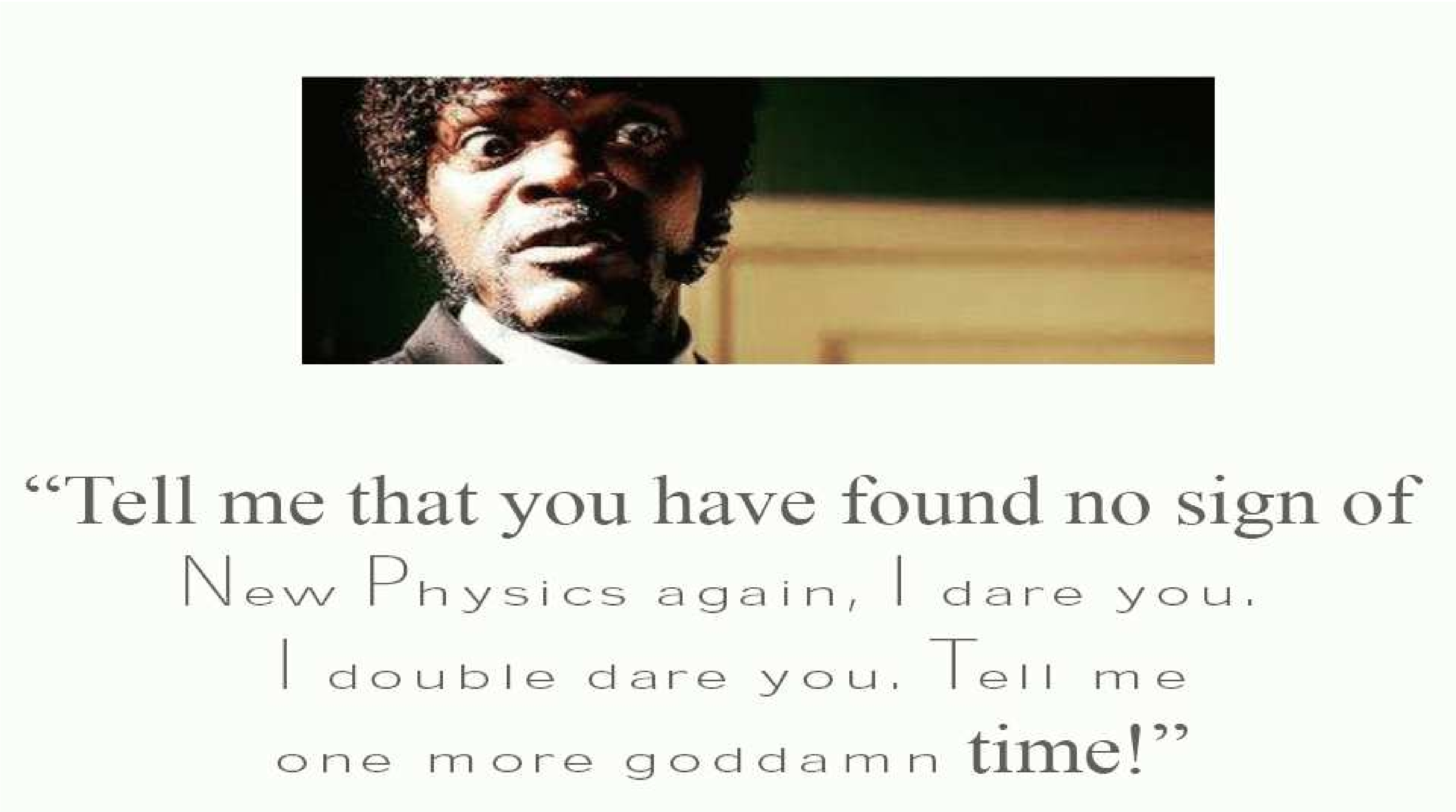

"Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!"

Possible BSM Explanations for the $(g-2)_\mu$ anomaly

Sven Heinemeyer, IFT (CSIC, Madrid)

Sussex/zoom, 06/2022

1. Introduction

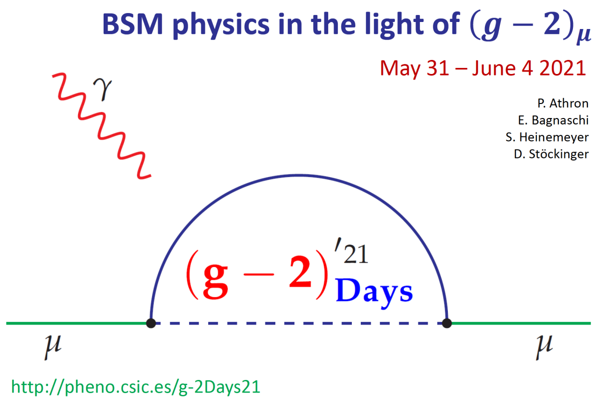
2. "Two Higgs Doublets are as natural as one"

3. "And I thought lepto-quarks were dead . . ."

4. "SUSY fits like a glove"

5. "There's always the axion"

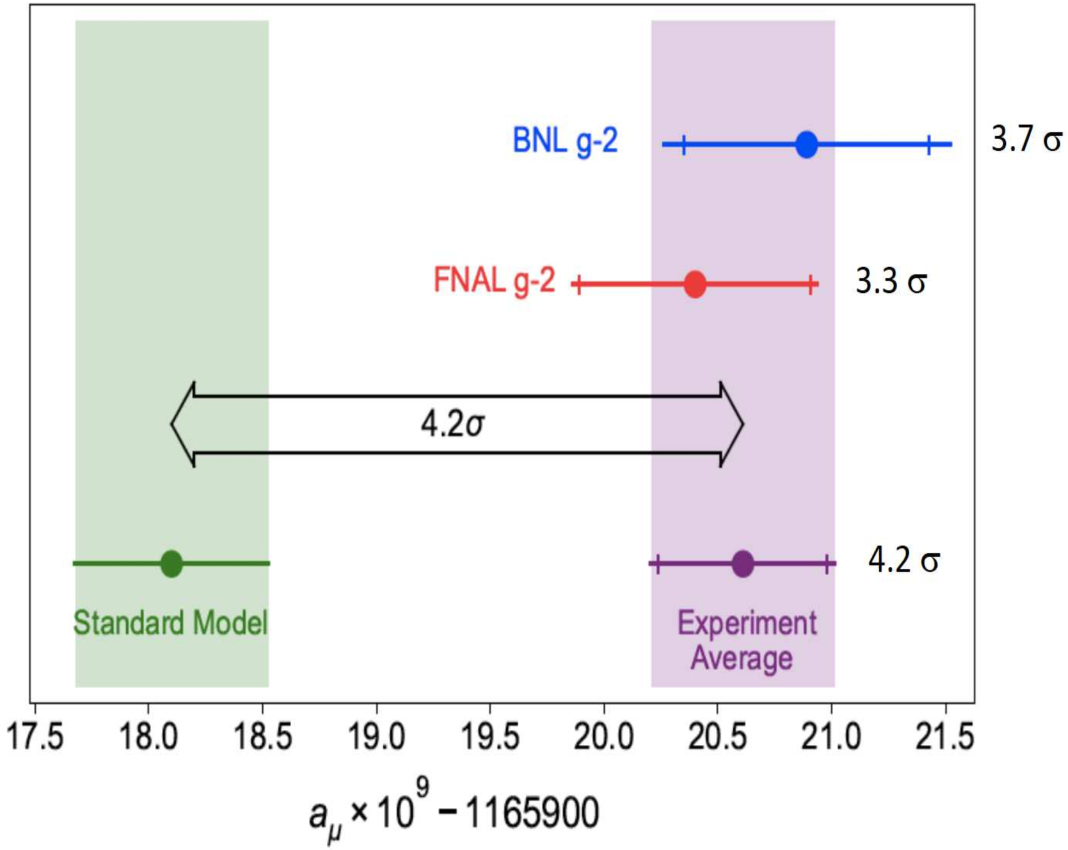
6. Conclusions



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:



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

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discrepancy $\approx 2 \times a_\mu^{\rm SM,weak}$

but: expect $a_\mu^{\rm NP} \sim a_\mu^{\rm SM,weak} \times \left(\frac{M_W}{M_{\rm NP}}\right)^2 \times$ couplings

$$a_\mu \sim \frac{m_\mu \times (\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping parameter})}{M^2_{\rm typical}}$$

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

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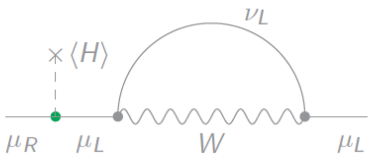
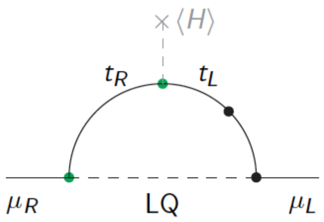
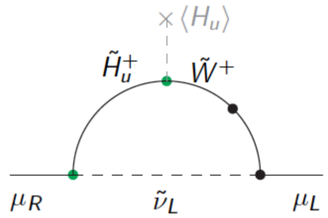
- EWSM: $\alpha \frac{m_\mu^2}{M_W^2}$



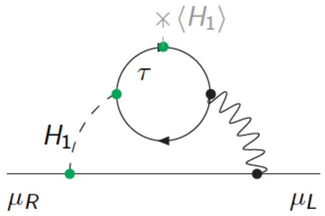
- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\rm LQ}}$



- SUSY: $\alpha \frac{m_\mu^2 \tan\beta}{M^2_{\rm SUSY}} \frac{\mu}{M_{\rm SUSY}}$



- 2HDM: $\alpha^2 \tan^2\beta \frac{m_\mu^2}{M_H^2}$



- rad. m_μ $\sim \frac{m_\mu^2}{M^2_{\rm NP}}$

2. "Two Higgs Doublets are as natural as one" (2HDM)

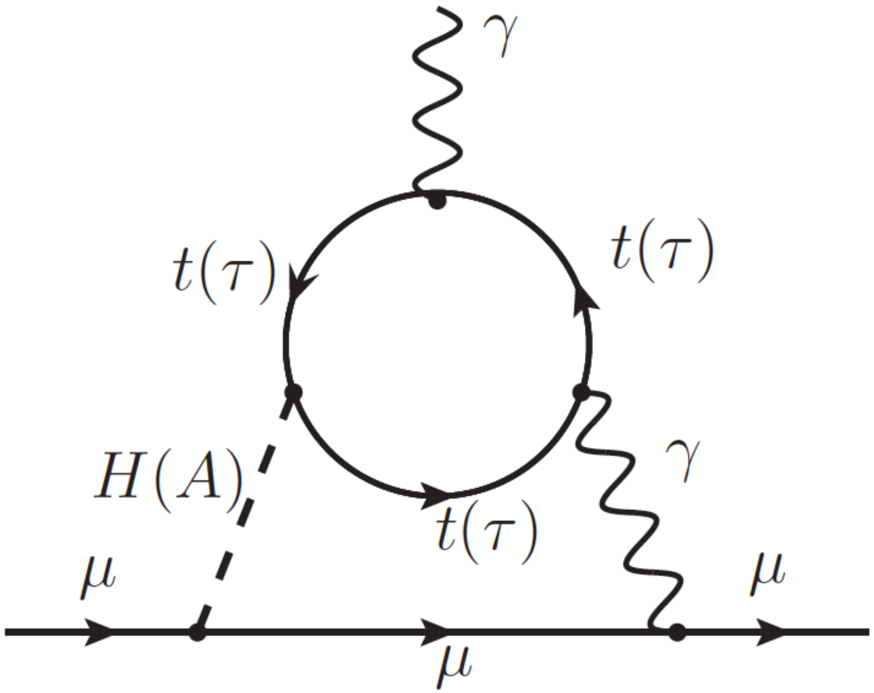
Extension of the Z_2 symmetry to fermions determines four types:

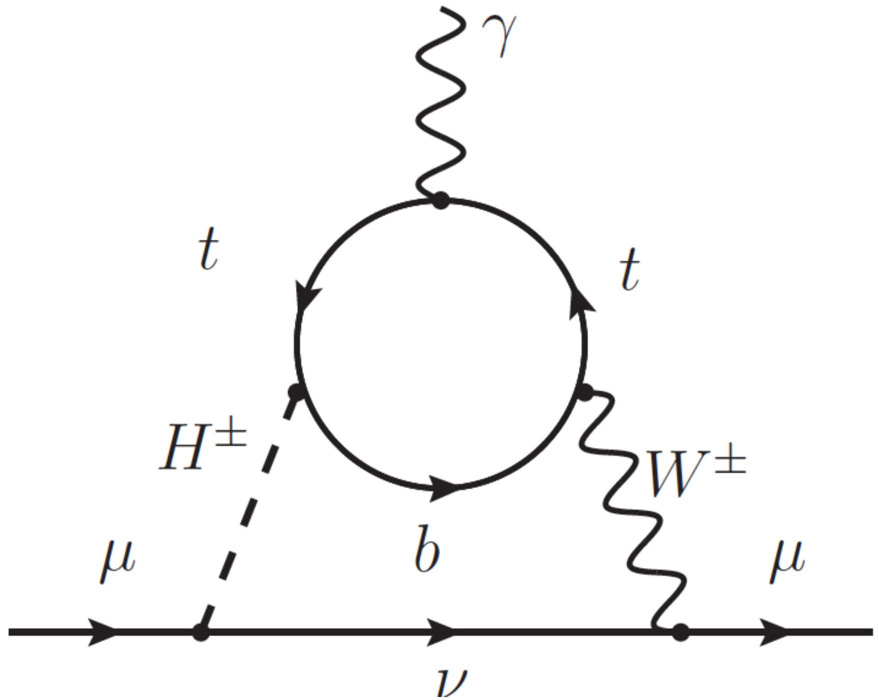
	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

Couplings to fermions:

	u-type (c_{Att})	d-type (c_{Abb})	leptons ($c_{A\tau\tau}$)
type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
type II	$\cot\beta$	$\tan\beta$	$\tan\beta$
type III/X (lepton-specific)	$\cot\beta$	$\cot\beta$	$\tan\beta$
type IV/Y (flipped)	$\cot\beta$	$\tan\beta$	$\cot\beta$

Barr-Zee diagrams:



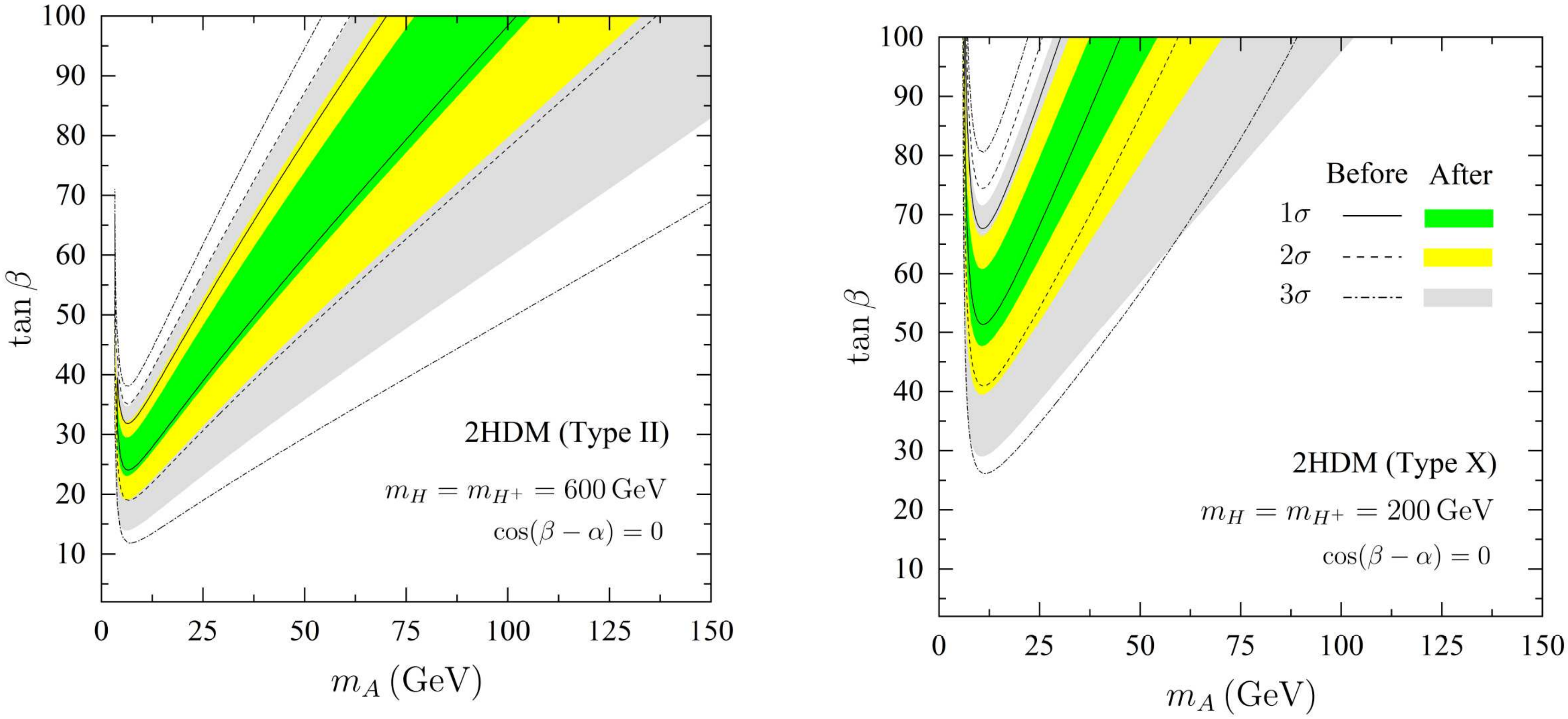


Known since long:

Light A at high $\tan\beta$ can explain the $(g-2)_\mu$ result

$\Rightarrow$ in type II and X: enhanced couplings to μ's

Updated 2HDM results: [P. Ferreira, B. Goncalvez, F. Joaquim, M. Sher '21]



Taking EWPO into account: $\Rightarrow M_{H^\pm} \lesssim 200$ GeV

type II: problems with $b \to s\gamma$

$\Rightarrow$ only type X is in agreement with $(g-2)_\mu$, EWPO and flavor observables

$\Rightarrow$ Not taken into account here: $h_{125} \to AA$ ...

