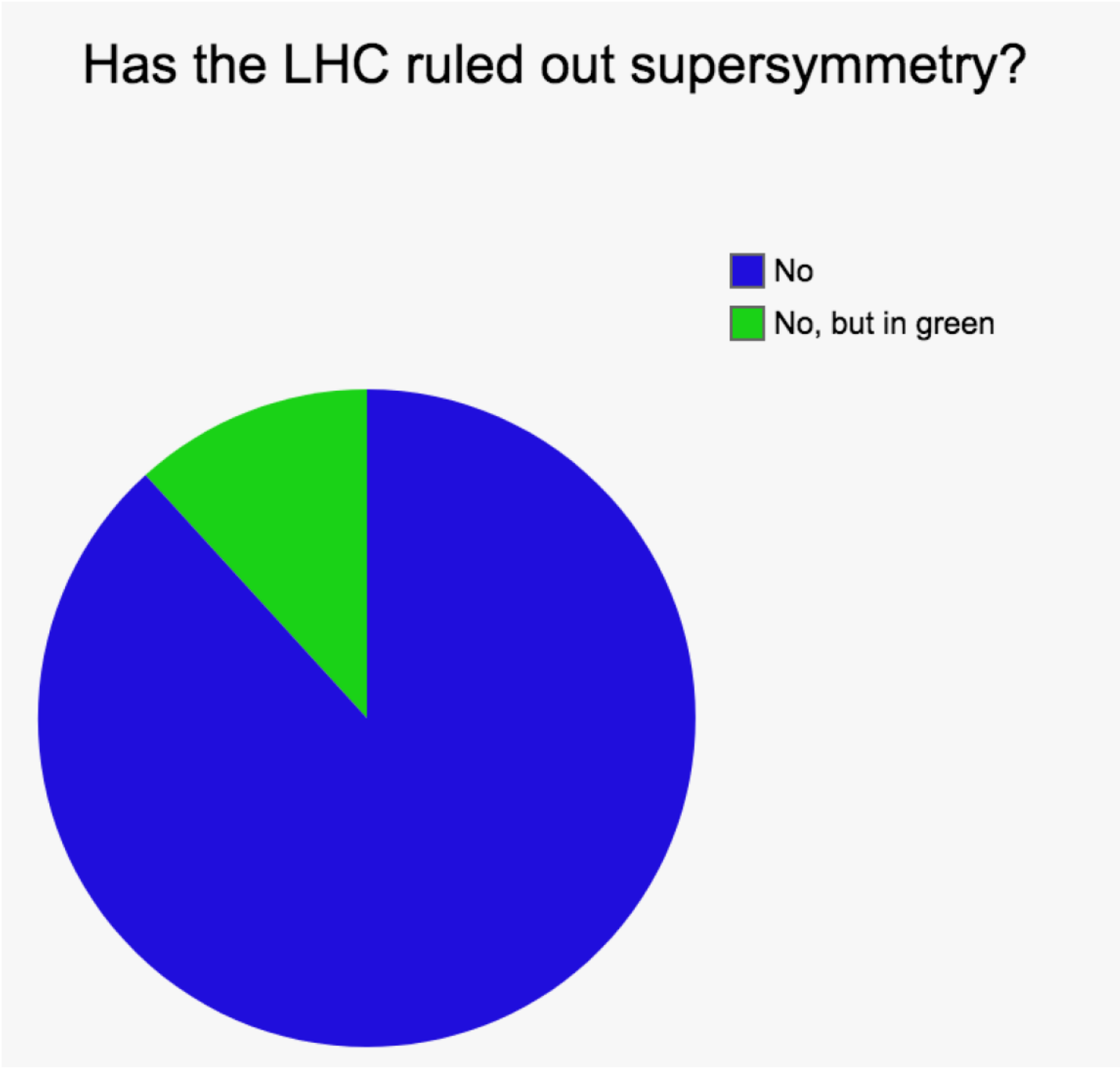

Has the LHC ruled out supersymmetry?
No
No, but in green

SUSY 2024

Theory meets Experiment

Madrid, 10 – 14 June 2024

Pre-SUSY school: 3 – 7 June 2024

International Advisory Committee

Ignatios Antoniadis
Csaba Balazs
Marcela Carena
Mirjam Cvetic
Athanasios Dedes
Keith Dienes
Herbert Dreiner
Bhaskar Dutta
John Ellis
Jonathan L. Feng
Gian F. Giudice
Monoranjan Guchait
John F. Gunion
Kaoru Hagiwara
Tao Han
Gordon L. Kane
Dimitri Kazakov
Steve King
Pyungwon Ko
Paul G. Langacker
Tianjun Li
Joseph D. Lykken
Mario Martinez
Rabindra N. Mohapatra
Stefano Moretti
Pran Nath
Apostolos Pilaftsis
Fernando Quevedo
Mariano Quirós
Barbara Szczerbinska

Local Organizing Committee

Ernesto Arganda
Pepe Barbón
Guillermo Ballesteros
María Cepeda
David Cerdeño
Begoña de la Cruz
Sven Heinemeyer (chair)
Luis Ibáñez (co-chair)
Sachiko Kuroyanagi
Luca Merlo
Jesús Moreno

DM and Collider Probes

Sven Heinemeyer, IFT (CSIC, Madrid)

Madrid, 11/2023

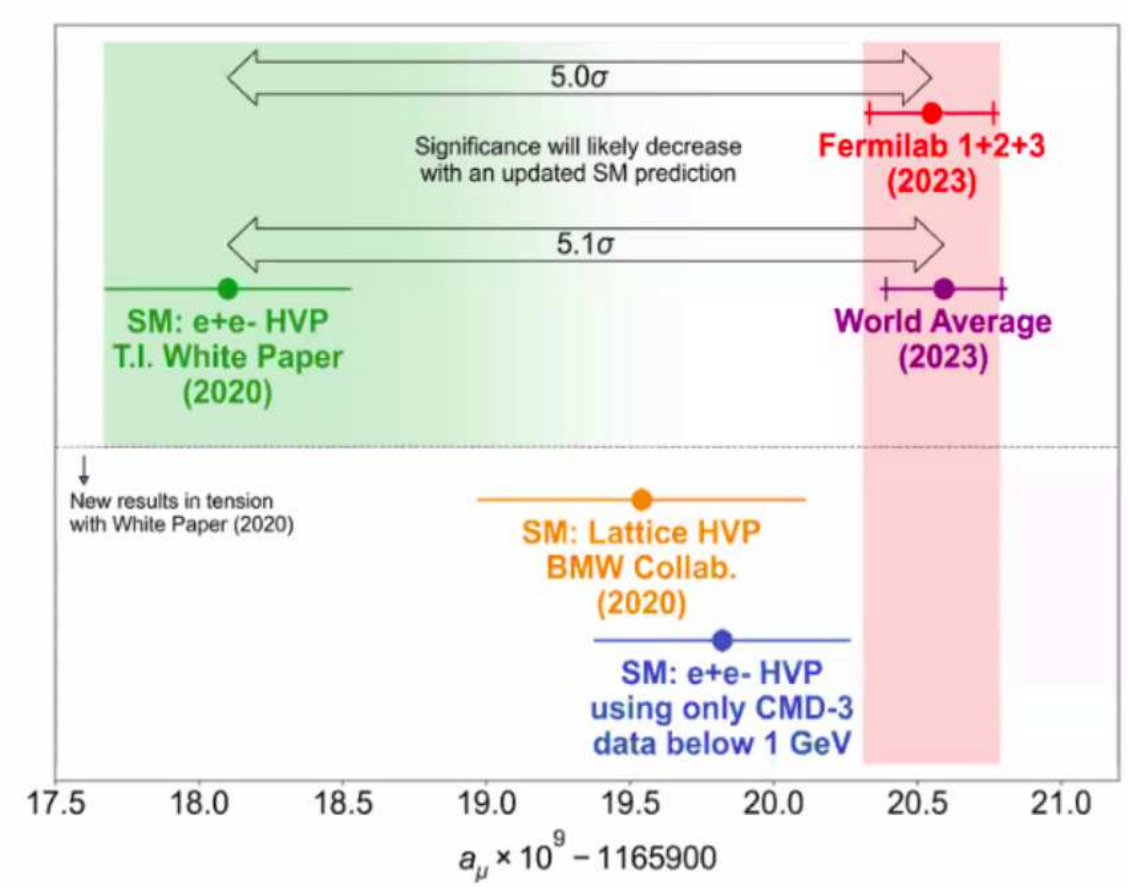
In collaboration with: *Manimala Chakraborti, Ipsita Saha*

1. The main idea
2. Evidence for low-energy SUSY?!
3. What we can say so far . . .
4. Outlook

1. The main idea

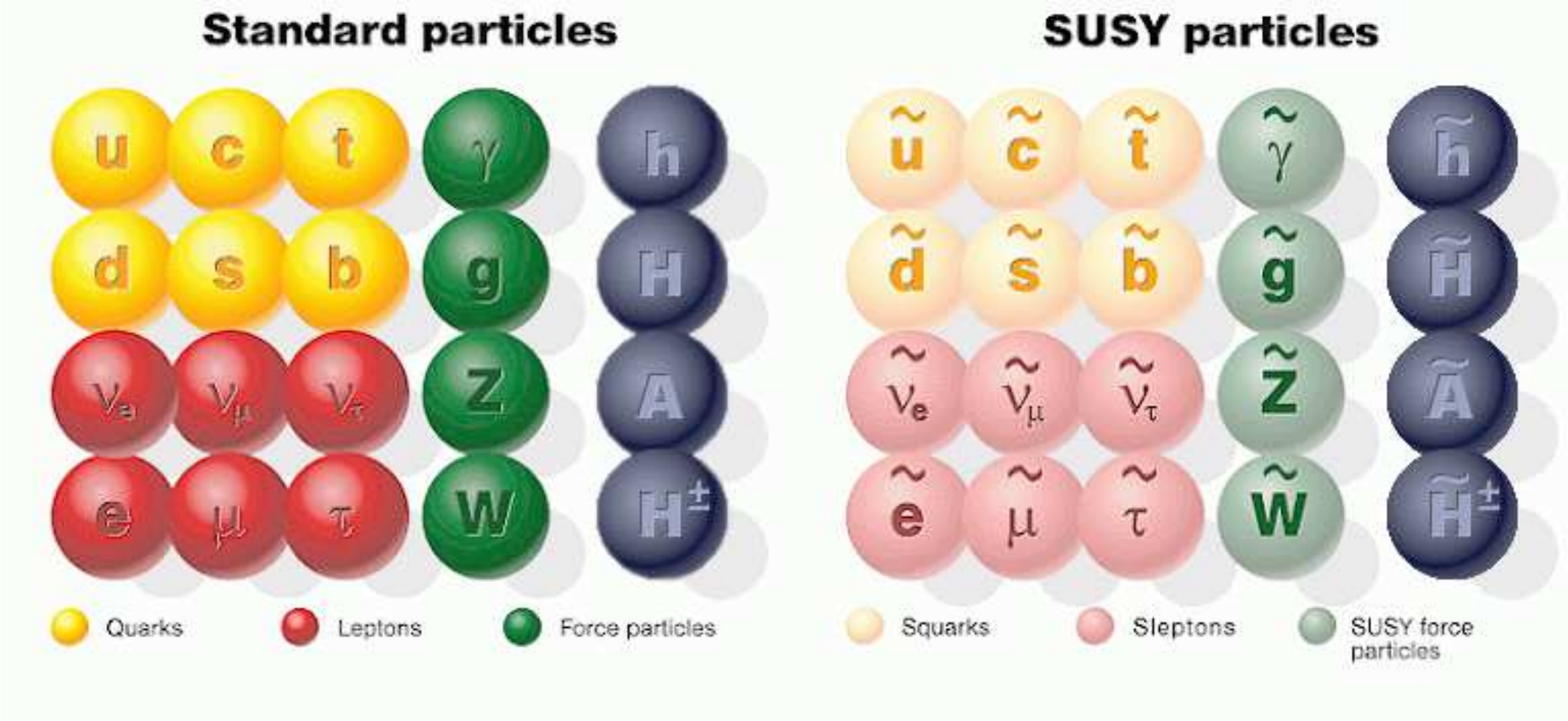
The anomalous magnetic moment of the muon: $a_\mu \equiv (g-2)_\mu/2$

