New Pope, Leo XIV:

Pope Leo XIV: ‘There Couldn’t Be A Better Time To Get The Fuck Out Of America Forever’

Consistent Excesses in SUSY DM searches at the LHC

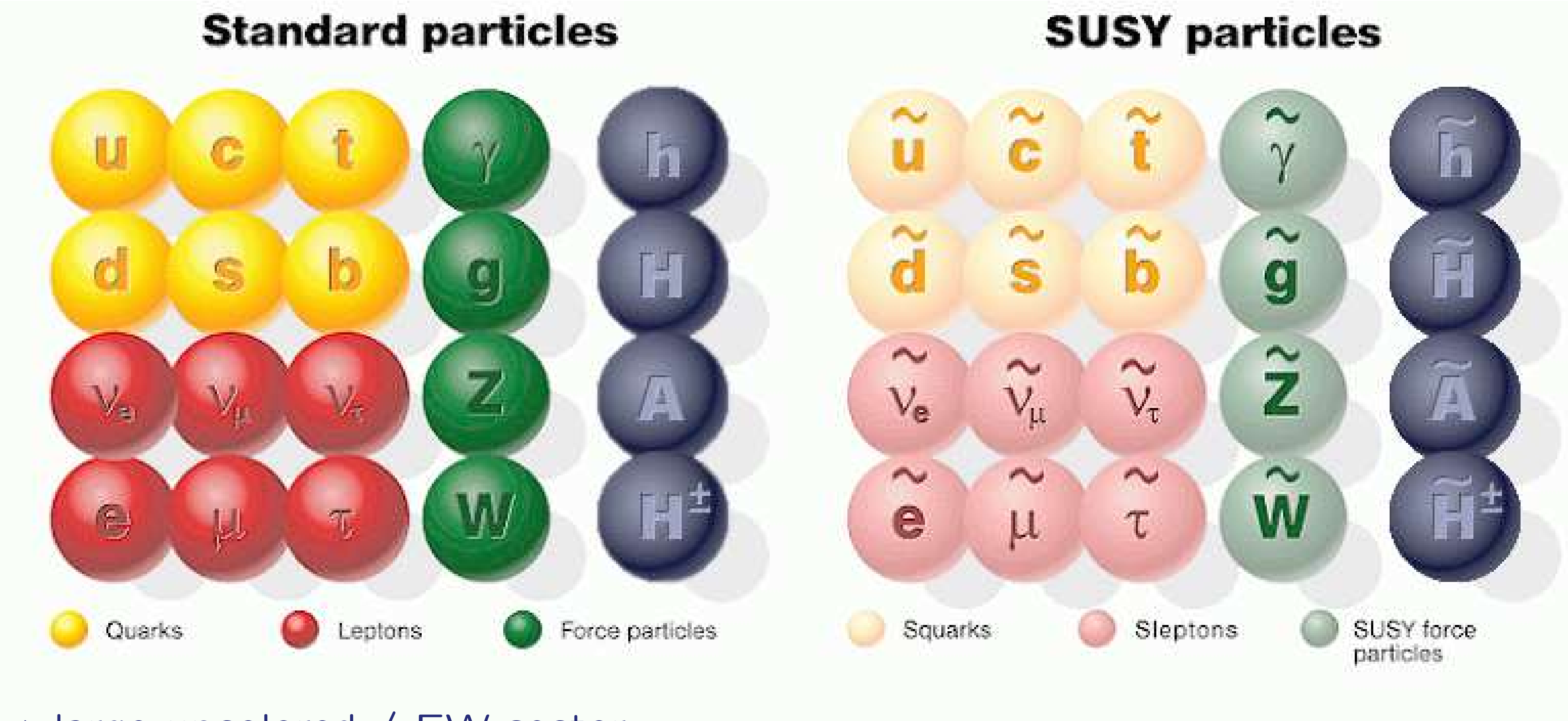
Sven Heinemeyer, IFT (CSIC, Madrid)

Santander, 06/2025

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

1. The main idea

The MSSM



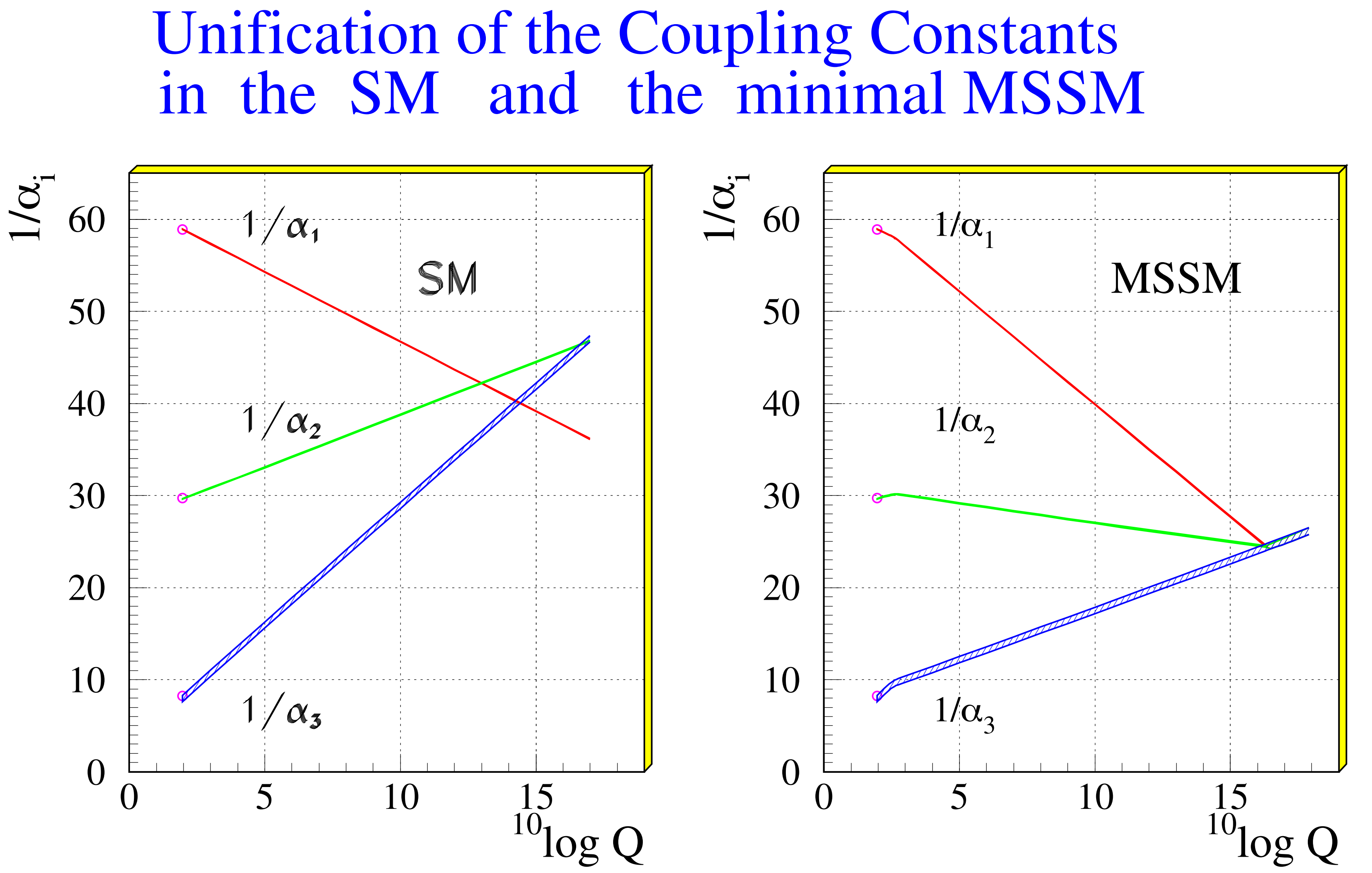
⇒ large uncolored / EW sector

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

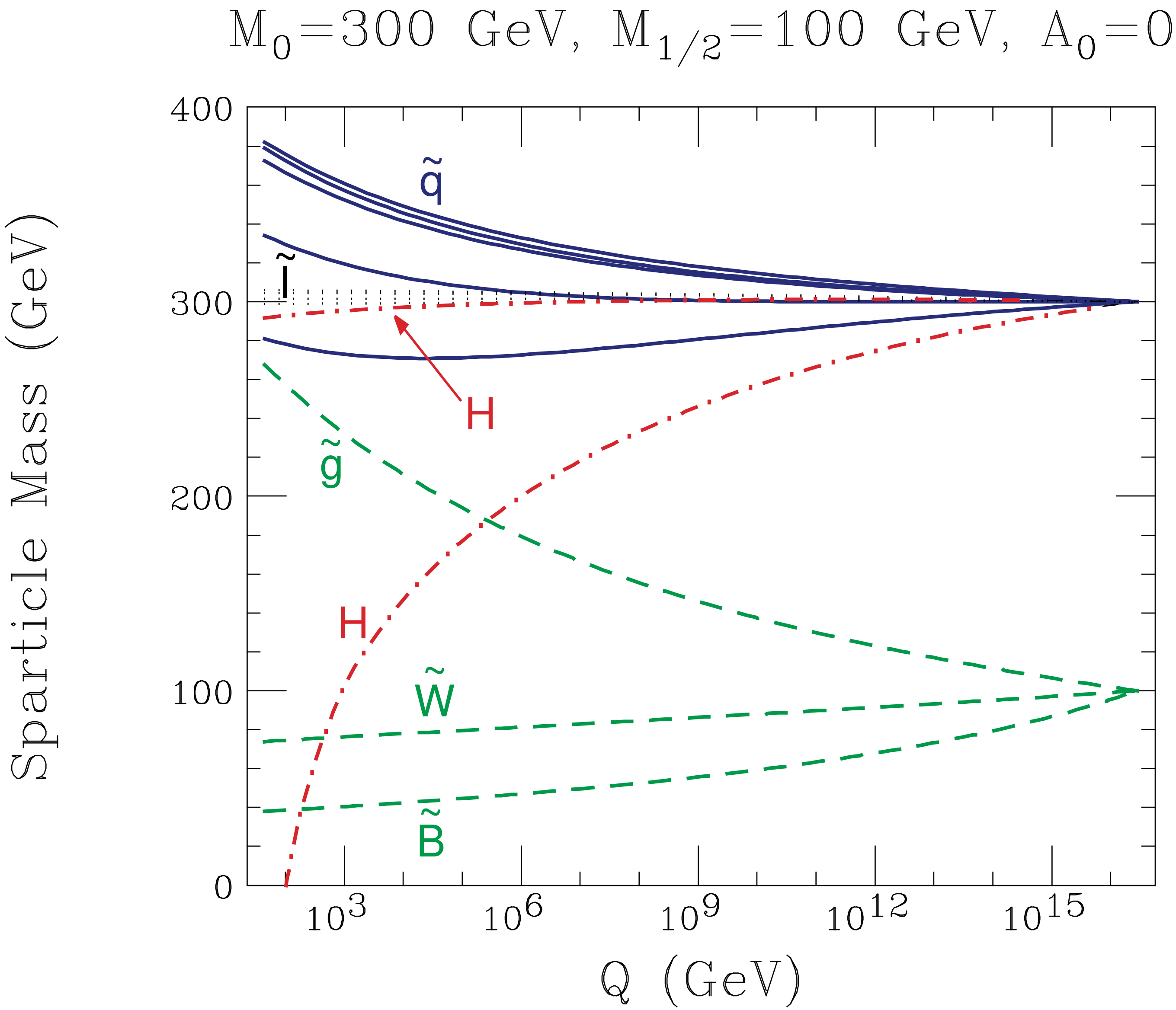
Amazing feature of the MSSM:

[Amaldi, de Boer, Fürstenau '92]



$\Rightarrow$ SUSY is naturally imbedded in a Grand Unified Theory (GUT)

Unification at the GUT scale:



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

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

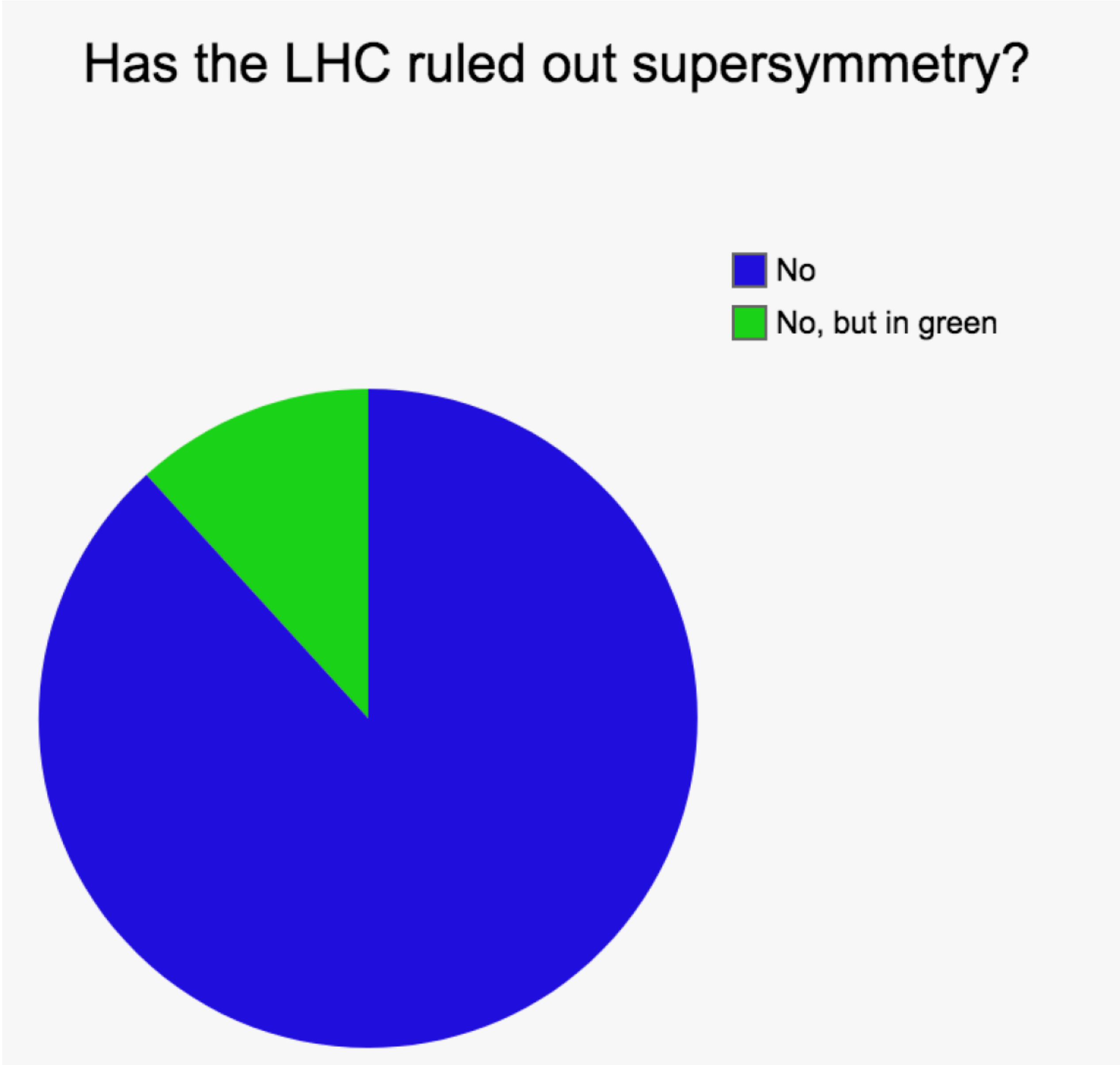
D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)
relic DM density as upper limit (full relic density: $m_{\tilde{\chi}_1^0} \sim 1$ TeV)

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

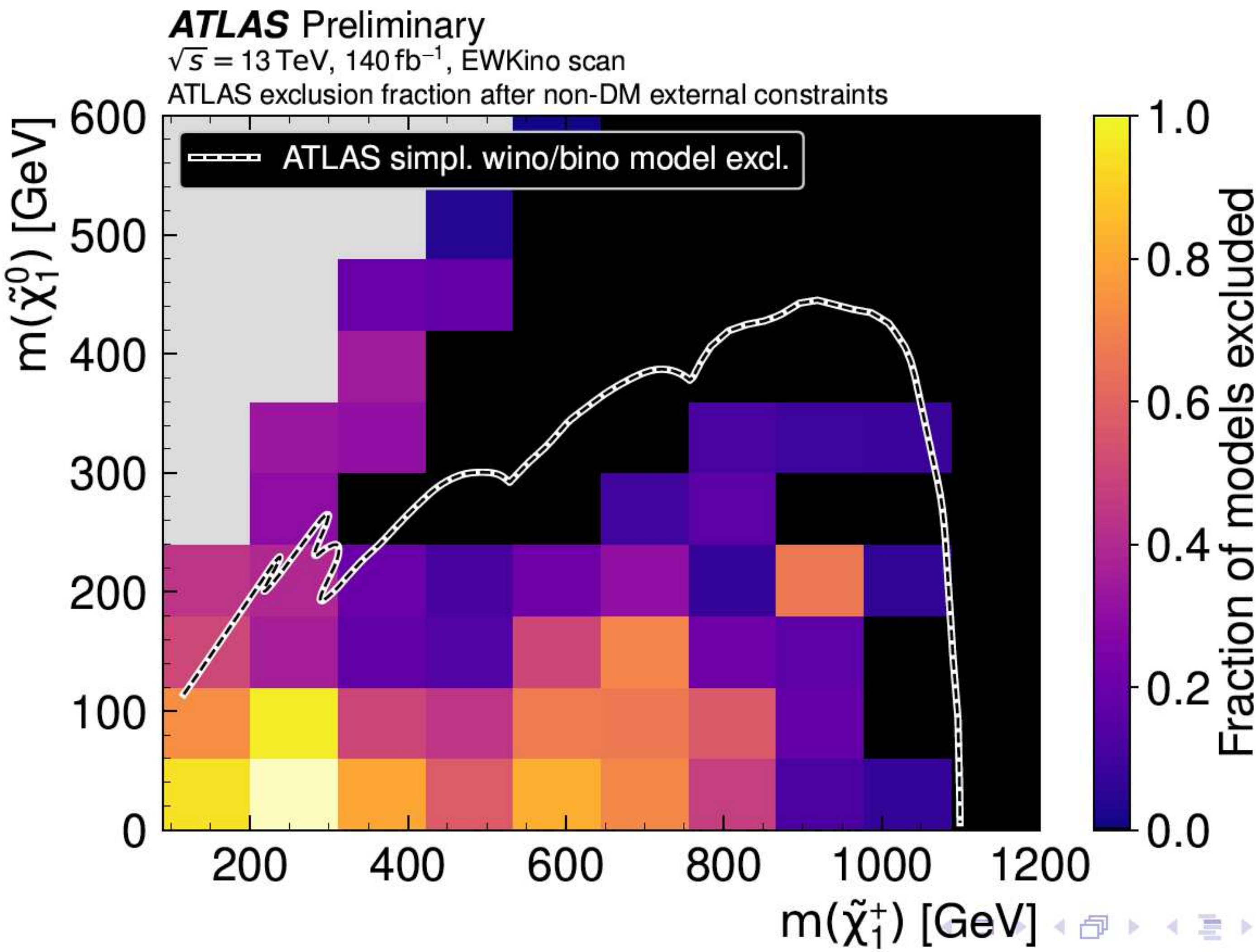
$m_{\tilde{g}} \gtrsim 2$ TeV $\Rightarrow M_1 \sim M_2/2 \gtrsim 350$ GeV

2. Evidence for low-energy SUSY?!

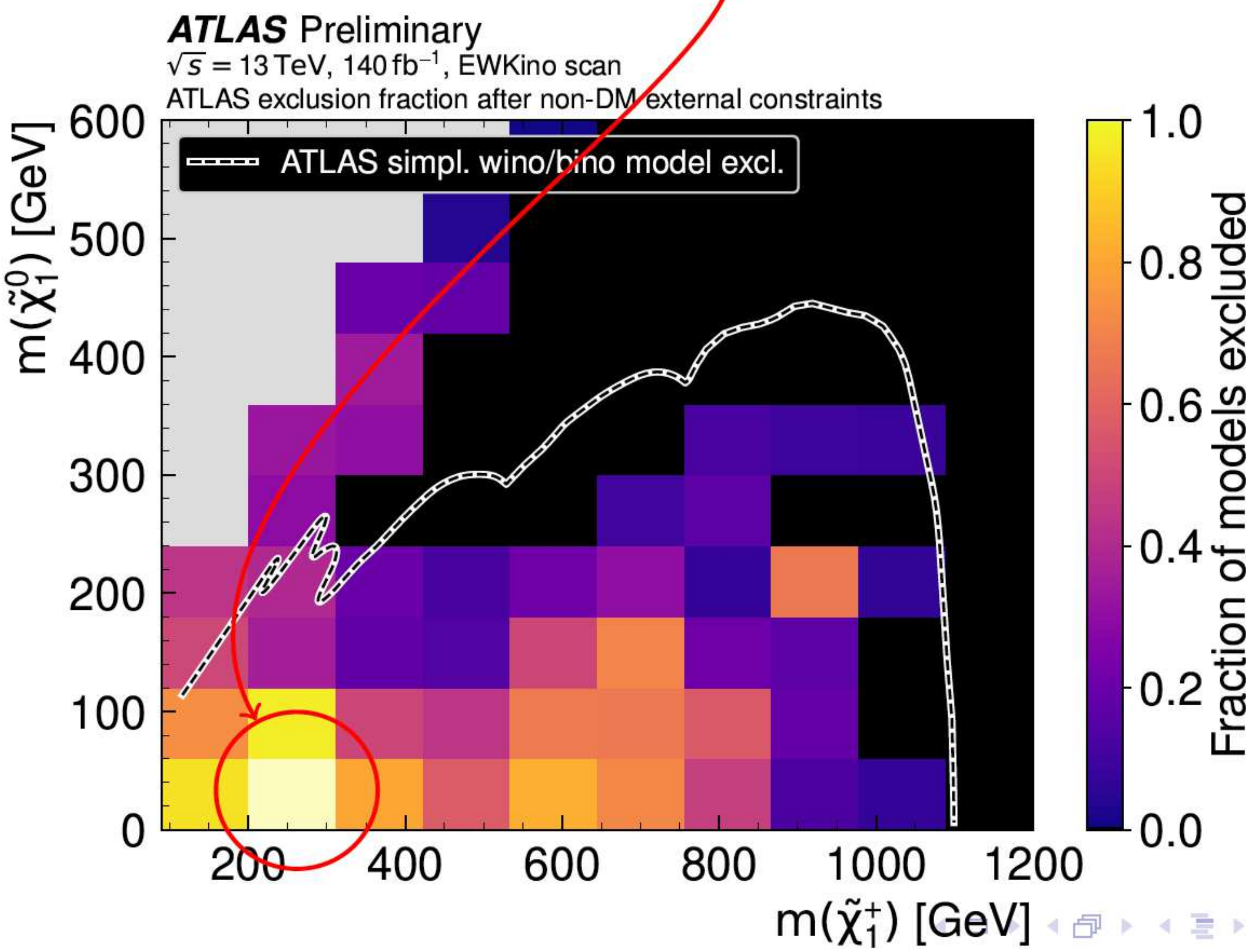


What have the LHC searches excluded?

