

So, is this “dark matter”  
in the room with us right now?



# $(g - 2)_\mu$ and SUSY Dark Matter at the ILC/CLIC

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Paestum, 10/2023

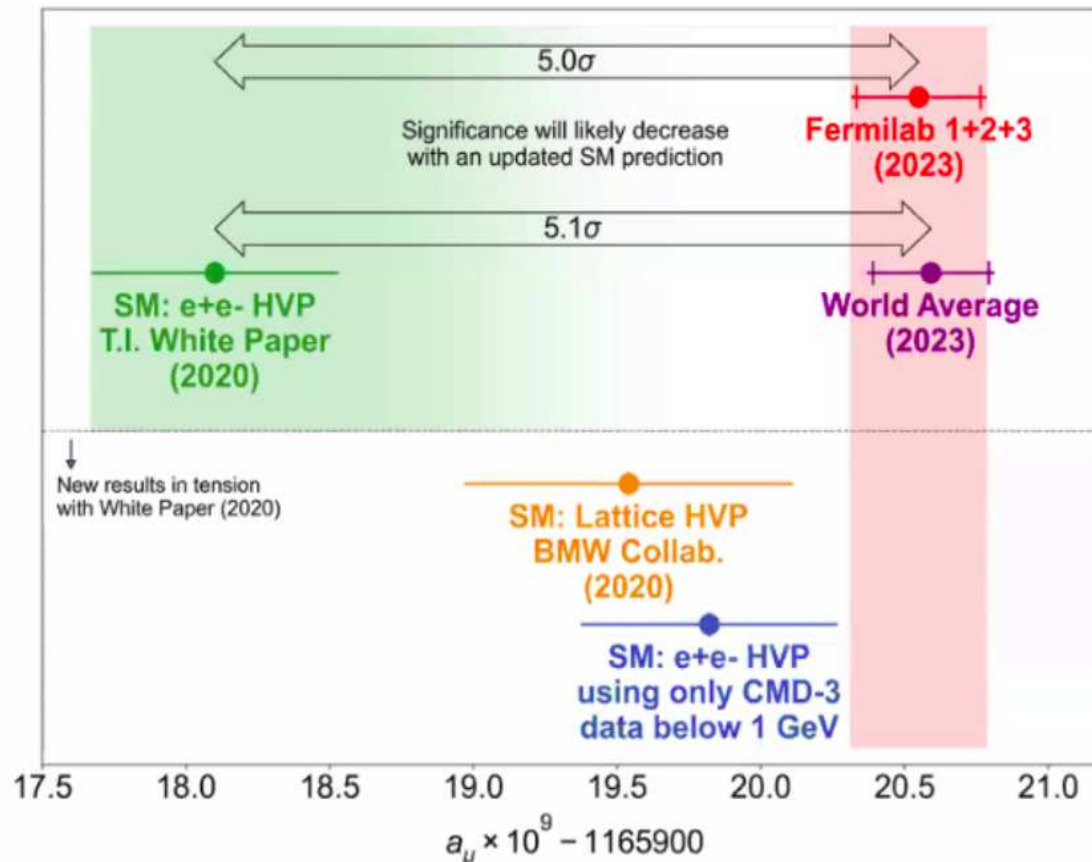
In collaboration with: *M. Chakraborti, I. Saha, C. Schappacher*

1. The main idea
2. Results for (nearly) all SUSY scenarios: Direct Detection prospects
3. ILC/CLIC come to rescue
4. Conclusions

# 1. The main idea

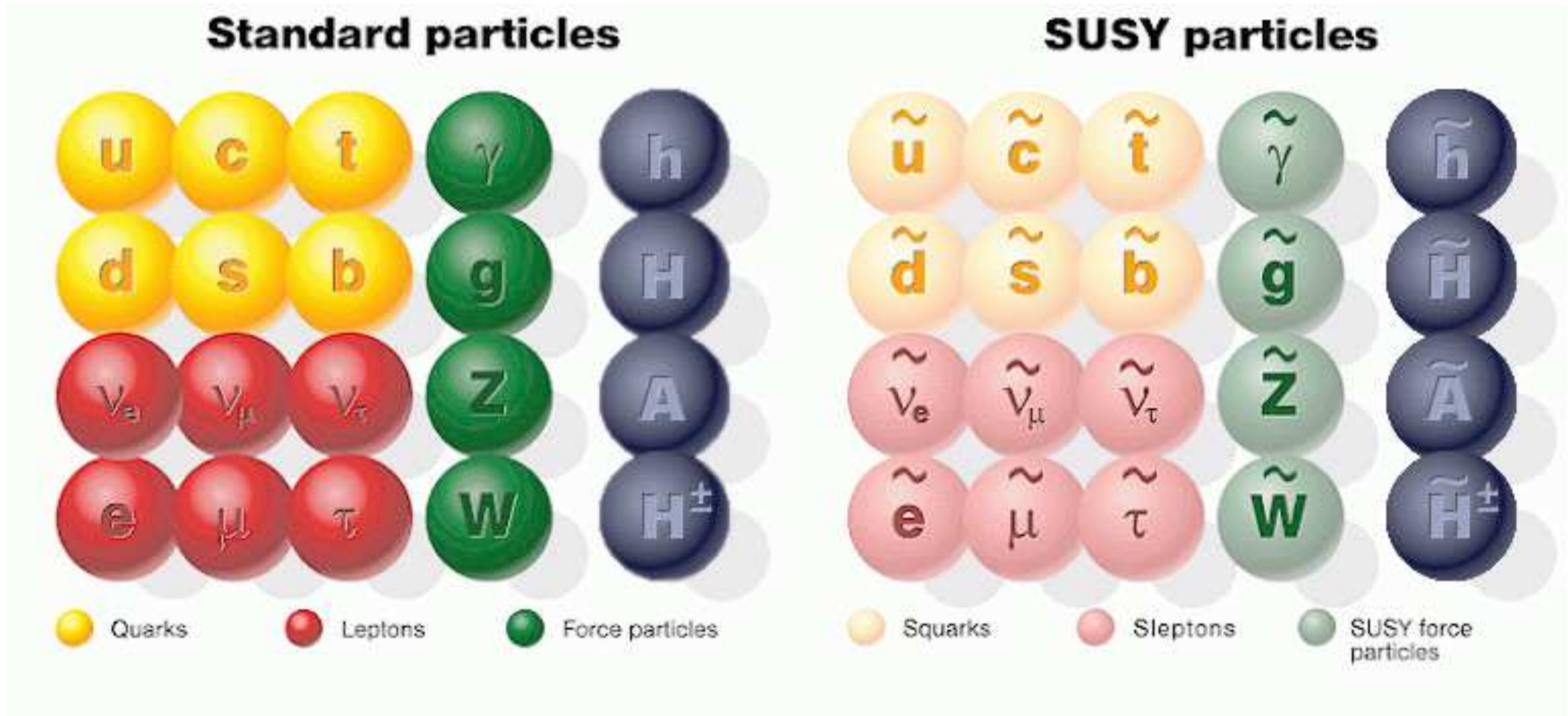
The anomalous magnetic moment of the muon:  $a_\mu \equiv (g - 2)_\mu/2$

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



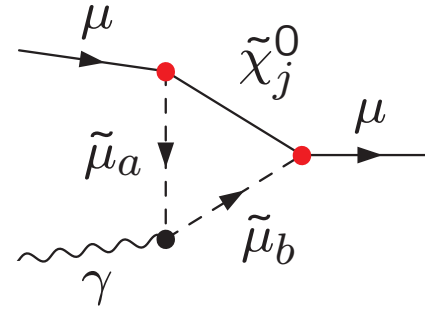
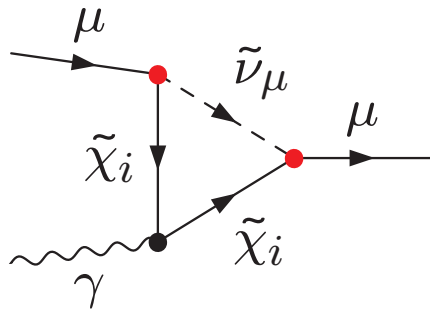
⇒ large uncolored / EW sector

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

Sleptons:  $M_{\tilde{l}_L}, M_{\tilde{l}_R}$  (for now equal for all 3 generations)

## 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 Future Colliders

## $(g - 2)_\mu$ 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

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

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

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

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

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

$\Rightarrow$  predictions for future experiments?!



## 2. Prospects for Direct Detection Experiments



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

Parameter scan:

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

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

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

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

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

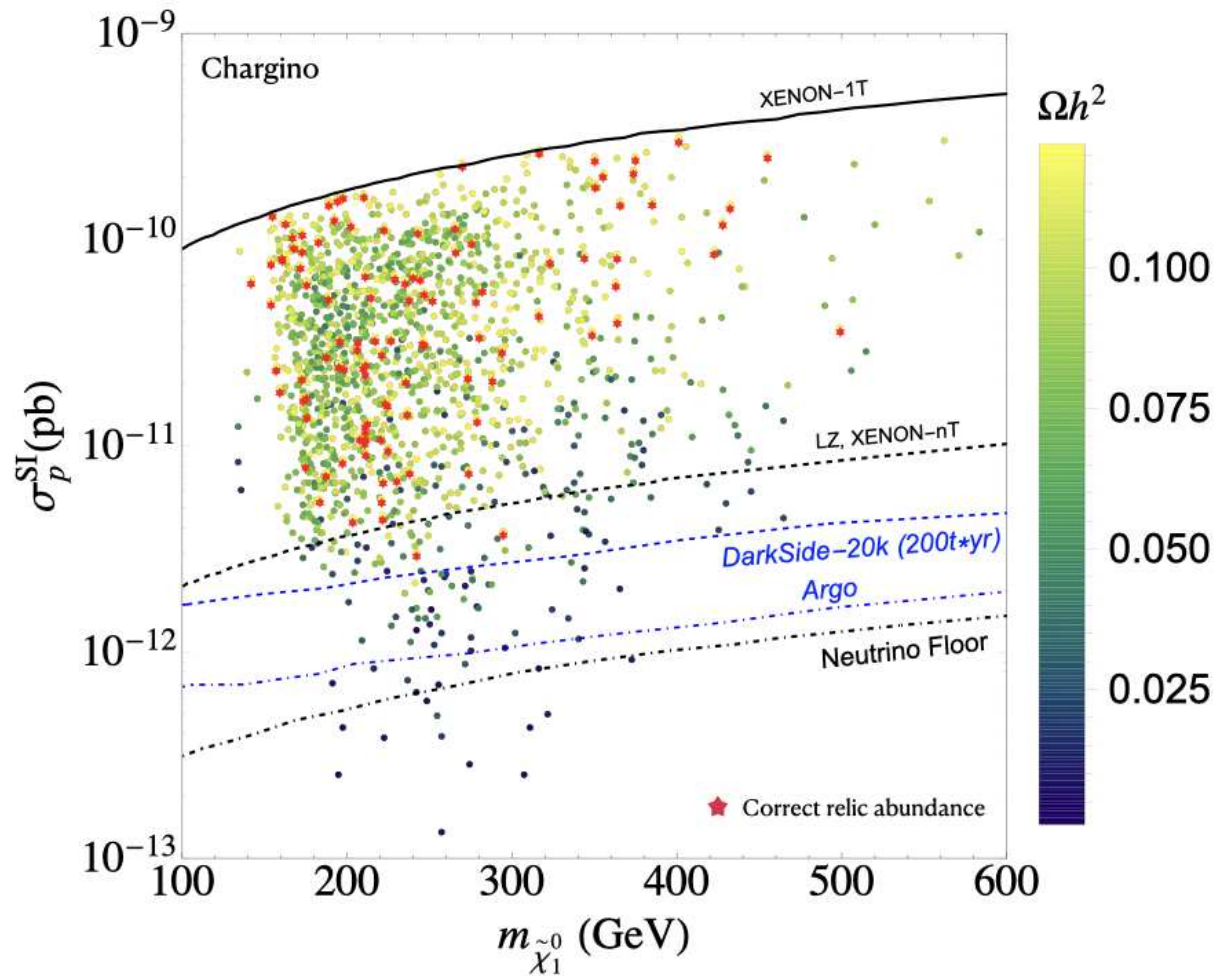
$$m_{\tilde{R}} = m_{\tilde{L}} .$$

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

relic DM density can be 100% fulfilled

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

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



⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

## B/C) Bino DM with slepton co-annihilation

Parameter scan:

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

$$M_1 \leq M_2 \leq 10M_1 ,$$

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

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

$$\text{Case-L: } M_1 \leq m_{\tilde{L}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{R}} \leq 10M_1 .$$

$$\text{Case-R: } M_1 \leq m_{\tilde{R}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{L}} \leq 10M_1 .$$

relic DM density can be 100% fulfilled

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

## B/C) Bino DM with slepton co-annihilation

Parameter scan:

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

$$M_1 \leq M_2 \leq 10M_1 ,$$

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

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

$$\text{Case-L: } M_1 \leq m_{\tilde{L}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{R}} \leq 10M_1 .$$

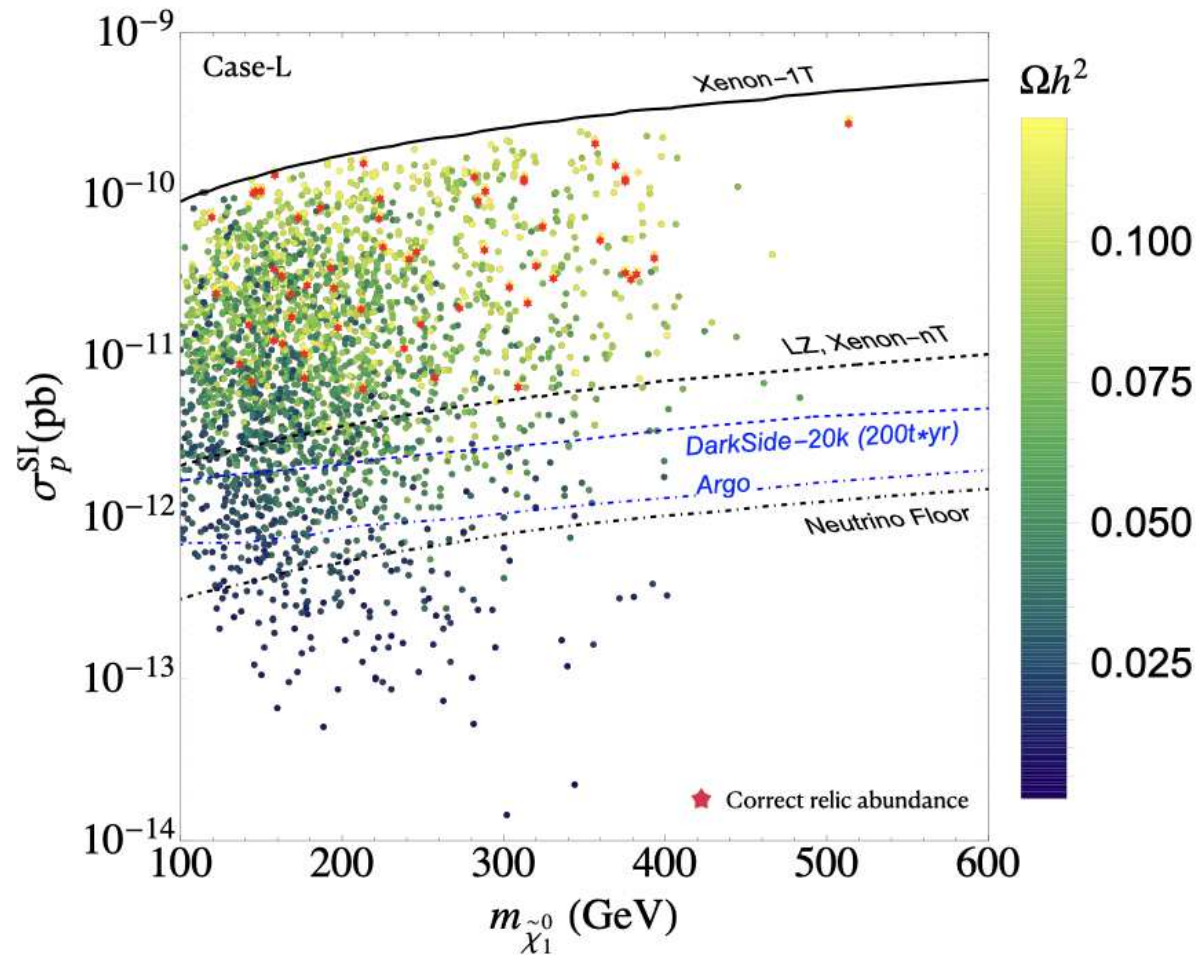
$$\text{Case-R: } M_1 \leq m_{\tilde{R}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{L}} \leq 10M_1 .$$

relic DM density can be 100% fulfilled

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

$\Rightarrow$  funny that nobody ever complained here ...

