Discovering Supersymmetry and Dark Matter at the International Linear Collider

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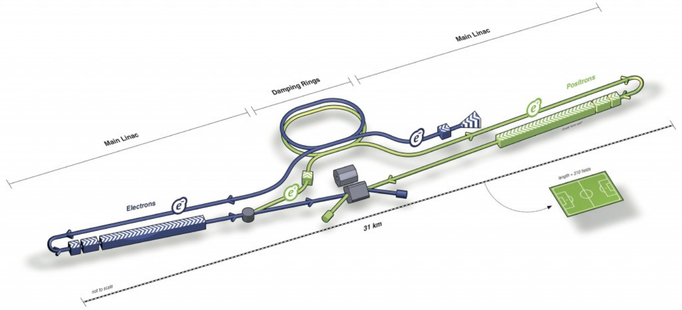
ICHEP, Valencia, July, 2014

Outline

The ILC



- A linear e^+e^- collider.
- E_{CMS} tunable between 200 and 500 GeV, upgradable to 1 TeV.
- Total length 31 km
- $\int \mathcal{L} \sim 500$ fb^{-1} in 2 years
- Polarisation e$^-$: 80% (e$^+$: $\geq$ 30%)
- 2 experiments, sharing one interaction region.
- Concurrent running with the LHC

The ILC is not LHC

- Lepton-collider: Initial state is known.
- Production is EW ⇒
  - Small theoretical uncertainties.
  - No “underlaying event”.
  - Low cross-sections wrt. LHC, also for background.
  - Trigger-less operation.
  - High precision (sub-%) measurements needed, to extend our knowledge beyond LEP, Tevatron, LHC.

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The ILC : Detectors

- 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 Suisse Romande (or Schleswig-Holstein, or Conneticut) relative to earth.
- Importance of this for the following: $\gamma\gamma$ rejection :

SUSY signal and $\gamma\gamma$ background ... and with an ISR photon in addition

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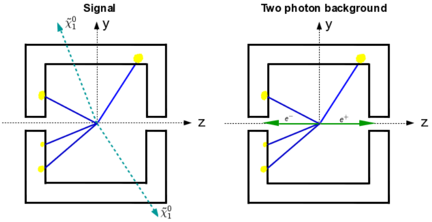

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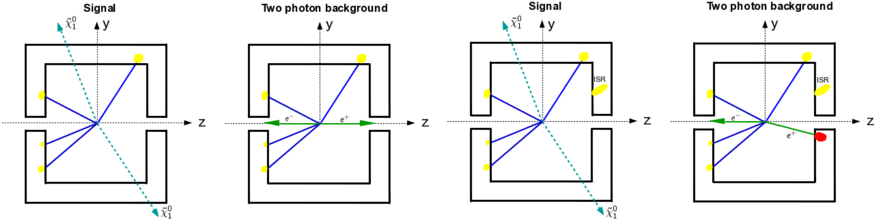
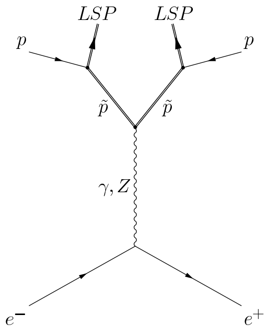


Loop-hole free SUSY searches

- 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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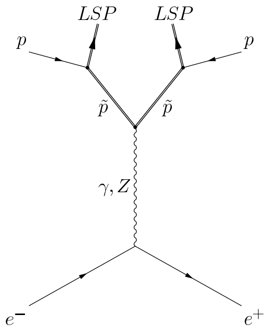

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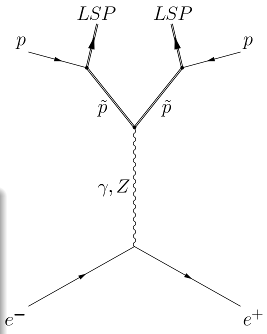

- Model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a hand-full of plots
- Cf. "simplified models" at LHC!

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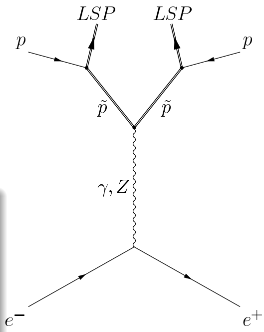

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Simplified models

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent, at LHC model dependent.

