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

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[1]Largely based on `arXiv:2003.12391`

Problems with the standard model

The standard model works excellently - but there are problems:

- Theory-experiment discrepancies
  - g-2 of the muon
  - Flavour anomalies
  - Maybe M_W
- Lack of explanations
  - What is dark matter and dark energy?
  - Naturalness and the hierarchy problem: Why is the Higgs mass so small, and why does it remains so?
  - Why do the coupling constants not unify?
  - Neutrinos are weird...
  - Why is charge quantised?
  - The SM gets the cosmological constant wrong by 120 orders of magnitude?!
  - Fermi-Dirac statistics and infinitely dense black holes?

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The need for BSM

So we need models beyond the SM. Two types:

- Well defined, but incomplete models tailored to address some of the issues
  - Simplified models
  - Portal models
- Complete self-consistent models. Not so many on the market:
  - Extra dimensions
  - Compositness
  - Leptoquarks
  - And SUSY.

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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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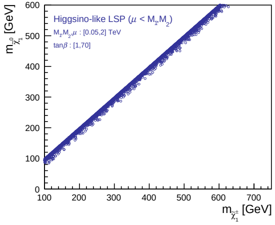

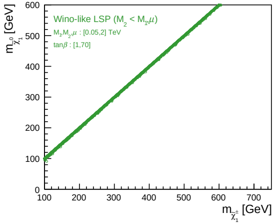

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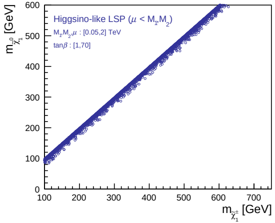

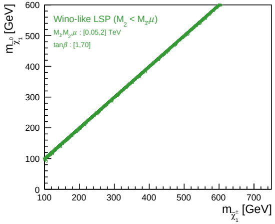

SUSY at future e^+e^- Higgs/EW/Tops factories

Wrt. LEP/SLC:

- Any Higgs factory
  - Increased luminosity
  - Improved detector technologies
- For linear Higgs factories
  - Centre-of-mass energy
  - Beam polarisation
  - More hermetic
  - Trigger-less operation of the detectors

Wrt. hadron colliders:

- Microscopic beam-spot
- Cleaner environment
- Known initial state
- Trigger-less operation of the detectors
- Hermetic detectors

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

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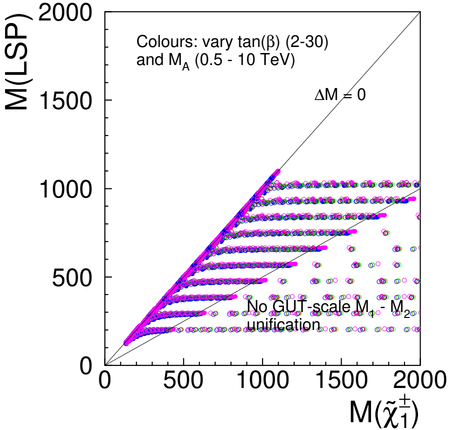
Aspects of the spectrum

- 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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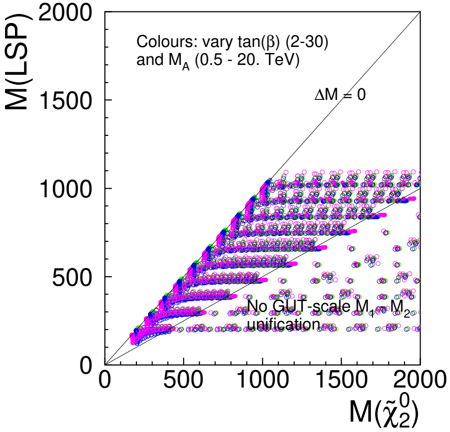

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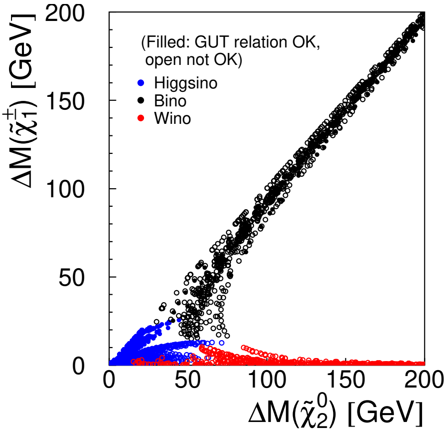
Another angle: $\Delta(M)$ for $\tilde{\chi}_1^{\pm}$ vs. that of $\tilde{\chi}_2^0$: Important experimentally

- 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



How to extrapolate one $\sqrt{s}$ to an other ?

Like this, for expected efficiencies:

- For the background, the total measured energy scales up or down linearly with $\sqrt{s}$.
- Away from resonances, the angular distributions do not change with $\sqrt{s}$, so that transverse quantities - or projected ones in any direction in the rest-frame - scales linearly with $\sqrt{s}$.
- Now for a typical pair-production signal:

$$P_{T\ max} = P_{max} = \frac{\sqrt{s}}{4}\left[1 - \left(\frac{M_{lsp}}{M_{nlsp}}\right)^2\right]\left[1 + \sqrt{1 - \left(\frac{M_{nlsp}}{\sqrt{s}/2}\right)^2}\right]$$

If one scales both M_{nlsp} and M_{lsp} by $\sqrt{s}$, both brackets remain unchanged, so that $P_{T\ max}$ scales E_{beam}, just like the background. NB: This is just kinematics, - not SUSY specific !

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The S/B at one $\sqrt{s}$ will be the same as that at another $\sqrt{s}$ if one scales the kinematic cuts and the SUSY masses with the ratio of the two $\sqrt{s}$.

At a lepton-collider, $\sqrt{s}$ is a known, at a hadron collider it varies. At a *symmetric* lepton-collider, the rest-frame is the lab-frame, and not only transverse quantities scale.

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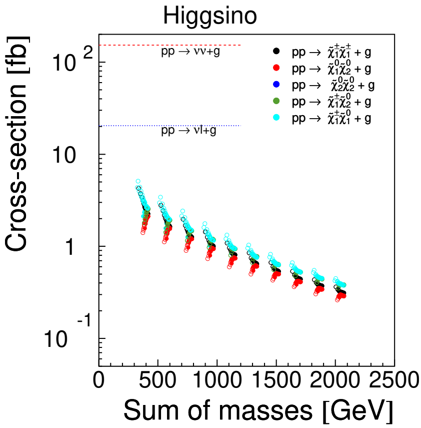
SUSY cross-sections at FCChh

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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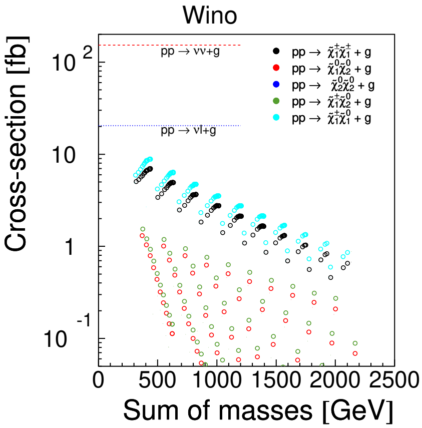

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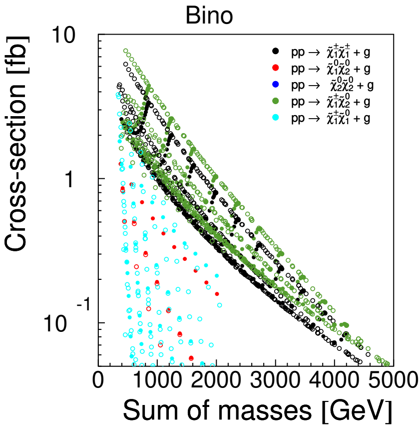