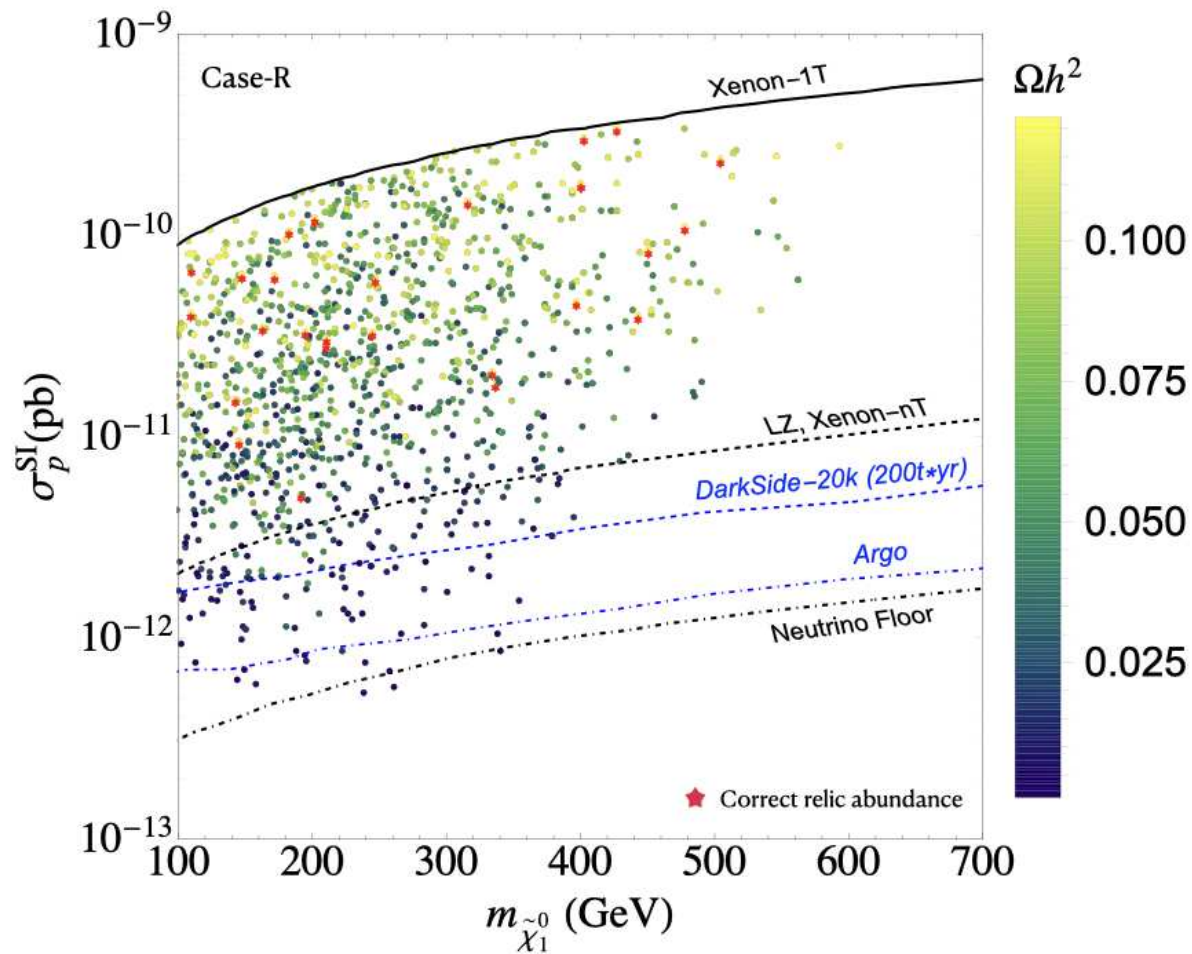
Case-L: results in the  $m_{\tilde{\chi}_1^0} - \sigma_p^{\text{SI}}$  plane:



⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

Case-R: results in the  $m_{\tilde{\chi}_1^0} - \sigma_p^{SI}$  plane:



⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

## D) Higgsino DM

Parameter scan:

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

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

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

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

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

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

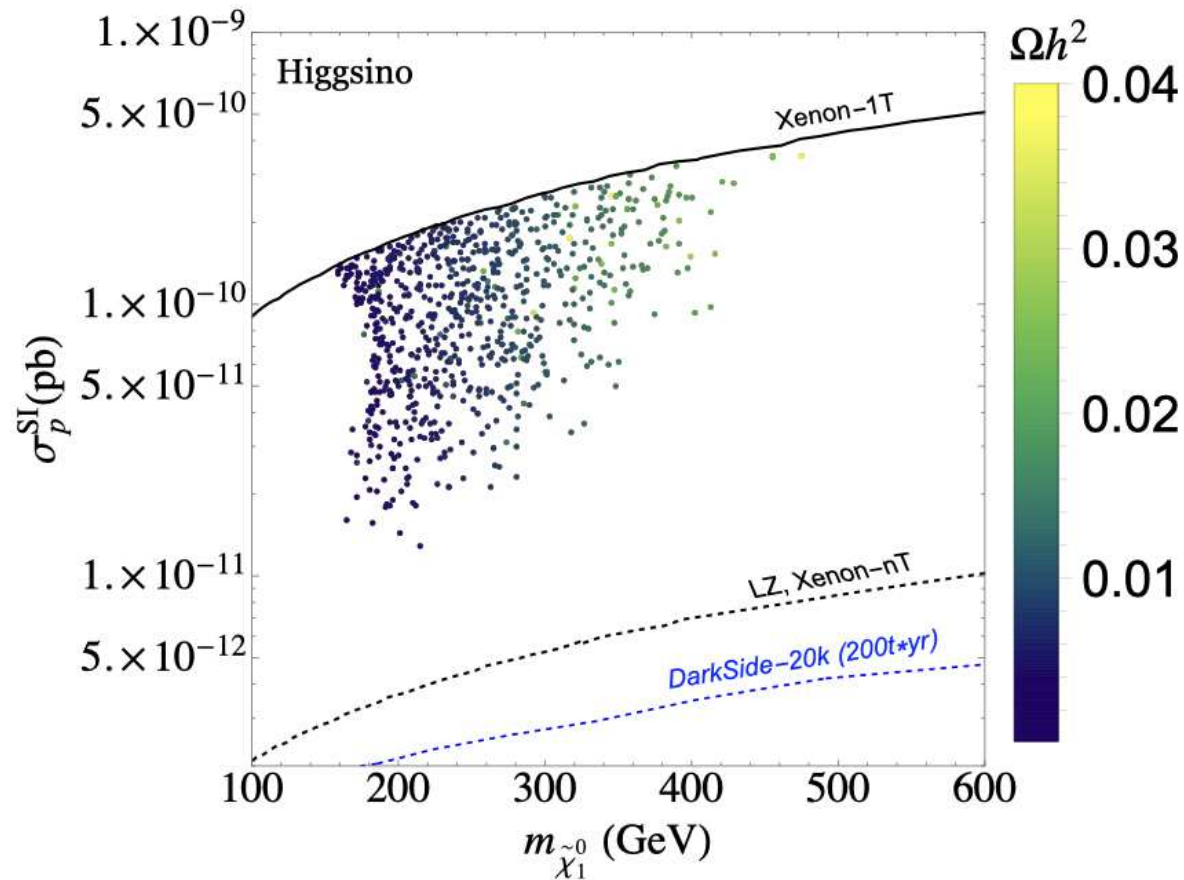
Full DM relic density reached only for  $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$

$\Rightarrow$  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

## E) Wino DM

Parameter scan:

$$100 \text{ GeV} \leq M_2 \leq 1.5 \text{ TeV} ,$$

$$1.1M_2 \leq M_1 \leq 10M_2 ,$$

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

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

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

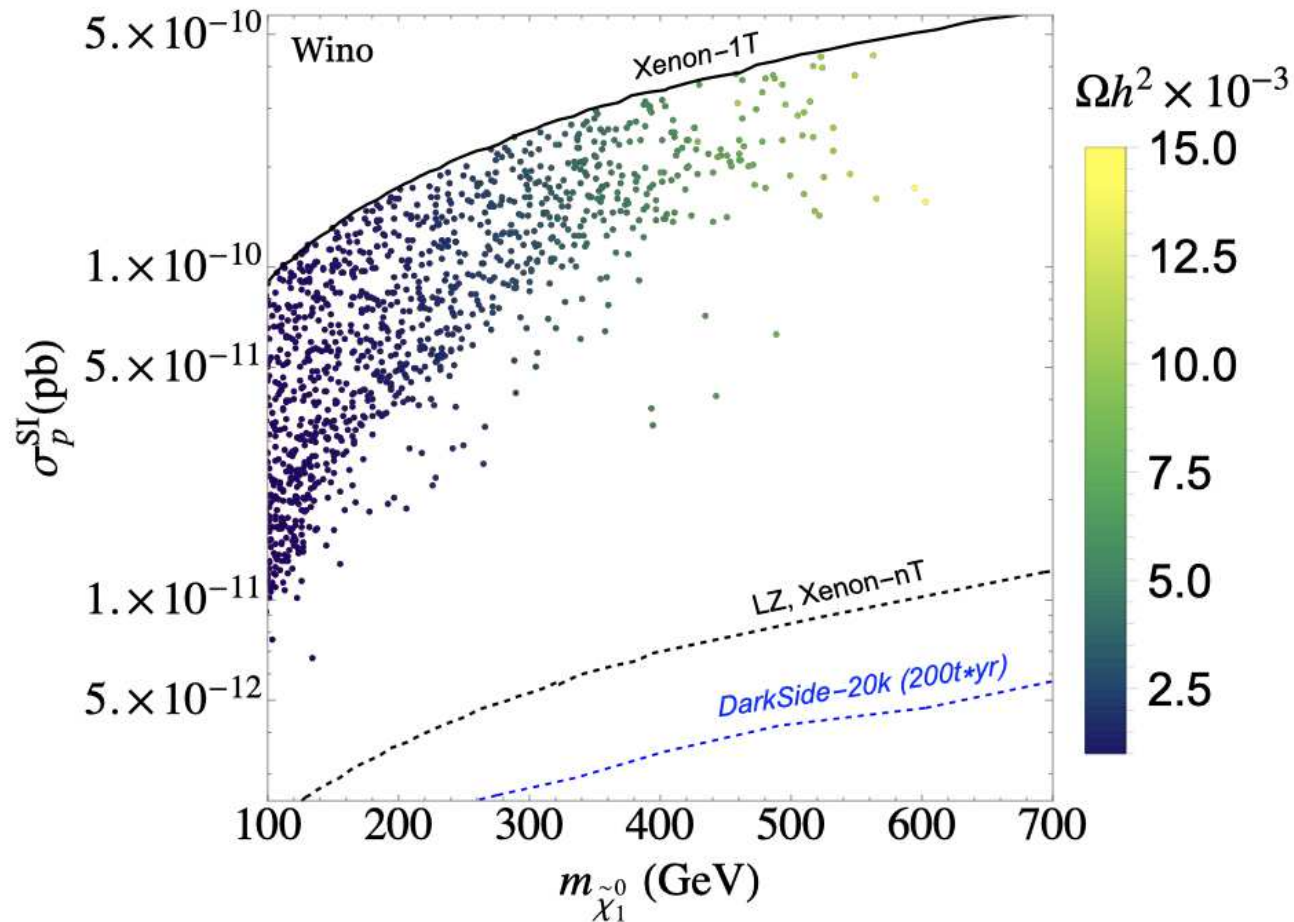
$$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$$

Full DM relic density reached only for  $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV}$

