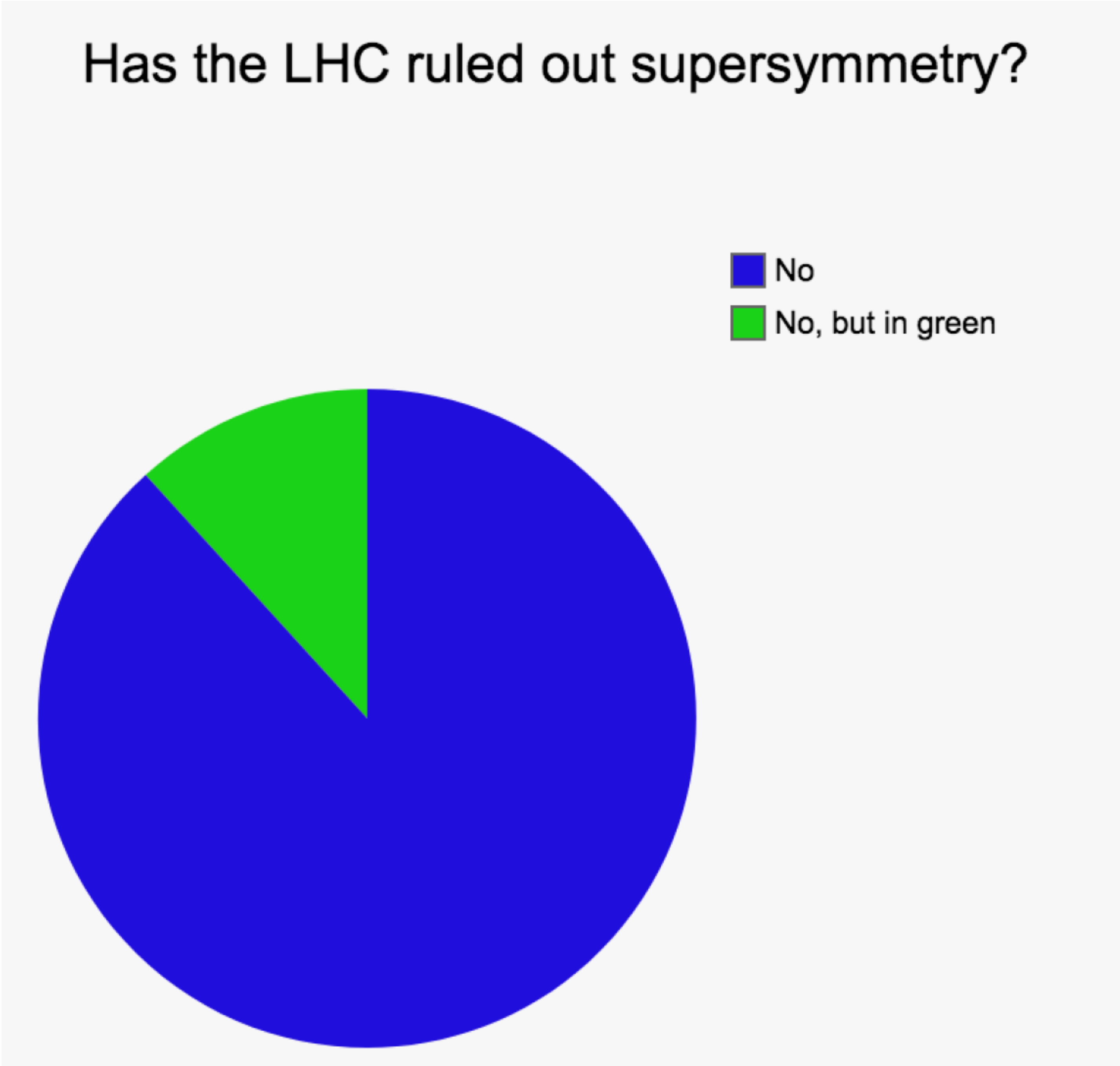

Has the LHC ruled out supersymmetry?
No
No, but in green

SUSY Dark Matter at the LHC?!

Sven Heinemeyer, IFT/MultiDark (CSIC, Madrid)

Xichang, 08/2025

1. The main idea

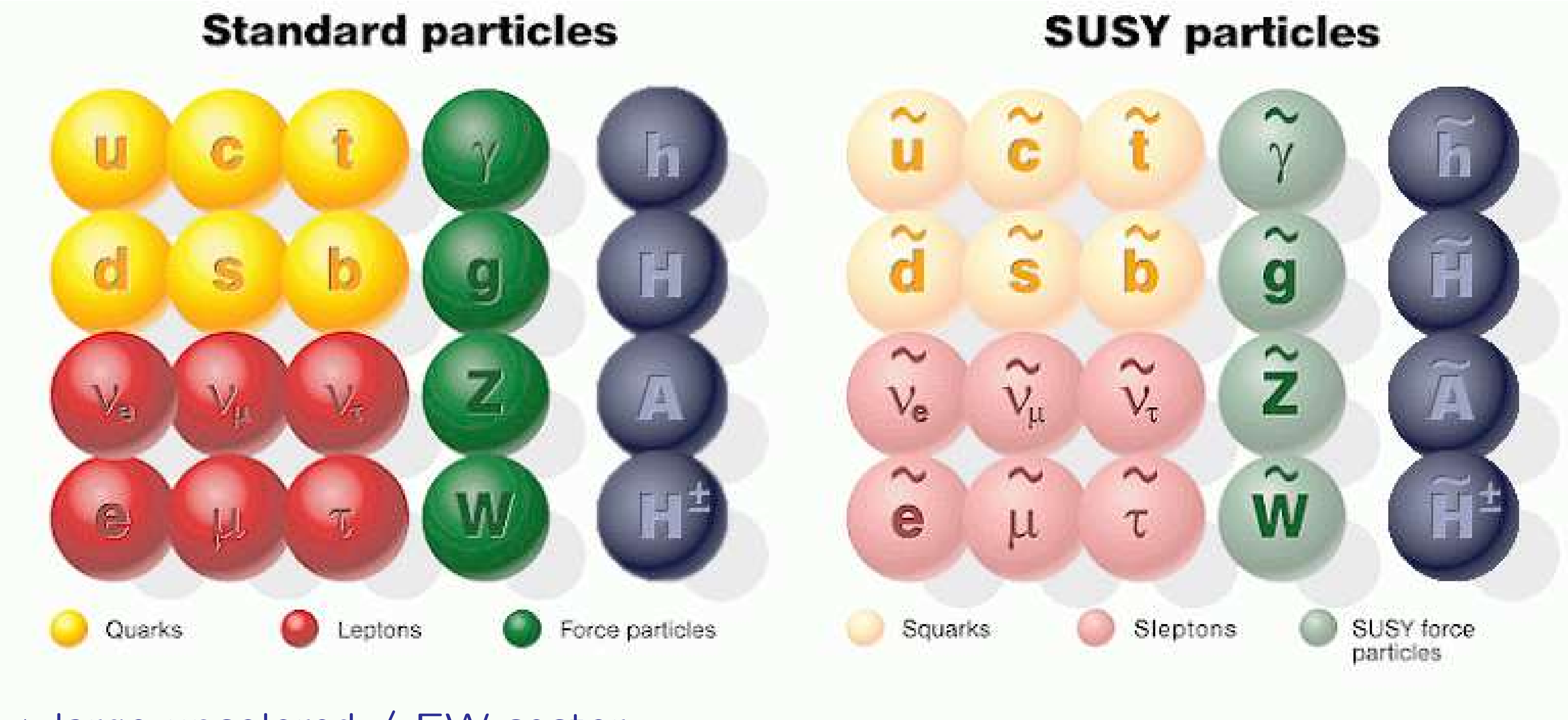
2. Evidence for low-energy SUSY?!

3. Wino/bino vs. higgsino DM

4. Conclusions

1. The main idea

The MSSM



$\Rightarrow$ large uncolored / EW sector

charginos/neutralinos: M_1, M_2, μ, $\tan\beta$ $\Rightarrow$ 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.)

Many options for the correct relic density:

A) wino/bino DM with chargino co-annihilation ($M_1 \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled

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

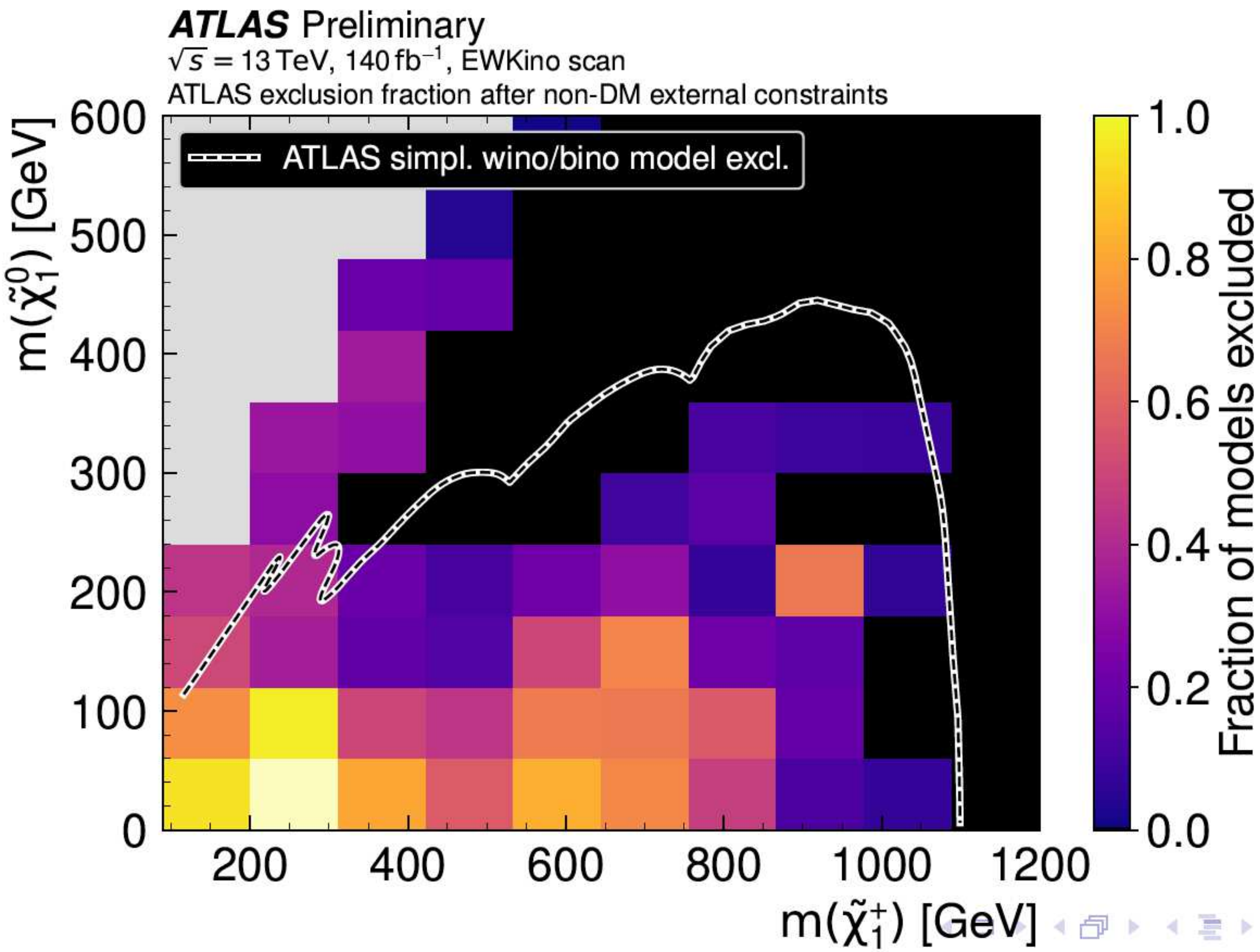
D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)
relic DM density as upper limit (full relic density: $m_{\tilde{\chi}_1^0} \sim 1$ TeV)

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 (full relic density: $m_{\tilde{\chi}_1^0} \sim 3$ TeV)

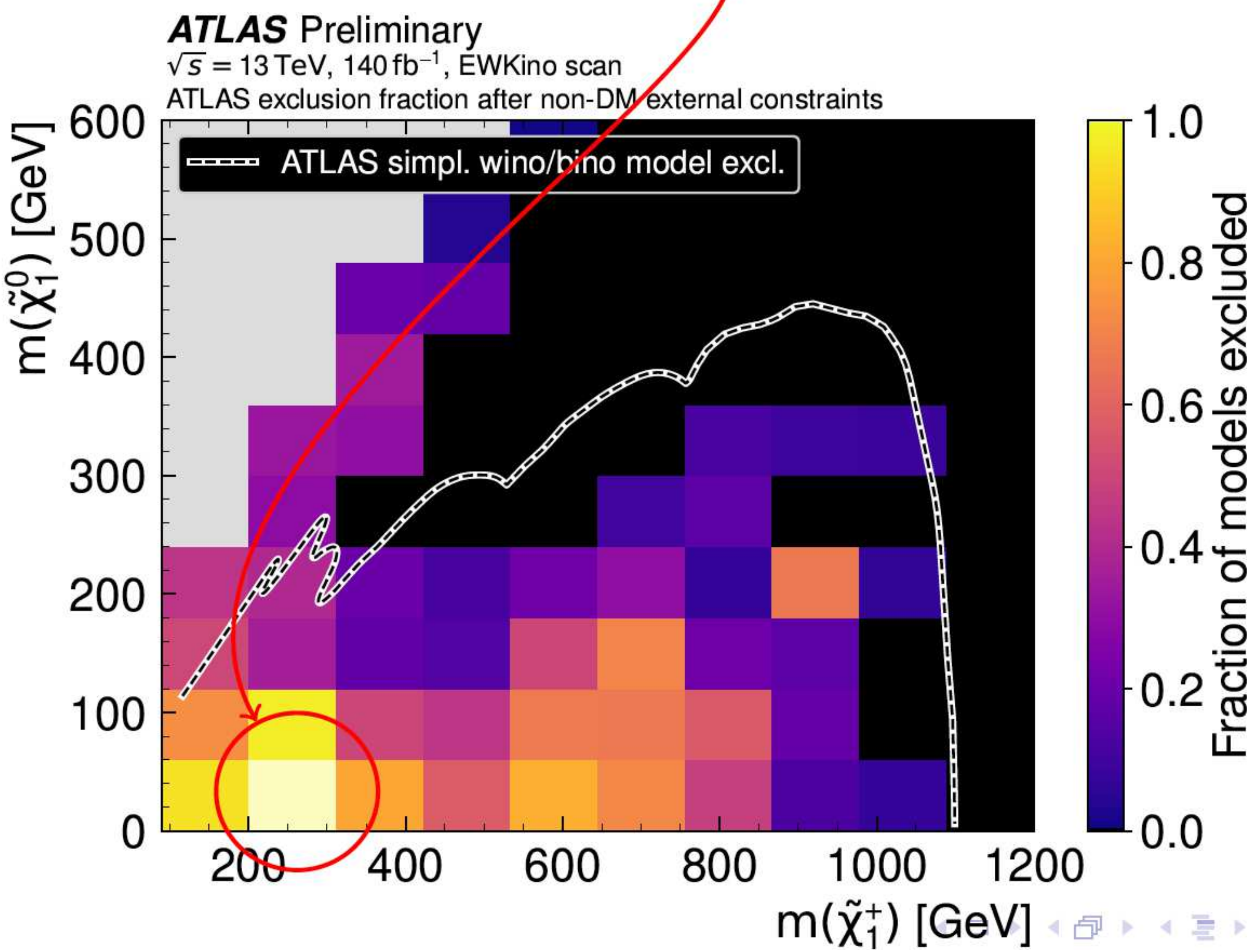
GUT-based scenarios: $M_1 \sim M_2/2 \sim M_3/6$
$\Rightarrow$ only possible for B/C and D

$m_{\tilde{g}} \gtrsim 2$ TeV $\Rightarrow M_1 \sim M_2/2 \gtrsim 350$ GeV

2. Evidence for low-energy SUSY?!


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}, EWKino scan
ATLAS exclusion fraction after non-DM external constraints
ATLAS simpl. wino/bino model excl.
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_1^{\pm})$ [GeV]
Fraction of models excluded
0
100
200
300
400
500
600
200
400
600
800
1000
1200
0.0
0.2
0.4
0.6
0.8
1.0

Only this one is actually excluded !



