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

$(g-2)_\mu$ and SUSY:

ILC and CLIC Physics Opportunities

Sven Heinemeyer, IFT (CSIC, Madrid)

Hamburg, 10/2022

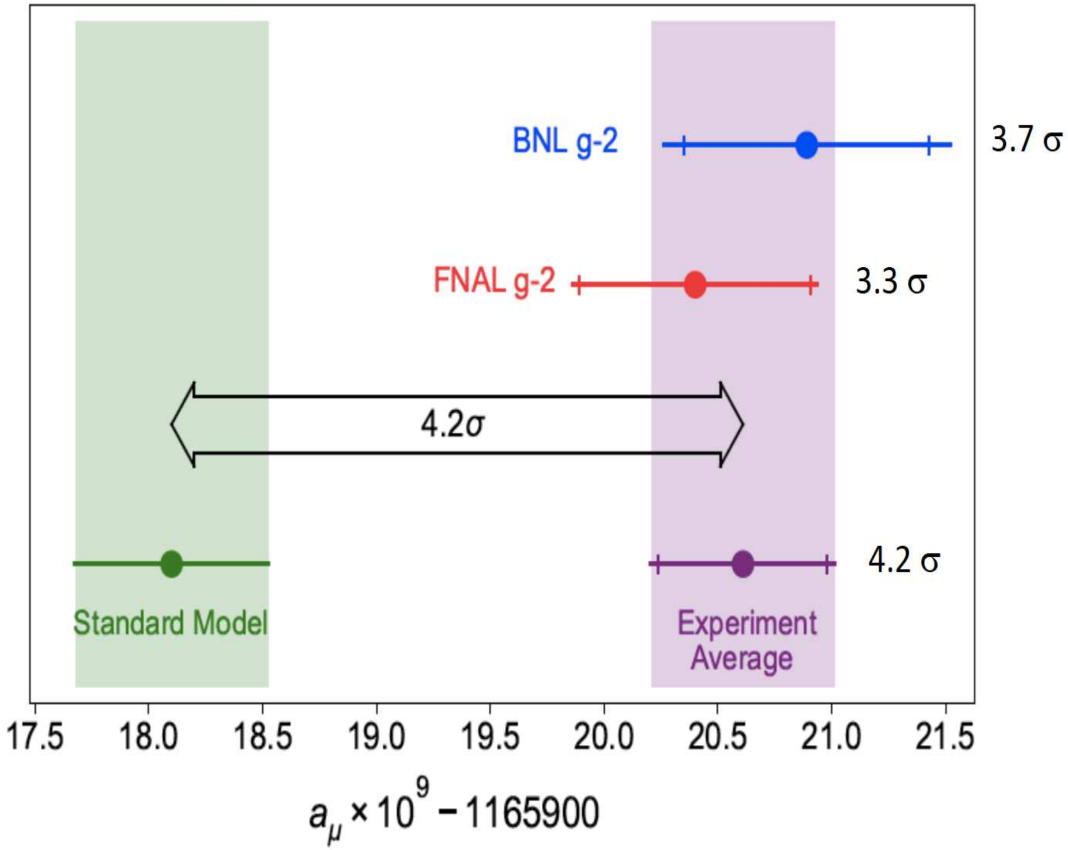
with *M. Chakraborti, I. Saha, C. Schappacher*

- Introduction
- Prospects for Direct Detection experiments
- ILC and CLIC physics opportunities
- Conclusions

1. Introduction

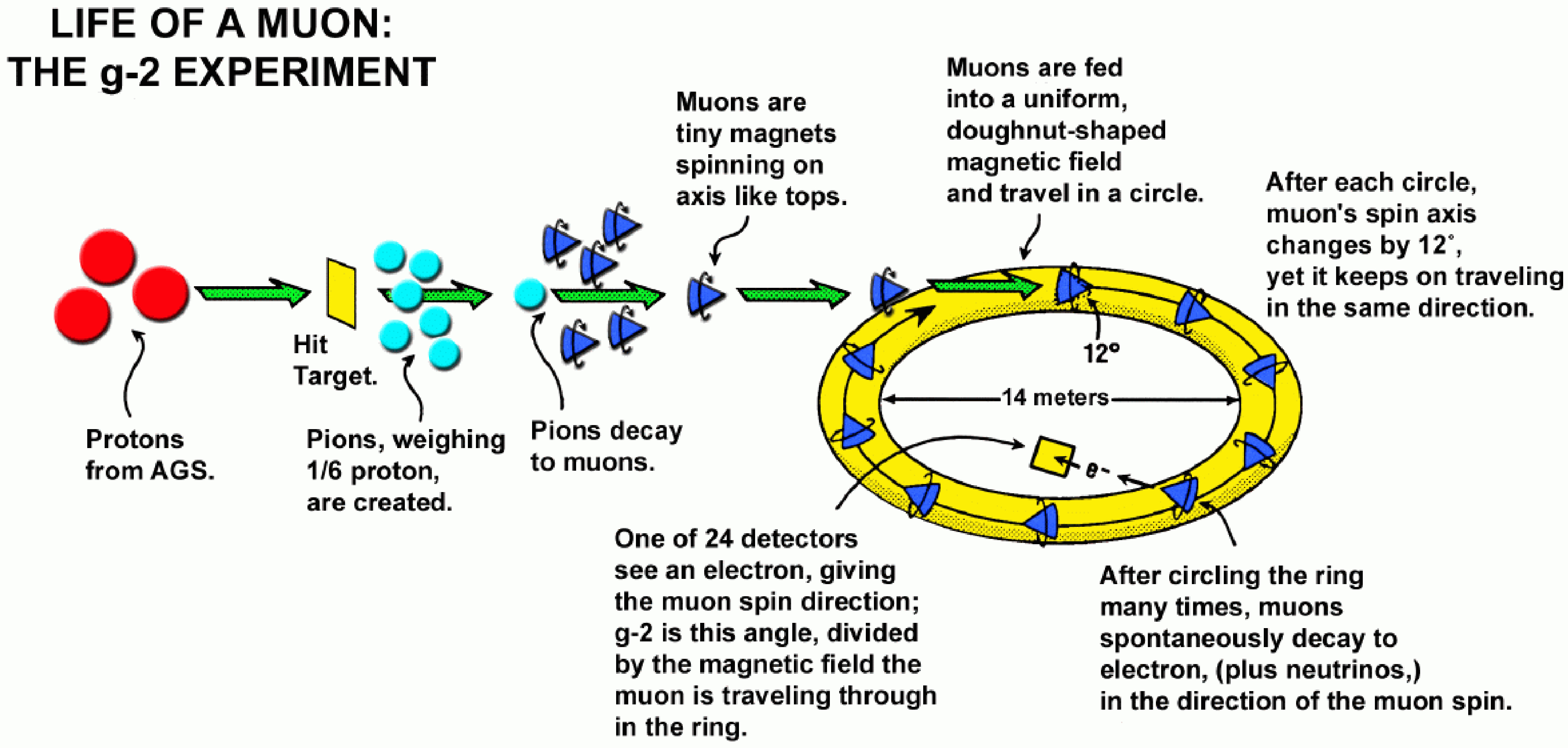
The anomalous magnetic moment of the muon: $a_\mu \equiv (g-2)_\mu/2$

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



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.1 \pm 5.9) \times 10^{-10} \quad : \; 4.2\,\sigma$$

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

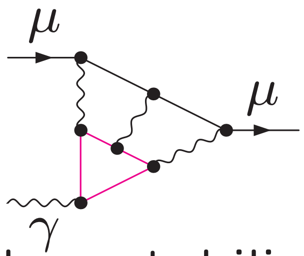


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

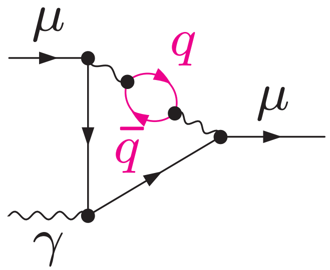
Theory of $(g-2)_\mu$:

– the light-by-light contribution:



