

# Has the LHC ruled out supersymmetry?



# SUSY DM and recent excesses at the LHC

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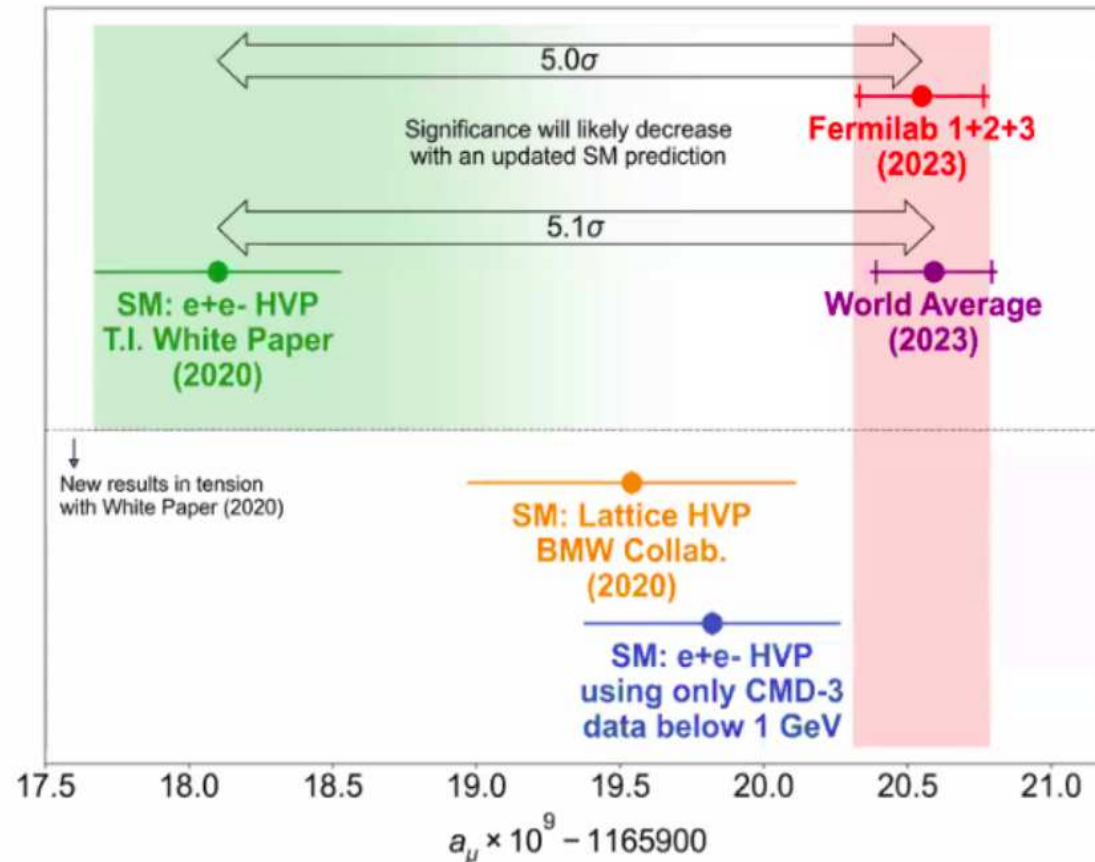
In collaboration with: *M. Chakraborti, I. Saha*

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

# 1. The main idea

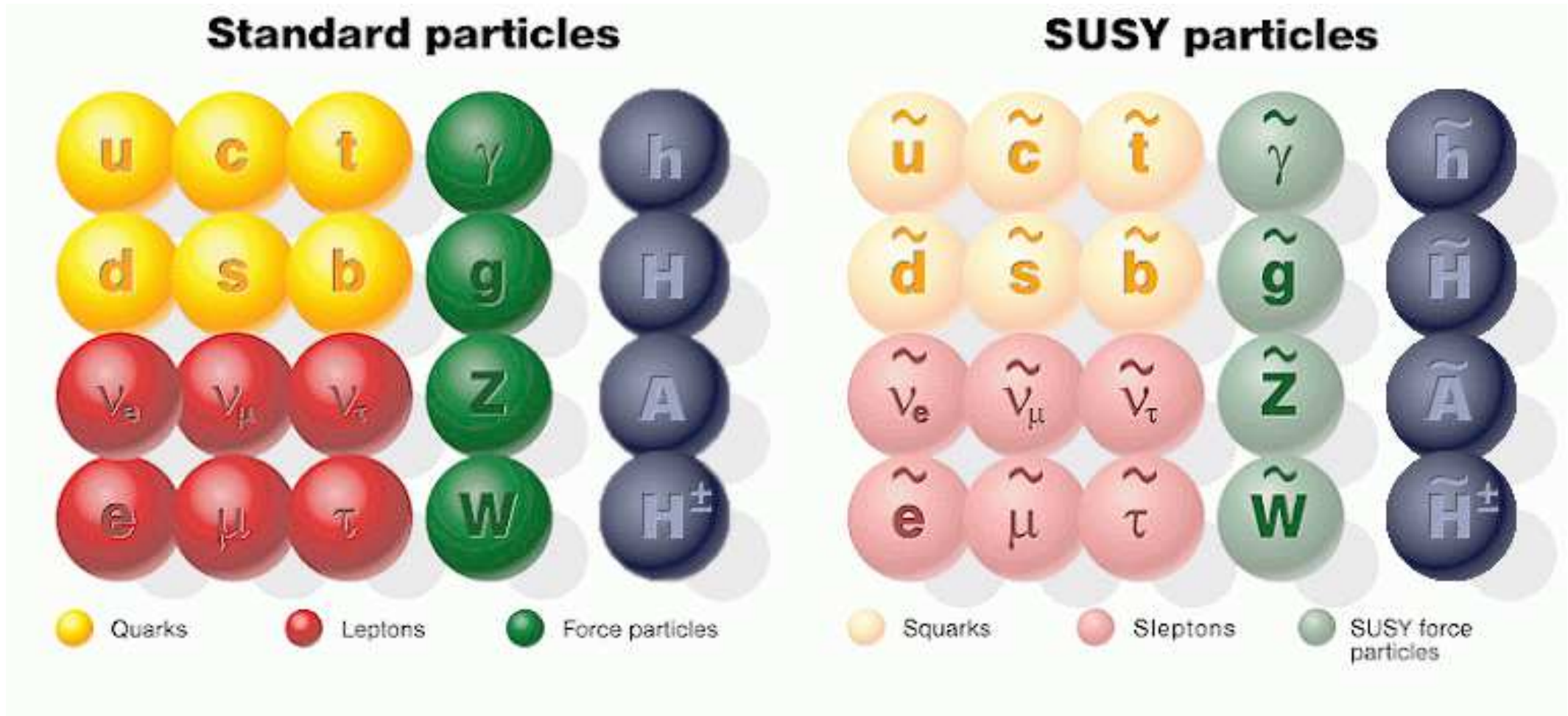
The anomalous magnetic moment of the muon:  $a_\mu \equiv (g - 2)_\mu/2$

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



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

# The MSSM



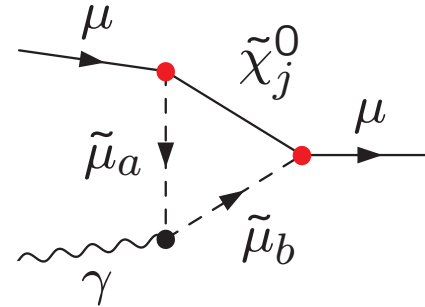
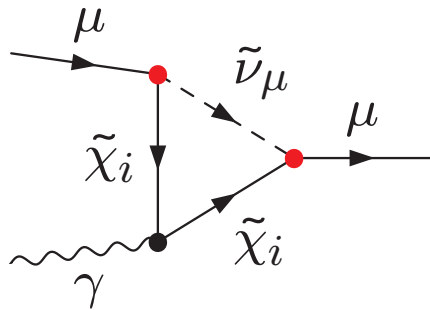
⇒ large uncolored / EW sector