⇒ Our "models" predict low chargino/neutralino masses

Possible search channels:

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

Possible kinematic situations:

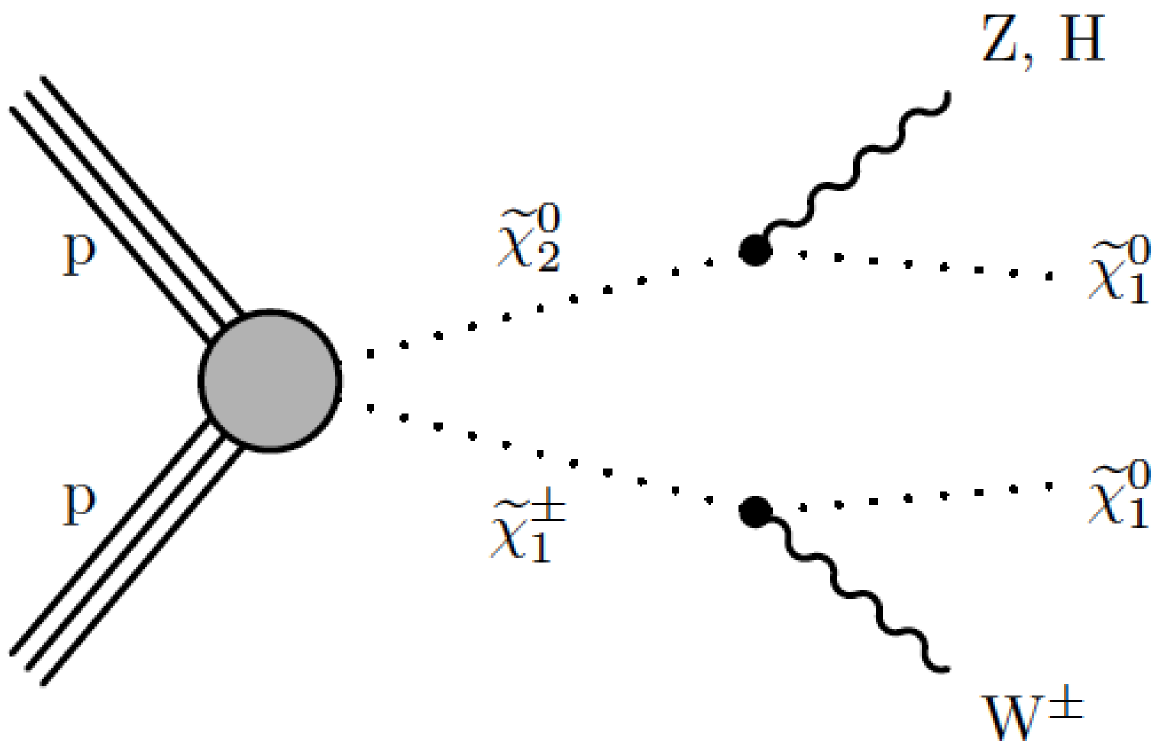
- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

⇒ 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:



Possible scenario: "compressed" spectra w/ heavy sleptons:

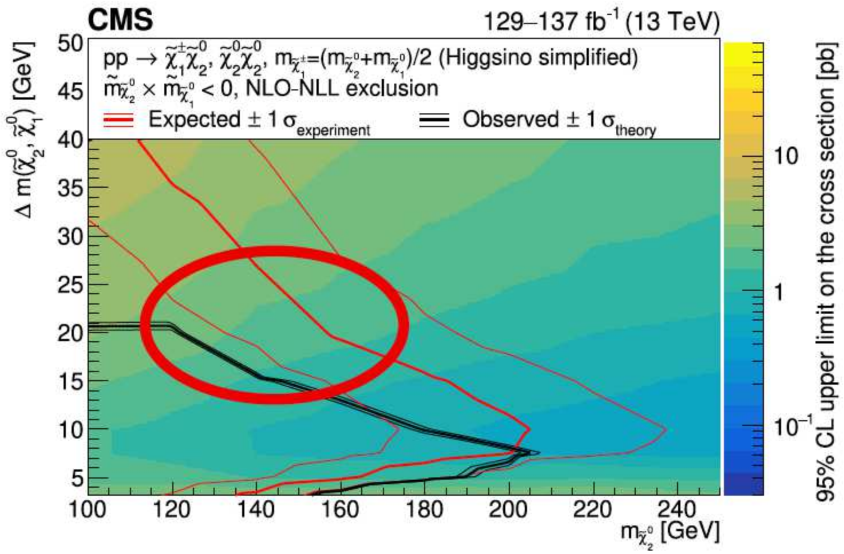
$Z^* \to \ell^+\ell^-$ (or $q\bar{q}$), $W^* \to \ell\nu_\ell$ (or $q\bar{q}'$) $(\ell = e, \mu)$

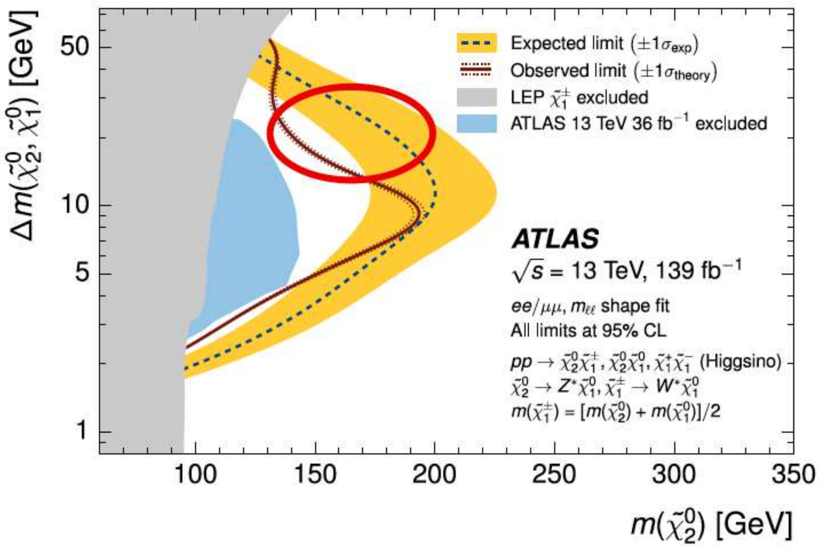
⇒ two experimental signatures: 2 or 3 soft leptons

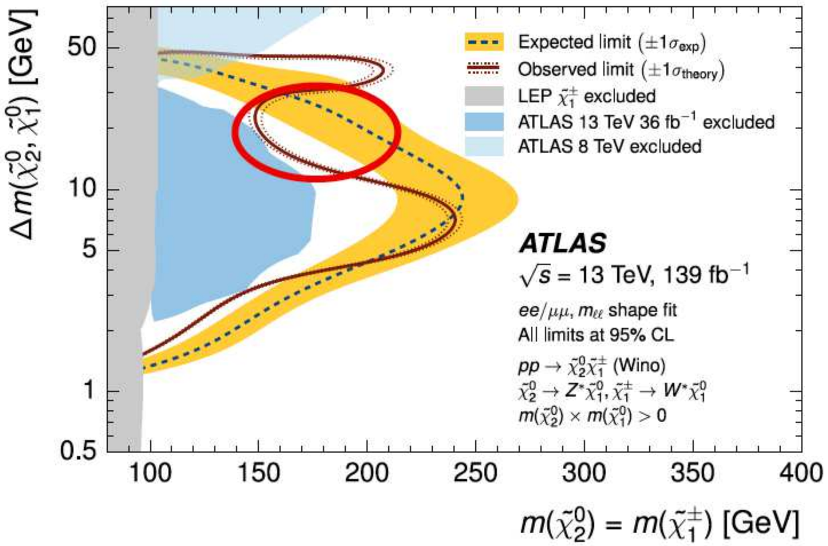
⇒ two experiments: ATLAS and CMS ⇒ experimental results?

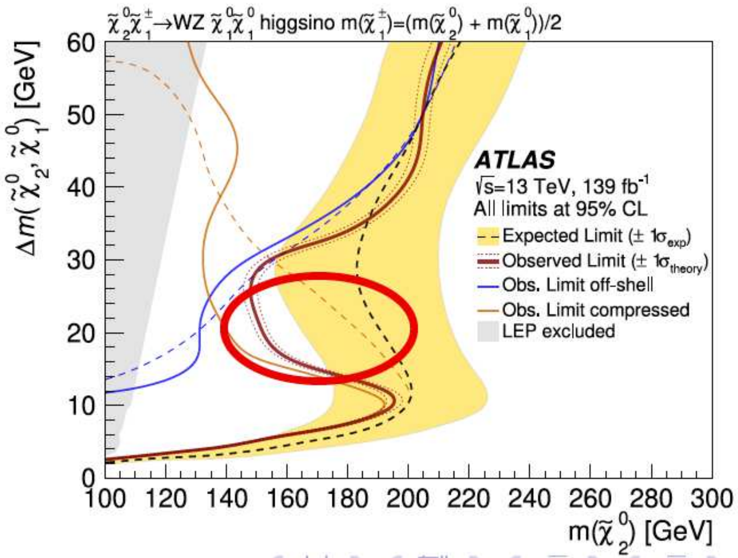
Results: “compressed” spectra w/ heavy sleptons:

[*taken from M. Berggren ’23*]

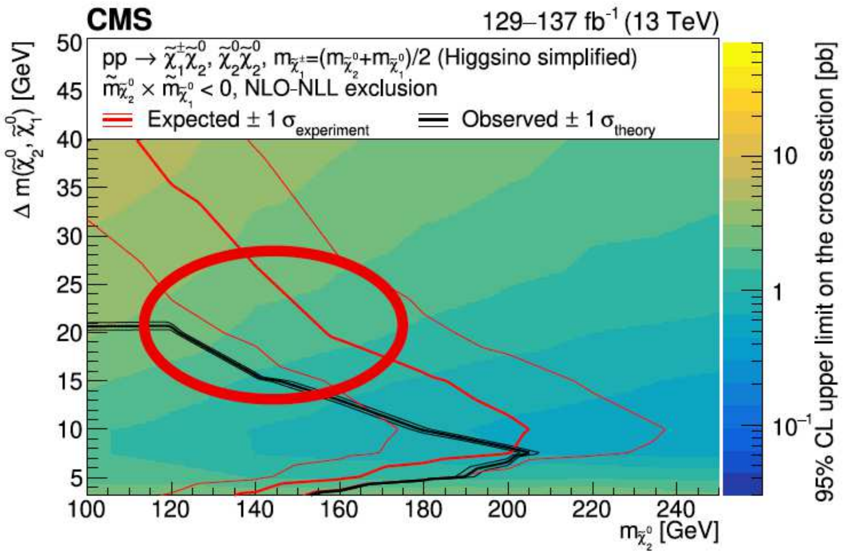


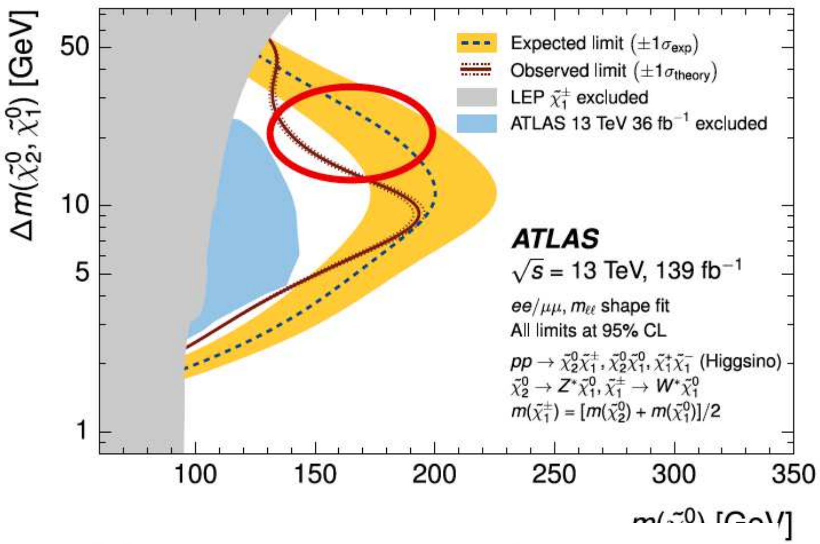


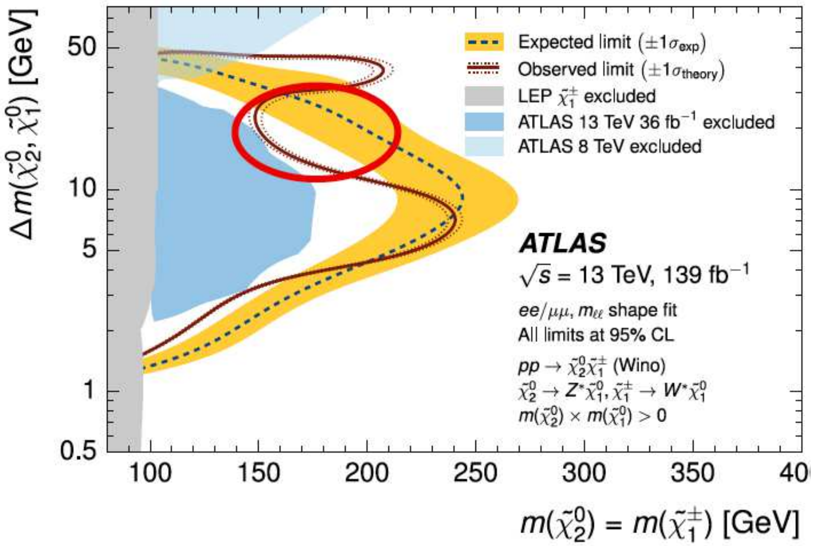


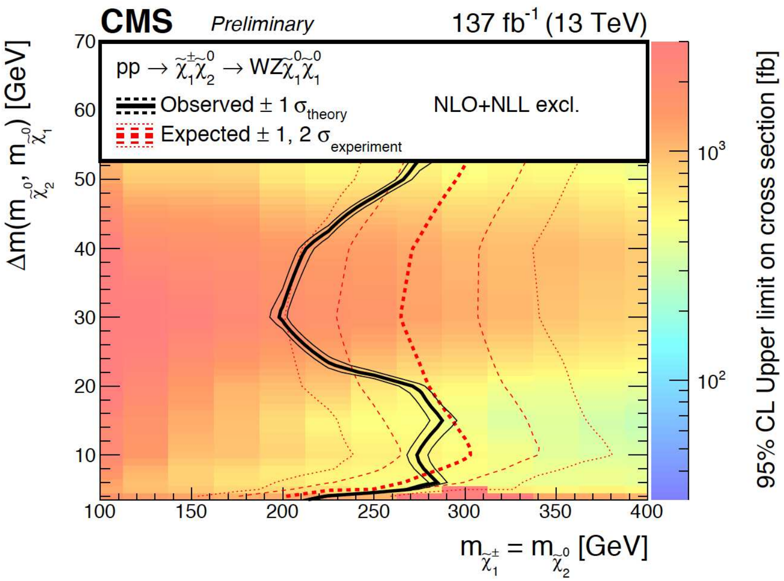


⇒ planes: $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm}$ vs. $\Delta m = m_{\tilde\chi_2^0} - m_{\tilde\chi_1^0}$









⇒ planes: $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm}$ vs. $\Delta m = m_{\tilde\chi_2^0} - m_{\tilde\chi_1^0}$

Consistent excesses point towards:

– $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \gtrsim 200$ GeV
– $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}\,(20$ GeV$)$

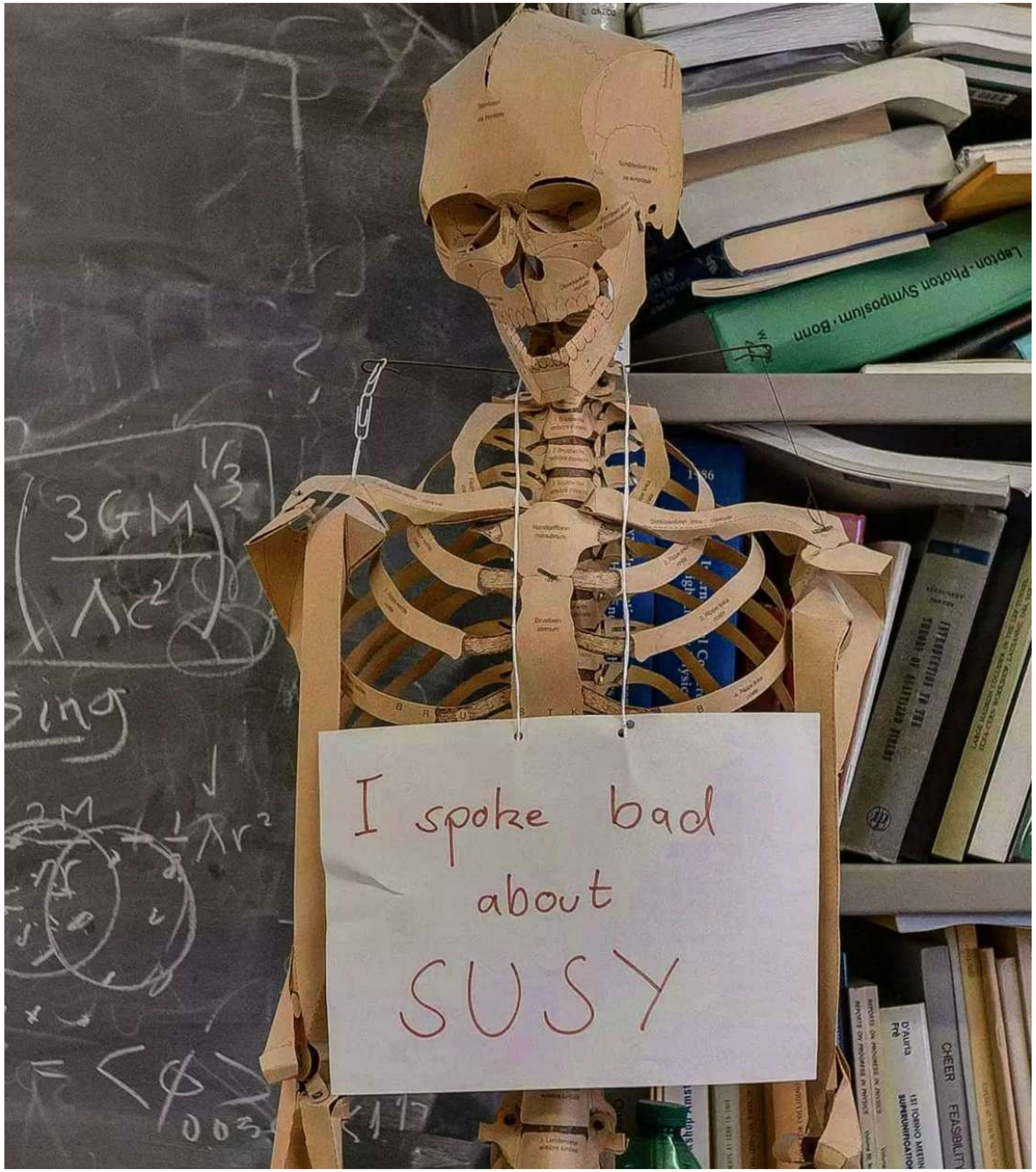
A) wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
Never: $M_1 \sim M_2\,/2$ $\boxed{\Rightarrow \text{not GUT-based}}$

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 (full relic density: $m_{\tilde{\chi}_1^0} \sim 1$ TeV)
Possible: $M_1 \sim M_2\,/2$ $\boxed{\Rightarrow \text{can be GUT-based}}$

$\Rightarrow$ can they fit the excesses?