Both discover and exclude up to some GeV from the kinematic limit !

- A few examples (M.B. arXiv:1308.1461)
  - $\tilde{\mu}_R$ NLSP
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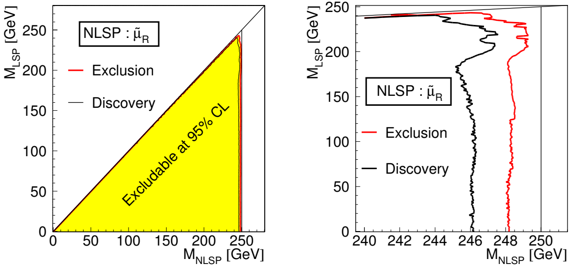

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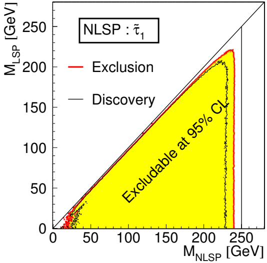

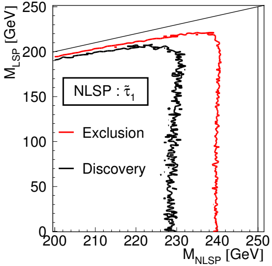

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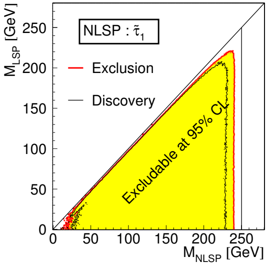

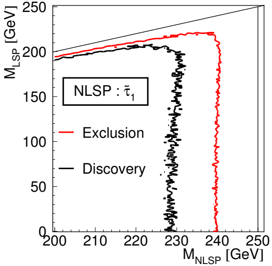

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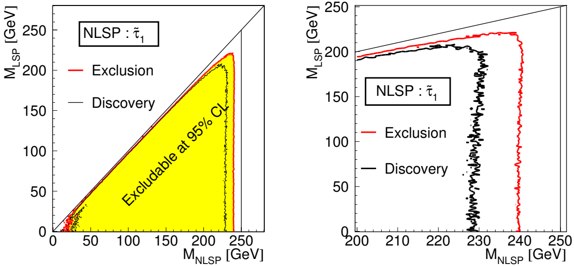

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- Compare with LHC, here Atlas (arXiv:1403.5294v1):
  - Di- and tri-lepton searches, $M_{\tilde{\chi}_2^0} = M_{\tilde{\chi}_1^\pm}$, Br($\chi \rightarrow W^{(*)}/Z^{(*)}$)=100%.
- Note cut x-axis! Here is LEP, $\tilde{\chi}_1^\pm$ only, any decay-mode !
- Below thick line: No GUT-scale gaugino mass-unification.
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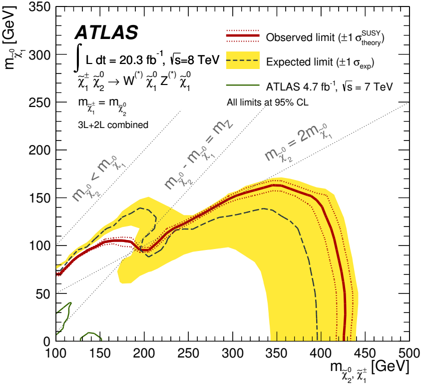

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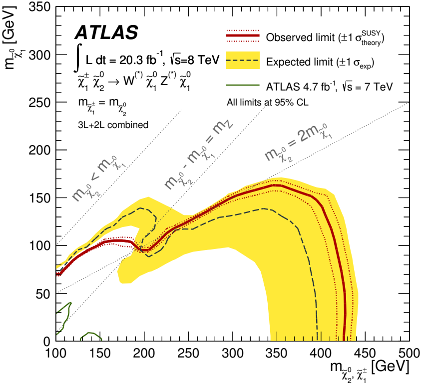