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

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

## 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

### 3. ILC/CLIC come to rescue

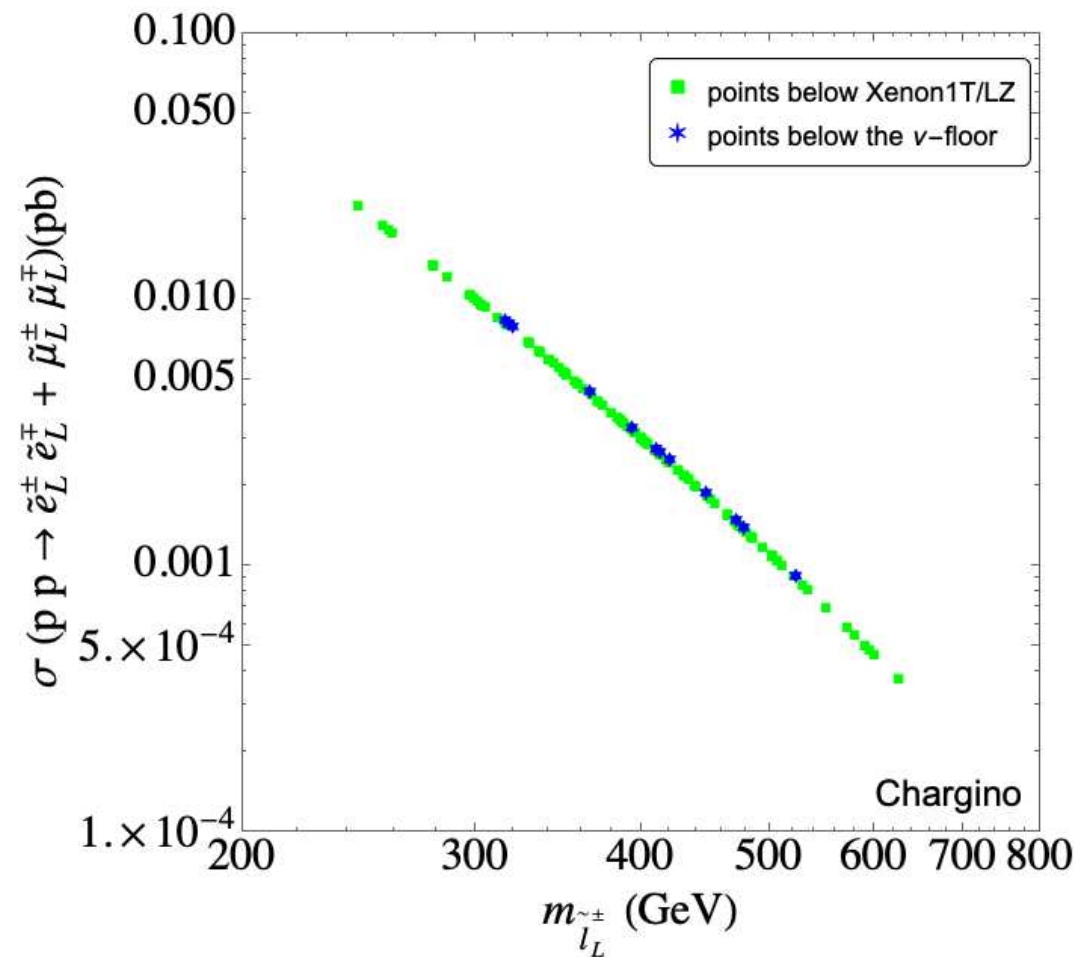
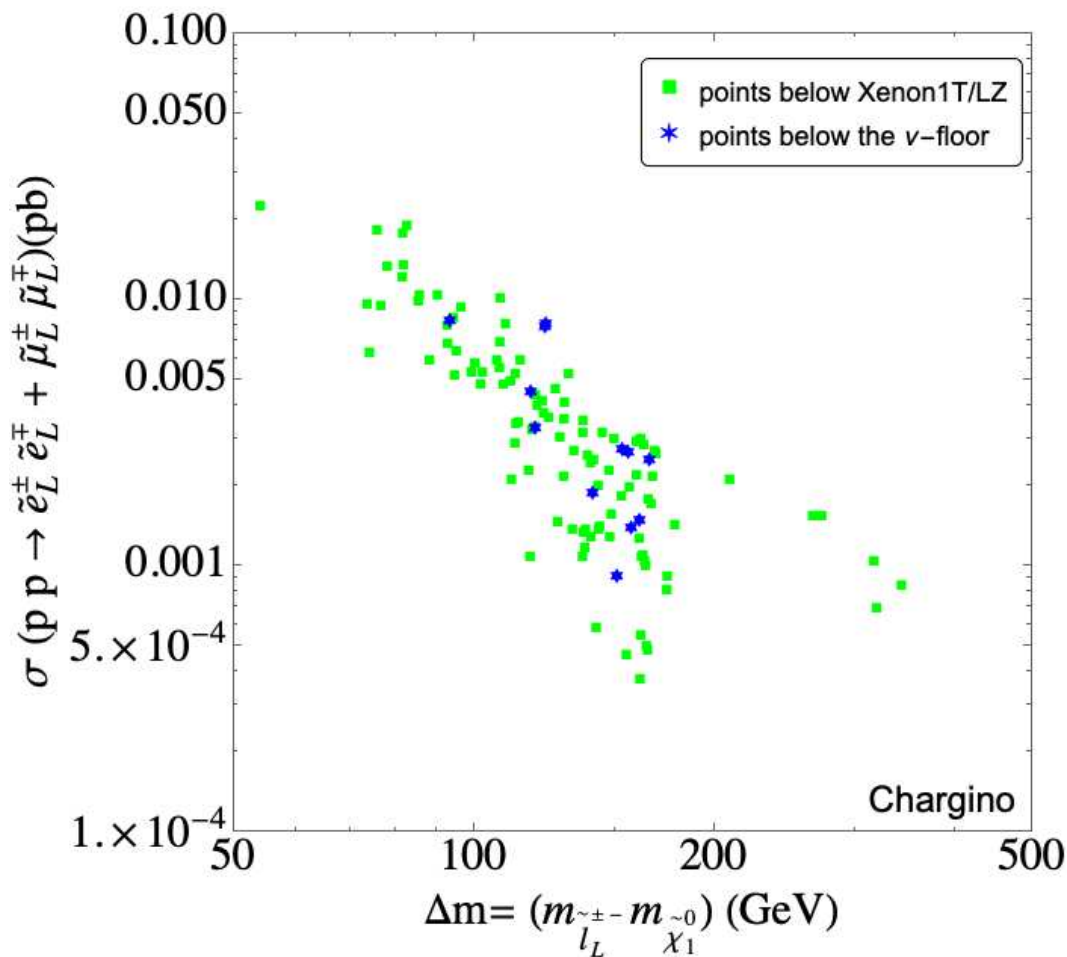
#### Scenarios A/B/C:

- ⇒ partially(!) covered by XENON-nT/LZ
- ⇒ but can even go below even the neutrino floor
- ⇒ (HL-)LHC has naturally problems because of compressed spectra
- ⇒ (HL-)LHC must go for heavier particles
- ⇒ compressed spectra “easy” for  $e^+e^-$  colliders
- ⇒ physics opportunities for ILC/CLIC?!

#### Scenarios D/E:

- ⇒ everything covered by XENON-nT/LZ
- ⇒ Direct Detection experiments cover the full parameter space
- ⇒ what can be learned at ILC/CLIC?
  
- ⇒ ILC and CLIC physics opportunities (in the light of (HL-)LHC . . .)

# (HL-)LHC cross sections for $\tilde{\chi}_1^\pm$ -coannihilation (non-compressed):

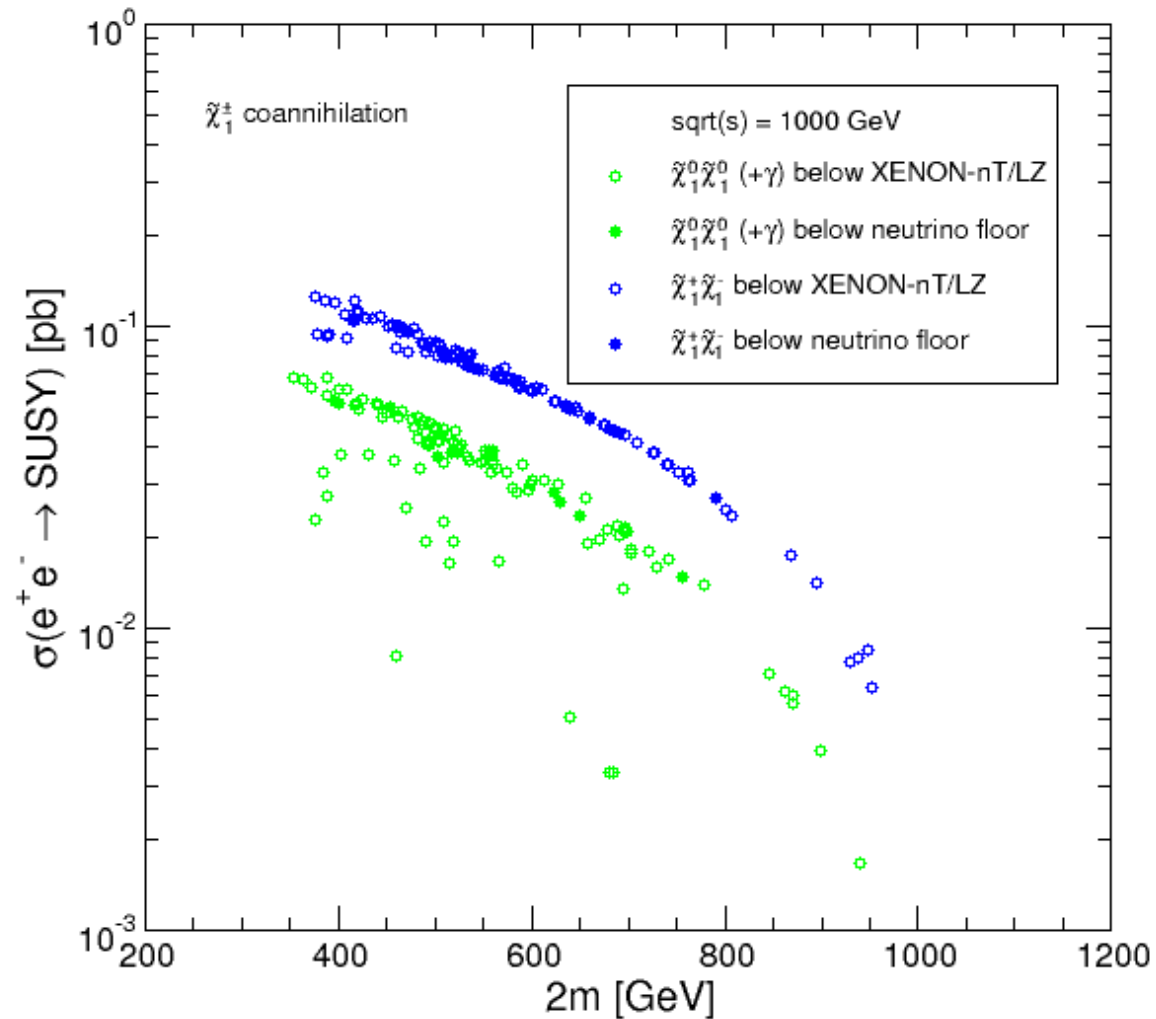


$\Rightarrow$  XS above 0.4 fb  $\Rightarrow$  more than 1200 events

$\Rightarrow$  even better for "BNF" points: XS above 1 fb

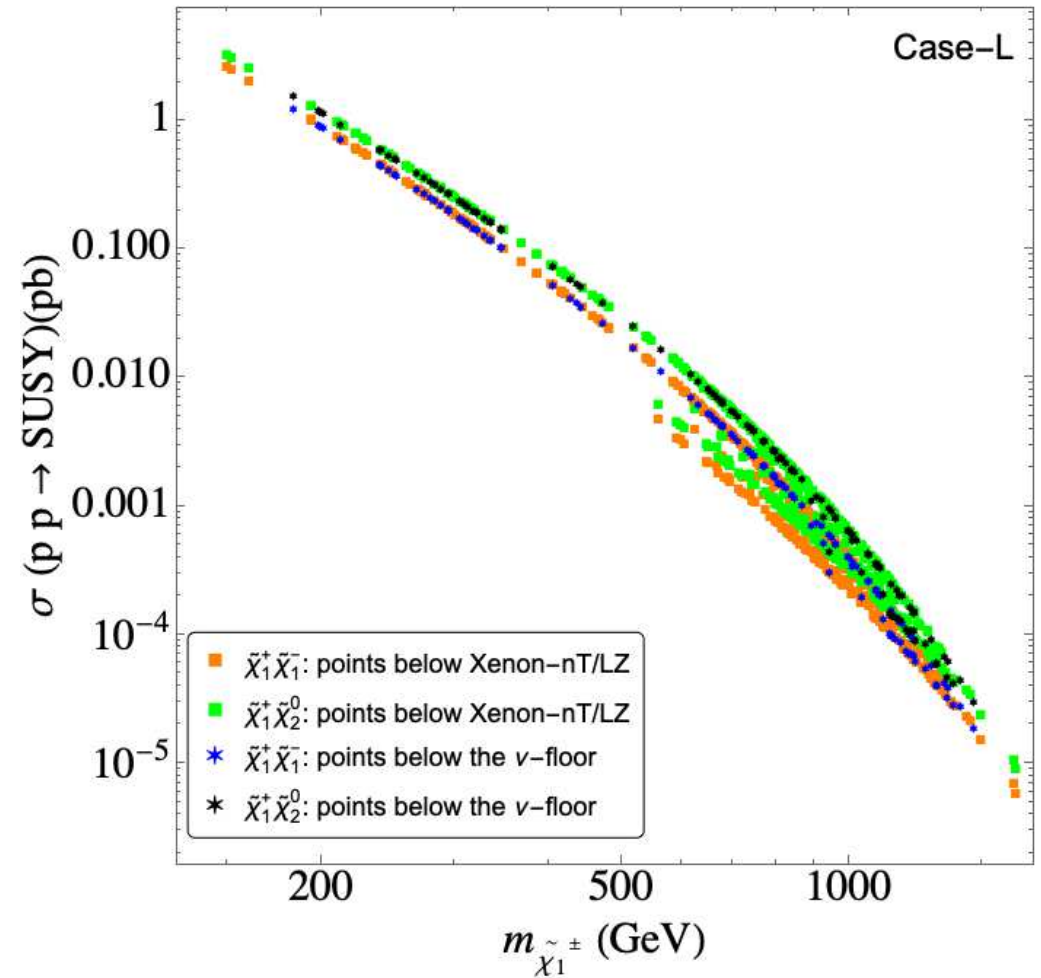
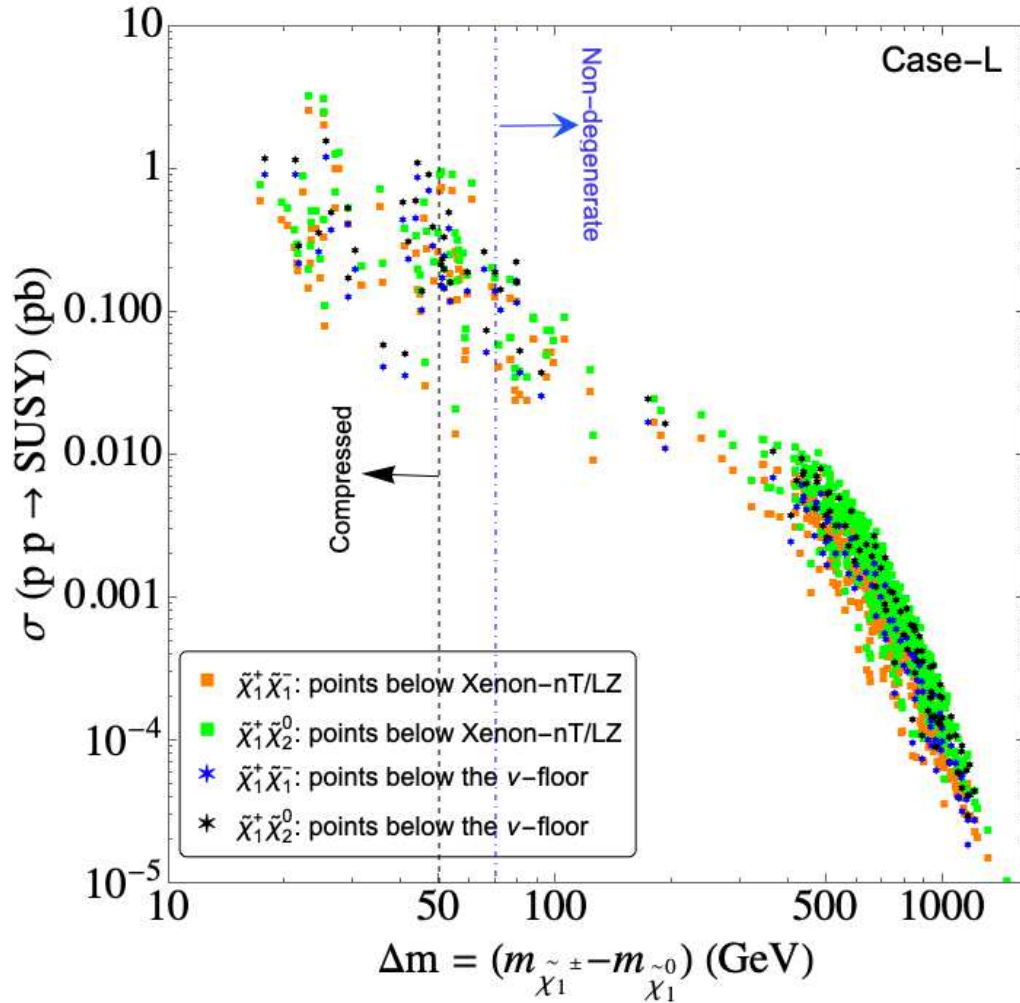
But: detailed (HL-)LHC analysis missing! (spectra not too compressed!)