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

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 $a_\mu$ :

Feynman diagrams for MSSM 1L corrections:



- Diagrams with chargino/sneutrino exchange
- Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

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

$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a : \sim m_\mu \tan \beta$$

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

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

## 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)

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

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

## Dark Matter relic density: MicrOmegas

$$\begin{aligned} \Omega_{\text{CDM}} h^2 &= 0.120 \pm 0.001 \\ \text{or } \Omega_{\text{CDM}} h^2 &\leq 0.122 \end{aligned}$$

(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

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

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  $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV}$ )

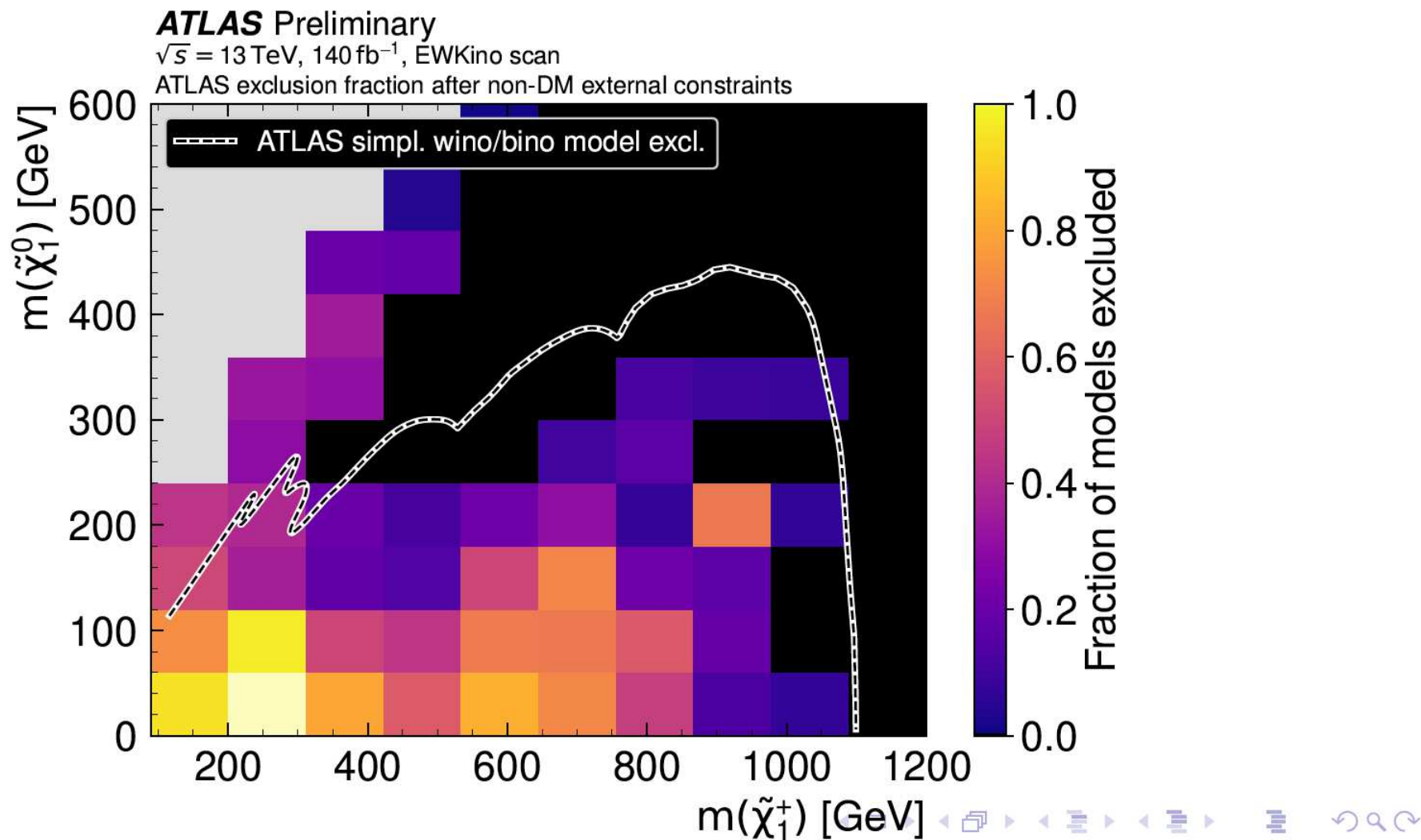
$$\Rightarrow m_{(N)\text{LSP}} \lesssim 600 \text{ GeV}$$

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

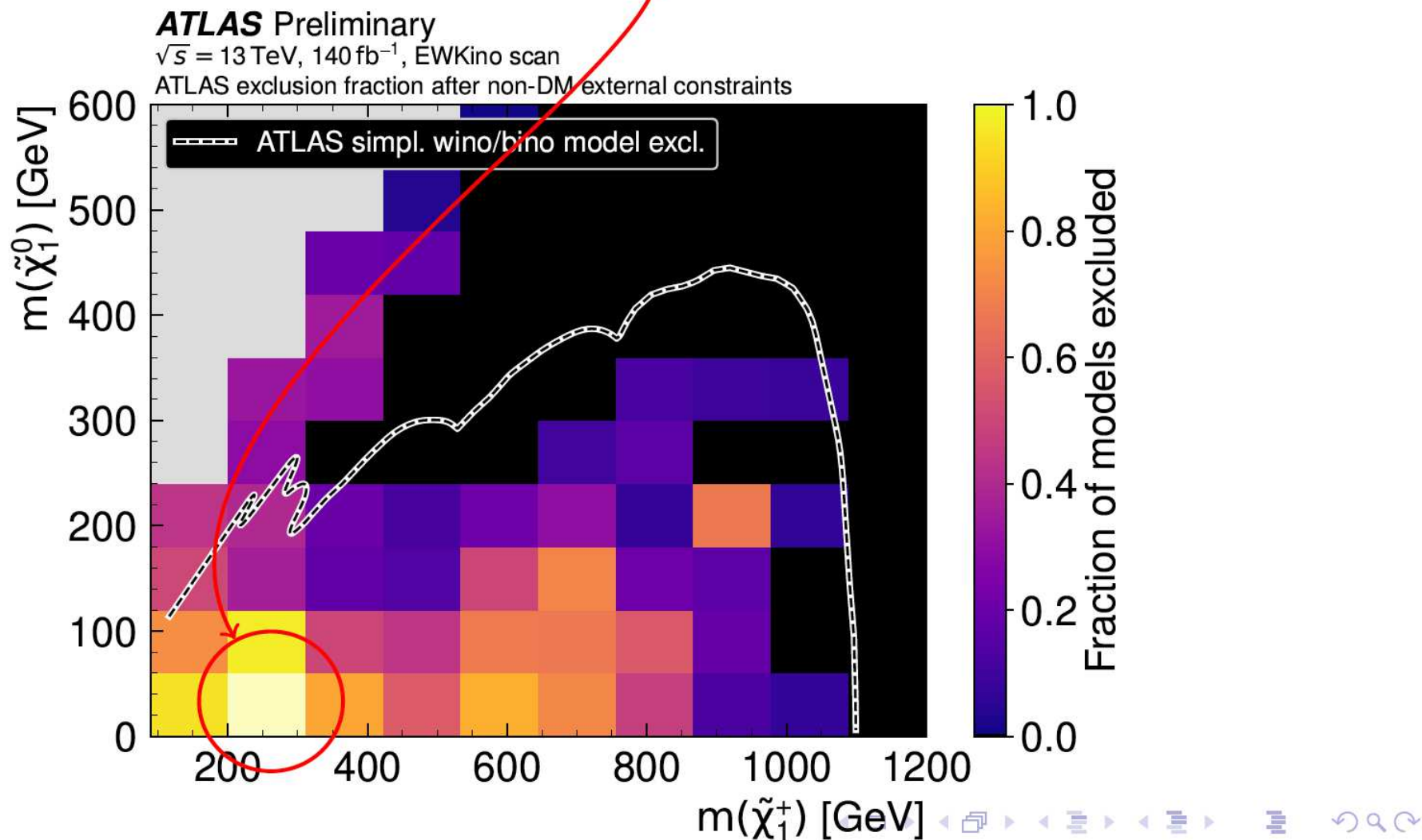


## 2. Evidence for low-energy SUSY?!





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:

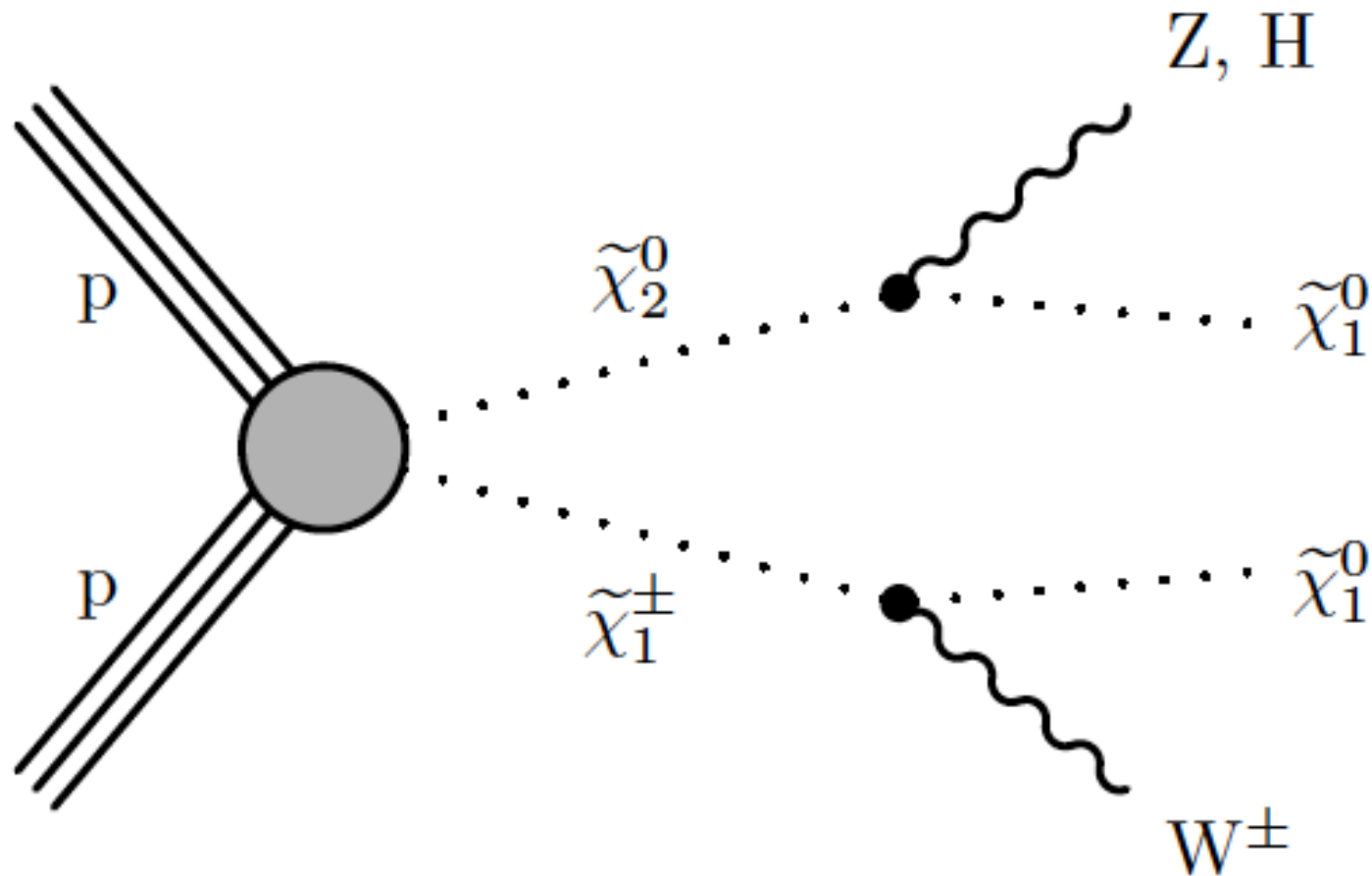
- **non-compressed** spectra: on-shell decays to  $H/Z, W^\pm$
- **compressed** spectra: off-shell decays to  $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

