Interpretation of muon (g-2) and W-mass in MSSM

IPSITA SAHA

APEC Seminar, 22/04/2022

Based on :

hep-ph/2203.15710

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EPJC 81 (2021) 12,1114, EPJC 81 (2021) 12 ,1069

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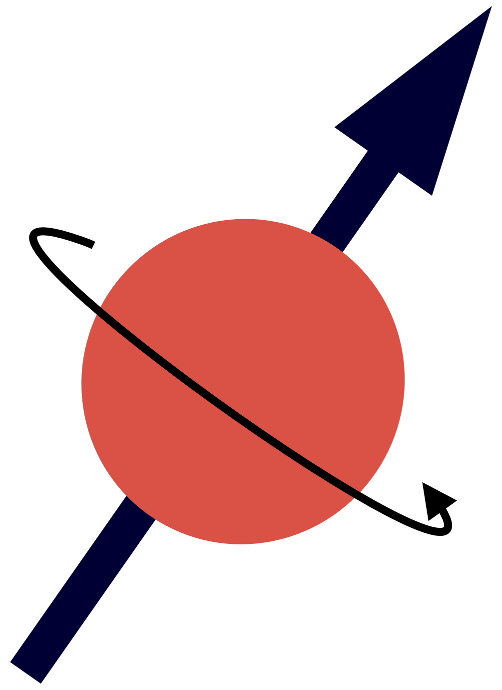
The Muon Anomalous Magnetic Moment

The muon magnetic moment

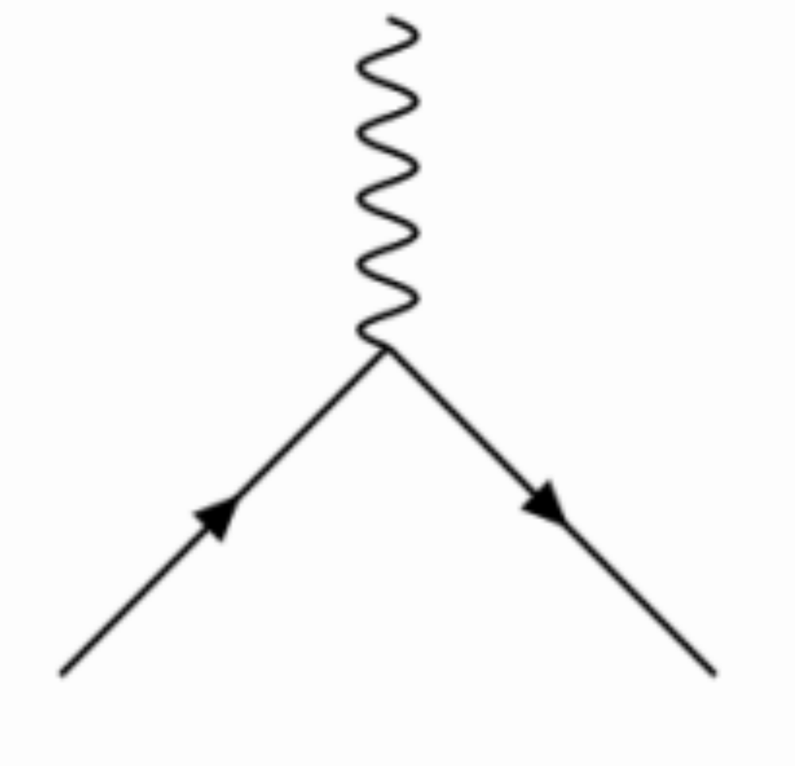
Magnetic moment of charged muon



$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

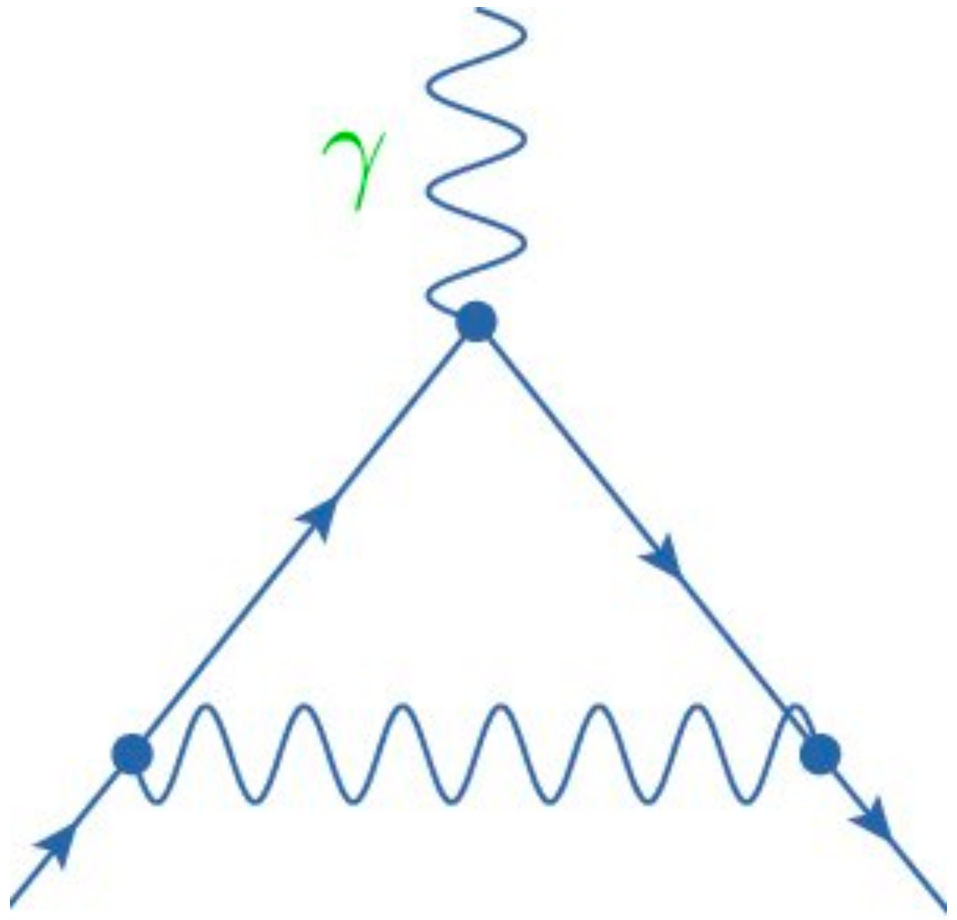
$$\mu = (1 + a)\frac{e\hbar}{2m} \longrightarrow a = \frac{g-2}{2}$$

Dirac moment



Pauli moment

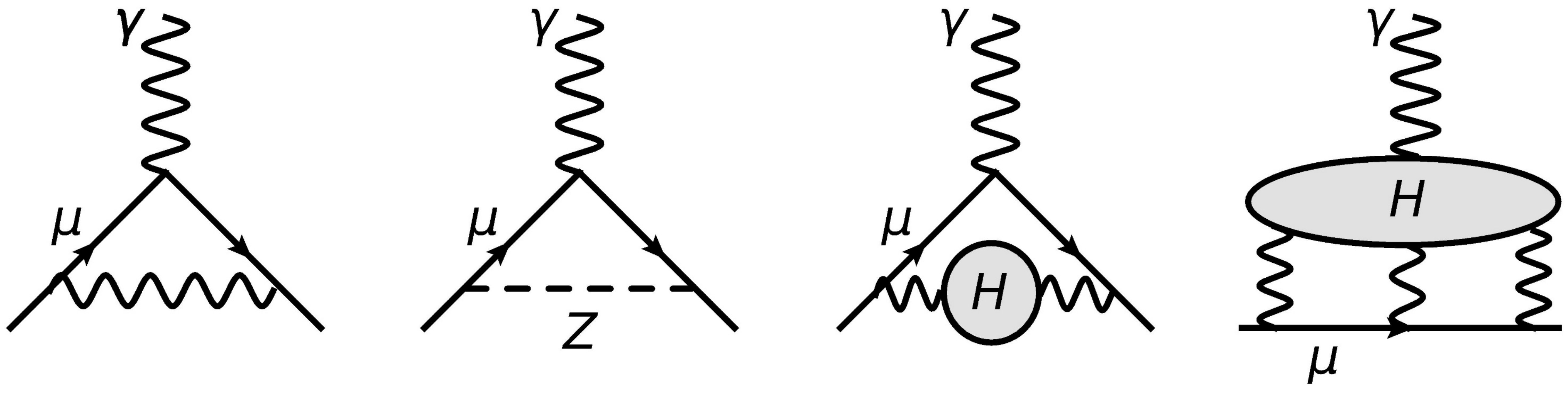
$$a = \frac{\alpha}{2\pi} \approx 0.00116...$$



Radiative correction, Schwinger (1948)

Muon (g-2)

Standard Model Contributions

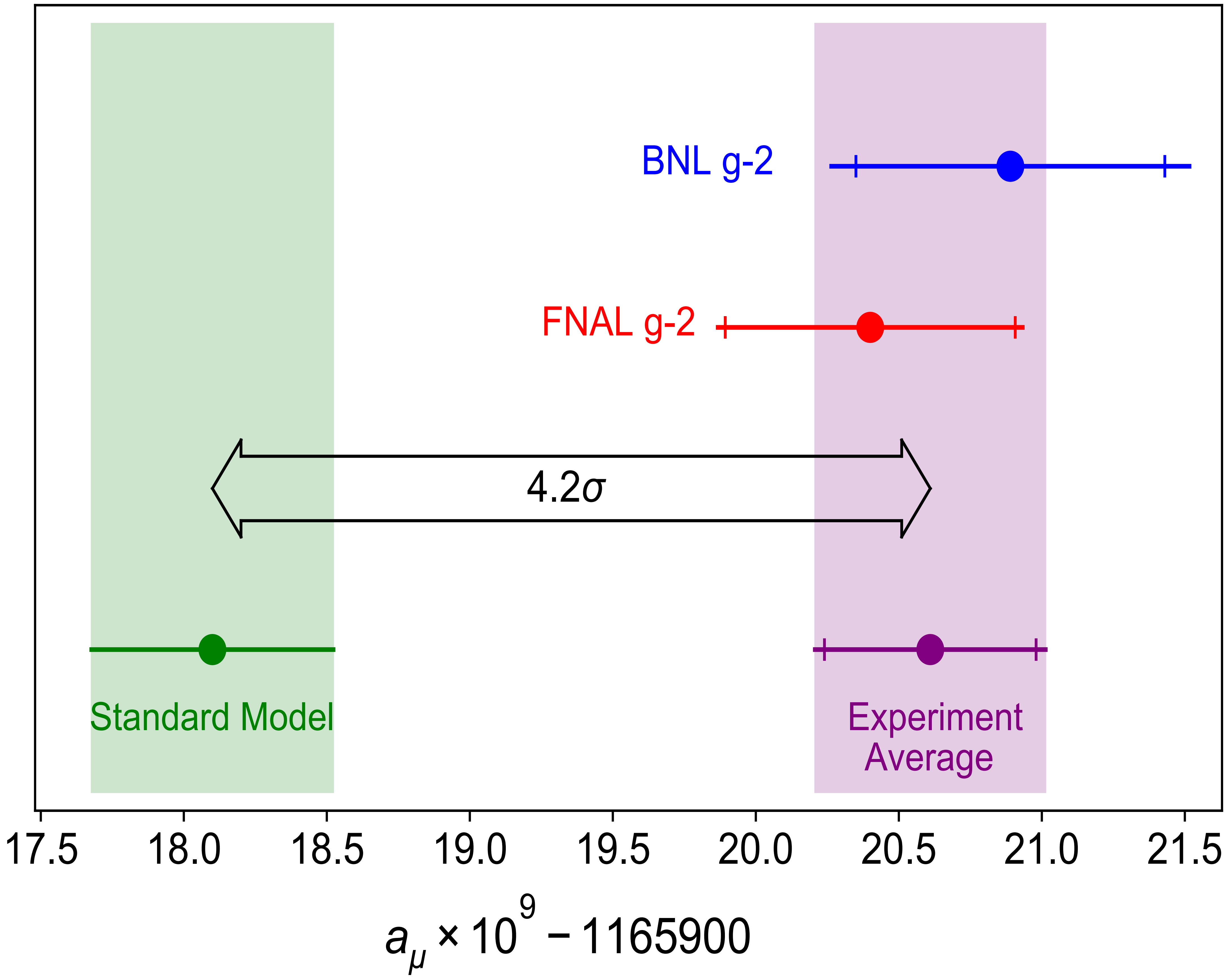


QED EW HVP HLbL

Data/Lattice Lattice

$$a_\mu^{\text{SM}} = 116\ 591\ 810(43) \times 10^{-11}$$

$$a_\mu^{\text{EXP}} = 116\ 592\ 061(41) \times 10^{-11}$$



Muon g-2 experiment at Fermilab aims at 4 x BNL precision

- Abi *et al* PRL '21
- Aoyama *et al* '20

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

Muon (g-2)

Muon coupling to magnetic field:

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

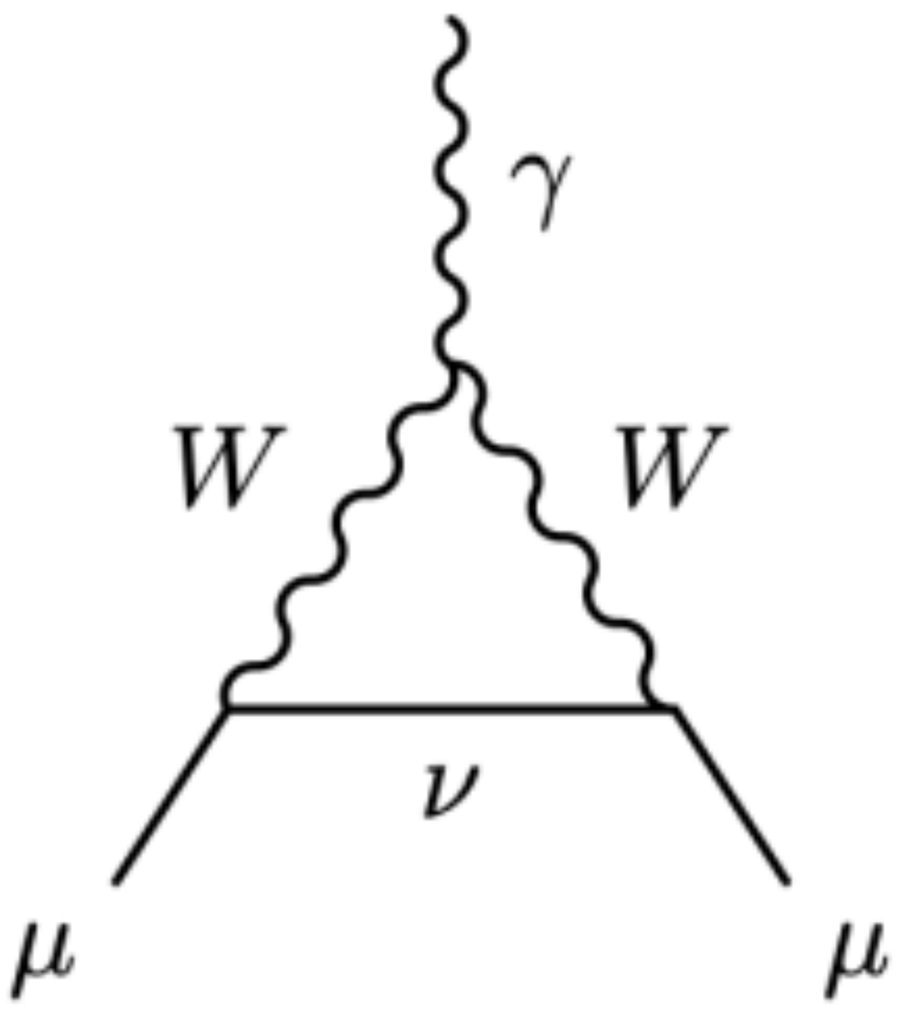
$$F_2(0) = a_\mu$$

Effective Operator:

$$\mathscr{L}_{\text{eff}} = \frac{ea_\mu}{2m_\mu}\bar{\mu}\sigma_{\mu\nu}\mu F^{\mu\nu}$$