Overview about the current experimental and SM (theory) result:



$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (24.9 \pm 4.8) \times 10^{-10} \;\; : 5.1\,\sigma$ ($\lesssim 2\,\sigma$ for BWM)

The MSSM



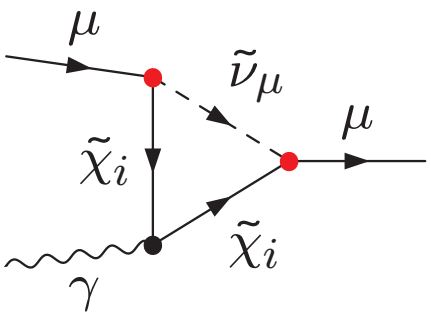
$\Rightarrow$ large uncolored / EW sector

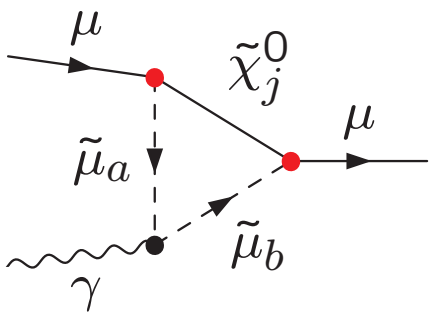
charginos/neutralinos: M_1, M_2, μ, $\tan\beta$

Sleptons: $M_{\tilde{l}_L}$, $M_{\tilde{l}_R}$ (equal for all 3 generations, or different 1.2. vs. 3.)

SUSY can easily explain the 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: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

The main idea:

- scan the relevant EW SUSY parameter space

- impose all relevant experimental constraints:
  - $(g-2)_\mu$
  - Dark Matter relic density
  - Dark Matter direct detection
  - LHC searches for EW particles

- Dark Matter relic density requires a mechanism to reduce the density in the early universe
  - bino/wino DM with chargino co-annihilation
  - bino DM with slepton co-annihilation
  - higgsino DM
  - wino DM

- obtain lower and upper limits on the various EW particle masses

- evaluate the prospects for future searches: DD and (HL-)LHC

$(g-2)_\mu$ constraint: (GM2Calc)

$$\text{old: } \Delta a_\mu^{\text{old}} = (25.1 \pm 5.9) \times 10^{-10}$$
$$\text{new: } \Delta a_\mu^{\text{new}} = (24.9 \pm 4.8) \times 10^{-10}$$

$\Rightarrow$ all results for $\Delta a_\mu^{\text{old}} (\equiv \Delta a_\mu)$

Dark Matter relic density: MicrOmegas

$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\text{or} \quad \Omega_{\text{CDM}} h^2 \leq 0.122$$

(as taken from [*Planck '18*])

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)

[*Xenon collab. '18*] $\Rightarrow$ LZ update yield no qualitative change

Results for (nearly) all SUSY scenarios

A) bino/wino 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)

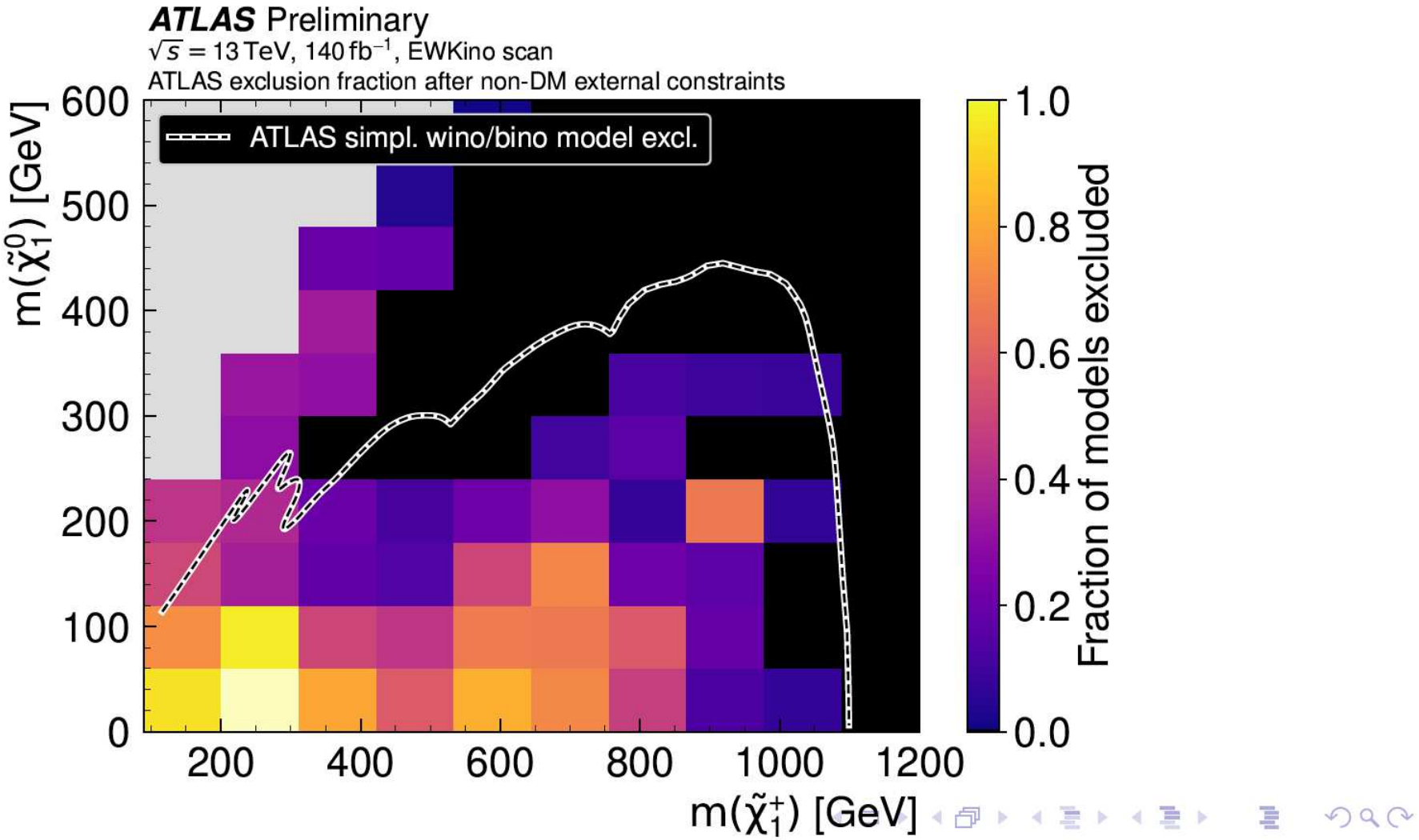
$\Rightarrow m_{\text{(N)LSP}} \lesssim 600$ GeV

$\Rightarrow$ all scenarios can be covered by DD $\oplus \sim 1000$ GeV e^+e^- collider!

2. Evidence for low-energy SUSY?!

What have the LHC searches excluded?

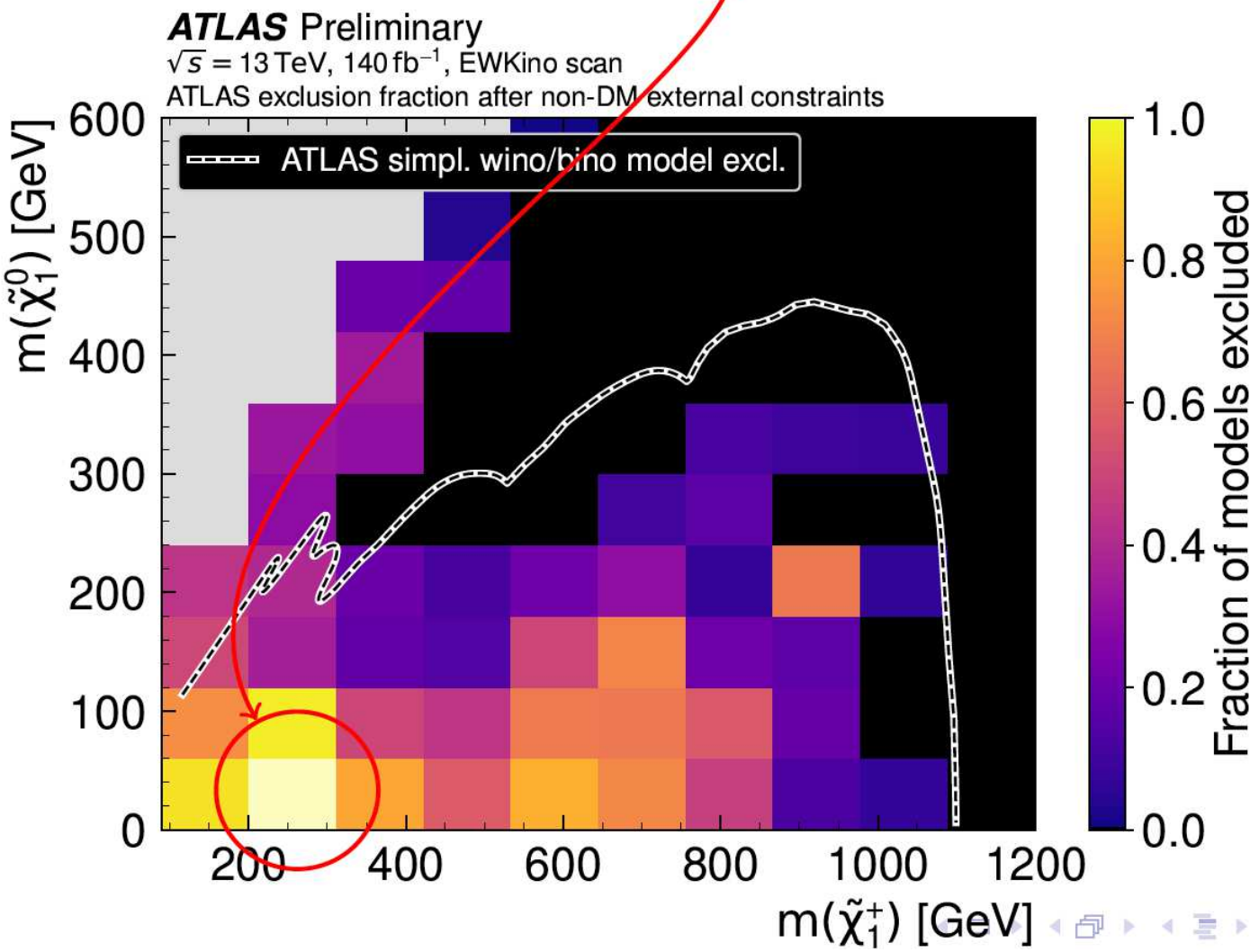
[taken from M. Berggren '23]



