Mikael Berggren\(^1\)

on behalf of the ILC Physics and Detector Study

\(^1\)DESY, Hamburg

ICHEP, Chicago, II, August, 2016
Outline

1. The ILC
2. Why compressed spectra
   - Compressed spectra: Naturalness
   - Compressed spectra: DM
   - Compressed spectra: Why not seen @ LHC?
   - Compressed spectra: Why seeable @ ILC?
   - Compressed spectra: The data
3. The Stau-coannihilation STCx models
   - DM from cosmology and accelerators
     - STC4 sleptons @ 500 GeV
     - STC4 @ 500 GeV: Prospects for mixing measurements
4. Conclusions
The ILC

- A linear $e^+e^-$ collider.
- $E_{CMS}$ tunable between 250 and 500 GeV, upgradable to 1 TeV.
- Total length 34 km
- $\int \mathcal{L} \sim 250 \text{ fb}^{-1}/\text{year}$. 20 year plan in place.
- Polarisation $e^-$: 80%, $e^+$: $\geq$ 30%.
- 2 experiments, but only one interaction region.
- Concurrent running with the LHC.
- Under government study in Japan.
The ILC

- A linear $e^+e^-$ collider.
- $E_{CMS}$ tunable between 250 and 500 GeV, upgradable to 1 TeV.
- Total length 34 km
- $\int \mathcal{L} \sim 250 \text{ fb}^{-1}$/year. 20 year plan in place.
- Polarisation $e^-: 80\%$, $e^+: \geq 30\%$.
- 2 experiments, but only one interaction region.
- Concurrent running with the LHC.
- Under government study in Japan.
The ILC is not LHC

- Lepton-collider: Initial state is known.
- Production is **EW** \( \Rightarrow \)
  - Small theoretical uncertainties.
  - No “underlying event”.
  - Low cross-sections wrt. LHC, also for background.
  - But: \( \gamma \gamma \)-processes...
- Trigger-less operation.
- Extremely small beam-spot: 5 nm \( \times \) 100 nm \( \times \) 150 \( \mu \)m.

- Low background \( \Rightarrow \) detectors can be:
  - Thin: few % \( X_0 \) in front of calorimeters
  - Very close to IP: first layer of VXD at 1.5 cm.
  - Close to \( 4\pi \): holes for beam-pipe only few cm = 0.2 msr un-covered
    = Area of Connecticut relative to earth.
The ILC is not LHC

- **Lepton-collider:** Initial state is Known.
- **Production is EW ⇒**
  - Small theoretical uncertainties.
  - No “underlying event”.
  - Low cross-sections wrt. LHC, also for background.
    - But: $\gamma\gamma$-processes...
  - **Trigger-less** operation.
- Extremely small beam-spot: $5 \text{ nm} \times 100 \text{ nm} \times 150 \mu\text{m}$.

- **Low background ⇒ detectors can be:**
  - Thin: few % $X_0$ in front of calorimeters
  - Very close to IP: first layer of VXD at 1.5 cm.
  - Close to $4\pi$: holes for beam-pipe only few cm = 0.2 msr un-covered
    = Area of Connecticut relative to earth.
The ILC is not LHC

- Lepton-collider: Initial state is **known**.
- Production is **EW** ⇒
  - Small theoretical uncertainties.
  - No “underlying event”.
  - Low cross-sections wrt. LHC, also for background.
    - But: $\gamma\gamma$-processes...
  - **Trigger-less** operation.
- Extremely **small beam-spot**: $5 \text{ nm} \times 100 \text{ nm} \times 150 \mu\text{m}$.
- Low background ⇒ detectors can be:
  - Thin: few % $X_0$ in front of calorimeters
  - Very close to IP: first layer of VXD at 1.5 cm.
  - Close to $4\pi$: holes for beam-pipe only few cm = 0.2 msr un-covered
    = Area of Connecticut relative to earth.
The ILC is not LHC

- Lepton-collider: Initial state is known.
- Production is EW ⇒
  - Small theoretical uncertainties.
  - No “underlying event”.
  - Low cross-sections wrt. LHC, also for background.
    - But: $\gamma\gamma$-processes...
  - Trigger-less operation.
- Extremely small beam-spot: 5 nm × 100 nm × 150 µm.
- Low background ⇒ detectors can be:
  - Thin: few % $X_0$ in front of calorimeters
  - Very close to IP: first layer of VXD at 1.5 cm.
  - Close to $4\pi$: holes for beam-pipe only few cm = 0.2 msr un-covered = Area of Connecticut relative to earth.
Why compressed spectra?

Why would one expect the spectrum to be compressed?
Why compressed spectra? Natural SUSY: Light, degenerate higgsinos

Because it is natural!

- Natural SUSY:
  - \[ m_Z^2 = 2 \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{1 - \tan^2 \beta} - 2 |\mu|^2 \]
  - Implies low fine-tuning \( \Rightarrow \mu = \mathcal{O}(\text{weak scale}) \) \( \Rightarrow \) lightest bosinos mainly higgsino \( \Rightarrow \) close in mass \( \Rightarrow \) Compressed spectrum

- However: Not enough Dark Matter
- For more on this: Talk by J. List and H. Baer in this session.
Why compressed spectra? Natural SUSY: Light, degenerate higgsinos

Because it is natural!

- Natural SUSY:
  \[ m_Z^2 = 2 \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{1 - \tan^2 \beta} - 2 |\mu|^2 \]
  \[ \Rightarrow \text{Low fine-tuning} \Rightarrow \mu = \mathcal{O}(\text{weak scale}) \Rightarrow \text{lightest bosinos mainly higgsino} \Rightarrow \text{close in mass} \Rightarrow \text{Compressed spectrum} \]

- However: Not enough Dark Matter
  
  For more on this: Talk by J. List and H. Baer in this session.
Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

Because it is natural !

- Natural SUSY:
  \[ m_Z^2 = 2 \frac{m_{Hu}^2 \tan^2 \beta - m_{Hd}^2}{1 - \tan^2 \beta} - 2 |\mu|^2 \]
  \[ \Rightarrow \text{Low fine-tuning} \Rightarrow \mu = \mathcal{O} \text{(weak scale)} \Rightarrow \text{lightest bosinos mainly higgsino} \Rightarrow \text{close in mass} \Rightarrow \text{Compressed spectrum} \]

- However: Not enough Dark Matter

- For more on this: Talk by J. List and H. Baer in this session.
Why compressed spectra? DM and the weak miracle

Because actually *can* give the right Dark Matter!

- Need balance between early universe production and decay.
- One compelling option is $\tilde{\tau}$ Co-annihilation. For this to contribute: Early universe density of $\tilde{\tau}$ and $\tilde{\chi}_1^0$ similar $\Rightarrow$ Once again Compressed spectrum.
Why compressed spectra? DM and the weak miracle

Because actually *can* give the right Dark Matter!

- Need balance between early universe production and decay.
- One compelling option is \( \tilde{\tau} \) Co-annihilation. For this to contribute: Early universe density of \( \tilde{\tau} \) and \( \tilde{\chi}_1^0 \) similar \( \Rightarrow \) Once again Compressed spectrum.
Because actually *can* give the right Dark Matter!