[*taken from M. Berggren '23*]



Only this one is actually excluded !



$\Rightarrow$ 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:

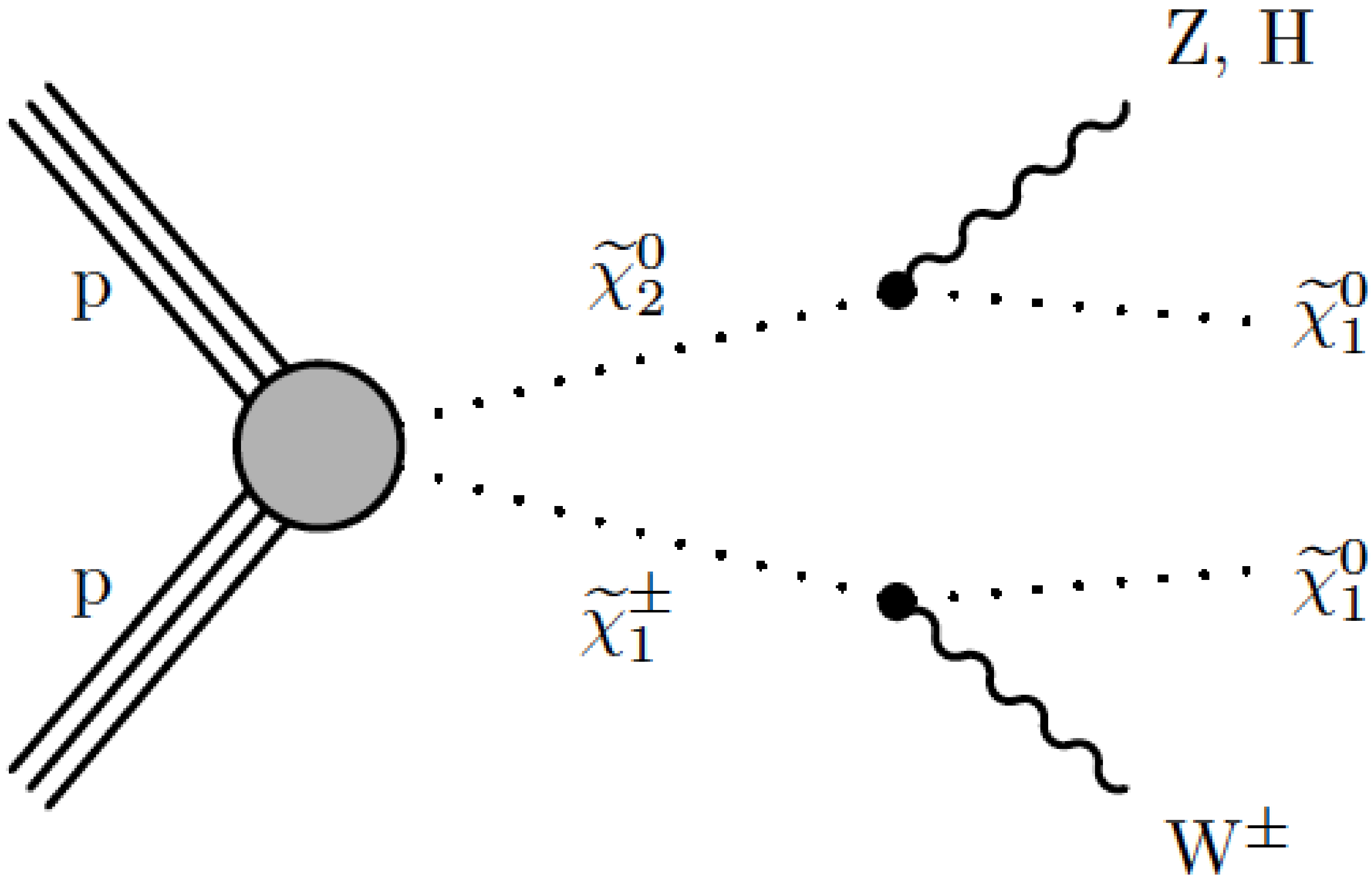
- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

$\Rightarrow$ only one of these can be realized

$\Rightarrow$ only one of them should show up in the LHC searches

⇒ Our "models" predict low chargino/neutralino masses

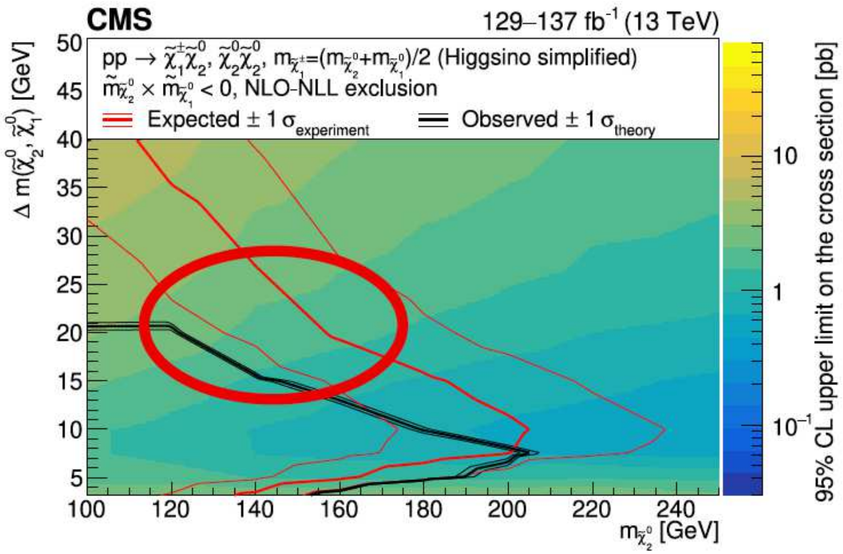
Golden mode at the LHC:

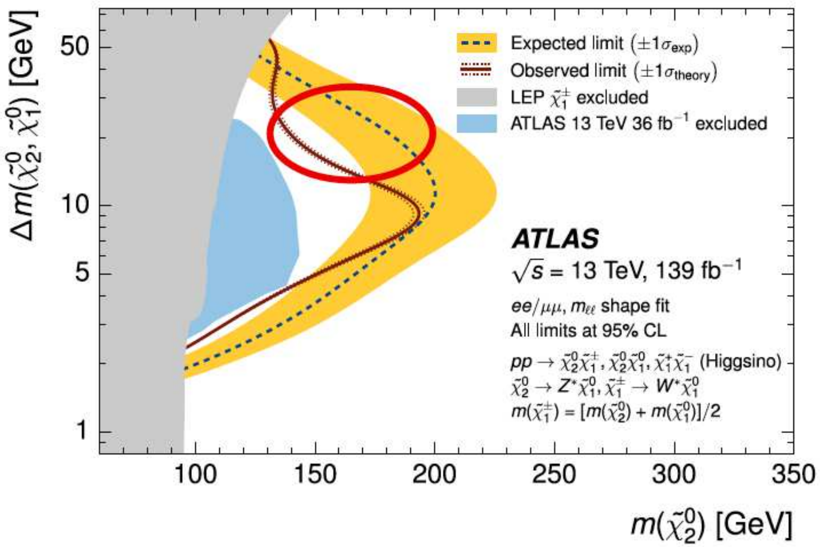


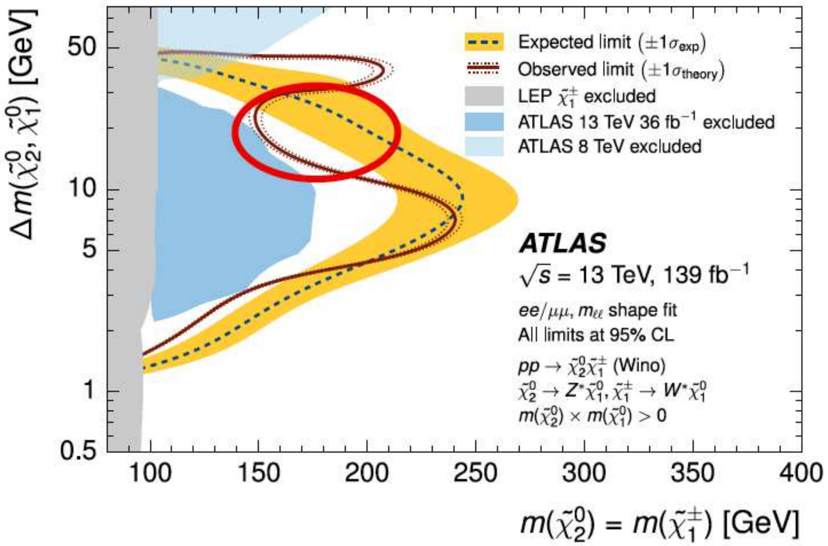
⇒ experimental results?

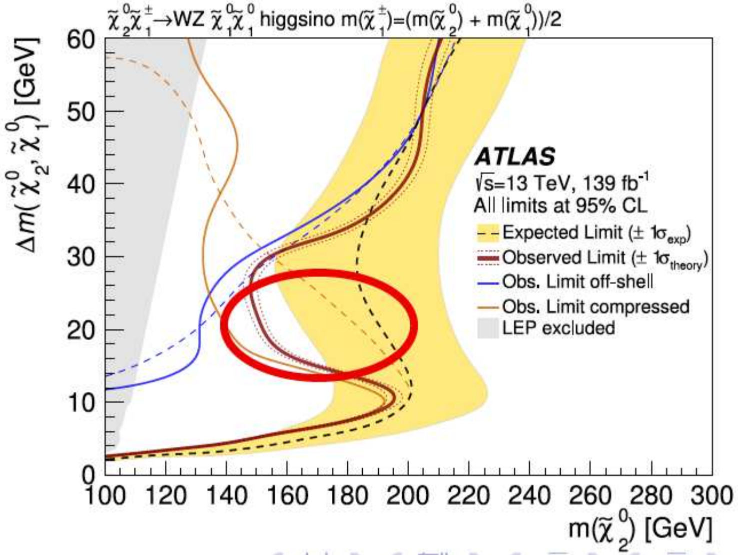
Results: “compressed” spectra w/ heavy sleptons:

[*taken from M. Berggren ’23*]

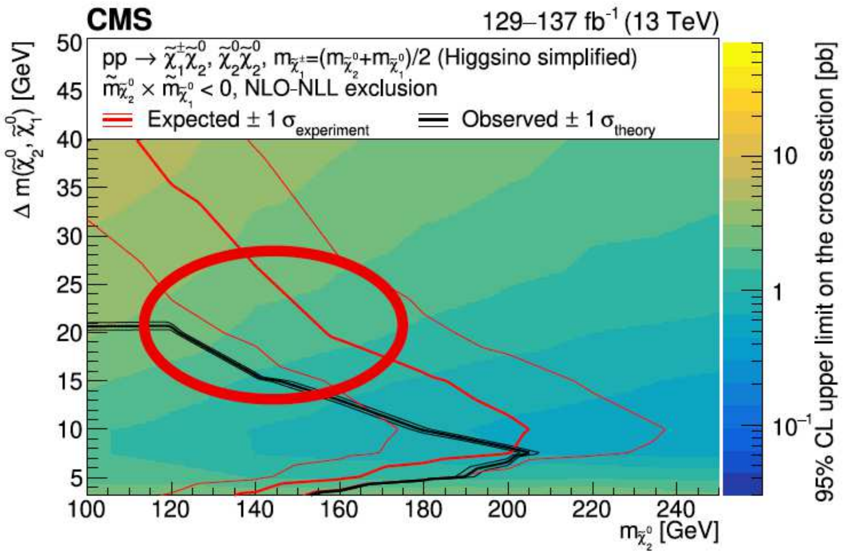


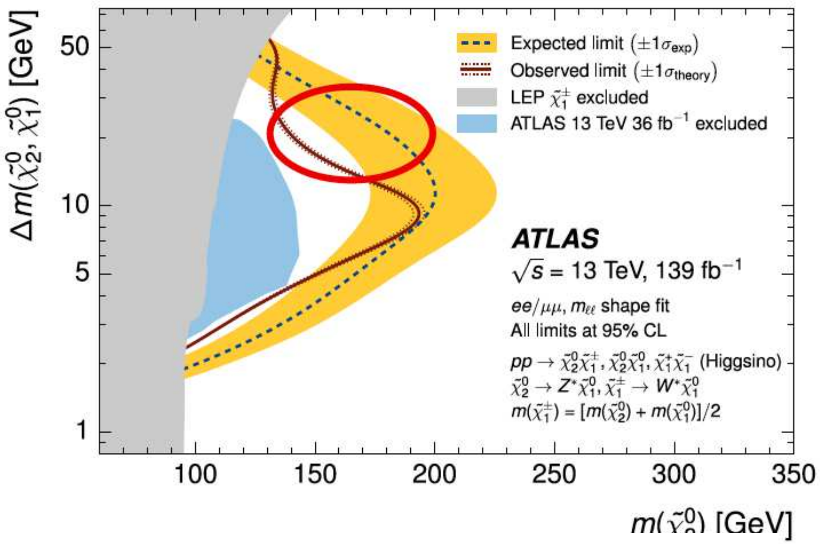


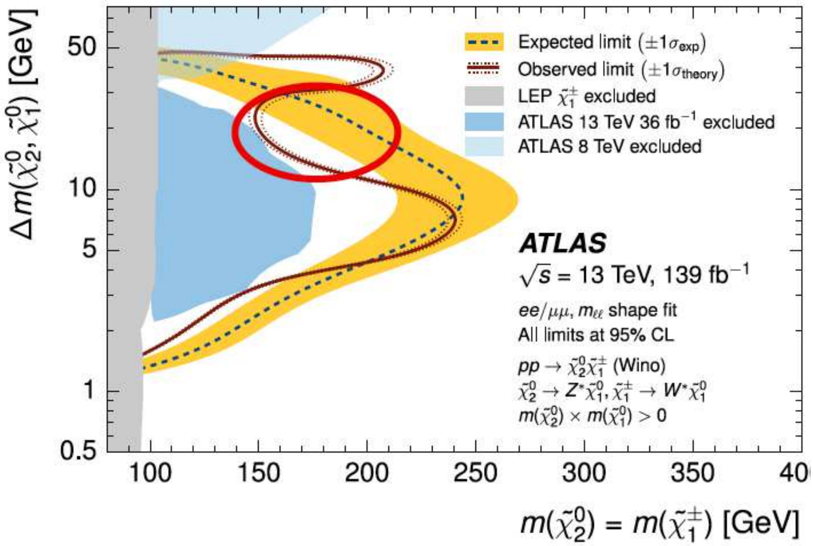


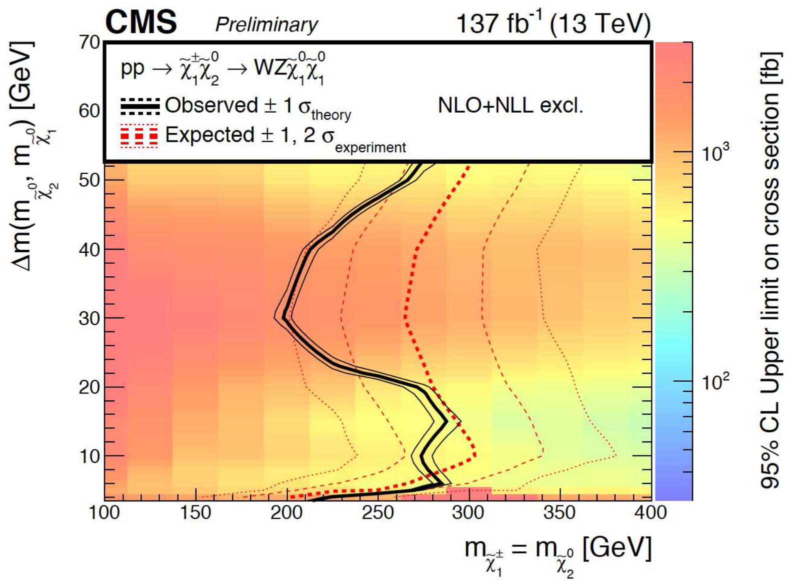


 one more CMS analysis:









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$)$

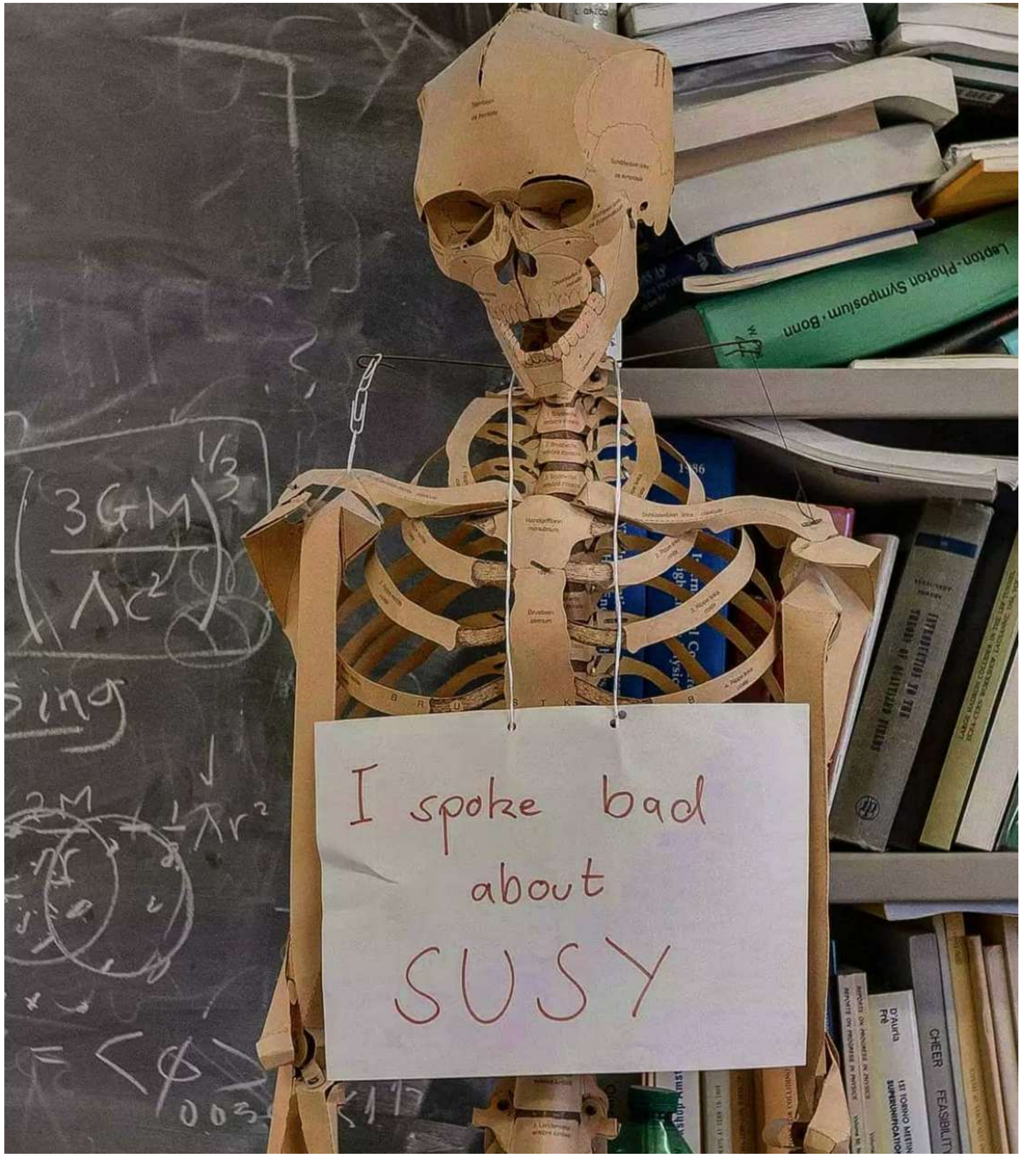
A) wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
Never: $M_1 \sim M_2\,/2$ ⇒ not GUT-based

