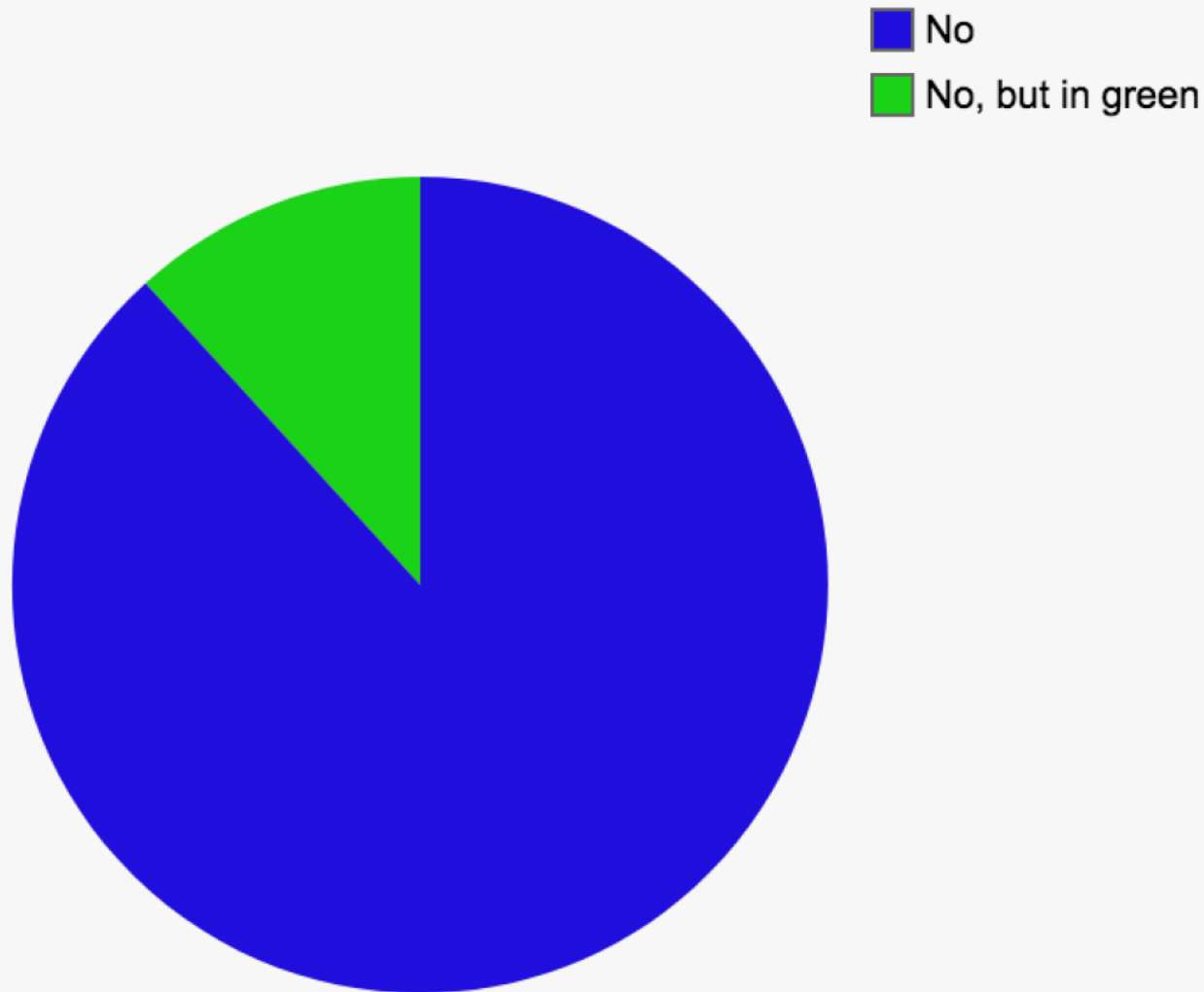


Has the LHC ruled out supersymmetry?



Finally: Dark Matter at the LHC

Sven Heinemeyer, IFT (CSIC, Madrid)

Valencia, 01/2024

1. What connects us?
2. Dark Matter at the LHC
3. Outlook

⇒ some photos
⇒ some physics (with a photo intermezzo)
⇒ some more photos

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germans, who found their home in Spain :-)

1. What connects us?

- not really the physics (well . . .)
⇒ no joint physics papers
 - a similar history . . .
germans, who found their home in Spain :-)
 - Since 14 years: **MultiDark**
(consolider, red consolider, red, . . .) **MultiDark forever :-)**
⇒ joint convenor of the LHC/DM WG
(→ my short physics example)
- ⇒ from our second workshop, June 2010:

From our second workshop, June 2010:

Convenors:

- Mario Gómez
- Martin Hirsch
- S.H.

Topics:

- LFV in SUSY and DM connection
 - DM as a constraint (of SUSY)
 - refined DM calculations within SUSY
 - DM in MSSM extension (NMSSM, cMSSM, ...)
 - seesaw neutrino models and DM implications
 - DM in RPV models
 - neutrinos at the LHC and DM implications
 - neutrinos and alternative DM candidates
 - sneutrino DM and the LHC
 - DM and mass measurements at the LHC
- ⇒ discussion at this workshop!

Photos: a sad story ...

⇒ very difficult to find photos with Martin
(at least for me)

