

Has the LHC ruled out supersymmetry?



Consistent Excesses in the search for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$: MSSM implications

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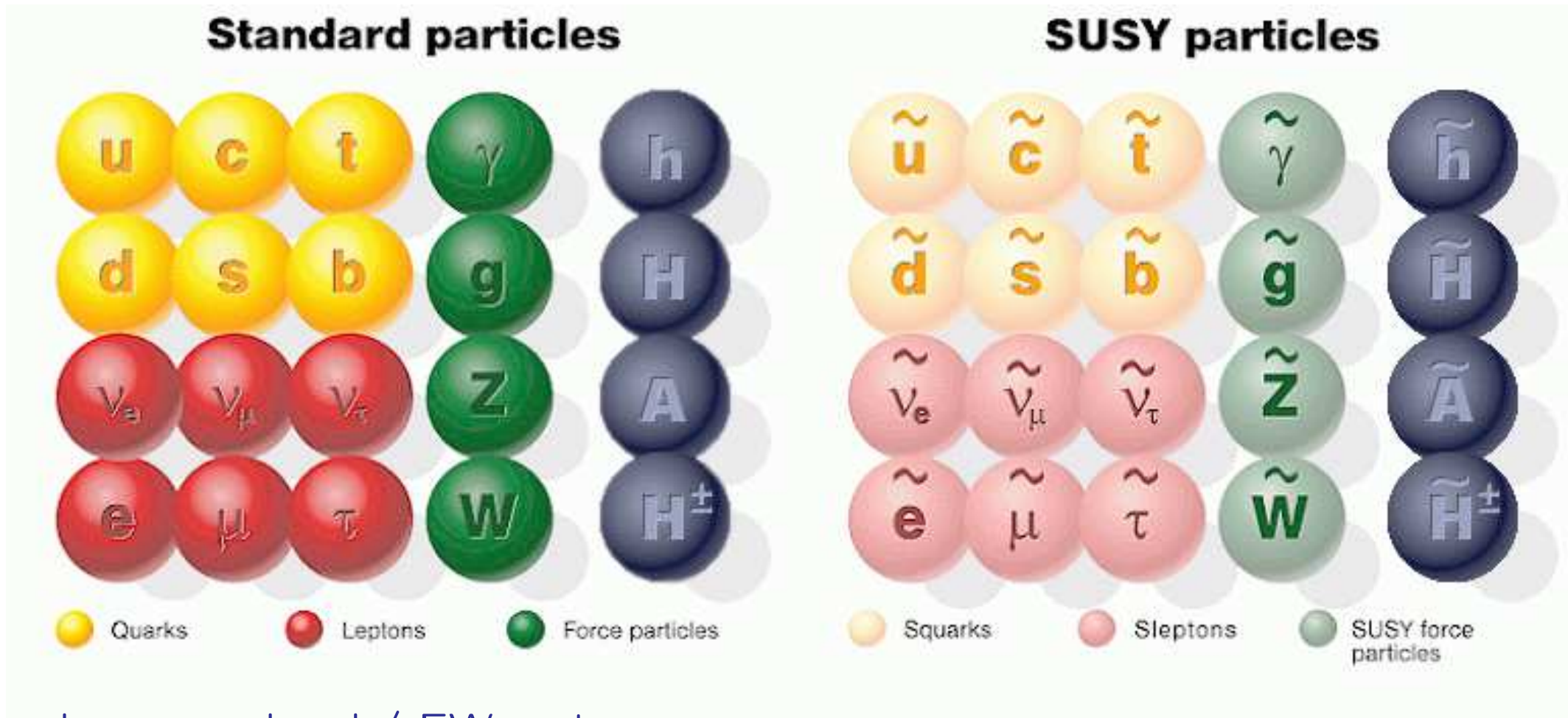
Madrid, 06/2024

In collaboration with: *Manimala Chakraborti, Ipsita Saha*
[arXiv:2403.14759]

1. The main idea
2. Evidence for low-energy SUSY?!
3. Wino/bino vs. higgsino DM
4. Conclusions

1. The main idea

The MSSM



⇒ large uncolored / EW sector

charginos/neutralinos: $M_1, M_2, \mu, \tan \beta$ ⇒ Dark Matter candidate: $\tilde{\chi}_1^0$

Sleptons: $M_{\tilde{l}_L}, M_{\tilde{l}_R}$ (equal for all 3 generations, or different 1.2. vs. 3.)

Theoretically many options:

[M. Chakraborti, S.H., I. Saha '20/21]

A) wino/bino DM with chargino co-annihilation ($M_1 \sim M_2 \lesssim \mu$)

relic DM density 100% fulfilled

$\Rightarrow m_{(N)LSP} \lesssim 650(700) \text{ GeV}$

B/C) bino DM with slepton co-annihilation ($M_1 \lesssim M_2, \mu$)

relic DM density 100% fulfilled

\Rightarrow two cases: all 3 generations degenerate vs. 3rd generation independent

$\Rightarrow m_{(N)LSP} \lesssim 550(600) \text{ GeV}$

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$)

$\Rightarrow m_{(N)LSP} \lesssim 500 \text{ GeV}$

E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$ ($M_2 \lesssim M_1, \mu$)

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV}$)

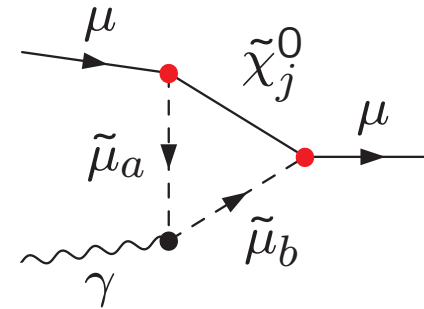
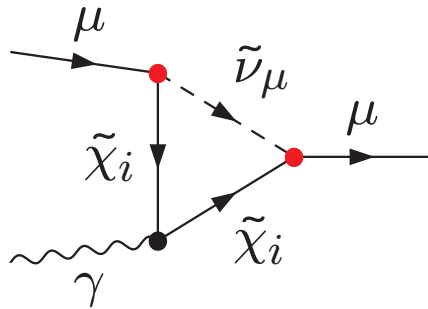
$\Rightarrow m_{(N)LSP} \lesssim 600 \text{ GeV}$

Upper limits on $m_{(N)LSP}$: assume 5σ deviation in $(g-2)_\mu$

$\Rightarrow 2\sigma$ deviation achieved by heavier sleptons (in A/D/E)

SUSY can easily explain “any” deviation in a_μ :

Feynman diagrams for MSSM 1L corrections:



- Diagrams with chargino/sneutrino exchange
- Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu : \sim m_\mu \tan \beta$$

$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a : \sim m_\mu \tan \beta$$

$$\text{SM, EW 1L: } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$$

$$\text{MSSM, 1L: } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan \beta$$

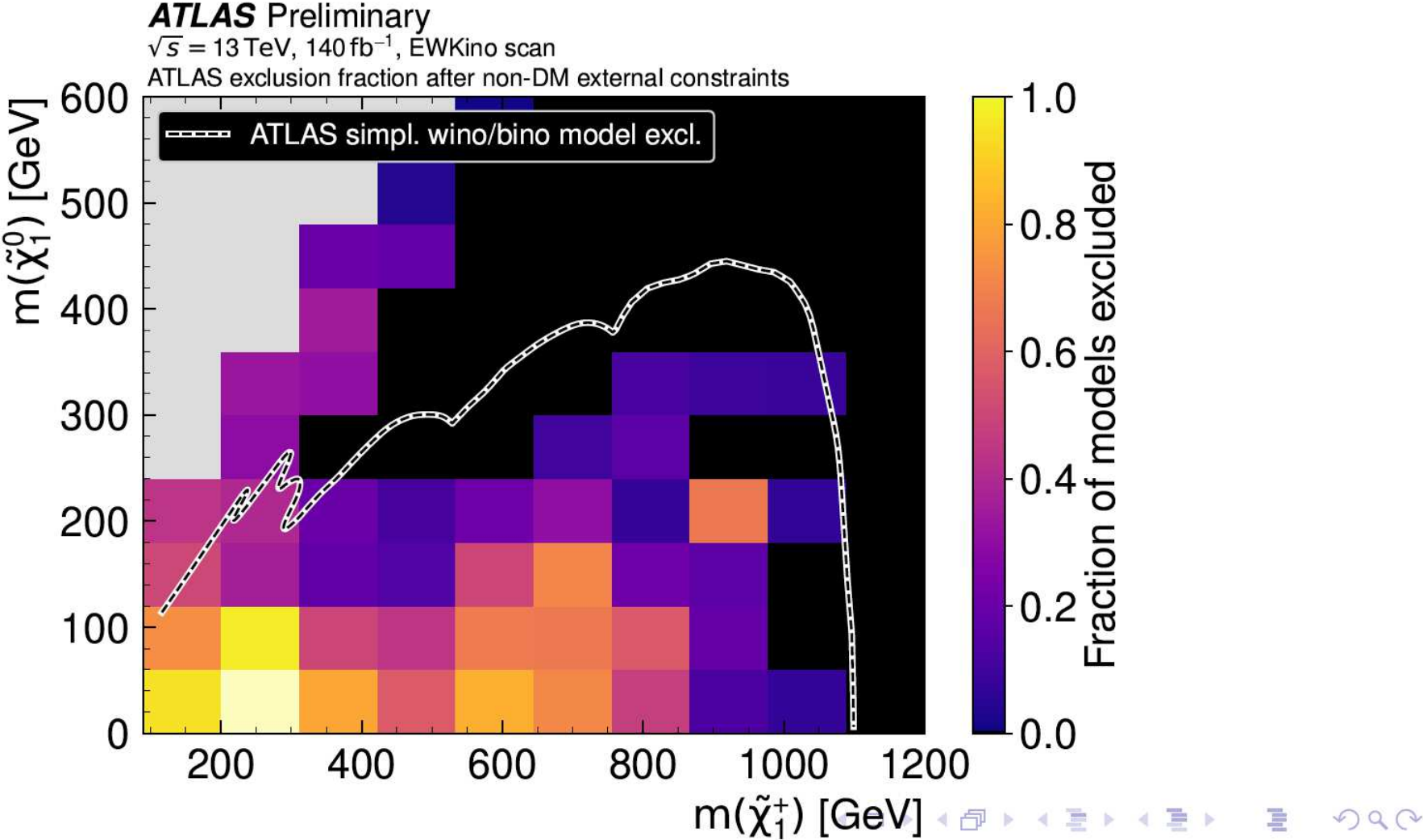
\Rightarrow slepton masses control the size of $\Delta a_\mu^{\text{MSSM}}$