New physics contribution

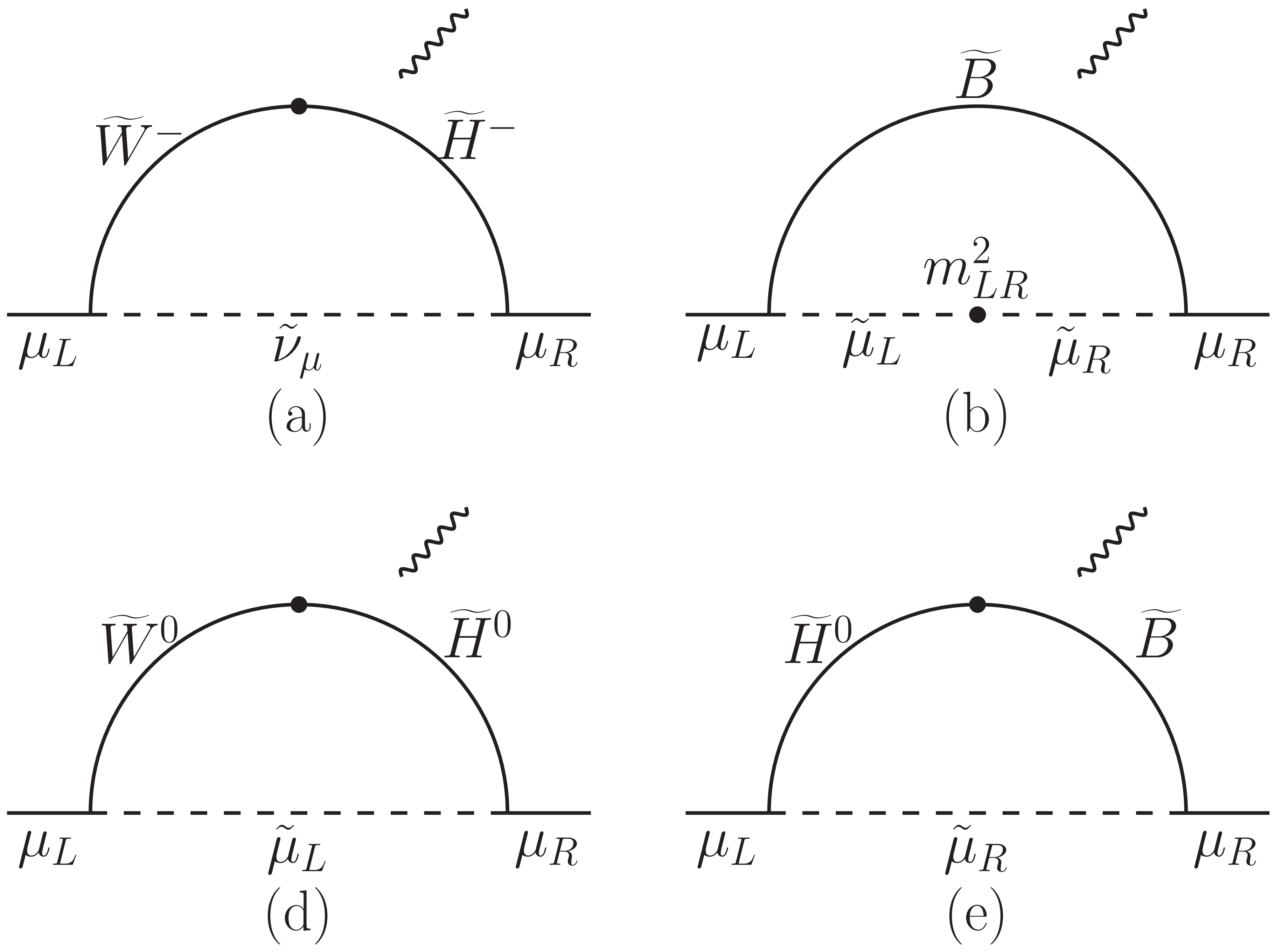
Chiral Enhancement, Large Coupling, Light non-standard particles ....



$$a_\mu \sim \frac{\alpha}{\pi}\frac{m_\mu^2}{m_W^2}$$

Muon (g-2) in SUSY

SUSY contributions from Chargino, Sleptons and Neutralino



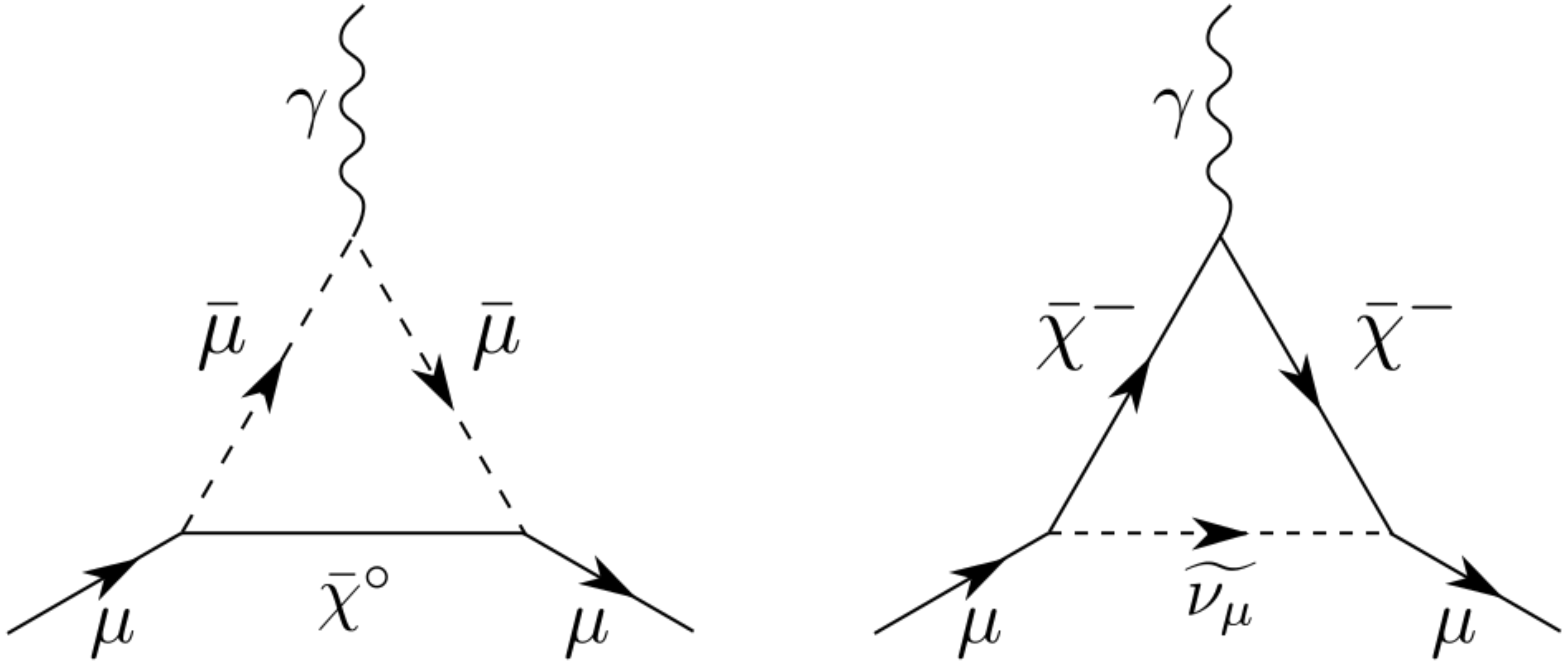
Mass insertion approximation

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) = \frac{\alpha_Y}{8\pi} \frac{m_\mu^2}{M_1 \mu} \tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_L}}, \frac{\mu^2}{m_{\tilde{\mu}_L}}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) = \frac{\alpha_Y}{4\pi} \frac{m_\mu^2 M_1 \mu}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}} \tan\beta \cdot f_N\left(\frac{m^2_{\tilde{\mu}_L}}{M_1^2}, \frac{m^2_{\tilde{\mu}_R}}{M_1^2}\right)$$

T. Moroi '96, M.Endo, K. Hamaguchi, S. Iwamoto, Yoshinaga '13

Muon (g-2) in SUSY



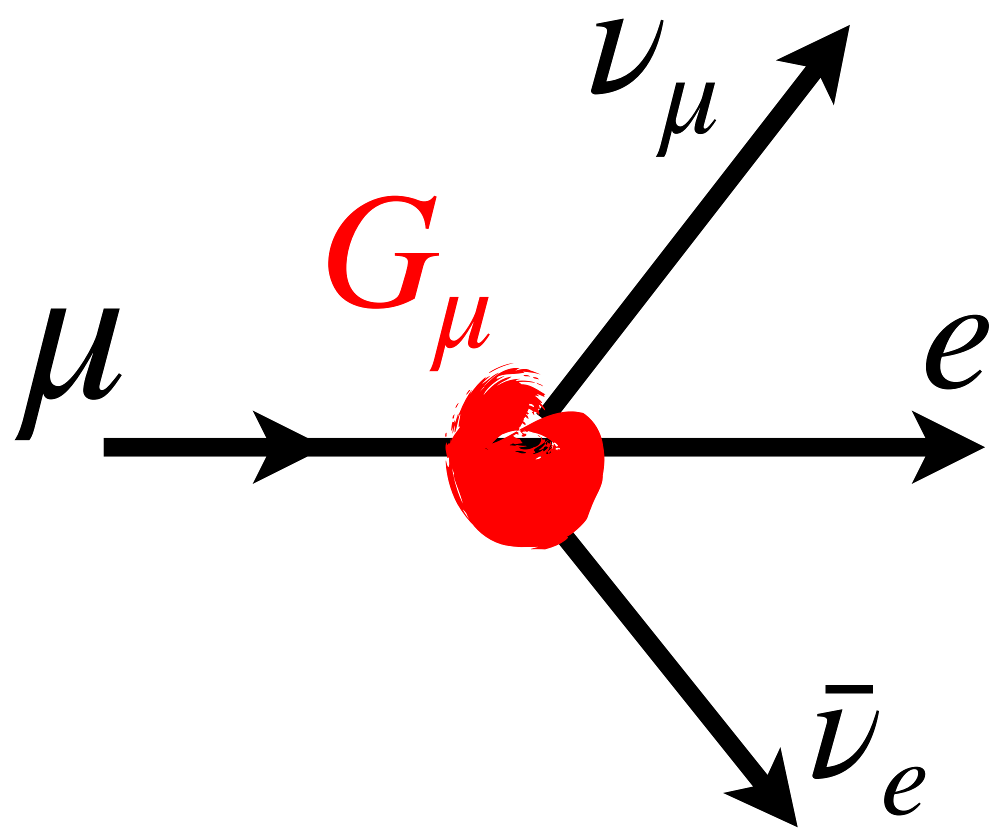
- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop
- SM EW 1 loop : $\frac{\alpha}{\pi}\frac{m_{\mu}^{2}}{M_{W}^{2}}$. MSSM , 1 loop : $\frac{\alpha}{\pi}\frac{m_{\mu}^{2}}{M_{SUSY}^{2}} \times tan\beta$
- SUSY can easily explain anomaly : upper limits on EW super partner masses

K.Hagiwara, K.Ma, S. Mukhopadhyaya '17, T. Yanagida, W.Yu, N.Yokozaki '16, '20, '21

S. AbdusSalam et. al '11, E. Bagnashi et. al '15, P. Cox, C. Han, T. Yanagida '18, '19 '21, M.Endo, K. Hamaguchi, S. Iwamoto, T. Kitahara '20 '21

The W-boson Mass

Theoretical Prediction of W-mass



$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Radiative corrections

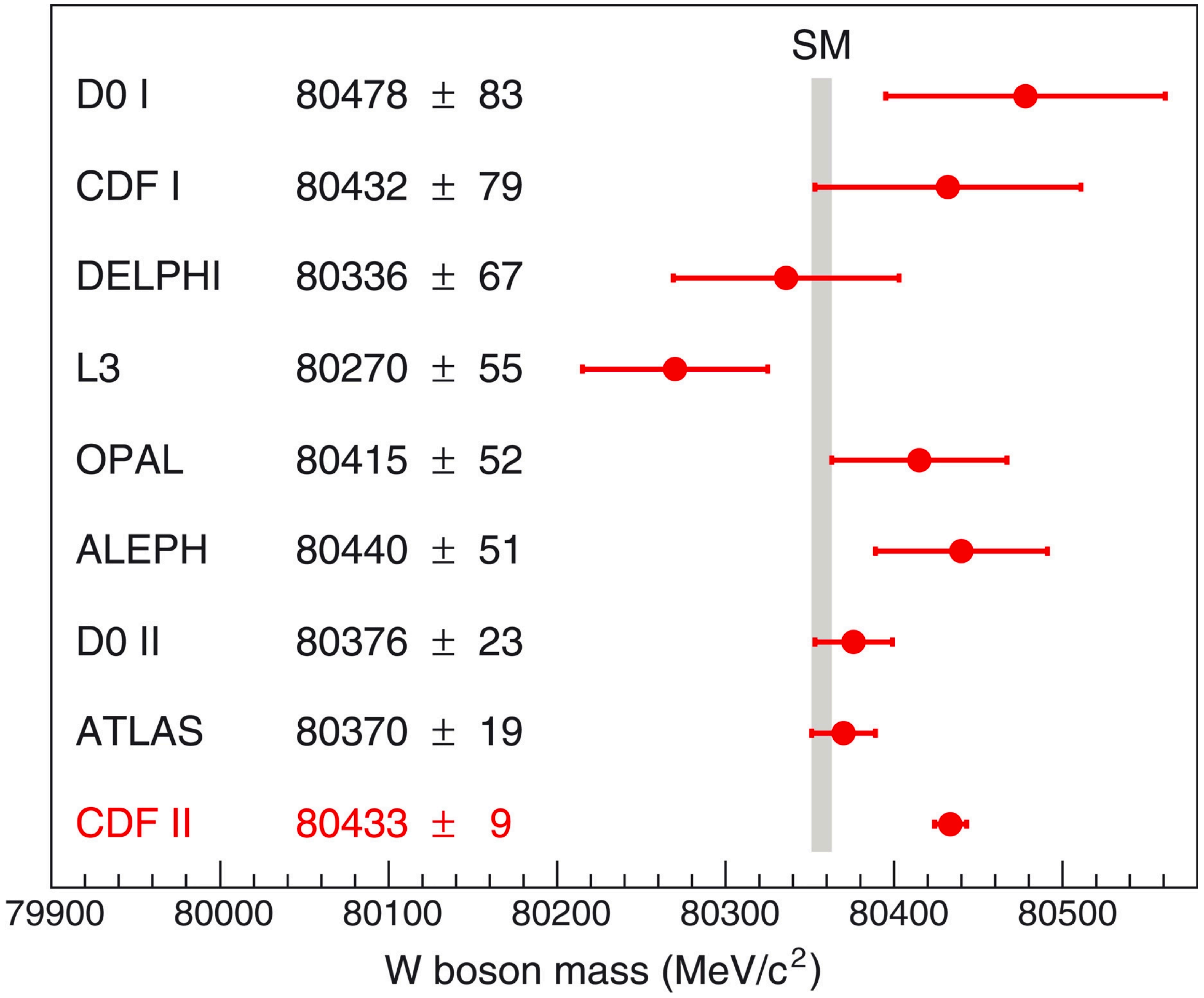
One loop correction to the SM:

$$\Delta r=\Delta\alpha\left(\ln\frac{M_f}{M_Z}\right)+\Delta\rho(m_t^2)+\Delta r_{\text{rem}}\left(\ln\frac{M_H}{M_Z}\right)$$

$M_W^{\text{SM}}=80.357\pm0.006\ \text{GeV}$ PDG 2020

$M_W^{\text{exp}}=80.379\pm0.012\ \text{GeV}$ → Experimental average w/o CDF-II result

W-Mass at CDF-II



Science 376, 170–176 (2022)

Tevatron at 1.96 TeV with 8.8 fb^{-1}

$$M_W|_{\text{CDF-II}} = 80433 \pm 9.4 \ (\text{MeV})$$

$$M_W|_{\text{CDF+D0}} = 80427 \pm 8.9 \ (\text{MeV})$$

$$M_W|_{\text{CDF+D0+LEP}} = 80424 \pm 8.7 \ (\text{MeV})$$

$$M_W^{\text{SM}} = 80.357 \pm 0.006 \ \text{GeV}$$

One-loop contribution

One loop contribution to Δr can be divided into four classes.

- SM-like contributions of quark and leptons to gauge bosons self-energies.
- SUSY contributions of squarks and sleptons to gauge boson self-energies.
- SM contributions from the gauge and Higgs sector that contains the vertex and box diagrams.
- SUSY contributions from neutralinos and charginos in self-energies, vertex diagram and box diagram.