# ILC1000 cross sections for $\tilde{\chi}_1^\pm$ -coannihilation (compressed):



⇒ ILC1000 can cover everything!

# (HL-)LHC cross sections for $\tilde{l}$ -coannihilation case-L (non-compressed):

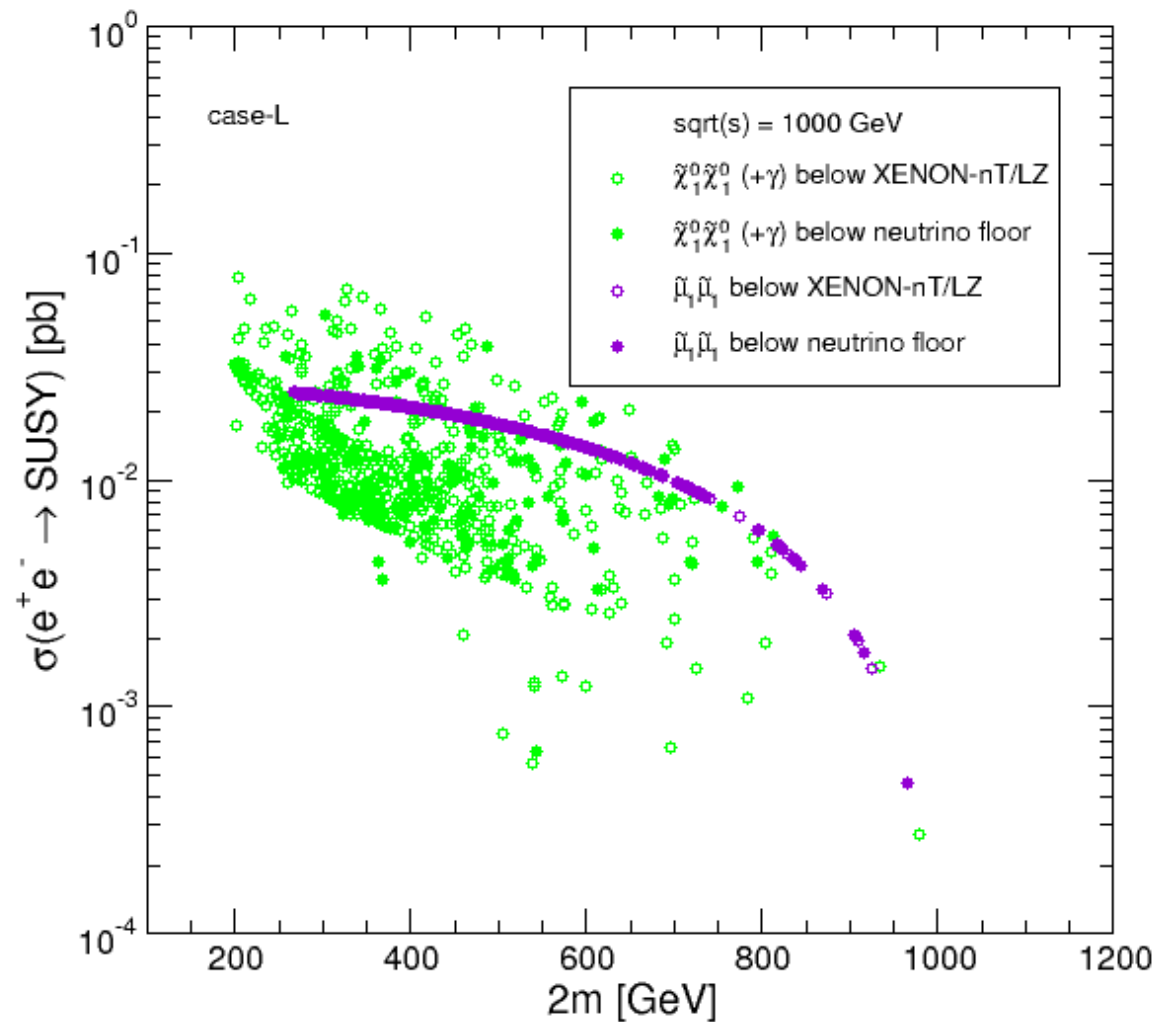


⇒ XS above 0.01 fb ⇒ more than 30 events

⇒ no improvement for “BNF” points!

⇒ high-energy  $e^+e^-$  collider needed (CLIC3000)!

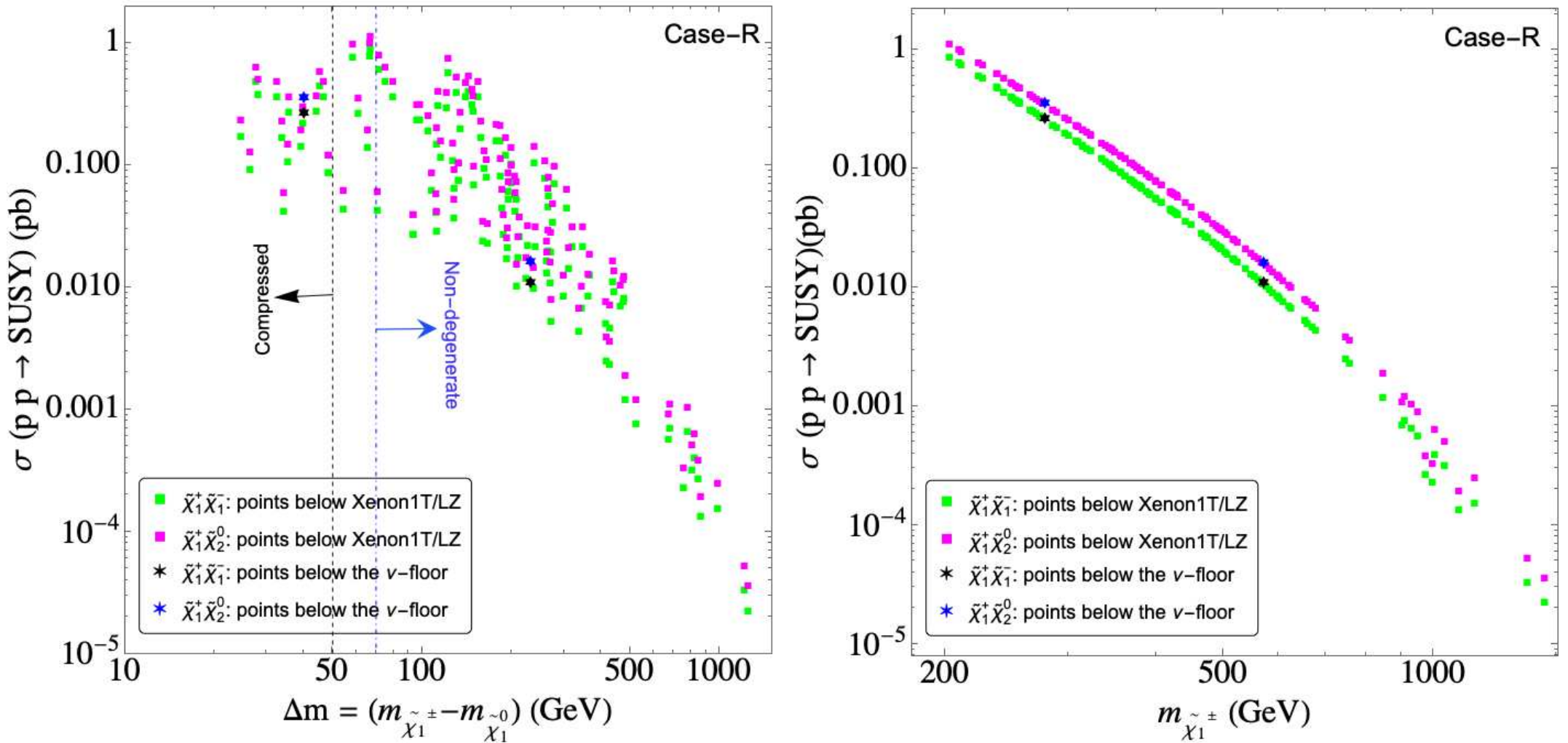
## ILC1000 cross sections for $\tilde{l}$ -coannihilation case-L (compressed):



$\Rightarrow$  ILC1000 can cover everything!



(HL-)LHC cross sections for  $\tilde{l}$ -coannihilation case-R (non-compressed):

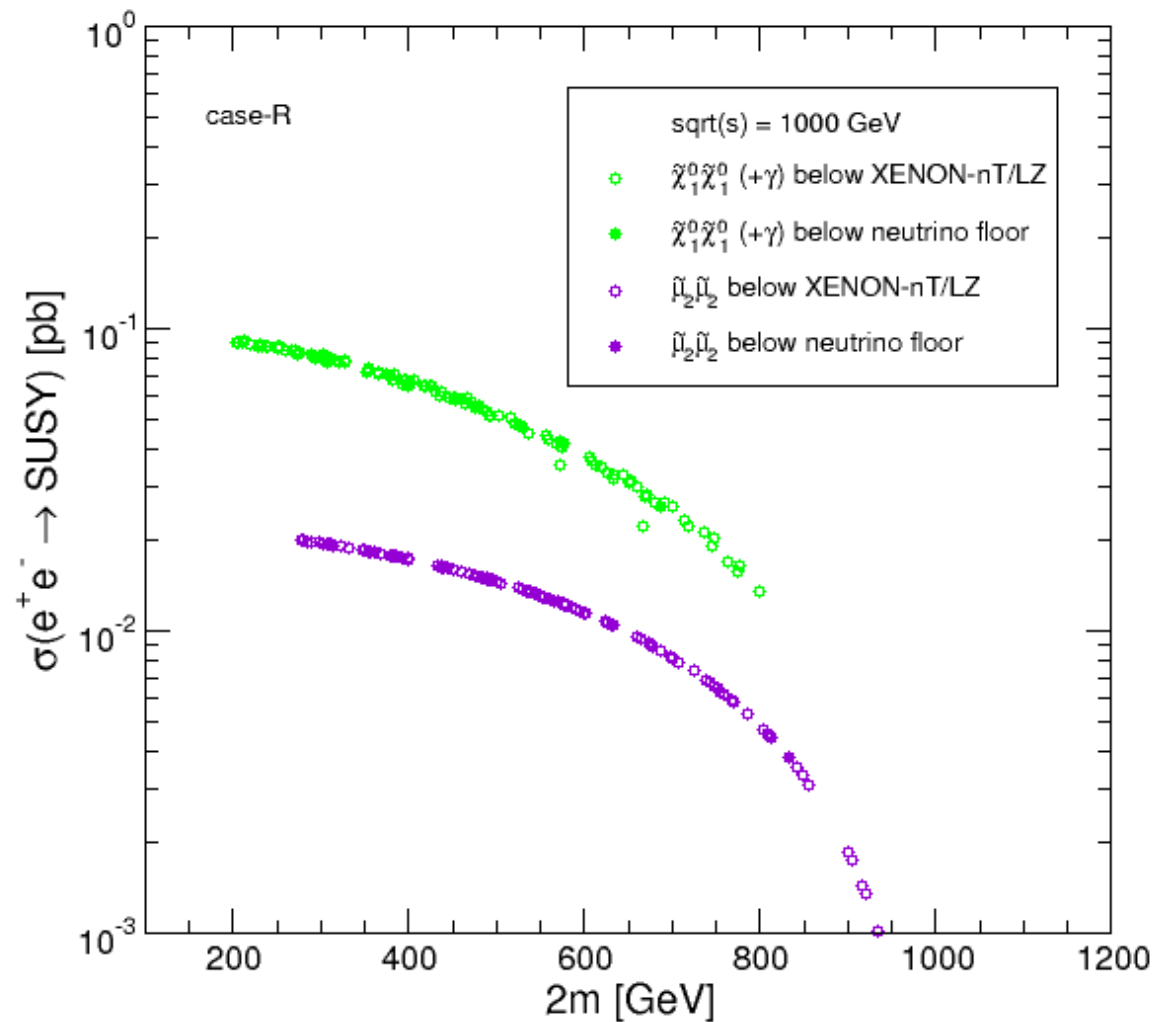


$\Rightarrow$  XS above 0.04 fb  $\Rightarrow$  more than 120 events

$\Rightarrow$  very good for "BNF" points: XS above 10 fb

But: detailed (HL-)LHC analysis missing! (spectra can be compressed!)