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: $M_1 \sim M_2\,/2$ ⇒ can be GUT-based

⇒ 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:

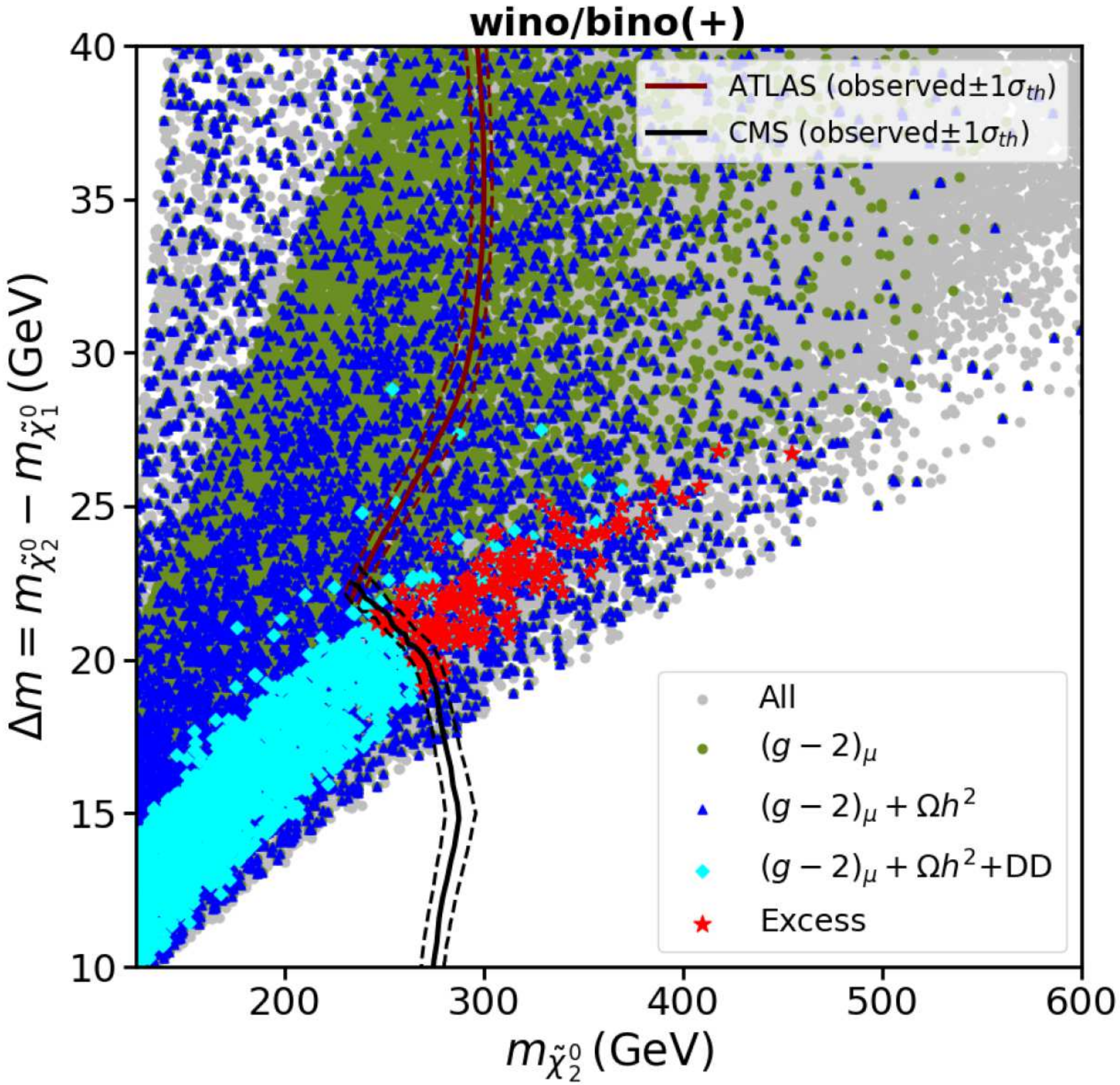
$$100 \text{ GeV} \le |M_1| \le 400 \text{ GeV} \;,$$
$$|M_1| \le M_2 \le 1.1|M_1| \;,$$
$$1.1|M_1| \le \mu \le 10|M_1|,$$
$$2 \le \tan\beta \le 60,$$
$$100 \text{ GeV} \le m_{\tilde{L}} \le 1.5 \text{ TeV},$$
$$m_{\tilde{R}} = m_{\tilde{L}} \;.$$

(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
$\Rightarrow m_{\text{(N)LSP}} \lesssim 600(650)$ GeV
(original scan assuming a $5\,\sigma$ deviation in $(g-2)_\mu$)

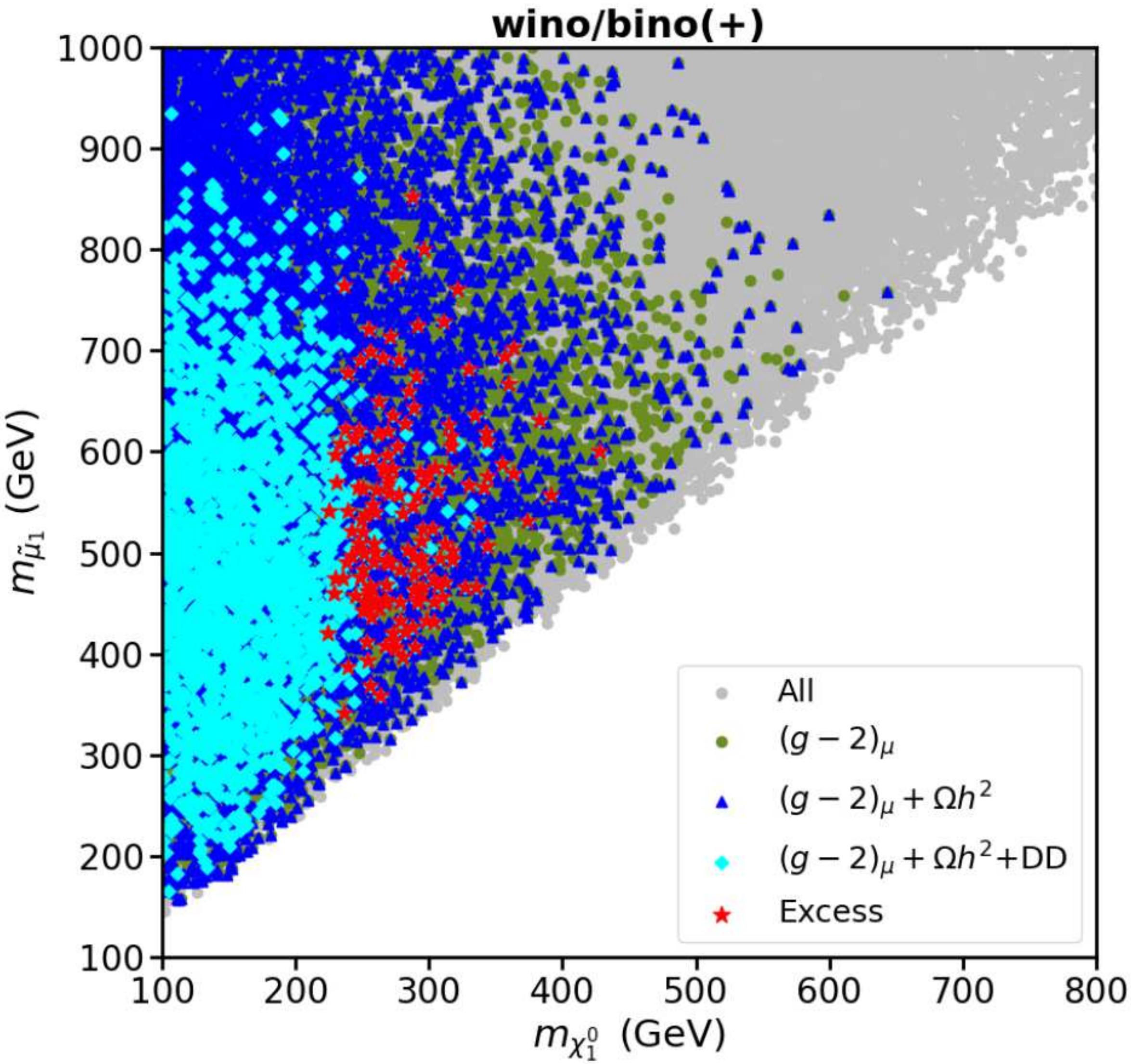
wino/bino(+): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



⇒ excesses not fully at the same Δm . . .

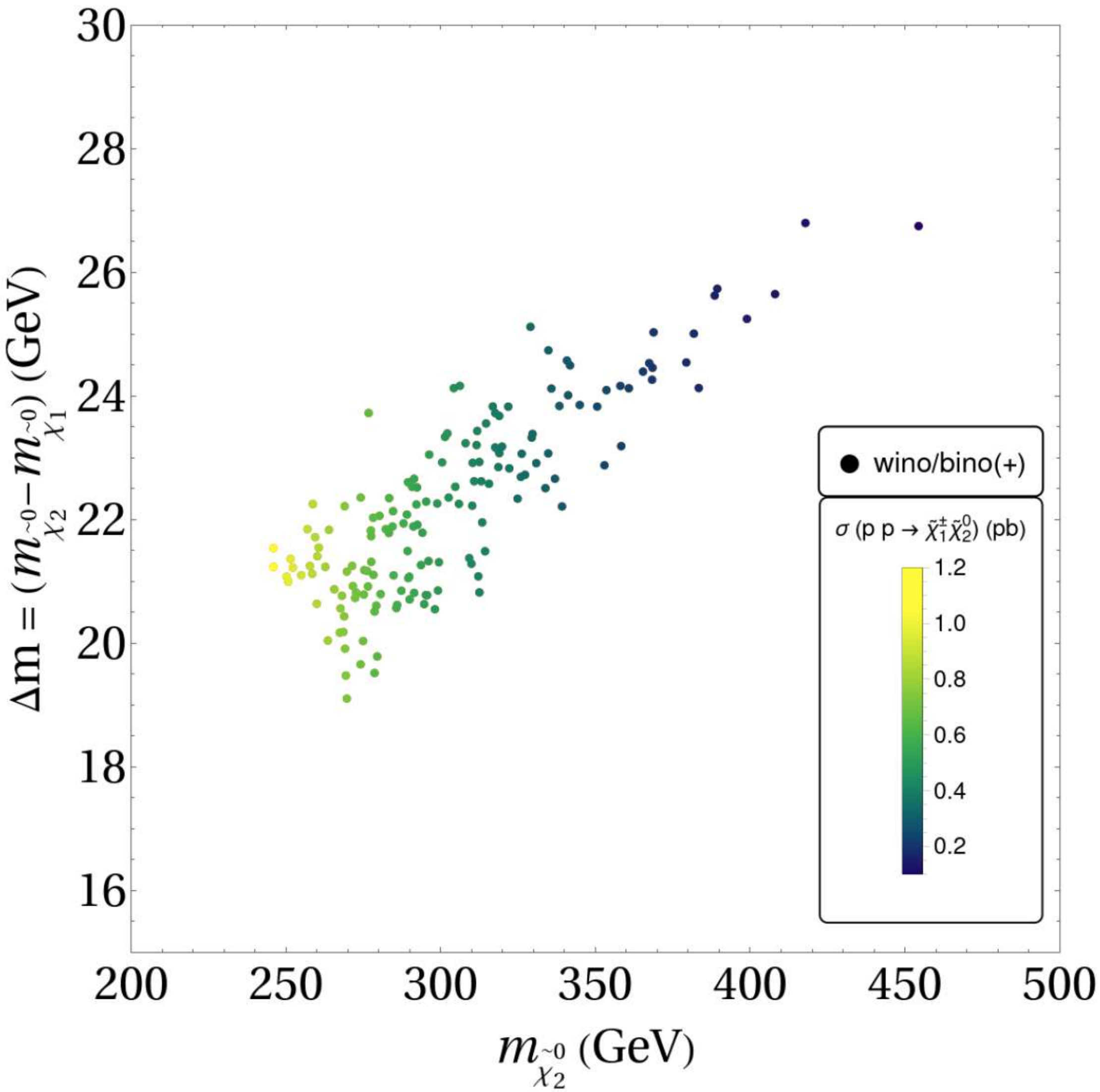
⇒ but many “good points” at $\Delta m \sim 20$ GeV

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



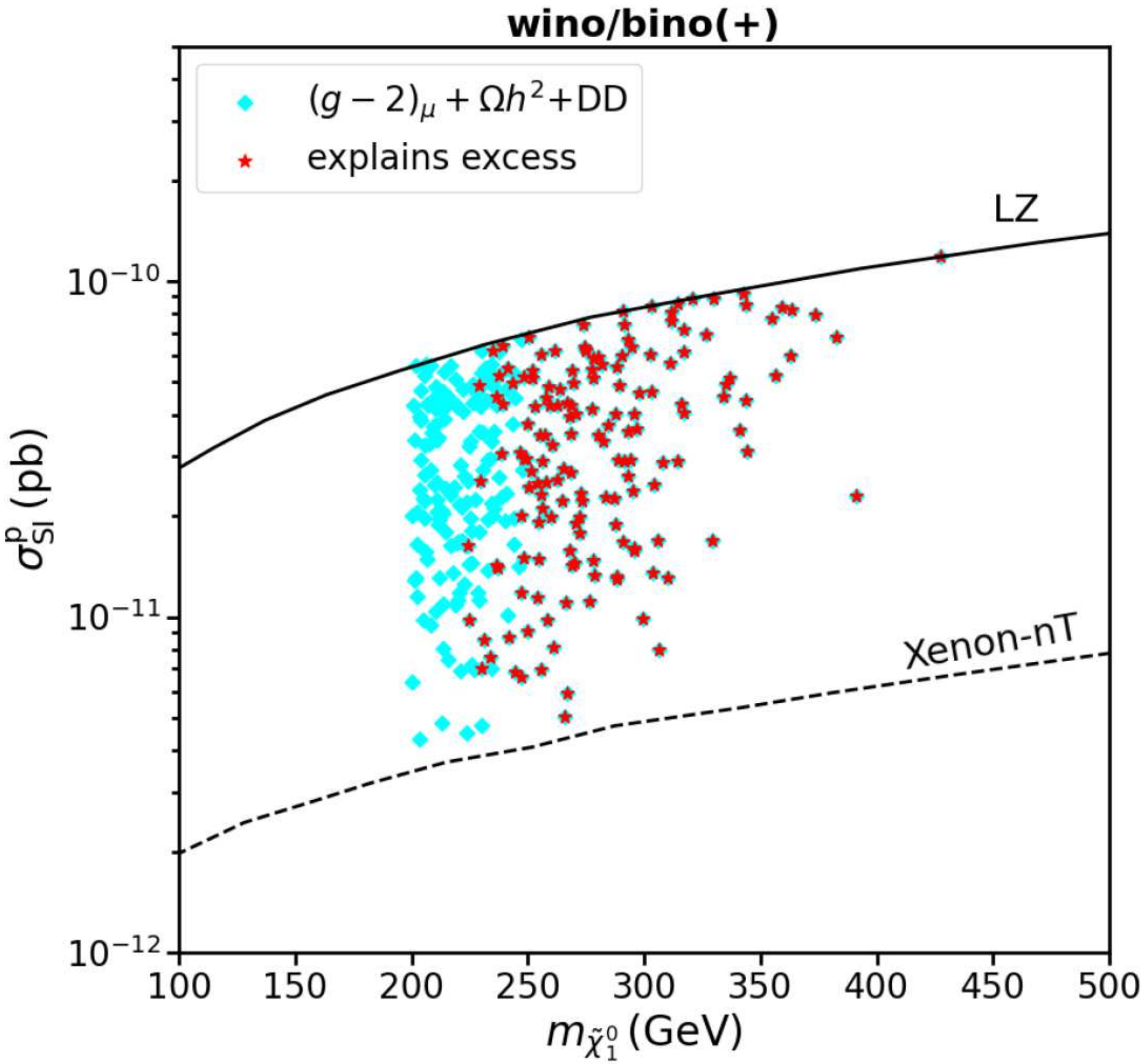
$\Rightarrow$ no limits on slepton masses (as expected)

wino/bino(+): LHC cross sections:



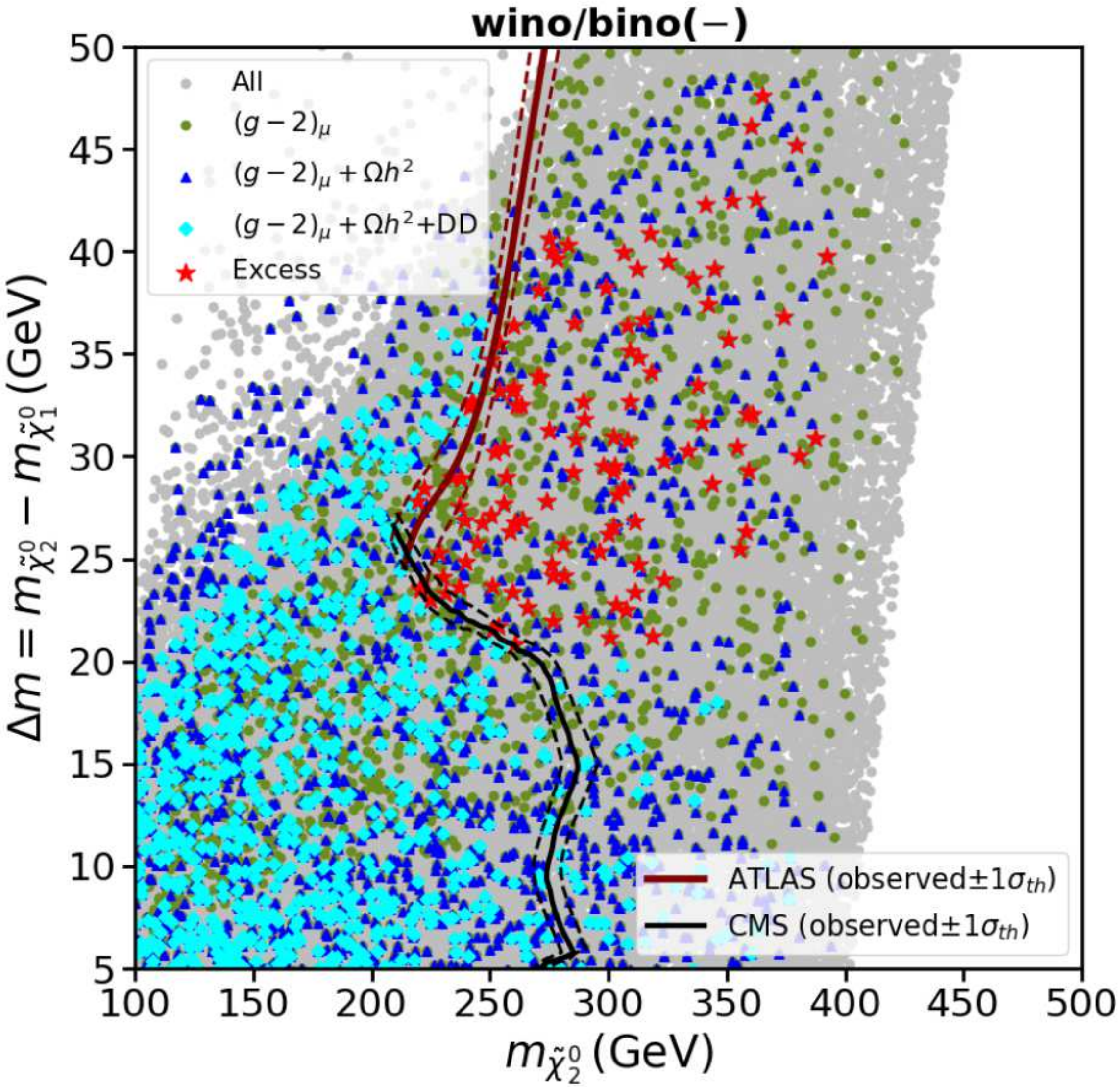
⇒ for lower massess XS have roughly the size required by excesses

wino/bino(+): direct detection prospects:



$\Rightarrow$ wino/bino(+)/$\tilde{\chi}^\pm_1$ co-annihiliation will be covered by XENON-nT/LZ

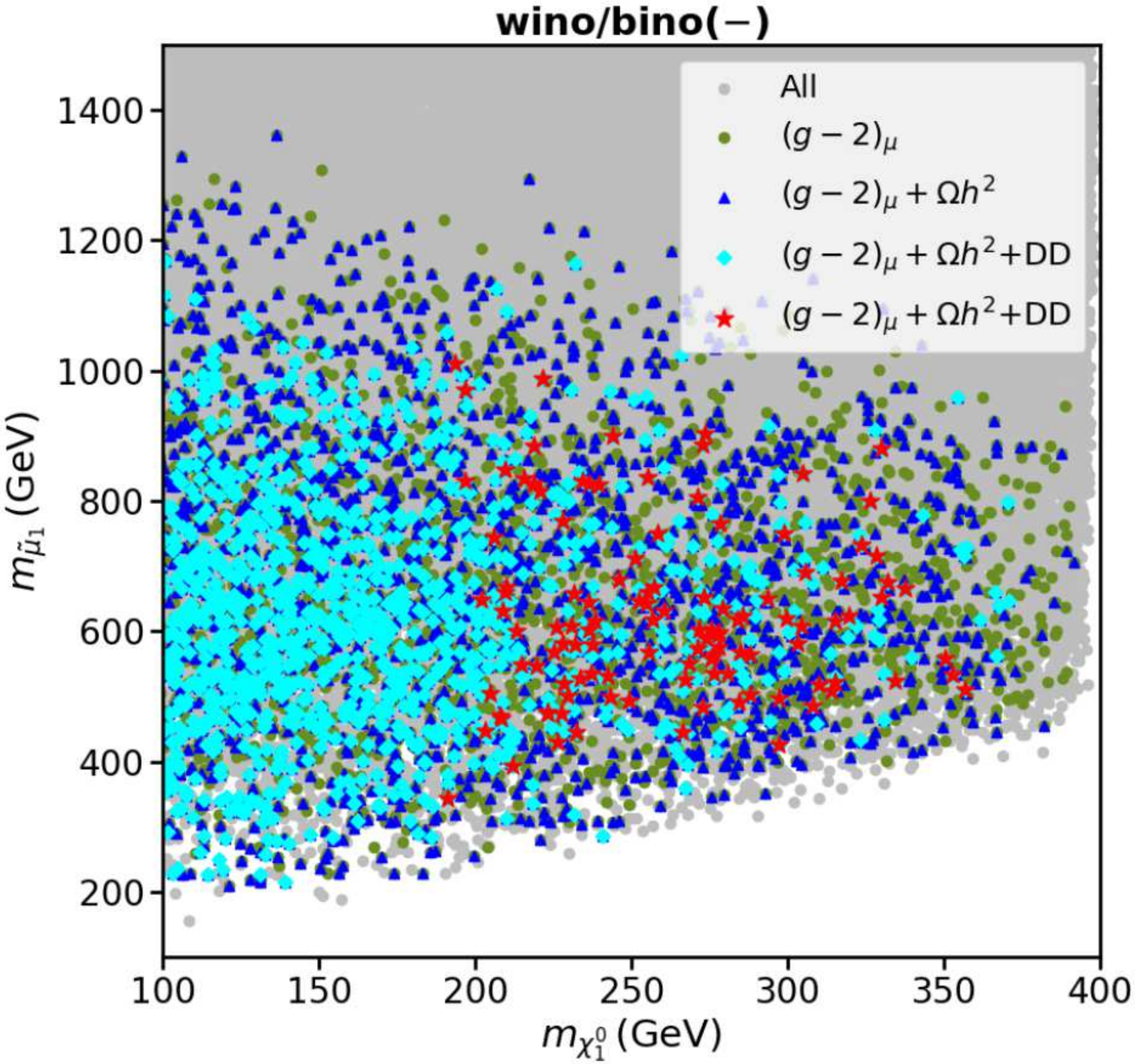
wino/bino(−): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



⇒ 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:



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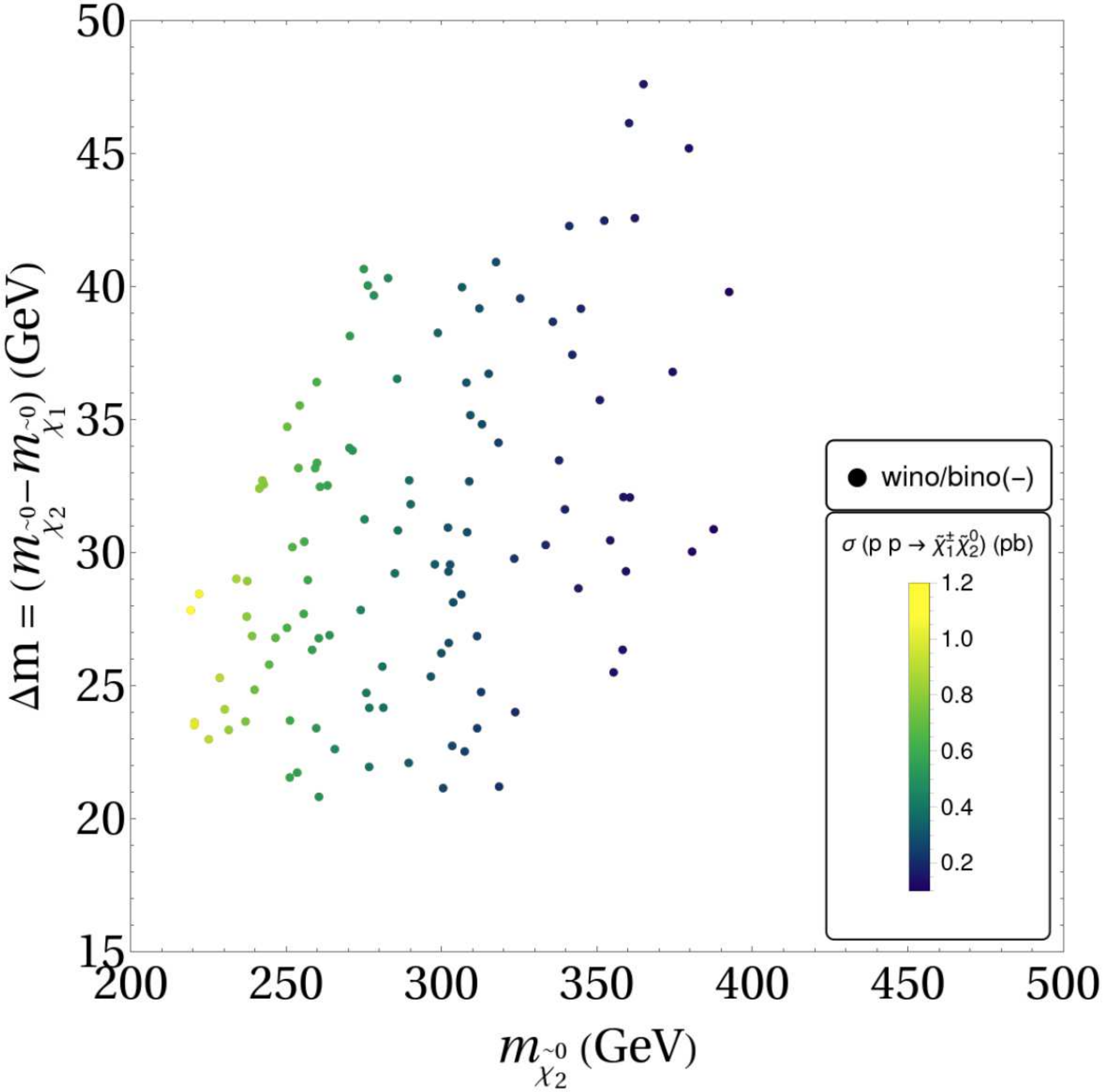
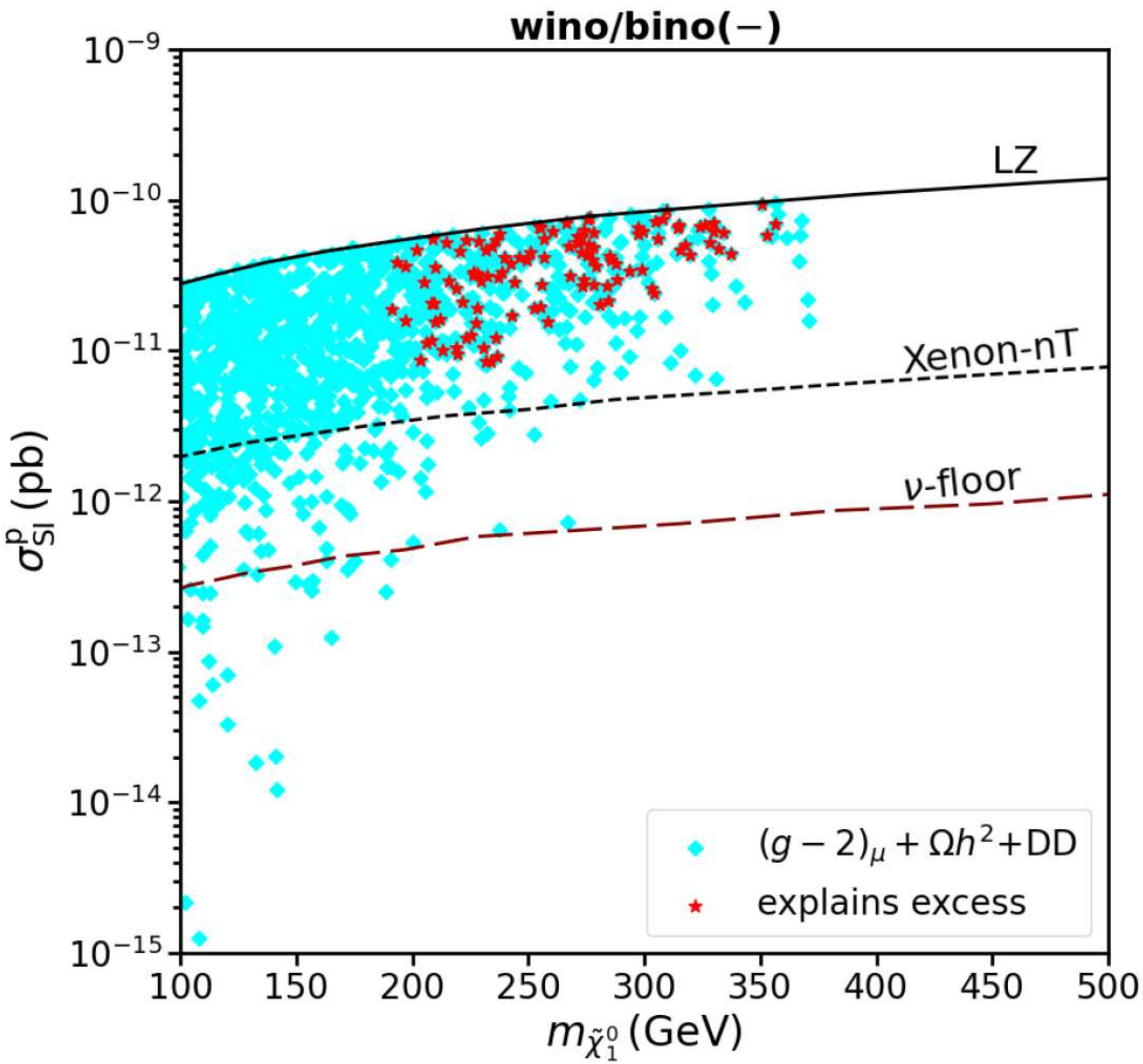


⇒ for lower masses XS have roughly the size required by excesses

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

Q: How can this scenario be tested at future experiments

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A: At a (sufficiently) high-energy e^+e^- collider* we can

– pair produce the charginos
– measure the LSP mass
– fit/measure all relevant Lagrangian parameters
– reconstruct/recalculate the relic density
– compare with measured value
– closure test of the model

[*J. Becks, R. Heine, S.H., F. Lika, G. Moortgat-Pick, WIP*]

* ILC/CLIC/. . .

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* ILC/CLIC/. . .

⇒ next talk by Gudi (among other things)

D) Higgsino DM

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

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

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

$$1.1 M_2 \le \mu \le 10\mu\ ,$$

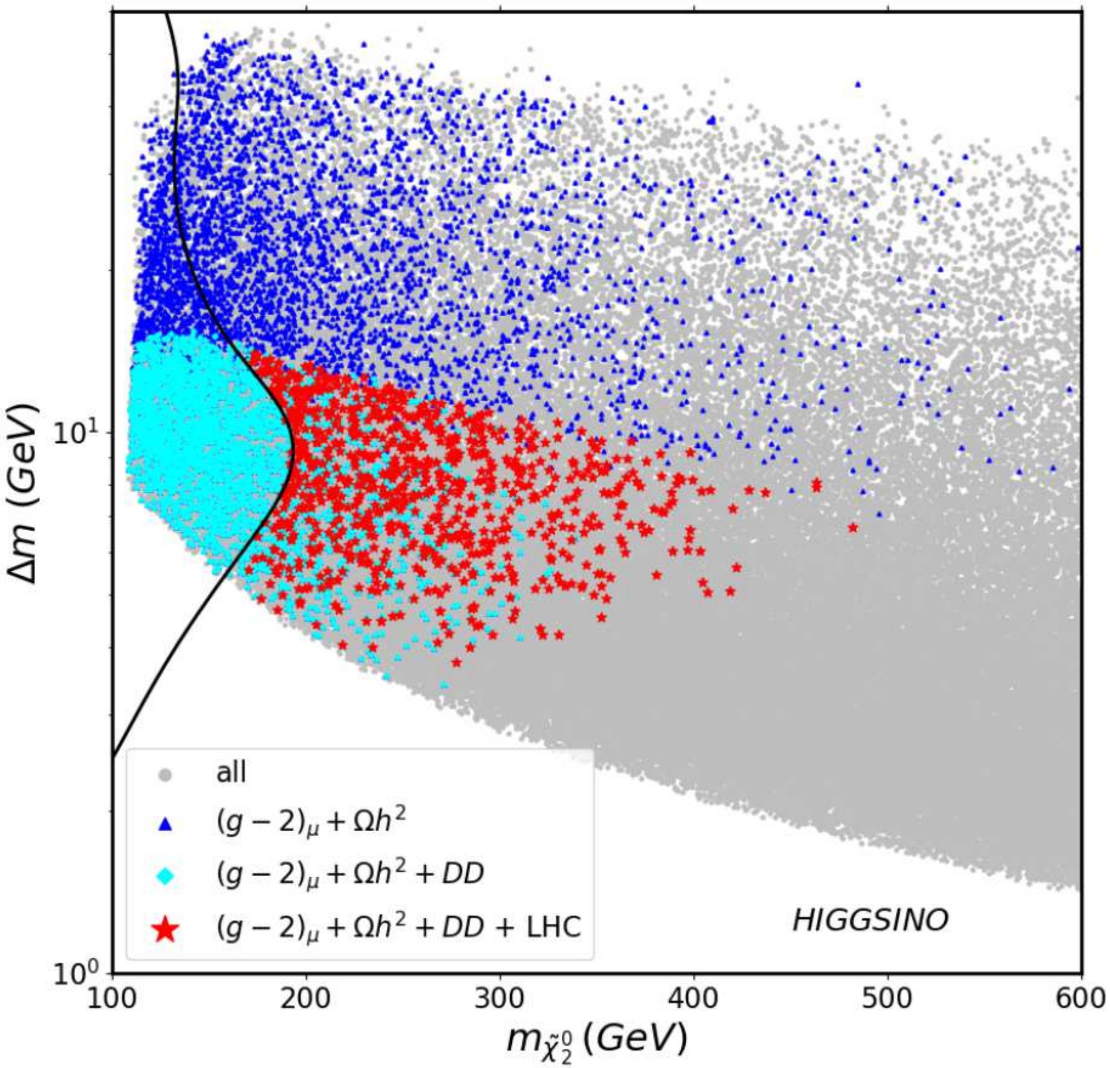
$$5 \le \tan\beta \le 60,$$

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

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

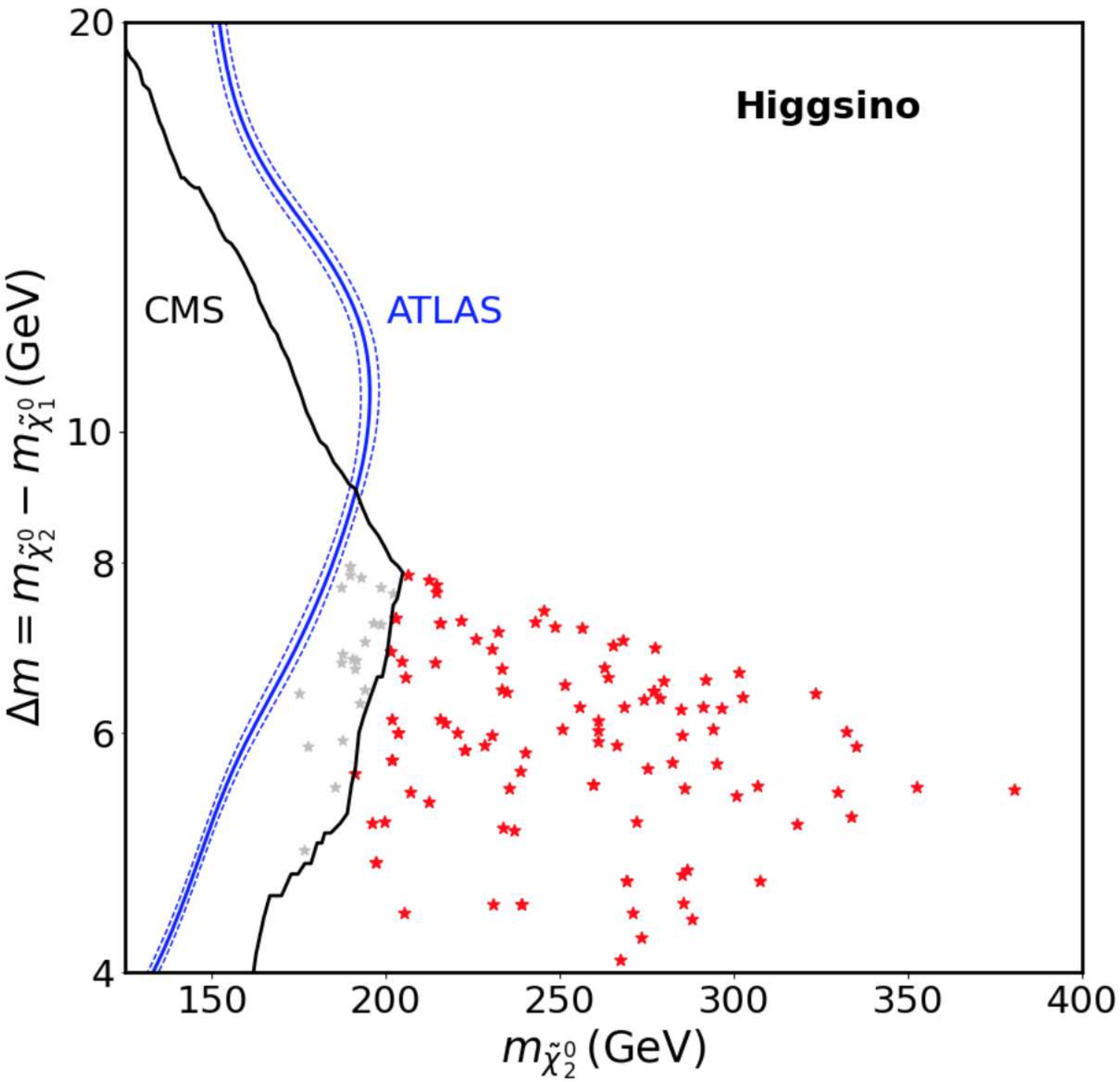
Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with a $5\,\sigma$ deviation in $(g-2)_\mu$
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