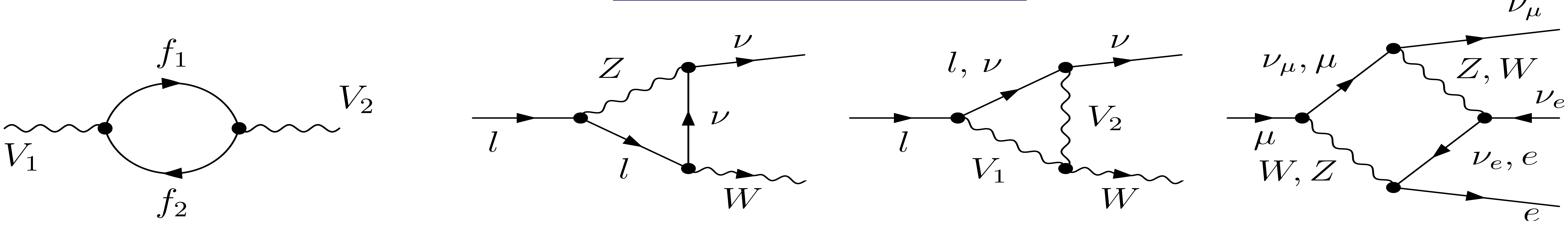
$$\Delta r = \Delta r(M_W, M_Z, m_t, \alpha, \alpha_s, \ldots, X)$$

$$X = M_{H^{\rm SM}} \quad ({\rm SM}),$$
$$X = M_h, M_H, M_A, M_{H^\pm}, \tan\beta, M_{\tilde{f}}, A_f, m_{\tilde{\chi}^{0,\pm}}, \ldots \quad ({\rm MSSM})$$

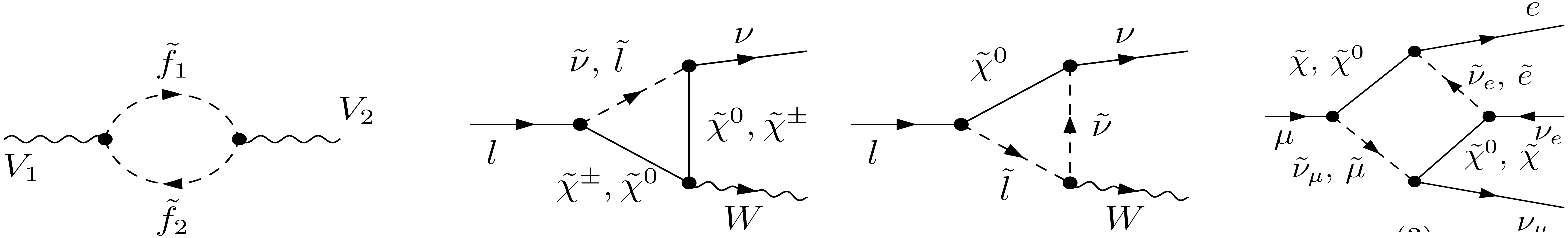
Δr is evaluated in an iterative procedure.

One-loop contribution

SM CONTRIBUTION



MSSM CONTRIBUTION



Isospin splitting :

Leading contribution induced by the mass splitting

$$\Delta\rho = \frac{\Sigma_T^{ZZ}(0)}{M_Z^2} - \frac{\Sigma_T^{WW}(0)}{M_W^2}.$$

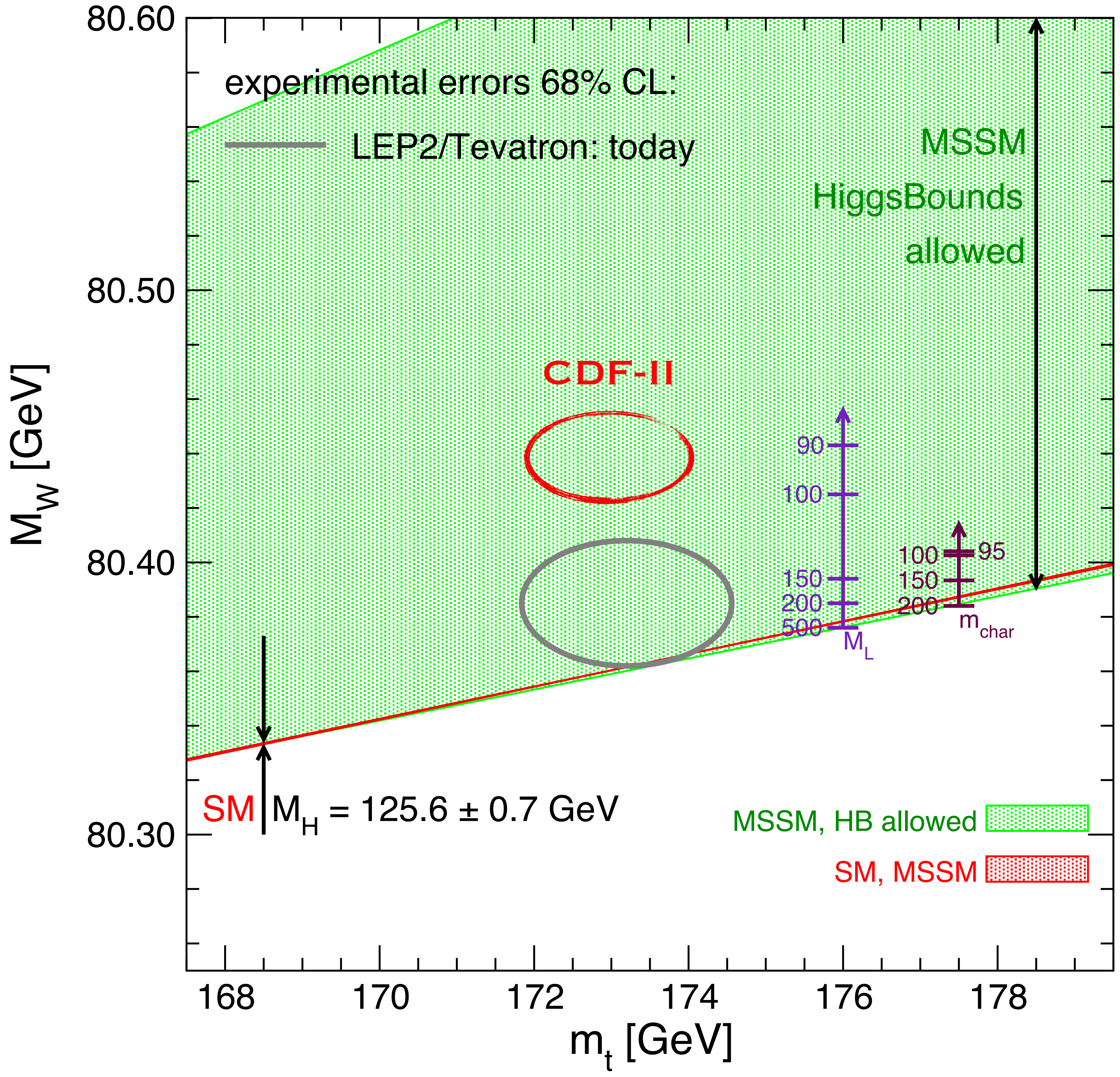
In MSSM, particularly important for third generation squarks.

Previous study

S. Heinemeyer, W. Hollik, G. Weiglein, L. Zeuge '13

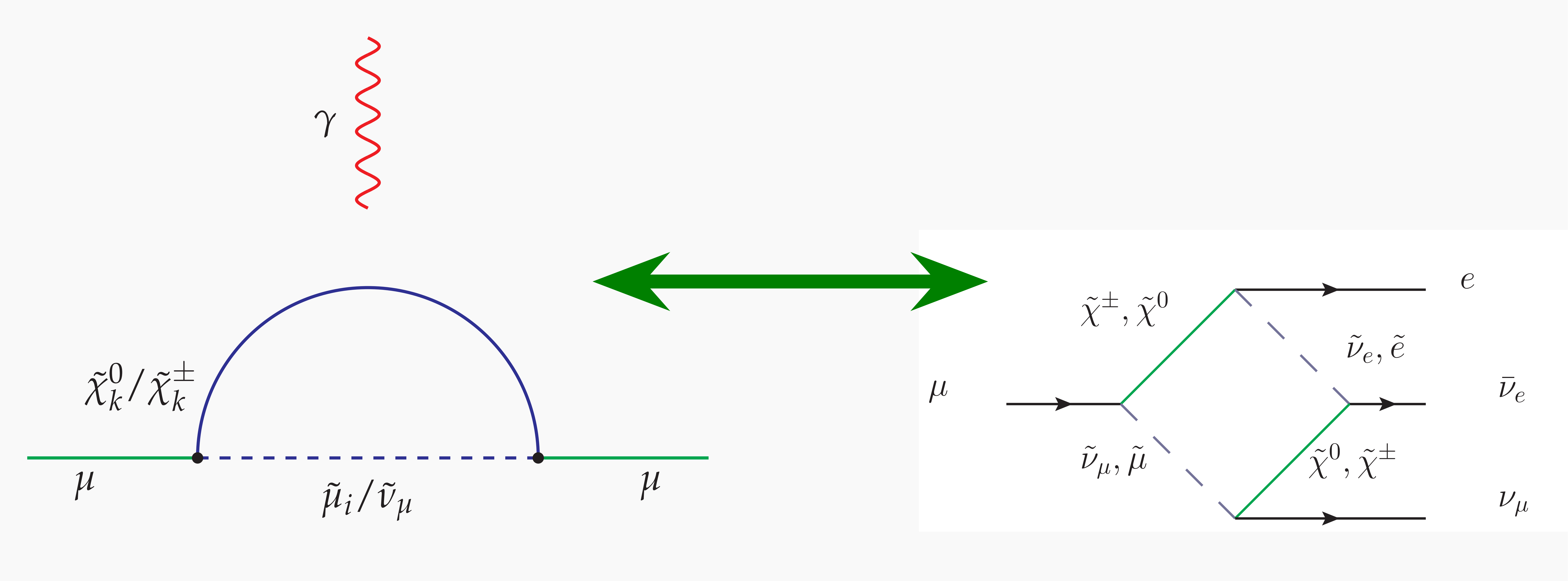
Parameter	Minimum	Maximum
μ	-2000	2000
$M_{\tilde{E}_{1,2,3}} = M_{\tilde{L}_{1,2,3}}$	100	2000
$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}}$	500	2000
$M_{\tilde{Q}_3}$	100	2000
$M_{\tilde{U}_3}$	100	2000
$M_{\tilde{D}_3}$	100	2000
$A_e = A_\mu = A_\tau$	-3 $M_{\tilde{E}}$	3 $M_{\tilde{E}}$
$A_u = A_d = A_c = A_s$	-3 $M_{\tilde{Q}_{12}}$	3 $M_{\tilde{Q}_{12}}$
A_b	-3 $\max(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$	3 $\max(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$
A_t	-3 $\max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	3 $\max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
$\tan\beta$	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

$$M_1 = 5/3\, s_{\rm w}^2/c_{\rm w}^2\, M_2$$



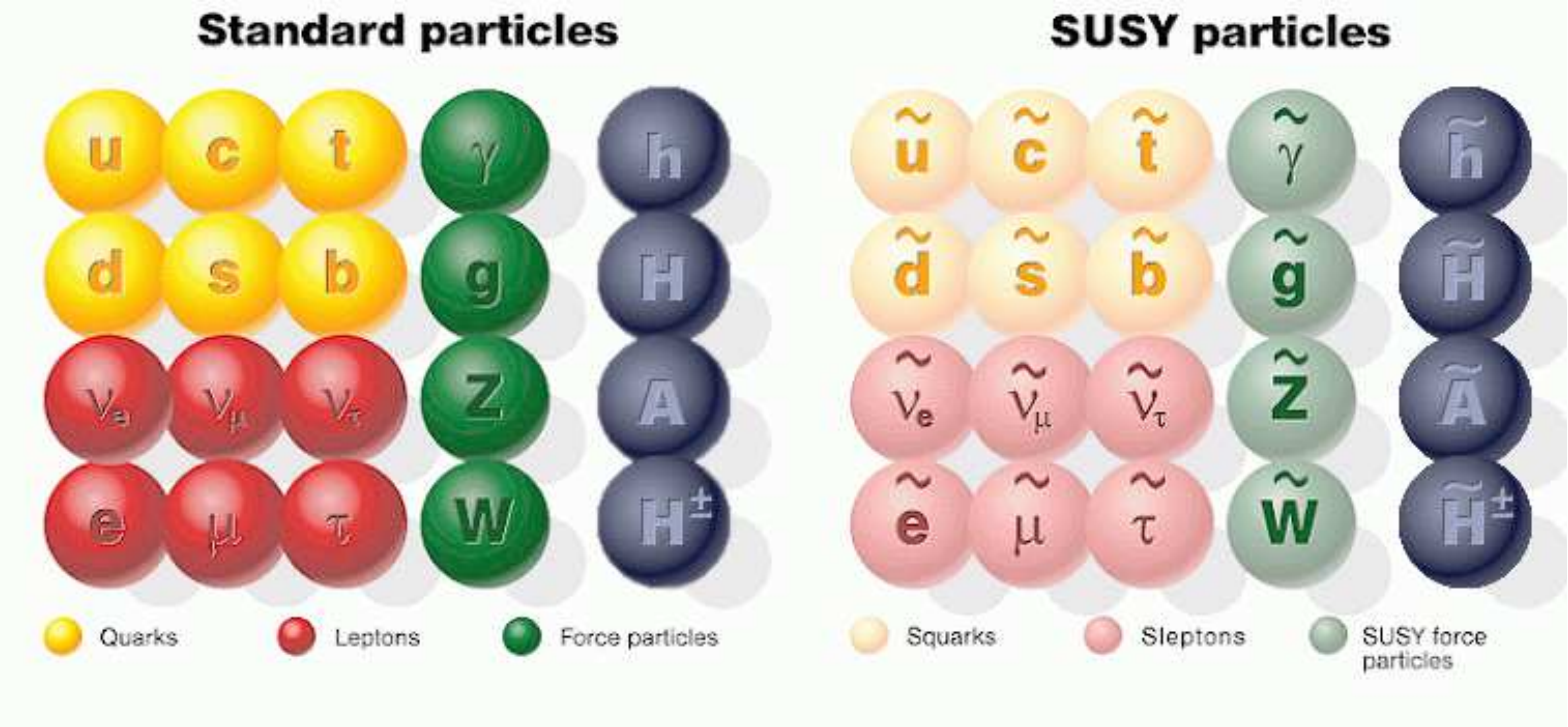
Motivation

- ✓ The lightest electroweakinos and sleptons are important for both observables.
- ✓ Is there a correlation between the values assumed by muon (g-2) and MW in the MSSM?
- ✓ Assuming that the neutralino contributes to the observed DM relic density, is there a correlation with specific DM mechanisms?



Electroweak-MSSM

The MSSM



Standard particles
SUSY particles
u
c
t
γ
h
d
s
b
g
H
Z
A
e
μ
τ
W
H±
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

EW Gauginos

Masses and mixing are determined by U(1) and SU(2) gaugino masses M_1, M_2 and Higgs mass parameter μ.

