Direct searches at ILC (and other lepton colliders)

Mikael Berggren[1]
on behalf of the ICFA-IDT-WG3 BSM group

[1]DESY, Hamburg

Snowmass, Seattle, July, 2022

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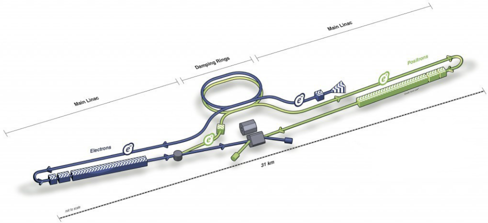
The ILC strong points for searches

- e^+e^- collider with E_{CMS} = 250 - 500 (- 1000) GeV, and polarised beams
- e^+e^- means EW-production $\Rightarrow$ 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 $\Rightarrow$ initial state known
- 22 year running $\rightarrow$ 2 ab^{-1} @ 250 GeV + 4 ab^{-1} @ 500 GeV.
- Construction under political consideration in Japan.



BSM at ILC

In this talk: Concentrating on

- SUSY:
  - *The* most complete theory of BSM.
  - Most studied model with serious simulation: In most cases, full simulation of ILD, with all SM backgrounds, all beam-induced backgrounds included.
  - Serves as a boiler-plate for BSM: almost any new topology can be obtained in SUSY...
  - Under some stress(?) by LHC. However, ILC offers
    - Complete coverage of Compressed spectra - the most interesting case.
    - Loop-hole free searches.
- + A few slides on non-SUSY BSMs...

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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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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 $\sim$ a few TeV.
- Also vary other parameters (β, M_A, $M_{sfermion}$) with less impact.
- No other prejudice.

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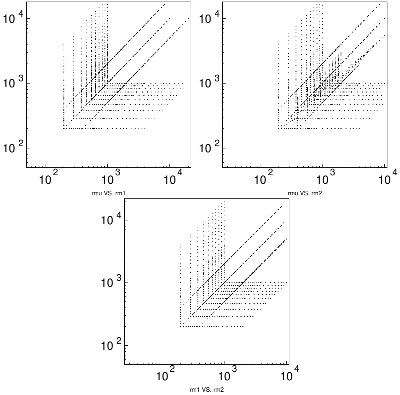
The cube

Specifically, like this:

- μ vs. M_1
- μ vs. M_2
- M_1 vs. M_2

Use `SPheno 4.0.5beta` to calculate spectra and BR:s, and use `Whizard 2.8.0` for cross-sections

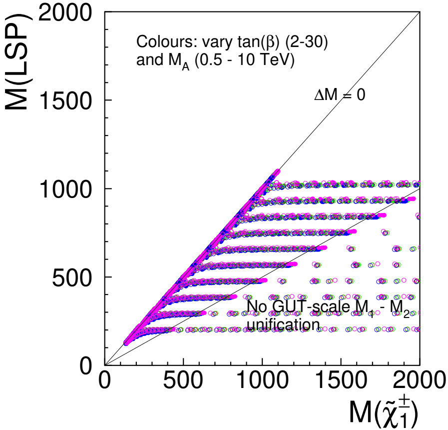


What happens with spectra, cross-sections, BRs when exploiting this "cube"?

Aspects of the spectrum

More in detail

- M_{LSP} vs. $M_{\tilde{\chi}_1^{\pm}}$
- M_{LSP} vs. $M_{\tilde{\chi}_2^0}$
- Colours indicate different settings of the secondary parameters (lesson is that they don't matter much...)
- Open circles indicated cases where GUT-scale unification of M_1 and M_2 is not possible



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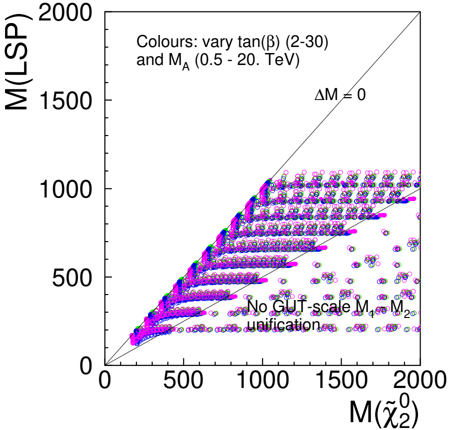
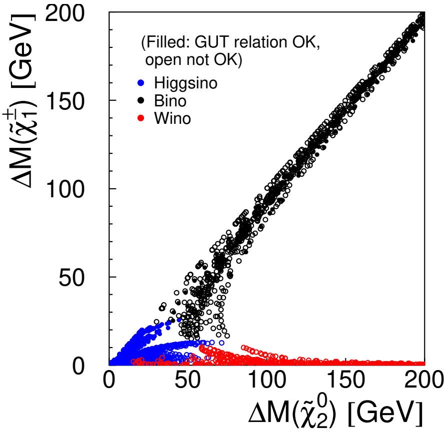


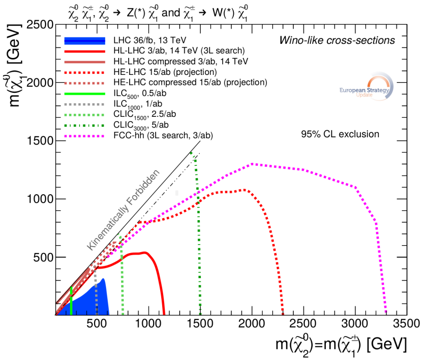
Aspects of the spectrum

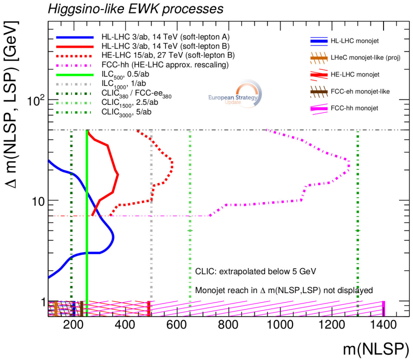
Another angle: $\Delta(M)$ for $\tilde{\chi}_1^{\pm}$ vs. that of $\tilde{\chi}_2^0$: Important experimentally

- 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



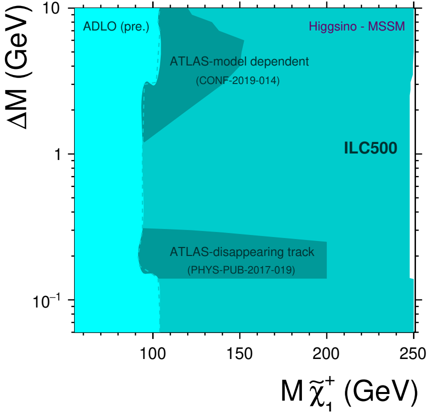
SUSY In The Briefing-book: Bino or Higgsino/Wino LSP (ie. large or small Δ_M)