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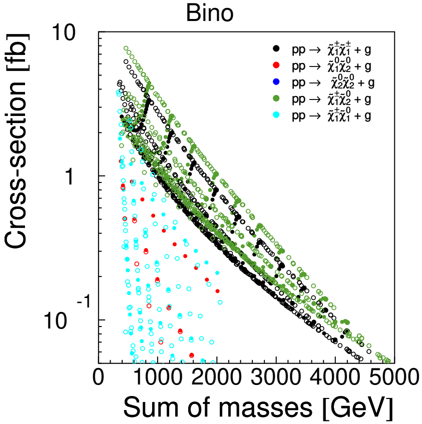
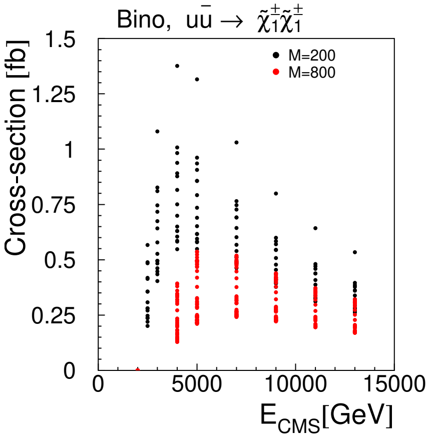


SUSY cross-sections at FCChh: Why exponential fall-off

- Consider *fixed* $\sqrt{s} = m_{qq}$, 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)
- $\Rightarrow$ Events at a given bino-mass comes from certain (broad) region of m_{qq}
- $\Rightarrow$ the bino-mass is a (linear) function m_{qq}
- So, the cross-section follows the exponential fall of m_{qq}



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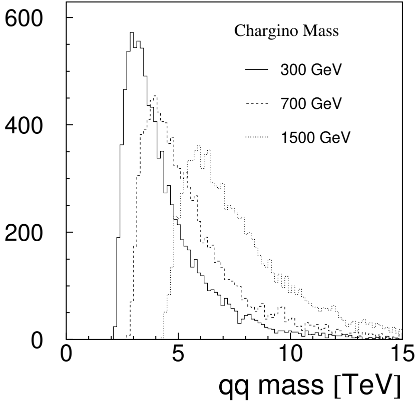

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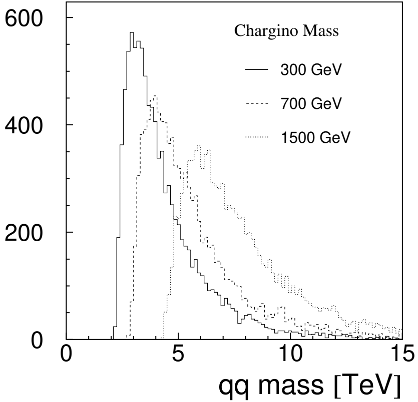

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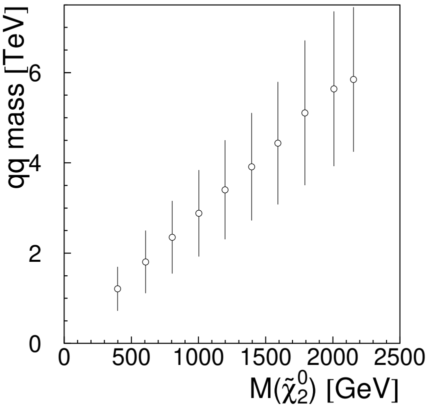

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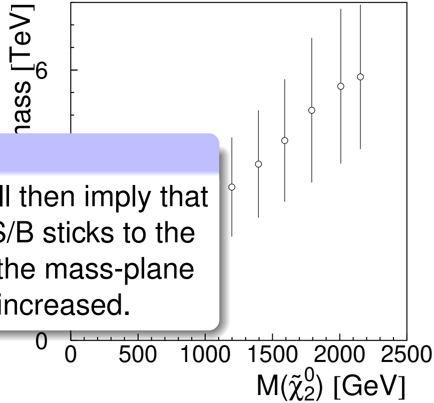
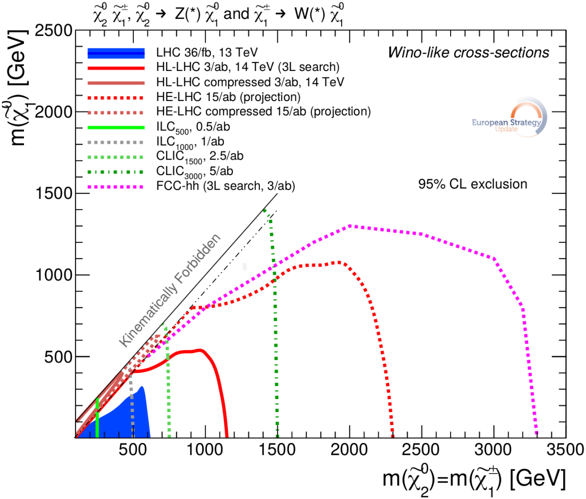
Uptake

The conjuncture will then imply that one expects that S/B sticks to the same diagonal in the mass-plane as energy is increased.



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

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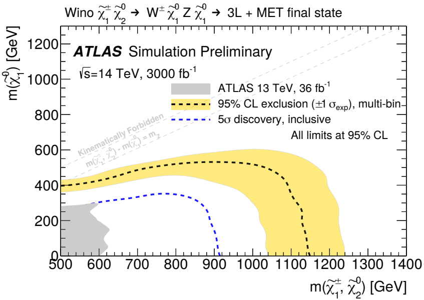

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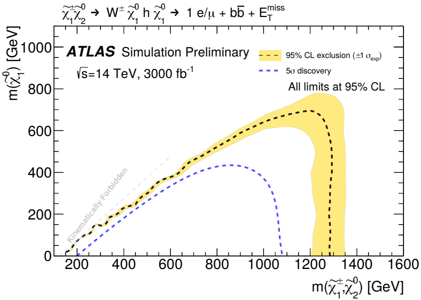

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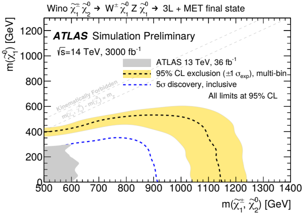

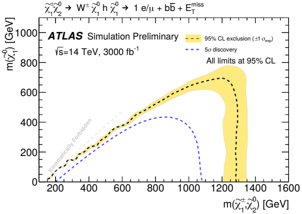

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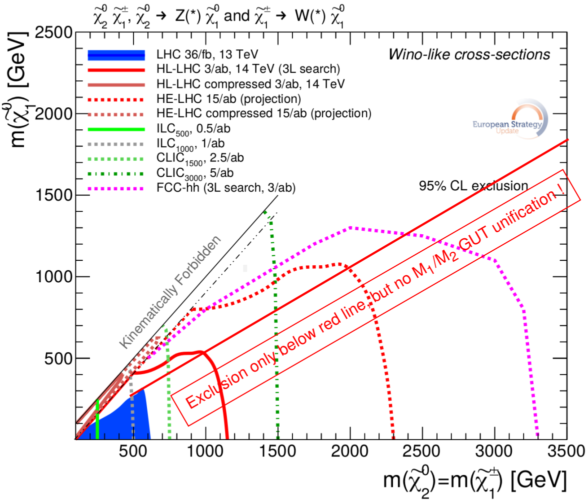
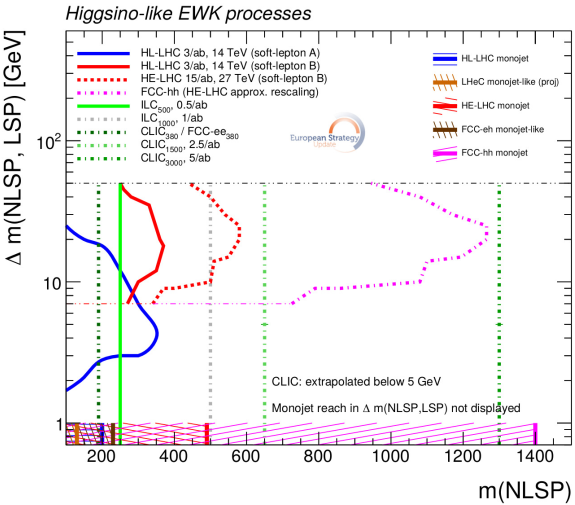


