Non-Simplified SUSY: Stau Coannihilation at LHC and ILC

M. Berggren, A. Cakir, J. List, A. Lobanov, I.-A. Melzer-Pellmann

Snowmass 2013
Seattle Workshop
Outline

Introduction

- LHC Analyses
- ILC Analyses
- Summary
Snowmass 2013

Input from all frontiers:

Chip Brock: “Accomplish the goals by evaluating the physics... and telling stories”
Energy Frontier Goals (from Chip Brock)

**EF Goals:**

I. **What scientific targets can be achieved before ~2018?**
   
   *at design specifications with $\int dt \sim 100 \text{ fb}^{-1}$?*

II. **What are the scientific cases which motivate HL LHC running:**

   - "Phase 1": circa 2022 with $\int dt \sim 300 \text{ fb}^{-1}$
   - "Phase 2": circa 2030 with $\int dt \sim 3000 \text{ fb}^{-1}$

   How do the envisioned upgrade paths inform those goals?
   Specifically, to what extent is precision Higgs Boson physics possible?

III. **Is there a scientific necessity for a “Higgs Factory”?**

IV. **Is there a scientific case today for experiments at higher energies beyond 2030?**

   - A high energy LHC?
   - High energy lepton collider?
   - Lepton-hadron collider?
   - VLHC?
Energy Frontier Goals (from Chip Brock)

**EF Goals:**

I. **Articulate to scientific audiences**
   
   *To other Particle Physicists:*
   
   EF science in the context of the Intensity and Cosmic Frontiers’ goals

   *To other scientists*

II. **Justify to governmental audiences**
   
   OHEP, EPP, OSTP, Congress...beyond our direct agencies

   Not only science, but the internationalization of science

III. **Explain to non-specialist audiences**
   
   Universities

   Public
   
   Lectures
   
   Written documentation
   
   Attractive on-line presence
Storyline

- What if LHC sees some kind of signal, but cannot distinguish between
  - Is it SUSY or other BSM models?
  - Is it more than one new particle?
  - What are the masses and other properties of the new particles?
  - Can LHC distinguish between different production processes?
  - Do we see THE dark matter?

- Can ILC add information and see particles that LHC cannot see (or at least not distinguish)?
  - LHC: discovery of colored states
  - ILC: precise measurement of EW states
Choose a full model that is compatible with all recent observations, e.g.:

- Higgs @ 125 GeV
- Relic density
- Latest results of direct dark matter searches

Full model chosen as example here:
SUSY pMSSM model with small mass difference (10 GeV) between stau and LSP
- Four models with differing stop masses:

| Model name | Mass parameter of right-handed top quark / GeV | Stop mass / GeV |
|------------|----------------------------------------------|----------------|
| STC4       | 400                                          | 293            |
| STC5       | 500                                          | 416            |
| STC6       | 600                                          | 527            |
| STC8       | 800                                          | 736            |
Full Spectrum STC4

- Low stop mass → large direct stop production cross section
Relatively low stop mass $\rightarrow$ direct stop production cross section much smaller than in STC4
Full Spectrum STC6

EWkino production gains more weight
EWkino production has largest cross section
Lower part of STC8 Spectrum

- Many different decays at lower masses
Cross sections for all models

- Inclusive cross sections
  - LO calculated with Pythia6
  - NLO calculated for most sub-processes with Prospino2.1
  - STC4 dominated by direct stop production
  - EWkino cross sections quite dominating in the other scenarios
  - 33 TeV cross section to be taken with some caveat – PDFs not known here...
Sub-process cross sections for STC8

- NLO calculated where possible
- Gluino-gluino production
  \( \sim 0.2 \text{ fb} \)
  \( \rightarrow \) expect \( \sim 600 \) events at 3000 fb-1
- Direct production of first 2 generations \( \sim 20 \text{ fb} \)
  \( \rightarrow \) 60,000 events
  \( \rightarrow \) expect more sensitivity for these (e.g. search for high-energetic jets and MET, no b-tags)
- EWkino production dominates

![Graph showing cross sections for different processes at the LHC](image)
Where we are...

