"Here be SUSY" - Prospects for SUSY searches at future colliders [1]

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

[1]Largely based on `arXiv:2003.12391`

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.
- If the LSP is higgsino or wino, EW sector is "compressed". Only for bino-LSP can the difference be large.
- So, most sparticle-decays are via cascades, with small $\Delta(M)$ at the end.
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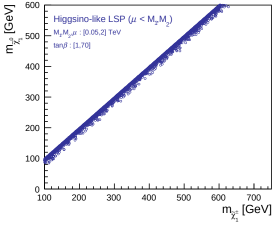

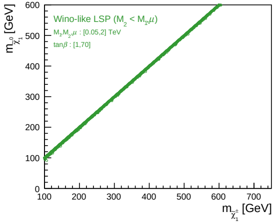

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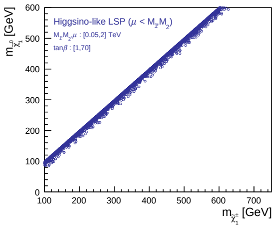

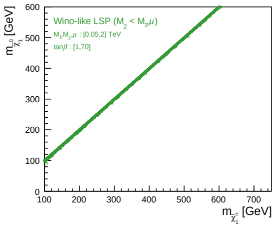

What *would* be seen at colliders in the worst case?

- MSSM, R-parity conservation (R-parity violation always easier at e^+e^-)
- sfermions not NLSP (idem, except $\tilde{\tau}$ but even worse for *pp* ...)
- 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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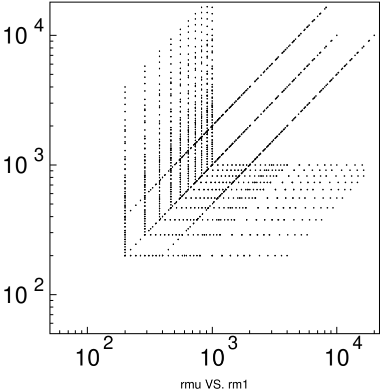
The cube

Specifically, like this:

- μ vs. M_1
- μ vs. M_2
- M_1 vs. M_2

Use `SPheno 4.0.3` to calculate spectra and BR:s
Use `Whizard 2.8.0` for cross-sections



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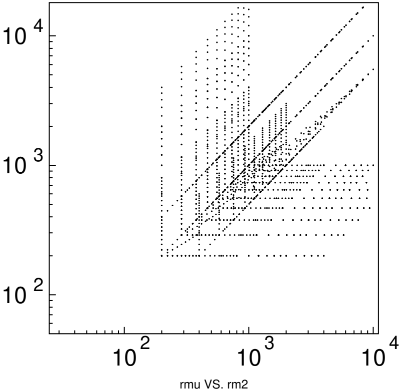

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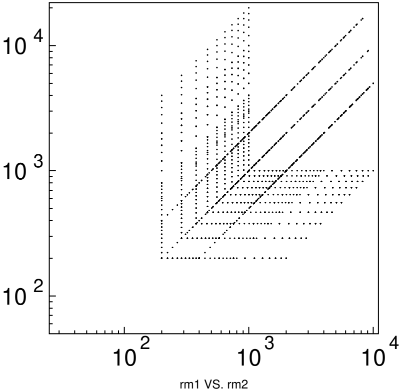

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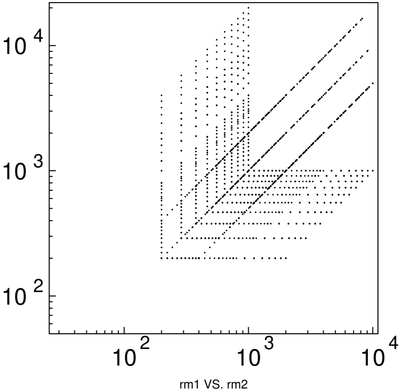

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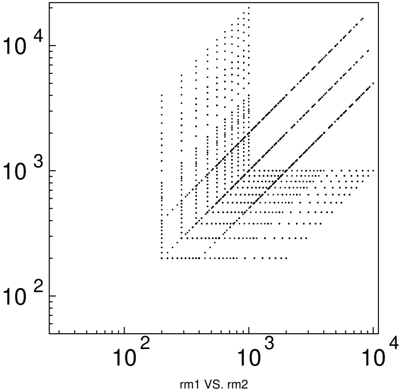
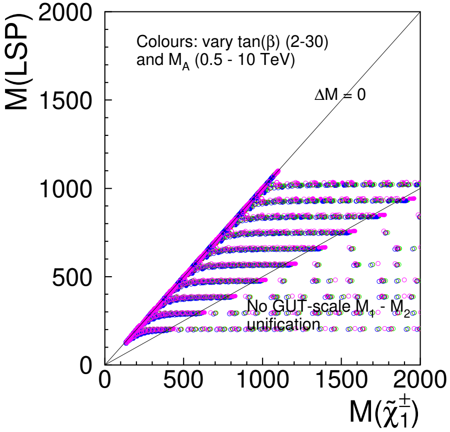
What happens with spectra, cross-sections, BRs when exploiting this "cube"?



Aspects of the spectrum

- 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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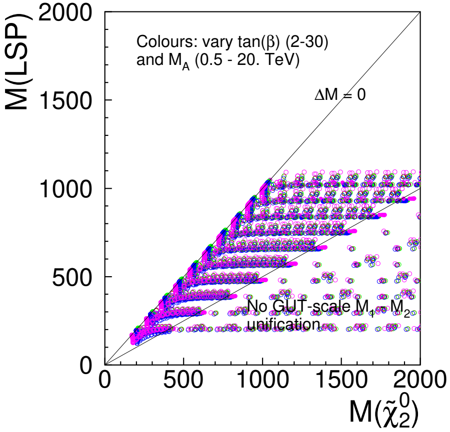
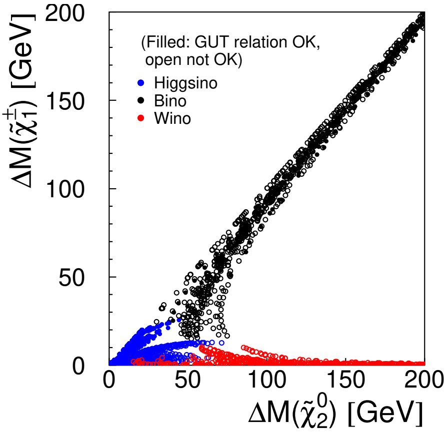