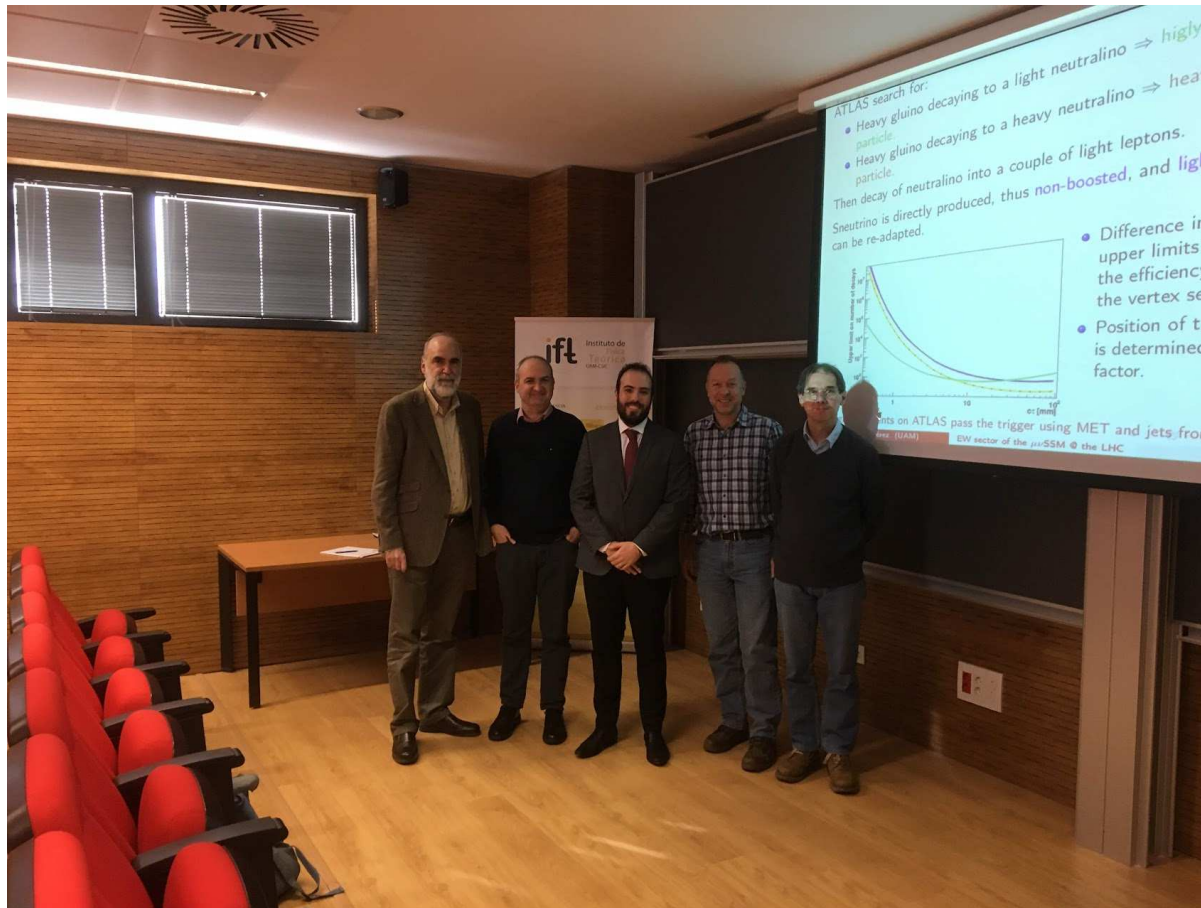
⇒ seems Martin is working (in his office) all the time ;-)

Photos: a sad story ...

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First photo I found: PhD defense 2019



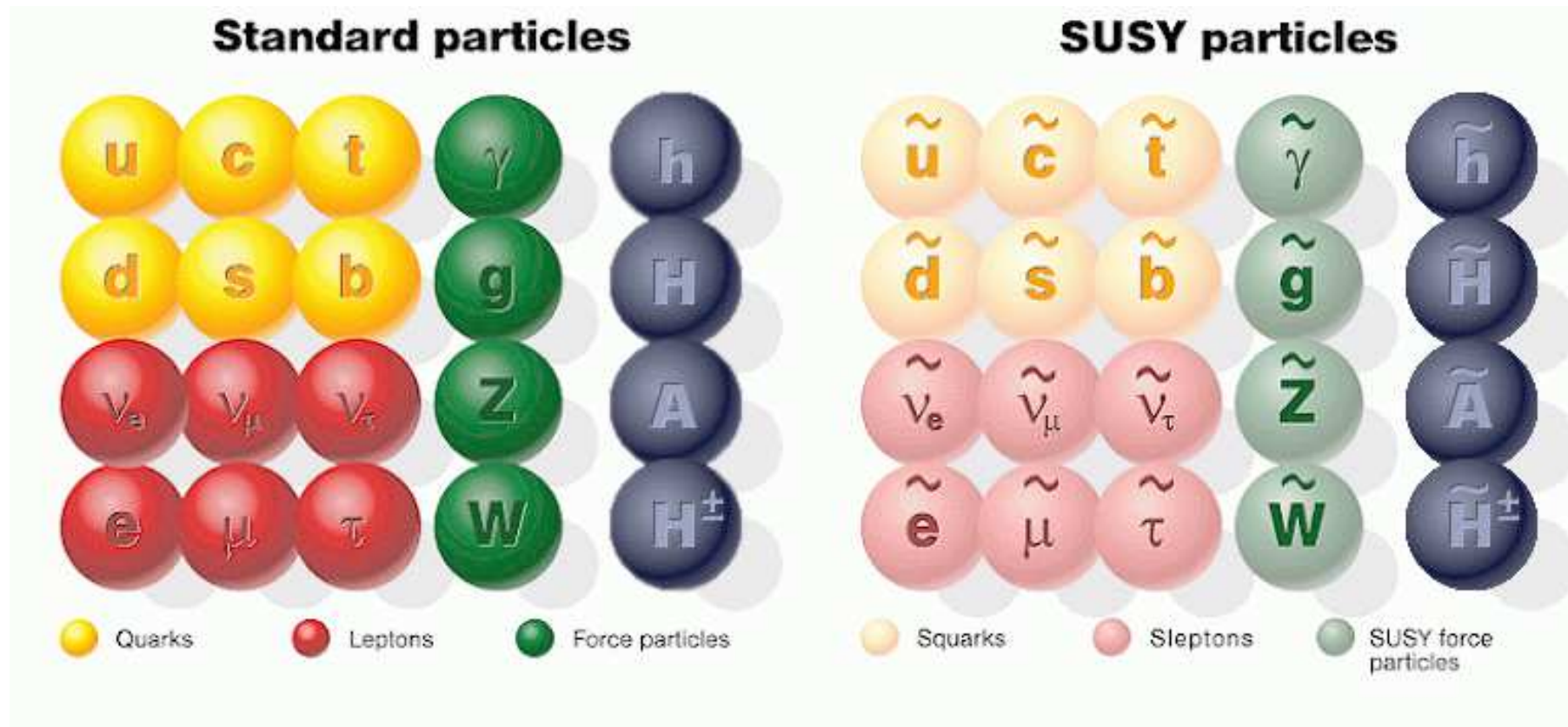
One more pre-pandemic: MultiDark WS Huelva 2019:



⇒ did he anticipate what was coming?

