New physics searches with the ILD detector at the ILC

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on behalf of the ILD concept group

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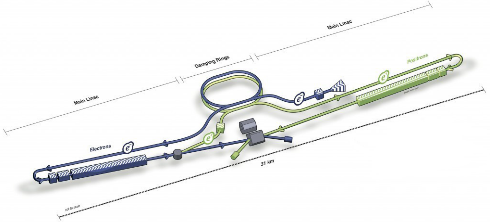
The ILC strong points for searches

- e^+e^- collider with E_{CMS} = 250 - 500 (- 1000) GeV, and polarised beams
- e^+e^- means EW-production ⇒ Low background.
  - Detectors w/ $\sim 4\pi$ coverage.
  - Rad. hardness not needed: only few % X_0 in front of calorimeters.
  - No trigger
- e^+e^- means colliding point-like objects ⇒ initial state known
- 20 year running → 2 ab^{-1} @ 250 GeV, 4 ab^{-1} @ 500 GeV.
- Construction under political consideration in Japan.



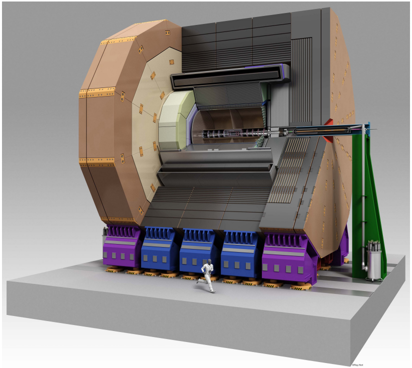
The ILD concept (arXiv:2003.01116)

Physics requirements, SM and BSM:

- $\sigma(1/p_\perp) = 2 \times 10^{-5}$ GeV^{-1}
- JER $\sim$ 3-4%
- $\sigma(d_0) < 5\mu$
- particle Id (PID)
- hermeticity down to 5 mrad
- triggerless operation.

Leads to key features of the detector:

- low mass tracker with PID:
  - Main device: TPC
  - Enhanced by silicon
- High granularity calorimeters optimised for particle flow
- Power-pulsing.



BSM at ILC

In this talk: Concentrating on

- SUSY:
  - *The* most complete theory of BSM.
  - Serves as a boiler-plate for BSM: almost any new topology can be obtained in SUSY...
  - Most studied model with serious simulation: In most cases, full simulation of ILD, with all SM backgrounds, all beam-induced backgrounds included.
  - Under some stress(?) by LHC. However, ILC offers
    - Loop-hole free searches.
    - Complete coverage of Compressed spectra - the most interesting case.
- + A few slides on non-SUSY BSMs...
- Won't mention Dark Matter: Listen to Filip Zarnecki's talk after the break !

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SUSY: What *do* we know ?

Naturalness, hierarchy, DM, g-2 all prefer light electroweak sector.

- Except for 3rd gen. squarks, the coloured sector doesn't enter the game.
- Many models and the global set of constraints from observation points to a compressed spectrum.
- So, most sparticle-decays are via cascades, with small $\Delta(M)$ at the end.
- For this, current LHC limits are for specific models. LEP2 sets the scene.

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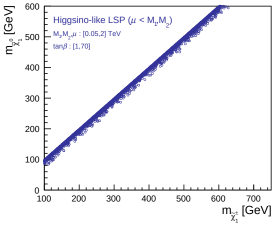
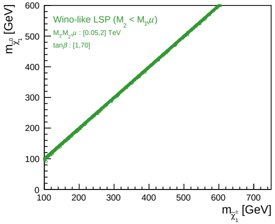
Why compressed spectra ?

- Higgsino or Wino LSP:
  - If the LSP is Higgsino or a Wino, several other bosinos *must* be close to the LSP.
  - $\Rightarrow$ Compressed spectrum.
    - In addition: if the LSP is higgsino: *Natural SUSY*:
    - $m_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2|\mu|^2$
    - Low fine-tuning $\Rightarrow \mu = \mathcal{O}(m_Z)$
- Bino LSP: Overabundance of DM.
  - 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 $\Rightarrow$ Compressed spectrum.