2. Evidence for low-energy SUSY?!

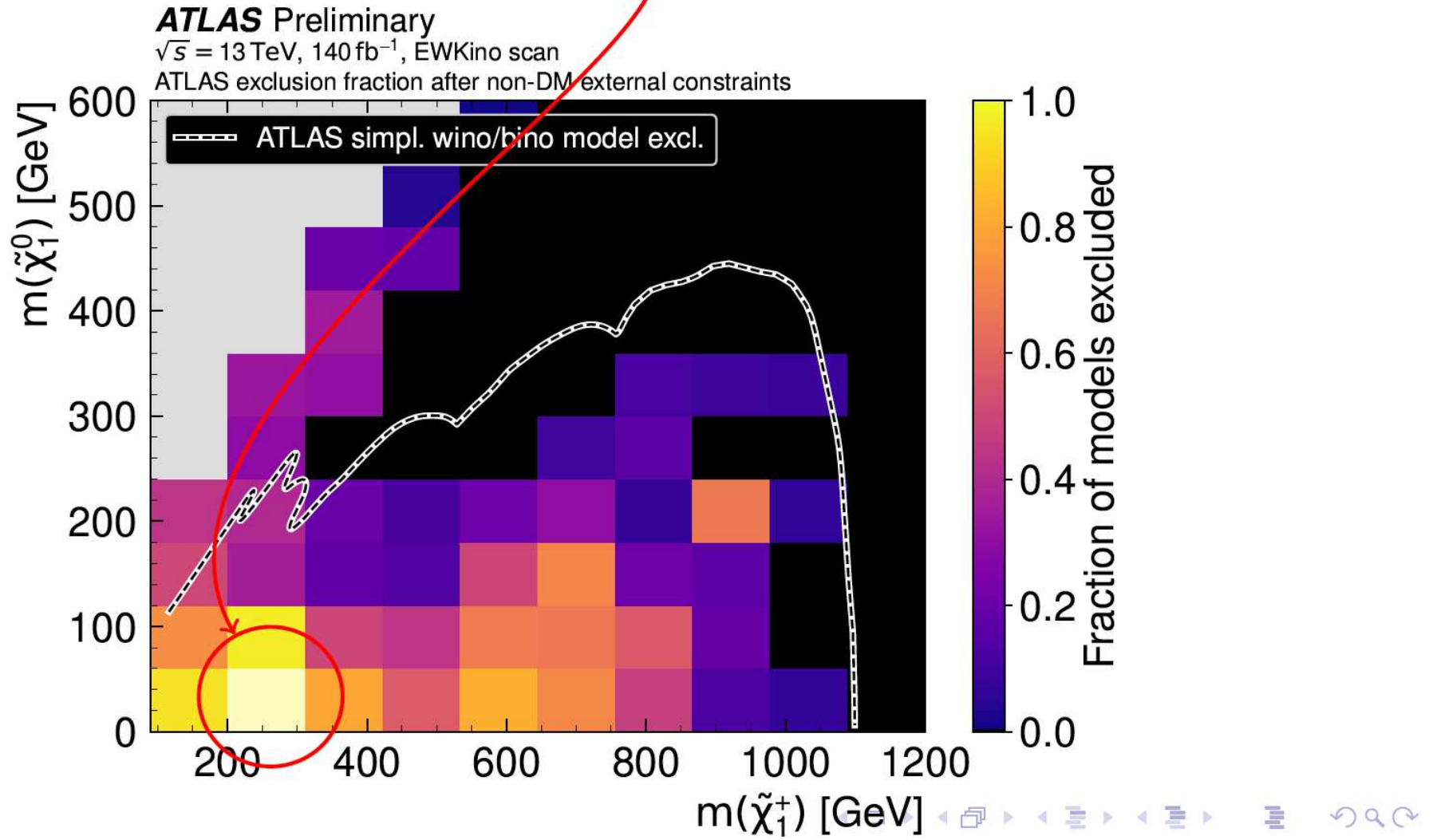


What have the LHC searches excluded?

[taken from M. Berggren '23]



Only this one is actually excluded !



⇒ Our “models” predict low chargino/neutralino masses

Possible search channels:

- $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X$
- $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + H/Z$
- $pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 H/Z \tilde{\chi}_1^0 W^\pm$
- $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^+ \tilde{\chi}_1^0 W^-$
- ...

Possible kinematic situations:

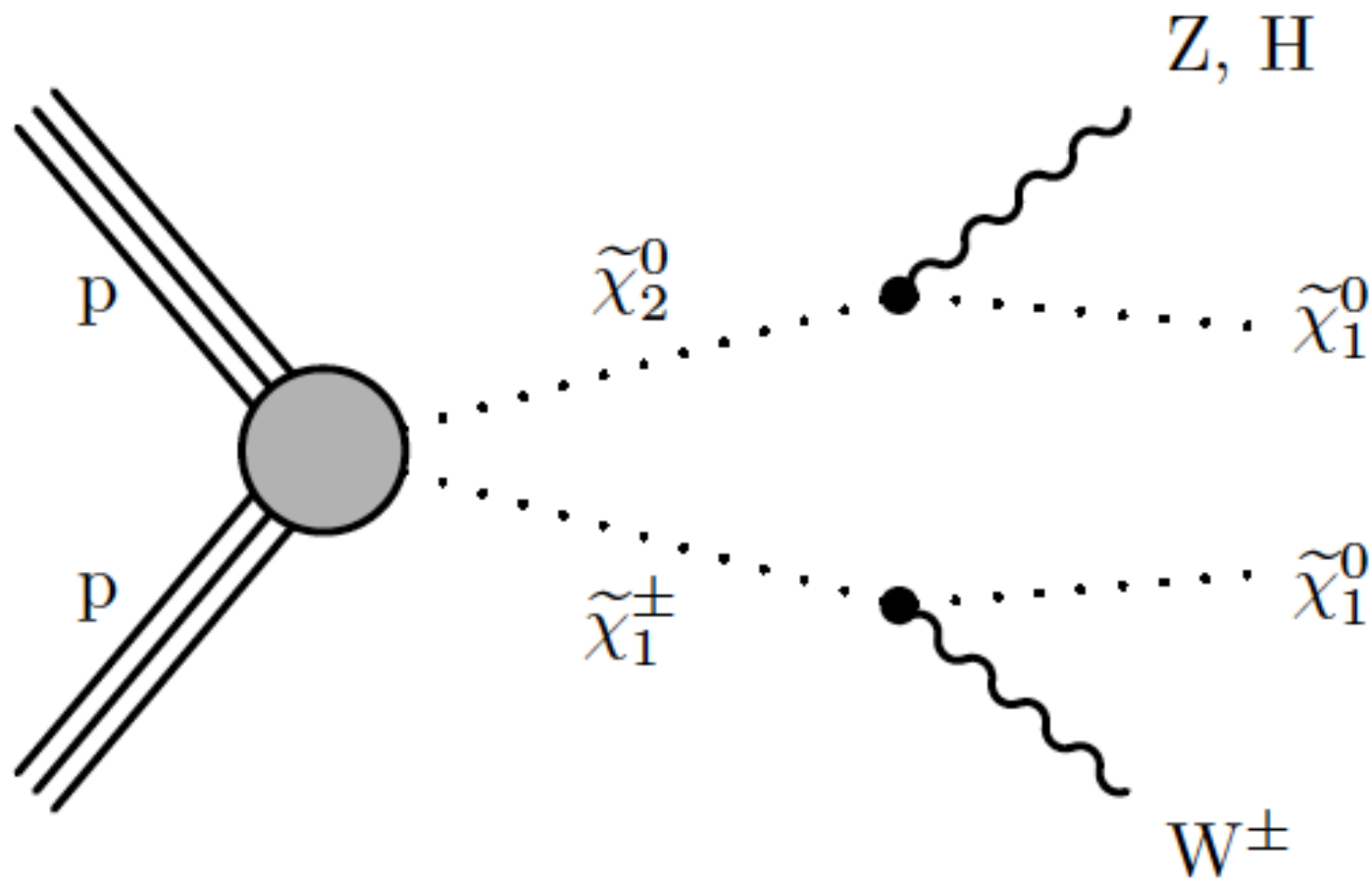
- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to Z, W^\pm
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

⇒ only one of these can be realized

⇒ only one of them should show up in the LHC searches

⇒ Our “models” predict low chargino/neutralino masses

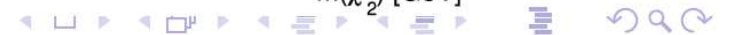
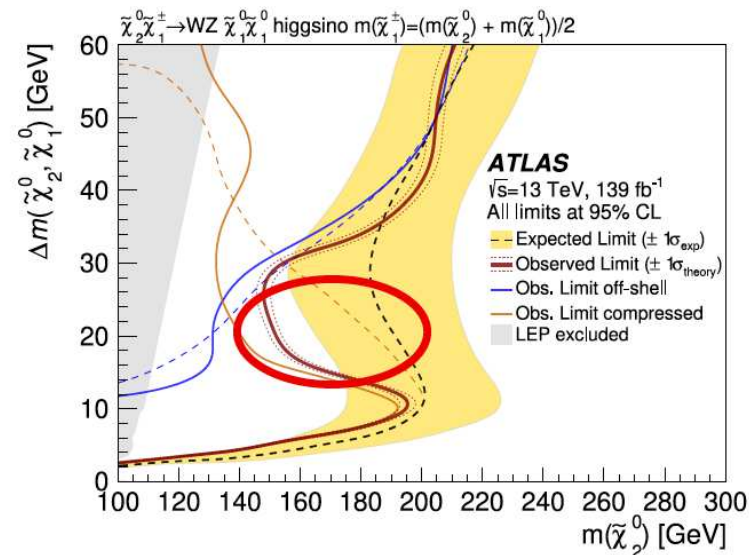
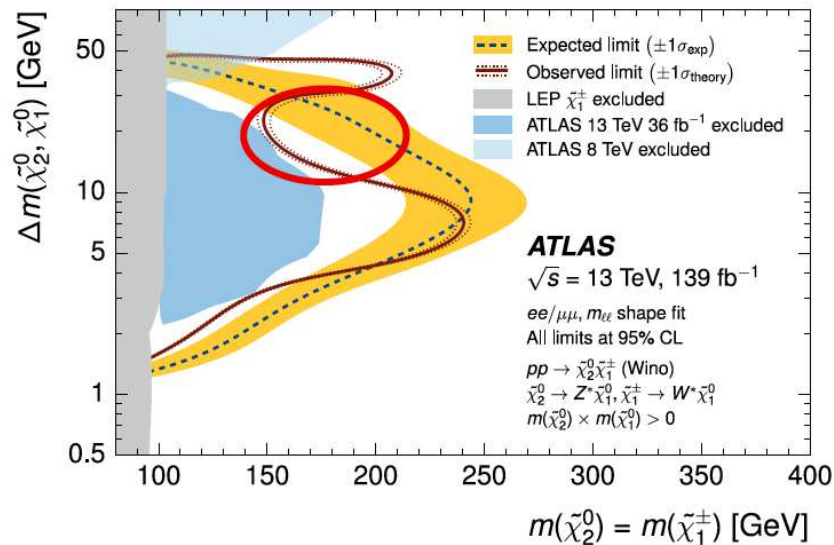
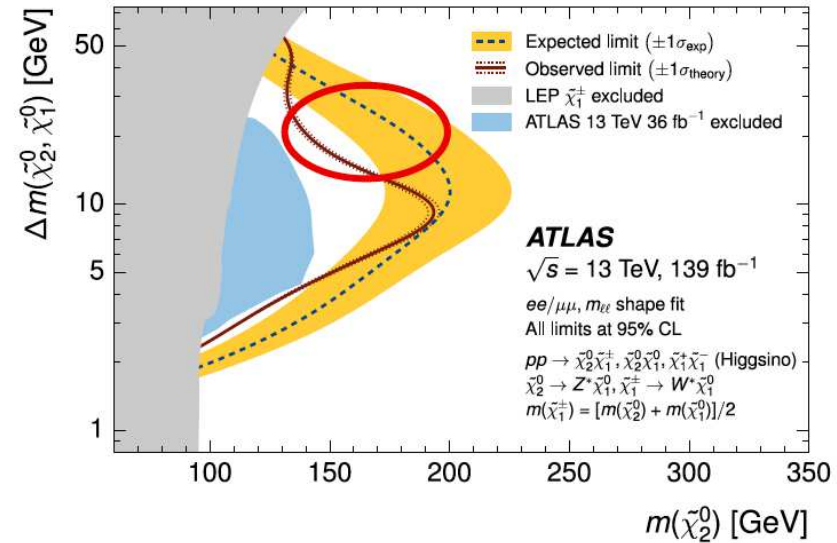
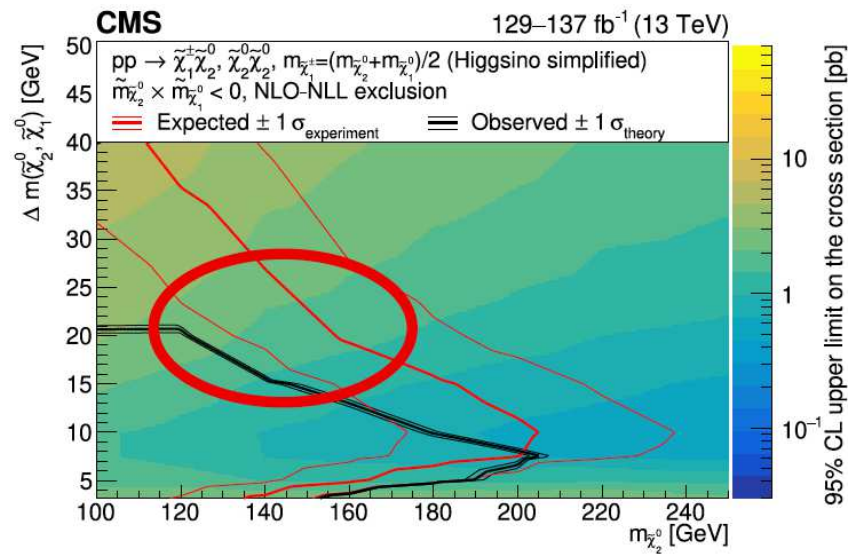
Golden mode at the LHC:

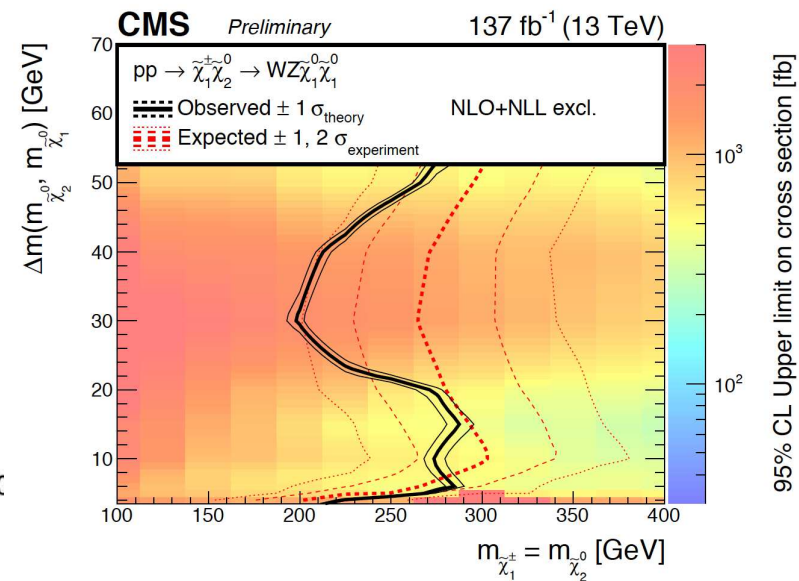
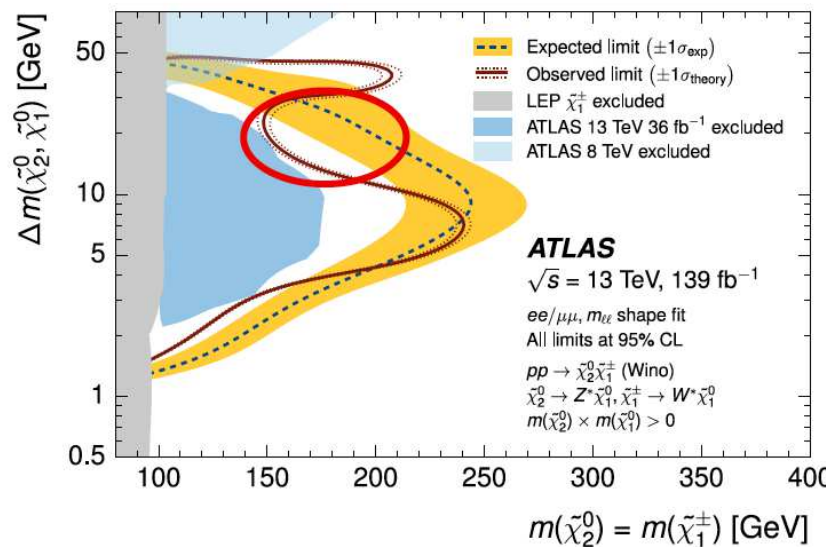
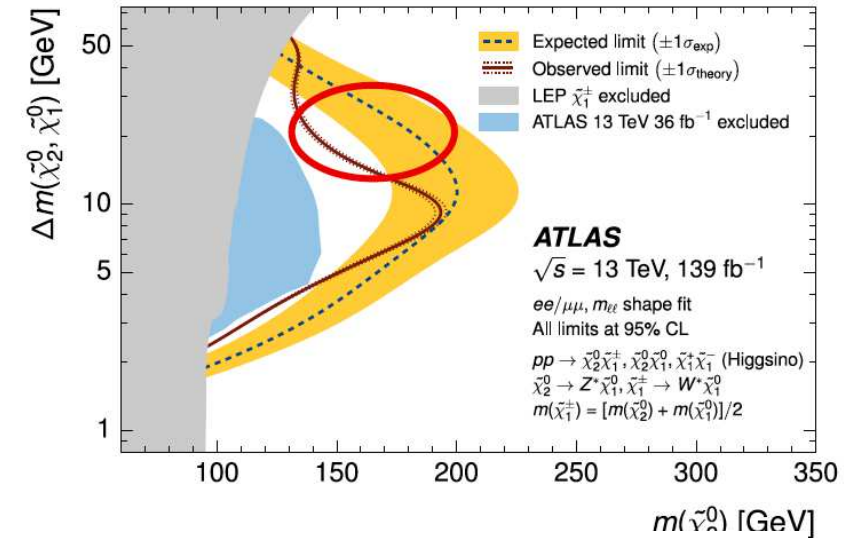
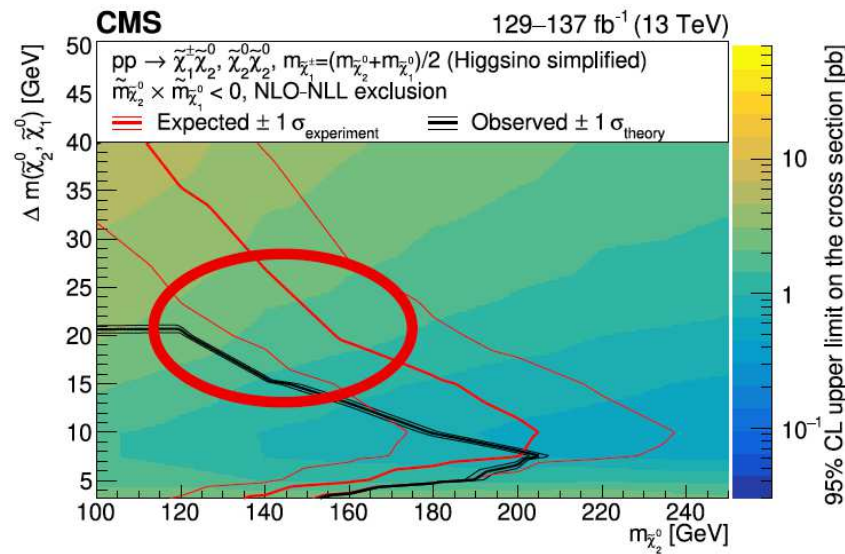


⇒ experimental results?

Results: “compressed” spectra w/ heavy sleptons:

[taken from M. Berggren '23]





Two possible scenarios:

- $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$
- $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(20 \text{ GeV})$

A) wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)

relic DM density 100% fulfilled

$$\Rightarrow m_{(N)\text{LSP}} \lesssim 650(700) \text{ GeV}$$

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim |M_1|, M_2$)

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$)

$$\Rightarrow m_{(N)\text{LSP}} \lesssim 500 \text{ GeV}$$

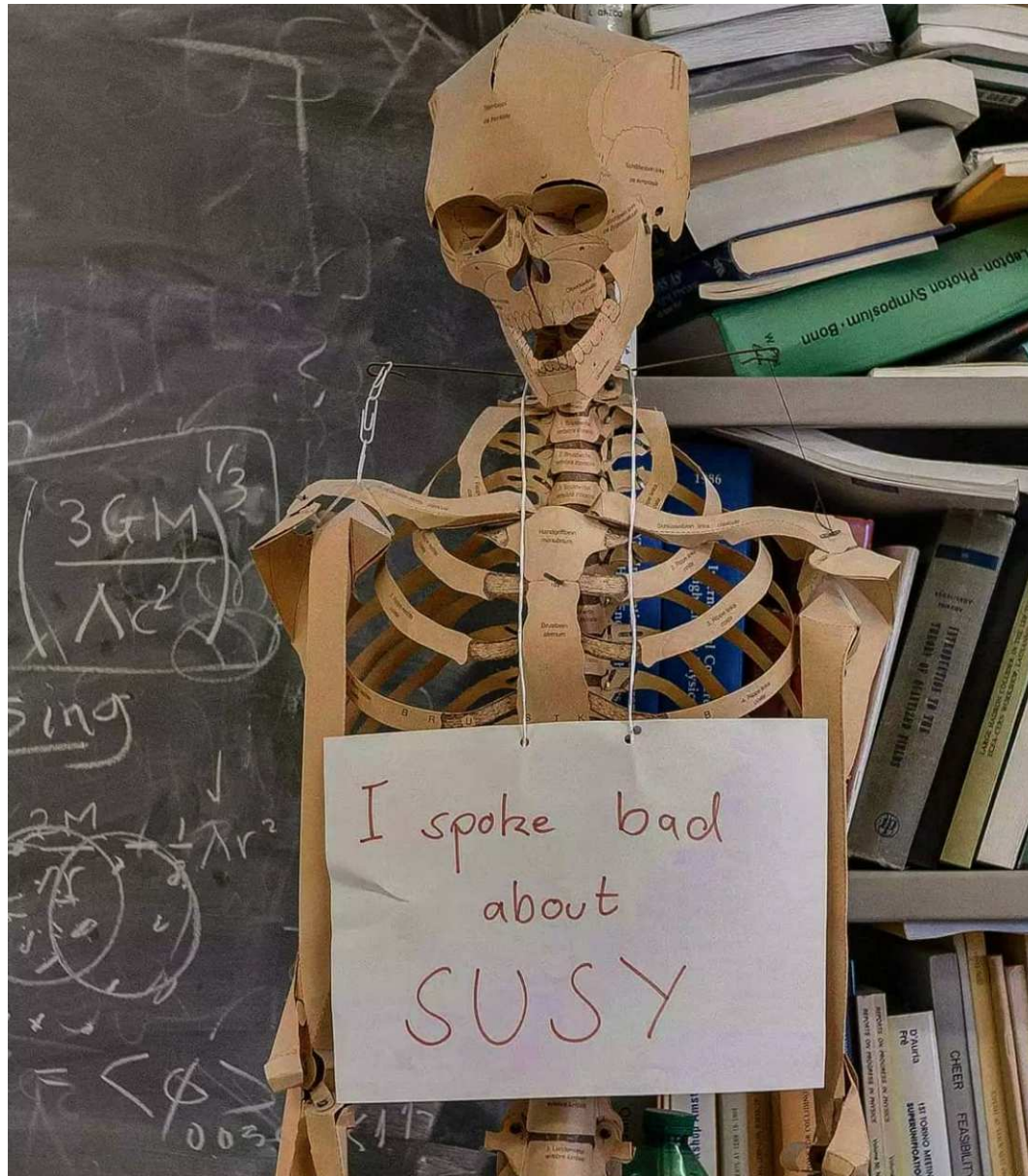
\Rightarrow can they fit the excesses?

