ILC perspective on SUSY searches

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Outline

1. SUSY: What *do* we know ?
2. SUSY In The Briefing-book
   - Bino LSP
   - Wino/Higgsino LSP
3. SUSY at ILC
   - Picture gallery
4. Conclusions

SUSY: What *do* we know ?

Naturalness, hierarchy, DM, g-2 all prefers light electro-weak sector.

- Except for 3d gen. squarks, the coloured sector - where pp machines excel - doesn't enter the game.
- Both if the LSP is mainly higgsino or mainly wino, electro-weak sector is "compressed".
- Then, most sparticle-decays are via cascades. At the end of these cascades, the mass difference is small.
- For this, current limits from LHC are only for specific models, and LEP2 sets the scene.
- Same goes for sleptons in general, and the $\tilde{\tau}$ in particular.

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What *would* be seen at colliders in the worst case?

- MSSM, R-parity conservation (R-parity violation always easier at e^+e^-)
  - Caveat: also CP-conservation. The experimental implication of CP violation needs study
- sfermions not NLSP (idem, except $\tilde{\tau}$ but even worse for FCChh...)
- Then: LSP is Bino, Wino, or Higgsino (more or less pure), same for the NLSP
- M_1, M_2 and μ are the main-players.
- Consider any values, and combinations of signs, up to values that makes the bosinos out-of-reach for any new facility ∼ a few TeV.
- Also vary other parameters (β, M_A, $M_{sfermion}$) with less impact.
- No other prejudice.

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Aspects of the spectrum

With a broad brush:

- For Higgsino-like LSP,
- for Wino-like LSP,

and

- for Bino-like LSP

Ie. Except for Bino-LSP, the LSP-NLSP splitting is small !

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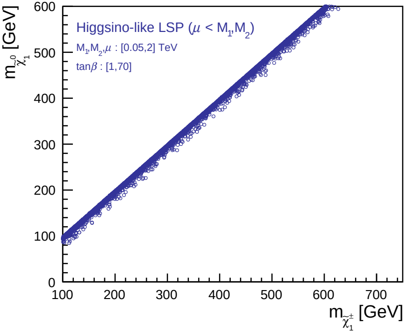

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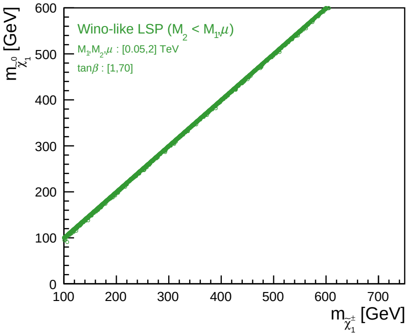

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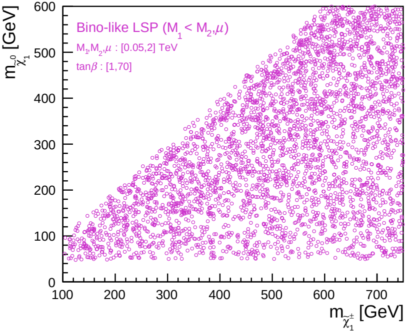

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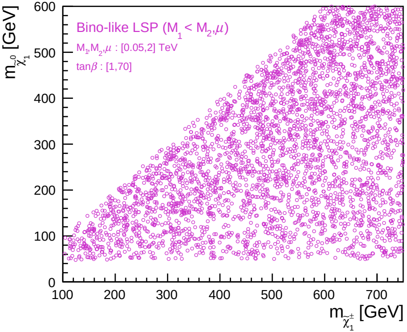
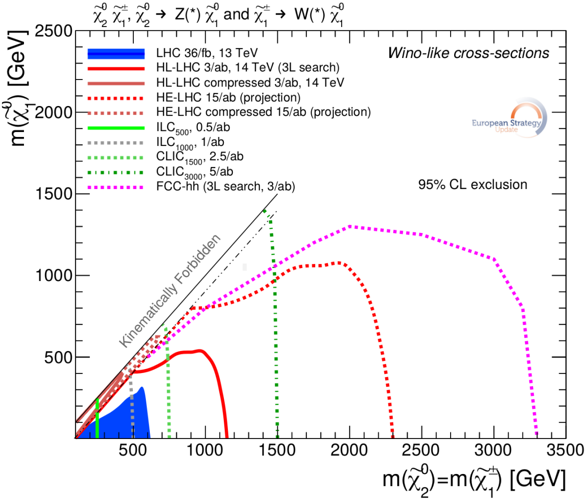


SUSY In The Briefing-book: Bino LSP (ie. large Δ_M)



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- From PHYS-PUB-2018-04 (ATLAS HL-LHC projection). Then extrapolated (up *and down*)
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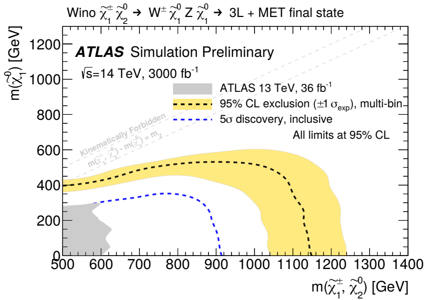
- This is for the best decay mode!
- The other decay mode
- Better at M_{LSP}=0, weaker at lower Δ_M.



