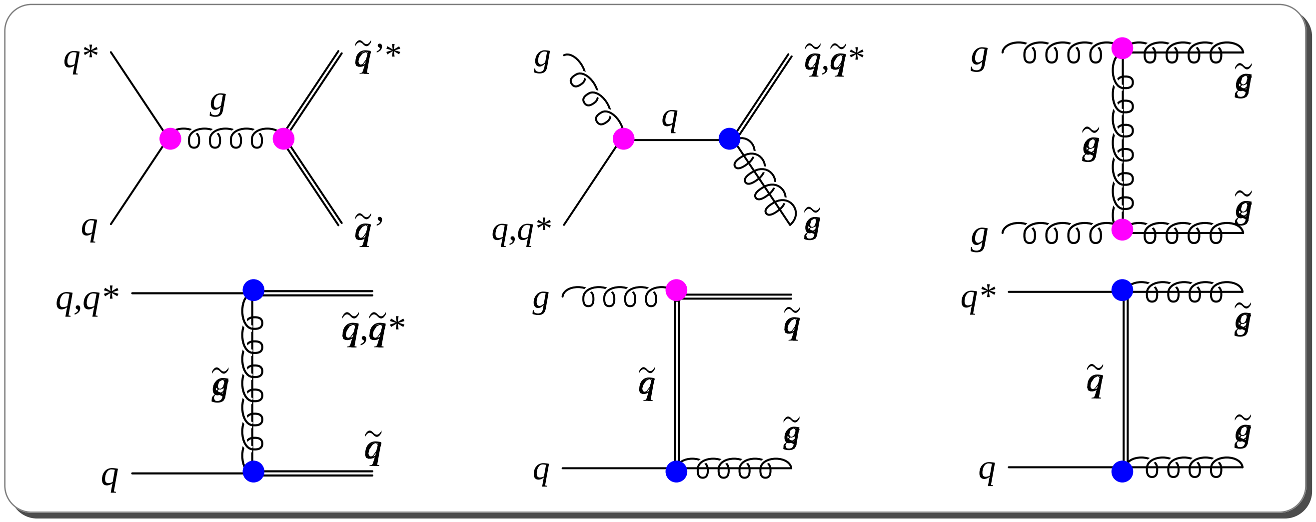
Difficult at e^+e^- colliders: Brandenburg, Maniatis, Weber '02

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

- Need large center-of-mass energy $\mathcal{O}$(2 TeV)
- Small cross-section $\mathcal{O}$(fb) for $q\tilde{q}\tilde{g}$ production
  → including BRs the statistics very low compared to background

Alternative: Measure QCD production process at LHC

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



gauge coupling g_s

Yukawa coupling $\hat{g}_s$

Signal processes at LHC

Maximal information when tracking squark charges

Tagging of squark charge
through chargino decay chain:

$$\tilde{u}_{\mathrm{L}} \to d\,\tilde{\chi}_1^+ \to d\,l^+\,\nu_l\,\tilde{\chi}_1^0$$
$$\tilde{d}_{\mathrm{L}} \to u\,\tilde{\chi}_1^- \to u\,l^-\,\bar{\nu}_l\,\tilde{\chi}_1^0$$

Signature: Two $\underbrace{\text{same-sign}}_{\text{Reduces SM background}}$ leptons, two hard jets, missing energy

Contributing processes:

$$\begin{array}{l} pp \to \tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{L}} \\ \left.\begin{array}{l} pp \to \tilde{q}_{\mathrm{L}}\tilde{g} \\ pp \to \tilde{g}\tilde{q}_{\mathrm{L}} \end{array}\right\} \tilde{g} \to q\,\tilde{q}_{\mathrm{L}} \end{array}$$

Problem: Separate $\tilde{q}$ from $\tilde{g}$ production

→ Gluinos produce extra (hard) jet:

$$\tilde{g} \to q\,\tilde{q}_{\mathrm{L}}$$

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

Benchmark scenario

Scenario similar to SPS1a, but with larger gluino mass

$$\begin{array}{lll} M_1 = 99 & m_{\mathrm{L}} = 197 & m_{\mathrm{Q1}} = 540 \\ M_2 = 193 & m_{\mathrm{R}} = 136 & m_{\mathrm{U1}} = 522 \\ M_3 = 700 & \tan\beta = 10 & m_{\mathrm{D1}} = 520 \\ \mu = 352 & A_\tau = -254 & \end{array} \quad \rightarrow \quad \begin{array}{ll} m_{\tilde{u}_{\mathrm{L}}} = 537 & m_{\tilde{\chi}_1^0} = 96 \\ m_{\tilde{d}_{\mathrm{L}}} = 543 & m_{\tilde{\chi}_2^0} = 177 \\ m_{\tilde{\tau}_1} = 133 & m_{\tilde{\chi}_1^\pm} = 176 \\ m_{\tilde{g}} = 700 & m_{\tilde{\chi}_{3,4}^0} \sim 360 \end{array}$$

Interesting decay chain:

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

LHC backgrounds:

$t\bar{t}$

$W^\pm W^\pm jj$

$(W^\pm Z)$

Cuts:

veto on bottom jets

2 jets with $p_{\mathrm{T,jets}} > 200$ GeV

$\not{E} > 300$ GeV

Analysis I: Total cross-section

Cross-sections after cuts:

$\tilde{q}_{\mathsf{L}}\tilde{q}_{\mathsf{L}}$	$\tilde{q}_{\mathsf{L}}\tilde{q}^*_{\mathsf{L}}$	$\tilde{q}_{\mathsf{L}}\tilde{g}$	$\tilde{g}\tilde{g}$	SM	with 300 fb^{-1}:
6.1 fb	3.1 fb	5.8 fb	0.8 fb	0.6 fb	$\sim$ 5000 signal events

Interpretation in terms of Yukawa coupling $\hat{g}_{\mathsf{s}}$:

Use cross-section formulae with $\hat{g}_{\mathsf{s}}$ as variable parameter

	$\delta[\hat{g}_{\mathsf{s}}/g_{\mathsf{s}}]$
Statistics for 300 fb^{-1}	0.6%
PDF uncertainty	1.4%
NNLO corrections*	2.0%
Mass measurements $\Delta m_{\tilde{q}} = 10$ GeV	2.0%
$\Delta m_{\tilde{g}} = 12$ GeV	1.0%
	3.4%

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

Analysis II: Cross-section ratios

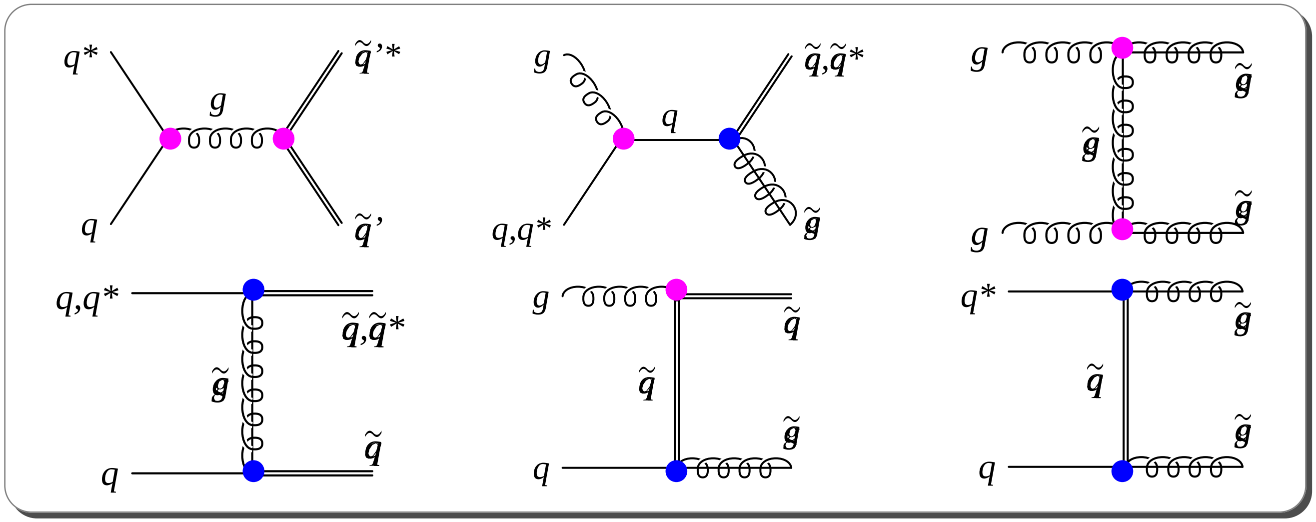
Measure not absolute cross-section, but ratio of cross-sections

Use all processes that can lead to same-sign lepton signal

$\tilde{g} \longrightarrow q\,\tilde{q}_\mathsf{L}$

gauge coupling g_S

Yukawa coupling $\hat{g}_\mathsf{S}$



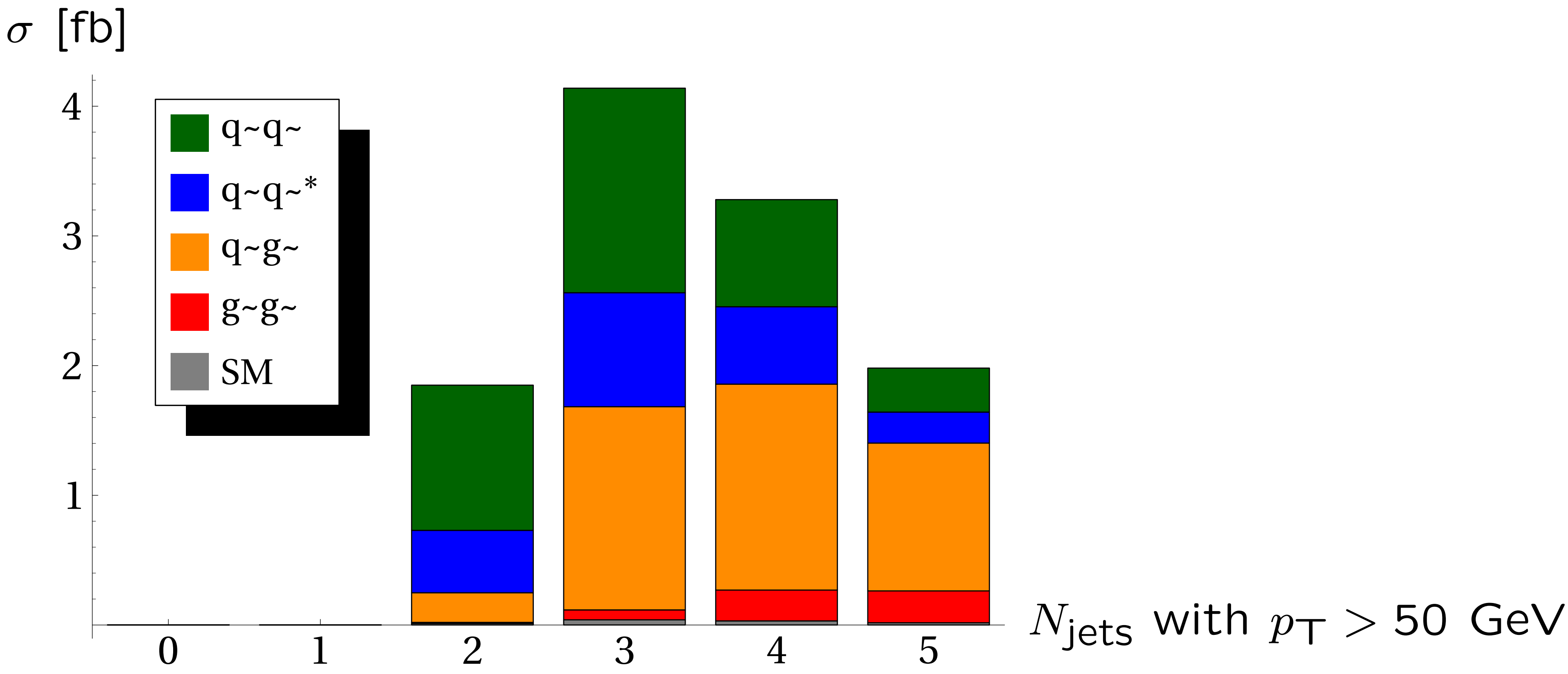
$$\sigma[\tilde{q}\tilde{q}] \sim \hat{g}_\mathsf{S}^4$$
$$\sigma[\tilde{q}\tilde{q}^*] \sim A\hat{g}_\mathsf{S}^4 + Bg_\mathsf{S}^4$$

