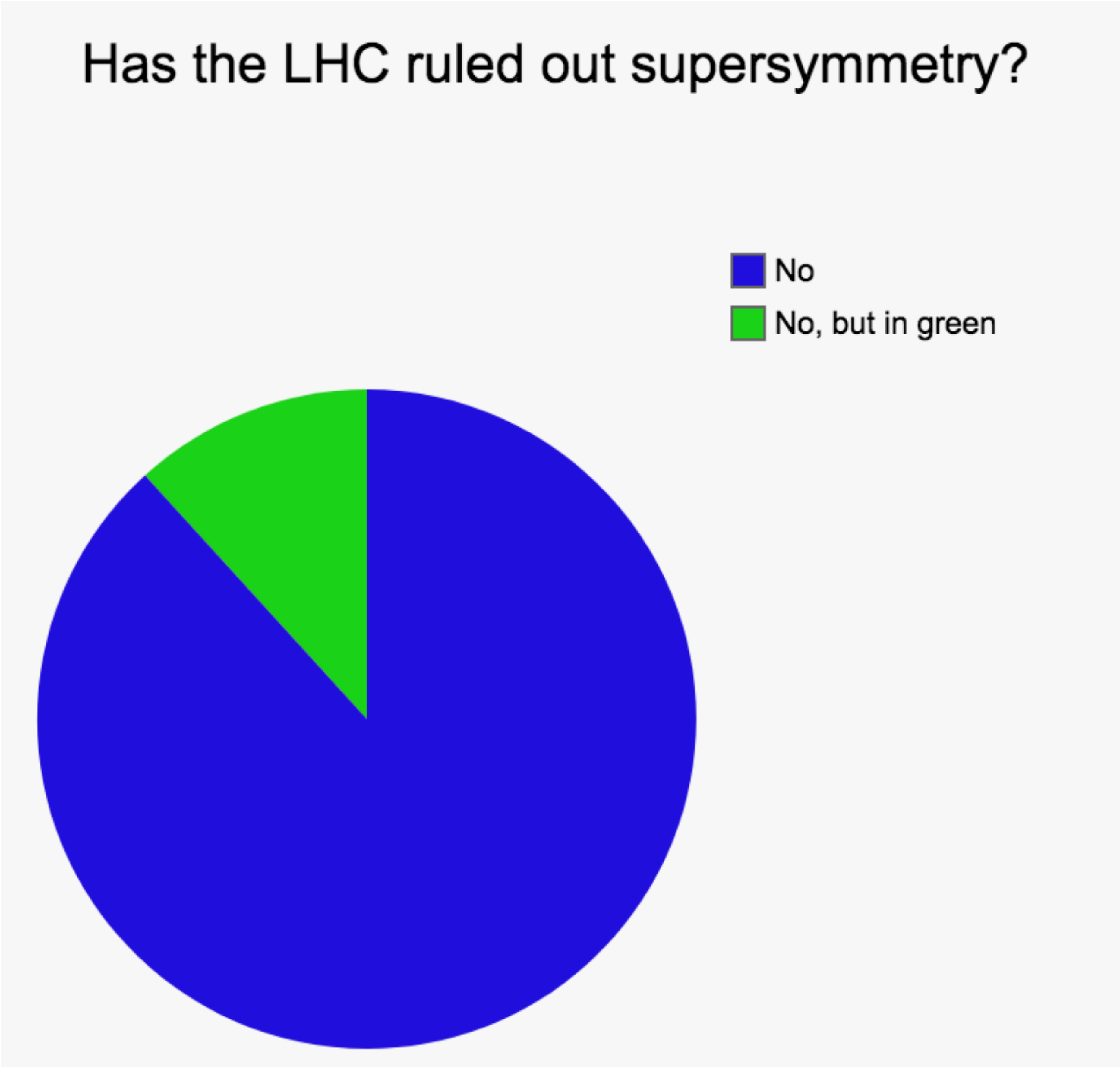
Has the LHC ruled out supersymmetry?
No
No, but in green


SUSY 2024
Theory meets Experiment
Madrid, 10 – 14 June 2024
Pre-SUSY school: 3 – 7 June 2024
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SUSY searches at the LHC:
Consistent Excesses at ATLAS and CMS

Sven Heinemeyer, IFT (CSIC, Madrid)

Madrid, 05/2024

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

1. The main idea

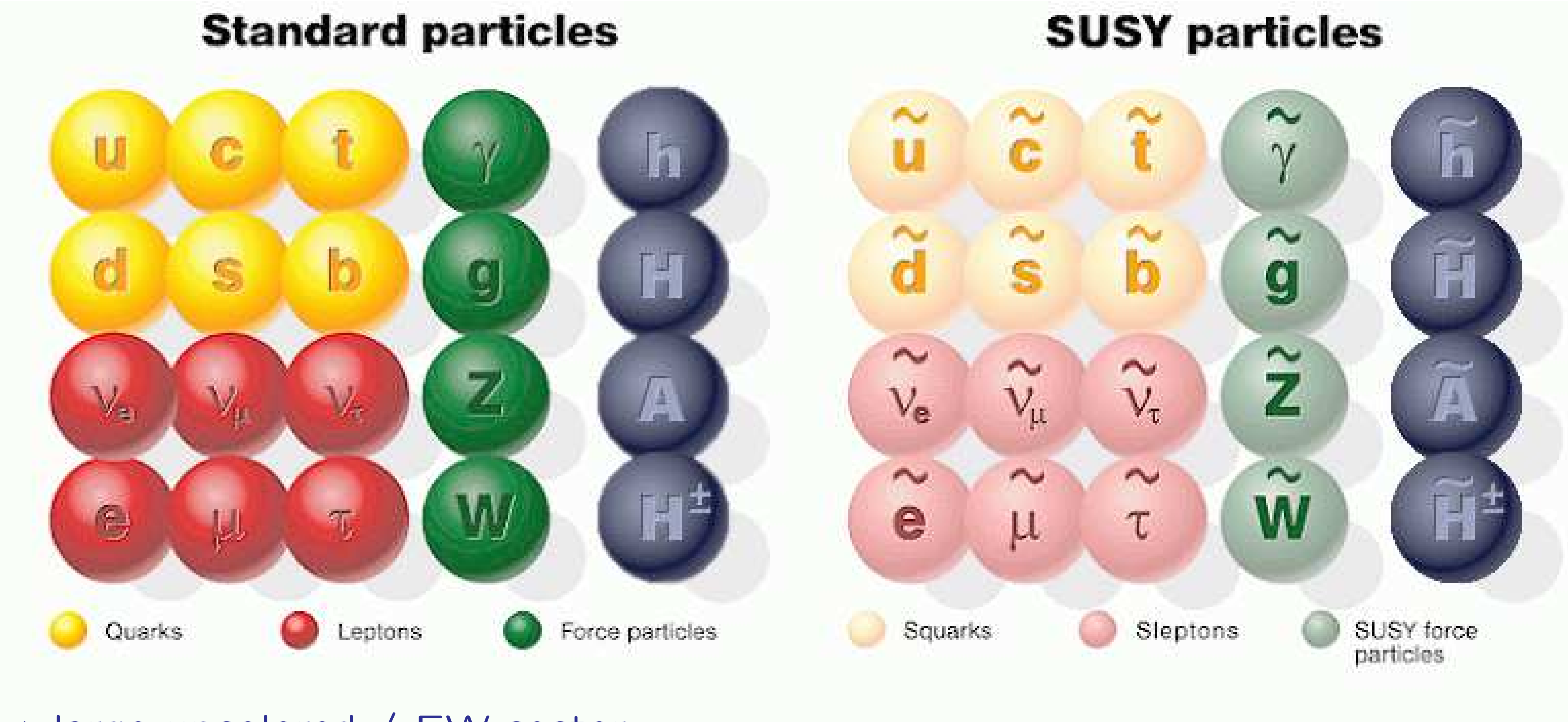
2. Evidence for low-energy SUSY?!

3. Wino/bino vs. higgsino DM

4. Conclusions

1. The main idea

The MSSM



⇒ large uncolored / EW sector

charginos/neutralinos: M_1, M_2, 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.)

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 $5\,\sigma$ 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:

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

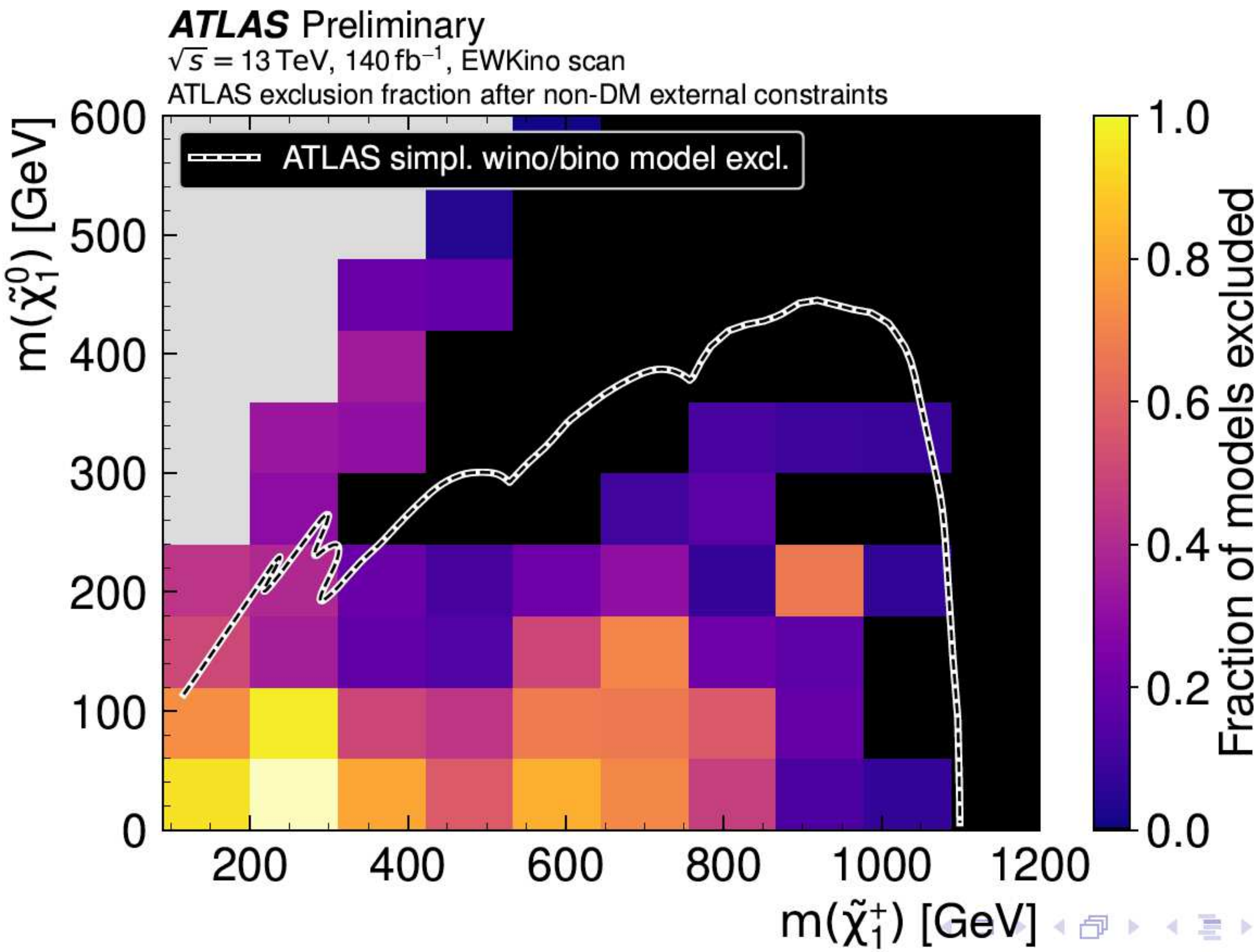
SM, EW 1L: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}$