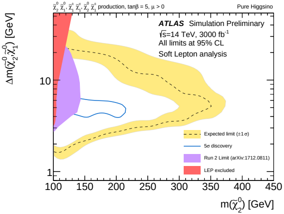
NB: e^+e^- curves are certain discovery, pp are possible exclusion !!!

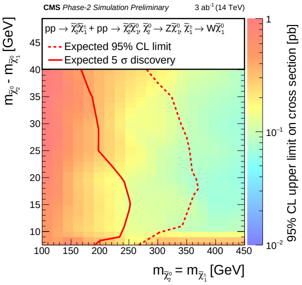
SUSY In The Briefing-book: Wino/Higgsino LSP



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.





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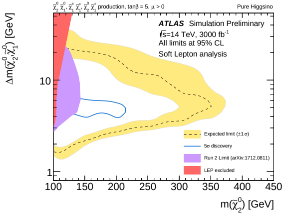

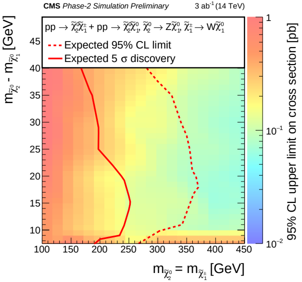

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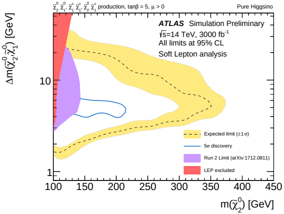
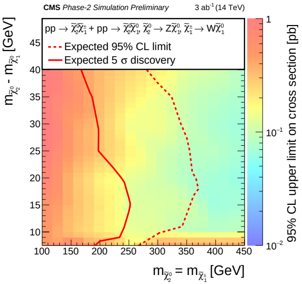
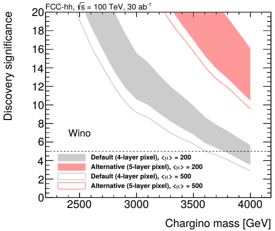
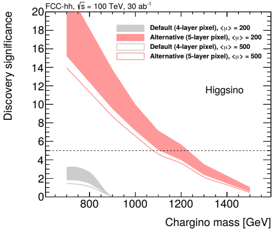




SUSY In The Briefing book: Wino/Higgsino LSP - Very low $\Delta(M)$ sources

- The “Disappearing tracks” was done by FCChh (in the CDR)
  - FCChh-detector w/ FCChh-ish PU (but still too small: 500 vs. CDR number 955)
  - For higgsinos: Only *just* reaches 2 σ
  - But: Assumes only SM loops for mass-splitting, i.e. not SUSY mixing.
  - A mass-difference $\sim$ 400 MeV needed, And:
  - $\Delta(M)$ 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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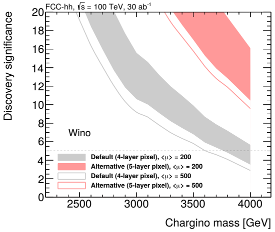

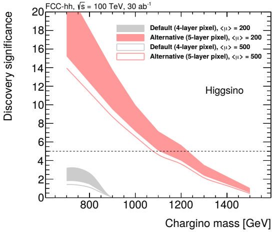

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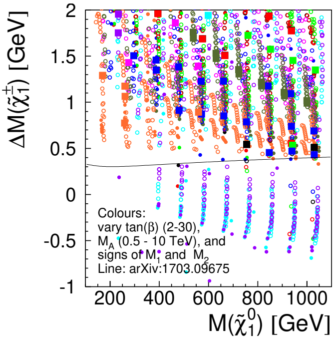

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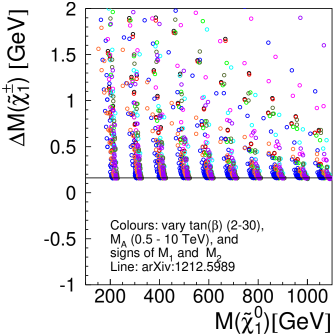

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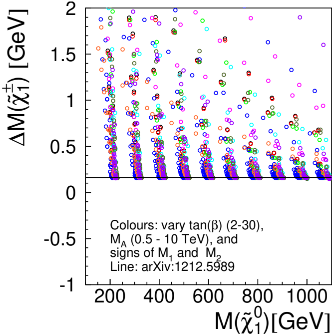

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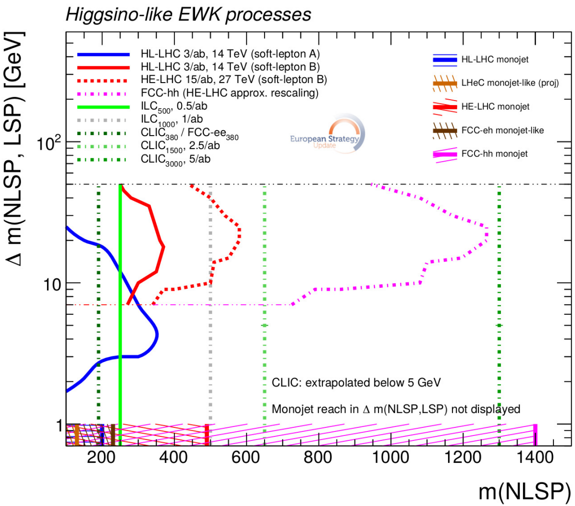
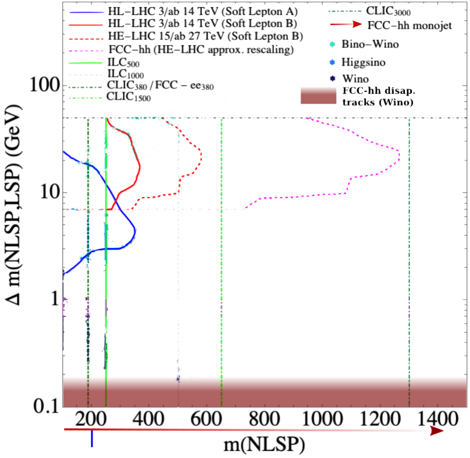


So: Disappearing tracks exclusion is actually off the scale !

