SUSY at future colliders: Will e^+e^--colliders be relevant? [1]

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[1]DESY, Hamburg

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CLUSTER OF EXCELLENCE
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[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.
- For this, current limits from LHC are only for specific models, and LEP2 sets the scene.

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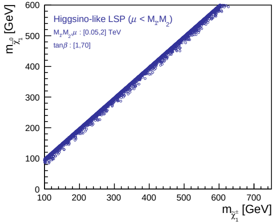

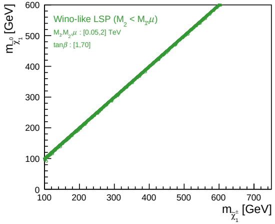

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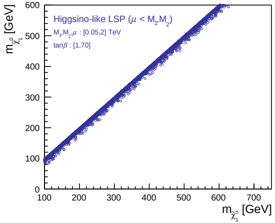

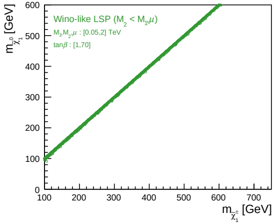

What *would* be seen at colliders in the worst case?

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

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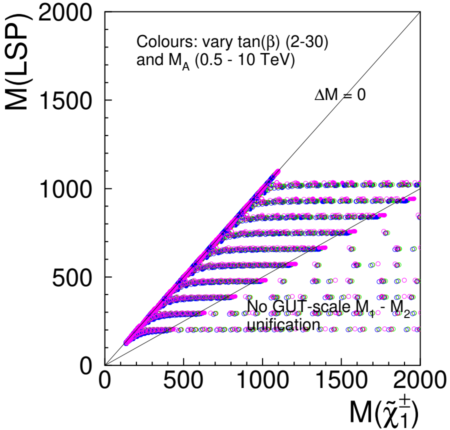
What happens with spectra, cross-sections, BRs when exploiting this “cube”?

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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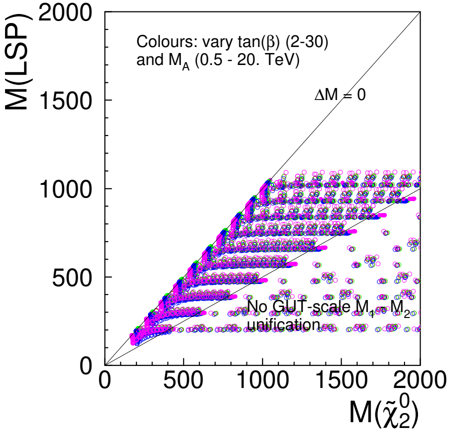

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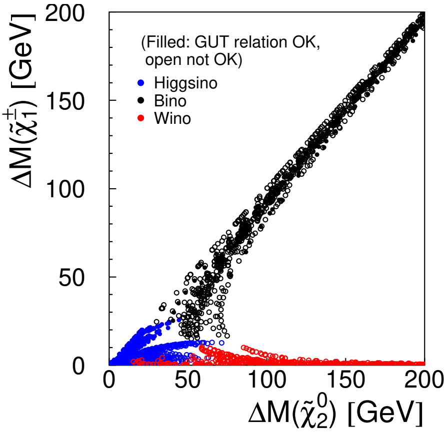
Another angle: $\Delta(M)$ for $\tilde{\chi}_1^\pm$ vs. that of $\tilde{\chi}_2^0$: Important experimentally

- 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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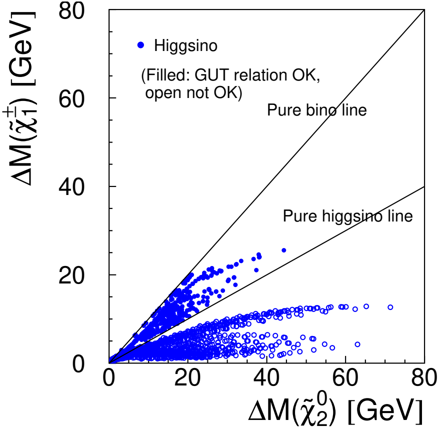
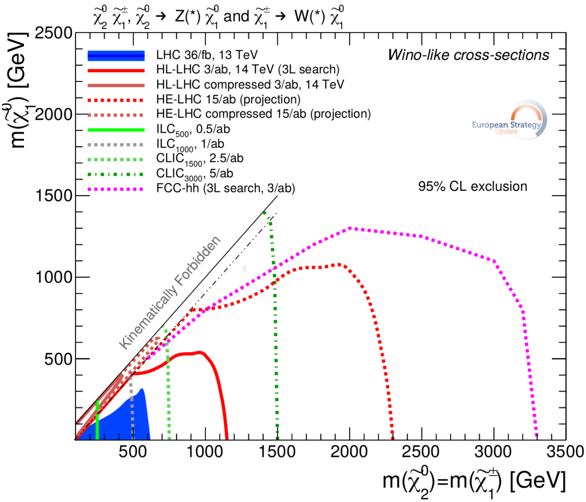


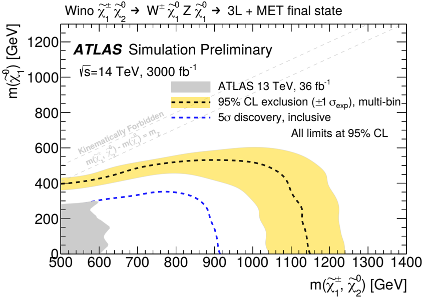
SUSY In The Briefing-book: Bino LSP (ie. large $\Delta(M)$)



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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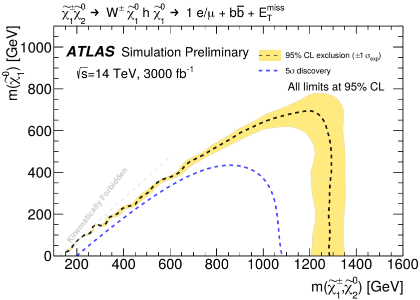

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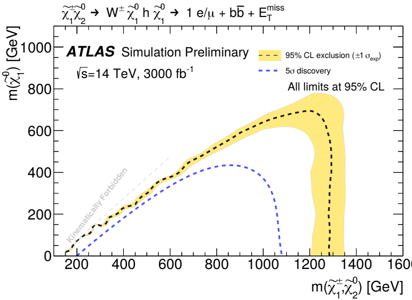

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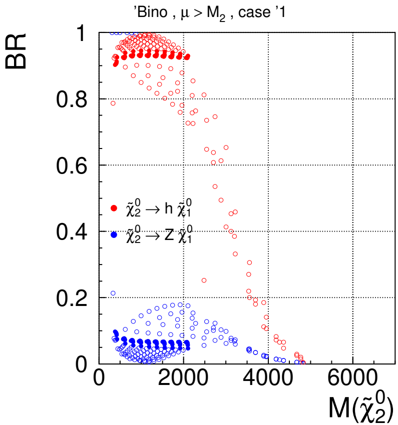

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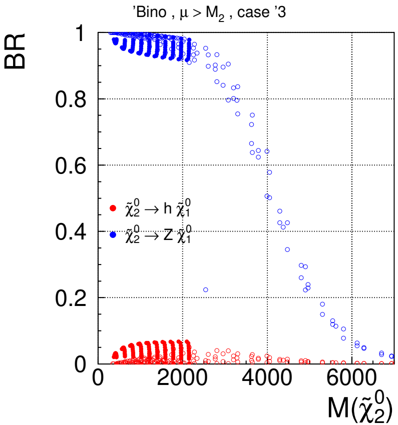

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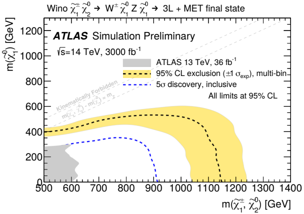

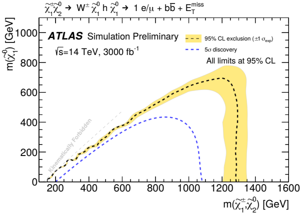

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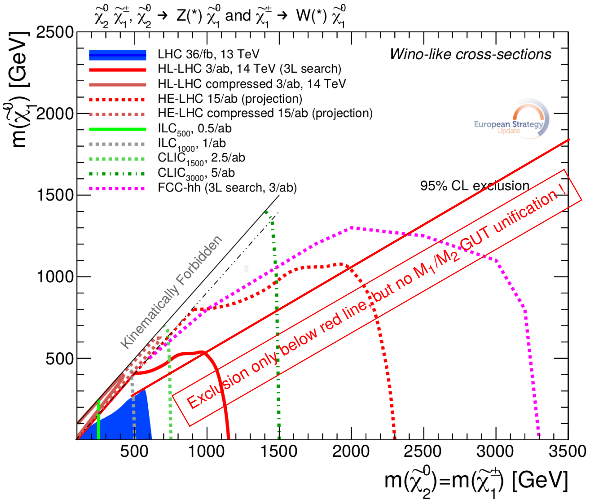