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



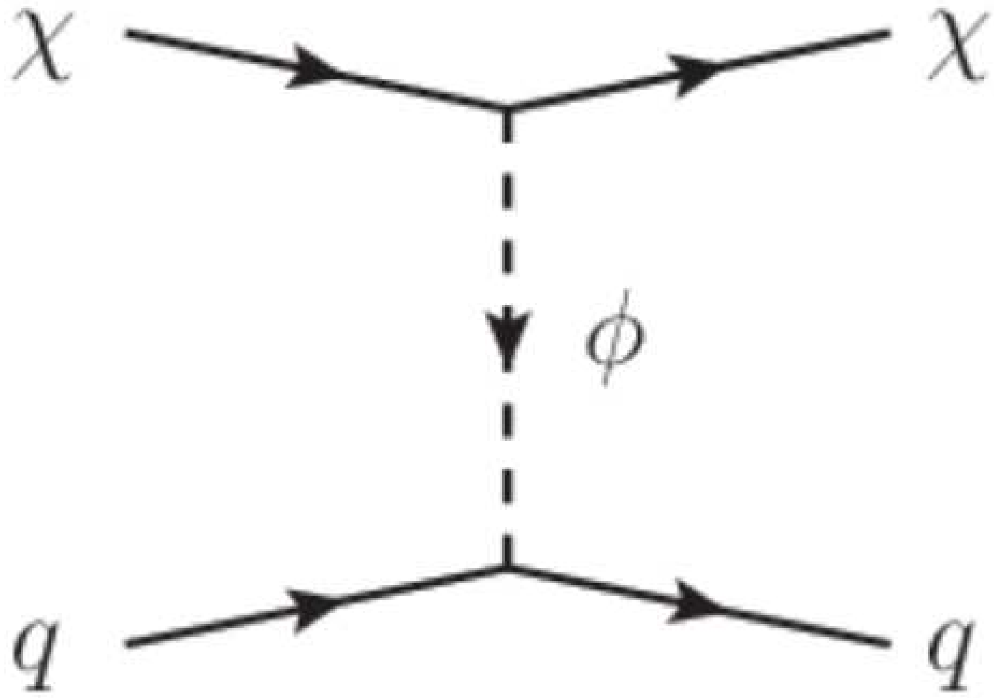
$\Rightarrow$ direct detection is the limiting factor on Δm

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



⇒ excess not fitted :-(⇒ DD cuts away the "good points"

Problematic diagram for higgsino DM DD:



$\phi = h, H$

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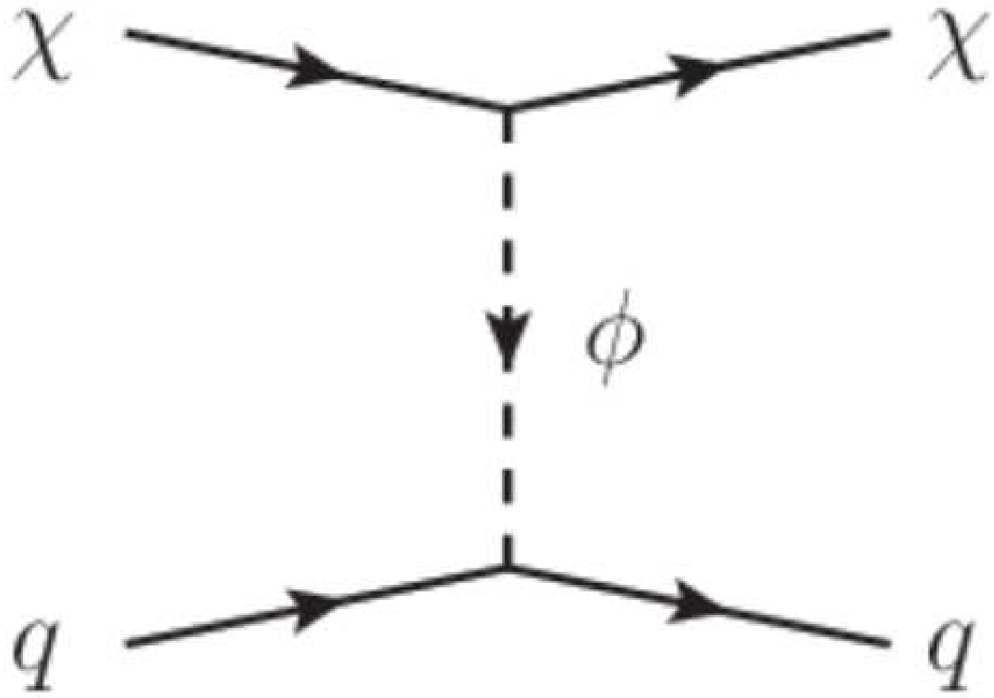


$\phi = h, H$

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

$\Rightarrow$ new scan with $M_1 < 0$

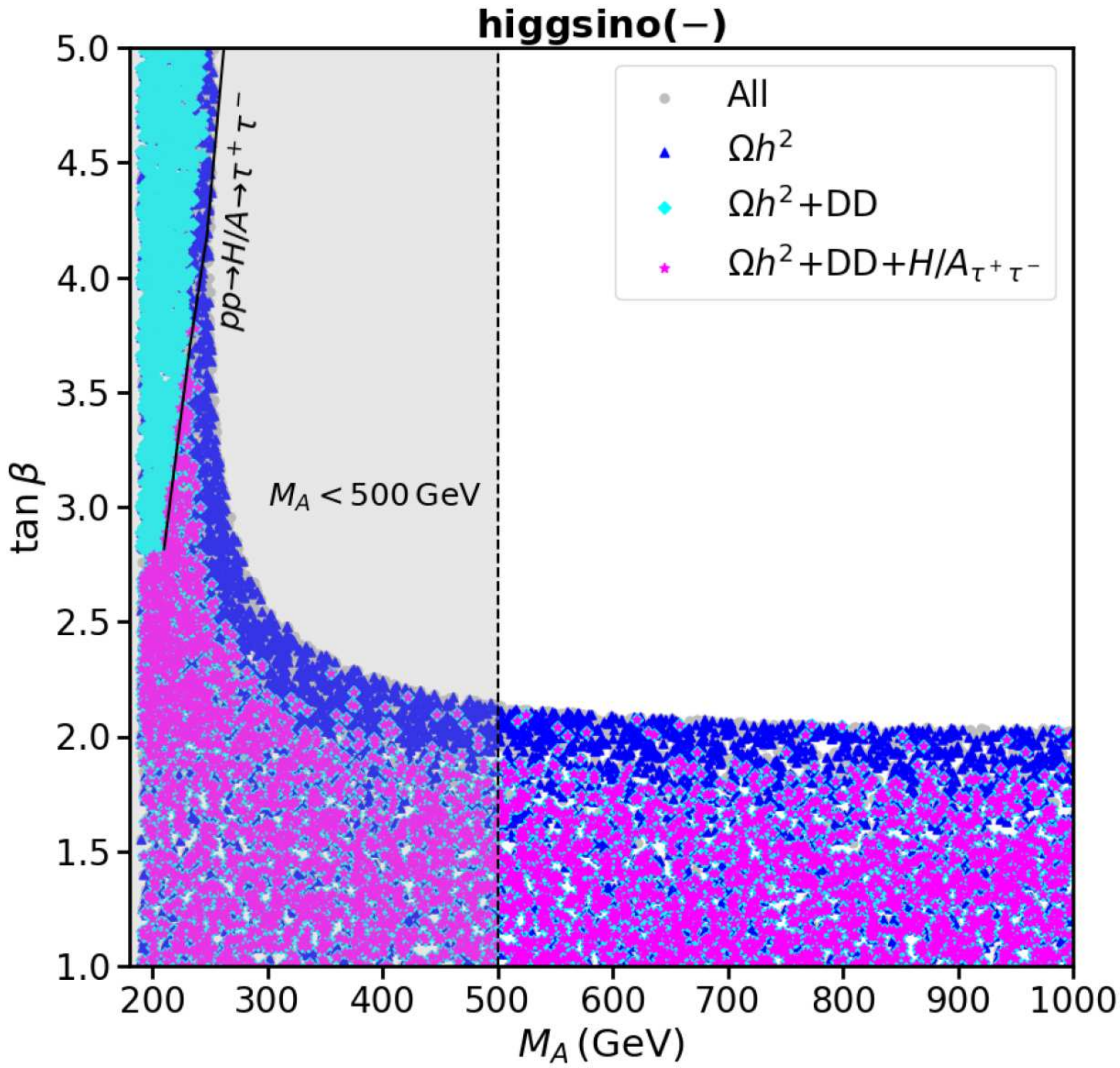
New scan with $M_1 \times \mu < 0$

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

Condition on μ and M_1: exact blind spot conditions

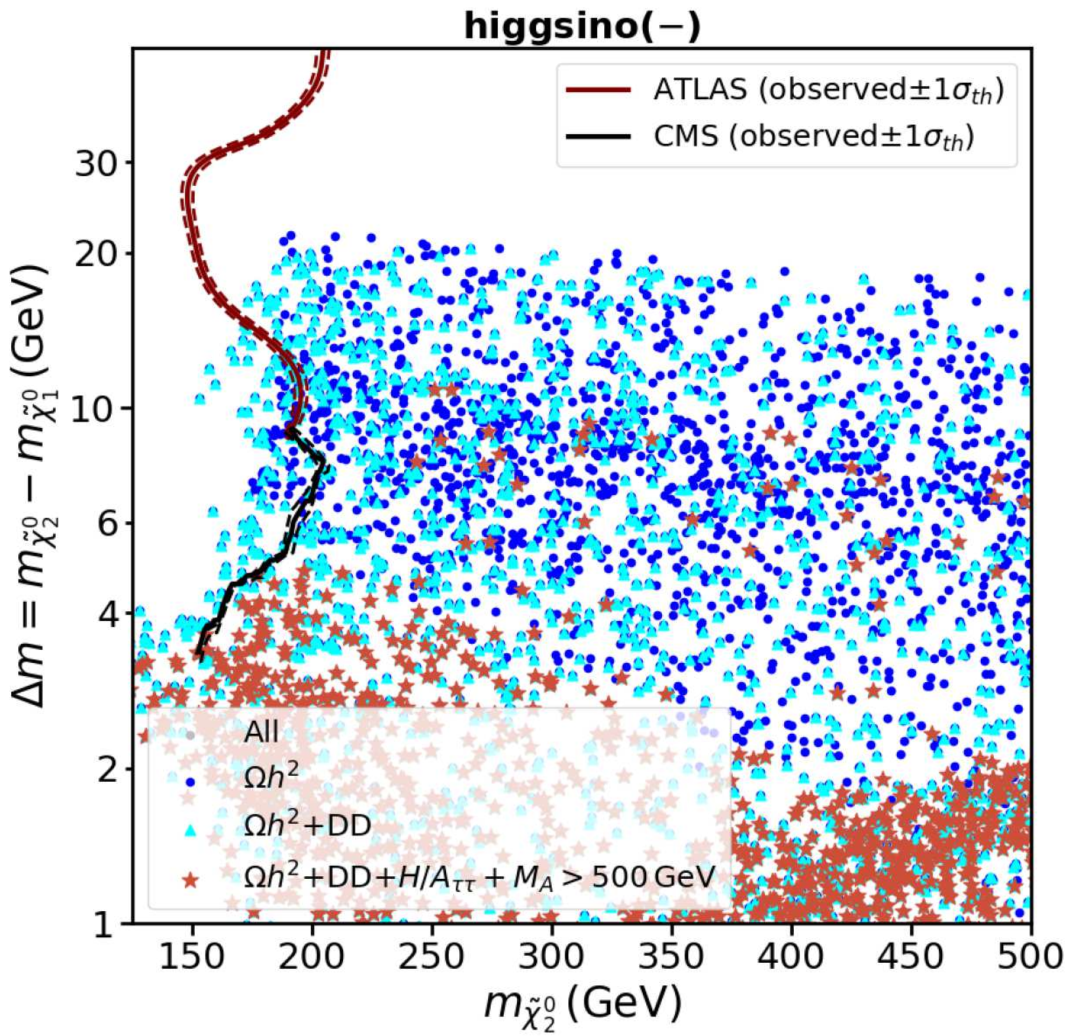
relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

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



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

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



⇒ restrictions still cut away the “good parameter space”

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

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: $M_1 \sim M_2/2$ $\Rightarrow$ 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)

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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!

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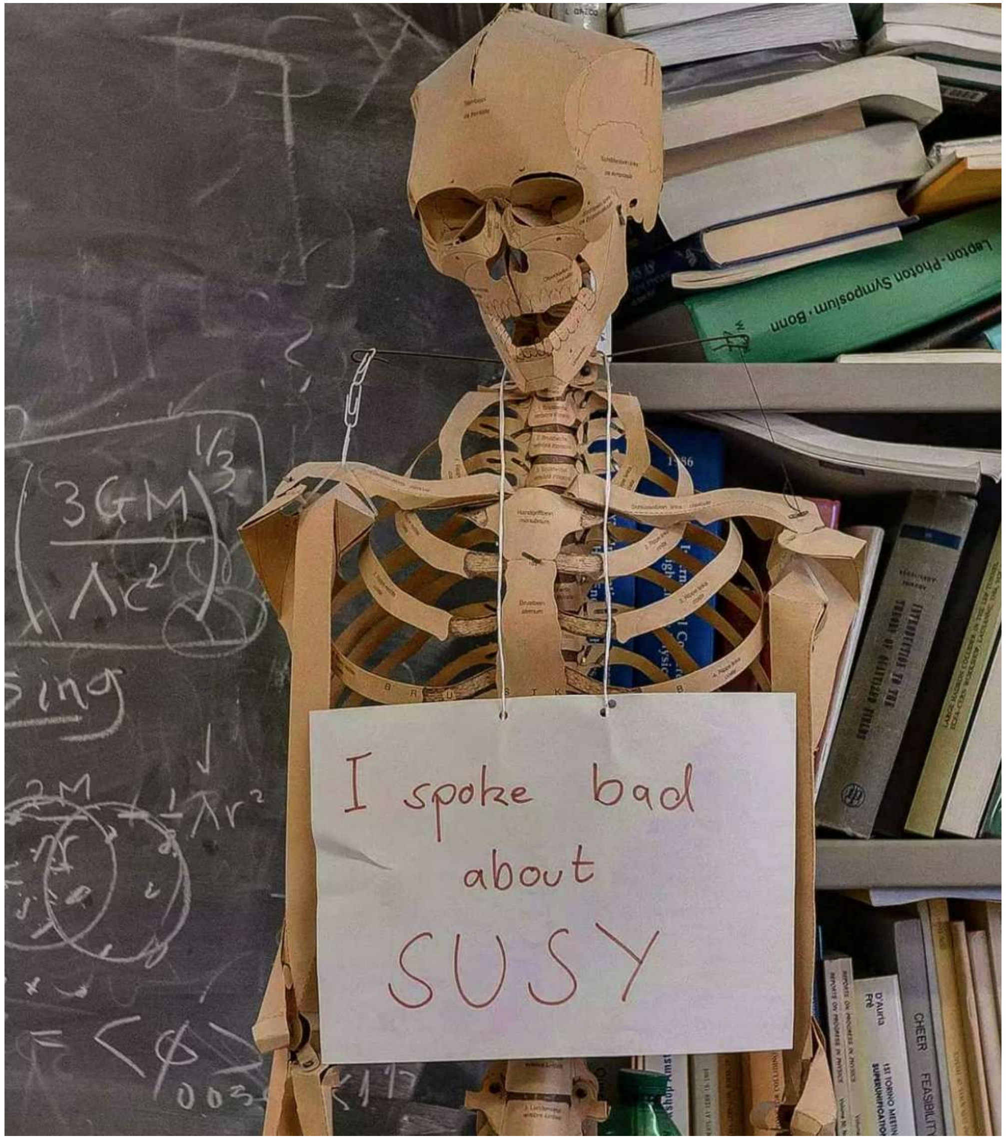
4. Solution for GUT-based scenarios

[*E. Bagnaschi, M. Chakraborti, S.H., I. Saha, WIP*]



As expected: no time

GUT-based solution: NMSSM

$\Rightarrow$ LSP singlino like

$\Rightarrow$ avoid DD bounds

$\Rightarrow$ $\mu \lesssim M_1 \sim M_2/2 \sim M_3/6$

with $M_3 = m_{\tilde{g}} \gtrsim 2$ TeV

– average mass gap ok
– "good" mass gap favors full relic density
– interesting prospects for next round of DD experiments

$\Rightarrow$ see back-up

5. 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, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20 - 25$ GeV
- MSSM wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)
  $\Rightarrow$ fits well the excesses! $\Rightarrow$ good prospects for DD experiments
  Never: $M_1 \sim M_2/2$ $\Rightarrow$ not GUT-based
  MSSM higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim |M_1|, M_2$)
  $\Rightarrow$ does not fit the excesses
  Possible: $M_1 \sim M_2/2$ $\Rightarrow$ can be GUT-based
- GUT-based solution: NMSSM $\Rightarrow$ LSP singlino like $\Rightarrow$ avoid DD bounds

  $\Rightarrow \mu \lesssim M_1 \sim M_2/2 \sim M_3/6$ ($M_3 = m_{\tilde{g}} \gtrsim 2$ TeV) $\Rightarrow$ can be GUT based

  – average mass gap ok, larger mass gap favors full relic density
  – interesting prospects for next round of DD experiments


Higgs Days at Santander 2025
Theory meets Experiment
8 – 12 September
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Celso.Martinez@cern.ch
http://hdays.csic.es


Further Questions?

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

MSSM Higgs sector: Two Higgs doublets

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

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

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

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

$$
\begin{aligned}
V = \; & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

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

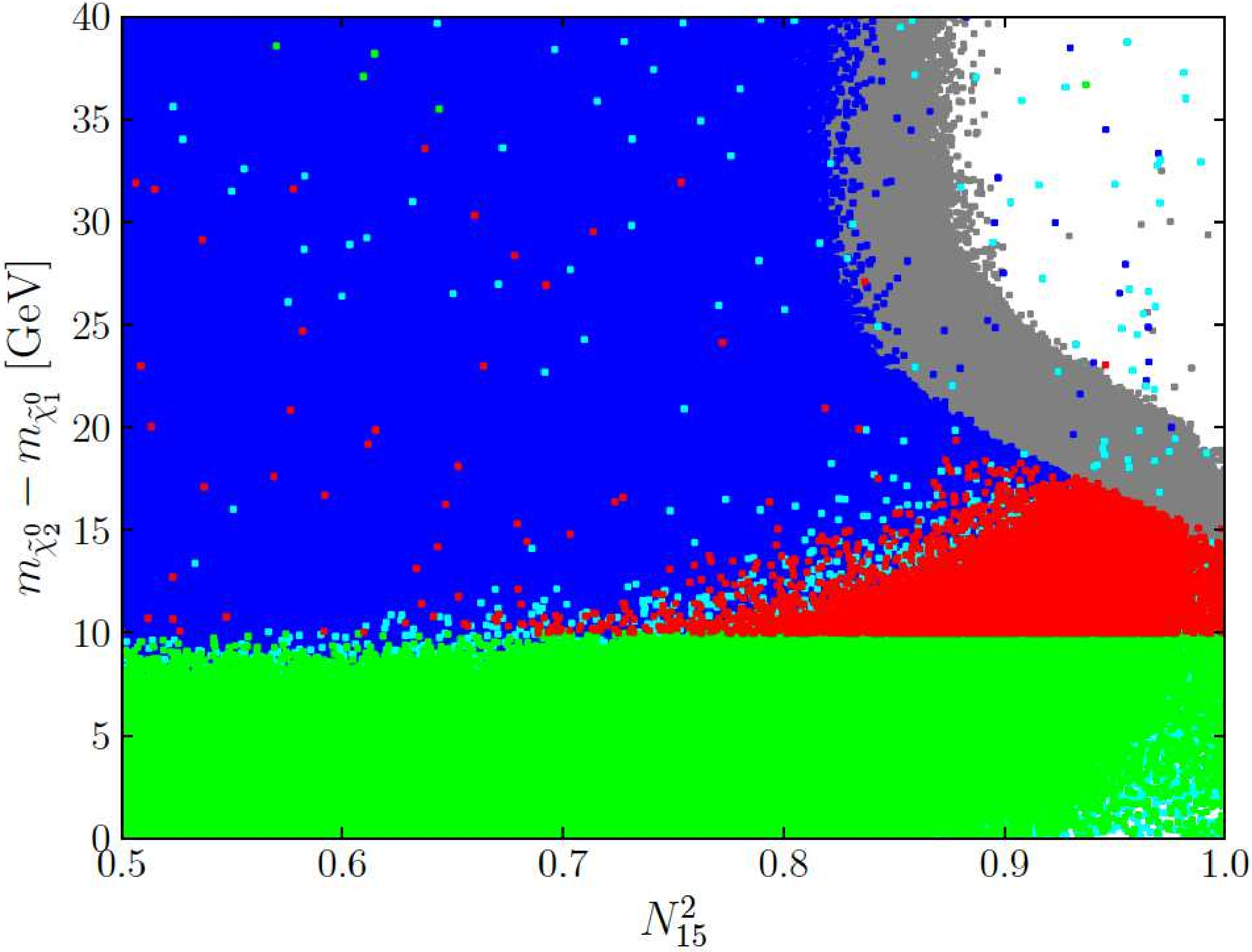
$$\to \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4, \tilde{\chi}^0_5$$

⇒ 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(−): Singlino component:

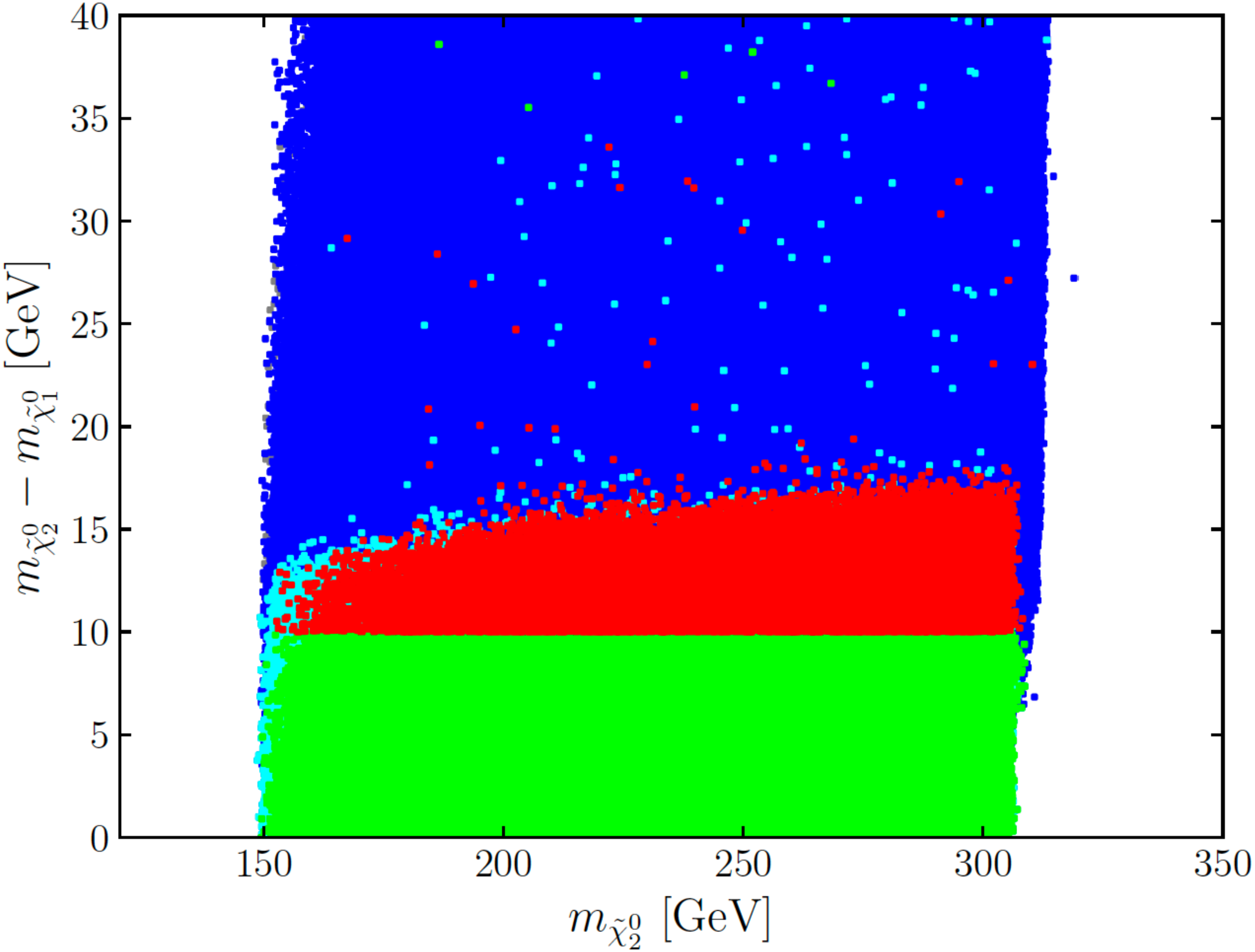
[*PRELIMINARY*]



$\Rightarrow$ larger Δm yields $N_{15}^2 \sim 0.93$

higgsino(−): $m_{\tilde{\chi}_2^0}$-Δm plane:

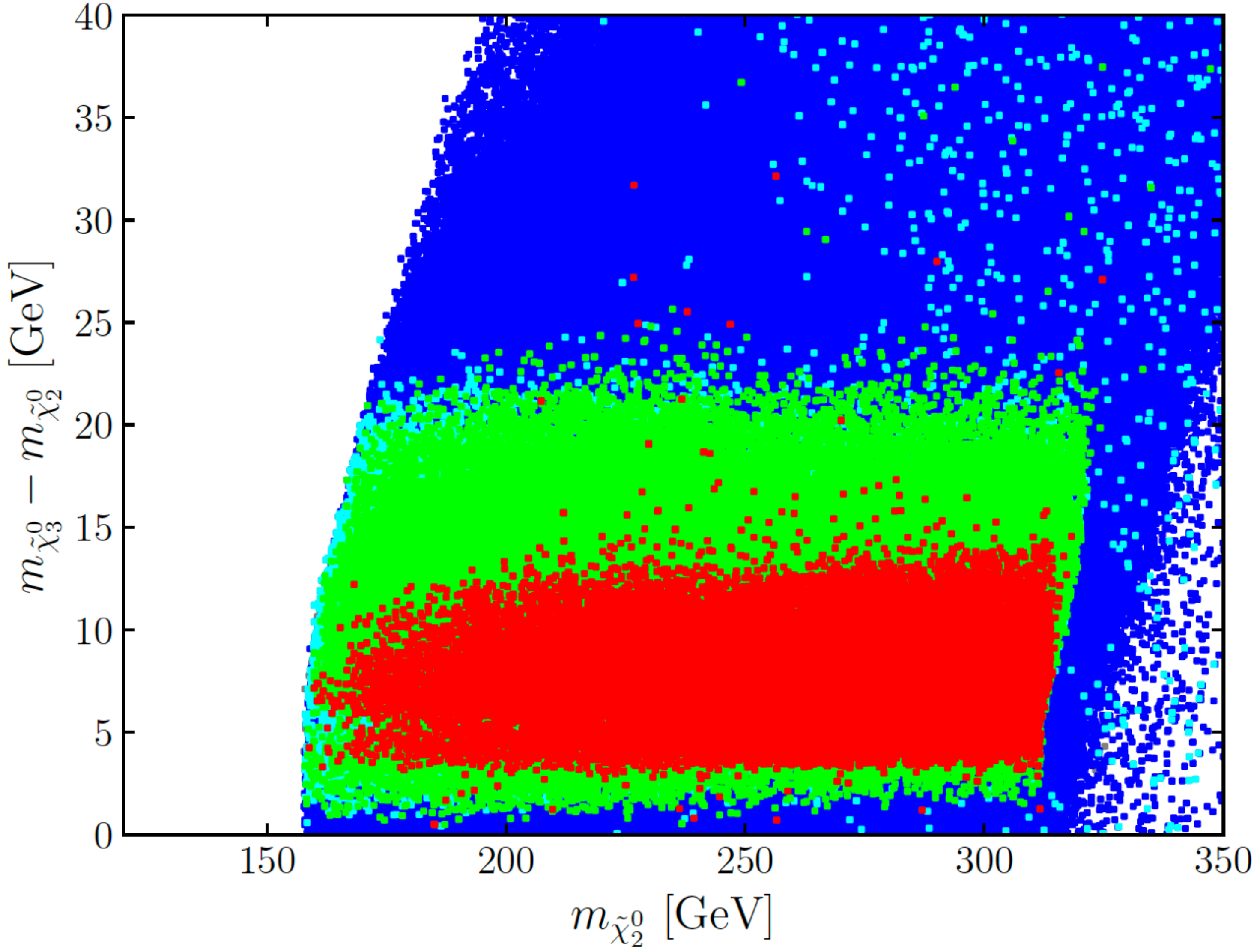
[PRELIMINARY]



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

higgsino(−): more than one Δm:

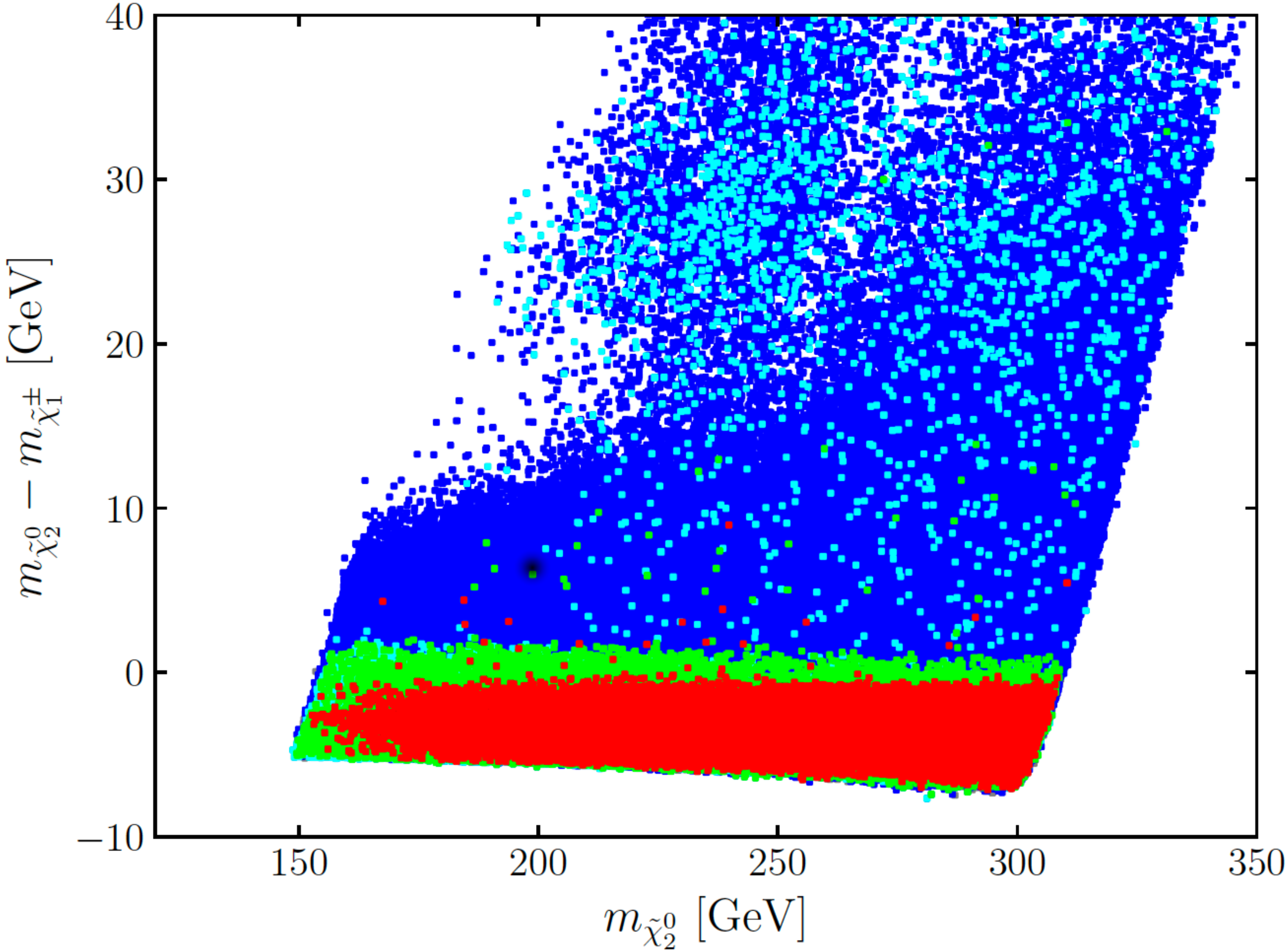
[*PRELIMINARY*]



⇒ large mass gap, better for the excesses

higgsino(−): more than one Δm:

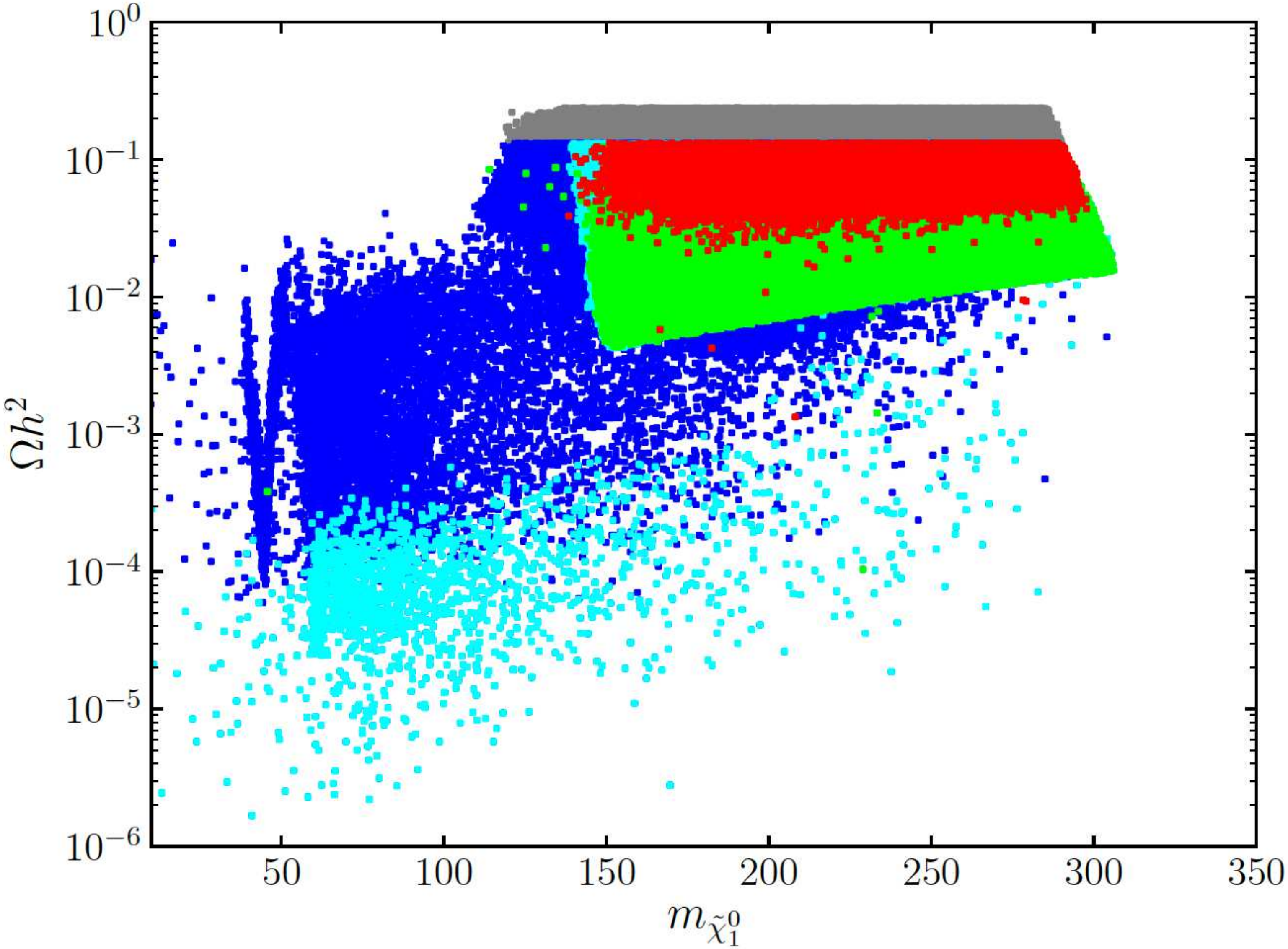
[*PRELIMINARY*]



⇒ large mass gap, better for the excesses

higgsino(−): DM relic density:

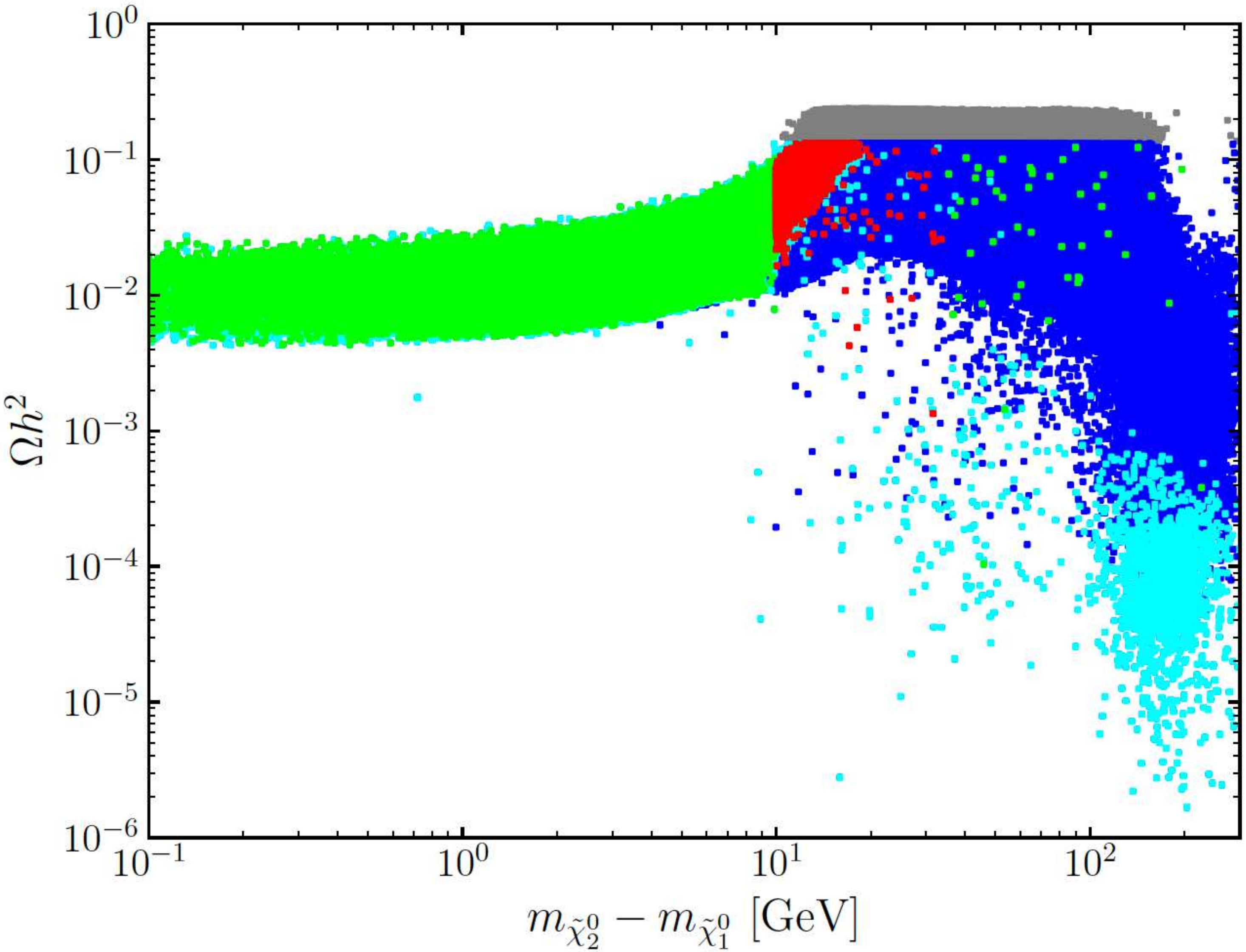
[*PRELIMINARY*]



⇒ singlino can give the full DM density

higgsino(−): DM relic density:

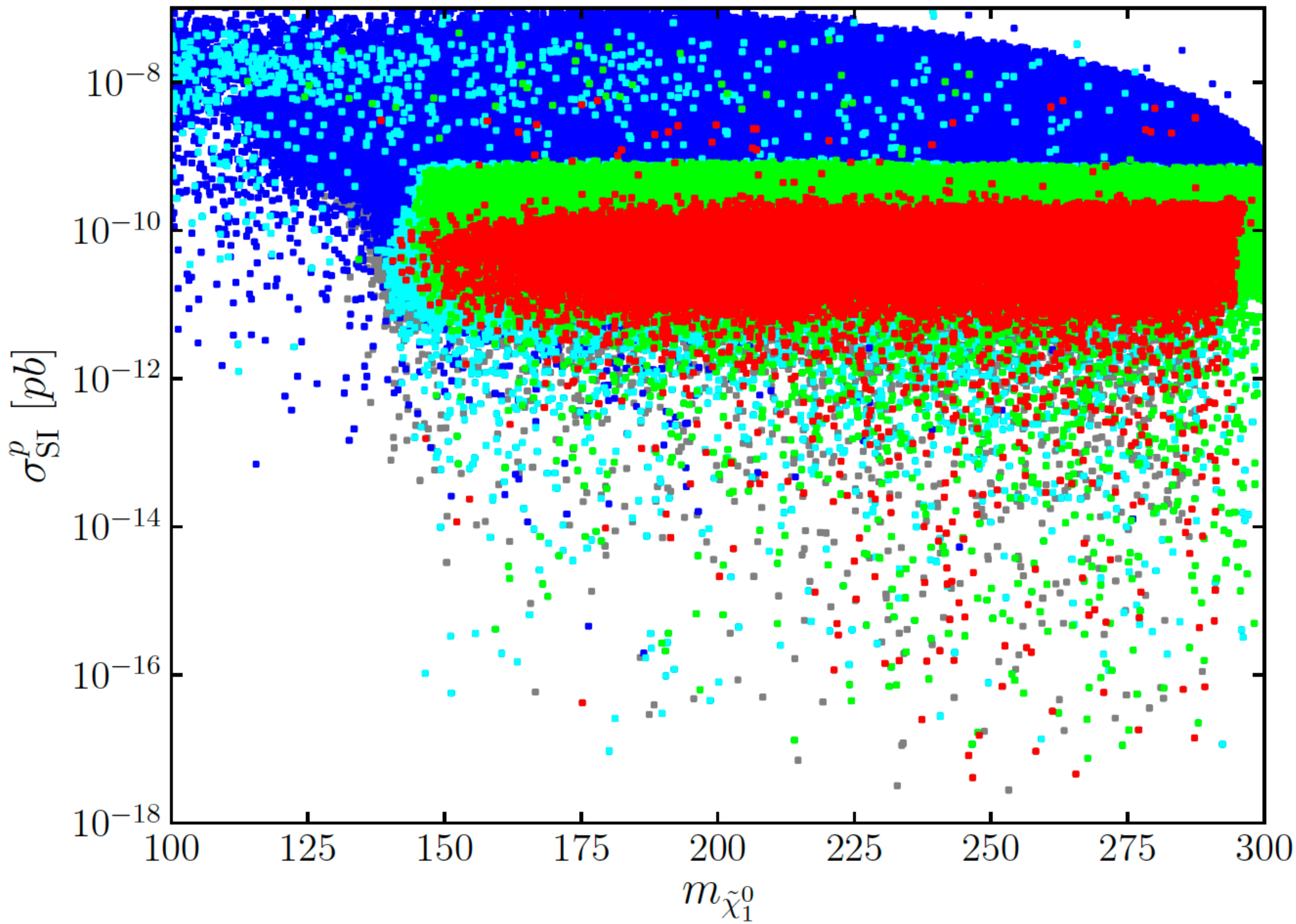
[*PRELIMINARY*]



⇒ larger mass gap favors full relic density

higgsino(−): predictions for DD experiments

[*PRELIMINARY*]



⇒ good prospects for next round of DD experiments

6. Reconstruction of wino/bino DM at the ILC

[J. Becks, R. Heine, S.H., F. Lika, G. Moortgat-Pick, PREL.]