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:

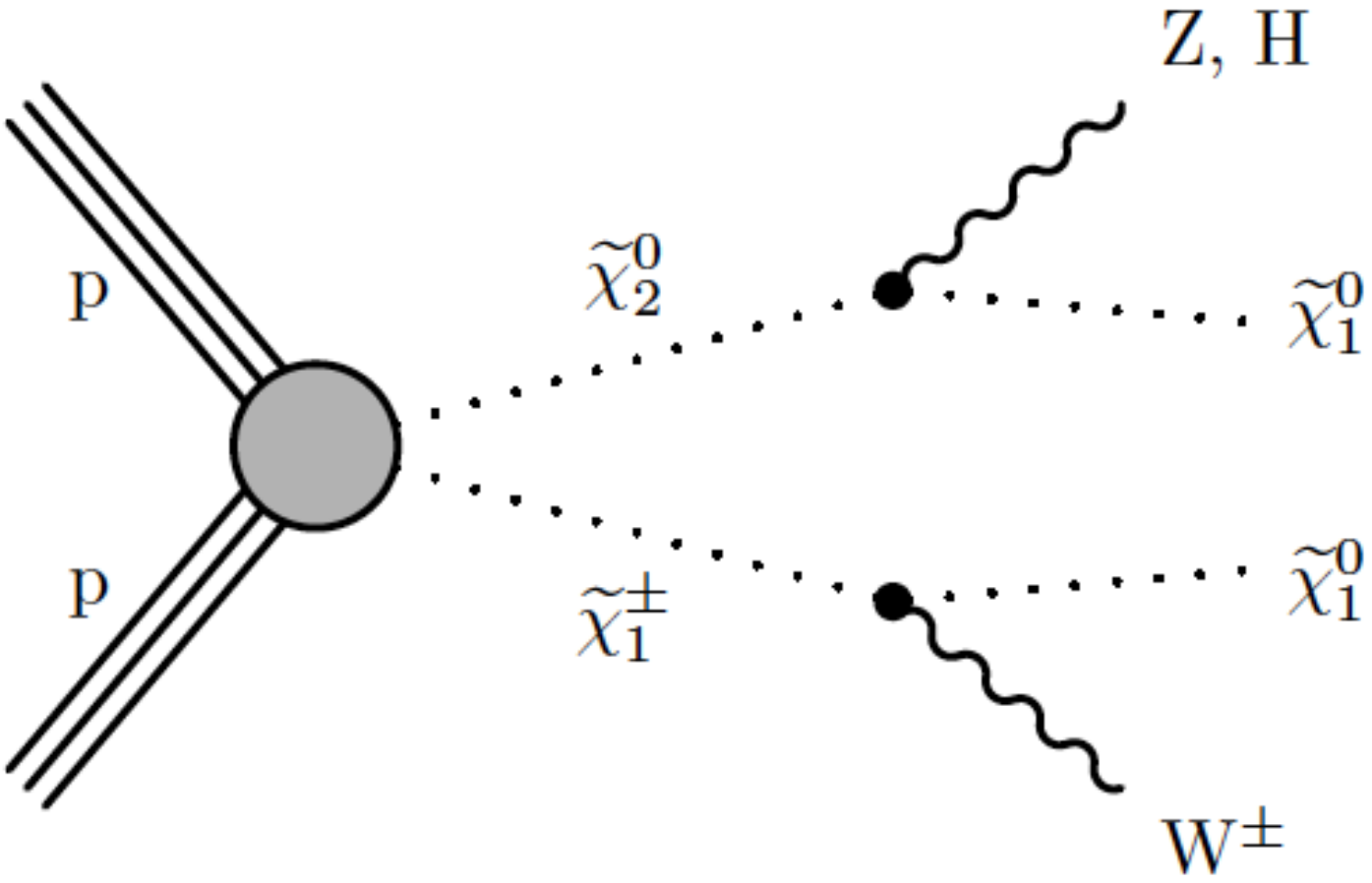
- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

$\Rightarrow$ only one of these can be realized

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

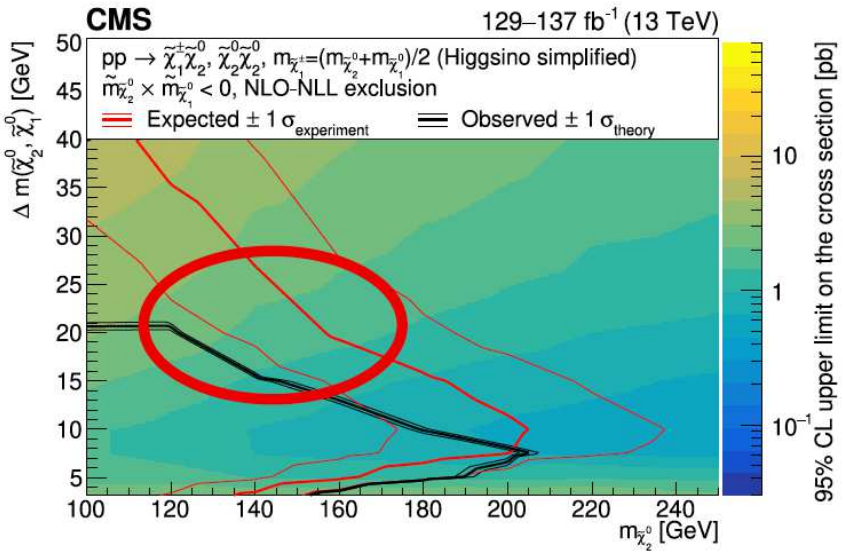
⇒ Our "models" predict low chargino/neutralino masses

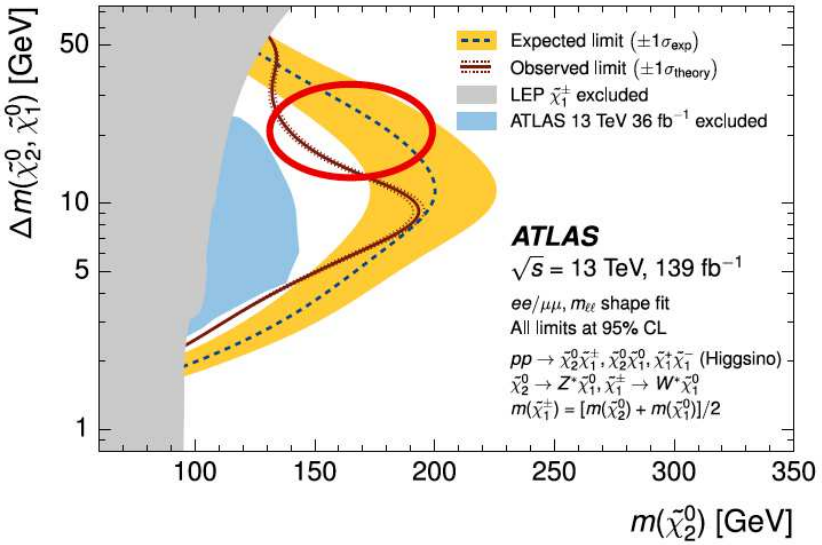
Golden mode at the LHC:

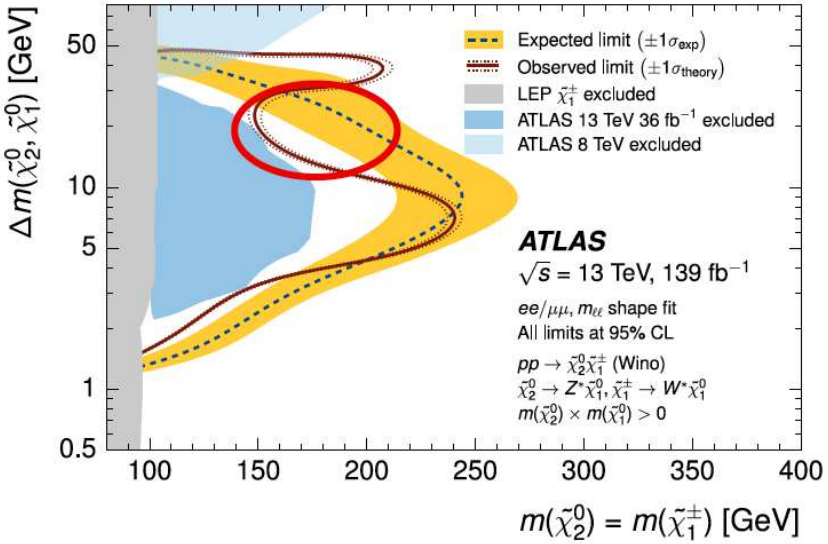


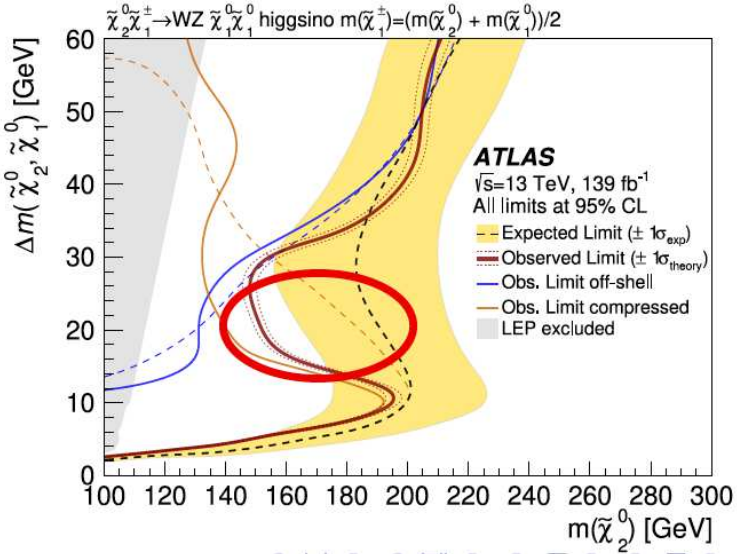
⇒ experimental results?