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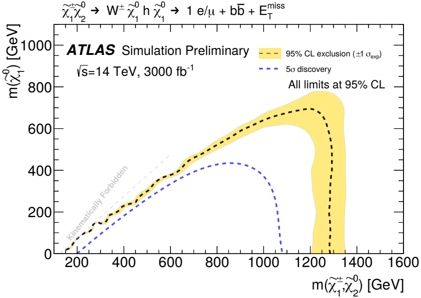
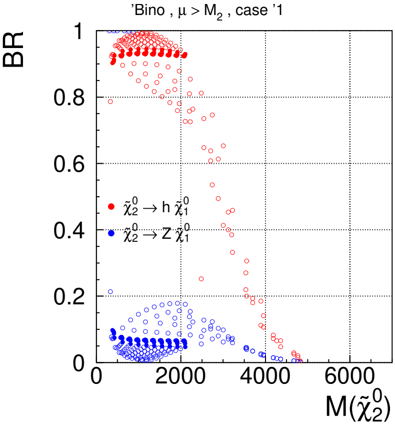


Bino LSP: BRs

Why is the decay-mode an issue? Here's why :

- Vary relative signs of μ, M_1, and M_2, for $\mu > M_2$
- Conclusion: Whether the Z or the H decay-mode of $\tilde{\chi}_2^0$ dominates is pure speculation and
- The exclusion-region is the *intersection* of the two plots, not the *union*!



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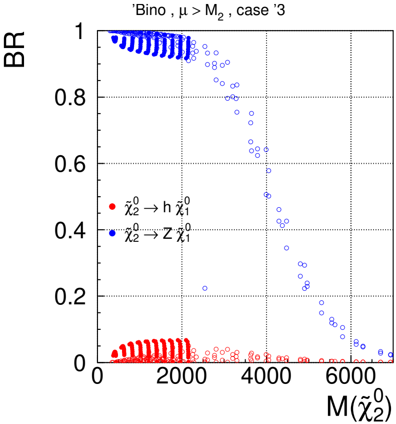

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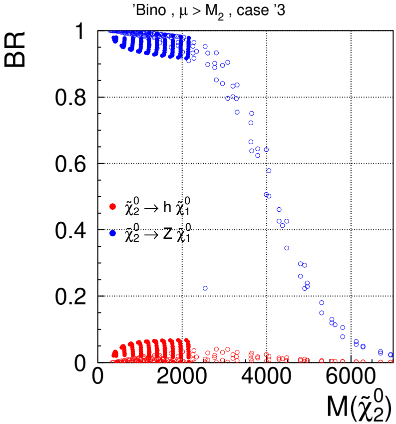

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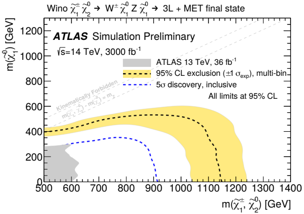

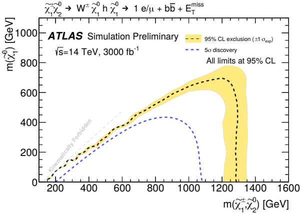

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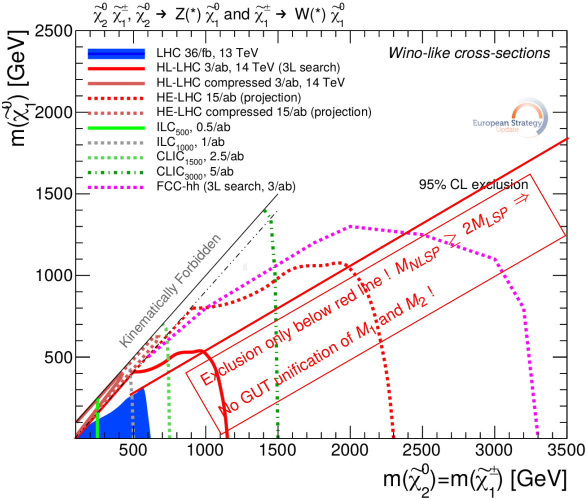

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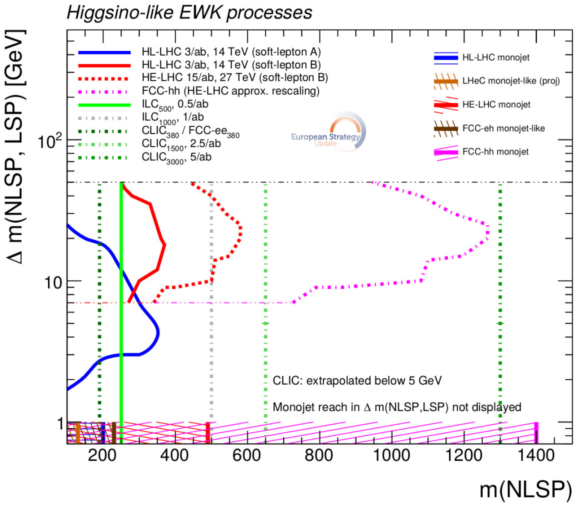
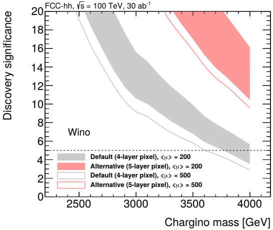
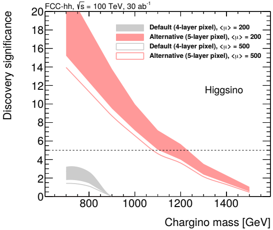


SUSY In The Briefing book: Wino/Higgsino LSP - Sources

(Don’t look at the pink curves - they correspond to a detector that is never considered anywhere else i the CDR)

- The “Disappearing tracks” was done by FCChh (in the CDR)
  - FCChh-detector (better than ATLAS in this case: first layer of VD closer.)
  - FCChh-ish PU (but still to small: 500 vs. CDR number 955)
  - For higgsinos: Only *just* reaches 2 σ





