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

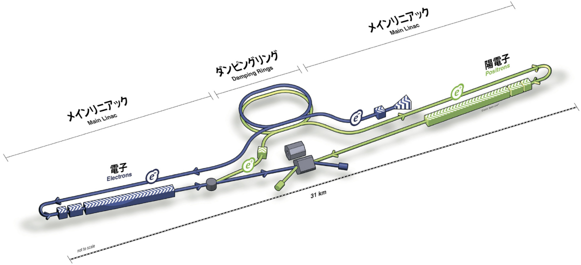
Mikael Berggren[1]
on behalf of the ILC Physics and Detector Study

[1]DESY, Hamburg

ICHEP, Chicago, Il, August, 2016

Outline

The ILC



ILC Scheme | ©www.form-one.de

- A linear e^+e^- collider.
- E_{CMS} tunable between 250 and 500 GeV, upgradable to 1 TeV.
- Total length 31 km
- $\int \mathcal{L} \sim 250$ 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.

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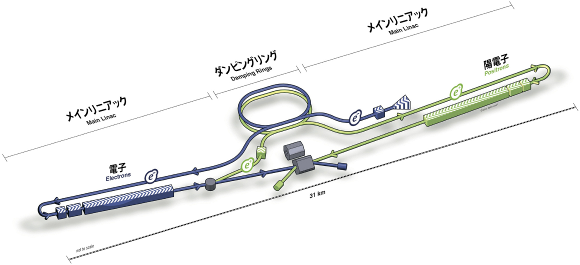

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The ILC is not LHC

- 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).
  - If multi-TeV gaugino masses:
    - $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ pure higgsino. Rest of SUSY at multi-TeV.
    - $M_{\tilde{\chi}_{1,2}^0}, M_{\tilde{\chi}_1^\pm} \approx \mu$
    - Degenerate (ΔM is 1 GeV or less)
  - Or: Radiative driven natural susy
    - Still $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ almost pure higgsino
    - ΔM still small, but more like 10-20 GeV.
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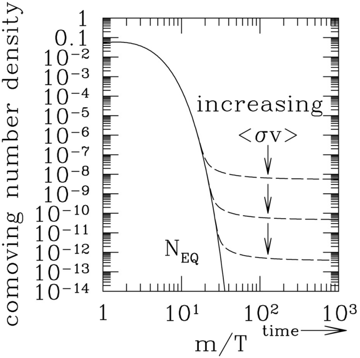
Why compressed spectra ? DM and the weak miracle

Because 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.
- Often the main process (from Matercode)



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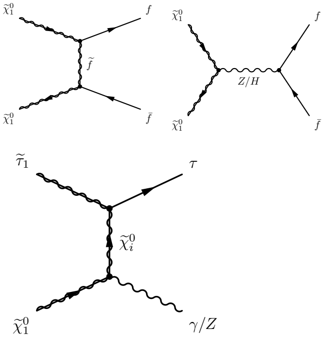

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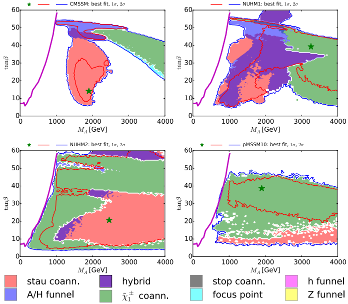
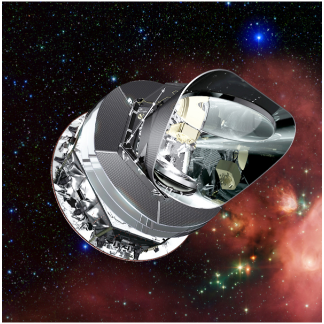


DM: Needed precision

- Plank: 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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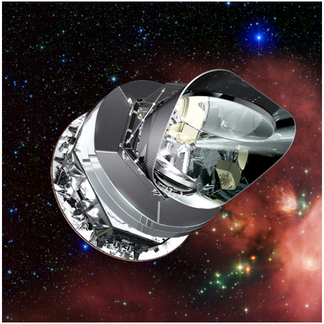