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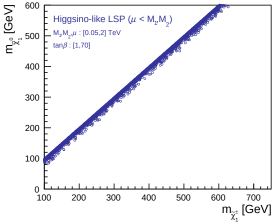

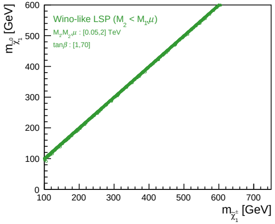

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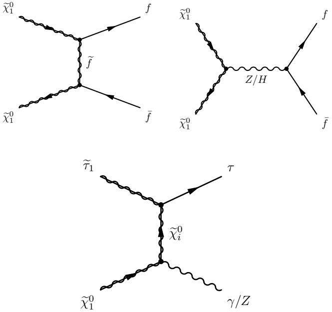

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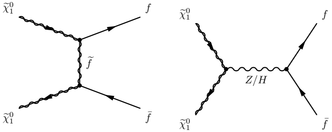
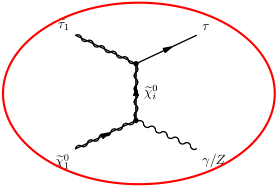
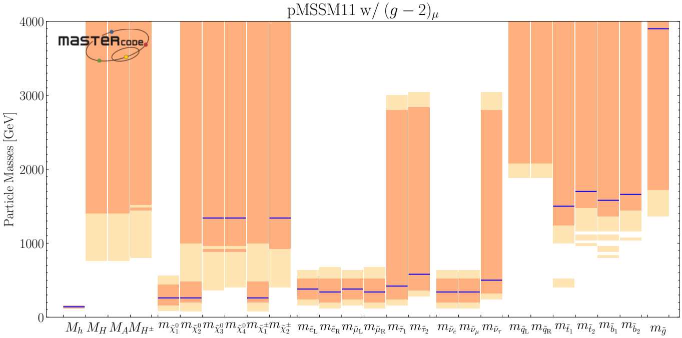




Why compressed spectra ? Global fits

pMSSM11 fit by Mastercode to LHC13/LEP/g-2/DM(=100% LSP)/precision observables (arXiv:1710.11091):



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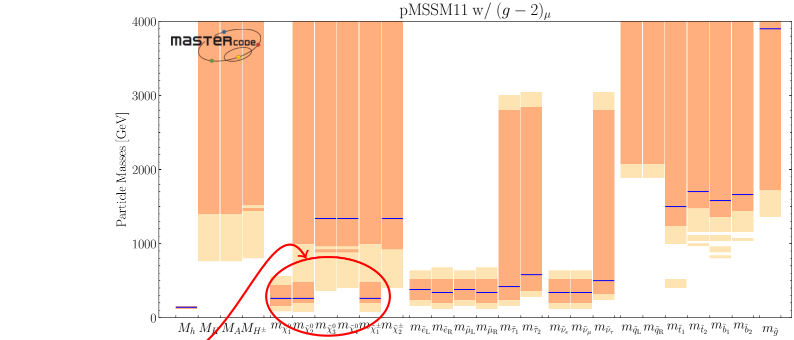

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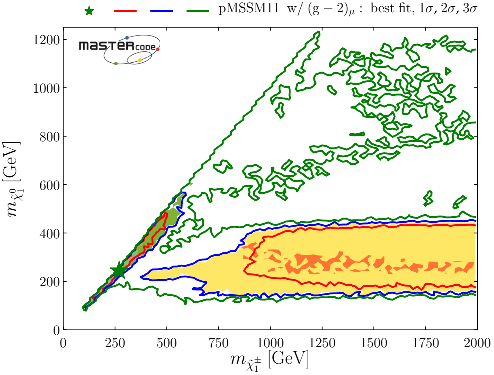

$M_{\tilde{\chi}_1^\pm}$ - $M_{\tilde{\chi}_1^0}$ plane

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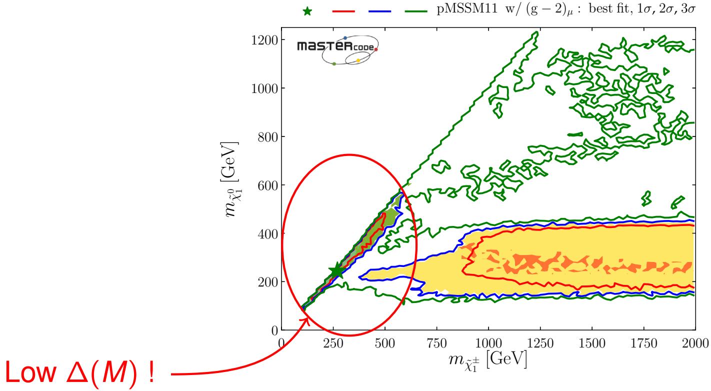
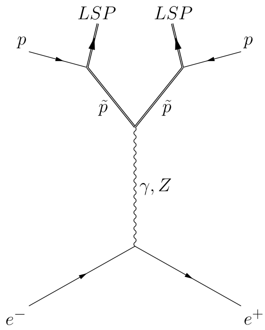


$M_{\tilde{\chi}^\pm_1}$ - $M_{\tilde{\chi}^0_1}$ plane

SUSY@ILC: Loop-hole free 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, and it must have 100 % BR to it’s SM-partner and the LSP.