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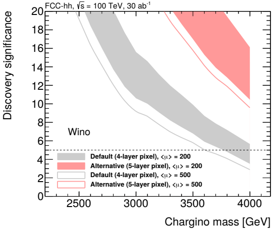
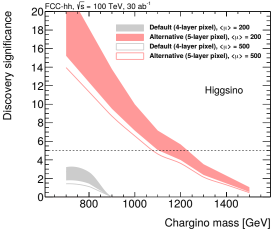
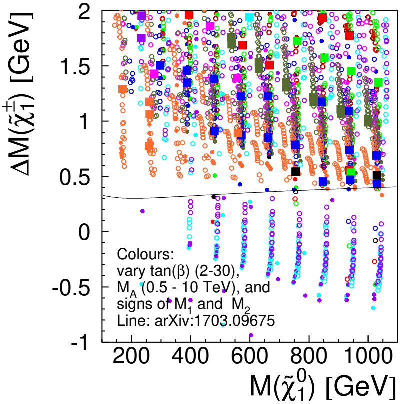




Key element for “Disappearing tracks”: $\Delta(M)$

- Higgsino LSP. The line is the absolute limit mentioned in the BB.
- Let other parameters vary, any signs, M_1 and M_2 close to μ .... Note that the LSP often would be the $\tilde{\chi}_1^{\pm}$!
- Reason: 1703.09675 considers *only SM* effects on the mass-splitting, ie. that M_1 and $M_2 >> \mu$
- Same for Wino LSP.



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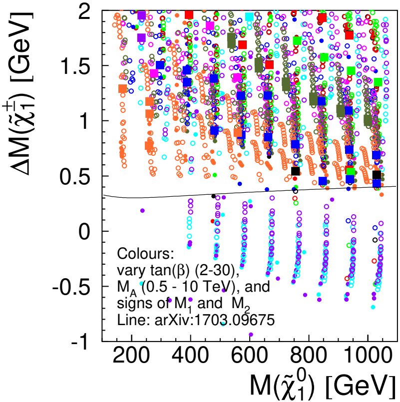

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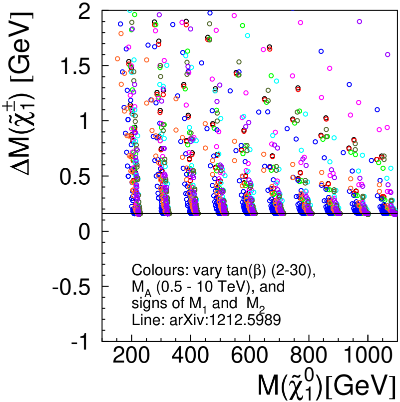

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Why is this important?

- Because $c\tau$ depends on $\Delta(M)$, and $c\tau$ needs to be macroscopic to get “Disappearing tracks”
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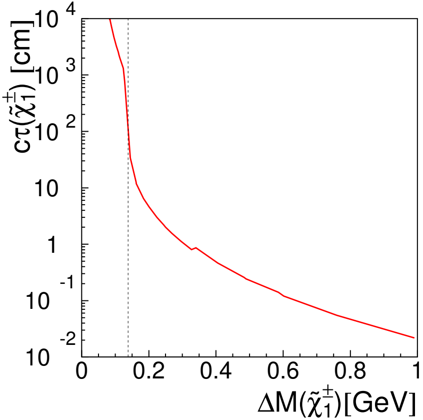

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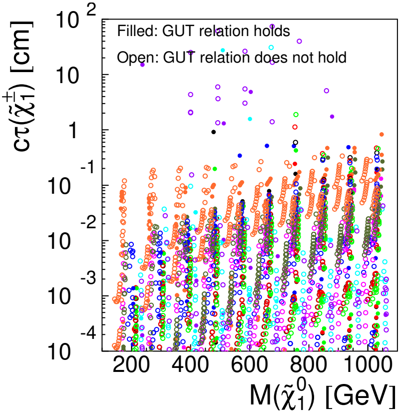

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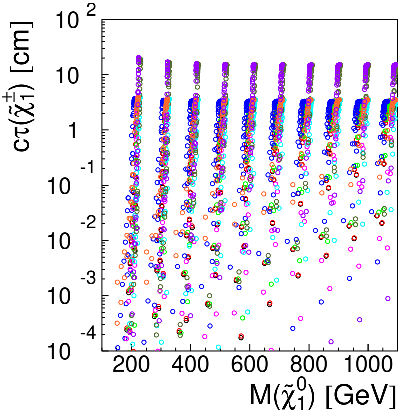

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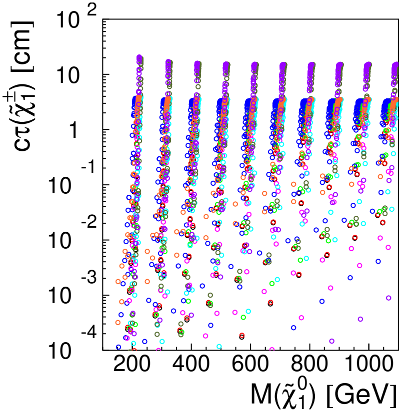