Aspects of the spectrum

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
- 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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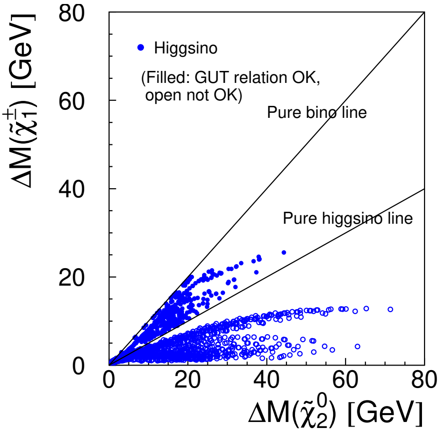
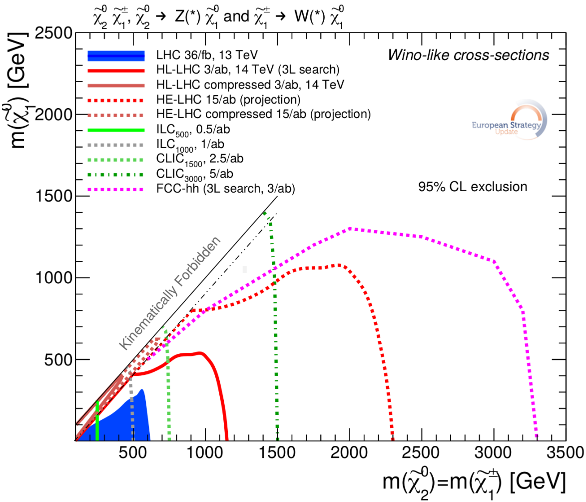


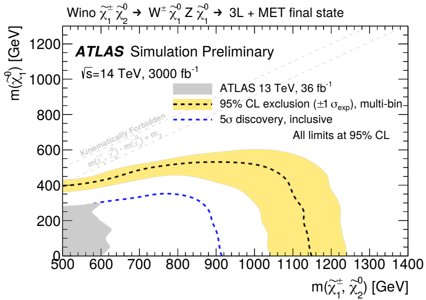
SUSY In The Briefing-book: Bino LSP (ie. large $\Delta(M)$)



NB: e^+e^- curves are certain discovery, pp are possible exclusion !!!

SUSY In The Briefing-book: Bino LSP - Sources

- `ATL-PHYS-PUB-2018-048`, ATLAS HL-LHC projection, extrapolated (up *and down*)
- This is for the best mode!
- The other decay mode
- Better at M_{LSP}=0, weaker at lower Δ_M.
- Why is the decay-mode an issue? Here's why :
  - Vary signs of μ, M_1, and M_2
- So: The exclusion-region is the *intersection* of the two plots, not the *union*!



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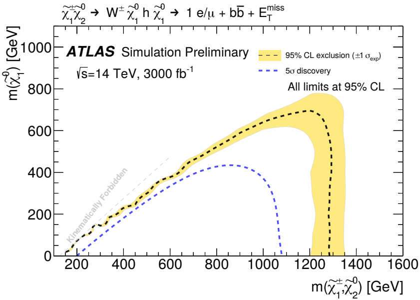

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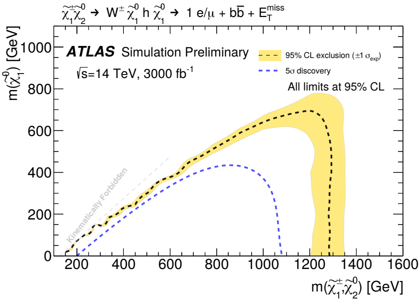

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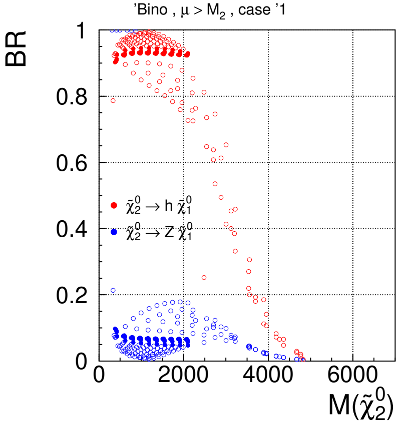

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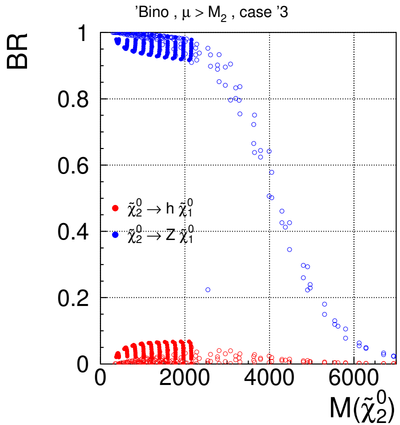

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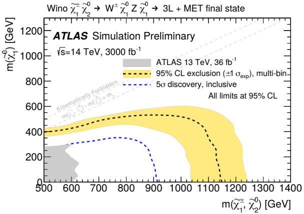
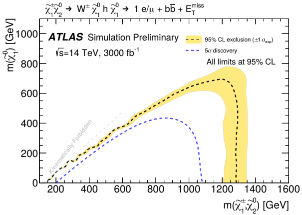
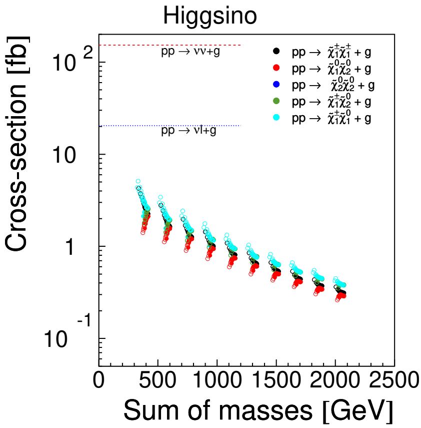




SUSY cross-sections at FCChh

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

- Higgsino LSP
- Wino LSP
- or Bino LSP
- Note: Can vary by $\sim$ factor 2
- Note: Exponential fall with mass



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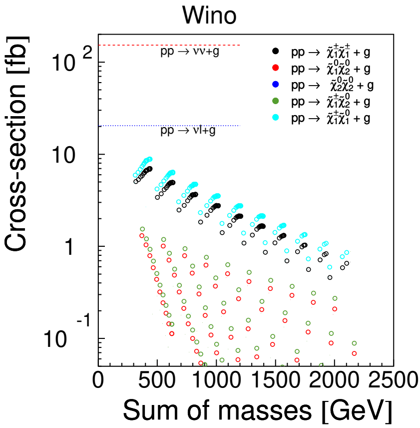