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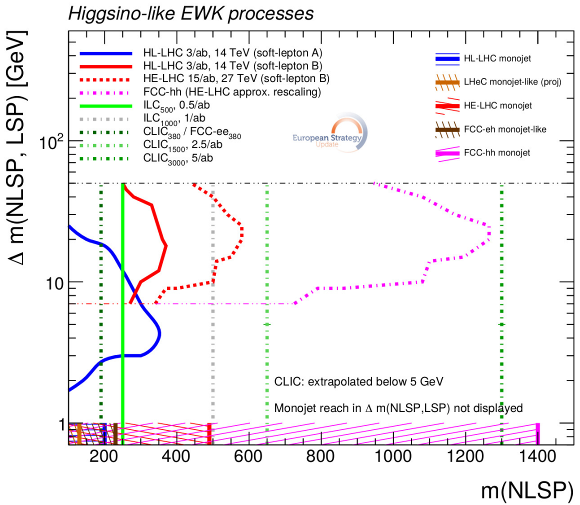

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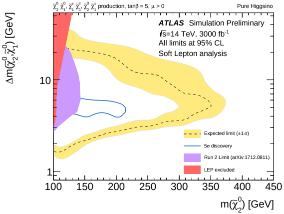
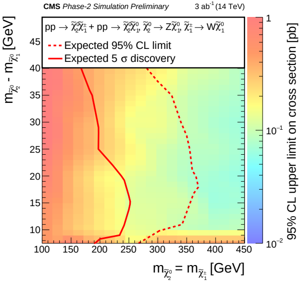
- Soft lepton analysis:
  - ATLAS HL-LHC projection `ATL-PHYS-PUB-2018-031`.
  - CMS HE-LHC projection (and extrapolated to FCChh) `CMS-PAS-FTR-18-001`.
- Crucial experimental issue: lepton ID
  - To separate e/μ/π, particles must reach calorimeter.
  - ... and FCChh detector has both higher B-field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





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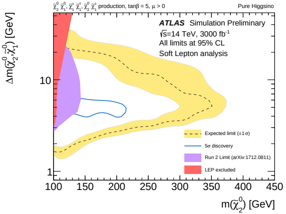

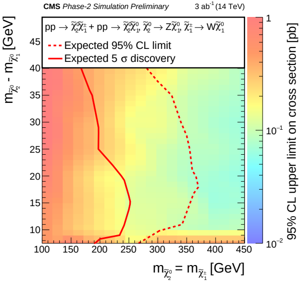

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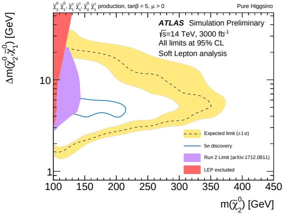
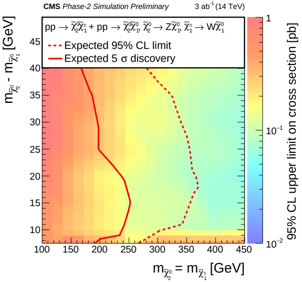
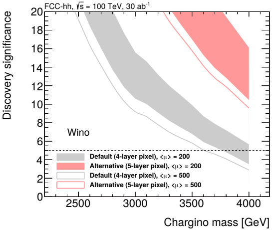


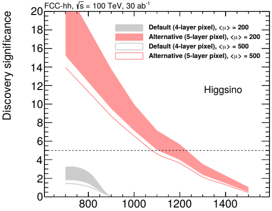


SUSY In The Briefing book: Wino/Higgsino LSP - Very low $\Delta(M)$ sources

(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
- A study of the "mono-X" method was done in `arXiv:1805.00015`, but it is too rudimetary in the experimental aspects to allow for any conclusions.





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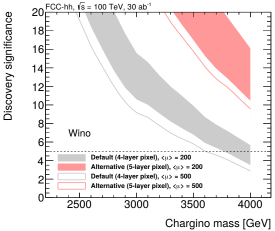

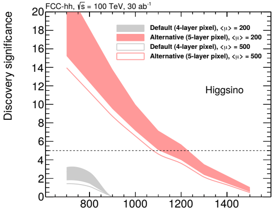

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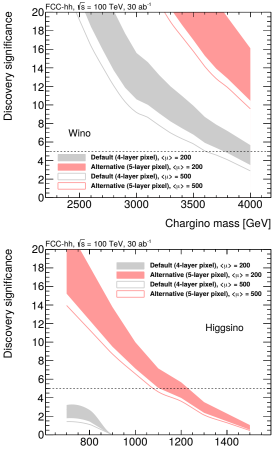

Key element for "Disappearing tracks": $\Delta(M)$

Why is this important?

- Because $c\tau$ depends on $\Delta(M)$, and $c\tau$ needs to be macroscopic to get "Disappearing tracks".
- Cf. `arXiv:1712.02118` where ATLAS found that $c\tau$ needs to be $\sim$ 6 cm.
- $c\tau$ 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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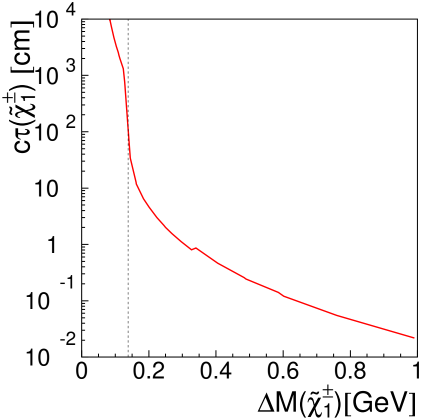

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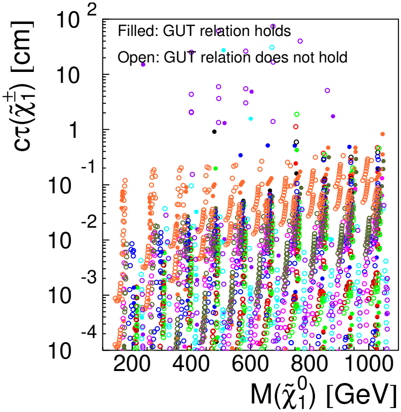

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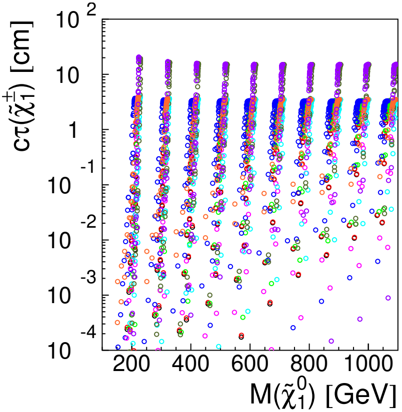
- Cf. `arXiv:1712.02118` where ATLAS found that $c\tau$ needs to be $\sim$ 6 cm.
- $c\tau$ for Higgsino LSP
- ... and Wino LSP
- Conclusion: Not at all sure that that lifetime will be large. Good chances - no guarantee - for Wino, unlikely for Higgsino.