- Introduction
- LHC Analyses
- ILC Analyses
- Summary
Reach of current 8 TeV Analyses

- Full-hadronic analysis from ATLAS: ATLAS-CONF-2013-001
- \( m_{\text{stop}} = 293 \text{ GeV} \) and \( m_{N1} = 95 \text{ GeV} \) lies in excluded region, but...

![Diagram showing exclusion limits in the \( m_{\tilde{t}} - m_{\tilde{\chi}^0_1} \) plane for \( \Delta m = 5 \text{ GeV} \). The black, dashed line shows the expected limit if theoretical uncertainties on the signal are neglected. The yellow band shows the \( \pm 1 \sigma \) uncertainty on the expected limit. The red solid line shows the nominal observed limit, while the red dashed lines show its variation if theory uncertainties on the signal are taken into account.]

\[ \int L \, dt = 12.8 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]
Reach of current 8 TeV Analyses

Full-hadronic analysis from ATLAS: ATLAS-CONF-2013-001

Cut flow from ATLAS

| Description | Signal region |
|-------------|---------------|
| **SR1**     | **SR2**       | **SR3a** | **SR3b** |
| Trigger     | $E_T^{miss}$ trigger > 99% efficient for $E_T^{miss}$ > 150 GeV |
| Event cleaning | Common to all SR |
| Lepton veto | No $e/\mu$ with $p_T > 10$ GeV |
| $E_T^{miss}$ | $>$ 150 GeV | $>$ 200 GeV | $>$ 150 GeV | $>$ 250 GeV |
| Leading jet $p_T (j_1)$ | $>$ 130 GeV, $|\eta| < 2.8$ | $>$ 60 GeV, $|\eta| < 2.8$ | $>$ 130 GeV, $|\eta| < 2.8$ | $>$ 150 GeV, $|\eta| < 2.8$ |
| Second jet $p_T (j_2)$ | $>$ 50 GeV, $|\eta| < 2.8$ | $>$ 60 GeV, $|\eta| < 2.8$ | $>$ 30 GeV, $|\eta| < 110$ GeV |
| Third jet $p_T (j_3)$ | veto event if $p_T (j_3) > 50$ GeV, $|\eta| < 2.8$ | $>$ 30 GeV, $|\eta| < 2.8$ |
| $\Delta\phi (E_T^{miss}, j_1)$ | . | . | > 2.5 |
| jet $b$-tagging ($|\eta| < 2.5$) | $j_1$ and $j_2$ tagged | $j_1$ anti-tagged, $j_2$ and $j_3$ tagged |
| $\Delta\eta_{tag}$ | $>$ 0.4 ($n=2$) | $>$ 0.4 ($n=3$) |
| $E_T^{miss}/m_{eff}(j, j_2, j_3)$ | . | . | > 0.25 |
| $m_{CT}$ | > 150, 200, 250, 300 GeV | > 100 GeV | . |
| $H_{T,x}$ | . | < 50 GeV, $x = 2$ | < 50 GeV, $x = 3$ |

Table 2 compares the SR1 selection efficiencies for sbottom production and the corresponding stop pair sample with a 100% branching ratio.

The mass difference between the stau and the sbottom is assumed to be either 5 or 20 GeV. The signal samples are generated using Pythia 6 [21], using the PDF set CT10.

The distributions of the third hardest jet and the number of leptons are shown in Figure 1.

The lepton veto decreases with increasing $x$-tagging $(|\eta| < 2.5)$, due to the presence of additional leptons passing the object trigger.

Here, we investigate the discovery reach for stop decays without leptons in the final state with analyses following the spirit of those currently performed by ATLAS [1] on the 2012 data. Signal and background are generated with Delphes 3.0.9 [8] as used by possible amount, we restrict ourselves here to a simple estimation based on the simulation of the above mentioned processes.