Since it does not work, vector-like leptons can be introduced:

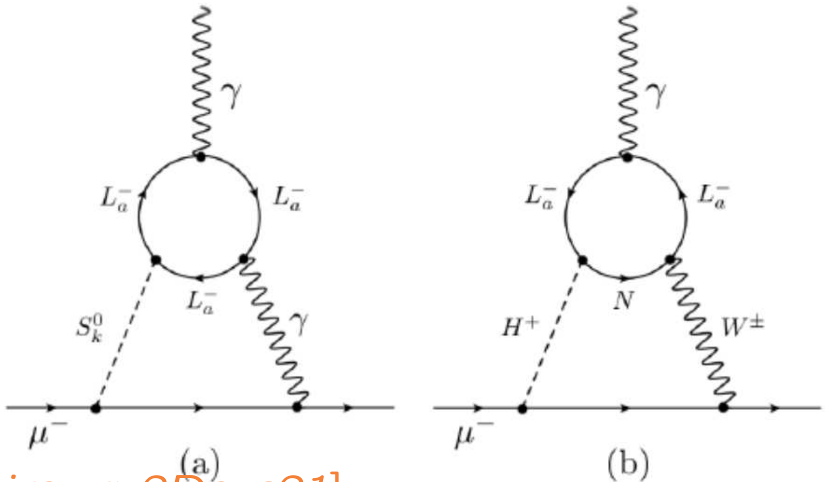
VECTOR-LIKE LEPTONS

Introduce single generation of Vector-Like Leptons (VLL), right and left SU(2) doublets $\chi_{L,R} = (N\ ,\ E)^T_{L,R}$, and left-and-right singlets E_L and E_R, with a lagrangian given by

$$-\mathcal{L}_{\rm VLL} = m_L \overline{\chi_L}\chi_R + m_E \overline{E_L} E_R + \lambda_L \overline{\chi_R}\Phi_1 E_L + \lambda_R \overline{\chi_L}\Phi_1 E_R + \text{H.c.}\,,$$

The L and E fields are electrically charged, N is neutral.

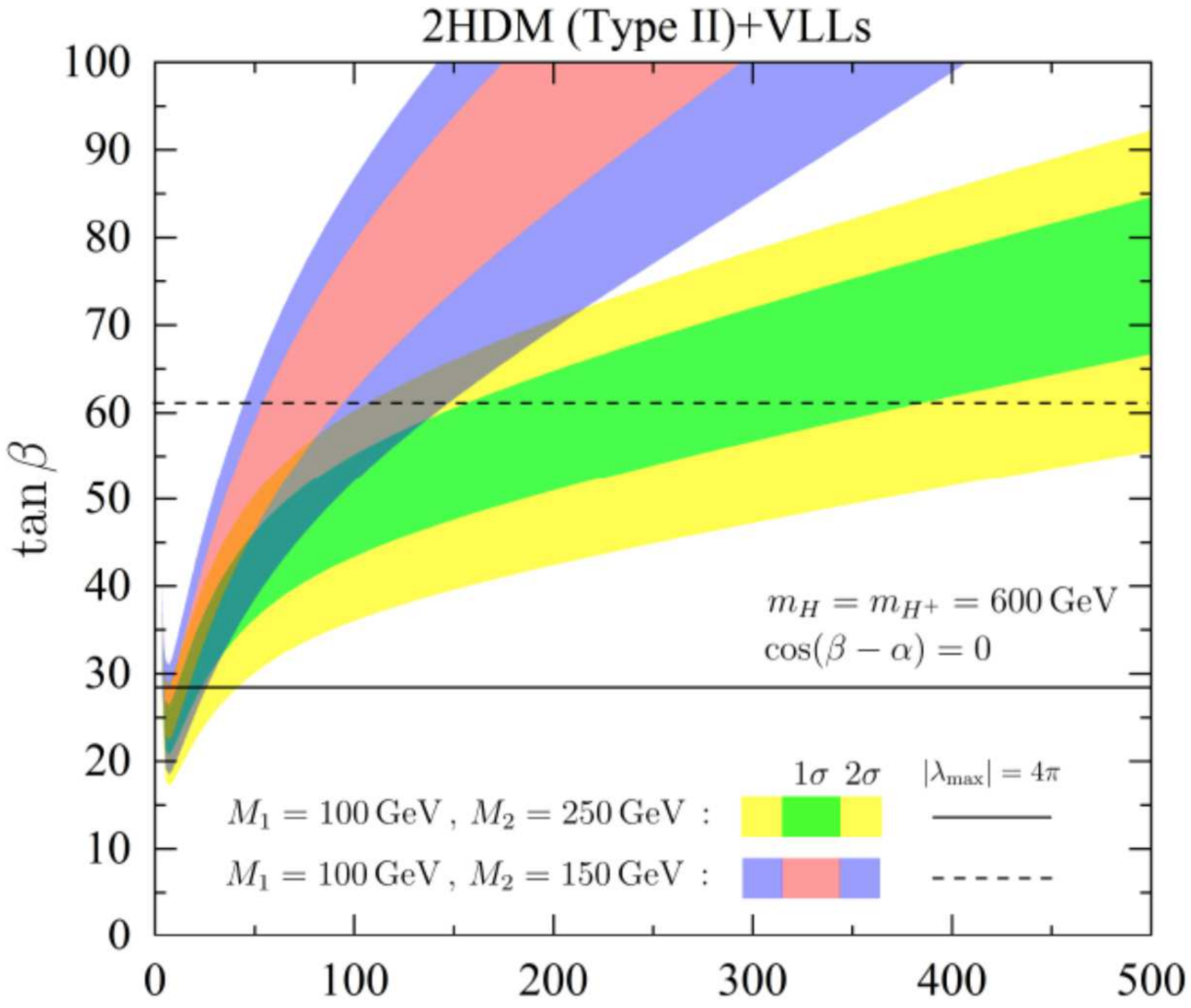
Since there is no mixing with muons, the VLLs willchange the 2-loop contributions via new diagrams:



[*taken from talk by P. Ferreira, g-2Days21*]

Results in the 2HDM+VLL type II:

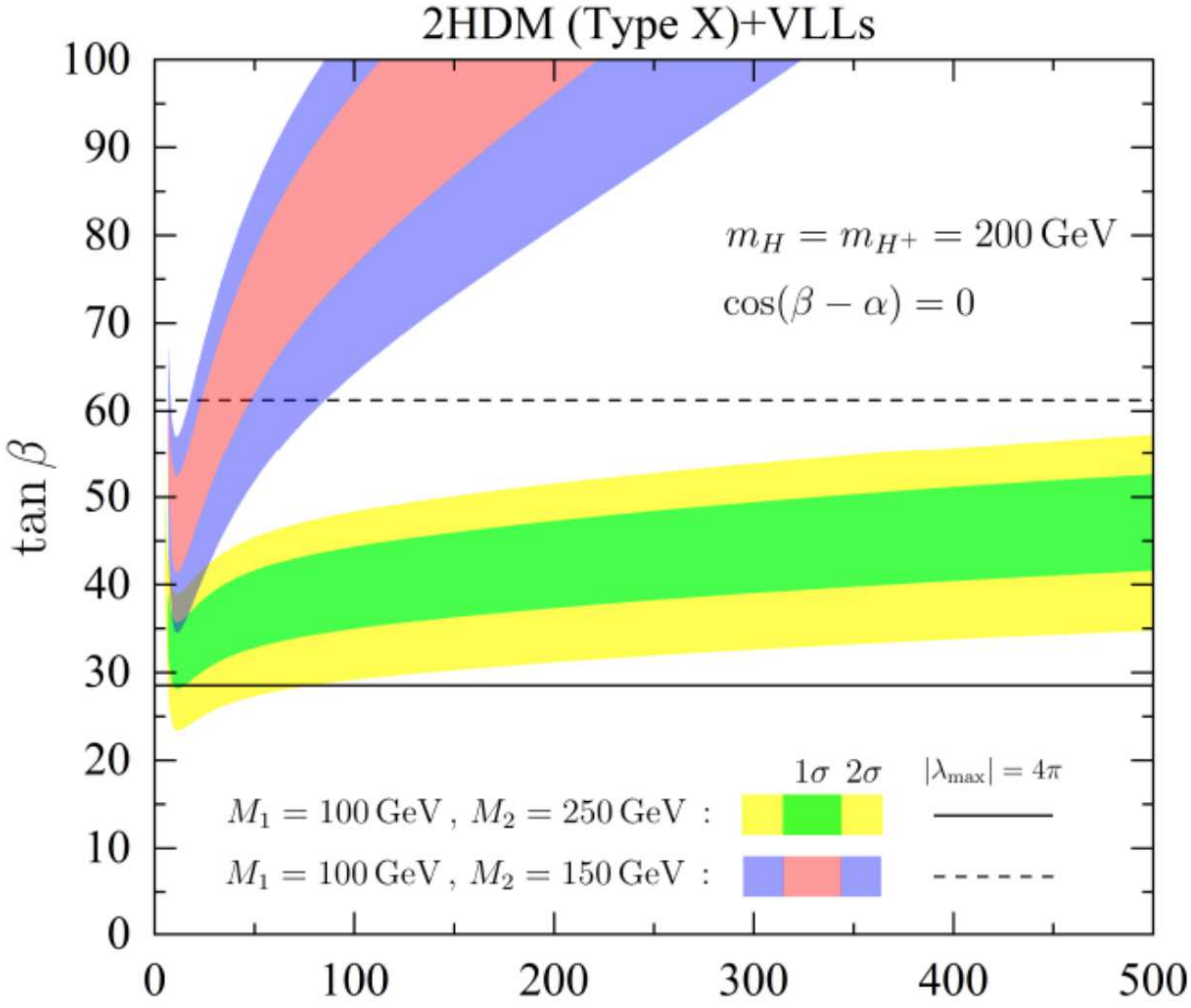
[*taken from P. Ferreira, g-2Days21*]



⇒ better, but very large values of $\lambda_{L,R}$ required

Results in the 2HDM+VLL type X:

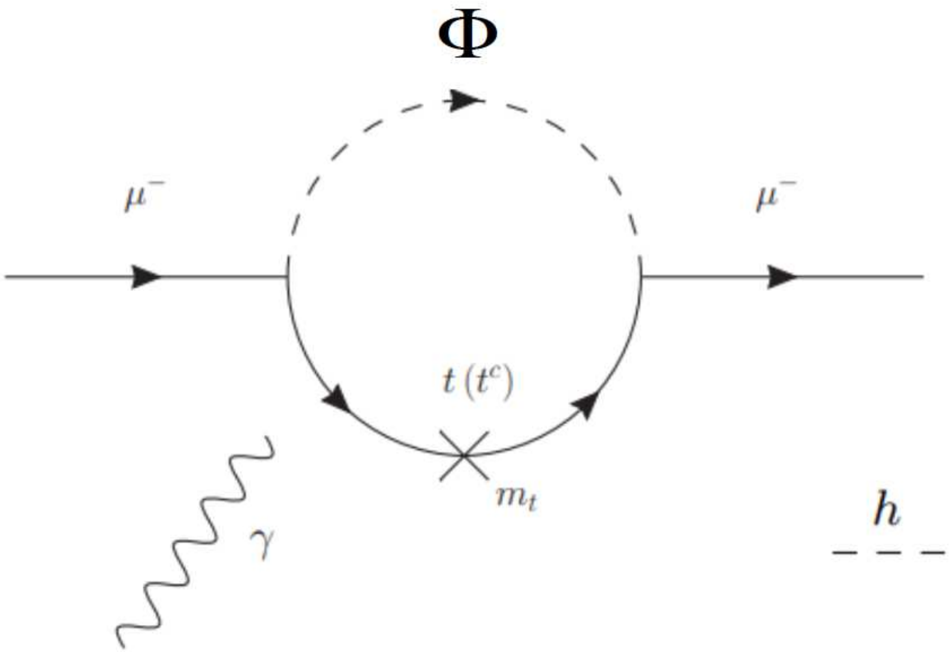
[taken from P. Ferreira, g-2Days21]

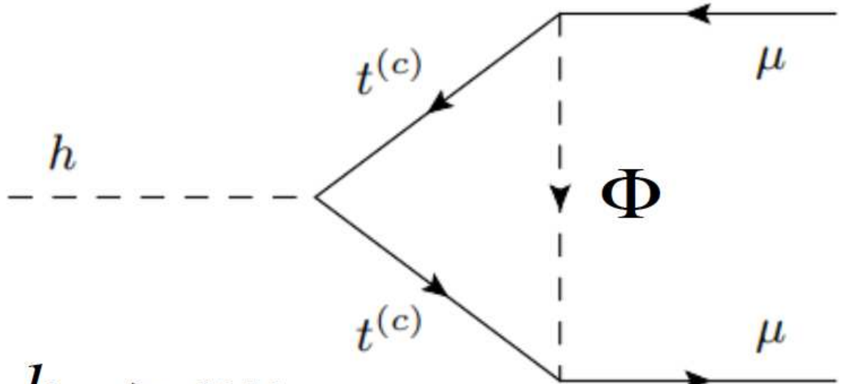


⇒ better, but very large values of $\lambda_{L,R}$ required

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



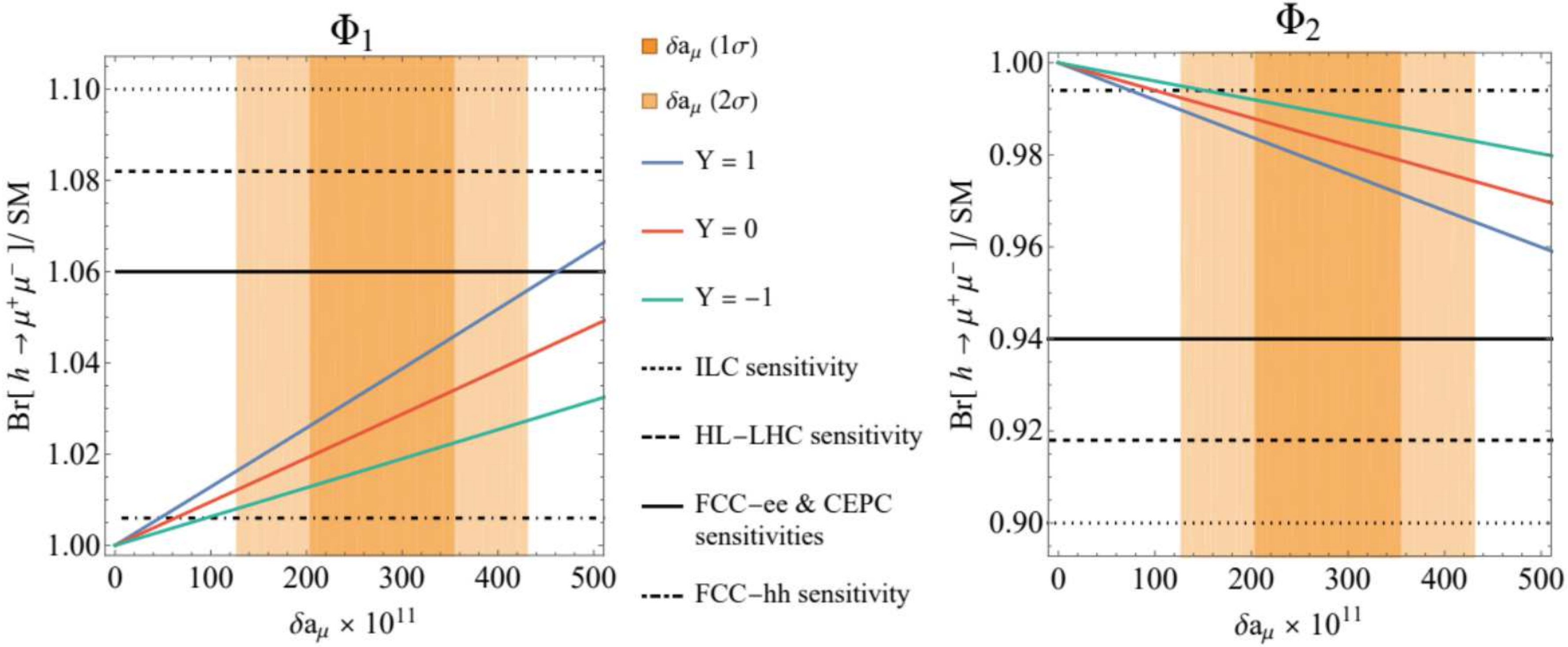


- m_t/m_μ enhanced effect $h \to \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \to \mu\mu$