3. Wino/bino vs. higgsino DM

[*M. Chakraborti, S.H., I. Saha '24*]



A) Wino/bino DM with chargino co-annihilation

Parameter scan:

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

$$|M_1| \le M_2 \le 1.1|M_1|\ ,$$

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

$$2 \le \tan\beta \le 60,$$

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

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

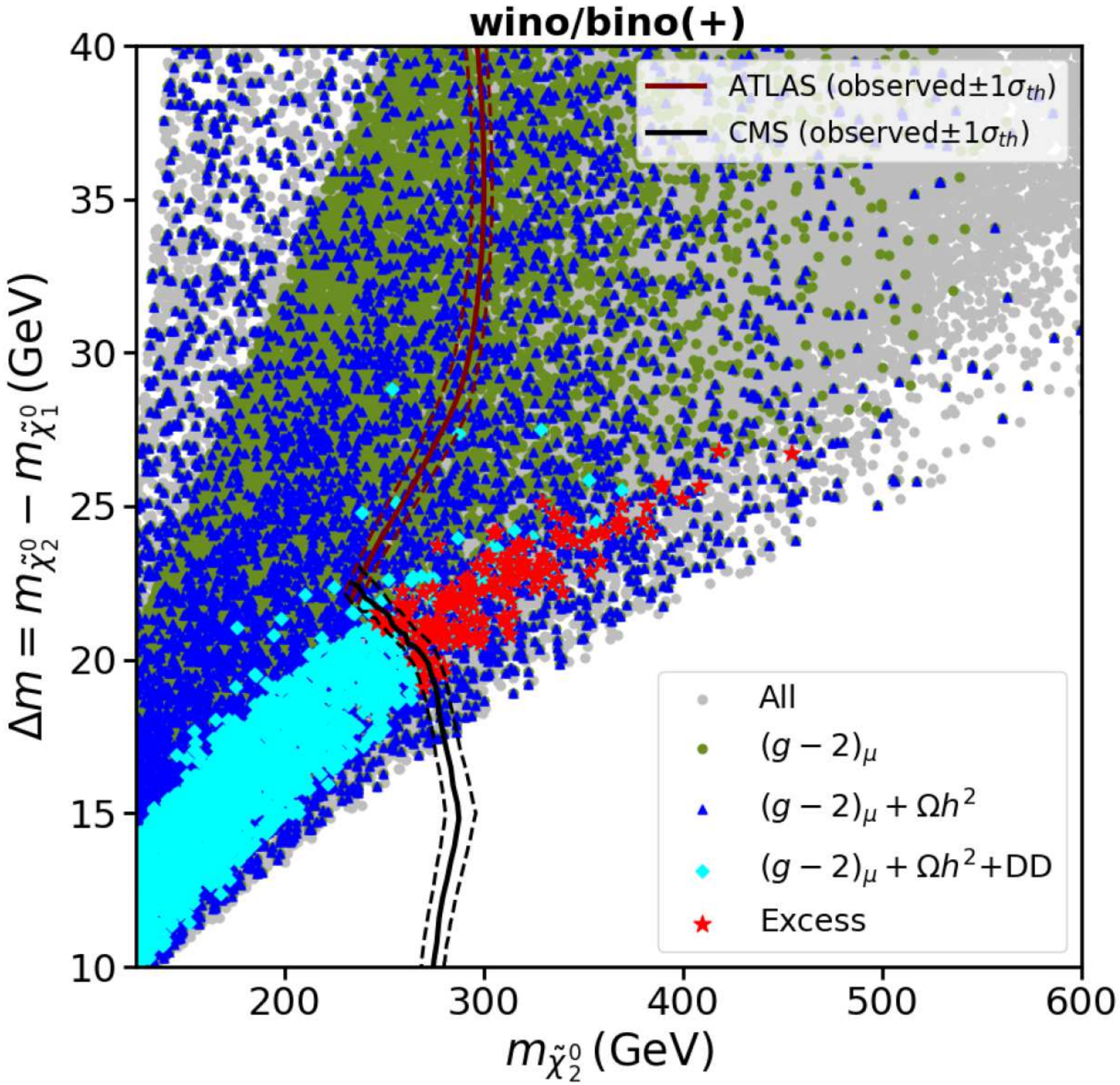
(latter condition only to make the analysis simpler, no relevant effect)

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

wino/bino(−): $M_1 \times \mu < 0$

relic DM density can be 100% fulfilled

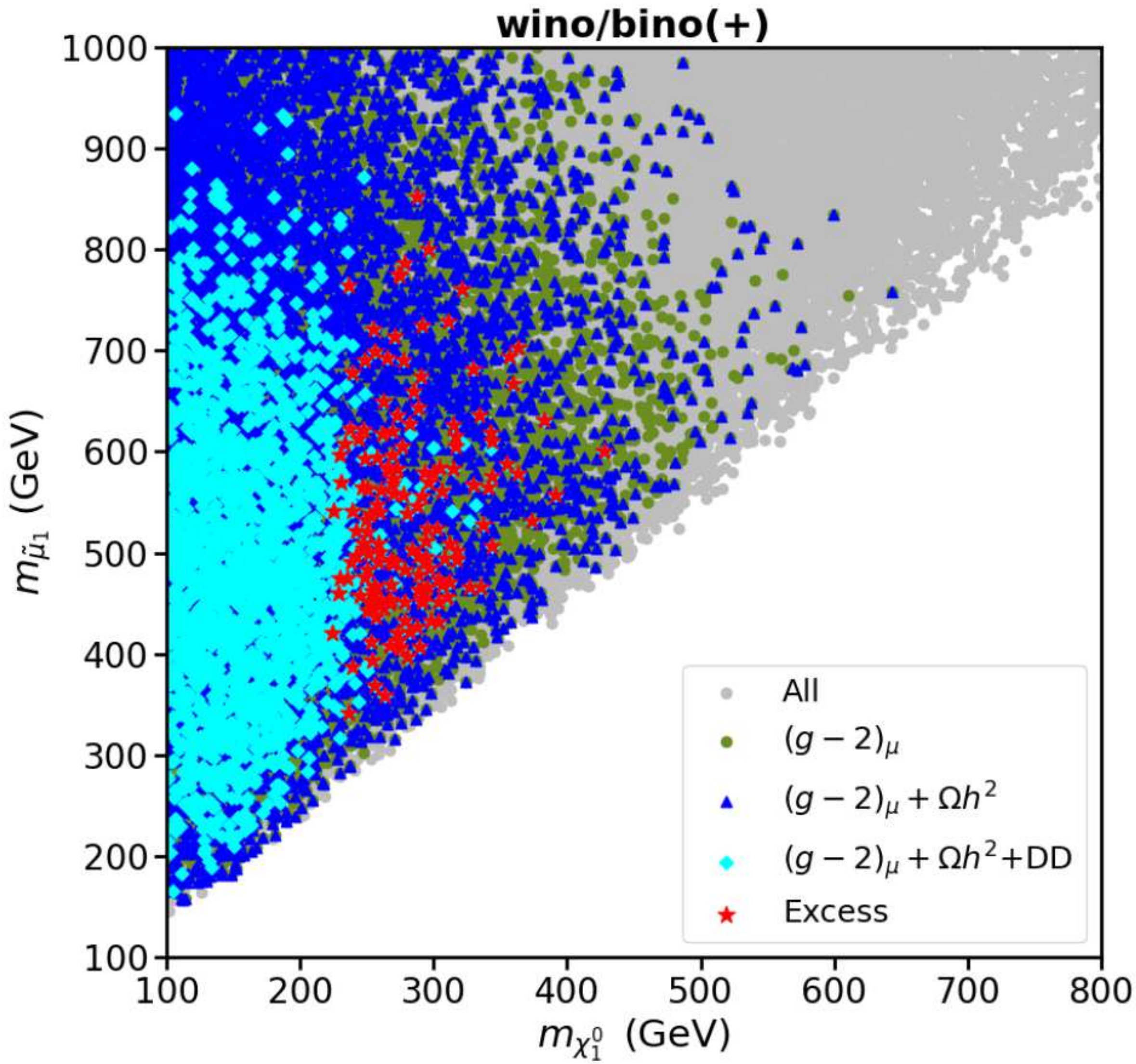
wino/bino(+): results in the $m_{\tilde{\chi}^0_2}$-Δm plane:



$\Rightarrow$ excesses not fully at the same Δm . . .

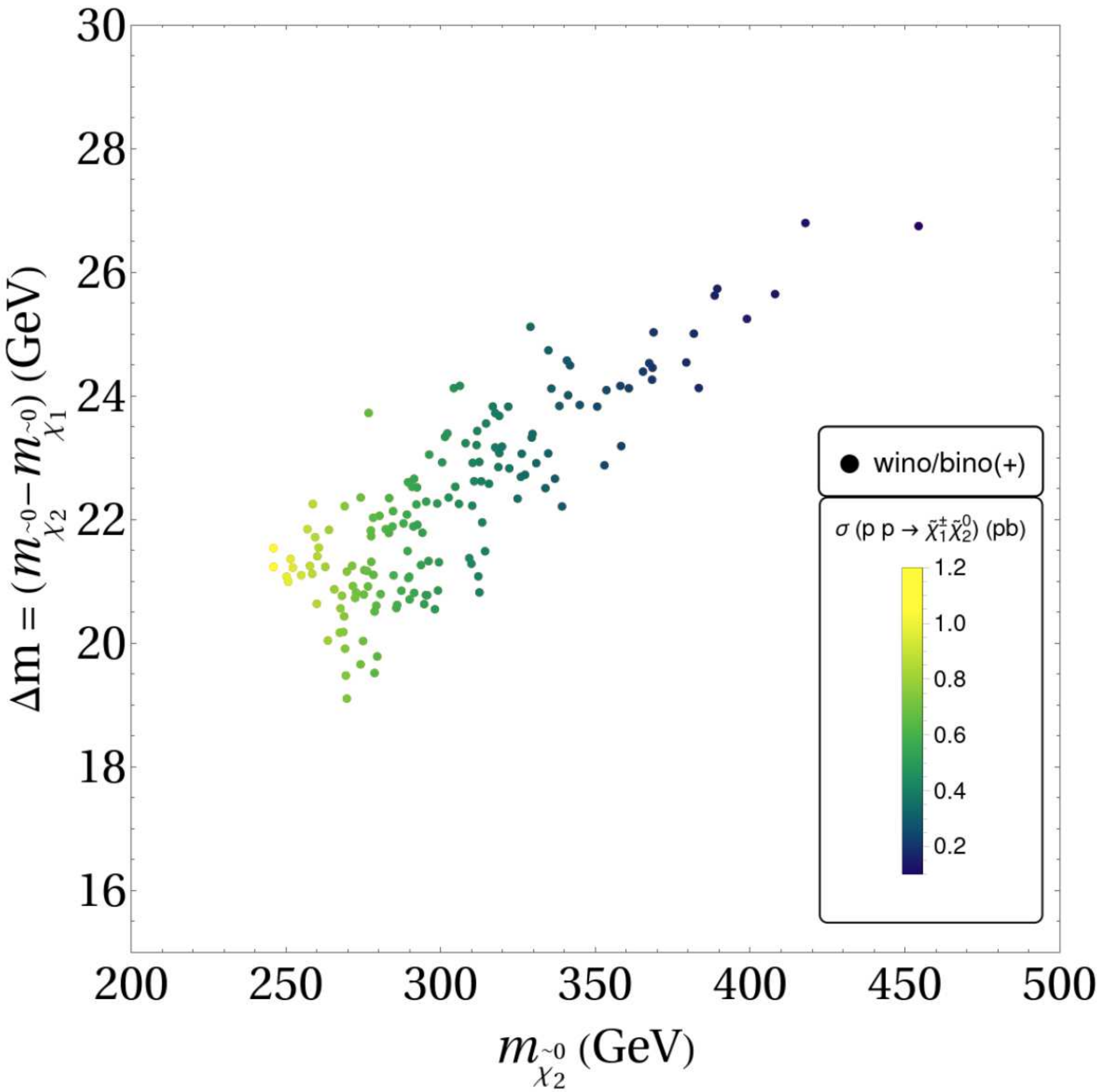
$\Rightarrow$ but many "good points" at $\Delta m \sim 20$ GeV

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



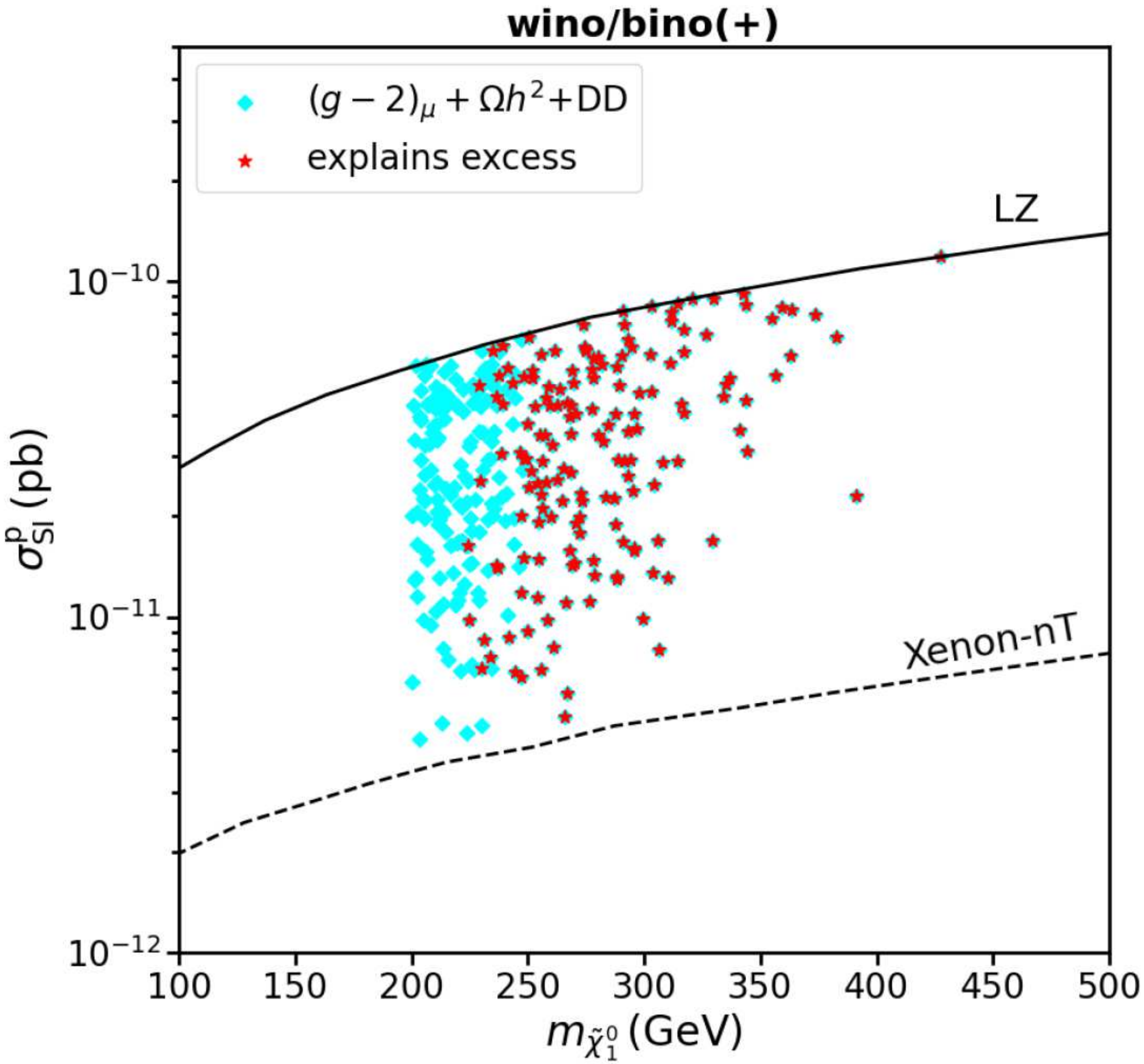
$\Rightarrow$ no limits on slepton masses (as expected)

wino/bino(+): LHC cross sections:



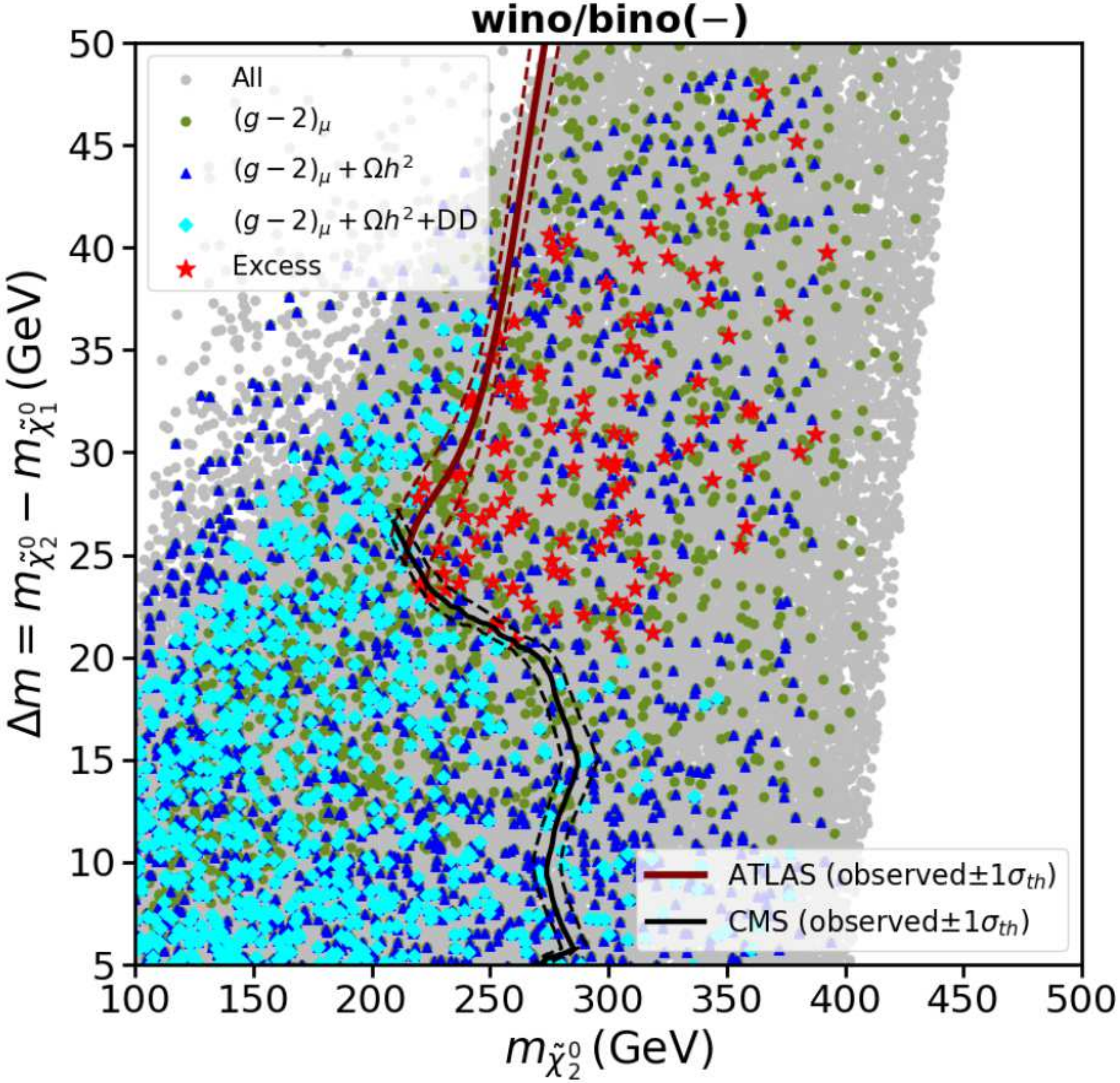
$\Rightarrow$ for lower massess XS have roughly the size required by excesses

wino/bino(+): direct detection prospects:



$\Rightarrow$ wino/bino(+)/$\tilde\chi_1^\pm$ co-annihiliation will be covered by XENON-nT/LZ

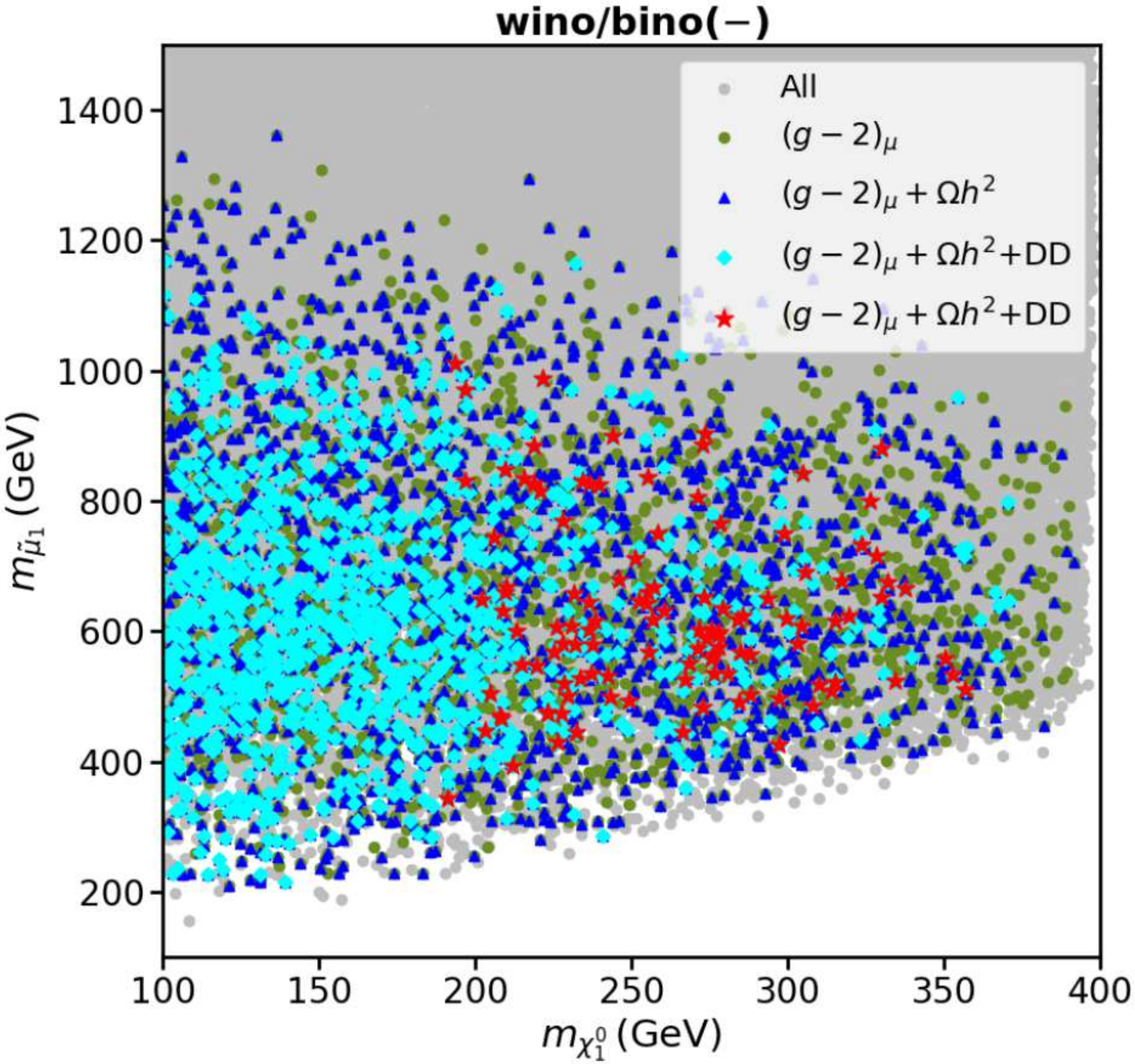
wino/bino(−): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



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

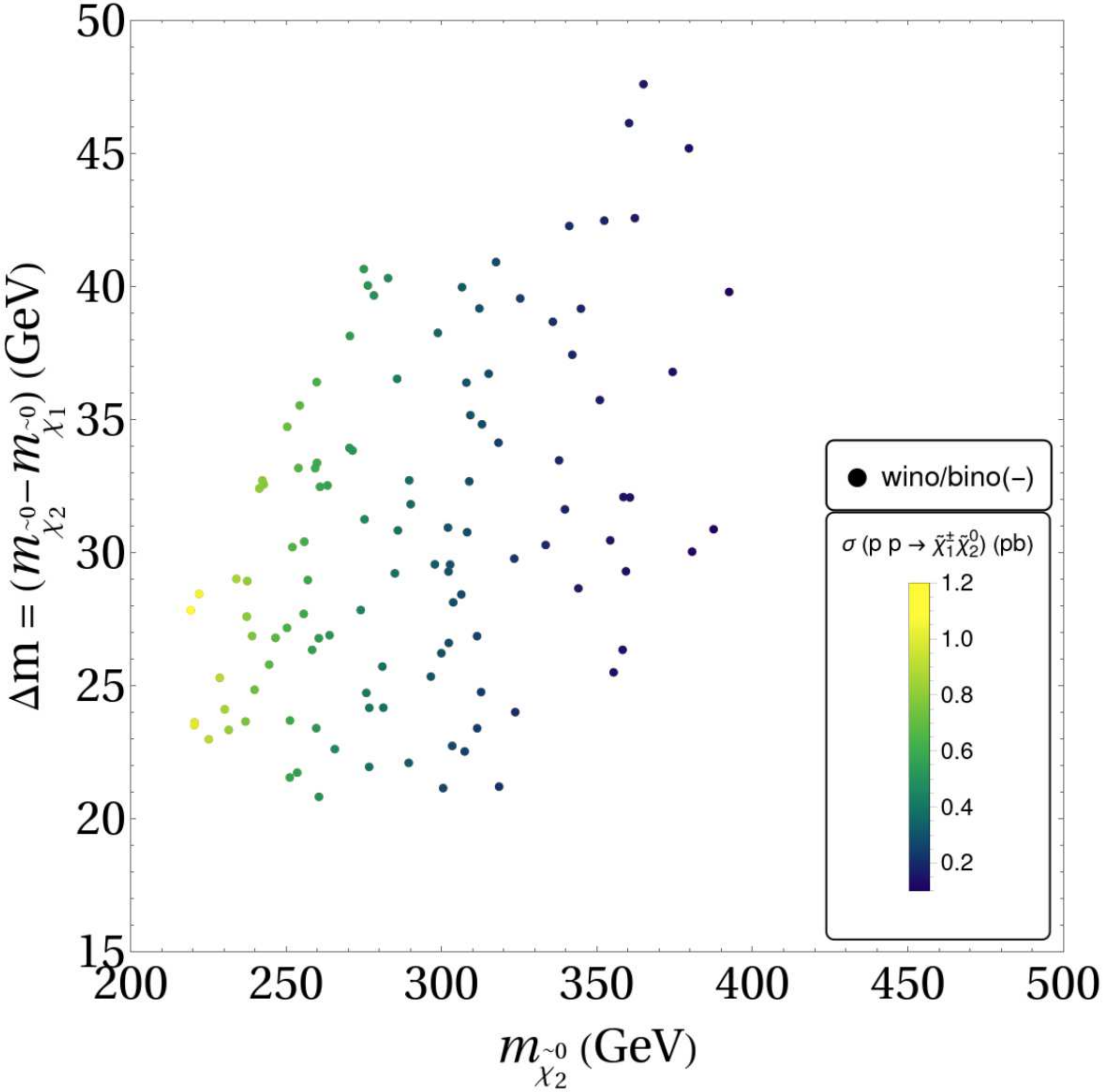
⇒ but many "good points" at $\Delta m \sim 25$ GeV

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



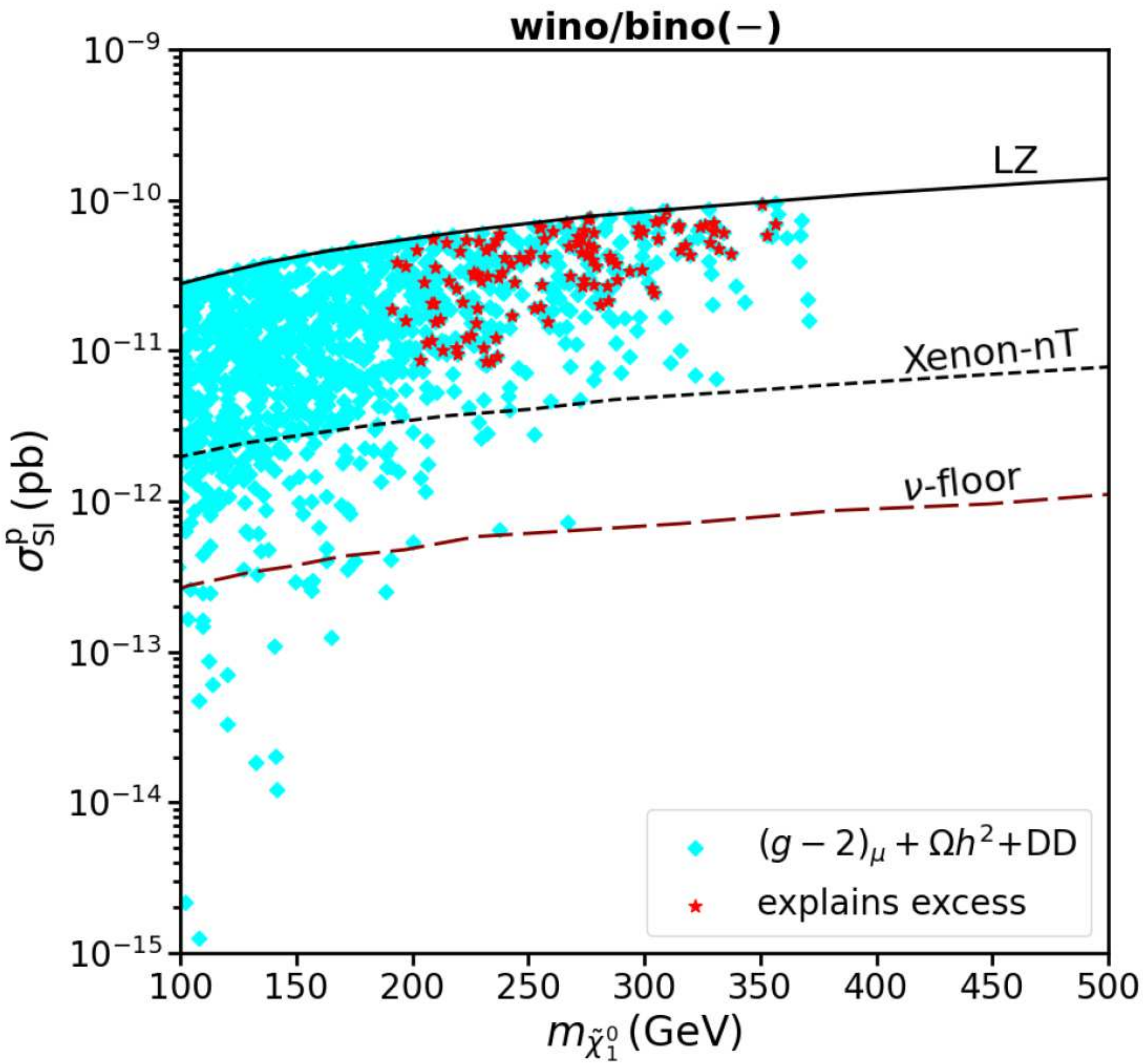
⇒ no limits on slepton masses (as expected)

wino/bino(−): LHC cross sections:



⇒ for lower masses XS have roughly the size required by excesses

wino/bino(−): direct detection prospects:



⇒ wino/bino(−)/$\tilde\chi_1^\pm$ co-annihiliation will be covered by XENON-nT/LZ