Neutralino: $\tilde{B}$, $\tilde{W}^3$, H_u^0, H_d^0 — Mass Diag. → $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$

Neutralino Mass Matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z\, c_\beta\, s_W & M_Z\, s_\beta\, s_W \\ 0 & M_2 & M_Z\, c_\beta\, cW & -M_Z\, s_\beta\, cW \\ -M_Z\, c_\beta\, s_W & M_Z\, c_\beta\, c_W & 0 & -\mu \\ M_Z\, s_\beta\, s_W & -M_Z\, s_\beta\, c_W & -\mu & 0 \end{pmatrix}$$

Chargino: $\tilde{W}^\pm$, $H_{u/d}^\pm$ — Mass Diag. → $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$

Chargino Mass Matrix

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} M_W c_\beta \\ \sqrt{2} M_W s_\beta & \mu \end{pmatrix}$$

LSP in RPC

DM

Four Parameters → $M_1, M_2, \mu, \tan\beta$

Sleptons

Slepton Mass Matrix

$$M^2_{\tilde{L}} = \begin{pmatrix} m_l^2 + m_{LL}^2 & m_l X_l \\ m_l X_l & m_l^2 + m_{RR}^2 \end{pmatrix}$$

$$m_{LL}^2 = m_{\tilde{L}}^2 + (I_l^{3L} - Q_f s_w^2) M_z^2 c_{2\beta}$$

$$m_{RR}^2 = m_{\tilde{R}}^2 + Q_f s_w^2 M_z^2 c_{2\beta}$$

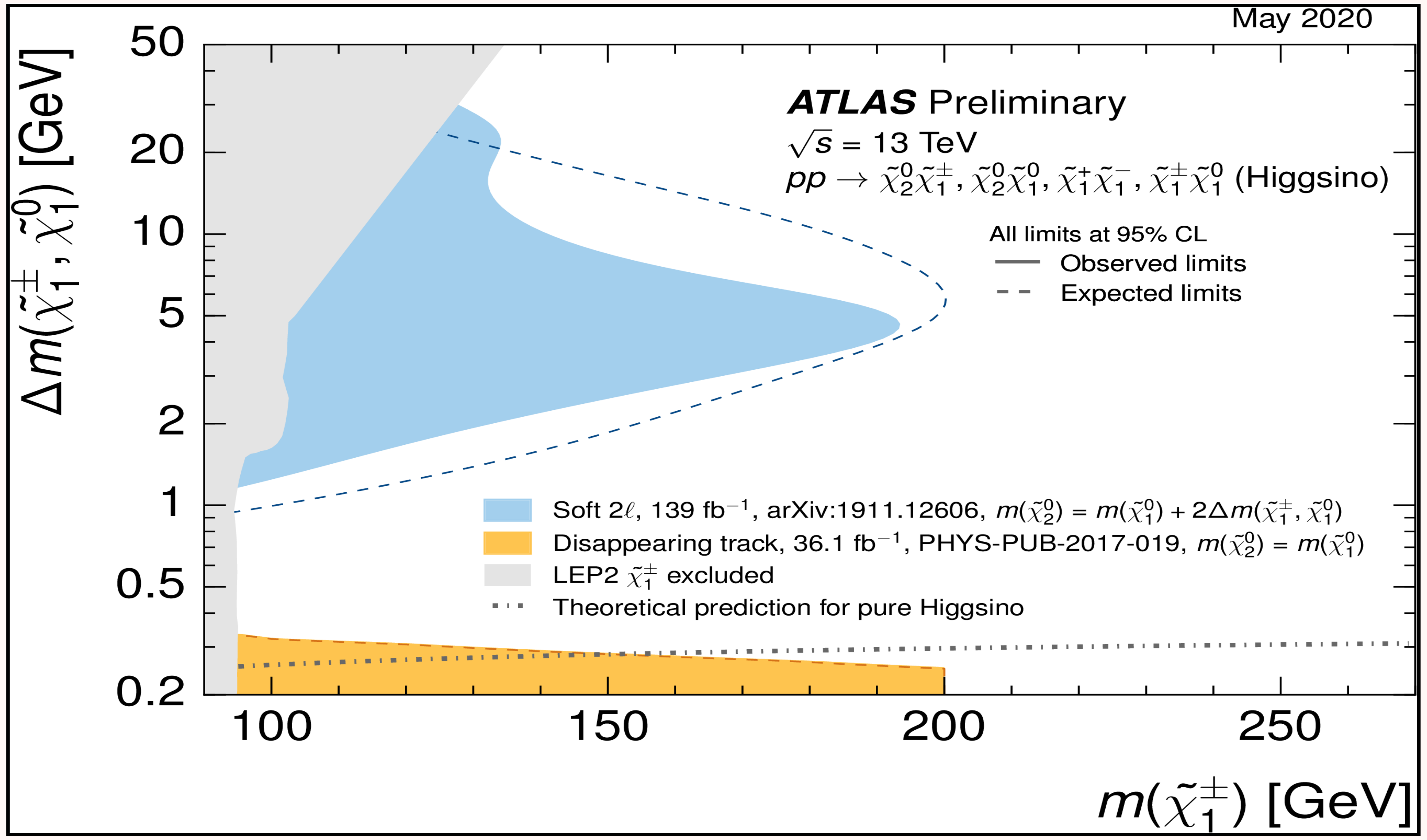
$$X_l = A_l - \mu (\tan\beta)^{2 I_l^{3L}}$$

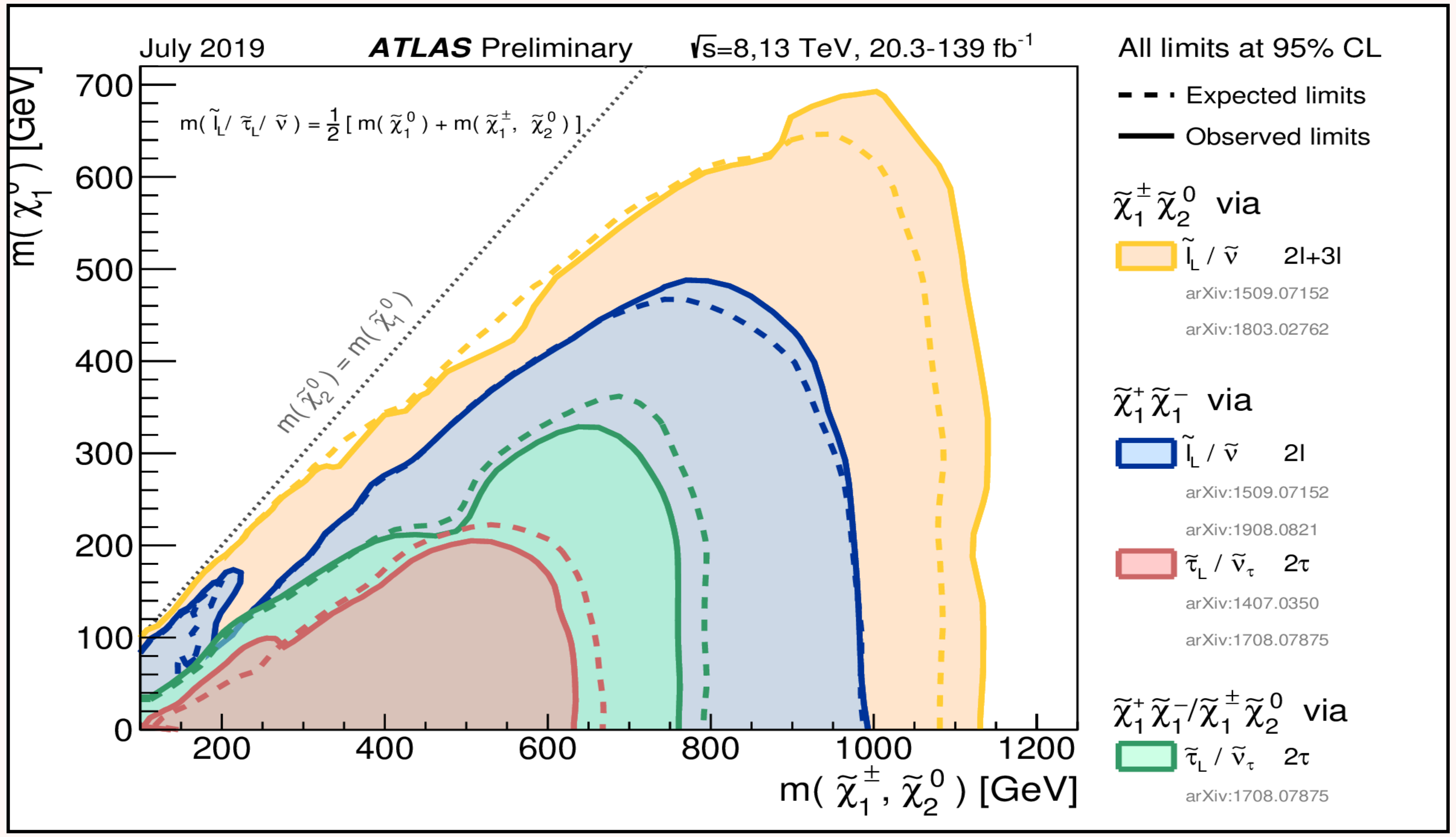
PARAMETERS → $M_1, M_2, \mu, \tan\beta\,, m_{\tilde{L}}\,, m_{\tilde{R}}$

First two gens. $m_{\tilde{l}_1} \sim m_{LL}$ $\quad m_{\tilde{l}_2} \sim m_{RR}$

Constraints from DM and LHC searches on EW-MSSM

Electroweak MSSM at LHC





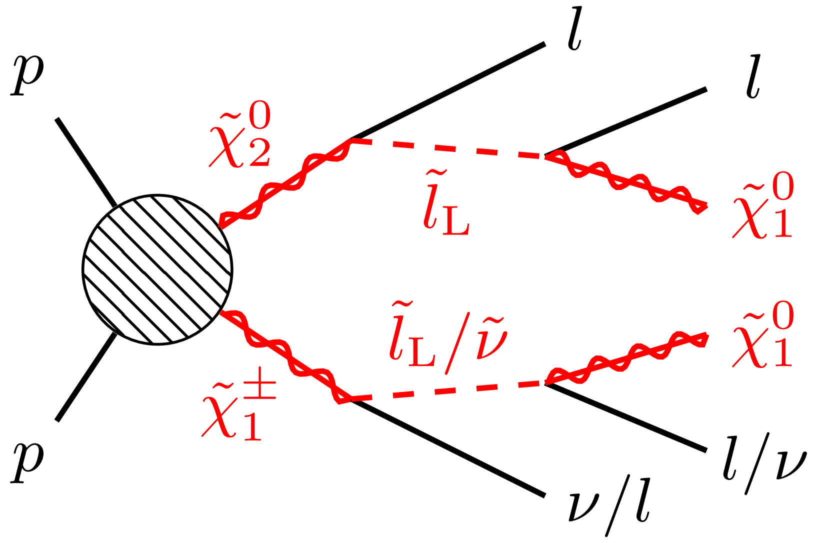
- ★ EW sector may be hiding the key to new physics.
- ★ Modest production cross section, mass bounds from the LHC comparably weak.
- ★ May show up elsewhere : DM experiments, $(g-2)_\mu$ ..

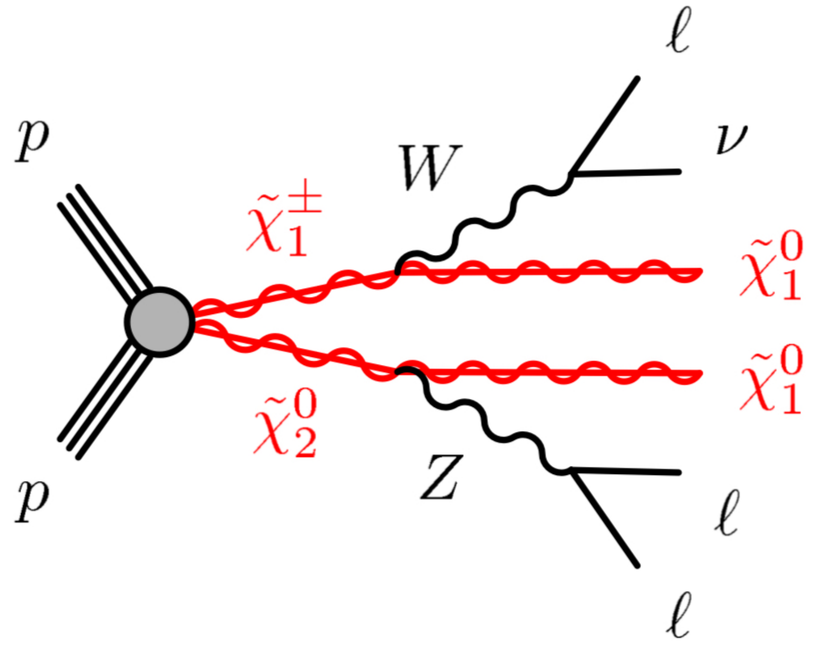
Relevant searches at the LHC

- Trilepton searches

  ATLAS [1803.02762]