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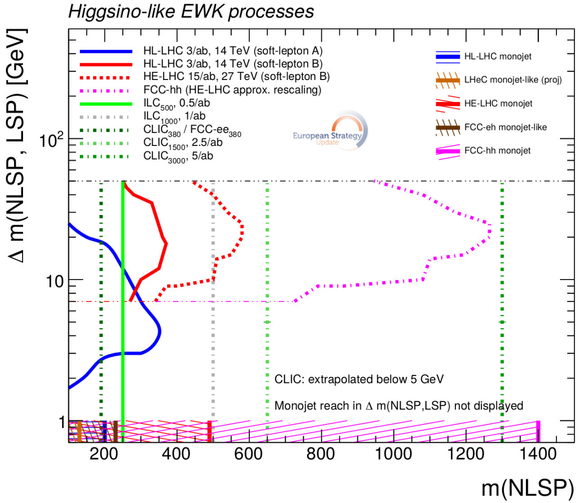
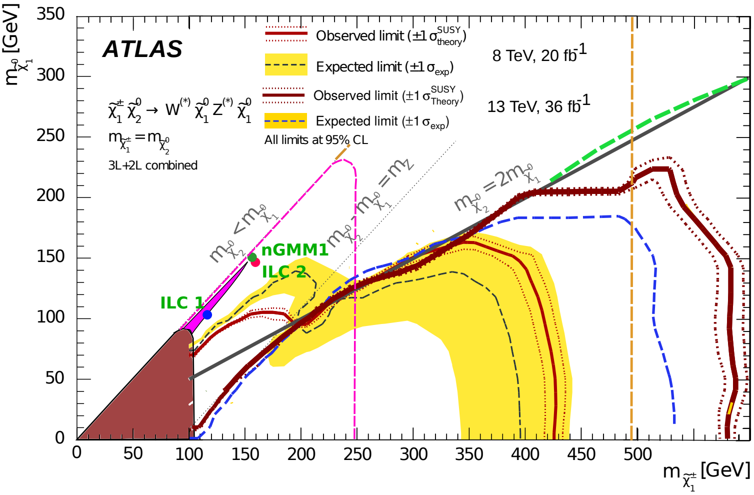


So: Disappearing tracks exclusion is actually off the scale !

SUSY: All-in-one



SUSY at ILC

- Exclusion = Discovery !
- Exclusion **is** Exclusion
- SUSY search = SUSY measurement
- Model testing
- Experimentally, SUSY at ILC more like a B-factory than PP

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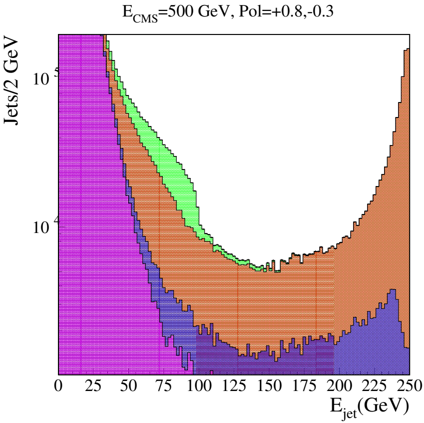
- Just select low multiplicity events...
- Selectrons after one week ...
- Exclusion and discovery
  - Smuon NLSP
  - Stau NLSP
- Chargino NLSP with low $\Delta(M)$, extrapolated from LEP II



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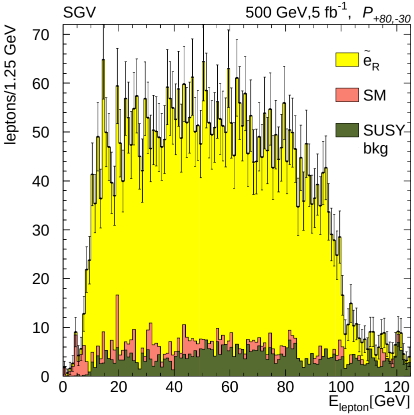

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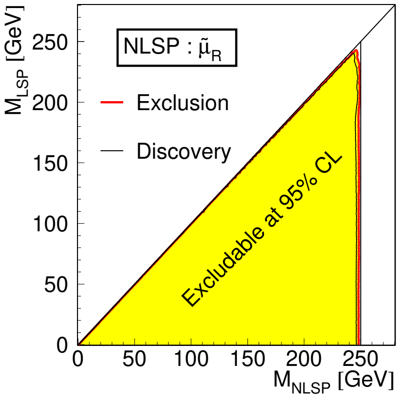

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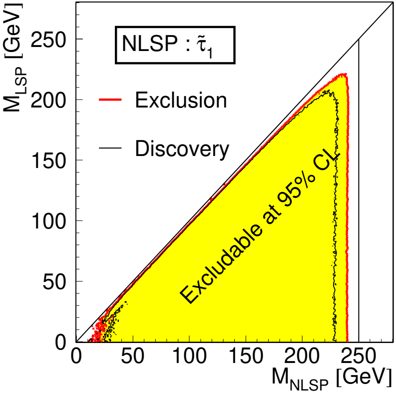

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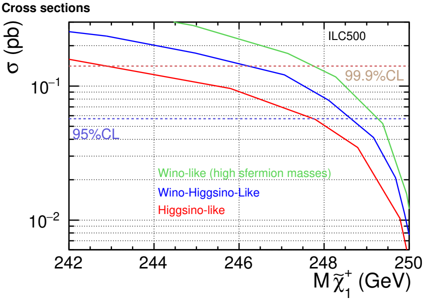

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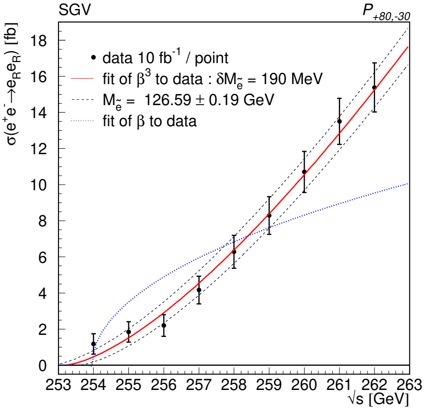