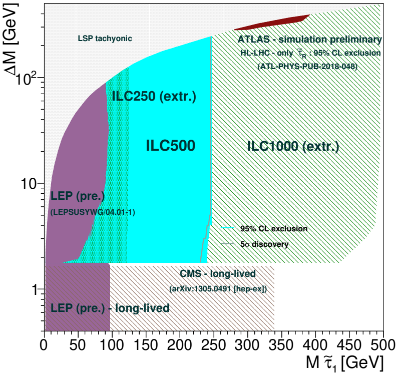




ILC projection for Higgsino or $\tilde{\tau}$ NLSP

From arXiv:2002.01239





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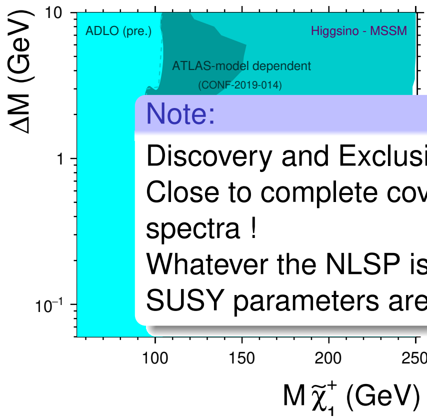
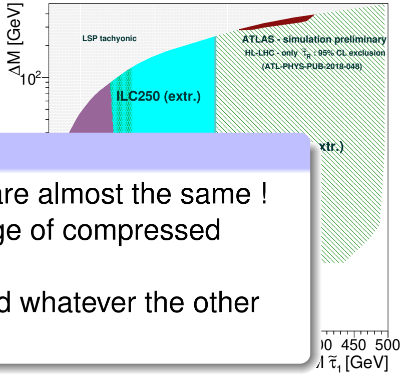


Note:

Discovery and Exclusion are almost the same !
Close to complete coverage of compressed spectra !
Whatever the NLSP is, and whatever the other SUSY parameters are !



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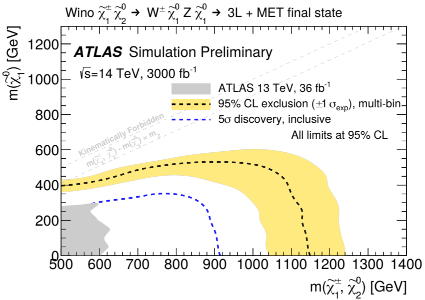
SUSY In The Briefing-book: Bino LSP - pp Sources

- From PHYS-PUB-2018-04 (ATLAS HL-LHC projection). Then extrapolated (up *and down*)
- Note that the BB curve is exclusion, not discovery!
- This is for the best decay mode!
- The other decay mode
- Better at M_{LSP}=0, weaker at lower Δ_M.
- Which dominates depends on relative signs of μ, M_1, and M_2 (See backup).



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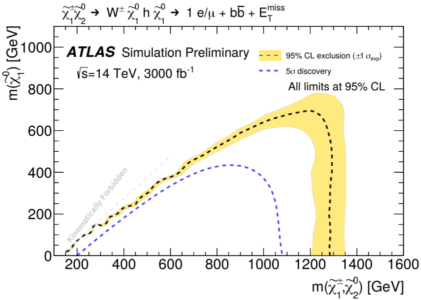

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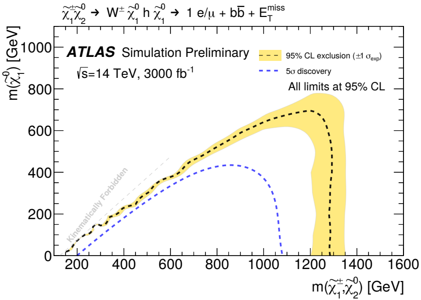

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So:

The exclusion-region is the *intersection* of the two plots, not the *union*!

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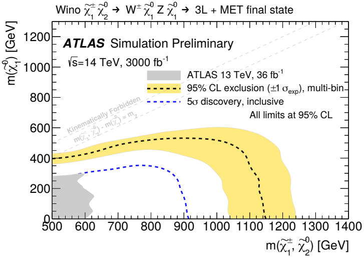
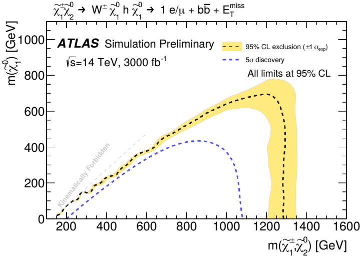
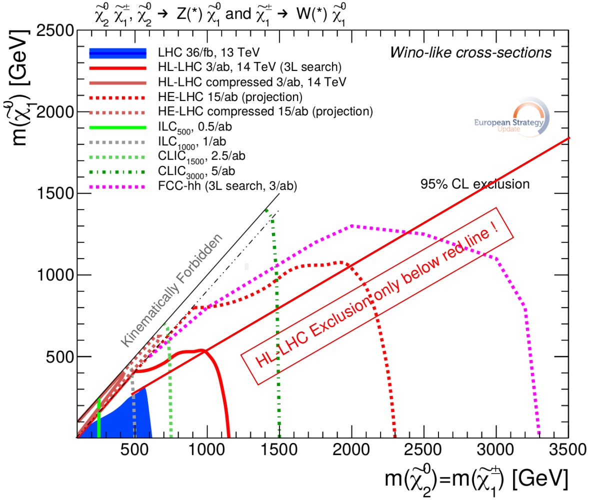
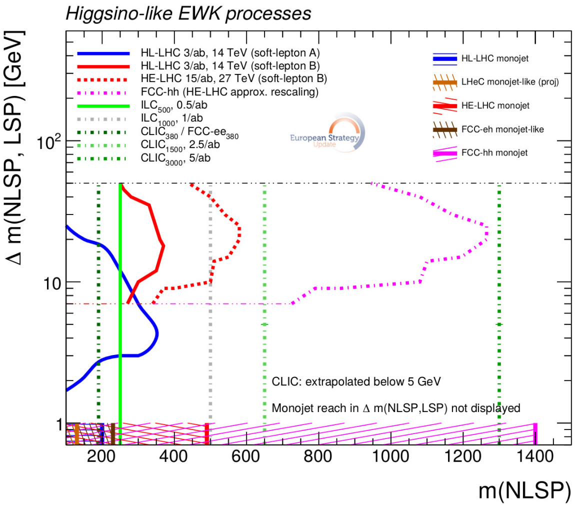




SUSY In The Briefing-book: Bino LSP (ie. large Δ_M) - Reloaded

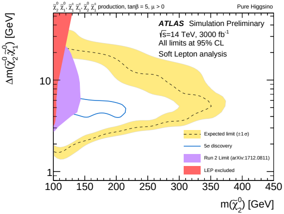


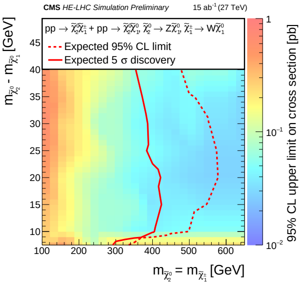
SUSY In The Briefing-book: Wino/Higgsino LSP



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

- Soft lepton analysis:
  - ATLAS HL-LHC projection `ATL-PHYS-PUB-2018-031`.
  - CMS HE-LHC projection (and extrapolated to FCChh) `CMS-PAS-FTR-18-001`.
- Crucial experimental issue: lepton ID
  - To separate $e/\mu/\pi$, particles must reach calorimeter.
  - ... and FCChh detector has both higher B-field and calorimeter radius (and CMS has that wrt. ATLAS)
- Unlikely that lower $\Delta(M)$ will be excluded in future.