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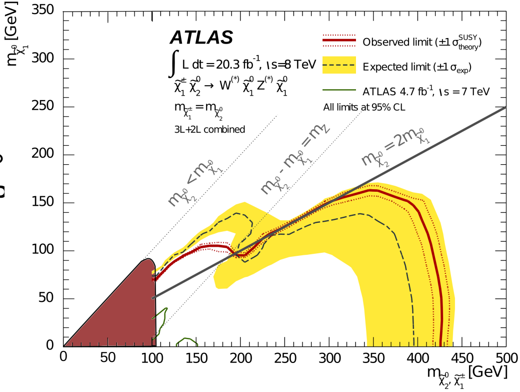

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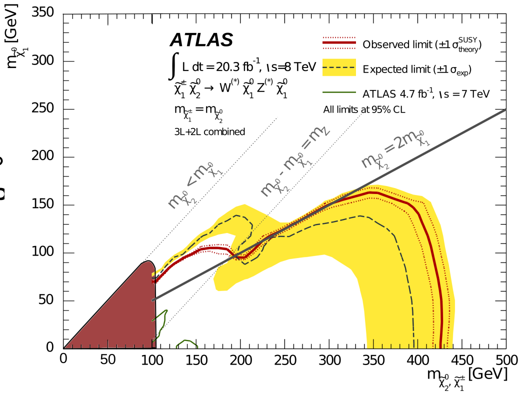

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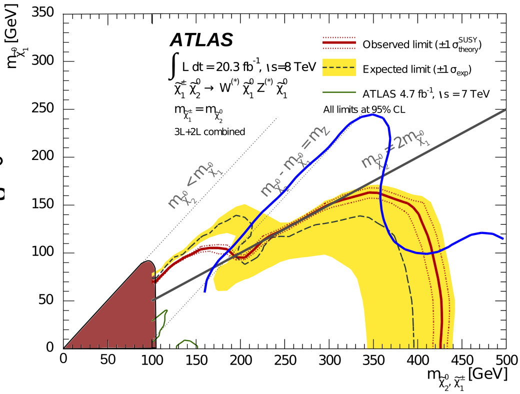

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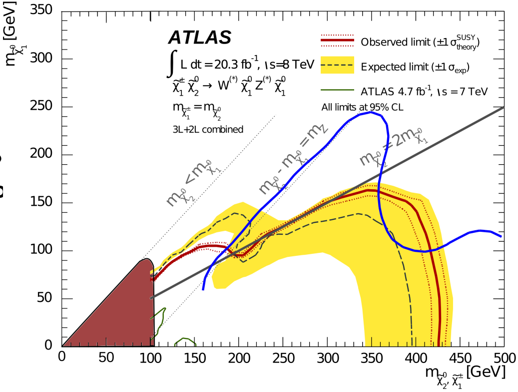

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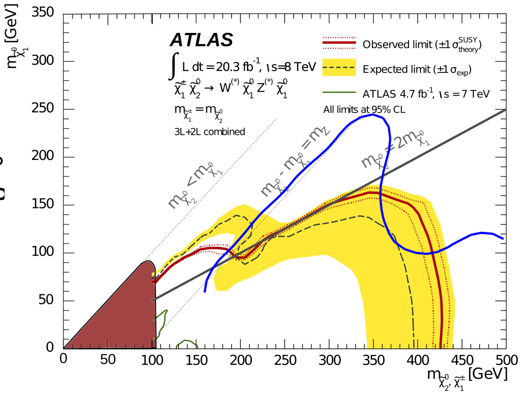

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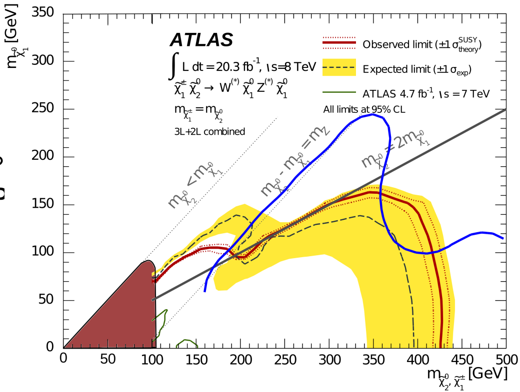

