SUSY model and dark matter determination in the compressed-spectrum region at the ILC.

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on behalf of the ILC Physics and Detector Study

[1]DESY, Hamburg

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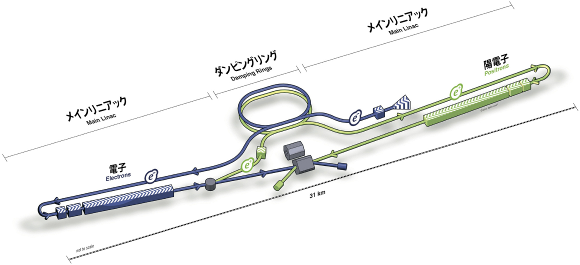
Outline

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 accelertors
     - 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 fb^{-1}/year. 20 year plan in place.
- Polarisation e$^-$: 80% , e$^+$: $\geq$ 30%.
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- Concurrent running with the LHC.
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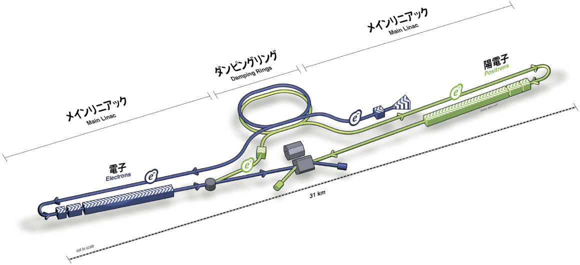

ILC Scheme | ©www.form-one.de

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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 $\times$ 100 nm $\times$ 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 4π: holes for beam-pipe only few cm = 0.2 msr un-covered = Area of Connecticut relative to earth.

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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:
  - $m_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2|\mu|^2$
  - $\Rightarrow$ Low fine-tuning $\Rightarrow \mu = \mathcal{O}$(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.

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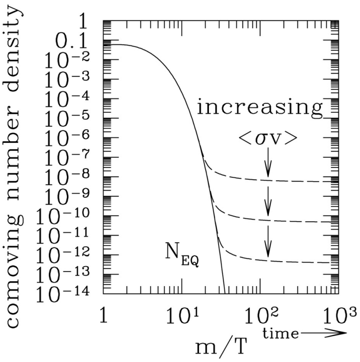
Why compressed spectra ? DM and the weak miracle

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 ⇒ Once again Compressed spectrum.



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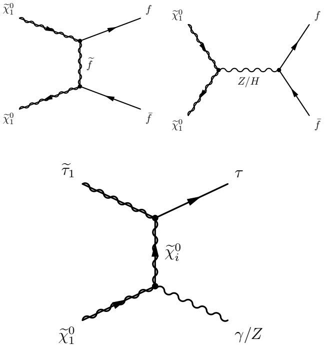

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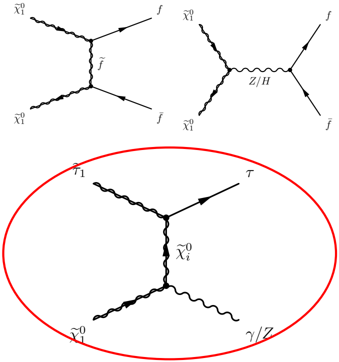

Why not seen @ LHC ?

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: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$\rightarrow$LSP + visible with soft spectrum.
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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 σ) (M.B. arXiv:1308.1461)
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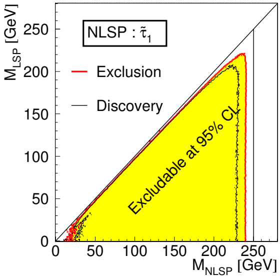

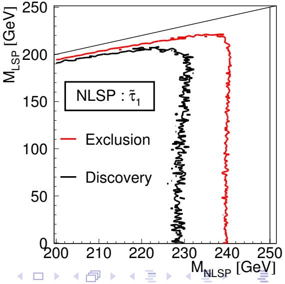

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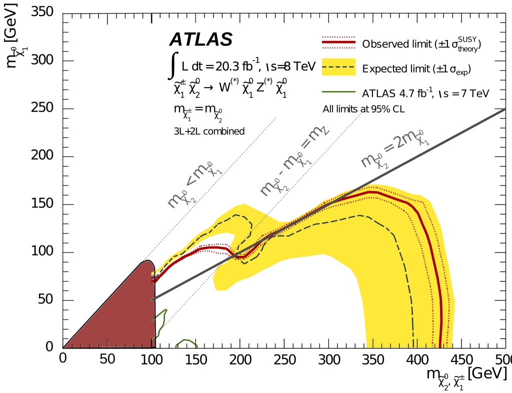