⇒ low mass points now excluded ⇒ would have been a problem for DD

D) Higgsino DM

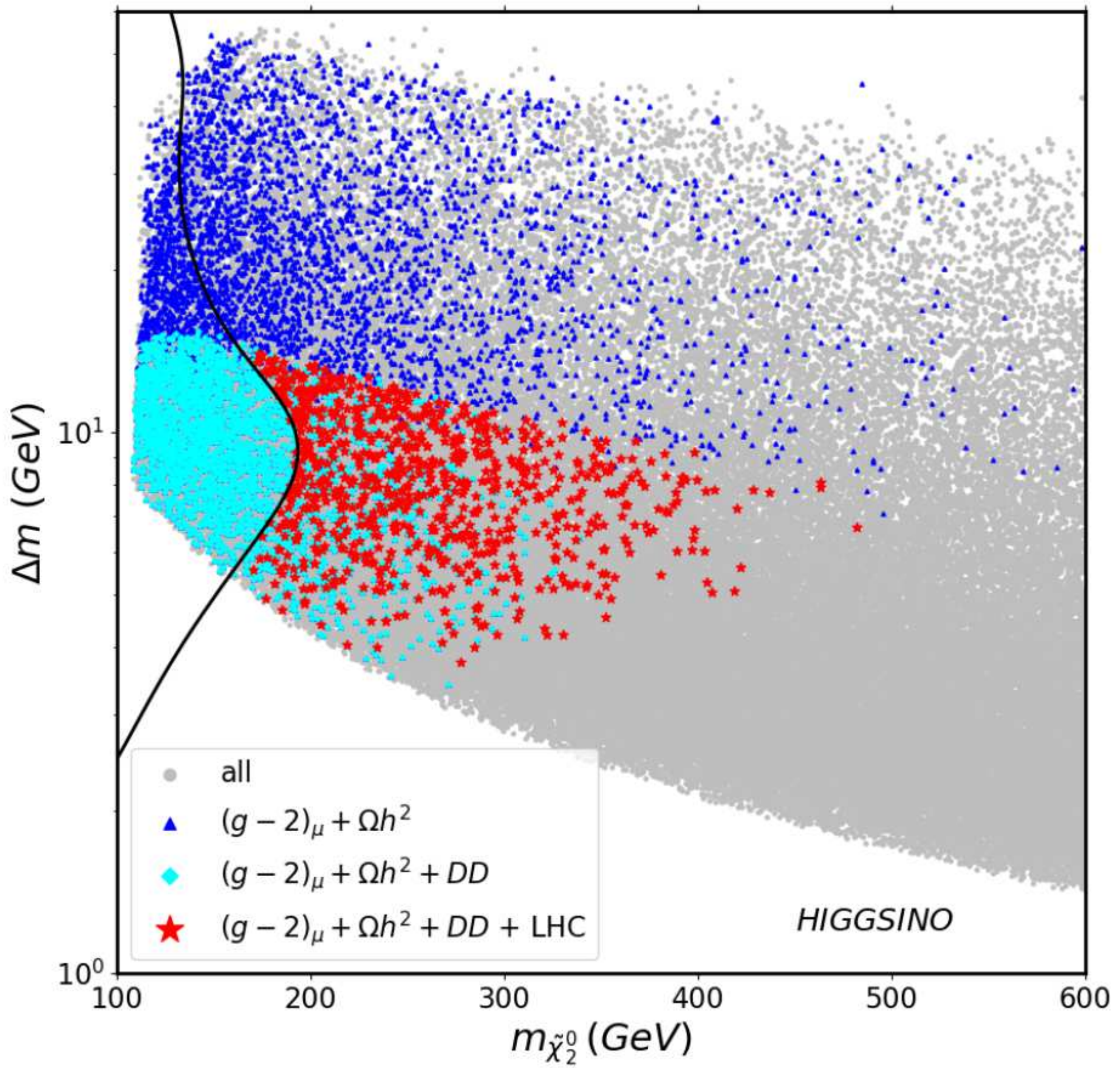
Original parameter scan: $(M_1 \times \mu > 0)$

$$
\begin{aligned}
100\ \text{GeV} \le \mu &\le 1.2\ \text{TeV}\ , \\
1.1\mu \le M_1 &\le 10\mu\ , \\
1.1 M_2 \le \mu &\le 10\mu\ , \\
5 \le \tan\beta &\le 60, \\
100\ \text{GeV} \le m_{\tilde{L}}, m_{\tilde{R}} &\le 2\ \text{TeV},
\end{aligned}
$$

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

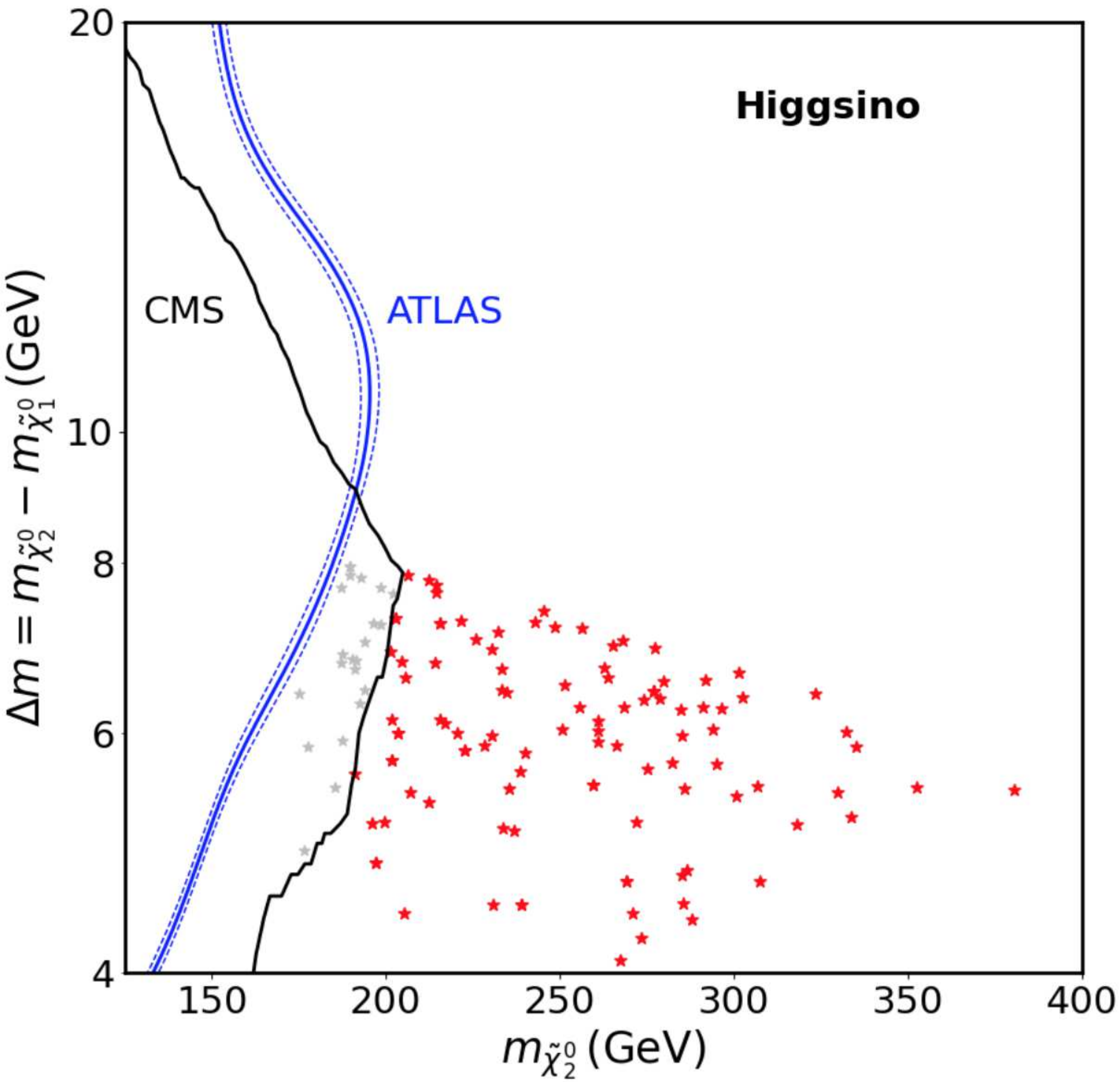
Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with the excesses

Results in the $m_{\tilde{\chi}_2^0}$-Δm plane with OLD DD bound: [2021]



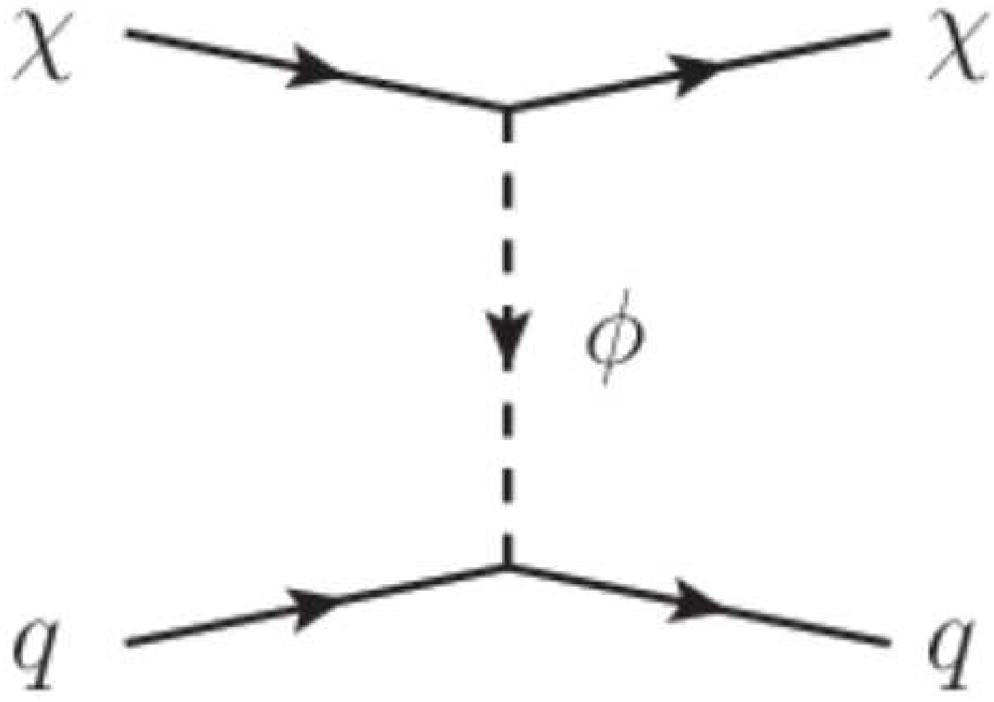
$\Rightarrow$ direct detection is the limiting factor on Δm

Results in the $m_{\tilde{\chi}_2^0}$-Δm plane with new DD bound: [*PRELIMINARY*]



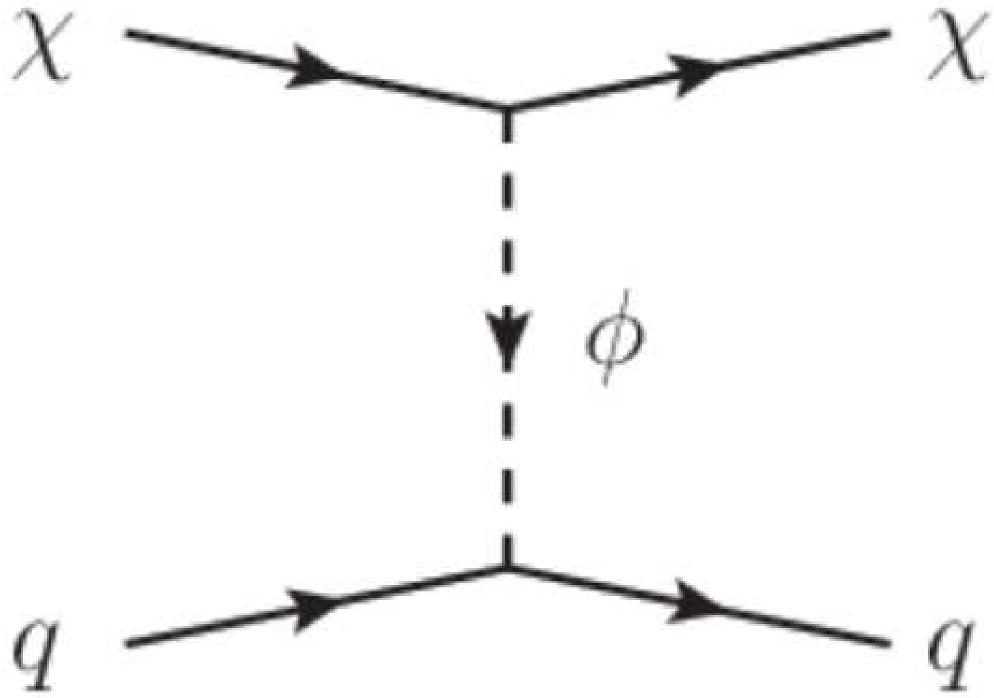
$\Rightarrow$ excess not fitted :-($\Rightarrow$ DD cuts away the "good points"

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 $M_1 < 0$

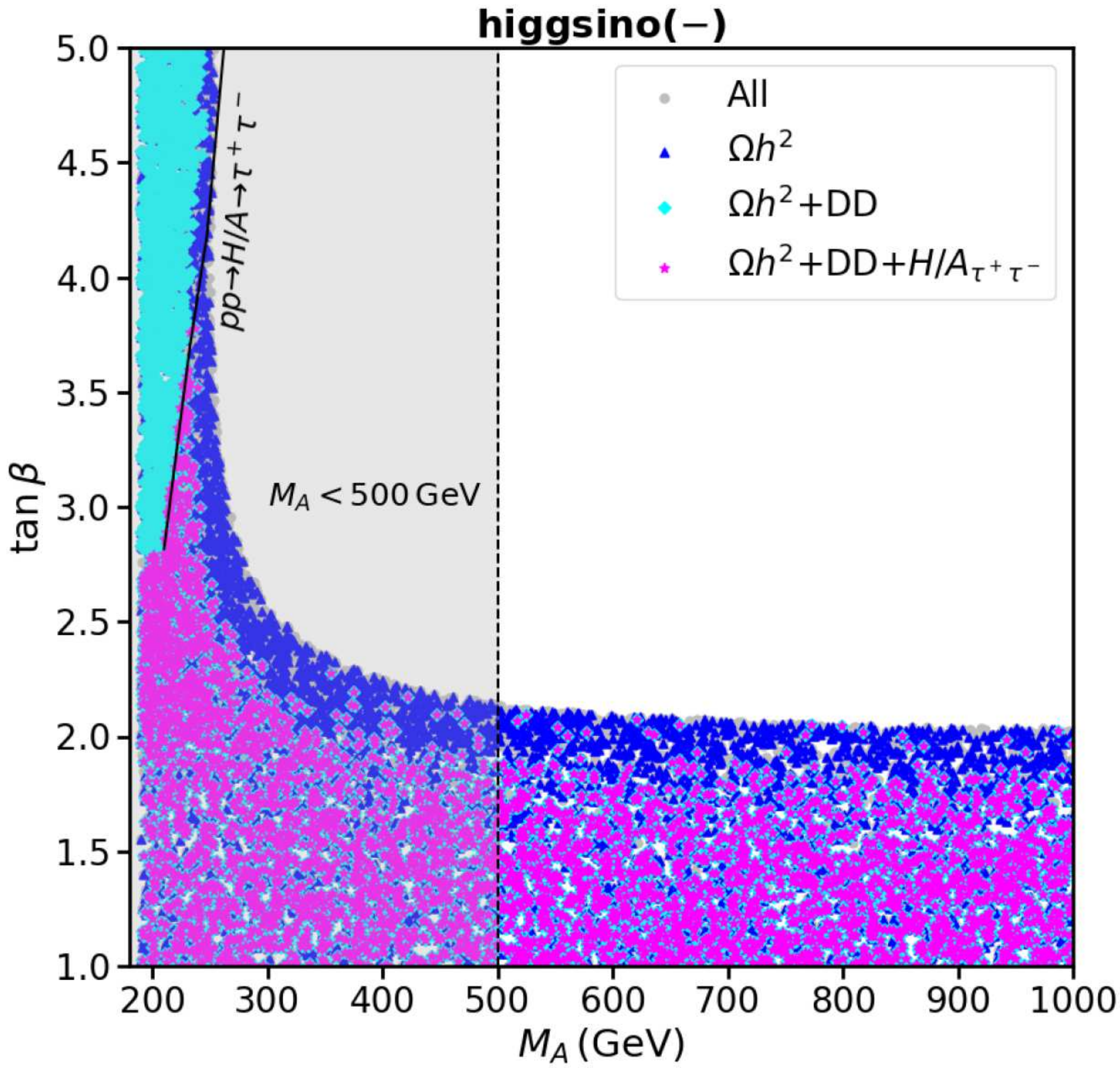
New scan with $M_1 \times \mu < 0$

$$
\begin{aligned}
-190 \text{ GeV} \leq M_1 \leq -1500 \text{ GeV} \;, \\
M_2 = 2 \text{ TeV} \;, \\
\mu = \frac{-2 M_1 \tan\beta}{4 + x_1 \tan^2\beta}, \quad x_1 = \frac{m_h^2}{m_H^2} \;, \\
5 \leq \tan\beta \leq 50 \;, \\
190 \leq M_A \leq 1200 \;, \\
2 M_1 \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 1500 \text{ GeV} \;,
\end{aligned}
$$