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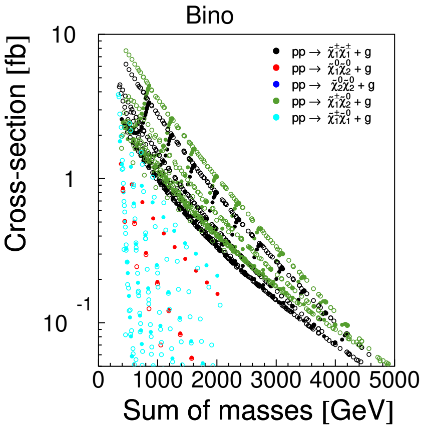

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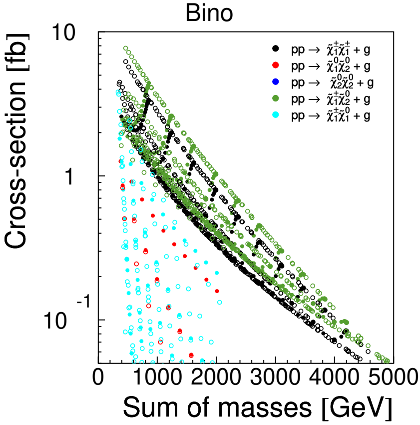
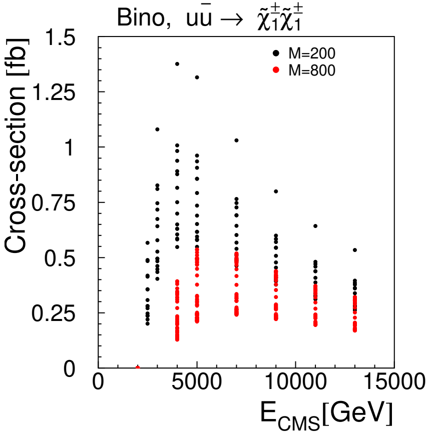


SUSY cross-sections at FCChh: Why exponential fall-off

- 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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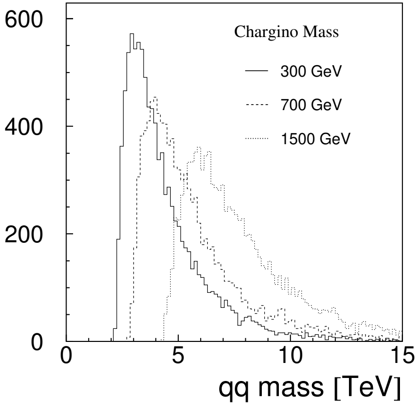

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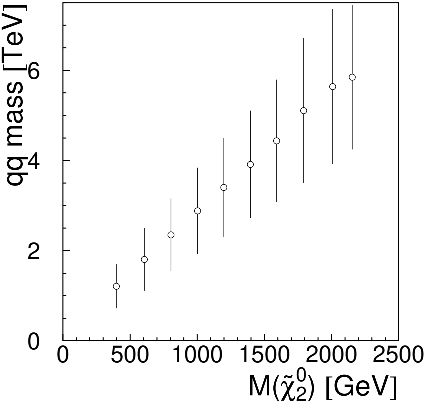
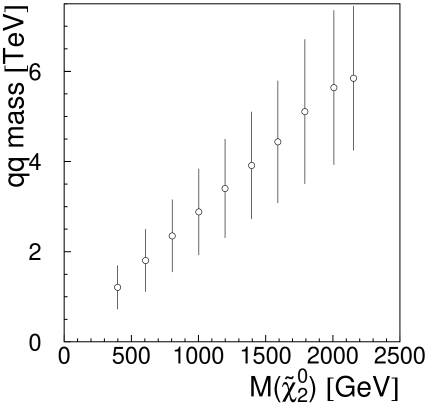


SUSY cross-sections at FCChh: Concequence of linear relation

- 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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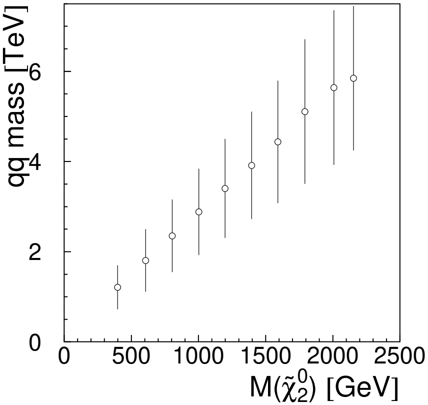

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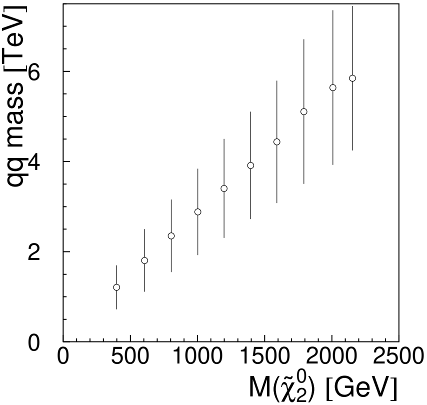

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Uptake

Expect that the limit sticks to the same diagonal as energy/luminousity is increased, but extends in the hoirzontal direction.

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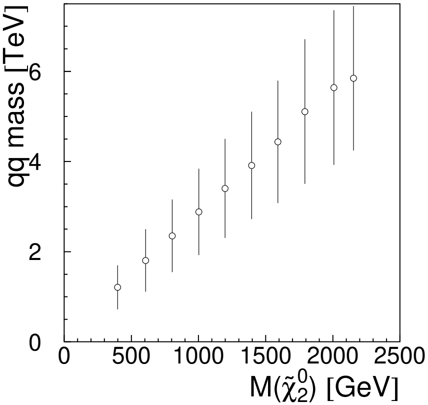
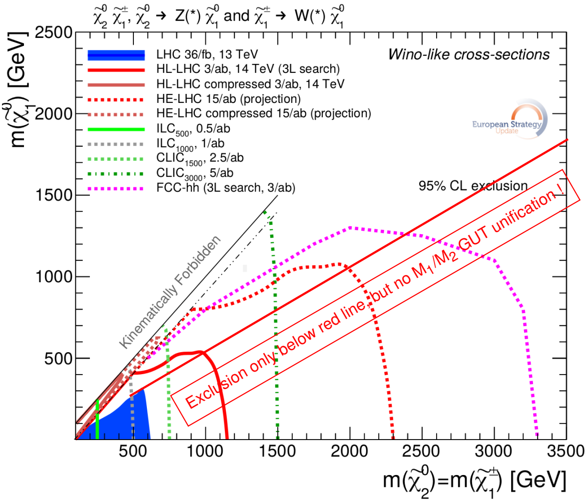


SUSY In The Briefing-book: Bino LSP (ie. large Δ_M)