- Need balance between early universe production and decay.
- One compelling option is \( \tilde{\tau} \) Co-annihilation. For this to contribute: Early universe density of \( \tilde{\tau} \) and \( \tilde{\chi}_1^0 \) similar \( \Rightarrow \) Once again Compressed spectrum.
Why not seen @ LHC?

Recall:

- LHC’s strongly excludes 1:st & 2:nd gen. \(\tilde{q}\):s and the \(\tilde{g}\). These states have no influence on DM, g-2, naturalness, ...
- I.e.: The reason that CMSSM is dead is the irrelevant part!

So: Remove connection (1:st & 2:nd gen \(\tilde{q}\):s and the \(\tilde{g}\)) \(\leftrightarrow\) (3:rd gen. \(\tilde{q}\):s and EW-sector). Price: more free parameters.

And: If spectrum is compressed: Long decay-cascades @ LHC, ending up at a NLSP \(\rightarrow\) LSP + visible with soft spectrum.

I.e.: NOT a large missing \(E_T\) model, NOR a simplified one \(\Rightarrow\) weaker limits.
Why not seen @ LHC ?

Recall:

- LHC’s strongly excludes 1:st & 2:nd gen. $\tilde{q}$:s and the $\tilde{g}$. These states have no influence on DM, g-2, naturalness, ...
- Ie. : The reason that CMSSM is dead is the *irrelevant part*!
- So: Remove connection (1:st & 2:nd gen $\tilde{q}$:s and the $\tilde{g}$) $\leftrightarrow$ (3:rd gen. $\tilde{q}$:s and EW-sector). Price: more free parameters.
- And: If spectrum is compressed: Long decay-cascades @ LHC, ending up at a NLSP $\rightarrow$ LSP + visible with soft spectrum.
- Ie.: *NOT* a large missing $E_T$ model, *NOR* a simplified one $\Rightarrow$ weaker limits.
Recall:

- LHC’s strongly excludes 1:st & 2:nd gen. $\tilde{q}$:s and the $\tilde{g}$. These states have no influence on DM, g-2, naturalness, ...
- Ie. : The reason that CMSSM is dead is the *irrelevant part*!
- So: Remove connection (1:st & 2:nd gen $\tilde{q}$:s and the $\tilde{g}$) ↔ (3:d gen. $\tilde{q}$:s and EW-sector). Price: more free parameters.
- And: If spectrum is compressed: *Long decay-cascades @ LHC*, ending up at a NLSP → LSP + visible with soft spectrum.

Ie.: *NOT* a large missing $E_T$ model, *NOR* a simplified one ⇒ weaker limits.
Recall:

- LHC’s strongly excludes 1:st & 2:nd gen. $\tilde{q}$:s and the $\tilde{g}$. These states have no influence on DM, g-2, naturalness, ...
- Ie. : The reason that CMSSM is dead is the *irrelevant part*!
- So: Remove connection (1:st & 2:nd gen $\tilde{q}$:s and the $\tilde{g}$) ↔ (3:rd gen. $\tilde{q}$:s and EW-sector). Price: more free parameters.
- And: If spectrum is compressed: Long decay-cascades @ LHC, ending up at a NLSP → LSP + visible with soft spectrum.
- Ie.: *NOT* a large missing $E_T$ model, *NOR* a simplified one ⇒ weaker limits.
Why compressed spectra

Why seeable @ ILC?

- Simplified methods at hadron and lepton machines are **different beasts**.
- At lepton machines they are quite **model independent**: At least the NLSP *has* 100% BR to the LSP!
  - Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) ($\sigma$ (M.B. arXiv:1308.1461))
  - Cf. LHC+LEP
Why seeable @ ILC?

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent: At least the NLSP has 100% BR to the LSP!
- Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)
- Cf. LHC+LEP
Simplified methods at hadron and lepton machines are different beasts.

At lepton machines they are quite model independent: At least the NLSP has 100% BR to the LSP!

Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)

Cf. LHC+LEP
Simplified methods at hadron and lepton machines are different beasts.

At lepton machines they are quite model independent: At least the NLSP has 100% BR to the LSP!

Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)

Cf. LHC+LEP, HiLumi LHC
Why seeable @ ILC?

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent: At least the NLSP has 100% BR to the LSP!
- Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)
- Cf. LHC+LEP, HiLumi LHC

Compressed region!
Why compressed spectra

Why seeable @ ILC ?

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent: At least the NLSP has 100 % BR to the LSP!
- Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)
- Cf. LHC+LEP, HiLumi LHC, ILC500

Compressed region!
Why seeable @ ILC?

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent: At least the NLSP has 100% BR to the LSP!
- Eg. $\tilde{\tau}_1$ NLSP (minimal $\sigma$) (M.B. arXiv:1308.1461)
- Cf. LHC+LEP, HiLumi LHC, ILC500 and ILC1000

Compressed spectra: Why seeable @ ILC?
Why compressed spectra?

Global fits

Because it fits the observations best!

\textbf{pMSSM10 prediction: best-fit masses}

\begin{align*}
&M_{h^0} \quad M_{H^0} \quad M_{A^0} \quad M_{H^\pm} \\
&m_{\chi^0_1} \quad m_{\chi^0_2} \quad m_{\chi^0_3} \quad m_{\chi^0_4} \\
&m_{\tilde{l}^L} \quad m_{\tilde{l}^R} \quad m_{\tilde{\tau}^1} \quad m_{\tilde{\tau}^2} \\
&m_{\tilde{q}^L} \quad m_{\tilde{q}^R} \quad m_{\tilde{t}^1} \quad m_{\tilde{t}^2} \\
&m_{\tilde{b}^1} \quad m_{\tilde{b}^2} \quad m_{\tilde{g}}
\end{align*}

⇒ high colored masses
⇒ relatively low electroweak masses
partially with not too large ranges
⇒ clear prediction for ILC and CLIC

Sven Heinemeyer, LCWS15, Whistler, 03.11.2015
The Stau-coannihilation STC\(x\) models

M.B. & al. EPJC, 76(4),1 (2016)

High mass squarks+gluino

Not seen by HiLumiLHC: too low x-sect

Well-tempered higgs, bosino

Varying 3-gen squarks and slepton sector.

LHC would see signs of this sector

LHC will see these

Simulating STC\(x\)

At LHC14: Studied with DELPHES using the "Snowmass samples"

At ILC: Studied with SGV using the "DBD samples"

Mikael Berggren (DESY)

SUSY models and DM at ILC

ICHEP 2016 11 / 19
High mass squarks+gluino

Well-tempered higgs, bosino and slepton sector.

Varying 3-gen squarks
The Stau-coannihilation STCx models

M.B. & al. EPJC, 76(4),1 (2016)

High mass squarks+gluino

Simulating STCx

- At LHC14: Studied with DELPHES using the “Snowmass samples”
- At ILC: Studied with SGV using the “DBD samples”

Well-tempered higgs, bosino and slepton sector.