Other analyses in a similar direction:

[D. Aguin, B. Fuks, M. Goodsell and T. Murphy, arXiv:2404.12423]

[U. Ellwanger, C. Hugonie, S. King and S. Moretti, arXiv:2404.19338]

3. Wino/bino vs. higgsino DM



A) Wino/bino DM with chargino co-annihilation

Parameter scan:

$$100 \text{ GeV} \leq |M_1| \leq 400 \text{ GeV} ,$$

$$|M_1| \leq M_2 \leq 1.1|M_1| ,$$

$$1.1|M_1| \leq \mu \leq 10|M_1| ,$$

$$2 \leq \tan \beta \leq 60 ,$$

$$100 \text{ GeV} \leq m_{\tilde{L}} \leq 1.5 \text{ TeV} ,$$

$$m_{\tilde{R}} = m_{\tilde{L}} .$$

(latter condition only to make the analysis simpler, no relevant effect)

wino/bino(+): $M_1 \times \mu > 0$

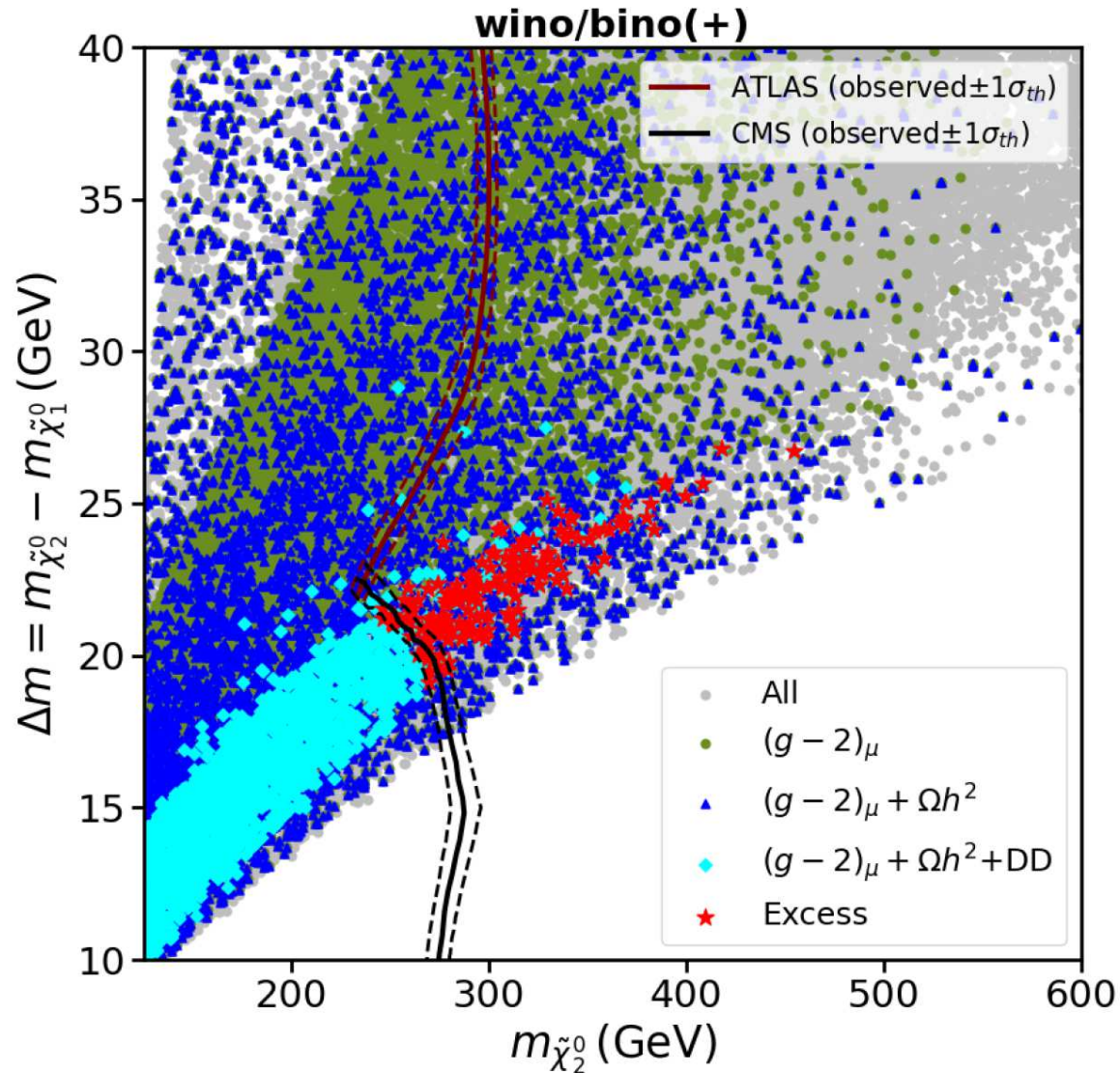
wino/bino(-): $M_1 \times \mu < 0$

relic DM density can be 100% fulfilled

$\Rightarrow m_{(N)\text{LSP}} \lesssim 600(650) \text{ GeV}$

(original scan assuming a 5σ deviation in $(g-2)_\mu$)

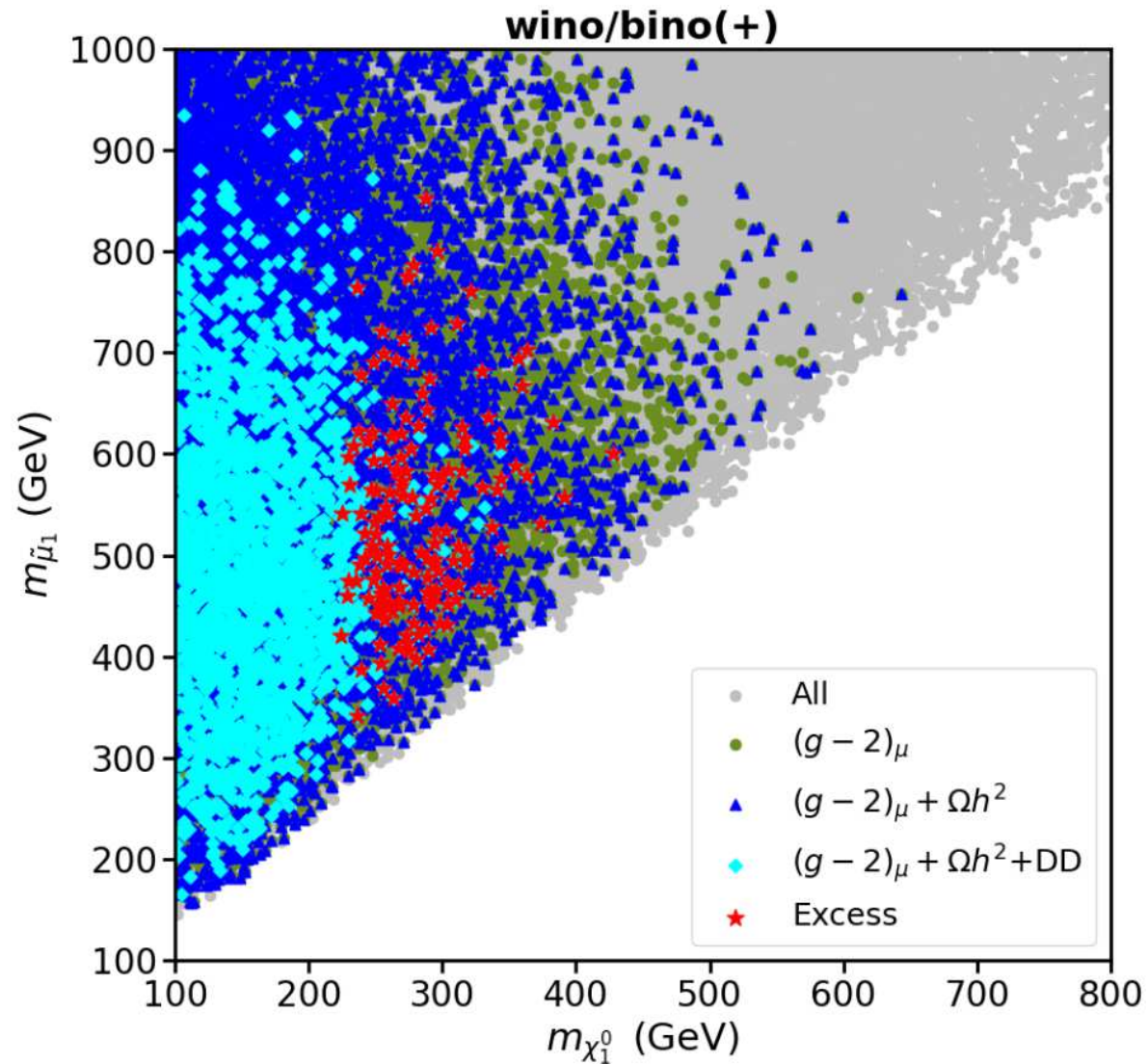
wino/bino(+): results in the $m_{\tilde{\chi}_2^0} - \Delta m$ plane:



⇒ excesses not fully at the same Δm ...