Condition on μ and M_1: exact blind spot conditions

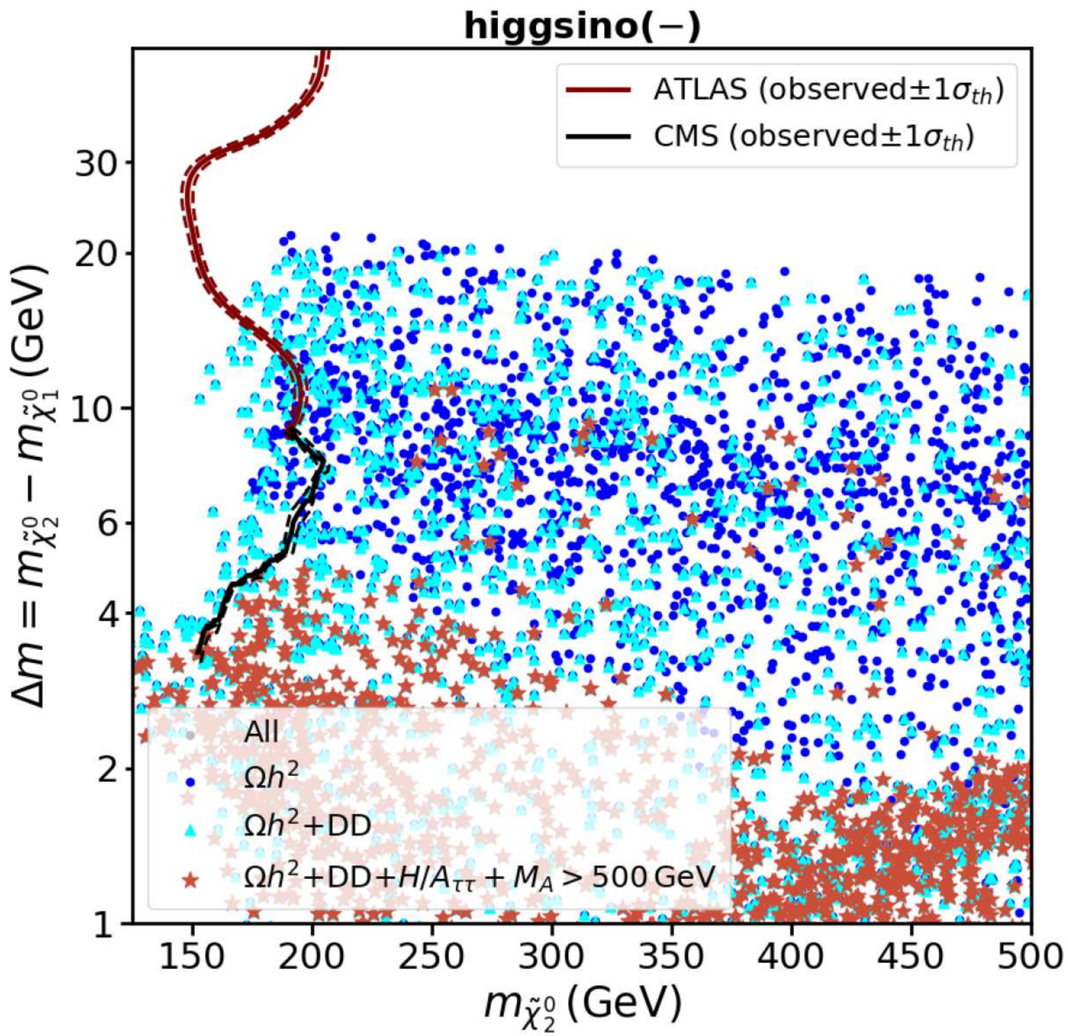
relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

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



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

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

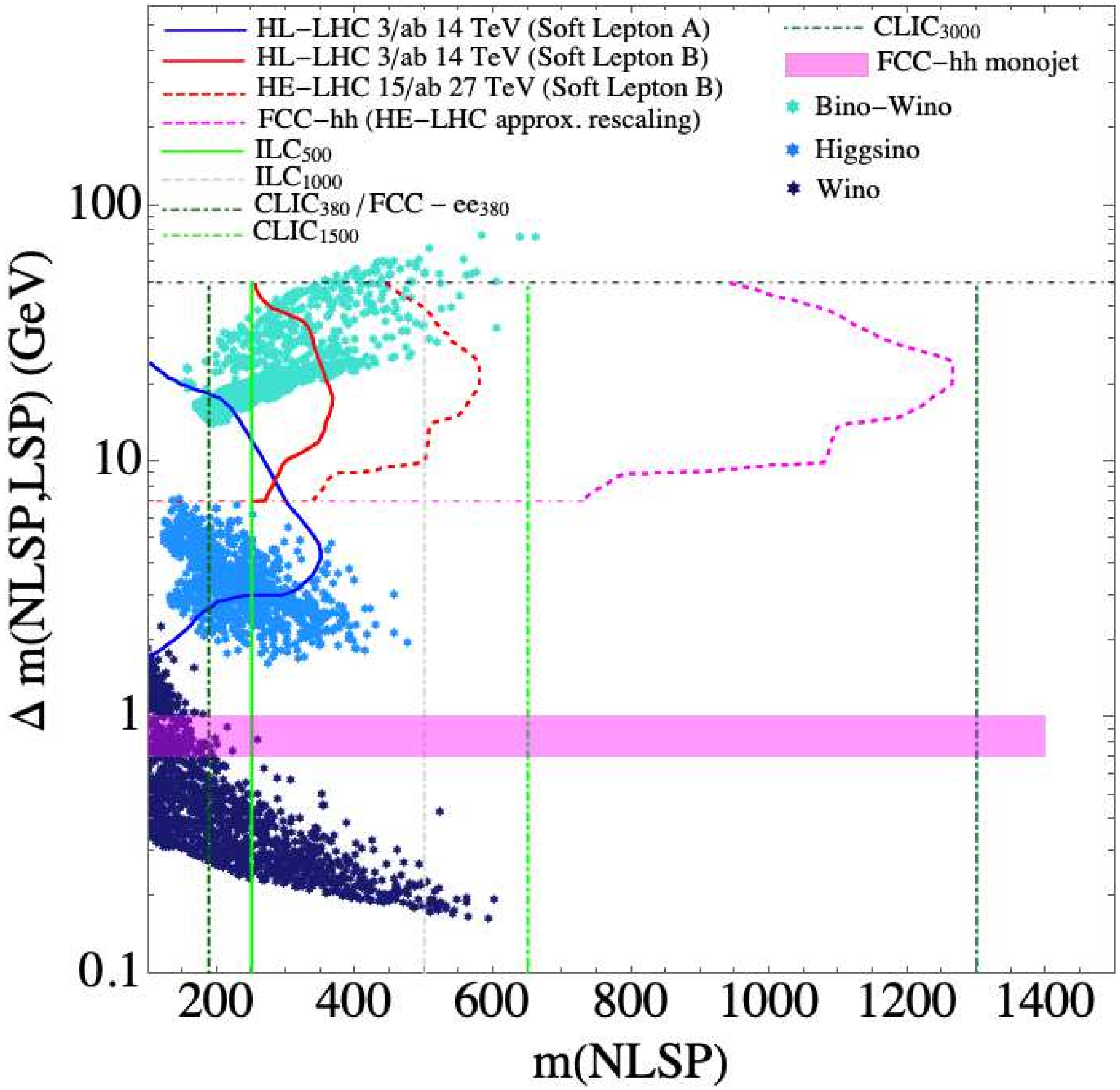


$\Rightarrow$ restrictions still cut away the "good parameter space"

$\Rightarrow$ higgsino(−) does not work (in the MSSM)

Compressed spectra at current and future colliders

Higgsino, wino and bino/wino DM:



⇒ excesses can be covered “in any case” at the ILC500/ILC1000

4. Conclusinos

- For the first time consistent excesses in ATLAS and CMS in SUSY searches have been observed.

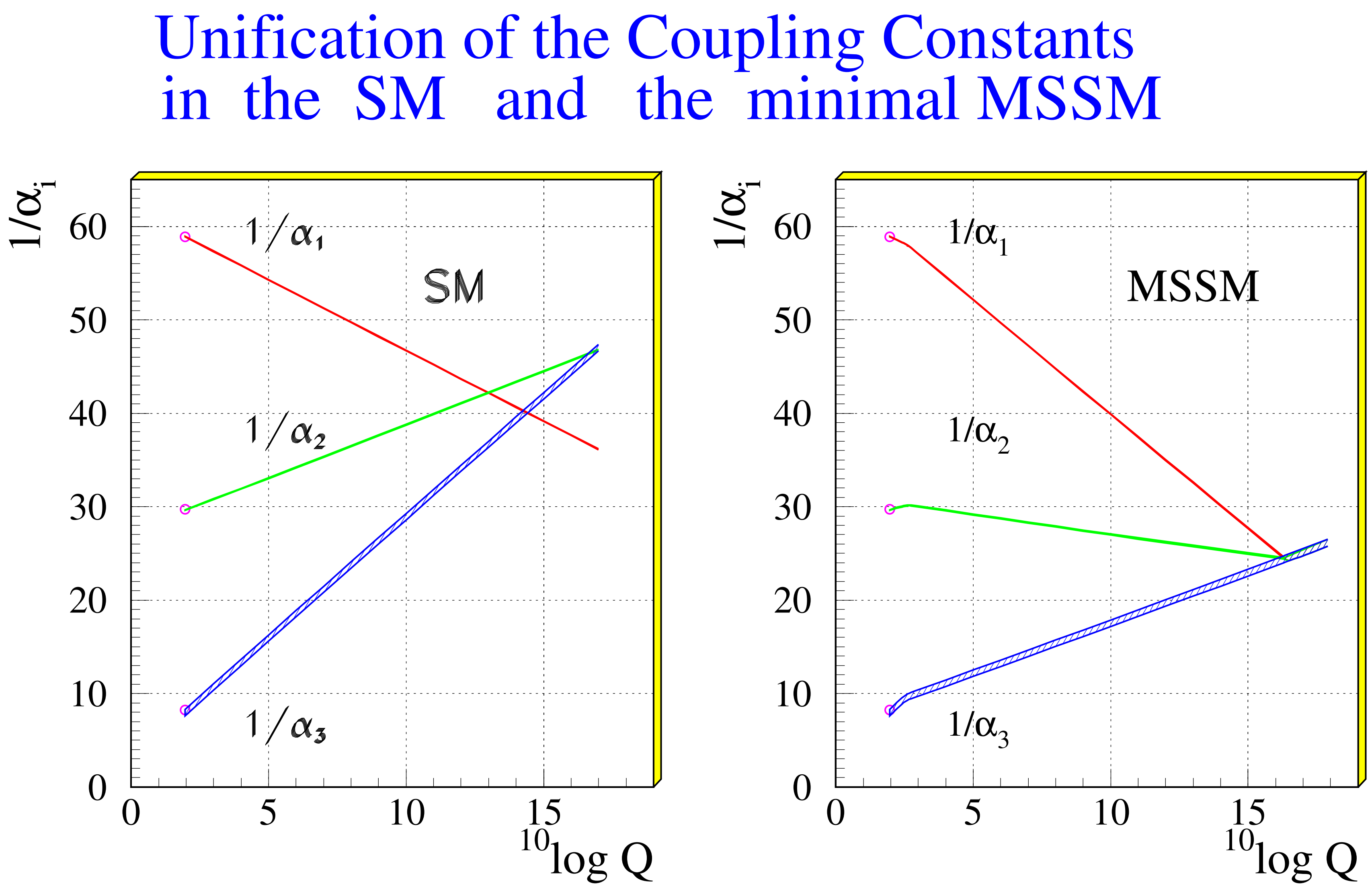
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 Z^* \; \tilde{\chi}_1^0 W^*$
  with $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 200$ GeV, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV

- 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 $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 Z^* \; \tilde{\chi}_1^0 W^*$: $2l$ and $\not{E}_T$, $3l$ and $\not{E}_T$ as well as the mono-jet searches. The masses would be $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 250$ GeV and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV. While each search and experiment individually is not significant by itself, the occurence 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.

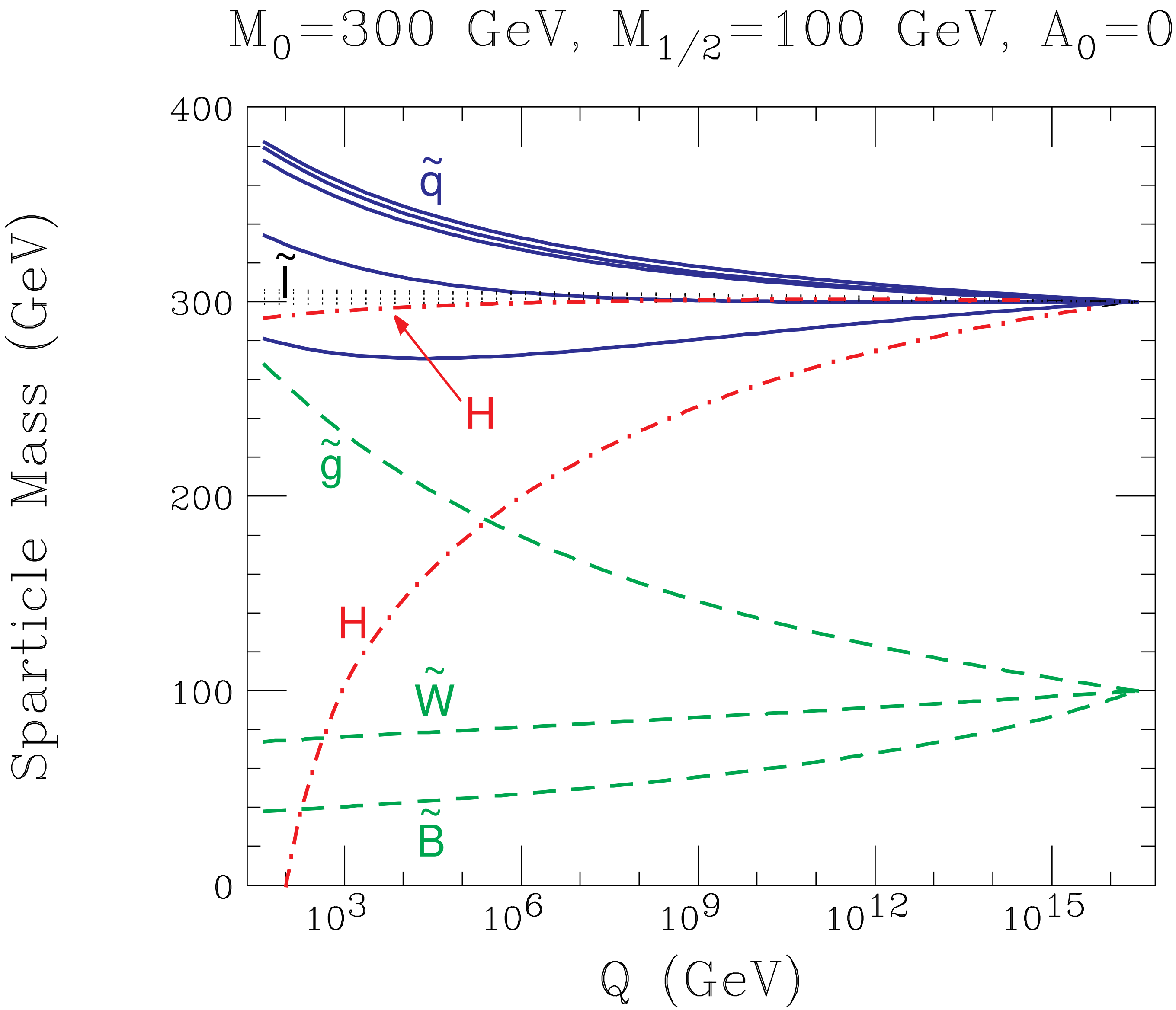

Further Questions?

Amazing feature of the MSSM: [Amaldi, de Boer, Fürstenau '92]



⇒ SUSY is naturally imbedded in a Grand Unified Theory (GUT)

Unification at the GUT scale:



$\Rightarrow$ ("usual") GUT prediction: $M_1 \sim M_2/2 \sim M_3/6$ with $M_3 = m_{\tilde{g}} \gtrsim 2$ TeV

Mini summary of MSSM:

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

relic DM density 100% fulfilled

$\Rightarrow$ fits well the excesses!

Never: $M_1 \sim M_2\,/2$ $\boxed{\Rightarrow \text{not GUT-based}}$

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 (full relic density: $m_{\tilde{\chi}_1^0} \sim 1$ TeV)

$\Rightarrow$ does not fit the excesses Possible: $M_1 \sim M_2\,/2$ $\boxed{\Rightarrow \text{can be GUT-based}}$

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Solution?

Mini summary of MSSM:

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$\Rightarrow$ does not fit the excesses Possible: $M_1 \sim M_2/2$ $\boxed{\Rightarrow \text{can be GUT-based}}$

Solution?

Go beyond the MSSM

– add a singlet: NMSSM
  $\Rightarrow$ some preliminary results

– add non-holomorphic μ-terms: NHSSM [*M. Rehman, S.H. WIP*]
  $\Rightarrow$ still too preliminary, next time!

Mini summary of MSSM:

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

$\Rightarrow$ does not fit the excesses Possible: $M_1 \sim M_2/2$ $\boxed{\Rightarrow \text{can be GUT-based}}$

Solution?