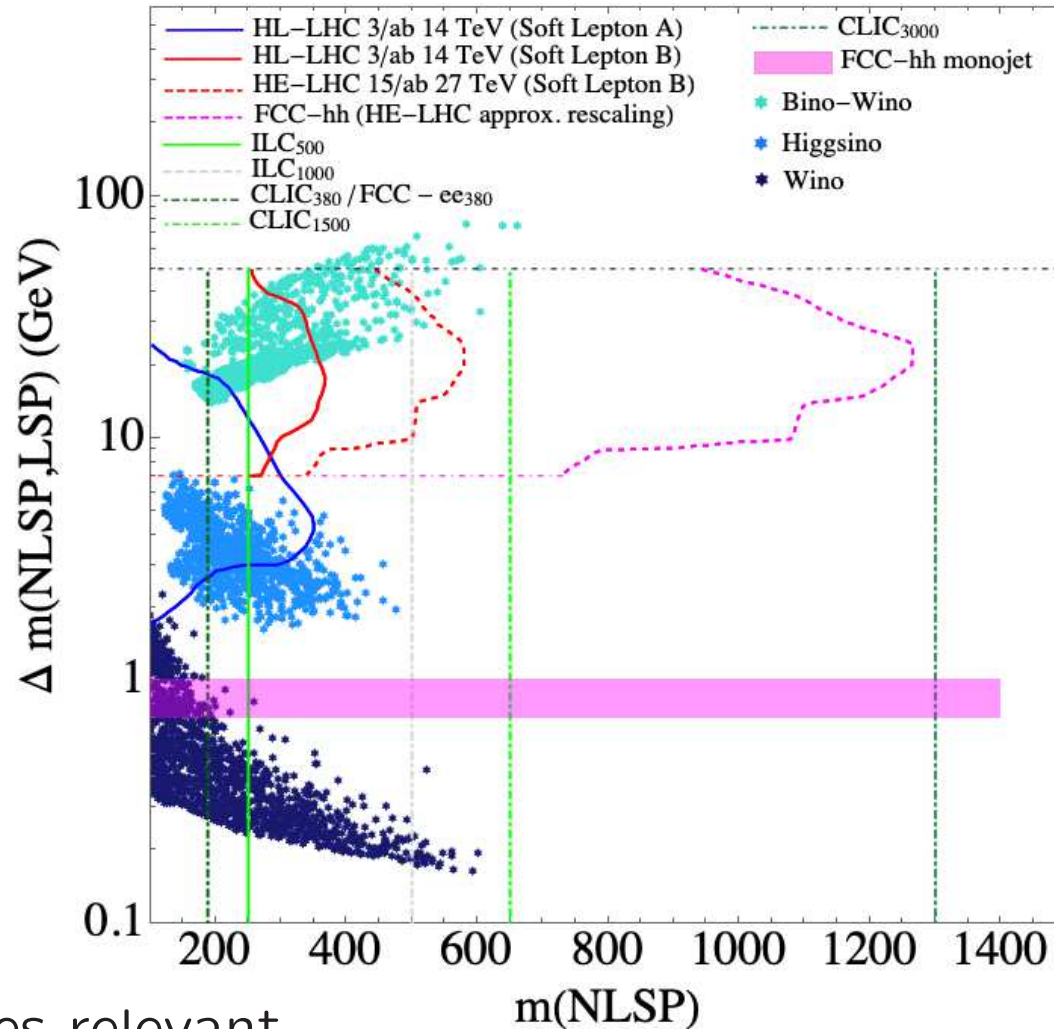
## ILC1000 cross sections for $\tilde{l}$ -coannihilation case-R (compressed):



$\Rightarrow$  ILC1000 can cover everything!

# Compressed spectra at current and future colliders

## Higgsino, wino and bino/wino DM:



- current searches relevant
- HL-LHC searches can cover some part of the parameter space
- ILC/CLIC needed to cover these scenarios

## 4. Conclusinos

- $(g - 2)_\mu$  is real  $\Rightarrow$  (relatively) light EW particles  $\Rightarrow$  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/FCs
- A) bino/wino DM with chargino coann. (DM full):  $m_{(N)LSP} \lesssim 650(700)$  GeV  
B/C) bino DM with slepton coann. (DM full):  $m_{(N)LSP} \lesssim 650(700)$  GeV  
D) higgsino eDM  $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$  (DM u.l.):  $m_{(N)LSP} \lesssim 500$  GeV  
E) wino DM  $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$  (DM u.l.):  $m_{(N)LSP} \lesssim 600$  GeV
- Direct Detection prospects:
  - bino/wino DM with  $\tilde{\chi}_1^\pm$ -coann., bino DM with  $\tilde{l}$ -coann.:  
allowed points go below Xenon-nT/LZ and even neutrino floor
  - higgsino/wino DM: DD experiments cover everything
- Interplay with FCs: DM  $\Leftrightarrow$  compressed spectra  $\Rightarrow pp$  :- ( ,  $e^+e^-$  :-)  
below X-nT/LZ: HL-LHC:  $\sigma \gtrsim 0.5 - 0.1$  fb  $\Rightarrow$  prospects unclear  
ILC1000: can cover everything easily



Further Questions?

## 5. The missing channel

### B/C) Bino DM with slepton co-annihilation

Parameter scan:

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

$$M_1 \leq M_2 \leq 10M_1 ,$$

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

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

$$\text{Case-L: } M_1 \leq m_{\tilde{L}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{R}} \leq 10M_1 .$$

$$\text{Case-R: } M_1 \leq m_{\tilde{R}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{L}} \leq 10M_1 .$$

relic DM density can be 100% fulfilled

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

$\Rightarrow$  funny that nobody ever complained here ...

## Potential problem:

Slepton co-annihilation directly linked to  $(g - 2)_\mu$

⇒ slepton mass parameters chosen identical for all three generations

⇒ what happens if stau co-annihilation is chosen,  
and no directly link to smuons contributing to  $(g - 2)_\mu$  is made ??

## Parameter scan for stau co-annihilation:

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

$$1.1M_1 \leq M_2 \leq 10M_1 ,$$

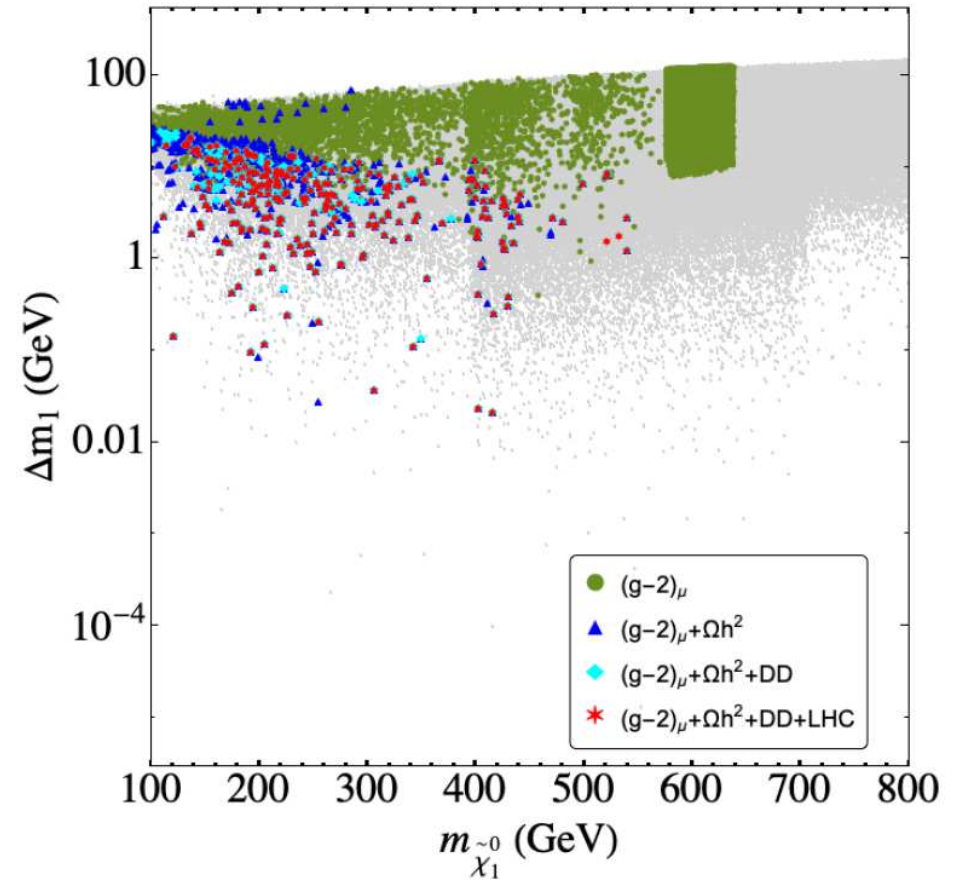
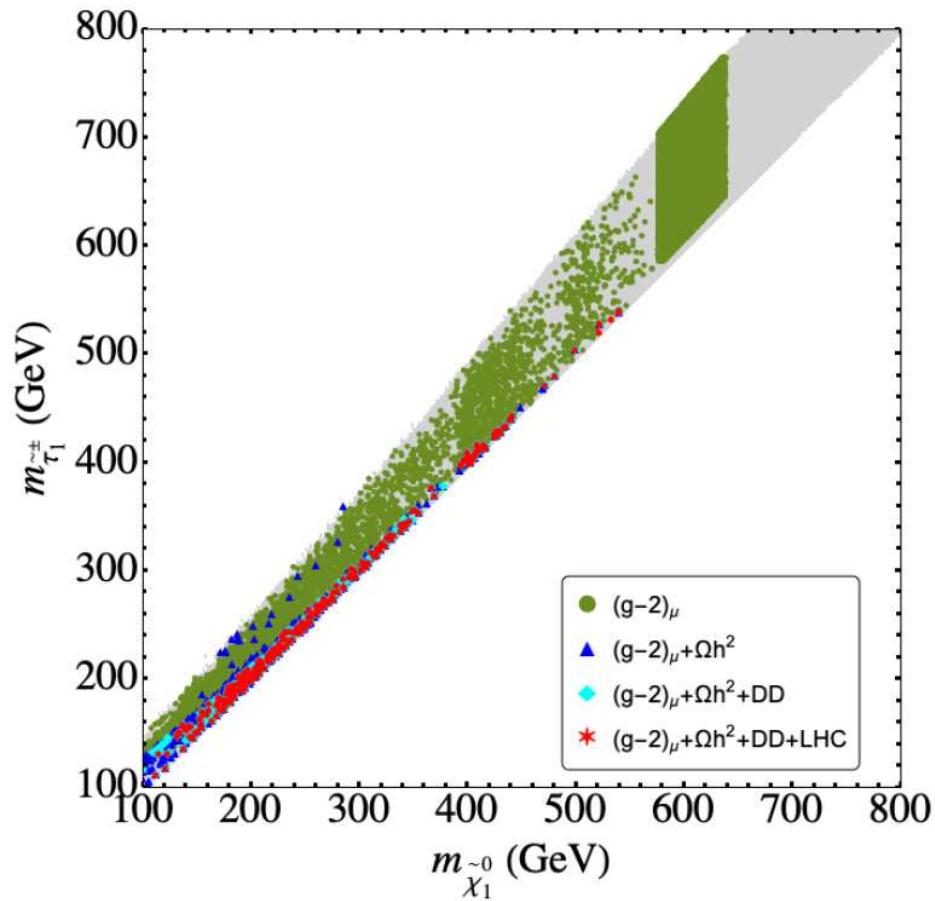
$$1.1M_1 \leq \mu \leq 10M_1 ,$$

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

$$1.1M_1 \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 10M_1 ,$$

$$A_\tau^2 \leq 7.5(m_{\tilde{\tau}_L}^2 + m_{\tilde{\tau}_R}^2) - 3\mu^2 ,$$

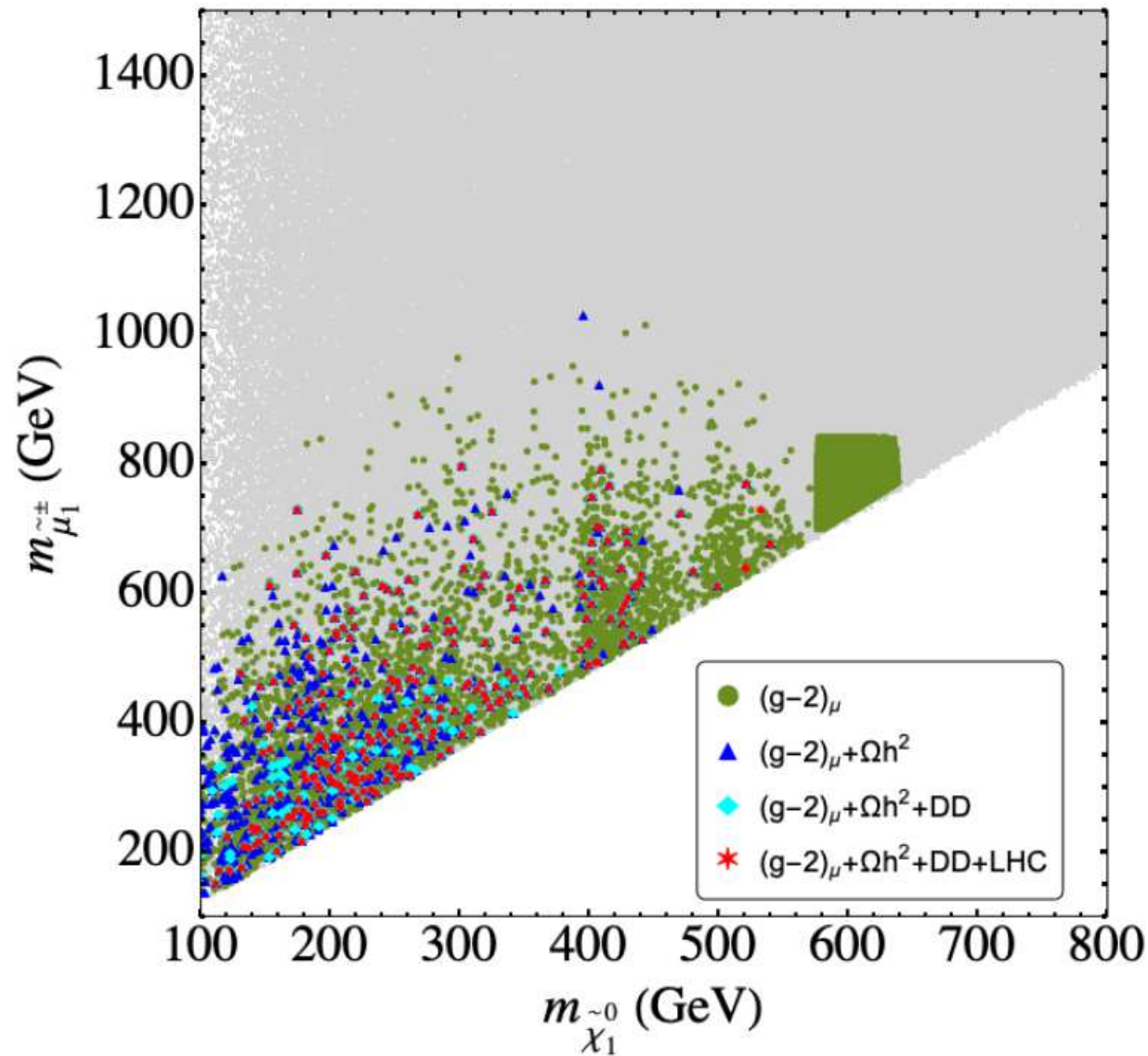
$$\text{Stau-L/R: } M_1 \leq m_{\tilde{\tau}_{L/R}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{\tau}_{R/L}} \leq 10M_1.$$