Varying 3-gen squarks
The Stau-coannihilation STCx models

M.B. & al. EPJC, 76(4),1 (2016)

High mass squarks+gluino
Not seen by HiLumiLHC: too low x-sect

Well-tempered higgs, bosino
Varying 3-gen squarks
and slepton sector.

LHC will see these

LHC would see signs of this sector
The Stau-coannihilation STCx models

The STCx benchmark @ ILC

Zoomed STCx mass-spectrum

At the ILC@500 GeV:
- Signal: Typically a few leptons + LSP:s ⇒ Low multiplicity events. Central, much missing energy. Cross-sections up to 1 pb+.
- Often cascades over $\tilde{\tau}_1$.
- $\Delta(M) \sim 10$ GeV ⇒ $E_{\tau} \in [2.3, 45.5]$ GeV.

Background:
- Real missing energy = ZZ, WW $\to \ell\ell\nu\nu$
- Fake missing energy = $\gamma\gamma$ processes, ISR, single IVB.

Mikael Berggren (DESY)
The Stau-coannihilation STCx models

The STCx benchmark @ ILC

Cross-sections

At the ILC@500 GeV:
- Signal: Typically a few leptons + LSP:s
  - Low multiplicity events.
  - Central, much missing energy.
  - Cross-sections up to 1 pb+.
  - Often cascades over \( \tilde{\tau}_1 \).
  - \( \Delta(M) \sim 10 \text{ GeV} \)
  - \( E_{\tau} \in [2.3, 4.5] \text{ GeV} \).
- Background:
  - Real missing energy = ZZ, WW → \( \ell\ell\nu\nu \)
  - Fake missing energy = γγ processes, ISR, single IVB.

Mikael Berggren (DESY) SUSY models and DM at ILC ICHEP 2016 12 / 19
The STC\(x\) benchmark @ ILC

Cross-sections

\[ \sigma \text{ [fb]} \]

⇒ At the ILC@500 GeV:

**Signal:**

- Typically: a few leptons + LSP:s \( \Rightarrow \)
  - Low multiplicity events.
  - Central, much missing energy.
- Cross-sections up to 1 pb+.
- Often cascades over \( \tilde{\tau}_1 \).
- \( \Delta(M) \sim 10 \text{ GeV} \Rightarrow E_\tau \in [2.3, 45.5] \text{ GeV} \).

**Background:**

- Real missing energy = \(ZZ, WW \rightarrow \ell\ell\nu\nu\)
- Fake missing energy = \(\gamma\gamma\) processes, ISR, single IVB.
The Stau-coannihilation STC\(x\) models

The STC\(x\) benchmark @ ILC

Cross-sections

⇒ At the ILC@500 GeV:

**Signal:**
- Typically: a few leptons + LSP:s ⇒
  - Low multiplicity events.
  - Central, much missing energy.
- Cross-sections up to 1 pb+.
- Often cascades over \(\tilde{\tau}_1\).
- \(\Delta(M) \sim 10\) GeV ⇒ \(E_\tau \in [2.3, 45.5]\) GeV.

**Background:**
- Real missing energy = ZZ, WW \(\to \ell\ell\nu\nu\)
- Fake missing energy = \(\gamma\gamma\) processes, ISR, single IVB.
The Stau-coannihilation STCx models

The STCx benchmark @ ILC

Cross-sections

⇒ At the ILC@500 GeV:

Signal:

- Typically: a few leptons + LSP:s ⇒
  - Low multiplicity events.
  - Central, much missing energy.
- Cross-sections up to 1 pb+.
- Often cascades over $\tilde{\tau}_1$.
- $\Delta(M) \sim 10$ GeV $\Rightarrow E_\tau \in [2.3, 45.5]$ GeV.

Background:

- Real missing energy $= ZZ, WW \rightarrow l\ell\nu\nu$
- Fake missing energy $= \gamma\gamma$ processes, ISR, single IVB.
DM: Needed precision

- Planck: Cosmological abundance from CMB: $\Delta = 2\%$.

Accelerator:

- Relic abundance using micrOMEGAs:
  - $1\%$ variation of $M_{\tilde{\tau}}$ or $M_{\tilde{\chi}_1^0}$ changes abundance by $5\%$.
  - $1\%$ variation of $\theta_{\tilde{\tau}}$ or $N_{11}$ changes abundance by $1\%$ and $3.5\%$, respectively.
- Much less sensitive to other masses/mixings.
DM: Needed precision

- Planck: Cosmological abundance from CMB: $\Delta = 2\%$.

**Accelerator:**

- Relic abundance using micrOMEGAs:
  - $\Rightarrow 1\%$ variation of $M_{\tilde{\tau}}$ or $M_{\tilde{\chi}_1^0}$ changes abundance by 5%.
  - $\Rightarrow 1\%$ variation of $\theta_{\tilde{\tau}}$ or $N_{11}$ changes abundance by 1% and 3.5%, respectively.
  - Much less sensitive to other masses/mixings.
DM: Needed precision

- Planck: Cosmological abundance from CMB: $\Delta = 2\%$.

Accelerator:

- Relic abundance using micrOMEGAs:
  - $1\%$ variation of $M_\tau$ or $M_{\tilde{\chi}_1^0}$ changes abundance by $5\%$.
  - $1\%$ variation of $\theta_\tau$ or $N_{11}$ changes abundance by $1\%$ and $3.5\%$, respectively.
  - Much less sensitive to other masses/mixings.

DM: Needed precision

- Planck: Cosmological abundance from CMB: $\Delta=2\%$.

Accelerator:
- Relic abundance using micrOMEGAs:
  - $1\%$ variation of $M_{\tilde{\tau}}$ or $M_{\tilde{\chi}_1^0}$ change abundance by 5\%.
  - $1\%$ variation of $\theta_{\tilde{\tau}}$ or $N_{11}$ changes abundance by 1\% and 3.5\% respectively.
- Much less sensitive to other masses/mixings.

So: To match Planck, need per mil LSP and NLSP masses, percent LSP and NLSP mixings!
How to reach the needed precision?

Look at pair-production

\[ E'_{\text{max}} = E_{\text{Beam}} \frac{2}{2} \left( 1 - \left( \frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{\ell}}} \right)^2 \right) \left( 1 \pm \sqrt{1 - \left( \frac{M_{\tilde{\ell}}}{E_{\text{Beam}}} \right)^2} \right) \]

- Two observables (\( E'_{\text{max}} \)) and two parameters (\( M_{\tilde{\ell}} \) and \( M_{\tilde{\chi}_1^0} \)).
- For \( \tilde{e}_R \) and \( \tilde{\mu}_R \), \( E'_{\text{max}} \) can be measured very well at the ILC.
- \( E'_{\text{max}} \) can be well measured for \( \tilde{\tau}_1 \)
- \( \Rightarrow \) Use \( \tilde{e}_R \) and \( \tilde{\mu}_R \) to determine \( M_{\tilde{\chi}_1^0} \), end-point of \( E_{\tau-jet} \) for \( M_{\tilde{\tau}_1} \).
STC4 sleptons @ 500 GeV: $\tilde{\text{e}}$, $\tilde{\mu}$

- **Selections** for $\tilde{\mu}$ and $\tilde{\text{e}}$:
  - Correct charge.
  - $P_T$ wrt. beam and one $\ell$ wrt the other.
  - Tag and probe, ie. accept one jet if the other is “in the box”.

