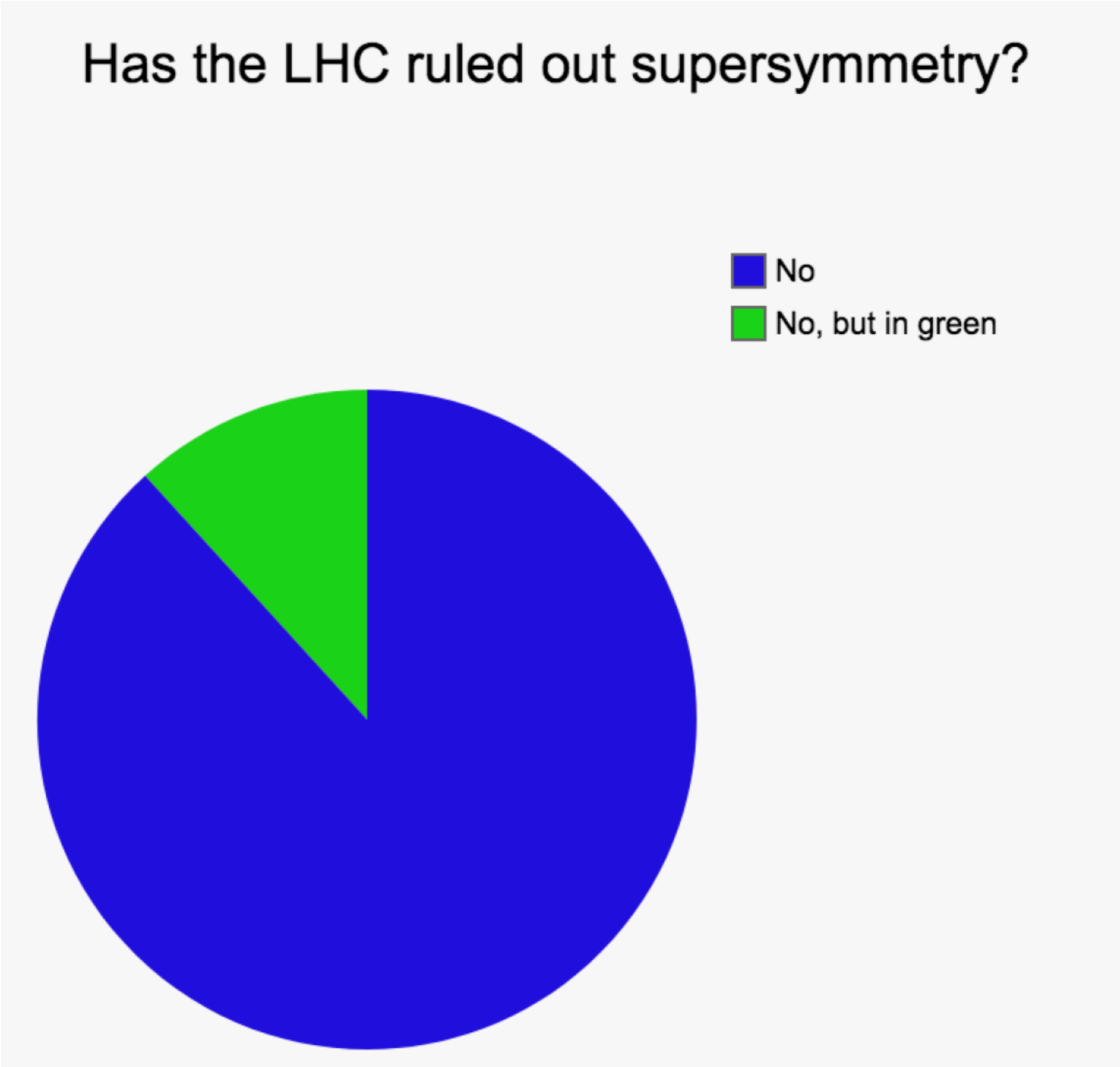

Has the LHC ruled out supersymmetry?
No
No, but in green

Consistent Excesses in SUSY searches at the LHC: Physics case for a Linear Collider

Sven Heinemeyer, IFT (CSIC, Madrid)

Tokyo, 07/2024

1. The main idea

2. Evidence for low-energy SUSY?!

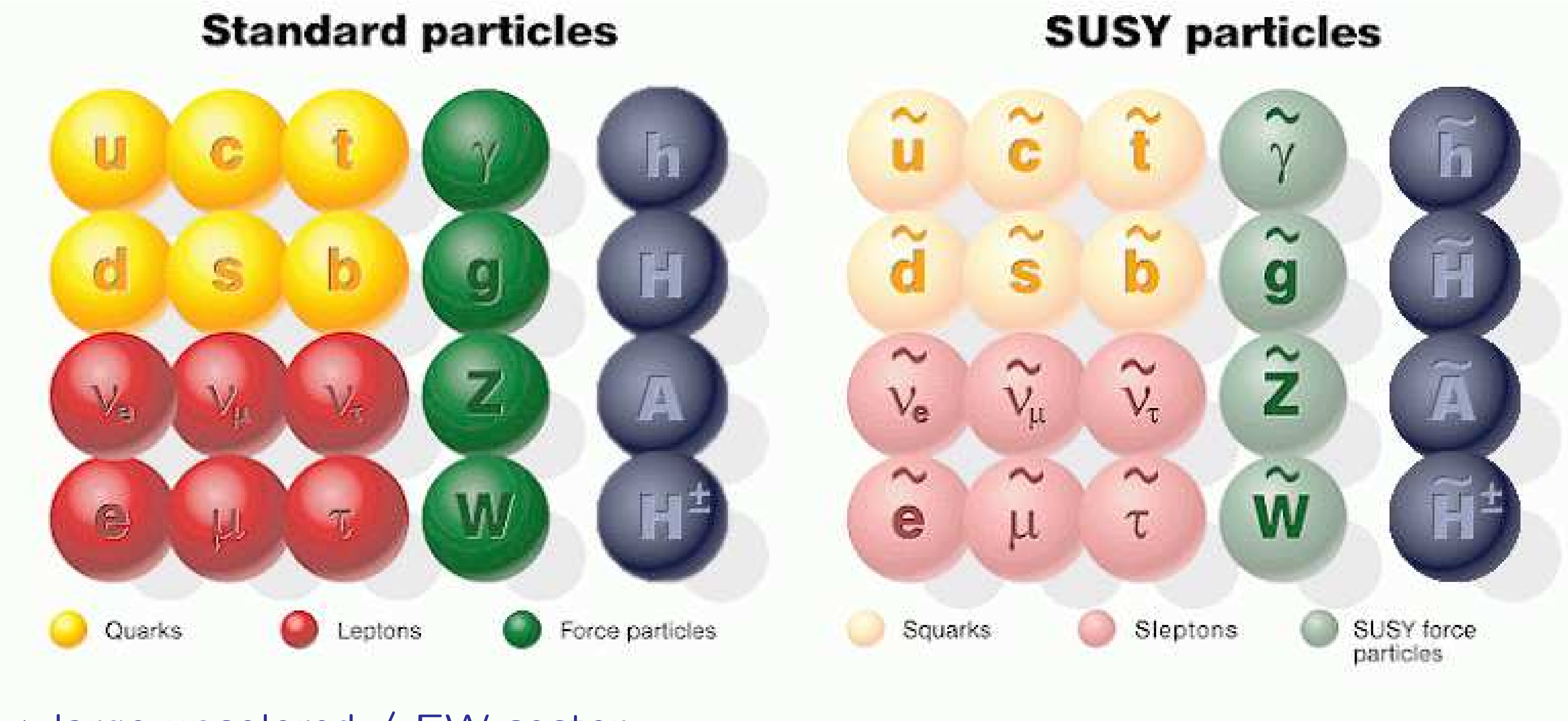
3. Wino/bino vs. higgsino DM

4. Reconstruction of wino/bino DM

5. 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.)

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
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 650(700) 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
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 550(600) 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 TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 500 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 TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 600 GeV

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

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

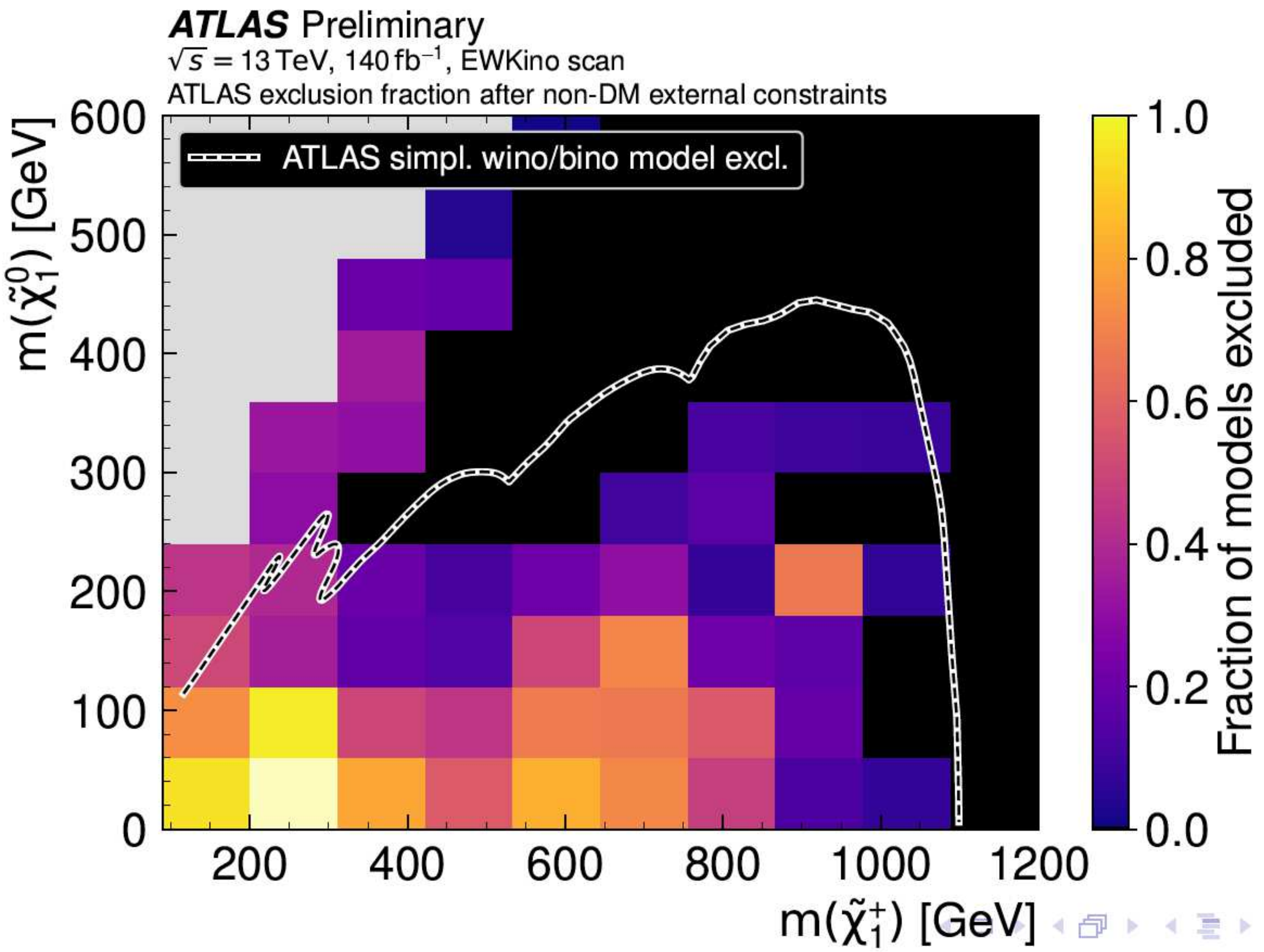
SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

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

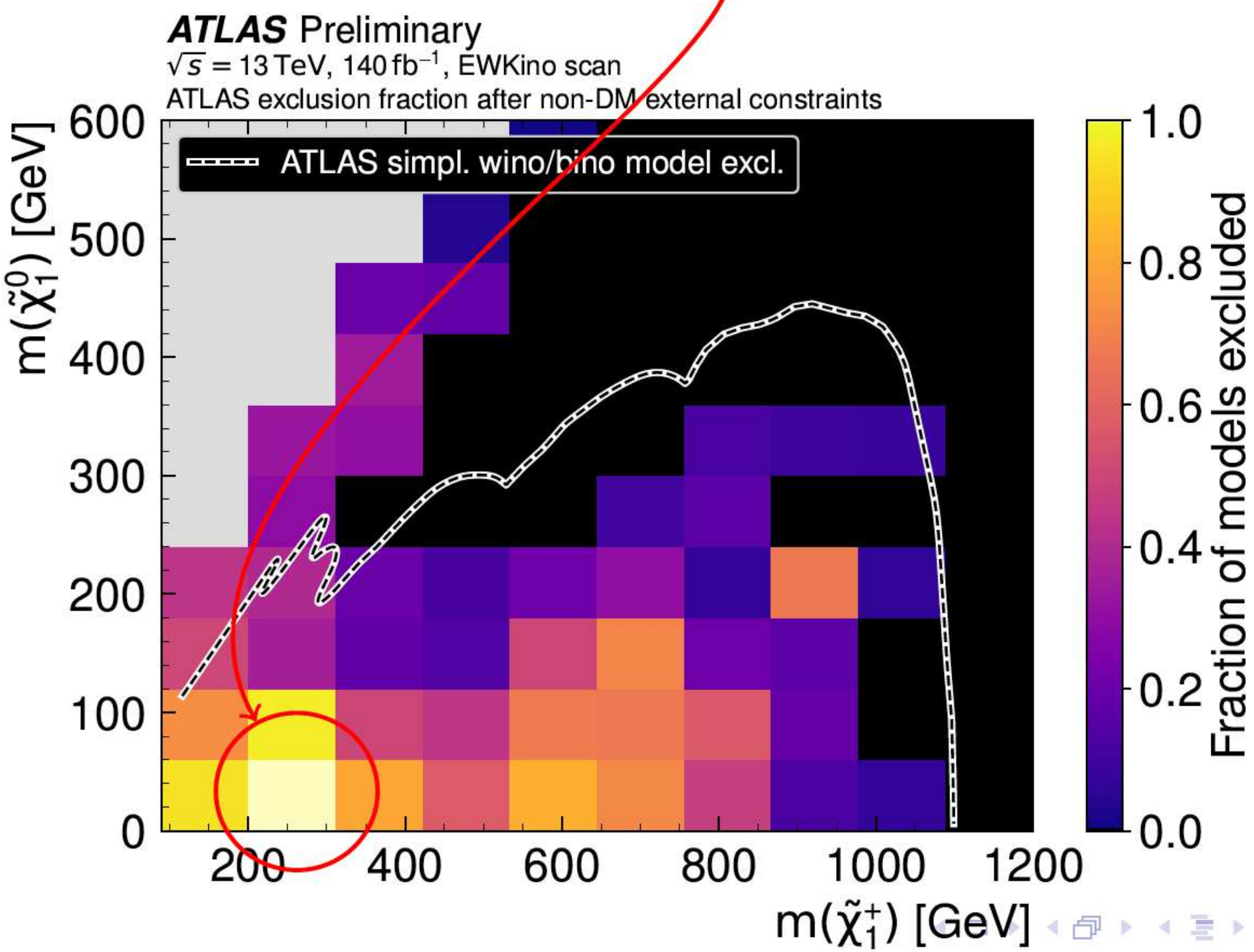
$\Rightarrow$ slepton masses constrol the size of $\Delta a_\mu^{\text{MSSM}}$

2. Evidence for low-energy SUSY?!

 [*taken from M. Berggren '23*]



Only this one is actually excluded !