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

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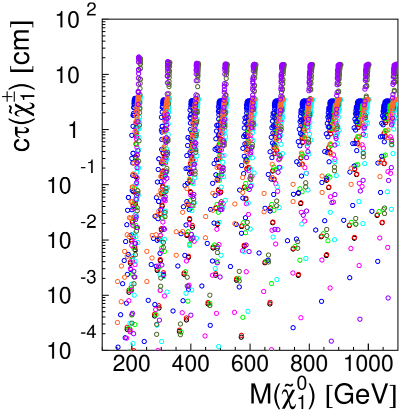
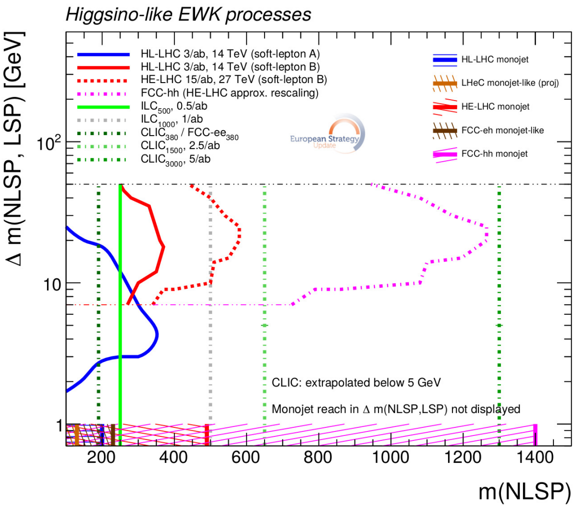
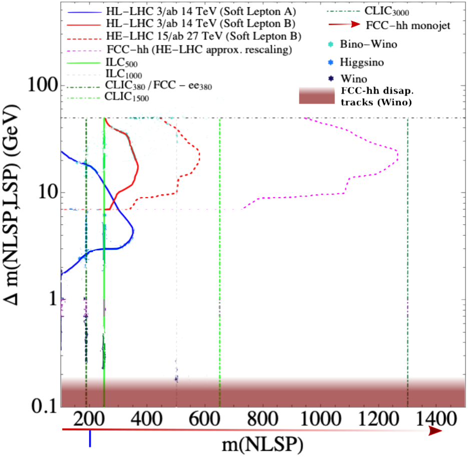


SUSY In The Briefing-book: Wino/Higgsino LSP



So: Disappearing tracks exclusion is actually off the scale !

SUSY In The Briefing-book: Re-boot



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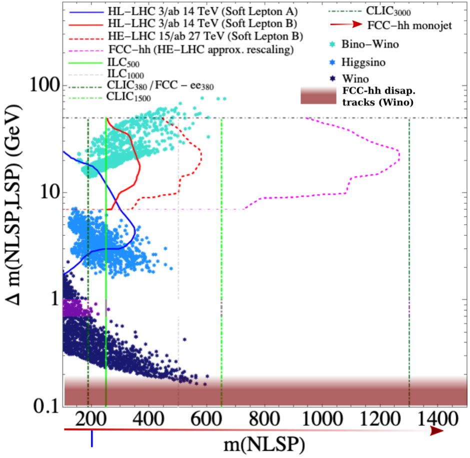
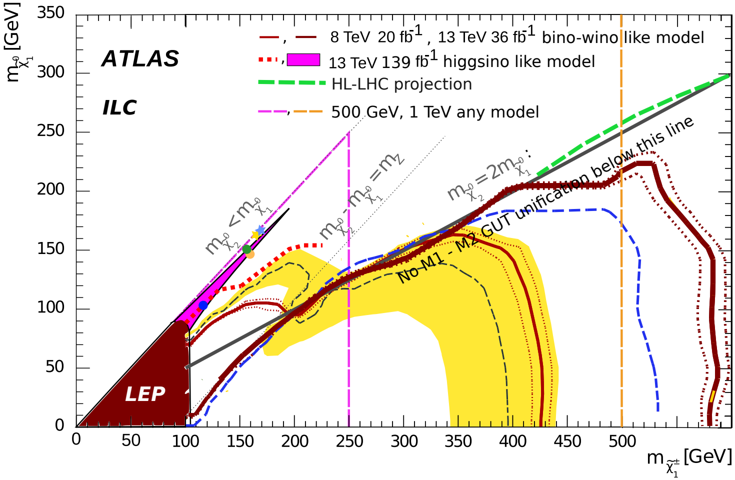


With models that are consitent with g-2 and no over-production of DM
From `arXiv:2103.13403`.

Summary: SUSY - All-in-one



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

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

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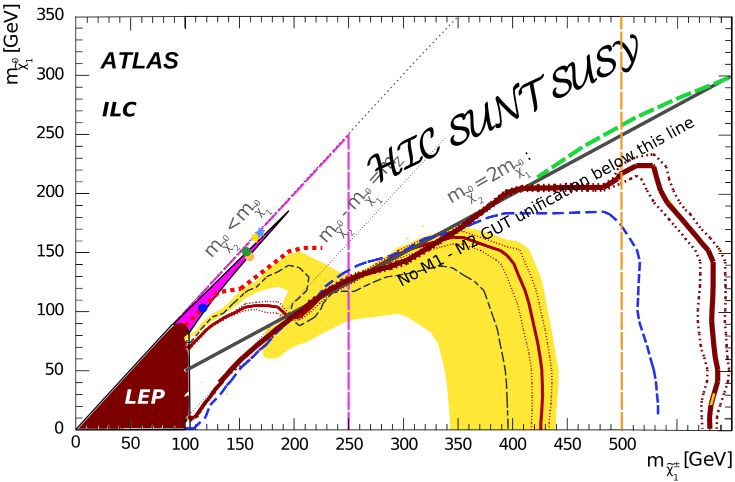

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Conclusions

- SUSY is not excluded.
- Even Plain vanilla SUSY is not excluded.
- HL-LHC might well discover SUSY, becuase future pp machines have
  - discovery potential to very high masses
  - but - to put it bluntly - NO exclusion potential: there will always be loopholes.
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- Except if a future pp machine discovers SUSY, which is a problem we'd like to have!

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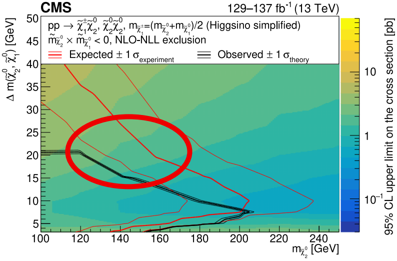
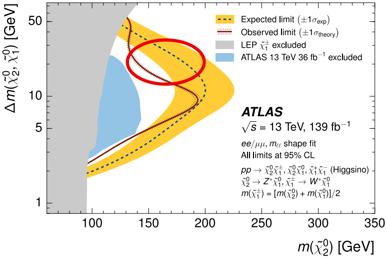
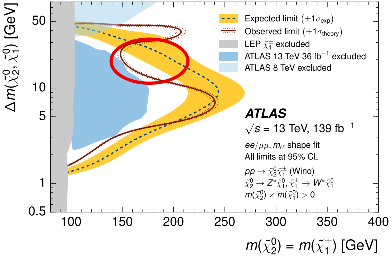
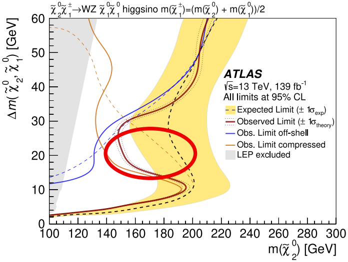
LHC Run 3 teaser: Maybe...