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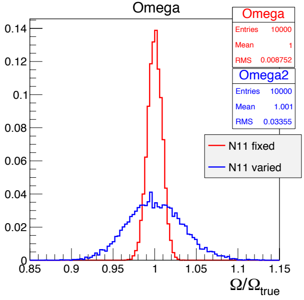

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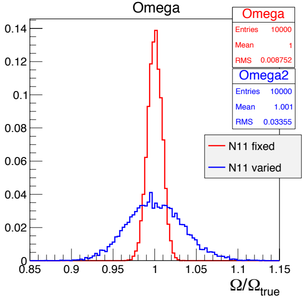

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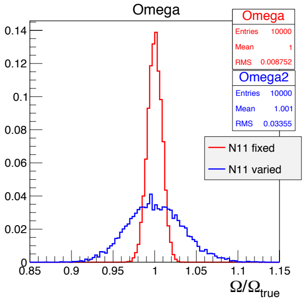

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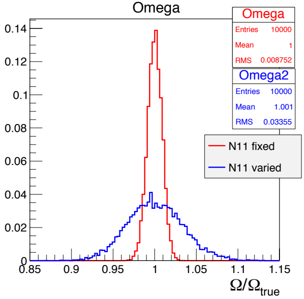

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So:

To *match* Plank, need per mil masses, percent mixings !

Why not seen @ LHC ?

Recall:

- LHC excludes 1:st & 2:nd generation squarks and gluinos. These states have no influence on DM, g-2, naturalness, ...
- Ie. : The reason that mSUGRA/CMSSM is dead is the *irrelevant part*!
- If spectrum is compressed: Long decay-cascades @ LHC, ending up at a NLSP→LSP + visible with soft spectrum.
- Ie. *NOT* a simplified model, *NOR* a large missing E_T one.
- Remove connection 1:st & 2:nd gen $\tilde{q}$:s and $\tilde{g}$ ↔ 3:d gen. $\tilde{q}$:s and EW-sector ⇒ Compressed spectra not excluded. Price: more free parameters.
- (Actually, the U(1) and SU(2) masses (M_1 and M_2) can still unify).
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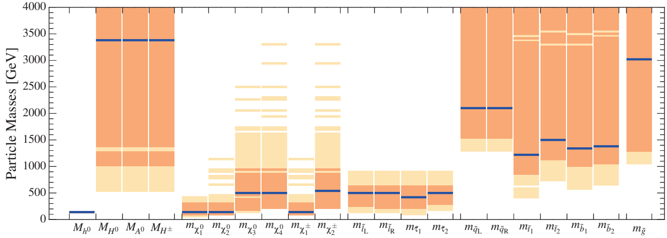
Why compressed spectra ? Global fits

Because it fits the observations best !

pMSSM10 prediction: best-fit masses

MasterCode [2015]