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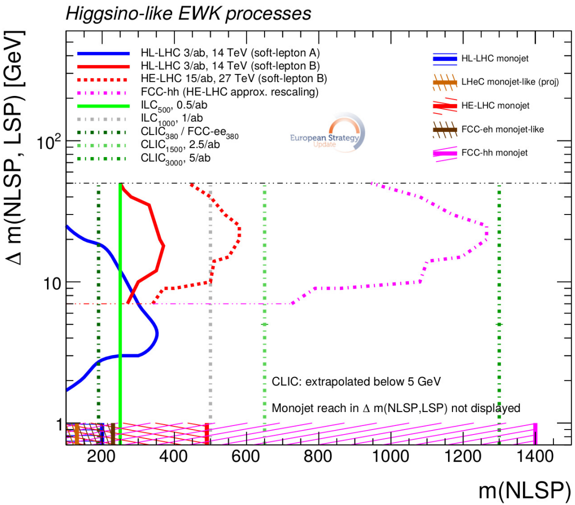
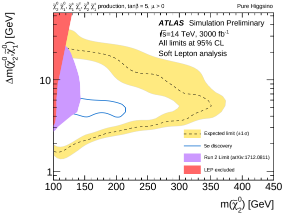
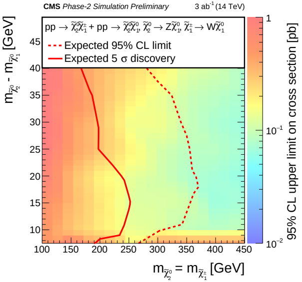


SUSY In The Briefing-book: Wino/Higgsino LSP - Soft lepton Sources

- 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.





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

- Soft lepton analysis:
  - ATLAS HL-LHC projection ATL-PHYS-PUB-2018-031.
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- Crucial experimental issue: lepton ID
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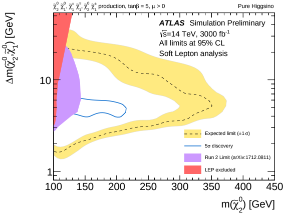

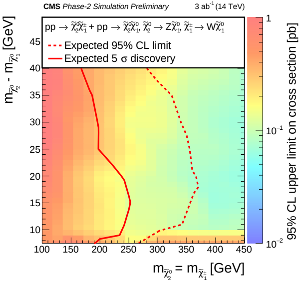

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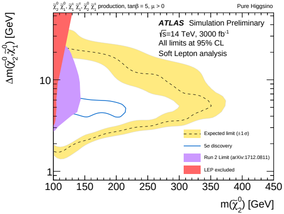

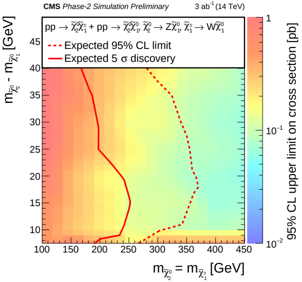

SUSY In The Briefing book: Wino/Higgsino LSP - Very low $\Delta(M)$ sources

(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
  - FCChh-ish PU (but still to small: 500 vs. CDR number 955)
  - Assumes only SM loops for mass-splitting, i.e. not SUSY mixing: The "other two" mass-parameres very large.
  - For higgsinos: Only *just* reaches 2 σ
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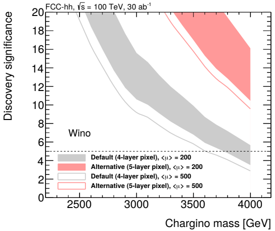

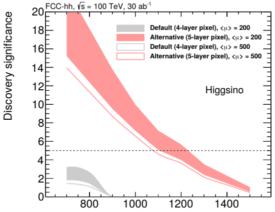

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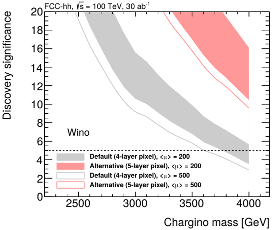

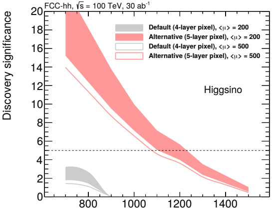

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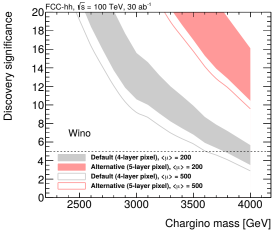

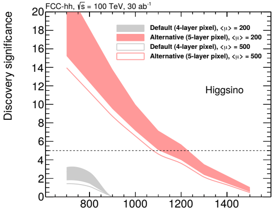

Key element for "Disappearing tracks": $\Delta(M)$

Why is this important?

- Because $c\tau$ depends on $\Delta(M)$, and $c\tau$ needs to be macroscopic to get "Disappearing tracks". Cf. ATLAS `arXiv:1712.02118`: $c\tau \gtrsim$ 6 cm needed.
- So $\Delta(M) \lesssim$ 500 MeV needed.
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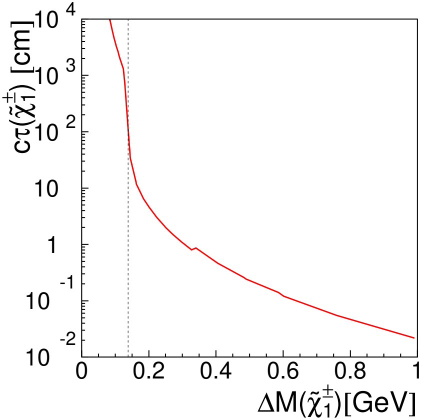

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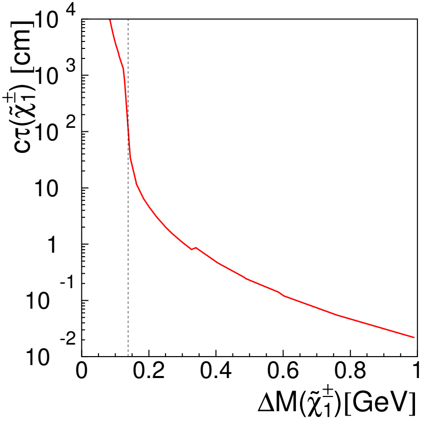

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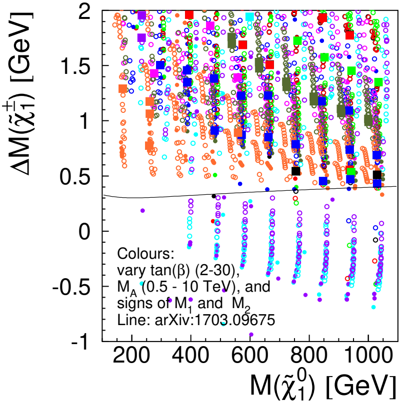