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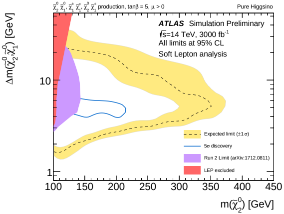

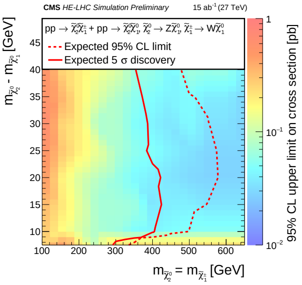

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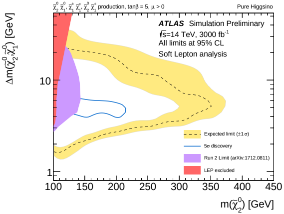
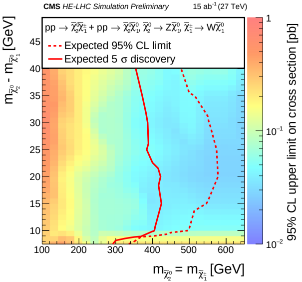
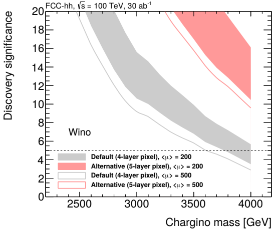
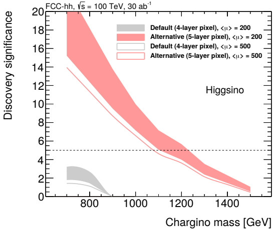




SUSY In The Briefing-book: Wino/Higgsino LSP - Very low $\Delta(M)$ pp Sources

- Two methods:
- "Mono-X"
  - Only a Delphes (w/ ATLAS card) analyis for FCChh. Systematics limited with assumed systematics than current LHC analyses (with 1/20:th of PU...)
- "Disappearing tracks"
  - FCChh-detector - FCChh-ish PU (but still to small: 500 vs. CDR number 955)
  - For higgsinos: Only *just* reaches 2 σ
  - (Don't look at the pink curves - they correspond to a detector that is never considered anywhere else i the CDR)





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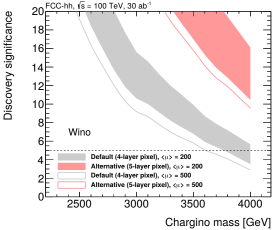

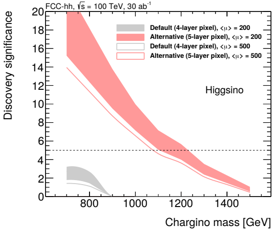

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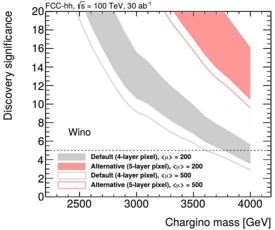

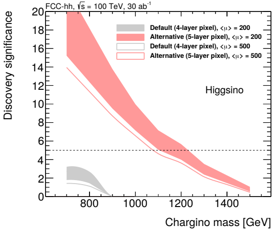

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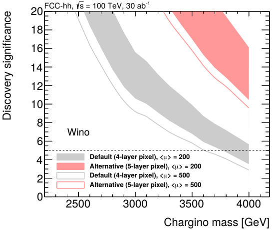

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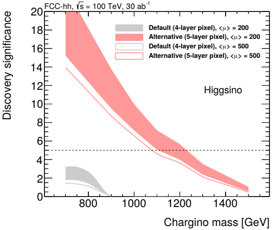

Key element for “Disappearing tracks”: $\Delta(M) \sim c\tau$

Why is this important?

- $c\tau$ needs to be macroscopic to get “Disappearing tracks”.
- Cf. `arXiv:1712.02118` where ATLAS found that $c\tau$ needs to be $\sim$ 6 cm.
- $c\tau$ for Higgsino LSP
- ... and Wino LSP
- Previous slide considered *only SM* effects on the mass-splitting, not SUSY mixings.

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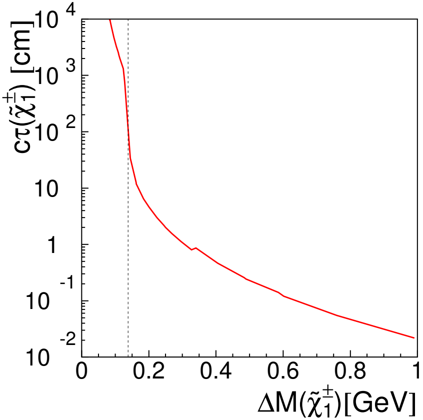

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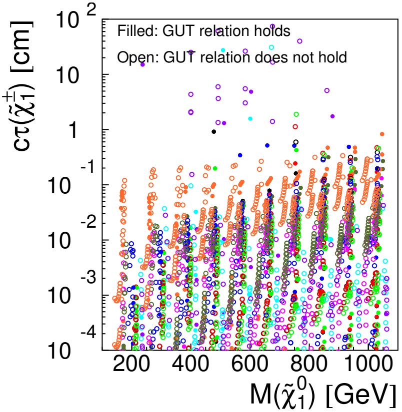

Key element for “Disappearing tracks”: $\Delta(M) \sim c\tau$

Why is this important?

- $c\tau$ needs to be macroscopic to get “Disappearing tracks”.
- Cf. `arXiv:1712.02118` where ATLAS found that $c\tau$ needs to be $\sim$ 6 cm.
- $c\tau$ for Higgsino LSP
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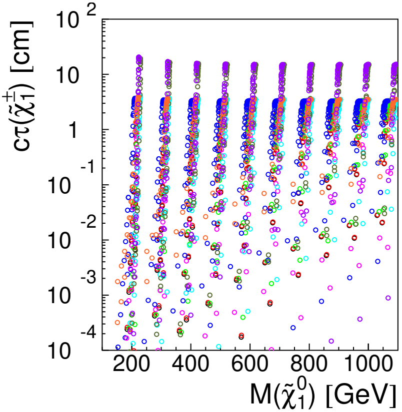

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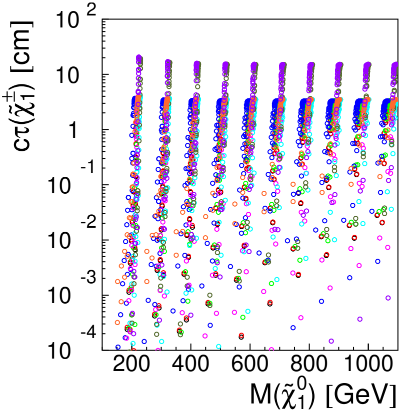

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Conclusion:

Not at all sure that that lifetime will be large. Good chances - no guarantee - for Wino, unlikely for Higgsino.