- **Further selections** for R:
  - Cuts on polar angle and angle between leptons.
  - $E_{\text{jet}}$, beam-pol 80%,-30%...
The Stau-coannihilation STC\(x\) models

DM from cosmology and accelerators

STC\(4\) sleptons @ 500 GeV: \(\tilde{\mu}, \tilde{\epsilon}\)

- **Selections** for \(\tilde{\mu}\) and \(\tilde{\epsilon}\):

  - Results from edges \((E_{CMS}=500, 500 \text{ fb}^{-1} @ [+0.8,-0.3])\)

  - **selectrons**:
    
    \[
    M_{\tilde{\epsilon}_R} = 126.20 \pm 0.21 \text{ GeV}/c^2 \\
    M_{\tilde{\chi}_1^0} = 95.47 \pm 0.16 \text{ GeV}/c^2
    \]

  - **smuons**:
    
    \[
    M_{\tilde{\mu}_R} = 126.01 \pm 0.51 \text{ GeV}/c^2 \\
    M_{\tilde{\chi}_1^0} = 95.47 \pm 0.38 \text{ GeV}/c^2
    \]

  - **combined**:
    
    \[
    \sigma_{M_{\tilde{\chi}_1^0}} = 147 \text{ MeV}/c^2 \\
    \sigma_{M_{\tilde{\ell}_R}} = 194 \text{ MeV}/c^2
    \]

Mikael Berggren  (DESY)  
SUSY models and DM at ILC  
ICHEP 2016  
15 / 19
STC4 sleptons @ 500 GeV: $\tilde{\tau}_1$

Selections for $\tilde{\tau}_1$:

- Correct charge.
- $P_T$ wrt. beam and one $\tau$ wrt the other.
- $M_{\text{jet}} < M_\tau$
- $E_{\text{vis}} < 120$ GeV, $M_{\text{vis}} \in [20, 87]$ GeV.
- Cuts on polar angle and angle between leptons.
- Little energy below 30 deg, or not in $\tau$-jet.
- At least one $\tau$-jet should be hadronic.
- Anti-$\gamma\gamma$ likelihood.
Fitting the $\tilde{\tau}$ end-points

- Only the upper end-point is relevant.
- Background subtraction:
  - Important SUSY background, but region above 45 GeV is signal free.
  - Fit exponential and extrapolate.
- Fit line to (data-background fit).
Fitting the $\tilde{\tau}$ end-points

- Only the upper end-point is relevant.
- Background subtraction:
  - Important SUSY background, but region above 45 GeV is signal free. Fit exponential and extrapolate.
- Fit line to (data-background fit).

Results for $\tilde{\tau}_1$

$$E_{\text{max}, \tilde{\tau}_1} = 44.49^{+0.11}_{-0.09} \text{GeV}$$

Translates to an error on the mass of 0.27 GeV/$c^2$, dominated by the error from $M_{\tilde{\chi}_1^0}$. 
Fitting the $\tilde{\tau}$ end-points

- Only the upper end-point is relevant.
- Background subtraction:
  - Important SUSY background, but region above 45 GeV is signal free.
  - Fit exponential and extrapolate.
  - Fit line to (data-background fit).
- Summary of slepton and bosino masses:
  - Per mil-level mass-measurements will be possible at the ILC

Results for $\tilde{\tau}_1$

$$E_{\text{max},\tilde{\tau}_1} = 44.49^{+0.11}_{-0.09} \text{ GeV}$$

Translates to an error on the mass of 0.27 GeV/$c^2$, dominated by the error from $M_{\tilde{\chi}_0^1}$. 

Mikael Berggren (DESY)  
SUSY models and DM at ILC  
ICHEP 2016  17 / 19
Prospects for mixing measurements

- $\theta_{\tilde{\tau}}$: Several options:
  - Absolute Cross-section: $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, P_{\text{beam}}) \times \beta^3/s$:
    - Once $M_{\tilde{\tau}}$ (and $E_{\text{CM}}$) is known only depends on $\theta_{\tilde{\tau}}$ (through $A$: complicated, but known).
  - Cross-section difference for RL and LR beams: The function $A$ also depends on beam-polarisation.
  - Percent-level measurement likely: mainly a cross-section measurement.

- $N_{11}$ (bino-ness of $\tilde{\chi}_1^0$):
  - Cross-section, but how to measure? Mono-photon search?
  - However, cross-section also depends on other elements of the neutralino-matrix, and on $M_{\tilde{\tau}}$.
  - Cross-sections for $\tilde{\chi}_1^0 \tilde{\chi}_2^0/\tilde{\chi}_2^0 \tilde{\chi}_1^0$ + beam-polarisation + t/s-channel separation from angular distributions.
  - BR:s in cascades when direct decay to SM+$\tilde{\chi}_1^0$ is substantial?
  - ...
  - Is percent-level measurement possible? Work in progress...
Prospects for mixing measurements

\( \theta_{\tilde{\tau}} \): Several options:

- **Absolute Cross-section**: \( \sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, P_{\text{beam}}) \times \beta^3/s \):
  
  Once \( M_{\tilde{\tau}} \) (and \( E_{CM} \)) is known only depends on \( \theta_{\tilde{\tau}} \) (through \( A \): complicated, but known).

- **Cross-section difference** for RL and LR beams: The function \( A \) also depends on beam-polarisation.

- **Percent-level measurement likely**: mainly a cross-section measurement.

\( N_{11} \) (bino-ness of \( \tilde{\chi}^0_1 \)):

- Cross-section, but how to measure? Mono-photon search?
- However, cross-section also depends on other elements of the neutralino-matrix, and on \( M_{\tilde{\chi}} \).
- Cross-sections for \( \tilde{\chi}^0_1 \tilde{\chi}^0_1/\tilde{\chi}^0_2 \tilde{\chi}^0_2 \) + beam-polarisation + t/s-channel separation from angular distributions.
- BR:s in cascades when direct decay to SM+\( \tilde{\chi}^0_1 \) is substantial?
- ...
- Is percent-level measurement possible? Work in progress...
Prospects for mixing measurements

- $\theta_{\tilde{\tau}}$: Several options:
  - Absolute Cross-section: $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, P_{\text{beam}}) \times \beta^3 / s$:
    Once $M_{\tilde{\tau}}$ (and $E_{\text{CM}}$) is known only depends on $\theta_{\tilde{\tau}}$ (through $A$: complicated, but known).
  - Cross-section difference for RL and LR beams: The function $A$ also depends on beam-polarisation.
  - Percent-level measurement likely: mainly a cross-section measurement.