2. Dark Matter at the LHC

- outcome of our MultiDark WG?! :-)
- no surprize: **SUSY DM**



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

relic DM density 100% fulfilled

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

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

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

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 $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$)

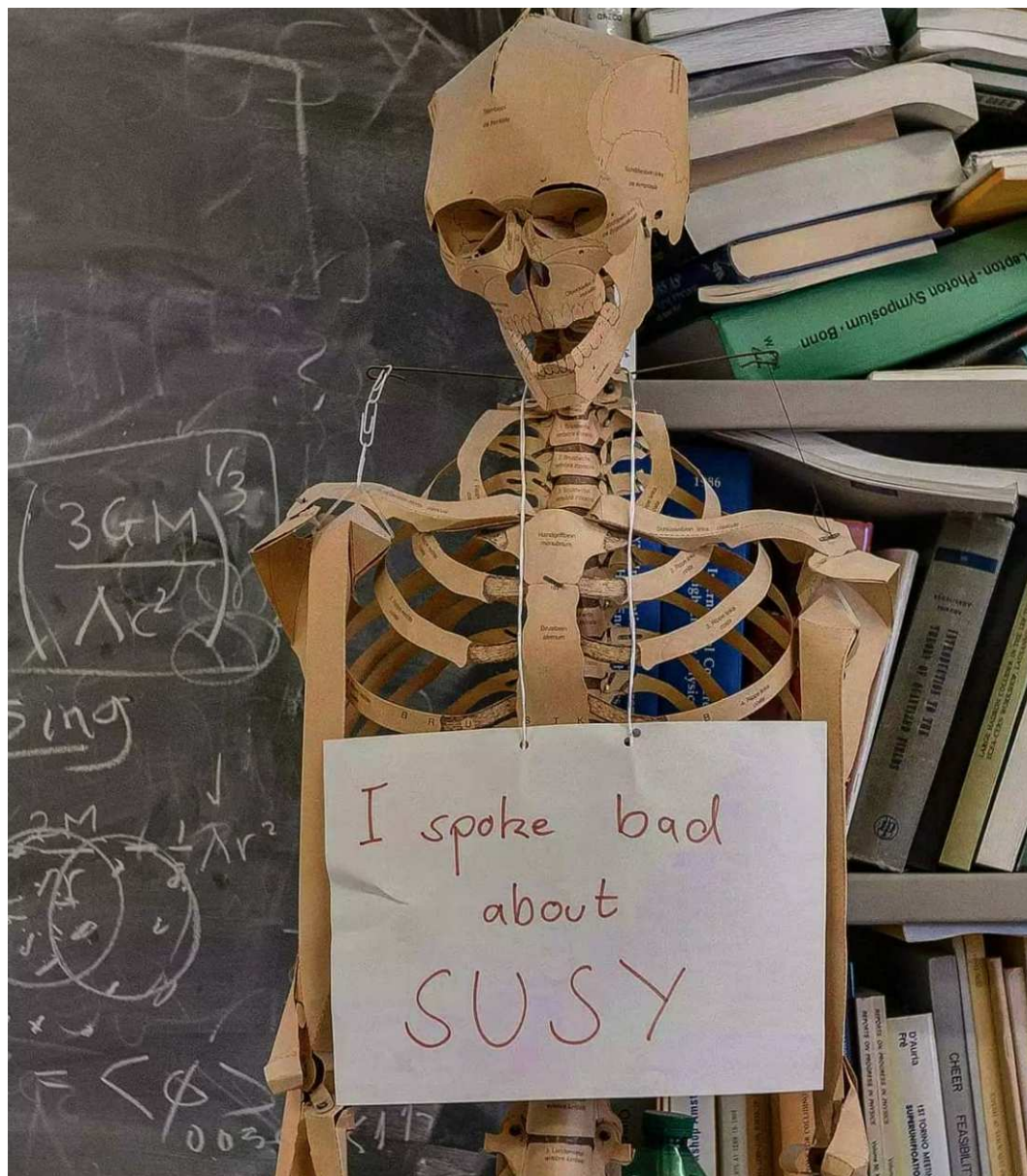
$\Rightarrow m_{(N)\text{LSP}} \lesssim 500 \text{ GeV}$

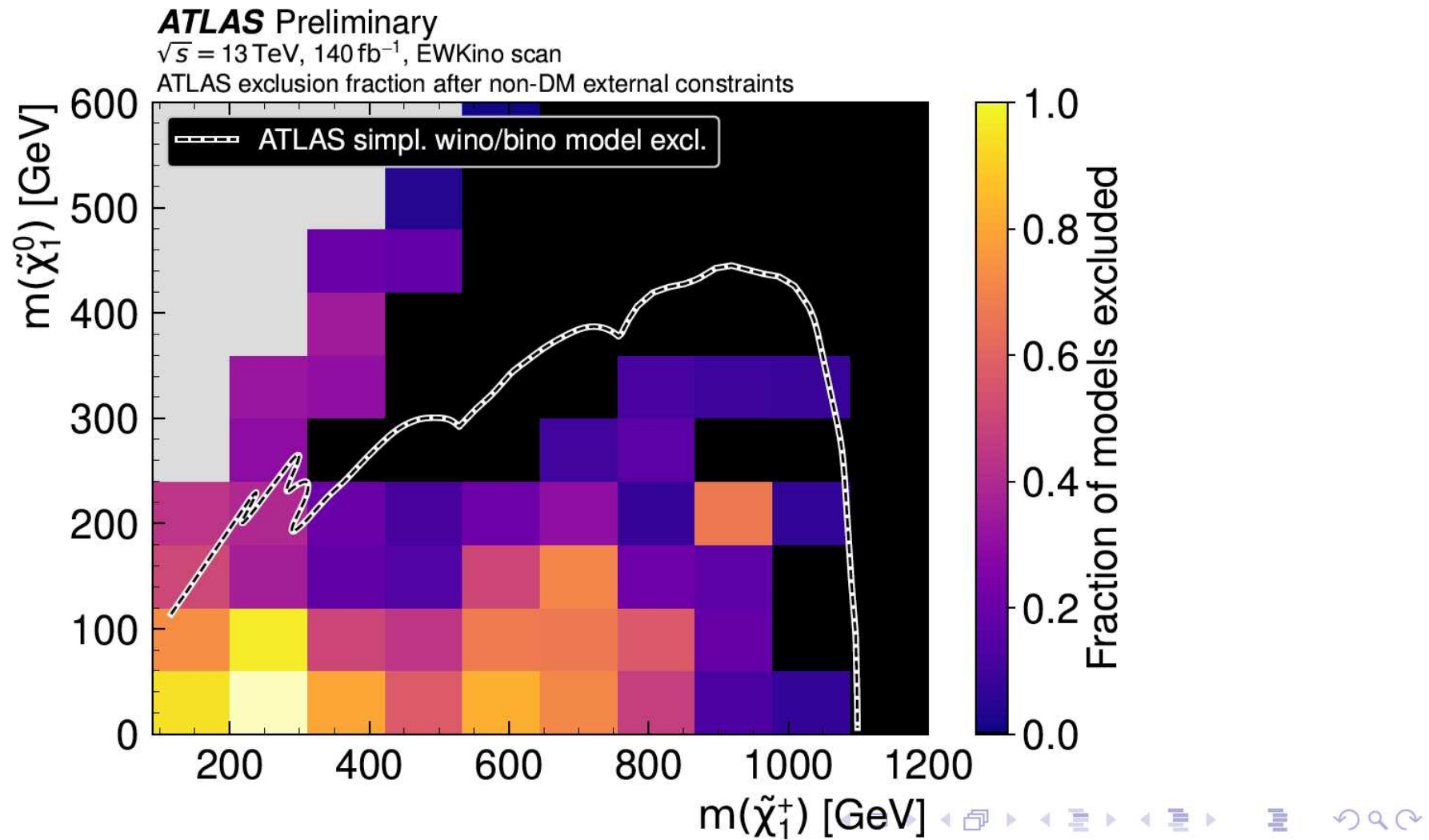
E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$ ($M_2 \lesssim M_1, \mu$)