⇒ Our "models" predict low chargino/neutralino masses

Possible search channels:

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

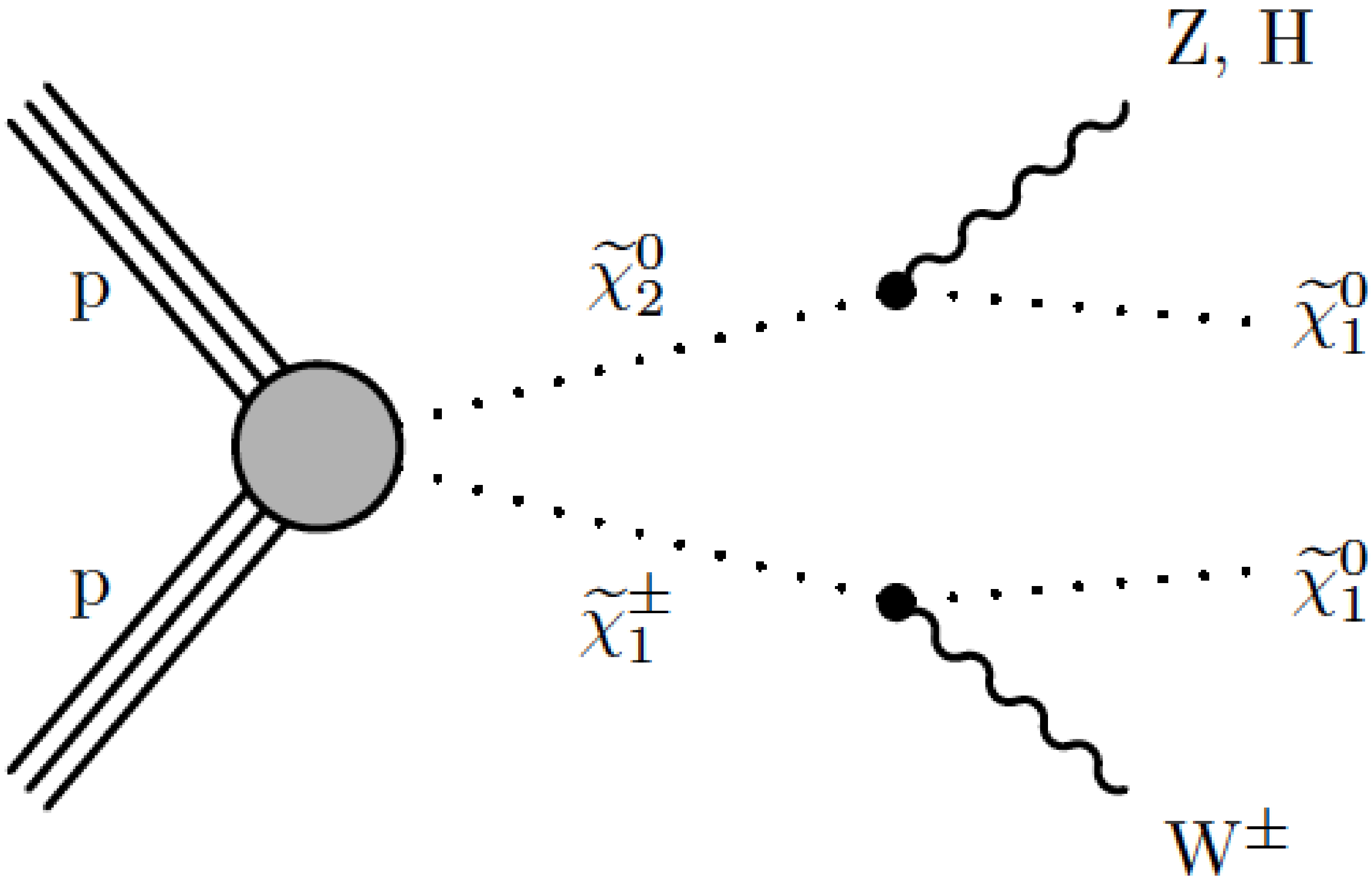
Possible kinematic situations:

– 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

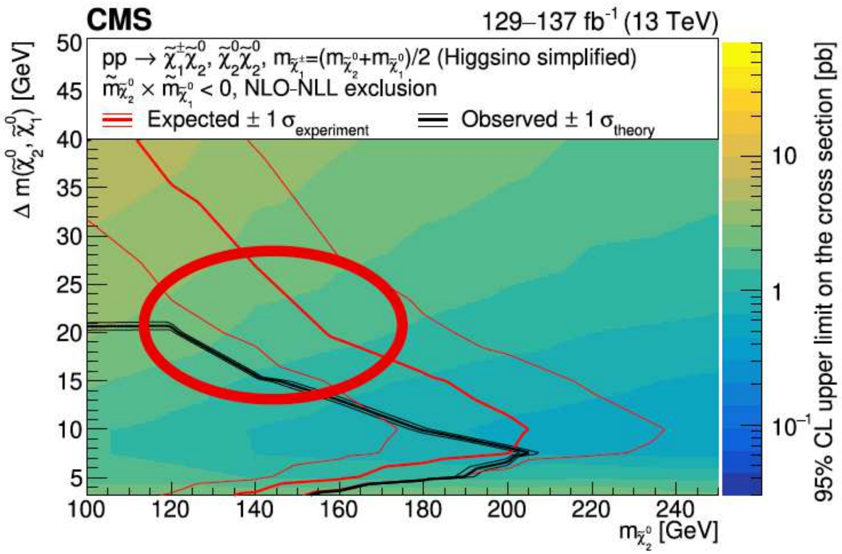
⇒ Our "models" predict low chargino/neutralino masses

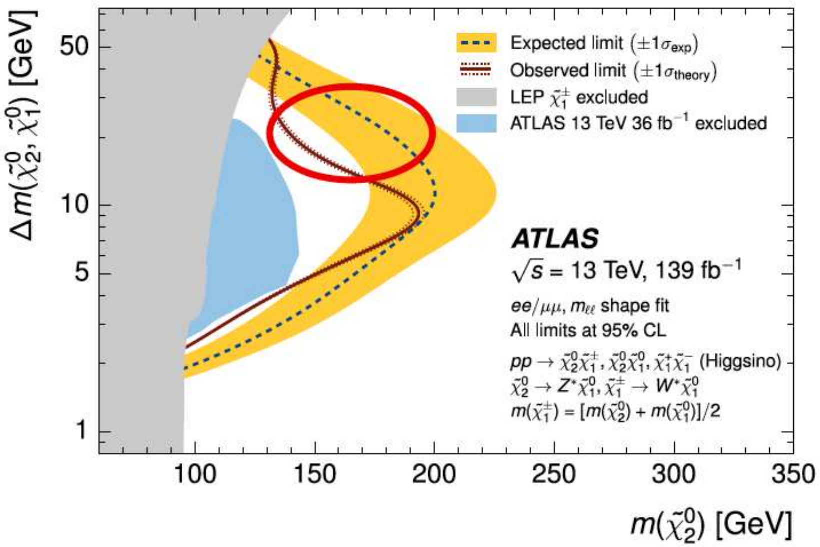
Golden mode at the LHC:

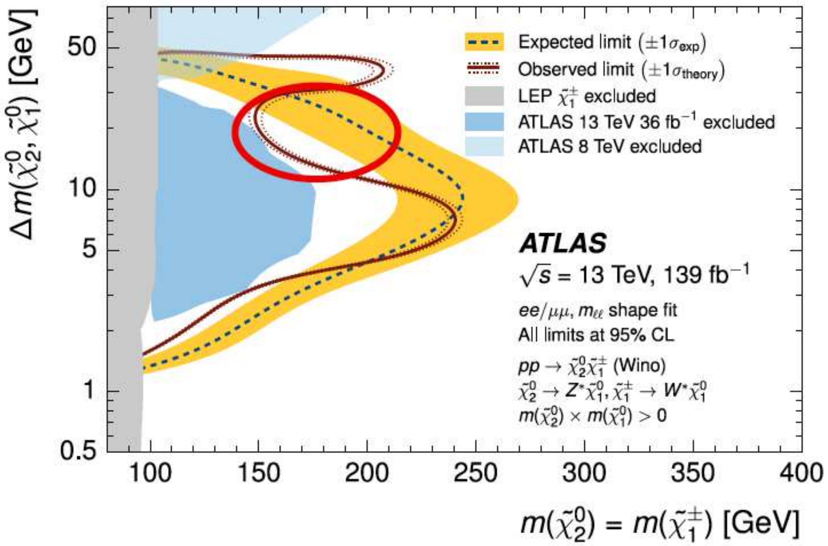


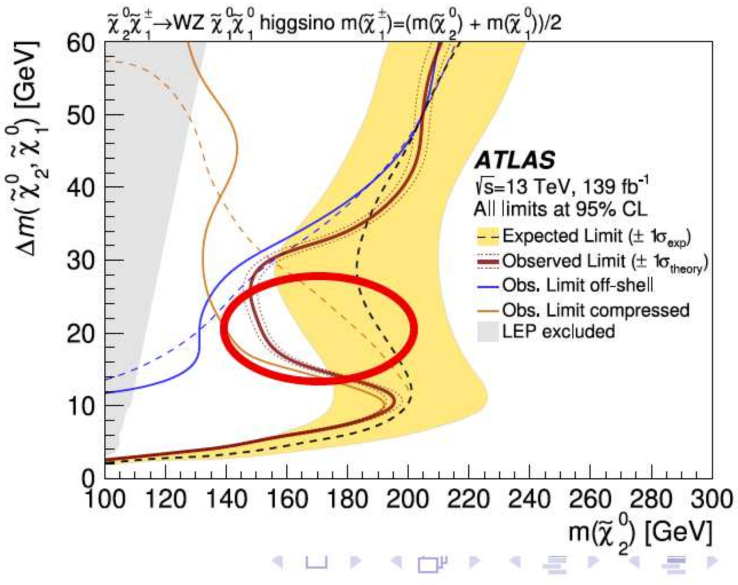
⇒ experimental results?

Results: “compressed” spectra w/ heavy sleptons: [*taken from M. Berggren ’23*]

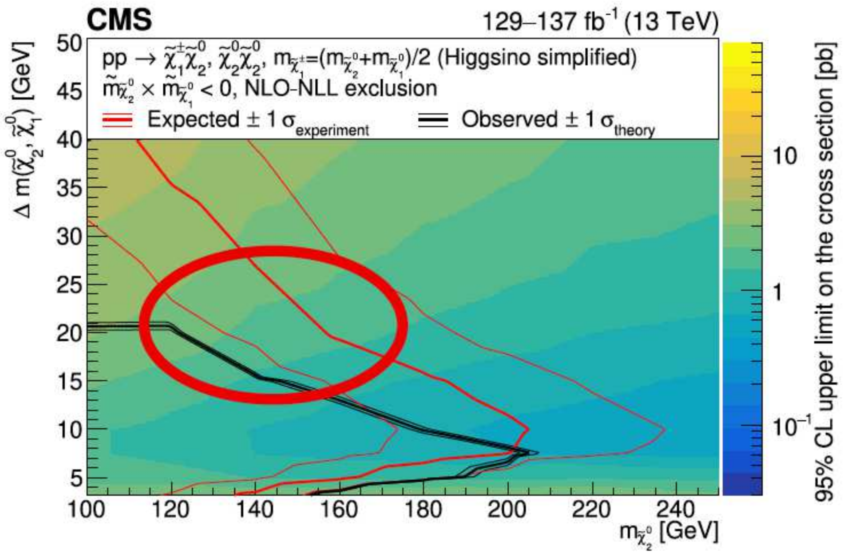


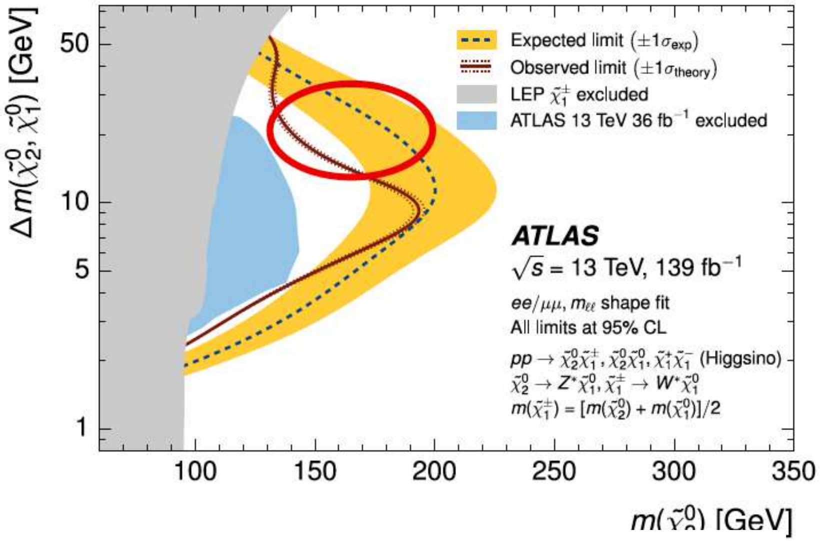


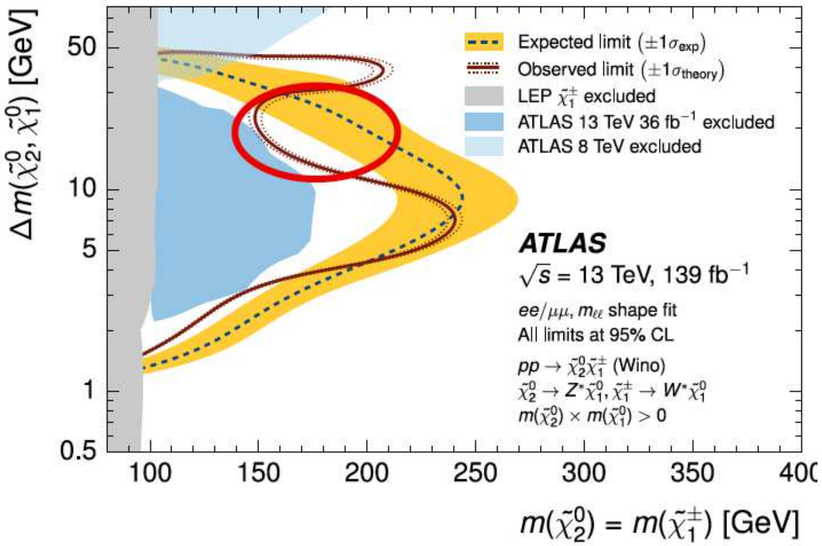


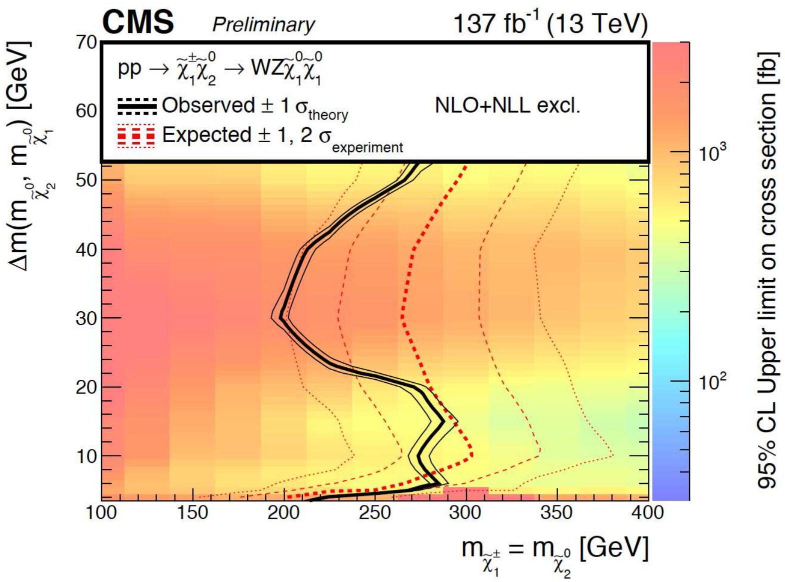


Results: “compressed” spectra w/ heavy sleptons: one more CMS analysis:









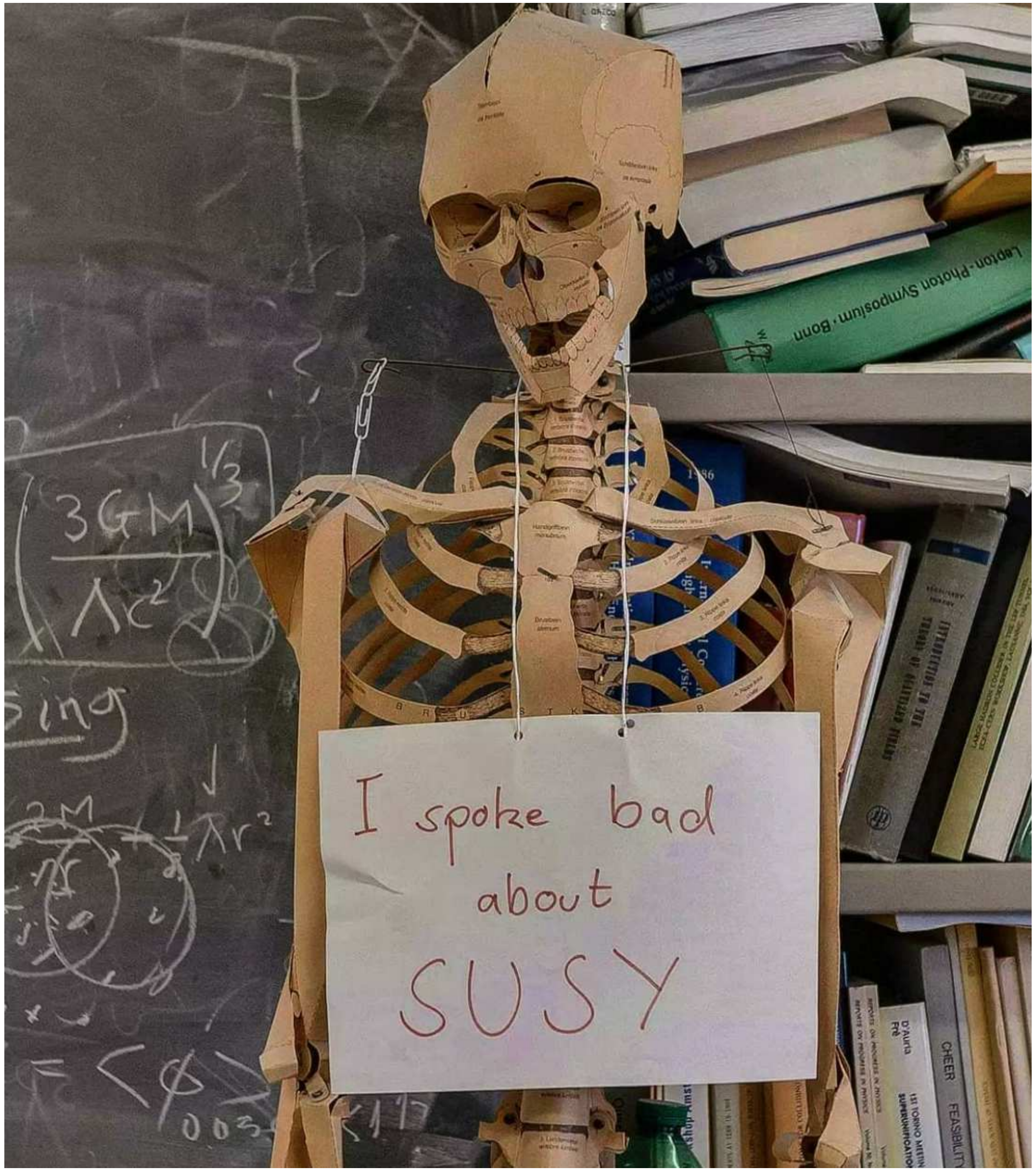
Two possible scenarios:

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

A) wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim 650(700)$ 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 $m_{\tilde{\chi}_1^0} \sim 1$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

$\Rightarrow$ can they fit the excesses?


I spoke bad about SUSY
Lepton-Photon Symposium · Bonn

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(+): $M_1 \times \mu > 0$

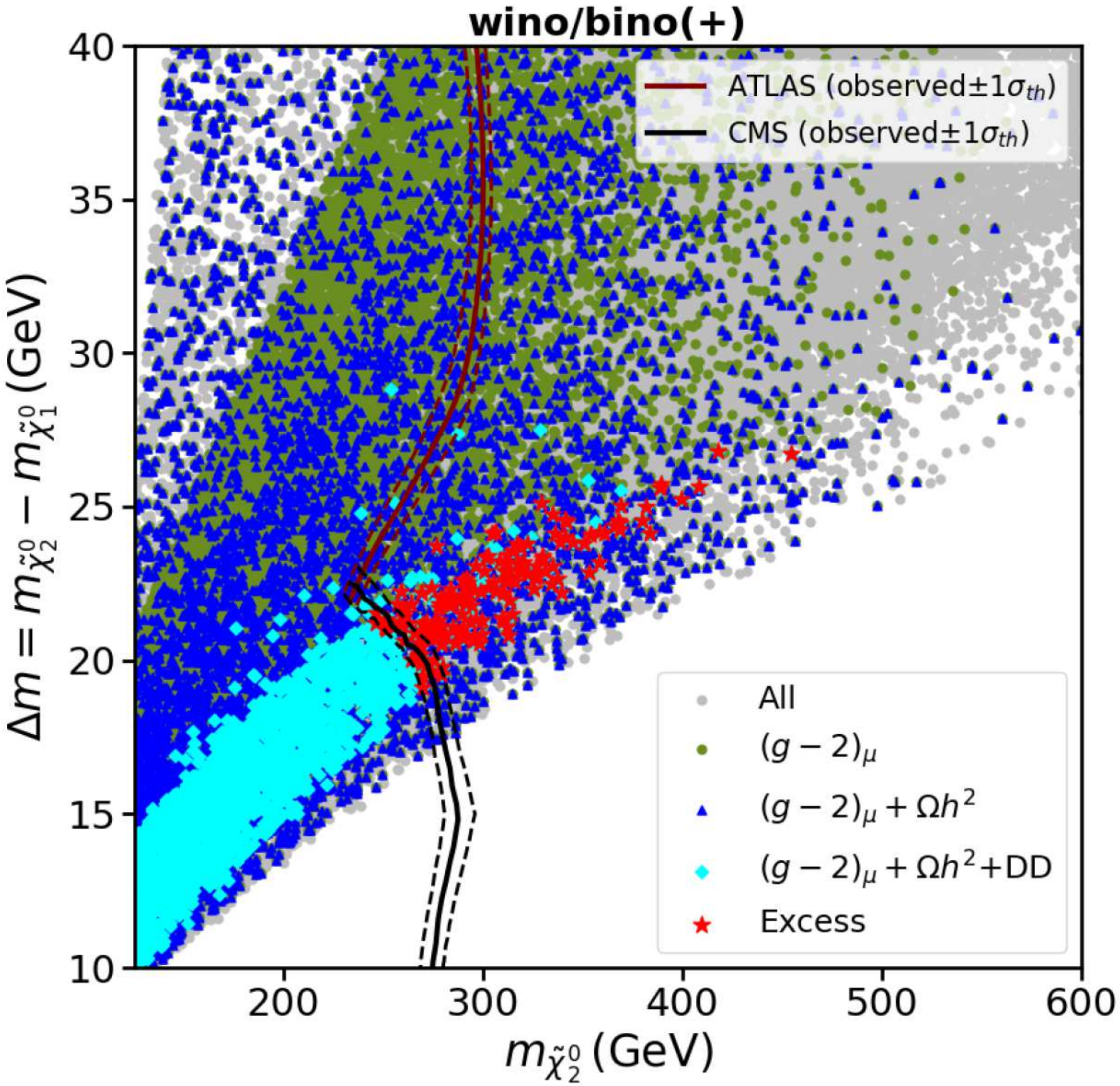
wino/bino(−): $M_1 \times \mu < 0$

relic DM density can be 100% fulfilled

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

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

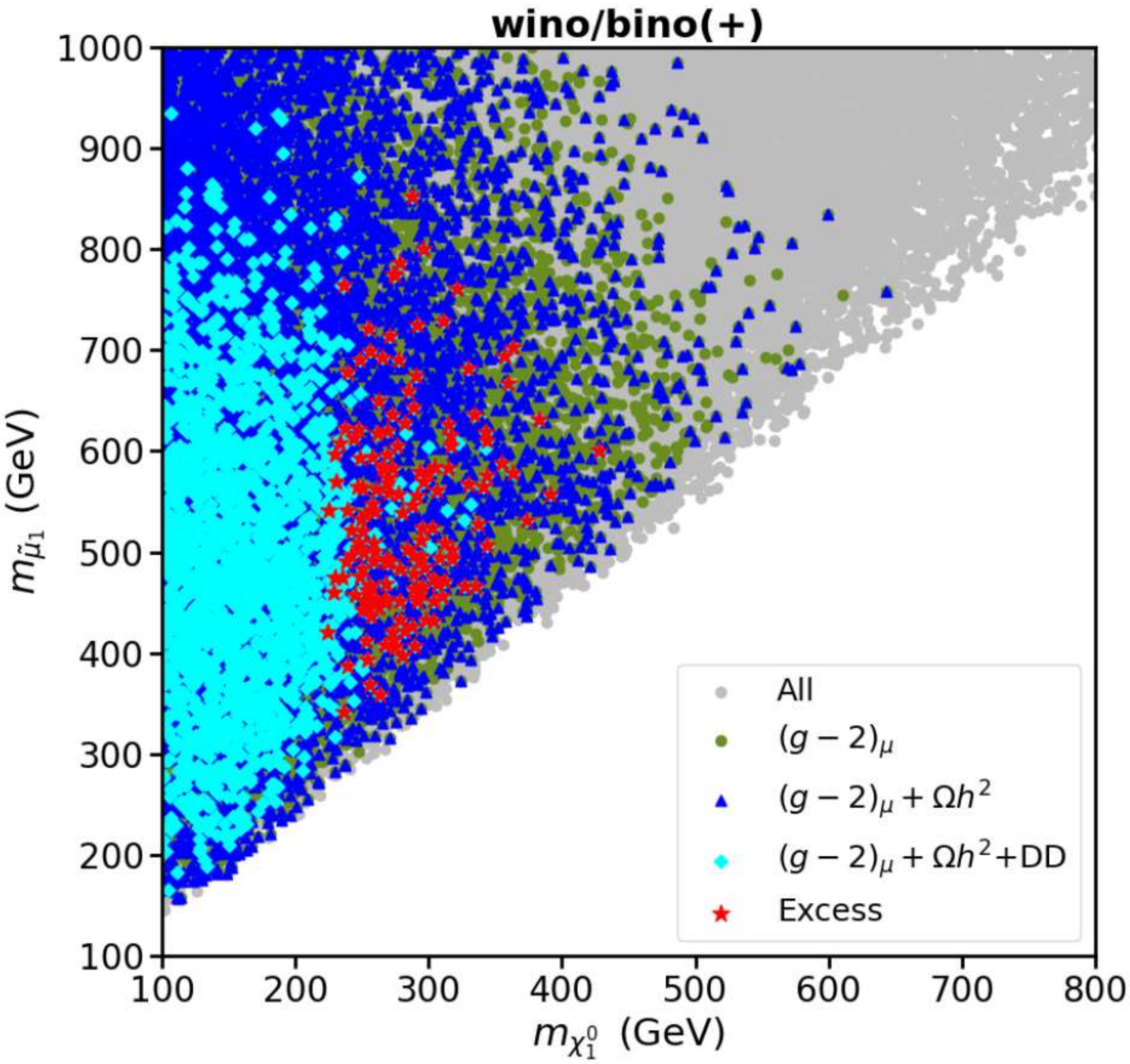
wino/bino(+): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



⇒ excesses not fully at the same Δm . . .

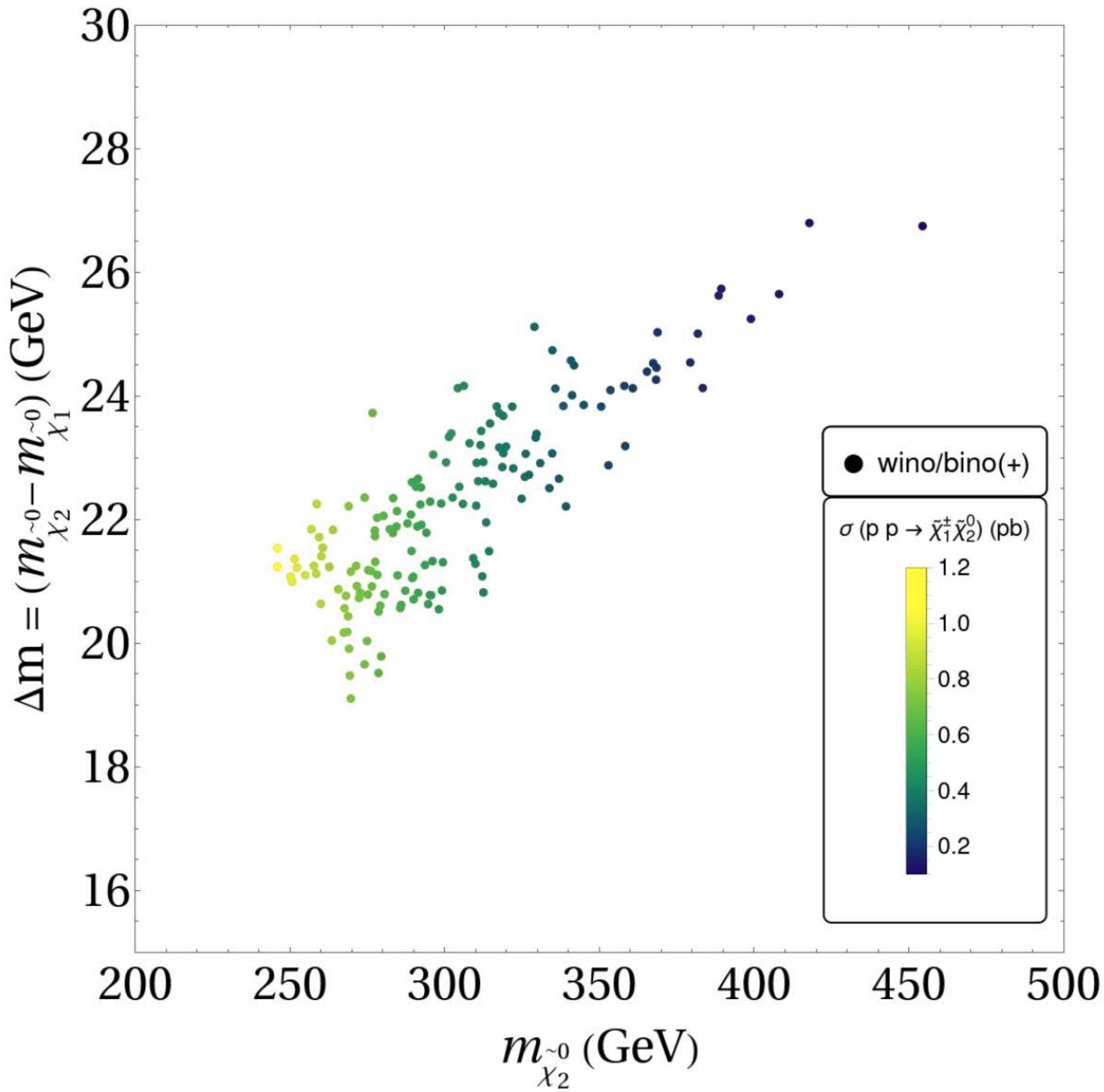
⇒ but many "good points" at $\Delta m \sim 20$ GeV