- $N_{11}$ (bino-ness of $\tilde{\chi}_1^0$):
  - Cross-section, but how to measure? Mono-photon search?
  - However, cross-section also depends on other elements of the neutralino-matrix, and on $M_\tilde{e}$
  - Cross-sections for $\tilde{\chi}_1^0 \tilde{\chi}_2^0 / \tilde{\chi}_2^0 \tilde{\chi}_1^0 + \text{beam-polarisation+ t/s-channel separation from angular distributions}.$
  - BR:s in cascades when direct decay to SM+$\tilde{\chi}_1^0$ is substantial?
  - ...
  - Is percent-level measurement possible? Work in progress...
Prospects for mixing measurements

$\theta_{\tilde{\tau}}$: Several options:

- **Absolute Cross-section**: $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, P_{\text{beam}}) \times \beta^3 / s$:
  Once $M_{\tilde{\tau}}$ (and $E_{\text{CM}}$) is known only depends on $\theta_{\tilde{\tau}}$ (through $A$: complicated, but known).

- **Cross-section difference** for RL and LR beams: The function $A$ also depends on beam-polarisation.

- **Percent-level measurement likely**: mainly a cross-section measurement.

$N_{11}$ (bino-ness of $\tilde{\chi}_1^0$):

- Cross-section, but how to measure? **Mono-photon** search?
- However, cross-section also depends on other elements of the neutralino-matrix, and on $M_{\tilde{\tau}}$

- Cross-sections for $\tilde{\chi}_1^0 \tilde{\chi}_2^0 / \tilde{\chi}_2^0 \tilde{\chi}_1^0$+beam-polarisation+ t/s-channel separation from angular distributions.

- **BR:s in cascades** when direct decay to SM+$\tilde{\chi}_1^0$ is substantial?
- ...

- **Is percent-level measurement possible?** Work in progress...
At ILC:

- SUSY models with a rich and compressed spectrum are still the best fit to data.
- They are **not** excluded by LHC (although the mSUGRA version of it is).
- Likely that LHC would discover such a model in the next few years, if it is there.
- In such models a rich spectrum is reachable by the ILC, and ILC will be able to corroborate on LHC discovery.
- In particular, ILC will be able to prove that the NP discovered at LHC is SUSY. Masses will be determined at per mil-level, mixings (probably) at percent-level.
- With such precisions, ILC will be capable to measure DM with a precision close to Planck’s CMB results.
Conclusions

At ILC:

- SUSY models with a rich and compressed spectrum are still the best fit to data.
- They are not excluded by LHC (although the mSUGRA version of it is).
- Likely that LHC would discover such a model in the next few years, if it is there.
- In such models a rich spectrum is reachable by the ILC, and ILC will be able to corroborate on LHC discovery.
- In particular, ILC will be able to prove that the NP discovered at LHC is SUSY. Masses will be determined at per mil-level, mixings (probably) at percent-level.
- With such precisions, ILC will be capable to measure DM with a precision close to Planck’s CMB results.
Conclusions

At ILC:

- SUSY models with a rich and compressed spectrum are still the best fit to data.
- They are not excluded by LHC (although the mSUGRA version of it is).
- Likely that LHC would discover such a model in the next few years, if it is there.
- In such models a rich spectrum is reachable by the ILC, and ILC will be able to corroborate on LHC discovery.
- In particular, ILC will be able to prove that the NP discovered at LHC is SUSY. Masses will be determined at per mil-level, mixings (probably) at percent-level.
- With such precisions, ILC will be capable to measure DM with a precision close to Planck’s CMB results.
Conclusions

At ILC:

- SUSY models with a rich and compressed spectrum are still the best fit to data.
- They are not excluded by LHC (although the mSUGRA version of it is).
- Likely that LHC would discover such a model in the next few years, if it is there.
- In such models a rich spectrum is reachable by the ILC, and ILC will be able to corroborate on LHC discovery.
- In particular, ILC will be able to prove that the NP discovered at LHC is SUSY. Masses will be determined at per mil-level, mixings (probably) at percent-level.
- With such precisions, ILC will be capable to measure DM with a precision close to Planck’s CMB results.
At ILC:

- SUSY models with a rich and compressed spectrum are still the best fit to data.
- They are not excluded by LHC (although the mSUGRA version of it is).
- Likely that LHC would discover such a model in the next few years, if it is there.
- In such models a rich spectrum is reachable by the ILC, and ILC will be able to corroborate on LHC discovery.
- In particular, ILC will be able to prove that the NP discovered at LHC is SUSY. Masses will be determined at per mil-level, mixings (probably) at percent-level.
- With such precisions, ILC will be capable to measure DM with a precision close to Planck’s CMB results.
Thank You!
BACKUP
STC4 bosinos @ 500 GeV: $\tilde{\chi}^0_1 \tilde{\chi}^0_2 \rightarrow \tilde{\tau}_1 \tau \tilde{\chi}^0_1$

- Signature: two $\tau$:s + nothing (like $\tilde{\tau}$-pairs)

- However: **Cascade decay**, meaning that the two $\tau$:s have **different spectra** ⇒ can often select first and second decay unambiguously

- The $\tau$ from $\tilde{\tau} \rightarrow \tau \tilde{\chi}^0_1$ decay ...

- ... and from $\tilde{\chi}^0_2 \rightarrow \tilde{\tau}_1 \tau$

- Endpoint of first decay: $\Delta = 1.6$ GeV ⇒ $\Delta(M_{\tilde{\chi}^0_2}) = ???$ MeV, assuming the error on $M_{\tilde{\tau}_1}$ from the previous slide.
Conclusions

STC4 bosinos @ 500 GeV: \( \tilde{\chi}_0^0 \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \tilde{\chi}_1^0 \)

- **Signature**: two \( \tau \):s + nothing (like \( \tilde{\tau} \)-pairs)

- **However**: Cascade decay, meaning that the two \( \tau \):s have **different spectra** ⇒ can often select first and second decay unambiguously

- The \( \tau \) from \( \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0 \) decay ...

- ... and from \( \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \)

- **Endpoint of first decay**: \( \Delta = 1.6 \text{ GeV} \) ⇒ \( \Delta(M_{\tilde{\chi}_2^0}) = ??? \text{ MeV} \), assuming the error on \( M_{\tilde{\tau}_1} \) from the previous slide.
Conclusions

**STC4 bosinos @ 500 GeV:** 
\[ \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \tilde{\chi}_1^0 \]

- **Signature:** two $\tau$:s + nothing (like $\tilde{\tau}$-pairs)
- **However:** Cascade decay, meaning that the two $\tau$:s have **different spectra**  
  \[ \Rightarrow \text{can often select first and second decay unambiguously} \]
- **The $\tau$ from $\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$ decay ...**
- **... and from $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$**
- **Endpoint of first decay:** $\Delta = 1.6$ GeV  
  \[ \Rightarrow \Delta(M_{\tilde{\chi}_2^0}) = ??? \text{ MeV, assuming the error on } M_{\tilde{\tau}_1} \text{ from the previous slide.} \]
STC4 bosinos @ 500 GeV: $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \tilde{\chi}_1^0$

- Signature: two $\tau$:s + nothing (like $\tilde{\tau}$-pairs)
- However: Cascade decay, meaning that the two $\tau$:s have different spectra
  $\Rightarrow$ can often select first and second decay unambiguously
- The $\tau$ from $\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$ decay ...
- ... and from $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$
- Endpoint of first decay: $\Delta = 1.6$ GeV
  $\Rightarrow \Delta(M_{\tilde{\chi}_2^0}) = ???$ MeV, assuming the error on $M_{\tilde{\tau}_1}$ from the previous slide.
Conclusions

Natural SUSY: Light, degenerate higgsinos

- **Few-body** decays and radiative decays (for $\tilde{\chi}_2^0$) (calculated with Herwig).