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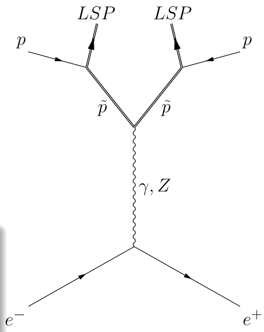

So, at ILC :

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- Repeat for all NLSP:s.
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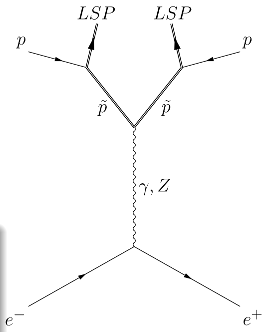

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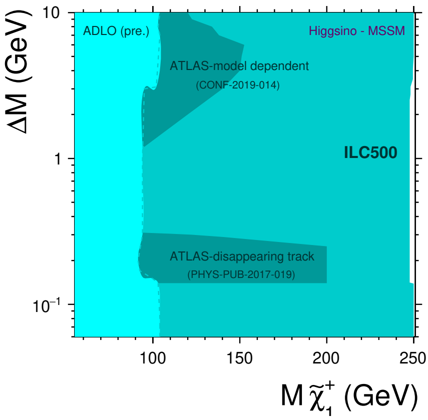
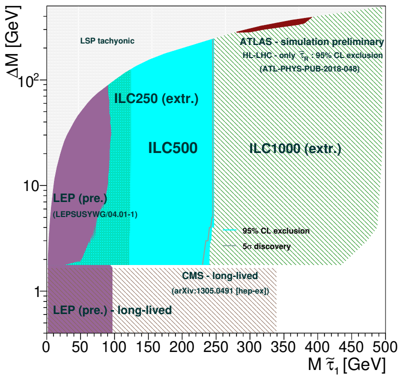
ILC projection for Higgsino or $\tilde{\tau}$ NLSP

From arXiv:2002.01239





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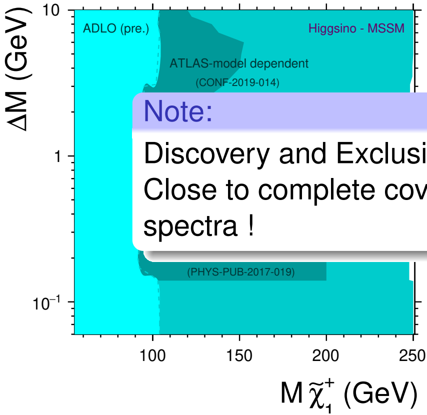

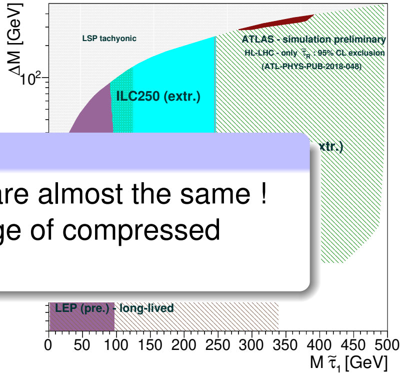

Note:

Discovery and Exclusion are almost the same !
Close to complete coverage of compressed spectra !

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At ILC: discovery in a week...

ILD fast detector simulation studies: Selectrons in a co-annihilation model (EPJC 76,183 (2016)), after:

- 5 $\text{fb}^{-1} \approx$ 1 week

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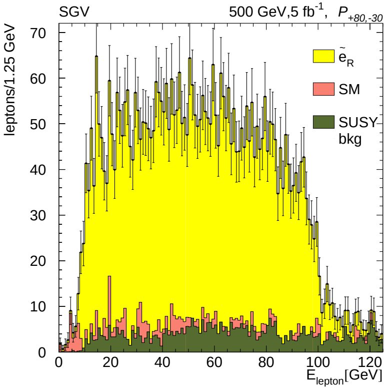

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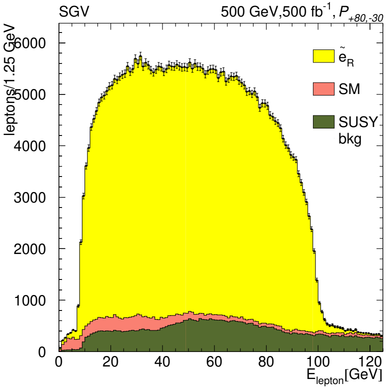