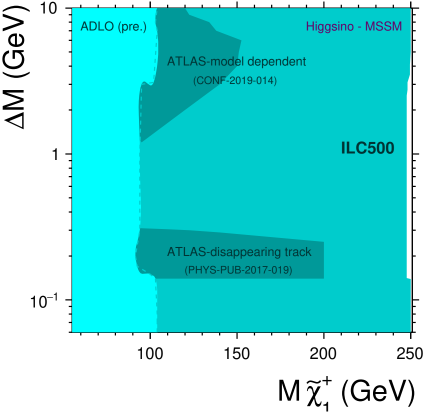
LH

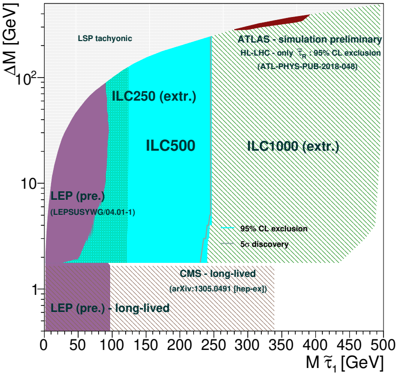
Backup

BACKUP SLIDES

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

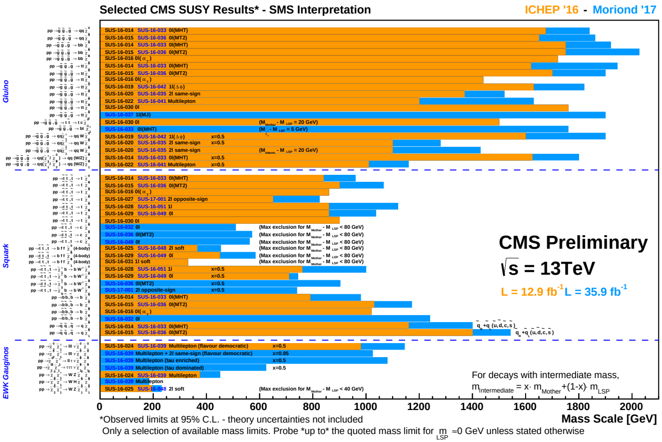
From arXiv:2002.01239



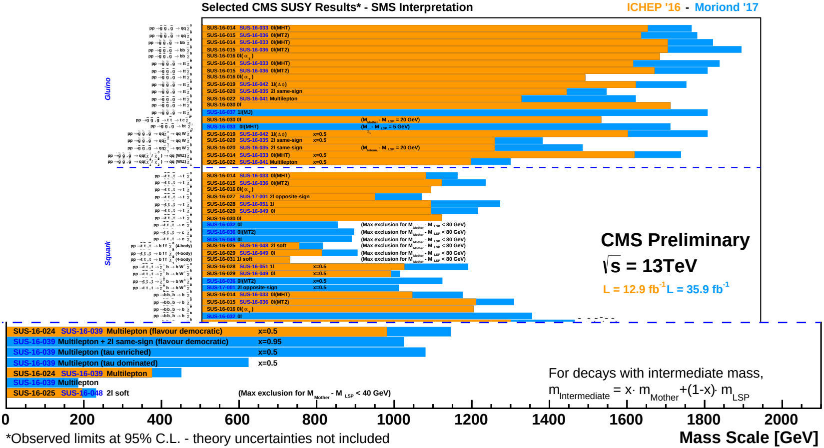


From arXiv:2105.08616

SUSY@LHC: Does this make us depressed ?



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

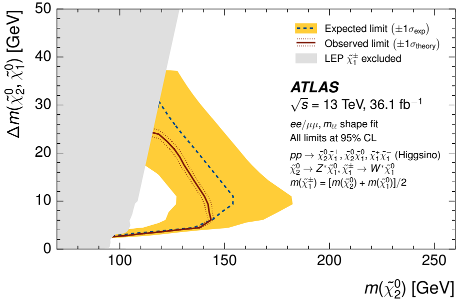


*Observed limits at 95% C.L. - theory uncertainties not included

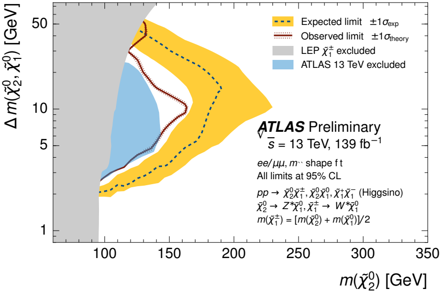
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

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

arXiv:1803.02762

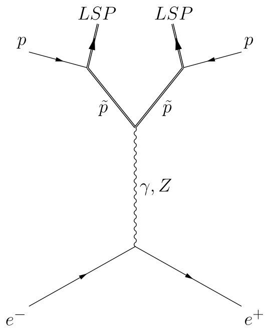


ATLAS-CONF-2019-01



Loop-hole free SUSY searches

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



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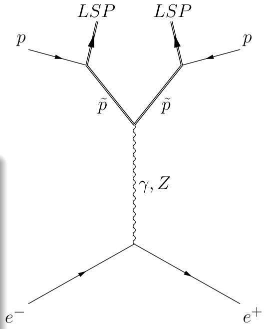
So, at an LC :

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



Simplified models

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

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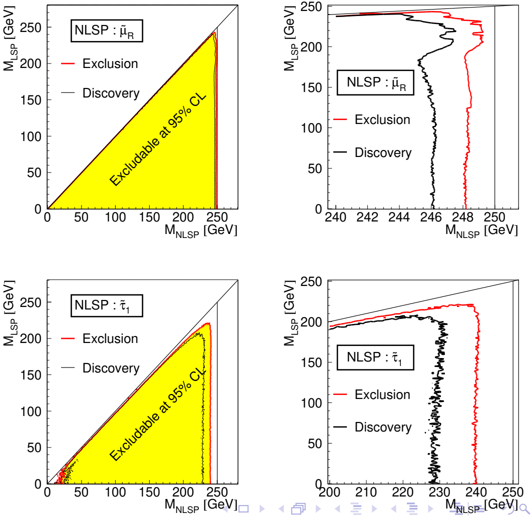

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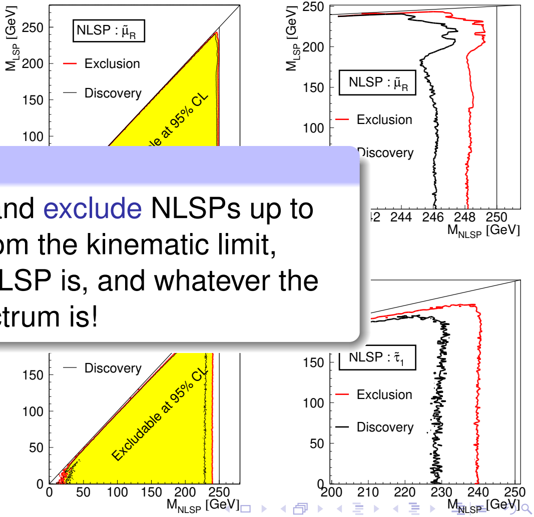
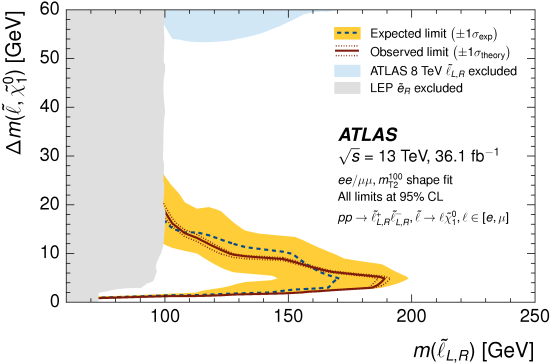


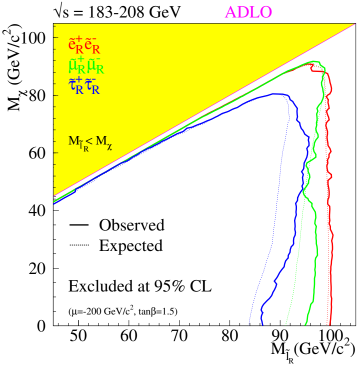
At ILC

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

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

arXiv:1803.02762

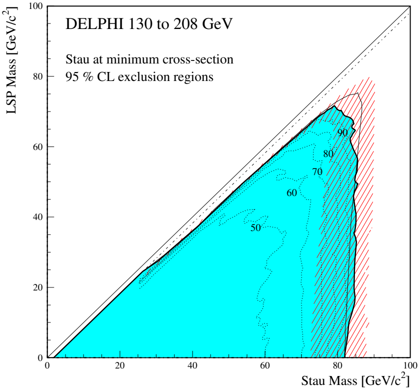


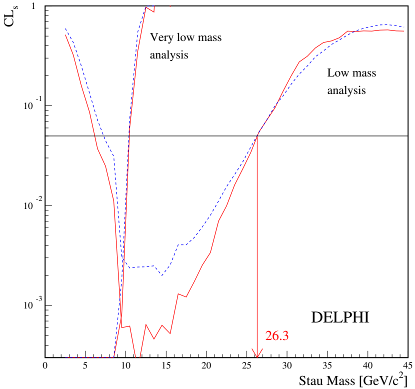


This is a *combined* limit, assuming $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{e}_L$ and $\tilde{e}_L$ all have the same mass !!!

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

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





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

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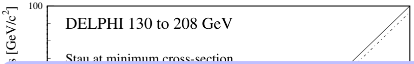
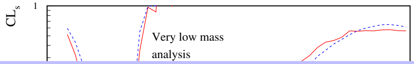
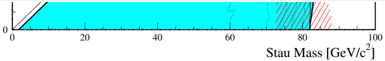
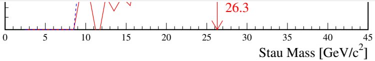




With 1000 times the luminosity and no trigger, the ILC at 250 will push the limits for all possible NLSPs to close to 125 GeV, and $\Delta(M) \approx 0$. The area covered will $\sim$ double the LEP ones. They are in the most compelling region of parameter-space.