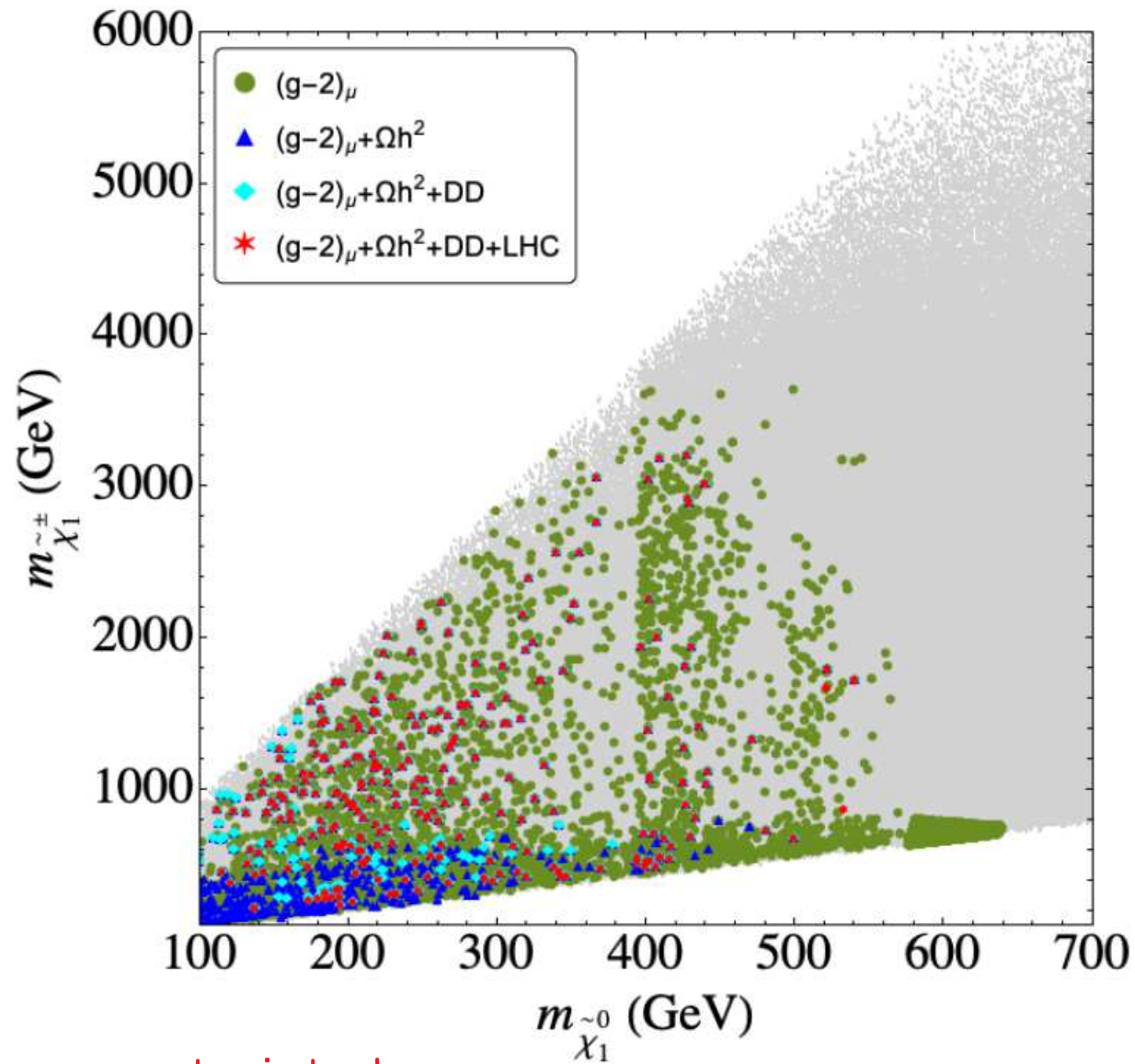
$\Rightarrow m_{(N)LSP} \lesssim 550 \text{ GeV}$

$\Rightarrow$  higher  $m_{\tilde{\chi}_1^0}$   $\Leftrightarrow$  smaller  $\Delta m_{\tilde{\tau}_1}$

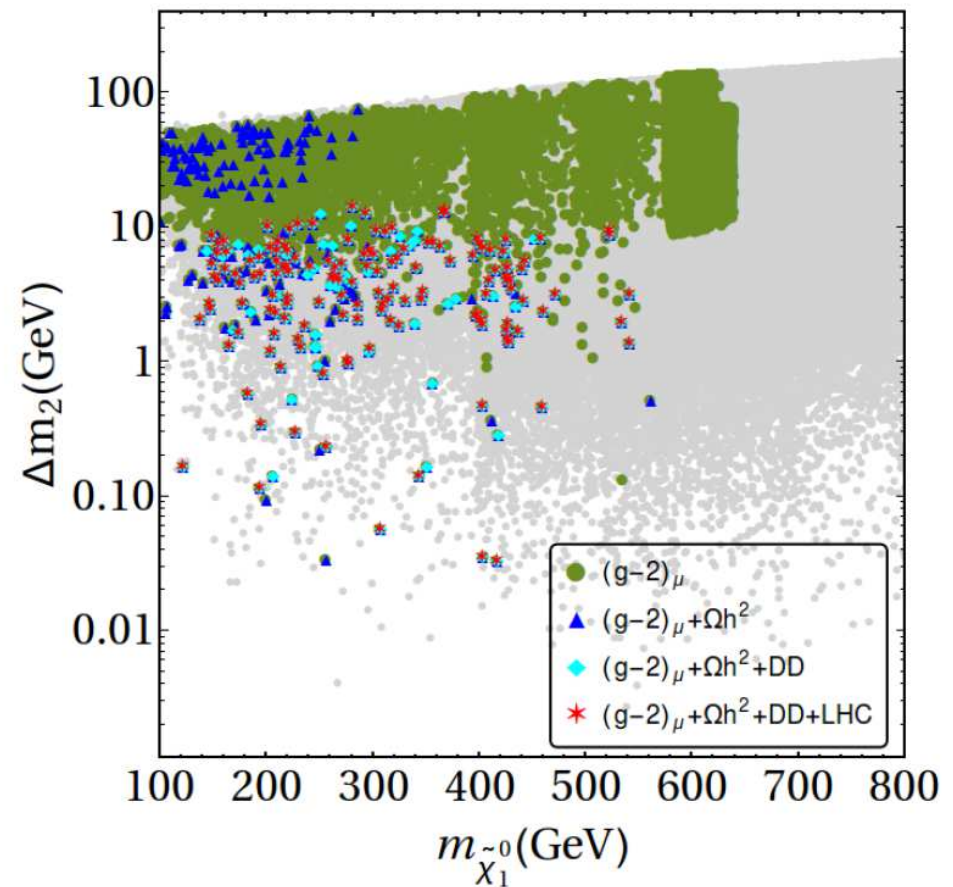
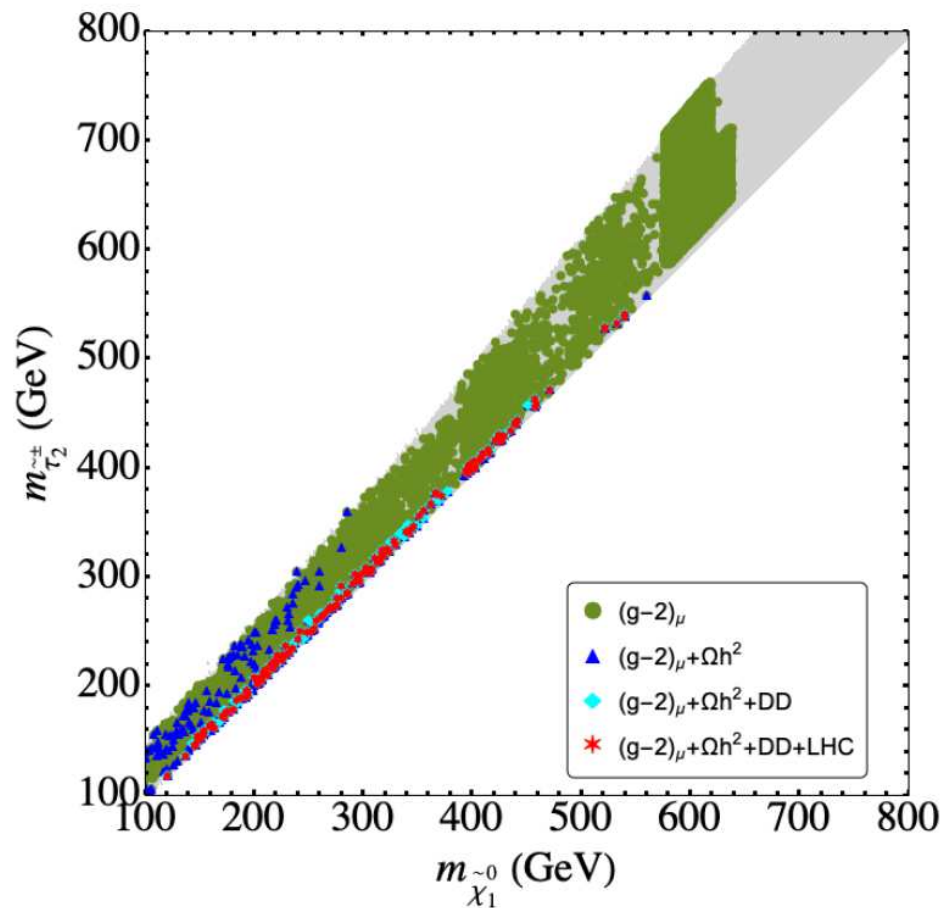




$\Rightarrow m_{\tilde{\mu}_1} \lesssim 800$  GeV (only  $\sim 100$  GeV higher than for  $\tilde{\mu}_1$ -coannihilation)



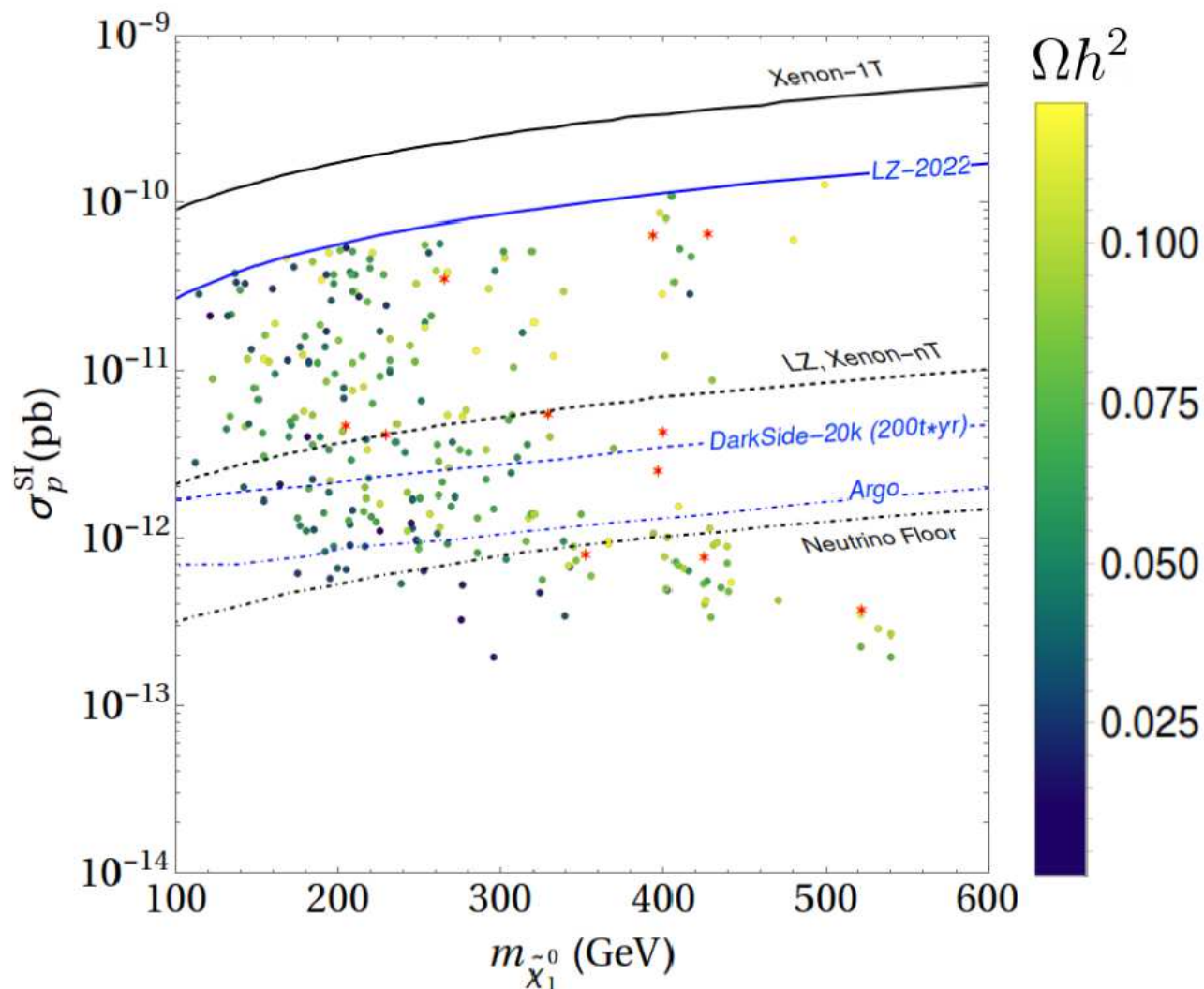
$\Rightarrow m_{\tilde{\chi}_1^\pm}$  nearly unconstrained