SUSY In The Briefing-book: Re-boot



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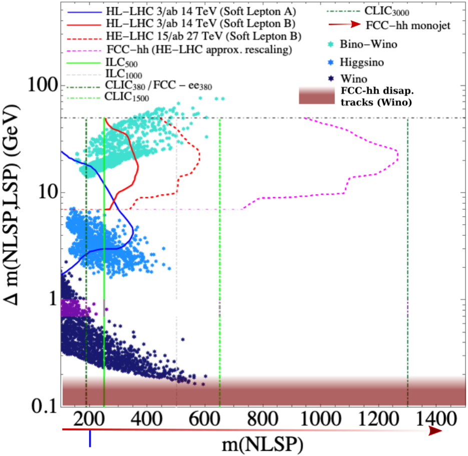
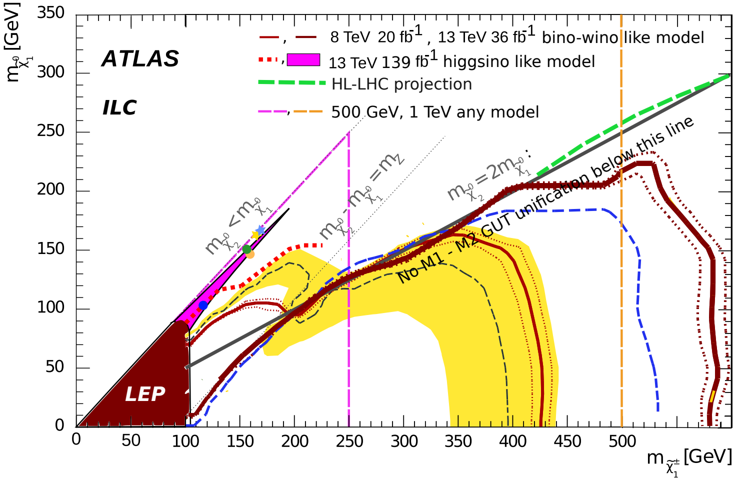


With models that are consistent with g-2 and no over-production of DM From `arXiv:2103.13403`.

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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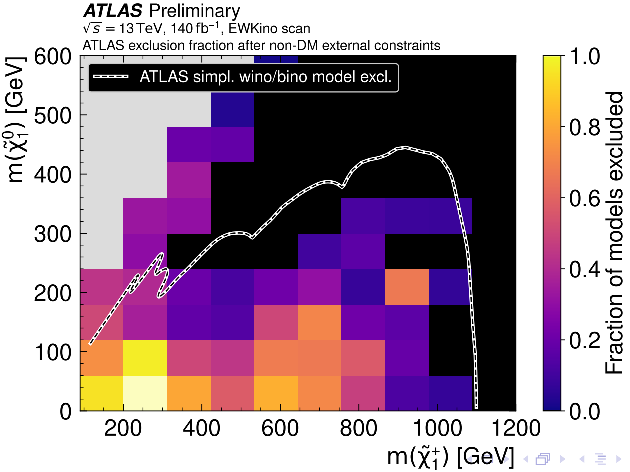

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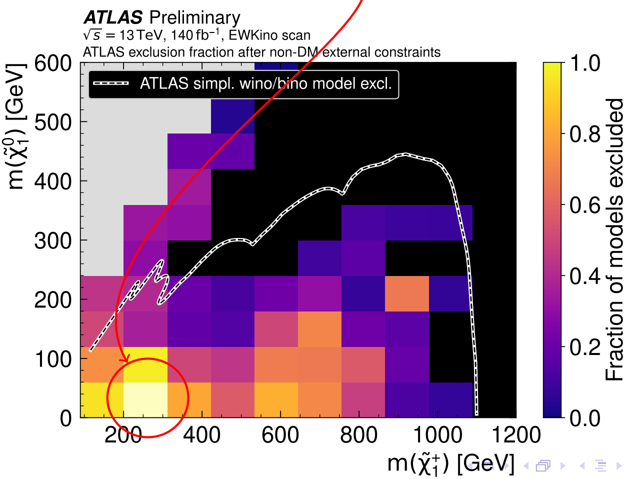
Only this one is actually excluded !



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

The Hunt-Lenox Globe (c:a 1510)

Hic Sunt Dracones

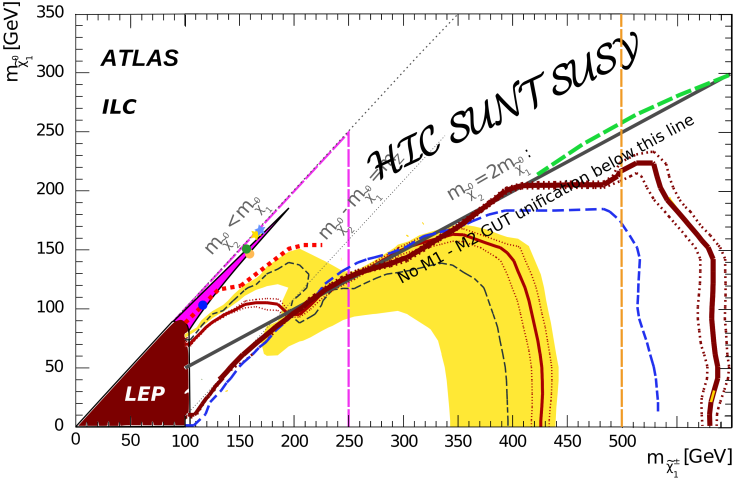
That is ∼ here


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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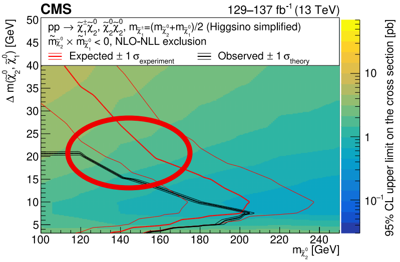
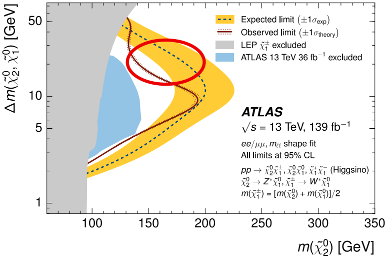
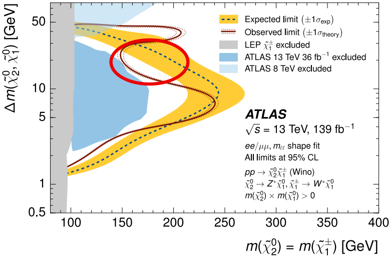
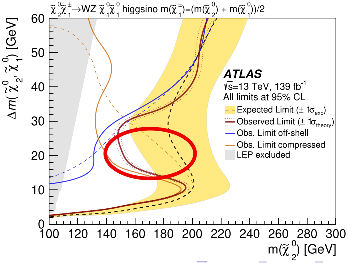
And...