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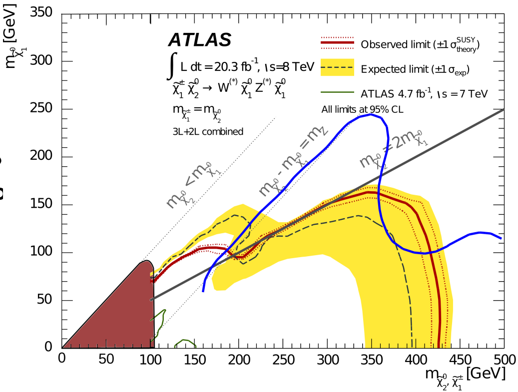

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WIMPs

- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ).
- Model-independent interpretation: **Effective operator approach**
  - Exclusion regions in M_χ/Λ plane, for each operator.
- Searches for direct WIMP production at collider - Need to make the invisible visible:
  - Require initial state radiation which will recoil against "nothing"
  - LHC: $pp \to \chi\chi g$ or $\chi\chi\gamma$
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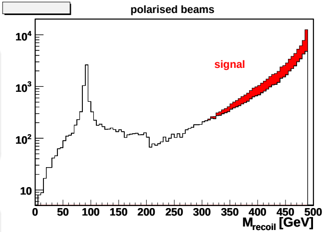
Irreducible Backgrounds

$ee \rightarrow \nu\nu\gamma$

- Recoil-mass peaks at M_Z
- “switched off” by $P(e^-)$=-1.

radiative Bhabha’s: $e^+e^- \rightarrow e^+e^-\gamma$

- mimics signal if e^+e^- undetected
- crucial to apply veto from low angle calorimeter



$P(e^-, e^+)$	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma$
$(0\%, 0\%)$	67%	23%
$(+80\%, -60\%)$	25%	75%

Systematic Uncertainties and Spectrum shape

Systematic Uncertainties: Quite imporant

- Luminosity: $\delta\mathcal{L}/\mathcal{L} = 0.11\%$
- beam energy spectrum: full difference between different ILC options $\Rightarrow$ 3% total.
- Polarization: $\delta P/P = 0.25\%$ per beam
- photon reconstruction efficiency: from data.

Spectrum shape: Gain senistivity, mitigate systematics

- counting experiment:
  - total number of signal S and background B
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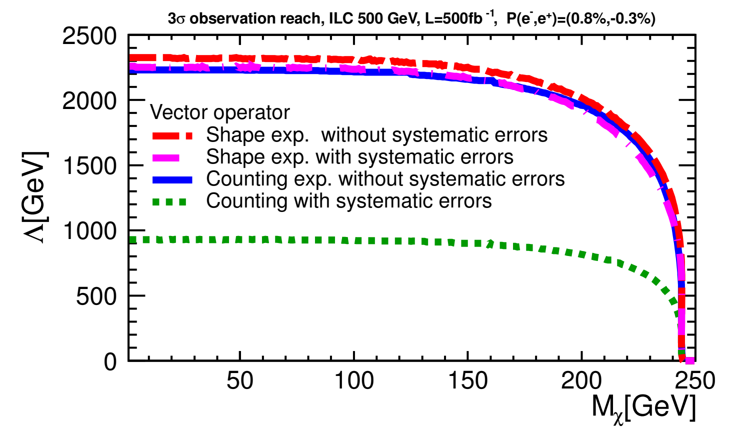
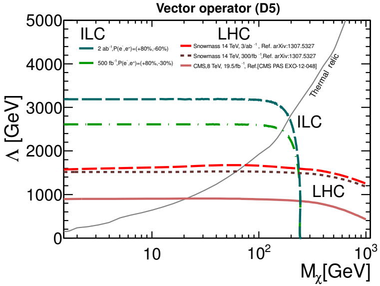


Comparison with current LHC Results

- Vector operator ("spin independent"), $S_\chi = 1/2$
- Axial-vector operator ("spin dependent"), $S_\chi = 1/2$
- LHC reaches higher masses, ILC smaller cross-section.