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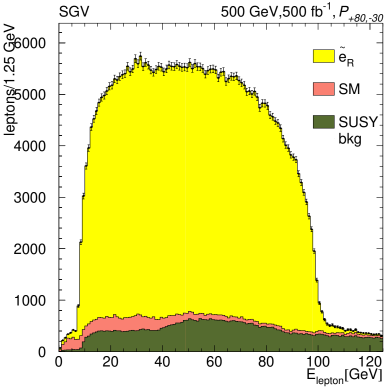

ILC = the LEP of SUSY

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- Typical slepton signal ($\tilde{\tau}$ and $\tilde{\mu}$), in a co-annihilation model (FastSim). (EPJC 76,183 (2016))
- Typical chargino signal...
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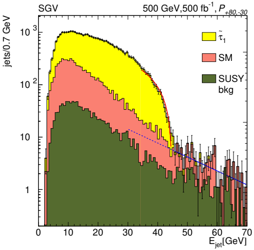

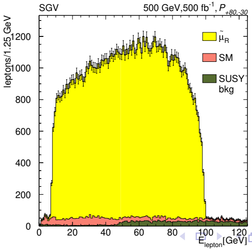

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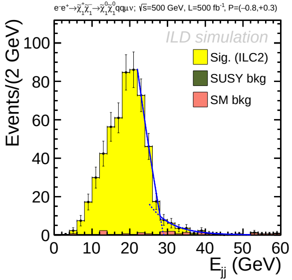

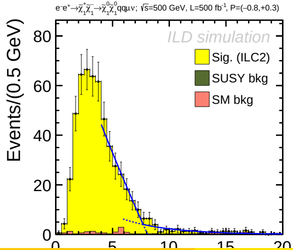

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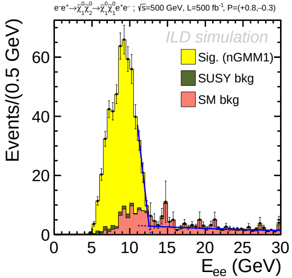

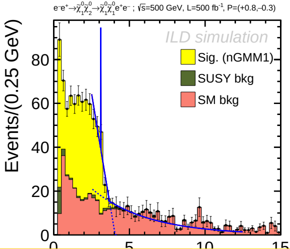

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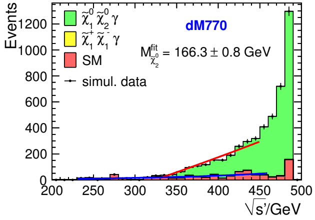

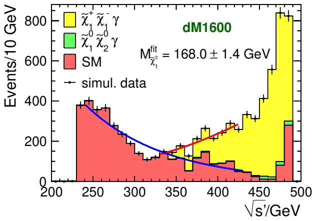

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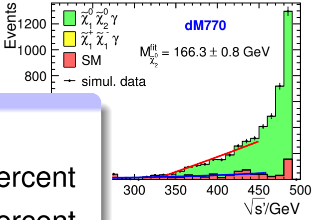
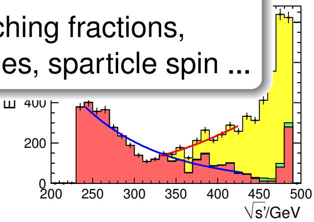
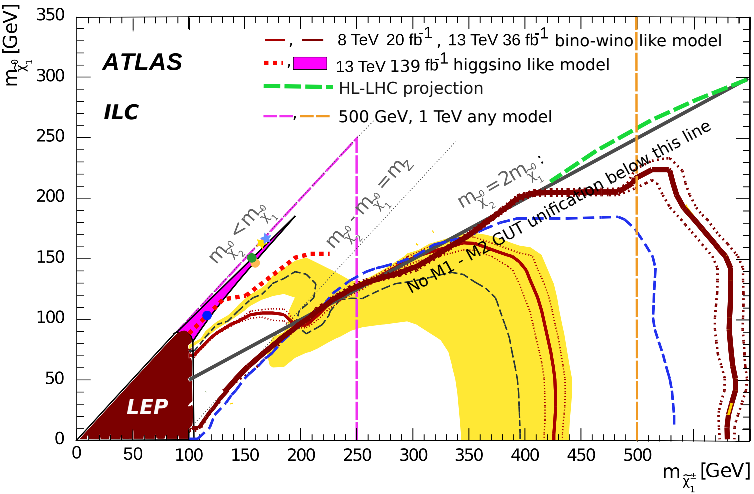




In all cases:

- SUSY masses to sub-percent
- Cross-sections to few percent
- Also: Branching fractions, mixing angles, sparticle spin ...