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









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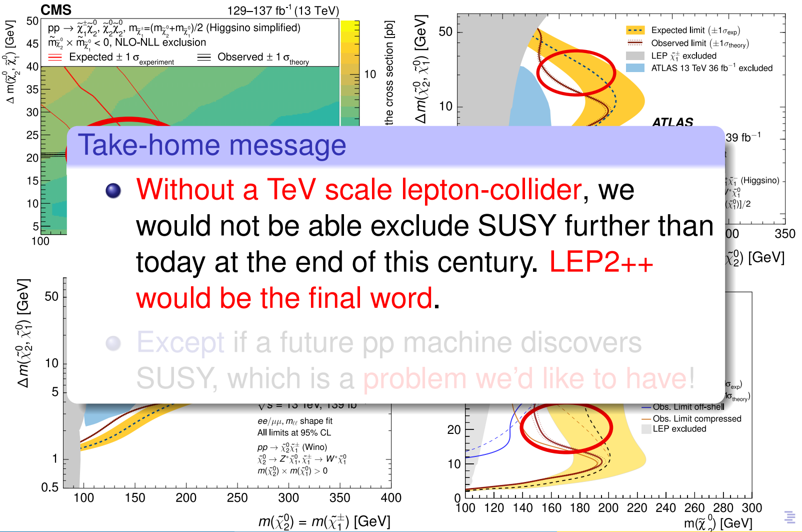

Take-home message

- 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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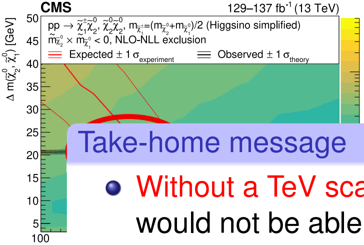

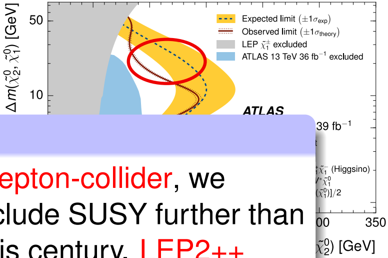

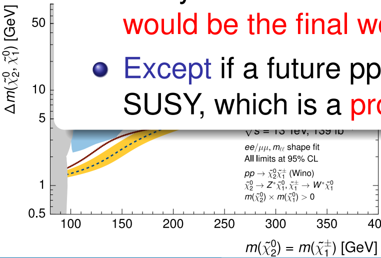

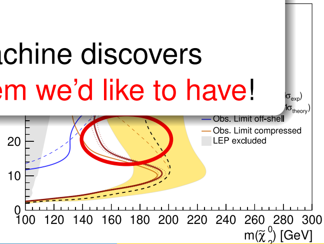

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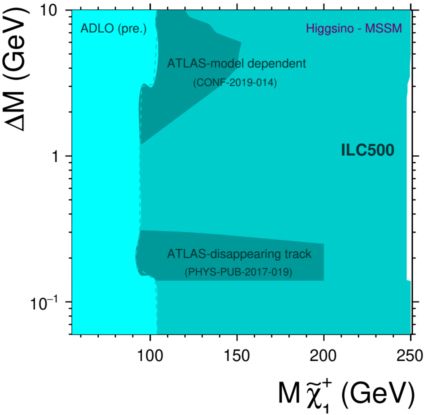
Thank You !

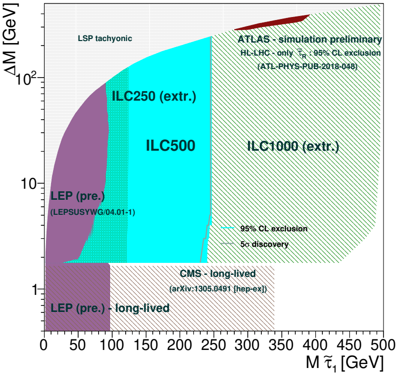
BACKUP

BACKUP SLIDES

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

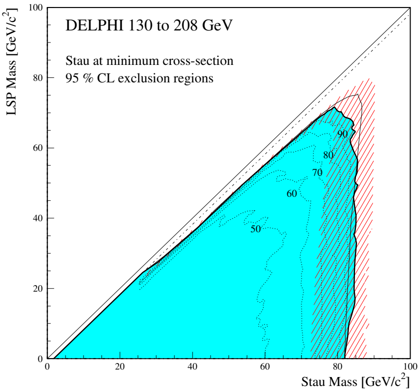
From arXiv:2002.01239

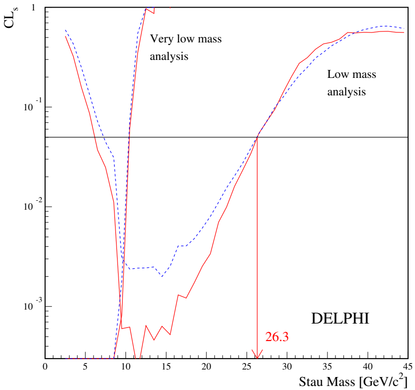




From arXiv:2105.08616

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





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

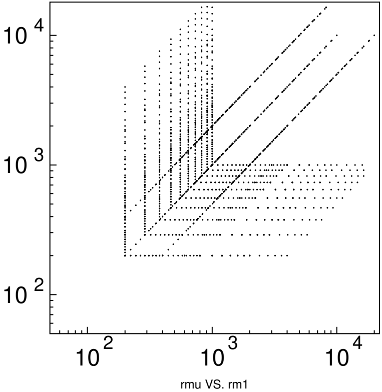
The cube

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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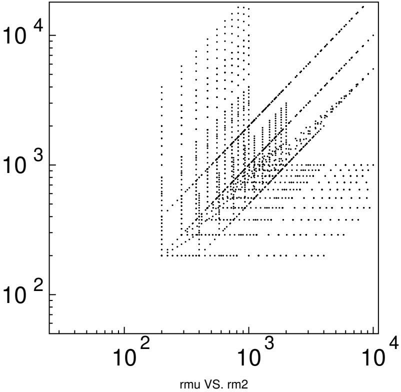

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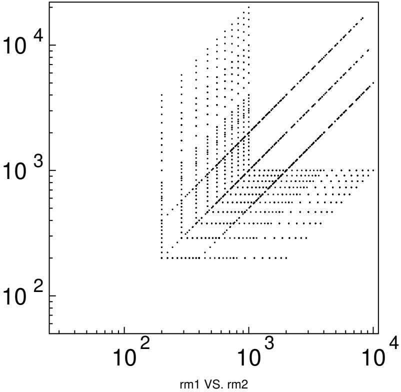

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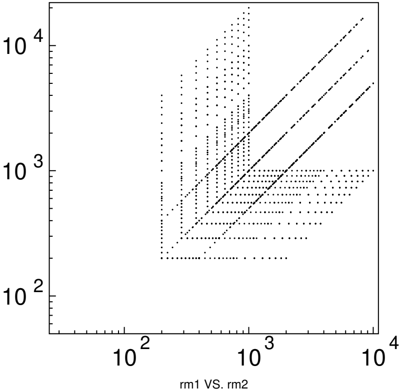

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s

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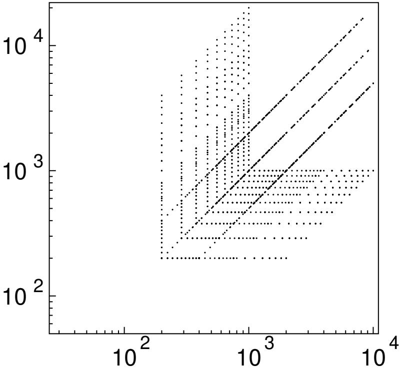
c

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



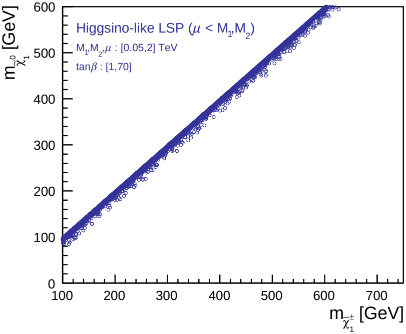
Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

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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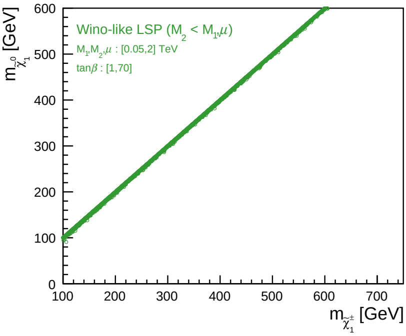

Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

Why would one expect the spectrum to be compressed ?