⇒ 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

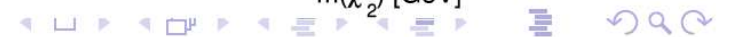
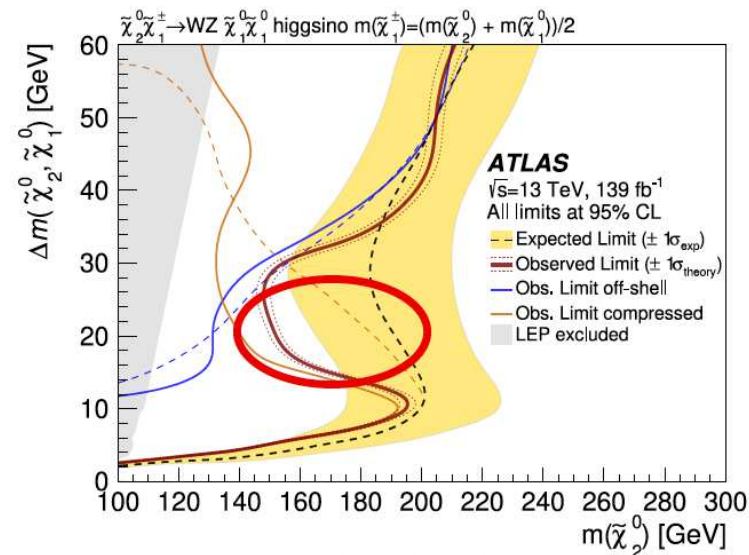
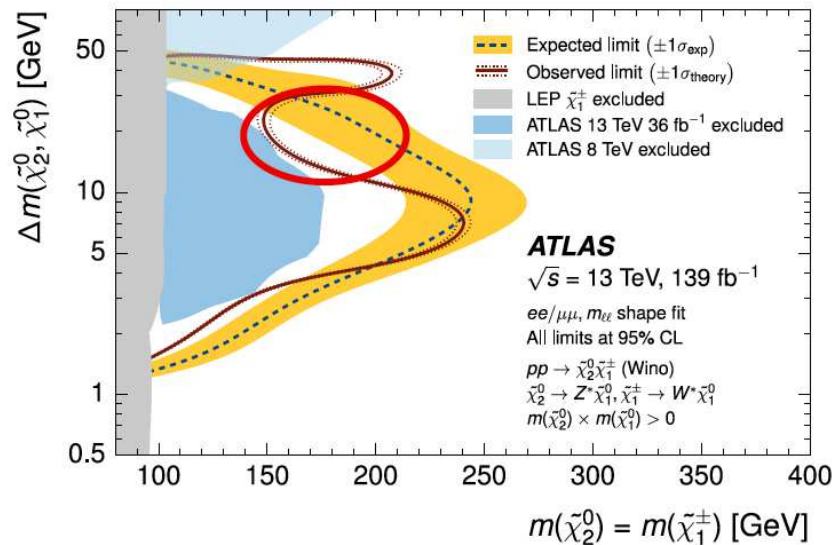
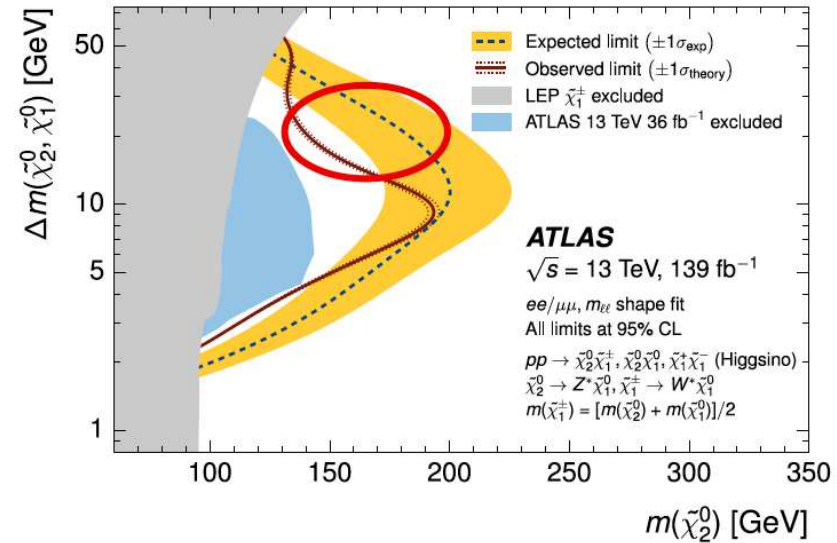
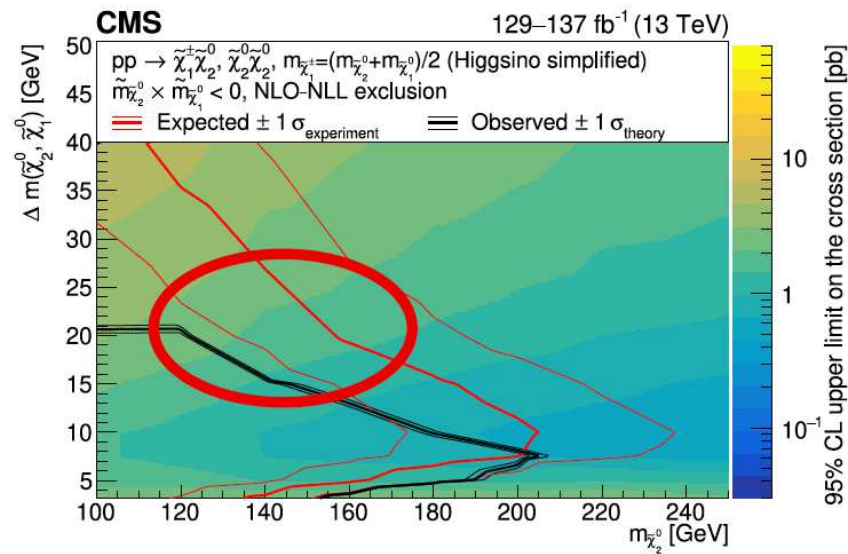
Golden mode at the LHC:

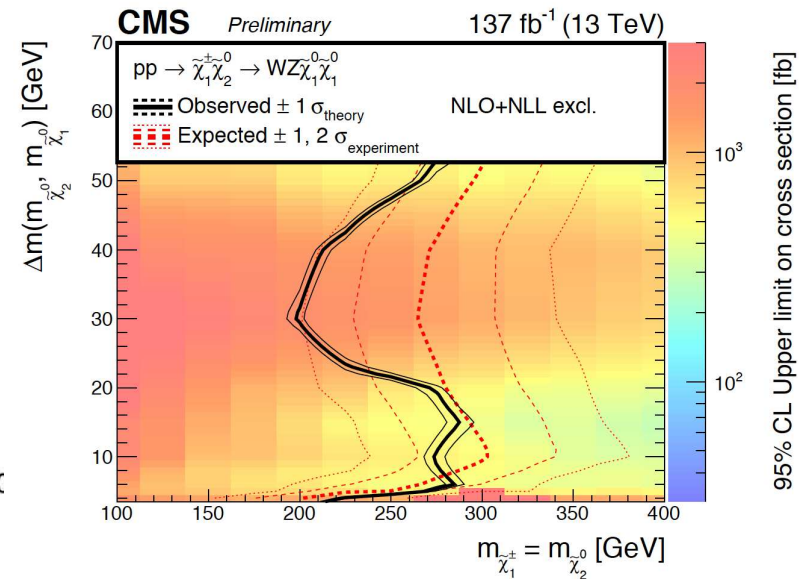
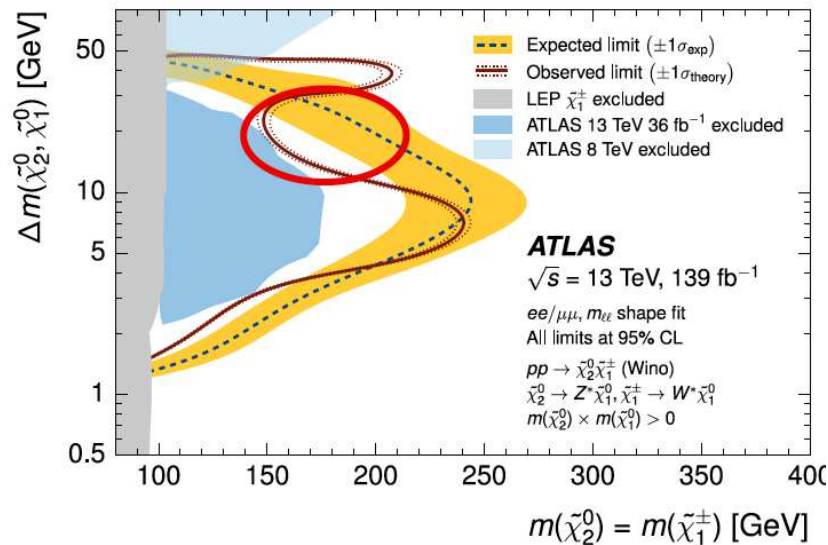
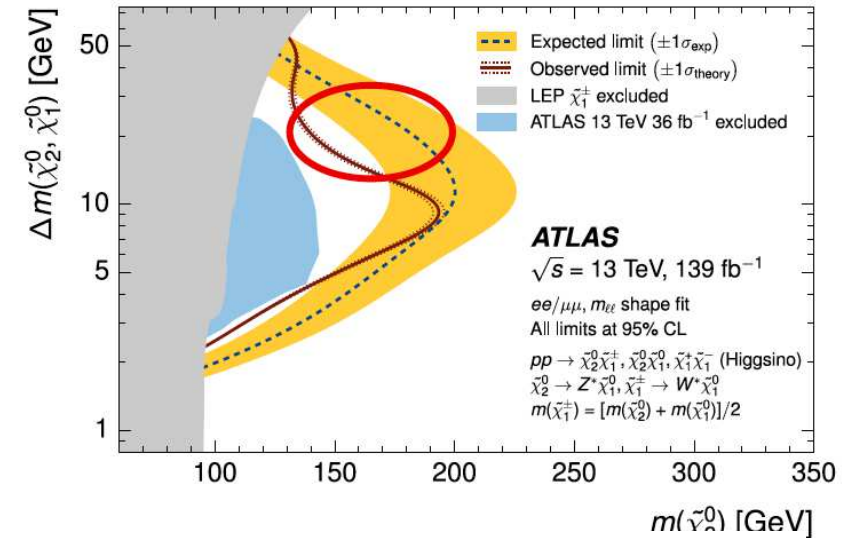
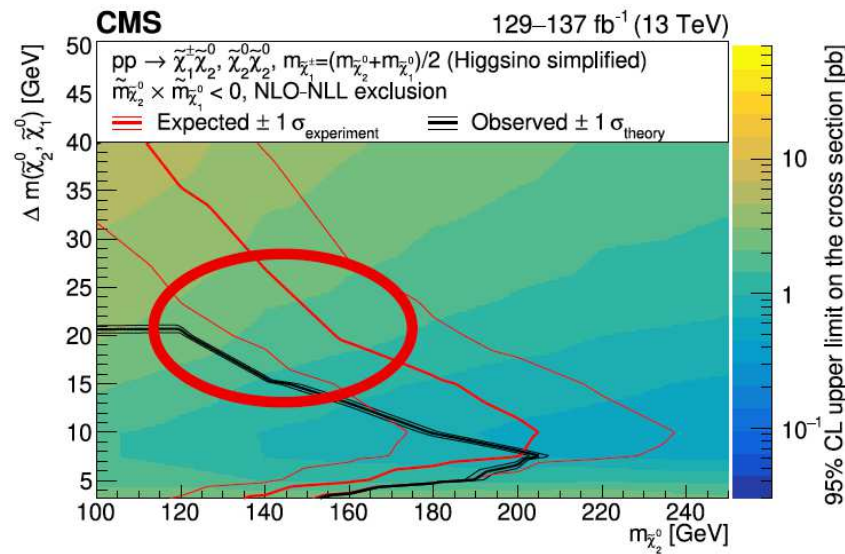