A comparison to the recent ATLAS analysis has been performed for the model expected number of signal events for STC4 as generated with Delphes Snowmass det.

No observation with current analysis expected
Reach of current 8 TeV Analyses

CMS EWkino Analysis PAS-SUS-12-022

Mass parameters outside excluded region for case with stau mass in middle of C1 and N1 (even worse if stau closer to N1)

STC4-8
LHC: Search for Stops

Simple cut-and-count analysis, inspired by ATLAS 8 TeV full-hadronic analysis:

- Lepton veto (no identified lepton with $p_T > 10$ GeV)
- $N_{jets} > 3$
  - Jet1: $p_T > 120$ GeV
  - Jet2: $p_T > 80$ GeV
  - Jet3: $p_T > 70$ GeV
- $N_{btag} \geq 2$
- $dPhi(MET, Jet_{1,2}) > 0.5$
- $MET/M_{eff} > 0.25$
- $H_T > 1000$ GeV
- $MET > 500$ GeV
LHC: Search for Stops

Control plots before cut on MET, MET/M_{eff}, \Delta\phi(Jet1,2 and MET):

Delphes samples \sqrt{s} = 14 TeV, \int L dt = 300 fb^{-1}

- No PU
- stop STC4
- stop STC5
- stop STC6
- stop STC8
- tt+jets
- boson+jets

Delphes samples \sqrt{s} = 14 TeV, \int L dt = 300 fb^{-1}

- No PU
- stop STC4
- stop STC5
- stop STC6
- stop STC8
- tt+jets
- boson+jets
LHC: Search for Stops

| Cut                     | STC4  | STC5  | STC6  | STC8  | tt+jets | boson+jets |
|-------------------------|-------|-------|-------|-------|---------|------------|
| Presel                  | 2703890 | 856200 | 617099 | 538800 | 1.80002e+08 | 1.58575e+10 |
| Lepton Veto             | 737193 | 233168 | 168517 | 146843 | 1.27979e+08 | 2.32575e+09 |
| nJets >= 3              | 708440 | 224098 | 161879 | 141136 | 5.92435e+07 | 8.25922e+08 |
| $P_T^{J1} > 120\text{GeV}$ | 685382 | 216777 | 156634 | 136497 | 5.57657e+07 | 8.25922e+08 |
| $P_T^{J2} > 70\text{GeV}$ | 600203 | 189834 | 137302 | 119709 | 4.56697e+07 | 5.25214e+08 |
| $P_T^{J3} > 60\text{GeV}$ | 16927  | 131541 | 95454  | 83011  | 2.56063e+07 | 3.25545e+07 |
| btags >= 2              | 244239 | 76559  | 56190  | 48563  | 1.40112e+06 | 1.39993e+06 |
| HT > 1000 GeV           | 244239 | 76559  | 56190  | 48563  | 1.40112e+06 | 1.39993e+06 |
| min($\Delta \Phi$) > 0.5 | 7601   | 2306   | 1739   | 1528   | 1087     | 1053       |
| MET/M_{eff} > 0.2       | 6243   | 1875   | 1409   | 1253   | 177      | 496        |

Delphes samples $\sqrt{s} = 14$ TeV, $L_{\text{int}} = 300$ fb$^{-1}$

Delphes samples $\sqrt{s} = 14$ TeV, $L_{\text{int}} = 300$ fb$^{-1}$
LHC: Search for Stops

- Good visibility for all four models!

- Expect same sensitivity for direct stop search with one lepton

- Full-hadronic search has better sensitivity to direct sbottom production (decay without leptons), while semi-leptonic search is expected to yield best sensitivity for stop → top N1

- Possibility to distinguish between stop and sbottom by comparison of these two analyses and measured cross sections

- Sensitivity to production of 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks enhanced by requiring no b-jet, but we expect SUSY background from 3\textsuperscript{rd} generation squarks (to be checked)!