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

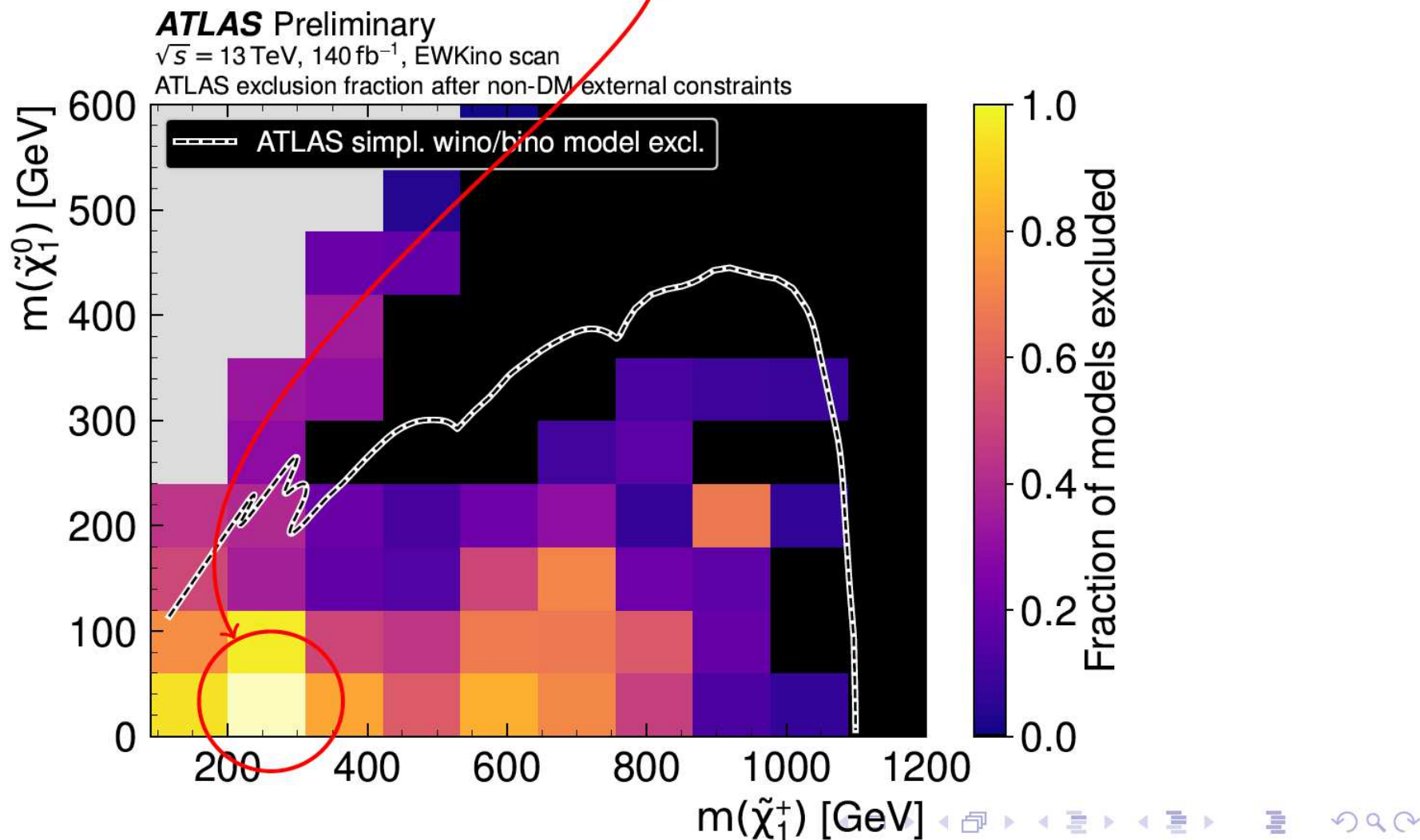
$\Rightarrow m_{(N)\text{LSP}} \lesssim 600 \text{ GeV}$

Evidence for low-energy SUSY (incl. DM)?!