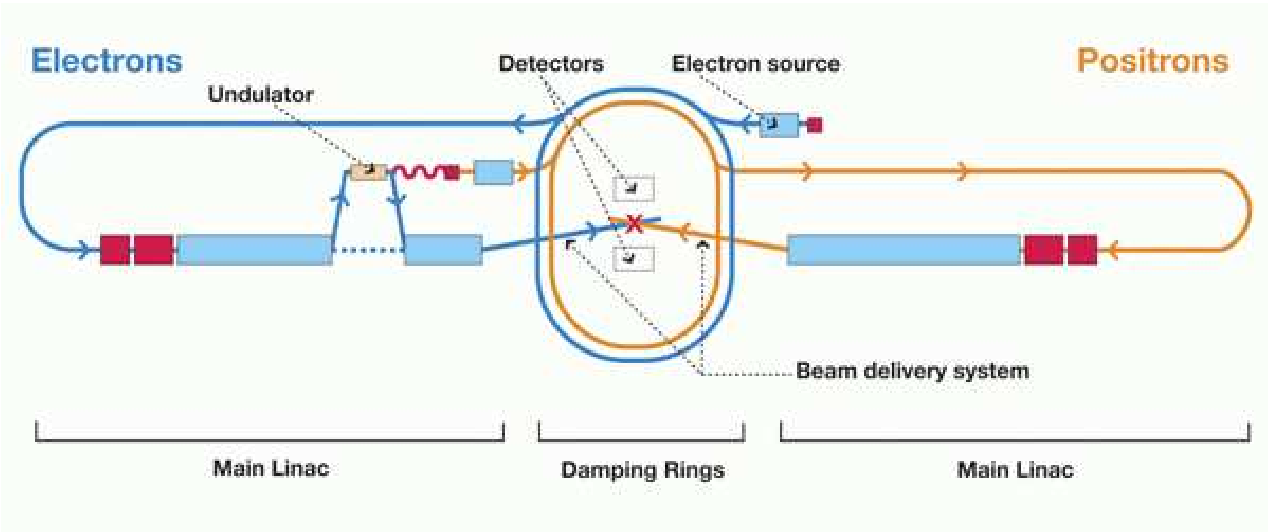
Mini overview of the International Linear Collider (ILC)

Mini overview of the International Linear Collider (ILC)

Linear e^+e^- collider, $\sqrt{s} = 250 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



– two detectors in one interaction region (push-pull)
– undulator based e^+ source
– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)
– tunable energy

The main idea:

1. Assume that (low-mass) wino-bino DM ($\tilde{\chi}_1^\pm$-coannihilation) is realized: $M_1 \lesssim M_2 \ll \mu$ (but for now $M_1 \times \mu > 0$).

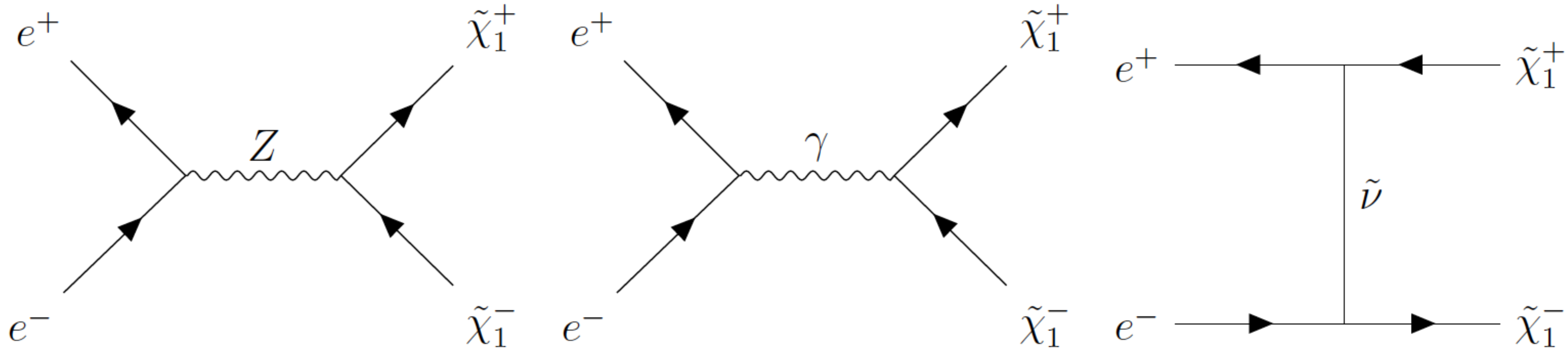
2. At the ILC500 we measure $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$.
XS measurement with two (good) polarizations and at $\sqrt{s} = 400, 500$ GeV.

3. This allows (in principle) to reconstruct M_1, M_2, μ, $m_{\tilde{\nu}_e}$, $\ldots$ – with uncertainties.
$\tan\beta$ assumed to be roughly known from other measurements.

4. With these parameters $\Omega_\chi h^2$ can be calculated – with uncertainties.

5. Comparison of $\Omega_\chi h^2$ with astrophysically measured value constitutes an important test of the model.

The Feynman diagrams:



$\Rightarrow m_{\tilde{\nu}_e}$ enters

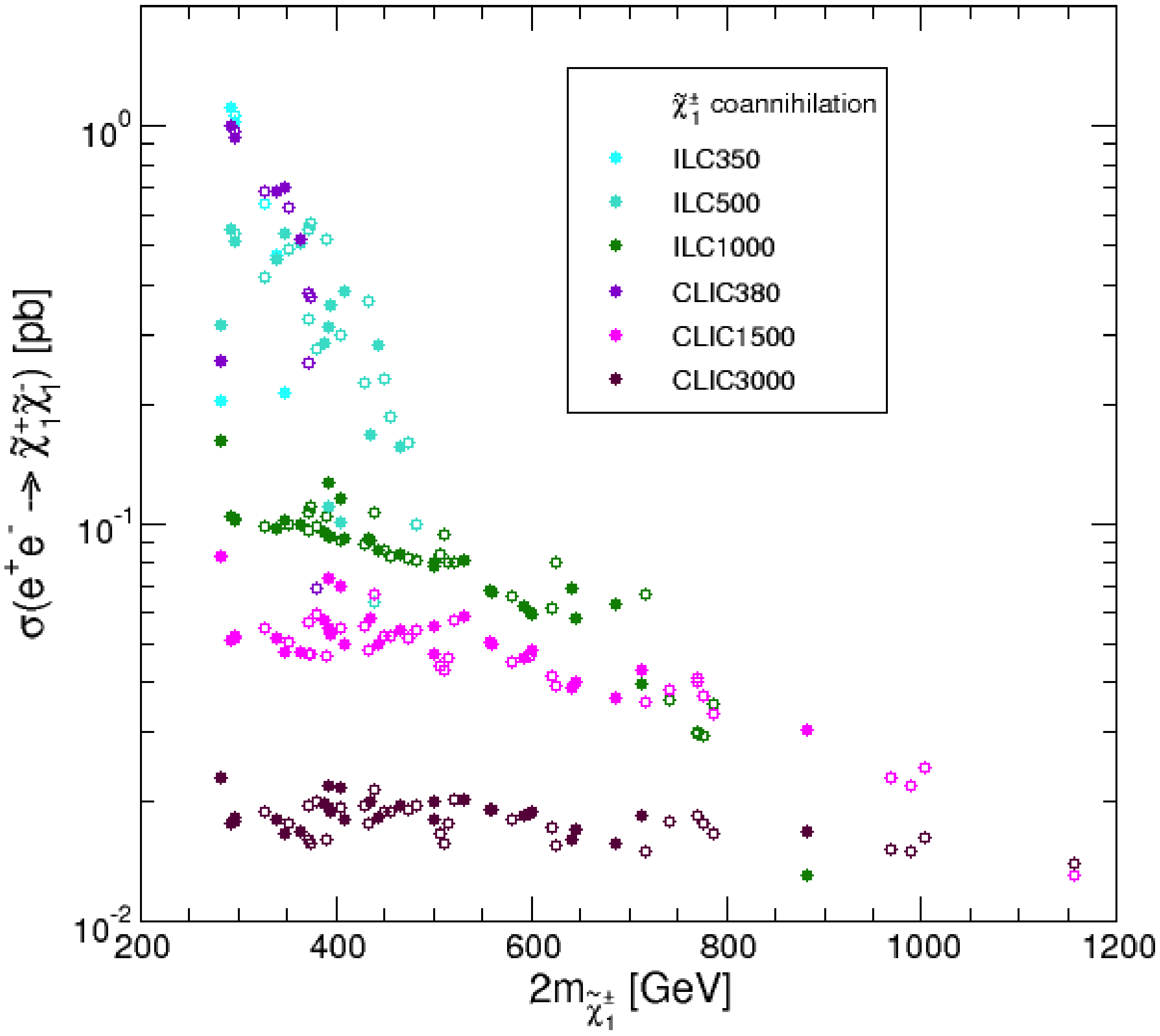
– so far tree-level analysis

– to be repeated including full one-loop corrections

– more involved parameter dependences

wino/bino(+): $\sigma(e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$:

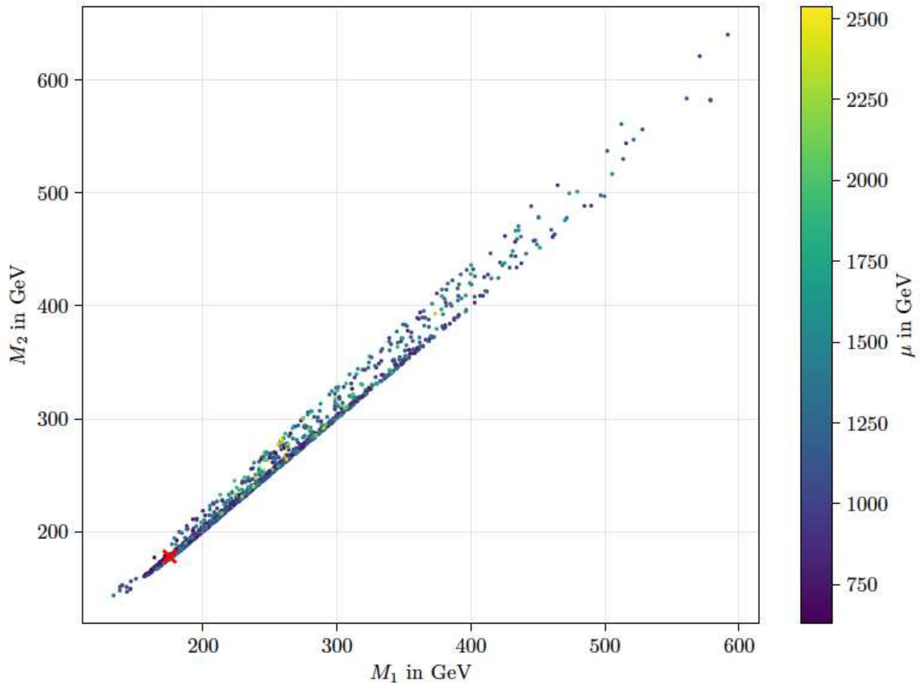
[*M. Chakraborti, S.H., I. Saha '20*]



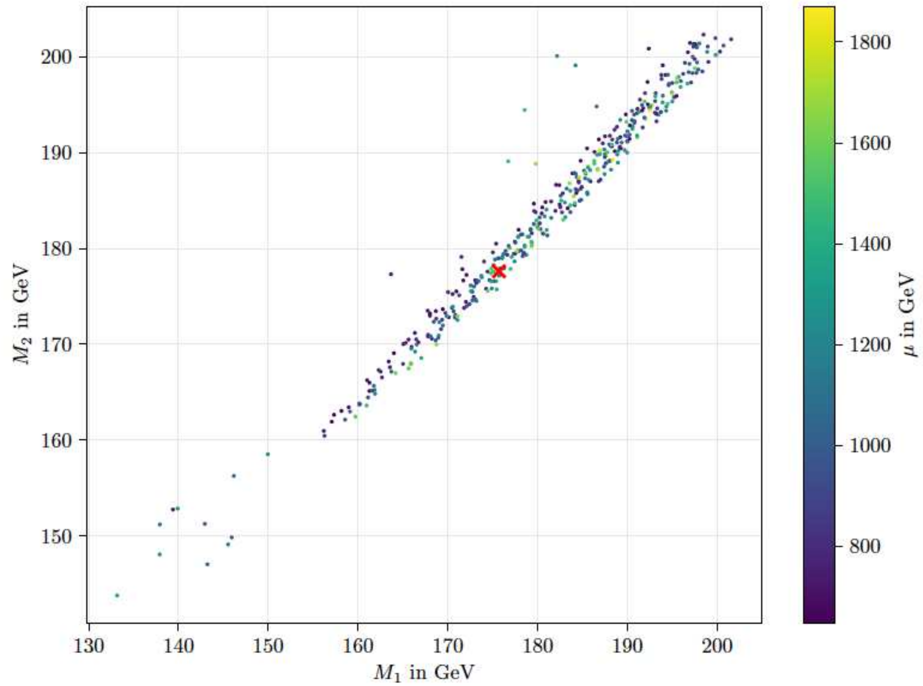
⇒ easy for ILC500/ILC1000 :-)

The parameter points:

full (original) set



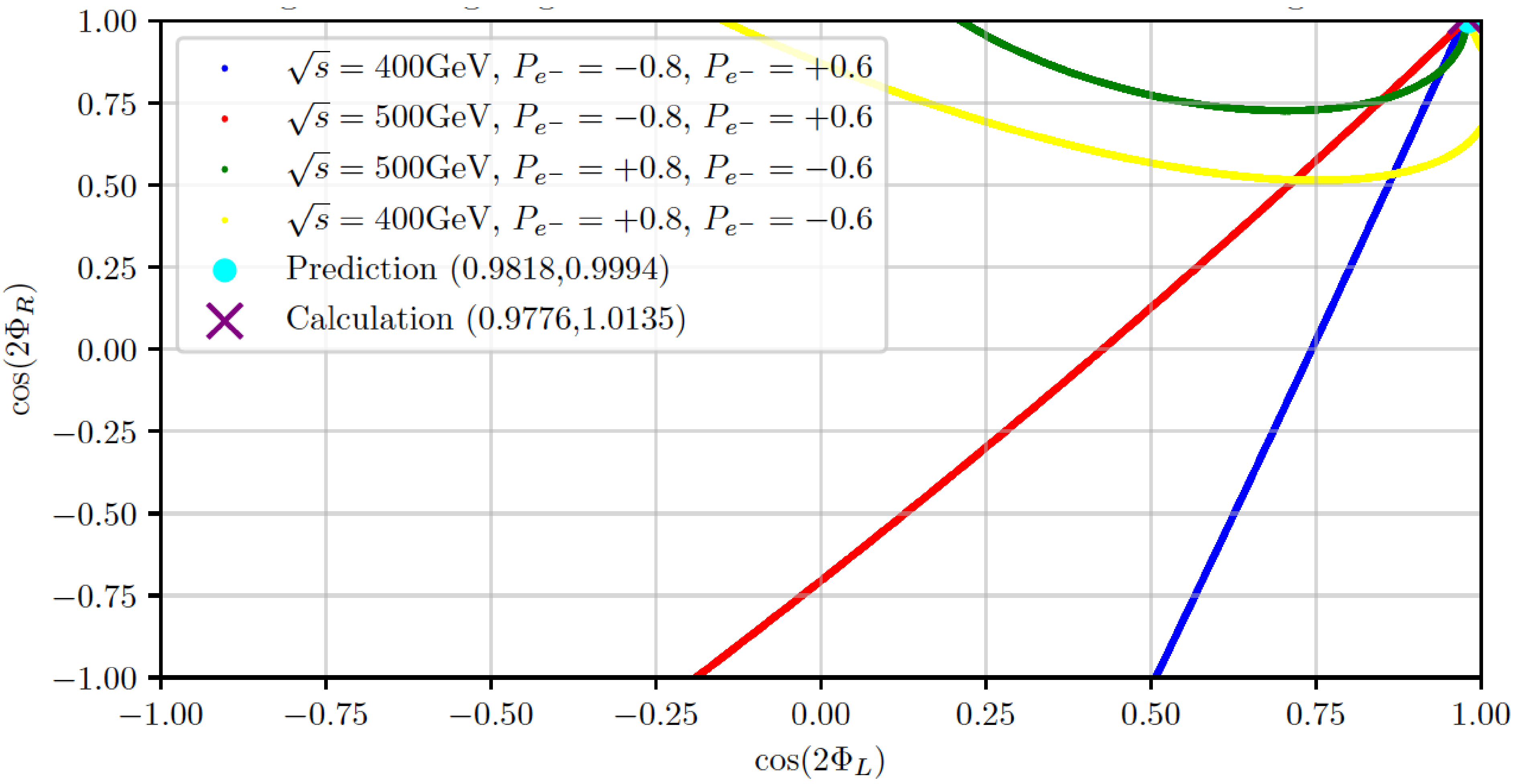
accessible set



⇒ only lower masses accessible

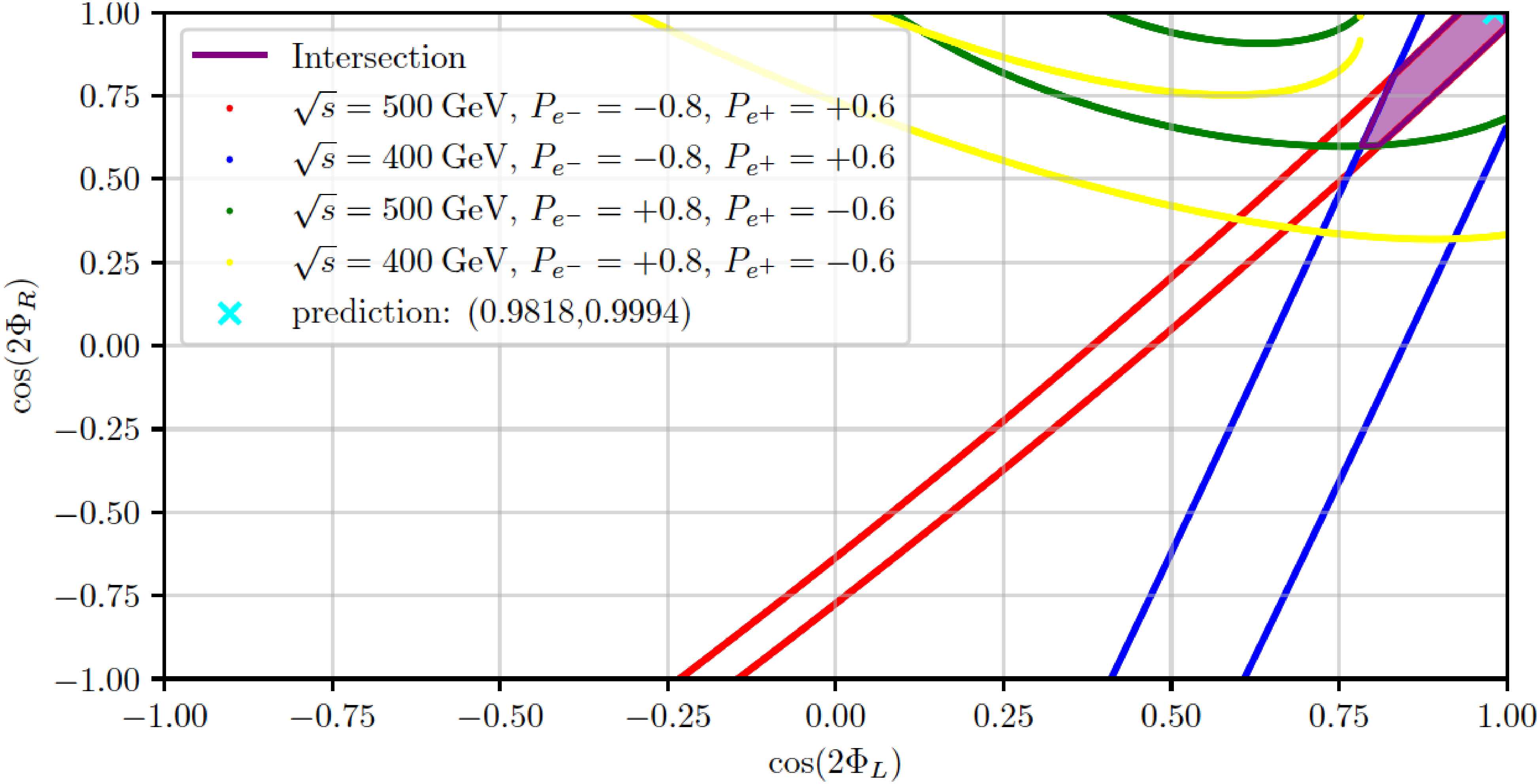
⇒ interesting points corresponding to the excesses covered . . .
(red star: example point)

Ellispses of four XS measurements:



⇒ four ellipses must meet – and they do!