$\Rightarrow$ correlation between $(g-2)_\mu$ and $\Gamma(h \to \mu\mu)$

a_μ vs $h \to \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation

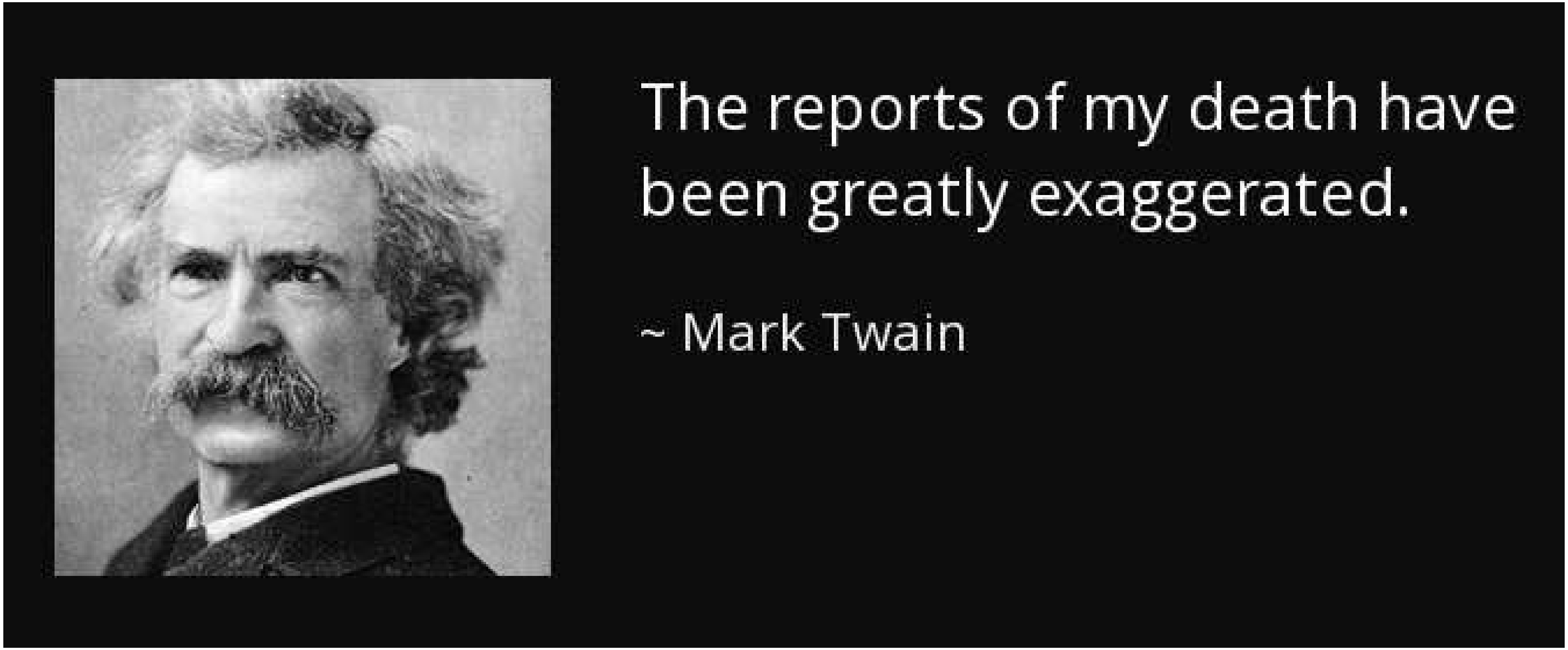


A.C., D. Mueller, F. Saturnino, 2008.02643

⇒ interesting prospects for future collider measurements

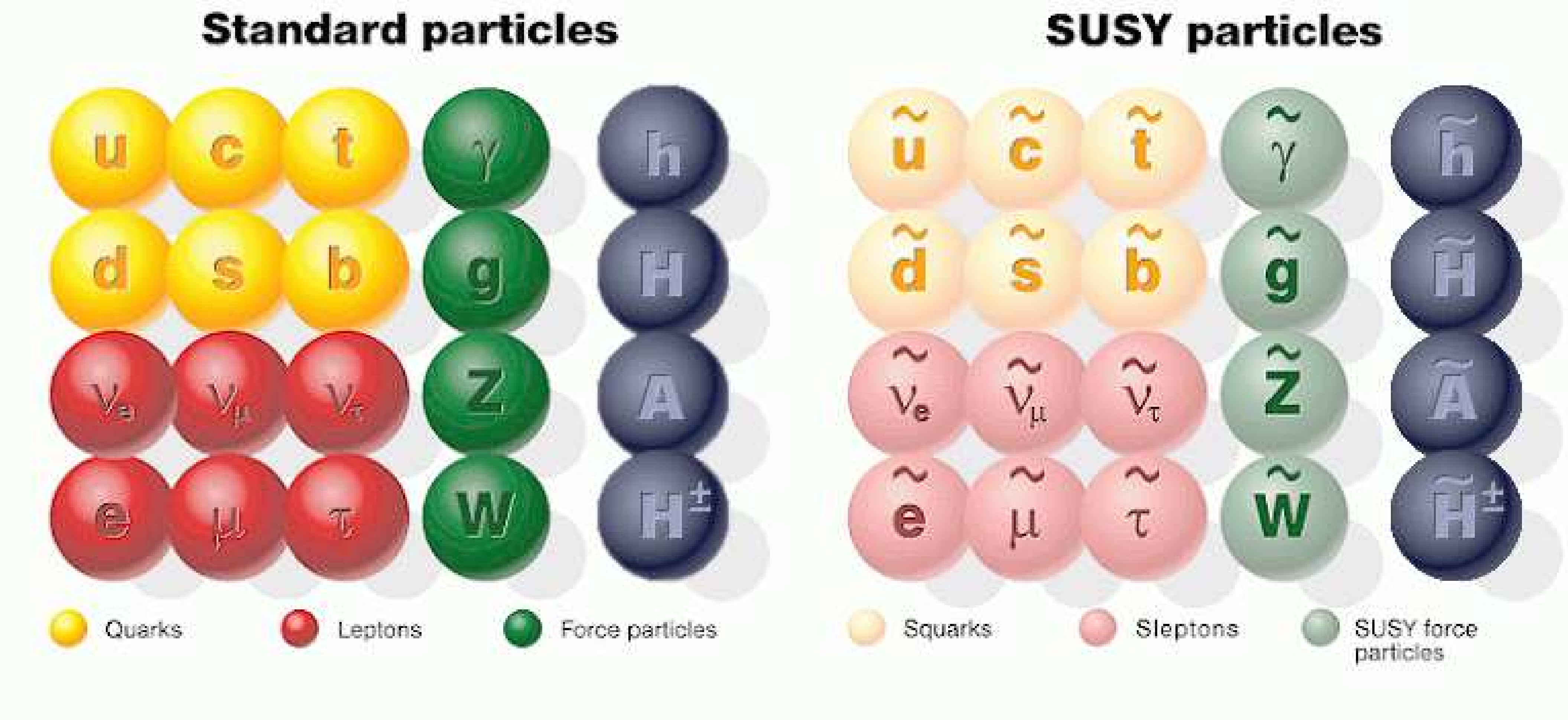
4. “SUSY fits like a glove”

→ quote by Bill Marciano after the BNL result came out in 2001



Simplest SUSY realization: the MSSM

Superpartners for Standard Model particles



⇒ 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:

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

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

$\Rightarrow$ neutralinos: mass eigenstates

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

$\Rightarrow$ 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

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

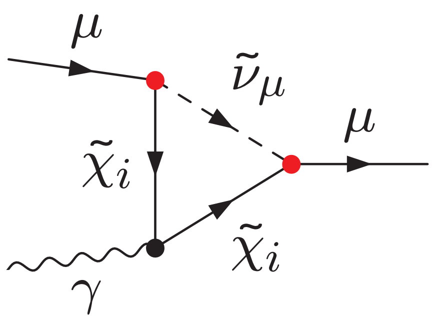
Sneutrino mass

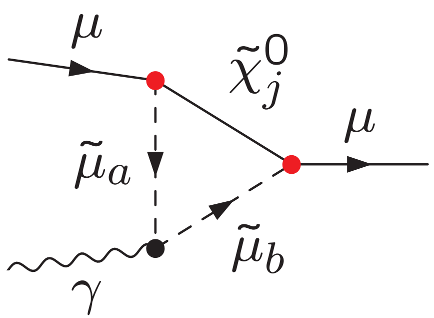
$$m^2_{\tilde{\nu}_l} = M^2_{\tilde{l}_L} + DT_\nu$$

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

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

$\Rightarrow$ 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.)

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⇒ SUSY could easily explain the “discrepancy”

⇒ a_μ can provide upper limits on the EW masses

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

If SUSY exists, it should fix $(g-2)_\mu$!
⇒ 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 the prospects for future searches

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

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

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

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

Dark Matter relic density: MicrOmegas

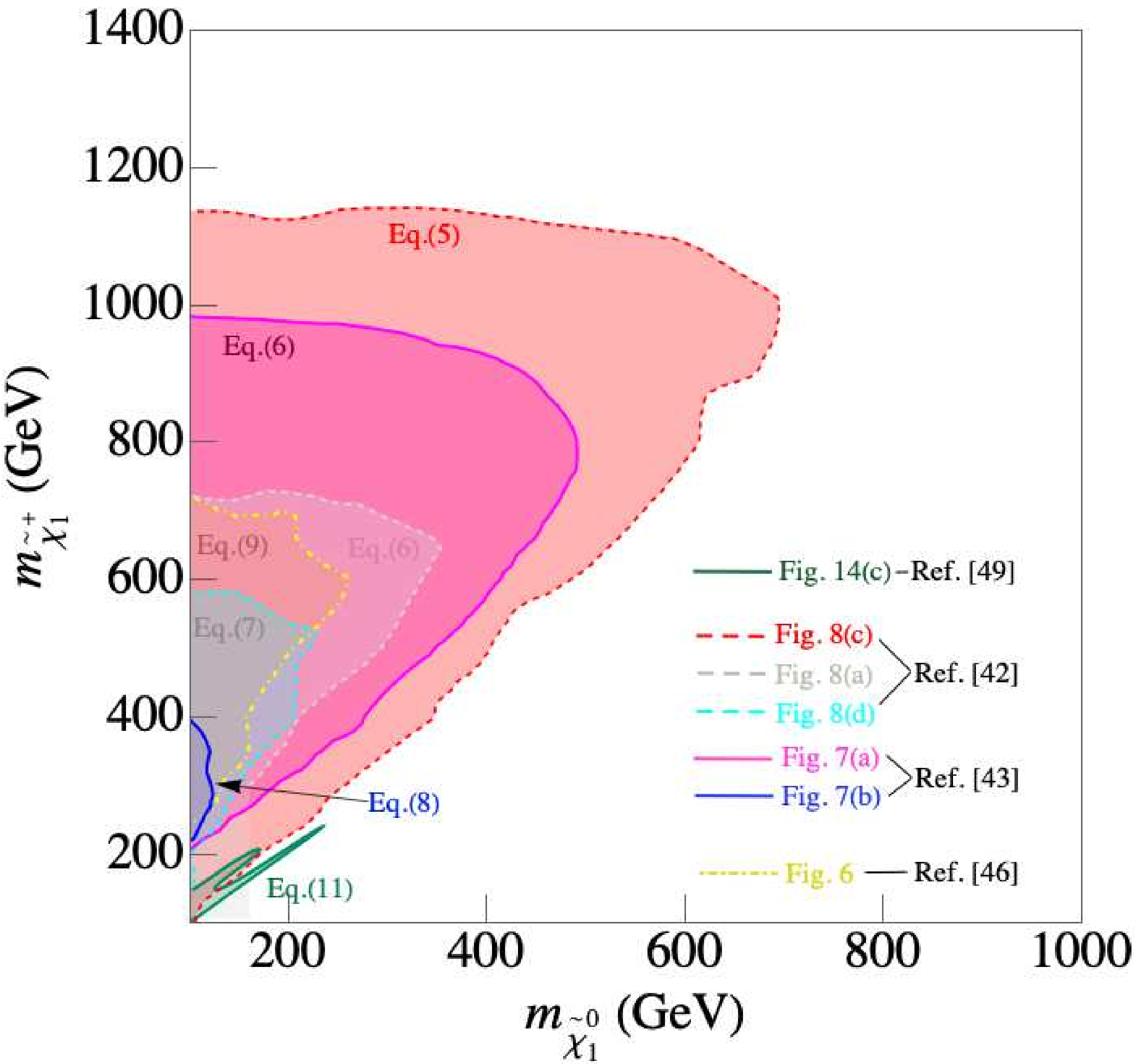
$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\text{or} \quad \Omega_{\text{CDM}} h^2 \leq 0.122$$

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

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)
[*Xenon collab. '18*]

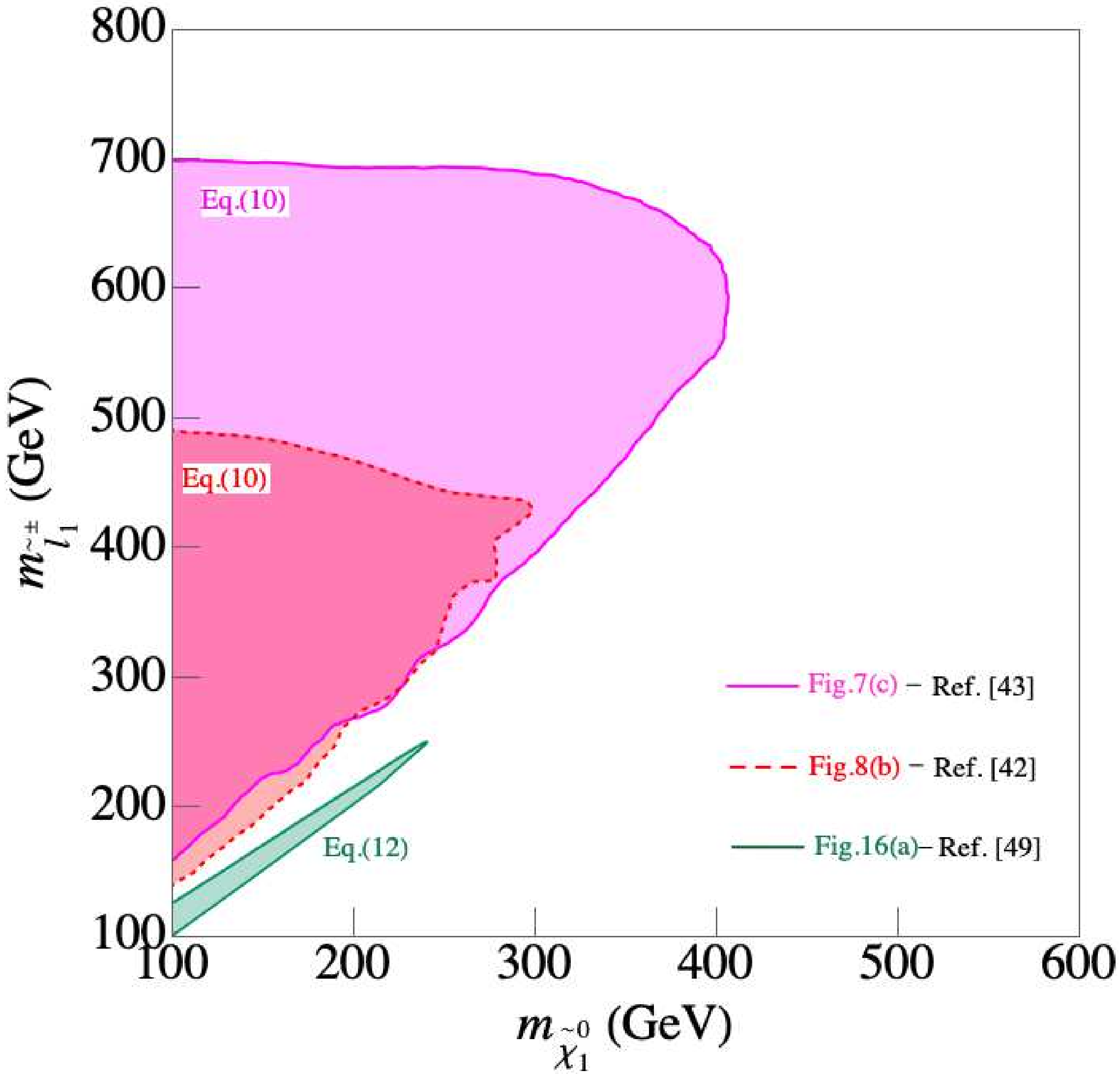
LHC exclusion bounds (I) (as given for Simplified Model Spectra (SMS))