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:

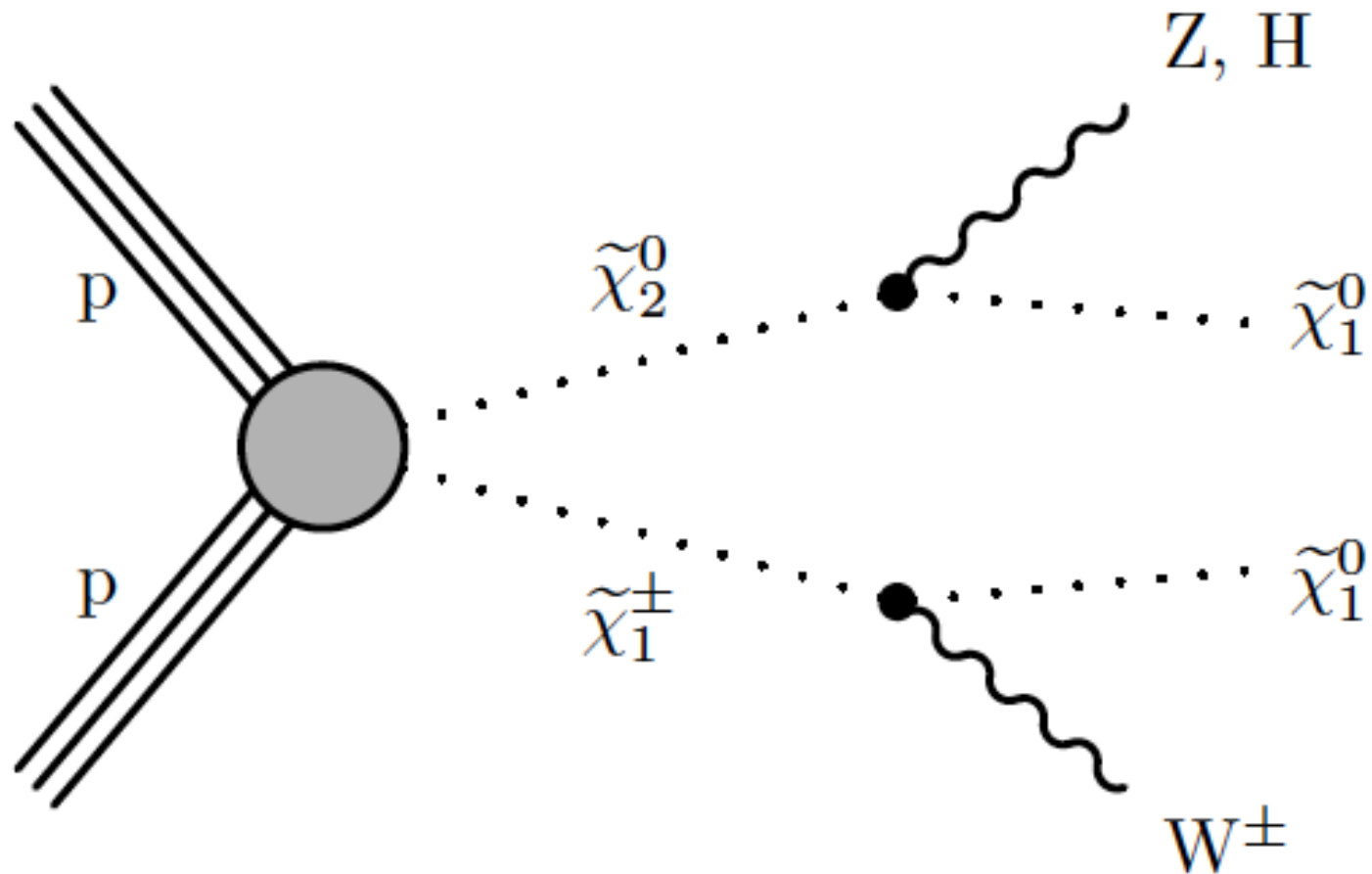
- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