Results: "compressed" spectra w/ heavy sleptons: [taken from M. Berggren '23]

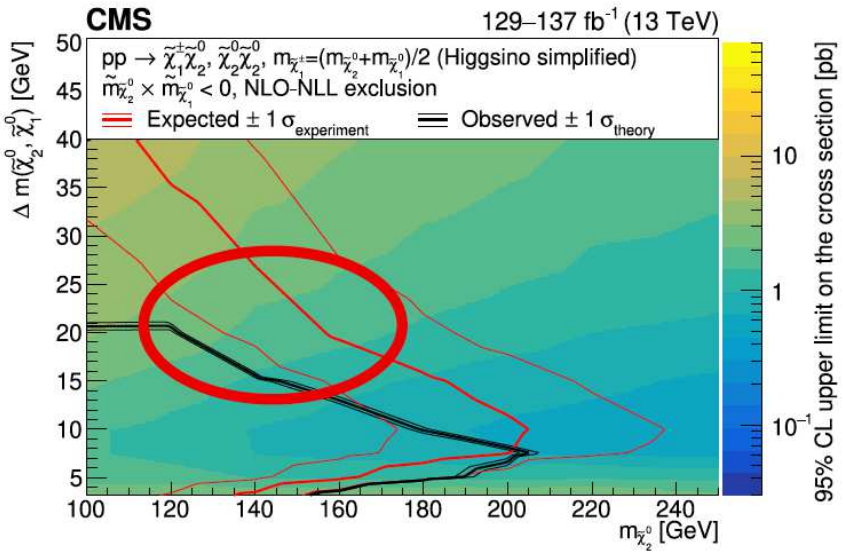


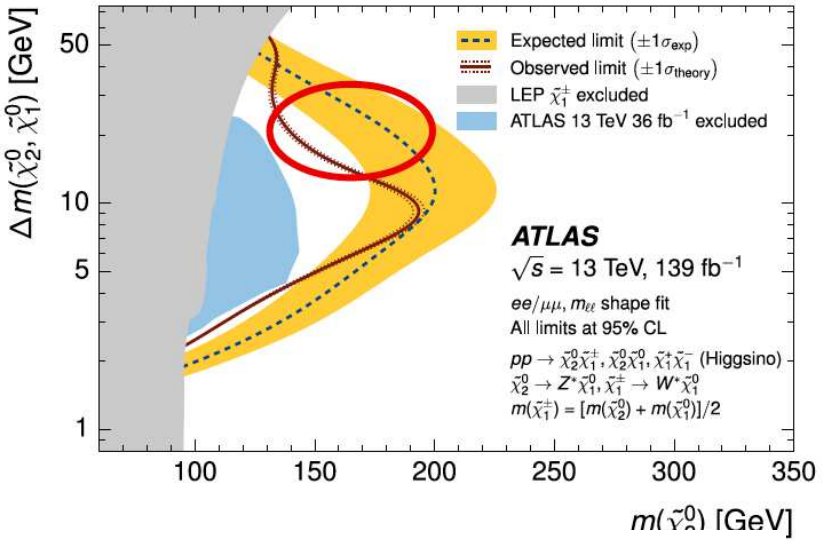


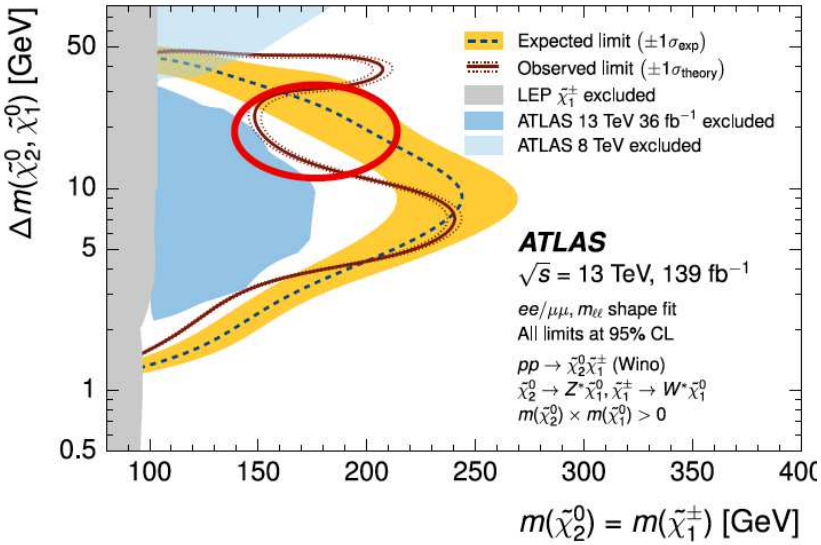


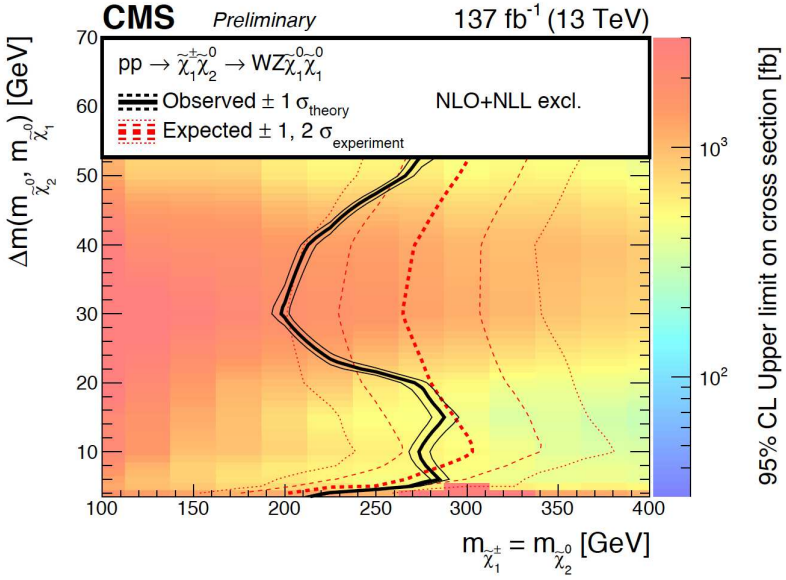


Results: "compressed" spectra w/ heavy sleptons: one more CMS analysis:









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

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

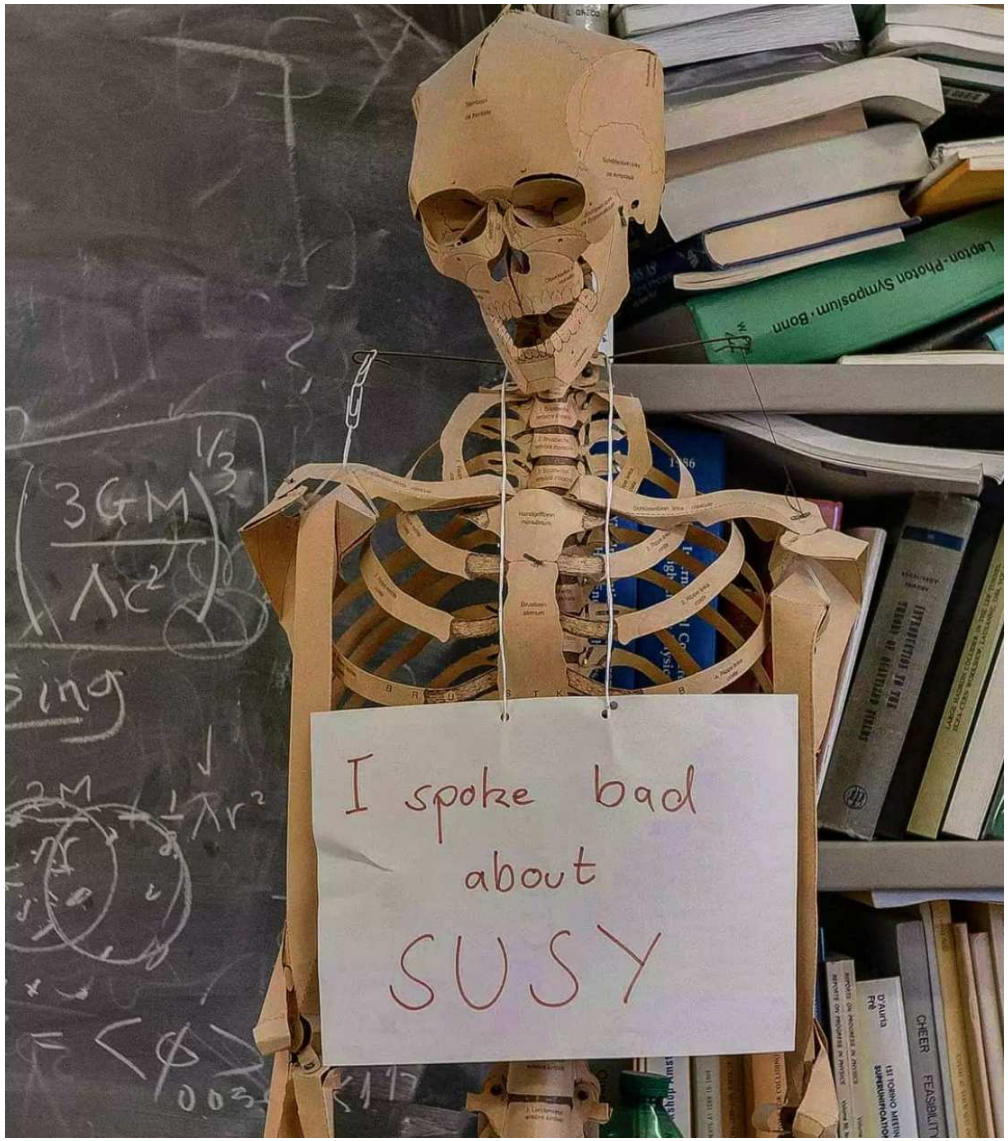
D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)

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?

3. What we have so far . . .



⇒ not too much - but we have time! ;-)

A) Bino/wino DM with chargino co-annihilation

Parameter scan:

$$100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV} ,$$

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

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

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

$$100 \text{ GeV} \leq m_{\tilde{L}} \leq 1 \text{ TeV},$$

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

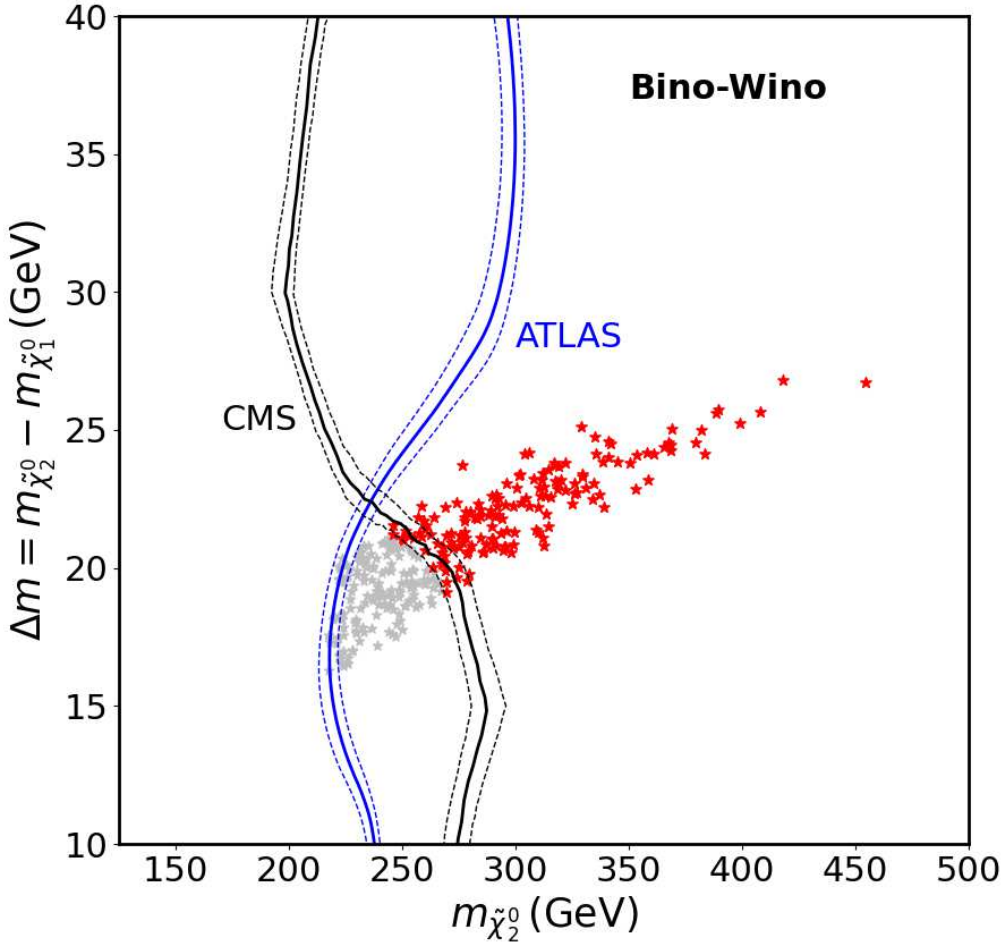
(latter condition only to make the analysis simpler, no relevant effect)