⇒ experimental results?

# Results: “compressed” spectra w/ heavy sleptons:

[taken from M. Berggren '23]





## Two possible scenarios:

- $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$
- $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10 \text{ GeV})$

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

relic DM density 100% fulfilled

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

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

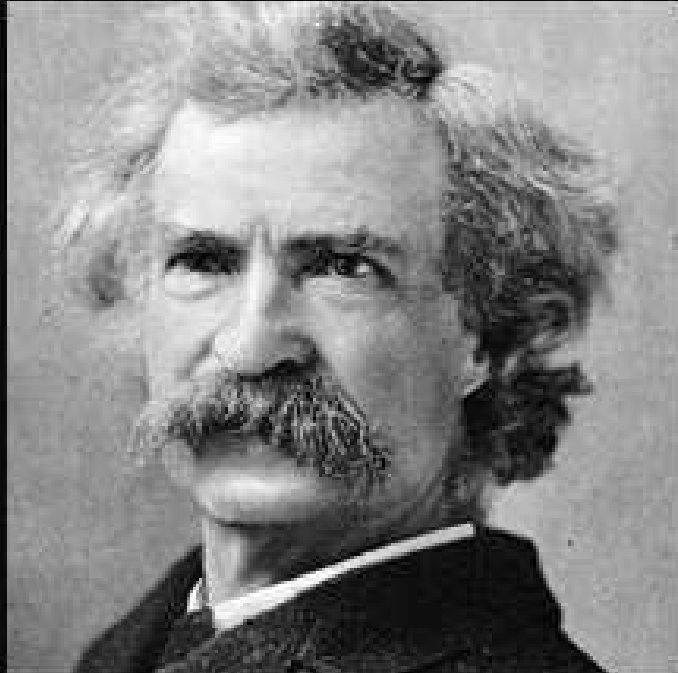
relic DM density as upper limit (otherwise  $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$ )

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

$\Rightarrow$  can they fit the excesses?



### 3. What we have so far ...



The reports of my death have  
been greatly exaggerated.

~ Mark Twain

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

## D) Higgsino DM

Parameter scan:

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

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

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

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

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

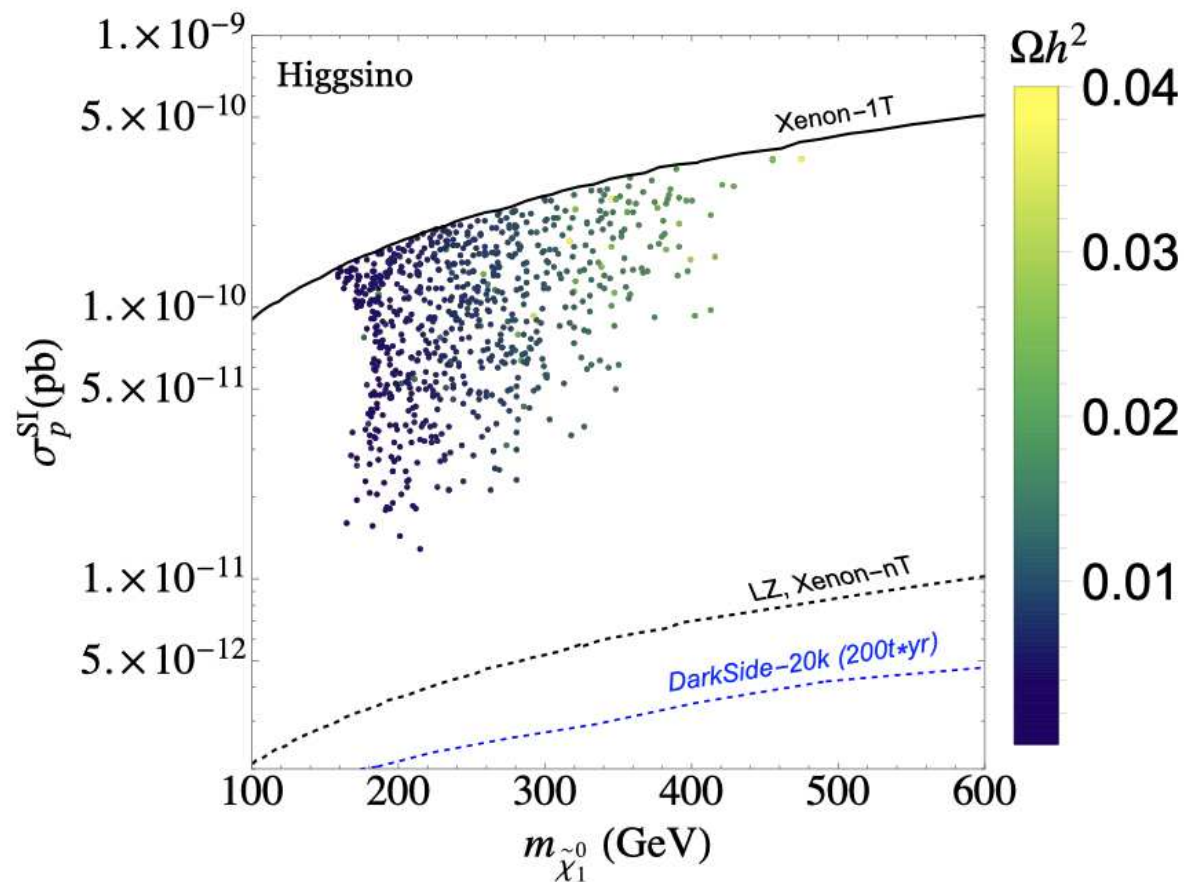
$$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$$