⇒ 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

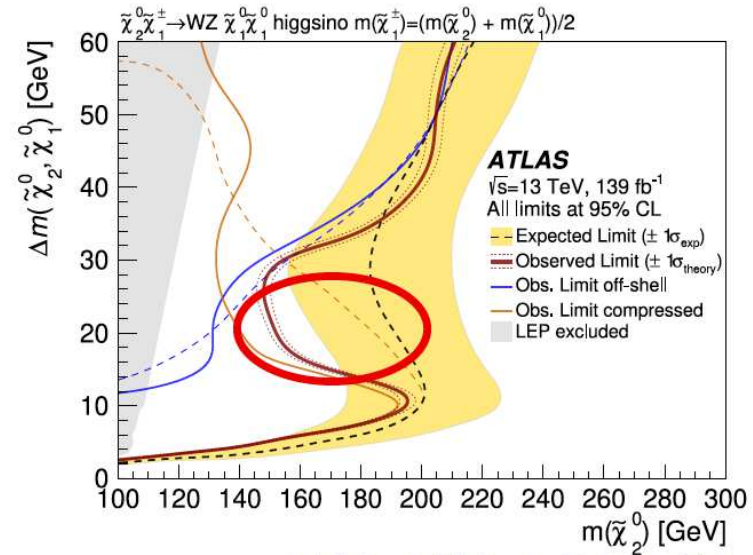
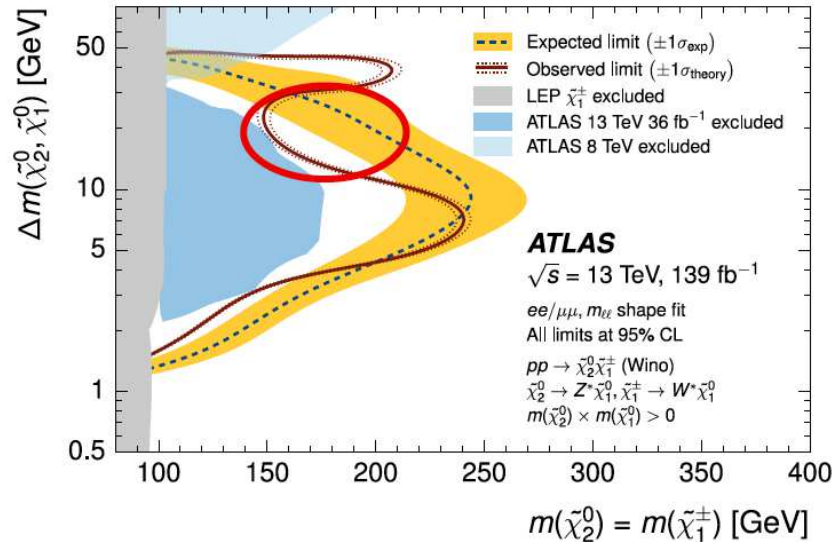
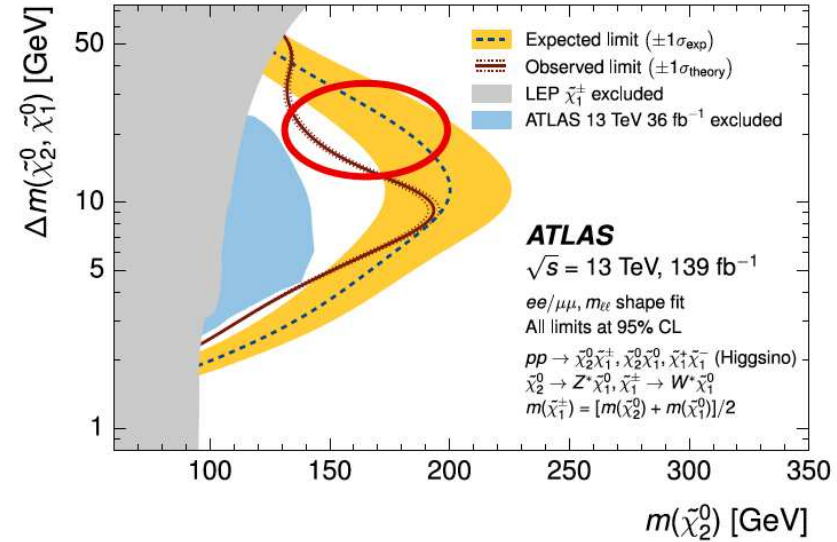
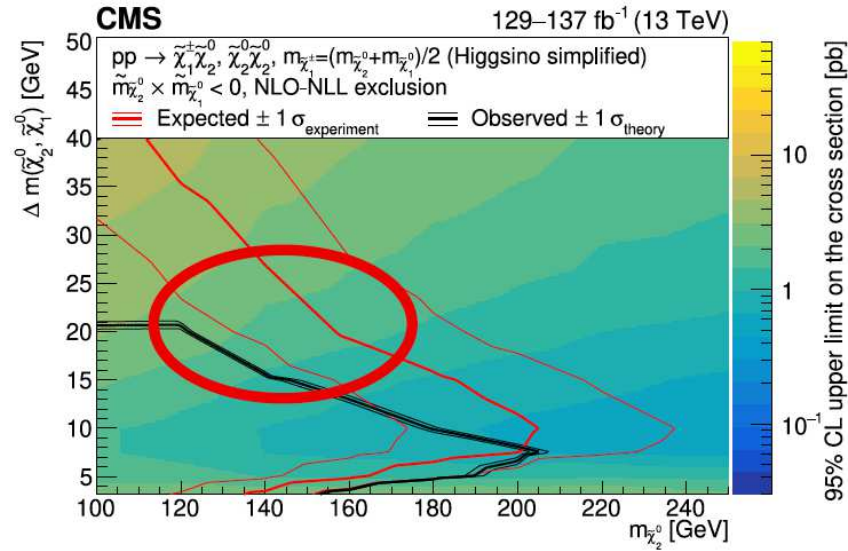
Golden mode at the LHC:



⇒ experimental results?

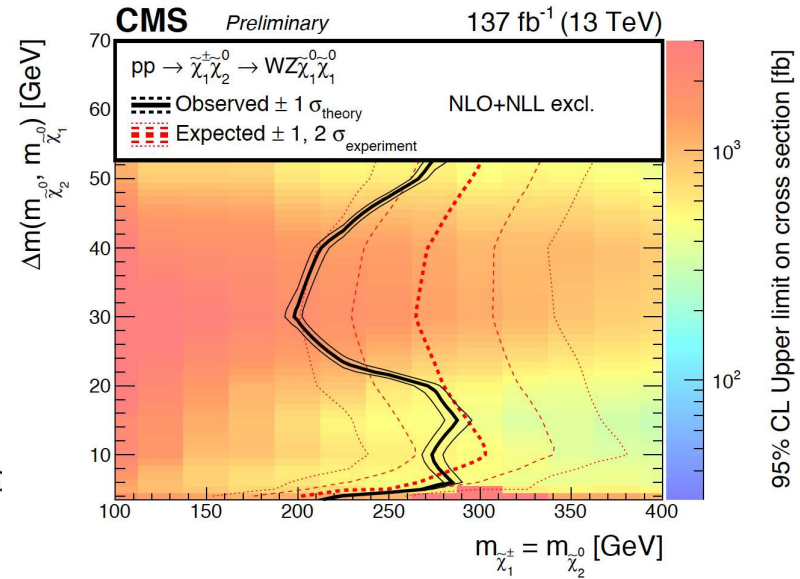
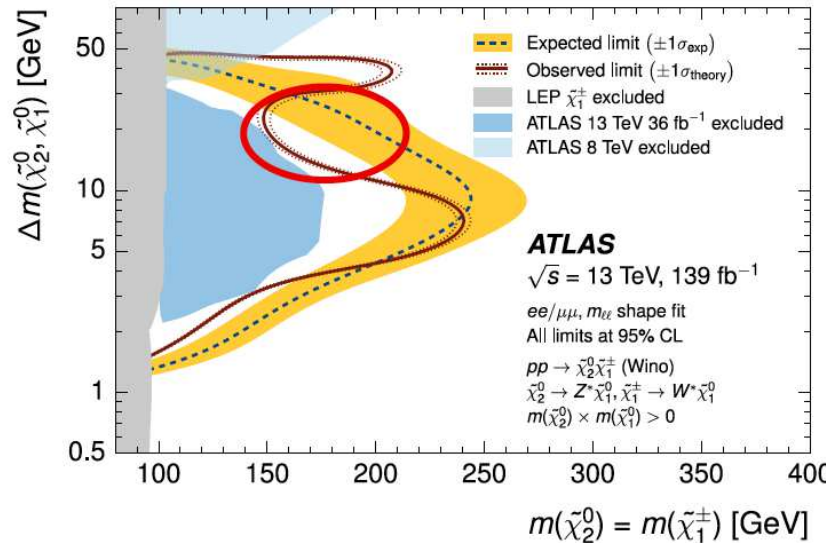
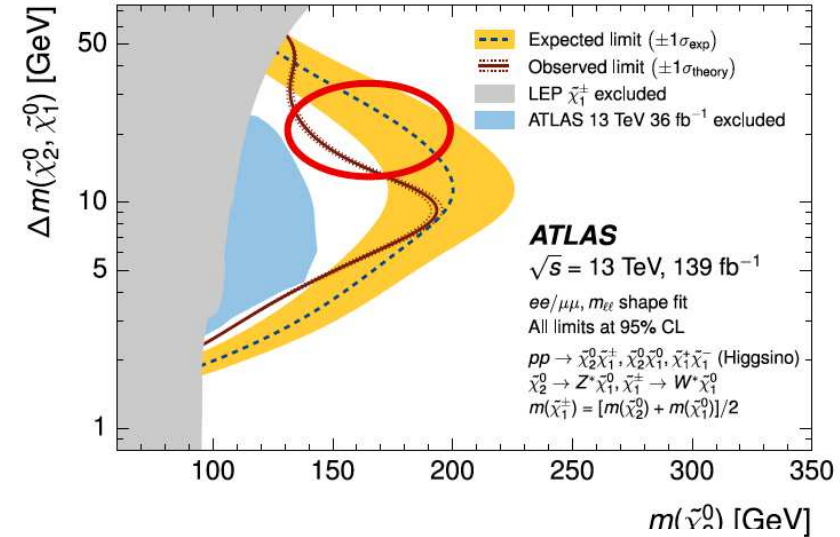
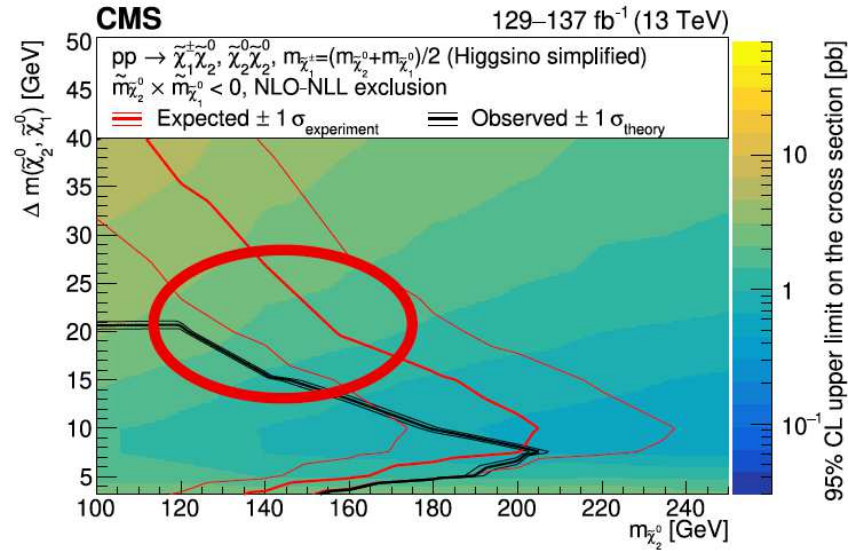
Results: “compressed” spectra w/ heavy sleptons:

[taken from M. Berggren '23]



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

relic DM density 100% fulfilled

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

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 $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$)

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

$\Rightarrow$ can they fit the excesses?

$\Rightarrow$ but first a short pandemic intermezzo!

Pandemic intermezzo: MultiDark WS 2021 (La Rabida)



⇒ but can we be sure it is him? With the mask...?

Pandemic intermezzo: MultiDark WS 2021 (La Rabida)



⇒ yes ... ;-)

Pandemic intermezzo: MultiDark WS 2021 (La Rabida)



⇒ only photo with Martin working at a workshop ...

Pandemic intermezzo: MultiDark WS 2021 (La Rabida)



⇒ funny hair day :-)

Example for a result:

A) Bino/wino DM with chargino co-annihilation

with $\mu \times M_1 < 0$

Parameter scan:

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

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

$$1.2|M_1| \leq \mu \leq 2 \text{ TeV} ,$$

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

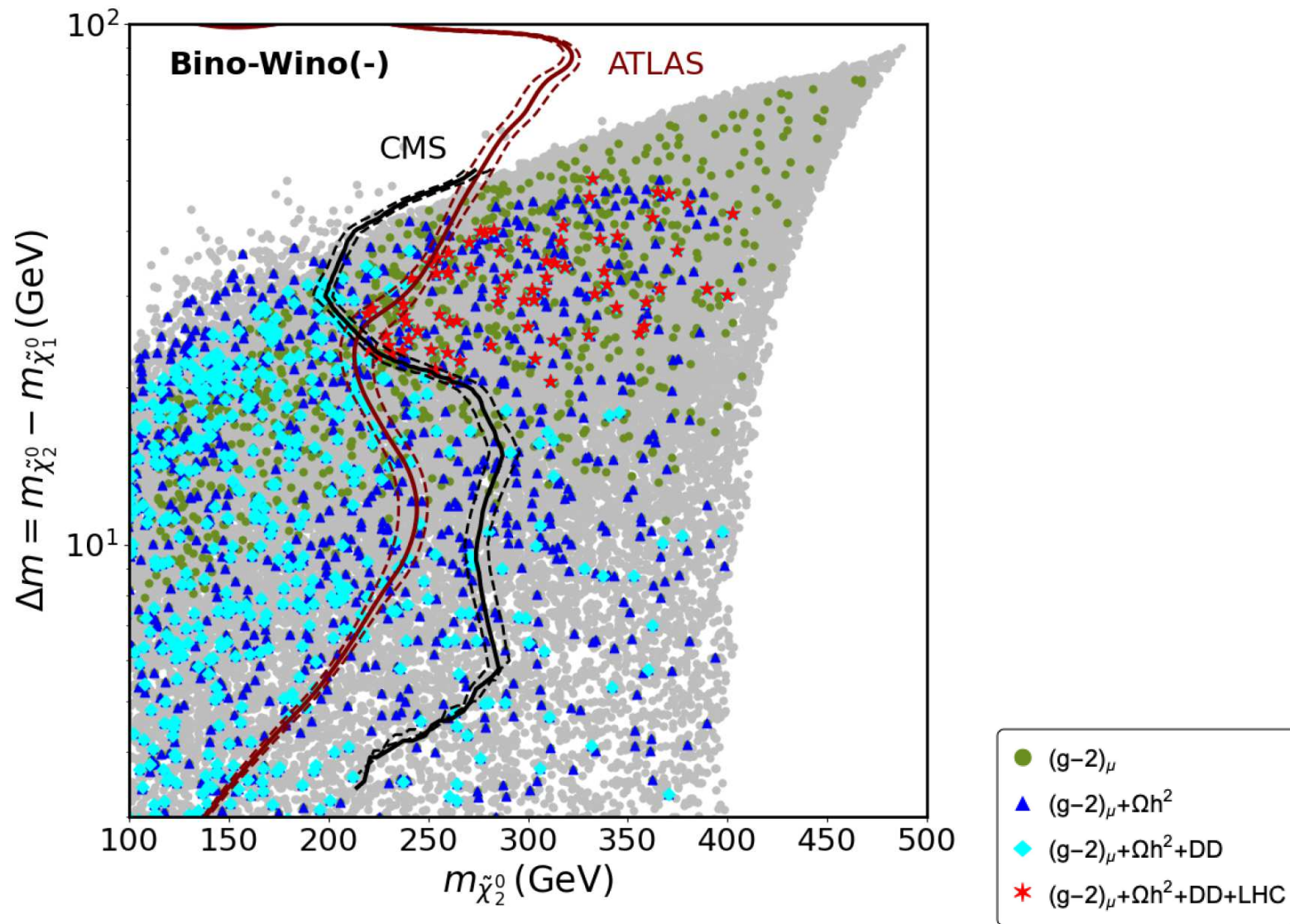
$$|M_1| \leq m_{\tilde{L}} = m_{\tilde{R}} \leq 1.5 \text{ TeV} ,$$