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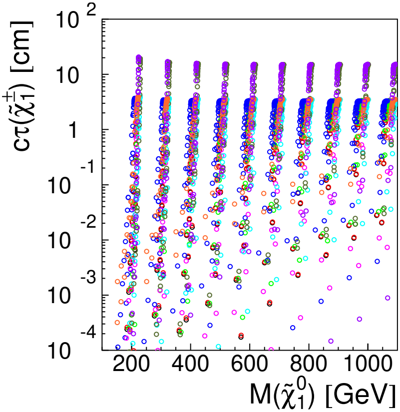
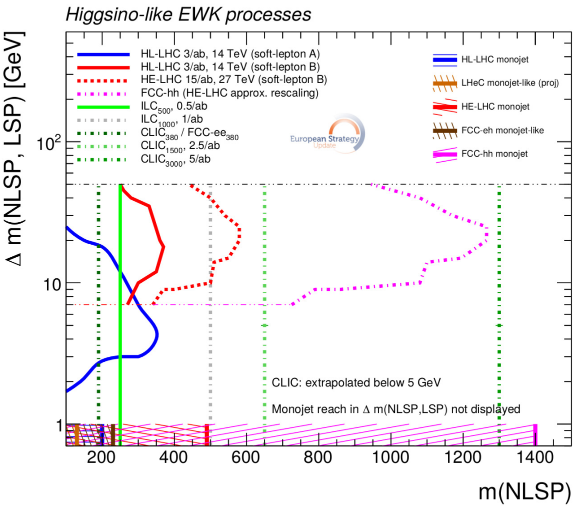
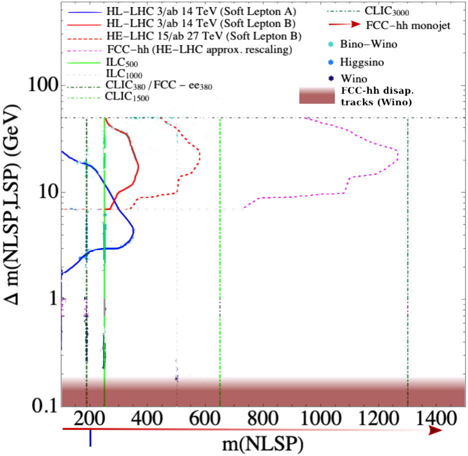


SUSY In The Briefing-book: Wino/Higgsino LSP



So: Disappearing tracks exclusion is actually off the scale !

SUSY In The Briefing-book: Reloaded



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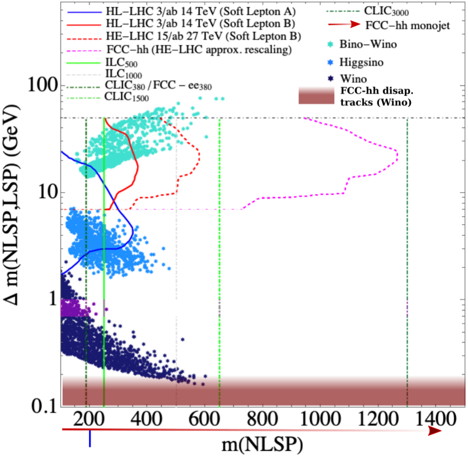
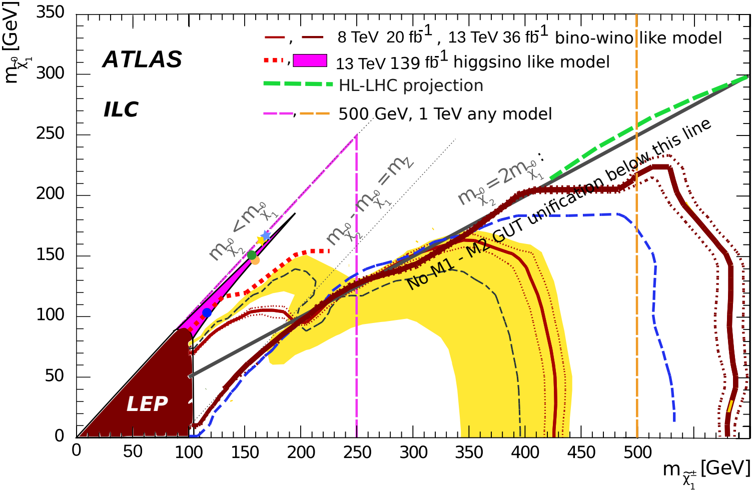


With models that are consitent with g-2 and no over-production of DM From `arXiv:2103.13403`.

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

At ILC: discovery in a week...

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

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

and

- 500 $\mathrm{fb}^{-1} \approx 2$ years.

Will never be in "3 σ limbo" !

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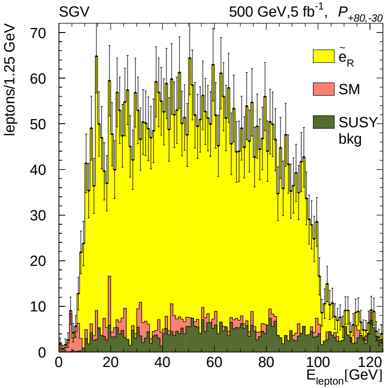

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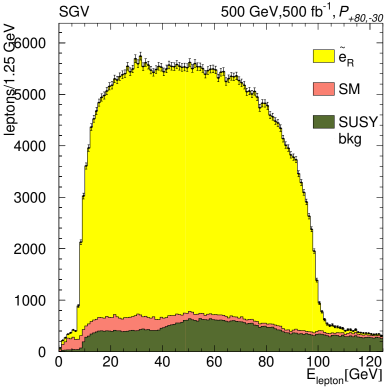

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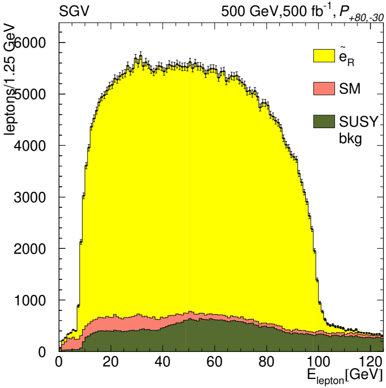

ILC = the LEP of SUSY

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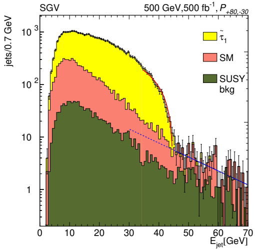

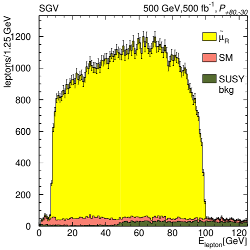

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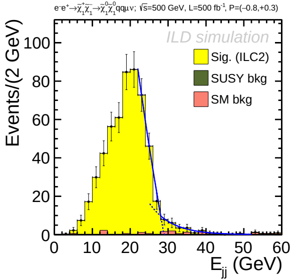

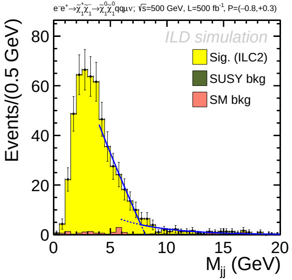

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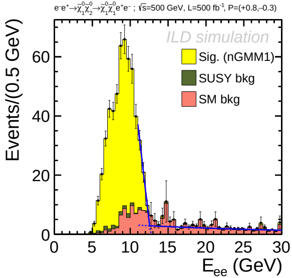

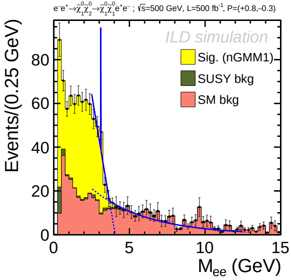

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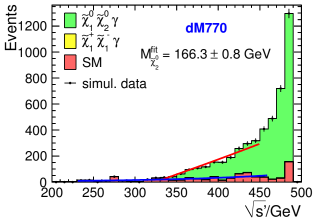