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

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

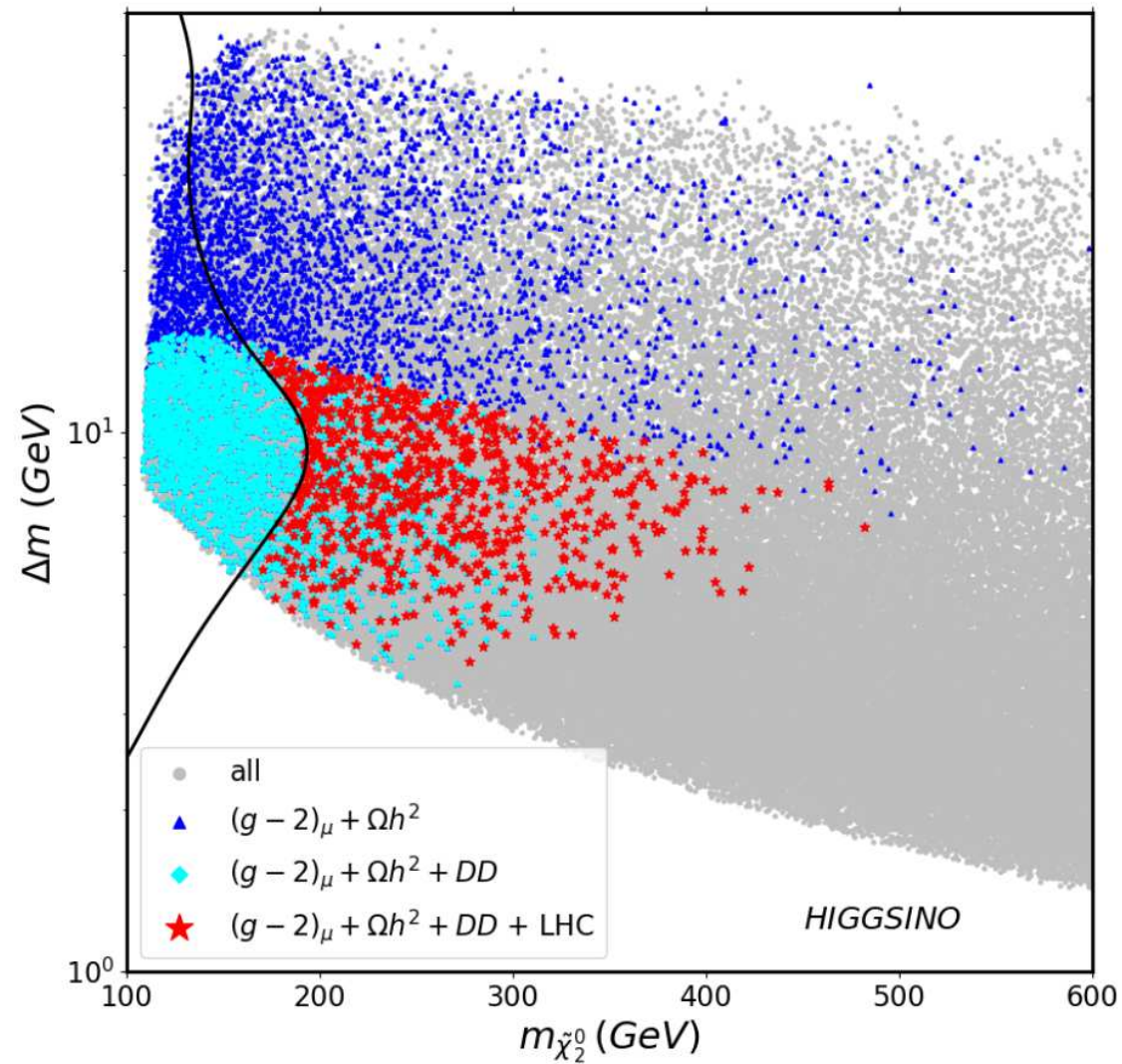
$\Rightarrow m_{(N)\text{LSP}} \lesssim 500 \text{ GeV}$

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

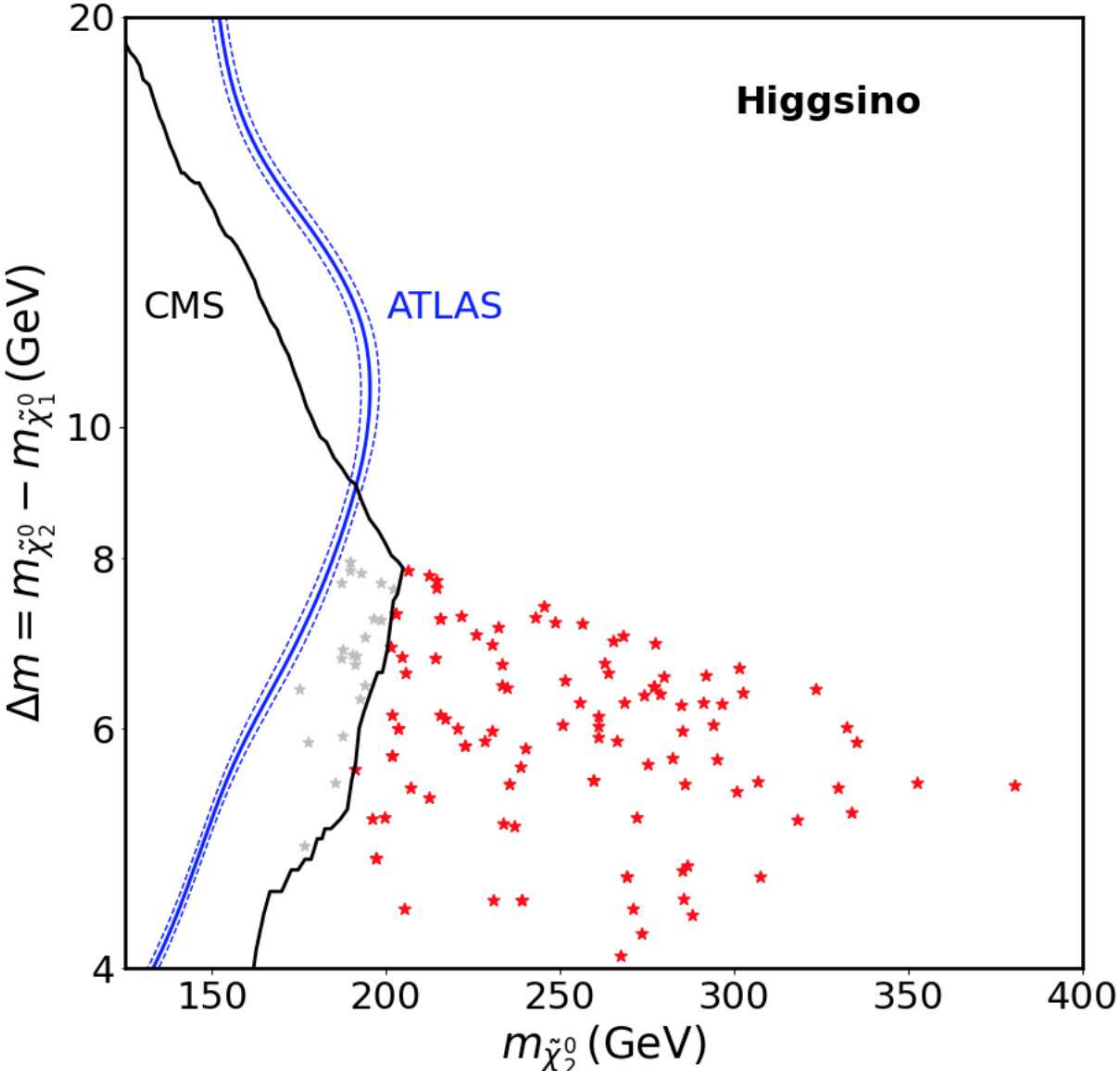


⇒ everything covered by XENON-nT/LZ

⇒ Direct Detection experiments cover the full parameter space



⇒ direct detection is the limiting factor on  $\Delta m$



⇒ excess not fitted :-)

## A) Bino/wino DM with chargino co-annihilation

Parameter scan:

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

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

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

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

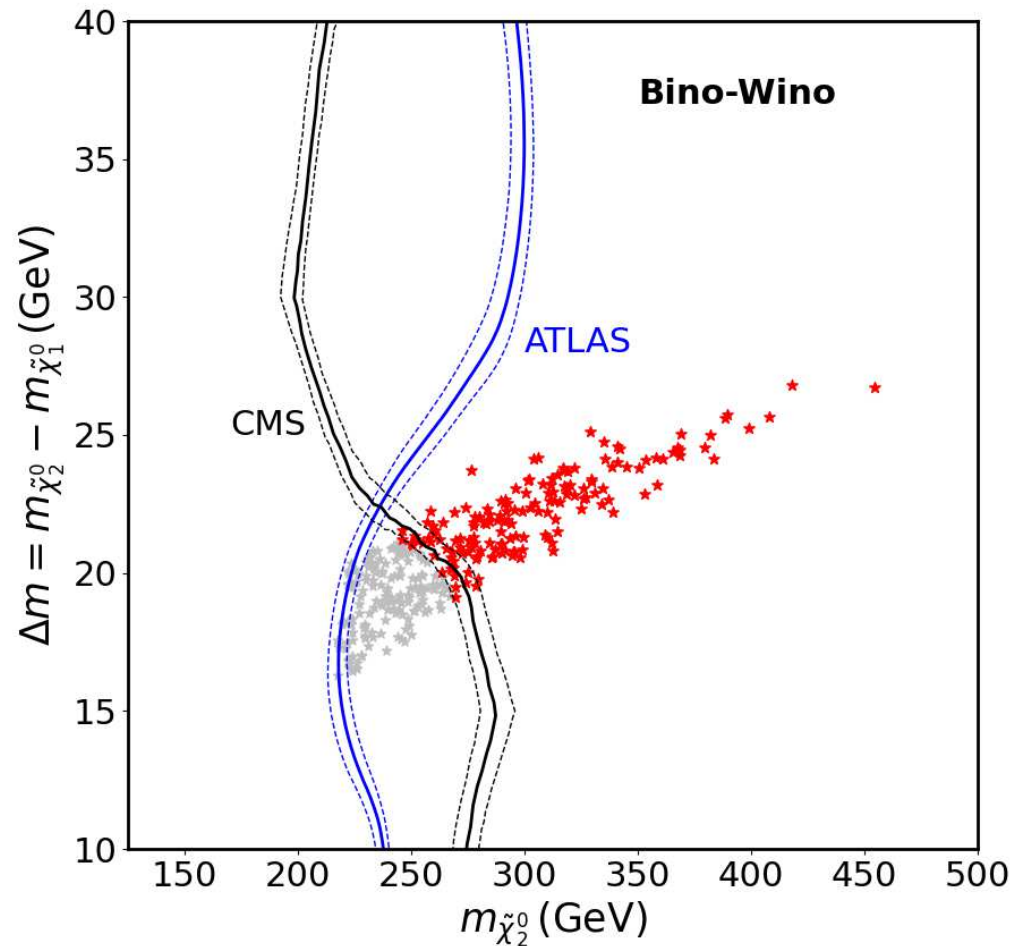
$$100 \text{ GeV} \leq m_{\tilde{L}} \leq 1 \text{ TeV} ,$$

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

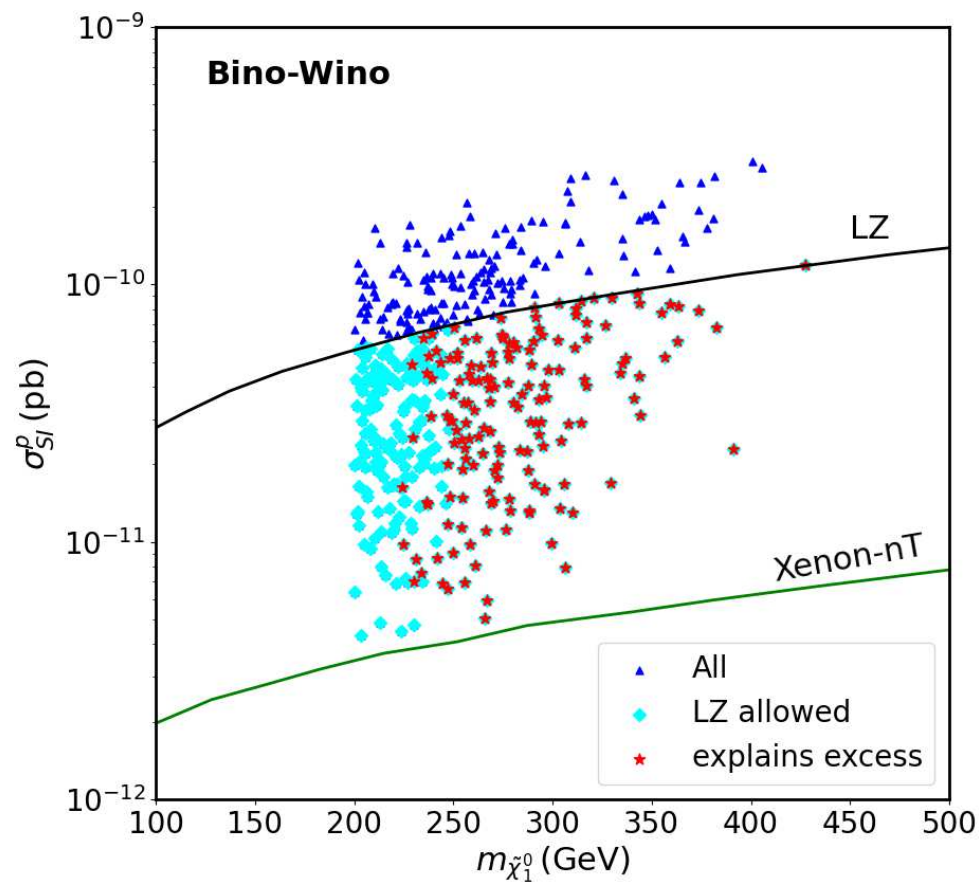
(latter condition only to make the analysis simpler, no relevant effect)