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

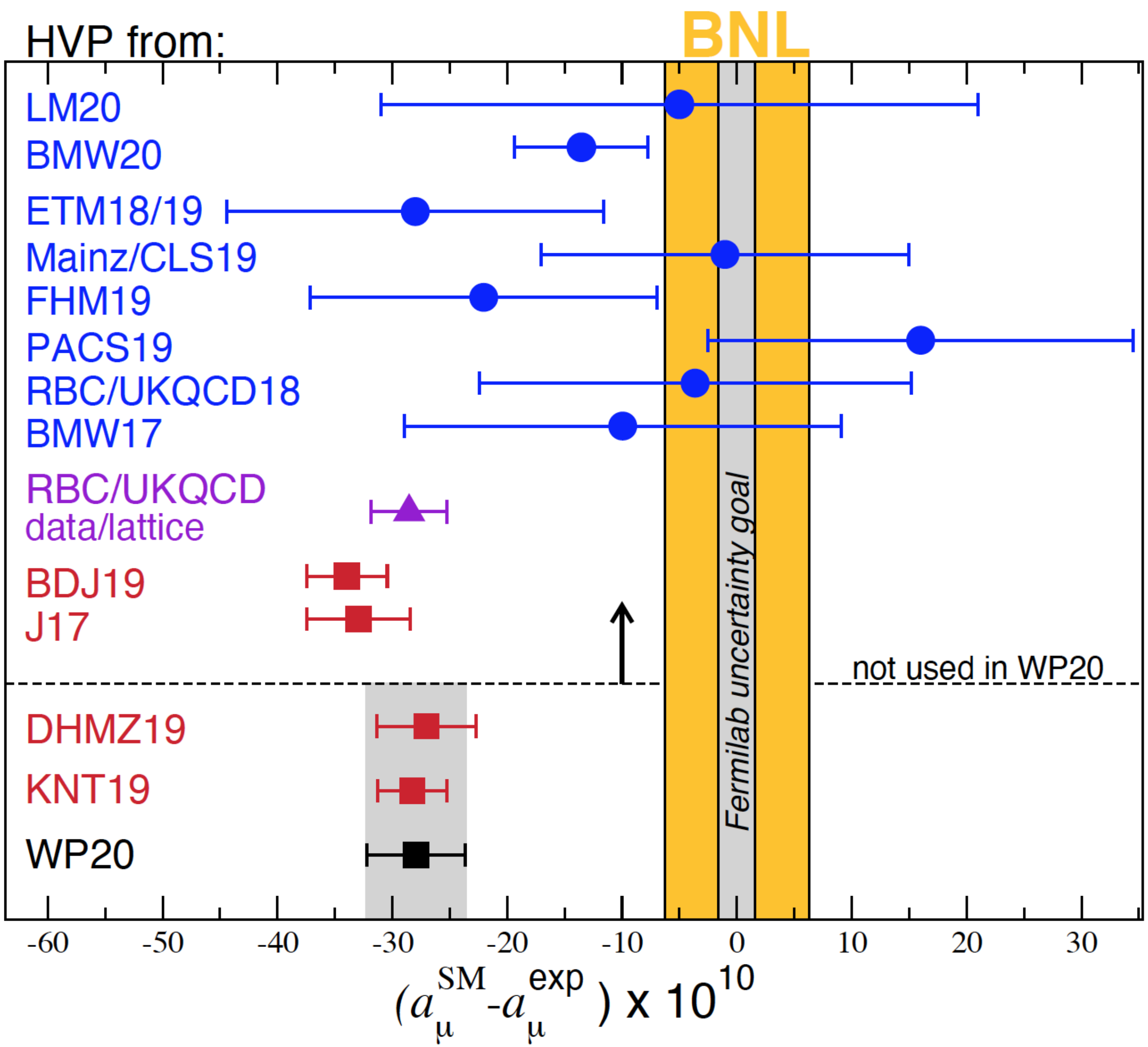
– the hadronic vacuum contribution:



'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]
$\Rightarrow$ still under discussion ... $\Rightarrow$ effectively not used anymore

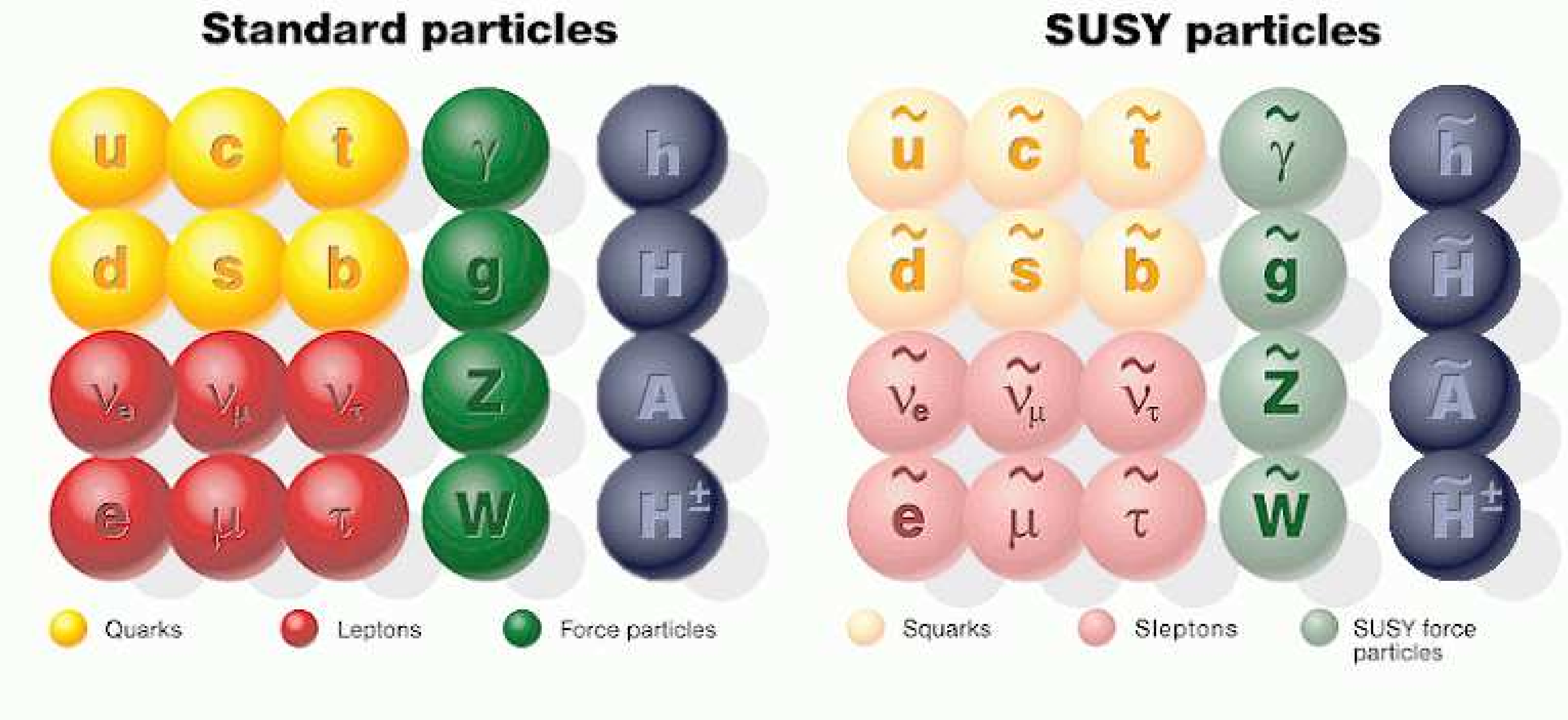
HVP summary:



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

The MSSM

Superpartners for Standard Model particles



$\Rightarrow$ large uncolored / EW sector

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

Diagonalization of the mass matrix:

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, M_W \\ \sqrt{2}\cos\beta\, M_W & \mu \end{pmatrix} ,$$

$$\mathbf{M}_{\tilde{\chi}^-} = \mathbf{V}^* \, \mathbf{X}^\top \, \mathbf{U}^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0,\, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

Diagonalization of mass matrix:

$$\mathbf{Y} = \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix},$$

$$\mathbf{M}_{\tilde{\chi}^0} = \mathbf{N}^* \, \mathbf{Y} \, \mathbf{N}^\dagger = \mathbf{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$$

⇒ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$
⇒ only one additional parameter

⇒ MSSM predicts mass relations between neutralinos and charginos

Scalar lepton sector of the MSSM

Charged slepton mass matrices

$$\mathbf{M}^2_{\tilde{l}} = \begin{pmatrix} M^2_{\tilde{l}_L} + m_l^2 + DT_{l_1} & m_l X_l \\ m_l X_l & M^2_{\tilde{l}_R} + m_l^2 + DT_{l_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{l}}} \begin{pmatrix} m^2_{\tilde{l}_1} & 0 \\ 0 & m^2_{\tilde{l}_2} \end{pmatrix}$$

with

$$X_l = A_l - \mu \tan\beta$$

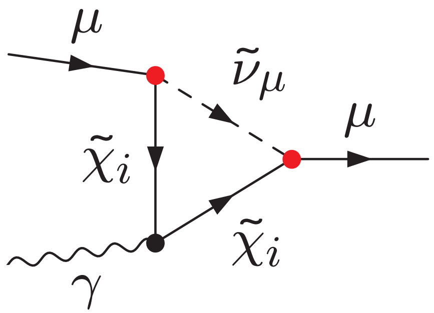
Sneutrino mass

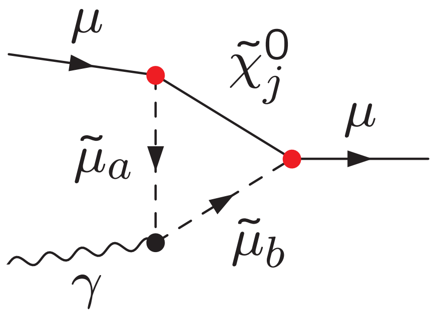
$$m^2_{\tilde{\nu}_l} = M^2_{\tilde{l}_L} + DT_\nu$$

Simplifying assumption: $M_{\tilde{l}_L}$ and $M_{\tilde{l}_R}$ identical for all three generations

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:

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

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

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

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100\text{ GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta\,\text{sign}(\mu)$$

$M_{\text{SUSY}} (= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

$$a_\mu^{\text{SUSY,1L}} = (-100\ldots+100) \times 10^{-10}$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.1 \pm 5.9) \times 10^{-10}$$

$\Rightarrow$ SUSY could easily explain the “discrepancy”

$\Rightarrow$ a_μ can provide upper limits on the EW masses

(by requiering agreement at the 95% C.L.)