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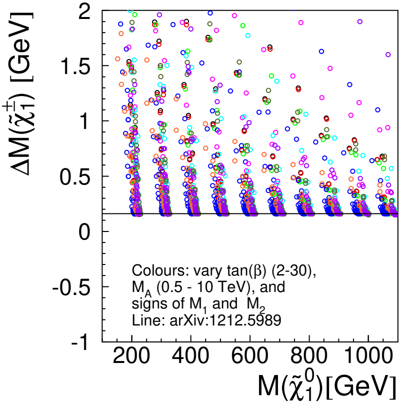

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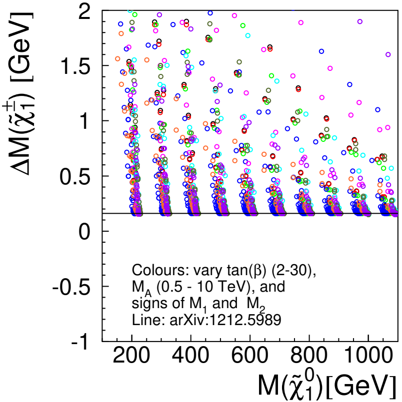

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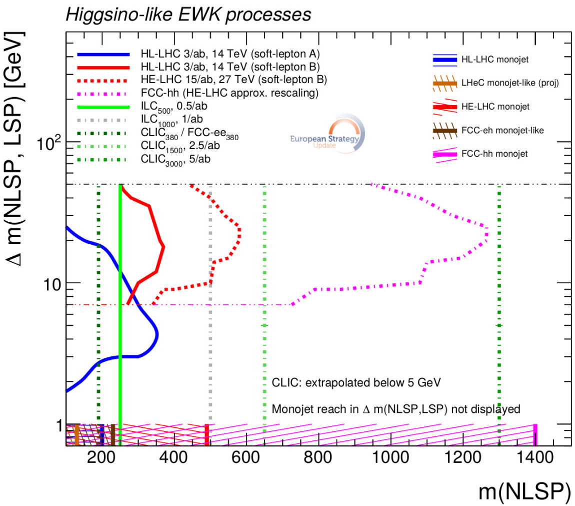
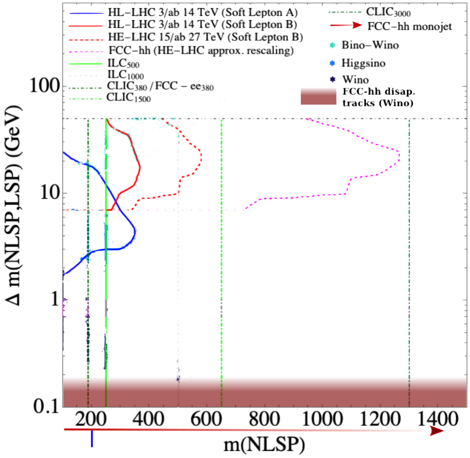
SUSY In The Briefing-book: Wino/Higgsino LSP



So: Disappearing tracks exclusion is actually off the scale !

SUSY In The Briefing-book: Re-boot



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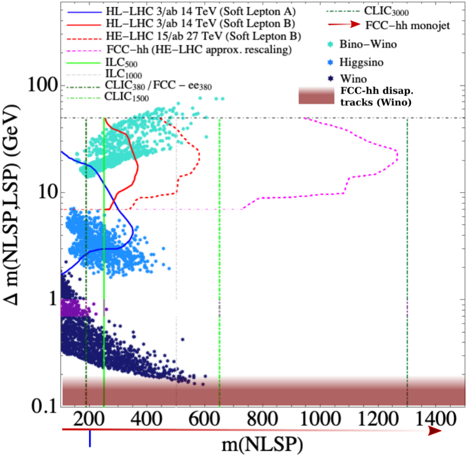
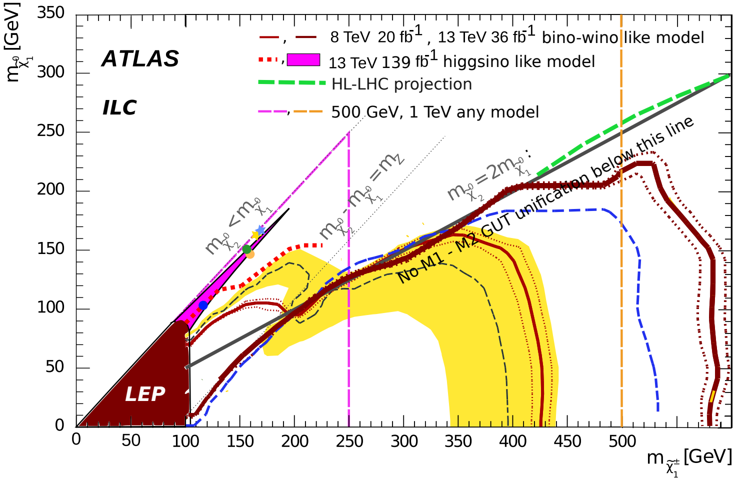


With models that are consitent with g-2 and no over-production of DM
From `arXiv:2103.13403`.

Summary: SUSY - All-in-one



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

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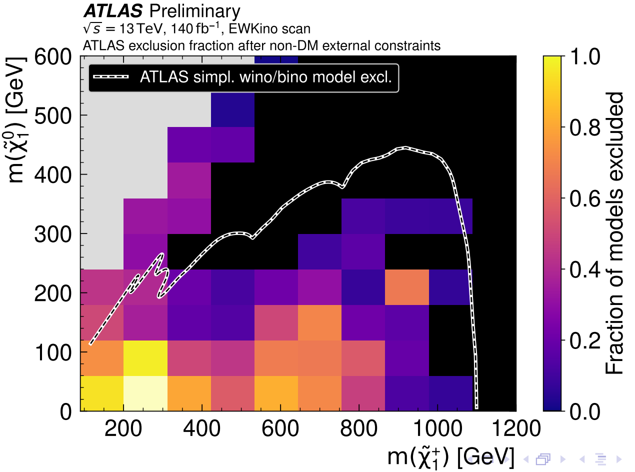
Hot off the press: ATLAS-CONF-2023-055: pMSSM-19 (-7) scan in M_{LSP} vs. $M_{\tilde{\chi}_1^\pm}$



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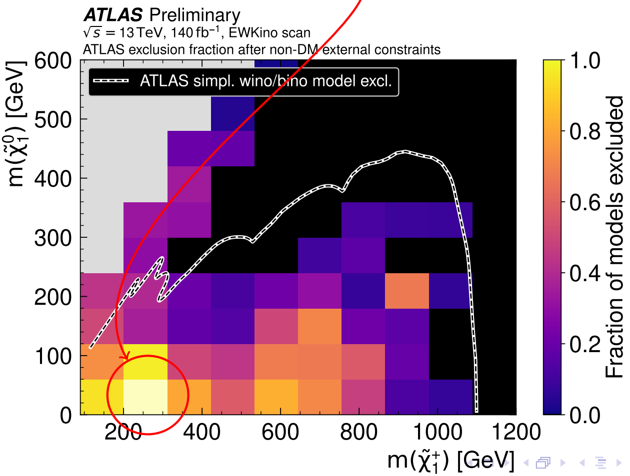
Only this one is actually excluded !