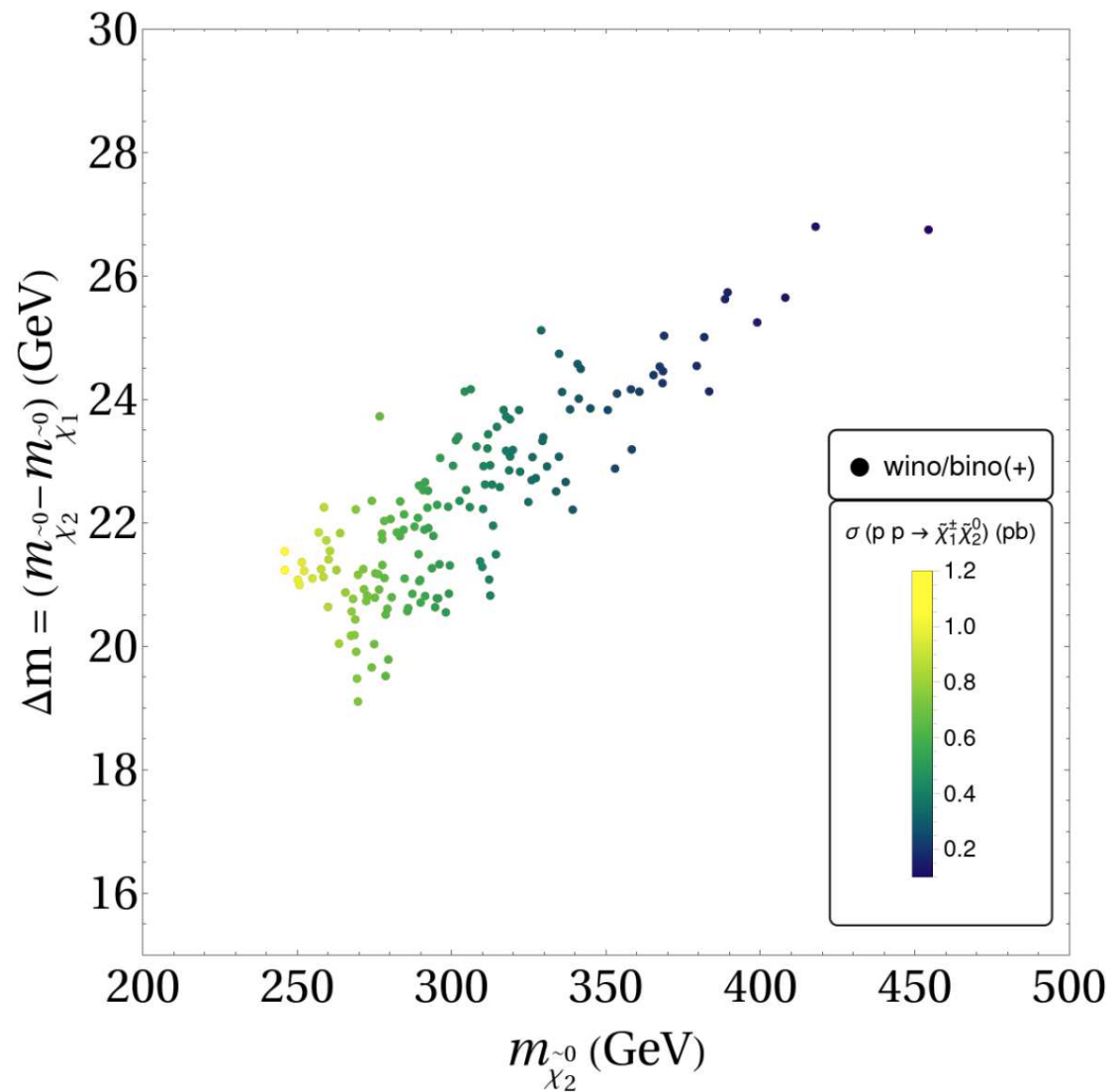
⇒ but many "good points" at $\Delta m \sim 20$ GeV

wino/bino(+): limits on slepton masses:



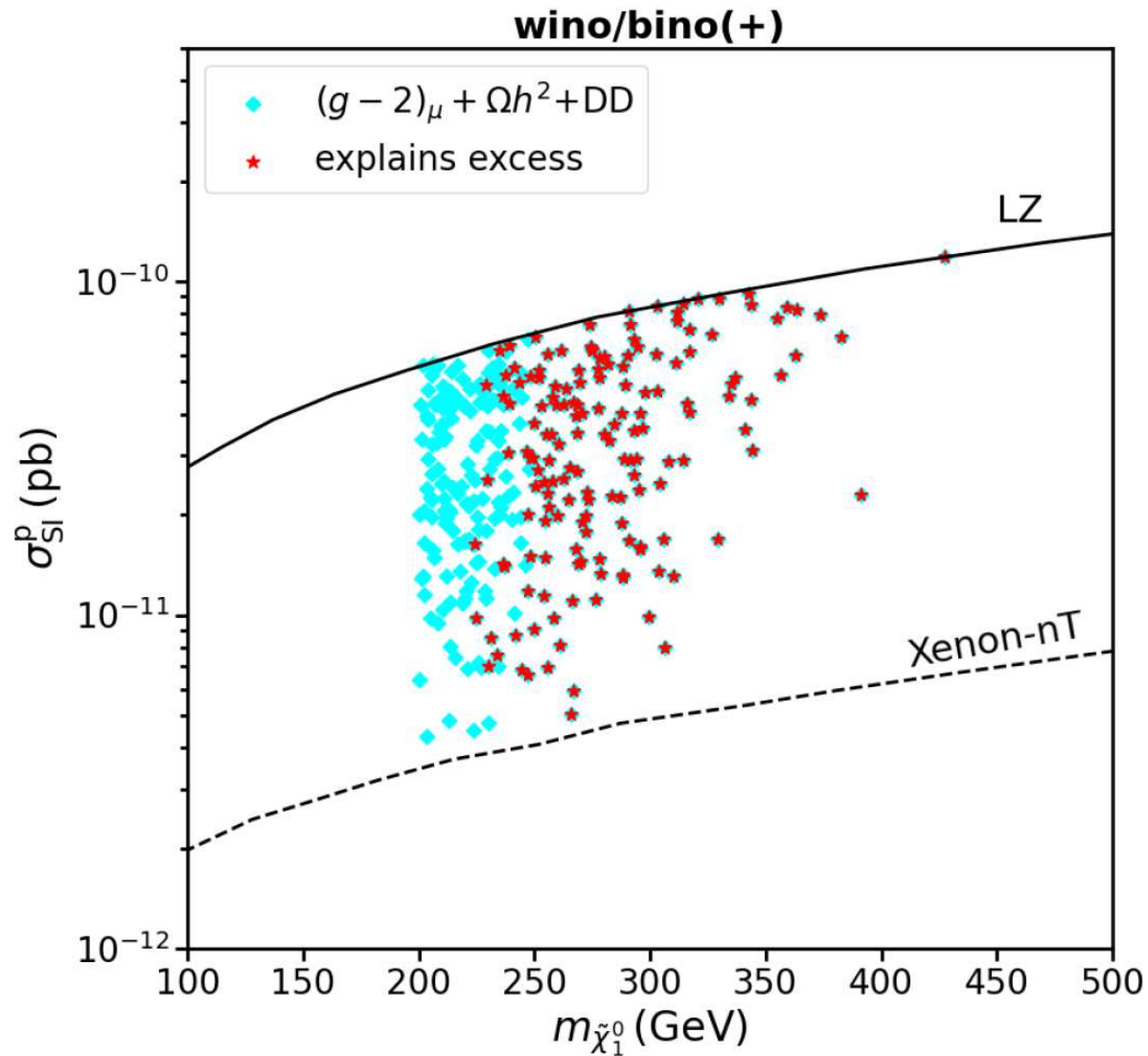
⇒ no limits on slepton masses (as expected)

wino/bino(+): LHC cross sections:



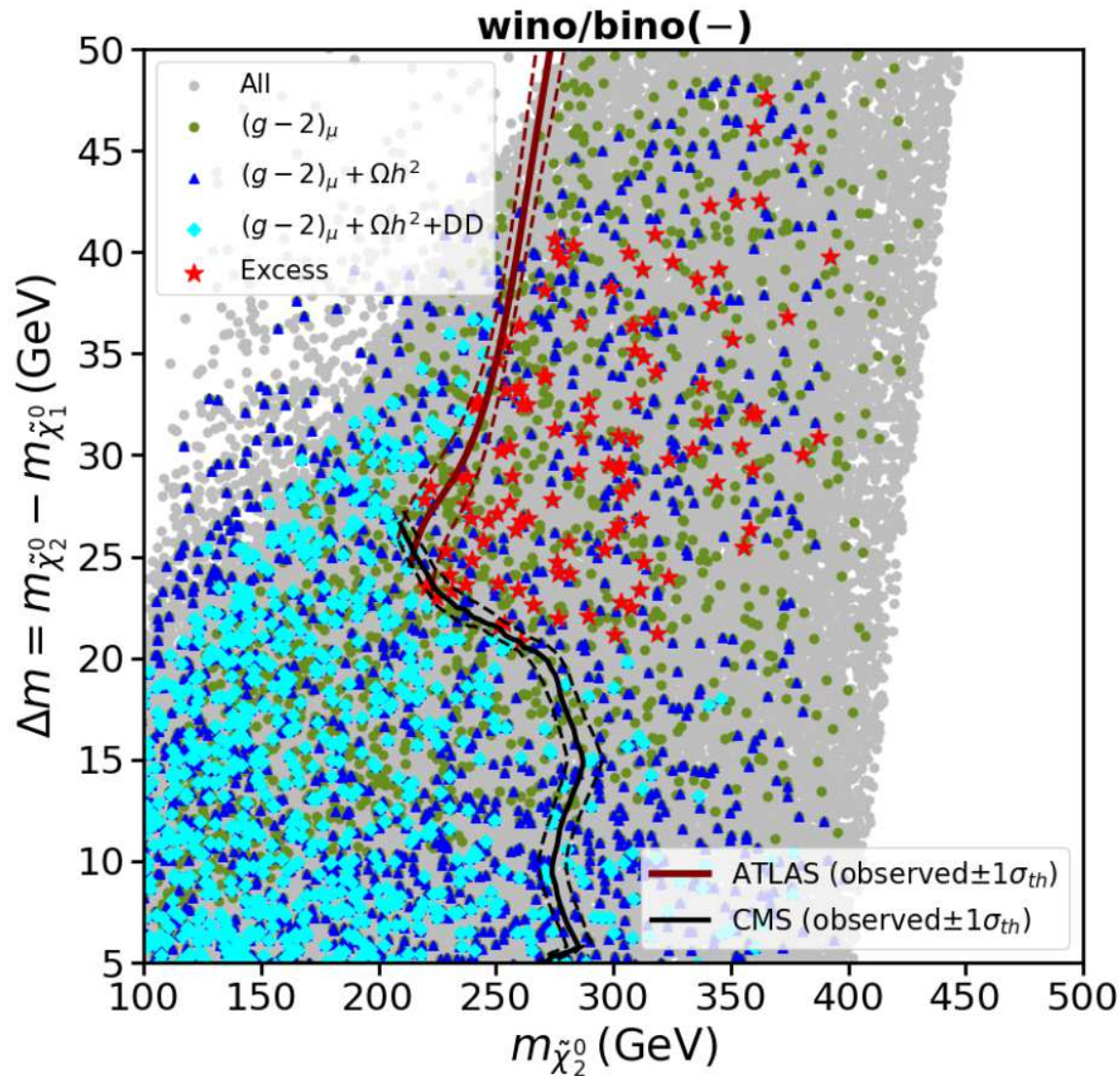
⇒ cross sections have roughly the size required by excesses

wino/bino(+): direct detection prospects:



\Rightarrow wino/bino(+)/ $\tilde{\chi}_1^\pm$ co-annihilation will be covered by XENON-nT/LZ