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100\ \text{GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta\ \text{sign}(\mu)$$

$M_{\text{SUSY}}(= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100 \ldots +100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (25.1 \pm 5.9) \times 10^{-10} \end{aligned}$$

$\Rightarrow$ SUSY could easily explain the "discrepancy"

$\Rightarrow$ a_μ can provide upper limits on the EW masses
(by requiering agreement at the 95% C.L.)

> If SUSY exists, it should fix $(g-2)_\mu$!
> $\Rightarrow$ there must be light EW SUSY particles!

The general idea: [M. Chakraborti, S.H., I. Saha '20, '21]

– 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 prospects for e^+e^- colliders!

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

$$\text{old: } \Delta a_\mu^{\text{old}} = (28.0 \pm 7.4) \times 10^{-10}$$
$$\text{new: } \Delta a_\mu^{\text{new}} = (25.1 \pm 5.9) \times 10^{-10}$$

⇒ some results for $\Delta a_\mu^{\text{new}} (\equiv \Delta a_\mu)$
some results only available for $\Delta a_\mu^{\text{old}}$

Note: $\Delta a_\mu^{\text{old}} - 2\,\sigma^{\text{old}} \approx \Delta a_\mu^{\text{new}} - 2\,\sigma^{\text{new}}$
⇒ upper limits on SUSY masses are not expected to change

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*]

Results for (nearly) all SUSY scenarios

A) bino/wino DM with chargino co-annihilation

relic DM density 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 650(700) GeV for new (and old) $(g-2)_\mu$

B/C) bino DM with slepton co-annihilation

relic DM density 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 650(700) GeV for new (and old) $(g-2)_\mu$

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$

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

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

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

$\Rightarrow$ predictions for future experiments?!

2. Prospects for Direct Detection Experiments

A) Bino/wino DM with chargino co-annihilation

Parameter scan:

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

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

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

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

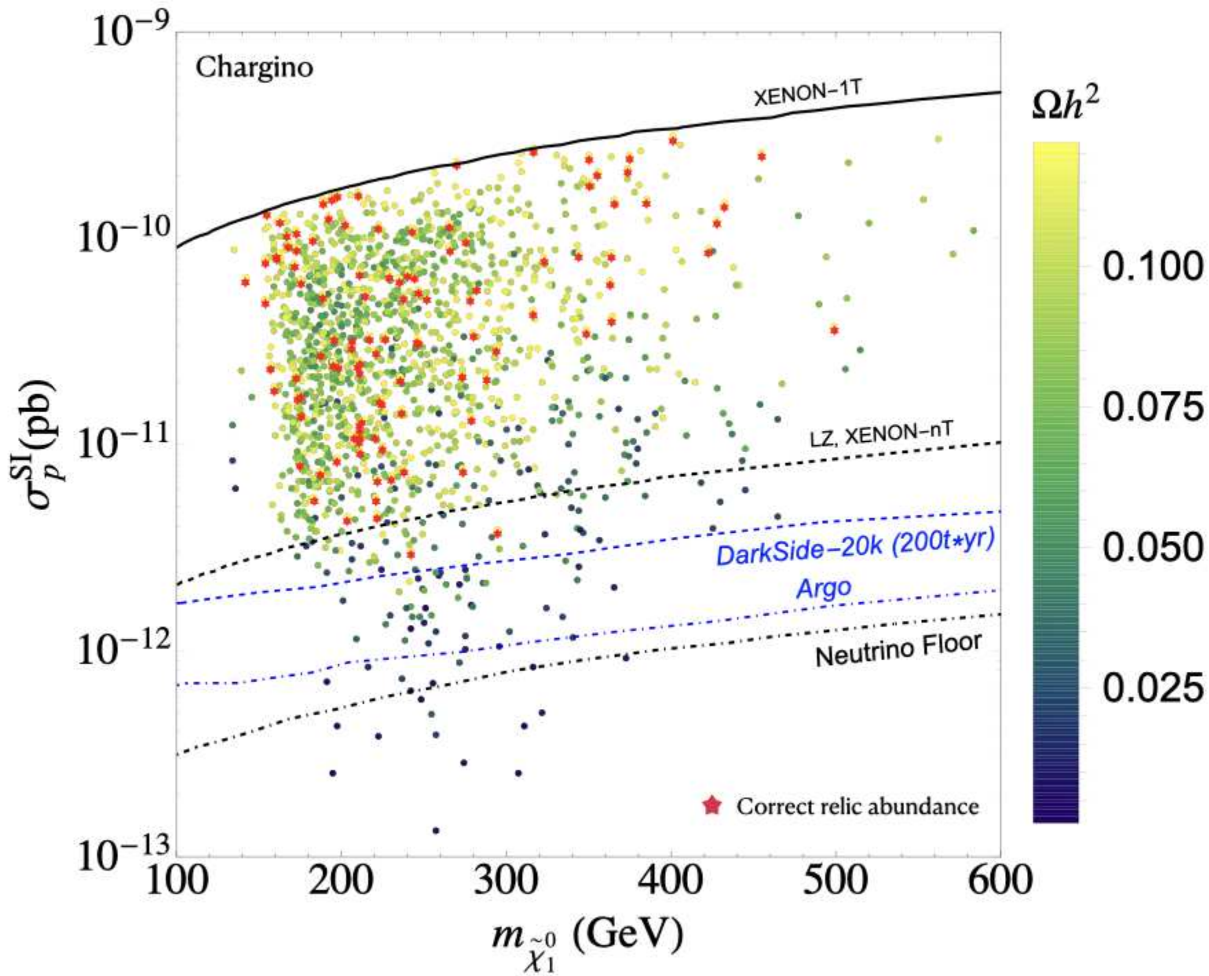
$$100 \text{ GeV} \leq m_{\tilde{L}} \leq 1 \text{ TeV},$$

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

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

relic DM density can be 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim 650(700)$ GeV

Results in the $m_{\tilde{\chi}_1^0}$-σ_p^{SI} plane: [*M. Chakraborti, S.H., I. Saha, C. Schappacher '21*]



⇒ 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:

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

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

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

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

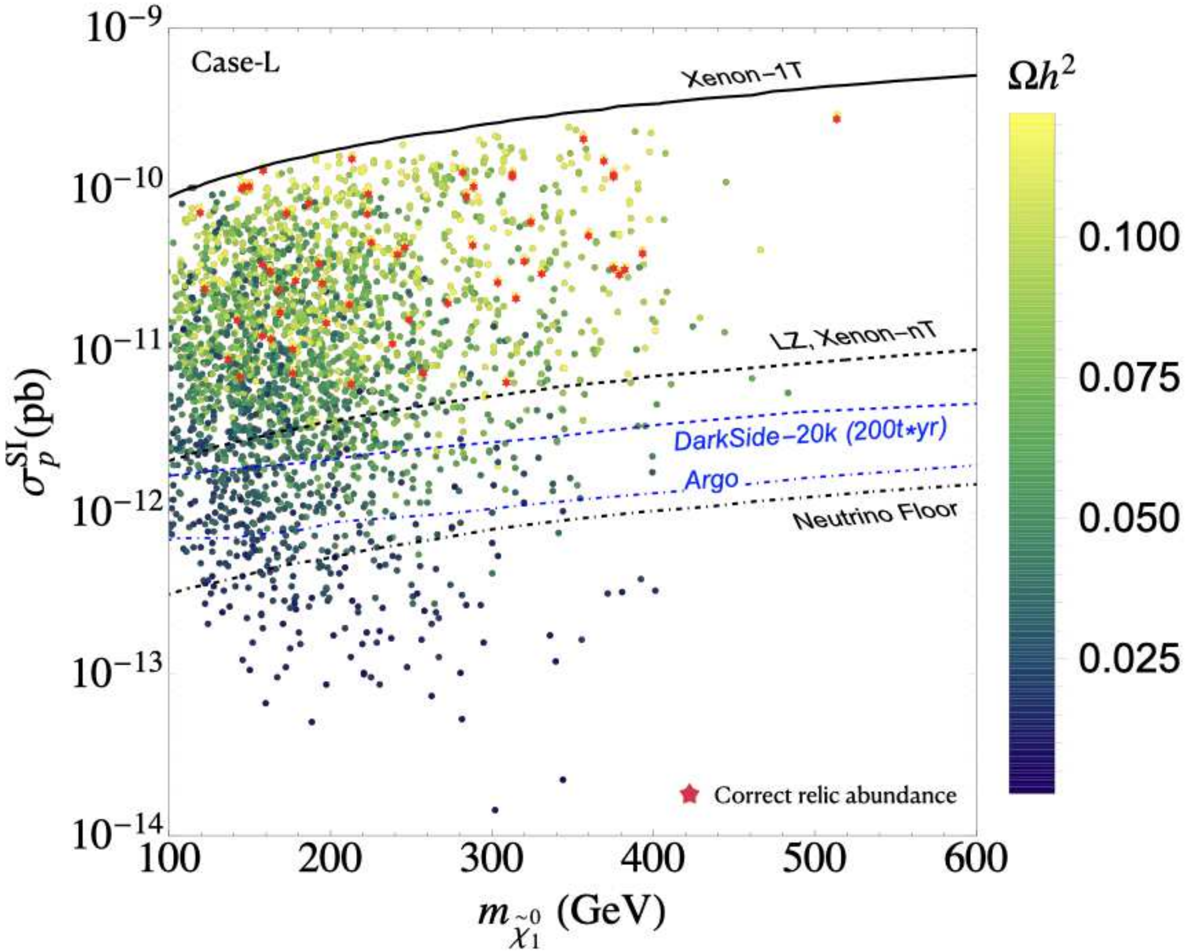
Case-L: $M_1 \leq m_{\tilde{L}} \leq 1.2 M_1,\quad M_1 \leq m_{\tilde{R}} \leq 10 M_1.$