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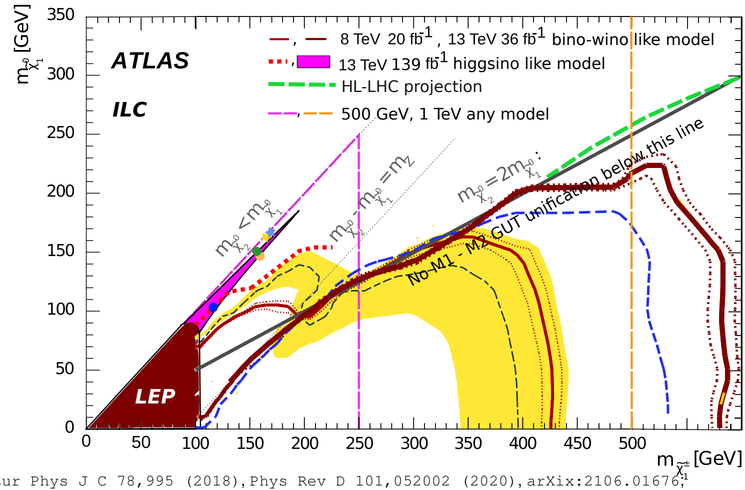

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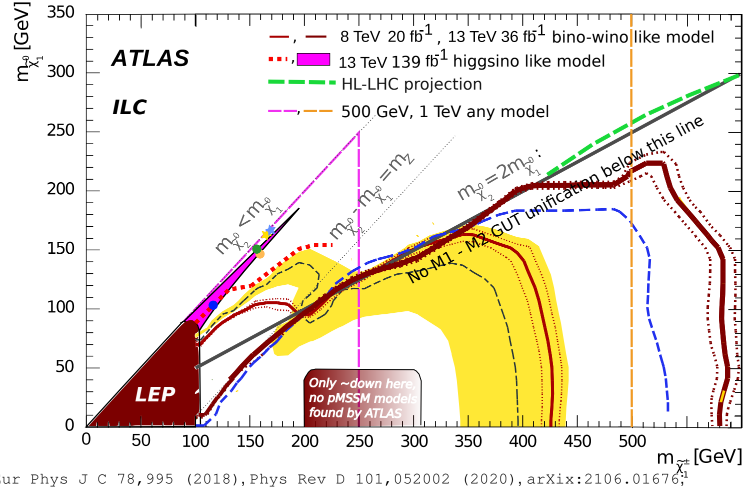
Summary: SUSY - All-in-one with latest info



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ATLAS-CONF-2023-055

Conclusions

- SUSY is not excluded.
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- HL-LHC might well discover SUSY, becuase future pp machines have
  - discovery potential to very high masses
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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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Why the title ?!

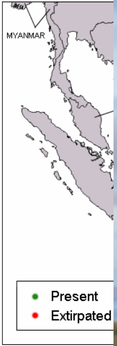
The Hunt-Lenox Globe (c:a 1510)

Hic Sunt Dracones

That is ∼ here

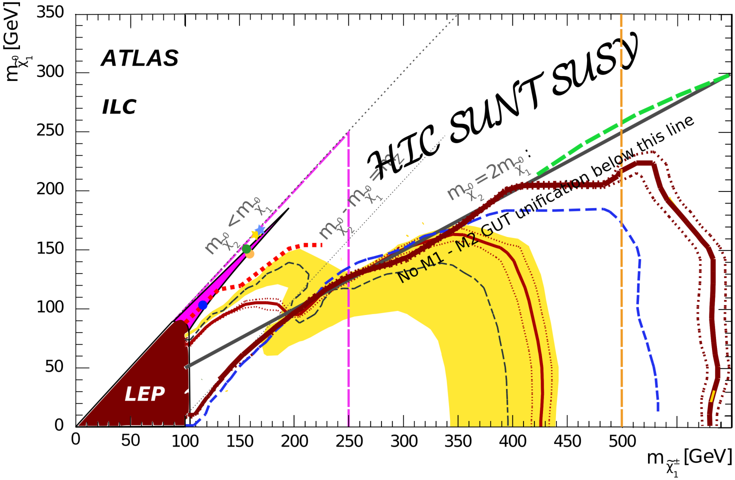

LAOS
MYANMAR
CAMBODIA
VIETNAM
MALAYSIA
INDONESIA
PAPUA NEW GUINEA
AUSTRALIA
Komodo
Flores (west)
Padar
Rinca
Gili Dasami
Gili Motang
Present
Extirpated

Yes - there actually *were* dragons there !



So...

Here be SUSY !



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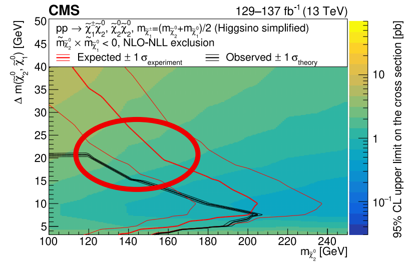
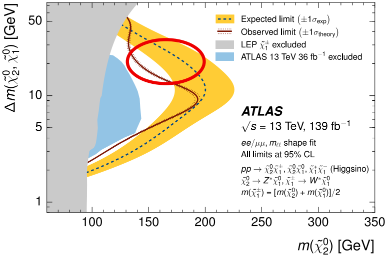
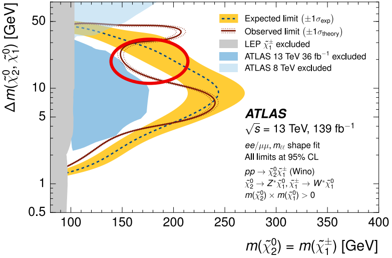
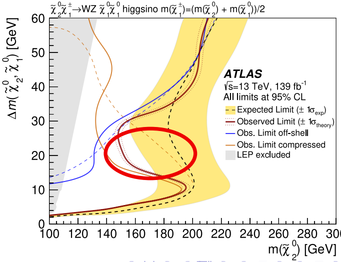
And...