⇒ 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))

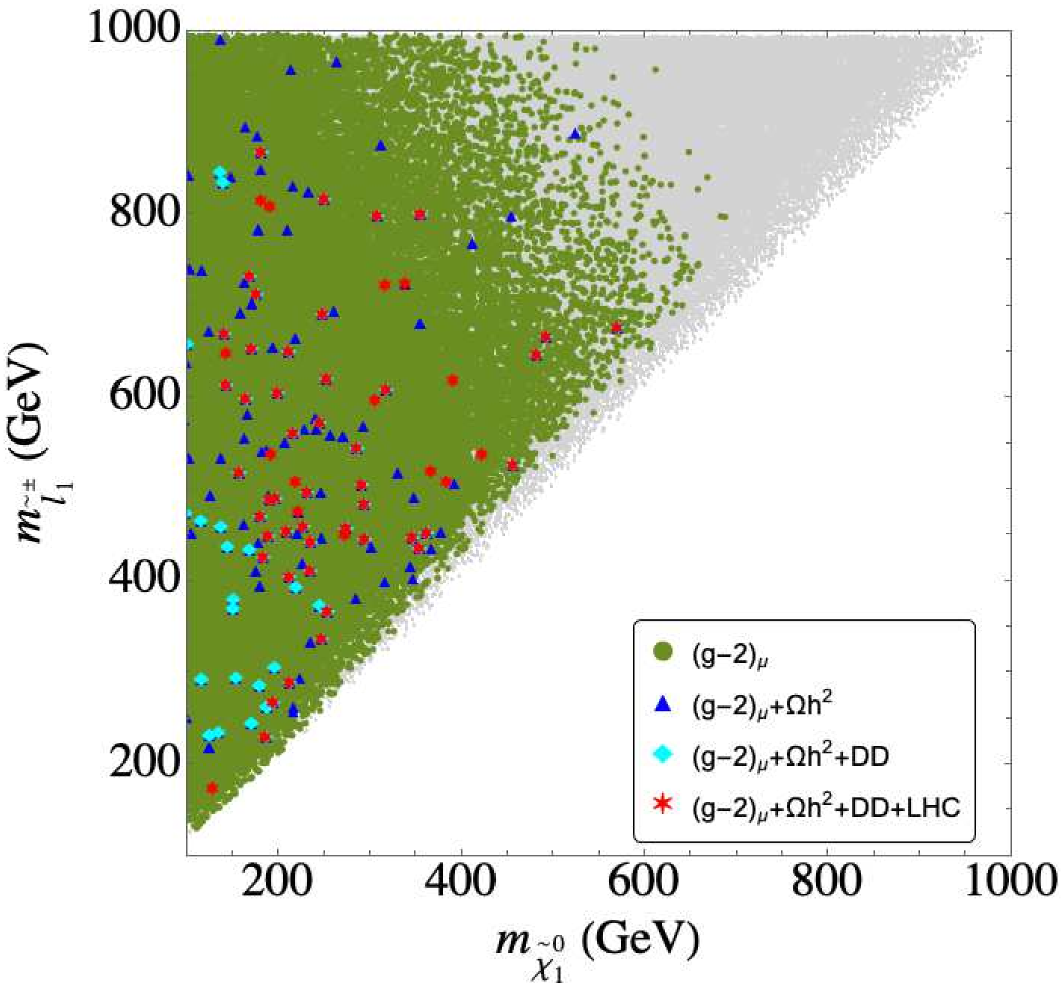


⇒ all newly included into CheckMate *[M.C & I.S.]*

Exception: compressed spectra ⇒ direct application

Example I: $\tilde{\chi}_1^{\pm}$-coannihilation: $m_{\tilde{\chi}_1^0}$-$m_{\tilde{l}_1}$ plane:

new $(g-2)_\mu$



⇒ important: $\tilde{l}$-pair production searches (10)

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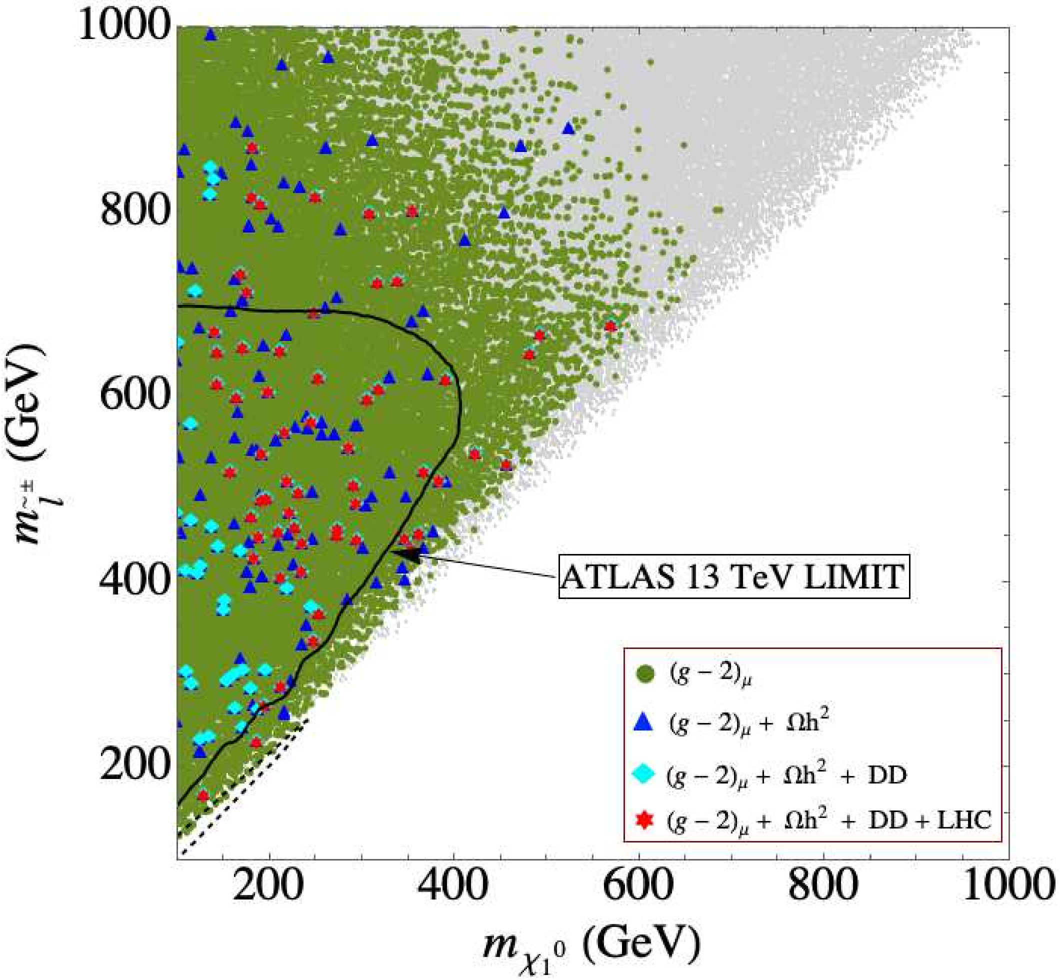
old $(g-2)_\mu$

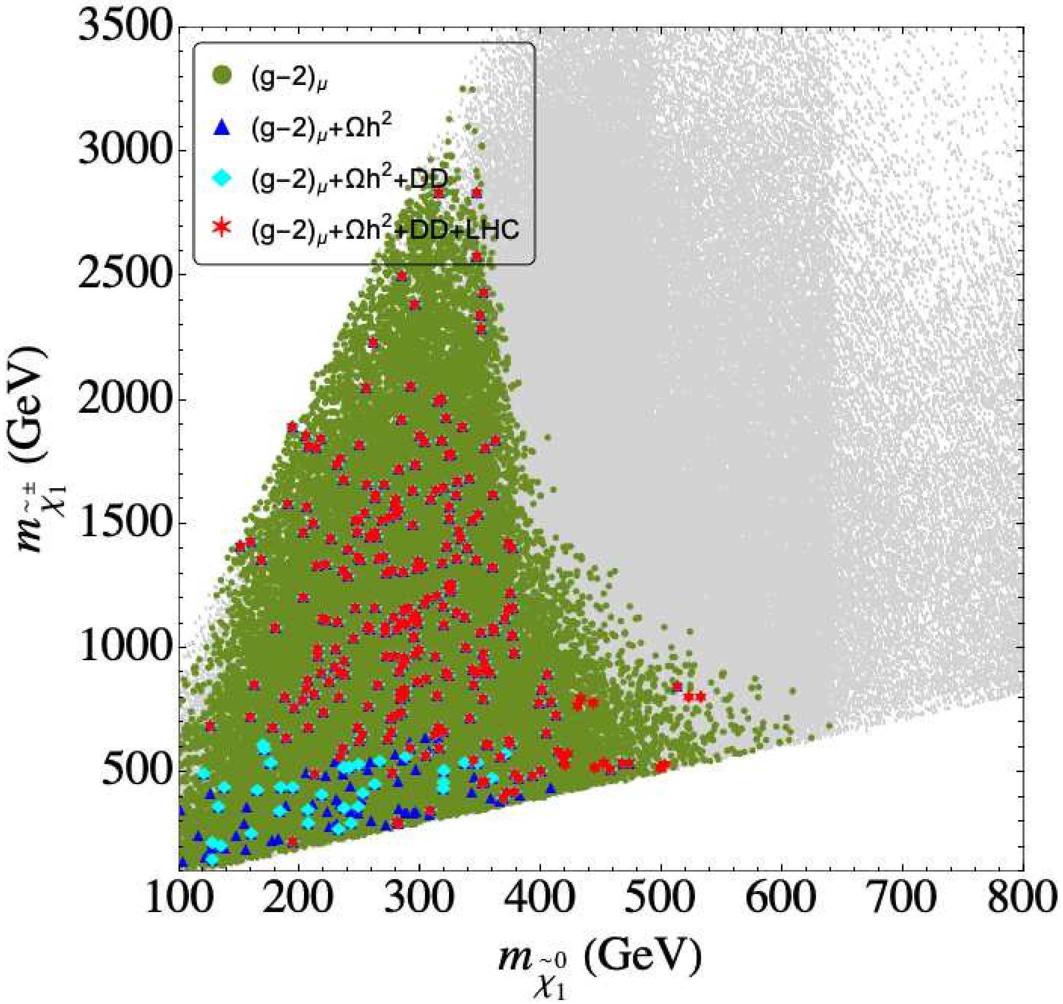


⇒ important: $\tilde{l}$-pair production searches (10)

⇒ naive application of LHC bounds fails

Example II: $\tilde{l}$-coannihilation: $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane:

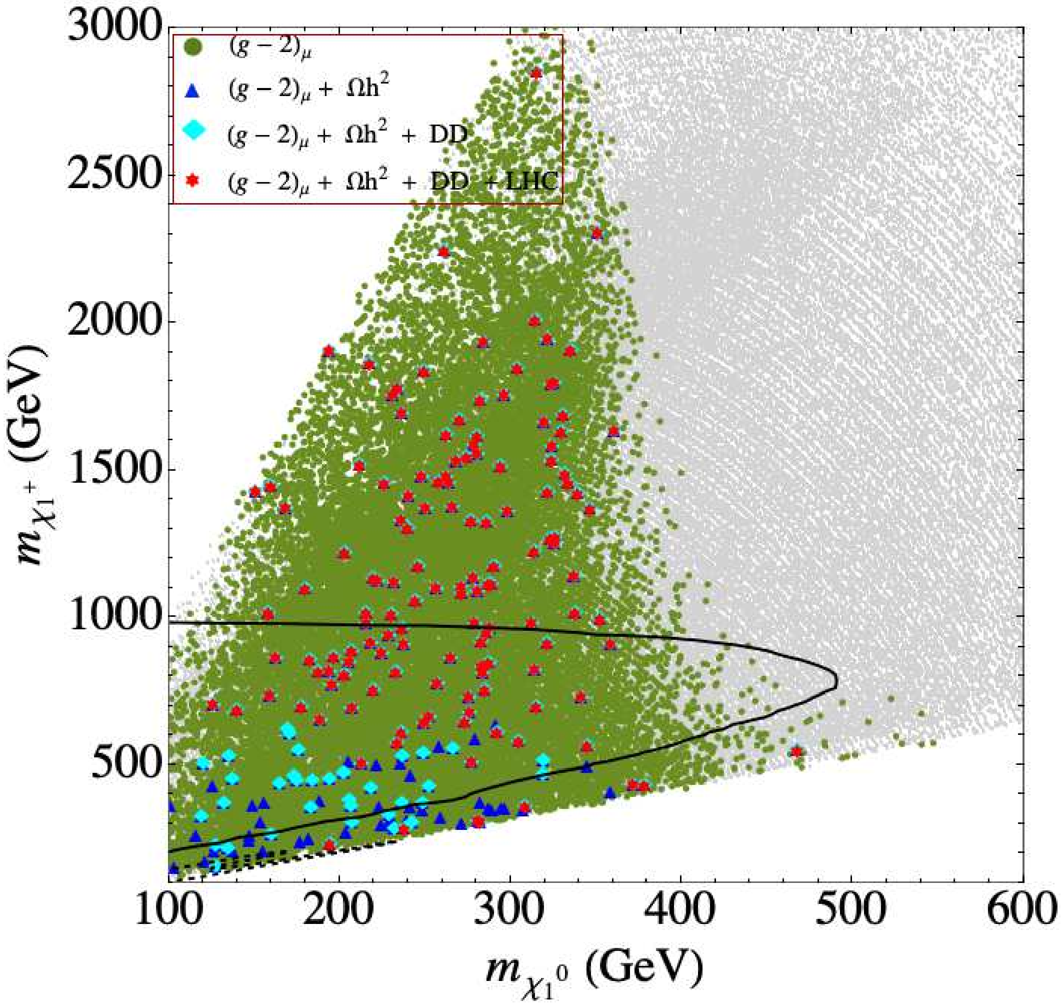
new $(g-2)_\mu$



⇒ important: $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production searches (5)