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

relic DM density can be 100% fulfilled

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

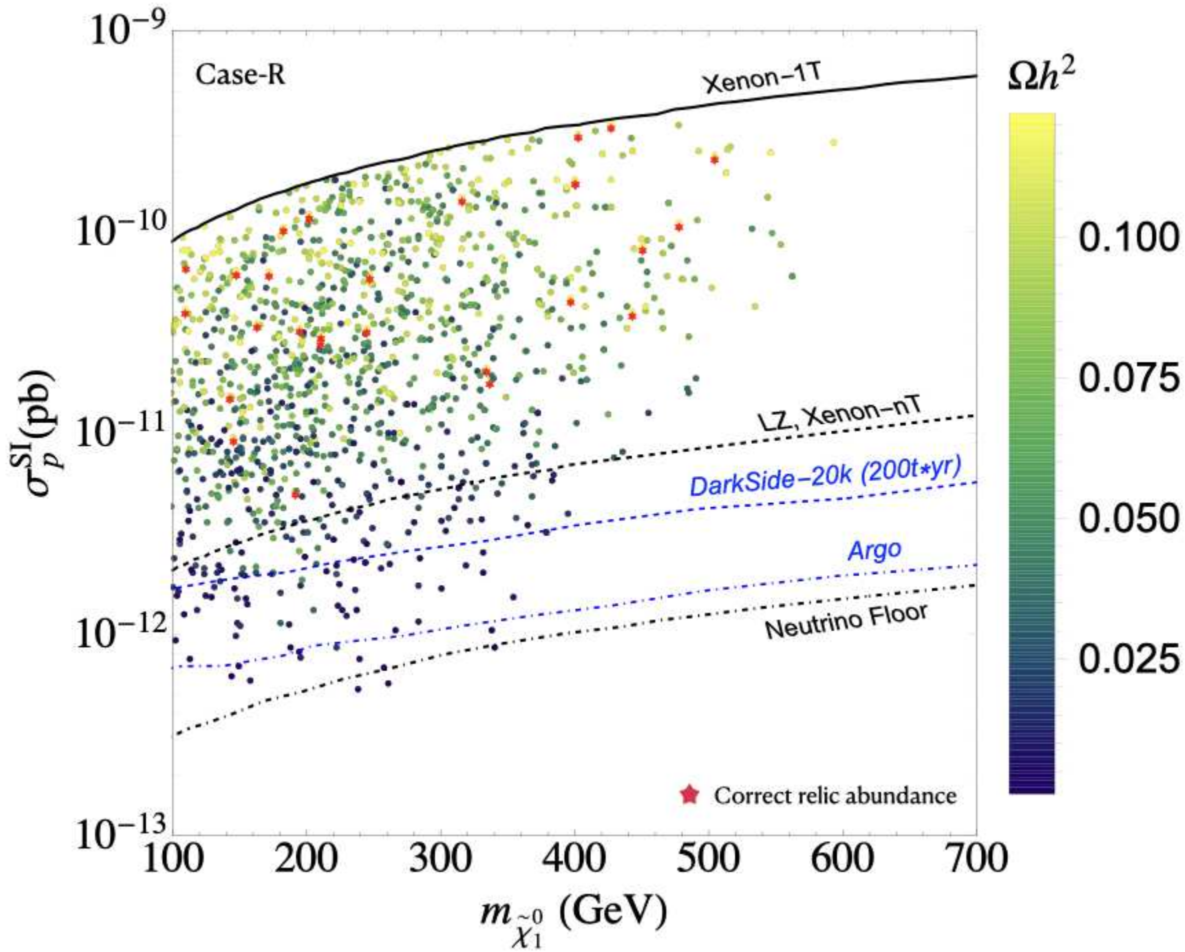
Case-L: results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\rm SI}$ plane: [M. Chakraborti, S.H., I. Saha, C. Schappacher '21]



⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

Case-R: results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\rm SI}$ plane: *[M. Chakraborti, S.H., I. Saha, C. Schappacher '21]*



⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

D) Higgsino DM

Parameter scan:

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

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

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

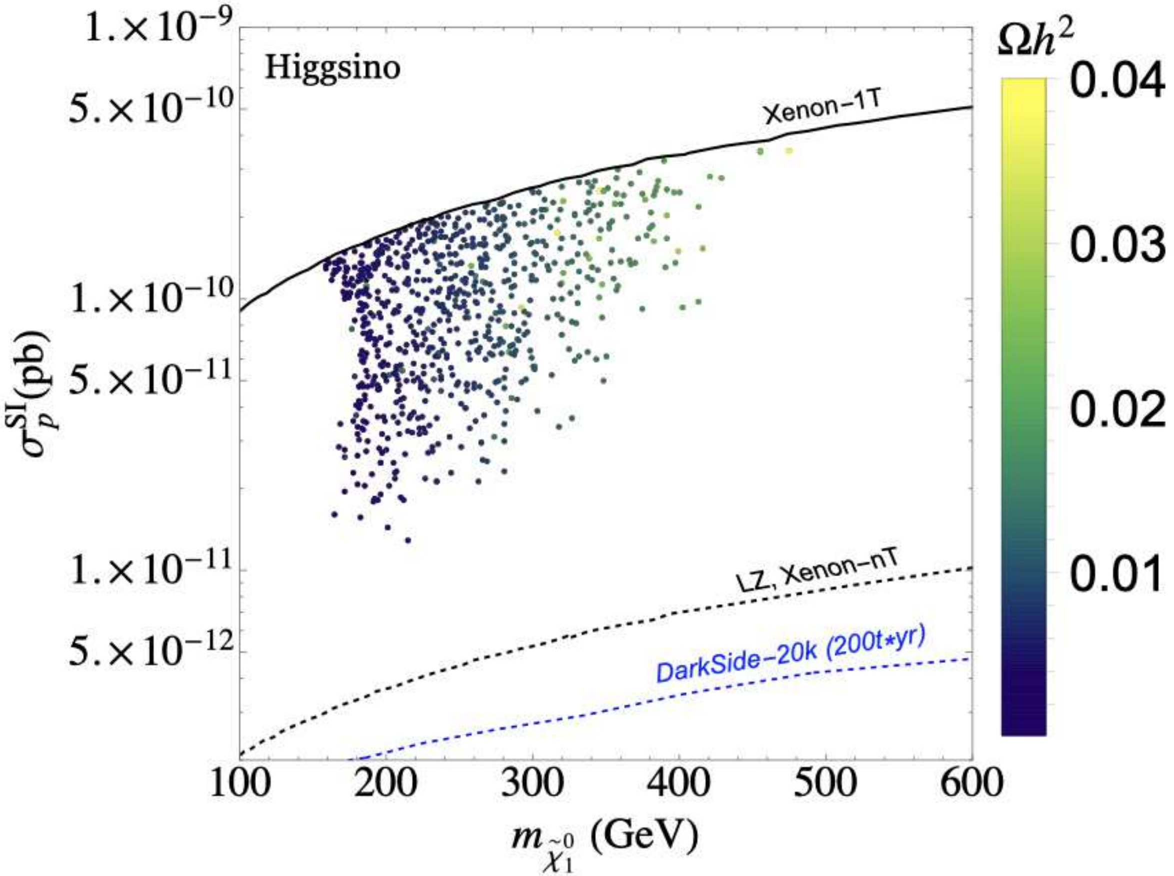
$$5 \leq \tan\beta \leq 60,$$

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

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

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with $(g-2)_\mu$
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

Results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\rm SI}$ plane: *[M. Chakraborti, S.H., I. Saha, C. Schappacher '21]*



⇒ everything covered by XENON-nT/LZ

⇒ Direct Detection experiments cover the full parameter space

E) Wino DM

Parameter scan:

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

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

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

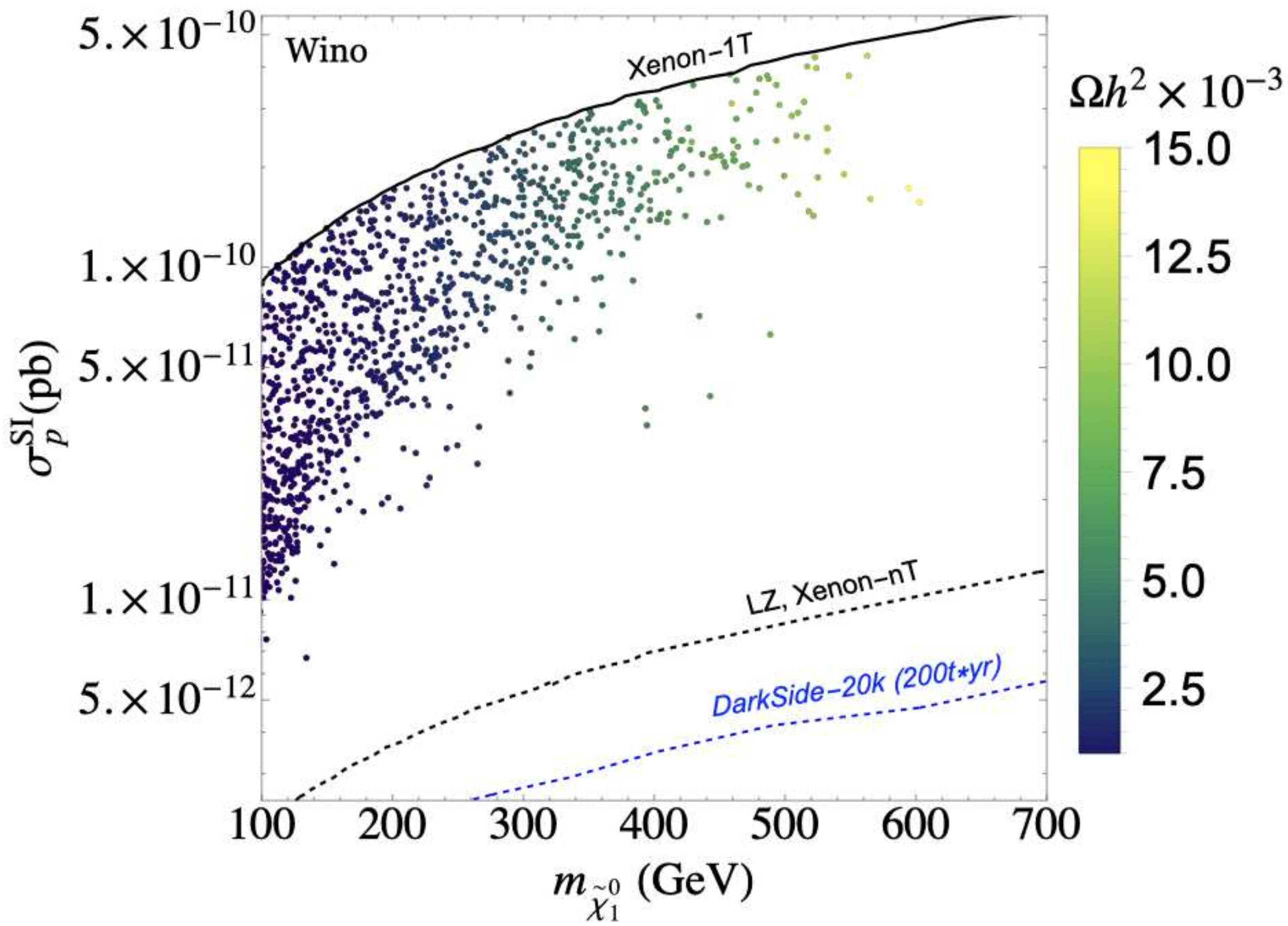
$$5 \leq \tan\beta \leq 60,$$

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

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

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 3$ TeV
$\Rightarrow$ incompatible with $(g-2)_\mu$
$\Rightarrow m_{\text{(N)LSP}} \lesssim 600$ GeV

Results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\rm SI}$ plane: [*M. Chakraborti, S.H., I. Saha, C. Schappacher '21*]



⇒ everything covered by XENON-nT/LZ

⇒ Direct Detection experiments cover the full parameter space

3. ILC and CLIC physics opportunities

Scenarios A/B/C:

⇒ large part covered by XENON-nT/LZ

⇒ but can go below even the neutrino floor

⇒ (HL-)LHC has naturally problems becaus 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

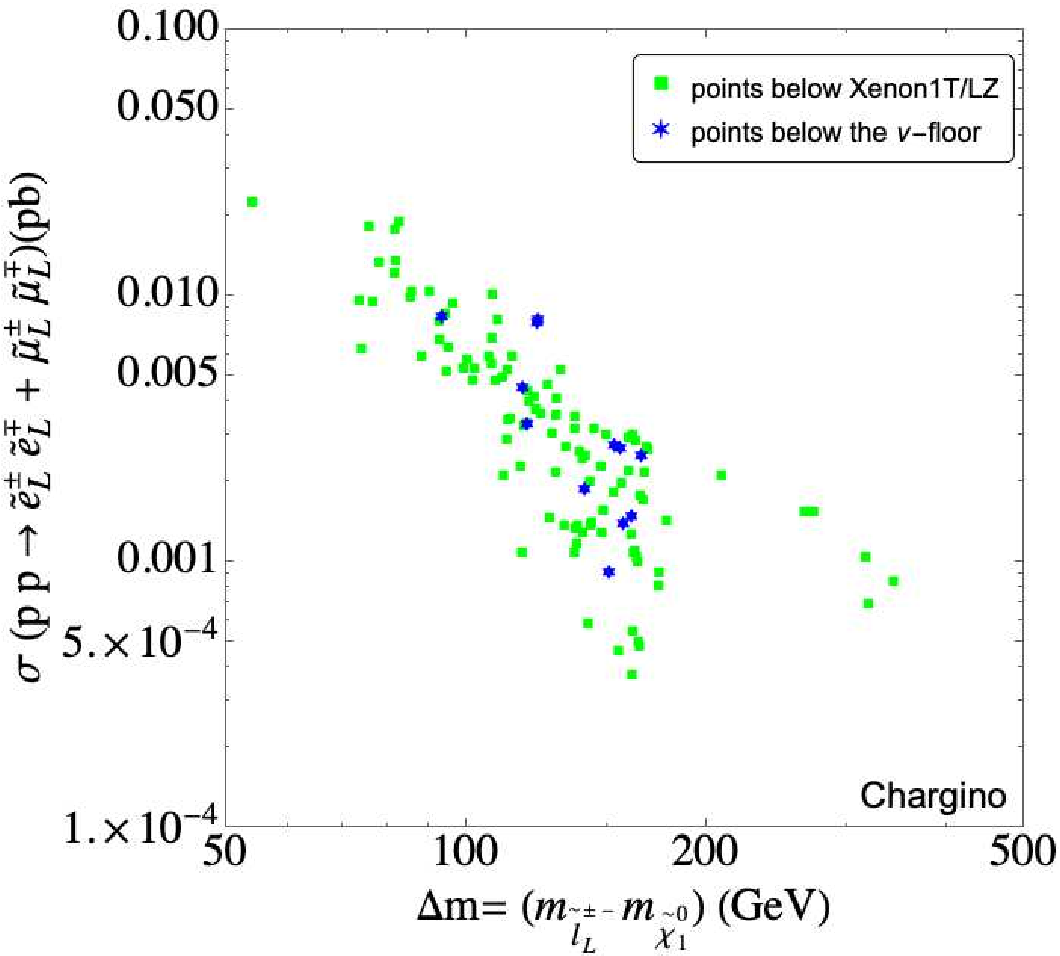
⇒ Direct Detection experiments cover the full parameter space

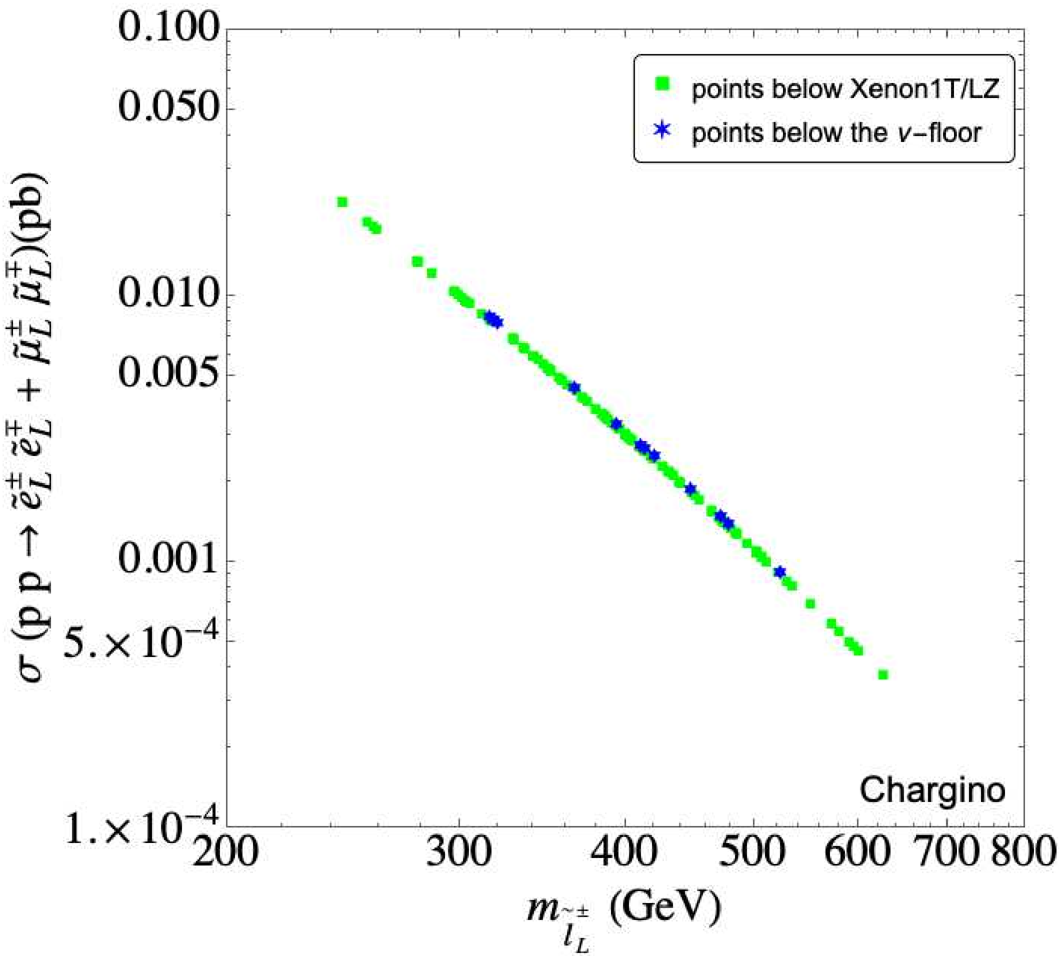
⇒ what can be learned at ILC/CLIC?