$$\sigma[\tilde{q}\tilde{g}] \sim \hat{g}_\mathsf{S}^2 g_\mathsf{S}^2$$

$$\sigma[\tilde{g}\tilde{g}] \sim A'\hat{g}_\mathsf{S}^4 + B'g_\mathsf{S}^4$$

Analysis II: Cross-section ratios

Can distinguish processes by dependence on extra jets



Analysis II: Cross-section ratios

- CP and weak isospin invariance:

$$\Rightarrow \quad \mathrm{BR}[\tilde{u}_\mathrm{L} \to d\tilde{\chi}_1^+] \approx \mathrm{BR}[\tilde{d}_\mathrm{L} \to u\tilde{\chi}_1^-]$$

in SPS1a: 65% $\approx$ 61%

- But: Large bino-wino mixing in neutralino sector can cause

$$\Gamma_\mathrm{tot}[\tilde{u}_\mathrm{L}] \neq \Gamma_\mathrm{tot}[\tilde{d}_\mathrm{L}]$$

$\tilde{\chi}^0$ mixing is small for large hierarchy $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0} \gg m_{\tilde{\chi}_1^0}$
(Can be tested at LHC/ILC)

Note: Signal selection depends on $m_{\tilde{g}} \gg m_{\tilde{q}} \gg m_{\tilde{\chi}_1^\pm} \gg m_{\tilde{\chi}_1^0}$

- Can also allow new electroweak singlets (e.g. NMSSM), since they modify $\Gamma_\mathrm{tot}[\tilde{u}_\mathrm{L}]$ and $\Gamma_\mathrm{tot}[\tilde{d}_\mathrm{L}]$ identically

Analysis II: Cross-section ratios

- Need to know $\mathrm{BR}[\tilde{g} \longrightarrow q\,\tilde{q}_{\mathrm{L}}]$

$$\mathrm{BR}[\tilde{g} \longrightarrow q\,\tilde{q}_{\mathrm{L}}] = \mathrm{const.} \times \hat{\alpha}_{\mathrm{s}} \frac{(m_{\tilde{g}}^2 - m_{\tilde{q}_{\mathrm{L}}}^2)^2}{m_{\tilde{g}}^3}$$

  Depends only on squark and gluino masses

- Decays into heavy flavour, $\tilde{g} \longrightarrow b\tilde{b}$, $\tilde{g} \longrightarrow t\tilde{t}$ are difficult due to mixings