SUSY bosinos - All-in-one

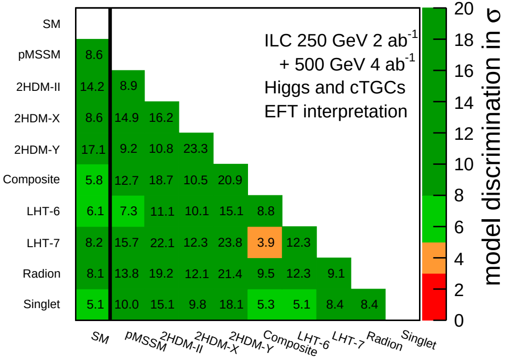


ATLAS Eur Phys J C 78,995 (2018), Phys Rev D 101,052002 (2020), arXix:2106.01676;

ATLAS HL-LHC ATL-PHYS-PUB-2018-048; ILC arXiv:2002.01239; LEP LEP LEPSUSYWG/02-04.1

Other BSM: a gallery

- BSM discovery and model separation from indirect searches.
- SMEFT study using ILC results on Higgs properties and TGCs (Phys. Rev. D 97,0535003 (2018))
- Select models that are not discoverable at HL-LHC.
- At ILC: Both separate at 5 σ from the SM, but also from eachother !



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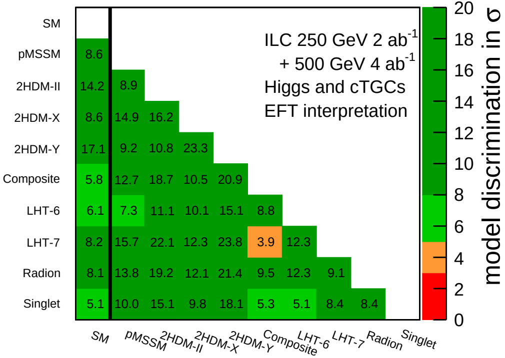

Other BSM: a gallery

- BSM discovery and model separation from indirect searches.
- SMEFT study using ILC results on Higgs properties and TGCs (Phys. Rev. D 97,0535003 (2018))
- Select models that are not discoverable at HL-LHC.
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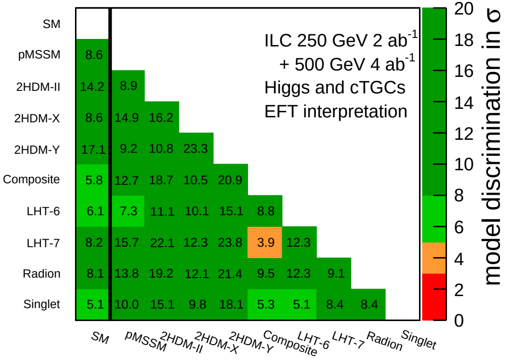

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion
pMSSM	8.6								
2HDM-II	14.2	8.9							
2HDM-X	8.6	14.9	16.2						
2HDM-Y	17.1	9.2	10.8	23.3					
Composite	5.8	12.7	18.7	10.5	20.9				
LHT-6	6.1	7.3	11.1	10.1	15.1	8.8			
LHT-7	8.2	15.7	22.1	12.3	23.8	3.9	12.3		
Radion	8.1	13.8	19.2	12.1	21.4	9.5	12.3	9.1	
Singlet	5.1	10.0	15.1	9.8	18.1	5.3	5.1	8.4	8.4

Other BSM: a gallery

- A new Higgs-like scalar (S, produced in $e^+e^- \rightarrow Z^* \rightarrow ZS$ with unknown decays ?
- Search for it in a decay-mode insensitive way: The recoil-mass, i.e. the mass of the system recoiling against the measured Z.
- Example peaks for a coupling equal to the an SM-Higgs at the same mass. (arXiv:2005.06265)
- $\Rightarrow$ exclude couplings down to a few percent of the SM-Higgs equivalent.
- Note importance of FullSim !

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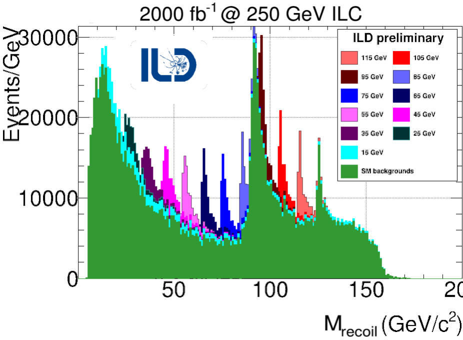

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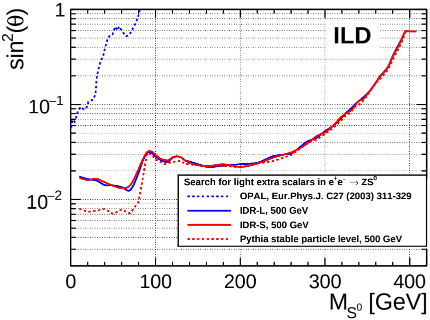