⇒ ILC and CLIC physics opportunities in the light of (HL-)LHC!

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

[*M. Chakraborti, S.H., I. Saha, C. Schappacher '21*]





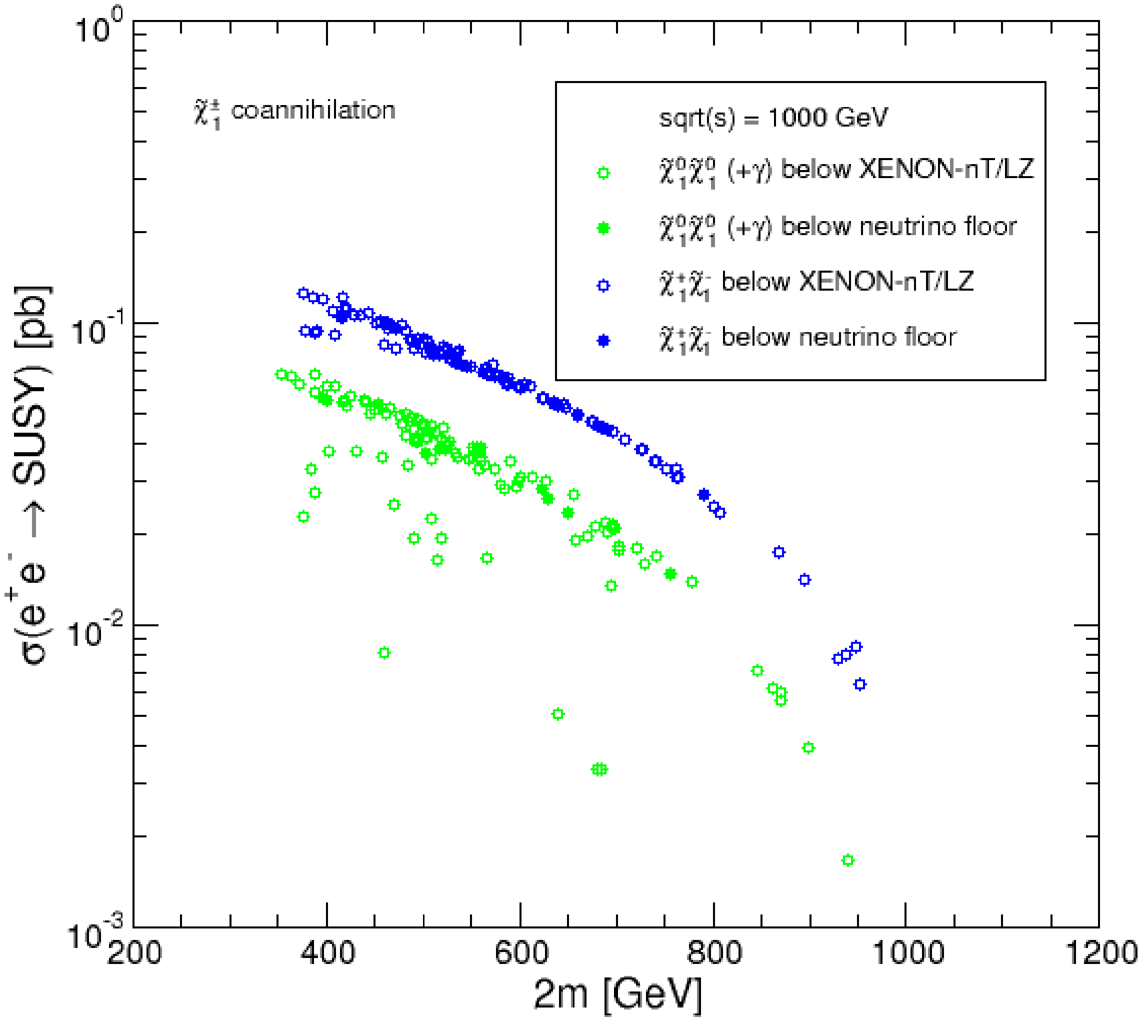
⇒ XS above 0.4 fb ⇒ more than 1200 events

⇒ 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):

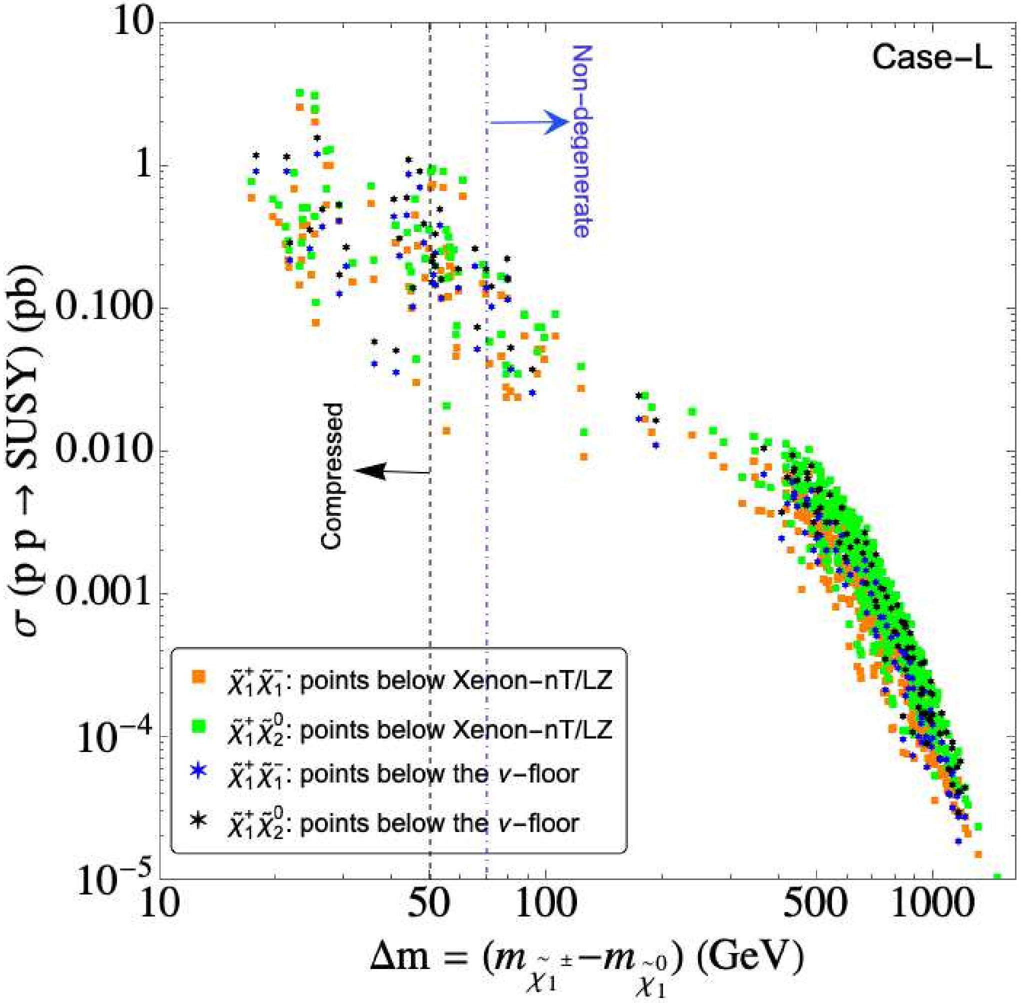
[M. Chakraborti, S.H., I. Saha, C. Schappacher '21]