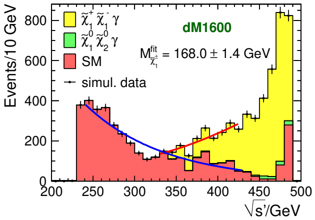

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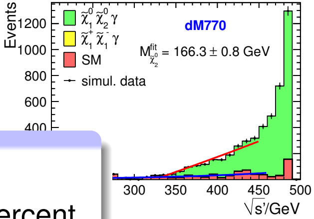

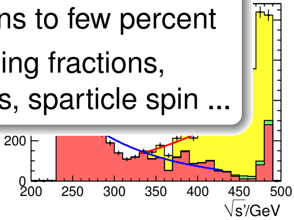

In all cases:

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

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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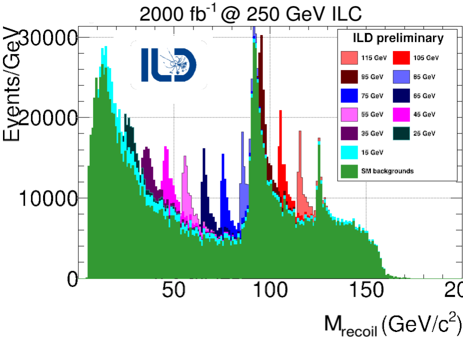

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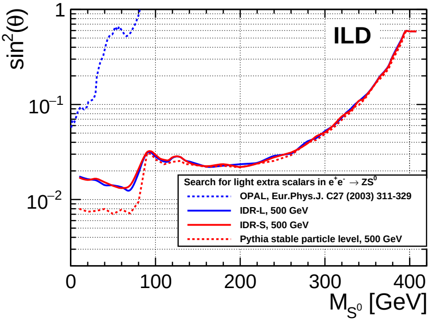

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- Dark photon/Z' : $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
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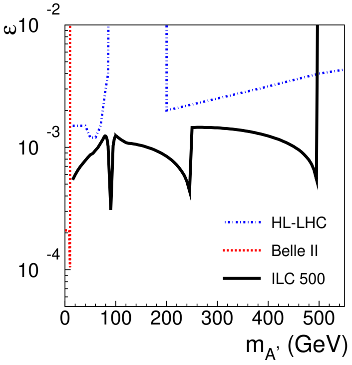

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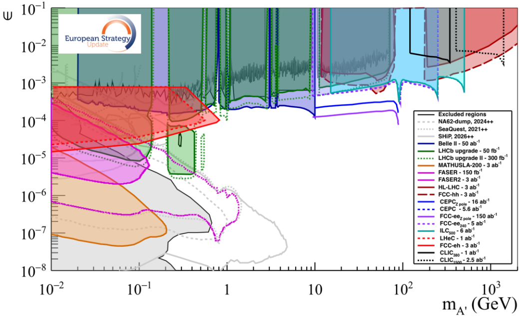
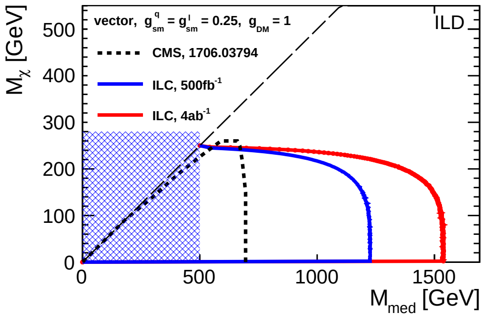


compared to others (from EPPSU).

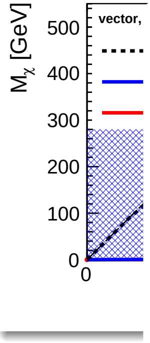
Other BSM: a gallery



DM from mono-γ (EFT)

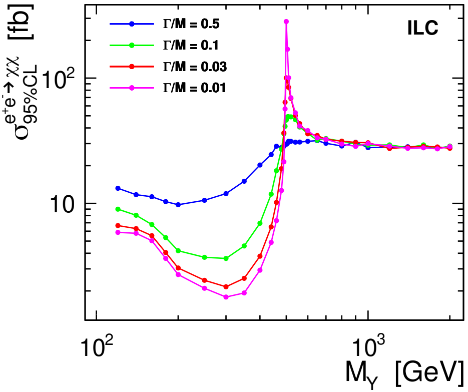
(Phys. Rev. D 101, 075053 (2020))

Other BSM: a gallery



DM from
(Phys. Rev. D 101,
075053 (2020))

DM from mono-γ (light mediator)



Conclusions

- SUSY is still alive - in fact, many well-motivated SUSY models are hardly toched by LHC limits. And will be so also after HL-LHC and even FCChh.
- The popular “bar-charts” for SUSY reach does not catch this - Better use M_{LSP} vs. M_{NLSP} plots. And show both discovery and exclusion reach !
- Sometimes, the capabilities for the direct discovery at the ILC exceed those of the HL-LHC: ILC provides well-defined initial state, clean environment, extendability and polarised beams. Detectors can be more precise,hermetic, and run trigger-less
- Many ILC - HL-LHC synergies from energy-reach vs. sensitivity.
  - SUSY: High mass vs. Low $\Delta(M)$. If SUSY is reachable at ILC, it precision measurements. Might be just what is needed for HL-LHC to transform a 3 σ excess to a discovery of a High mass state !
  - Dark matter, FIPS, ...: Leptophilic vs. Leptophobic - Higher mass and higher coupling vs. lower mass and lower coupling.

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More material:

- ILC snowmass whitepaper
- ILC input to the european strategy update
- The Potential of the ILC for Discovering New Particles

and references therein ...

Thank You !

Backup

BACKUP SLIDES

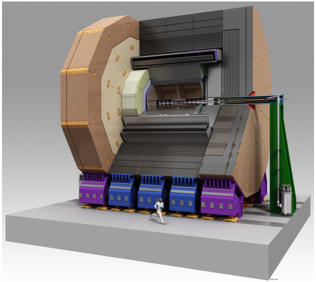
ILC Detectors: the ILD and SiD concepts

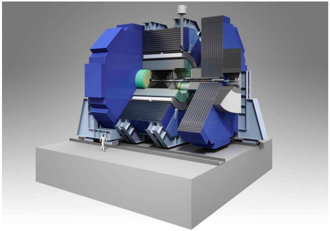
Physics requirements, SM and BSM:

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

Leads to key features of the detector:

- High granularity calorimeters optimised for particle flow
- Power-pulsing for low material.





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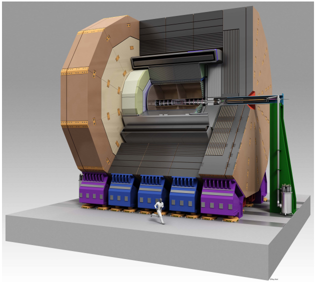
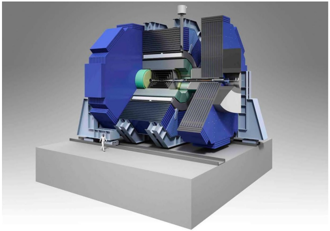
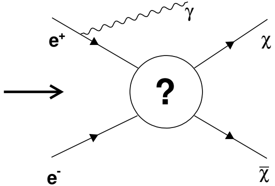
Both concepts can deliver!