Example II: $\tilde{l}$-coannihilation: $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane:

old $(g-2)_\mu$

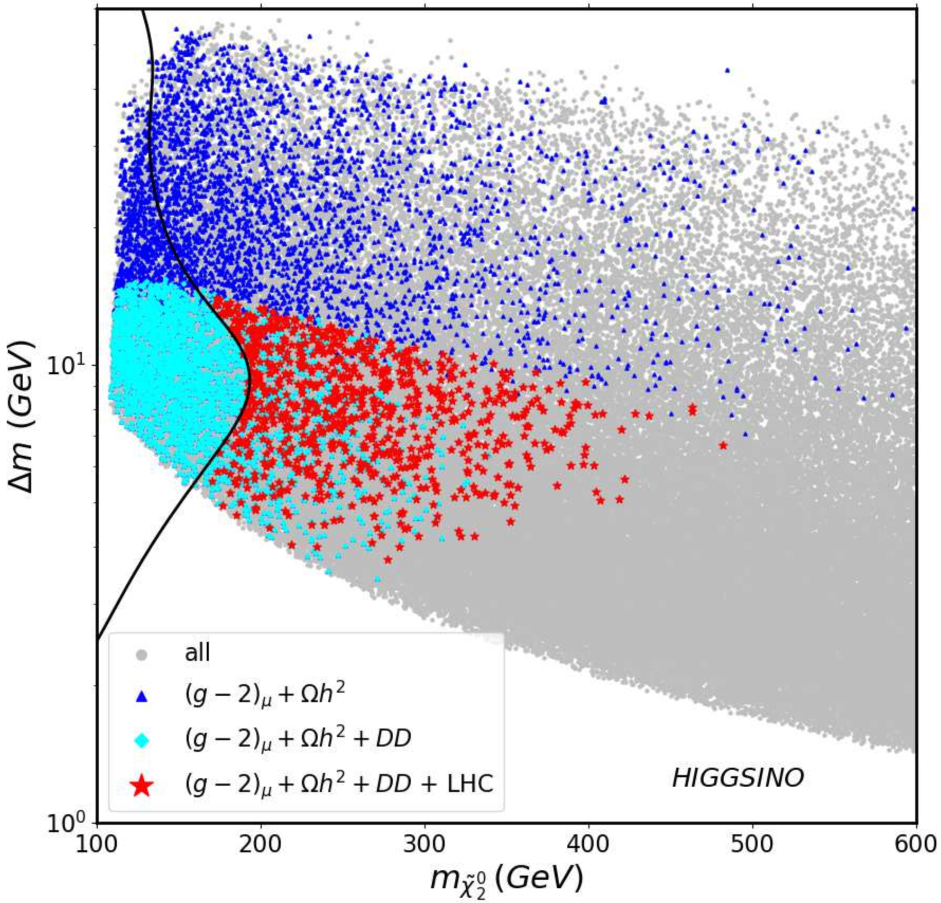


⇒ important: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production searches (5)

⇒ naive application of LHC bounds fails

Example III: higgsino DM: $m_{\tilde{\chi}_2^0}$-Δm plane:

old $(g-2)_\mu$

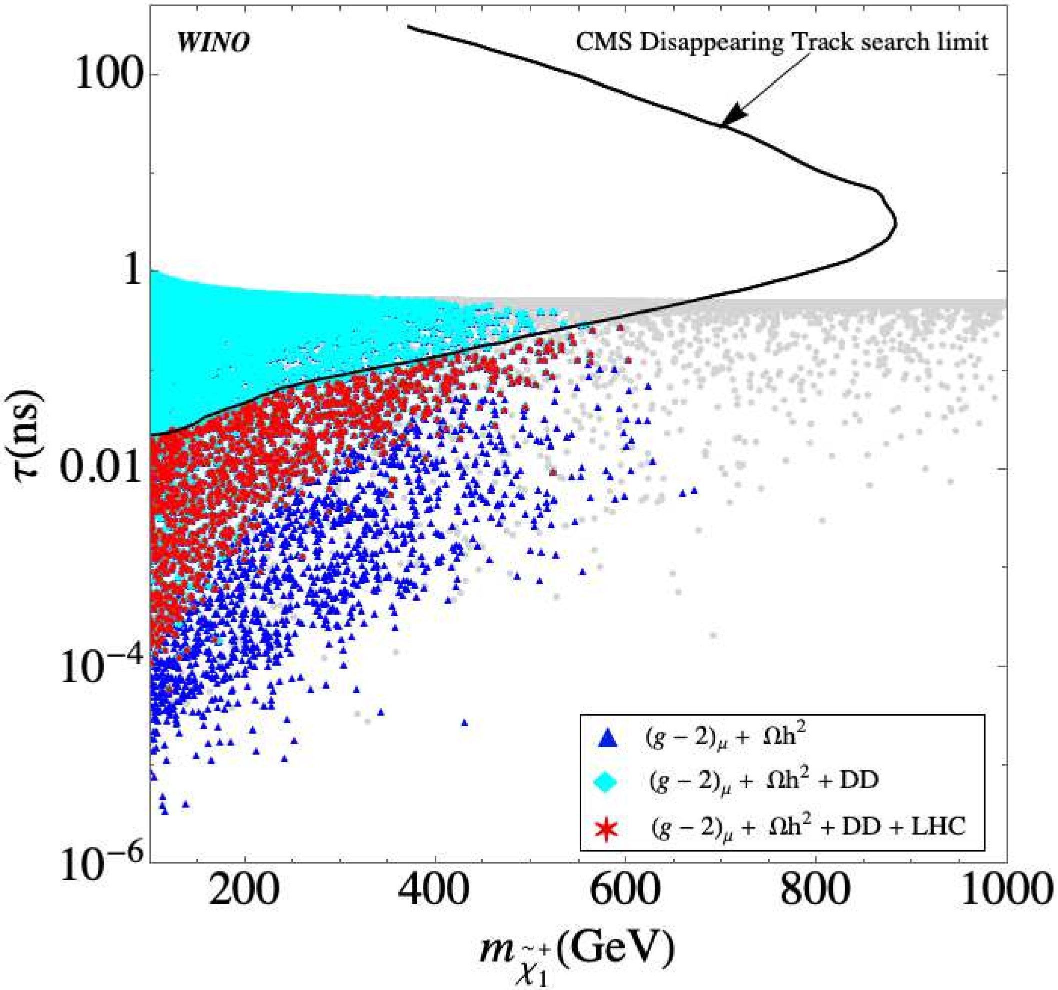


$\Rightarrow$ important: compressed spectra searches (11)

$\Rightarrow$ right where the model prediction sits $\Rightarrow$ very powerful

Example IV: wino DM: $m_{\tilde{\chi}_1^\pm}$-$\tau_{\tilde{\chi}_1^\pm}$ plane:

old $(g-2)_\mu$



⇒ important: disappearing track limit ⇒ $m_{\text{(N)LSP}} \lesssim$ 600 GeV

⇒ allowed parameter space squeezed by DD limits and disapp. tracks

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

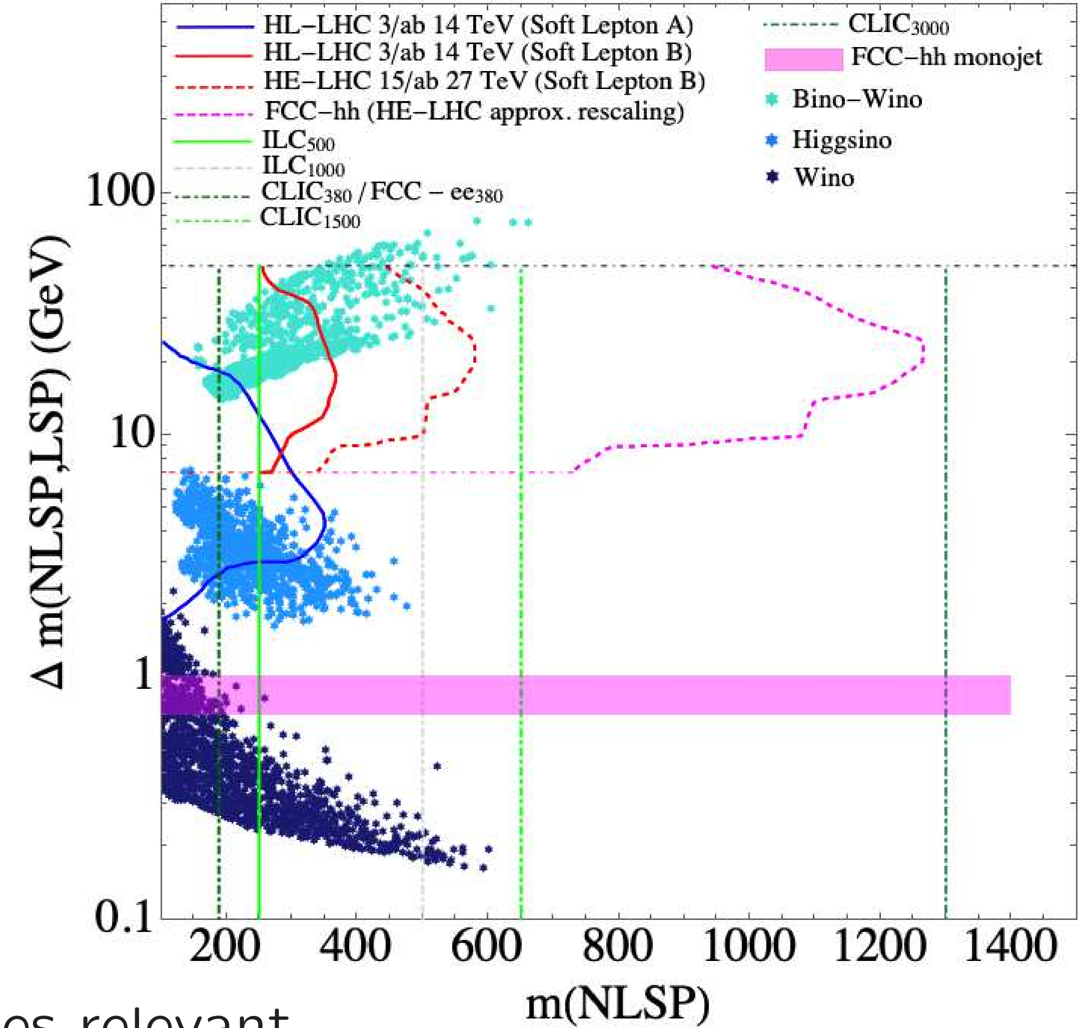
D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim$ 1 TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 500 GeV

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

$\Rightarrow$ predictions for future experiments?!

Compressed spectra at current and future colliders

Higgsino, wino and bino/wino DM:



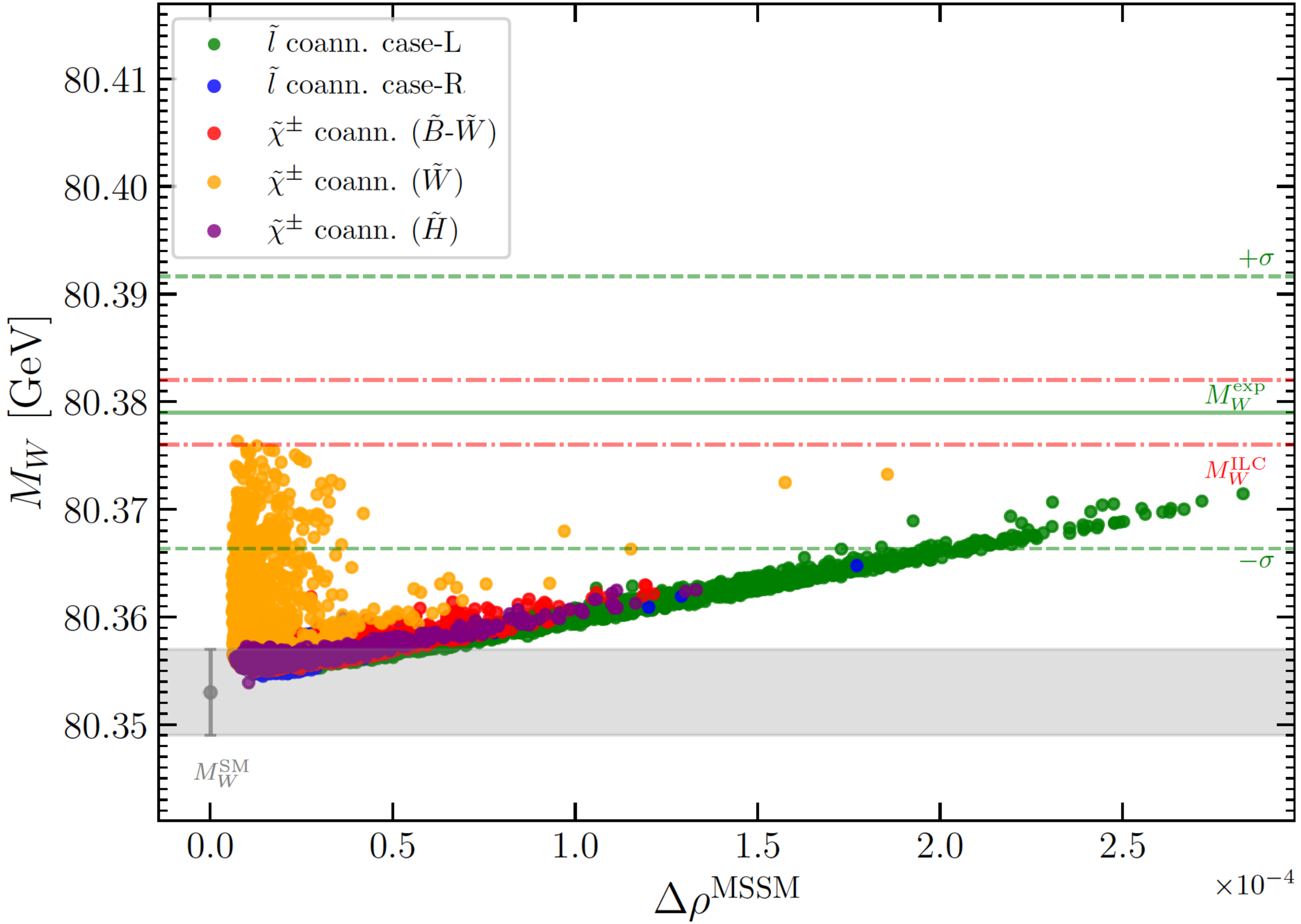
– current searches relevant

– HL-LHC searches can cover some part of the parameter space

– ILC/CLIC needed to cover these scenario

Prediction for M_W:

[E. Bagnaschi, M. Chakraborti, S.H., I. Saha, G. Weiglein '22]

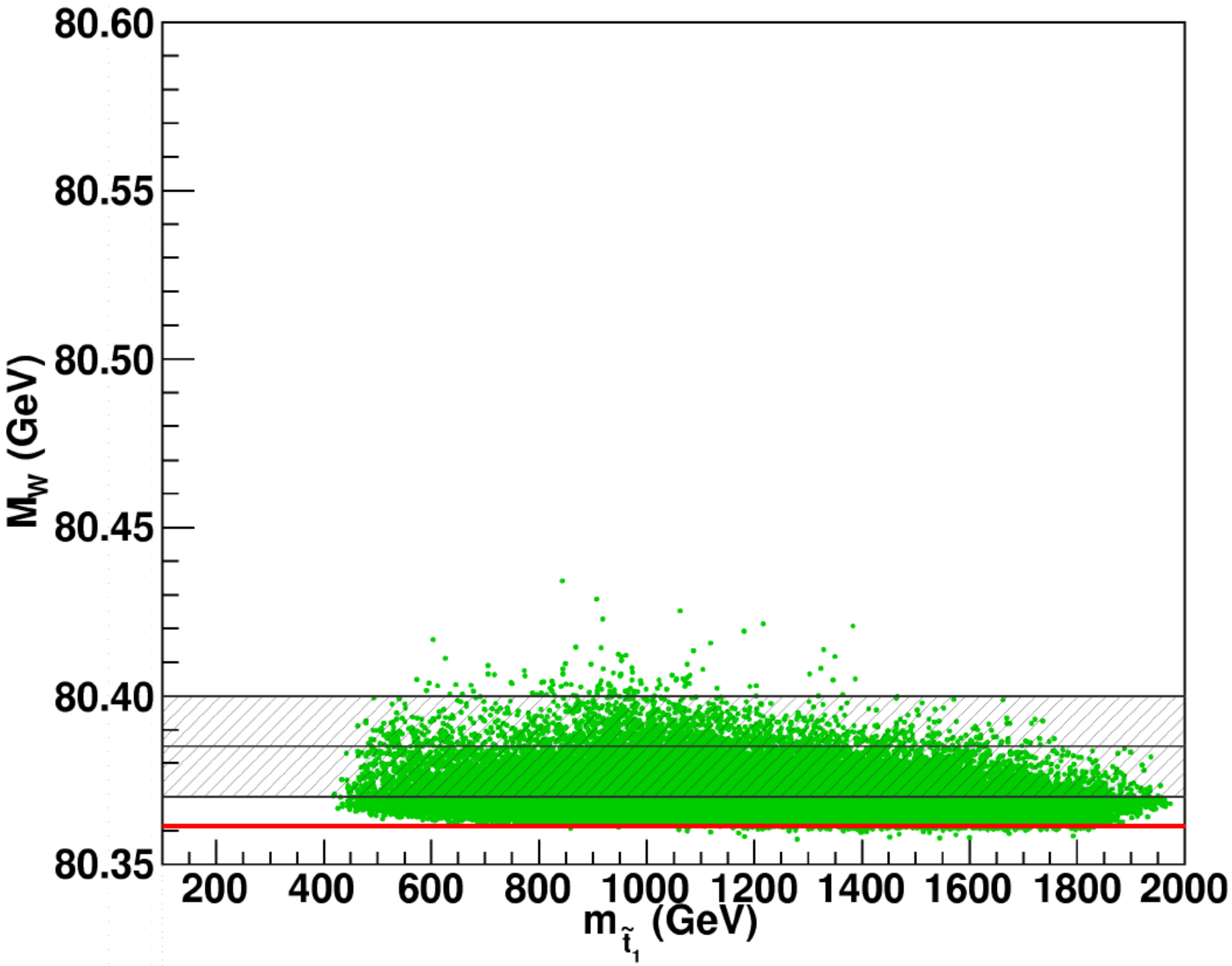


⇒ EW sector gives a large contribution to M_W

⇒ but far away from $M_W^{\rm CDF}$ ⇒ contributions from stops/sbottoms needed!