relic DM density can be 100% fulfilled

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

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

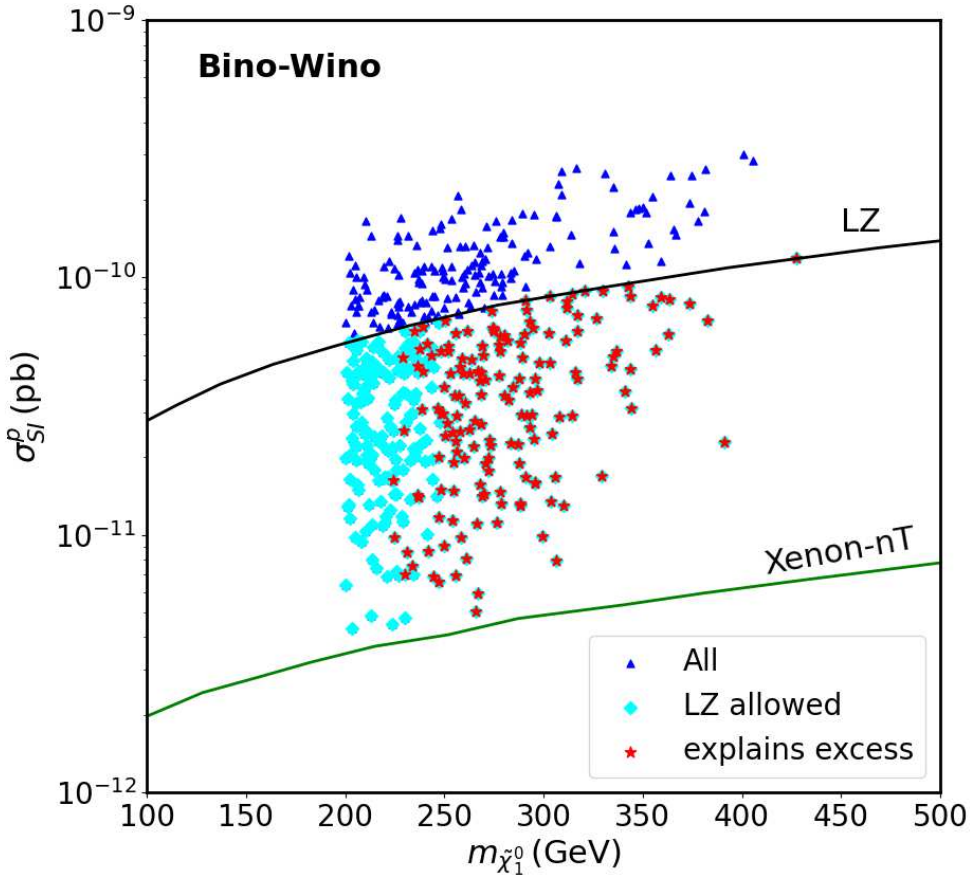
[*PRELIMINARY*]



$\Rightarrow$ excesses not fully at the same Δm . . . but at $\Delta m \sim 20$ GeV [*ATLAS*]

Results in the $m_{\tilde{\chi}_1^0}$-σ_p^{SI} plane:

[PRELIMINARY]



$\Rightarrow$ chargino co-annihiliation case will be covered by XENON-nT/LZ

D) Higgsino DM

Parameter scan:

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

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

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

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

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

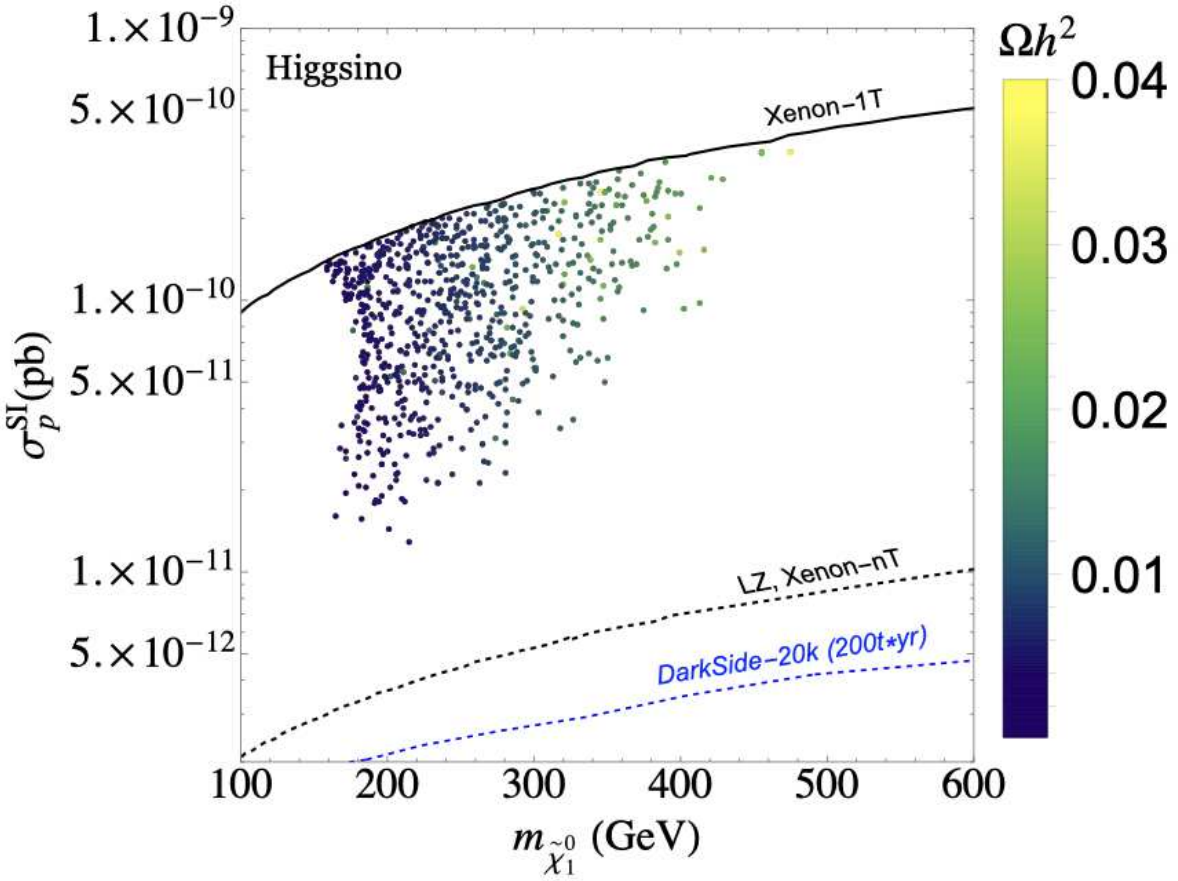
$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$

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

$\Rightarrow$ incompatible with $(g-2)_\mu$

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

Results in the $m_{\tilde{\chi}_1^0}$-σ_p^{SI} plane:

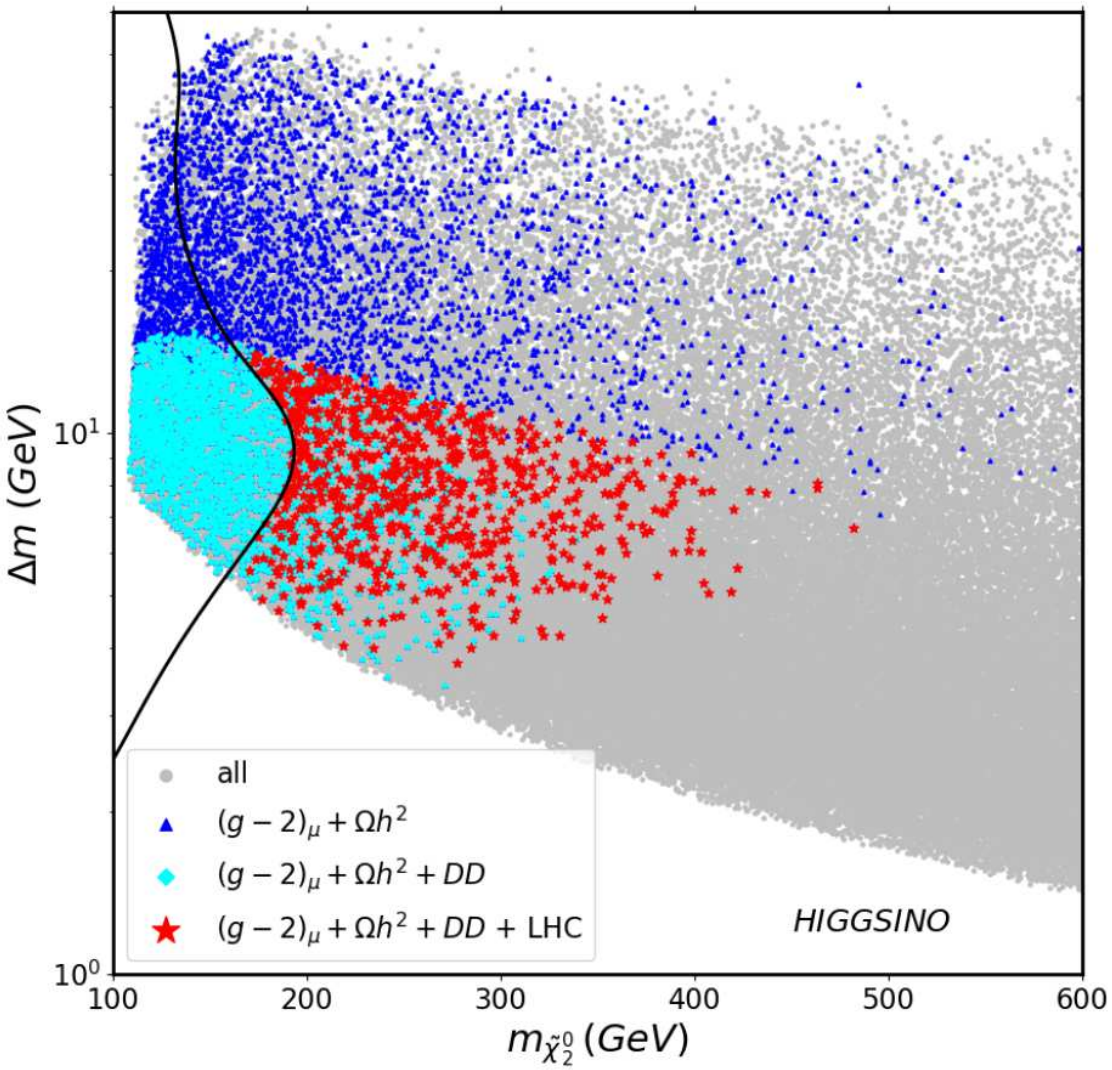


$\Rightarrow$ everything covered by XENON-nT/LZ

$\Rightarrow$ Direct Detection experiments cover the full parameter space

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

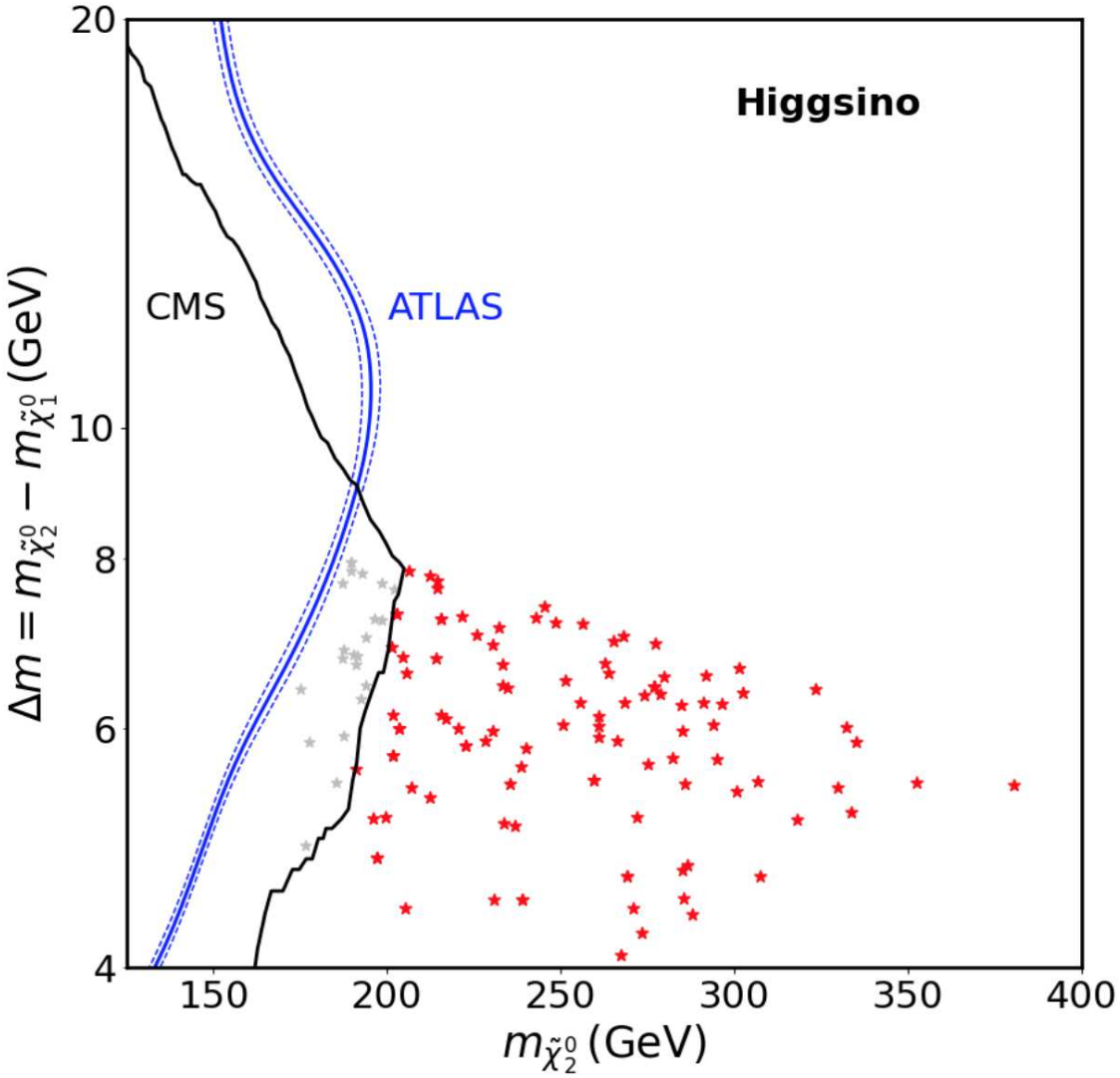
[2021]



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

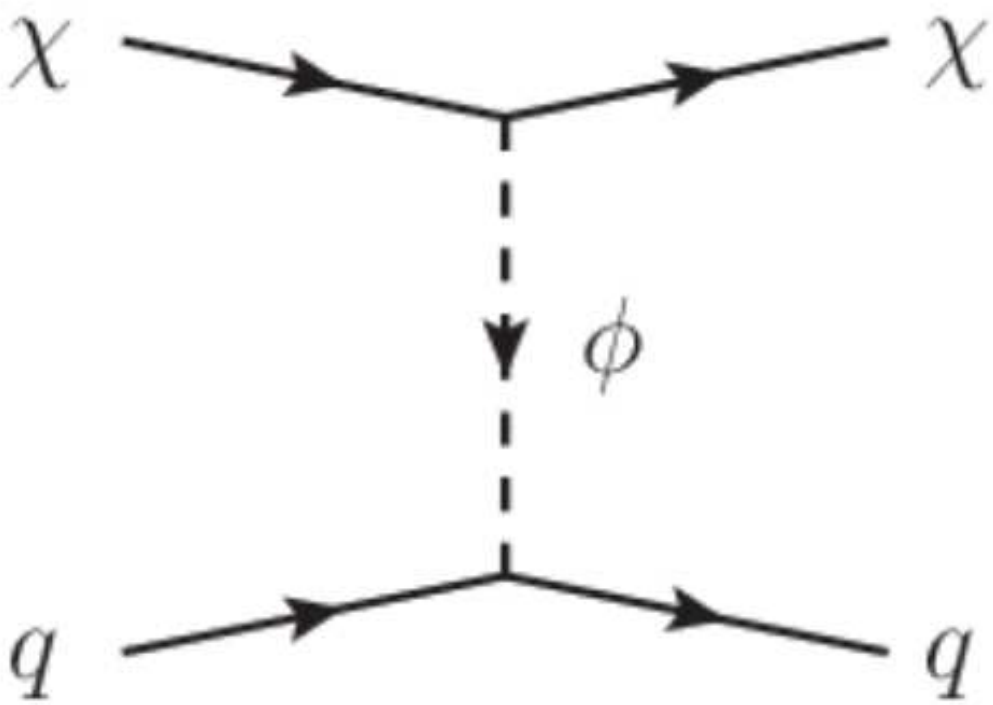
Results in the $m_{\tilde{\chi}_2^0}$-Δm plane

[*PRELIMINARY*]



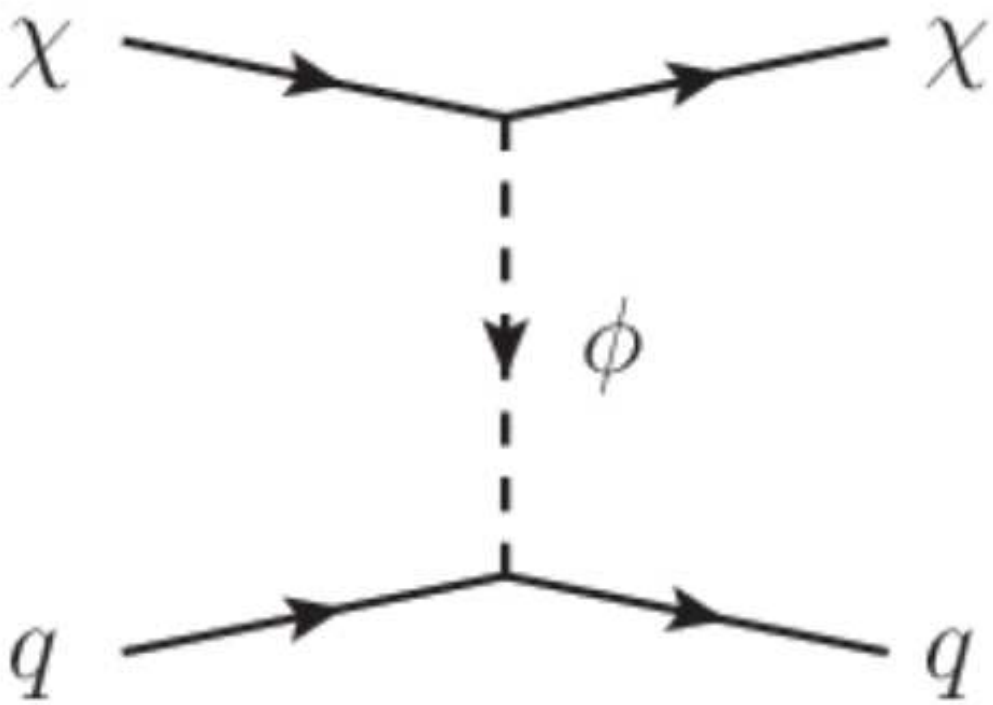
$\Rightarrow$ excess not fitted :-($\Rightarrow$ DD cuts away the "good points"

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 $M_1 < 0$

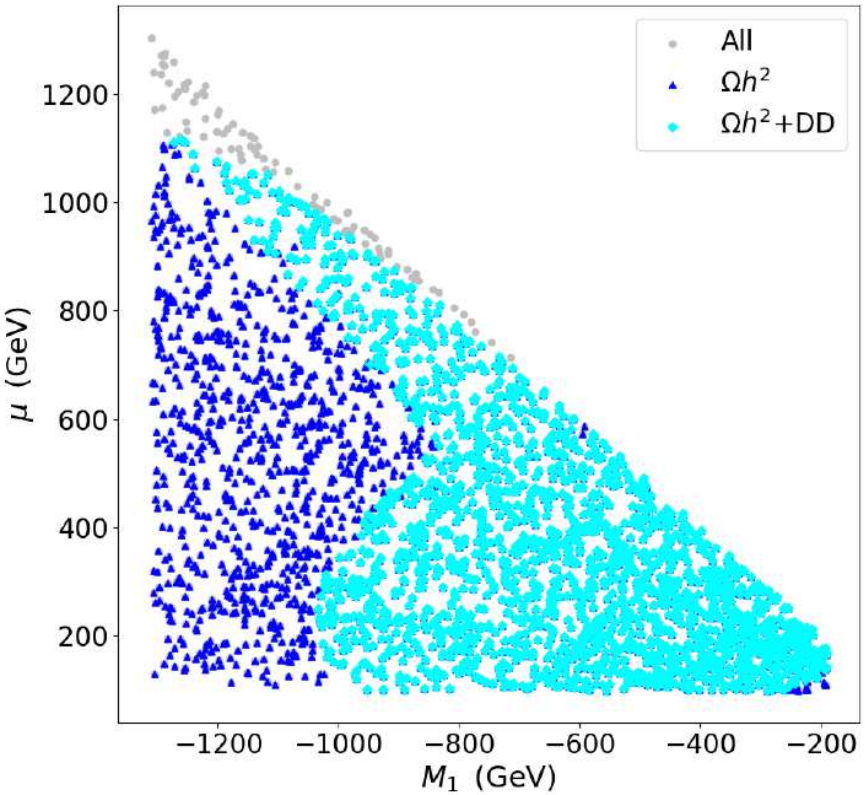
$$
\begin{aligned}
-190\ \text{GeV} \leq M_1 \leq -1500\ \text{GeV}\ , \\
M_2 = 2\ \text{TeV}\ , \\
\mu = \frac{-2M_1 \tan\beta}{4 + x_1 \tan^2\beta}, \quad x_1 = \frac{m_h^2}{m_H^2}\ , \\
5 \leq \tan\beta \leq 50\ , \\
190 \leq M_A \leq 1200\ , \\
2M_1 \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 1500\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