$$190 \text{ GeV} \leq M_A \leq 3 \text{ TeV} .$$

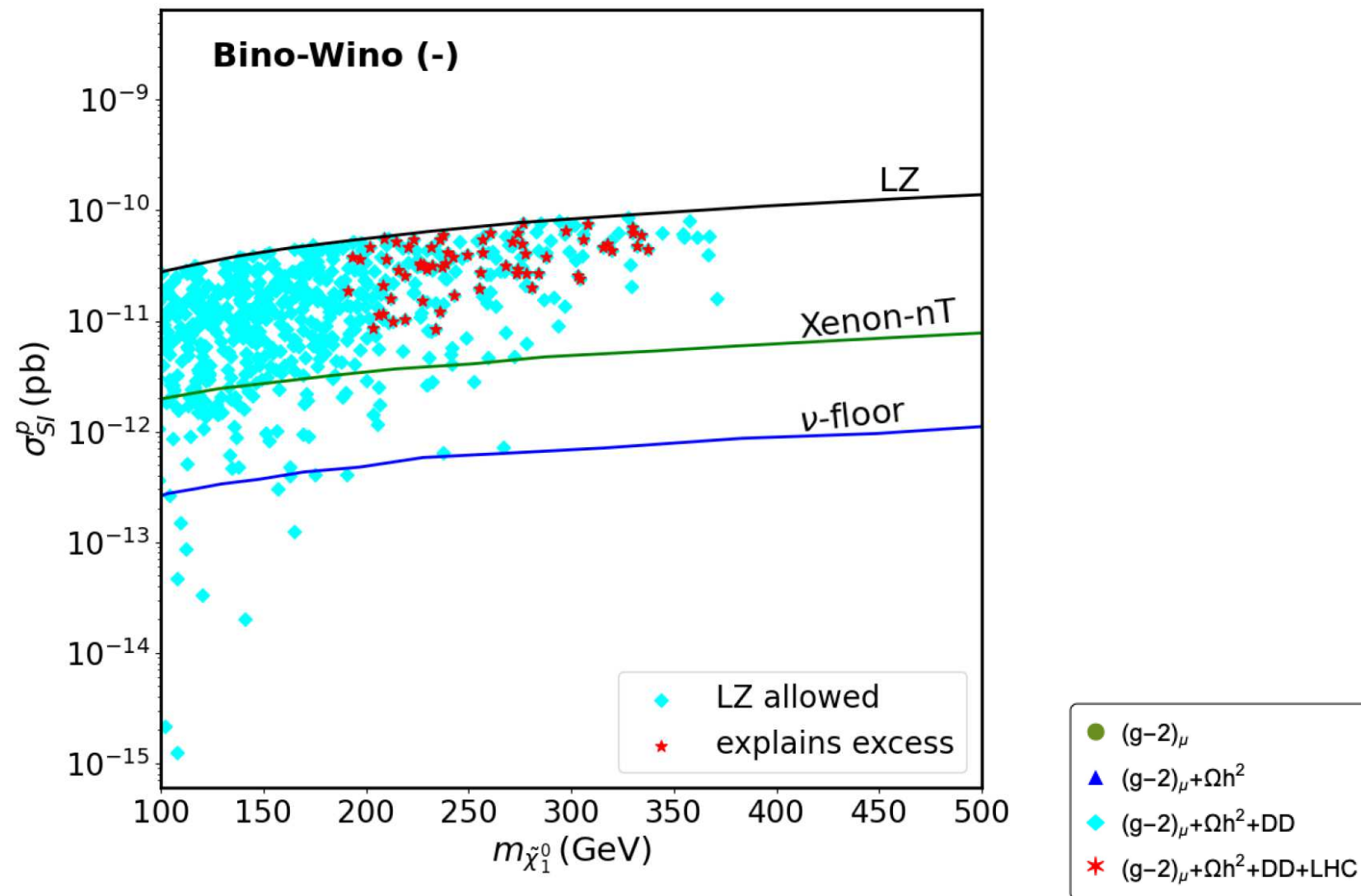
relic DM density can be 100% fulfilled

$\mu \times M_1 < 0$ could help with the Direct Detection constraints ...

... but no!



⇒ compatible excesses nicely covered by theory predictions



$\Rightarrow$ excess region will be covered by XENON-nT/LZ

3. Outlook: SUSY conferences

Finally, 2023, I met Martin at a SUSY conference:



And I hope to see you here as well!



SUSY 2024

Theory meets Experiment

Madrid, 10 – 14 June 2024
Pre-SUSY school: 3 – 7 June 2024

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María Cepeda	Luis Ibáñez (co-chair)	



Happy 60th birthday! Cheers!





Further Questions?