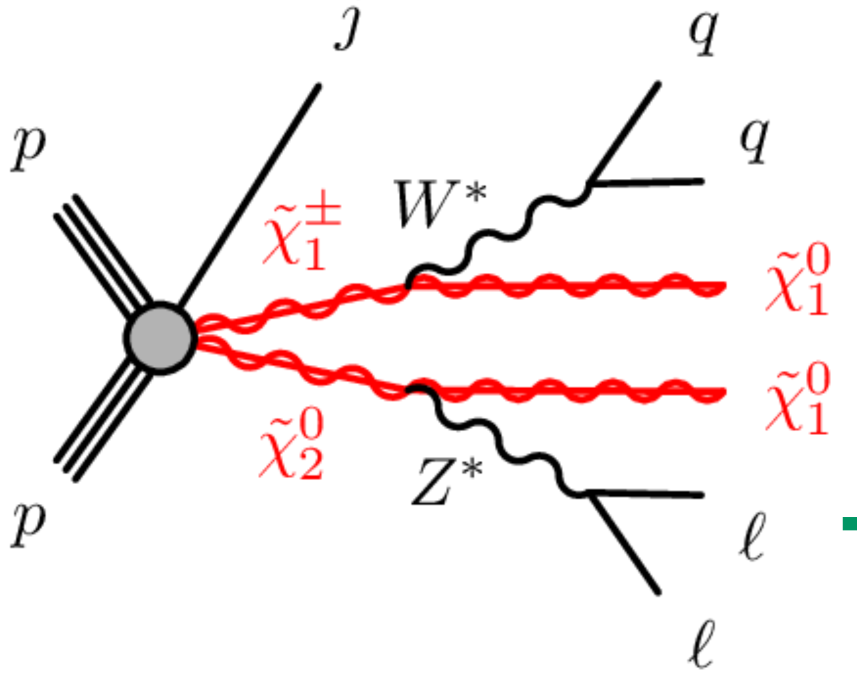
  13 TeV, 36 fb^{-1}

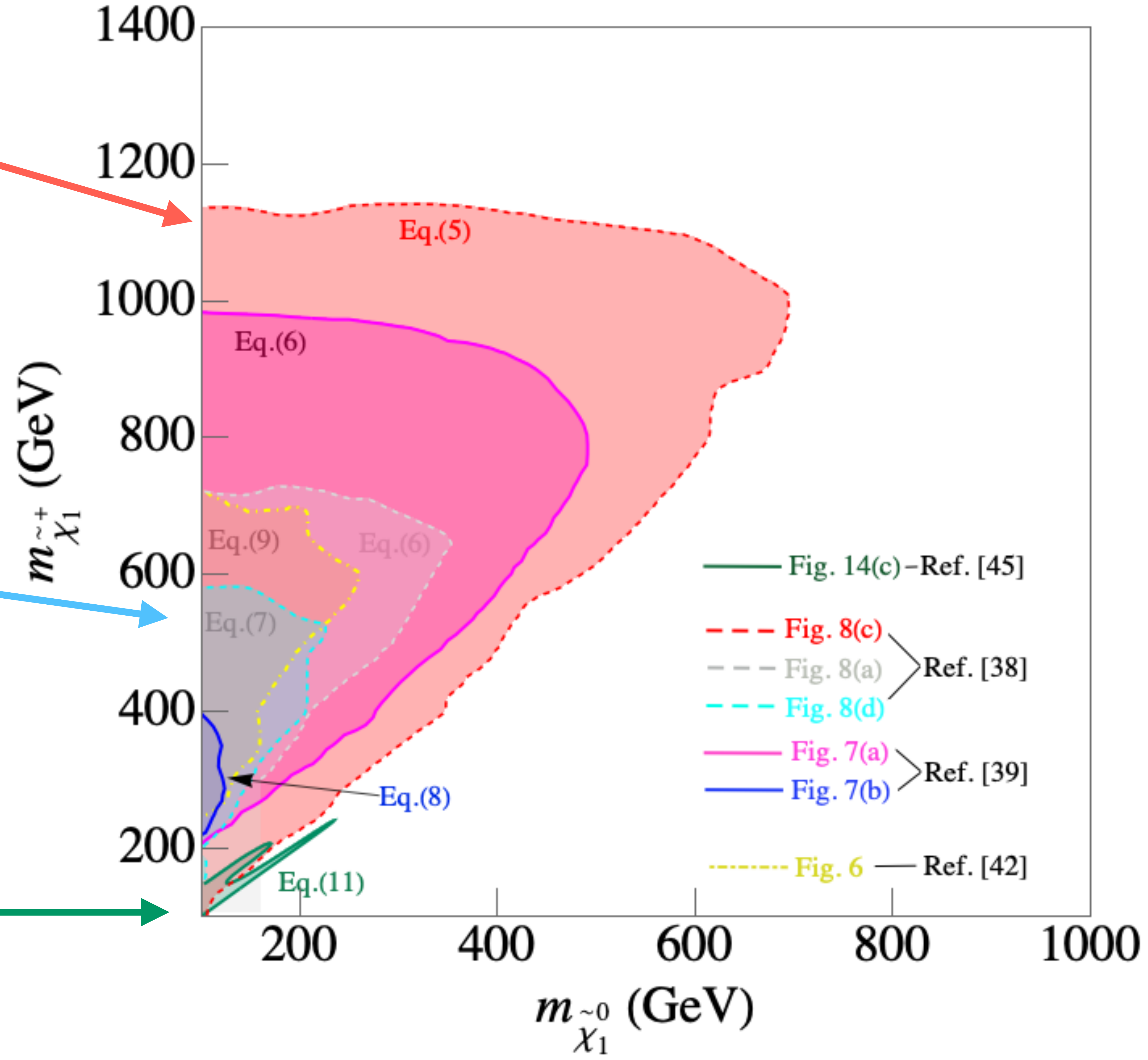




- Compressed spectra searches

  ATLAS 1911.12606





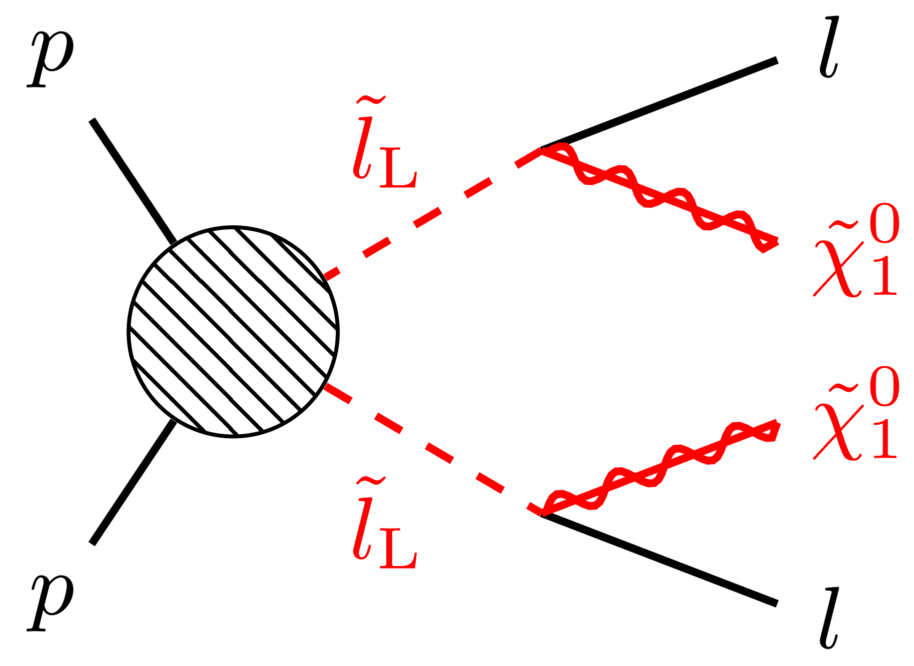
Proper recasting is important → **checkMATE**

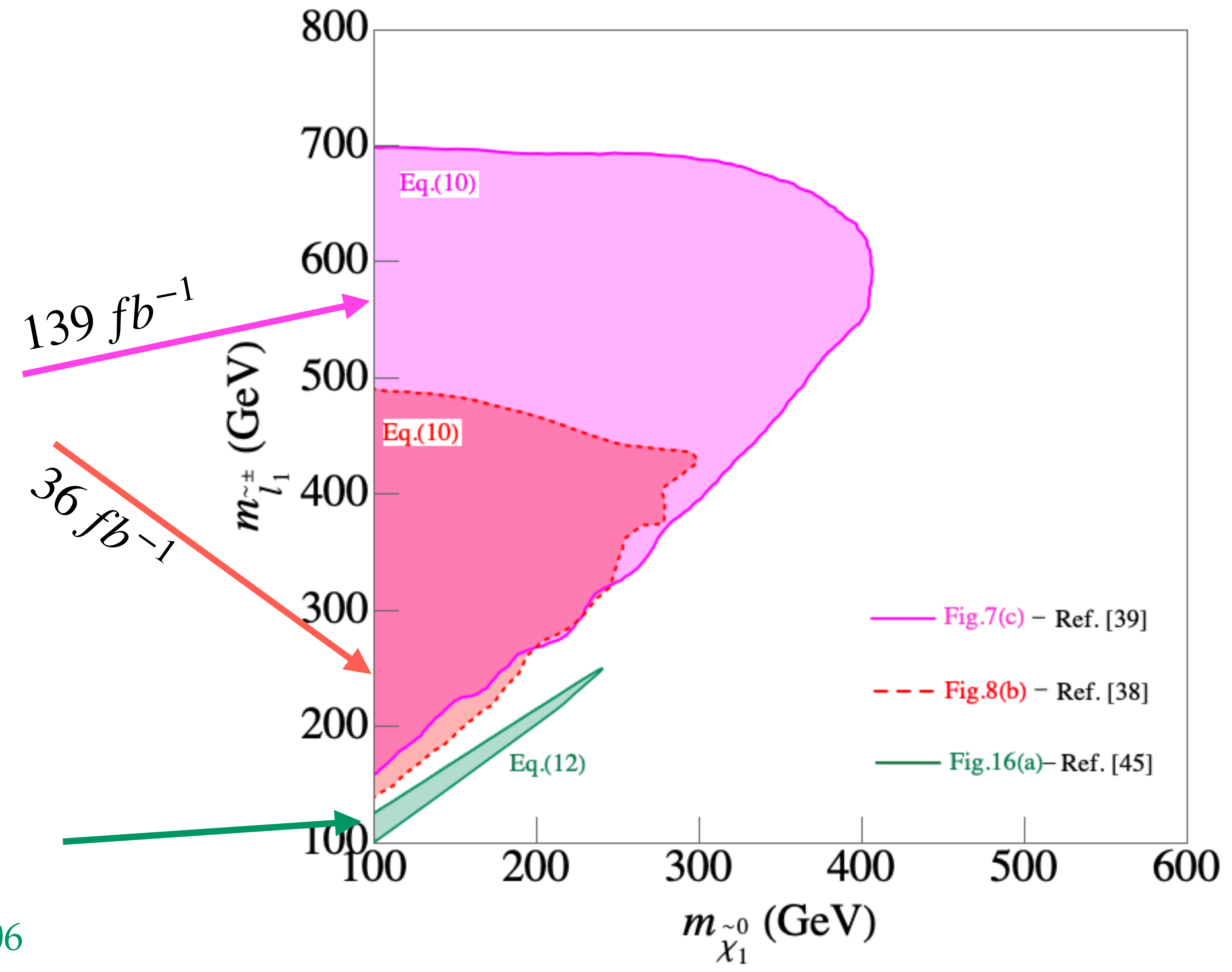
Relevant searches at the LHC

- Slepton pair production

ATLAS [1908.08215]

13 TeV, 139 fb^{-1}





COMPRESSED

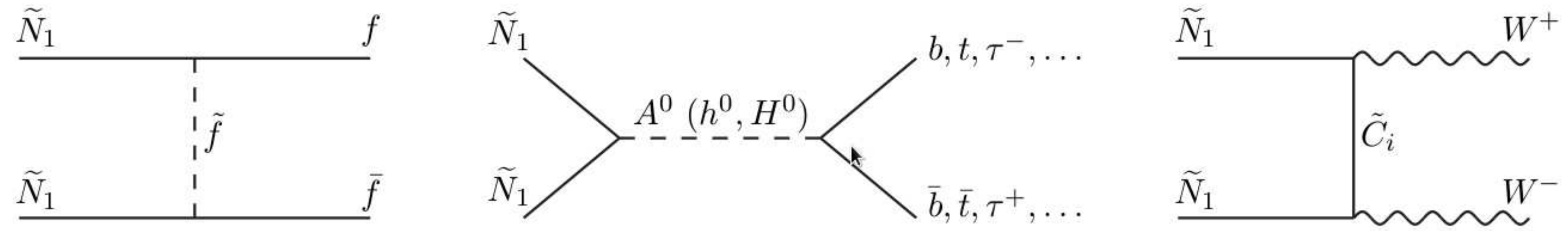
ATLAS 1911.12606

Proper recasting is important → **checkMATE**

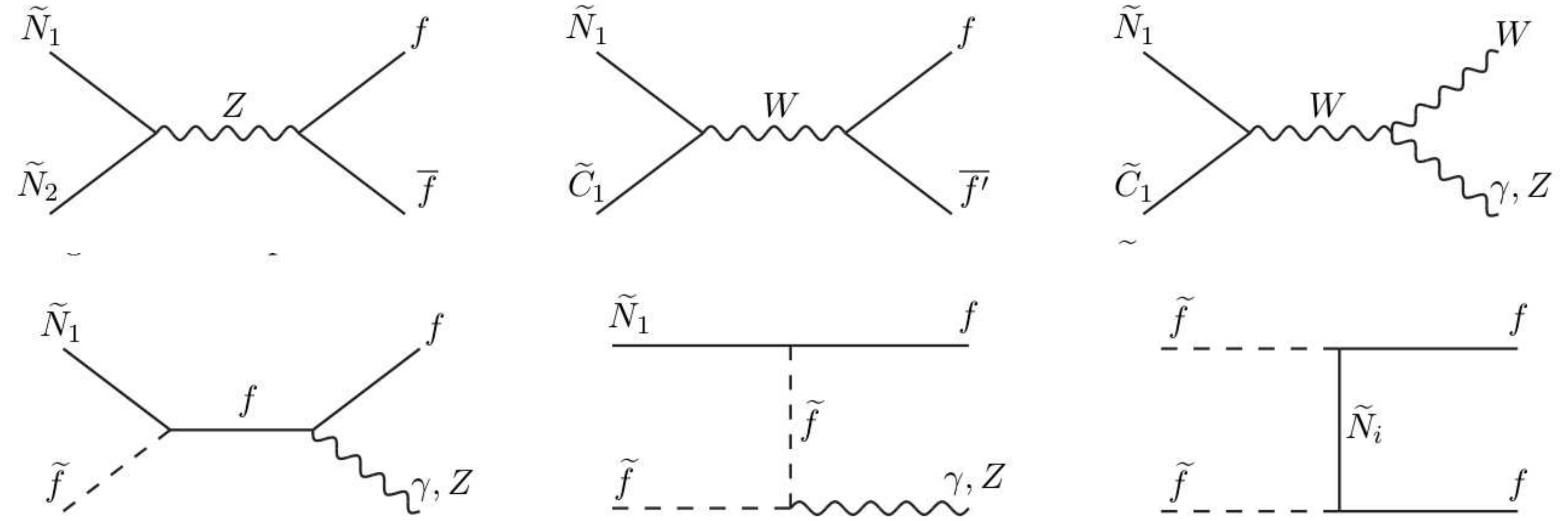
DM Constraints

Relic Density

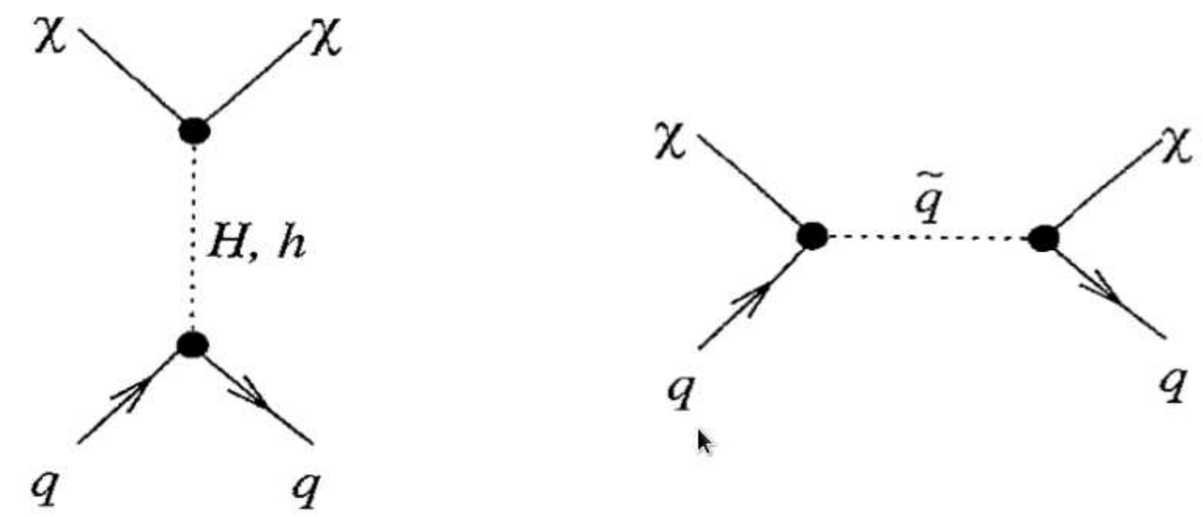
Some annihilation channels that could give right relic density :



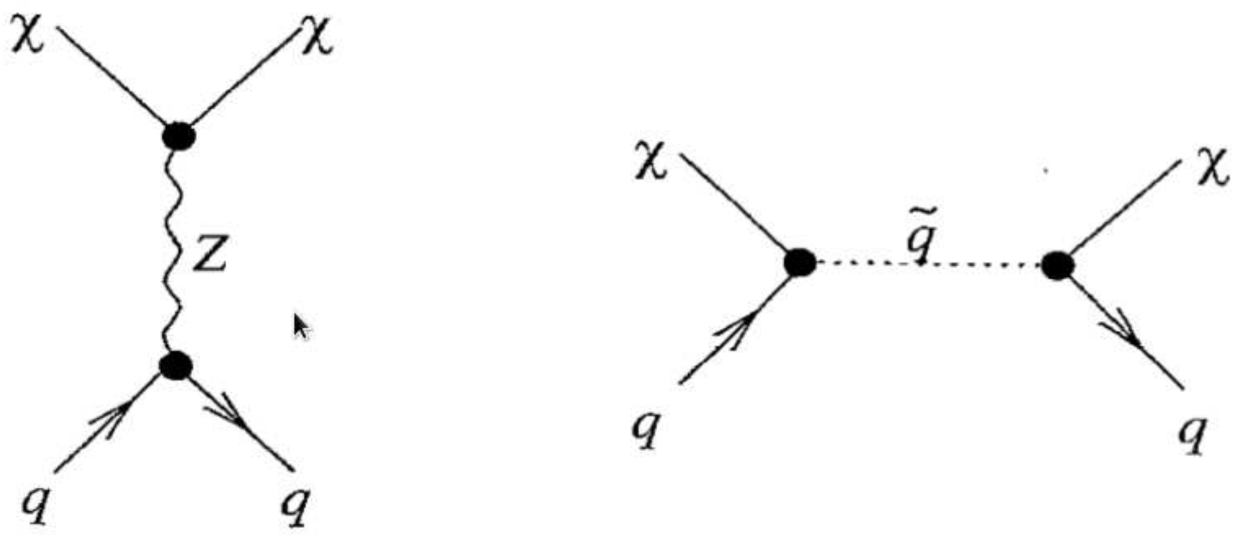
There can be coannihilations with sparticles of slightly heavier masses:



Direct Detection



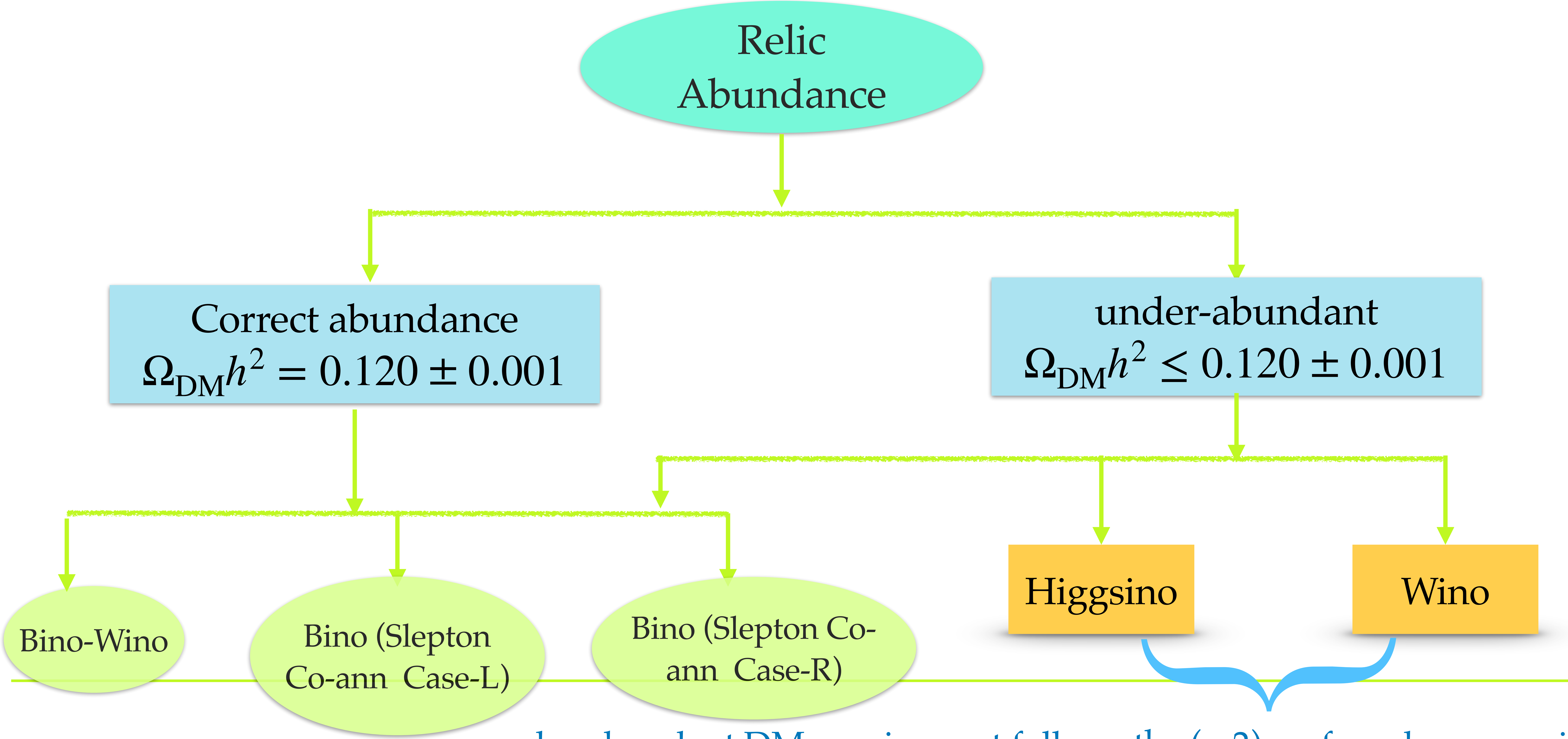
Diagrams contributing to SI interactions



Diagrams contributing to SD interactions

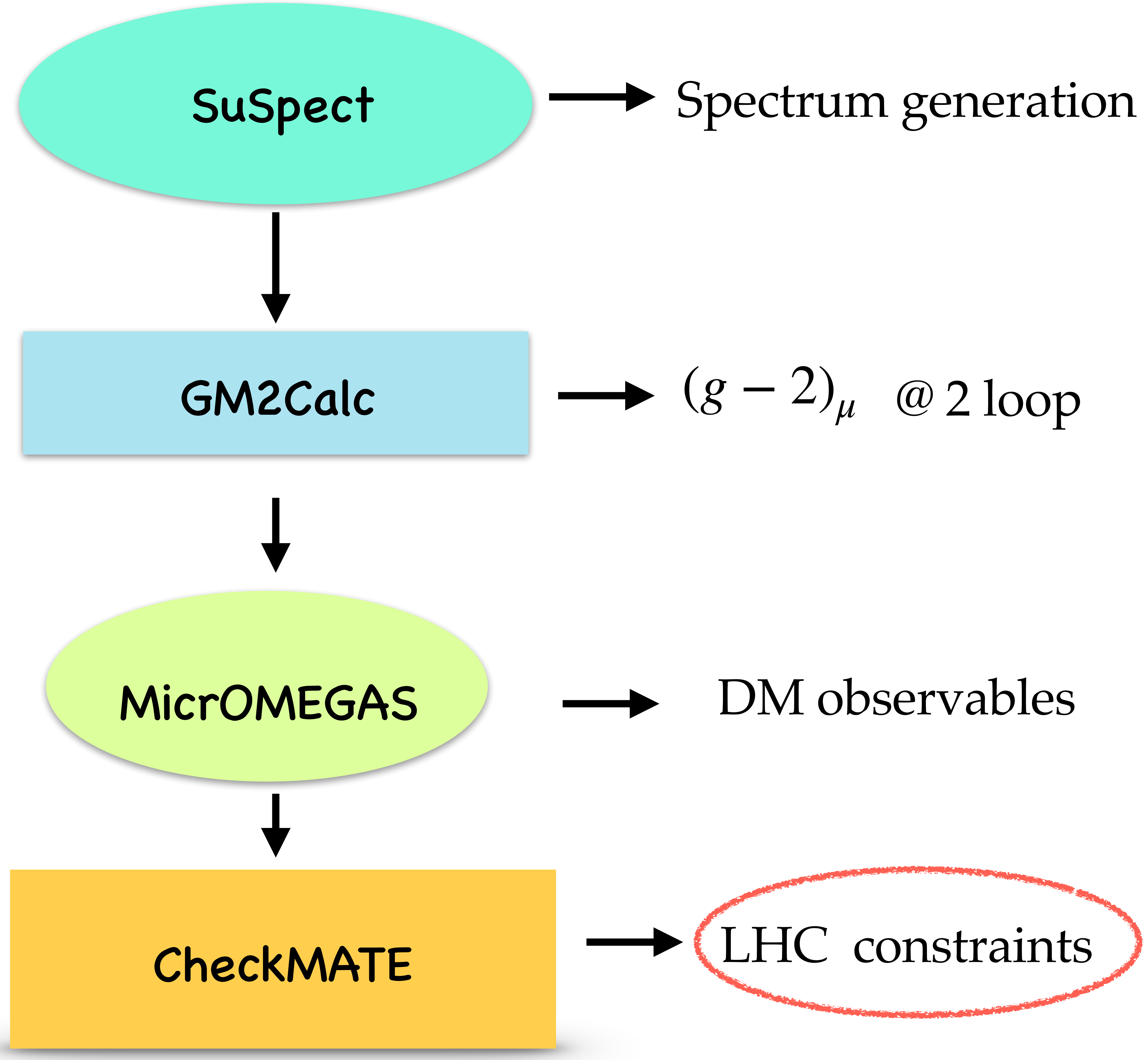
A well-tempered bino-wino or bino-higgsino LSP is favorable for chargino co-annihilation while a bino dominated LSP will work for slepton co-annihilation.

Classification based on DM nature



under-abundant DM requirement follows the (g-2) preferred mass region.

Analysis flow



Muon (g-2)

$$\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$$

Dark Matter Results

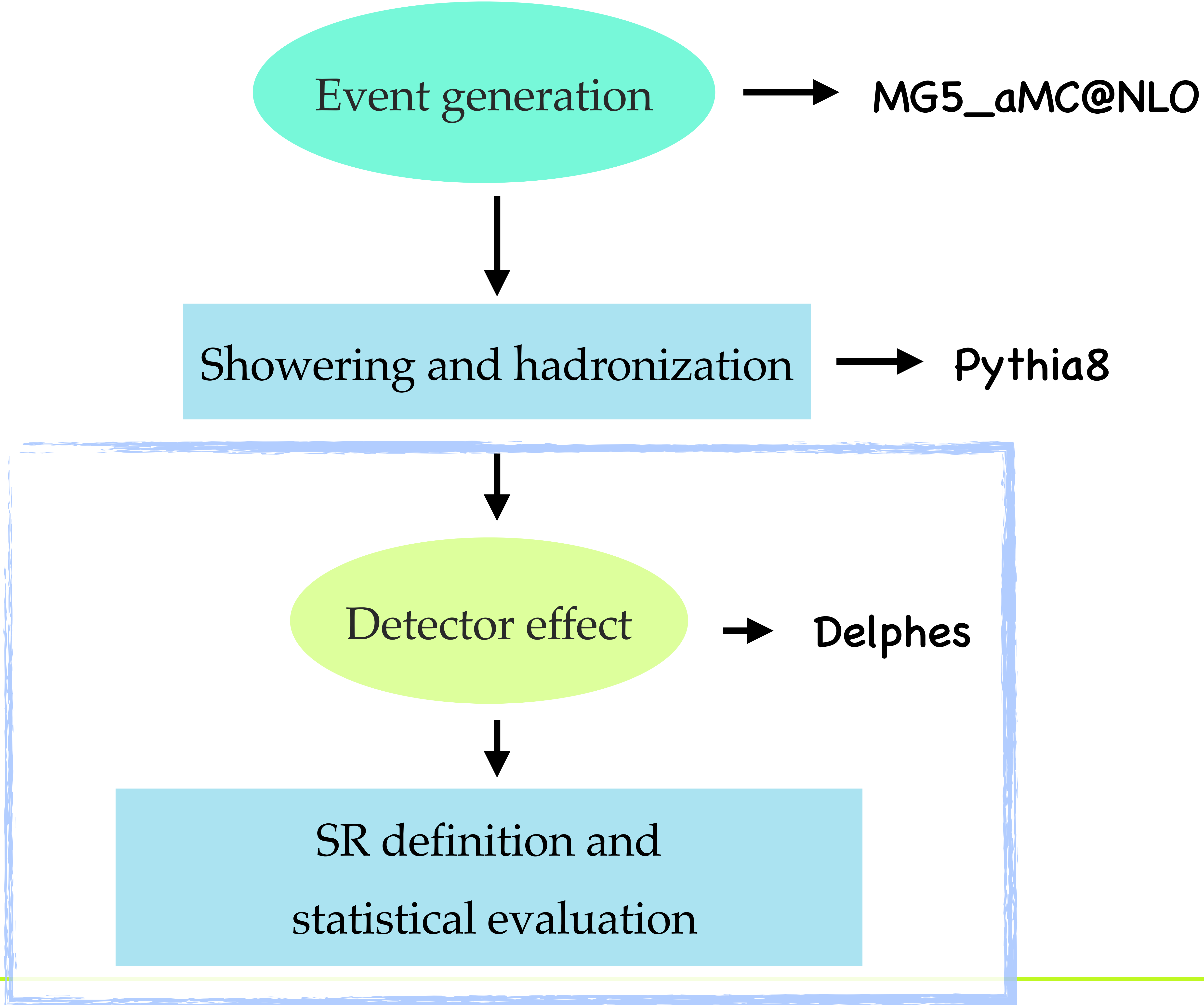
Correct (low) Relic abundance.

$$\Omega_{CDM} h^2 = (\leq)\, 0.120 \pm 0.001$$

Direct detection SI bounds from XENON1T

LHC searches recasting with CheckMATE

Drees, Dreiner, Schmeier, Tattersall, Kim '13
Kim, Schmeier, Tattersall, Rolbiecki '15
Dercks, Desai, Kim, Rolbiecki, Tattersall '16

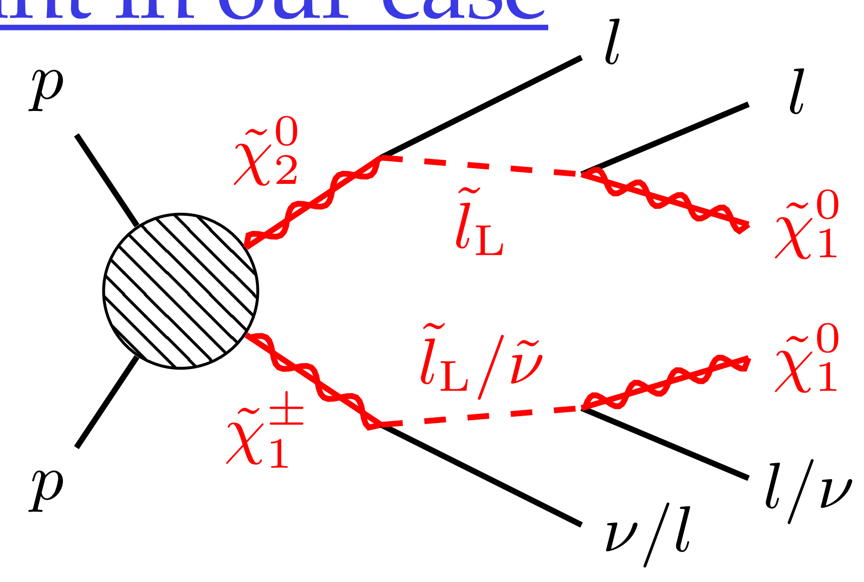


New analysis implementation

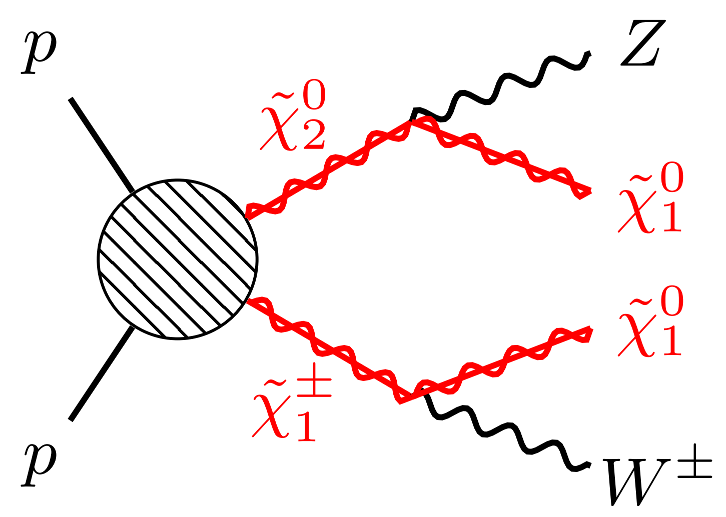
Most relevant in our case

Trilepton searches

- ATLAS [1803.02762]

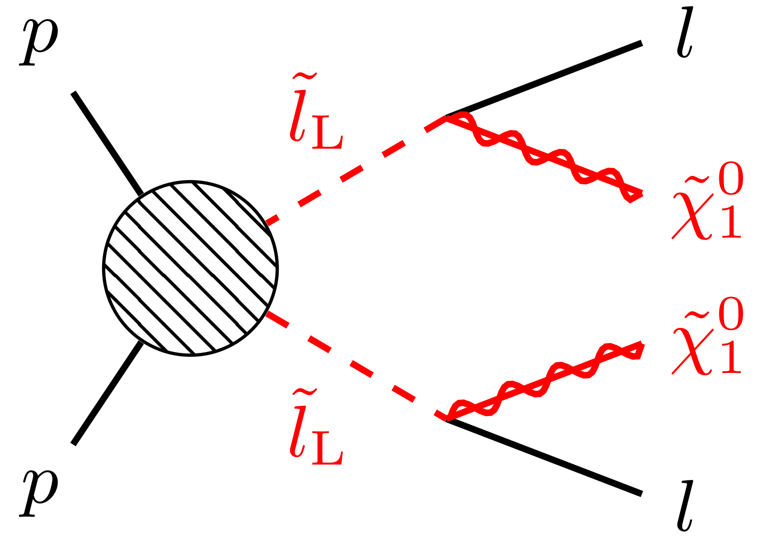


- ATLAS [1803.02762]