⇒ high colored masses

⇒ relatively low electroweak masses

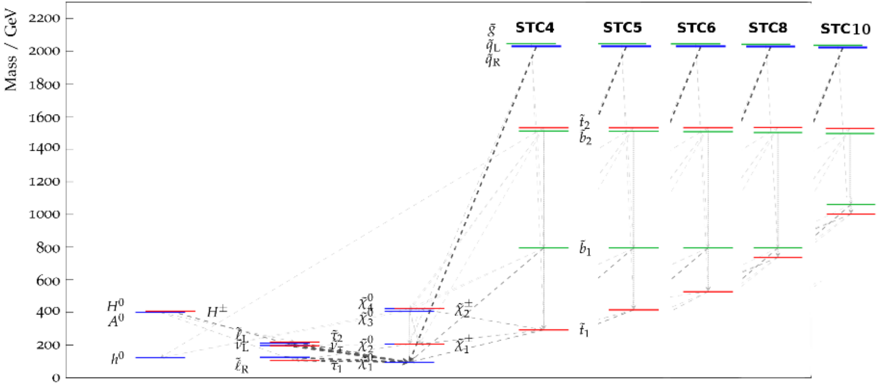
partially with not too large ranges

⇒ clear prediction for ILC and CLIC

Sven Heinemeyer, LCWS15, Whistler, 03.11.2015 14

The Stau-coannihilation STCx models

High mass squarks+gluino

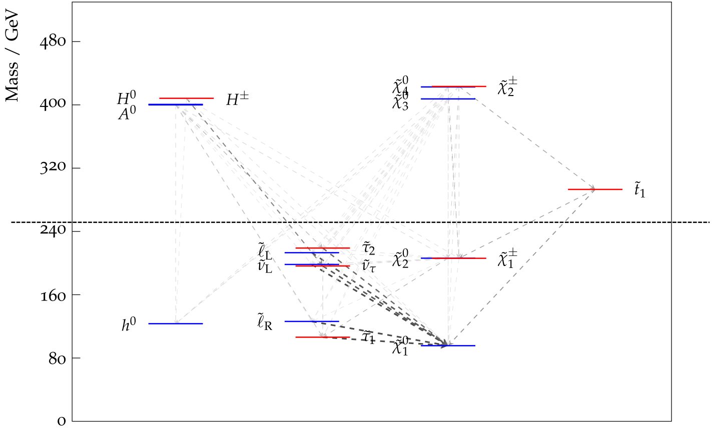


Well-tempered higgs, bosino and slepton sector

Varying 3-gen squarks

The STCx benchmark @ ILC

Zoomed STCx mass-spectrum



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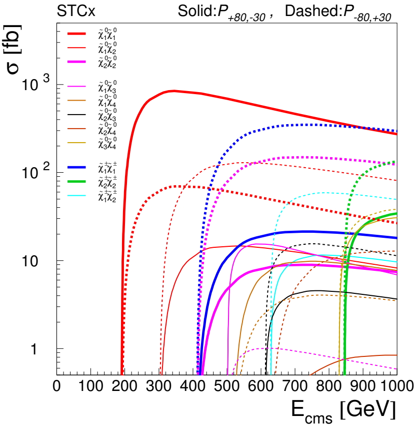
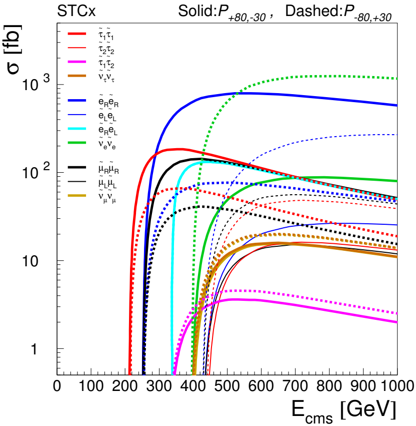
Cross-sections





The STCx benchmark @ ILC

Cross-sections

σ [fb]

⇒ 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, $WW \rightarrow \ell\ell\nu\nu$
- Fake missing energy = $\gamma\gamma$ processes, ISR, single IVB.

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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%...

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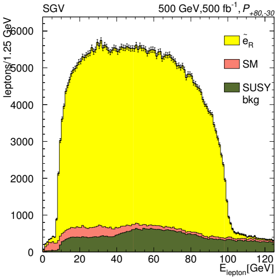

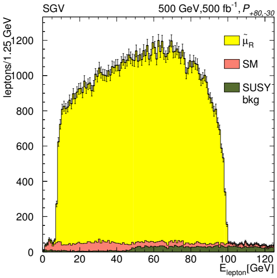

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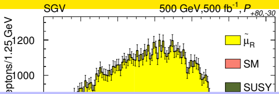


- Selections for $\tilde{\mu}$ and $\tilde{e}$:

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

selectrons:

$$M_{\tilde{e}_R} = 126.20 \pm 0.21 \text{ GeV}/c^2$$
$$M_{\tilde{\chi}_1^0} = 95.47 \pm 0.16 \text{ GeV}/c^2$$

smuons:

$$M_{\tilde{\mu}_R} = 126.01 \pm 0.51 \text{ GeV}/c^2$$
$$M_{\tilde{\chi}_1^0} = 95.47 \pm 0.38 \text{ GeV}/c^2$$

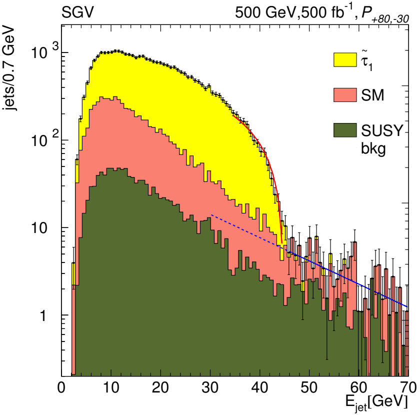
combined:

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

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

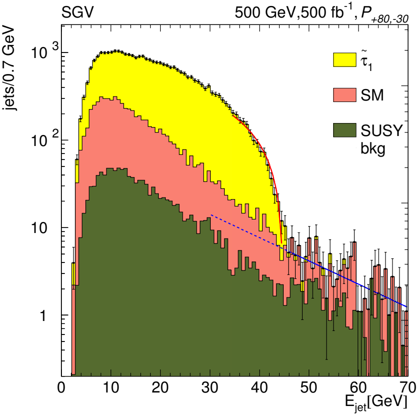
Selections for $\tilde{\tau}_1$:

- 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:
  - $\tilde{\tau}_1$: Important SUSY background,but region above 45 GeV is signal free. Fit exponential and extrapolate.
  - $\tilde{\tau}_2$: $\sim$ no SUSY background above 45 GeV. Take background from SM-only simulation and fit exponential.
- Fit line to (data-background fit).



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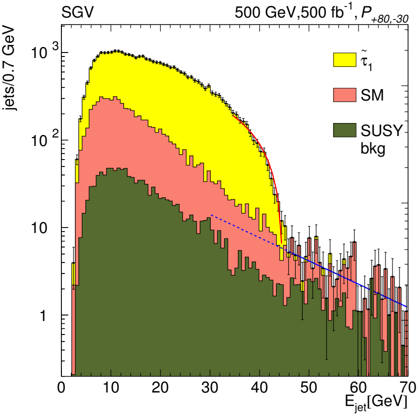
  - $\tilde{\tau}_2$: $\sim$ no SUSY background above 45 GeV. Take background from SM-only simulation and fit exponential.
- Fit line to (data-background fit).



Fitting the $\tilde{\tau}$ end-points

- Only the upper end-point is relevant.
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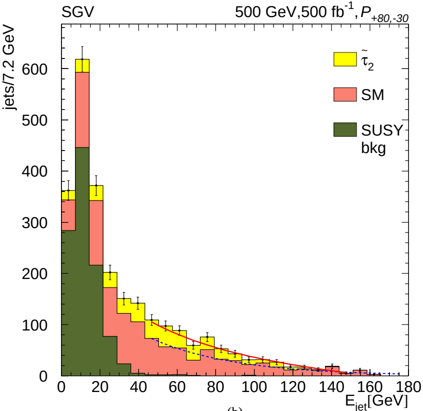

(b)

Fitting the $\tilde{\tau}$ end-points

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- Background subtraction:
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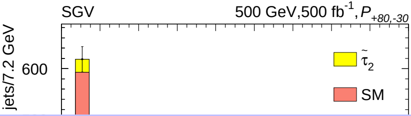

Results for $\tilde{\tau}_1$

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

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

SM only simulation and fit
exponential

Results for $\tilde{\tau}_2$

$E_{max,\tilde{\tau}_2} = 145.4^{+5.9}_{-4.4}\mathrm{GeV}$

Translates to an error on the mass of 5 GeV/c^2, dominated by the error from the end-point.

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 = 700 MeV $\Rightarrow \Delta(M_{\tilde{\chi}_2^0}) =$??? MeV, assuming the error on $M_{\tilde{\tau}_1}$ from the previous slide.