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





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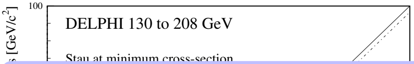

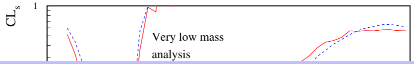

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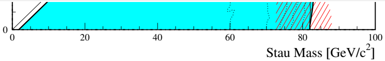

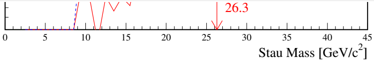

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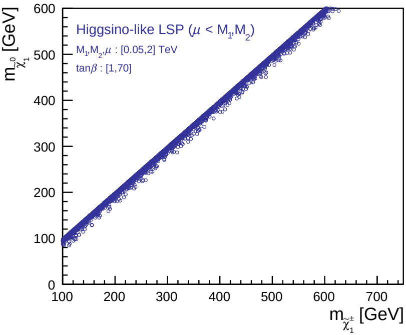
Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

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 ...

quite generic:
Parameter-scan by T. Tanabe:



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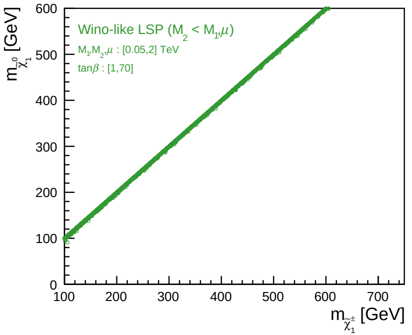

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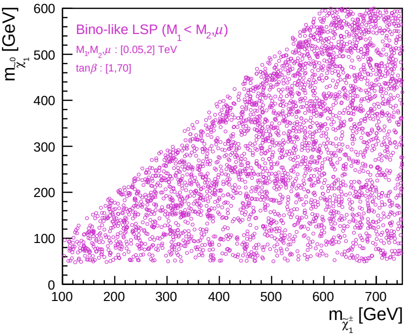

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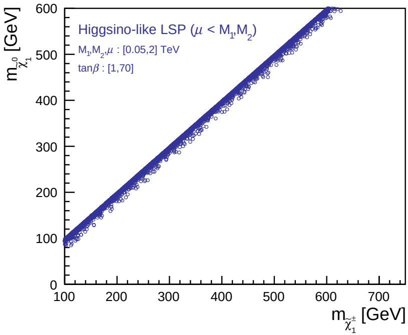
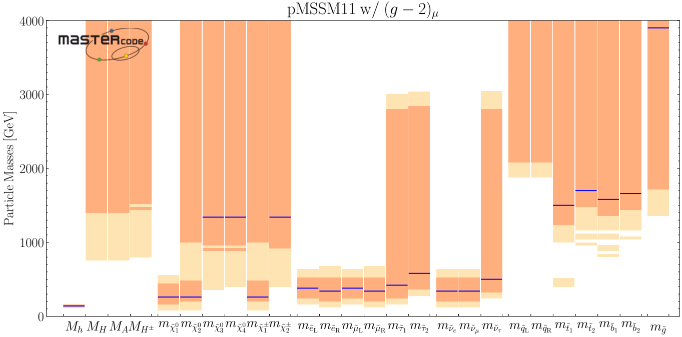


One approach: Global fits with prejudice

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



Sparticle Mass-spectrum

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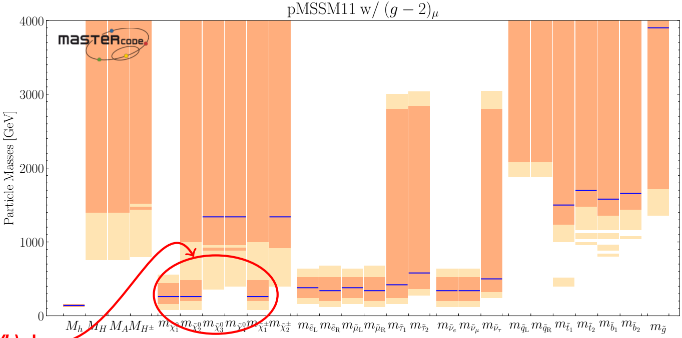

Low $\Delta(M)$!

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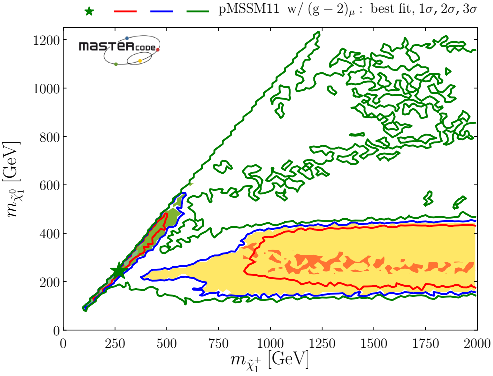

$M_{\tilde{\chi}^\pm_1}$ - $M_{\tilde{\chi}^0_1}$ plane

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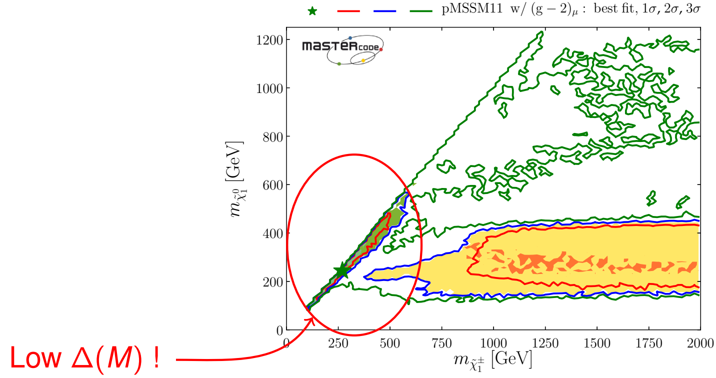

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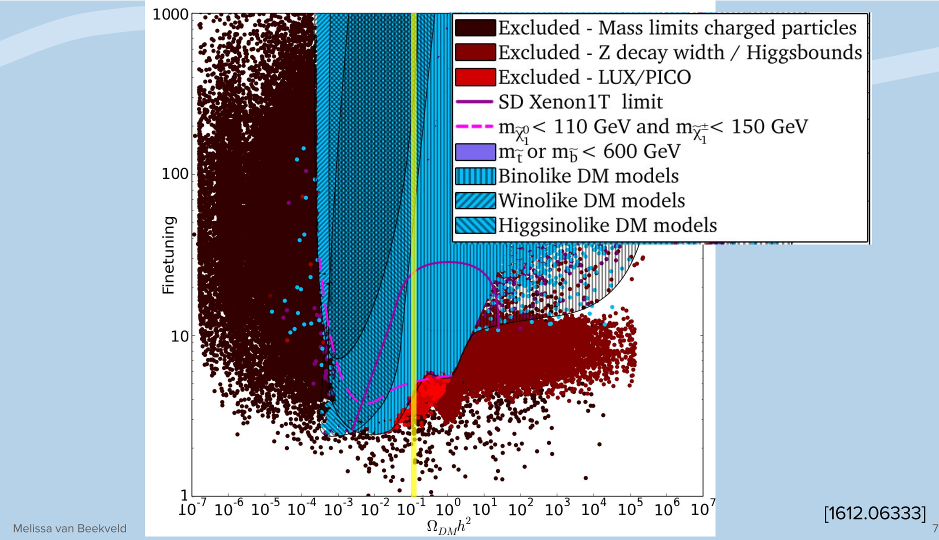
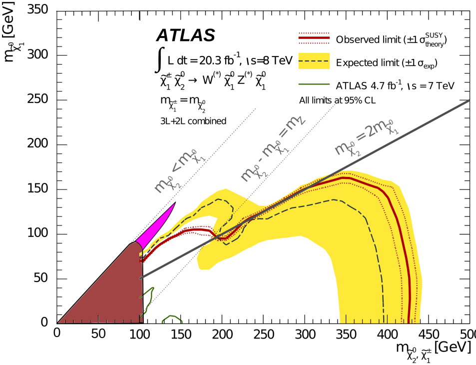


[1612.06333]

Compare LHC (Atlas) & ILC

- On the 7 TeV plot, with LEP (brown) and the low $\Delta(M)$ search (magenta)...
- At ILC: Various benchmarks studied w/ detailed simulation: $M_{\tilde{\chi}^0_1}$ = 100-170 GeV, $\Delta(M)$ = 0.8 to 20 GeV.
- Projected discovery reaches for LHC, HL-LHC, ILC-500, and ILC-1000.