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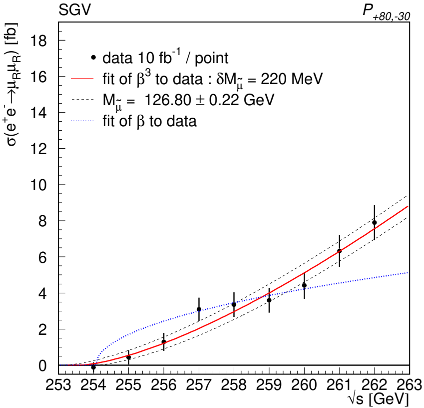

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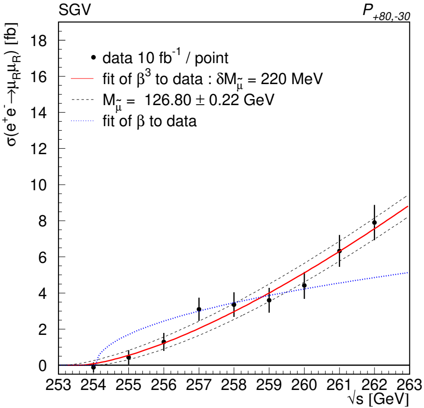

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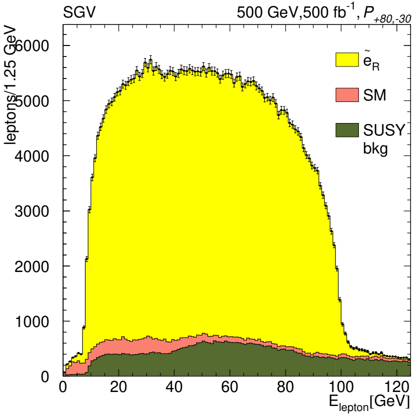

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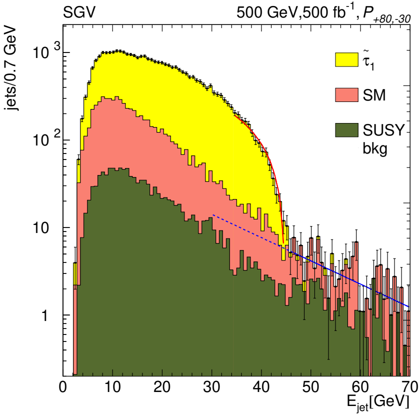

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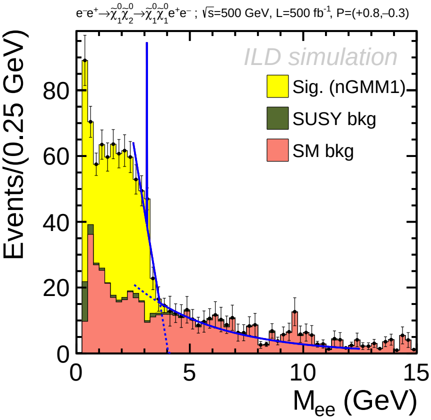
- Masses determined to ∼ 100 MeV = permil-level.



SUSY: Measure properties

- Selectron spectrum after ∼ one year....
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- and charginos.
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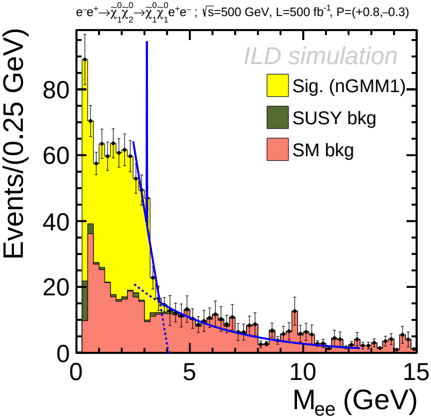
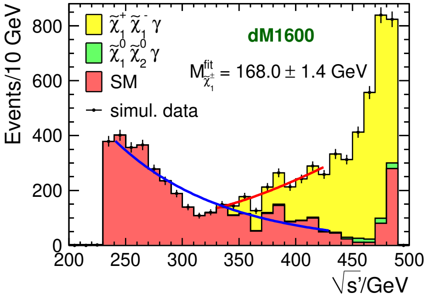


SUSY at ILC: Measure properties, even in tough cases

- Chargino mass determination with $\Delta(M)$ = 1.6 GeV ...
- Or neutralino mass with $\Delta(M)$ = 770 MeV.



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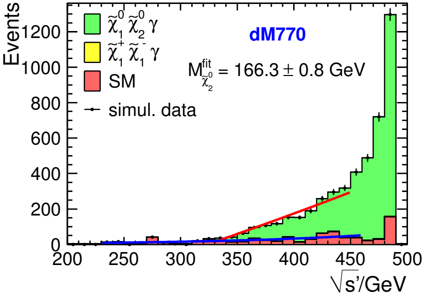
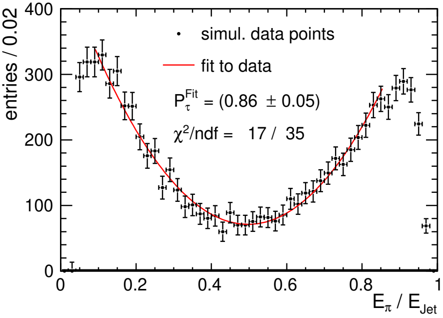


SUSY at ILC: Measure SUSY, not just mass

- Also other aspects. Here
  - Determine the polarisation of taus in stau decays
  - Direct handle on stau mixing.