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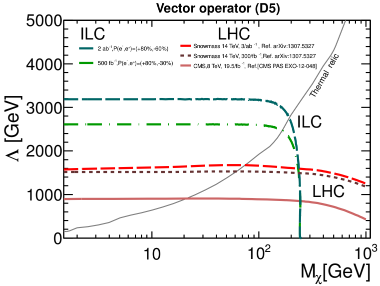

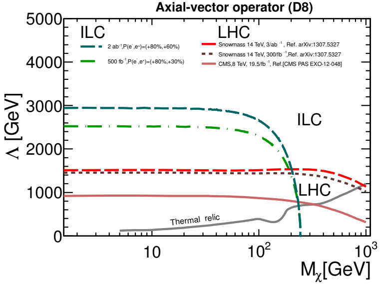

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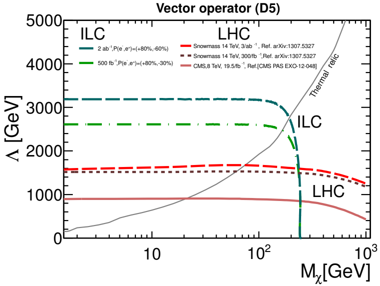

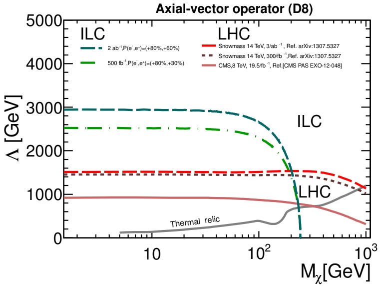

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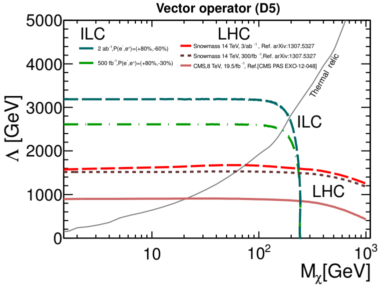

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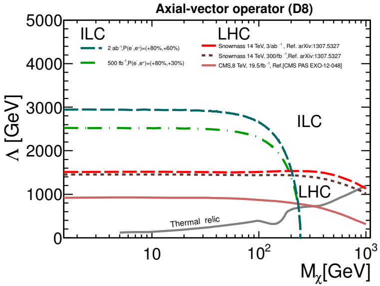
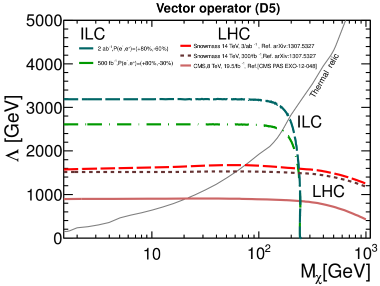


Comparison with current LHC Results

- Vector operator ("spin independent"), $S_\chi = 1/2$
- Axial-vector operator ("spin dependent"), $S_\chi = 1/2$
- LHC reaches higher masses, ILC smaller cross-section.



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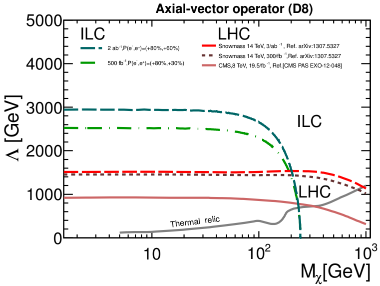

Natural SUSY: Light, degenerate higgsinos

- 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.
    - $M_{\tilde{\chi}_{1,2}^0}, M_{\tilde{\chi}_1^\pm} \approx \mu$
    - Degenerate (ΔM is 1 GeV or less)
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- Detailed simulation study of such a model: H. Sert, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki, M.B., EPJC (2013) 73:2660 [arXiv:1307.3566v2]

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  - dm1600: $\Delta(M)$=1.6 GeV, m_h=124 GeV, $M_{\tilde{\chi}_1^0}$=164.2 GeV.
  - dm770: $\Delta(M)$=0.77 GeV, m_h=127 GeV, $M_{\tilde{\chi}_1^0}$=166.6 GeV.
- $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ - no $\tilde{\chi}_i^0\tilde{\chi}_i^0$ due to weak isospin, no t-channel due to higgsino nature.
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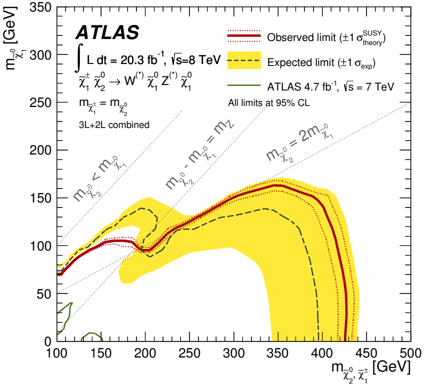