Other BSM: a gallery

- Dark photon/Z' : $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
- A tiny, narrow resonance, but still wide enough to make decays prompt.
- $\Rightarrow$ Look for a $\mu\mu$ resonance above background in $\mathrm{e^+e^-} \rightarrow Z' + \mathrm{ISR} \rightarrow \mu^+\mu^- + \mathrm{ISR}$.
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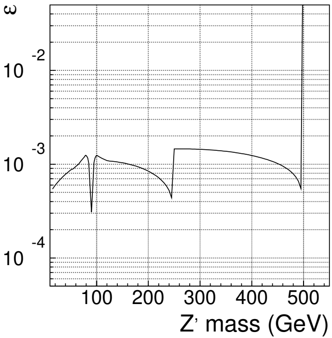

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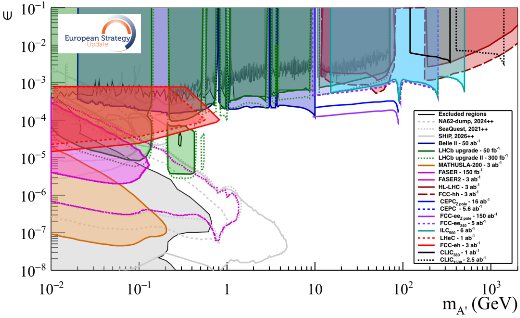

compared to others (from EPPSU).

Conclusions

- Sometimes, the capabilities for the direct discovery of new particles at the ILC exceed those of the LHC, since ILC provides
  - Well-defined initial state
  - Clean environment without QCD backgrounds
  - Extendability in energy and polarised beams
  - Detectors like ILD, factors more precise,hermetic, and with no need for triggering
- Many ILC - LHC synergies from energy-reach vs. sensitivity.
  - SUSY: High mass vs. Low $\Delta(M)$. If SUSY is reachable at ILC, it means 5 σ discovery, and precision measurements. This input might be just what is needed for LHC to transform a 3 σ excess to a discovery of states beyond the reach of ILC.
  - Dark matter, FIPS, ...: Leptophilic vs. Leptophobic - Higher mass and higher coupling vs. lower mass and lower coupling.
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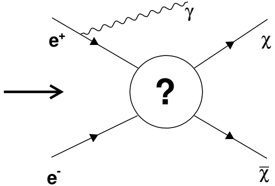
Thank You !

Backup

BACKUP SLIDES

Only WIMPs

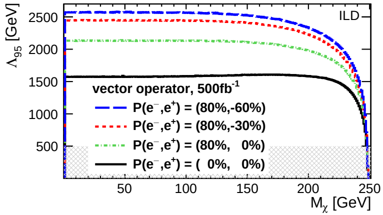
- What if this is the only accessible NP ?
- Search for direct WIMP pair-production at collider : Need to make the invisible visible:
  - Require initial state radiation which will recoil against “nothing” $\Rightarrow$ Mono-X search.
  - At ILC: $\mathrm{e}^+\mathrm{e}^- \rightarrow \chi\chi\gamma$, ie. X is a γ



- ILC simulation studies: arXiv:1206.6639v1, A. Chaus, Thesis, M. Habermehl, Thesis,in preparation.
- Model-independent Effective operator approach to “?”
  - Analyse as an effective four-point interaction. Strength = Λ.
    - Allowable if direct observation the mediator is beyond reach. Mostly true at ILC, but not at LHC !
  - Write down all possible Lorentz-structures of the operators.
  - Exclusion regions in M_χ/Λ plane, for each operator.

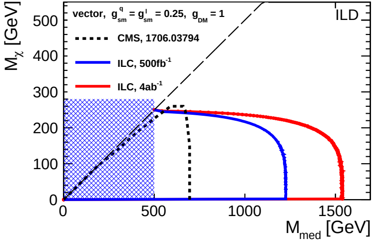
ILC and LHC exclusion

- Examples:
  - Vector operator ("spin independent"), Note how useful beam-polarisation is!
- At LHC, EffOp can't be used $\Rightarrow$ use "simplified models"
- Need to translate Λ to M_{med}: $M_{med} = \sqrt{g_{SM} g_{DM}} \Lambda$



ILC/LHC complementarity

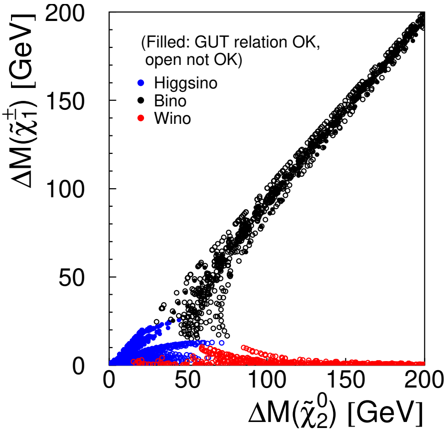
- LHC: coupling to hadrons, ILC: coupling to leptons.
- LHC has best M_χ reach, ILC best M_{med} reach