- More methods for mass measurements etc. for a different spectrum described in: http://arxiv.org/pdf/hep-ph/0410364v1.pdf
LHC: Search for EWkinos

- Search for same-sign leptons coming from:
  - N2 C1 production, where
    - N2 \rightarrow \text{stau tau} \rightarrow \text{tau tau N1}
    - C1 \rightarrow \text{tau N1}
  - expect at least same-sign + additional lepton

- Rough comparison to same-sign analysis in PAS CMS-12-022
  - 8 TeV signal yields less than 10 Events for STC4 (where 11 are observed in data and compatible with BG expectation)
LHC: Search for EWkinos

Result for 300 fb⁻¹ and 14 TeV:

| Cut                      | \(\tilde{\chi}^±\tilde{\chi}_2^0\) Production only | Inclusive signal | Vectorboson+jets |
|--------------------------|-----------------------------------------------|------------------|------------------|
| Presel                   | 552000                                       | 702000           | 127910741        |
| 2lepton req              | 10625                                        | 13725            | 891459           |
| \(E_T^{miss} > 120\) GeV | 5606                                         | 7330             | 44378            |
| SS req                   | 921                                          | 1193             | 2908             |
| Z veto                   | 723                                          | 958              | 1552             |
| 120 GeV < \(E_T^{miss}\) < 200 GeV |                                  |                  |                  |
| no b-jet, \(N_{jet} \leq 2\) | 187                                          | 224              | 854              |
| 120 GeV < \(E_T^{miss}\) < 200 GeV |                                  |                  |                  |
| no b-jet, \(N_{jet} \leq 2\) | 150                                          | 171              | 849              |
| no third lepton          |                                              |                  |                  |
| \(E_T^{miss} > 200\) GeV | 394                                          | 519              | 402              |
| \(E_T^{miss} > 200\) GeV, no third lepton | 280                                          | 384              | 401              |

- EWkino production expected to be visible
- Depending on selection SUSY background or SM background larger
- An optimized selection is of course necessary to further distinguish the new particles
LHC will be able access all four models, but:

- it will be difficult to identify the nature of the access
- EWkino identification partly lacking SUSY background
- staus very difficult for LHC
- will need ILC to further identify particle masses etc.
Where we are...

- Introduction
- LHC Analyses
- ILC Analyses
- Summary
At ILC (@ 500 GeV), all sleptons and bosinos can be produced with reasonable cross section (inclusive for both polarizations about 3pb)
ILC: Stau_1 Measurement

- Very clean signal after few cleaning cuts
- Stau_1 can be measured with precision of 200 MeV

**Endpoint determination**

**Cross section determination**
using region between arrows
ILC: Stau_2 Measurement

Not only stau_1, but also stau_2 can be measured with high precision up to 5 GeV:

- endpoint determination
- cross section determination using region between arrows
ILC: Measurement of \( m_{\mu\mu} \)

Reconstruction of invariant di-muon mass \( \rightarrow \) edge for smuon

![Graph showing yield versus invariant di-muon mass](image)

- Standard Model Background \((\times 1)\)
- SUSY background \((\times 10)\)
- \( e^+ e^- \rightarrow \chi^0_1 \chi^0_2 \rightarrow \tilde{\mu} \mu \rightarrow \mu \mu \chi^0_1 (\times 100) \)
- \( e^+ e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^- \rightarrow \mu \chi^0_1 \mu \chi^0_1 (\times 10) \)
ILC: Measurement of smuon

Reconstruction of invariant di-muon mass → edge for smuon

\[
\chi^2 / \text{ndf} = 20.57 / 26
\]

| Parameter          | Value          |
|--------------------|----------------|
| Background (B)     | 55.22 ± 2.93   |
| Edge (E)           | 82.5 ± 0.0     |
| Width (S)          | 1.747 ± 0.402  |
| Signal Amplitude (A)| 47.1 ± 5.8    |
| Signal Tail (T)    | 0.2713 ± 0.0785|
| Background Exp (BE)| 0.9554 ± 0.0647|
| Background Slope (BS)| -79.82 ± 5.61 |
ILC: Measurement of smuon

Mu energy spectrum (smu_L)

![Graph showing mu energy spectrum with different backgrounds and yields.]