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

$\Rightarrow$  Stau-L and Stau-R effectively identical in all respects

$\Rightarrow$  will only show Stau-L from now on

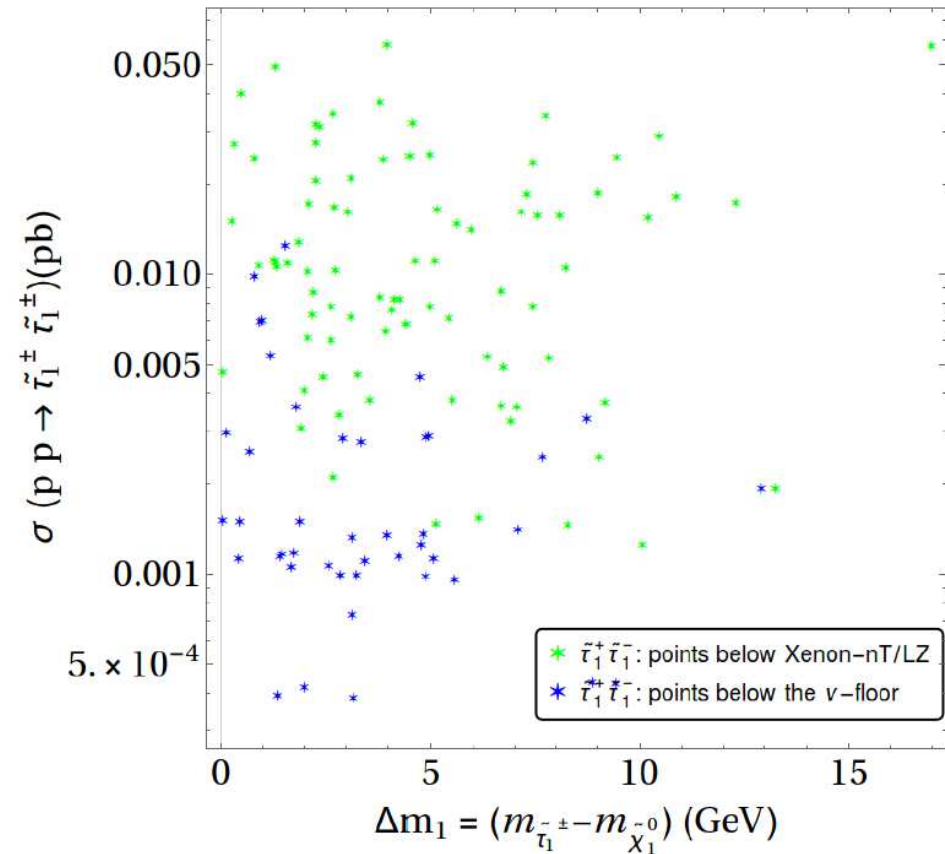
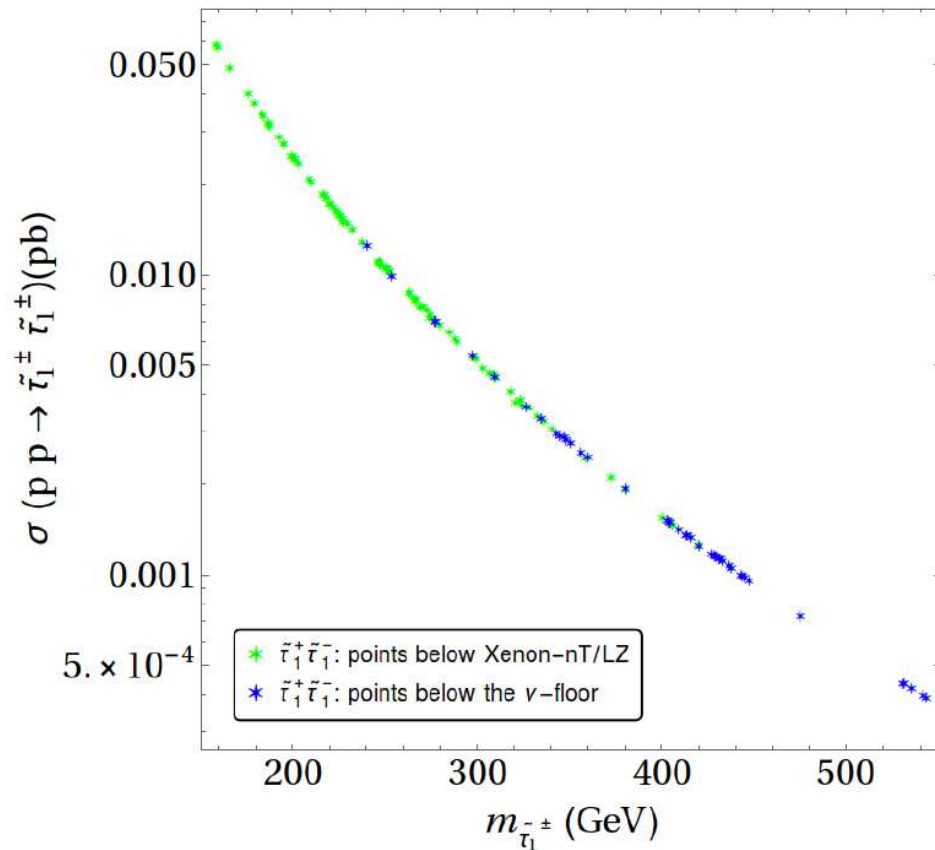


⇒ large part covered by Xenon-nT/LZ

⇒ but can go below even the neutrino floor (in particular for  $m_{\tilde{\chi}_1^0} \gtrsim 500$  GeV)

# Stau co-annihilation case-L: DD/HL-LHC complementarity: [PRELIMINARY]

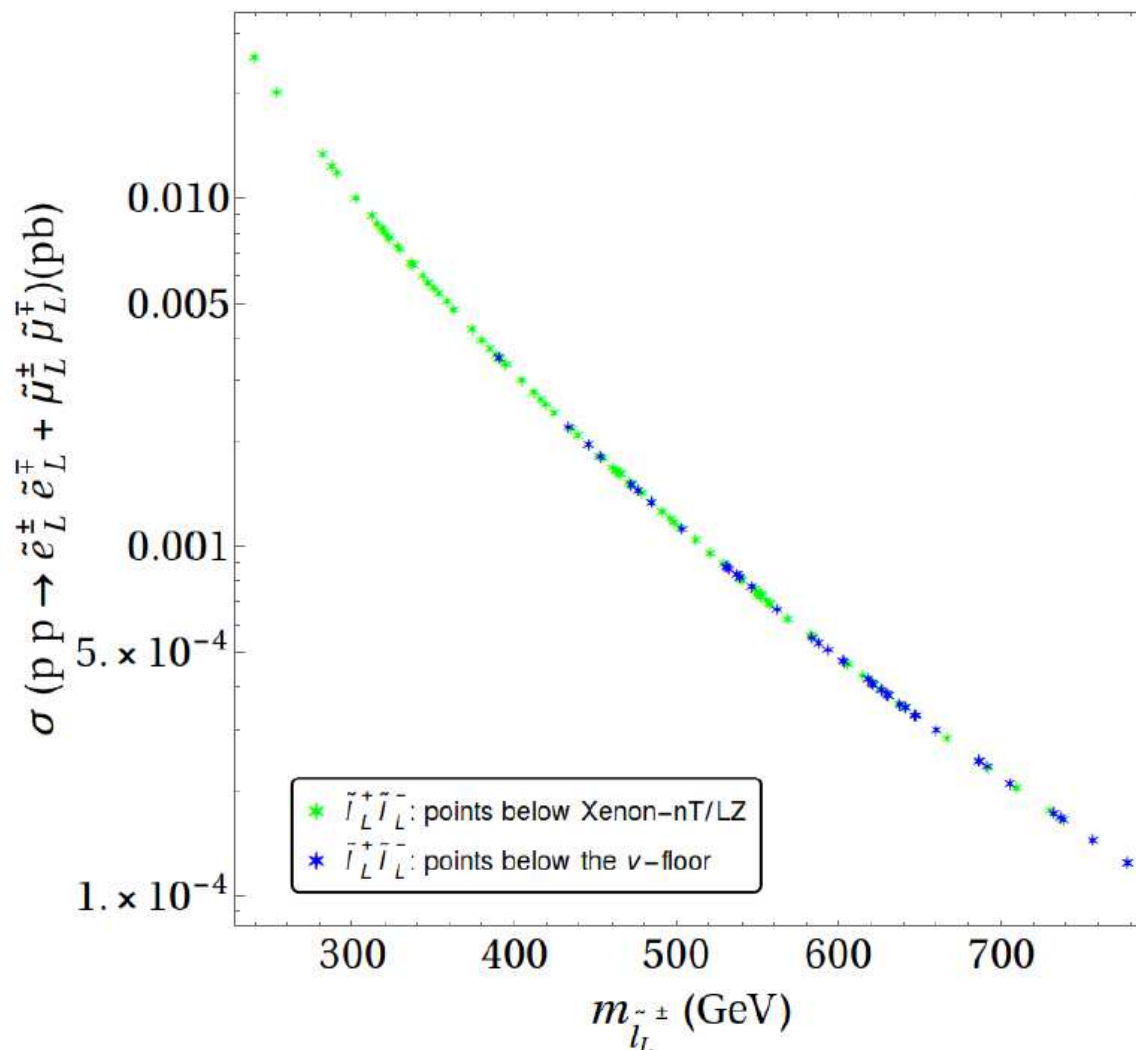
points below LZ limit:



⇒ possibly in the kinematic reach, but compressed spectra!

⇒ ILC/CLIC? ⇒ too heavy for ILC1000 :-)

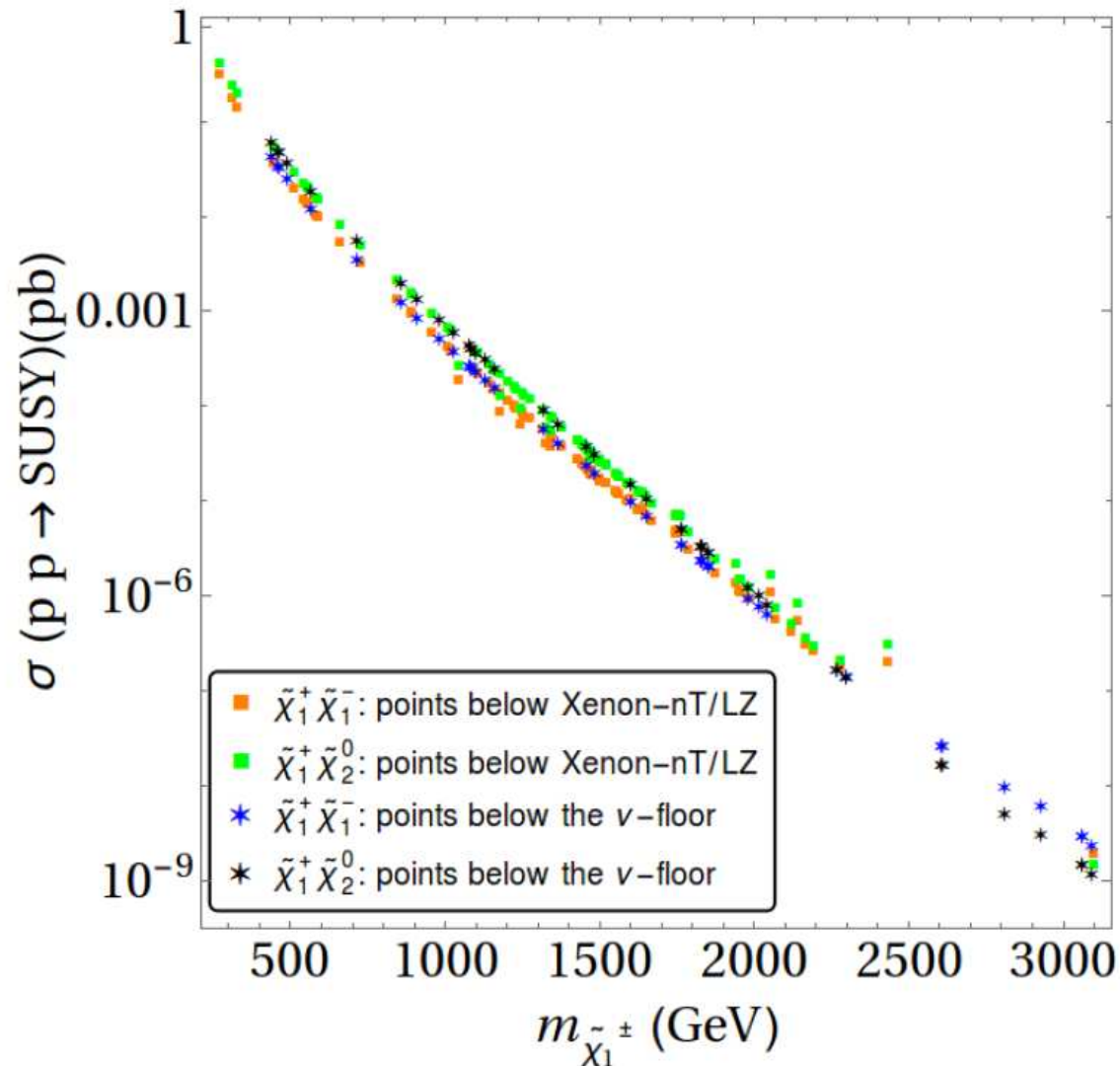
Stau co-annihilation case-L: DD/HL-LHC complementarity: [PRELIMINARY]  
points below LZ limit:



⇒ possibly in the kinematic reach, possibly outside

⇒ prospects unclear

Stau co-annihilation case-L: DD/HL-LHC complementarity: [PRELIMINARY]  
points below LZ limit:



⇒ possibly in the kinematic reach, possibly outside

⇒ prospects unclear

## LHC searches: (as given for Simplified Model Spectra (SMS))

### Decay via sleptons (3I)

$$\begin{aligned}\tilde{\chi}_1^\pm \tilde{\chi}_2^0 &\rightarrow (\tilde{l}^\pm \nu)(\tilde{l}^+ l^-) \rightarrow 3l + \cancel{E}_T , \\ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 &\rightarrow (l^\pm \tilde{\nu})(\tilde{l}^+ l^-) \rightarrow 3l + \cancel{E}_T\end{aligned}\quad (5)$$

### Decay via sleptons (2I)

$$\begin{aligned}\tilde{\chi}_1^+ \tilde{\chi}_1^- &\rightarrow (\tilde{l}^+ \nu)(\tilde{l}^- \nu) \rightarrow 2l + \cancel{E}_T , \\ \tilde{\chi}_1^+ \tilde{\chi}_1^- &\rightarrow (l^+ \tilde{\nu})(l^- \tilde{\nu}) \rightarrow 2l + \cancel{E}_T\end{aligned}\quad (6)$$

### Decay via gauge bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \rightarrow 3l + \cancel{E}_T , \quad (7a)$$

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \rightarrow 2l + \text{jets} + \cancel{E}_T , \quad (7b)$$

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (W^+ \tilde{\chi}_1^0)(W^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T \quad (8)$$



## Decay via Higgs bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(h \tilde{\chi}_1^0) \rightarrow l + b\bar{b} + \cancel{E}_T \quad (9)$$

## $\tilde{l}$ -pair production (2I)

$$\tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T \quad (10)$$

## Compressed spectra

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T + \text{ISR} , \quad (11)$$