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

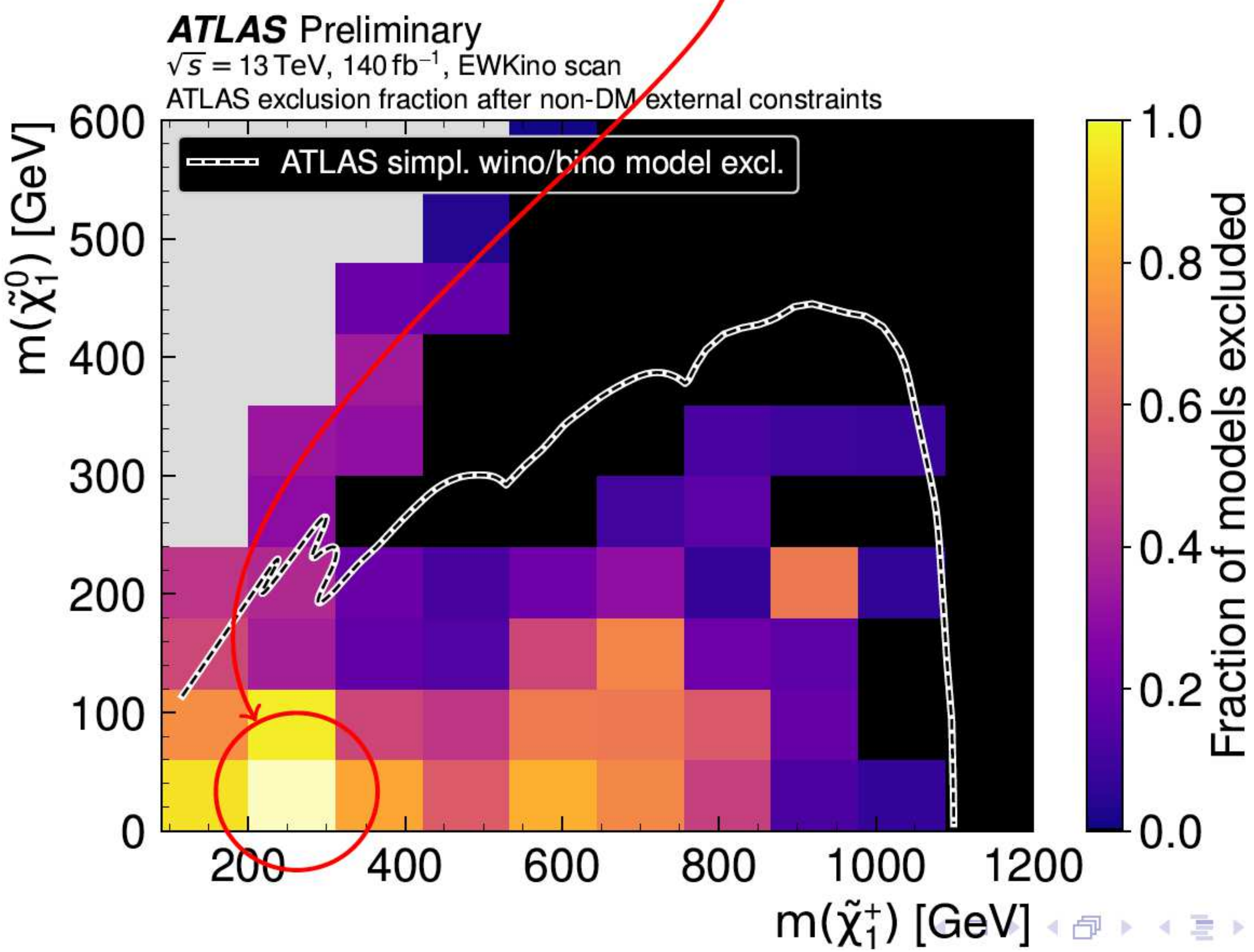
$\Rightarrow$ slepton masses constrol the size of $\Delta a_\mu^{\text{MSSM}}$

2. Evidence for low-energy SUSY?!

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:

– $pp \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 + X$
– $pp \to \tilde{\chi}^0_1 \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 + H/Z$
– $pp \to \tilde{\chi}^0_2 \tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 H/Z \; \tilde{\chi}^0_1 W^\pm$
– $pp \to \tilde{\chi}^+_1 \tilde{\chi}^-_1 \to \tilde{\chi}^0_1 W^+ \; \tilde{\chi}^0_1 W^-$
– ...

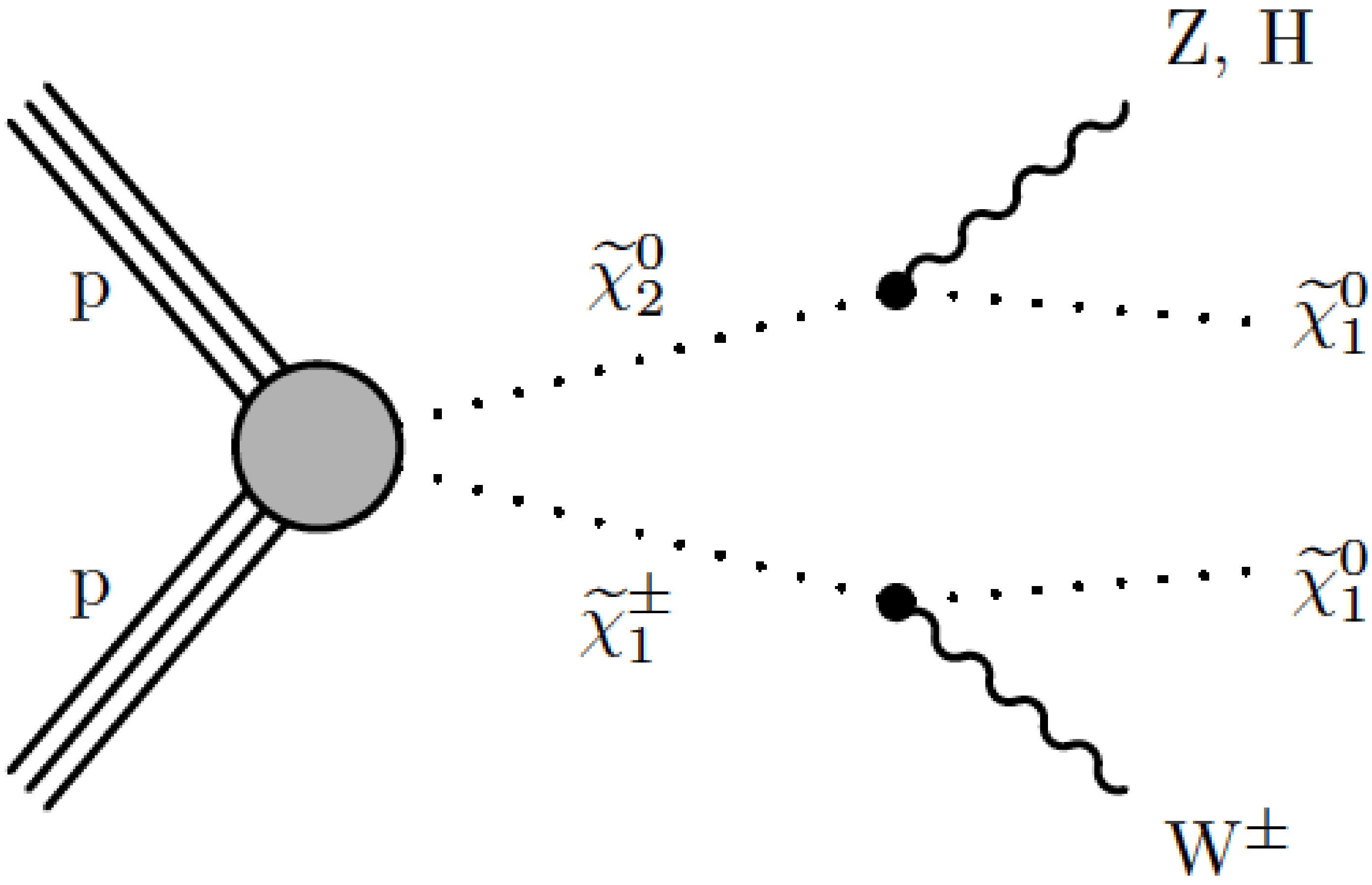
Possible kinematic situations:

– 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

$\Rightarrow$ Our "models" predict low chargino/neutralino masses

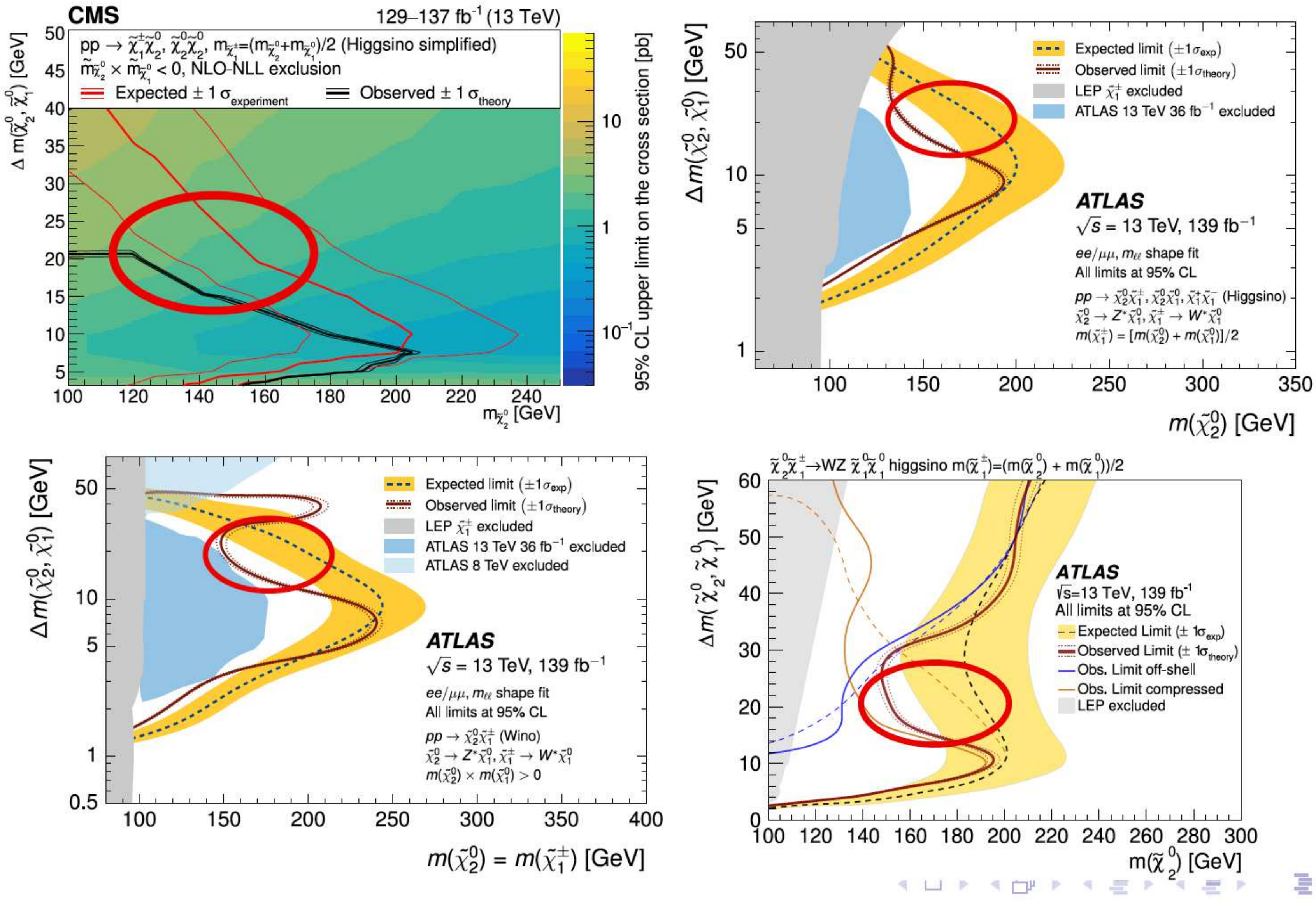
Golden mode at the LHC:



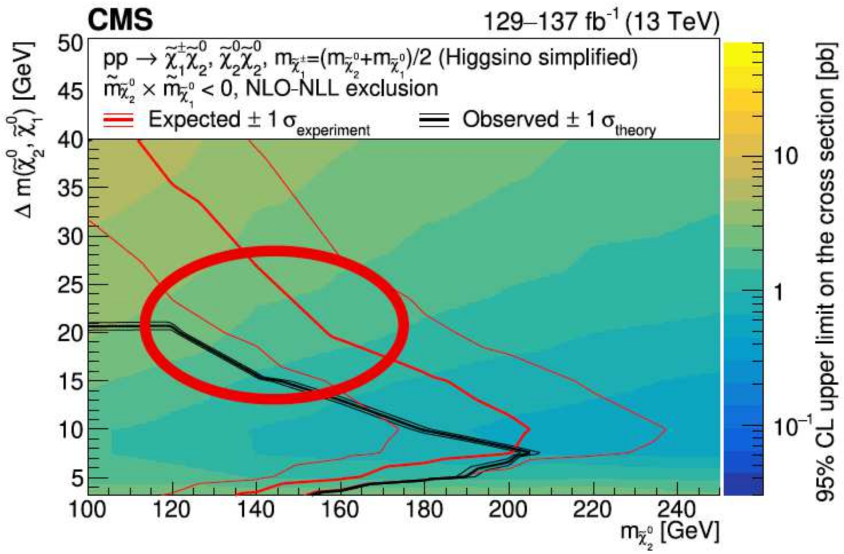
$\Rightarrow$ experimental results?

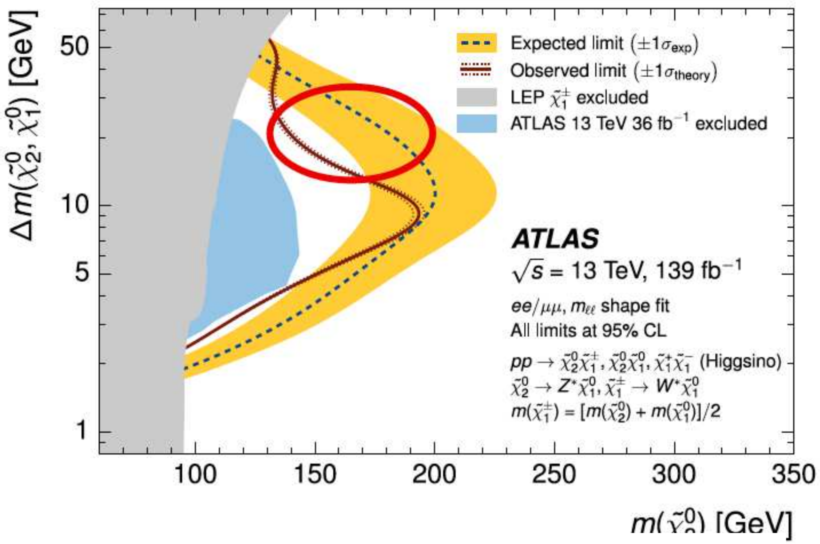
Results: “compressed” spectra w/ heavy sleptons:

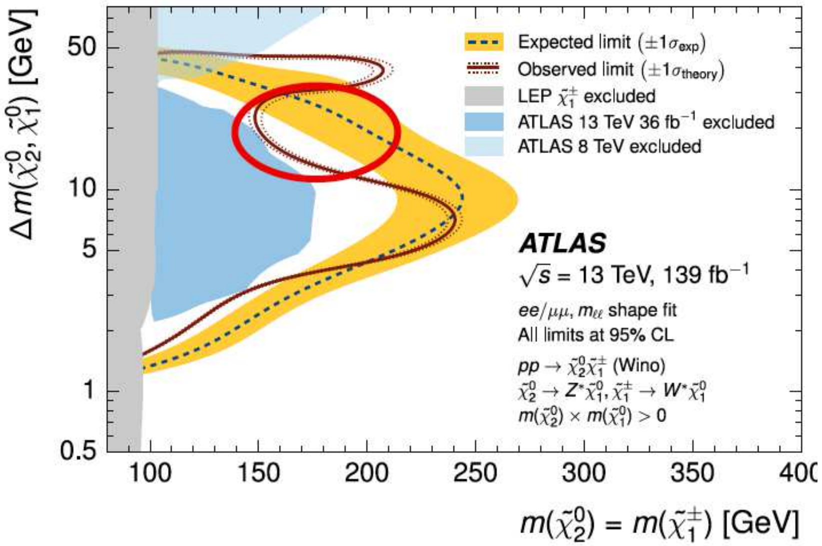
[*taken from M. Berggren ’23*]

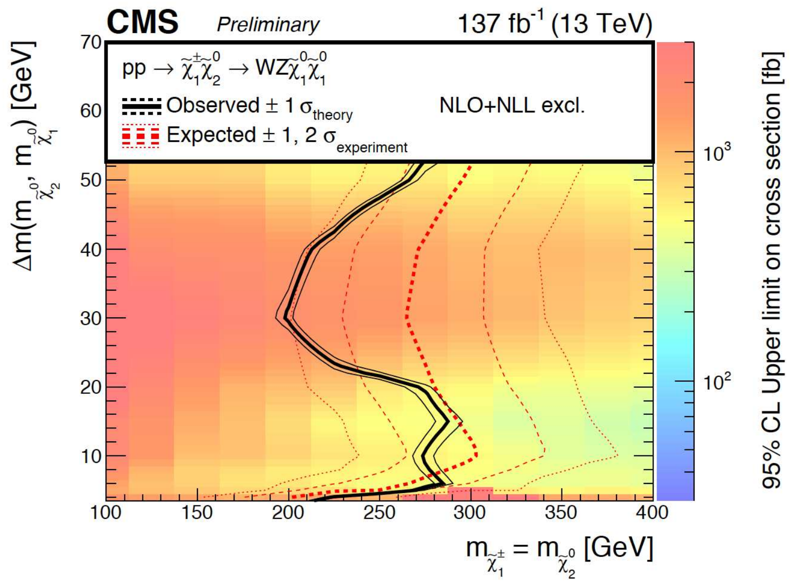


Results: “compressed” spectra w/ heavy sleptons: one more CMS analysis:









Two possible scenarios:

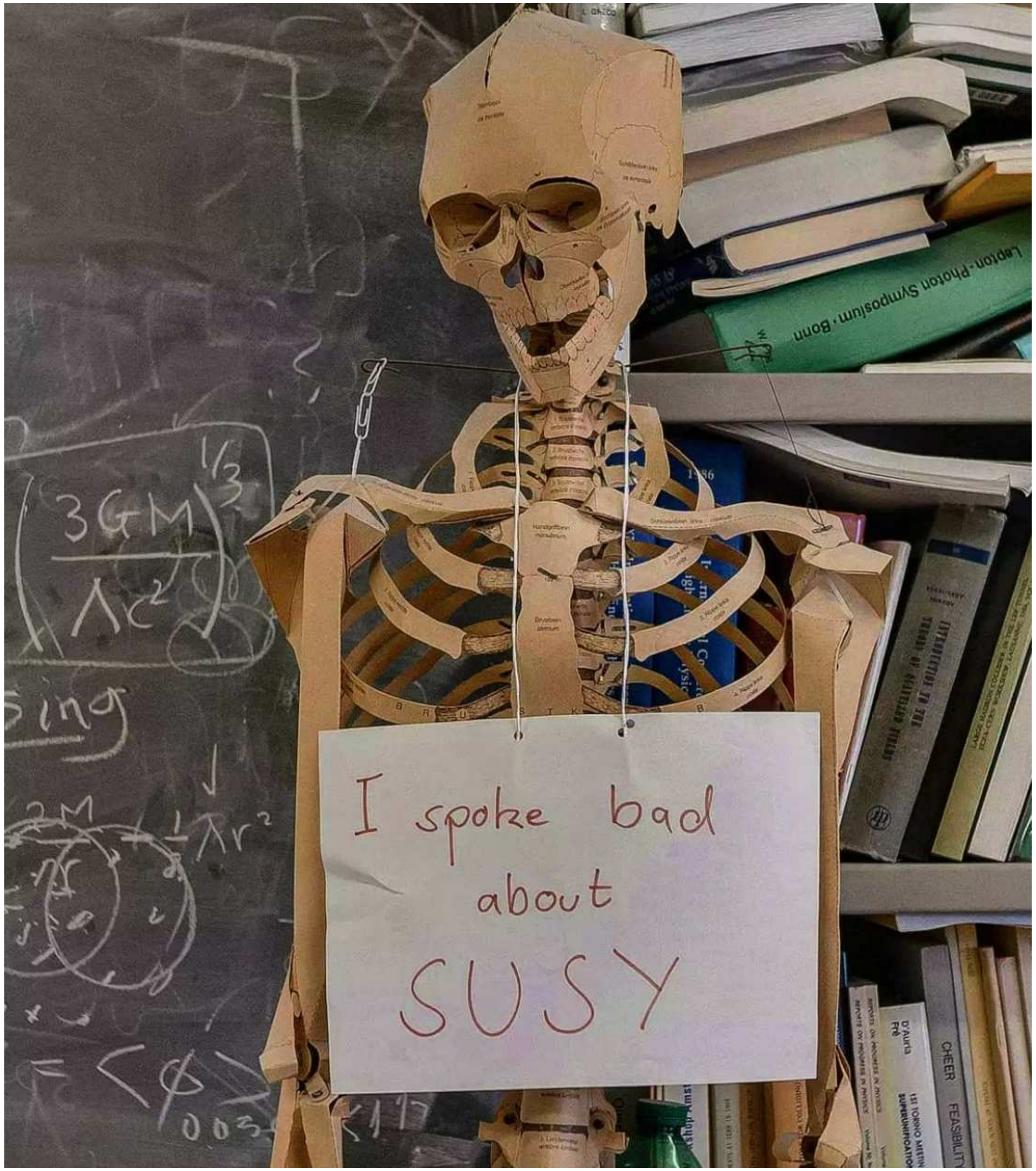
– $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$
– $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}\,(20~\text{GeV})$

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

$\Rightarrow$ can they fit the excesses?