SUSY at ILC: Full reconstruction

- Or, in a case with cascade-decays $\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \ell\tilde{\chi}_1^0$: Enough constraints to do full kinematic reconstruction.
- Smuon/Selectron
- Zoom in: Mass to less than 10 MeV
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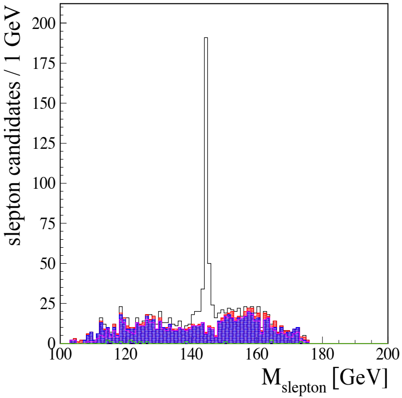

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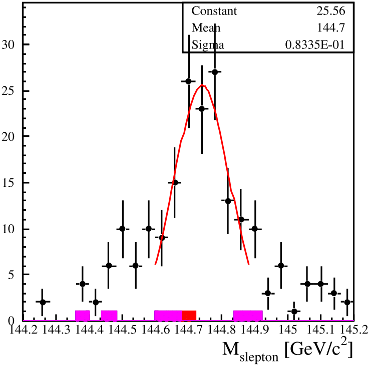

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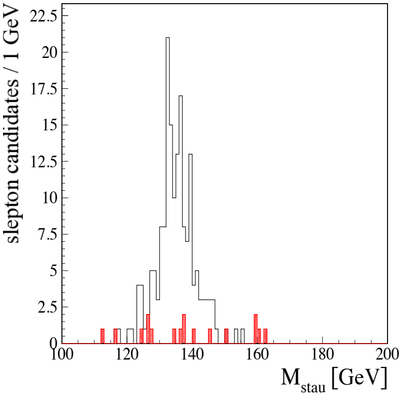
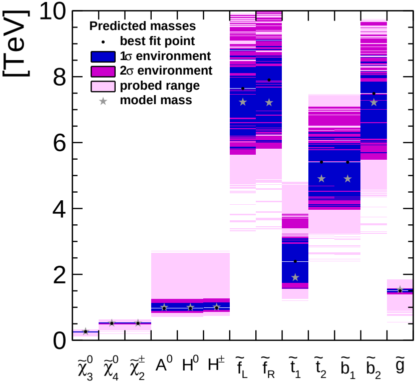


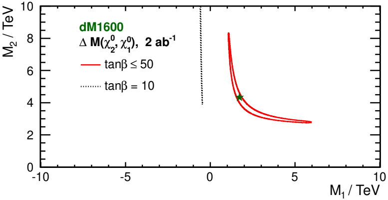
SUSY at ILC: Predict unseen states

- Assume a 10 parameter pMSSM and use constraints from ILC higgs, in addition to measured SUSY properties:
- Can predict the masses of the rest of the spectrum



SUSY at ILC: Test models

- Determine constraints on (multi-TeV) M_1 and M_2 from observations of higgsinos only
- Or test M_1 and M_2 unification at the GUT-scale
- ... and from that predict the gluino mass.



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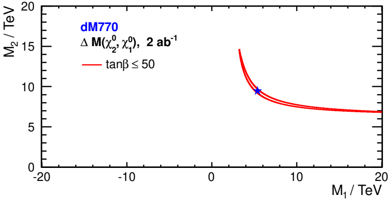

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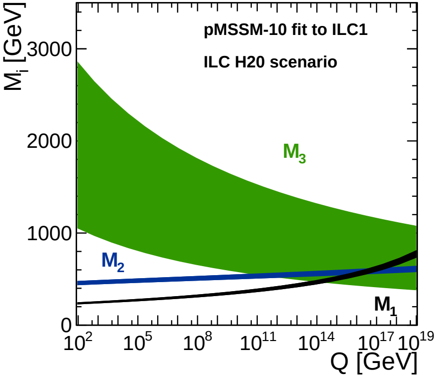

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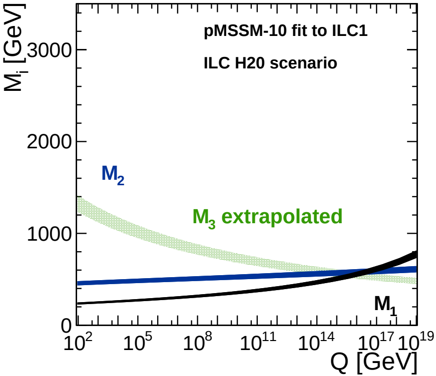

Conclusions

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    - Exclusion potential: Can exclude all models.
- Future pp machines have
    - discovery potential to very high masses
    - but - to put it bluntly - NO exclusion potential: always loopholes.
- Future TeV-scale ee machines have
    - Full discovery and exclusion potential up to the kinematic limit
- For the RPC-MSSM, most studies exist, usually with FullSim. Not much to be added for Snowmass. But, little has been done for:
    - RPV SUSY.
    - Extensions to MSSM - nMSSM, GMSB, ...
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Take-home message

- Without a TeV scale lepton-collider, we would not be able exclude SUSY further than today at the end of this century. LEP2++ would be the final word.
- Except if a future pp machine discovers SUSY, which is a problem we'd like to have!

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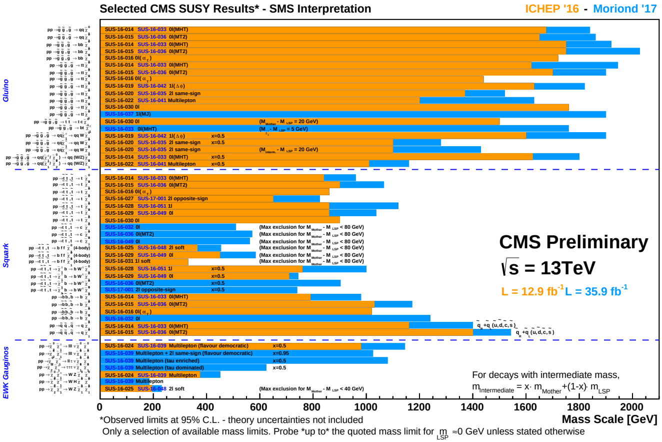
Thank You !