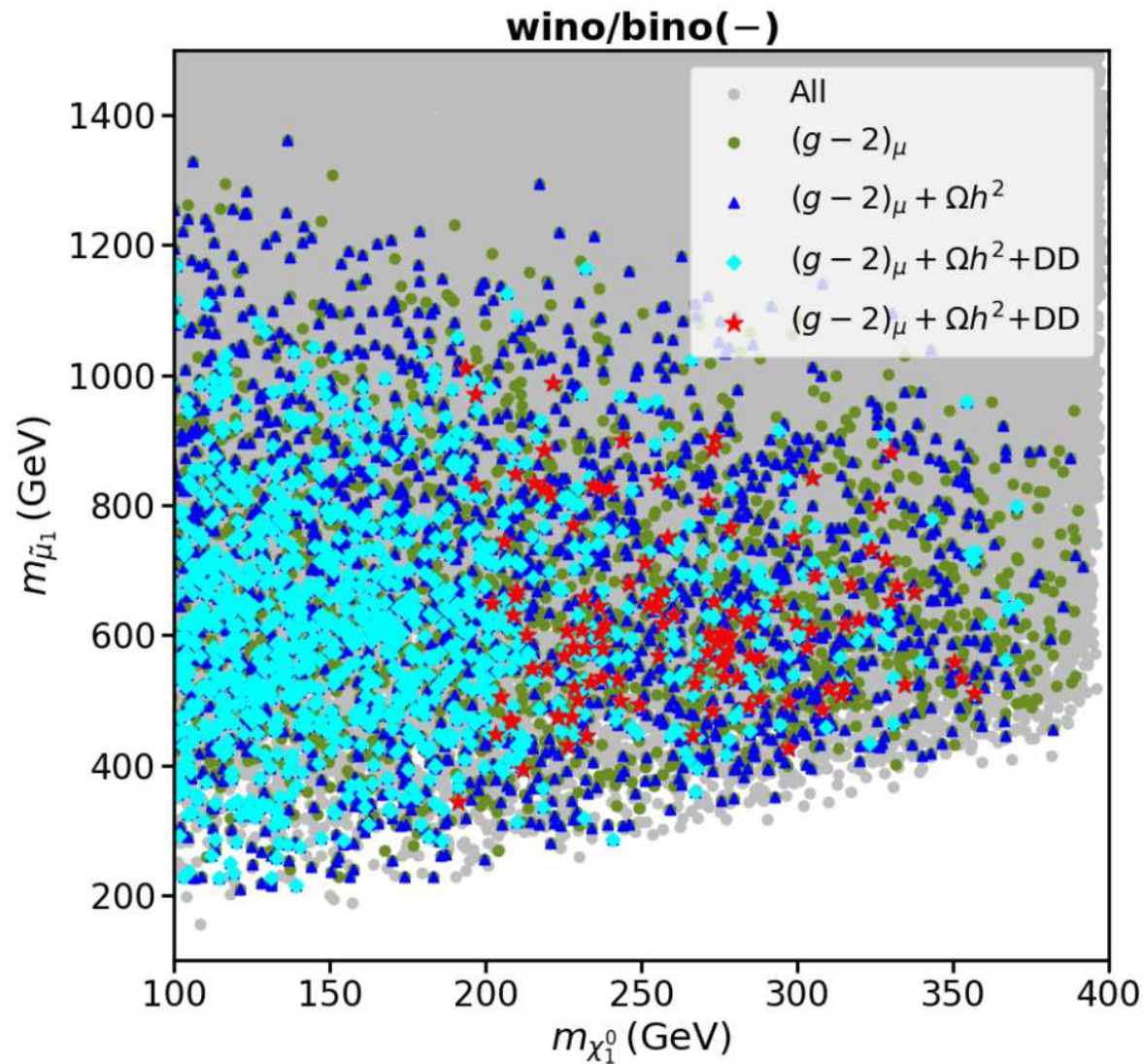
wino/bino(-): results in the $m_{\tilde{\chi}_2^0} - \Delta m$ plane:



⇒ ATLAS/CMS excesses agree better in Δm than for wino/bino(+)

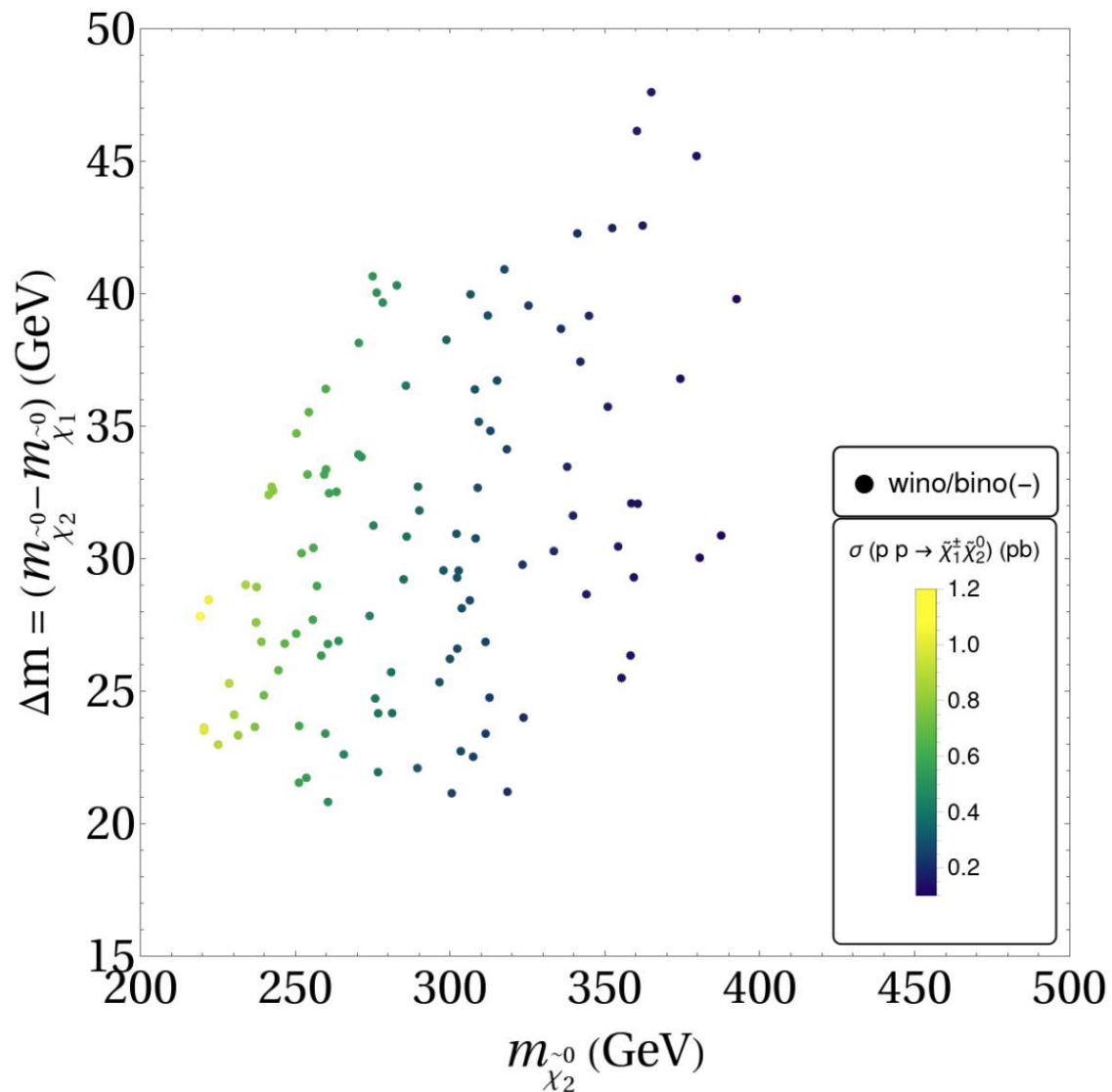
⇒ but many “good points” at $\Delta m \sim 25$ GeV

wino/bino(-): limits on slepton masses:



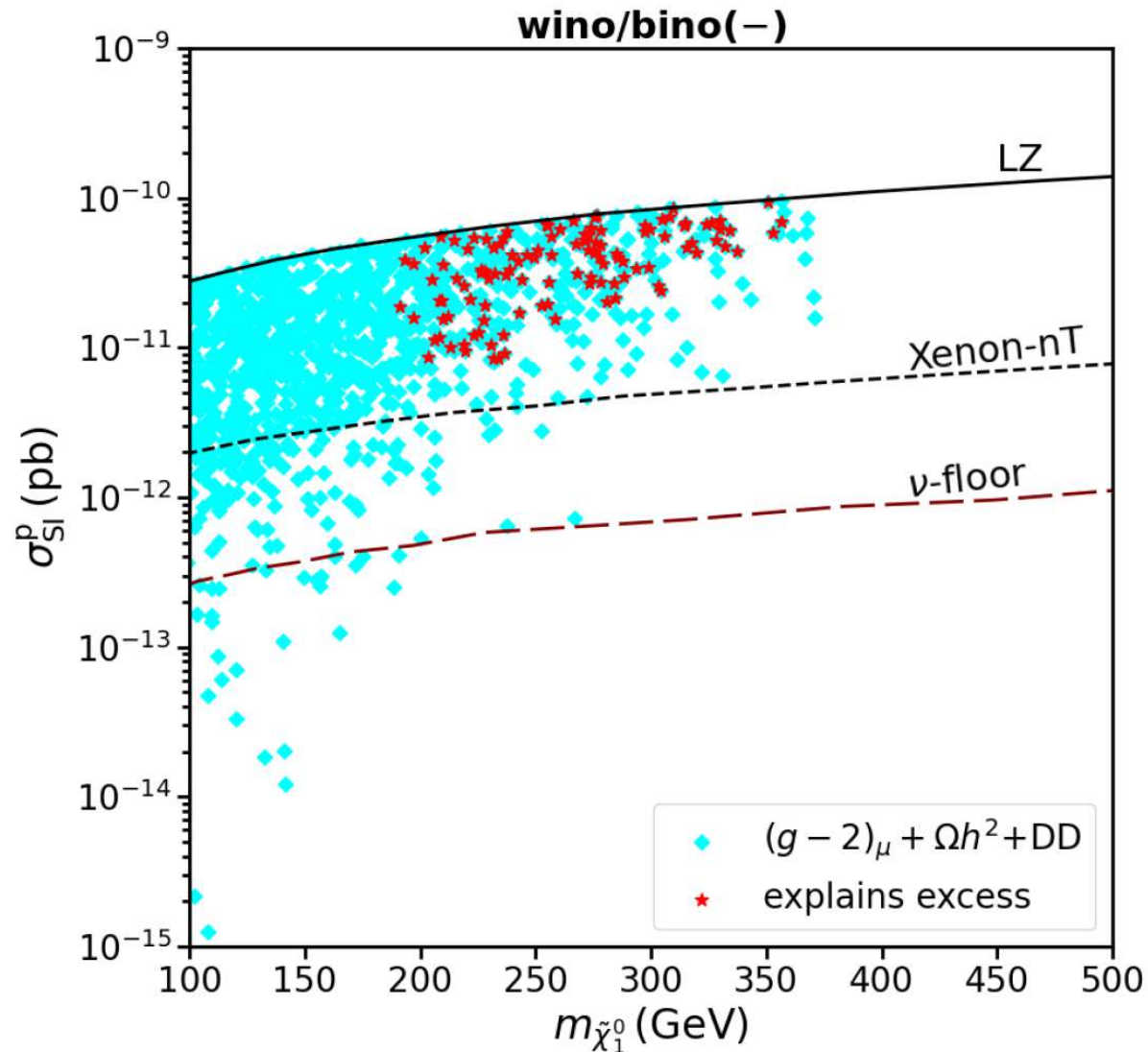
⇒ no limits on slepton masses (as expected)

wino/bino(-): LHC cross sections:



⇒ cross sections have roughly the size required by excesses

wino/bino(-): direct detection prospects:



\Rightarrow wino/bino(-)/ $\tilde{\chi}_1^\pm$ co-annihilation will be covered by XENON-nT/LZ
 \Rightarrow low mass points now excluded \Rightarrow would have been a problem for DD