relic DM density can be 100% fulfilled

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



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



⇒ chargino co-annihilation case will be covered by XENON-nT/LZ



## 4. Outlook

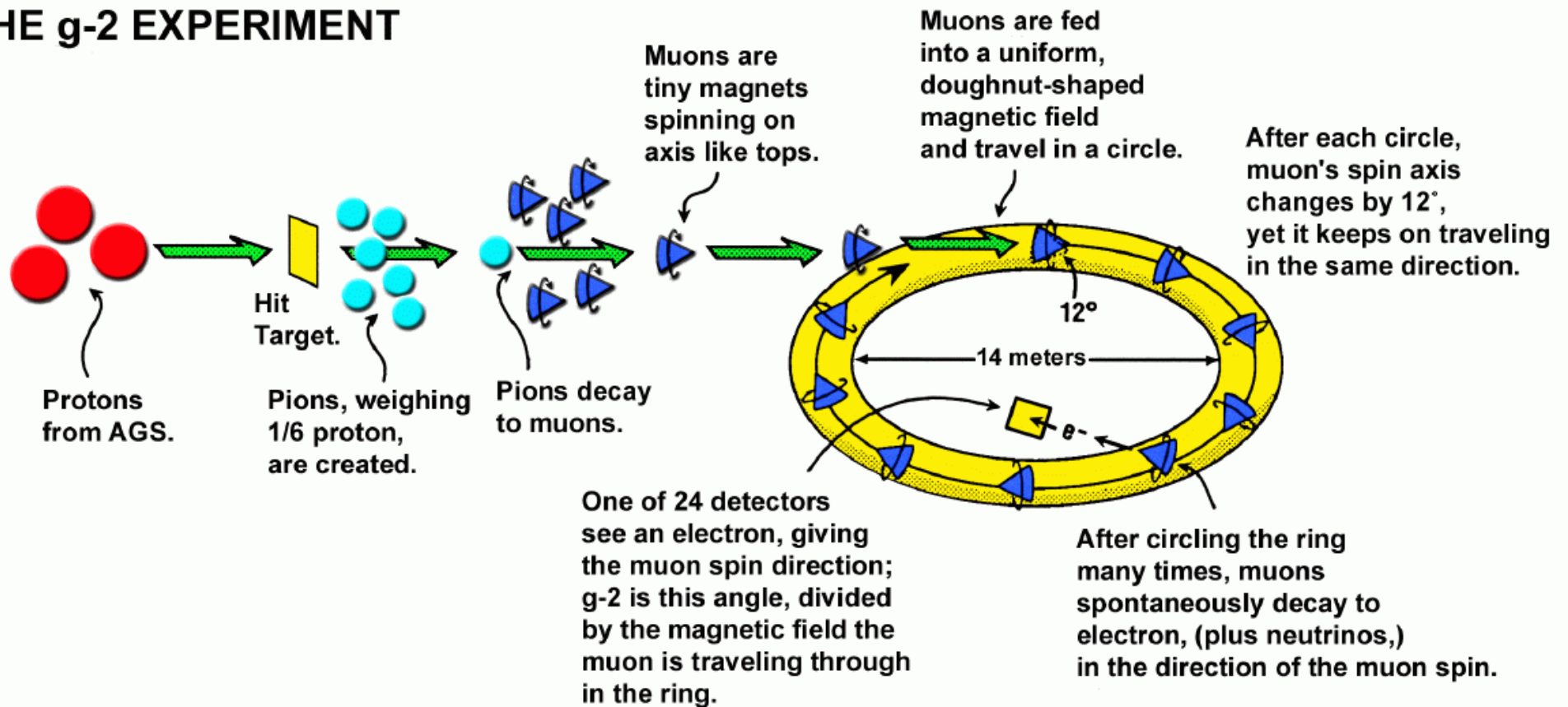
- Low energy electroweak SUSY can explain open questions  
⇒ focus on MSSM
- ⇒ scan the EW sector of the MSSM with all constraints:  
 $(g - 2)_\mu$ , DM relic density, DM DD, LHC EW searches  
⇒ upper limits on EW masses ⇒ evaluate prospects for DD/(HL-)LHC
- All(?) ATLAS and CMS searches with  $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$   
and  $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10 \text{ GeV})$  show excesses in the data
- 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.)  
⇒ DD searches limit  $\Delta m \lesssim 10 \text{ GeV}$  ⇒ excess not well fitted  
Way out: explore  $M_1 \times \mu < 0$  ⇒ reduction of  $\sigma_p^{\text{SI}}$
- Possible scenario: A) bino/wino DM with chargino coann. (DM full)  
⇒ ATLAS and CMS not fully compatible  
Good points: good prospects for Xenon-nT/LZ!  
Way ahead: test uncertainties in  $\Delta m$  determination



Further Questions?

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

## LIFE OF A MUON: THE g-2 EXPERIMENT

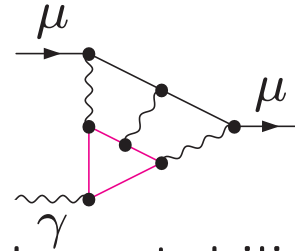


Coupling of muon to magnetic field :  $\mu - \mu - \gamma$  coupling

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

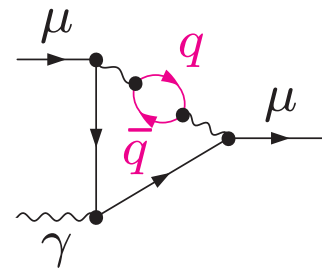
## Theory of $(g - 2)_\mu$ :

- the **light-by-light** contribution:



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

- the **hadronic vacuum** contribution:



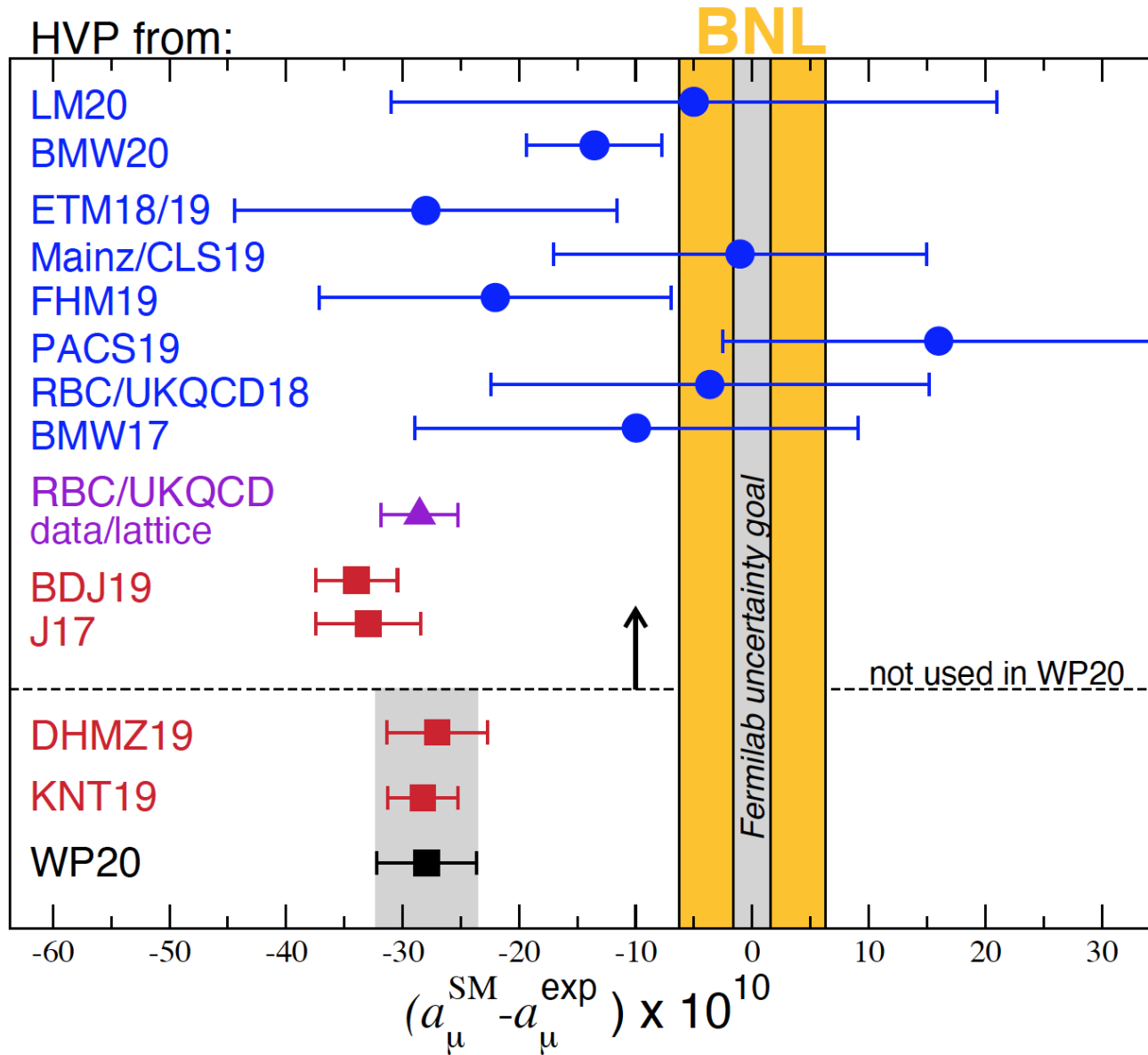
### 'direct' $e^+e^-$ data:

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

### $\tau$ data:

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

## HVP summary:



⇒ BMW20: difference to experimental data  $\sim 1.5 \sigma$