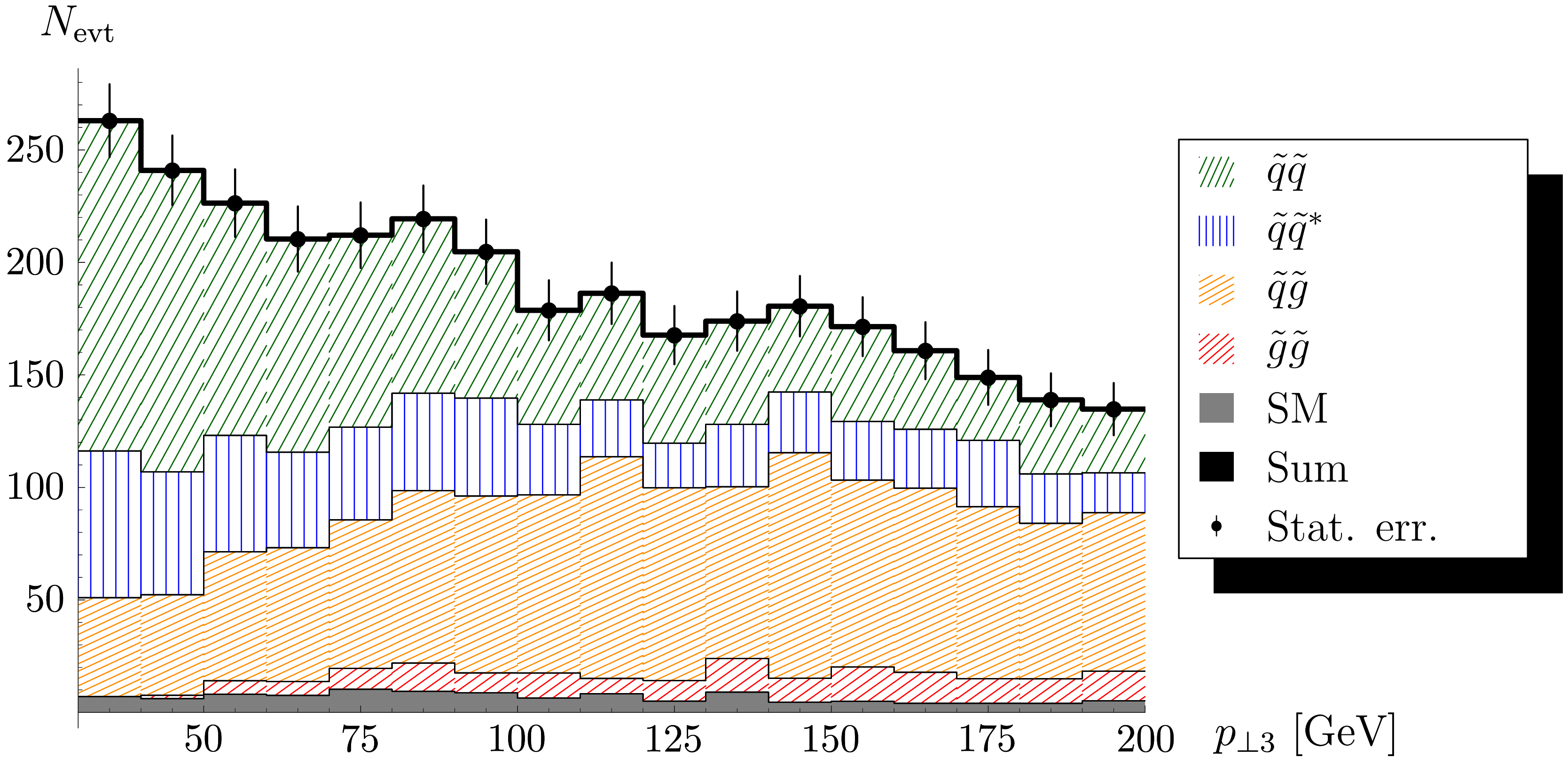
  → Reject with b veto

3rd jet radiation

Dependence on $p_{\mathrm{T,j3}}$:

Cuts to remove SM bkgd.:

$p_{\mathrm{T,j}} > 200$ GeV
$\not{E} > 300$ GeV
b-tagging



(for 300 fb^{-1})