- Standard Model Background ($\times 1$)
- SUSY background ($\times 10$)
- $e^+e^- \rightarrow \chi^0_1 \chi^0_2 \rightarrow \mu \mu \mu \chi^0_1 (\times 100)$
- $e^+e^- \rightarrow \mu^+\mu^- \rightarrow \mu \chi^0_1 \mu \chi^0_1 (\times 10)$
ILC: Measurement of $\text{smuon}_L$

Mu energy spectrum ($\text{smuon}_L$)

![Graph showing Mu energy spectrum with various components and fits]

| Energy (GeV) | Yield (500 fb$^{-1}$) |
|-------------|-----------------------|
| 50          | 12000                 |
| 100         | 8000                  |
| 200         | 6000                  |

- Standard Model Background ($\times 1$)
- SUSY background ($\times 10$)
- $e^+e^-\rightarrow \chi_0^2 \chi_0^2 \rightarrow \mu\mu\chi_0^2$ ($\times 100$)
- $e^+e^-\rightarrow \mu\mu\chi_0^2$ ($\times 10$)

- Amplitude (A) $2.94 \pm 48.92$
- Edge (E) $0.04 \pm 32.25$
- Slope (S) $1.10605 \pm 0.03249$
- Background (B) $1.65 \pm 38.21$

- $B+A/(1+\exp(x-E)/S)$
  - Signal
  - Background

- $\chi^2$ / ndf $29.73 / 26$
- Amplitude (A) $48.92 \pm 2.94$
- Edge (E) $32.25 \pm 0.04$
- Slope (S) $0.03249 \pm 1.10605$
- Background (B) $38.21 \pm 1.65$

![Graph showing Mu energy spectrum with various components and fits]

| Energy (GeV) | Yield (500 fb$^{-1}$) |
|-------------|-----------------------|
| 146         | 70                    |
| 150         | 60                    |
| 154         | 50                    |

- $\chi^2$ / ndf $8.39 / 14$
- Amplitude (A) $43.97 \pm 3.51$
- Edge (E) $151.5 \pm 0.2$
- Slope (S) $0.3775 \pm 0.1233$
- Background (B) $15.17 \pm 1.53$
ILC: Measurement of Stau Helicity

- Stau polarization: depends on
  - mixing angle $\theta_{\text{stau}}$ of the chiral eigenstates to mass eigenstates
  - amount of Higgsino and gaugino eigenstates of N1 (gaugino and fermions: conserving chirality; Higgsino: Yukawa coupling flips chirality)

- Ratio of pion over jet energy differs for different stau helicity

![Graphs showing the ratio $R = E_\pi / E_{\text{jet}}$ for different stau helicities:](image-url)
Where we are...

- Introduction
- LHC Analyses
- ILC Analyses

Summary
Summary and Conclusion

- LHC capable to see all four studied models, especially the light third generation squarks
- Expect sensitivity to distinguish between stop and sbottom due to different decays
- Gluino measurement difficult due to low cross section
- Sensitivity to EW sector at LHC very low due to stau decays – analysis still ongoing...

→ Need ILC for precision measurements of the EW sector
  → At ILC all sleptons and bosinos with masses low enough to be produced with ILC energy have reasonable cross section to be measured, e.g.:
  → Mass measurements of stau_1 and stau_2
  → Mass measurements of smuons
  → Measurement of stau helicity
Thank you for listening

Backup slides follow...
PU dependence

Jet energy resolution

Resolution degrades with higher PU (as expected)

MET resolution