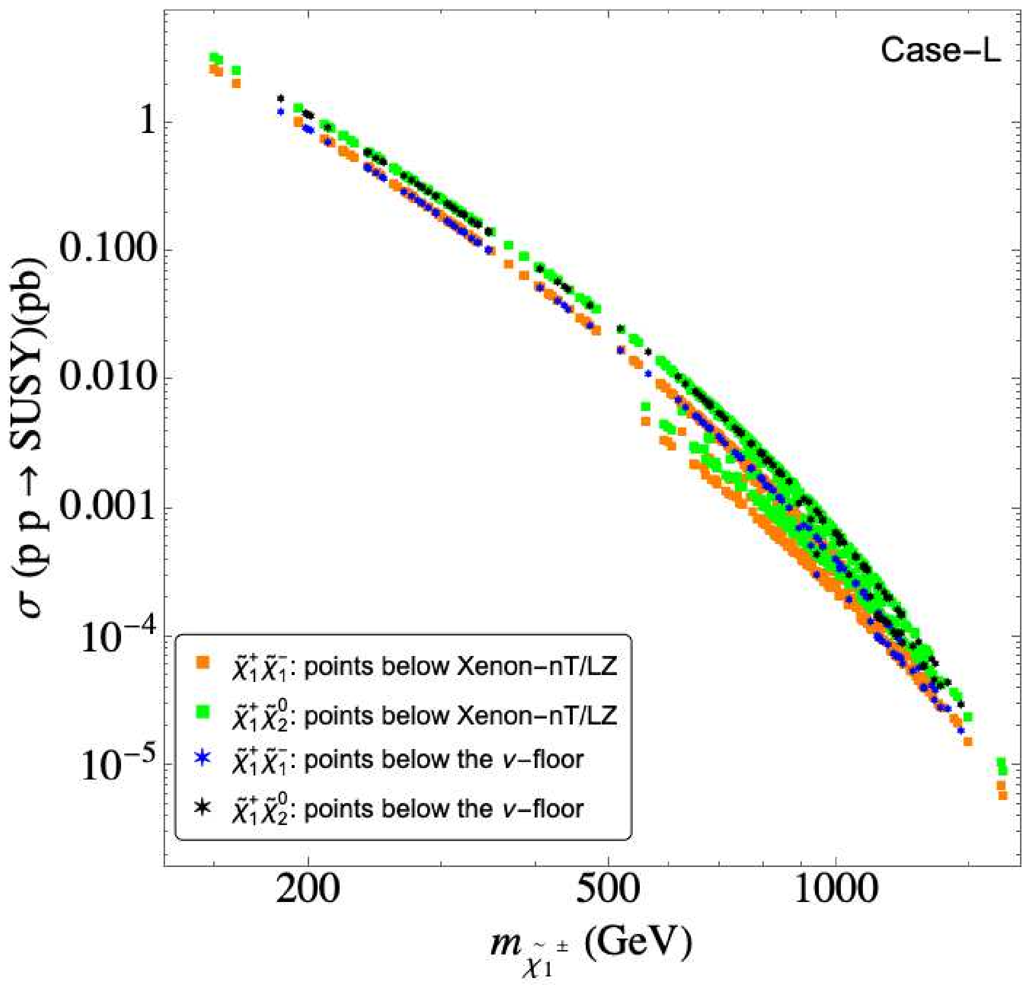


⇒ ILC1000 can cover everything!

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

[*M. Chakraborti, S.H., I. Saha, C. Schappacher '21*]





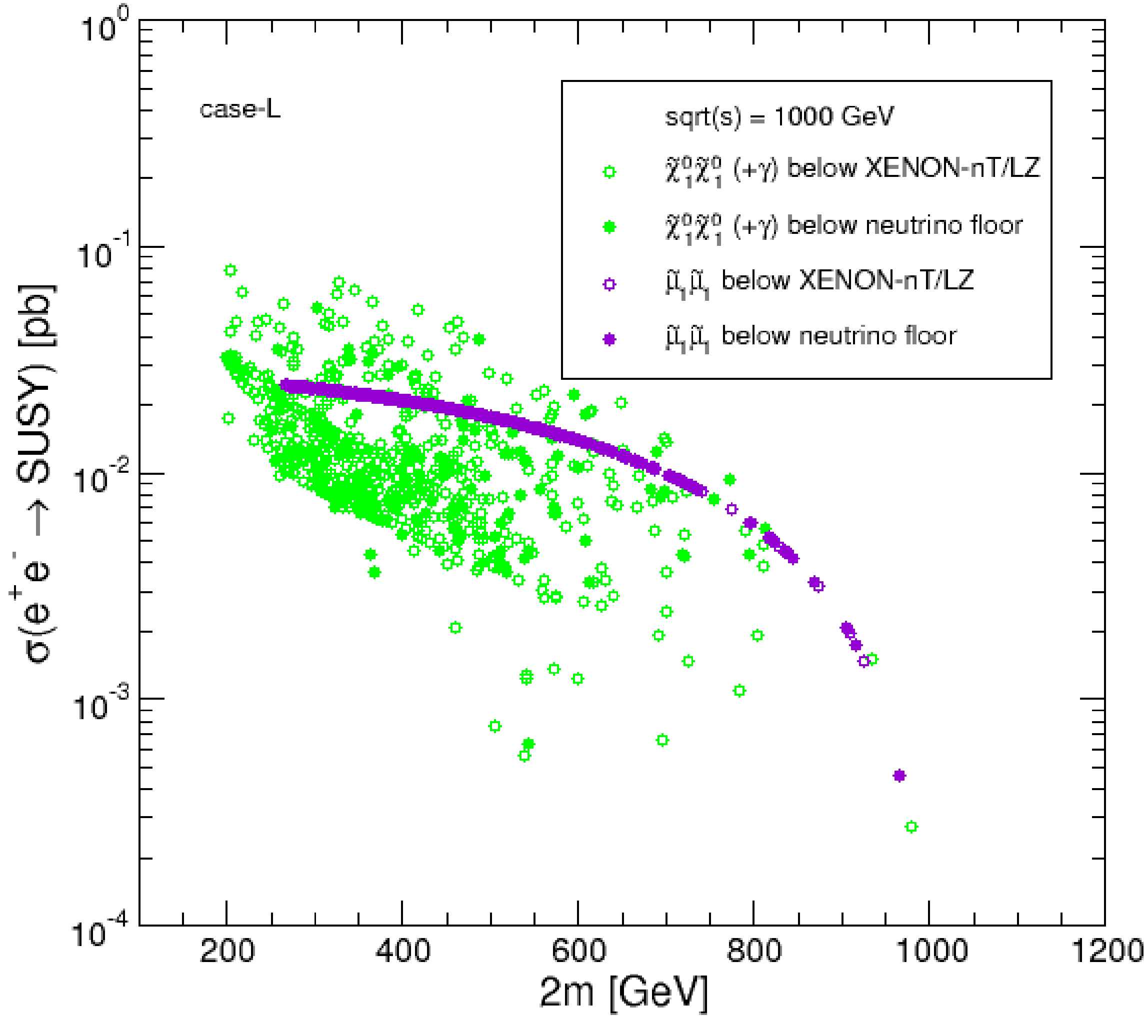
⇒ XS above 0.01 fb ⇒ more than 30 events

⇒ no improvement for "BNF" points!

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

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

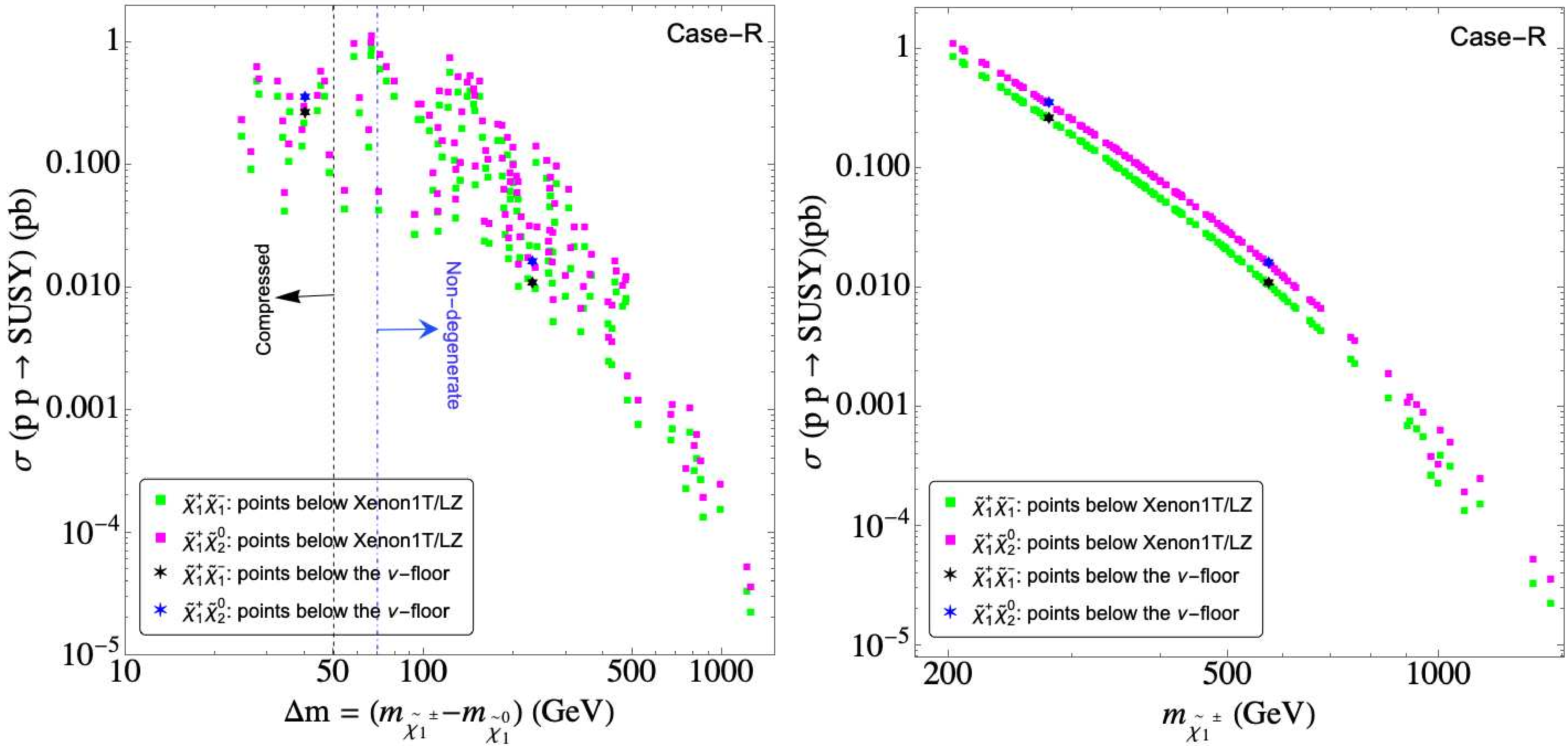
[M. Chakraborti, S.H., I. Saha, C. Schappacher '21]



⇒ ILC1000 can cover everything!