Effects of stops: [S.H., G. Weiglein, L. Zeune '13]

$\Rightarrow$ larger M_W without $(2/5 \leq m_{\tilde{t}_i}/m_{\tilde{b}_j} \leq 5/2)$



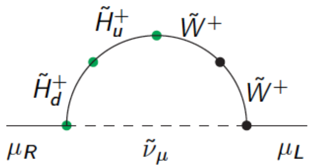
$\ldots \oplus m_{\tilde{b}_i} > 500$ GeV $\Rightarrow$ stop/sbottom effects can give rise to M_W^{CDF}!

Excursion: radiatively generated m_μ (for $\tan\beta \to \infty$)

[taken from talk by D. Stöckinger, g-2Days21]

a_μ and radiative muon mass: MSSM for $\tan\beta \to \infty$

[Bach,JH Park,DS,Stöckinger-Kim, '15]

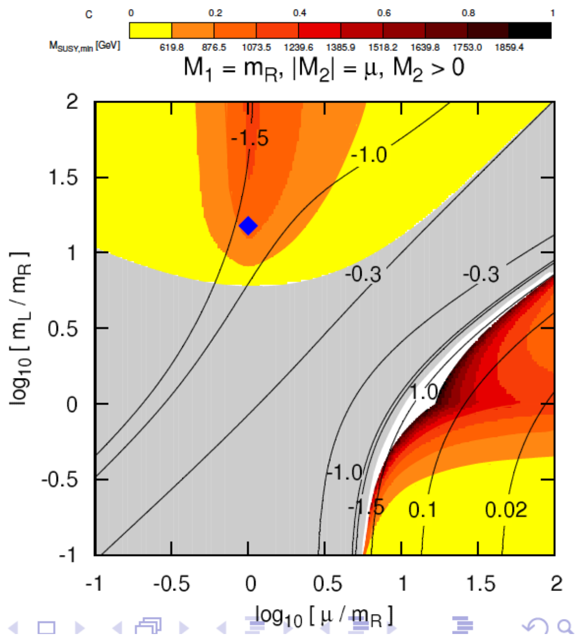


Idea: $v_d = 0 \rightsquigarrow m_\mu^{\rm tree} = y_\mu v_d = 0$

$$a_\mu^{\rm SUSY} \approx y_\mu v_u \times \text{loop}$$

$$m_\mu^{\rm pole} \approx \underbrace{y_\mu v_d}_{\text{usual approx.}} + \underbrace{y_\mu v_u \times \text{loop}}_{\text{now important}}$$

$$\Rightarrow a_\mu^{\rm SUSY} \longrightarrow \frac{\text{loop}}{\text{loop}}$$



New features for $\tan\beta \to \infty$:

- simpler behaviour, larger results

$$a_\mu(M_{\rm SUSY}) \approx -70\times10^{-10} \left(\frac{1\text{TeV}}{M_{\rm SUSY}}\right)^2$$

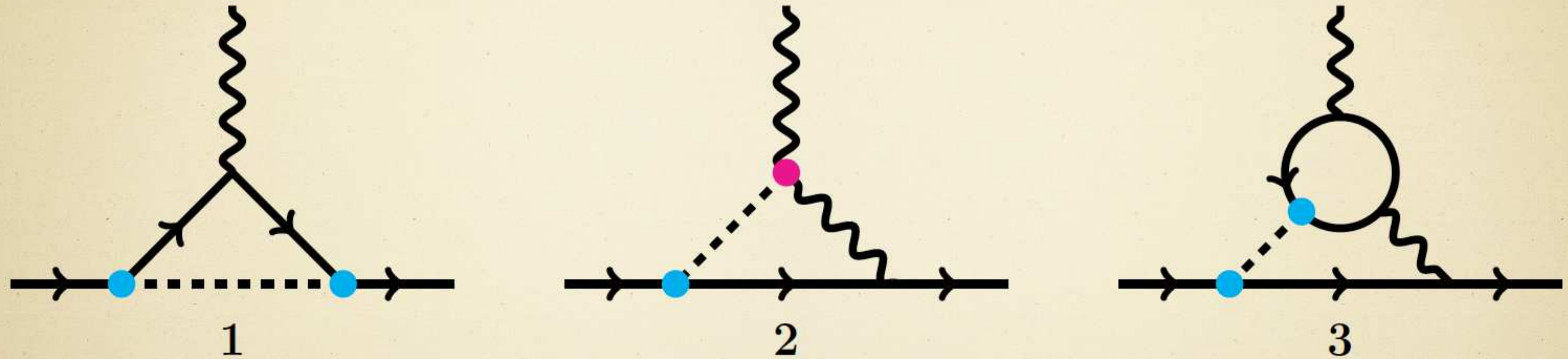
$$a_\mu(m_L \to \infty) \approx +36 \times 10^{-10} \left(\frac{1\text{TeV}}{M_{\rm SUSY}}\right)^2$$

5. "There is always the axion"

→ quote by Howie Baer on WIMP DM limits

Lagrangian and possible contributions (I):

$$\mathscr{L}_{\text{eff}} \supset \frac{c_{ii}}{2}\frac{\partial_\mu a}{f_a}\left(\bar{\ell}_i \gamma^\mu \gamma^5 \ell_i\right) + c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$



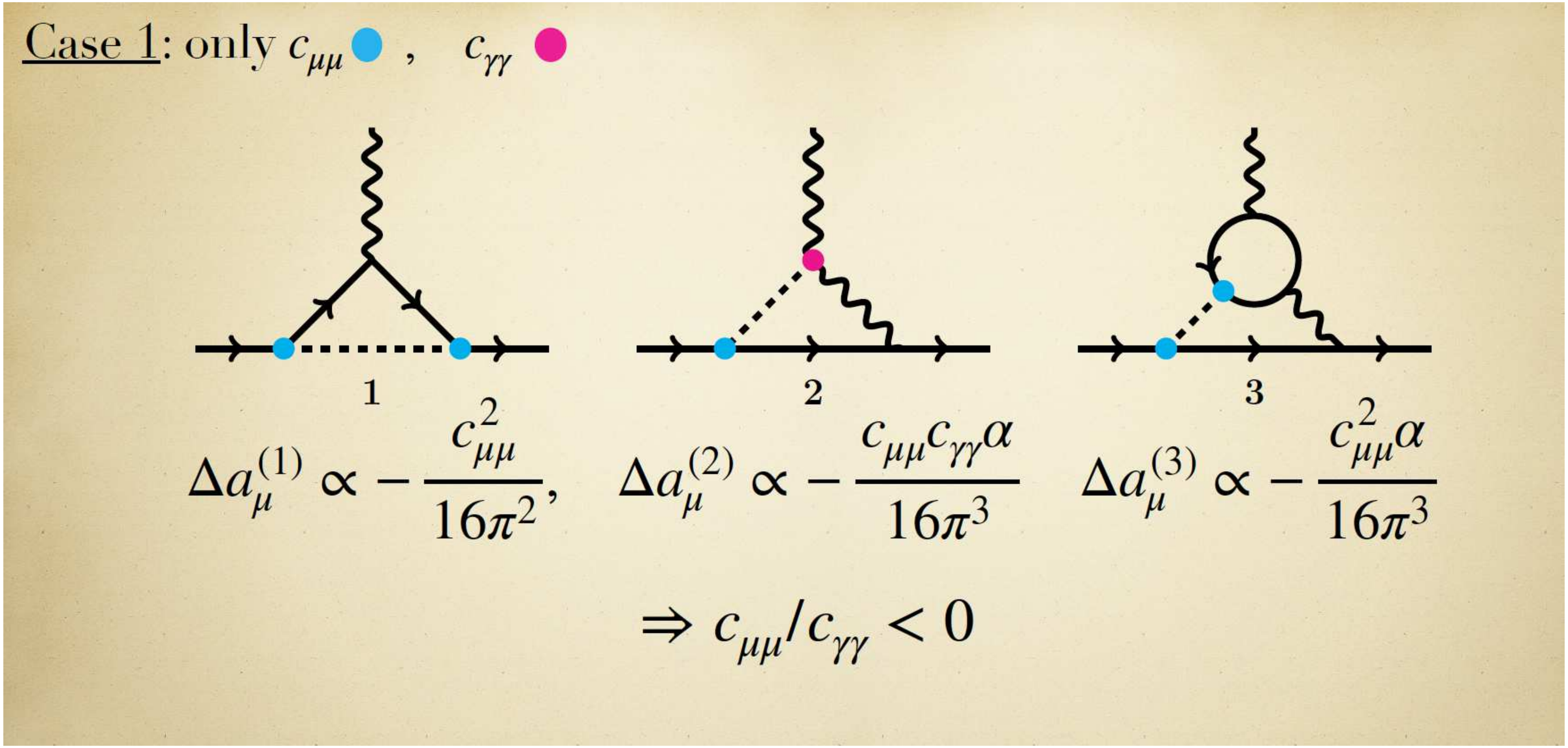
$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(2)} \propto -\frac{c_{\mu\mu}c_{\gamma\gamma}\alpha}{16\pi^3}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu}c_{ii}\alpha}{16\pi^3},$$

Chang et.al 2001; Marciano et.al. 2016; Bauer et.al. 2017.

Different combinations of the axion couplings: Darme et.al 2020

[*taken from talk by JJ. Fan, g-2Days21*]

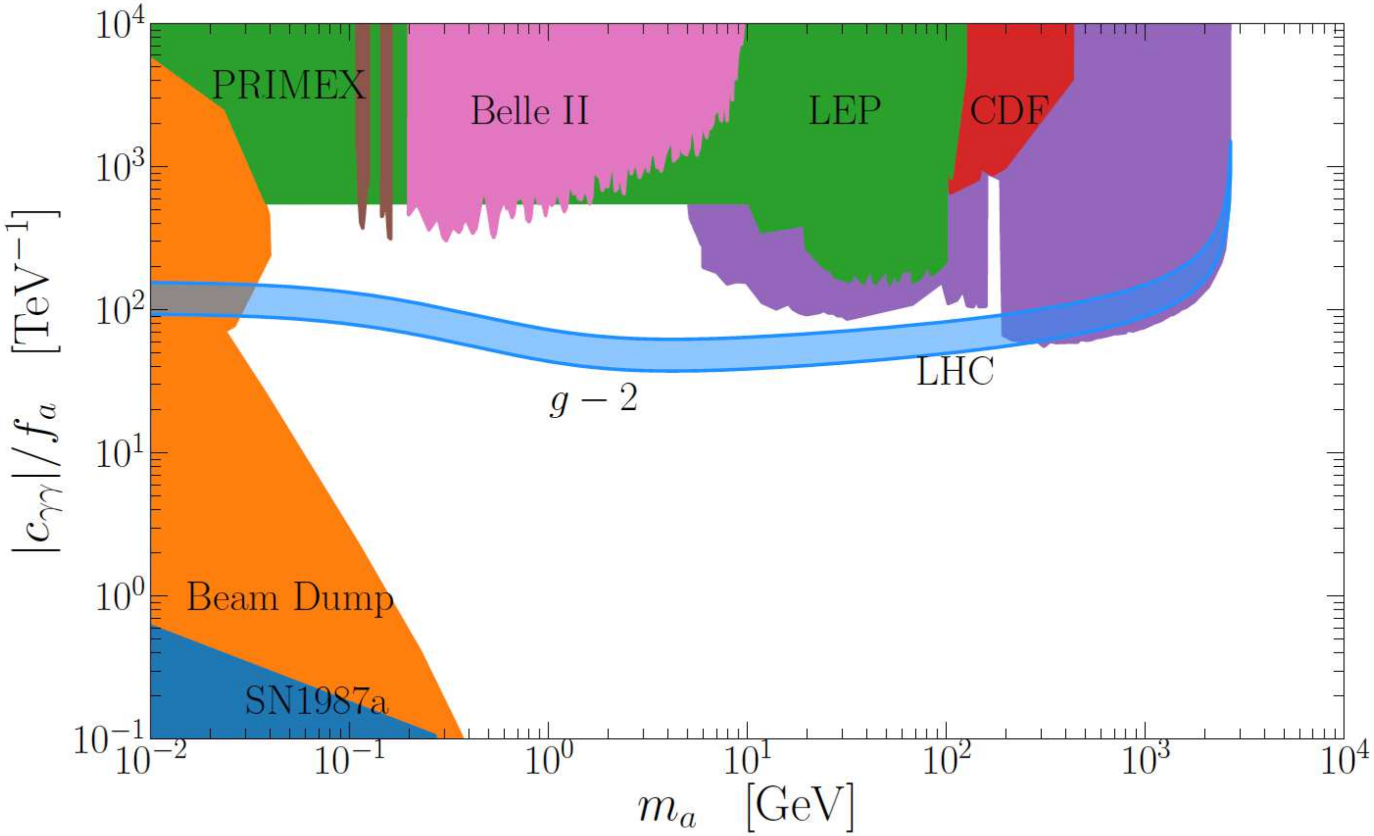
Lagrangian and possible contributions (II):



[*taken from talk by JJ. Fan, g-2Days21*]

Allowed parameter space for case 1:

[*M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21*]

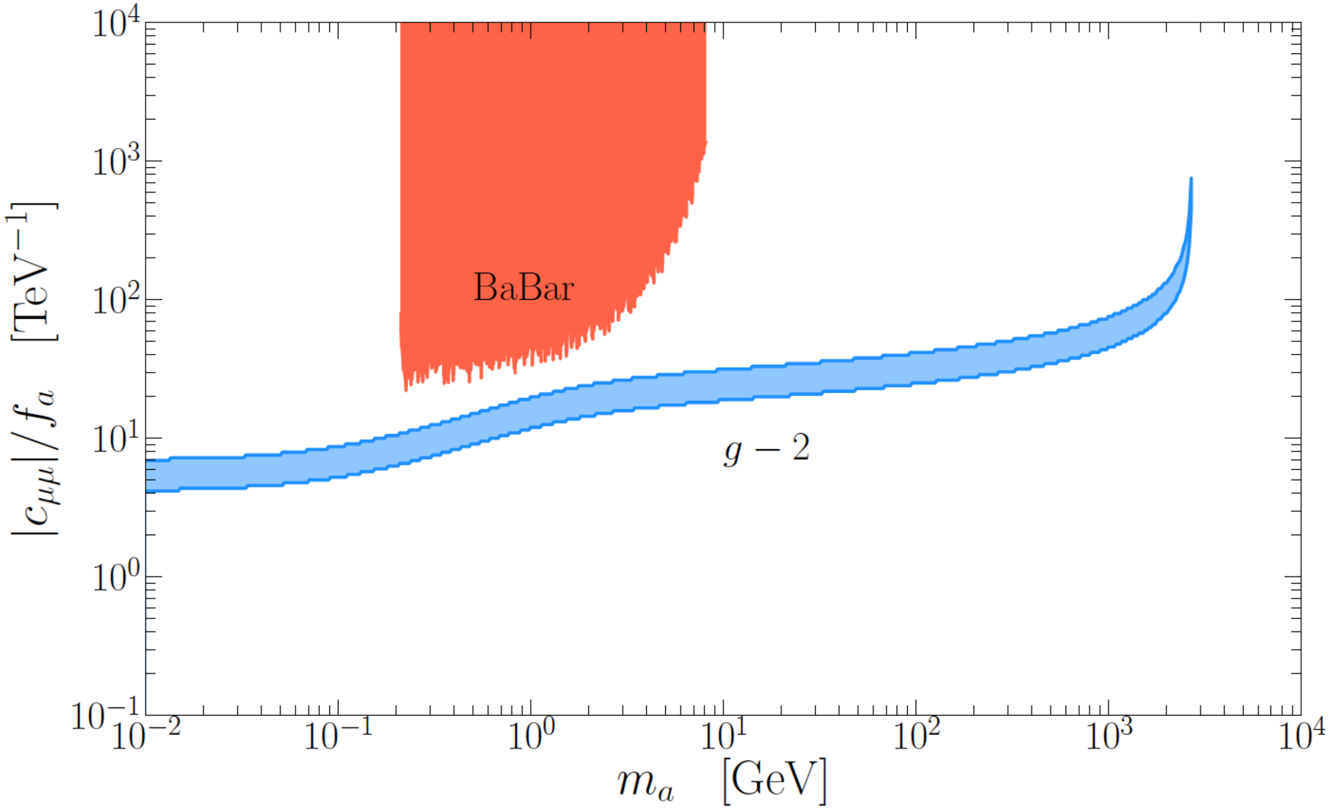


$$c_{\gamma\gamma}/c_{\mu\mu} < 0, \quad m_a \in [40\text{ MeV}, 200\text{ GeV}]$$