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



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

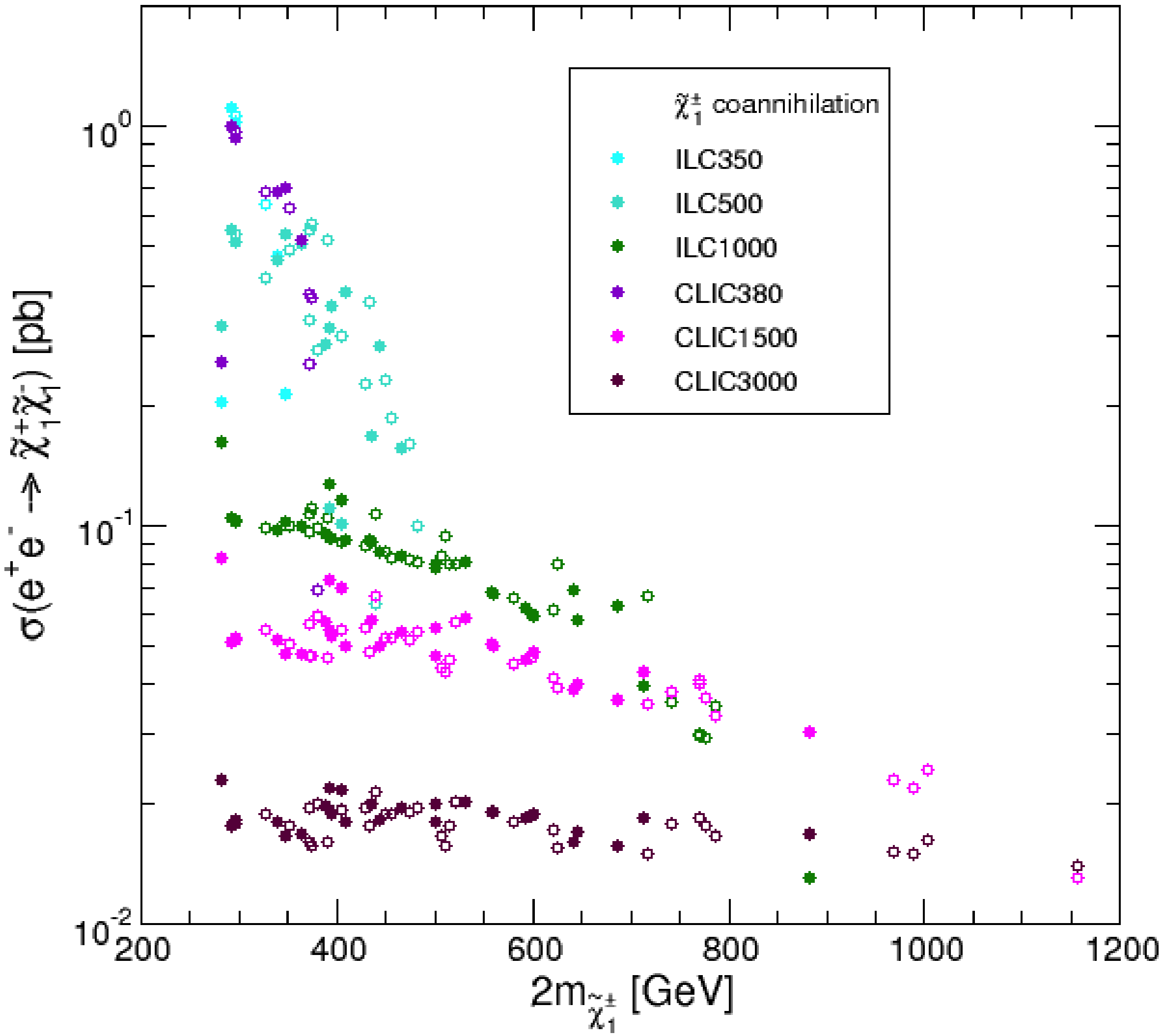
wino/bino(+): LHC cross sections:



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

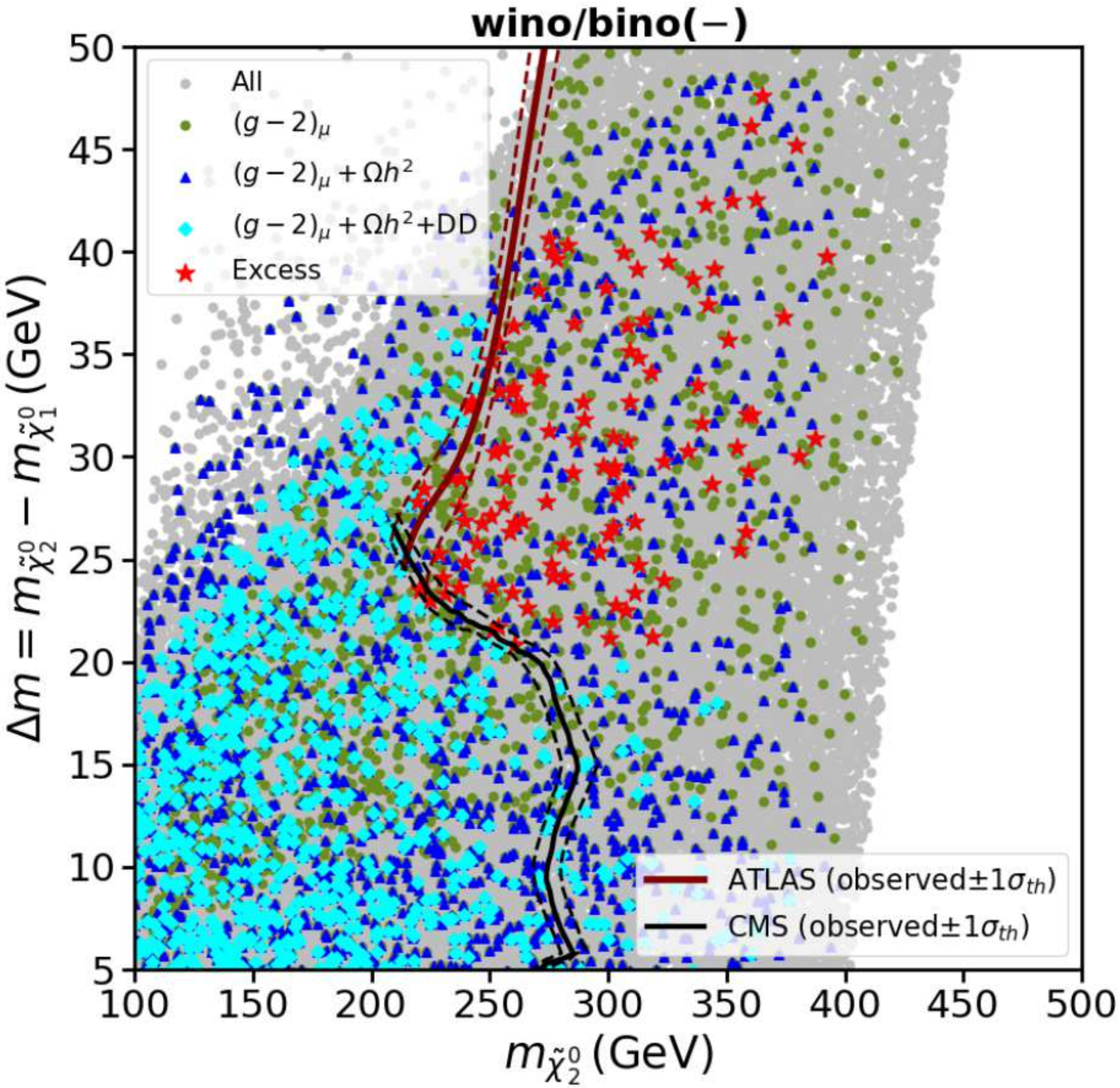
wino/bino(+): $\sigma(e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$:

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



⇒ easy for ILC500/ILC1000 :-)

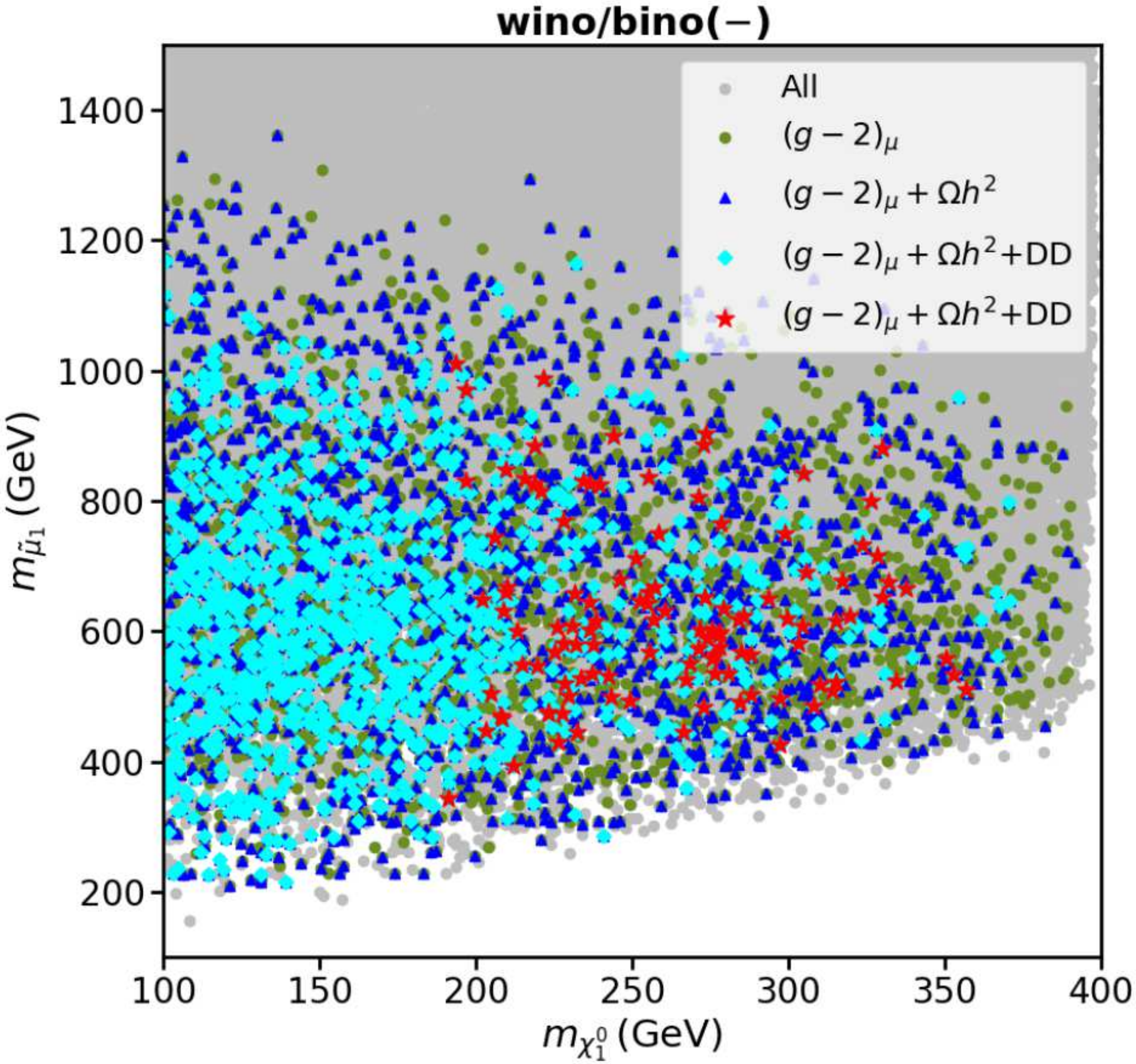
wino/bino(−): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



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

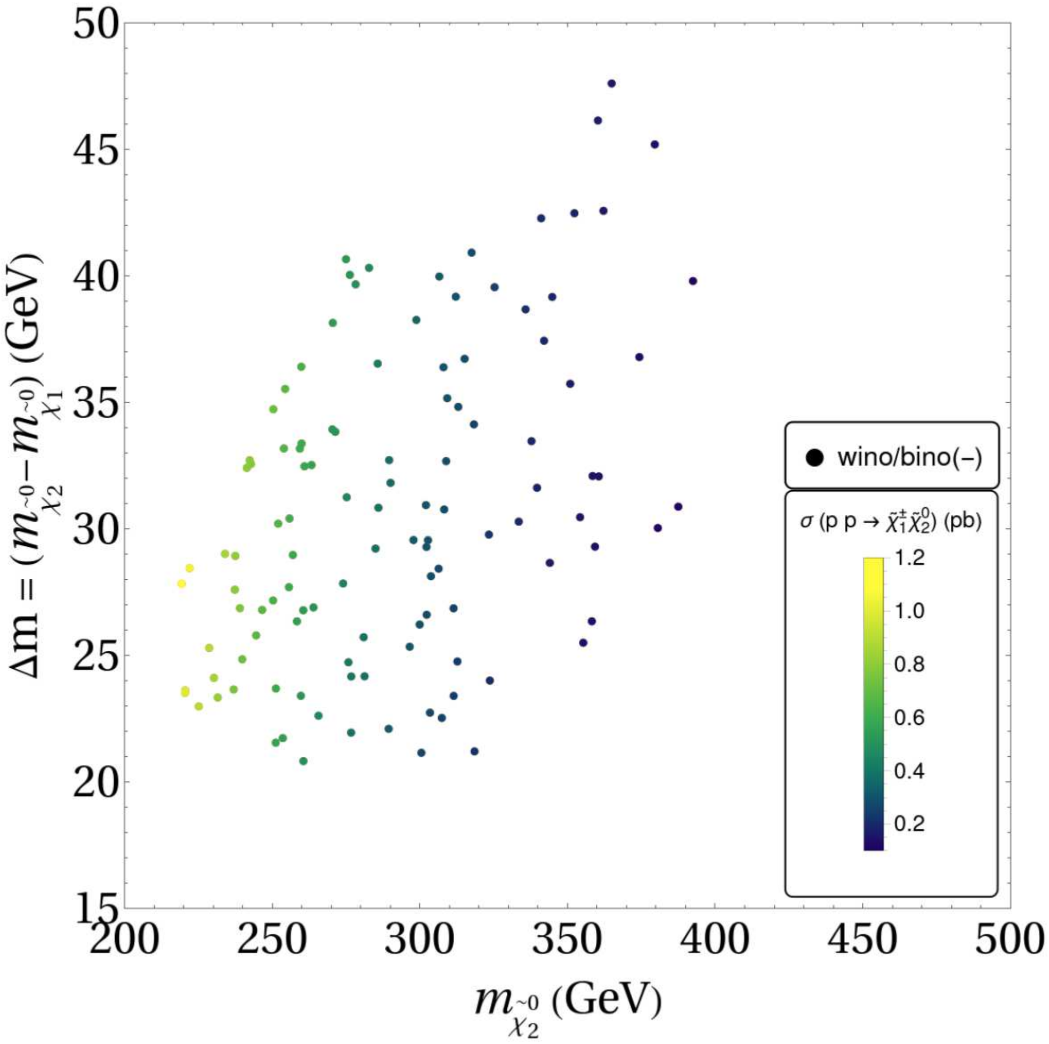
⇒ but many "good points" at $\Delta m \sim 25$ GeV

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

⇒ prospects for $\sigma(e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$ similar as in wino/bino(+)