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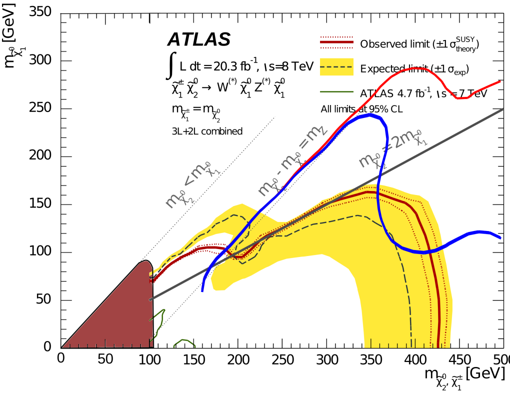

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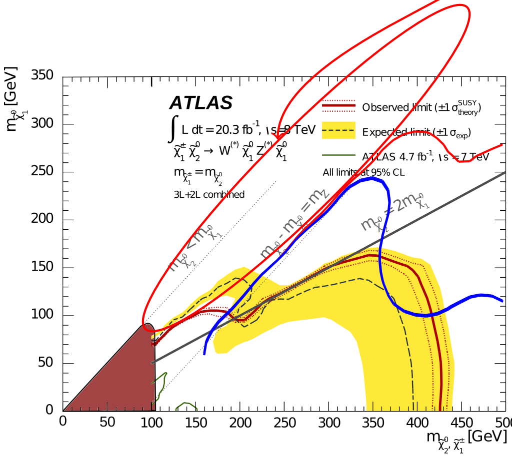
Compressed region !



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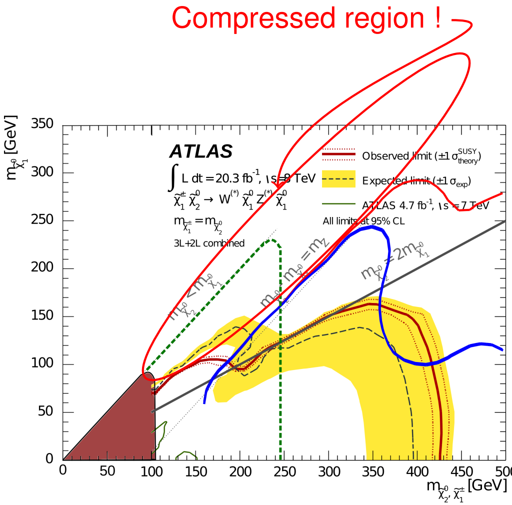

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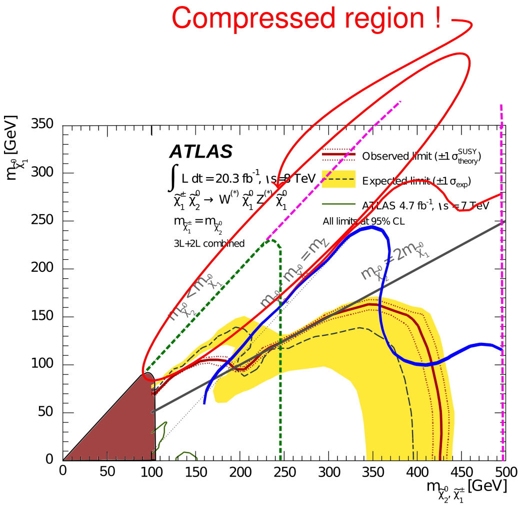
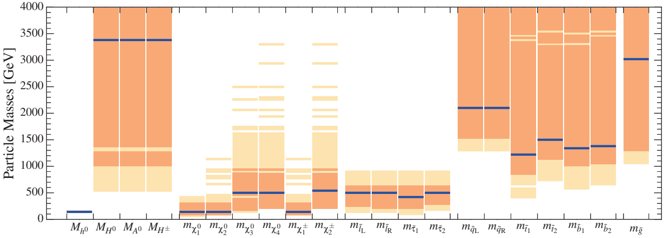


Why compressed spectra ? Global fits

Because it fits the observations best !

pMSSM10 prediction: best-fit masses

mastercode [2015]