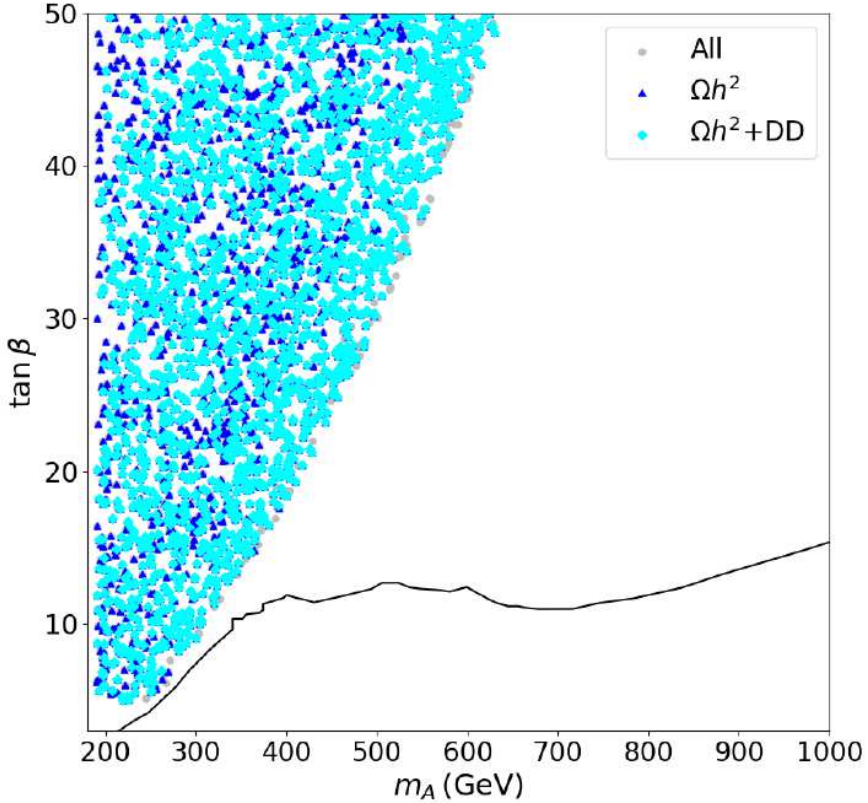
Condition on μ and M_1: exact blind spot conditions

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

First results with exact blind spot condition:

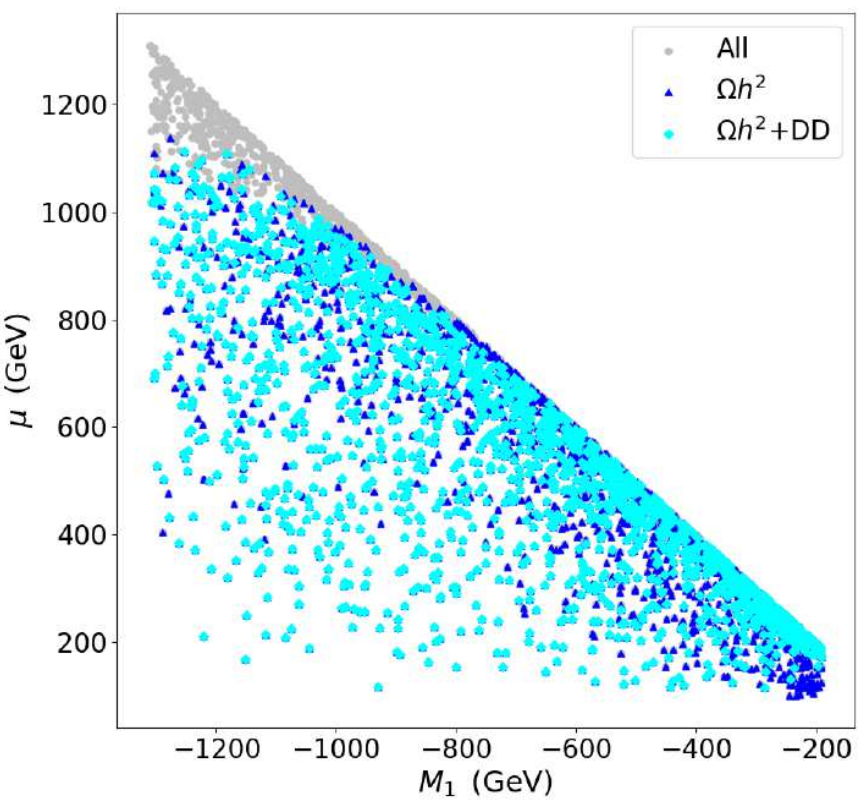
[PRELIMINARY]

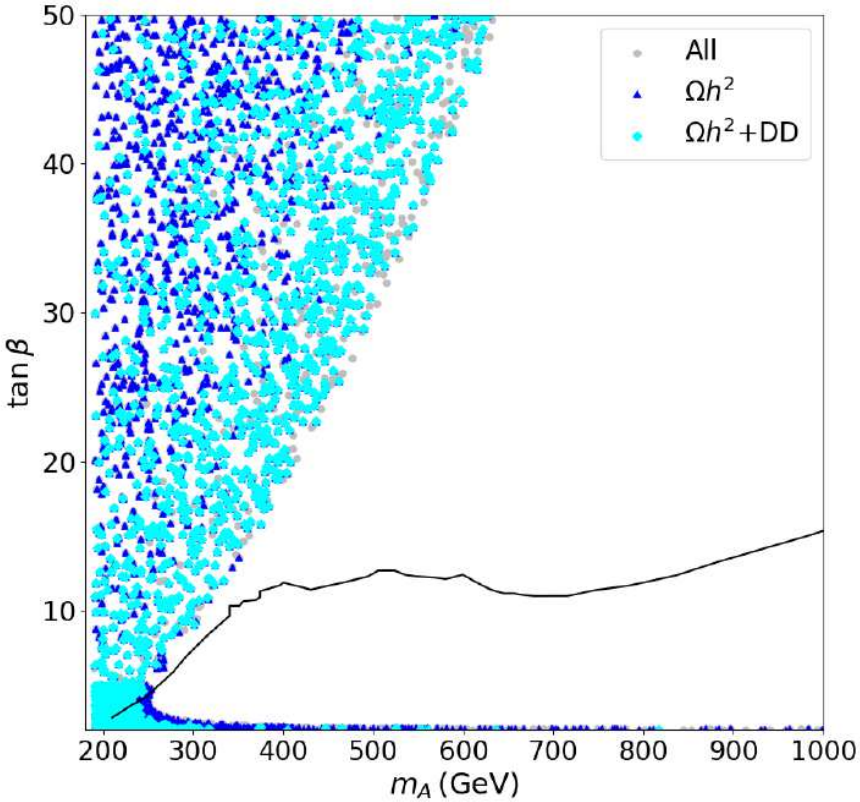




$\Rightarrow$ search for $H/A \to \tau^+\tau^-$ excludes this solution

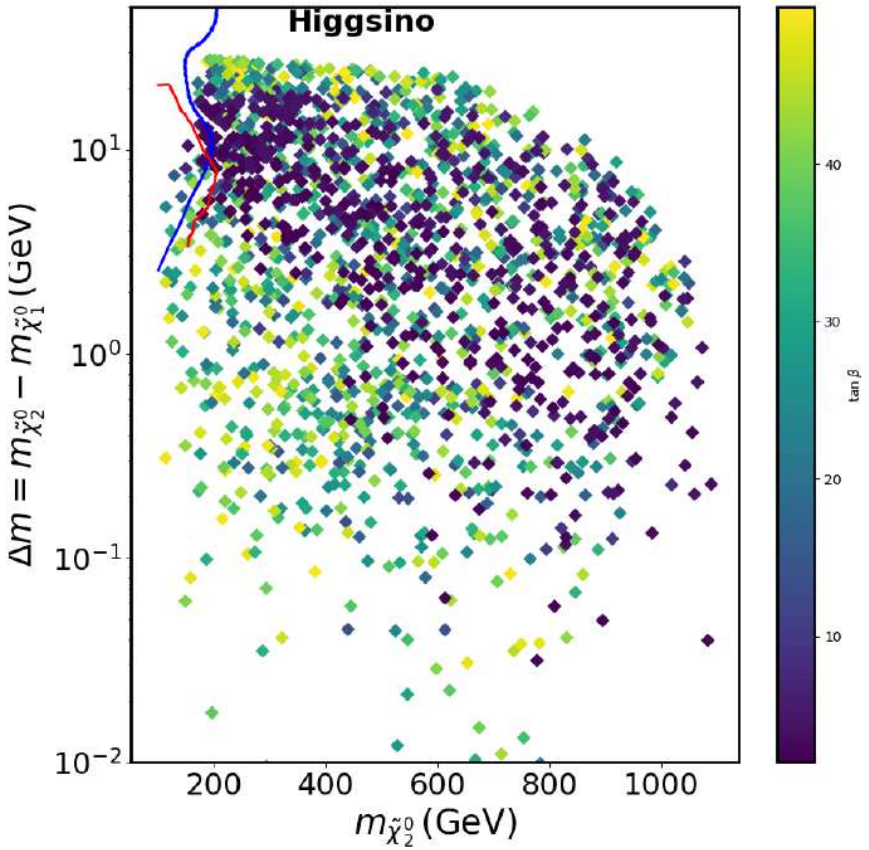
First results with relaxed blind spot condition: [*PRELIMINARY*]