- Separate $\tilde{\chi}_1^\pm$ from $\tilde{\chi}_2^0$: Either semi-leptonic f.s.: Only $\tilde{\chi}_1^\pm$, or $\gamma$: only $\tilde{\chi}_2^0$.

- $E_{ISR}$ gives reduced $\sqrt{s'}$: “auto-scan”. End-point gives masses to $\sim 1$ GeV.

- Close to end-point, $E_\pi$ gives $\Delta(M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_1^\pm})$ to $\sim 100$ MeV.
**Natural SUSY: Light, degenerate higgsinos**

- **Few-body** decays and radiative decays (for $\tilde{\chi}^0_2$) (calculated with Herwig).

- **Separate** $\tilde{\chi}^{\pm}_1$ from $\tilde{\chi}^0_2$: Either semi-leptonic f.s.: Only $\tilde{\chi}^{\pm}_1$, or $\gamma$: only $\tilde{\chi}^0_2$.

- $E_{ISR}$ gives reduced $\sqrt{s'}$: “auto-scan”. End-point gives masses to $\sim 1$ GeV.

- Close to end-point, $E_{\pi}$ gives $\Delta(M_{\tilde{\chi}^{0}_1}, M_{\tilde{\chi}^{\pm}_1})$ to $\sim 100$ MeV.
Conclusions

Natural SUSY: Light, degenerate higgsinos

- Few-body decays and radiative decays (for $\tilde{\chi}_2^0$) (calculated with Herwig).
- Separate $\tilde{\chi}_1^\pm$ from $\tilde{\chi}_2^0$: Either semi-leptonic f.s.: Only $\tilde{\chi}_1^\pm$, or $\gamma$: only $\tilde{\chi}_2^0$.
- $E_{ISR}$ gives reduced $\sqrt{s'}$: “auto-scan”. End-point gives masses to $\sim 1$ GeV.
- Close to end-point, $E_\pi$ gives $\Delta(M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_1^\pm})$ to $\sim 100$ MeV.
**Conclusions**

**Natural SUSY: Light, degenerate higgsinos**

- **Few-body** decays and radiative decays (for $\tilde{\chi}^0_2$) (calculated with Herwig).
- **Separate** $\tilde{\chi}^\pm_1$ from $\tilde{\chi}^0_2$: Either semi-leptonic f.s.: Only $\tilde{\chi}^\pm_1$, or $\gamma$: only $\tilde{\chi}^0_2$.
- $E_{ISR}$ gives reduced $\sqrt{s'}$: “auto-scan”. End-point gives masses to $\sim 1$ GeV.
- Close to end-point, $E_\pi$ gives $\Delta(M_{\tilde{\chi}^0_1}, M_{\tilde{\chi}^\pm_1})$ to $\sim 100$ MeV.
Natural SUSY: Light, degenerate higgsinos

- Use to extract the model-parameters $\mu$, $M_1$ and $M_2$ (little $\tan \beta$ dependence).
- $\mu$ can be determined to $\pm 4\%$.
- Limits on $M_1$ and $M_2$ after $\int \mathcal{L} = 2ab^{-1}$.
- For both models: Sign determined, allowed lower and upper limits on $M_2$ (for $dm1600$ also for $M_1$).
Natural SUSY: Light, degenerate higgsinos

- Use to extract the model-parameters $\mu$, $M_1$ and $M_2$ (little $\tan \beta$ dependence).
- $\mu$ can be determined to $\pm 4\%$.
- Limits on $M_1$ and $M_2$ after $\int \mathcal{L} = 2ab^{-1}$.
- For both models: Sign determined, allowed lower and upper limits on $M_2$ (for $dm_{1600}$ also for $M_1$).
STCx @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    - $\tilde{\chi}_k \tilde{\chi}_l^\pm > \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp > \tilde{\tau} \tilde{\tau} > \ell \ell > \tilde{\tau} \tilde{\tau} > \tilde{b} \tilde{b} > q q > \tilde{\chi}_k \tilde{\chi}_l^0 > g g$
    - ranging from 1.5 pb to 1 fb. $M_{\tilde{t}}$ and $M_{\tilde{b}}$ is 200 GeV higher in STC10
    - $\to$ Cross-sections for $\tilde{\tau}$ and $\tilde{b}$ $5 \times$ smaller in STC10 wrt STC8.
  - $\tilde{\chi}$ cascade-decays to $\tau$:s + the LSP in 75 % of the cases, often together with a boson ($Z$, $W$ or $h$).
    - For $\tilde{\chi}_0^0$, the rest is either only bosons, or "nothing" (ie. neutrinos).
    - For $\tilde{\chi}_\pm$ the rest is other leptons.
  - The $\tau$:s mostly come from $\tilde{\tau}_1 \to \tau \tilde{\chi}_0^0$, where the mass difference is only 10 GeV $\Rightarrow$ little missing energy.
  - $\tilde{b}$ mostly decays to $b \tilde{\chi}_0^0 : > 50 \%$ to $b \tilde{\chi}_1^0$. But also to $t \tilde{\chi}_1^\pm$ ($20\%$)
  - $\tilde{t}$ always goes to $t \tilde{\chi}_1^0$, but rarely to $t \tilde{\chi}_1^0$ ($\sim 10\%$).
  - The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STCx @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    \[ \tilde{\chi}_k^{\pm} \tilde{\chi}_l^{\pm} > \tilde{\chi}_k^{\pm} \tilde{\chi}_l^{\pm} > \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{t} \tilde{t} > \tilde{b} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_k^{0} \tilde{\chi}_l^{0} > \tilde{g} \tilde{g} \]
  - ranging from 1.5 pb to 1 fb. \(M_\tilde{t}\) and \(M_\tilde{b}\) is 200 GeV higher in STC10
  - \(\rightarrow\) Cross-sections for \(\tilde{t} \tilde{t}\) and \(\tilde{b} \tilde{b}\) 5 \(\times\) smaller in STC10 wrt STC8.
  - \(\tilde{\chi}\) cascade-decays to \(\tilde{\tau}:s\) + the LSP in 75 % of the cases, often together with a boson (\(Z, W\) or \(h\)).
    - For \(\tilde{\chi}^0\), the rest is either only bosons, or "nothing" (ie. neutrinos).
    - For \(\tilde{\chi}^{\pm}\) the rest is other leptons.
  - The \(\tilde{\tau}:s\) mostly come from \(\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0^{0}\), where the mass difference is only 10 GeV \(\Rightarrow\) little missing energy.
  - \(\tilde{b}\) mostly decays to \(b\tilde{\chi}^0: > 50\%\) to \(b\tilde{\chi}_1^{0}\). But also to \(t\tilde{\chi}^\pm (20\%)\)
  - \(\tilde{t}\) always goes to \(t\tilde{\chi}^0\), but rarely to \(t\tilde{\chi}_1^{0} (\sim 10\%)\).
  - The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).