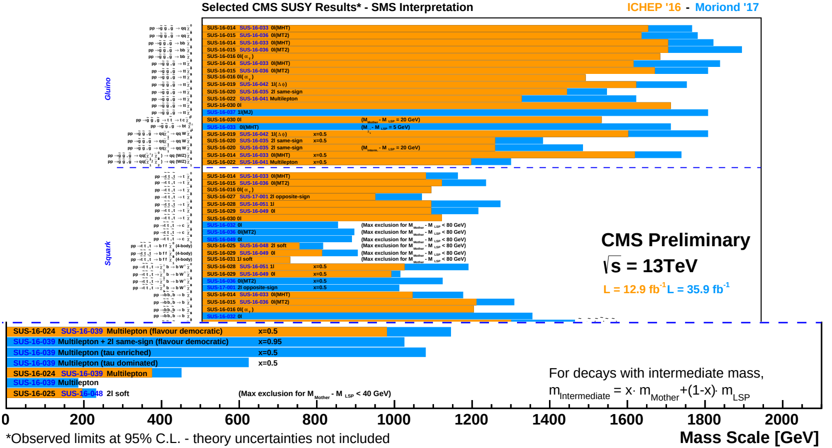
Backup

BACKUP SLIDES

SUSY@LHC: Does this make us depressed ?



SUSY@LHC: No! Read the fine-print !

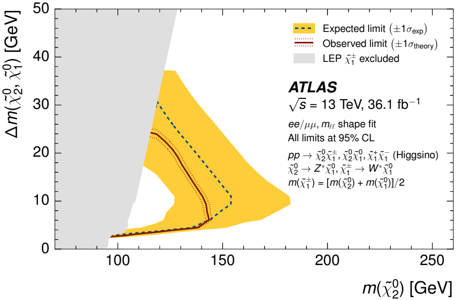


*Observed limits at 95% C.L. - theory uncertainties not included

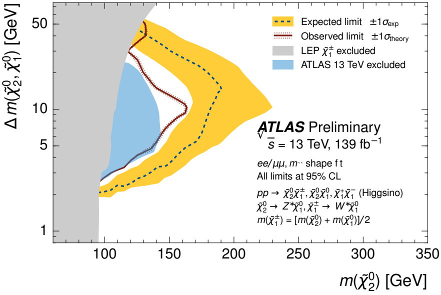
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

Latest Atlas (13 TeV, 36 and 139 fb^{-1}) on higgsinos

arXiv:1803.02762

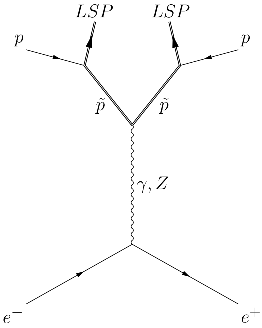


ATLAS-CONF-2019-01



Loop-hole free SUSY searches

- All is known for given masses, due to SUSY-principle: “sparticles couples as particles”.
- This doesn’t depend on the SUSY breaking mechanism !
- Obviously: There is one NLSP.



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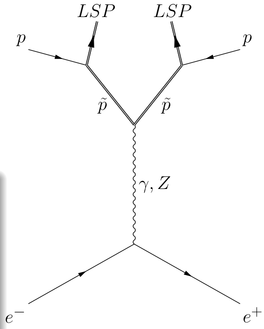

So, at an LC :

- Model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a hand-full of plots
- NLSP search ↔ “simplified models” @ LHC!

Simplified models

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent, at LHC model dependent.
- A few examples (M.B. arXiv:1308.1461)
  - $\tilde{\mu}_{\mathrm{R}}$ NLSP
  - $\tilde{\tau}_1$ NLSP (minimal σ).

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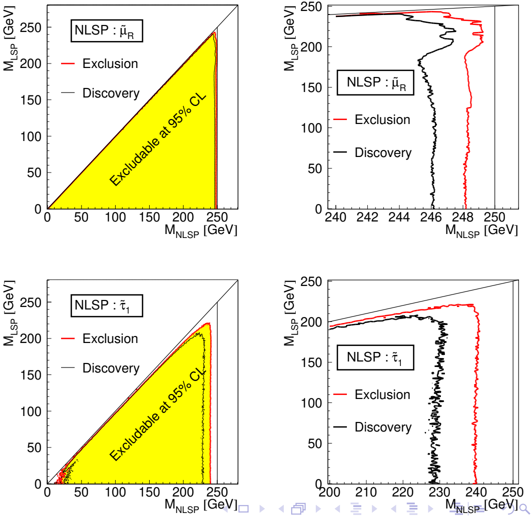