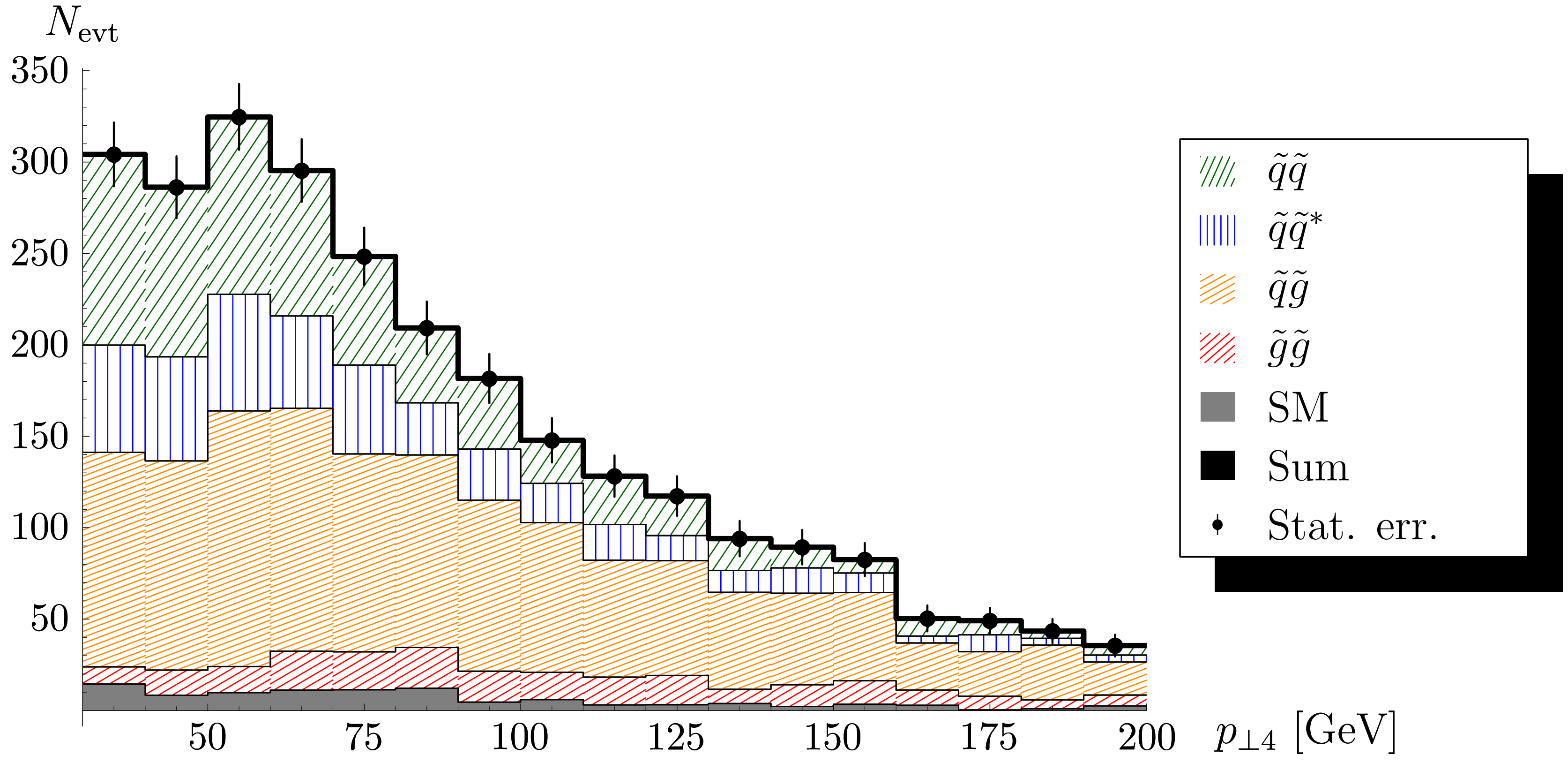
4th jet radiation

Cuts to remove SM bkgd.:

$p_{\mathrm{T,j}} > 200$ GeV
$\not{E} > 300$ GeV
b-tagging

Dependence on $p_{\mathrm{T,j4}}$:

$p_{\mathrm{T,j3}} > 50$ GeV

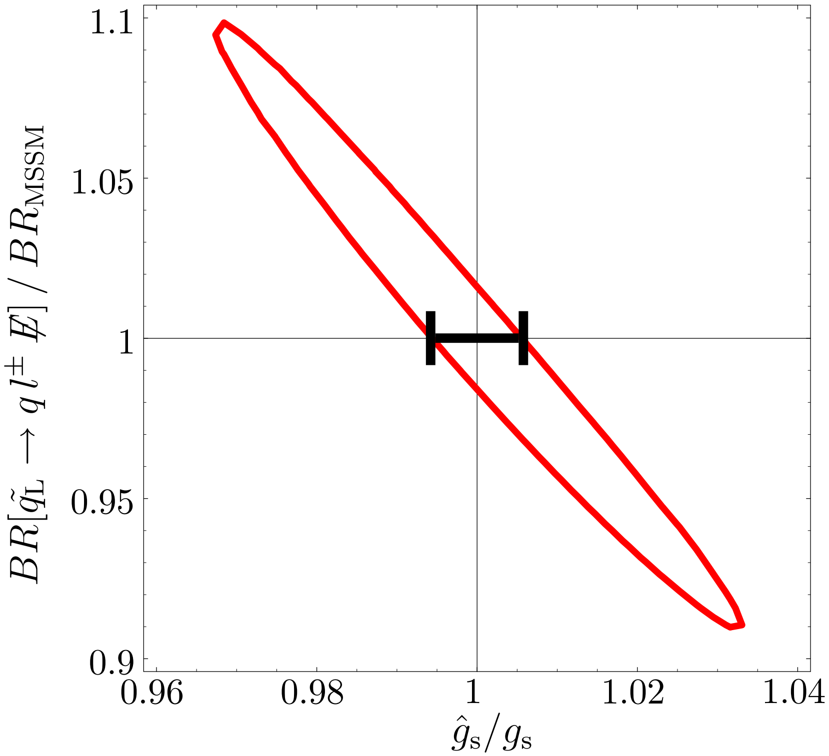


(for 300 fb^{-1})

Analysis II: Results

Fit independently $\widehat{g}_{\mathsf{s}}/g_{\mathsf{s}}$ and $\mathsf{BR}[\tilde{q}_{\mathsf{L}} - > q\, l^{\pm} \not{E}]$

error on	$\delta[\widehat{g}_{\mathsf{s}}/g_{\mathsf{s}}]$
Statistics for 300 fb^{-1}	3.3%
PDF uncertainty	2.9%
NNLO corrections	3.1%
$\Delta m_{\tilde{q}} = 10$ GeV	1.1%
$\Delta m_{\tilde{g}} = 12$ GeV	2.0%
	5.9%