$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots25\text{ GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}$$

Allowed parameter space for case 1:

[M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21]

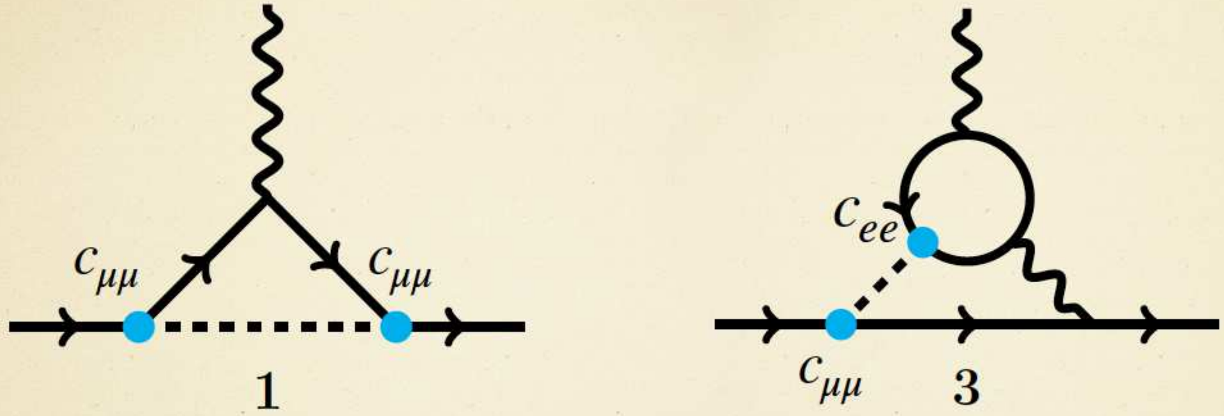


$$c_{\gamma\gamma}/c_{\mu\mu} < 0, \quad m_a \in [40\text{ MeV}, 200\text{ GeV}]$$

$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots25\text{ GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}$$

Lagrangian and possible contributions (III):

Case 2: only $c_{\mu\mu}$, c_{ee}



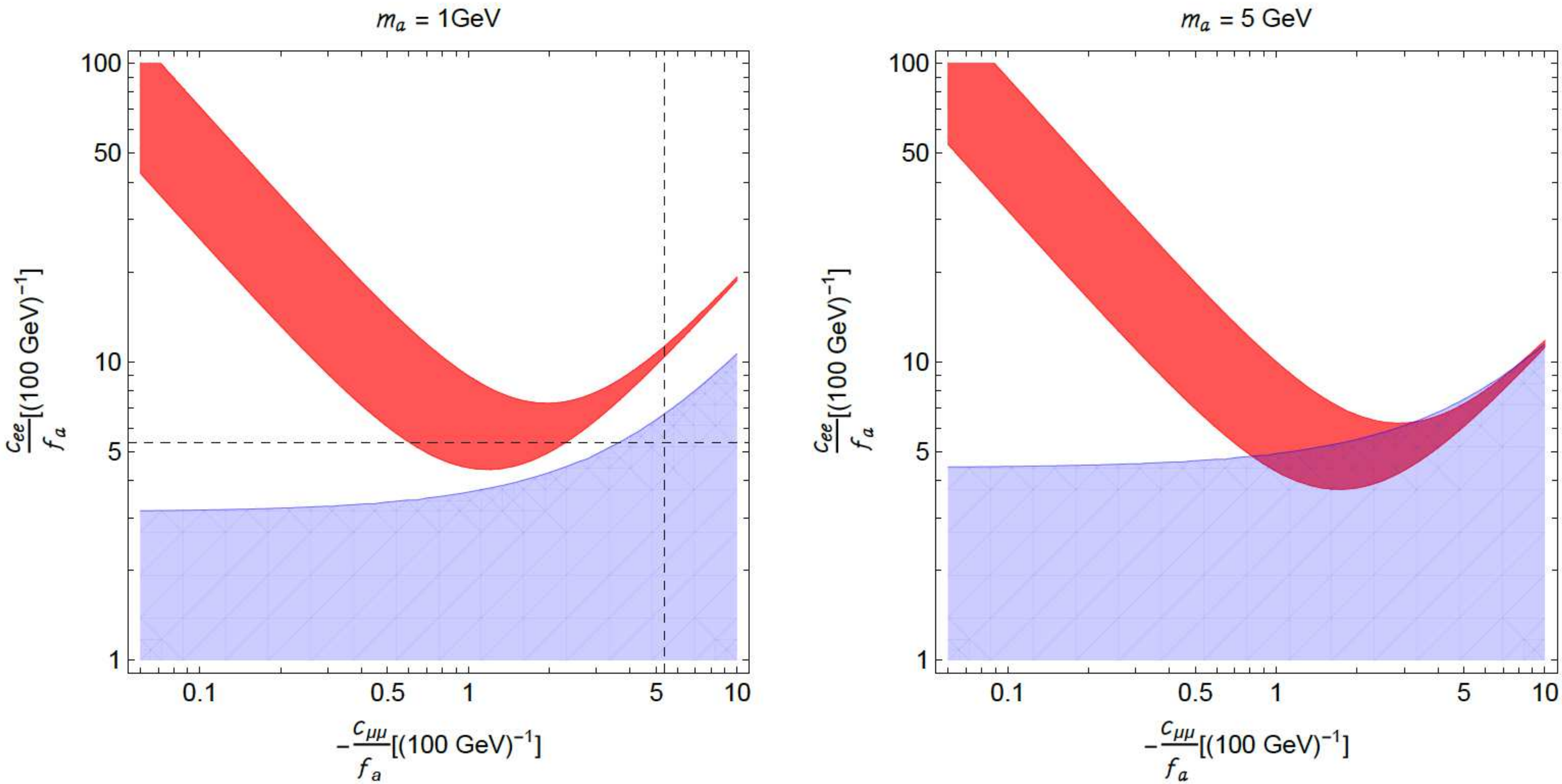
$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu} c_{ee} \alpha}{16\pi^3}$$

$$\Rightarrow c_{\mu\mu}/c_{ee} < 0$$

[*taken from talk by J. Fan, g-2Days21*]

Allowed parameter space for case 2:

[*M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21*]



$$m_a \gtrsim 2 \text{ GeV}, \quad c_{ee}/c_{\mu\mu} < 0$$

$$\left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100 \text{ GeV}, \quad \left|\frac{f_a}{c_{ee}}\right| \lesssim 25 \text{ GeV} \quad \text{for } m_a = 5 \text{ GeV}$$

Case 1:

$$c_{\gamma\gamma}/c_{\mu\mu} < 0, \quad m_a \in [40\text{ MeV}, 200\text{ GeV}]$$
$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots25\text{ GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}$$

Case 2:

$$m_a \gtrsim 2\text{ GeV}, \quad c_{ee}/c_{\mu\mu} < 0$$
$$\left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}, \quad \left|\frac{f_a}{c_{ee}}\right| \lesssim 25\text{ GeV} \quad \text{for } m_a = 5\text{ GeV}$$

$\Rightarrow$ axion couplings to SM must be unnaturally large!

$\Rightarrow$ only achieved by integrating out additional matter content

$\Rightarrow$ consider full UV-complete model?!

 [talk by D. Cerceño, g-2Days21]

μ-philic vector boson

Coupling to leptons

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\alpha\beta} X^{\alpha\beta} - \frac{\epsilon_Y}{2} B_{\alpha\beta} X^{\alpha\beta} - g_x\, j^X_\alpha\, X^\alpha - \frac{M_X^2}{2} X_\alpha X^\alpha$$

$U(1)_{L_\mu - L_\tau}$ $\quad j^{\mu-\tau}_\alpha = \bar{L}_2 \gamma_\alpha L_2 + \bar{\mu}_R \gamma_\alpha \mu_R - \bar{L}_3 \gamma_\alpha L_3 - \bar{\tau}_R \gamma_\alpha \tau_R$

- Simplest anomaly free extension

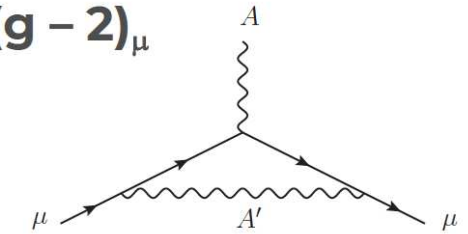
$U(1)_{L_\mu}$ $\quad j^{\mu}_\alpha = \bar{L}_2 \gamma_\alpha L_2 + \bar{\mu}_R \gamma_\alpha \mu_R + \sum_\psi Q_\psi \bar{\psi} \gamma_\alpha \psi$

- Needs extra fields to cancel anomalies
- Constrained by flavour-changing processes

Similar: light muon-philic vector boson

[talk by D. Cerceño, g-2Days21]

Light vector mediator as a solution to $(g-2)_\mu$



$$\Delta a_\mu = Q_\mu^{x^2} \frac{\alpha_x}{\pi} \int_0^1 \mathrm{d}u \, \frac{u^2(1-u)}{u^2 + \frac{(1-u)}{x_\mu^2}}$$

$\alpha_x = g_x^2/4\pi$

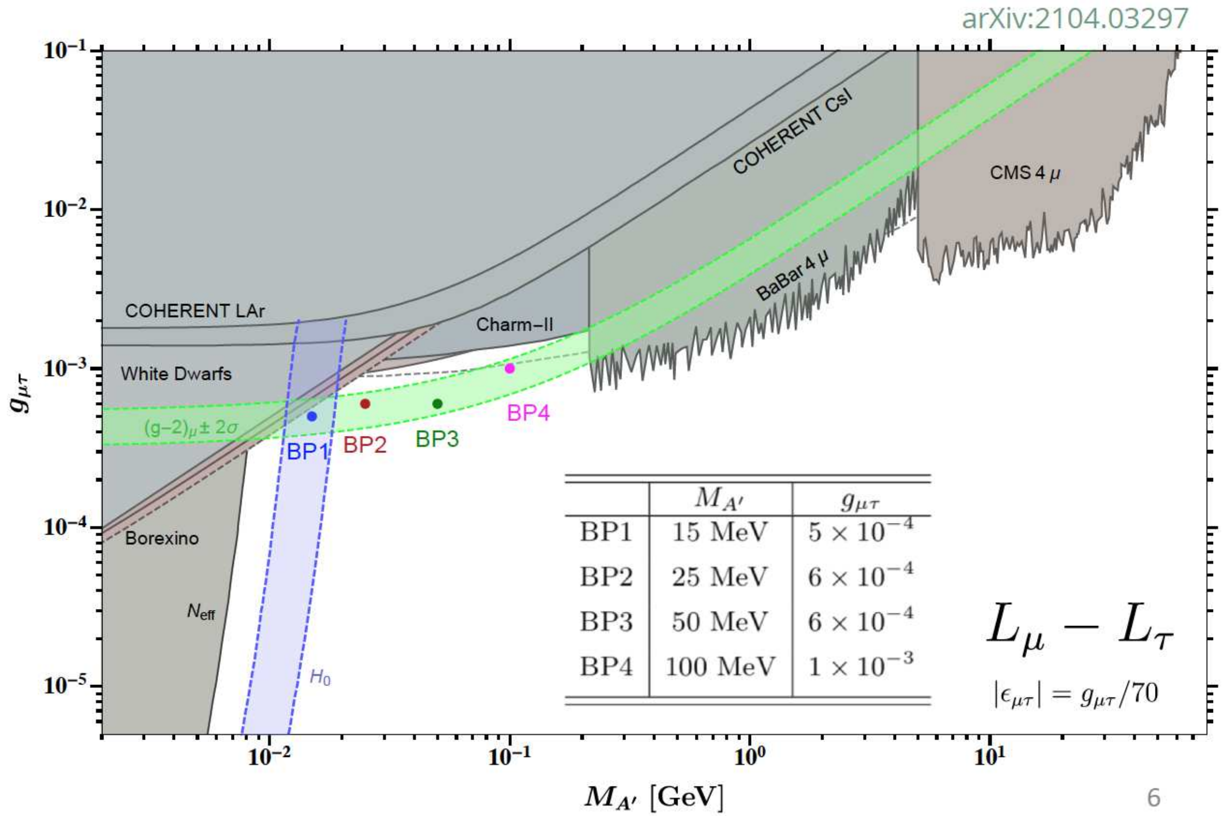
$x_\mu = m_\mu/M_{A'}$

Could also account for an observed tension in the Hubble parameter

($\Delta N_{eff} = 0.4$)

Escudero et al. (2019)

Araki et al. (2013)



6. Conclusinos

- new $(g-2)_\mu$ result confirms old result and deviation from the SM
  $(g-2)_\mu$ is real $\Rightarrow$ (relatively) light EW particles
- 2HDM: only type X can be in agreement with $(g-2)_\mu$, EWPO, flavor
  $\Rightarrow m_A \lesssim 50$ GeV, $\tan\beta \gtrsim 40$ $\Rightarrow$ not taken into account (yet): $h_{125} \to AA$
- Lepto-quarks: $\Rightarrow$ correlation with $\Gamma(h \to \mu\mu)$
- MSSM: 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 future prospects
- A) bino/wino DM with chargino coann. (DM full)
  B/C) bino DM with slepton coann. (DM full)
  D) higgsino eDM $m_{\tilde\chi_1^0} \sim m_{\tilde\chi_2^0} \sim m_{\tilde\chi_1^\pm} \sim \mu$ (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
  compressed spectra: good HL-LHC prospects, but ILC/CLIC needed
- Axions: in principle possible
  $\Rightarrow$ axion couplings to SM must be unnaturally large!
  $\Rightarrow$ integrating out additional matter content, full UV-complete model?


Further Questions?