Go beyond the MSSM

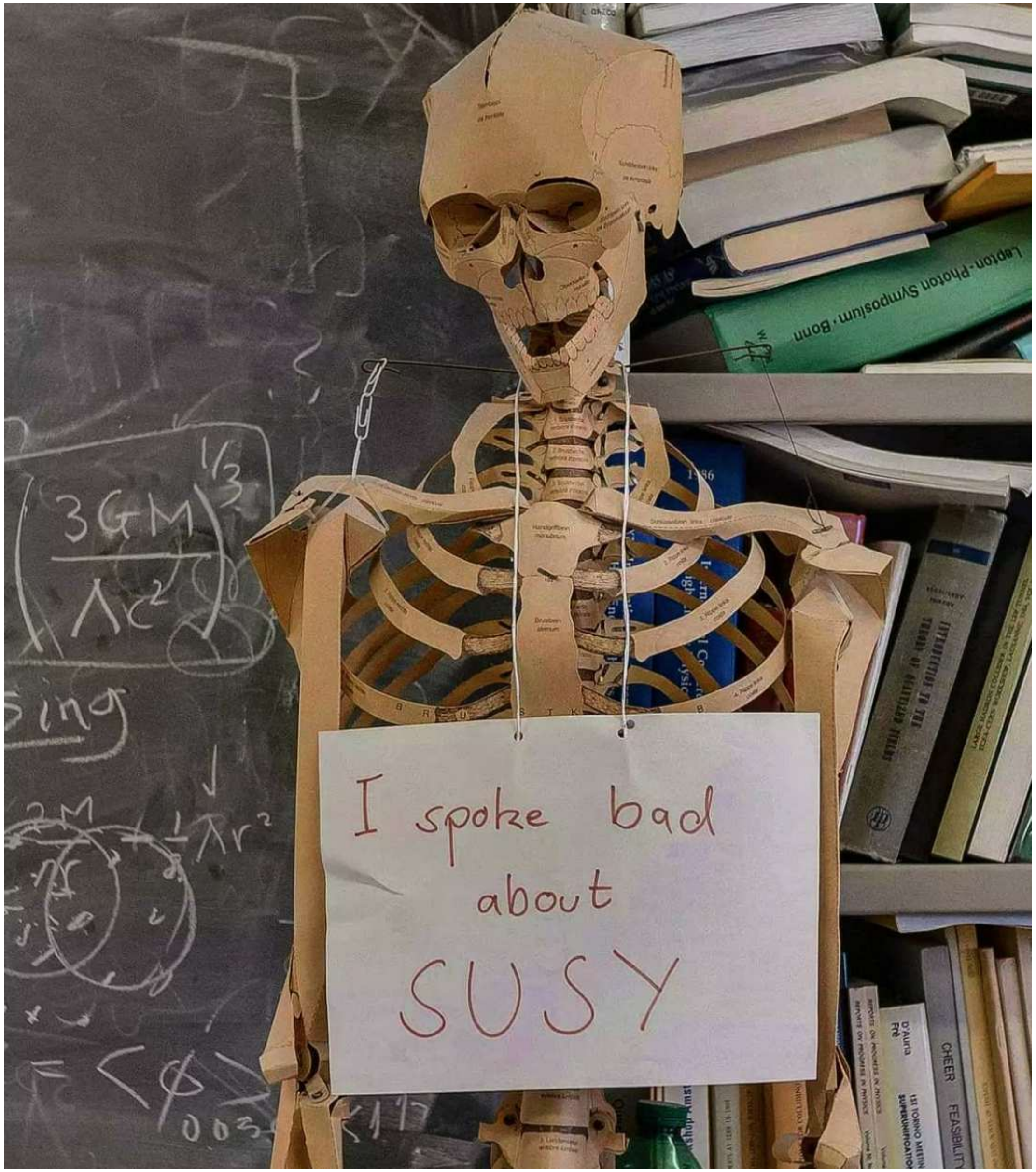
– add a singlet: NMSSM $\Leftarrow$ focus

$\Rightarrow$ some preliminary results

– add non-holomorphic μ-terms: NHSSM [*M. Rehman, S.H. WIP*]

$\Rightarrow$ still too preliminary, next time!

5. Solution for GUT-based scenarios



Our model: **NMSSM** (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = (\tilde{m}_1^2 + |\mu \quad|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \quad|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

Our model: **NMSSM** (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + I S_I
\end{aligned}
$$

$$
\begin{aligned}
V = &\ (\tilde{m}_1^2 + |\cancel{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\cancel{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
&+ |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\begin{aligned} \mathcal{CP}\text{−even} &: h_1, h_2, h_3 \\ \mathcal{CP}\text{−odd} &: a_1, a_2 \\ \text{charged} &: H^+, H^- \\ \text{Goldstones} &: G^0, G^+, G^- \end{aligned}$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

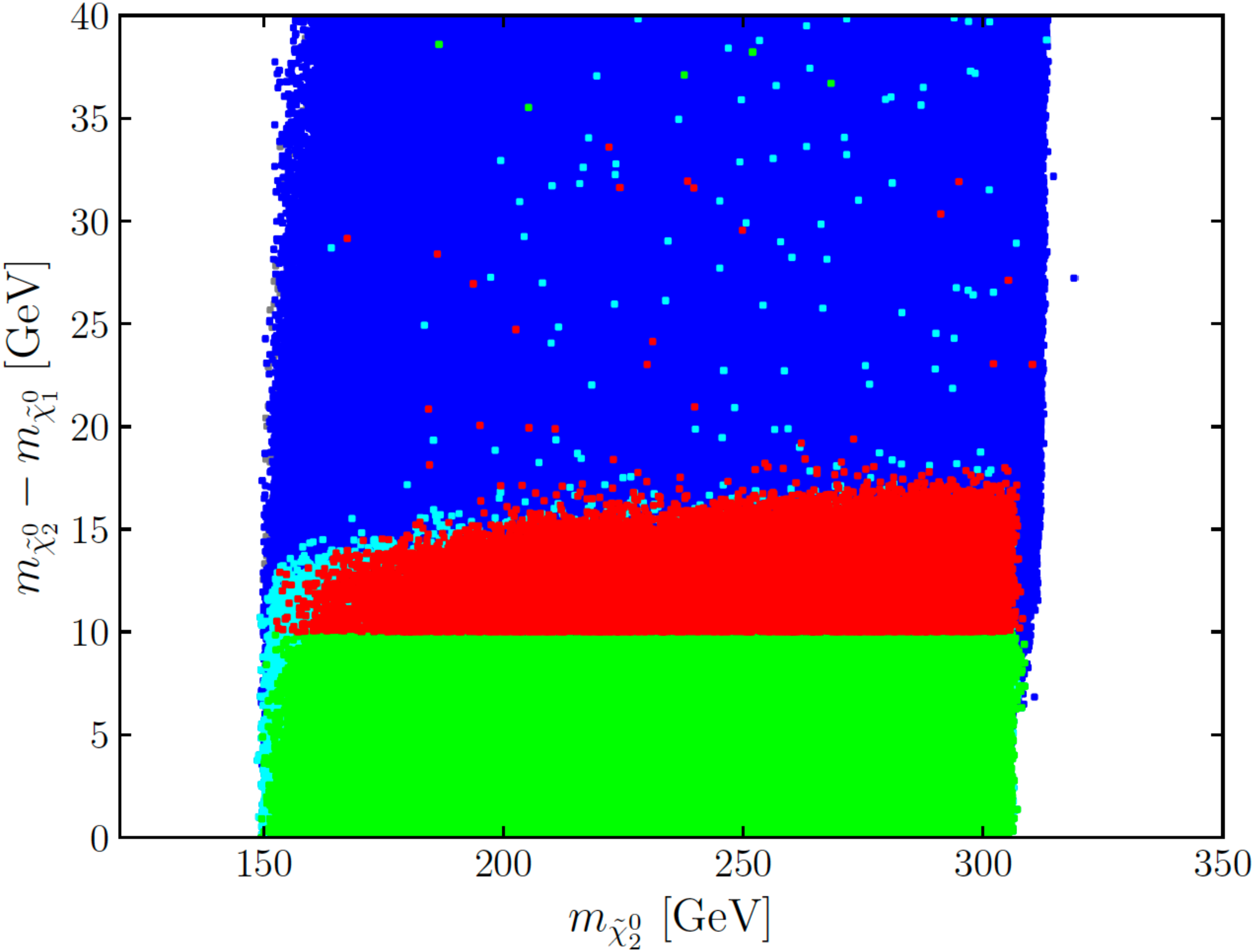
compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

⇒ make the LSP singlino-like ⇒ avoid DD bounds

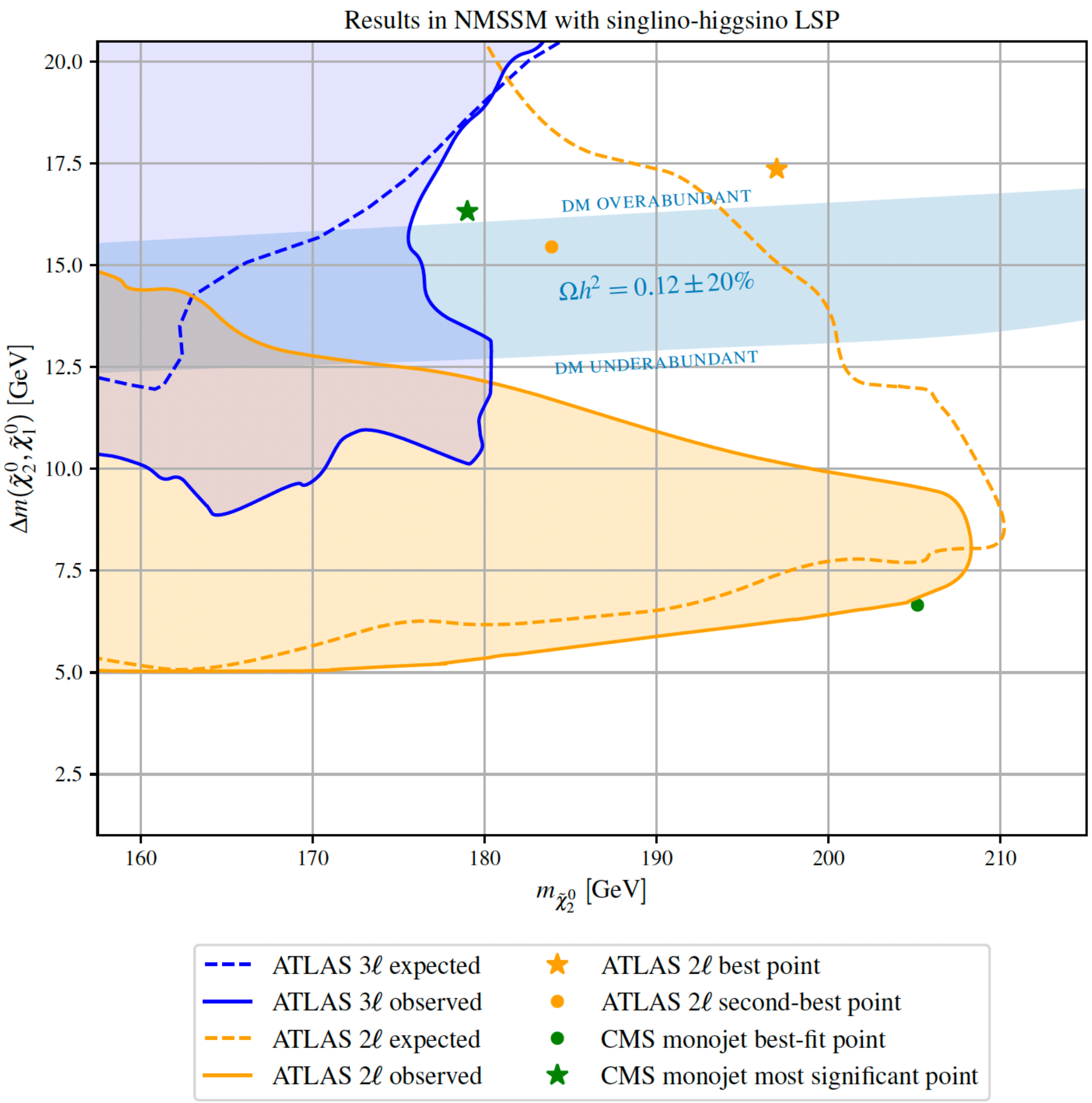
$$\Rightarrow \mu \lesssim M_1 \sim M_2/2 \sim M_3/6 \quad (M_3 = m_{\tilde{g}} \gtrsim 2\ \text{TeV})$$

higgsino(−): $m_{\tilde{\chi}_2^0}$-Δm plane: (no LHC bounds applied yet) *[PRELIMINARY]*

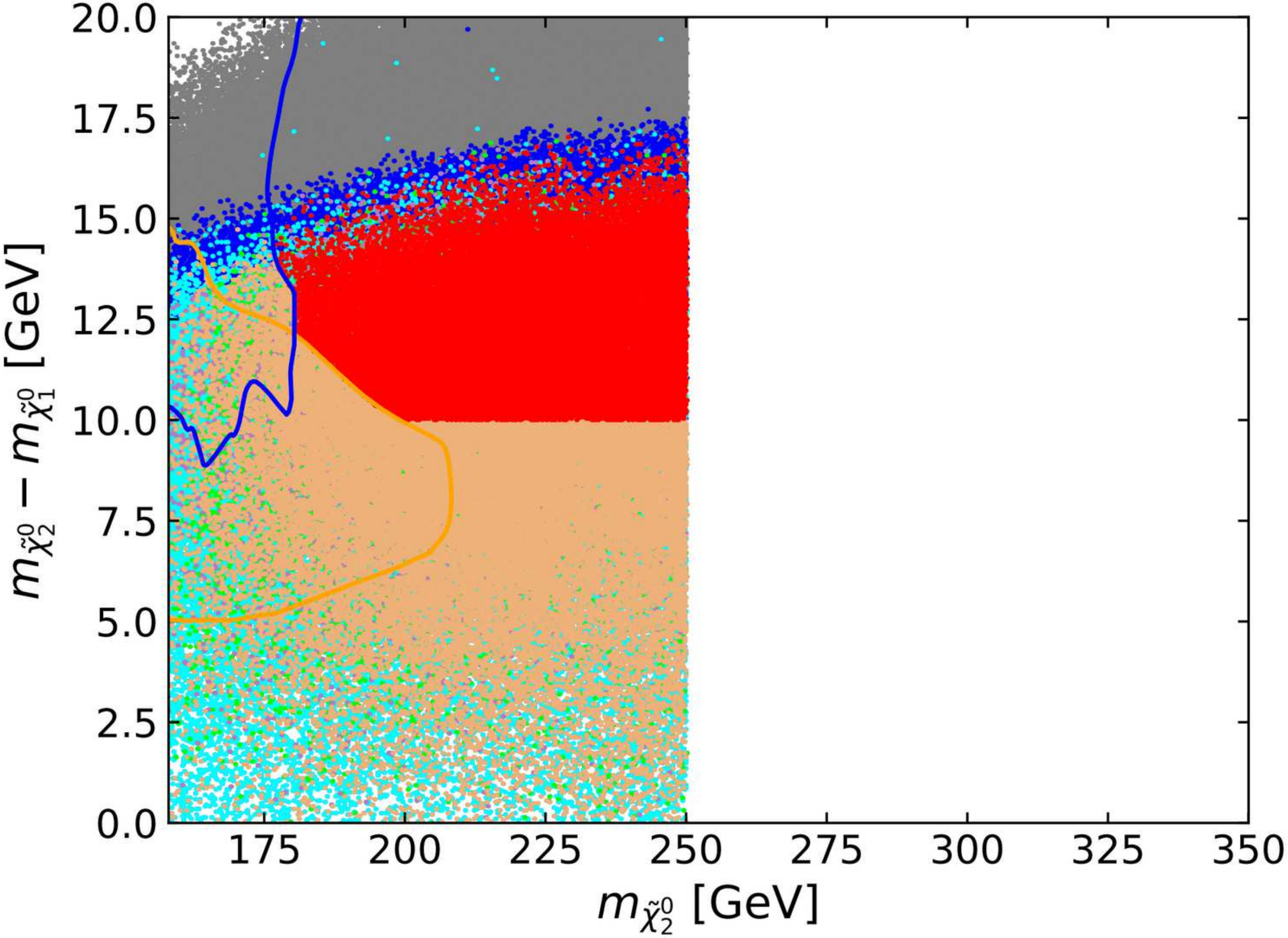


⇒ correct mass region to fit the excesses, Δm slightly small?