Main features at LHC 14 TeV:

- **Cross-sections:**
  \[ \tilde{\chi}_k^0 \tilde{\chi}_l^\pm > \tilde{\chi}_k^\pm \tilde{\chi}_l^\pm > \tilde{\tau} \tilde{\tau} > \ell \ell > \tilde{t} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_k^0 \tilde{\chi}_l^0 > \tilde{g} \tilde{g} \]

  ranging from 1.5 pb to 1 fb. \( M_{\tilde{t}} \) and \( M_{\tilde{b}} \) is 200 GeV higher in STC10

  \[ \rightarrow \text{Cross-sections for } \tilde{t} \tilde{b} \text{ and } 5 \times \text{ smaller in STC10 wrt STC8.} \]

- \( \tilde{\chi} \) cascade-decays to \( \tau : s + \) the LSP in 75 % of the cases, often together with a boson (\( Z, W \) or \( h \)).
  - For \( \tilde{\chi}^0 \), the rest is either only bosons, or "nothing" (ie. neutrinos).
  - For \( \tilde{\chi}^\pm \) the rest is other leptons.

- The \( \tau : s \) mostly come from \( \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0^0 \), where the mass difference is only 10 GeV \( \Rightarrow \text{little missing energy.} \)

- \( \tilde{b} \) mostly decays to \( b \tilde{\chi}_0^0 : > 50 \% \) to \( b \tilde{\chi}_1^0 \). But also to \( t \tilde{\chi}^\pm \) (20%).

- \( \tilde{t} \) always goes to \( t \tilde{\chi}_0^0 \), but rarely to \( t \tilde{\chi}_1^0 \) (\( \sim 10\% \)).

- The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STCx @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    - $\tilde{\chi}_k^0 \tilde{\chi}_l^\pm > \tilde{\chi}_k^\pm \tilde{\chi}_l^\pm > \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{t} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_k^0 \tilde{\chi}_l^0 > \tilde{g} \tilde{g}$
    - Ranging from 1.5 pb to 1 fb. $M_{\tilde{t}}$ and $M_{\tilde{b}}$ is 200 GeV higher in STC10.
  - $\tilde{\tau}$ and $\tilde{b}$ smaller in STC10 wrt STC8.
  - $\tilde{\chi}$ cascade-decays to $\tau$s + the LSP in 75% of the cases, often together with a boson ($Z$, $W$ or $h$).
    - For $\tilde{\chi}_1^0$, the rest is either only bosons, or "nothing" (ie. neutrinos).
    - For $\tilde{\chi}_1^\pm$ the rest is other leptons.
  - The $\tau$:s mostly come from $\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0^0$, where the mass difference is only 10 GeV $\Rightarrow$ little missing energy.
  - $\tilde{b}$ mostly decays to $b\tilde{\chi}_0^0 : > 50\%$ to $b\tilde{\chi}_1^0$. But also to $t\tilde{\chi}_1^\pm (20\%)$
  - $\tilde{t}$ always goes to $t\tilde{\chi}_0^0$, but rarely to $t\tilde{\chi}_1^0 (\sim 10\%)$.
  - The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).

Main features at LHC 14 TeV:

- **Cross-sections:**
  \[\tilde{\chi}_k^0 \tilde{\chi}_i^\pm > \tilde{\chi}_k^\pm \tilde{\chi}_i^0 > \tilde{\tau} \tilde{\ell} > \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{b} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_k^0 \tilde{\chi}_i^0 > \tilde{g} \tilde{g}\]
  ranging from 1.5 pb to 1 fb. \(M_\tilde{t}\) and \(M_\tilde{b}\) is 200 GeV higher in STC10
  → Cross-sections for \(\tilde{\tau} \tilde{\tau}\) and \(\tilde{b} \tilde{b}\) \(5 \times\) smaller in STC10 wrt STC8.

- \(\tilde{\chi}\) cascade-decays to \(\tau: s + \) the LSP in 75 % of the cases, often together with a boson (\(Z, W\) or \(h\)).
  - For \(\tilde{\chi}^0\), the rest is either only bosons, or "nothing" (ie. neutrinos).
  - For \(\tilde{\chi}^\pm\) the rest is other leptons.

- The \(\tau: s\) mostly come from \(\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0^0\), where the mass difference is only 10 GeV ⇒ little missing energy.

- \(\tilde{b}\) mostly decays to \(b \tilde{\chi}_0^0 : > 50 \%\) to \(b \tilde{\chi}_1^0\). But also to \(t \tilde{\chi}^\pm\) (20%).

- \(\tilde{t}\) always goes to \(t \tilde{\chi}_0^0\), but rarely to \(t \tilde{\chi}_1^0\) (\(\sim 10\%\)).

- The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).

Main features at LHC 14 TeV:

- Cross-sections:
  \[ \tilde{\chi}^0_k \tilde{\chi}^\pm_i > \tilde{\chi}^\pm_k \tilde{\chi}^\pm_i > \tilde{\tau} \tilde{\tau} > \ell \ell > \tilde{t} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}^0_0 \tilde{\chi}^0_i > \tilde{g} \tilde{g} \]
  ranging from 1.5 pb to 1 fb. \( M_{\tilde{t}} \) and \( M_{\tilde{b}} \) is 200 GeV higher in STC10
  \[ \rightarrow \text{Cross-sections for } \tilde{t} \tilde{t} \text{ and } \tilde{b} \tilde{b} \text{ 5 x smaller in STC10 wrt STC8.} \]

- \( \tilde{\chi} \) cascade-decays to \( \tau : s \) + the LSP in 75 % of the cases, often together with a boson (\( Z, W \) or \( h \)).
  - For \( \tilde{\chi}^0 \), the rest is either only bosons, or "nothing" (ie. neutrinos).
  - For \( \tilde{\chi}^\pm \) the rest is other leptons.

- The \( \tau : s \) mostly come from \( \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}^0_0 \), where the mass difference is only 10 GeV \( \Rightarrow \) little missing energy.

- \( \tilde{b} \) mostly decays to \( b \tilde{\chi}^0 \) : > 50 % to \( b \tilde{\chi}^0_1 \). But also to \( t \tilde{\chi}^\pm \) (20%)

- \( \tilde{t} \) always goes to \( t \tilde{\chi}^0 \), but rarely to \( t \tilde{\chi}^0_1 \) (\( \sim 10\% \)).

- The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.
STC\textit{x} @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  
  Cross-sections:
  \[ \tilde{\chi}_0^k \tilde{\chi}^\pm_l \tilde{\chi}^\pm_k \tilde{\chi}^\pm_l \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{t} \tilde{t} > \tilde{b} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_0^k \tilde{\chi}_0^l \]
  
  ranging from 1.5 pb to 1 fb.