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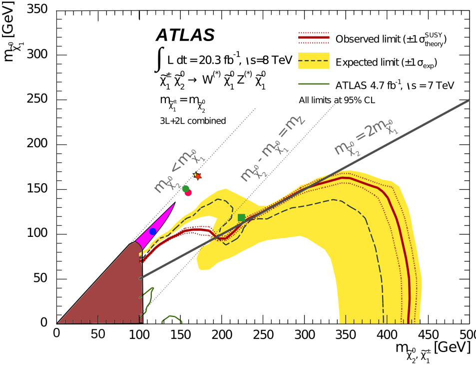

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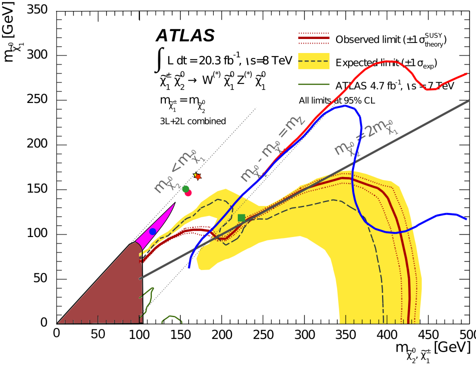

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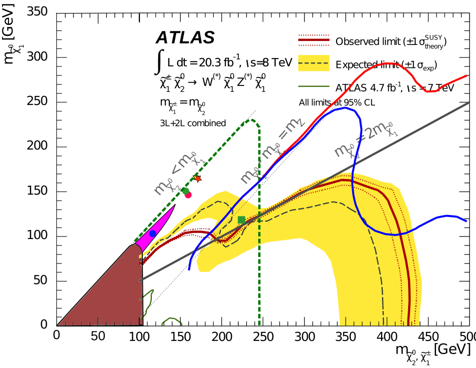

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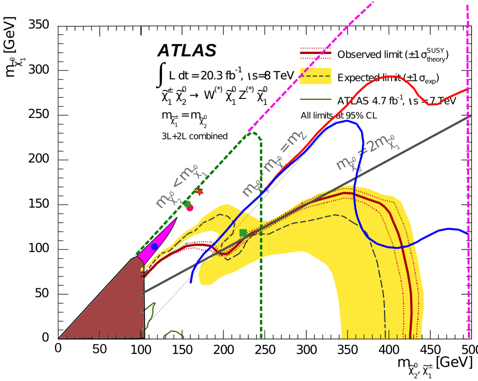

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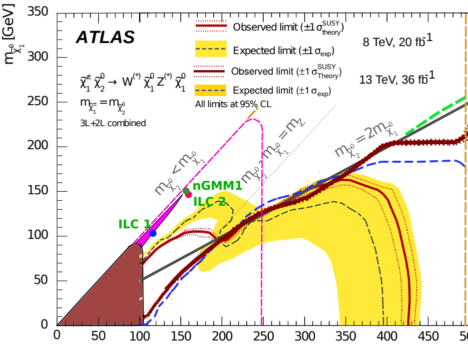
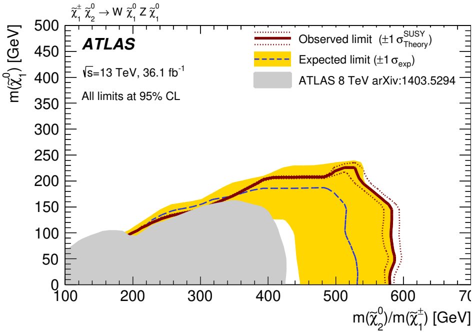


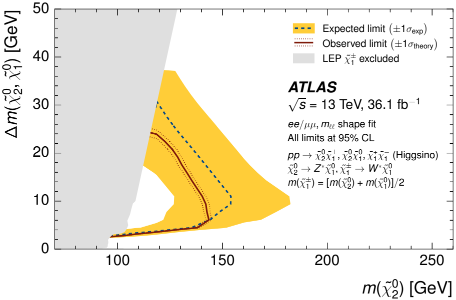
Latest Atlas (13 TeV, 36 fb^{-1}) on EWkinos

arXiv:1712.08119



$\sim$ same analysis as shown in talk. Only extends below the $M_{\tilde{\chi}_2^0}$ (or $M_{\tilde{\chi}_1^{\pm}}) > 2M_{\tilde{\chi}_2^0}$ line. *No progress in Higgsino region !*

arXiv:1803.02762

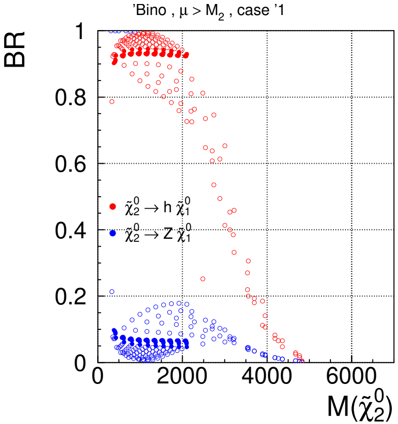


Same channel as in talk. Look at $\Delta(M) \sim 1$ GeV and $M_{\tilde{\chi}_2^0} \sim 160$ GeV. The actual limit is the LEP one. *Wrongly represented !*

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 $\tilde{\chi}^0_2$ dominates is pure speculation and
- The exclusion-region is the *intersection* of the two plots, not the *union*!



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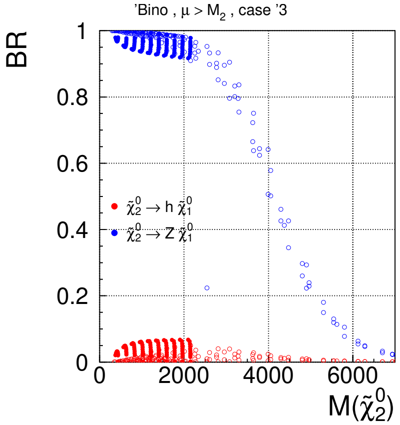

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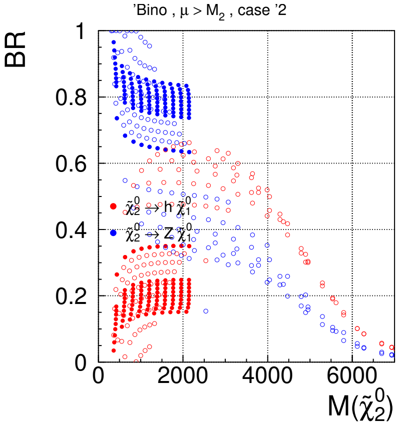

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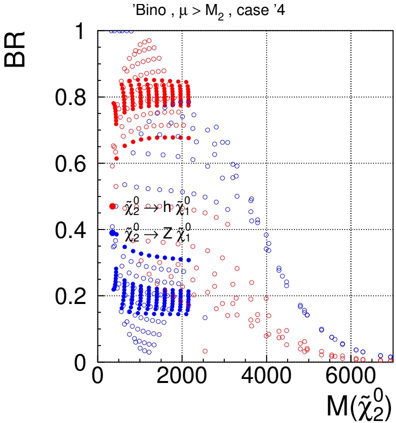

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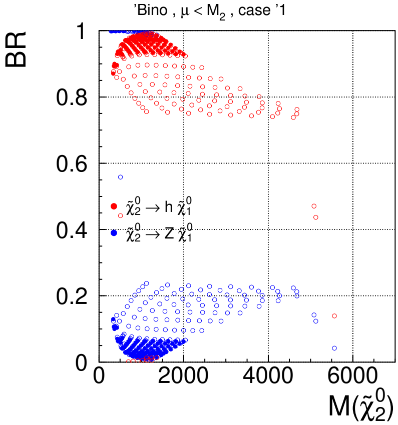

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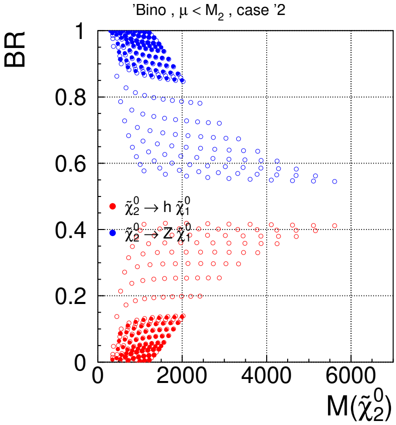

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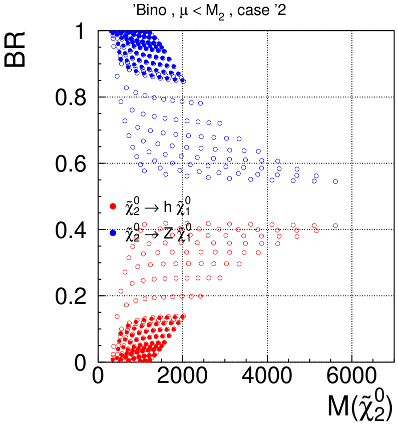