3. Wino/bino vs. higgsino DM



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

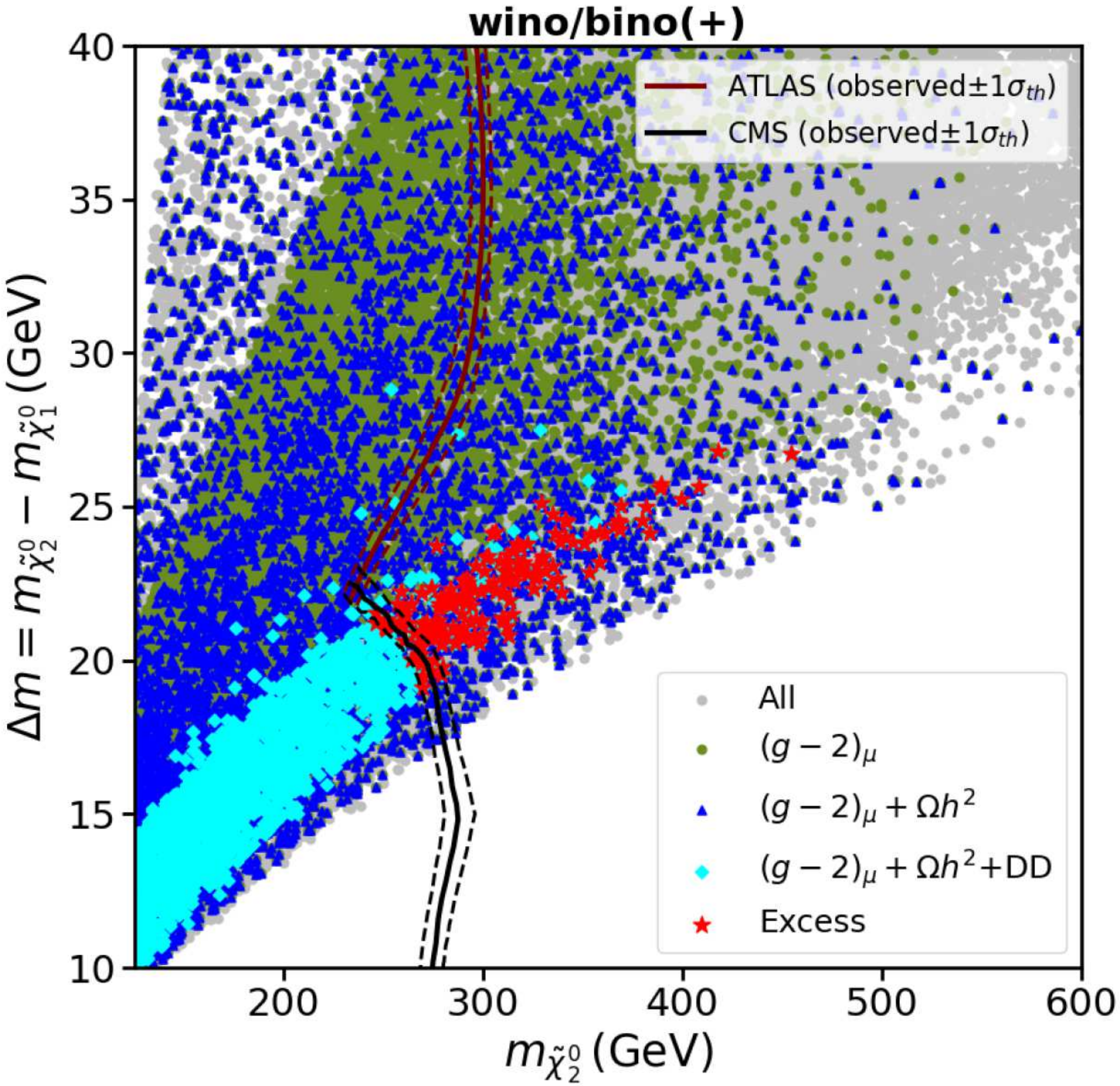
wino/bino(−): $M_1 \times \mu < 0$

relic DM density can be 100% fulfilled

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

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

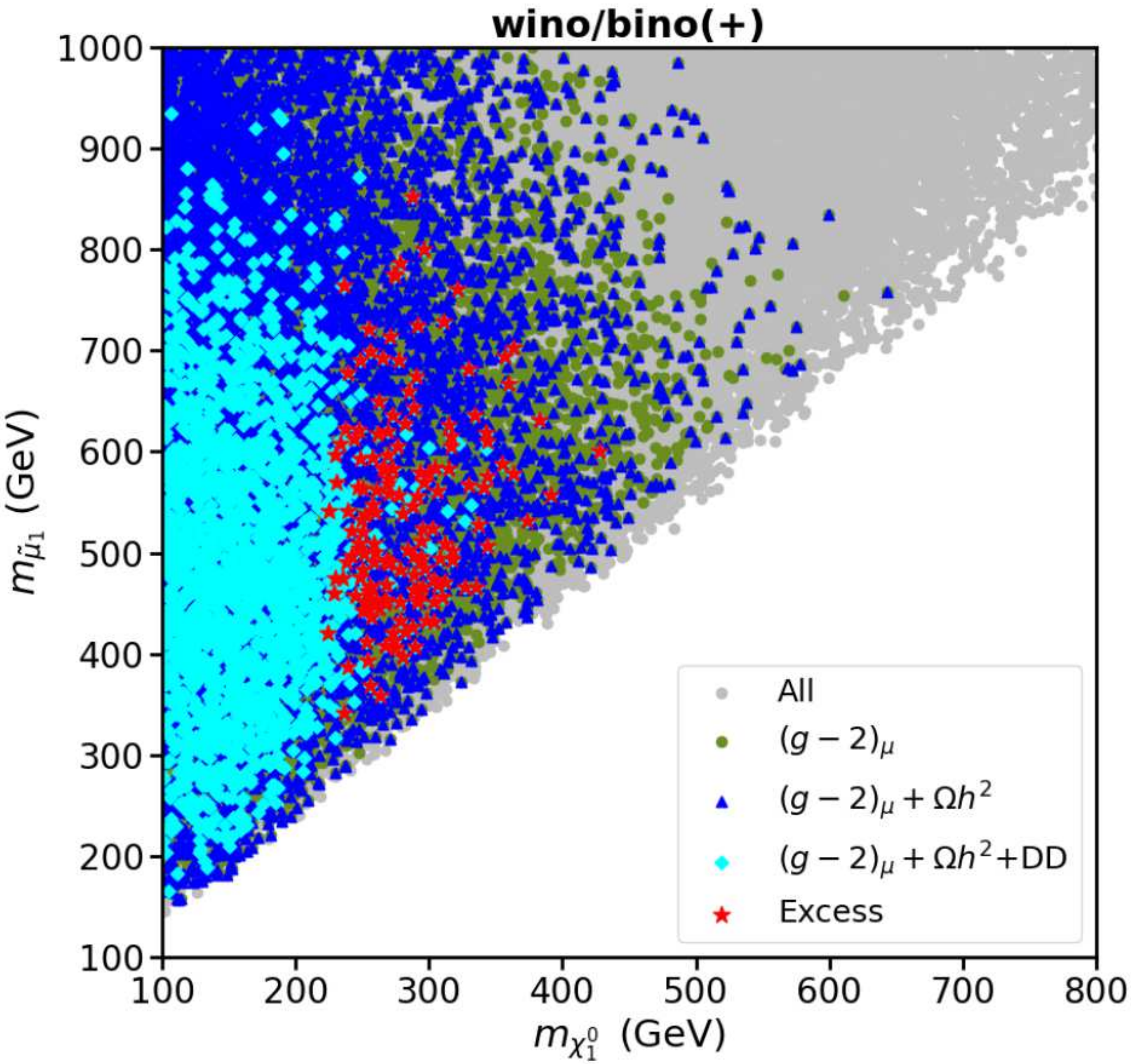
wino/bino(+): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



⇒ excesses not fully at the same Δm . . .

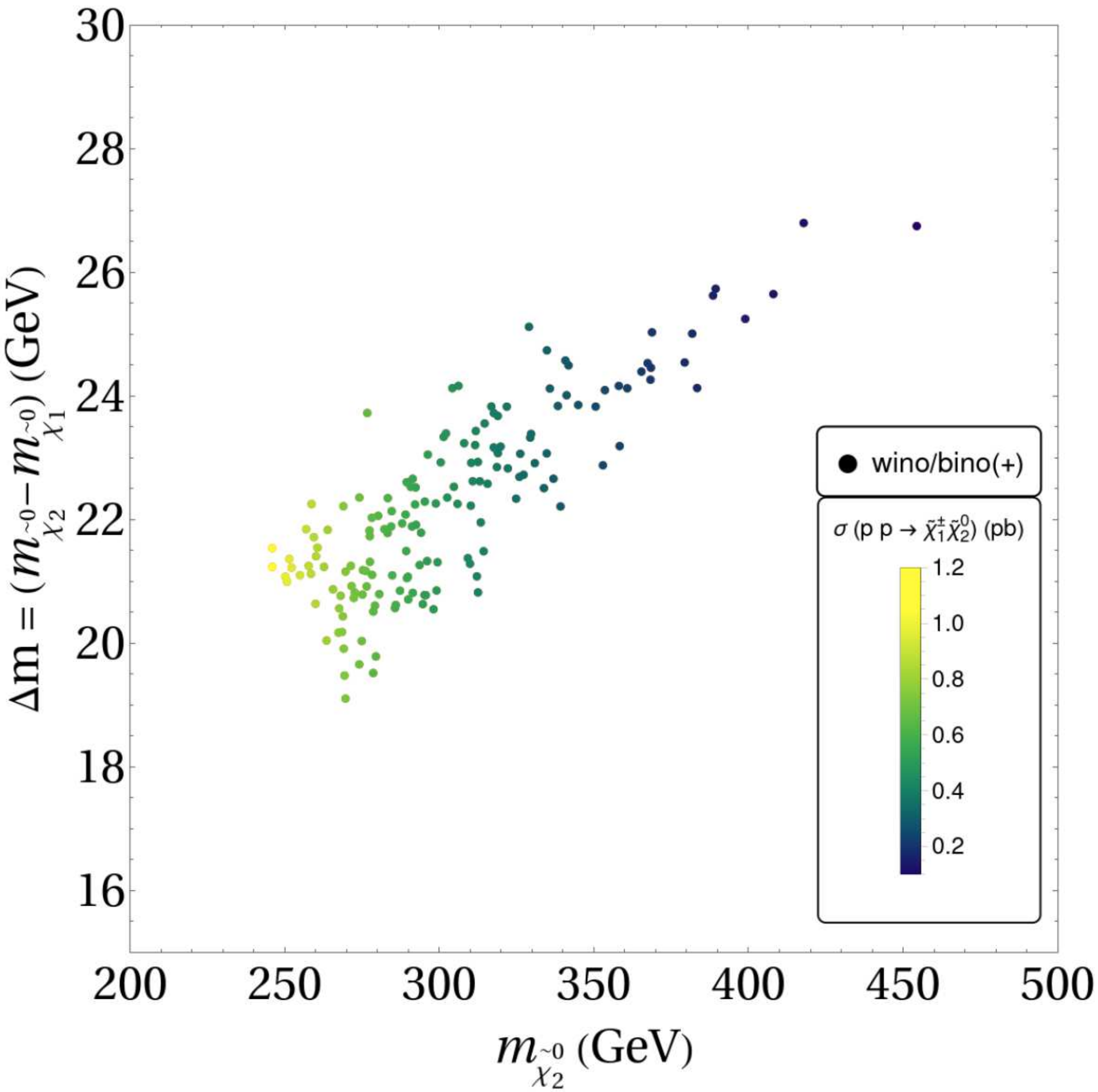
⇒ but many "good points" at $\Delta m \sim 20$ GeV