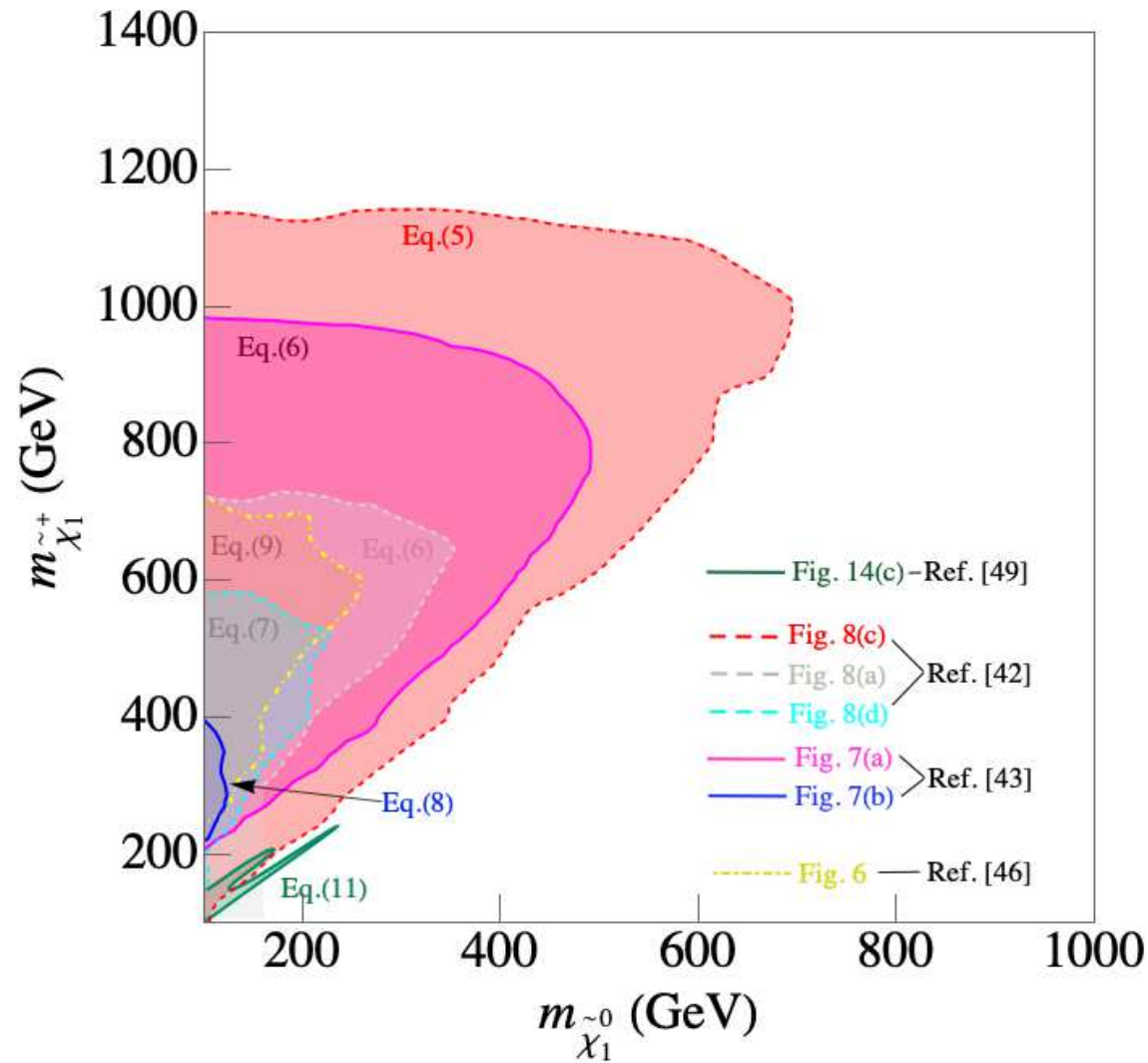
$$\tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T + \text{ISR} \quad (12)$$

## Searches involving Staus

$\Rightarrow$  all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra  $\Rightarrow$  direct application

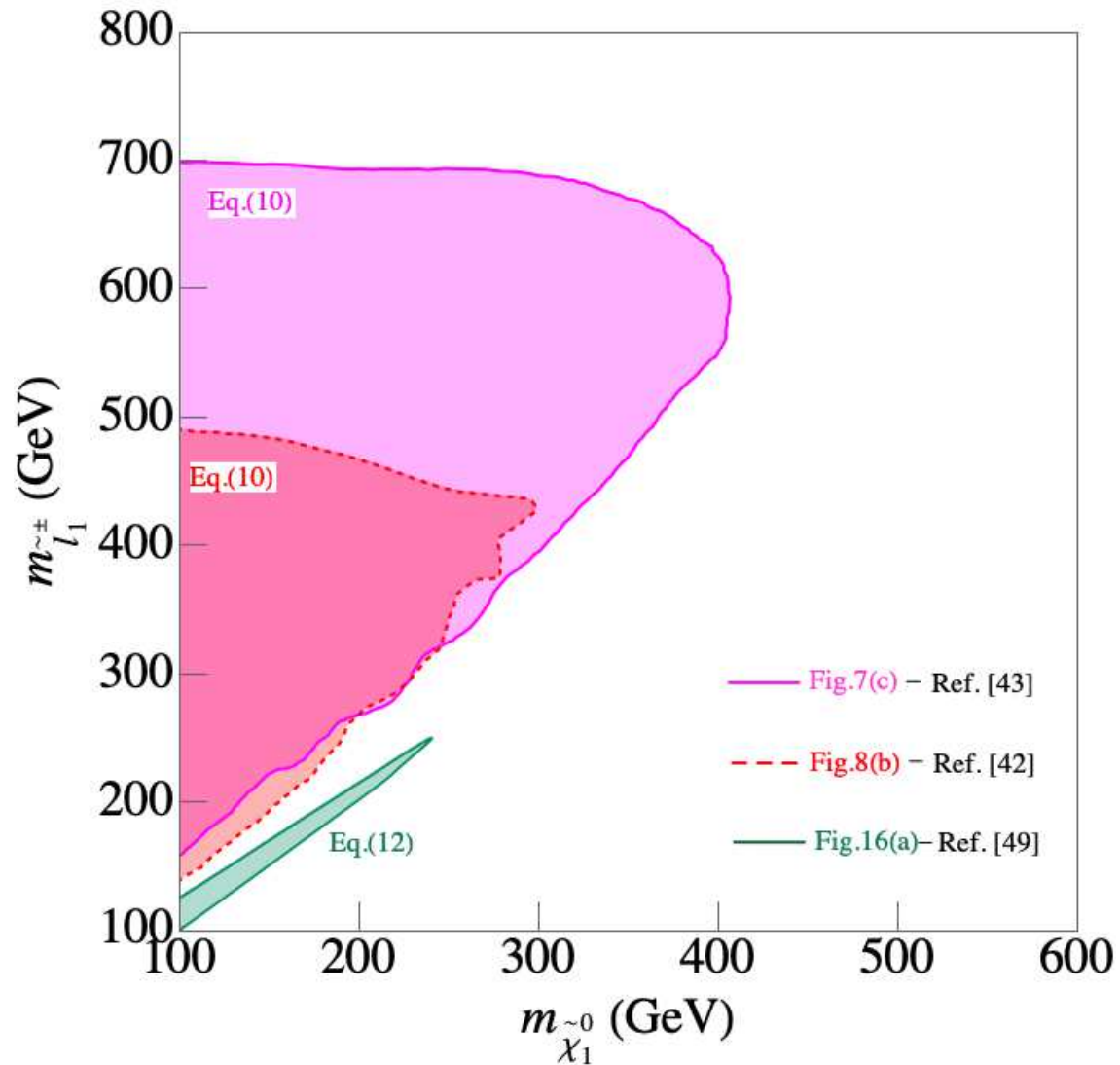
# LHC exclusion bounds (I) (as given for Simplified Model Spectra (SMS))



⇒ all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra ⇒ direct application

## LHC exclusion bounds (II) (as given for Simplified Model Spectra (SMS))



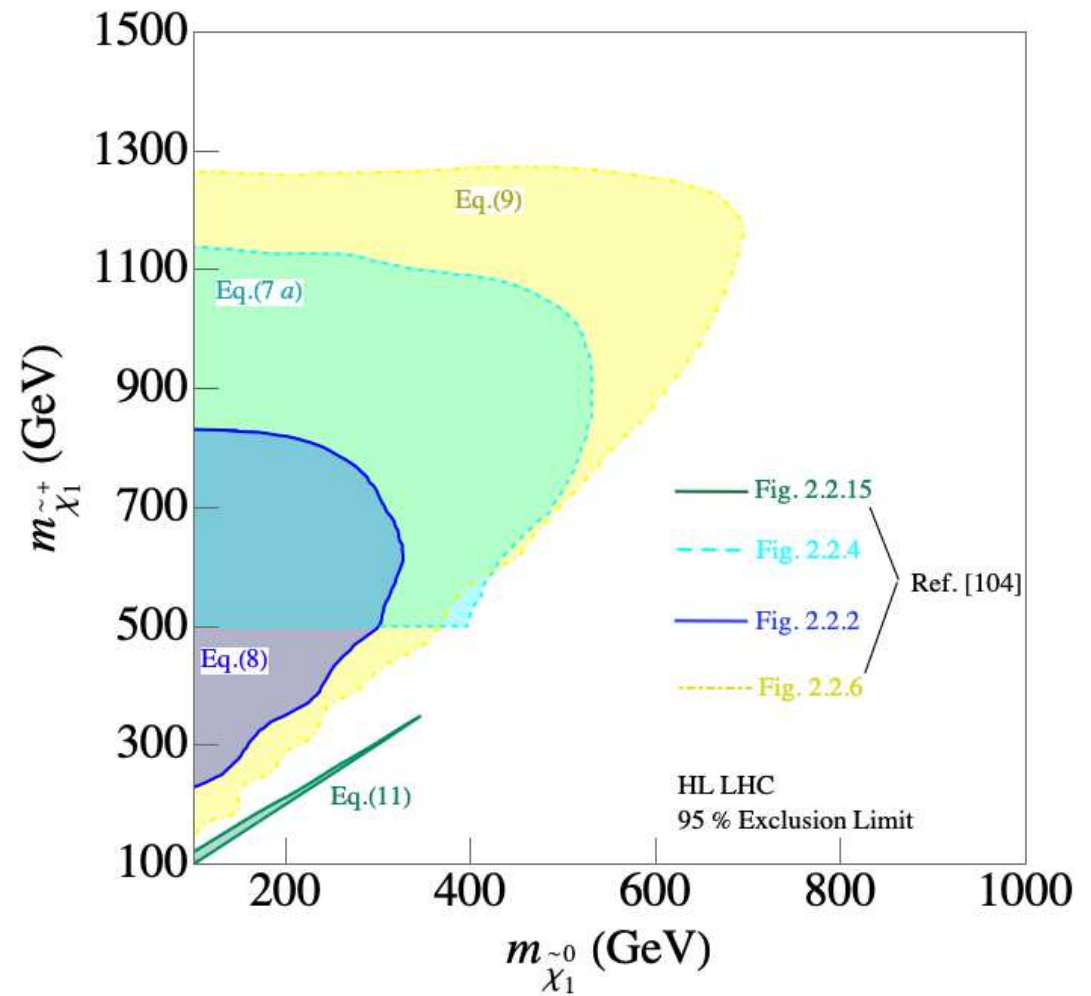
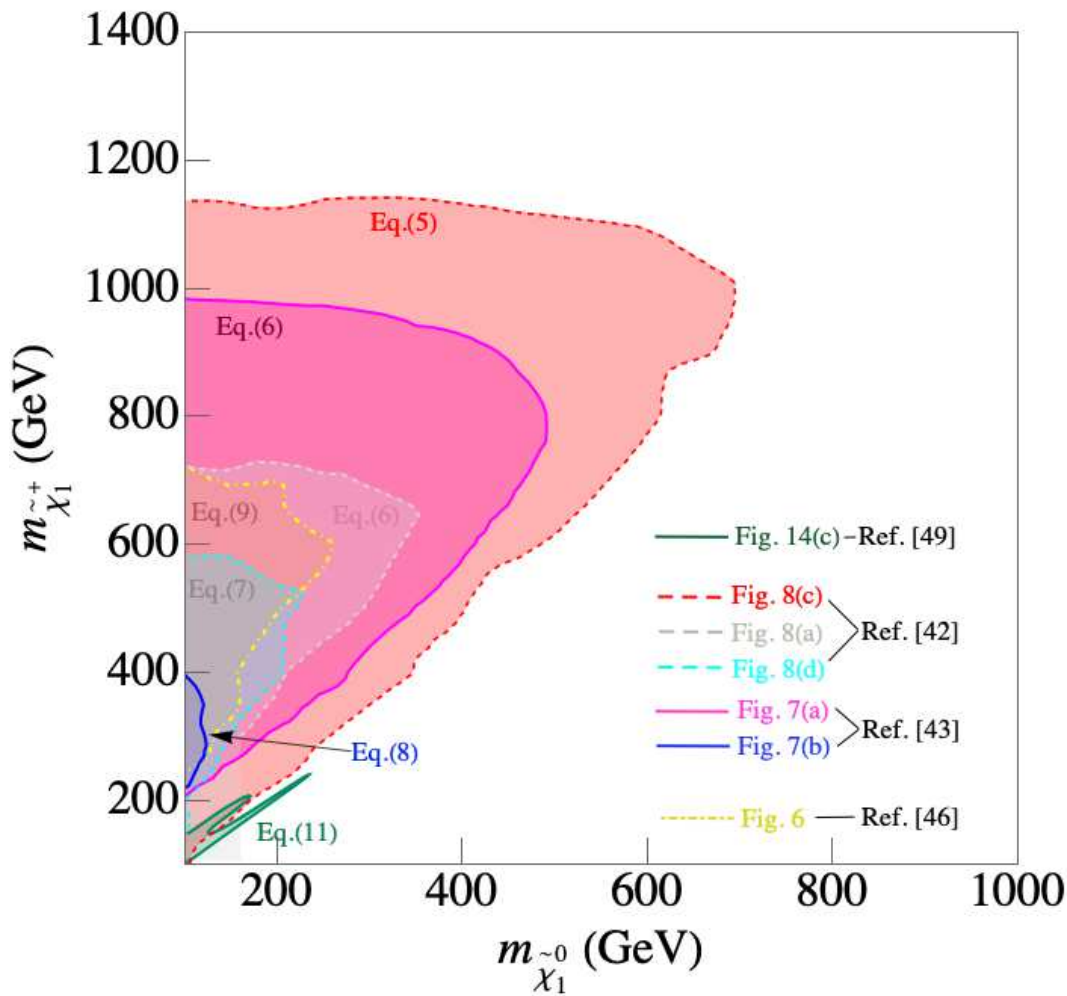
⇒ all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra ⇒ direct application

# LHC exclusion bounds vs. HL-LHC exclusion bounds

not all channels available

[YR18]



⇒ exclusion reach can be important

⇒ no CheckMate inclusion available . . .