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- Few-body decays and radiative decays (for $\tilde{\chi}_2^0$) (calculated with Herwig).
- Separate $\tilde{\chi}_1^{\pm}$ from $\tilde{\chi}_2^0$: Either semi-leptonic f.s.: Only $\tilde{\chi}_1^{\pm}$, or γ: only $\tilde{\chi}_2^0$.
- Tag using ISR photon, the look at rest of event.
- E_{ISR} gives reduced $\sqrt{s'}$: "auto-scan". End-point gives masses to $\sim$ 1 GeV.
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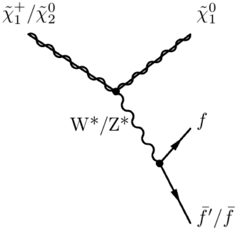

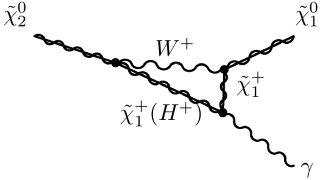

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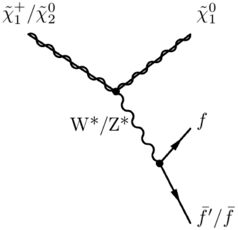

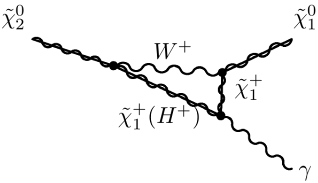

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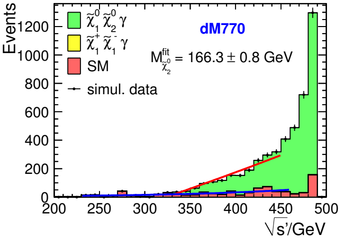

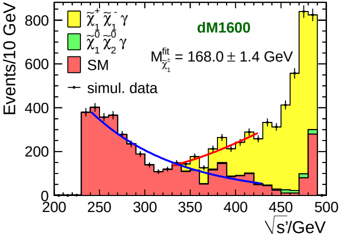

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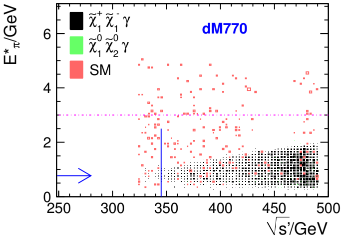

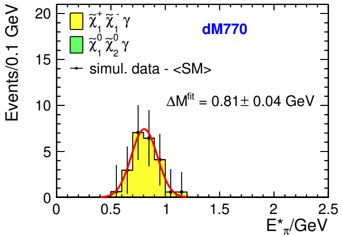

Natural SUSY: Light, degenerate higgsinos

- Use to extract the model-parameters μ, M_1 and M_2 (little tan β dependence).
- μ can be determined to $\pm$ 4 %.
- Limits on M_1 and M_2 after $\int \mathcal{L} = 2ab^{-1}$.
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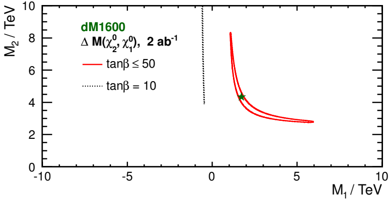

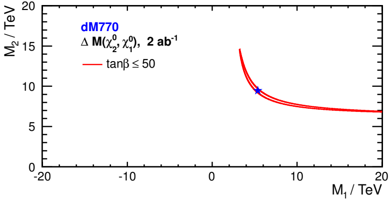

Conclusions

At ILC:

- Loop-hole free discovery potential for SUSY, up to the kinematic limit.
- Includes a vast region of moderate-to-small LSP-NLSP mass-differences, not explorable by hi-lumi LHC.
- In searches for dark matter, ILC yields orthogonal information to LHC and direct searches.
- Tests contact interaction scales up to 3-4 TeV.
- In addition: WIMP property determination (mass: 1-2%, helicity structure, spin of mediator) $\Rightarrow$ model discrimination
- Even in natural SUSY scenarios where the only sparticles below the multi TeV range are almost mass-degenerate higgsinos: ILC can discover, and determine model-parameters, high-mass sector ones included.

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