D) Higgsino DM

Original parameter scan: $(M_1 \times \mu > 0)$

$$100 \text{ GeV} \leq \mu \leq 1.2 \text{ TeV} ,$$

$$1.1\mu \leq M_1 \leq 10\mu ,$$

$$1.1M_2 \leq \mu \leq 10\mu ,$$

$$5 \leq \tan \beta \leq 60 ,$$

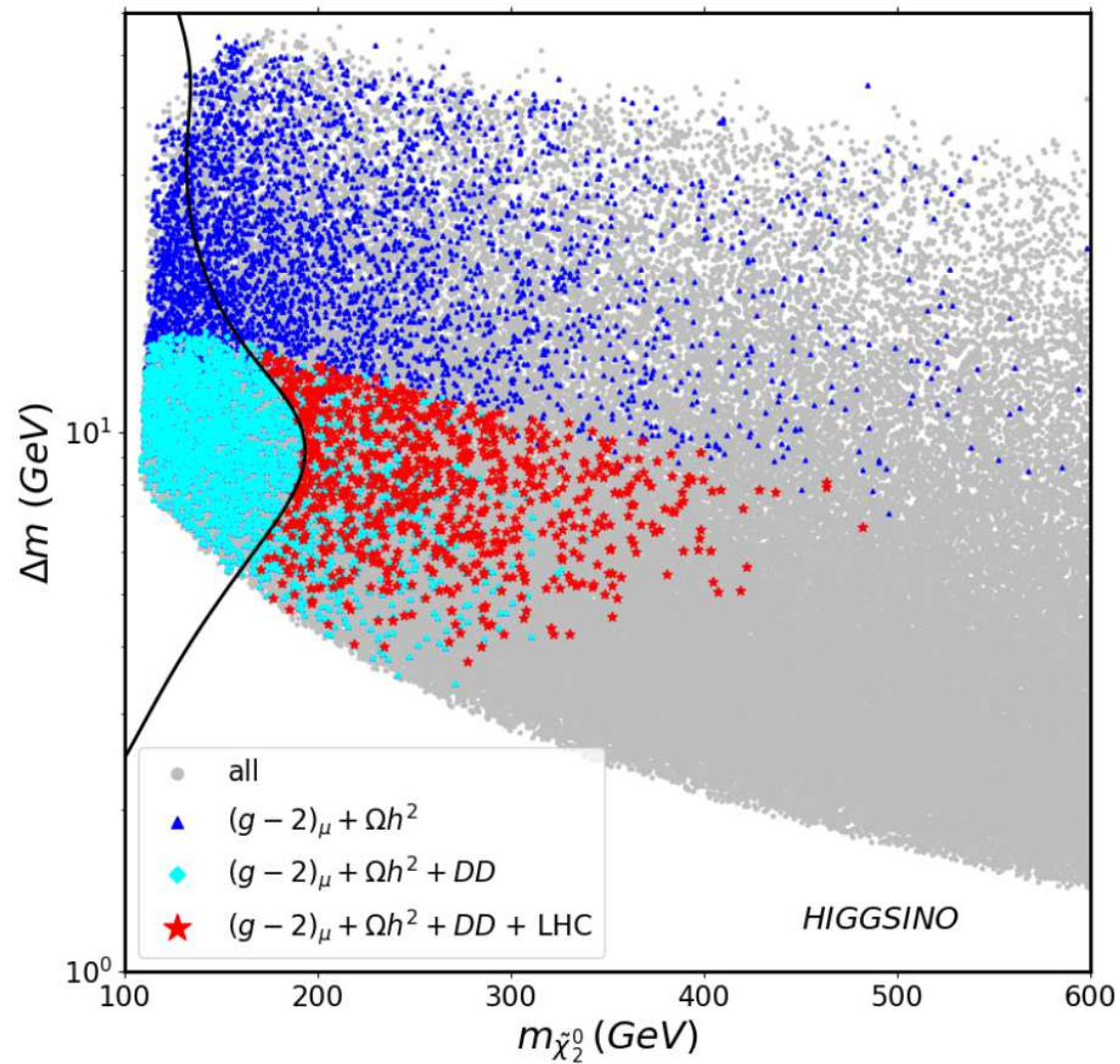
$$100 \text{ GeV} \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 2 \text{ TeV} ,$$

$$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$$

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$

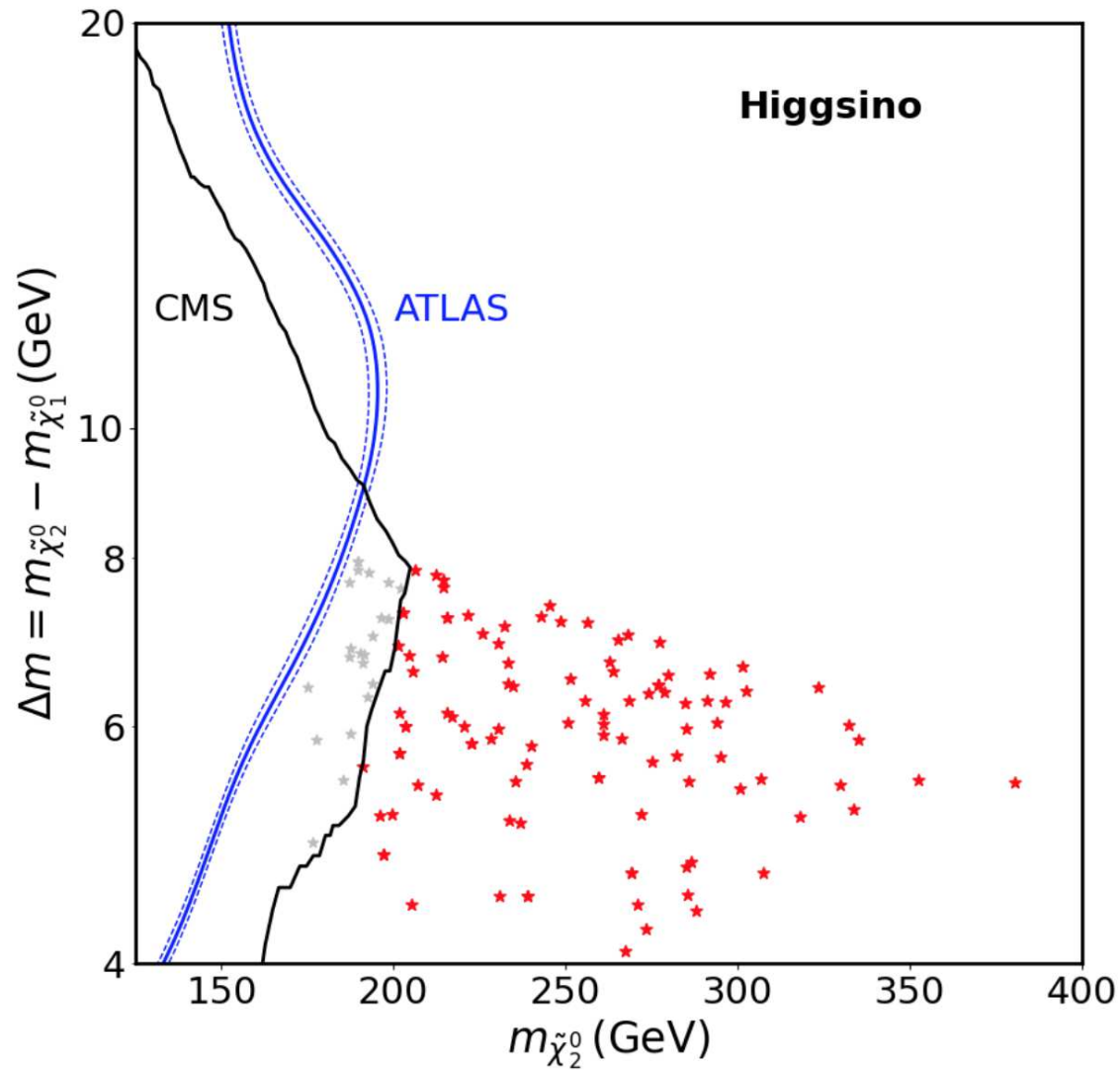
\Rightarrow incompatible with a 5σ deviation in $(g-2)_\mu$

$$\Rightarrow m_{(N)\text{LSP}} \lesssim 500 \text{ GeV}$$



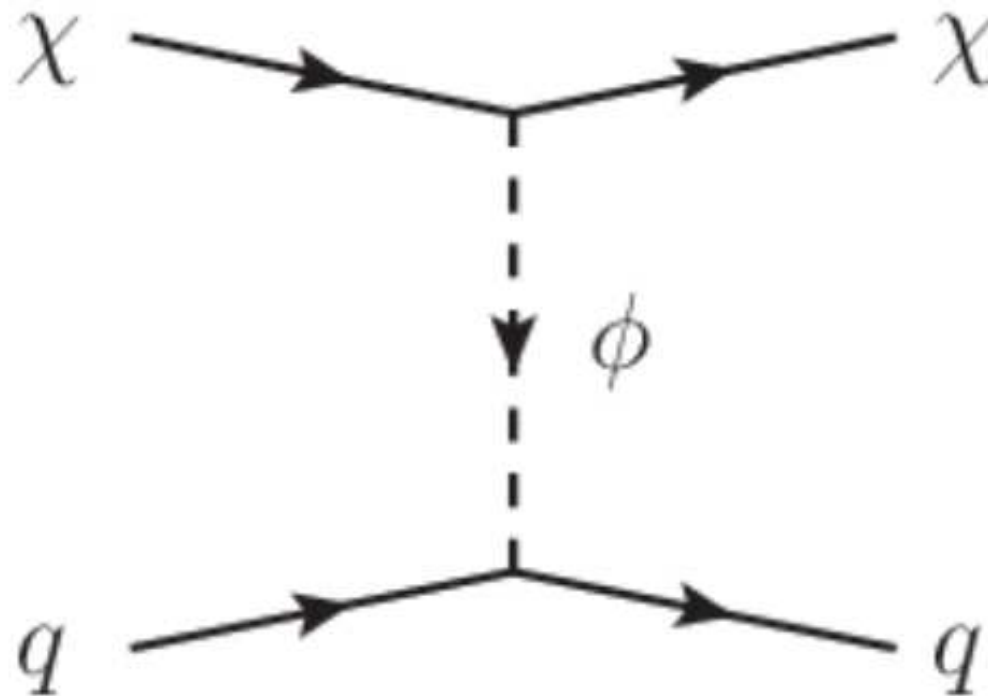
⇒ direct detection is the limiting factor on Δm