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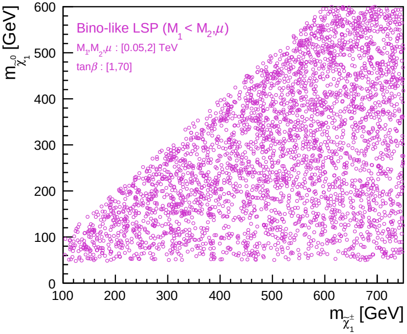

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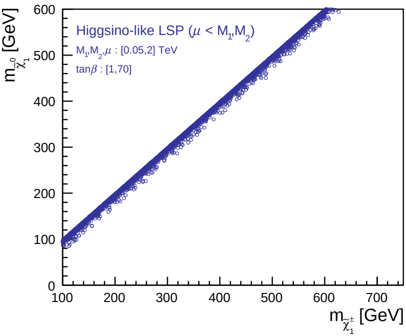

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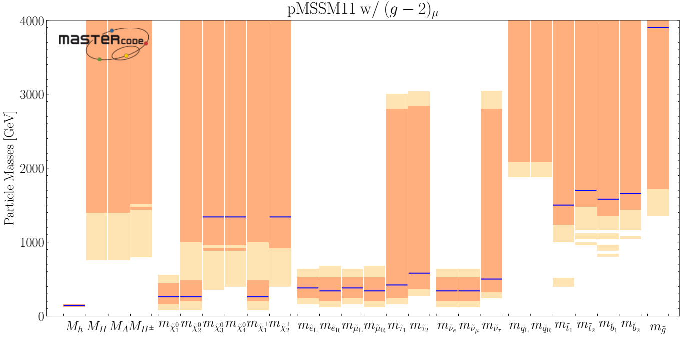

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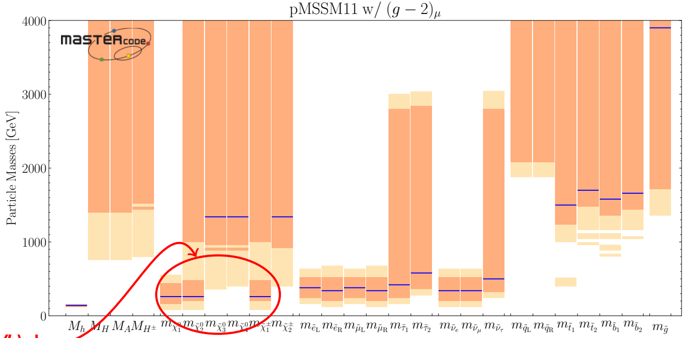

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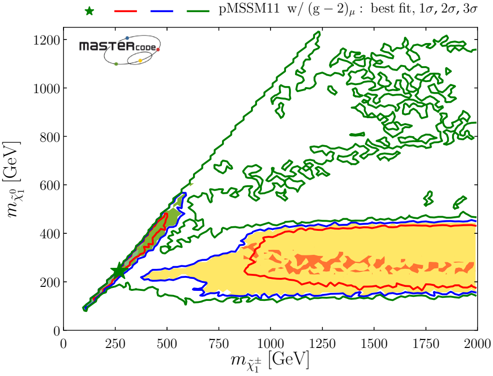

$M_{\tilde{\chi}_1^\pm}$ - $M_{\tilde{\chi}_1^0}$ plane

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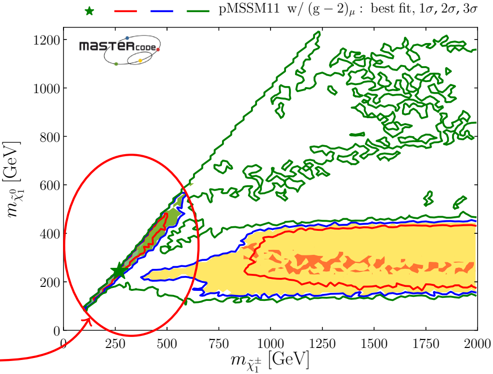

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SUSY cross-sections at FCChh

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
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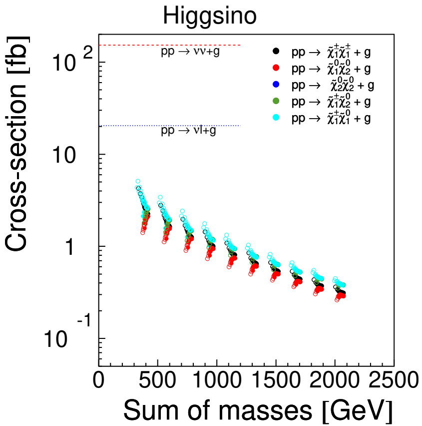

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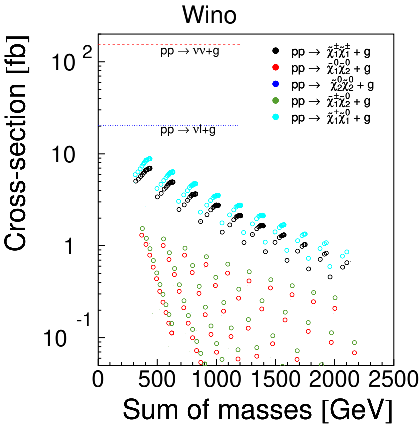

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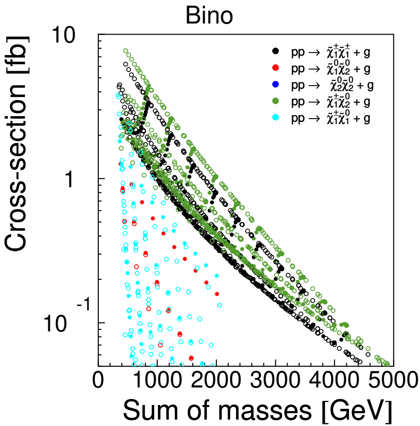

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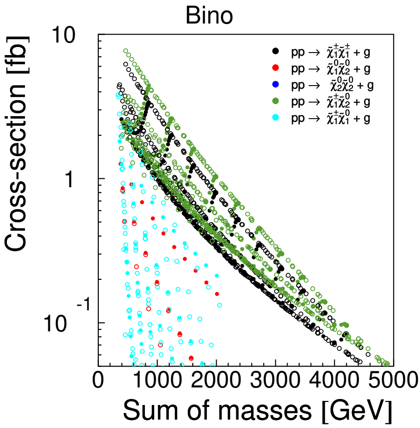

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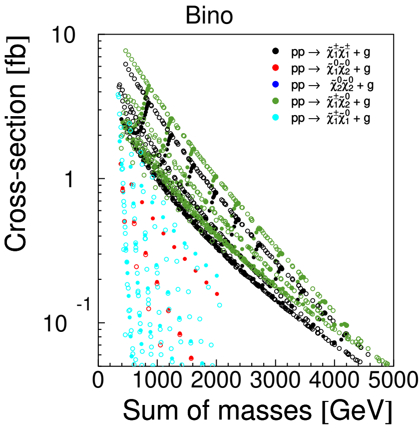

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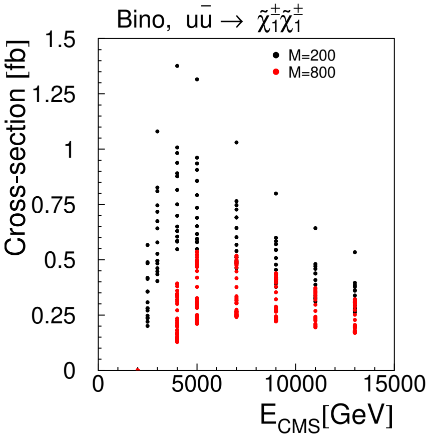