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



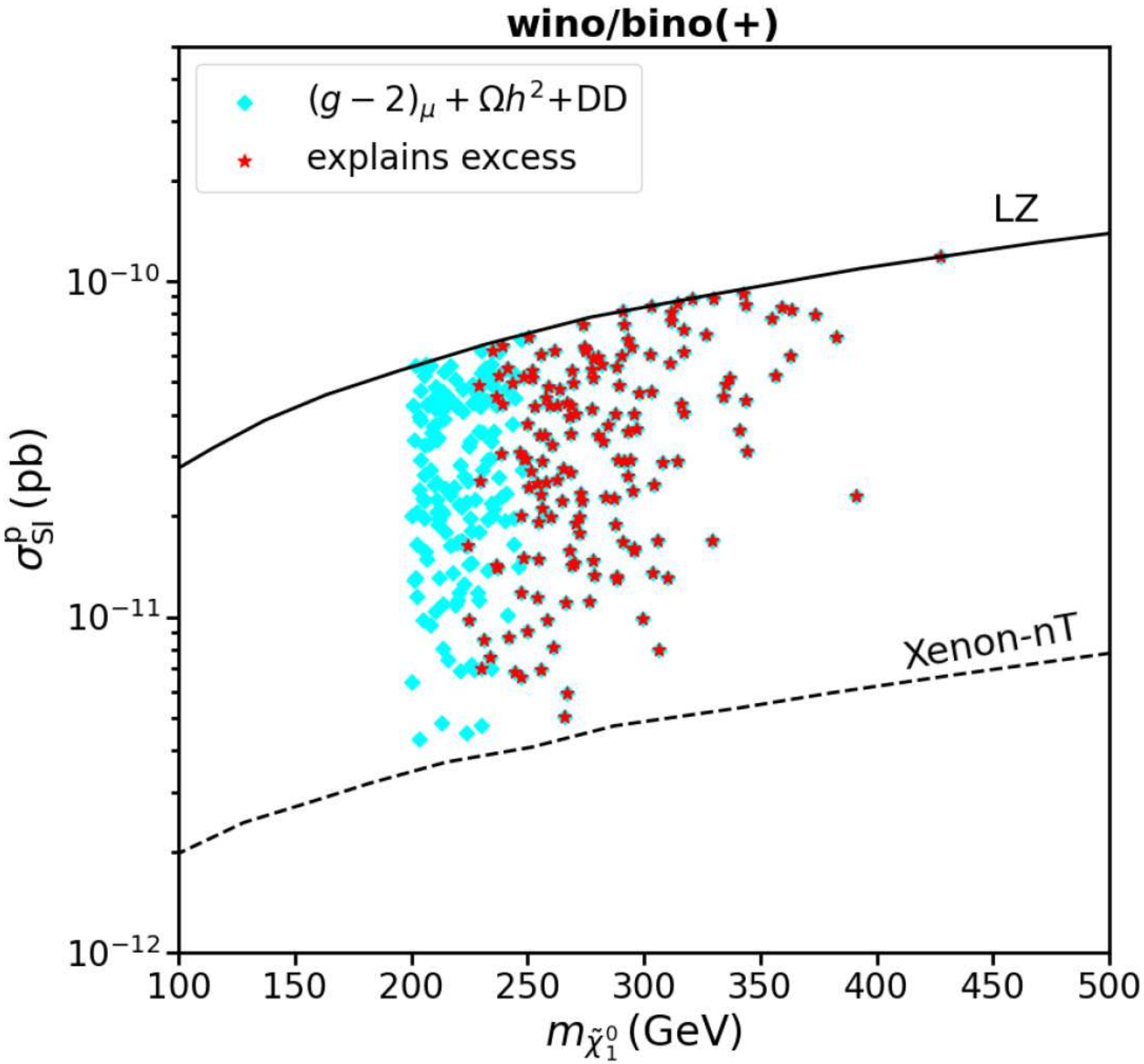
$\Rightarrow$ no limits on slepton masses (as expected)

wino/bino(+): LHC cross sections:



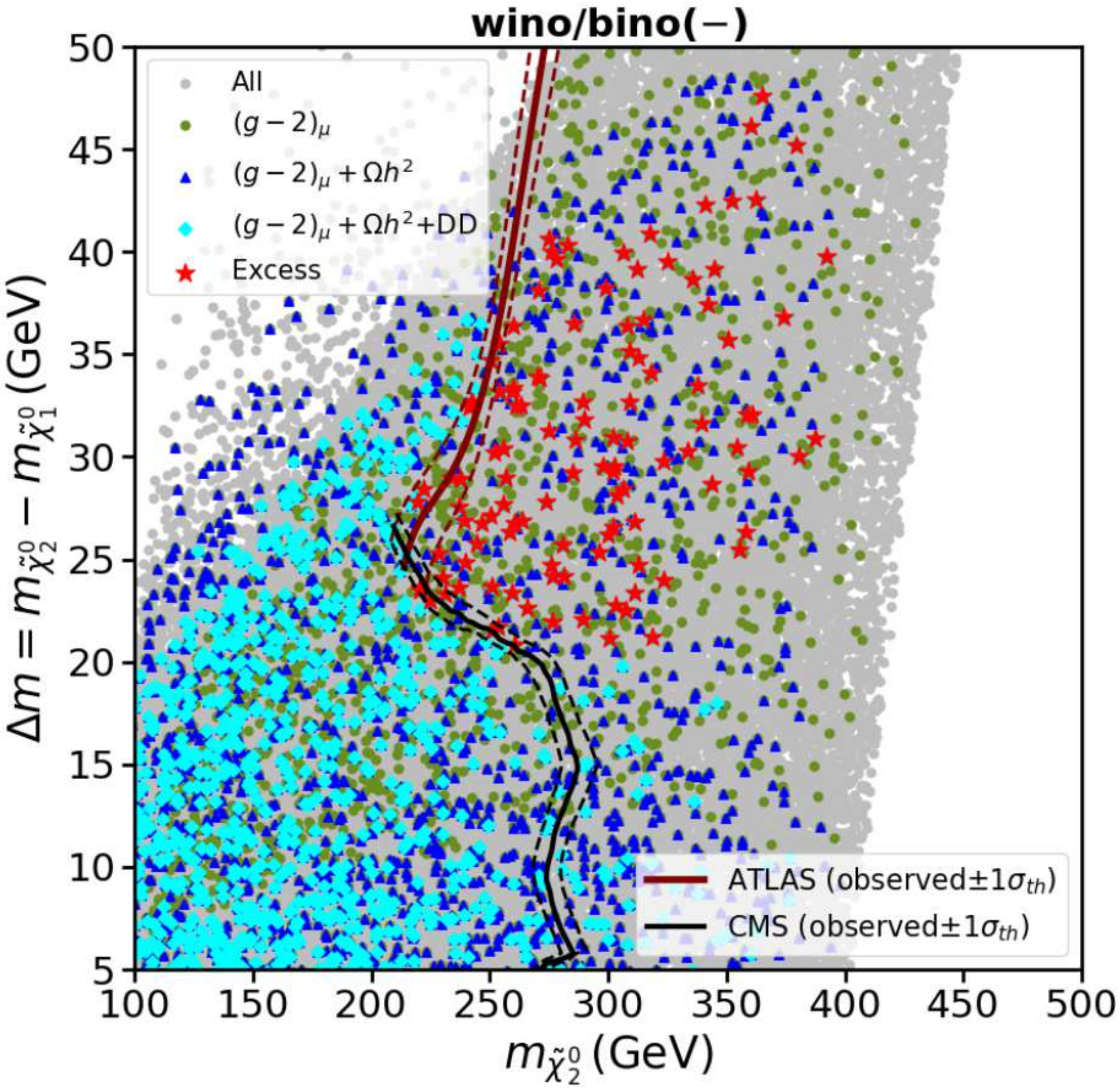
⇒ cross sections have roughly the size required by excesses

wino/bino(+): direct detection prospects:



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

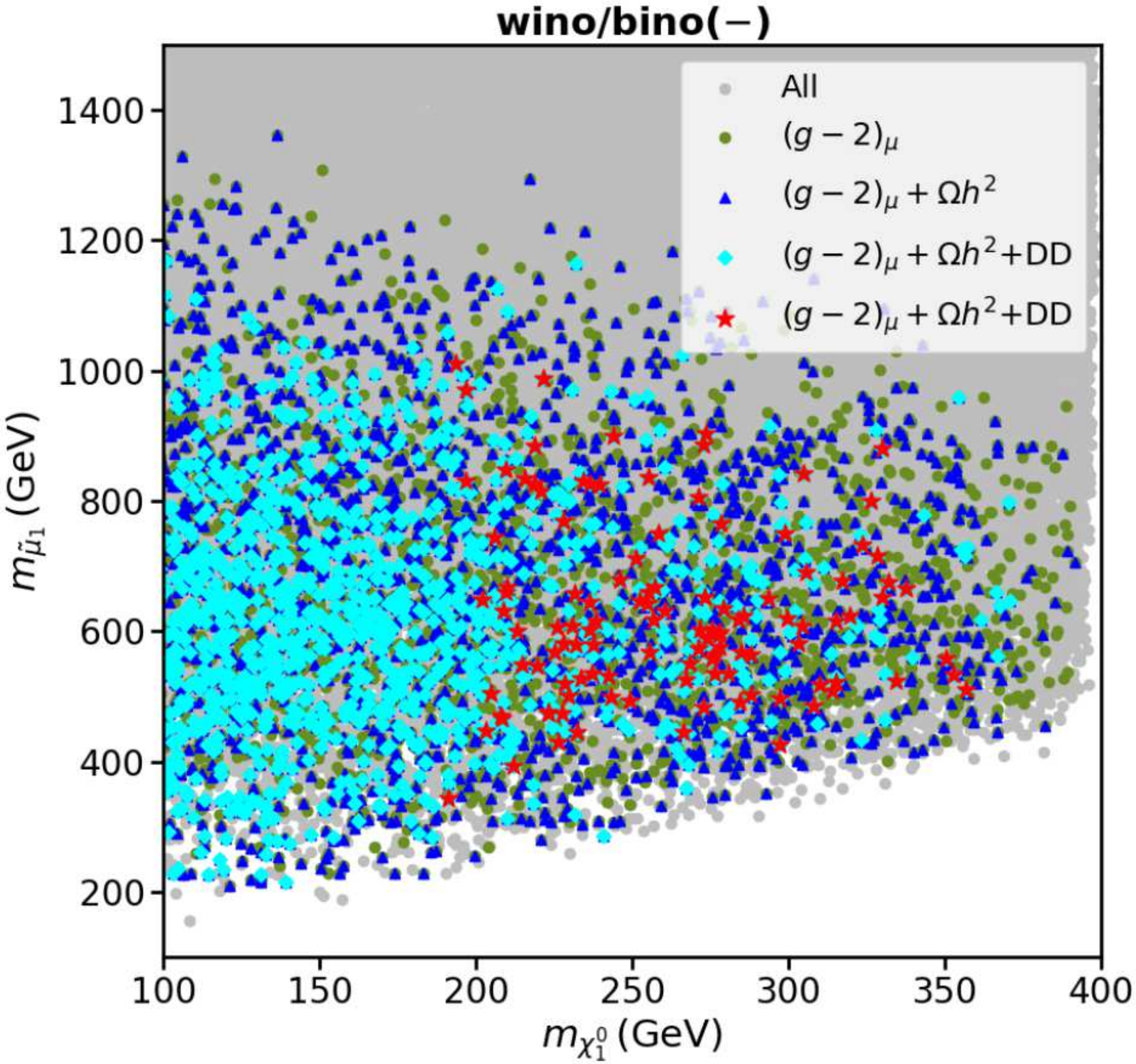
wino/bino(−): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:



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

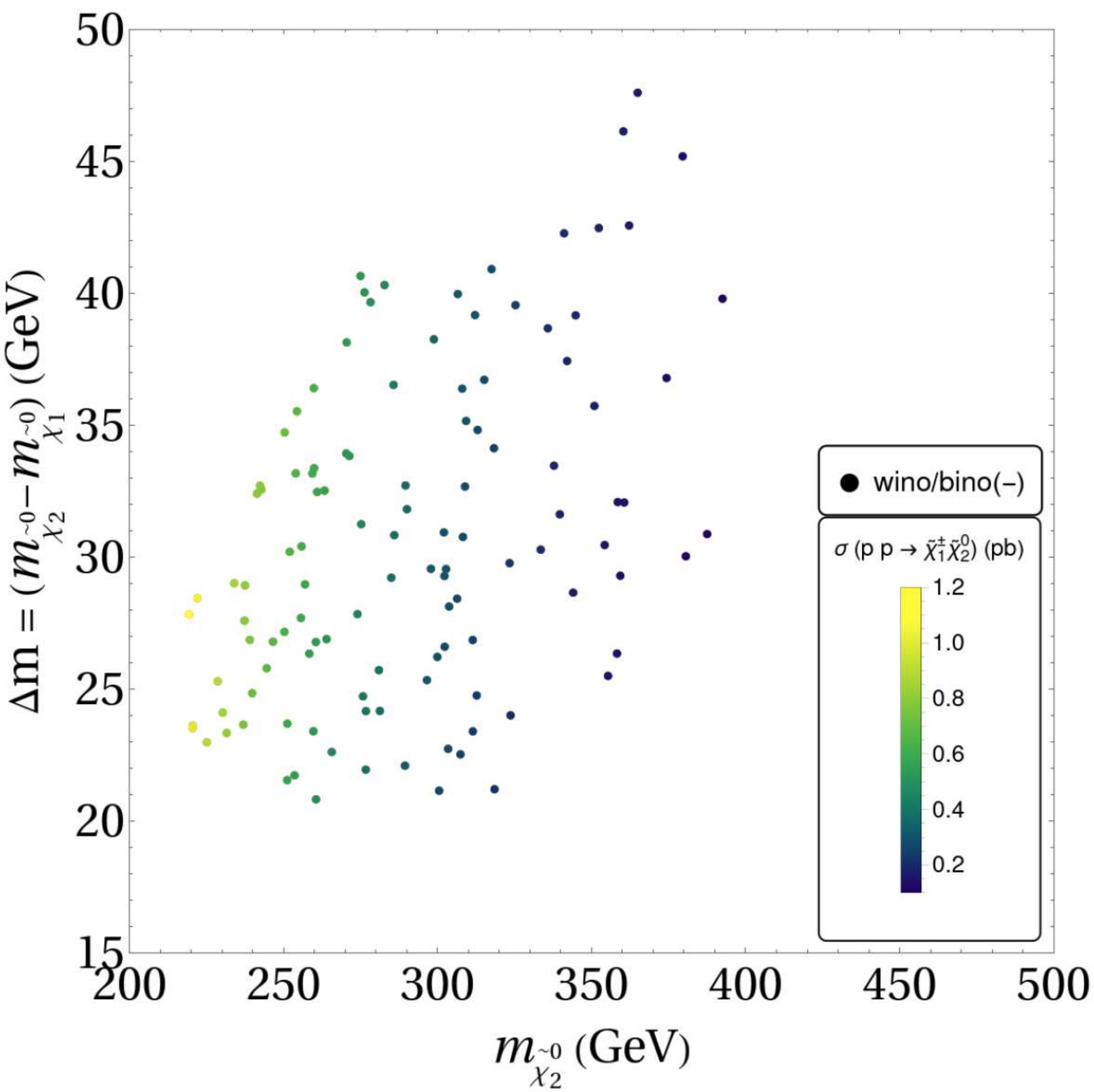
⇒ but many "good points" at $\Delta m \sim 25$ GeV

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



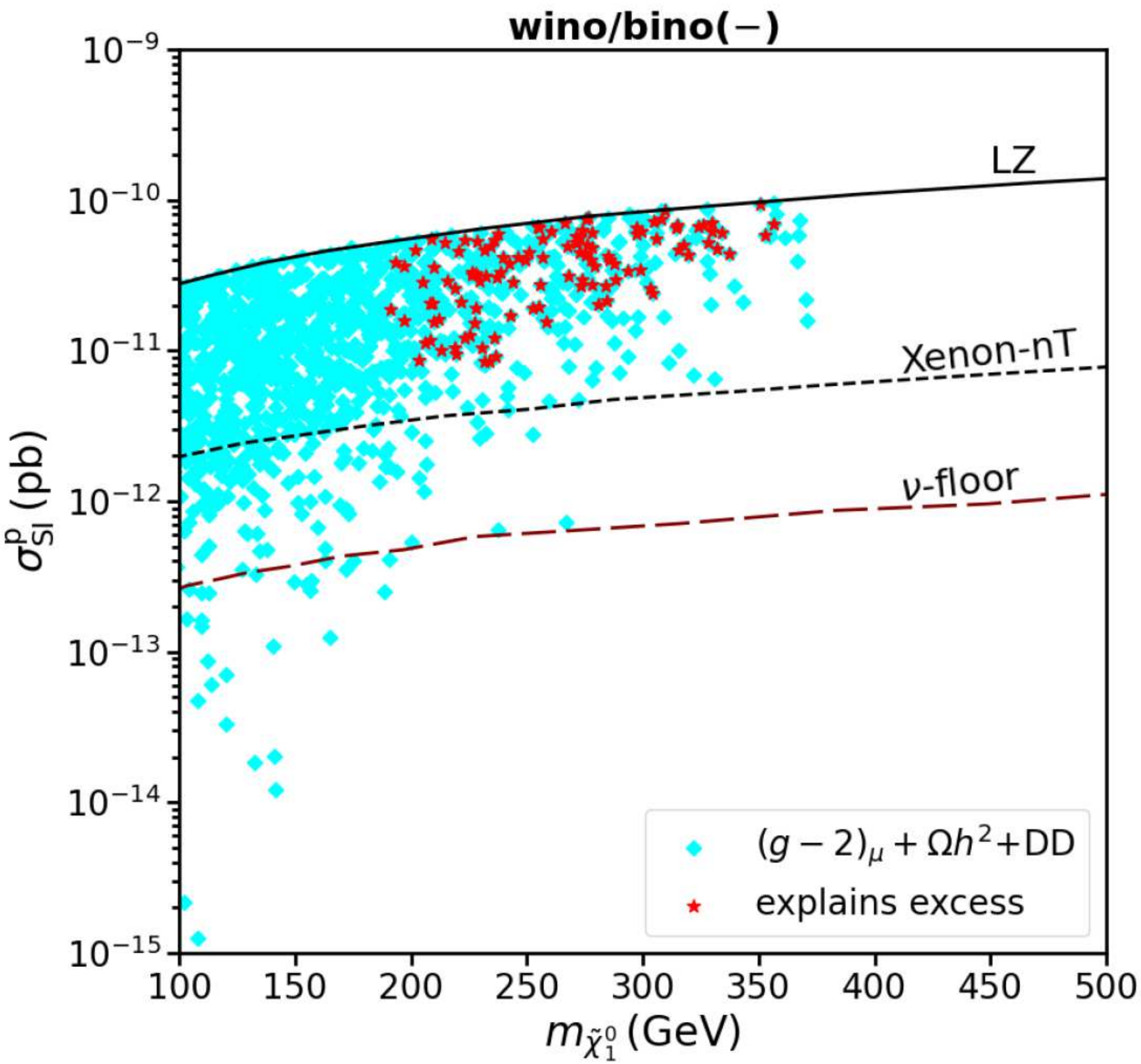
⇒ no limits on slepton masses (as expected)

wino/bino(−): LHC cross sections:



⇒ cross sections 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

$\Rightarrow$ low mass points now excluded $\Rightarrow$ would have been a problem for DD