Results in the $m_{\tilde{\chi}_2^0} - \Delta m$ plane



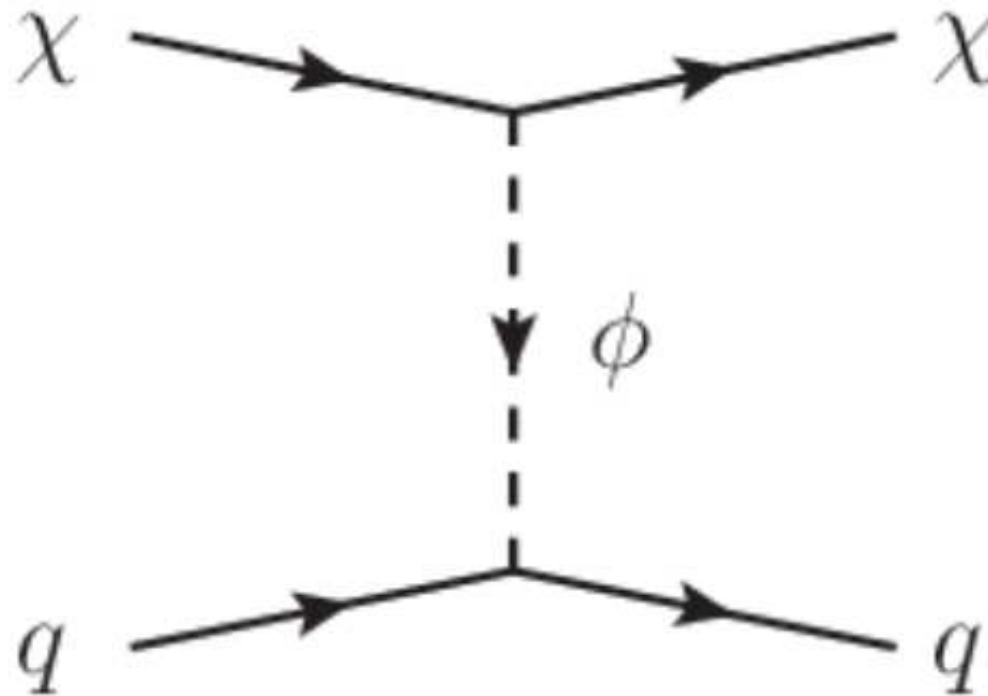
\Rightarrow excess not fitted :- (\Rightarrow DD cuts away the “good points”

Problematic diagram for higgsino DM DD:



$\phi = h, H$

Problematic diagram for higgsino DM DD:



$\phi = h, H$

\Rightarrow cancellation possible for $\mu \times M_1 < 0$ (“blind spots”)

\Rightarrow new scan with $M_1 < 0$

New scan with $M_1 \times \mu < 0$

$$-190 \text{ GeV} \leq M_1 \leq -1500 \text{ GeV} ,$$

$$M_2 = 2 \text{ TeV} ,$$

$$\mu = \frac{-2M_1 \tan \beta}{4 + x_1 \tan^2 \beta} , \quad x_1 = \frac{m_h^2}{m_H^2} ,$$

$$5 \leq \tan \beta \leq 50 ,$$

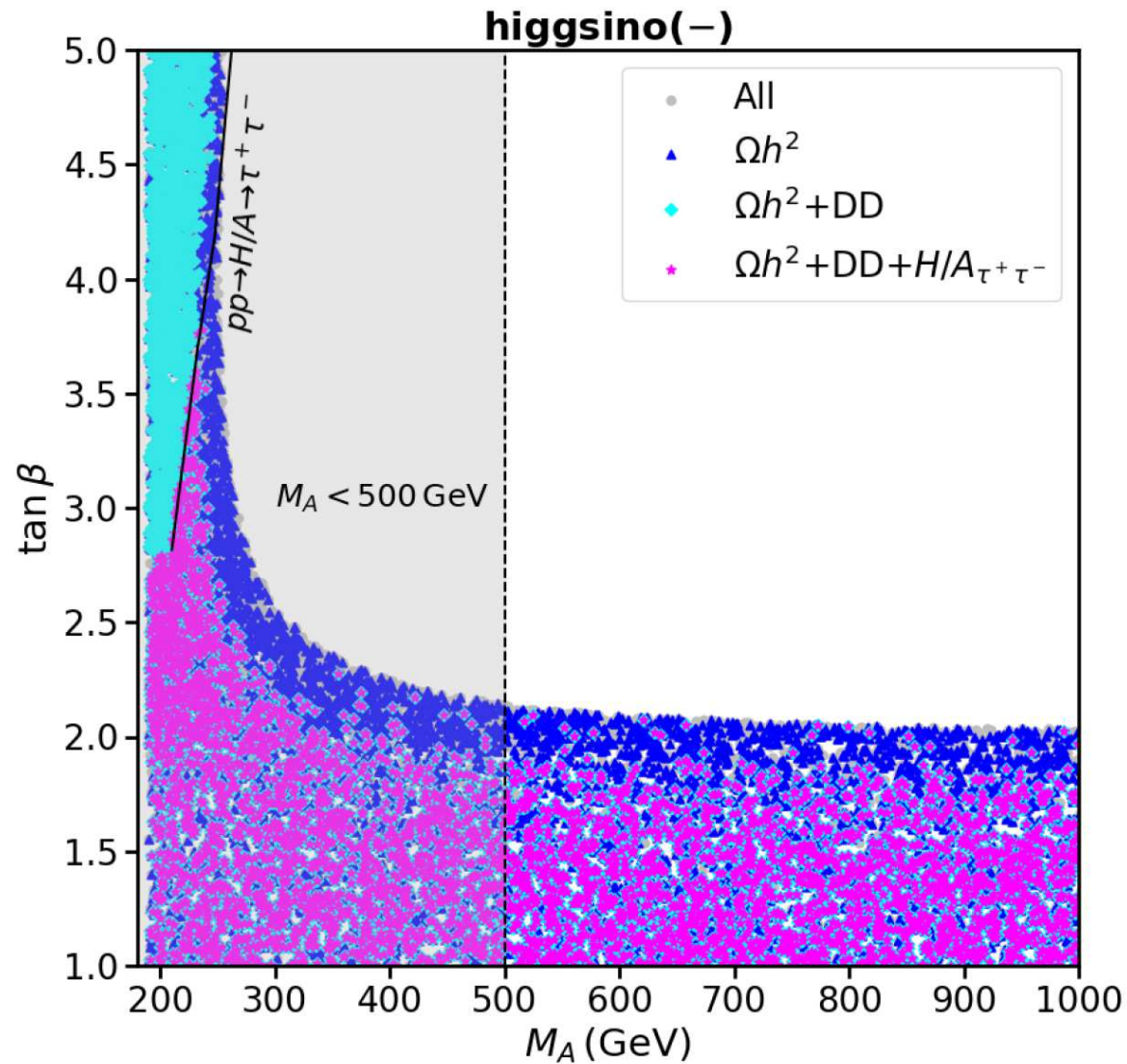
$$190 \leq M_A \leq 1200 ,$$

$$2M_1 \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 1500 \text{ GeV} ,$$

Condition on μ and M_1 : exact blind spot conditions

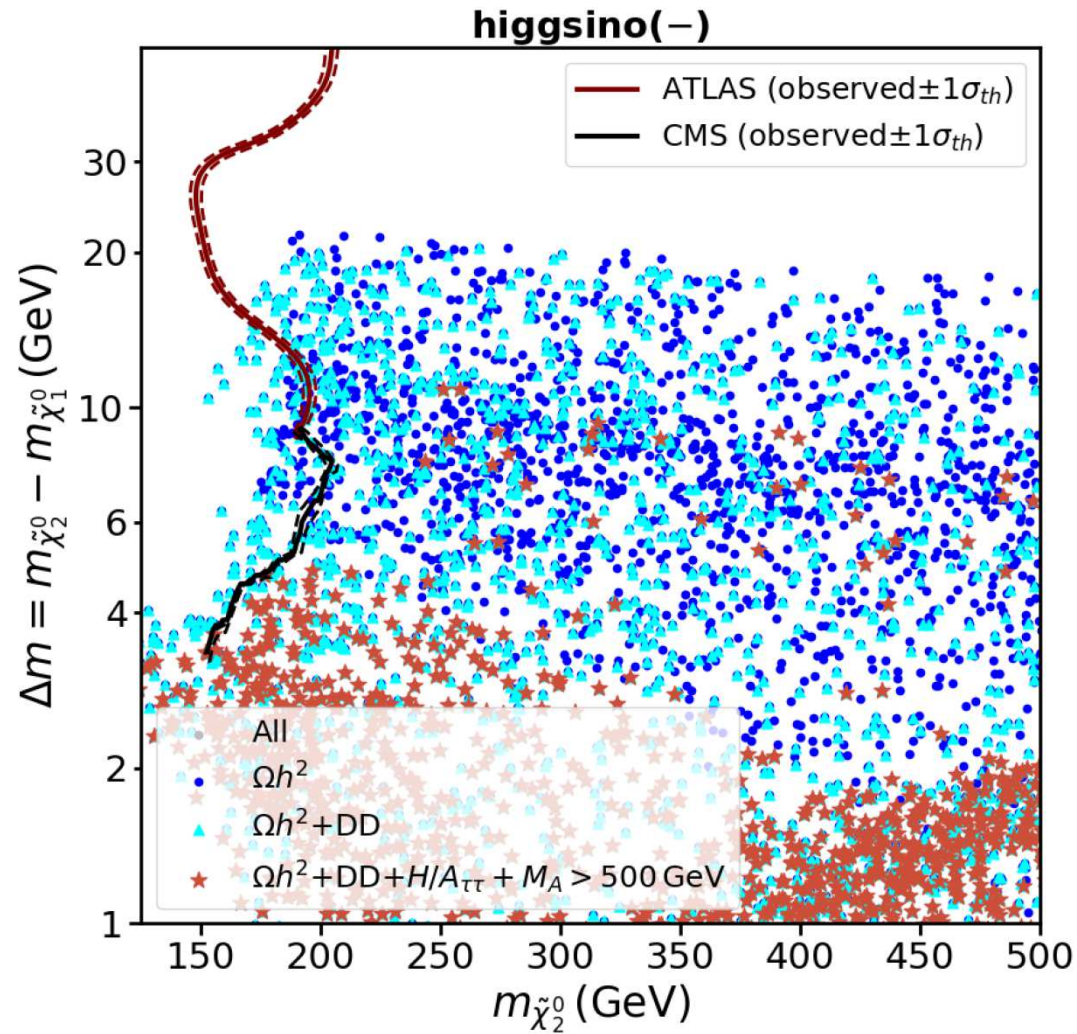
relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

New scan with $M_1 \times \mu < 0$



$\Rightarrow M_A \gtrsim 500$ GeV and $\tan \beta \lesssim 2$ allowed

New scan with $M_1 \times \mu < 0$



⇒ restrictions still cut away the “good parameter space”

⇒ higgsino(-) does not work (in the MSSM)

4. Conclusinos

- For the first time **consistent excesses in ATLAS and CMS in SUSY searches** have been observed.
- $pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 Z^* \tilde{\chi}_1^0 W^*$
with $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 250 \text{ GeV}$, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20 \text{ GeV}$
- Best-fit explanation in the **MSSM: wino/bino DM with $M_1 \times \mu < 0$**

For the first time, ATLAS and CMS see excesses in the search for SUSY particles that are in agreement with each other. These excesses are observed in three different searches in the processes $pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 Z^* \tilde{\chi}_1^0 W^*$: $2l$ and \cancel{E}_T , $3l$ and \cancel{E}_T as well as the mono-jet searches. The masses would be $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 250 \text{ GeV}$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20 \text{ GeV}$. While each search and experiment individually is not significant by itself, the occurrence of excesses in multiple search channels, observed by both ATLAS and CMS, gives rise to the hope that finally a glimpse of BSM physics has been observed. We are eagerly awaiting the corresponding upcoming Run 3 results.

A photograph of a man with reddish-brown hair looking up at a full-body Darth Vader figure. The scene is set in a dark, industrial environment with blue lighting from overhead fixtures. The text "Further Questions?" is overlaid in white on the left side of the image.

Further Questions?