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



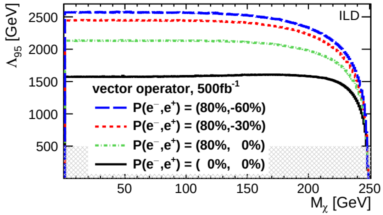
- ILC simulation studies: arXiv:1206.6639v1, A. Chaus, Thesis, M. Habermehl, Thesis,in preparation.
- Model-independent Effective operator approach to “?”
  - Analyse as an effective four-point interaction. Strength = Λ.
    - Allowable if direct observation the mediator is beyond reach. Mostly true 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.

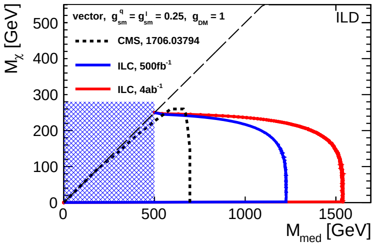
ILC and LHC exclusion

- 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

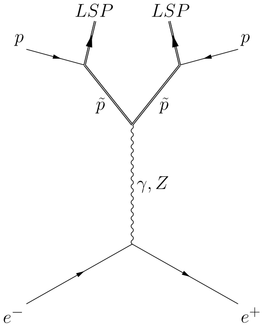
- LHC: coupling to hadrons, ILC: coupling to leptons.
- LHC has best M_χ reach, ILC best M_{med} reach





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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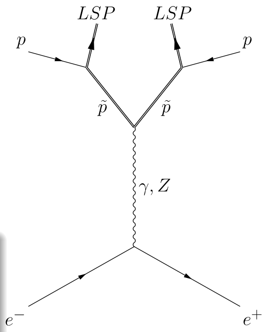
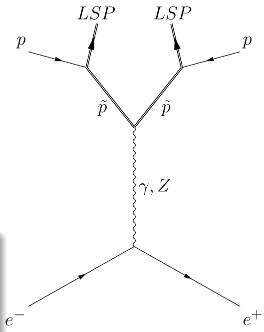


So, at ILC :

- Model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a few plots
- No fine-print!

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.



So, at ILC :

- Model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a few plots
- No fine-print!

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.
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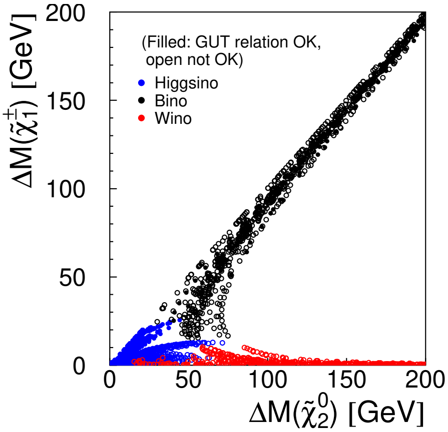
- But note, seldom on the "Higgsino line", ie. when the chargino is *exactly* in the middle of mass-gap between the first and second neutralino.



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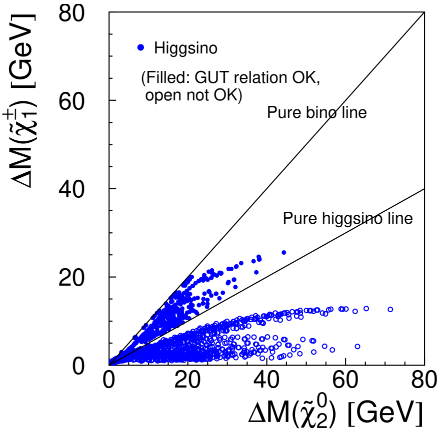

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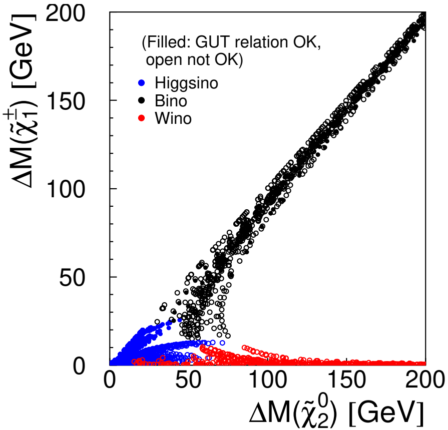
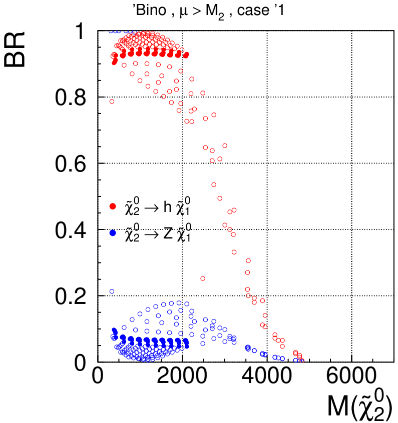


Bino LSP: BRs

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

- Vary relative signs of μ, M_1, and M_2
- For $\mu > M_2$
- or $\mu < M_2$
- 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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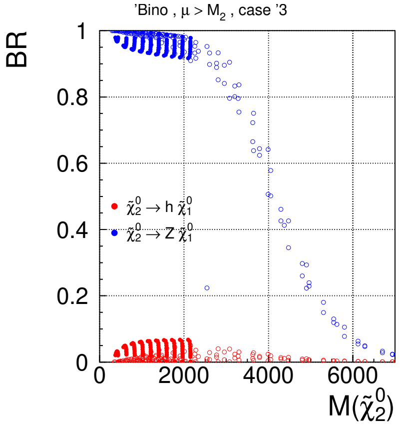

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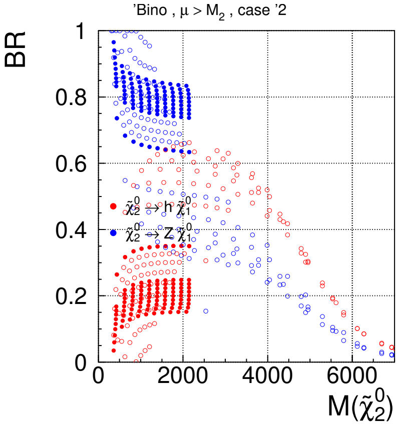

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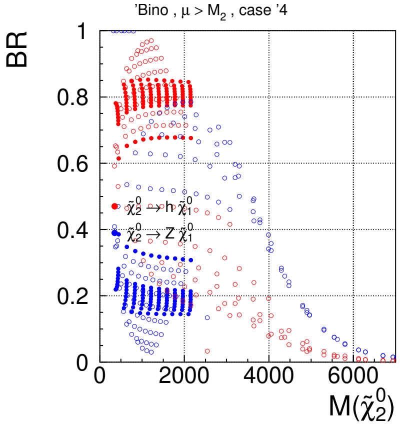

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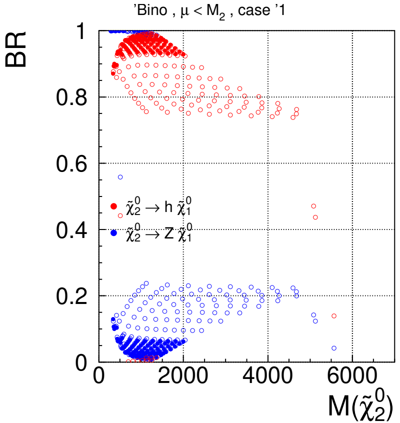