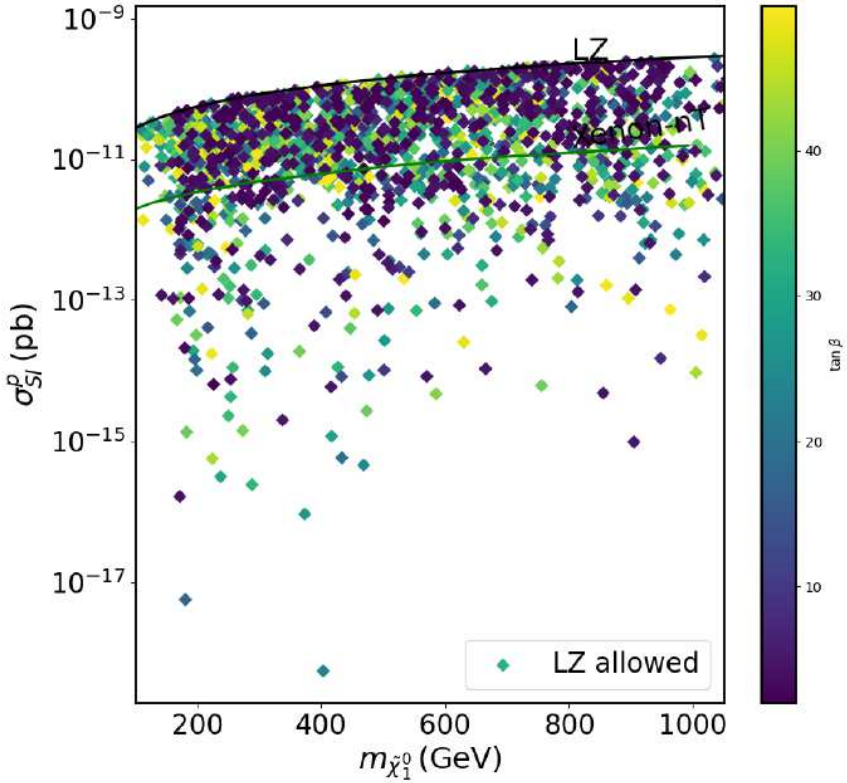




$\Rightarrow$ allowed points for low M_A and $\tan\beta$:-)

First results with relaxed blind spot condition: [*PRELIMINARY*]





$\Rightarrow$ allowed points for low M_A and $\tan\beta$:-)

4. Outlook

- Low energy electroweak SUSY can explain many[2] open questions
  $\Rightarrow$ focus on MSSM

- $\Rightarrow$ scan the EW sector of the MSSM with all constraints:
  $(g-2)_\mu$, DM relic density, DM DD, LHC EW searches
  $\Rightarrow$ upper limits on EW masses $\Rightarrow$ evaluate prospects for DD/(HL-)LHC

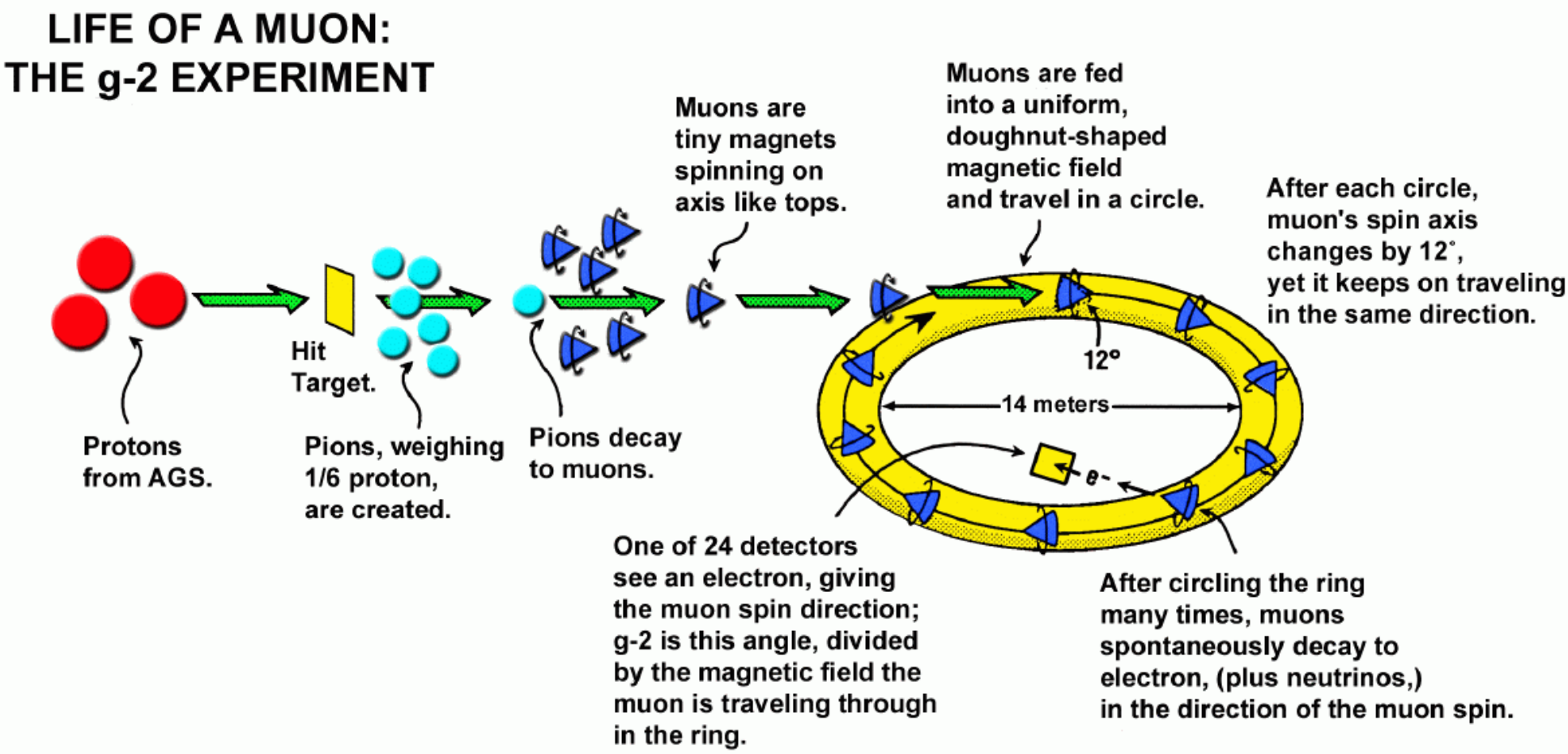
- All(?) ATLAS and CMS searches with $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$
  and $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}\,(20\ \text{GeV})$ show excesses in the data

- Possible scenario: A) bino/wino DM with chargino coann. (DM full)
  $\Rightarrow$ ATLAS and CMS not fully compatible
  Good points: good prospects for Xenon-nT/LZ!
  Way ahead: test uncertainties in Δm determination

- Possible scenario: D) higgsino DM $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ (DM u.l.)
  $\Rightarrow$ blind spot analysis!
  $\Rightarrow$ good points found for low M_A and low $\tan\beta$
  ToDo: check Higgs constraints, more extensive scan . . .


Further Questions?

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

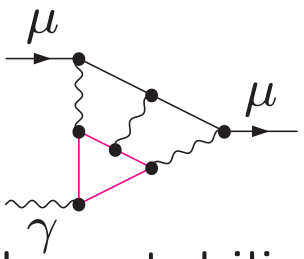


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

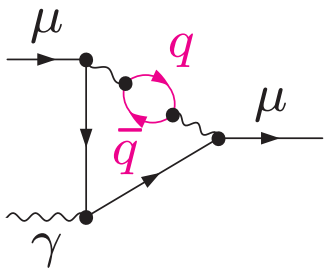
Theory of $(g-2)_\mu$:

– the light-by-light contribution:



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

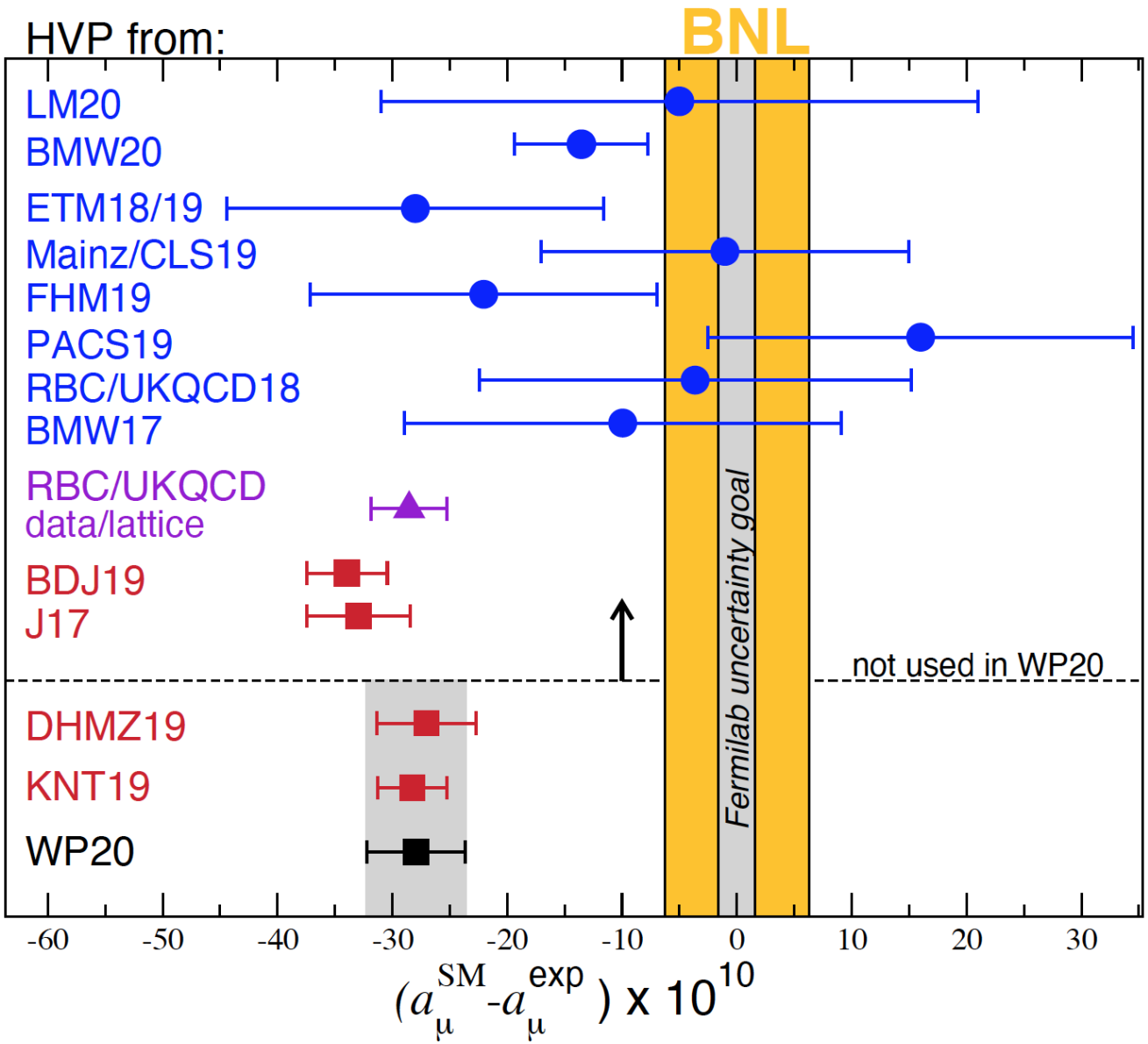
– the hadronic vacuum contribution:



'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 $\sim 1.5\,\sigma$