D) Higgsino DM

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

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

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

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

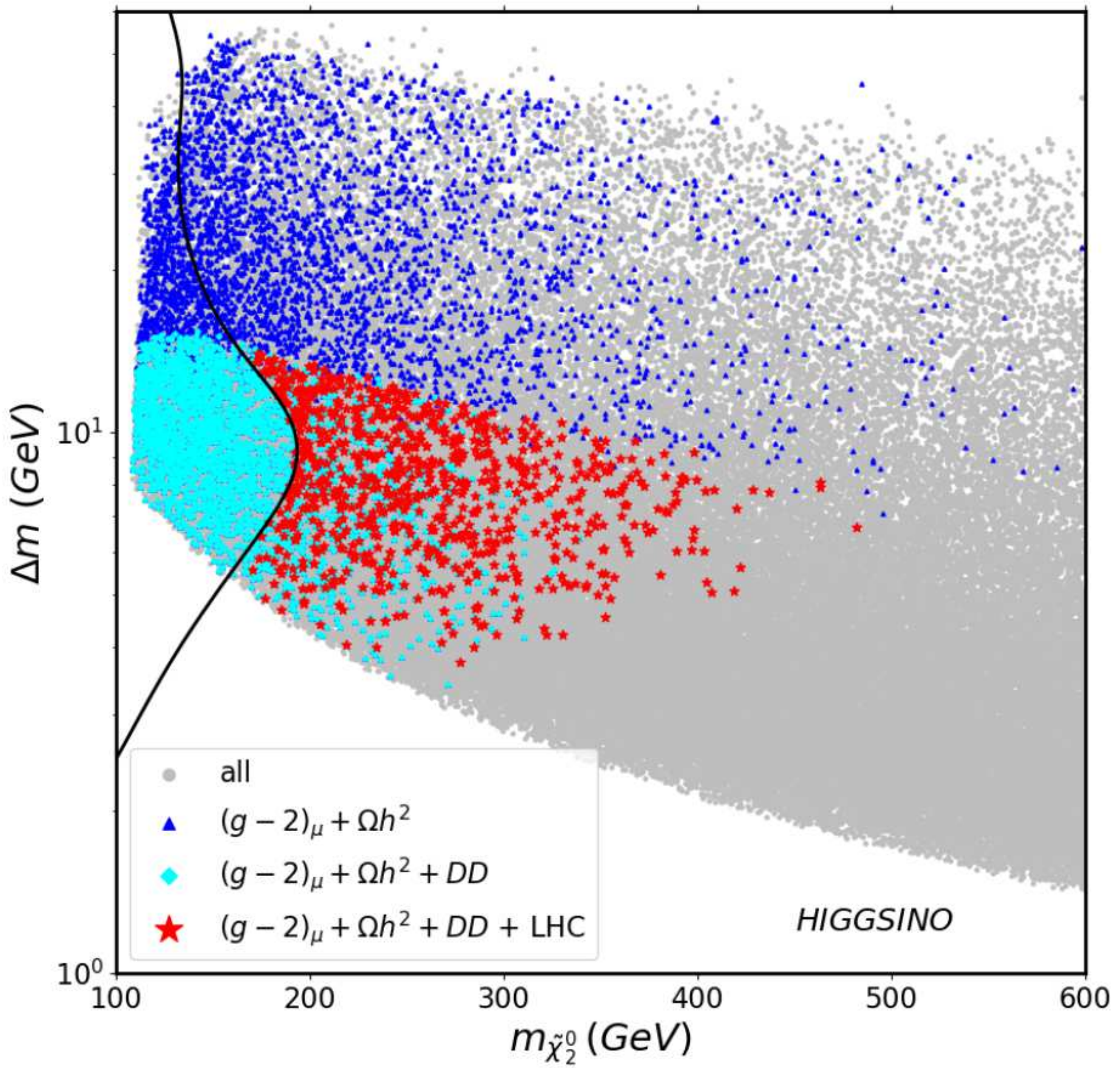
$$5 \le \tan\beta \le 60,$$

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

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

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

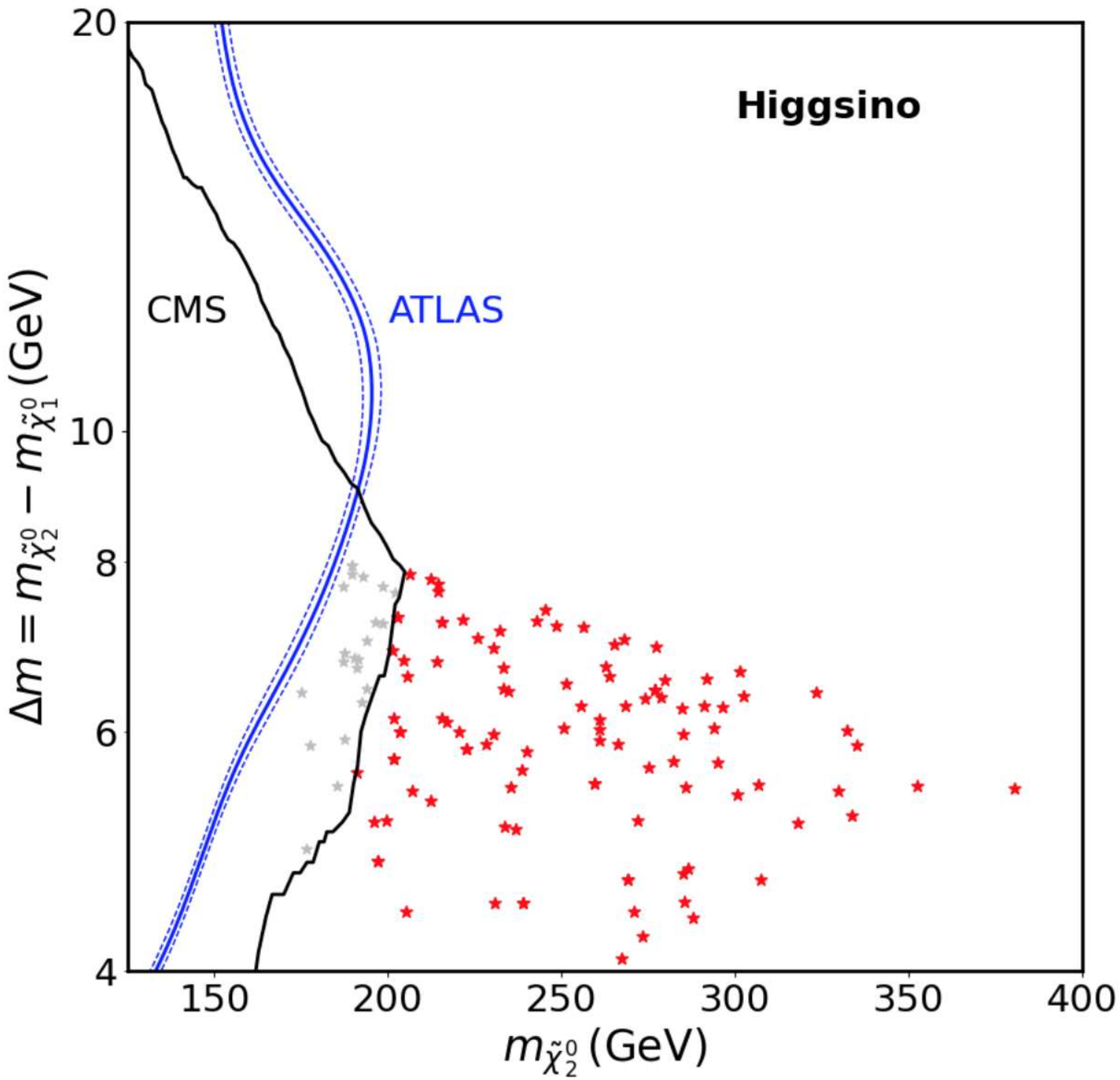
Results in the $m_{\tilde{\chi}_2^0}$-Δm plane with old DD bound: [2021]



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

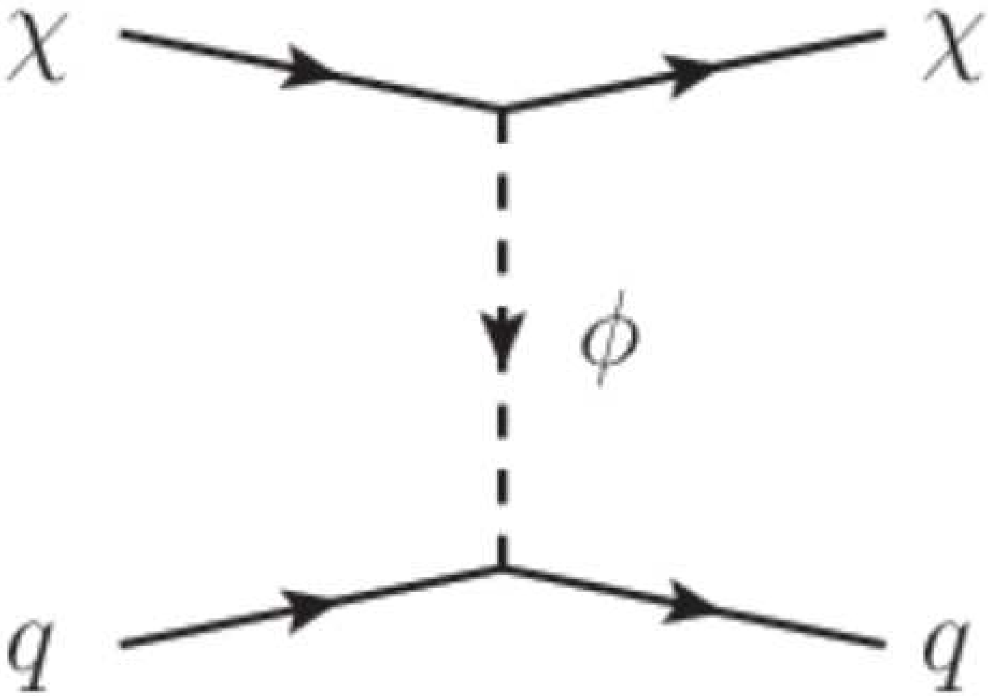
Results in the $m_{\tilde{\chi}_2^0}$-Δm plane

[*PRELIMINARY*]



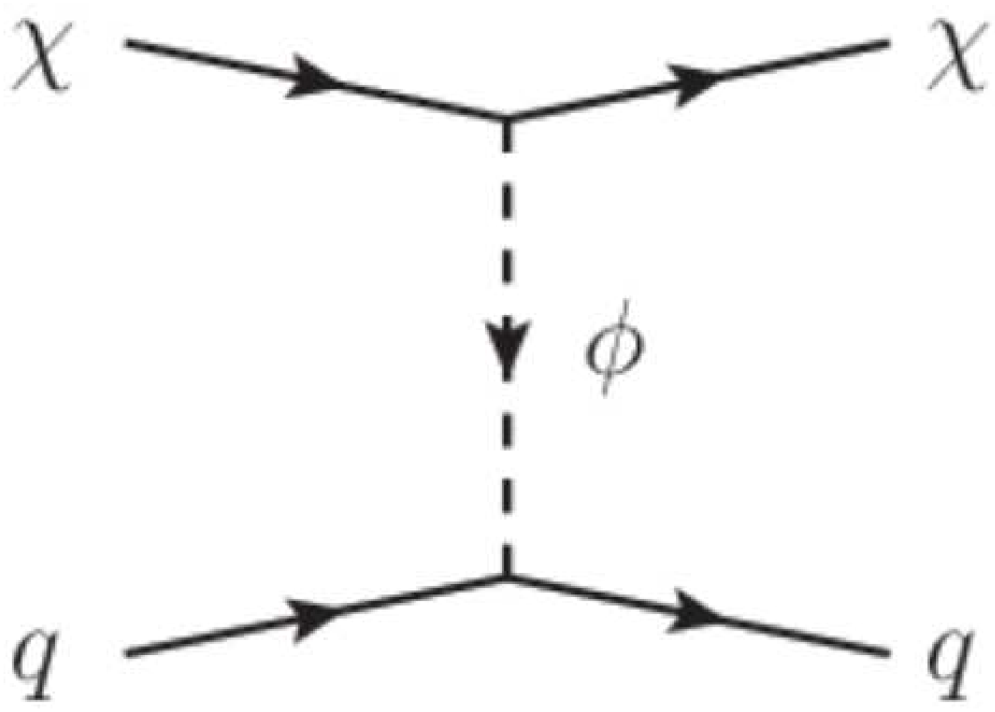
⇒ excess not fitted :-(⇒ DD cuts away the "good points"