Aspects of the spectrum

Another angle: $\Delta(M)$ for $\tilde{\chi}_1^{\pm}$ vs. that of $\tilde{\chi}_2^0$: Important experimentally

- Three regions:
  - Bino: Both the same, but can be anything.
  - Wino: $\Delta_{\tilde{\chi}_1^{\pm}}$ small, while $\Delta_{\tilde{\chi}_2^0}$ can be anything.
  - Higgsino: Both often small
- But note, seldom on the "Higgsino line", ie. when the chargino is *exactly* in the middle of mass-gap between the first and second neutralino.



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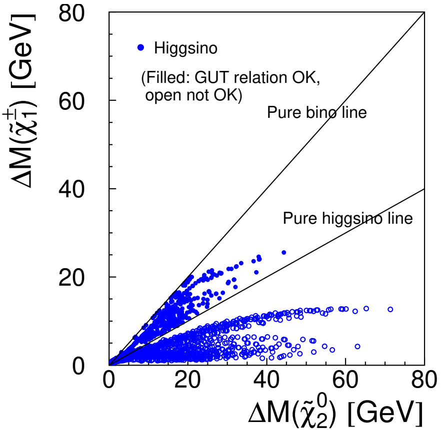

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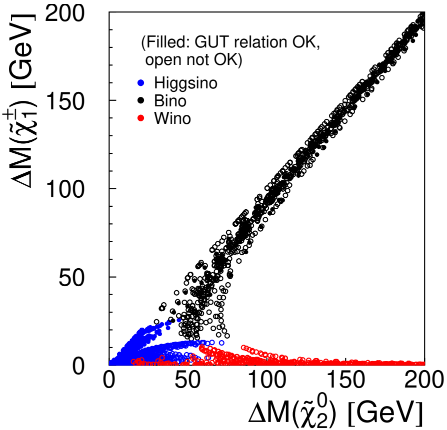

Key element for "Disappearing tracks": $\Delta(M)$

- Higgsino LSP.
- Zoom in. The line is the absolute limit mentioned in the BB.
- Reason: 1703.09675 considers *only SM* effects on the mass-splitting, ie. that M_1 and $M_2 >> \mu$
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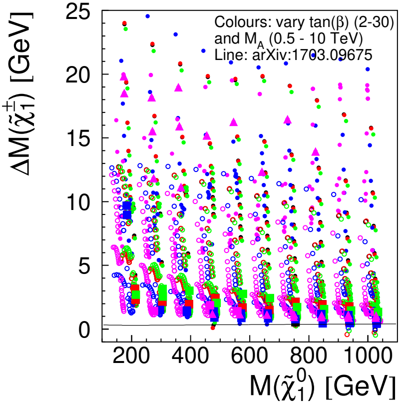

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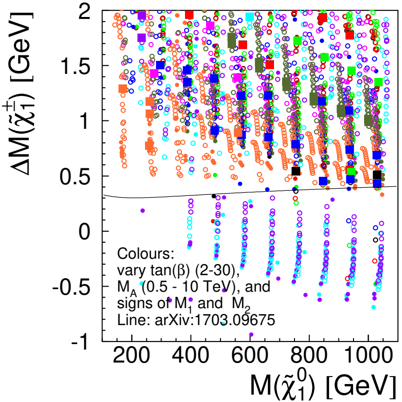

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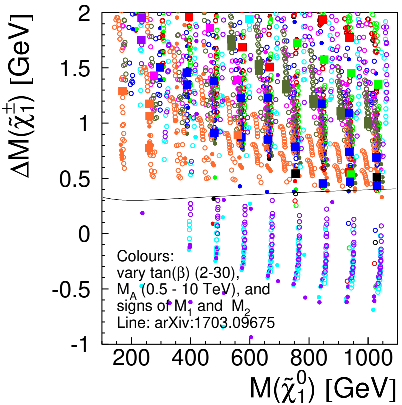

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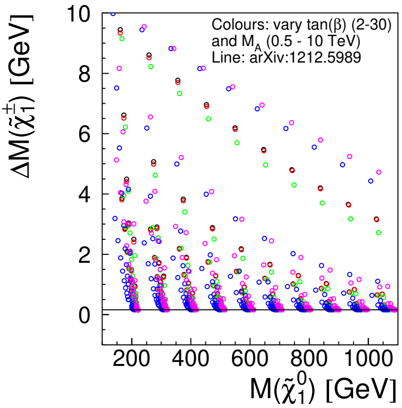