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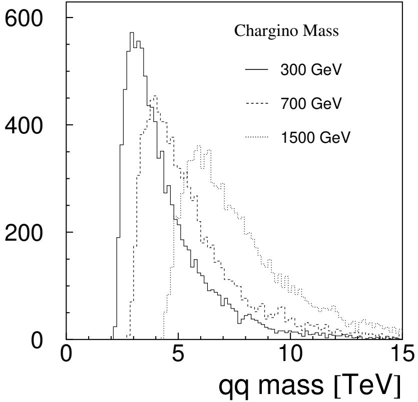

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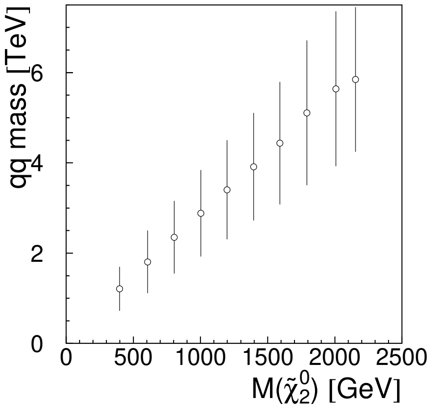

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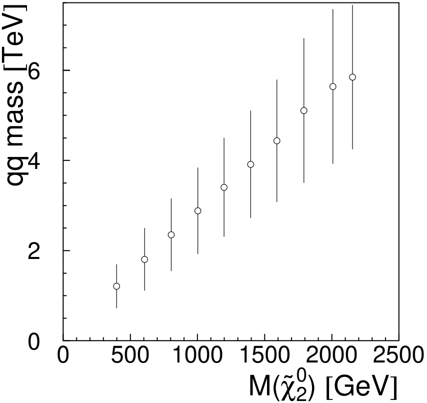

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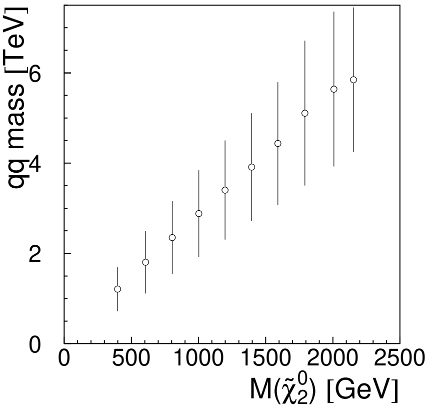

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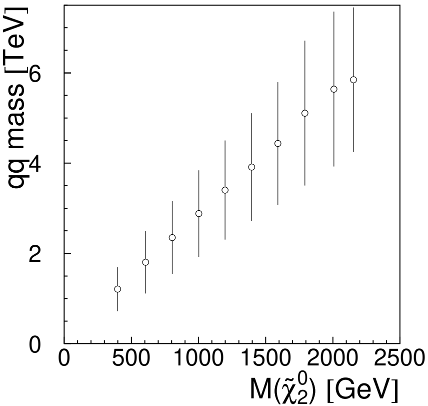

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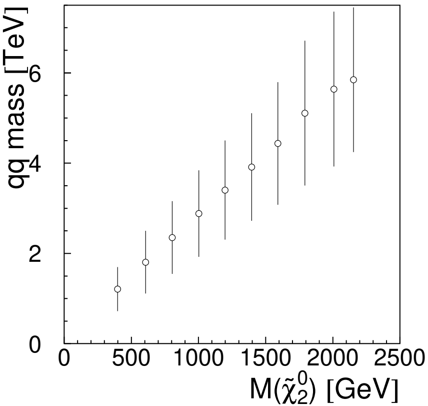

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Uptake

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

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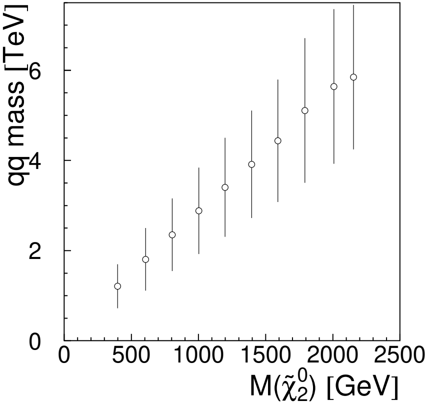

Key element for “Disappearing tracks”: $c\tau$

Why is this important?

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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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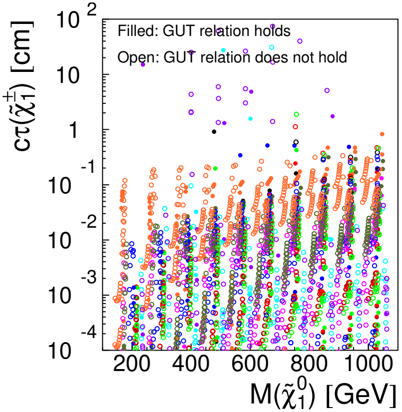

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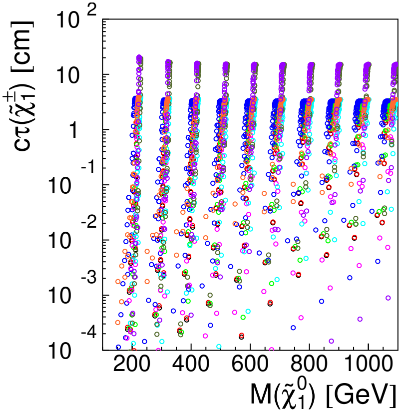

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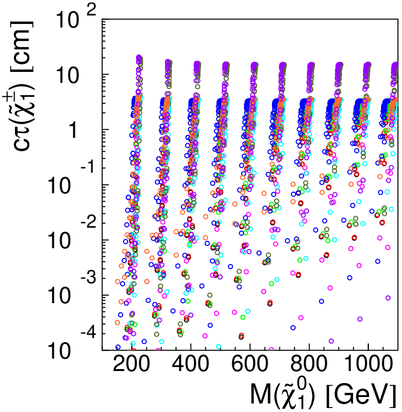
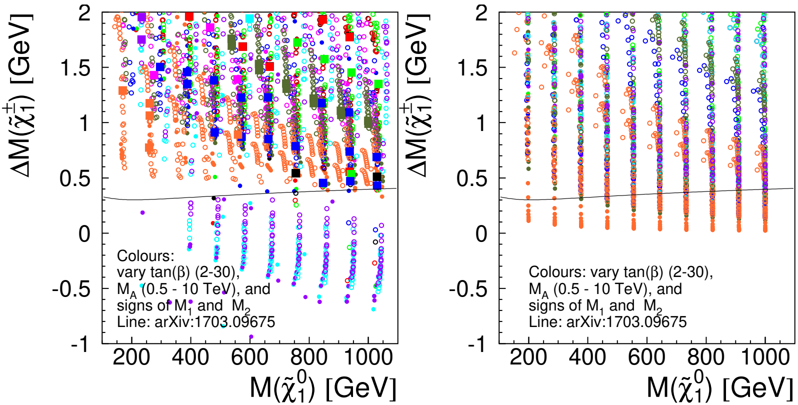


second opinion on Higgsino $\Delta(M)$: feynhiggs



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- ATL-PHYS-PUB-2018-048, ATLAS HL-LHC projection, extrapolated (up *and down*)
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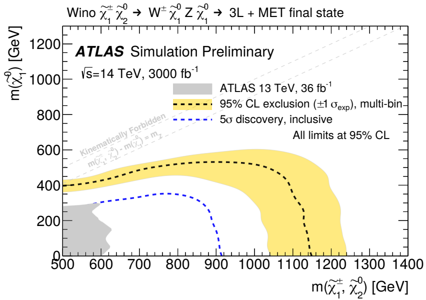