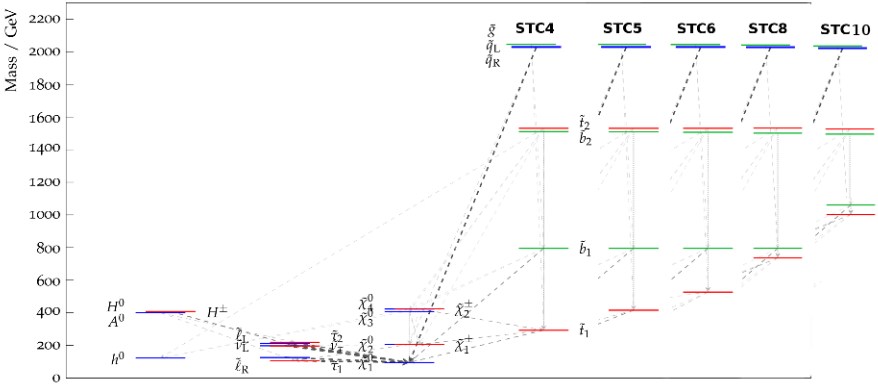
⇒ high colored masses

⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for ILC and CLIC

The Stau-coannihilation STCx models M.B. & al. EPJC, 76(4),1 (2016)



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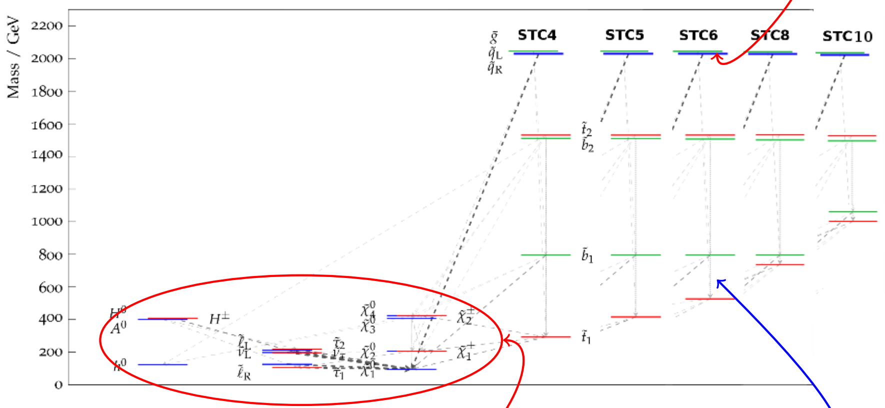
High mass squarks+gluino



Well-tempered higgs, bosino and slepton sector.

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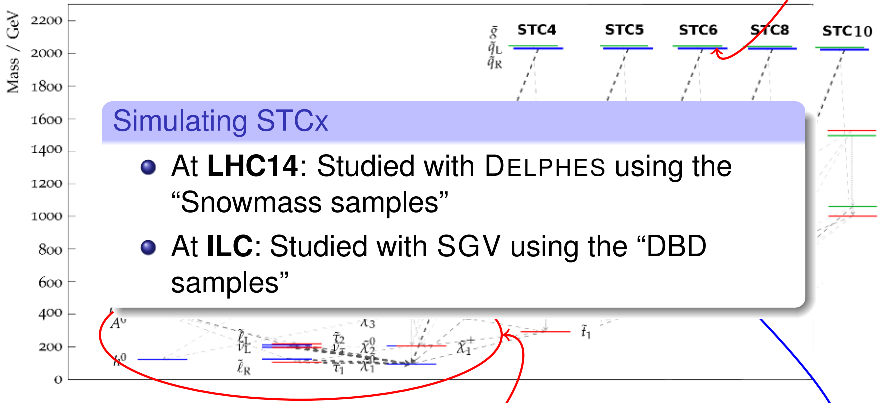

Simulating STCx

- At **LHC14**: Studied with DELPHES using the "Snowmass samples"
- At **ILC**: Studied with SGV using the "DBD samples"