Bino LSP: BRs

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

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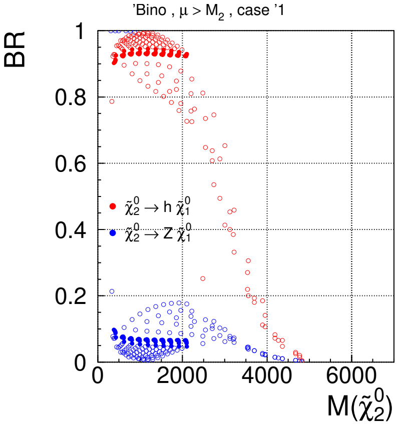
- Conclusion: Whether the Z or the H decay-mode of $\tilde{\chi}_2^0$ dominates is pure speculation and
- The exclusion-region is the *intersection* of the two plots, not the *union*!



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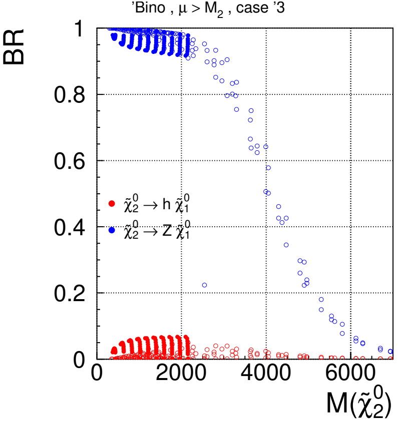

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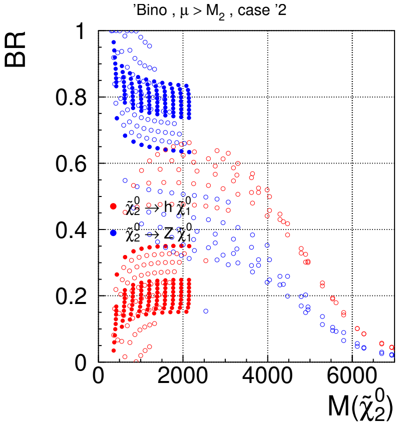

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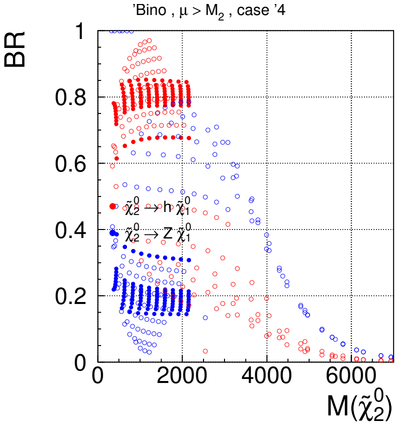

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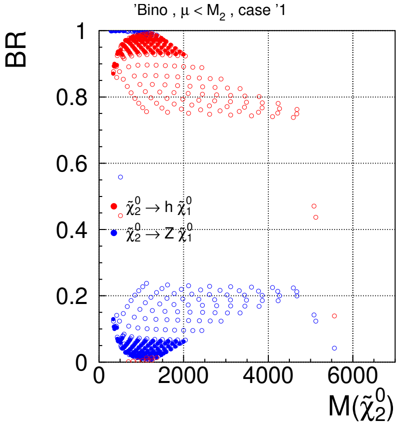

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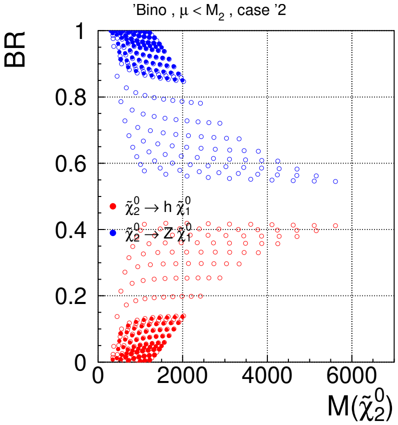

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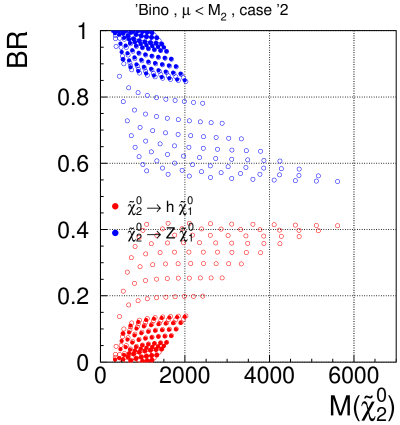

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