Analysis III: Generalized picture

- Allow arbitrary $\tilde{\chi}^0$ mixing

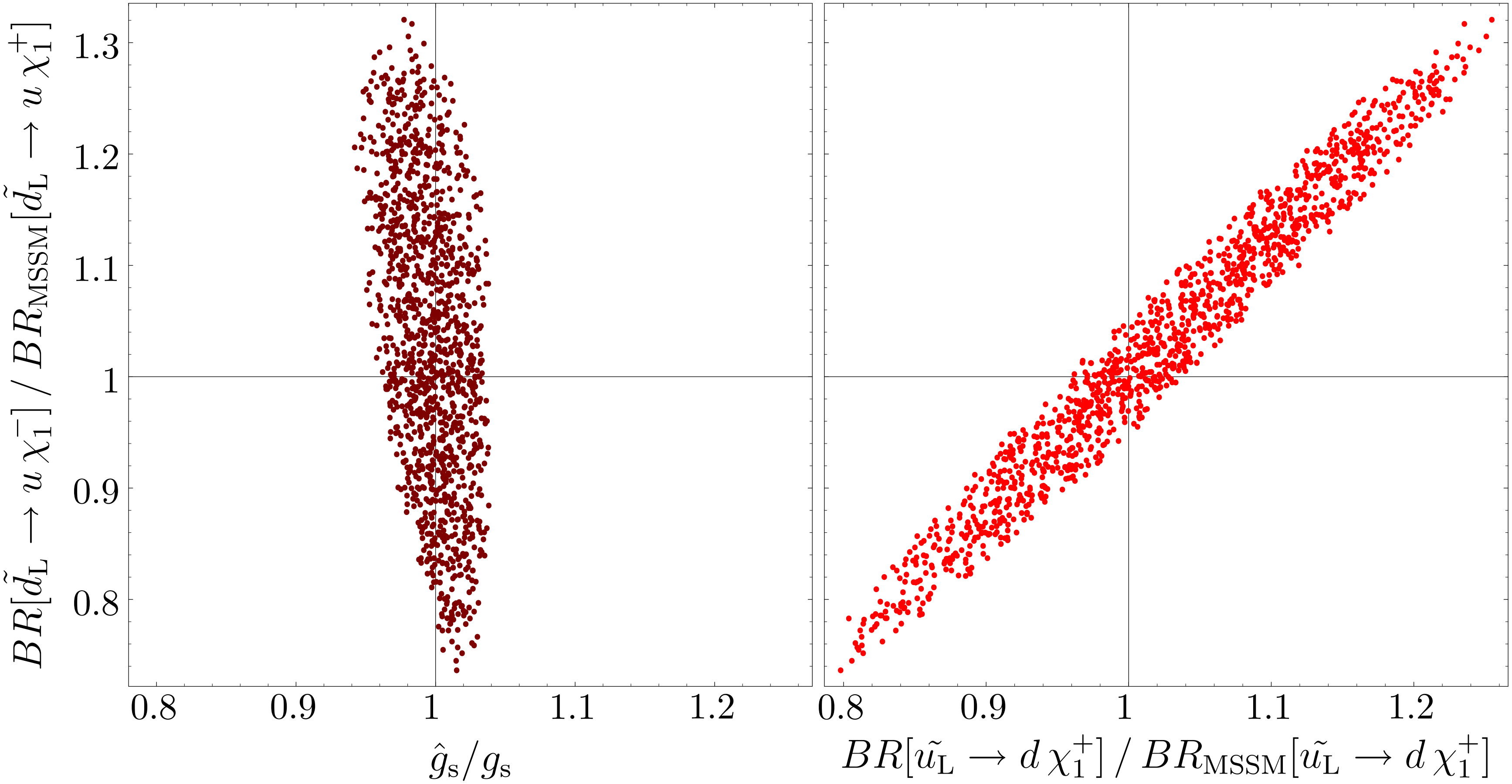
  $\rightarrow$ $BR(\tilde{u}_L \rightarrow \tilde{\chi}_1^+)$ and $BR(\tilde{d}_L \rightarrow \tilde{\chi}_1^-)$ undetermined

- Use in addition to p_T spectra also ratio of l^+l^+/l^-l^- in signal
  - $\tilde{\chi}_i^0$ give equal contribution to l^+l^+ and l^-l^-
  - Only $\tilde{\chi}_1^\pm$ create difference between l^+l^+ and l^-l^-

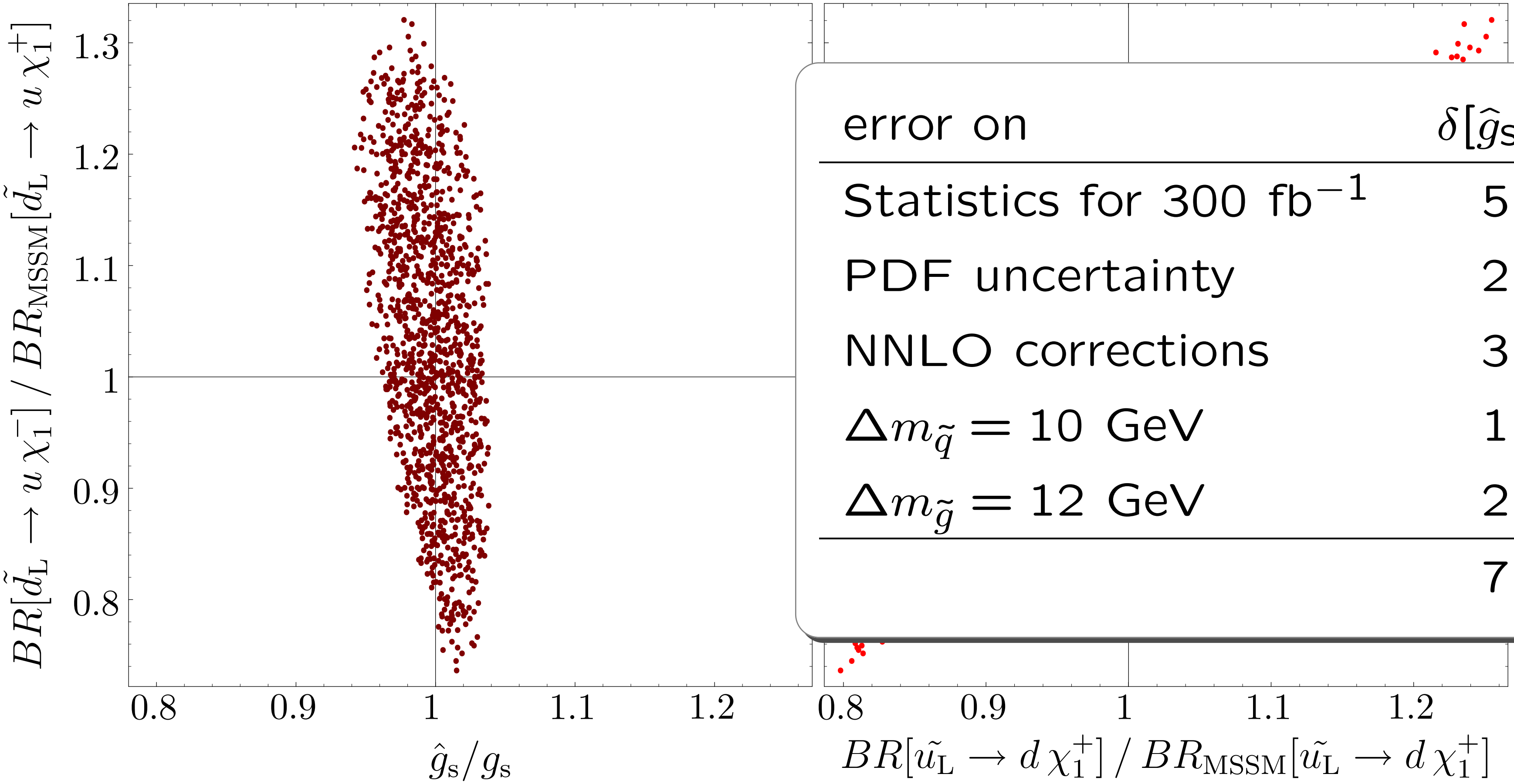
- Separate determination of $BR(\tilde{u}_L \rightarrow \tilde{\chi}_1^+)$ and $BR(\tilde{d}_L \rightarrow \tilde{\chi}_1^-)$ difficult