Maybe we start to see the breath of the dragon (latest LHC results...)









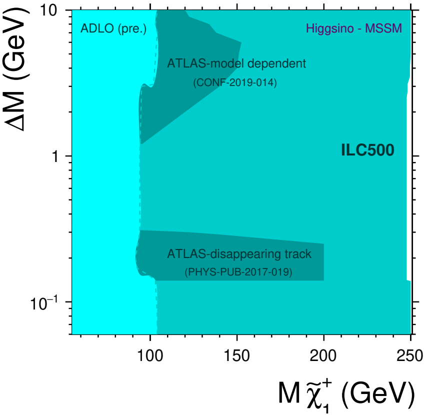
Thank You !

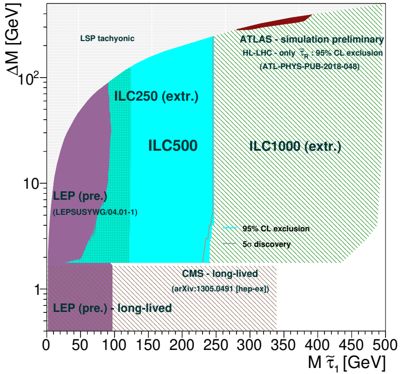
BACKUP

BACKUP SLIDES

ILC projection on Higgsinos and $\tilde{\tau}$:s

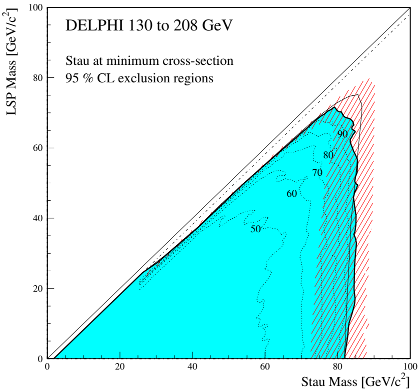
From `arXiv:2002.01239`

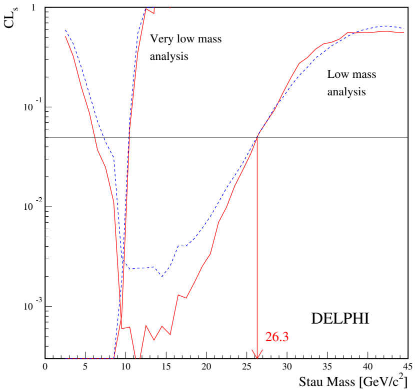




From `arXiv:2105.08616`

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





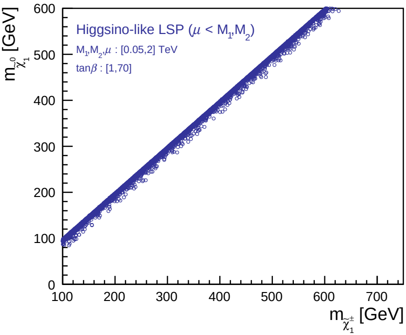
NB: a $\tilde{\tau}$ as light as 26.3 GeV is *not* excluded!

Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

Why would one expect the spectrum to be compressed ?

- 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).
- Wino-like LSP: Same conclusion.
- Only for Bino-like LSP, non-compressed occurs
- But also: the data ...

quite generic:
Parameter-scan by T. Tanabe:



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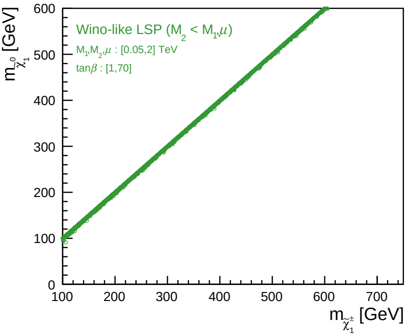

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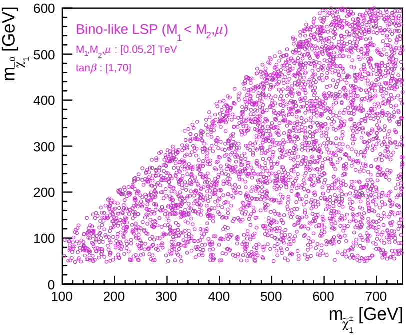

Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

Why would one expect the spectrum to be compressed ?

- 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).
- Wino-like LSP: Same conclusion.
- Only for Bino-like LSP, non-compressed occurs
- But also: the data ...

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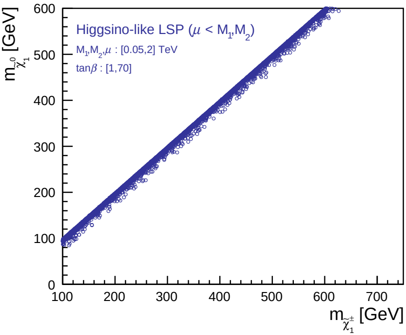
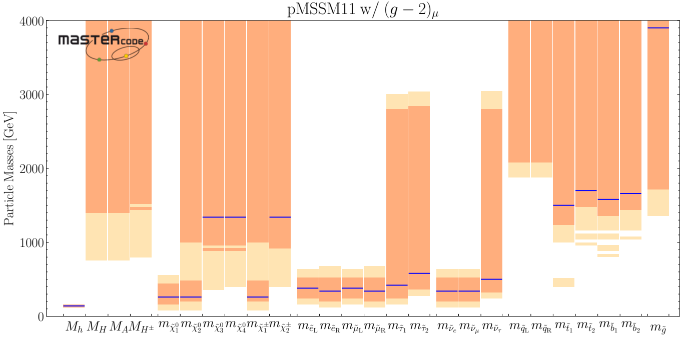


One approach: Global fits with prejudice

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



Sparticle Mass-spectrum

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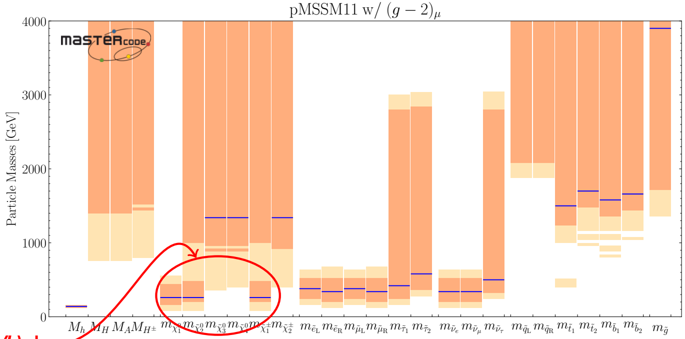

Low $\Delta(M)$!