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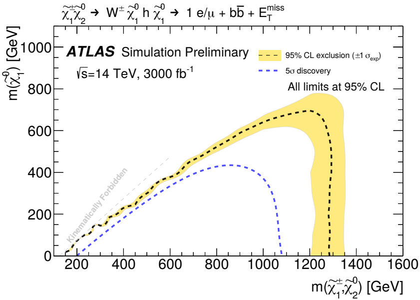

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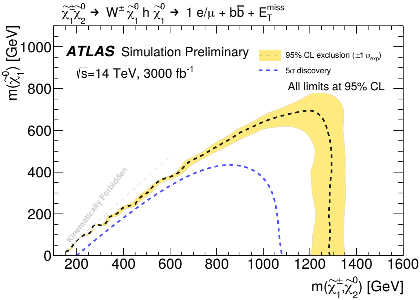

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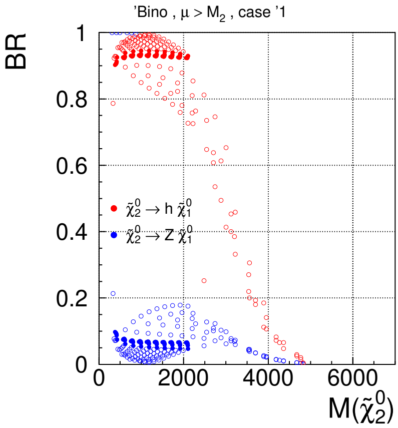

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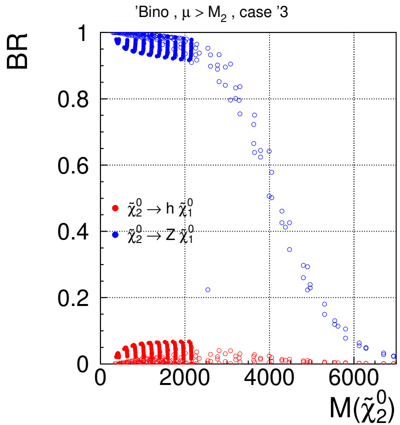

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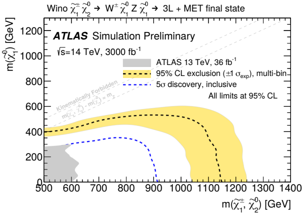

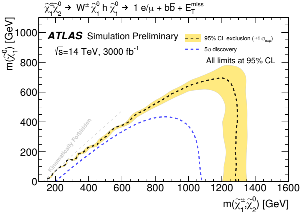

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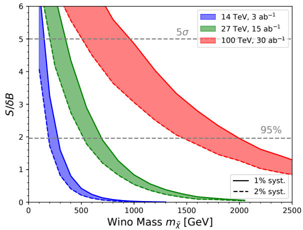

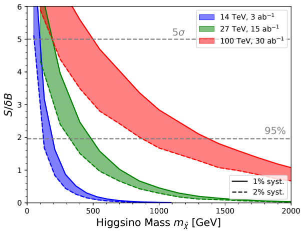

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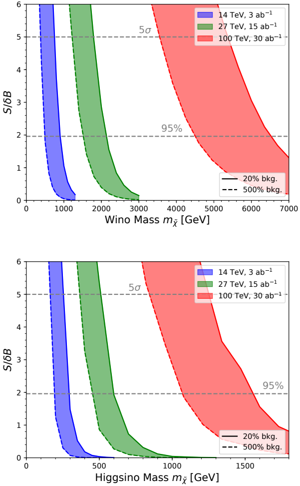

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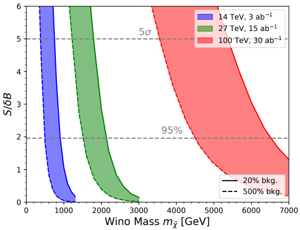

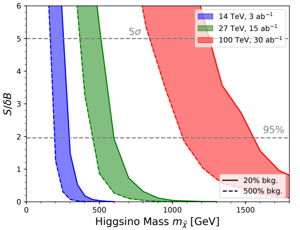

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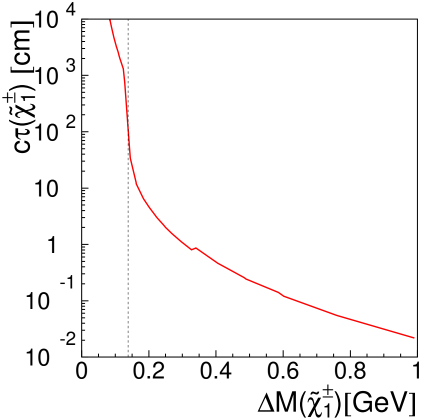

Key element for "Disappearing tracks": $\Delta(M)$

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.
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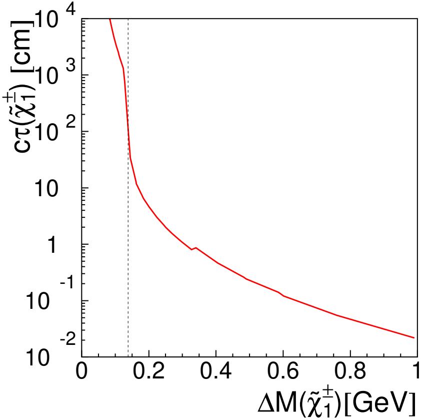

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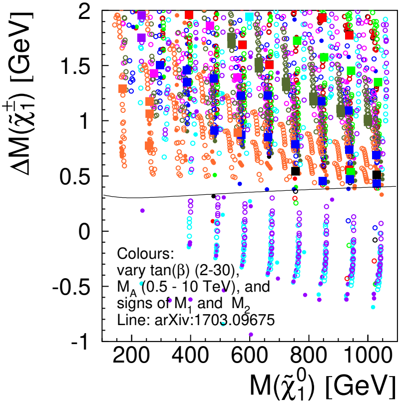

Lines are the "SM-loops only" predictions.

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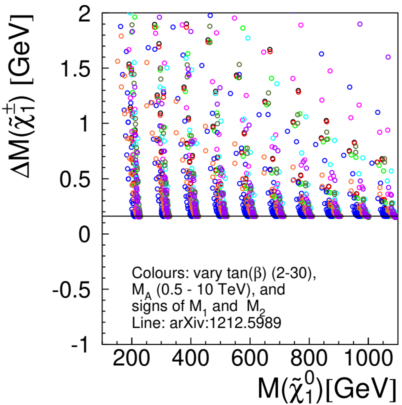

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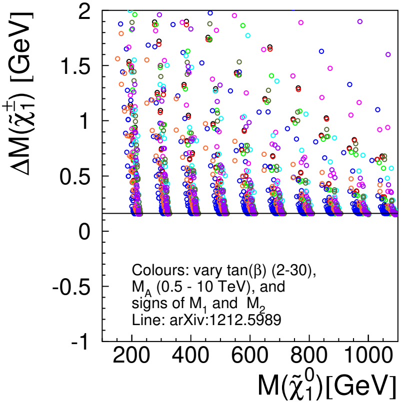

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