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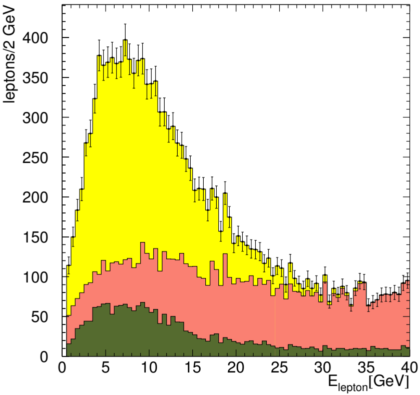

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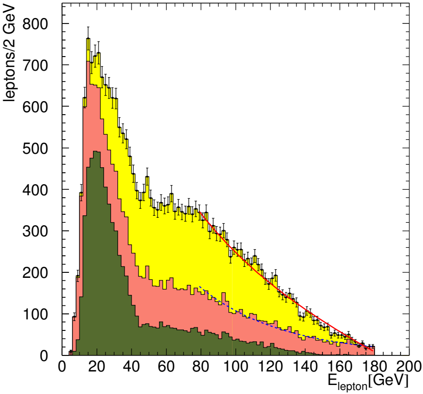

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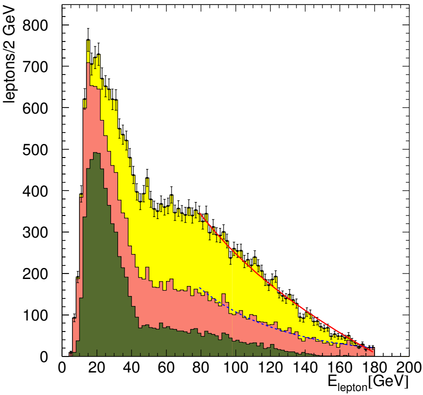

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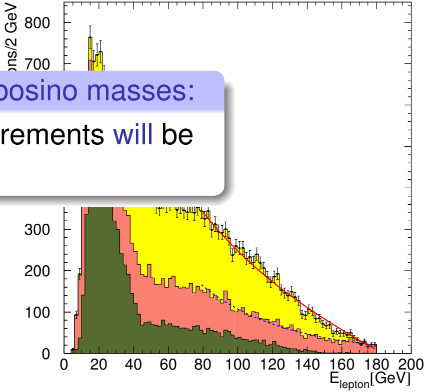
Summary of slepton and bosino masses:

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



Prospects for mixing measurements

- $\theta_{\tilde{\tau}}$: Several options:
  - Cross-section, once $M_{\tilde{\tau}}$ (and E_{CM}) is known only depends on $\theta_{\tilde{\tau}}$.
  - Cross-section difference for RL and LR: For clean signal for LR: lower E_{CM}.
  - If all sleptons are equal at the GUT scale: difference between $M_{\tilde{e}_R}$ and $M_{\tilde{\tau}}$ directly gives the mixing.
  - Cross-section of $\tilde{\tau}_1 \tilde{\tau}_2$ production useful, but very low rate.
  - Percent-level measurement likely.
- N_{11} (bino-ness of $\tilde{\chi}_1^0$):
  - Direct cross-section from mono-photon search (+ knowledge of $M_{\tilde{e}_R}$)? Other invisible channels ($\tilde{\nu}$ and $\tilde{\chi}_2^0 \to \nu\tilde{\nu}$): do it below threshold for these.
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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).
- Most likely LHC will discover it in the next few years, if it is there.
- In such models a rich spectrum reachable by the ILC, ILC will be able to corroborate on LHC discovery.
- In particular, 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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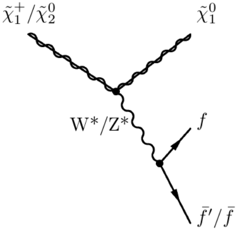
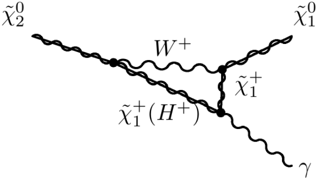
Thank You !