D) Higgsino DM

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

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

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

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

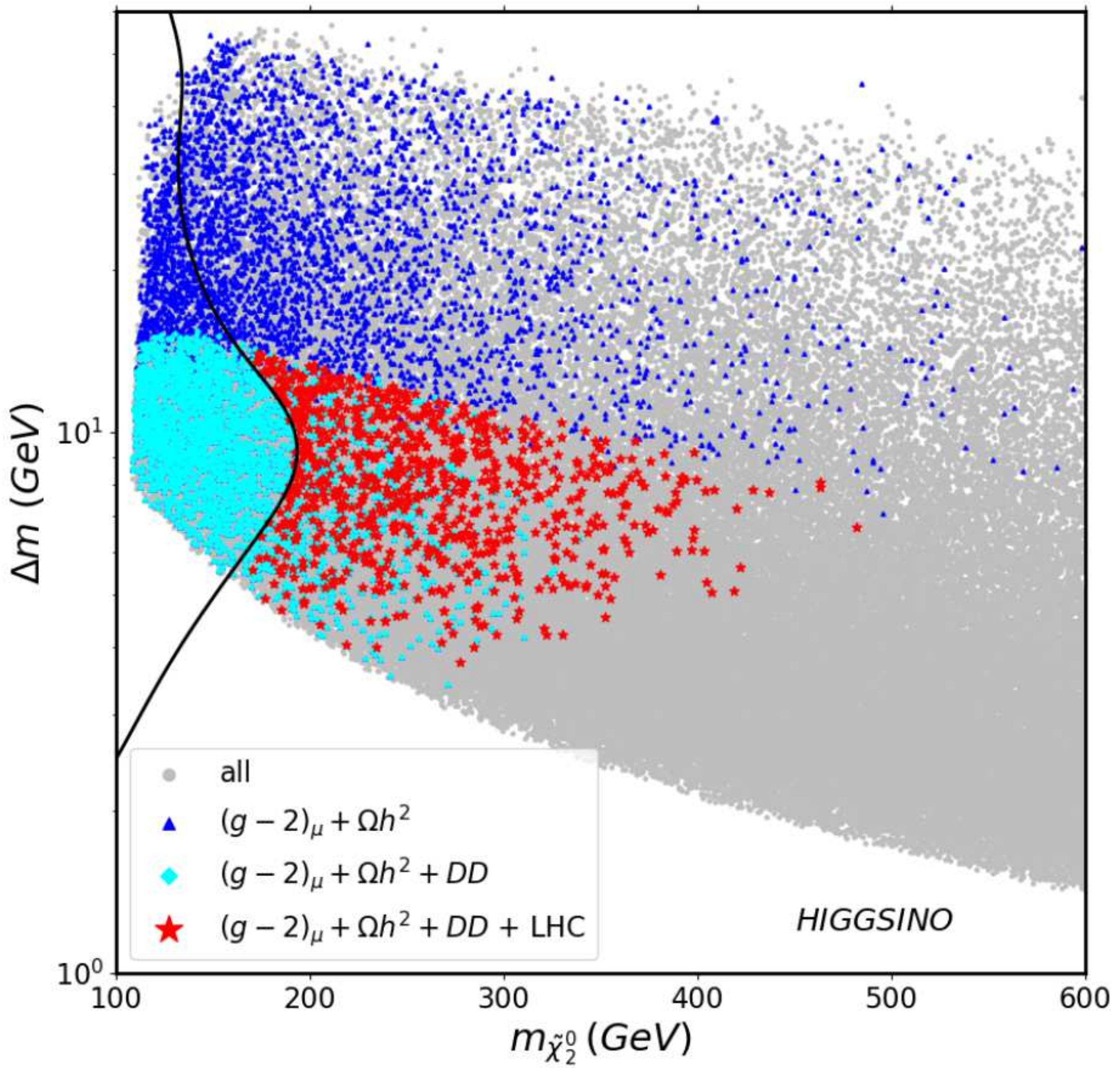
$$5 \leq \tan\beta \leq 60,$$

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

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

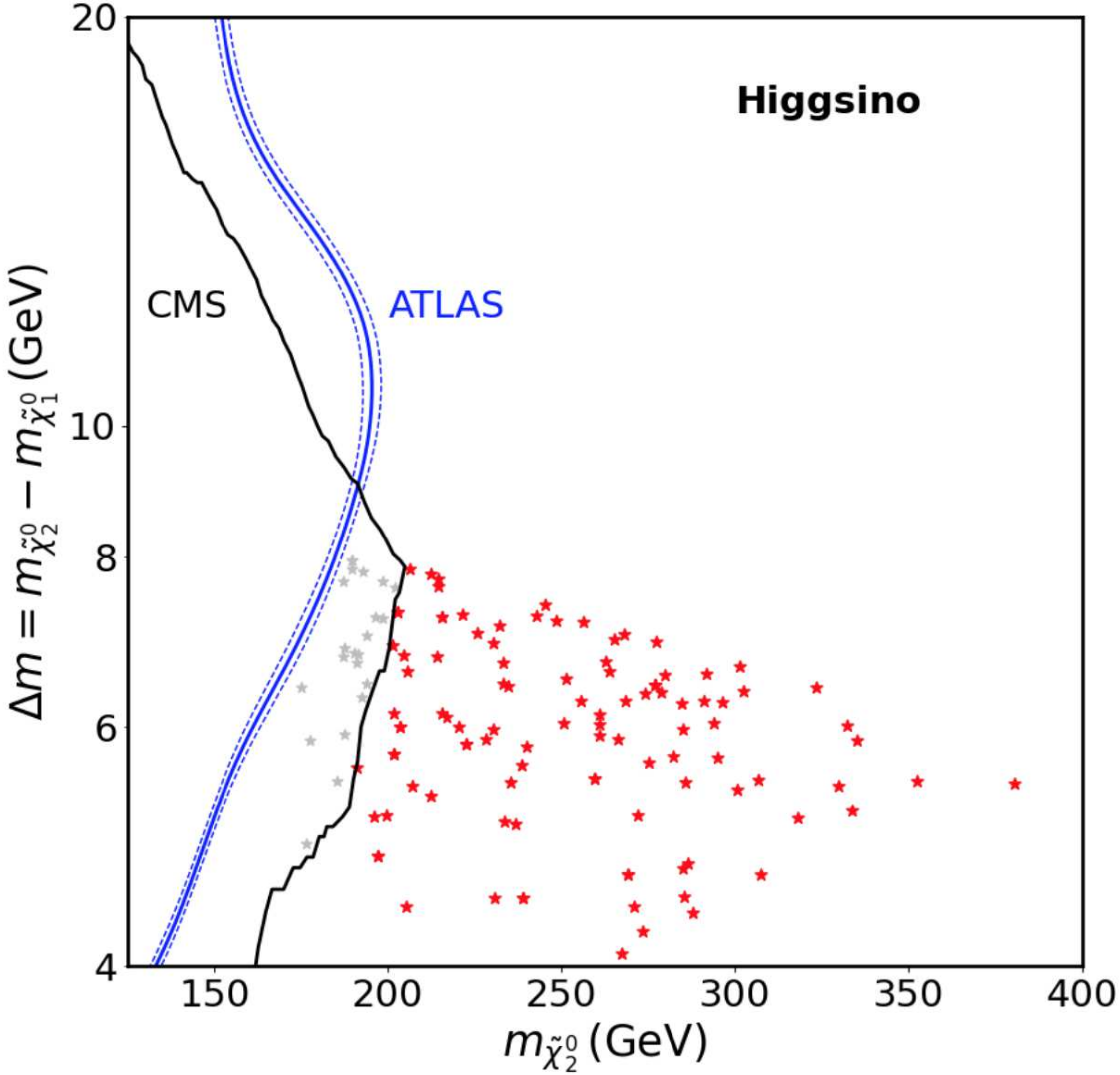
Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with a $5\,\sigma$ deviation in $(g-2)_\mu$
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

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



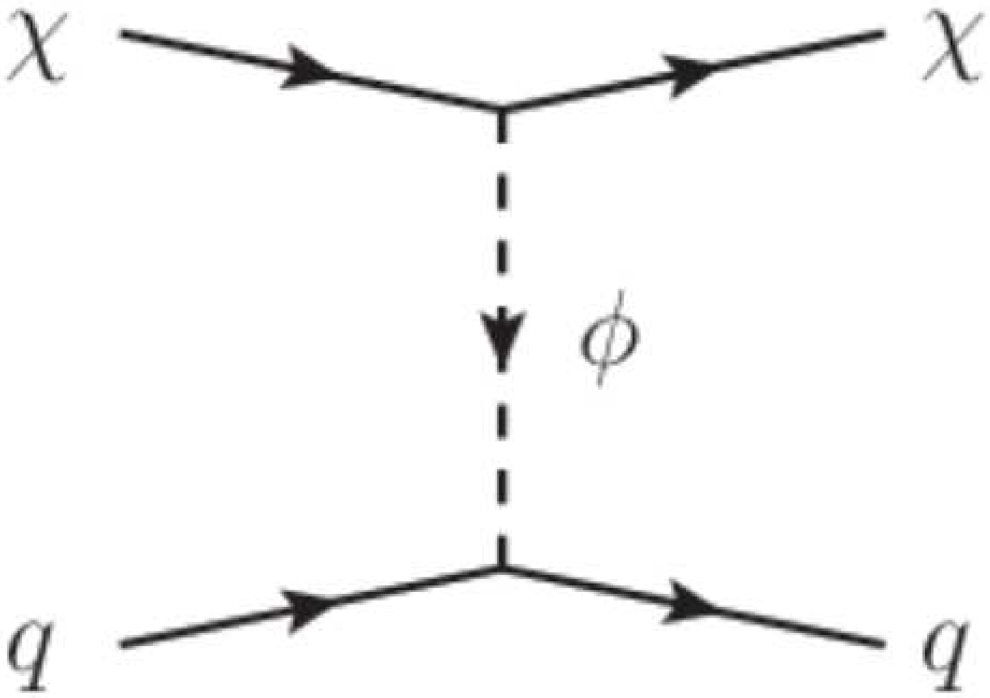
$\Rightarrow$ direct detection is the limiting factor on Δm

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



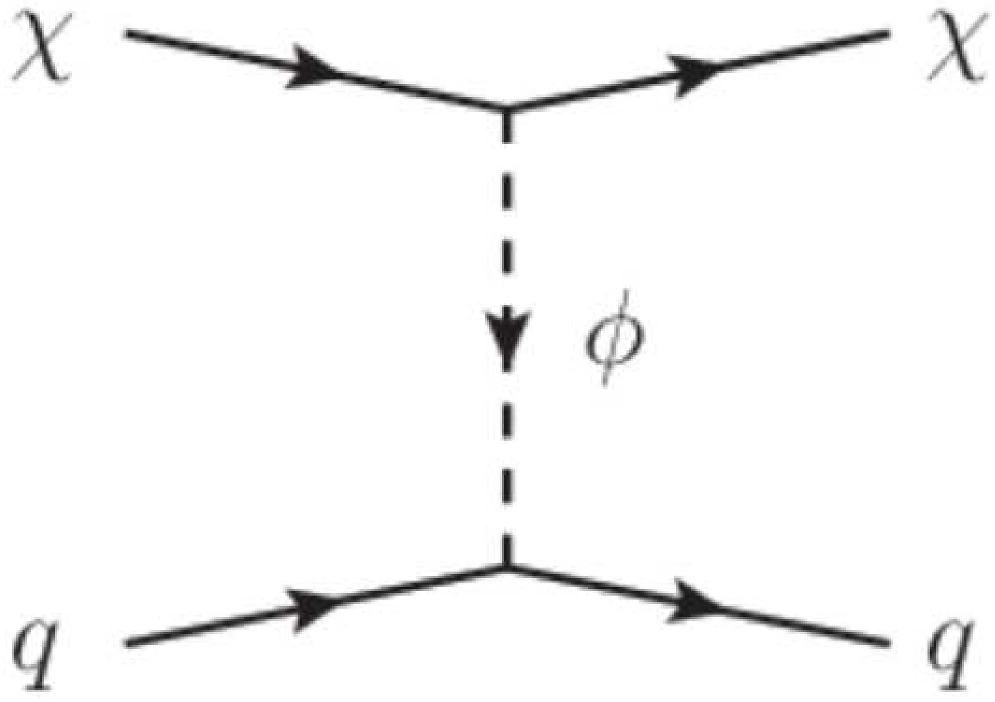
$\Rightarrow$ excess not fitted :-($\Rightarrow$ DD cuts away the "good points"

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 $M_1 < 0$

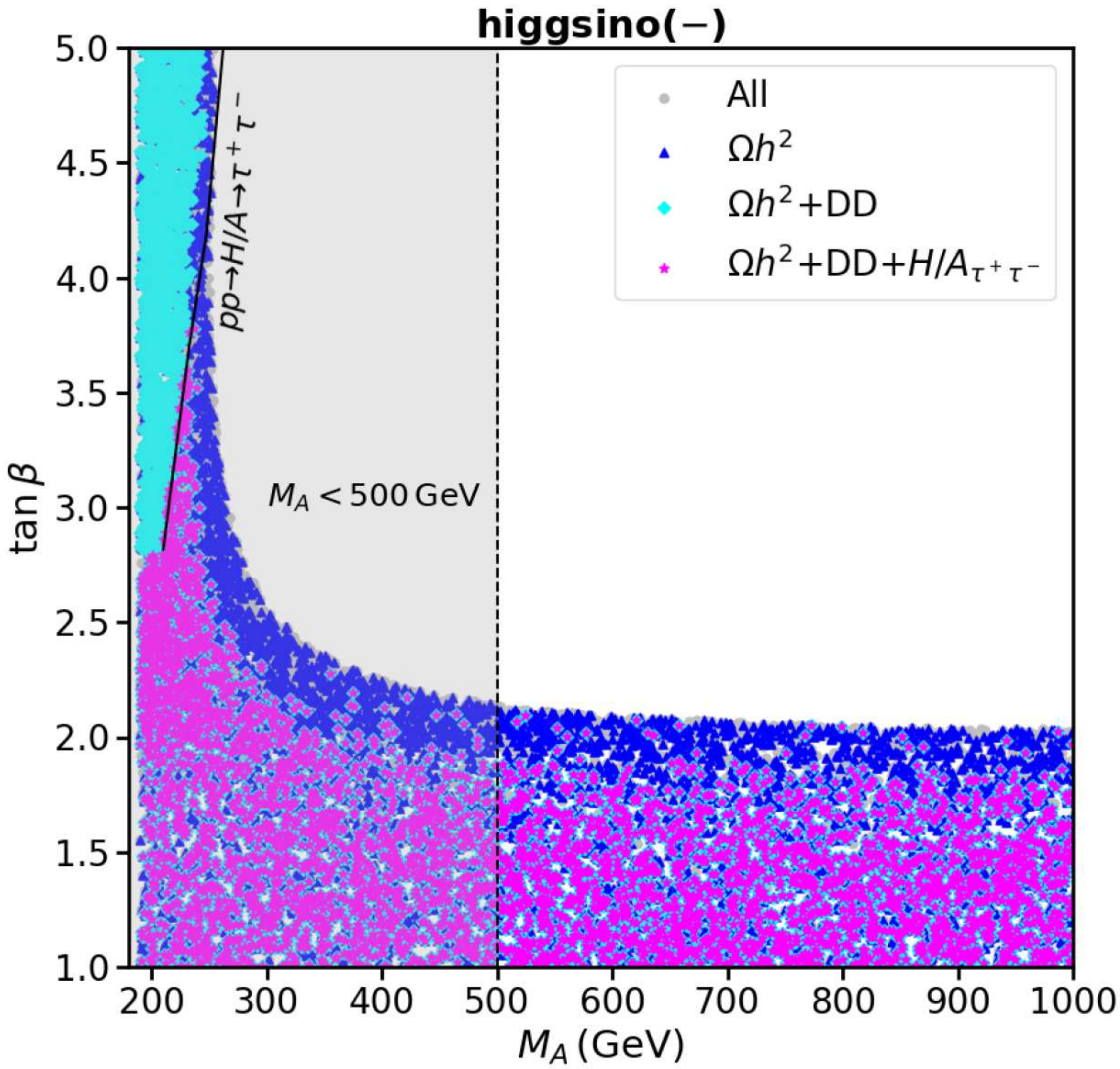
New scan with $M_1 \times \mu < 0$

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

Condition on μ and M_1: exact blind spot conditions

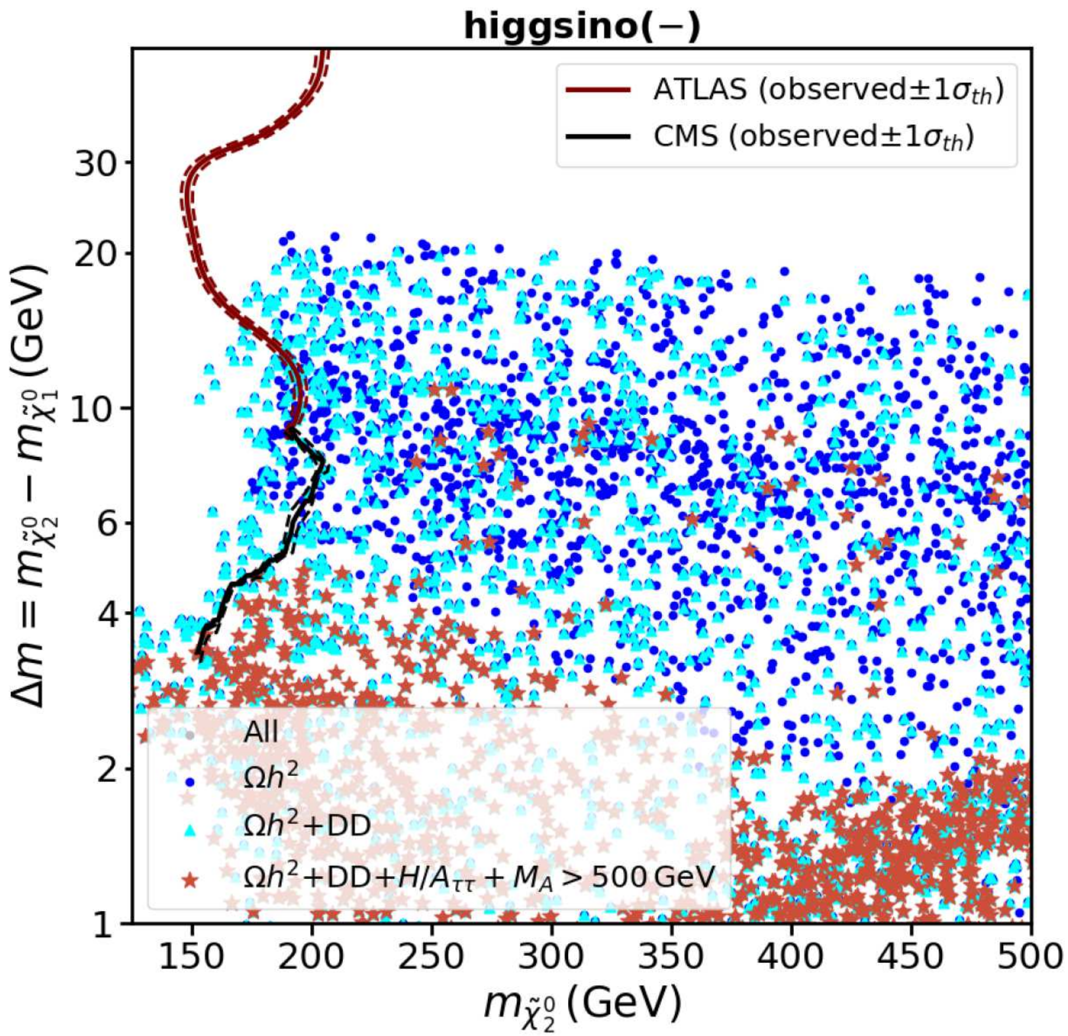
relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