  - \( M_{\tilde{t}} \) and \( M_{\tilde{b}} \) is 200 GeV higher in STC10.

  \( \Rightarrow \) Cross-sections for \( \tilde{\tau} \tilde{\tau} \) and \( \tilde{b} \tilde{b} \) 5 times smaller in STC10 wrt STC8.

  - \( \tilde{\chi}_0 \) cascade-decays to \( \tau \)'s + the LSP in 75\% of the cases, often together with a boson (\( Z \), \( W \) or \( h \)).
  - For \( \tilde{\chi}_0^\pm \), the rest is either only bosons, or "nothing" (i.e. neutrinos).
  - The \( \tau \)'s mostly come from \( \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0^0 \), where the mass difference is only 10 GeV \( \Rightarrow \) little missing energy.
  - \( \tilde{b} \) mostly decays to \( b \tilde{\chi}_0^0 \): > 50\% to \( b \tilde{\chi}_0^1 \). But also to \( t \tilde{\chi}_0^\pm \) (20\%).
  - \( \tilde{t} \) always goes to \( t \tilde{\chi}_0^0 \), but rarely to \( t \tilde{\chi}_0^1 \) (\( \sim \) 10\%).
  - The right-handed gen 1 and 2 squarks almost always decay directly to quark+LSP.

\( \Rightarrow \) LHC expectations

- Despite the high cross-section, the low amount of missing \( E_T \) and the long decay chains will make direct bosino and slepton observations hard.

- The simple decay-chains and very high missing \( E_T \) will make first- and second-generation squark production easy to detect.
  However, the cross-section is so low that it is still challenging.

- Third generation squark production constitute a good compromise between cross-section and visibility, and will be the most powerful discovery channel. The lower cross-section in STC10 is compensated by higher visibility.
STC\(x\) @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).

Main features at LHC 14 TeV:

\[
\tilde{\chi}_0^k \tilde{\chi}_0^l > \tilde{\chi}_\pm^k \tilde{\chi}_\pm^l > \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{t} \tilde{t} > \tilde{b} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_0^k \tilde{\chi}_0^l > \tilde{g} \tilde{g}
\]

Cross-sections ranging from 1.5 pb to 1 fb.

- \(M_{\tilde{t}}\) and \(M_{\tilde{b}}\) is 200 GeV higher in STC10.

- Cross-sections for \(\tilde{\tau}\) and \(\tilde{b}\) are 5 times smaller in STC10 wrt STC8.

- \(\tilde{\chi}_0\) cascade-decays to \(\tau\)s + the LSP in 75 % of the cases, often together with a boson (\(Z\), \(W\) or \(h\)).

- For \(\tilde{\chi}_\pm\), the rest is other leptons.

- The \(\tau\)s mostly come from \(\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0\), where the mass difference is only 10 GeV ⇒ little missing energy.

- \(\tilde{b}\) mostly decays to \(b\) \(\tilde{\chi}_0\) > 50 % to \(b\) \(\tilde{\chi}_0\). But also to \(t\) \(\tilde{\chi}_\pm\) (20%)

- \(\tilde{t}\) always goes to \(t\) \(\tilde{\chi}_0\), but rarely to \(t\) \(\tilde{\chi}_\pm\) (∼10%)

- The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.

⇒ LHC expectations

- Despite the high cross-section, the low amount of missing \(E_T\) and the long decay chains will make direct bosino and slepton observations hard.

- The simple decay-chains and very high missing \(E_T\) will make first- and second-generation squark production easy to detect. However, the cross-section is so low that it is still challenging.

- Third generation squark production constitute a good compromise between cross-section and visibility, and will be the most powerful discovery channel. The lower cross-section in STC10 is compensated by higher visibility.
STCx @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:

\[
\begin{align*}
&\tilde{\chi}_0^k \tilde{\chi}_\pm^l > \tilde{\chi}_\pm^k \tilde{\chi}_\pm^l > \tilde{\tau} \tilde{\tau} > \tilde{\ell} \tilde{\ell} > \tilde{t} \tilde{t} > \tilde{b} \tilde{b} > \tilde{q} \tilde{q} > \tilde{\chi}_0^k \tilde{\chi}_0^l > \tilde{g} \tilde{g}.
\end{align*}
\]

- \( M_{\tilde{t}} \) and \( M_{\tilde{b}} \) is 200 GeV higher in STC10.
- Cross-sections for \( \tilde{t} \tilde{t} \) and \( \tilde{b} \tilde{b} \) are 5 times smaller in STC10 wrt STC8.

- \( \tilde{\chi}_\pm \) cascade-decays to \( \tau \)'s + the LSP in 75% of the cases, often together with a boson (\( Z, W \) or \( h \)).

- For \( \tilde{\chi}_0 \), the rest is either only bosons, or "nothing" (i.e., neutrinos).

- For \( \tilde{\chi}_\pm \), the rest is other leptons.

- The \( \tau \)'s mostly come from \( \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_0 \), where the mass difference is only 10 GeV \( \Rightarrow \) little missing energy.

- \( \tilde{b} \) mostly decays to \( b \tilde{\chi}_0 \): > 50% to \( b \tilde{\chi}_0 \). But also to \( t \tilde{\chi}_\pm \) (20%).

- \( \tilde{t} \) always goes to \( t \tilde{\chi}_0 \), but rarely to \( t \tilde{\chi}_\pm \) (\( \sim 10\% \)).

- The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.

⇒ LHC expectations

- Despite the high cross-section, the low amount of missing \( E_T \) and the long decay chains will make direct bosino and slepton observations hard.

- The simple decay-chains and very high missing \( E_T \) will make first- and second-generation squark production easy to detect. However, the cross-section is so low that it is still challenging.

- Third generation squark production constitute a good compromise between cross-section and visibility, and will be the most powerful discovery channel. The lower cross-section in STC10 is compensated by higher visibility.
### Observables:

<table>
<thead>
<tr>
<th>Observable</th>
<th>Gives</th>
<th>If</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edges (or average and width)</td>
<td>Masses</td>
<td>... not too far from threshold</td>
</tr>
<tr>
<td>Shape of spectrum</td>
<td>Spin</td>
<td></td>
</tr>
<tr>
<td>Angular distributions</td>
<td>Mass, Spin</td>
<td></td>
</tr>
<tr>
<td>Invariant mass distributions from full reconstruction</td>
<td>Mass</td>
<td>... cascade decays</td>
</tr>
<tr>
<td>Angular distributions from full reconstruction</td>
<td>Spin, CP</td>
<td>... masses known</td>
</tr>
<tr>
<td>Un-polarised Cross-section in continuum</td>
<td>Mass, coupling</td>
<td></td>
</tr>
<tr>
<td>Polarised Cross-section in continuum</td>
<td>Mass, coupling, mixing</td>
<td></td>
</tr>
<tr>
<td>Decay product polarisation</td>
<td>Mixing</td>
<td>... $\bar{\tau}$ decays</td>
</tr>
<tr>
<td>Threshold-scan</td>
<td>Mass(es), Spin</td>
<td></td>
</tr>
</tbody>
</table>