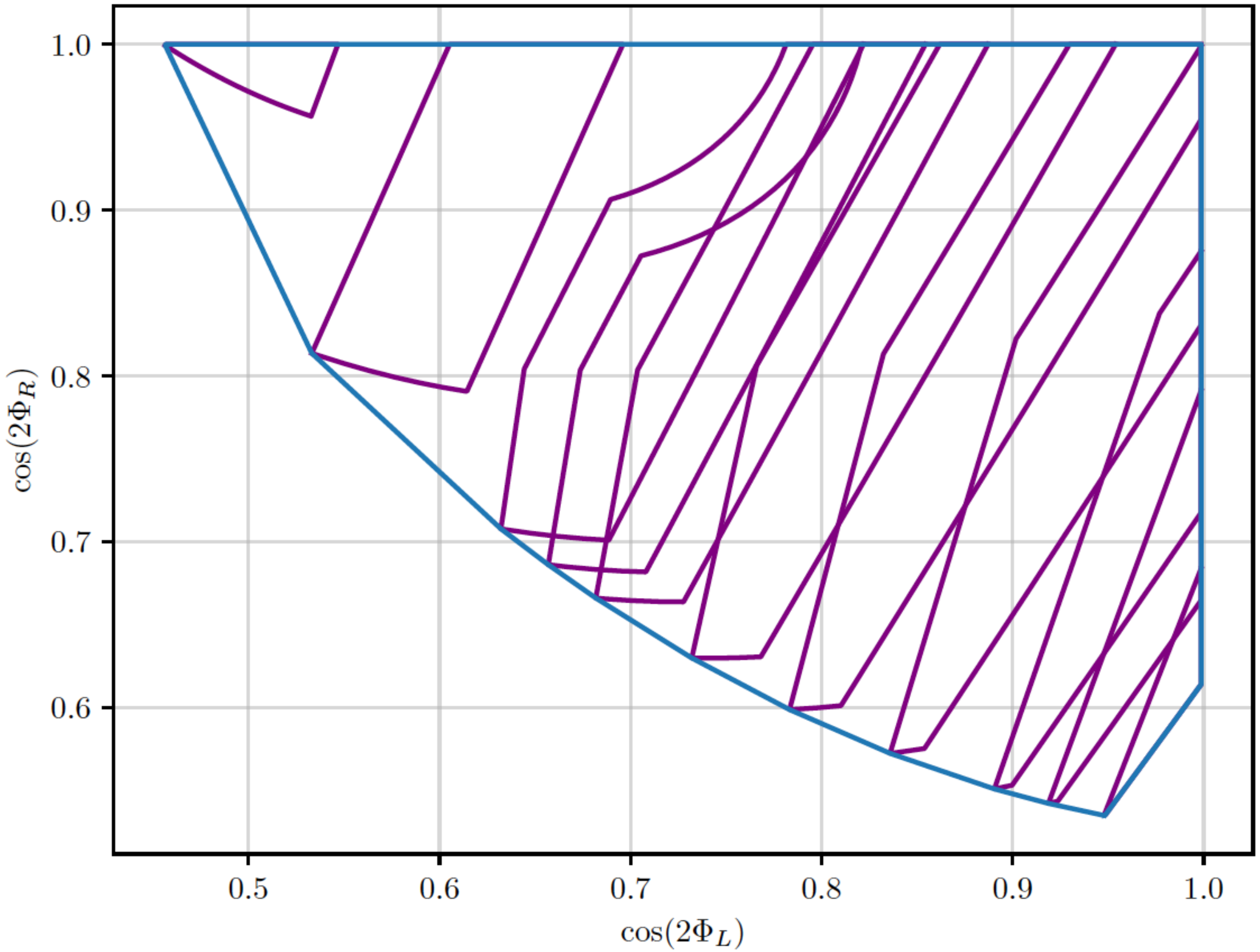
Ellispses of four XS measurements with uncertainties:



$\Rightarrow$ uncertainties lead to overlap region

So far used: correct, but unknown $m_{\tilde{\nu}_e}$ (too heavy for ILC500)

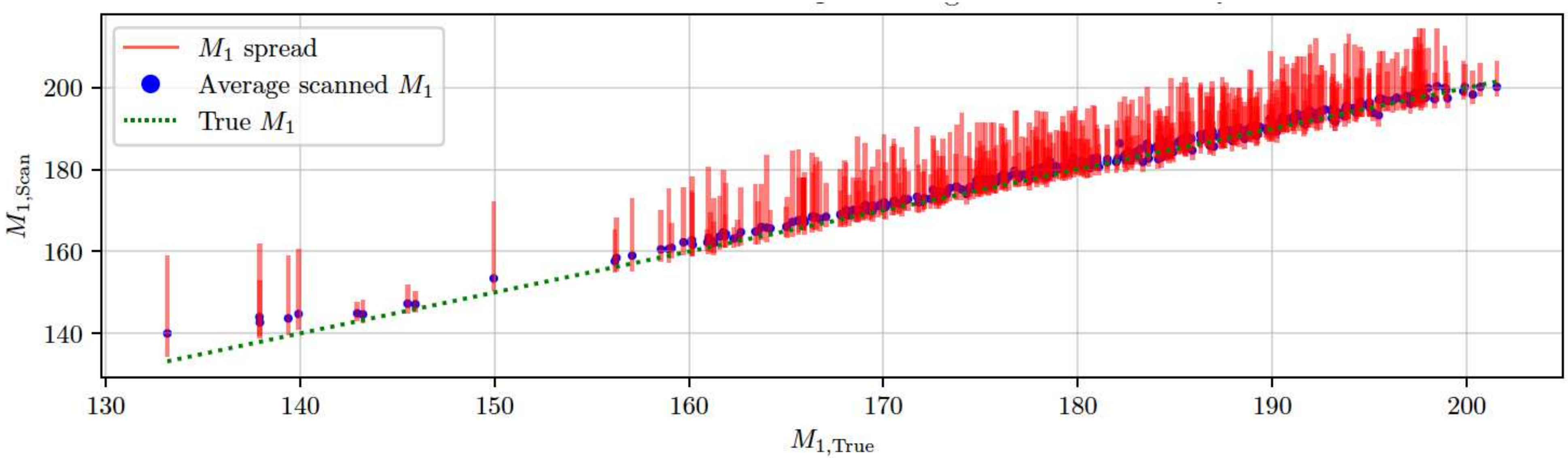
Variation of $m_{\tilde{\nu}_e}$:

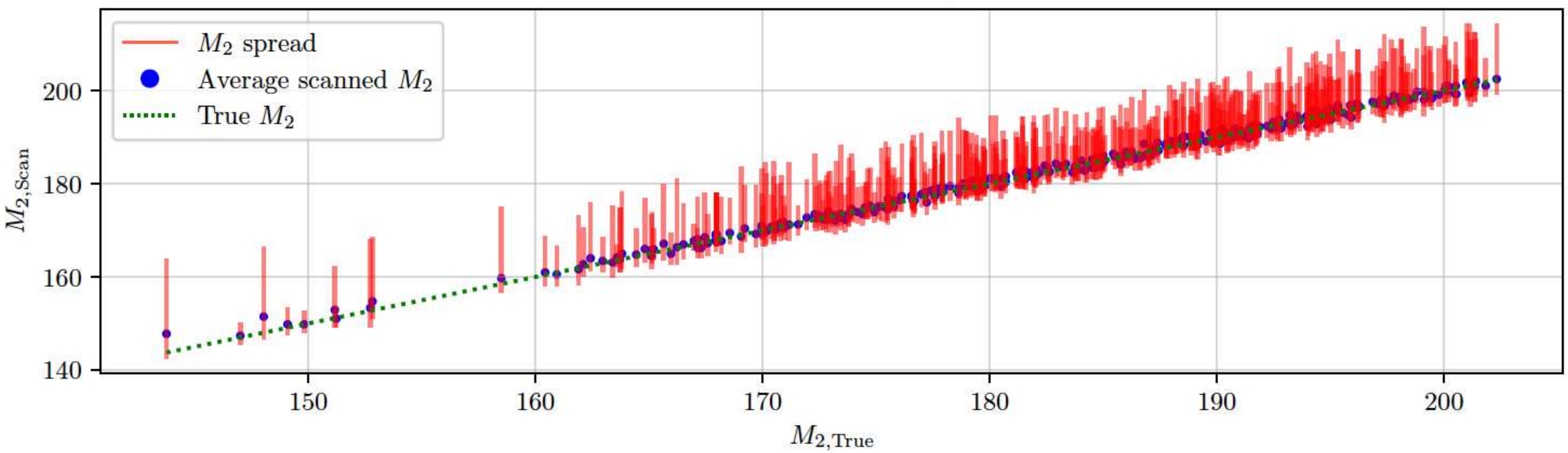


⇒ overlap region smeared out

⇒ indirect determination of $m_{\tilde{\nu}_e}$ (within $\lesssim \pm 100$ GeV)

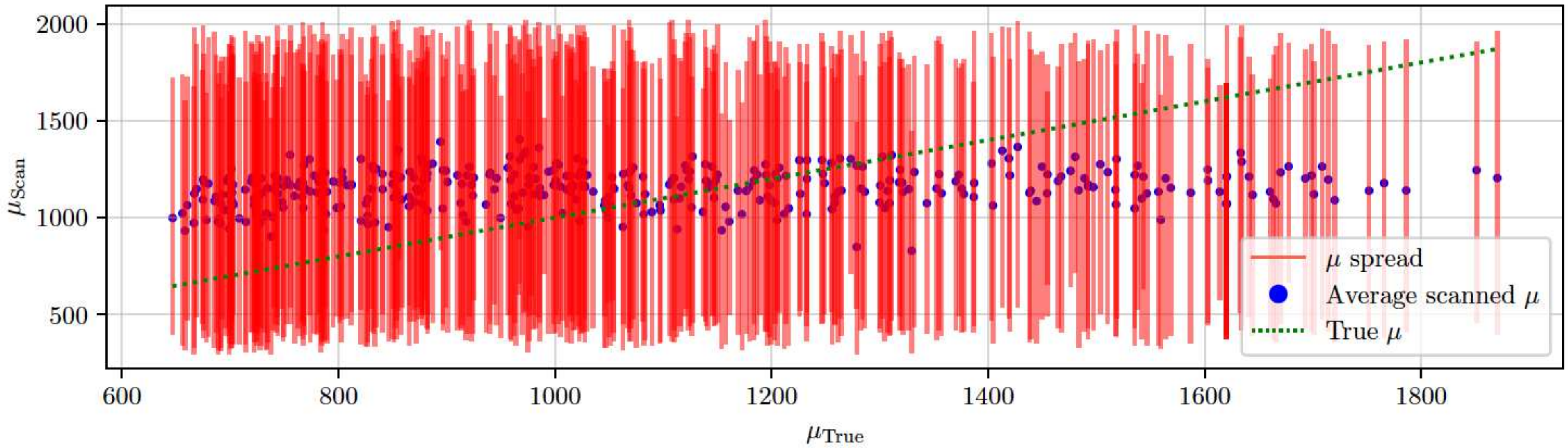
Reconstruction of M_1 and M_2:

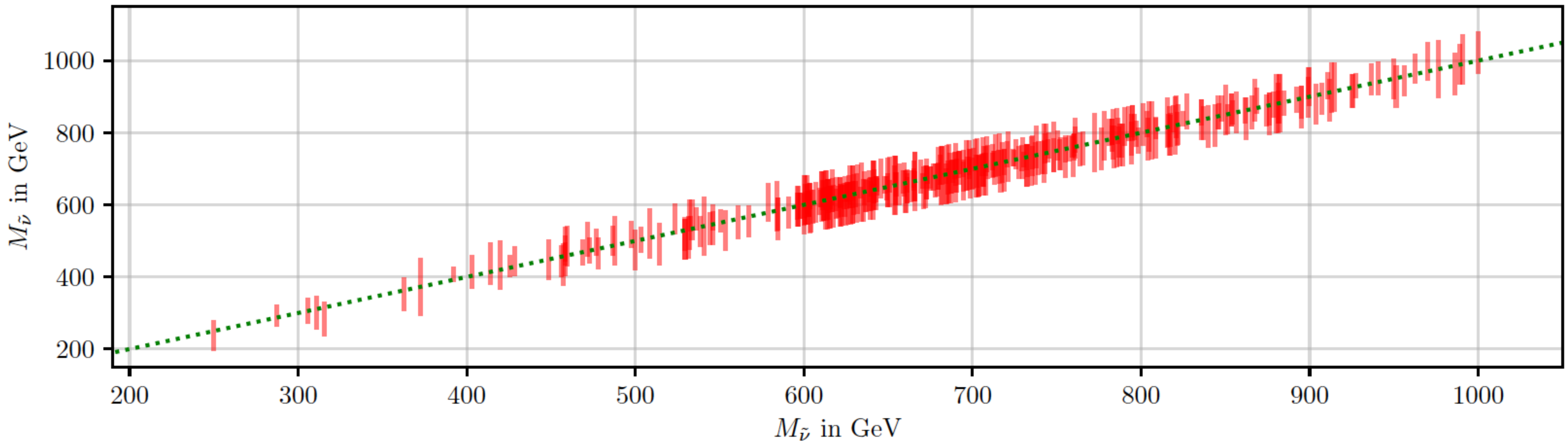




⇒ good reconstructions possible

Reconstruction of μ and $m_{\tilde{\nu}_e}$:

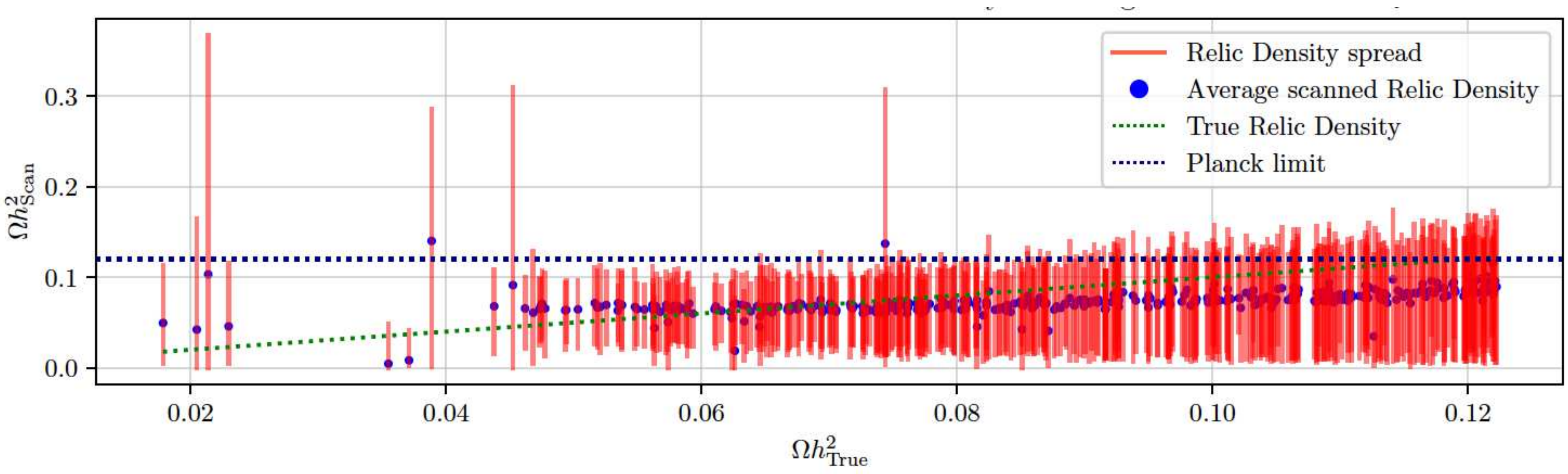




⇒ bad reconstruction of μ, good reconstruction of $m_{\tilde{\nu}_e}$

⇒ no problem, since μ is not very relevant in this scenario

Reconstruction of $\Omega_\chi h^2$:

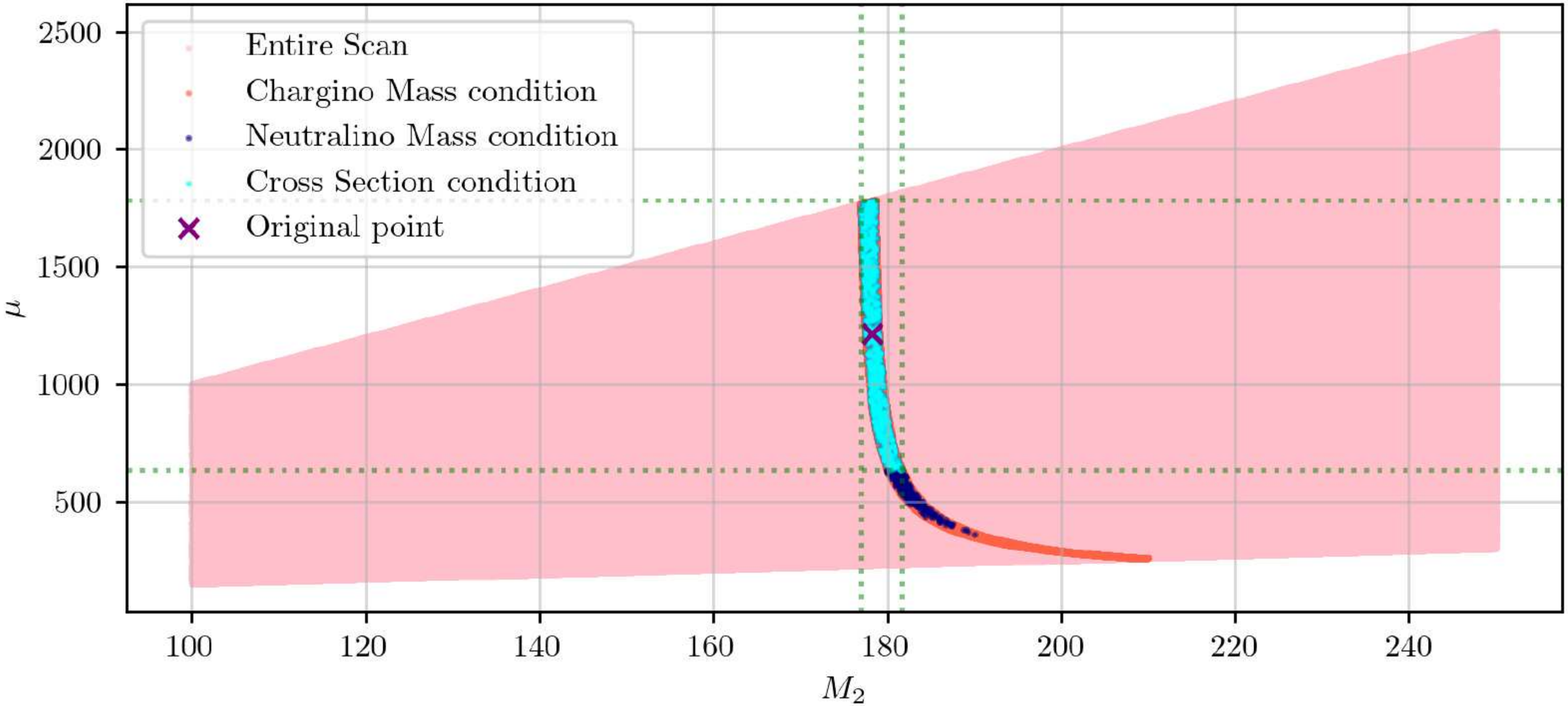


$\Rightarrow$ often large uncertainties - but not too bad either

$\Rightarrow$ reason: experimental uncertainties in M_1 and M_2

$\Rightarrow$ possible improvement: optimized $\sqrt{s}$

MSSM parameter determination:



– XS measurement very important
– M_2 well determined
– μ poorly determined (not very relevant in this scenario)