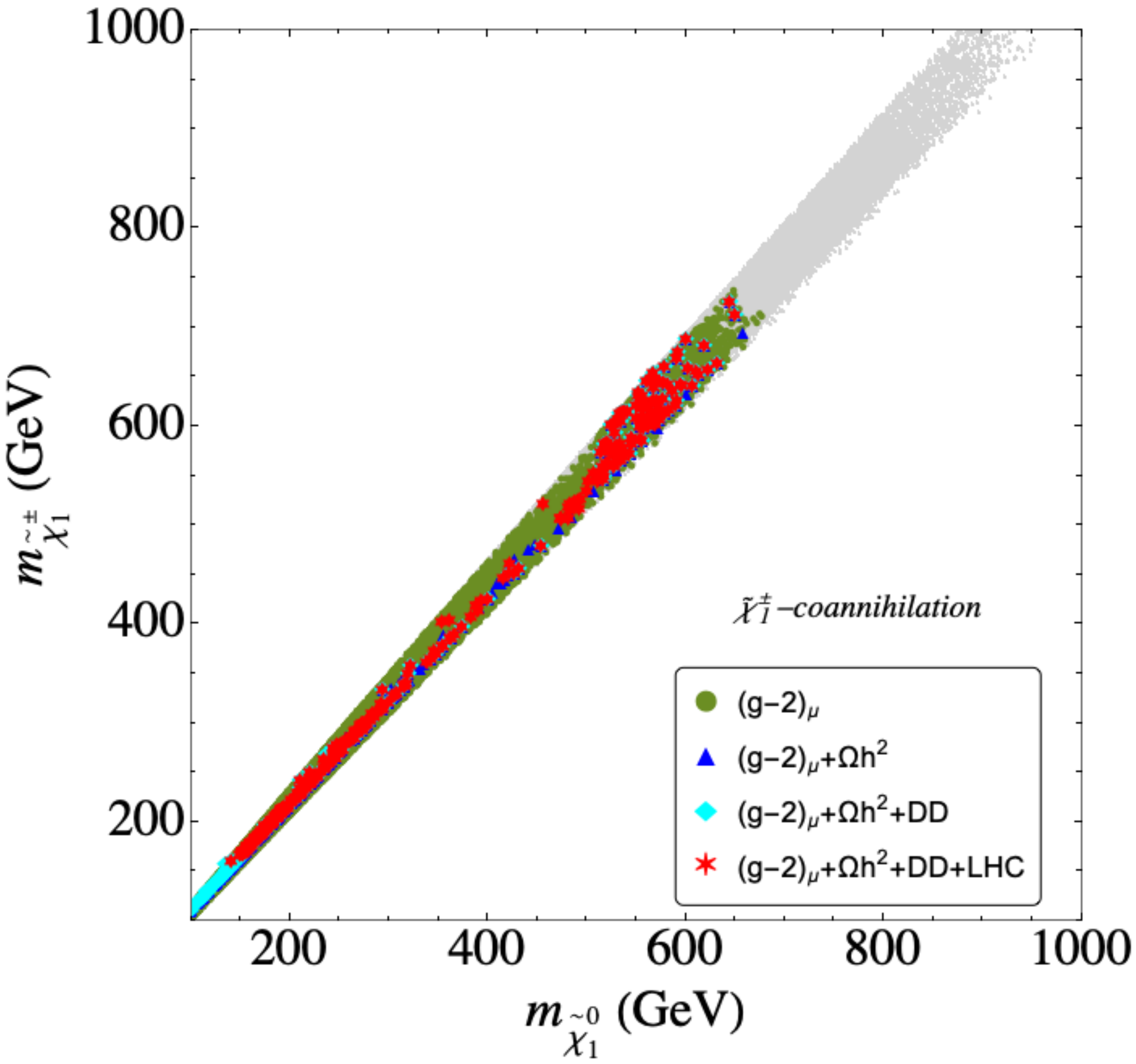
Dilepton searches

- ATLAS [1908.08215]



And, Compressed spectra searches.

Bino-Wino Co-annihilation (Correct abundance)



Bino-wino co-annihilation

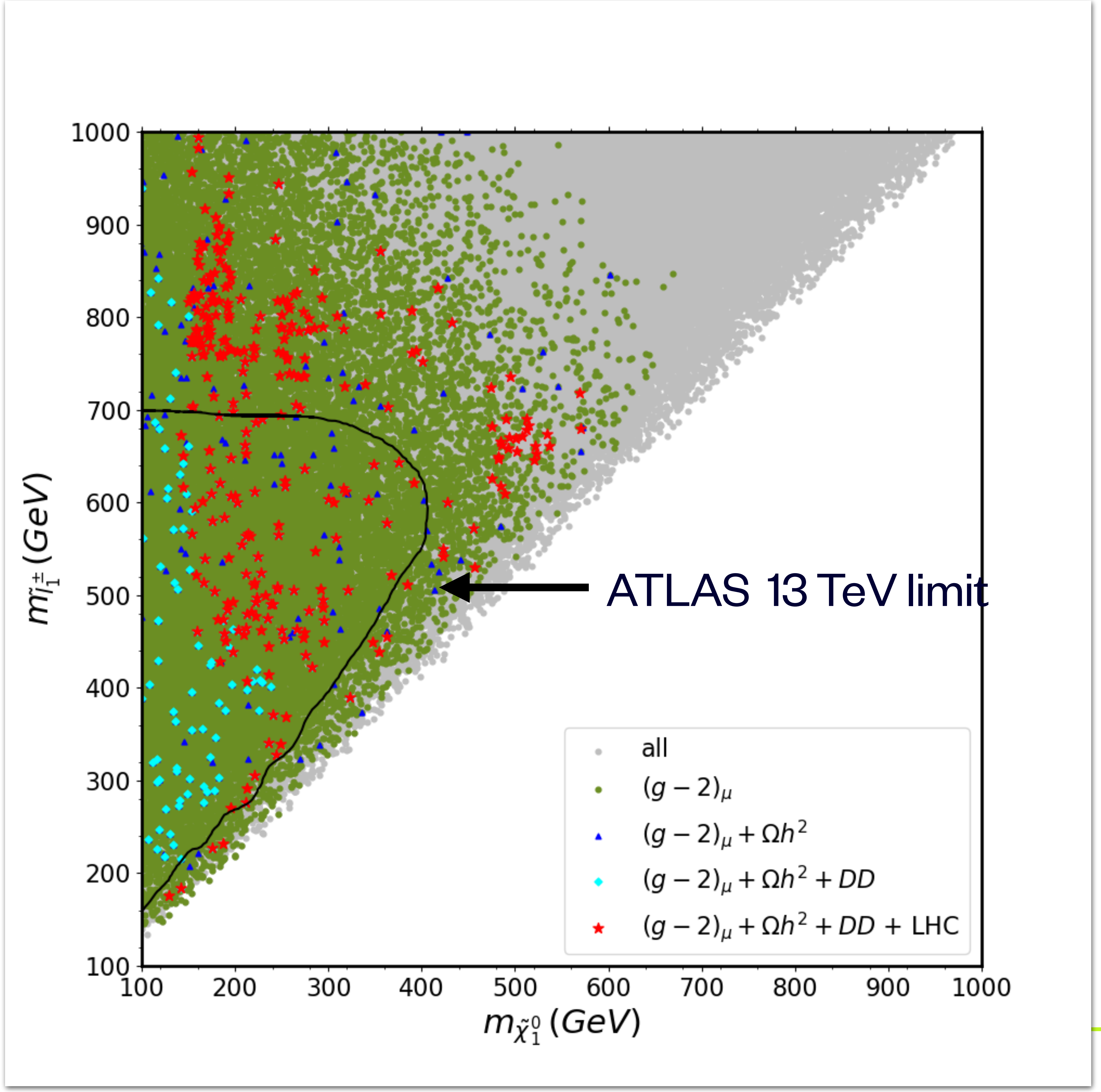
$$100\ \text{GeV} \le M_1 \le 1\ \text{TeV}\ , \quad M_1 \le M_2 \le 1.1 M_1\ ,$$
$$1.1 M_1 \le \mu \le 10 M_1, \quad 5 \le \tan\beta \le 60,$$
$$100\ \text{GeV} \le m_{\tilde{l}_L} \le 1\ \text{TeV}, \quad m_{\tilde{l}_R} = m_{\tilde{l}_L}\ .$$

Upper and lower bounds from $(g-2)_\mu$ and LHC searches (including compressed spectrum) respectively.

NLSP mass upper bound around 750 GeV.

EUR.PHYS.J.C 81 (2021) 12, 1114

Bino-Wino Co-annihilation



Additional LHC bounds come from slepton searches.

- Slepton-pair production →($2l$ + missing E_T) provides important search channel
- Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^{\pm}\nu_e(\nu_\mu)$

↓

Less no. of signal leptons.

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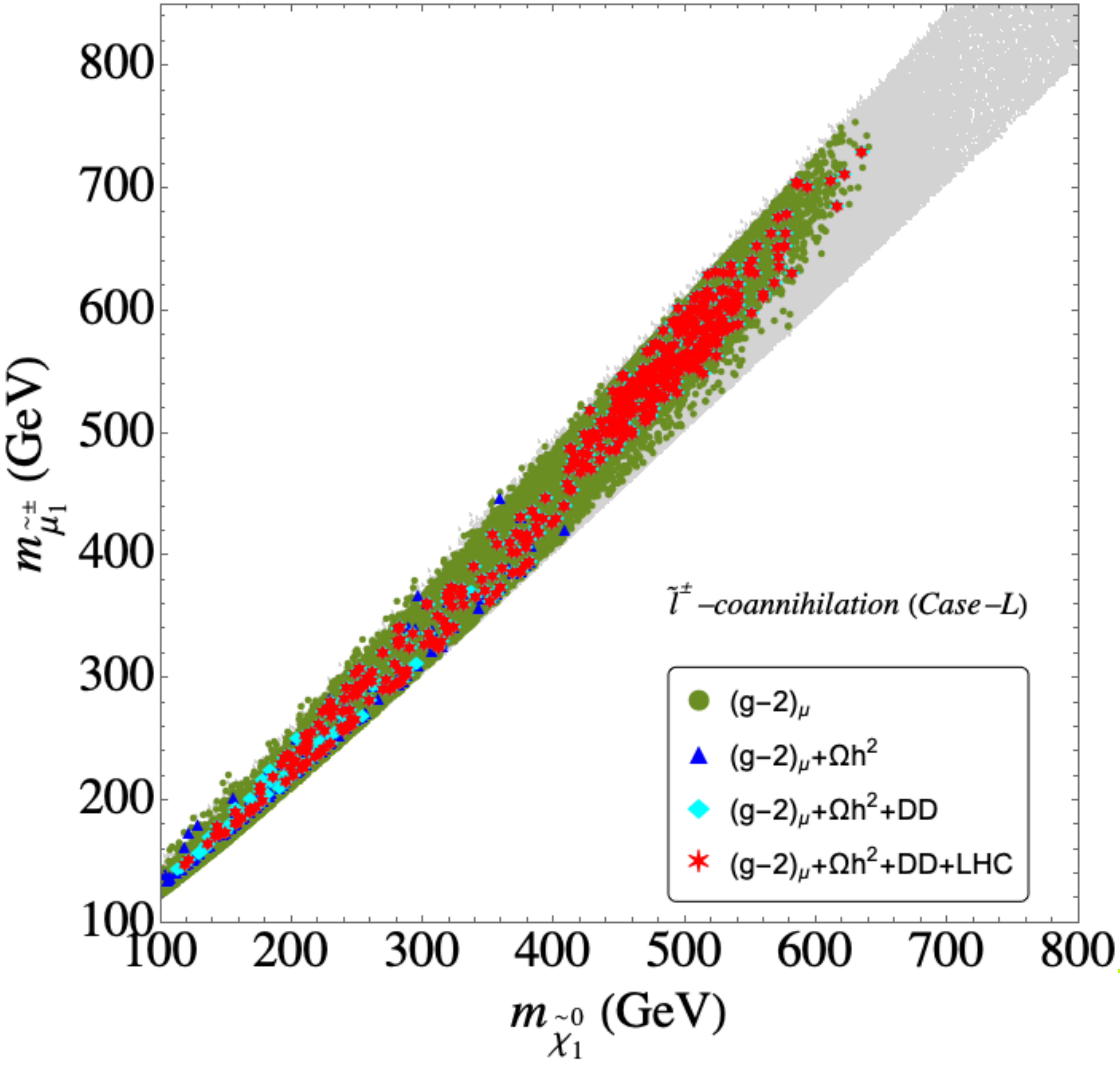
Slepton Co-annihilation: Case-L

(Correct abundance)

Case-L: SU(2) doublet



$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ , \quad M_1 \leq M_2 \leq 10 M_1\ ,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$M_1\ \text{GeV} \leq m_{\tilde{l}_L} \leq 1.2 M_1, \quad M_1 \leq m_{\tilde{l}_R} \leq 10 M_1\ .$$

The left-sleptons and sneutrinos are close in mass to the LSP. NLSP mass upper bound around 750 GeV.

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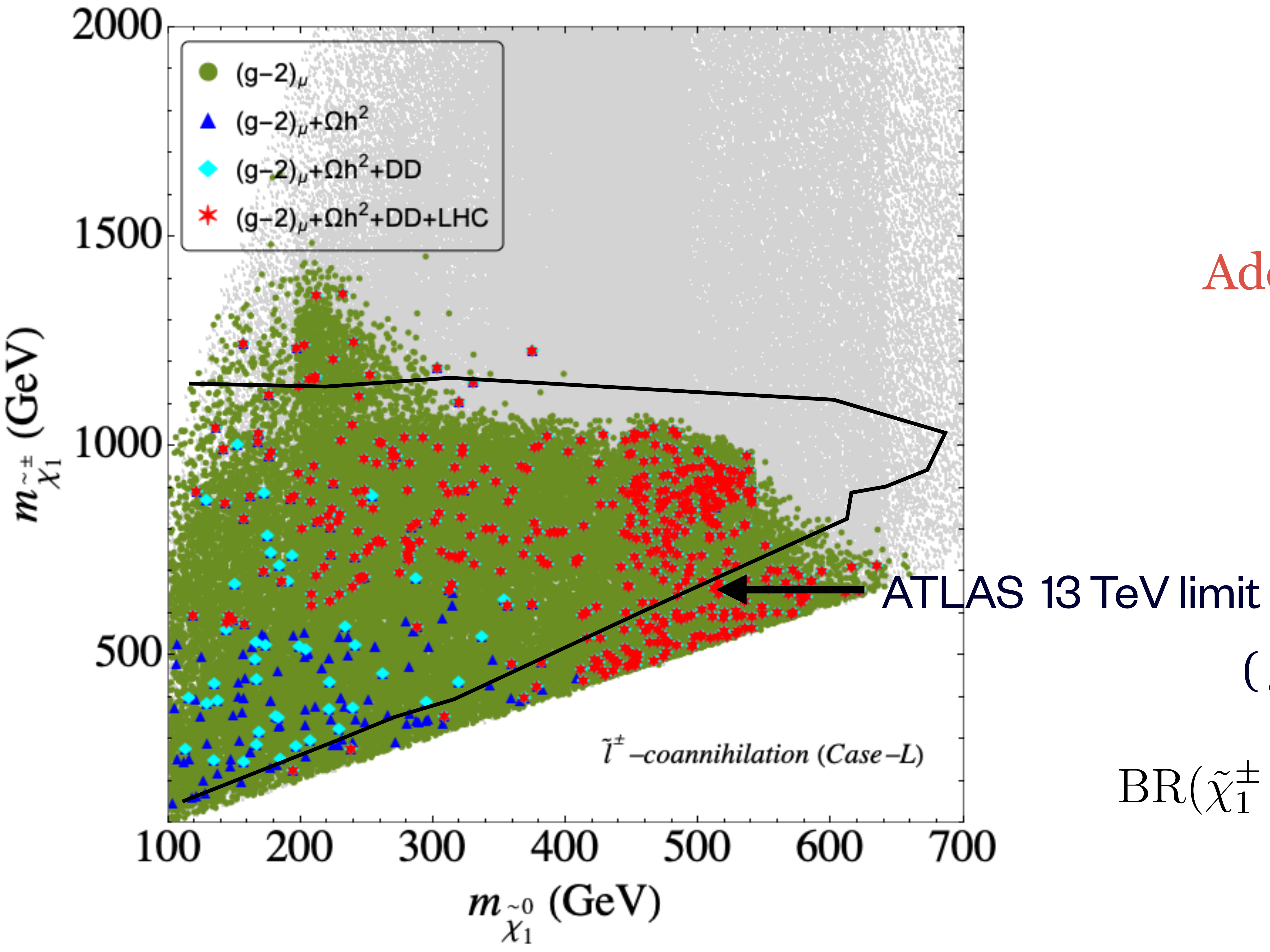
Slepton Co-annihilation: Case-L (Correct abundance)