  $\rightarrow$ Small sensitivity to squark flavour from PDF effects

Analysis III: Results



Analysis III: Results



error on	$\delta[\hat{g}_s/g_s]$
Statistics for 300 fb^{-1}	5.7%
PDF uncertainty	2.9%
NNLO corrections	3.1%
$\Delta m_{\tilde{q}} = 10$ GeV	1.1%
$\Delta m_{\tilde{g}} = 12$ GeV	2.0%
	7.5%

Conclusions

- Quest for SUSY involves the test of SUSY coupling relations:

  Fundamental identity
  gauge coupling = Yukawa coupling

- Using a dedicated LHC analysis, the strong SUSY coupling identity can be tested to the **%** level

  I: Full knowledge about model spectrum: $\delta\hat{g}_{\mathrm{s}} \sim 3.4\%$
  II: Assuming only $\tilde{\chi}^0$ mass hierarchy: $\delta\hat{g}_{\mathrm{s}} \sim 5.9\%$
  III: Allowing (almost) general N^{n}MSSM: $\delta\hat{g}_{\mathrm{s}} \sim 7.5\%$

- Encouraging prospects, but depends strongly on SUSY scenario!

Backup slides

Analysis I: Total cross-section

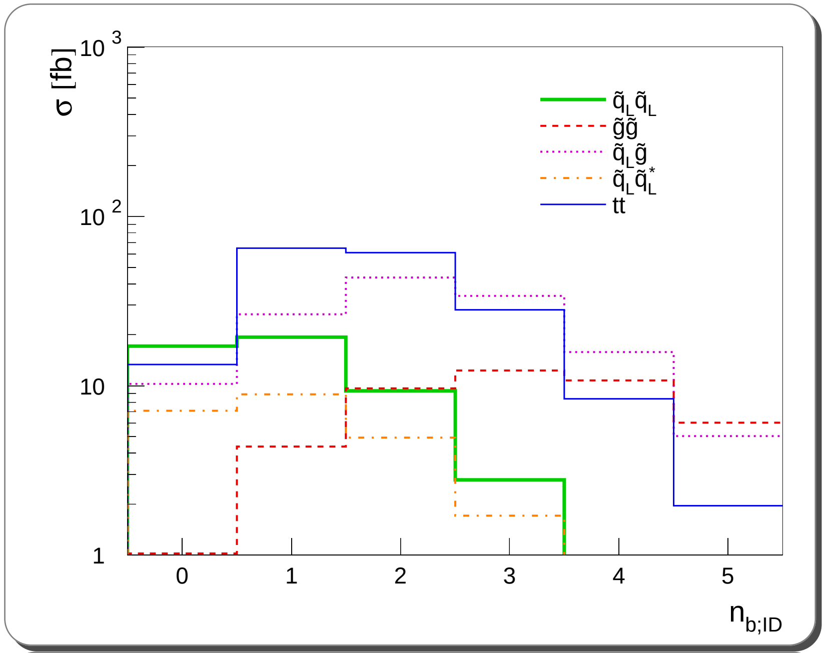
Assume that all squark BRs known
(or from e^+e^- collider)