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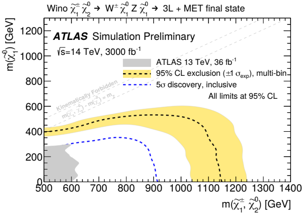
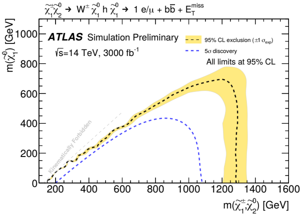
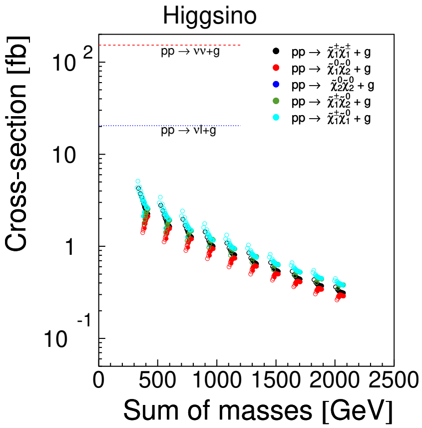




SUSY cross-sections at FCChh

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
- $\Rightarrow$ 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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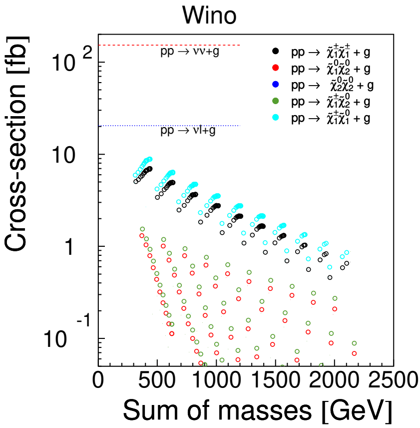

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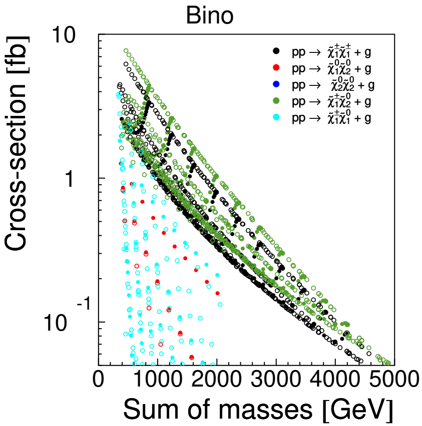

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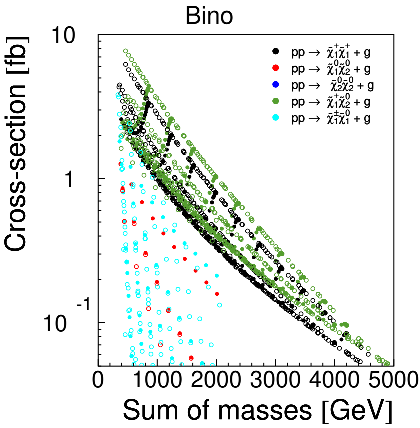

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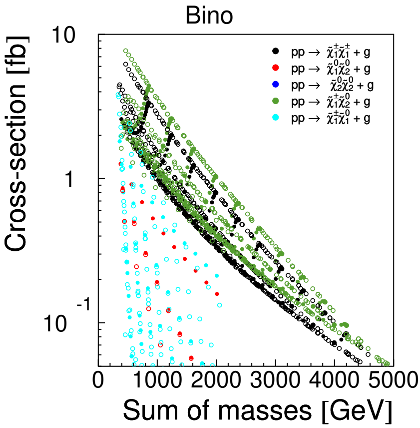
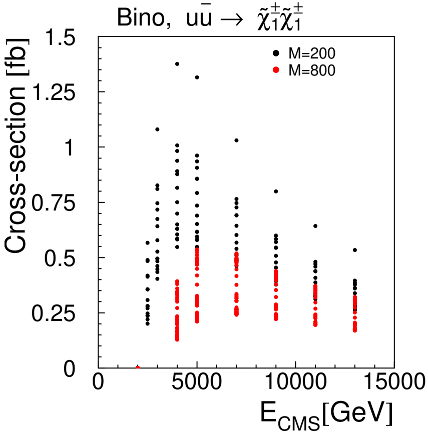


SUSY cross-sections at FCChh: Why exponential fall-off

- 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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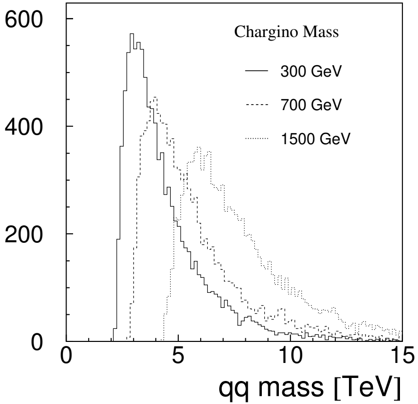

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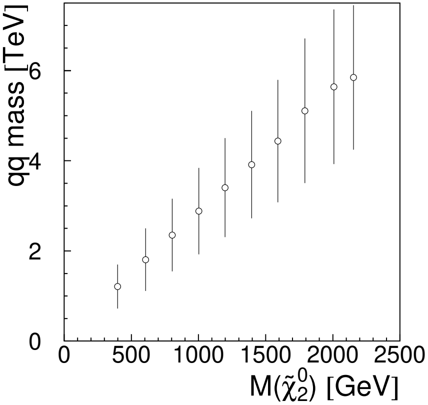

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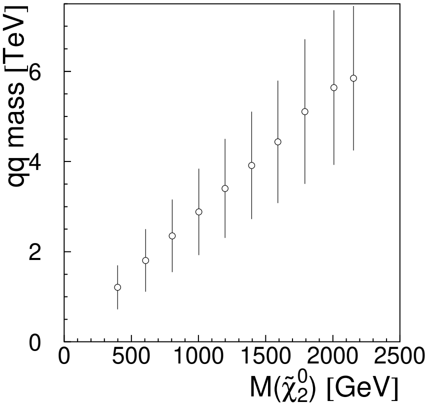
- m_{qq} (linear) function of bosino-mass
- At these mass-ratios, missing p_T is proportional to m_{qq}
- $\Rightarrow$ missing p_T increases linearly with bosino-mass.
- $\Rightarrow$ can increase missing p_T-cut linearly when looking for higher masses, with the same efficiency
- Then the background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



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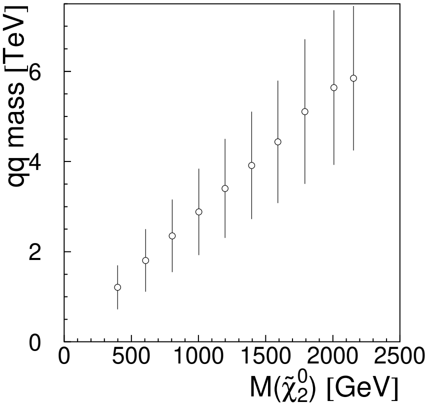

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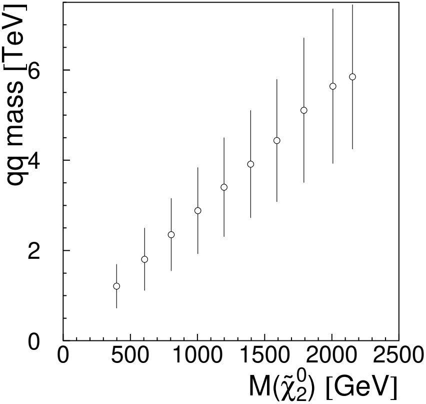

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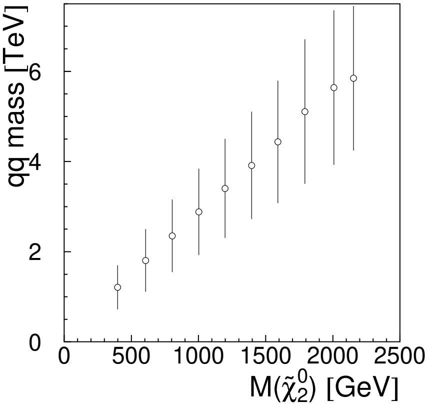