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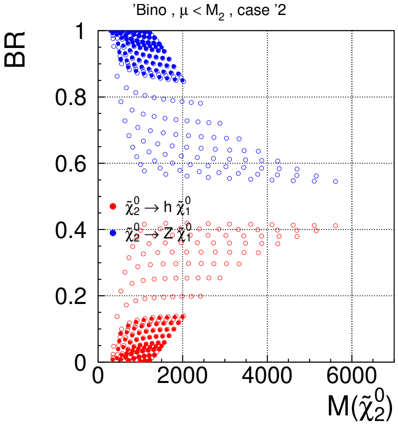

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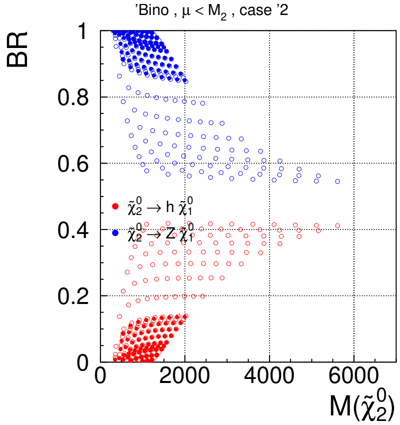

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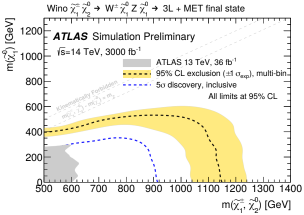

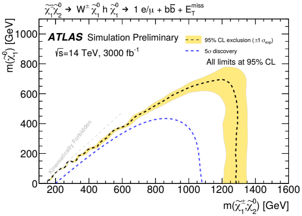

SUSY In The Briefing-book: Wino/Higgsino LSP - Very low $\Delta(M)$ pp Sources

- Two methods: “Mono-X” and “Disappearing tracks”
  - “Disappearing tracks”
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- 1805.00015, Based on DELPHES with ATLAS-card ($\Rightarrow$ LHC PU...)
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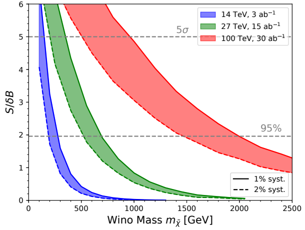

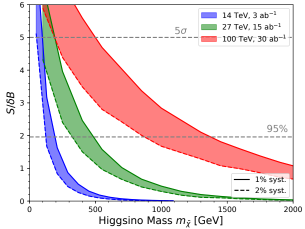

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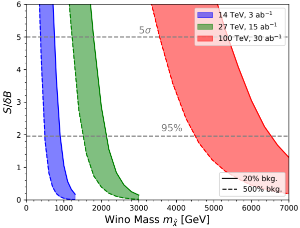

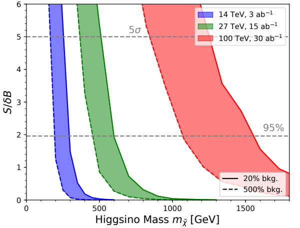

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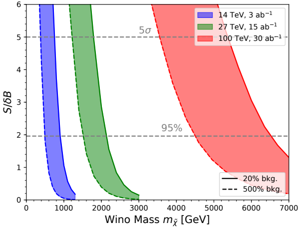

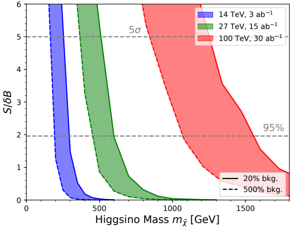

Key element for “Disappearing tracks”: $\Delta(M)$

- 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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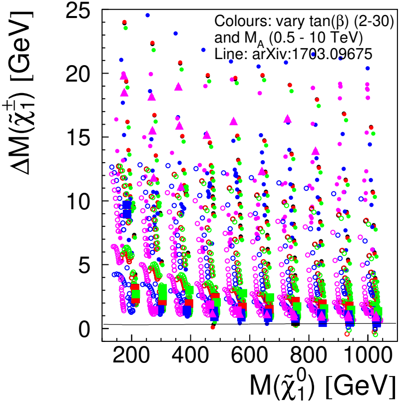

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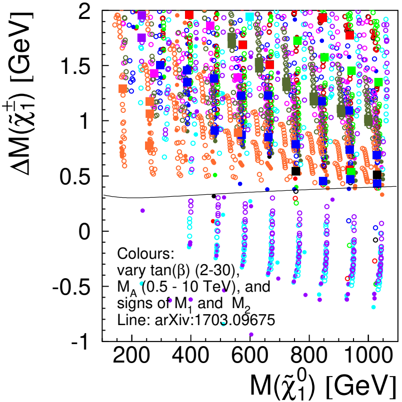

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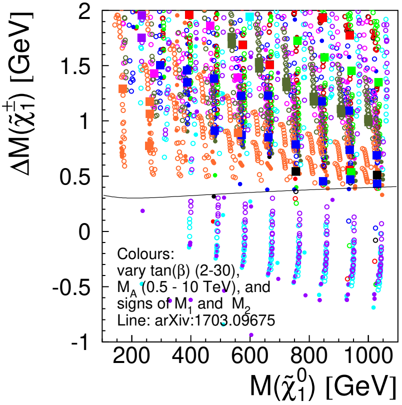

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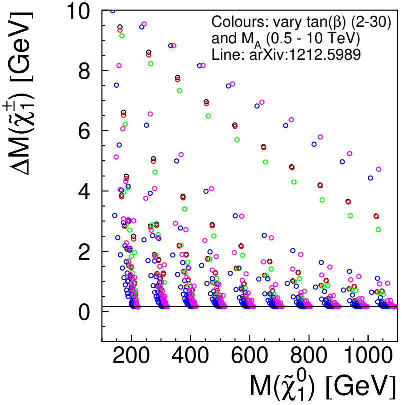
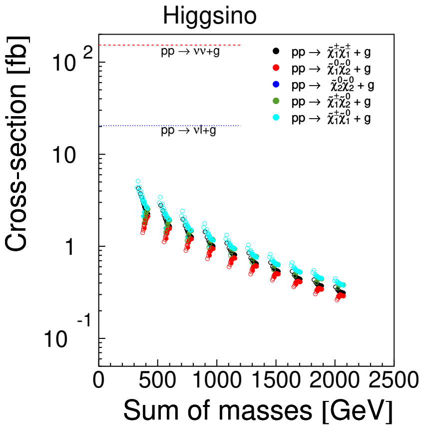


SUSY cross-sections at FCChh

Variation of cross-section for $pp \to$ uncoloured bosinos + gluon (CTEQ6L1 pdfs)

- Higgsino LSP
- Wino LSP
- or Bino LSP
- Note: Can vary by $\sim$ factor 2
- Note: Exponential fall with mass
- $\Rightarrow$ Will extend far beyond current at high $\Delta(M)$, but will stay below the $M_{NLSP} = 2 \times M_{LSP}$ line (see backup...)