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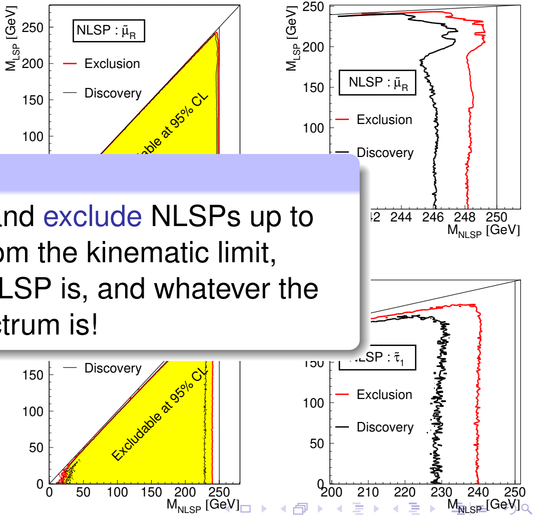
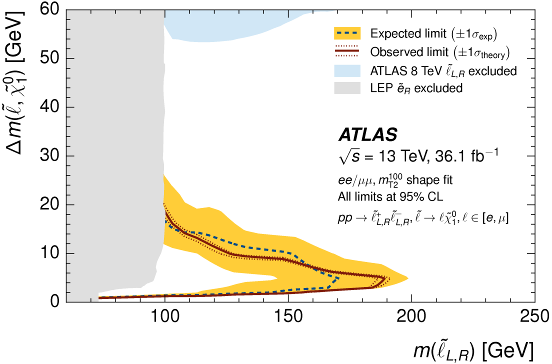


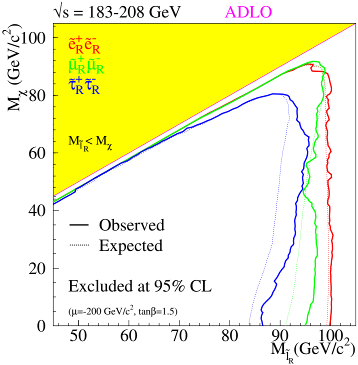
At ILC

Both discover and exclude NLSPs up to some GeV:s from the kinematic limit, whatever the NLSP is, and whatever the rest of the spectrum is!

Latest Atlas (13 TeV, 36 fb^{-1}) and LEP on sleptons

arXiv:1803.02762

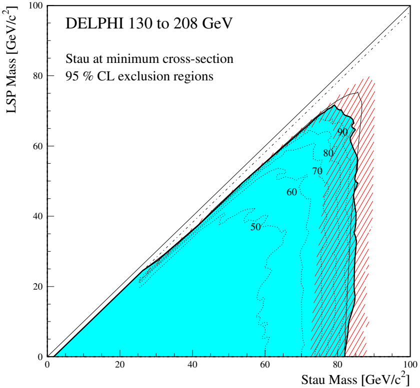


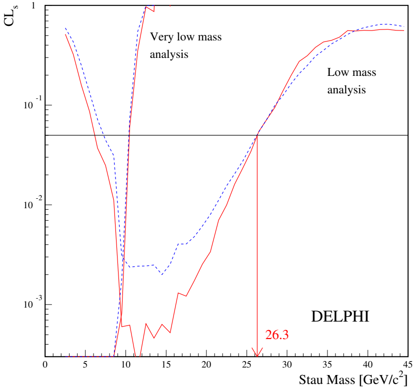


This is a *combined* limit, assuming $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{e}_L$ and $\tilde{e}_L$ all have the same mass !!!

This is $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$ *only*, separately!

In real life: LEP $\tilde{\tau}$ limits





NB: a $\tilde{\tau}$ as light as 26.3 GeV is *not* excluded!

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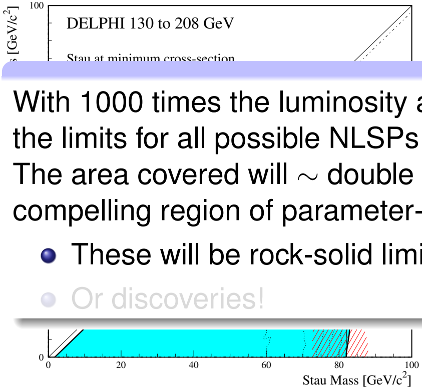

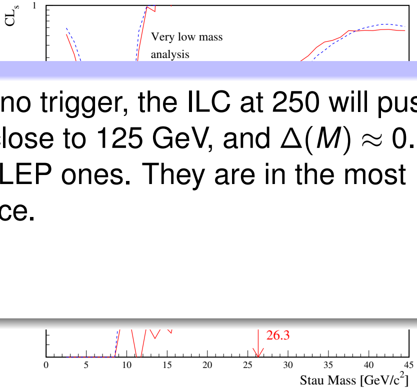

With 1000 times the luminosity and no trigger, the ILC at 250 will push the limits for all possible NLSPs to close to 125 GeV, and $\Delta(M) \approx 0$. The area covered will $\sim$ double the LEP ones. They are in the most compelling region of parameter-space.

- These will be rock-solid limits.
- Or discoveries!

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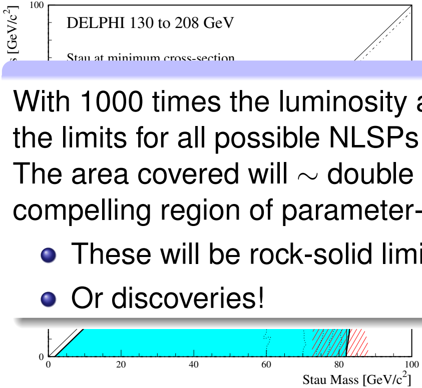

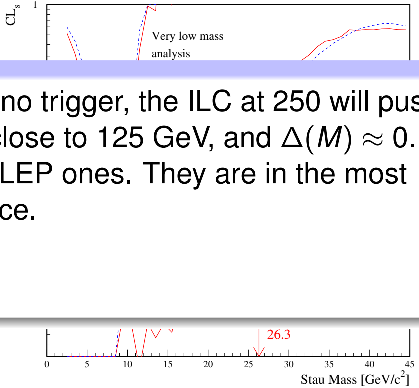

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