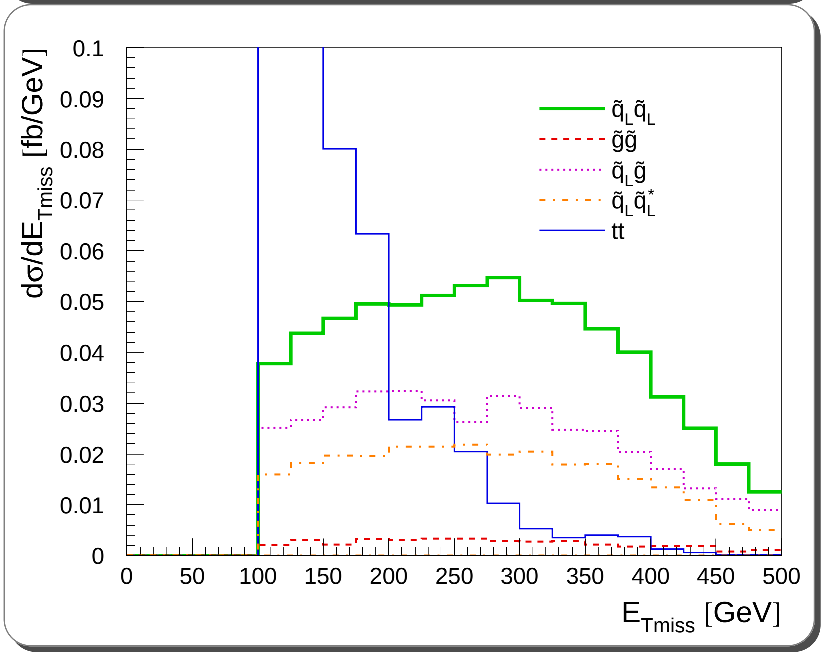
Selection of same-sign squark signal

1. at least 2 jets with $p_{\mathrm{T,j}} > 200$ GeV
   2 same-sign leptons, $p_{\mathrm{T,l}} > 7$ GeV

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

3. $\not{E} > 300$ GeV to cut SM background

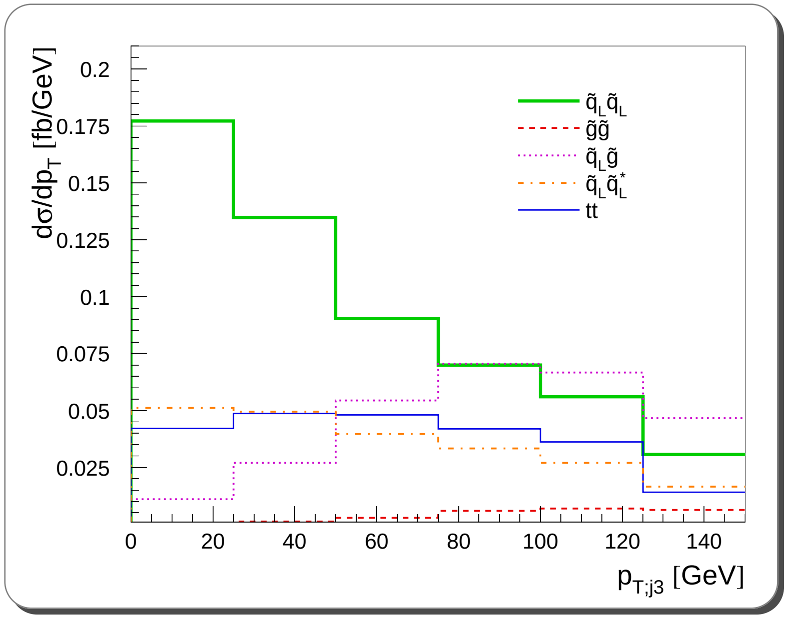




Analysis I: Total cross-section

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

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



Remaining cross-sections:

$\tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{L}}$	6.1 fb
$\tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{L}}^*$	3.1 fb
$\tilde{q}_{\mathrm{L}}\tilde{g}$	5.8 fb
$\tilde{g}\tilde{g}$	0.8 fb
SM	0.6 fb

with 300 fb^{-1}:

$\sim$ 5000 signal events

$\Delta_{\mathrm{stat}} = 1.5\%$ on total cross-section

Interpretation in terms of Yukawa coupling $\hat{g}_{\mathrm{s}}$:

Use cross-section formulae with $\hat{g}_{\mathrm{s}}$ as variable parameter

$\rightarrow \Delta\hat{g}_{\mathrm{s}} = 0.6\%$

Input from linear collider

Branching ratios in LHC decay chain:

$\tilde{u}_\mathsf{L} \to d\,\tilde{\chi}_1^+,\ \tilde{d}_\mathsf{L} \to u\,\tilde{\chi}_1^-,\ \tilde{\chi}_1^+ \to \tau^+\nu_\tau$

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

→ 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:

$\tilde{\chi}_1^+ \to \tau^+\nu_\tau\tilde{\chi}_1^0$	(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%)

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

Input from linear collider

Dominant SM background from $t\bar{t}$ and VV or VVV production

Can be reduced by cuts on $\not{E}$, E_j and m_jj

From generator-level analysis of signal and background:

($\sqrt{s} = 1.5$ TeV and $\mathcal{L} = 500$ fb^{-1})

$\tilde{u}_\mathsf{L} \rightarrow d\tilde{\chi}_1^+$ 67.7 ± 3.2 % $\tilde{d}_\mathsf{L} \rightarrow u\tilde{\chi}_1^-$ 63.9 ± 5.2 %

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}:

$\tilde{u}_\mathsf{L} \to$	$u\tilde{\chi}^0_1$	0.9 ± 0.5 %	$\tilde{d}_\mathsf{L} \to$	$d\tilde{\chi}^0_1$	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 %