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 $M_1 < 0$

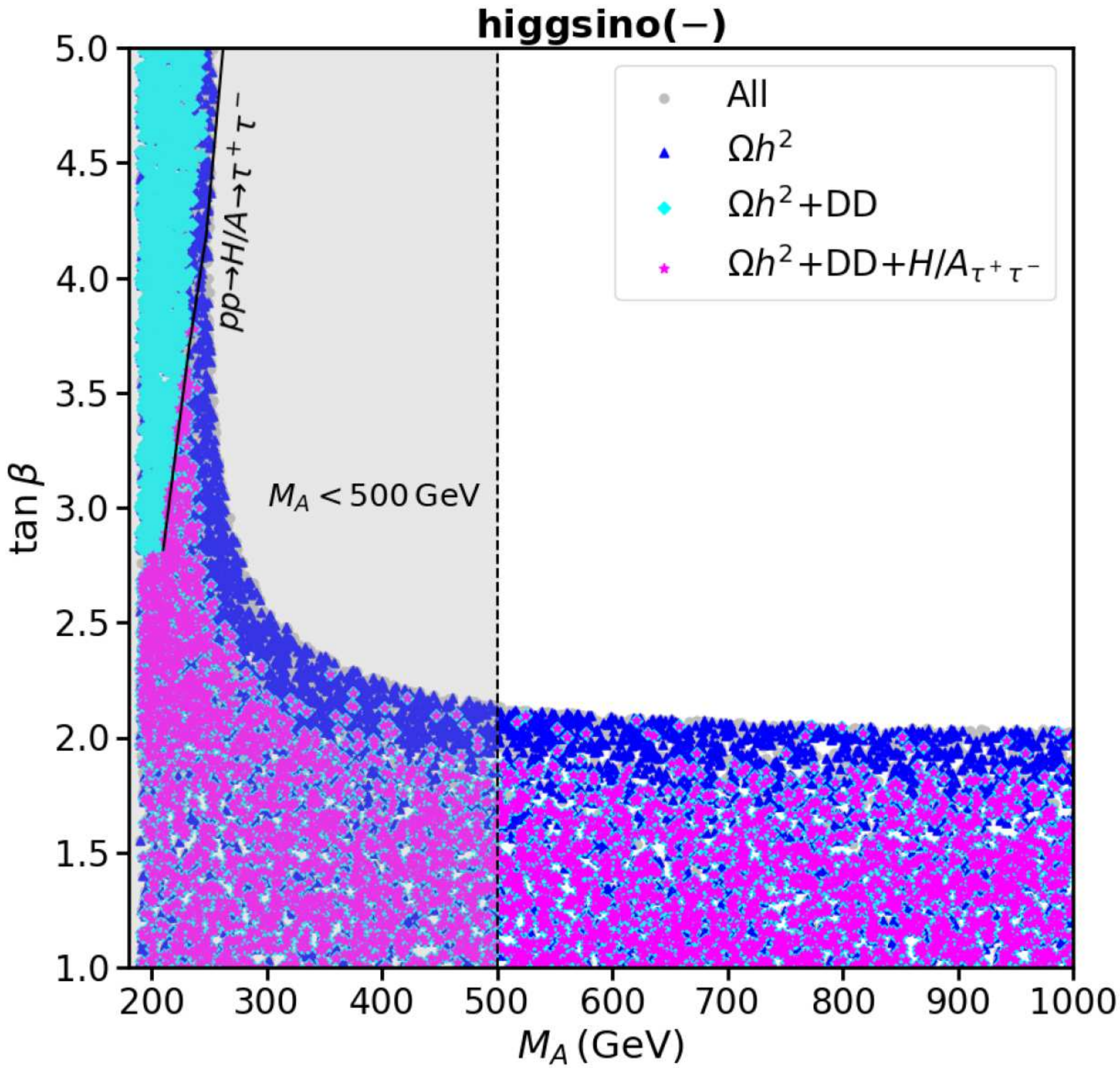
New scan with $M_1 \times \mu < 0$

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

Condition on μ and M_1: exact blind spot conditions

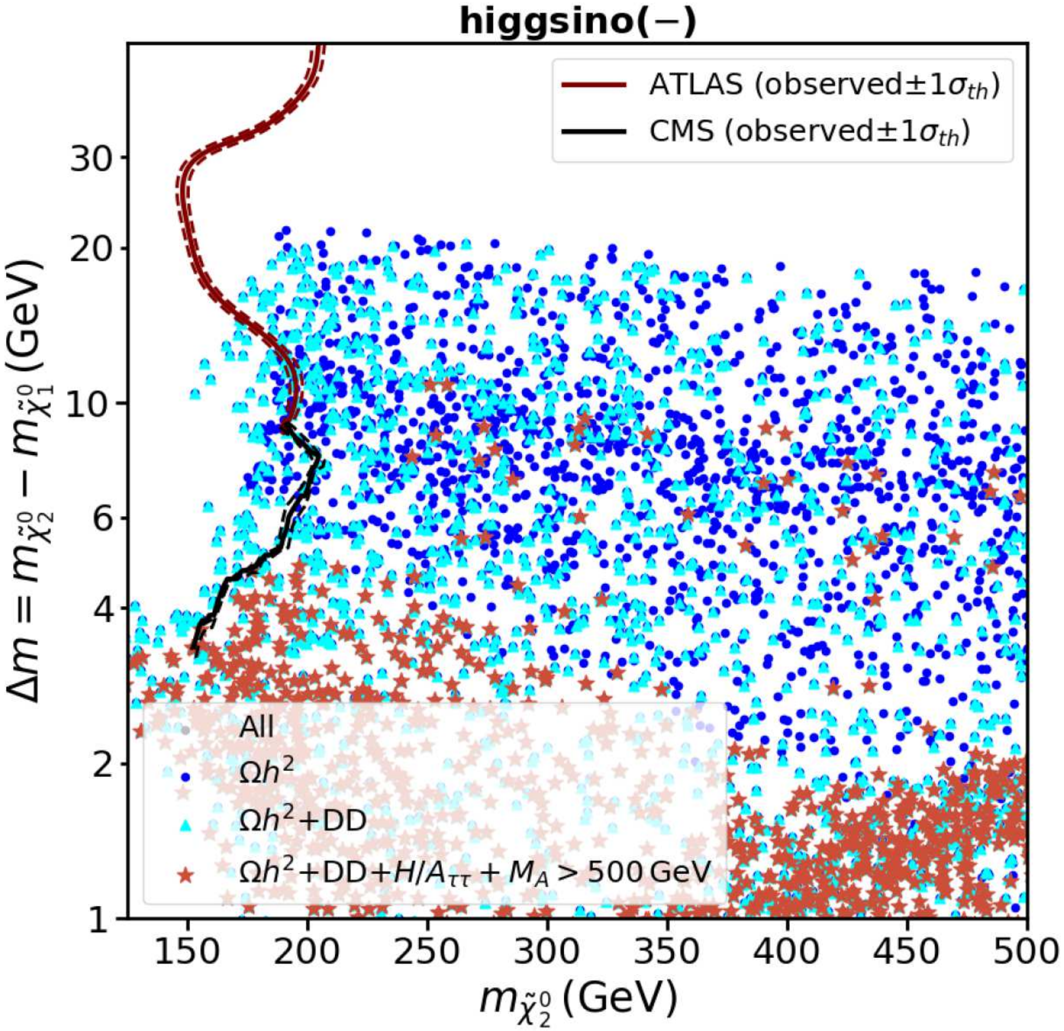
relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

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)

4. Conclusinos

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

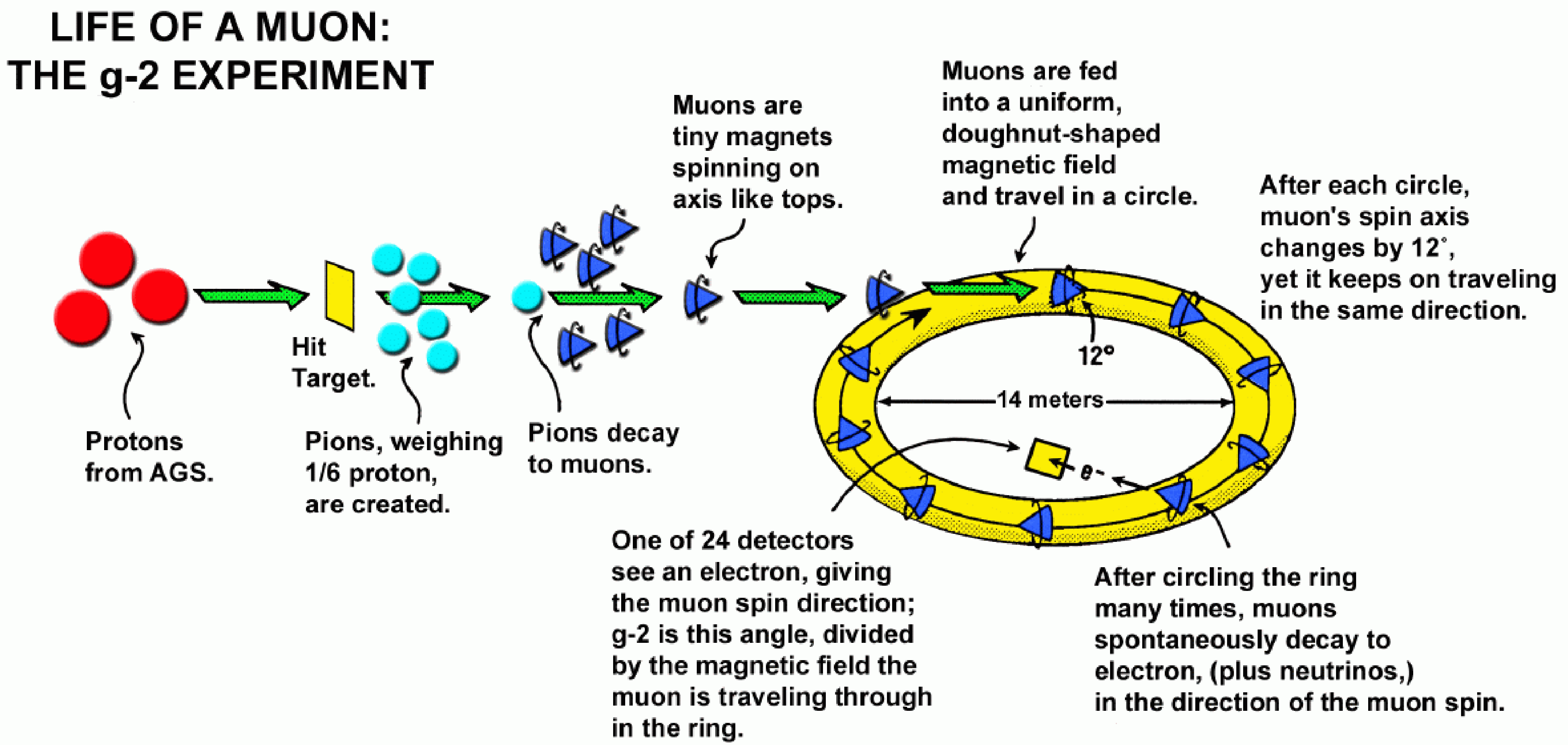
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 Z^* \, \tilde{\chi}_1^0 W^*$
  with $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 250$ GeV, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV

- Best-fit explanation in the MSSM: wino/bino DM with $M_1 \times \mu < 0$

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?

The $(g-2)_\mu$ experiment:

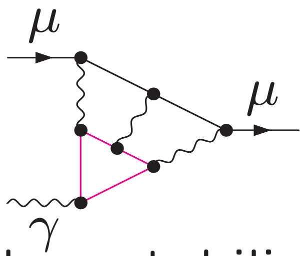


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu}\sigma^{\mu\nu}q_\nu F_2(q^2)\right]u(p)A_\mu \qquad F_2(0) = a_\mu$$

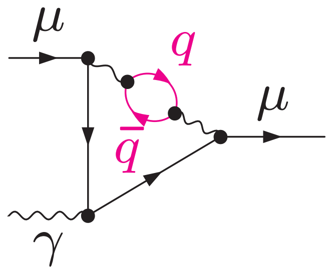
Theory of $(g-2)_\mu$:

– the light-by-light contribution:



2002: sign error discovered; since then stabilized
2021: confirmed by LQCD

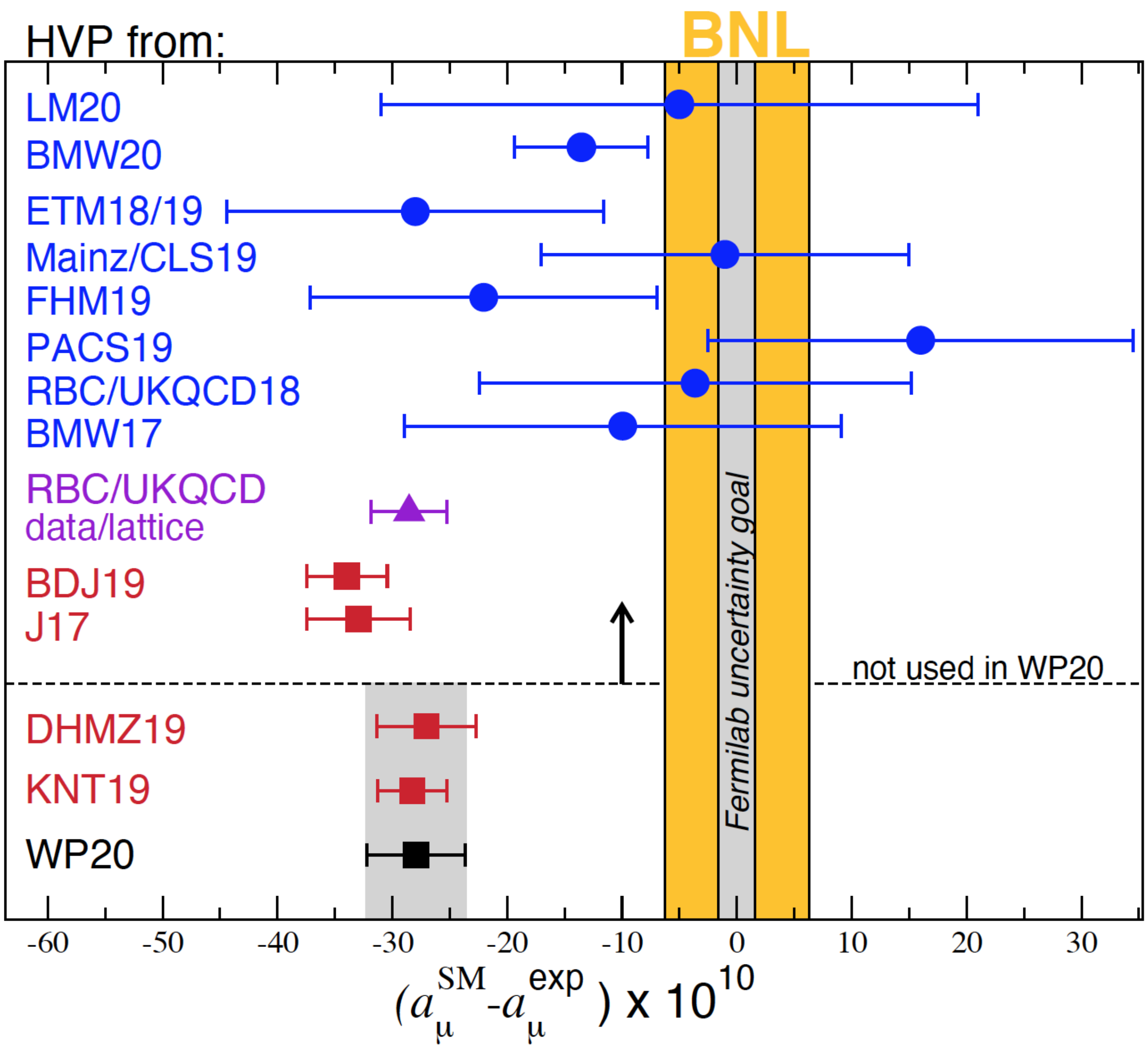
– the hadronic vacuum contribution:



'direct' e^+e^- data:
from CMD-II, SND, KLOE, BaBar (radiative return)
$\Rightarrow$ agree relarively well (also with old e^+e^- data)
$\Rightarrow$ tension with LQCD results

τ data:
tended to be closer to experimental result
inclusion of γ-ρ mixing: agreement with e^+e^- [F. Jegerlehner, R. Szafron '10]
$\Rightarrow$ not used anymore

HVP summary:



$\Rightarrow$ BMW20: difference to experimental data $\sim 1.5\,\sigma$