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



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

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

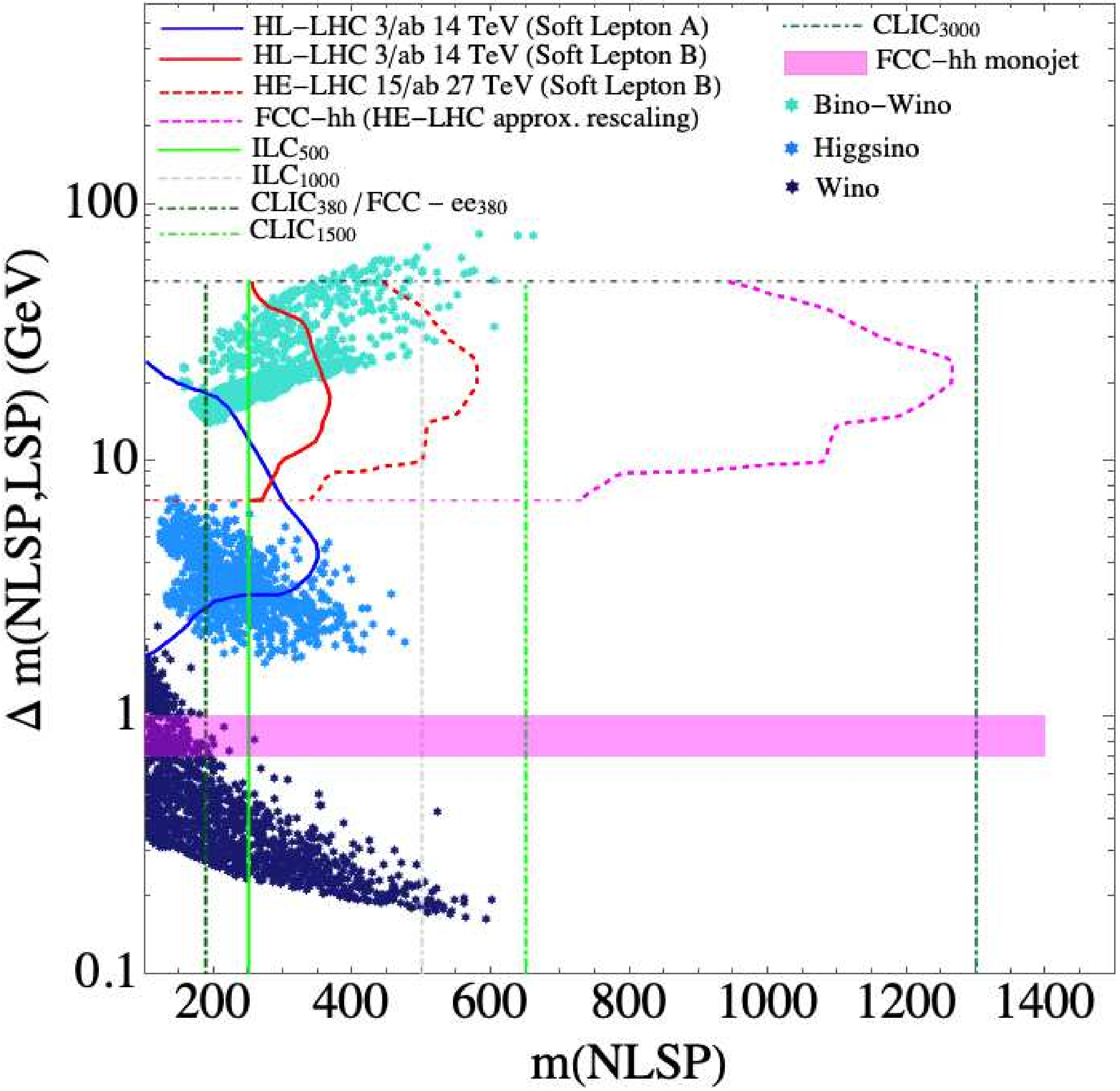


⇒ restrictions still cut away the "good parameter space"

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

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. Reconstruction of wino/bino DM

[S.H., F. Lika, G. Moortgat-Pick, PREL.]

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 $M_1 \times \mu > 0$).

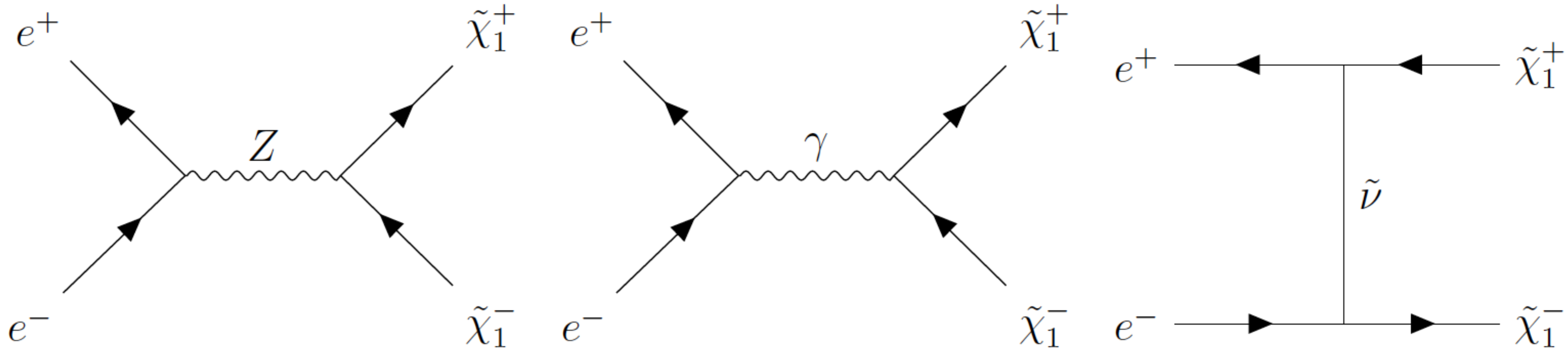
2. At the ILC500 we measure $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^{\pm}}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp})$.
XS measurement with two (good) polarizations and at $\sqrt{s} = 400, 500$ GeV.

3. This allows (in principle) to reconstruct M_1, M_2, μ, $m_{\tilde{\nu}_e}$, ... –
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:



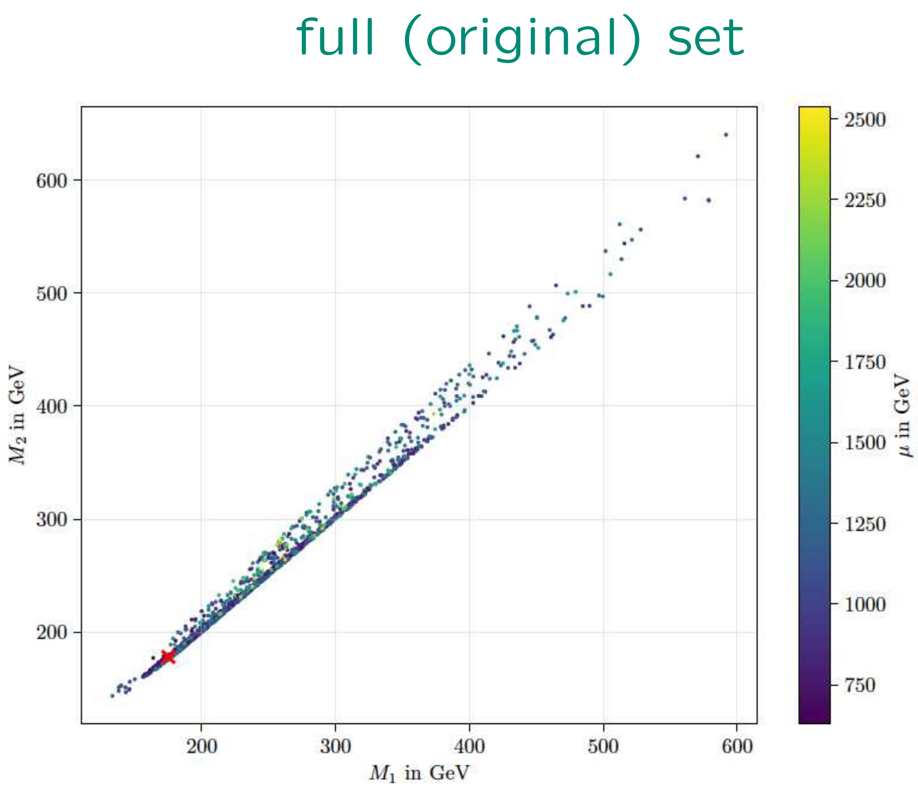
$\Rightarrow m_{\tilde{\nu}_e}$ enters

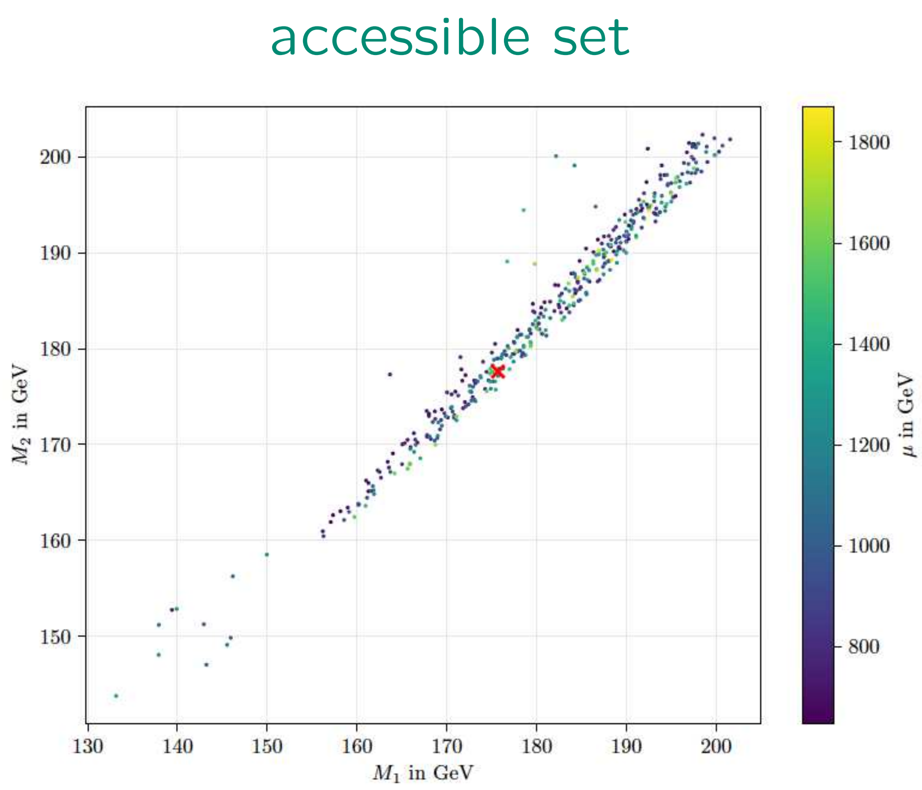
– so far tree-level analysis

– to be repeated including full one-loop corrections

– more involved parameter dependences

The parameter points:

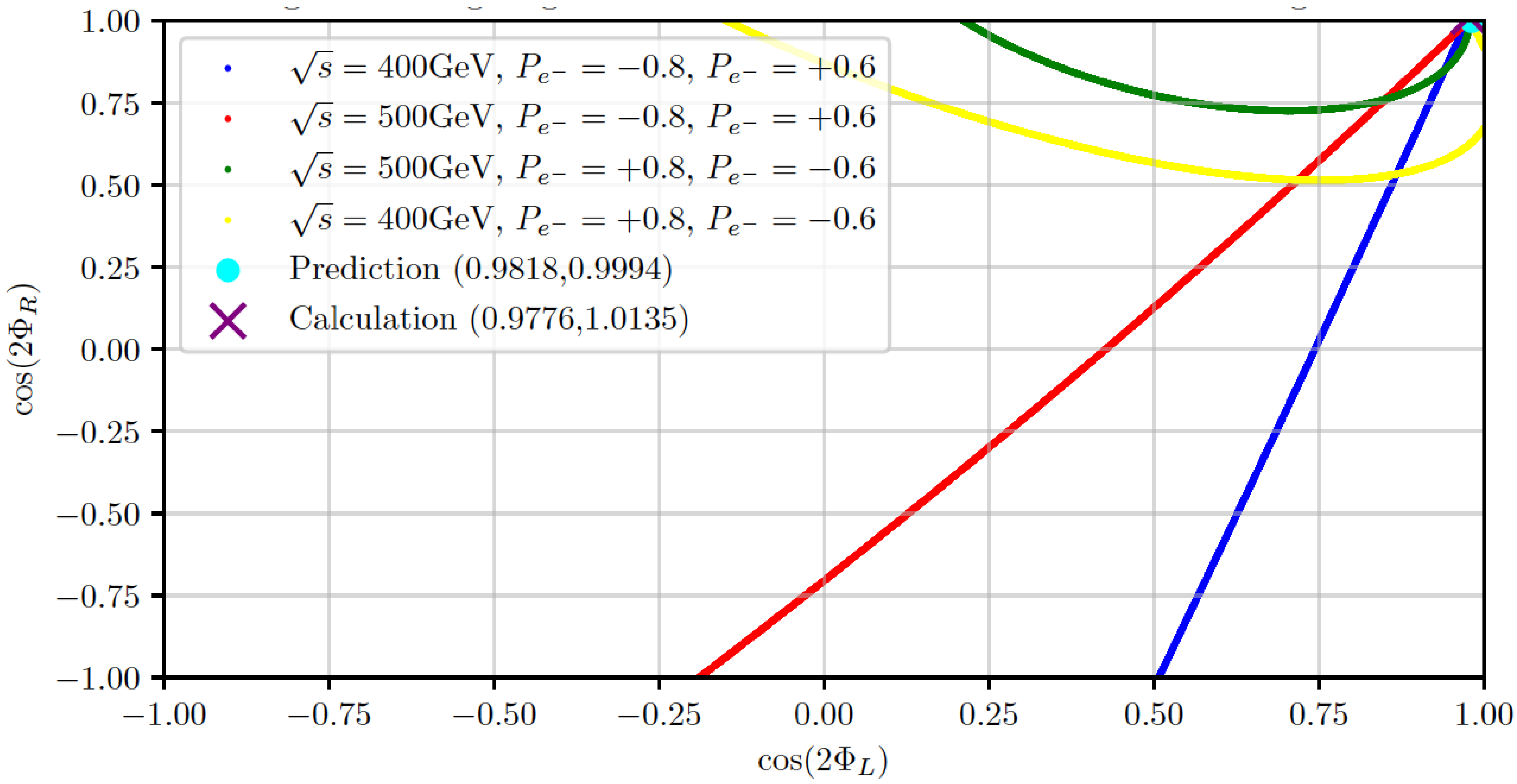




⇒ only lower masses accessible

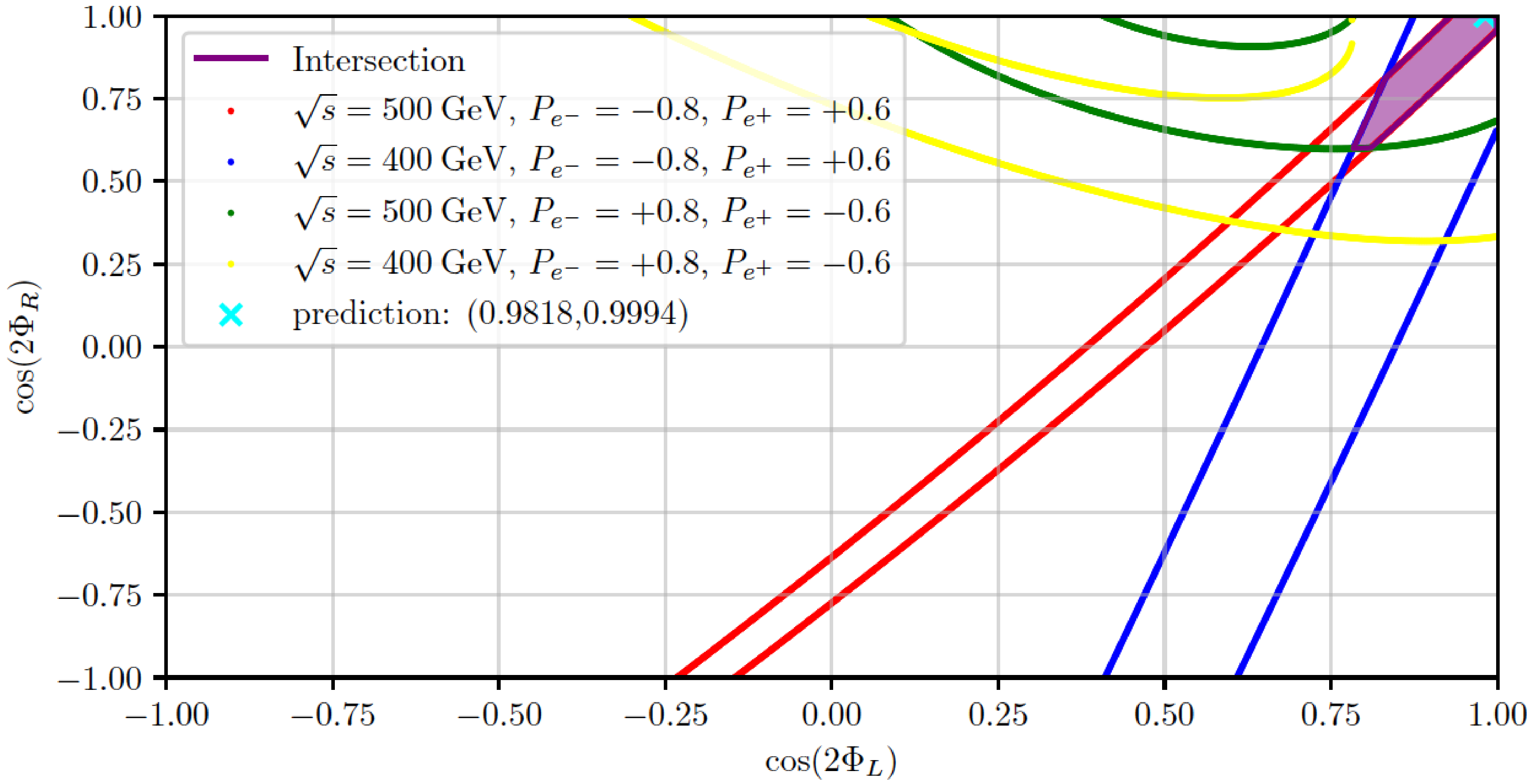
⇒ interesting points corresponding to the excesses covered . . .
(red star: example point)

Ellispses of four XS measurements:



⇒ four ellipses must meet – and they do!

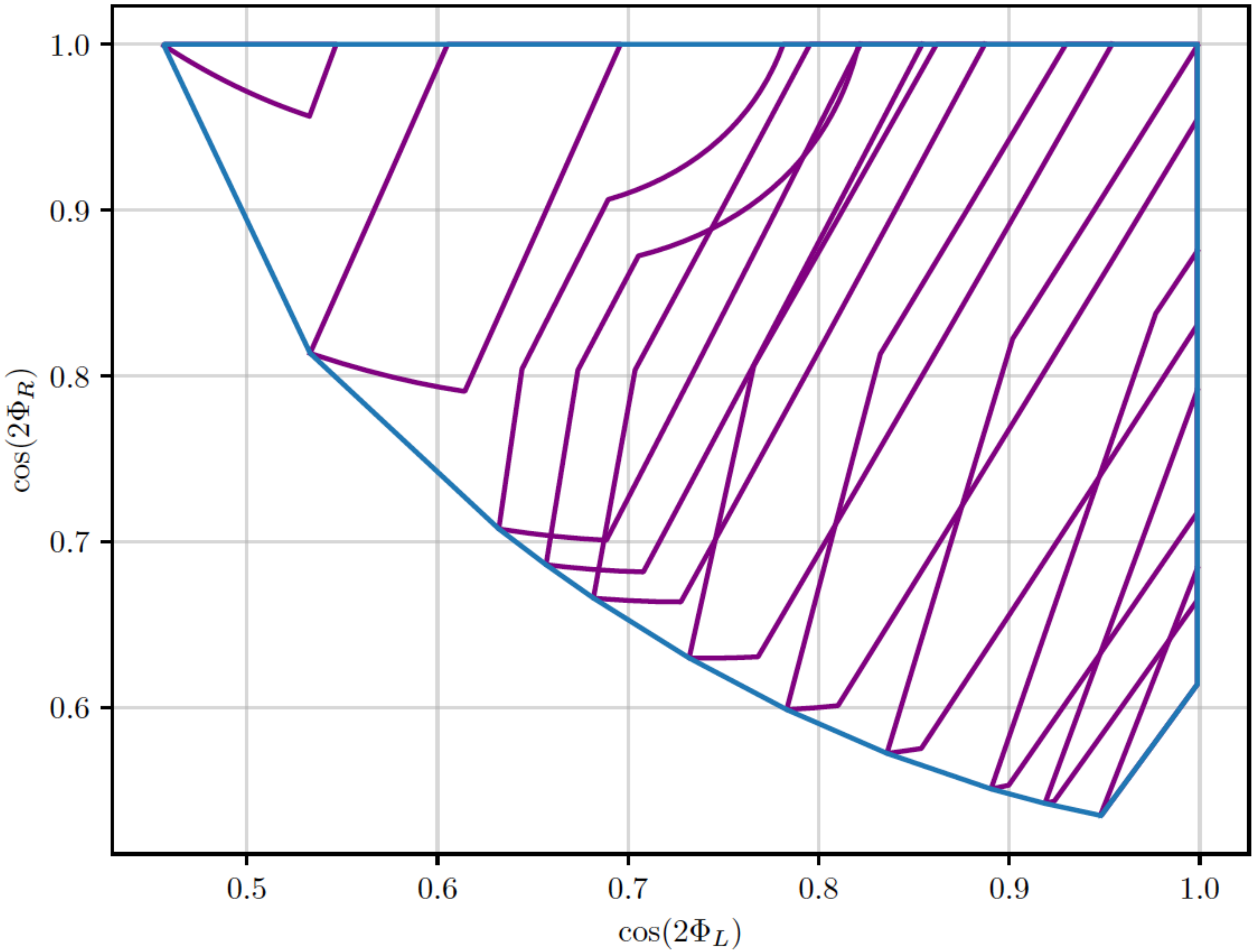
Ellispses of four XS measurements with uncertainties:



⇒ uncertainties lead to overlap region

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

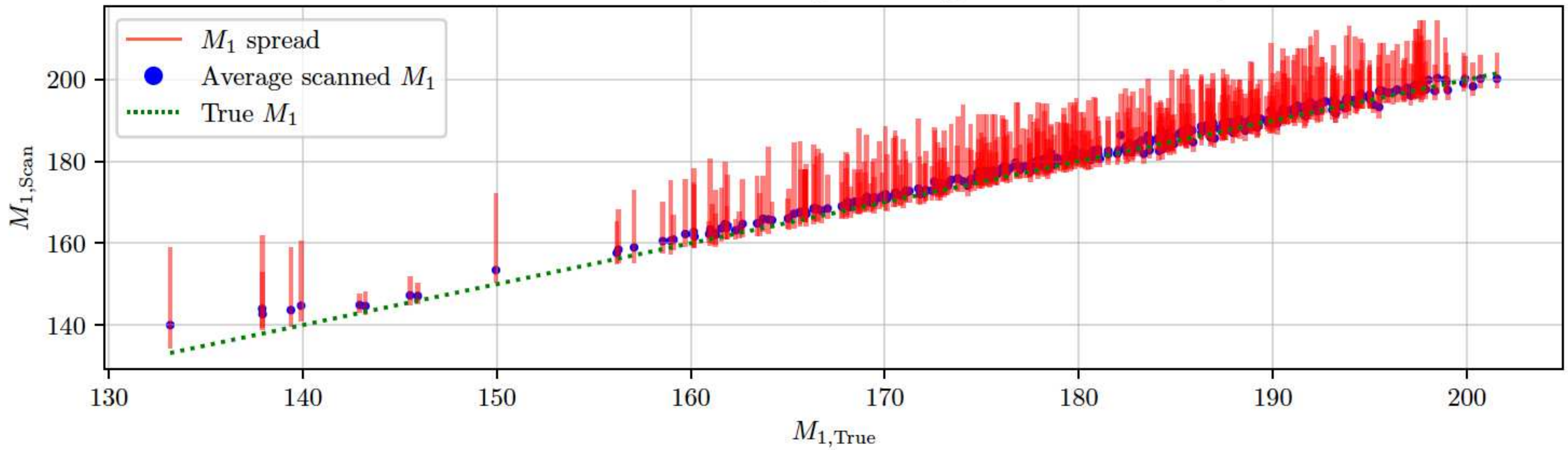
Variation of $m_{\tilde{\nu}_e}$:

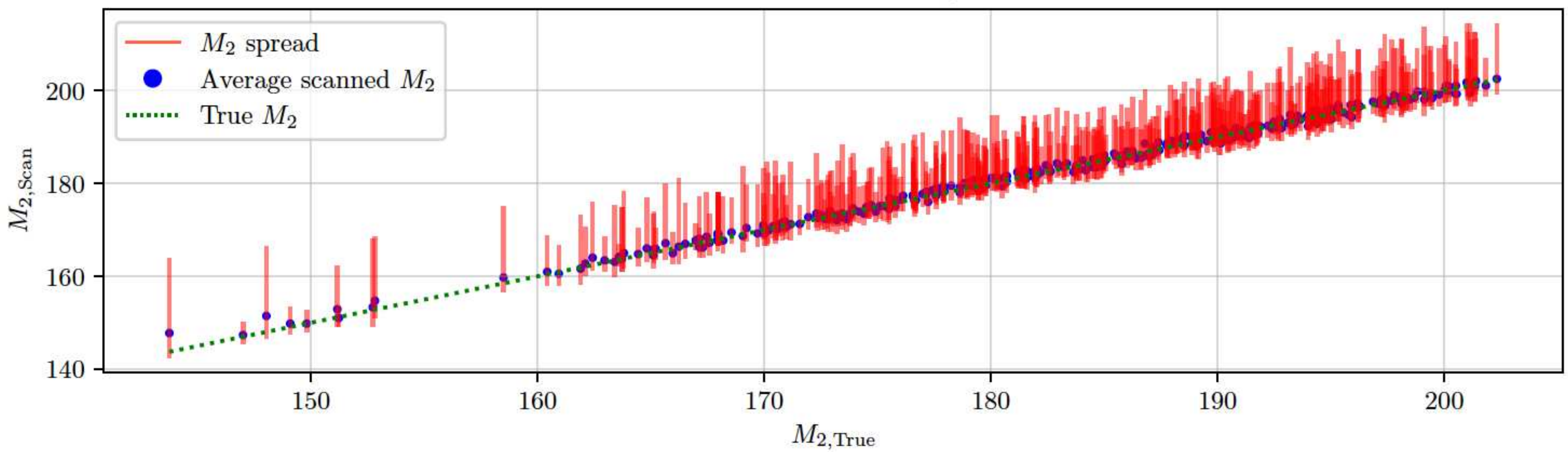


$\Rightarrow$ overlap region smeared out

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

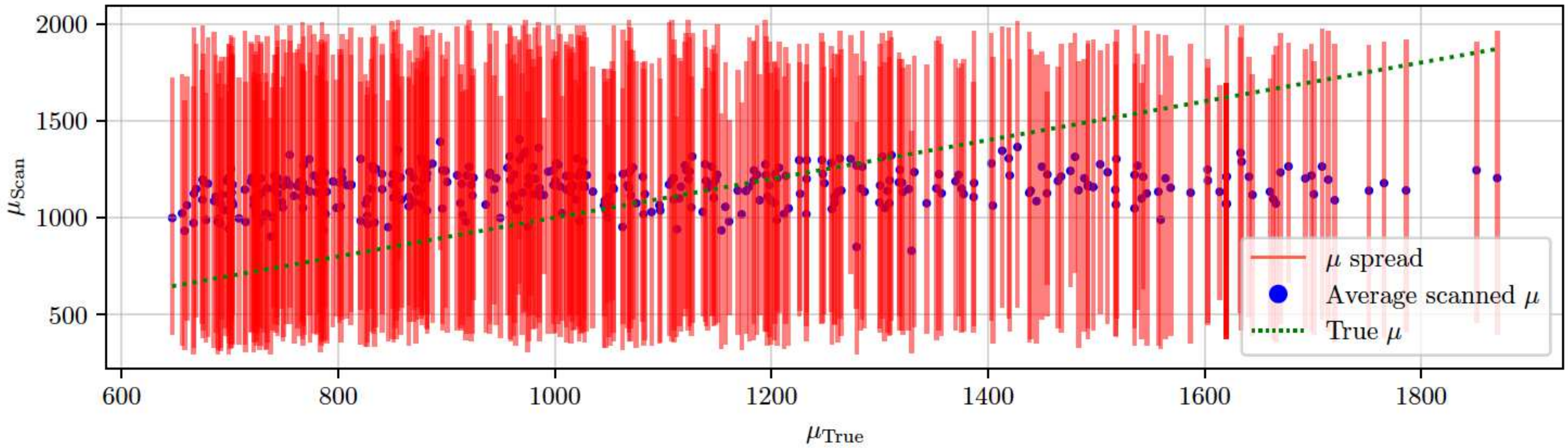
Reconstruction of M_1 and M_2:

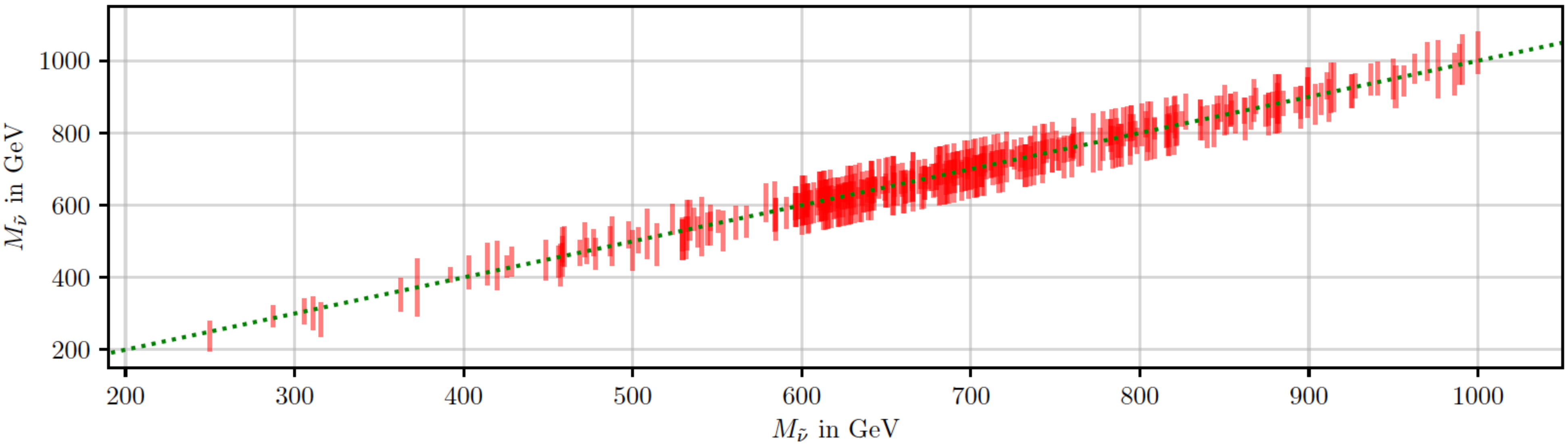




$\Rightarrow$ good reconstructions possible

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

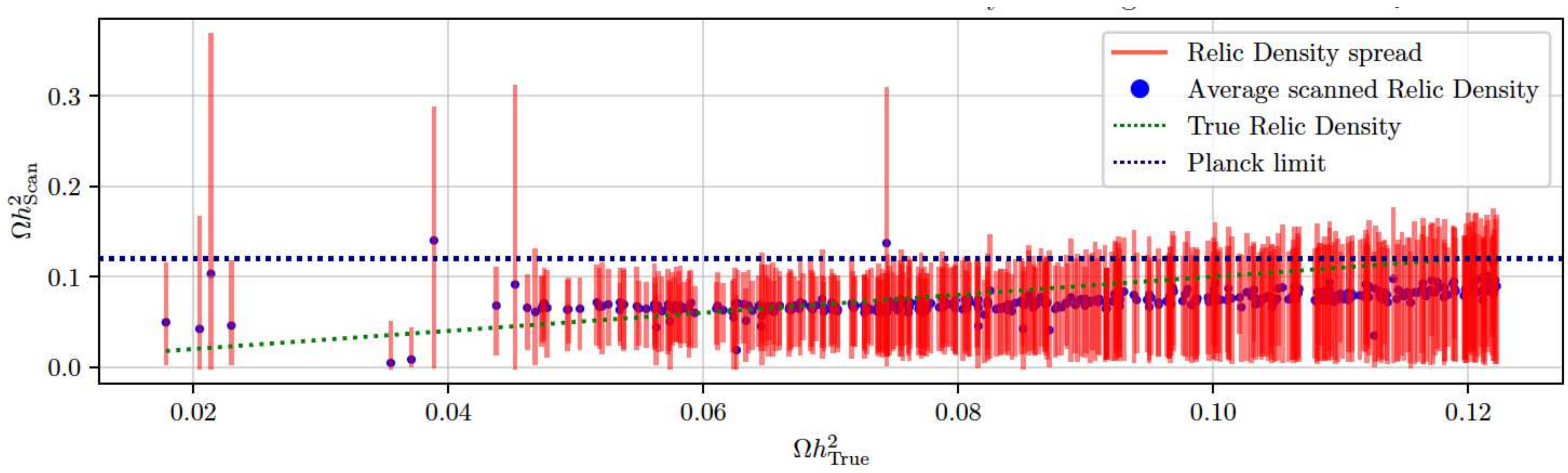




$\Rightarrow$ bad reconstruction of μ, good reconstruction of $m_{\tilde{\nu}_e}$

$\Rightarrow$ no problem, since μ is not very relevant in this scenario

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



⇒ often large uncertainties - but not too bad either

⇒ reason: experimental uncertainties in M_1 and M_2

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

5. Conclusinos

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

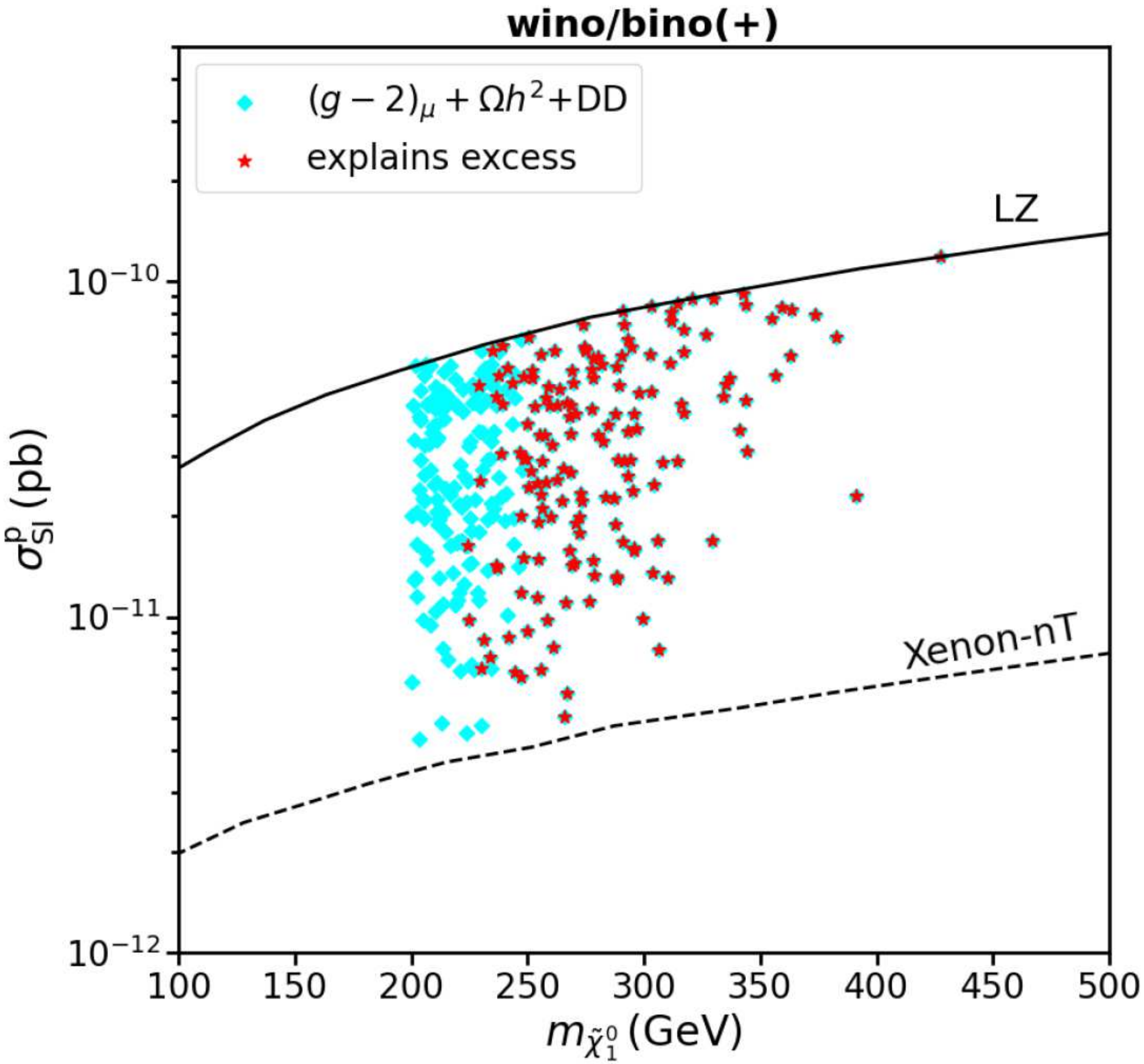
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 Z^* \, \tilde{\chi}_1^0 W^*$
  with $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^{\pm}} \gtrsim 250$ GeV, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV
- Best-fit explanation in the MSSM: wino/bino DM with $M_1 \times \mu < 0$

Nearly ideal situation for ILC500(+): parameter space covered

- $\Omega_\chi h^2$ reconstruction at ILC500:
  – scenario: wino/bino DM with $M_1 \times \mu > 0$
  – measurement of $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^{\pm}}$ and $\sigma(e^+ e- \to \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp})$
  – XS measurement with two polarizations and at $\sqrt{s} = 400, 500$ GeV
  – reconstruction of M_1, M_2, μ, $m_{\tilde{\nu}_e}$ (ind.!), . . . – with uncertainties
  – calculation of $\Omega_\chi h^2$ – with uncertainties
  $\Rightarrow$ “agreement” with astrophysical measurement

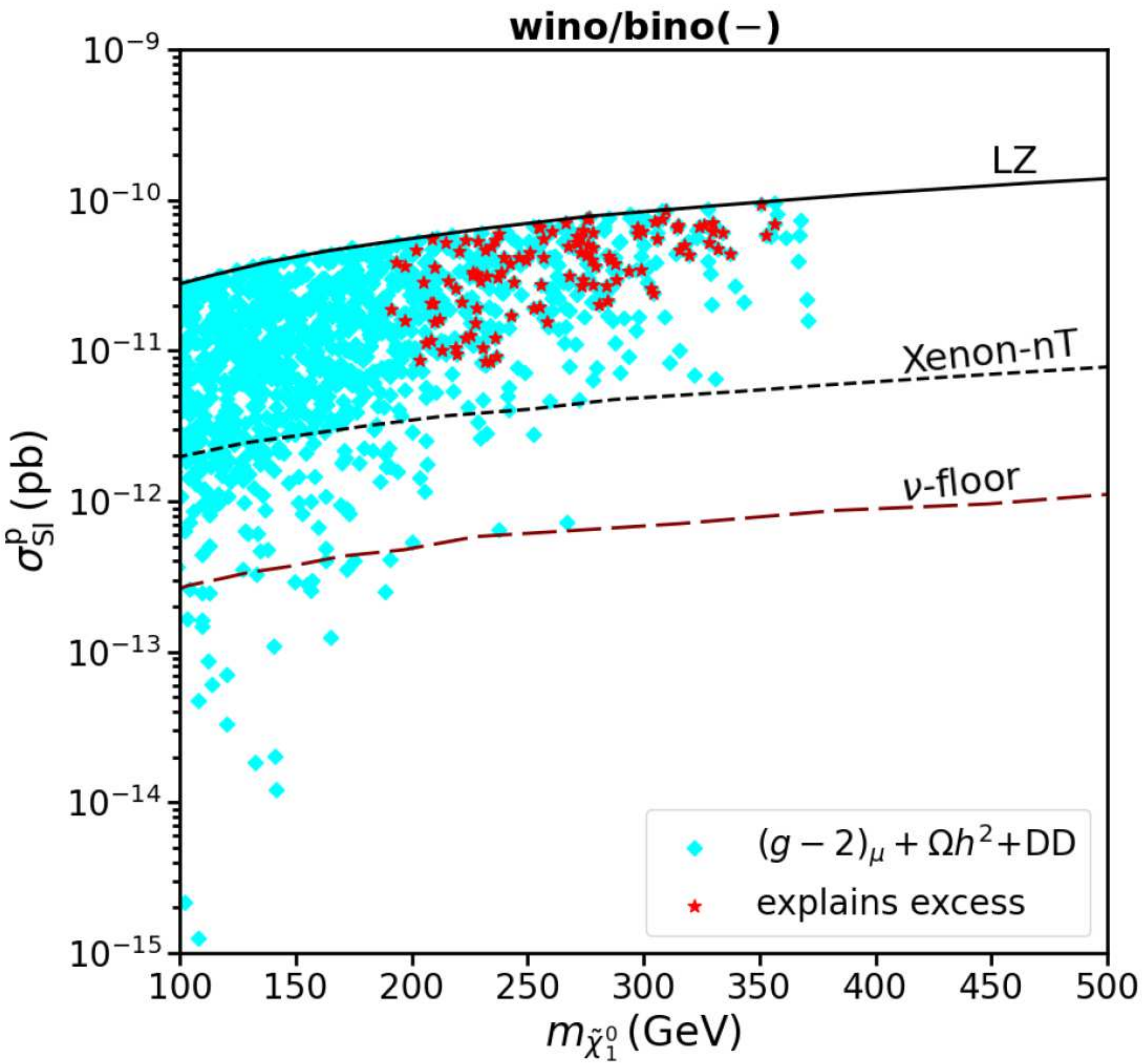

Further Questions?

wino/bino(+): direct detection prospects:



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

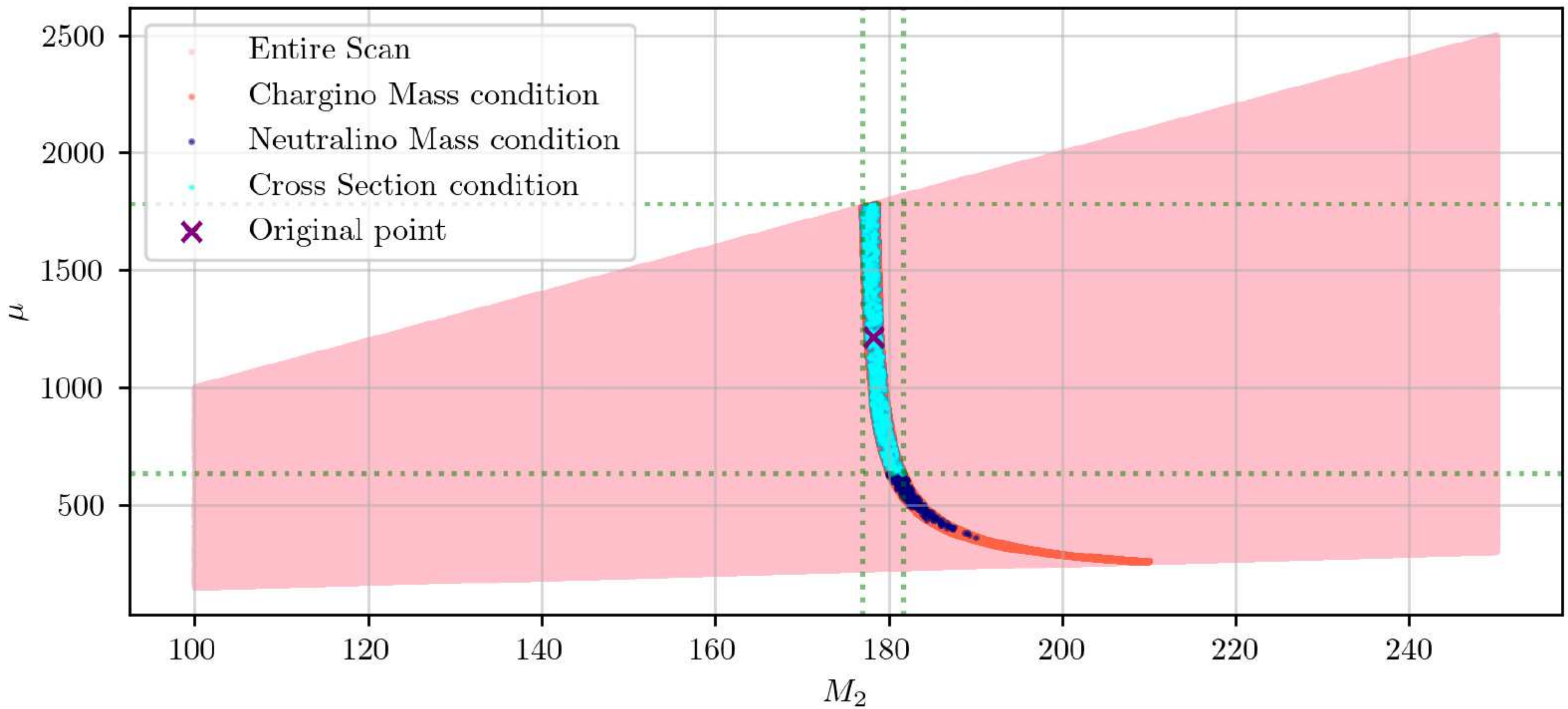
wino/bino(−): direct detection prospects:



⇒ 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

MSSM parameter determination:



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