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

Decay via sleptons (3l)

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (\tilde{l}^{\pm}\nu)(\tilde{l}^{+}l^{-}) \to 3l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (l^{\pm}\tilde{\nu})(\tilde{l}^{+}l^{-}) \to 3l + \not{E}_T \qquad (5)$$

Decay via sleptons (2l)

$$\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to (\tilde{l}^{+}\nu)(\tilde{l}^{-}\nu) \to 2l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to (l^{+}\tilde{\nu})(l^{-}\tilde{\nu}) \to 2l + \not{E}_T \qquad (6)$$

Decay via gauge bosons

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W\tilde{\chi}_1^0)(Z\tilde{\chi}_1^0) \to 3l + \not{E}_T \ , \qquad (7a)$$
$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W\tilde{\chi}_1^0)(Z\tilde{\chi}_1^0) \to 2l + \text{jets} + \not{E}_T \ , \qquad (7b)$$
$$\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to (W^{+}\tilde{\chi}_1^0)(W^{-}\tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (8)$$

Decay via Higgs bosons

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W\tilde{\chi}_1^0)(h\tilde{\chi}_1^0) \to l + b\bar{b} + \not{E}_T \qquad (9)$$

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

$$\tilde{l}^+\tilde{l}^- \to (l^+\tilde{\chi}_1^0)(l^-\tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (10)$$

Compressed spectra

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W^*\tilde{\chi}_1^0)(Z^*\tilde{\chi}_1^0) \to 2l + \not{E}_T + \text{ISR}\ , \qquad (11)$$
$$\tilde{l}^+\tilde{l}^- \to (l^+\tilde{\chi}_1^0)(l^-\tilde{\chi}_1^0) \to 2l + \not{E}_T + \text{ISR} \qquad (12)$$

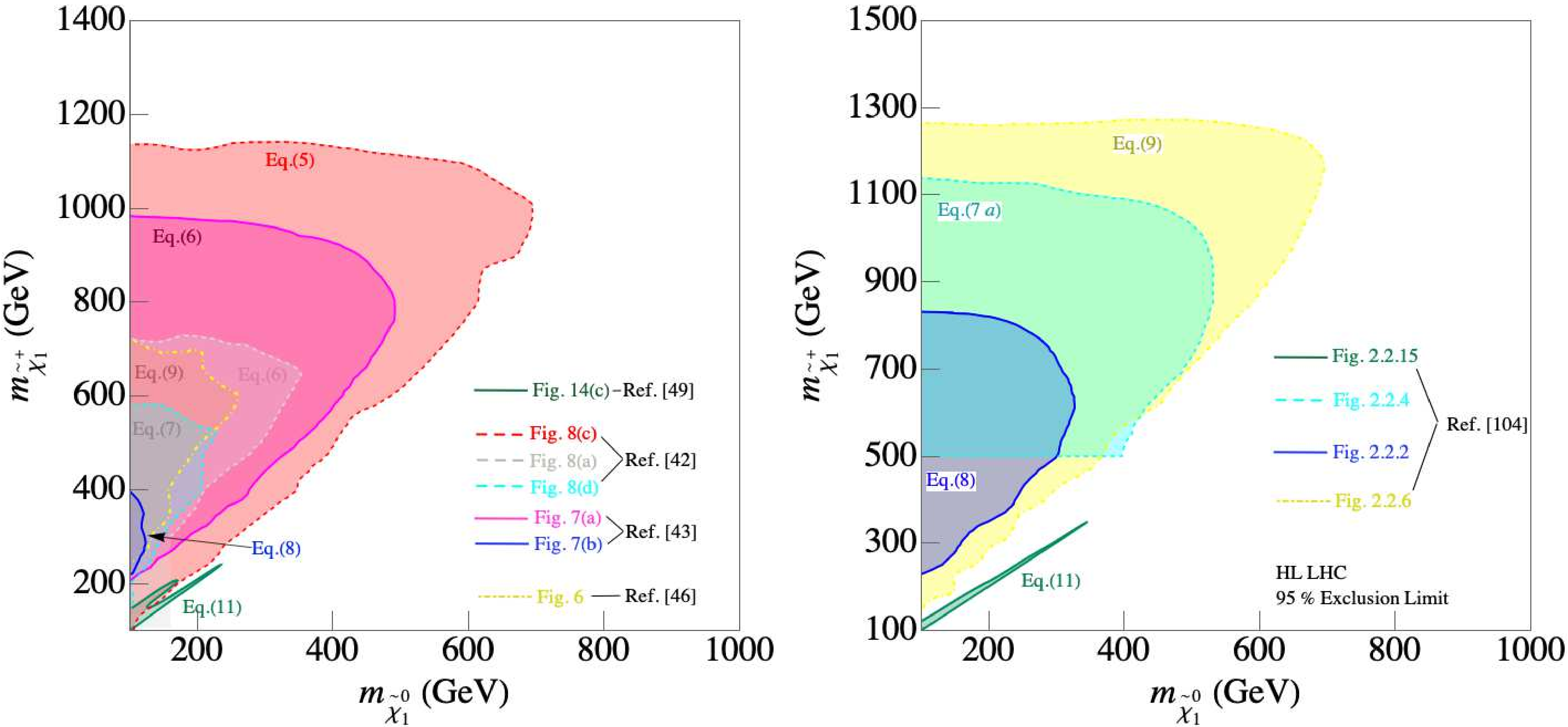
Searches involving Staus

⇒ 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*]

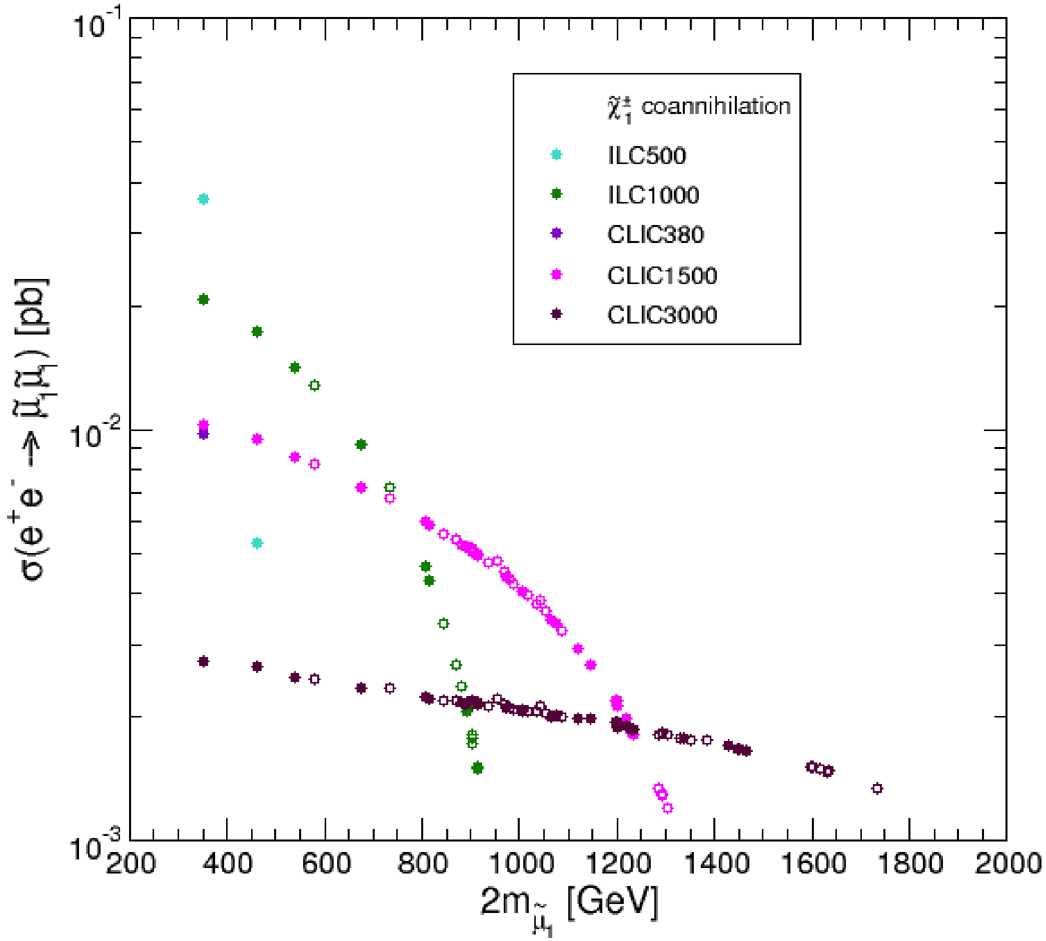


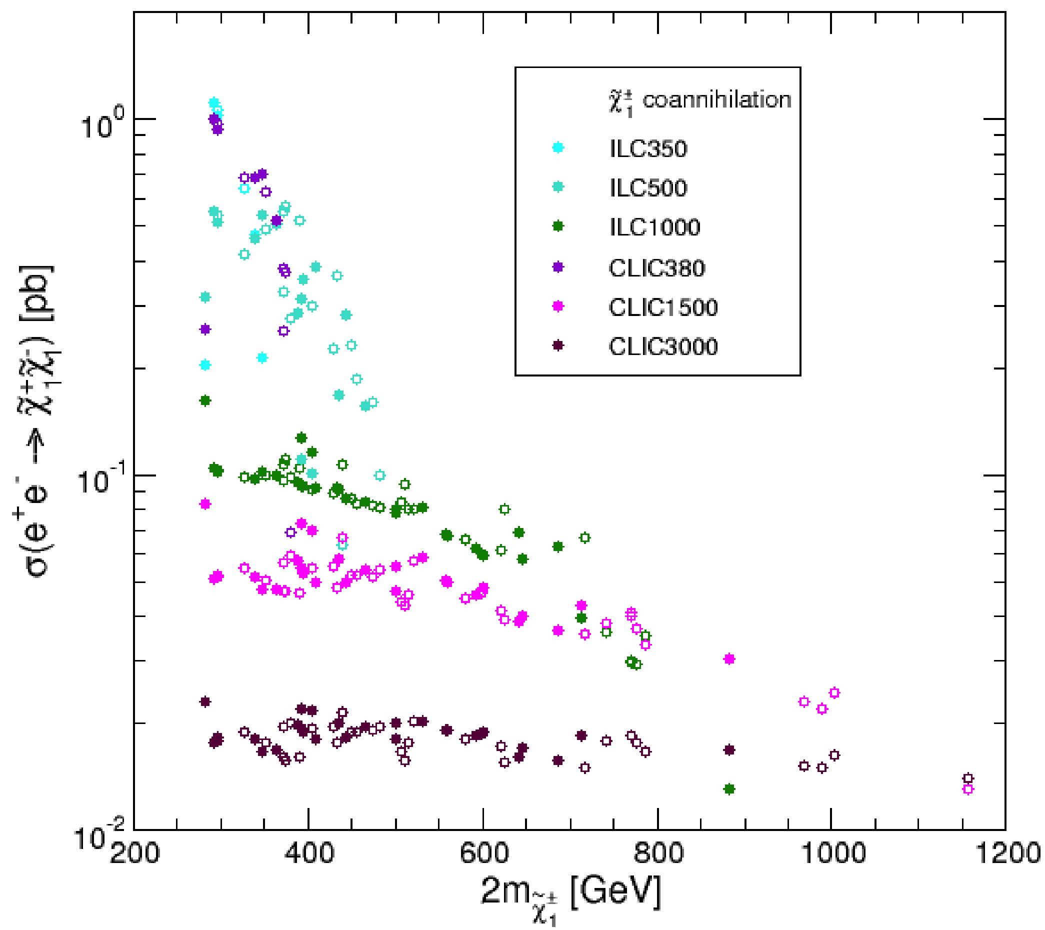
⇒ exclusion reach can be important

⇒ no CheckMate inclusion available . . .

Direct production at e^+e^- colliders (ILC/CLIC)

wino/bino DM with chargino co-ann. (open/full: "old" $(g-2)_\mu$)



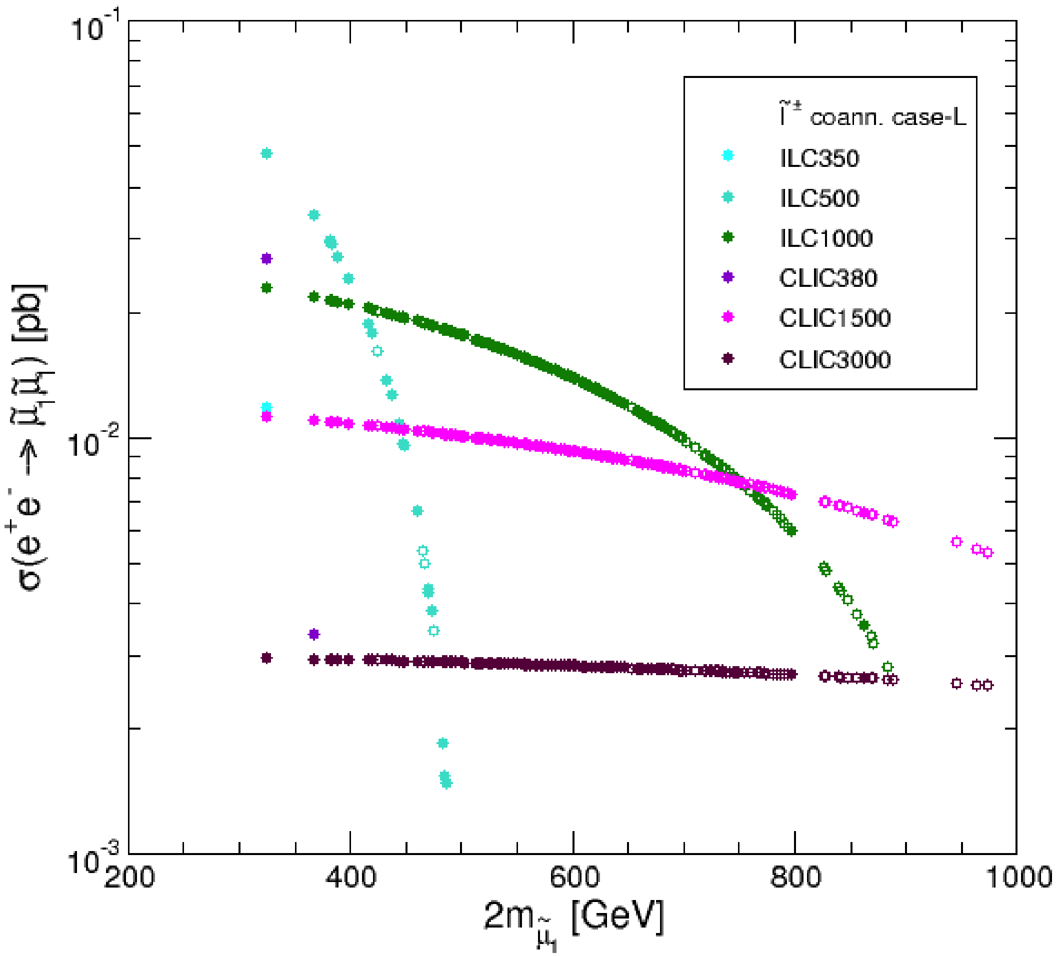


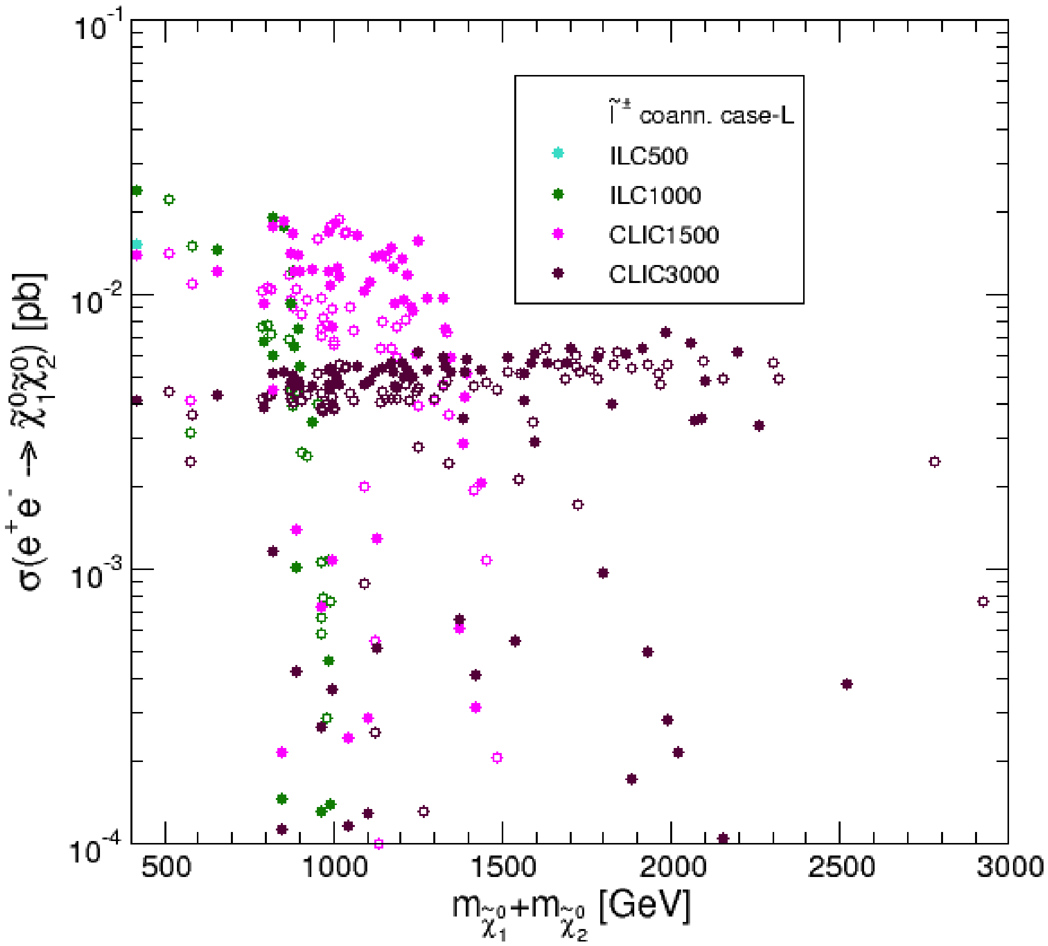
$\Rightarrow$ ILC has good prospects (particularly for $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$)

$\Rightarrow$ CLIC can cover evertything

Direct production at e^+e^- colliders (ILC/CLIC)

bino DM with slepton co-ann. (open/full: "old" $(g-2)_\mu$)





$\Rightarrow$ ILC can nearly covers full smuon channel (but not $\tilde{\chi}^0_1\tilde{\chi}^0_2$)

$\Rightarrow$ CLIC can cover evertything