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

[*M. Chakraborti, S.H., I. Saha, C. Schappacher '21*]



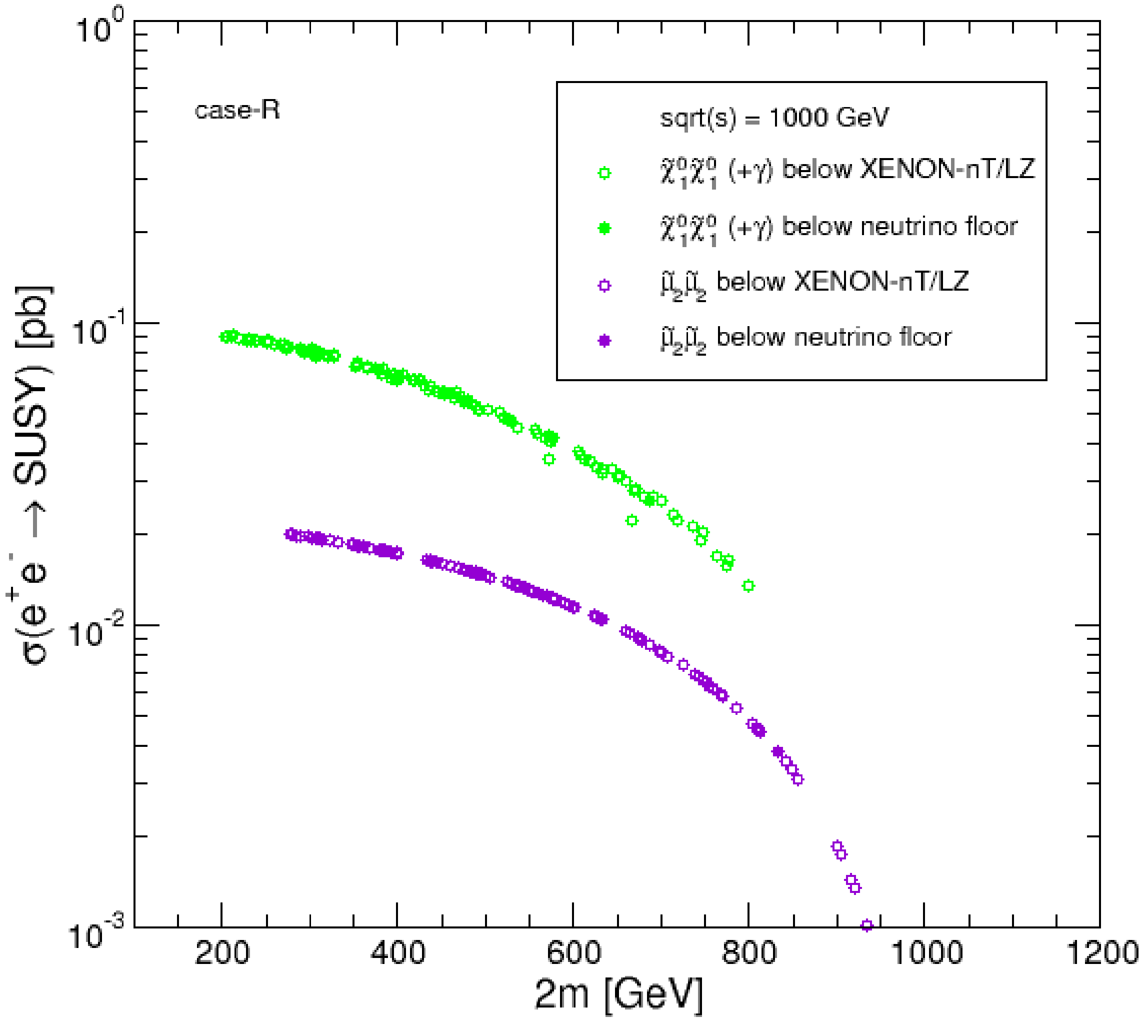
⇒ XS above 0.04 fb ⇒ more than 120 events

⇒ 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):

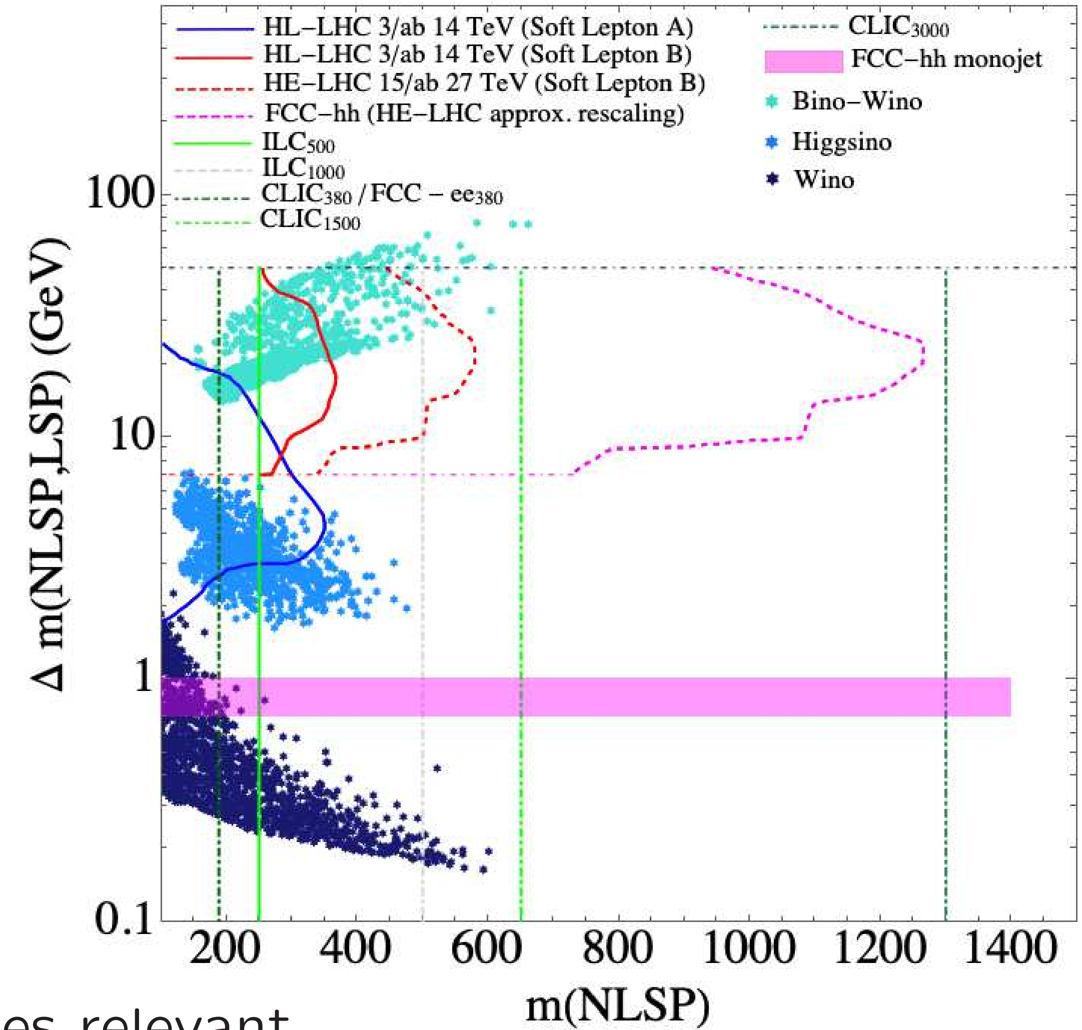
[M. Chakraborti, S.H., I. Saha, C. Schappacher '21]



⇒ 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 scenario

4. Conclusinos

- Indirect searches: $(g-2)_\mu \Rightarrow 4.2\,\sigma$ discrepancy

- General idea:
  - 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

- General results:

  A) bino/wino DM with chargino coann. (DM full)
  B/C) bino DM with slepton coann. (DM full)
  D) higgsino DM $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ (DM upper limit)
  E) wino DM $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$ (DM upper limit)
  $\Rightarrow$ clear upper limits, $m_{\text{(N)LSP}} \lesssim 600$ GeV confirmed

- Direct Detection experiments can cover part of parameter space
  - ILC can cover fully the remaining points
  - (HL-)LHC has problems with compressed spectra
  - ILC/CLIC can "easily" cover compressed spectra


Further Questions?