BACKUP

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 $\tilde{\chi}_2^0$.
- E_{ISR} gives reduced $\sqrt{s'}$: "auto-scan". End-point gives masses to $\sim$ 1 GeV.
- 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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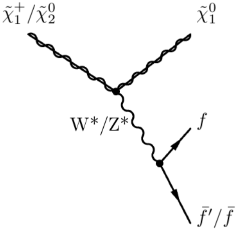

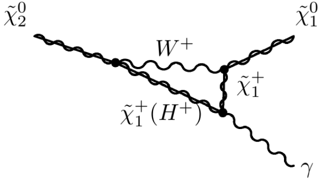

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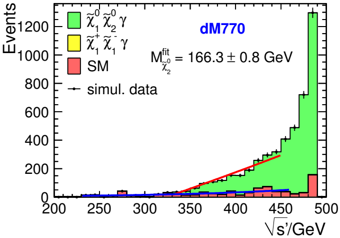

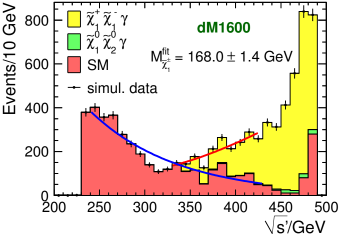

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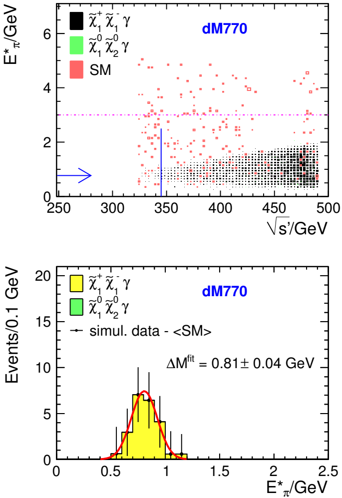

Natural SUSY: Light, degenerate higgsinos

- Use to extract the model-parameters μ, M_1 and M_2 (little $\tan\beta$ dependence).
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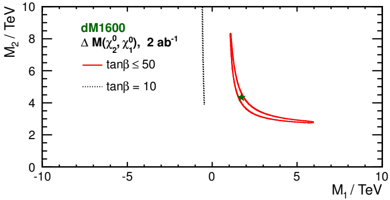

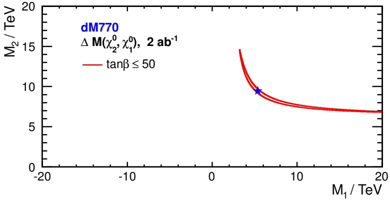

STCx @ LHC14

- STC8 and STC10 studied by I. Melee-Pullmans group at DEWY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    - $\tilde{\chi}^0_k\tilde{\chi}^\pm_l > \tilde{\chi}^\pm_k\tilde{\chi}^\pm_l > \tilde{\tau}\tilde{\tau} > \tilde{\ell}\tilde{\ell} > \tilde{\mathrm{t}}\tilde{\mathrm{t}} > \tilde{\mathrm{b}}\tilde{\mathrm{b}} > \tilde{q}\tilde{q} > \tilde{\chi}^0_k\tilde{\chi}^0_l > \tilde{g}\tilde{g}$

    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).
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  - $\tilde{\mathrm{t}}$ 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. Melee-Pullmans group at DEWY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    - $\tilde{\chi}^0_k \tilde{\chi}^\pm_l > \tilde{\chi}^\pm_k \tilde{\chi}^\pm_l > \tilde{\tau}\tilde{\tau} > \tilde{\ell}\tilde{\ell} > \tilde{t}\tilde{t} > \tilde{b}\tilde{b} > \tilde{q}\tilde{q} > \tilde{\chi}^0_k \tilde{\chi}^0_l > \tilde{g}\tilde{g}$

    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 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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⇒ 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.

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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	