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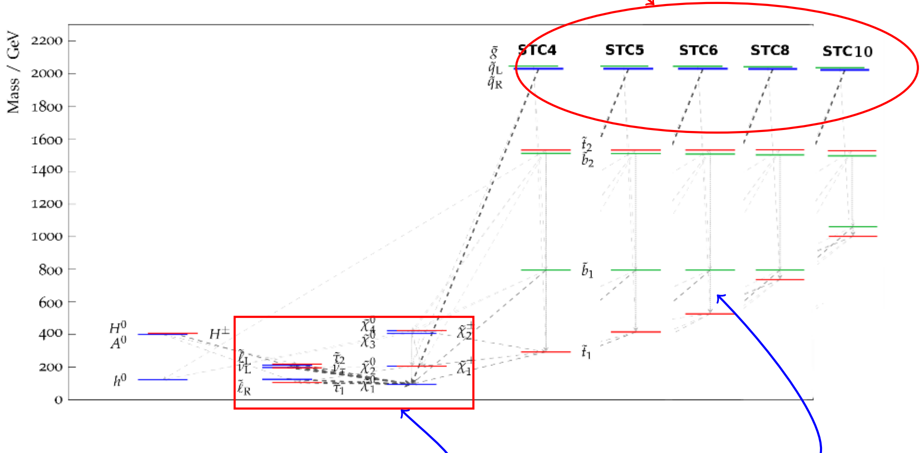
Not seen by HiLumiLHC: too low x-sect

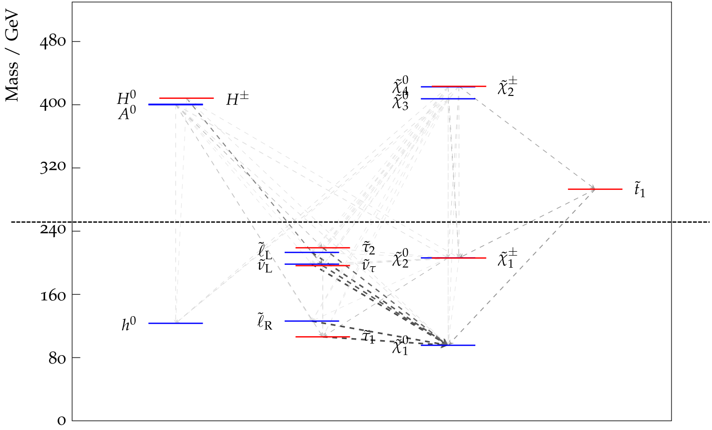


LHC would see signs of this sector

LHC will see these

The STCx benchmark @ ILC

Zoomed STCx mass-spectrum



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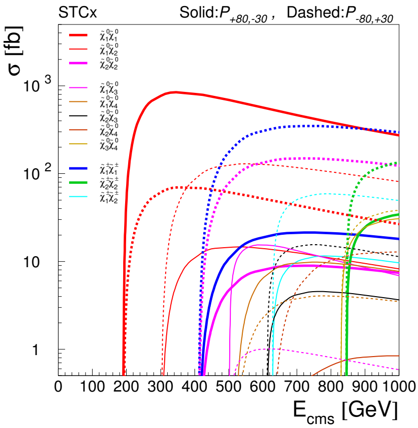
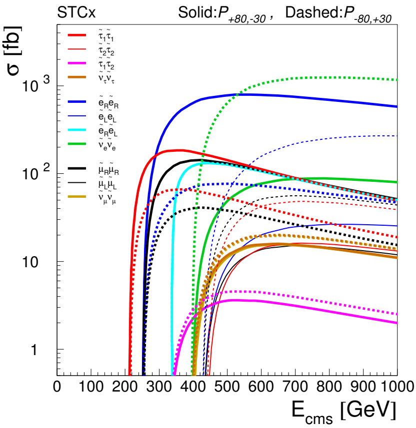
Cross-sections





The STCx benchmark @ ILC

Cross-sections

σ [fb]

$\Rightarrow$ 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 $\tilde{\tau}_1$.
- $\Delta(M) \sim 10$ GeV $\Rightarrow E_\tau \in [2.3, 45.5]$ GeV.