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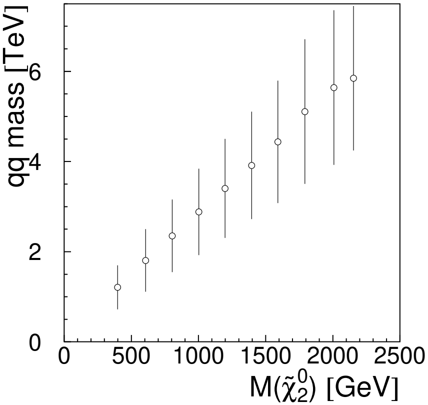
Uptake

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

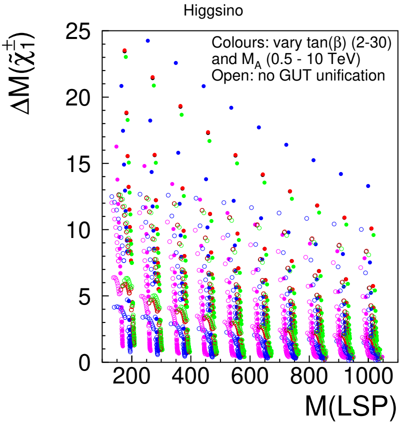
- Then the background decreases as much.
- S/B remains constant along lines in $M_{\tilde{\chi}_1^{\pm}}$ vs. M_{LSP}



Aspects of the spectrum :$\Delta(M)$

Yet another angle: $\Delta(M)$ for $\tilde{\chi}_1^{\pm}$ vs. M_{LSP}

- For Higgsino LSP
- For Wino LSP
- Note large spread possible!



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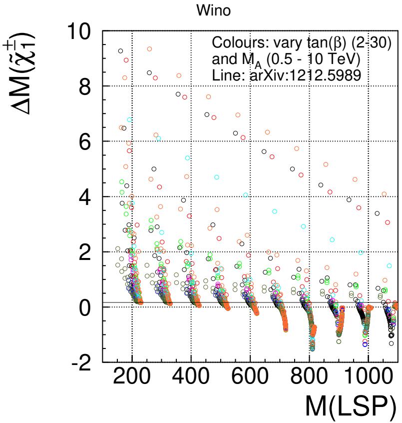

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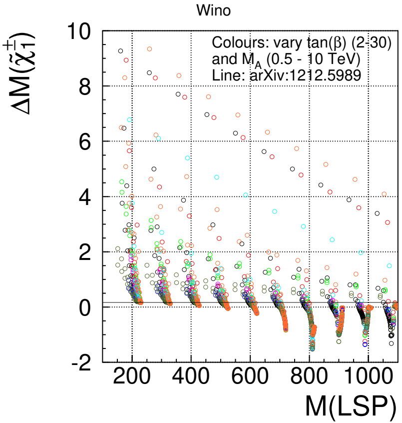
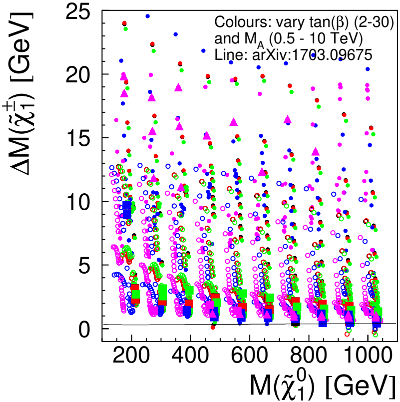


Key element for “Disappearing tracks”: $\Delta(M)$

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



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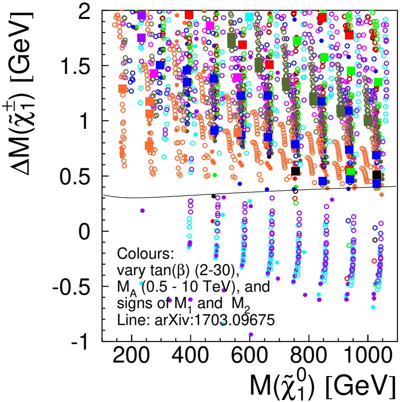

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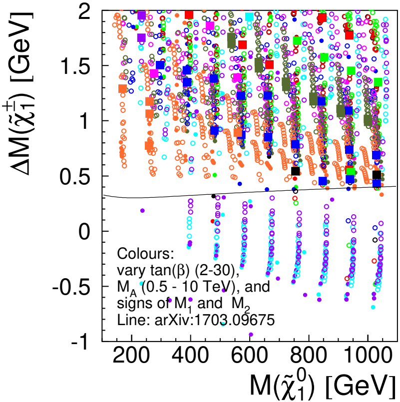

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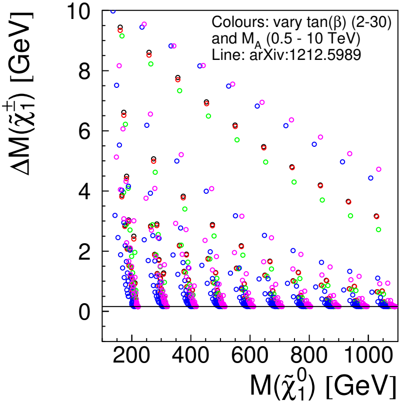
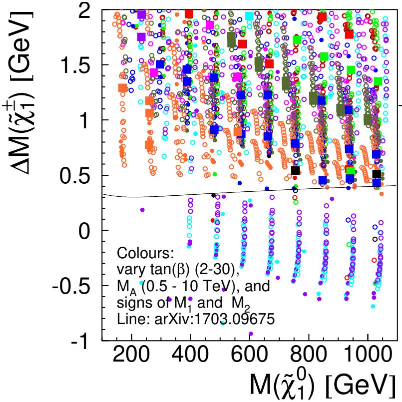
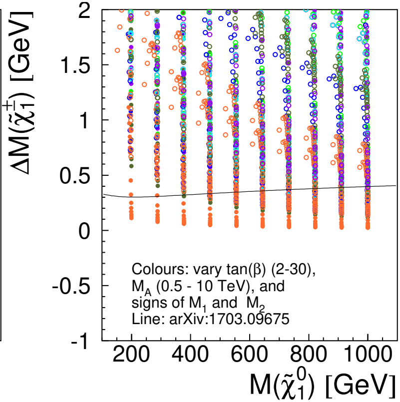


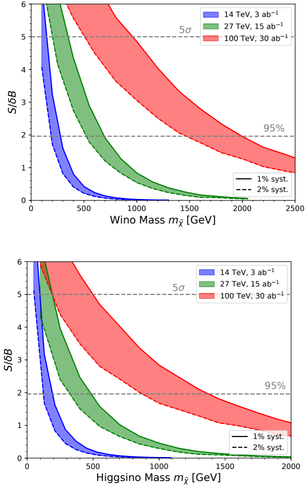
second opinion: feynhiggs





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

- Two methods: "Disappearing tracks" and "Mono-X"
  - "Disappearing tracks"
  - "Mono-X"
- `arxiv:1805.00015`, Based on DELPHES with ATLAS-card ($\Rightarrow$ LHC PU...)
- Both from the HE/HL-LHC input to ESU (*not* FCChh)
- Systematics-limited. Both ATLAS and CMS state $\sim$ 10% in existing "Mono-X" searches (PU 1/20 of FCChh)



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

- Two methods: “Disappearing tracks” and “Mono-X”
  - “Disappearing tracks”
  - “Mono-X”
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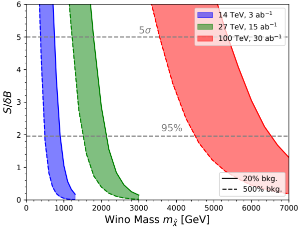

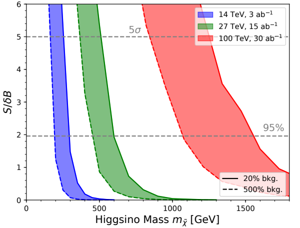

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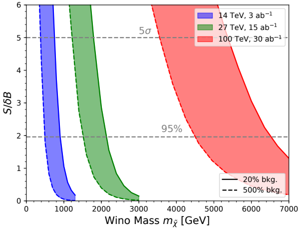

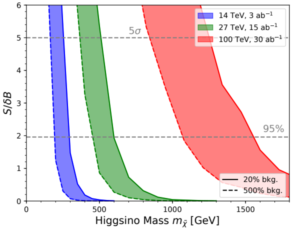

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