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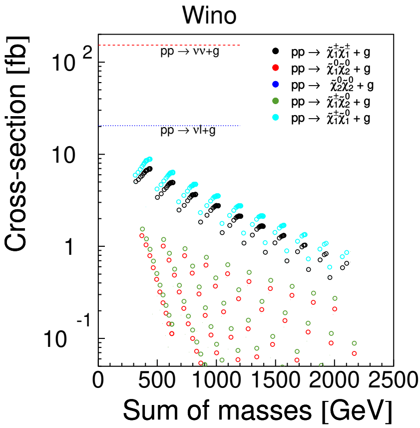

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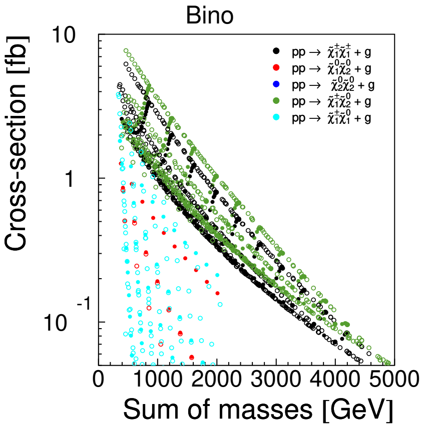

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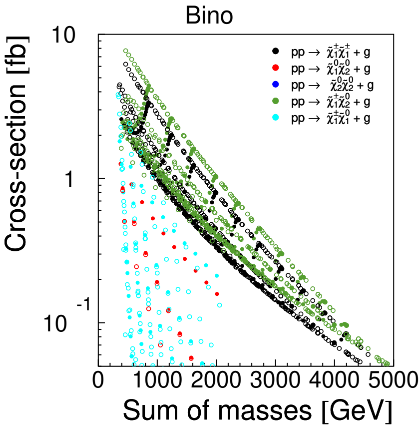

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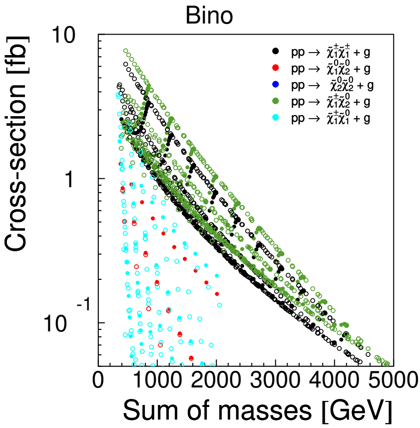
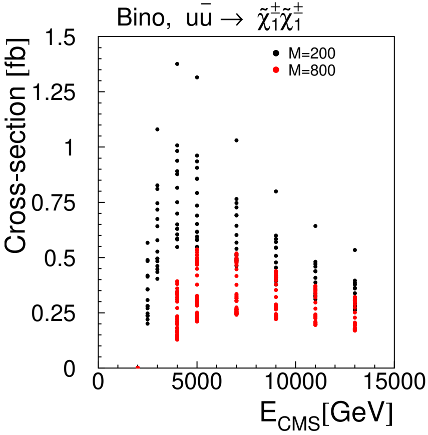


SUSY cross-sections at FCChh: Why exponential fall-off

- Consider *fixed* m_{qq}, at two masses: First rise w/ β, then fall-off w/ 1/s.
- Fold this with rapidly falling pdf:s (in particular for the sea)
- $\Rightarrow m_{qq}$ (linear) function of bino-mass



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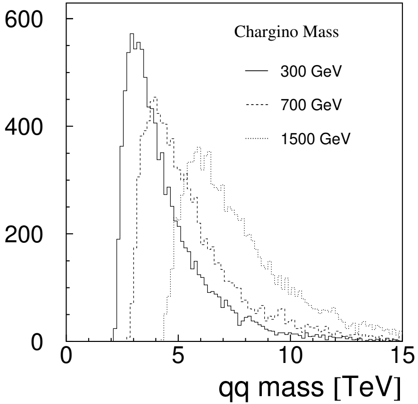

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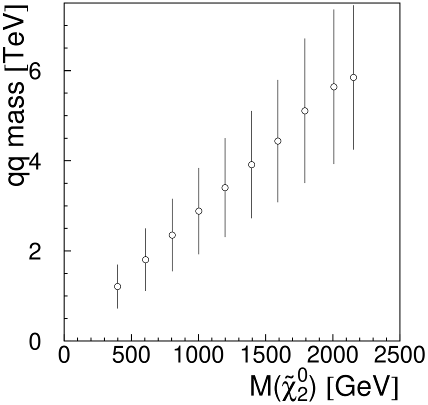

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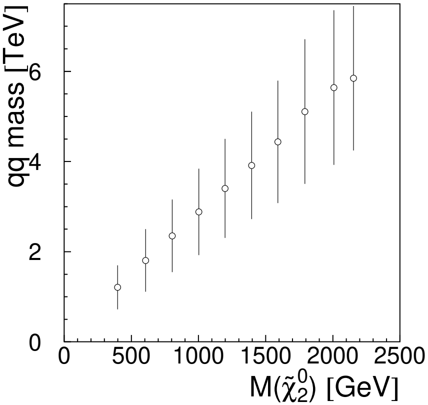
- m_{qq} (linear) function of bosino-mass
- At these mass-ratios, missing p_T is proportional to m_{qq}
- $\Rightarrow$ missing p_T increases linearly with bosino-mass.
- $\Rightarrow$ can increase missing p_T-cut linearly when looking for higher masses, with the same efficiency
- Then the background decreases as much.
- S/B remains constant along lines in $M_{\tilde{\chi}_1^\pm}$ vs. M_{LSP}



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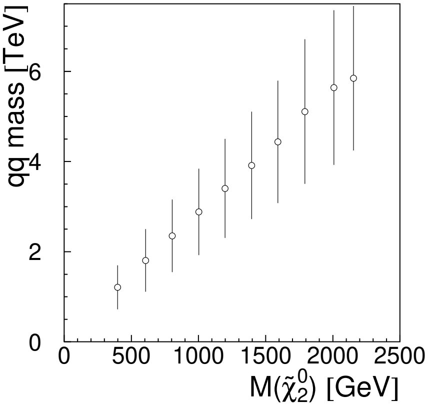

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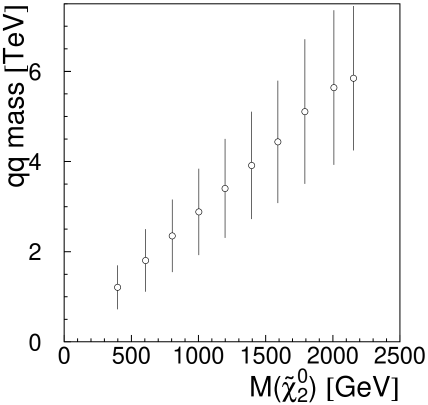

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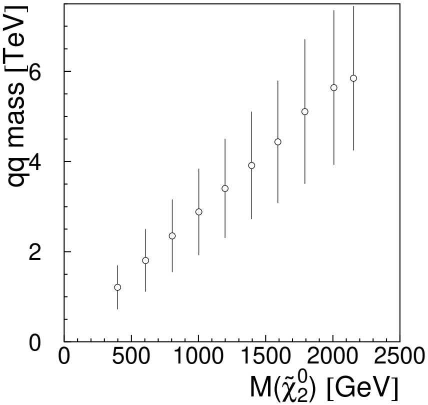

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Uptake

Expect that the limit sticks to the same diagonal as energy is increased.

- Then the background decreases as much.
- S/B remains constant along lines in $M_{\tilde{\chi}_1^{\pm}}$ vs. M_{LSP}