Background:

- Real missing energy = $ZZ, WW \rightarrow \ell\ell\nu\nu$
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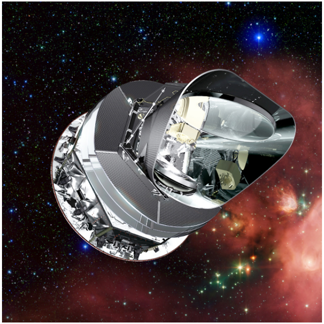
DM: Needed precision

- Planck: Cosmological abundance from CMB: Δ=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.
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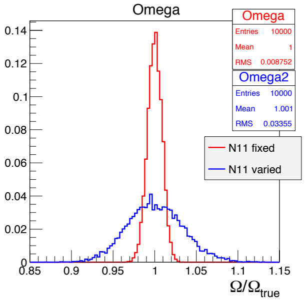

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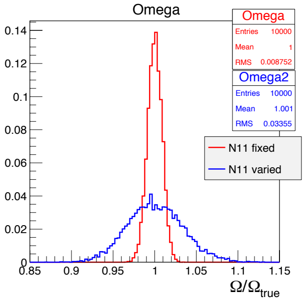

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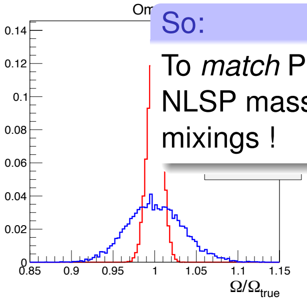

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So:

To *match* Planck, need per mil LSP and NLSP masses, percent LSP and NLSP mixings !

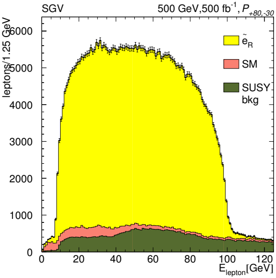
How to reach the needed precision?

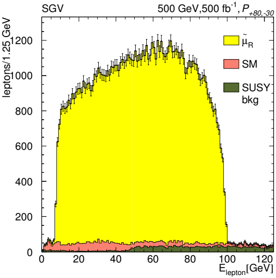
Look at pair-production

- $E'_{\substack{max\\min}} = \frac{E_{Beam}}{2}\left(1-\left(\frac{M_{\tilde{\chi}^0_1}}{M_{\tilde{\ell}}}\right)^2\right)\left(1\pm\sqrt{1-\left(\frac{M_{\tilde{\ell}}}{E_{Beam}}\right)^2}\right)$
- Two observables($E'_{\substack{max\\min}}$) and two parameters ($M_{\tilde{\ell}}$ and $M_{\tilde{\chi}^0_1}$).
- For $\tilde{\mathrm{e}}_{\mathrm{R}}$ and $\tilde{\mu}_{\mathrm{R}}$, $E'_{\substack{max\\min}}$ can be measured very well at the ILC.
- E'_{max} can be well measured for $\tilde{\tau}_1$
- $\Rightarrow$ Use $\tilde{\mathrm{e}}_{\mathrm{R}}$ and $\tilde{\mu}_{\mathrm{R}}$ to determine $M_{\tilde{\chi}^0_1}$, end-point of $E_{\tau-jet}$ for $M_{\tilde{\tau}_1}$.

STC4 sleptons @ 500 GeV:$\tilde{e}$, $\tilde{\mu}$

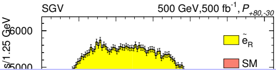
- Selections for $\tilde{\mu}$ and $\tilde{e}$:
  - Correct charge.
  - P_T wrt. beam and one ℓ wrt the other.
  - Tag and probe, ie. accept one jet if the other is “in the box”.
- Further selections for R:
  - Cuts on polar angle and angle between leptons.
- E_{jet}, beam-pol 80%,-30%...





STC4 sleptons @ 500 GeV: $\tilde{e}$, $\tilde{\mu}$

- Selections for $\tilde{\mu}$ and $\tilde{e}$:



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

selectrons:

$$M_{\tilde{e}_R} = 126.20 \pm 0.21 \text{ GeV}/c^2$$

$$M_{\tilde{\chi}^0_1} = 95.47 \pm 0.16 \text{ GeV}/c^2$$

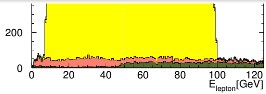
smuons:

$$M_{\tilde{\mu}_R} = 126.01 \pm 0.51 \text{ GeV}/c^2$$

$$M_{\tilde{\chi}^0_1} = 95.47 \pm 0.38 \text{ GeV}/c^2$$

combined:

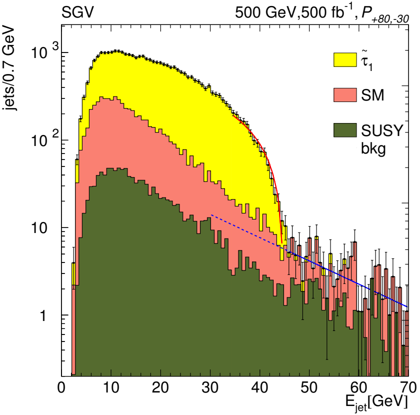
$$\sigma_{M_{\tilde{\chi}^0_0}} = 147 \text{ MeV}/c^2 \qquad \sigma_{M_{\tilde{\ell}_R}} = 194 \text{ MeV}/c^2$$



STC4 sleptons @ 500 GeV:$\tilde{\tau}_1$

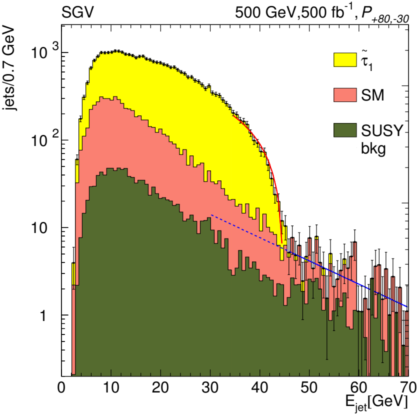
Selections for $\tilde{\tau}_1$:

- Correct charge.
- P_T wrt. beam and one τ wrt the other.
- $M_{jet} < M_\tau$
- $E_{vis} < 120$ GeV, $M_{vis} \in [20, 87]$ GeV.
- Cuts on polar angle and angle between leptons.
- Little energy below 30 deg, or not in τ-jet.
- At least one τ-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).



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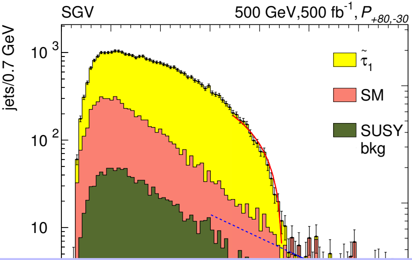

Results for $\tilde{\tau}_1$

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

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

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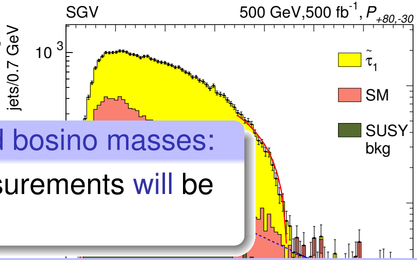

Summary of slepton and bosino masses:

Per mil-level mass-measurements will be possible at the ILC

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Prospects for mixing measurements

- $\theta_{\tilde{\tau}}$: Several options:
  - Absoulute Cross-section: $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, \mathcal{P}_{beam}) \times \beta^3/s$: 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 $\tilde{\chi}^0_1$):
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  - However, cross-section also depends on other elements of the neutralino-matrix, and on $M_{\tilde{e}}$
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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.
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Thank You !

BACKUP

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

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

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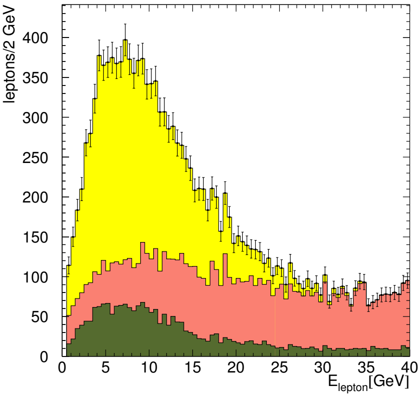

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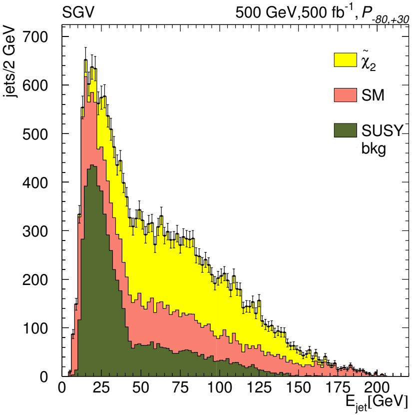

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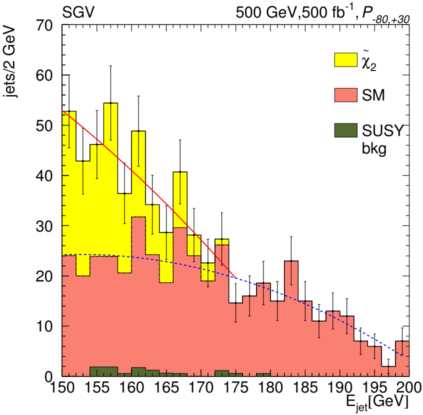