Take bounds from: [D. Agin, B. Fuks, M. Goodsell, T. Murphy '24]

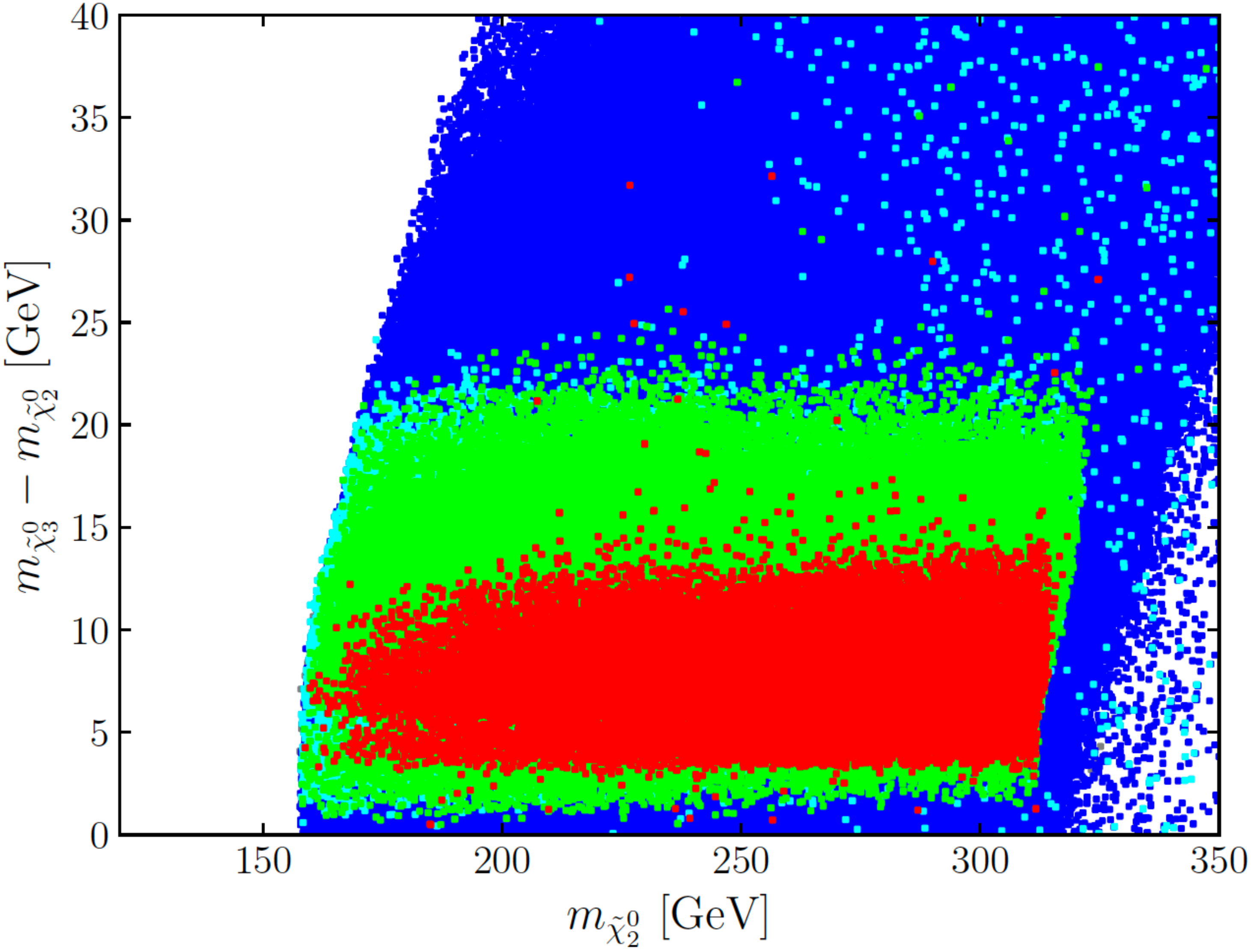


higgsino(−): $m_{\tilde{\chi}_2^0}$-Δm plane with LHC bounds included: *[PRELIMINARY]*



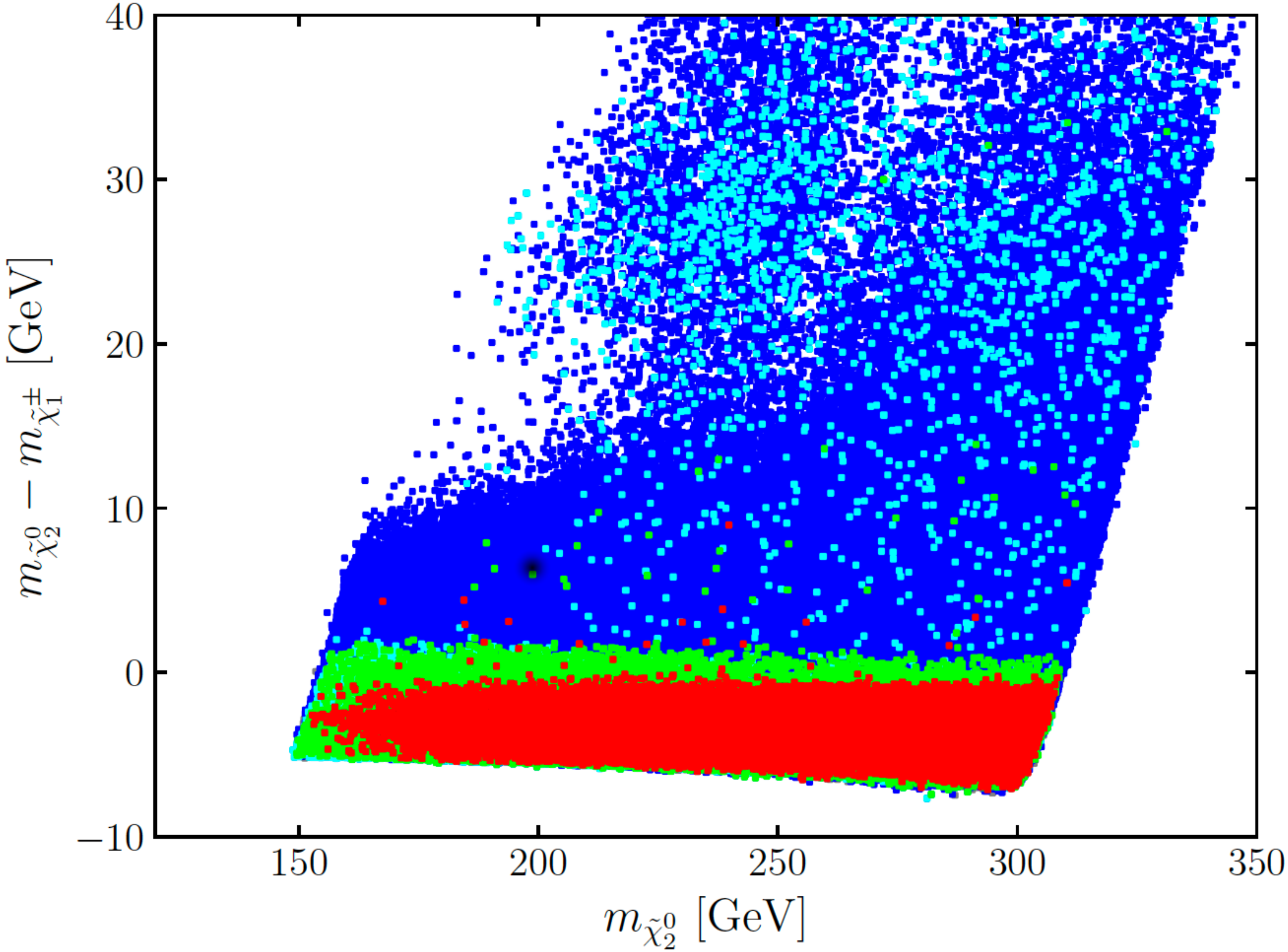
⇒ correct mass region to fit the excesses, Δm perfect!

higgsino($-$): more than one Δm: (no LHC bounds applied yet) *[PRELIMINARY]*



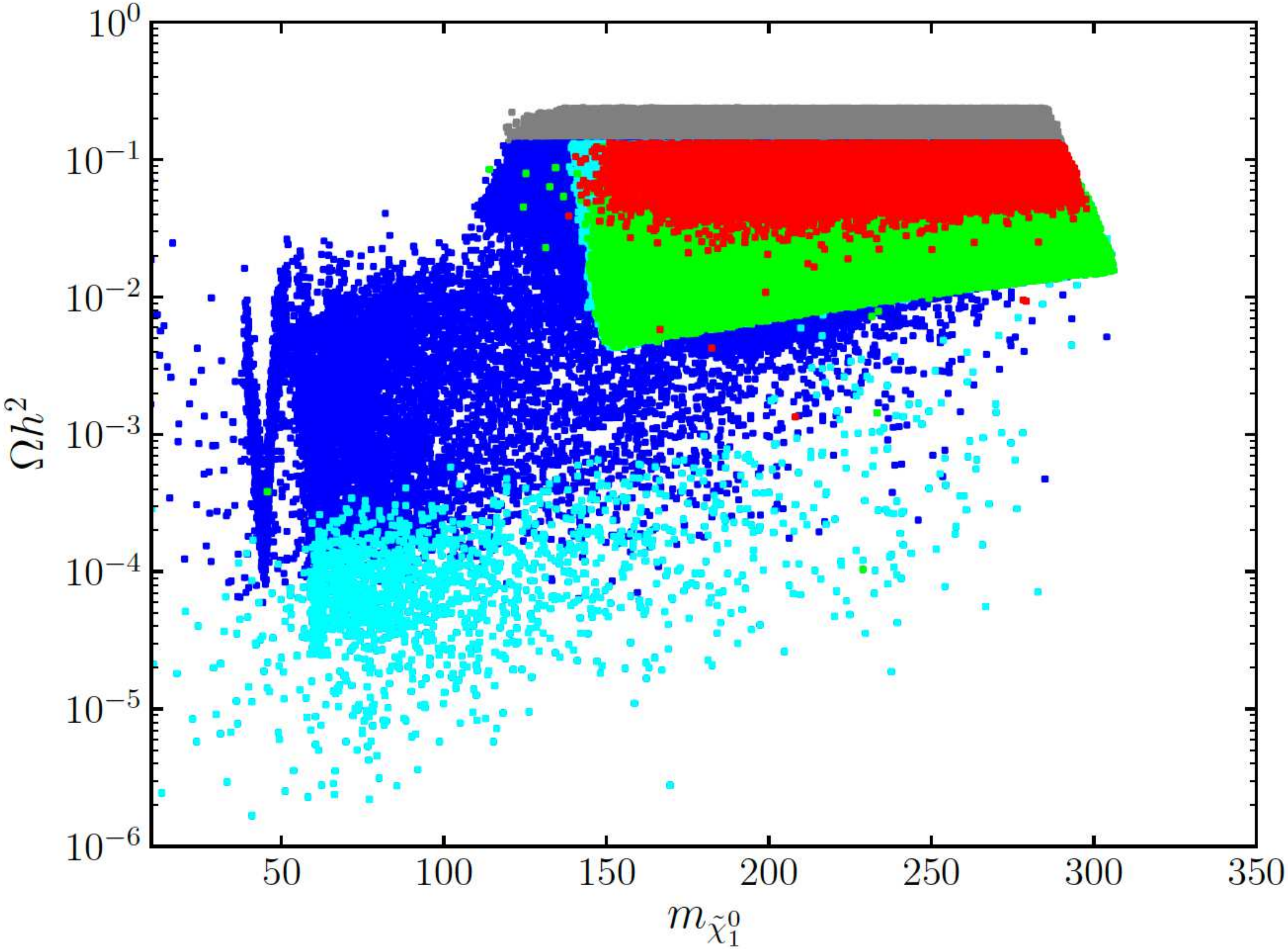
$\Rightarrow$ large mass gap, better for the excesses

higgsino(−): more than one Δm: (no LHC bounds applied yet) [PRELIMINARY]

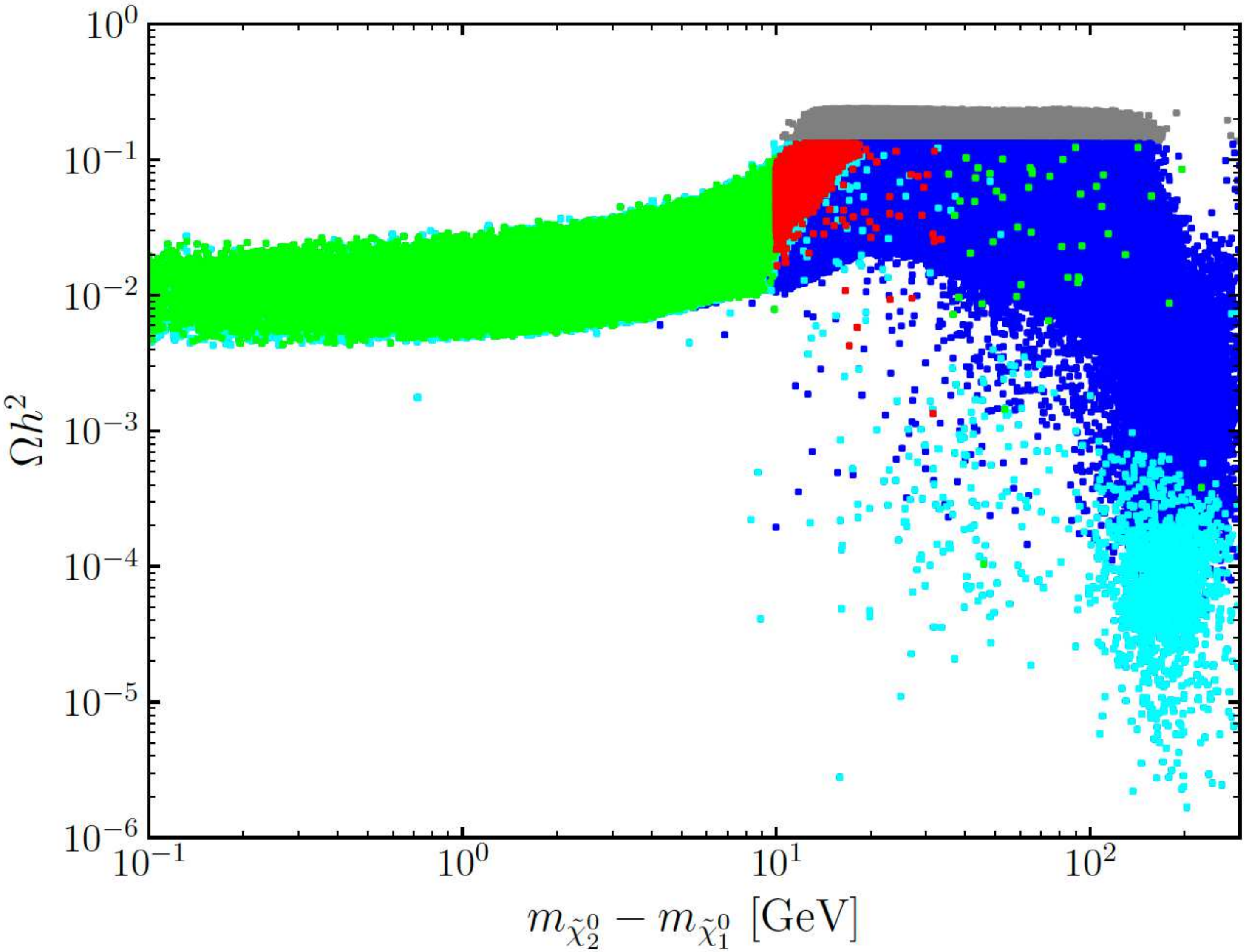


⇒ large mass gap, better for the excesses

higgsino(−): DM relic density: (no LHC bounds applied yet) [*PRELIMINARY*]



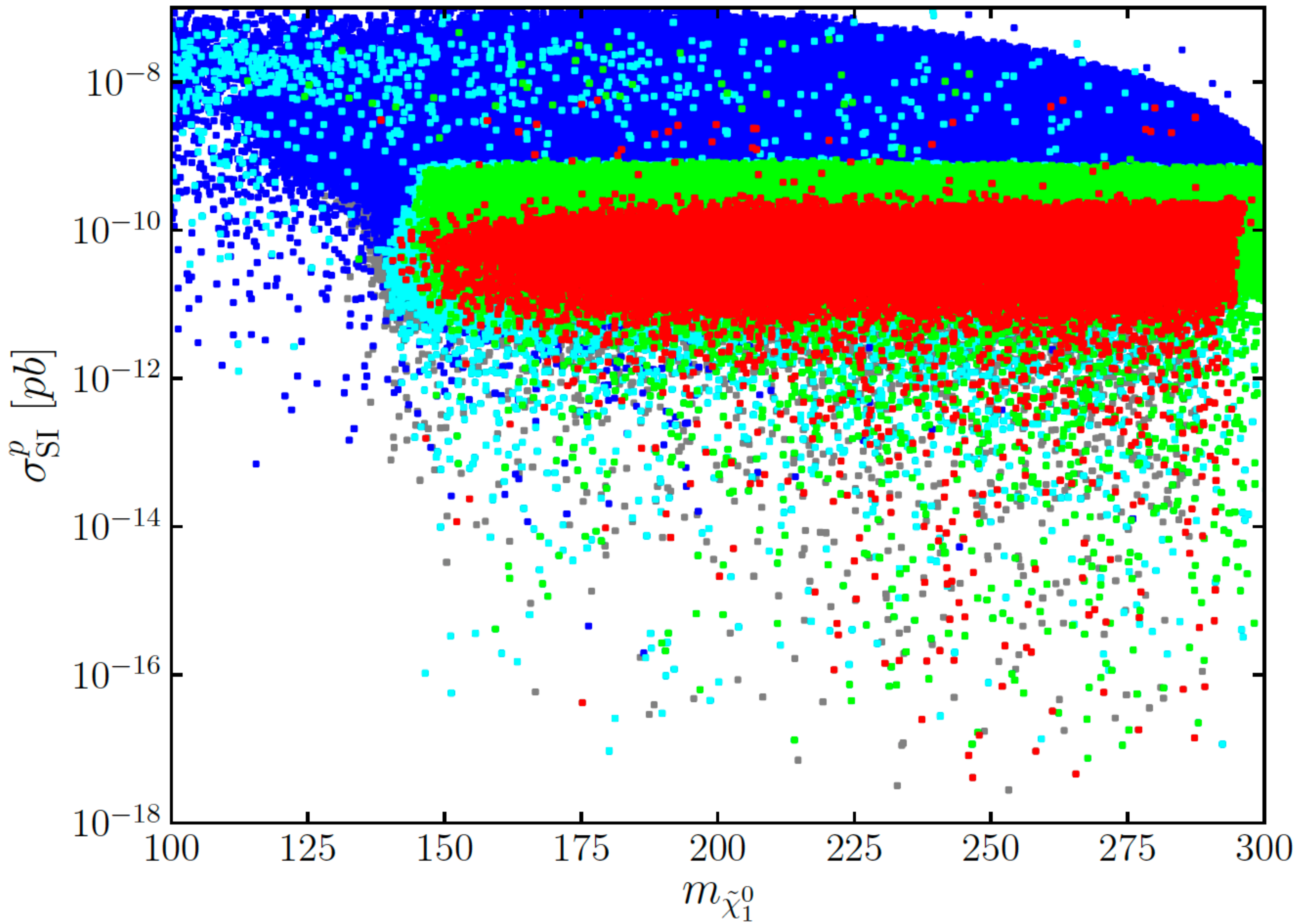
⇒ singlino can give the full DM density



⇒ larger mass gap favors full relic density

higgsino(−): predictions for DD experiments (no LHC bounds applied yet)

[PRELIMINARY]



⇒ good prospects for next round of DD experiments