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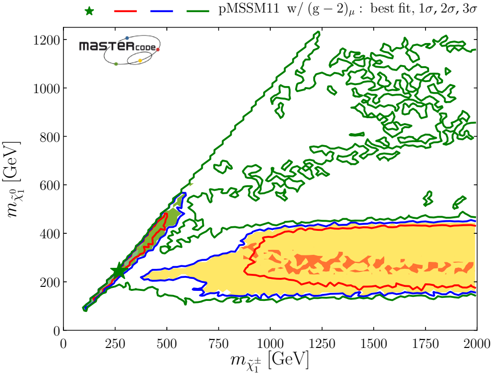

$M_{\tilde\chi_1^\pm}$ - $M_{\tilde\chi_1^0}$ plane

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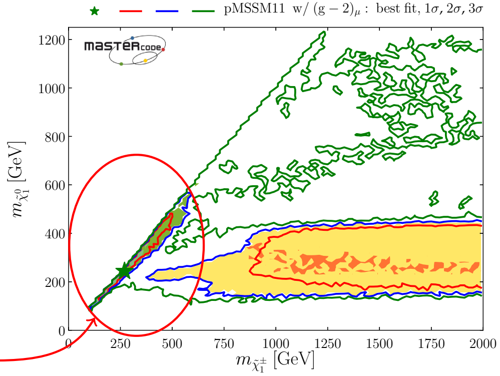

Low $\Delta(M)$!

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

Key element for "Disappearing tracks": $c\tau$

Why is this important?

- $c\tau$ needs to be macroscopic to get "Disappearing tracks". Cf. ATLAS `arXiv:1712.02118`: $c\tau \gtrsim$ 6 cm needed.
- $c\tau$ for Higgsino LSP
- ... and Wino LSP
- Conclusion: Not at all sure that that lifetime will be large. Good chances - no guarantee - for Wino, unlikely for Higgsino.

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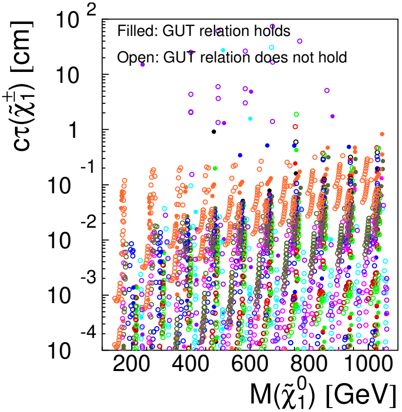

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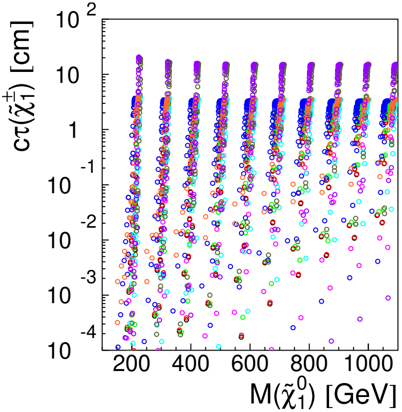

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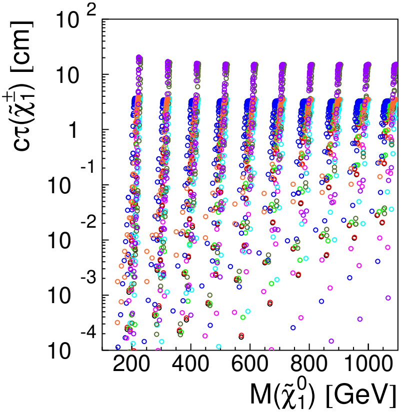
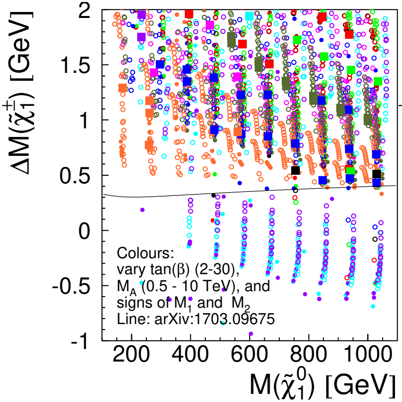
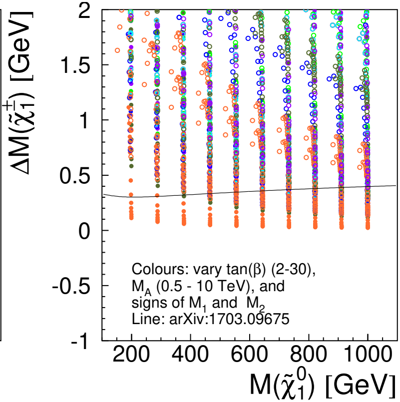


second opinion on Higgsino $\Delta(M)$: feynhiggs





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

- Two methods: “Disappearing tracks” and “Mono-X”
  - “Disappearing tracks” (see above)
  - and “Mono-X”
- arxiv:1805.00015, Based on DELPHES with ATLAS-card (⇒ LHC PU...)
- Both from the HE/HL-LHC input to ESU (*not* FCChh)
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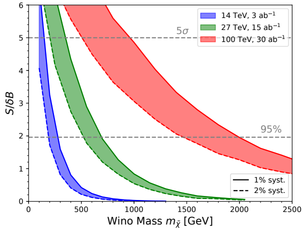

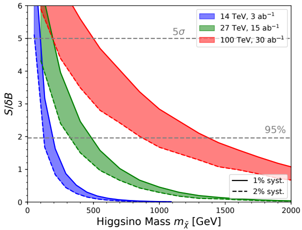

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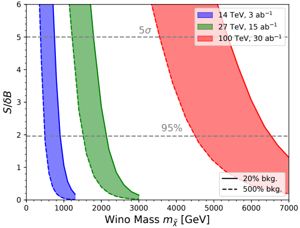

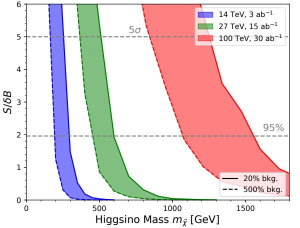

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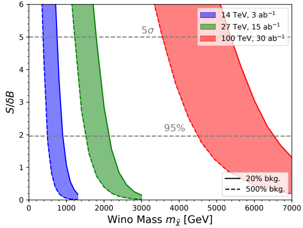

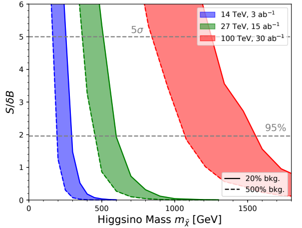

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