Natural SUSY: Light, degenerate higgsinos

- 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 γ: only $\tilde{\chi}_2^0$.
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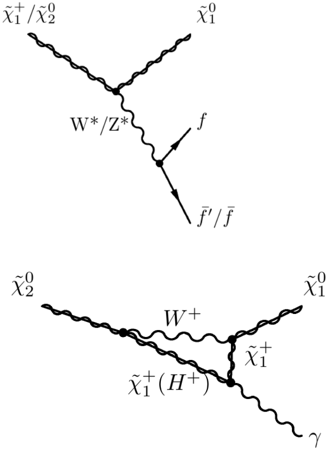
- Close to end-point, E_π gives $\Delta(M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_1^{\pm}})$ to $\sim$ 100 MeV.



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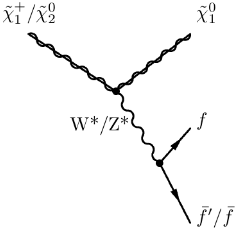

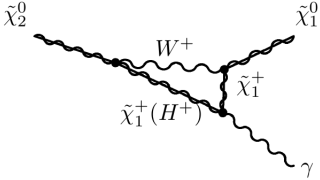

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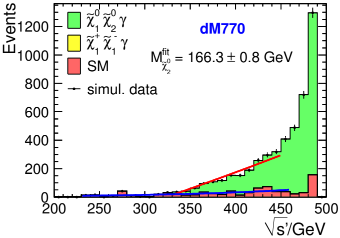

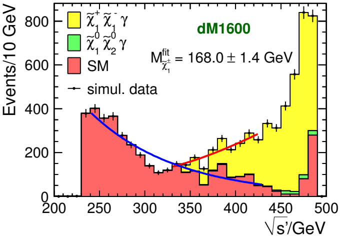

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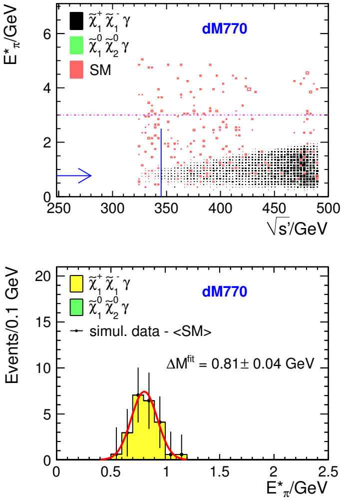

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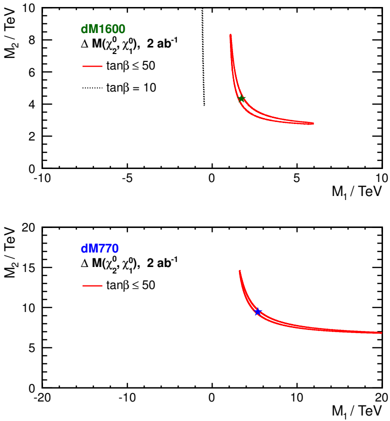

STCx @ LHC14

- STC8 and STC10 studied by I. Meltzer-Pullmans group at DESY with fastsim (Delphes).
- Main features at LHC 14 TeV:
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    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 τ: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).
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  - The τ: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.
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    ranging from 1.5 pb to 1 fb. $M_{\tilde{\mathrm{t}}}$ and $M_{\tilde{\mathrm{b}}}$ is 200 GeV higher in STC10

    $\rightarrow$ Cross-sections for $\tilde{\mathrm{t}}\tilde{\mathrm{t}}$ and $\tilde{\mathrm{b}}\tilde{\mathrm{b}}$ 5 $\times$ smaller in STC10 wrt STC8.
  - $\tilde{\chi}$ cascade-decays to τ: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 τ:s mostly come from $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}^0_0$, where the mass difference is only 10 $\mathrm{GeV} \Rightarrow$ little missing energy.
  - $\tilde{\mathrm{b}}$ mostly decays to $b\tilde{\chi}^0$: $>$ 50 % to $b\tilde{\chi}^0_1$. But also to $t\tilde{\chi}^\pm$ (20%)
  - $\tilde{\mathrm{t}}$ 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.

STCx @ LHC14

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

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