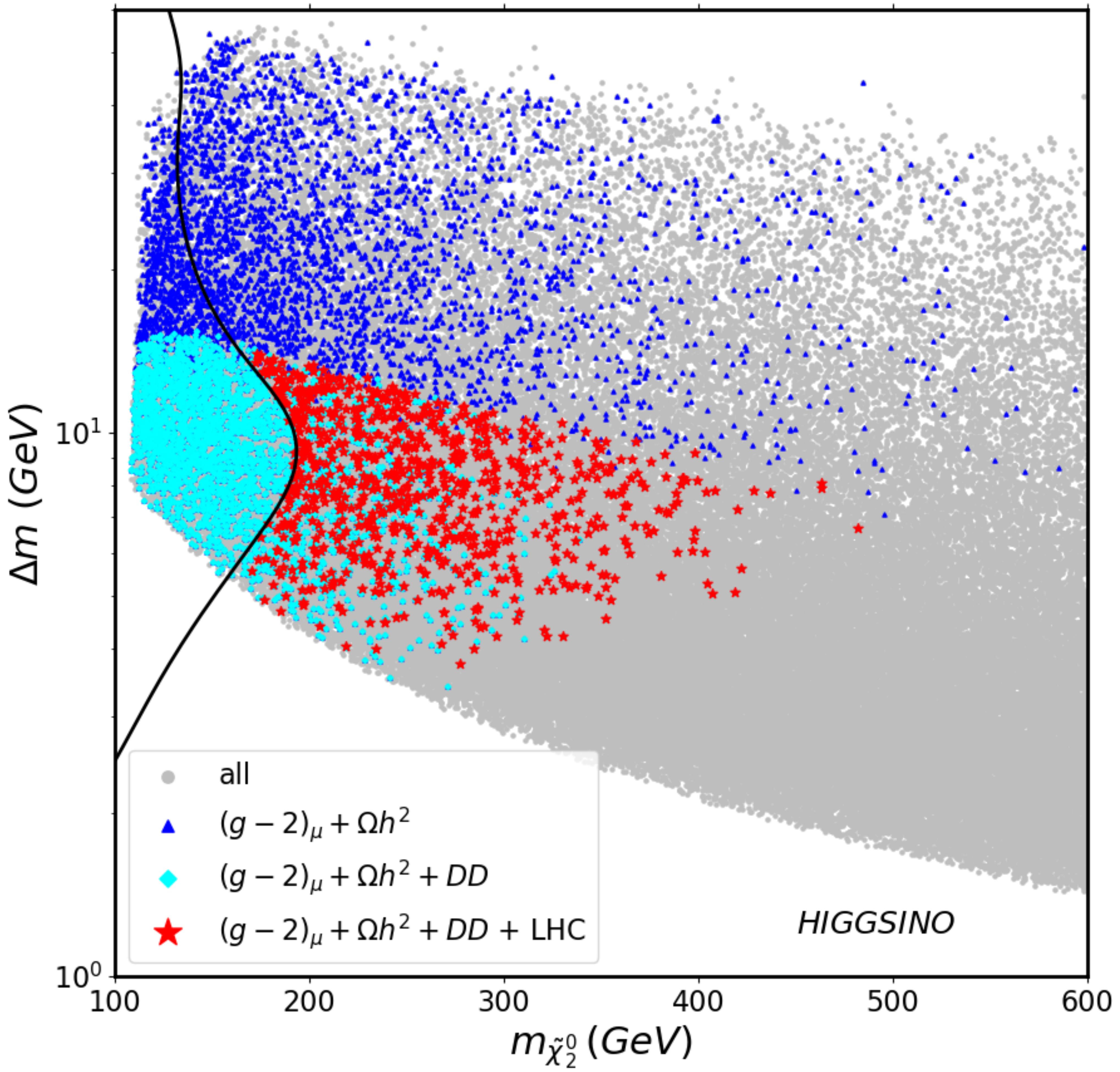
Additional LHC bounds come from chargino plus heavier neutralino searches.

($3l$ + missing E_T) exclusion limit weakens

$$\mathrm{BR}(\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1 \nu_\tau) \text{ and } \mathrm{BR}(\tilde{\chi}_2^{0} \to \tilde{\tau}_1 \tau), \mathrm{BR}(\tilde{\chi}_2^{0} \to \tilde{\nu}\nu)$$

Higgsino:

(Upper limit from relic abundance)



Higgsino

$$100 \text{ GeV} \leq \mu \leq 1.2 \text{ TeV} , \quad 1.1\mu \leq M_1 \leq 10\mu ,$$
$$1.1\mu \leq M_2 \leq 10\mu, \quad 5 \leq \tan\beta \leq 60,$$
$$100 \text{ GeV} \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 2 \text{ TeV} .$$

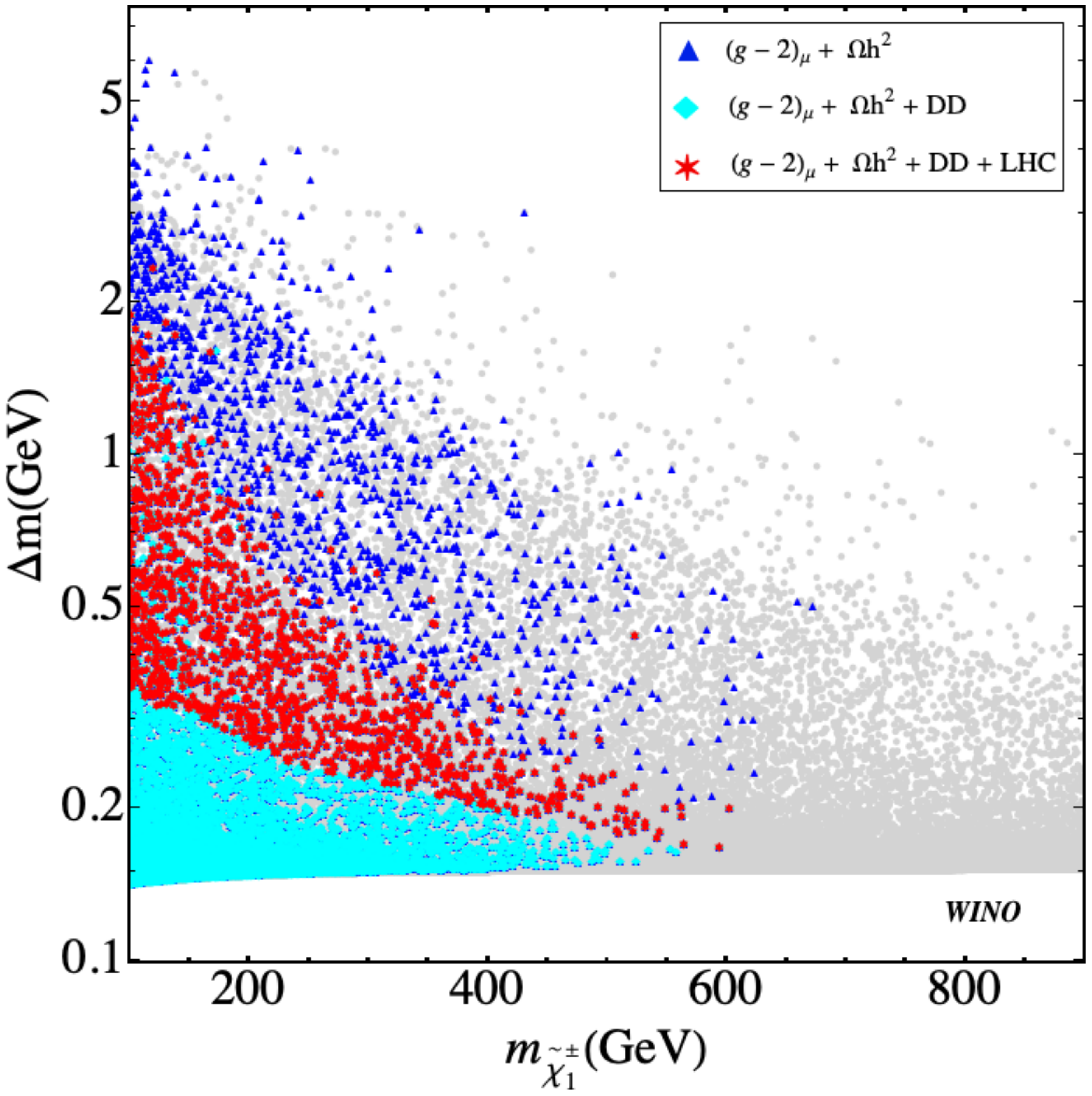
Chargino-neutralino compressed spectrum searches are important in addition to slepton searches.

FUTURE DIRECT DETECTION AND LHC CONSTRAINTS WILL BE IMPORTANT FOR THESE SCENARIOS.

EUR.PHYS.J.C 81 (2021) 12, 1069

Wino:

(Upper limit from relic abundance)



Wino

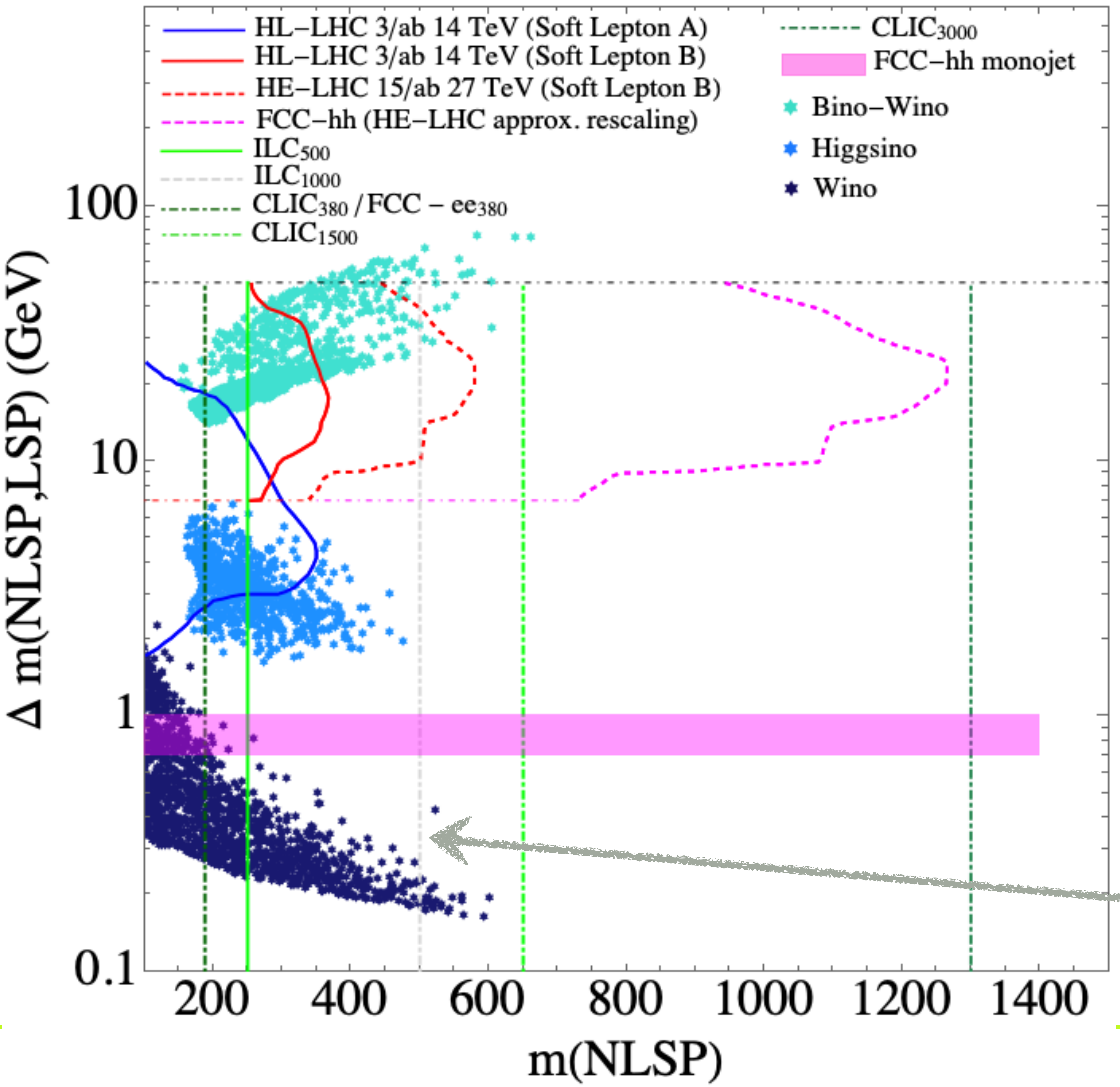
$$100 \text{ GeV} \le M_2 \le 1.5 \text{ TeV} , \quad 1.1 M_2 \le M_1 \le 10 M_2 ,$$
$$1.1 M_2 \le \mu \le 10 M_2, \quad 5 \le \tan\beta \le 60,$$
$$100 \text{ GeV} \le m_{\tilde{l}_L}, m_{\tilde{l}_R} \le 2 \text{ TeV} .$$

Disappearing track searches are relevant in addition to slepton searches.

FUTURE DIRECT DETECTION AND LHC CONSTRAINTS WILL BE IMPORTANT FOR THESE SCENARIOS.

EUR.PHYS.J.C 81 (2021) 12, 1069

Future prospects (under abundant DM)



ILC- 1 TeV reach

Compressed Chargino-Neutralino spectrum at future lepton colliders has high hope.

'Wino and Higgsino Factory'

$$\Omega_{CDM}h^2 \leq 0.120 \pm 0.001$$

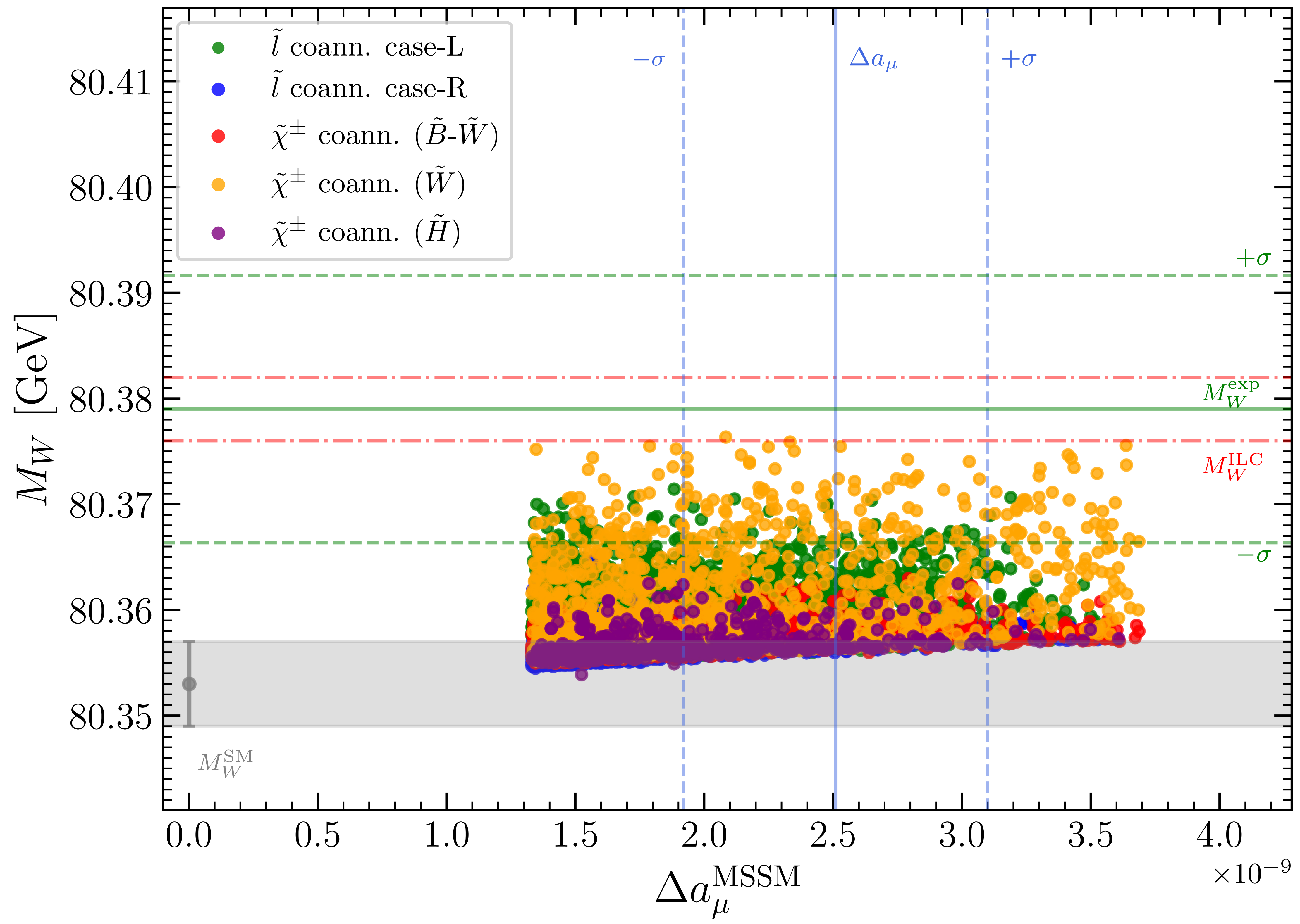
$$\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$$

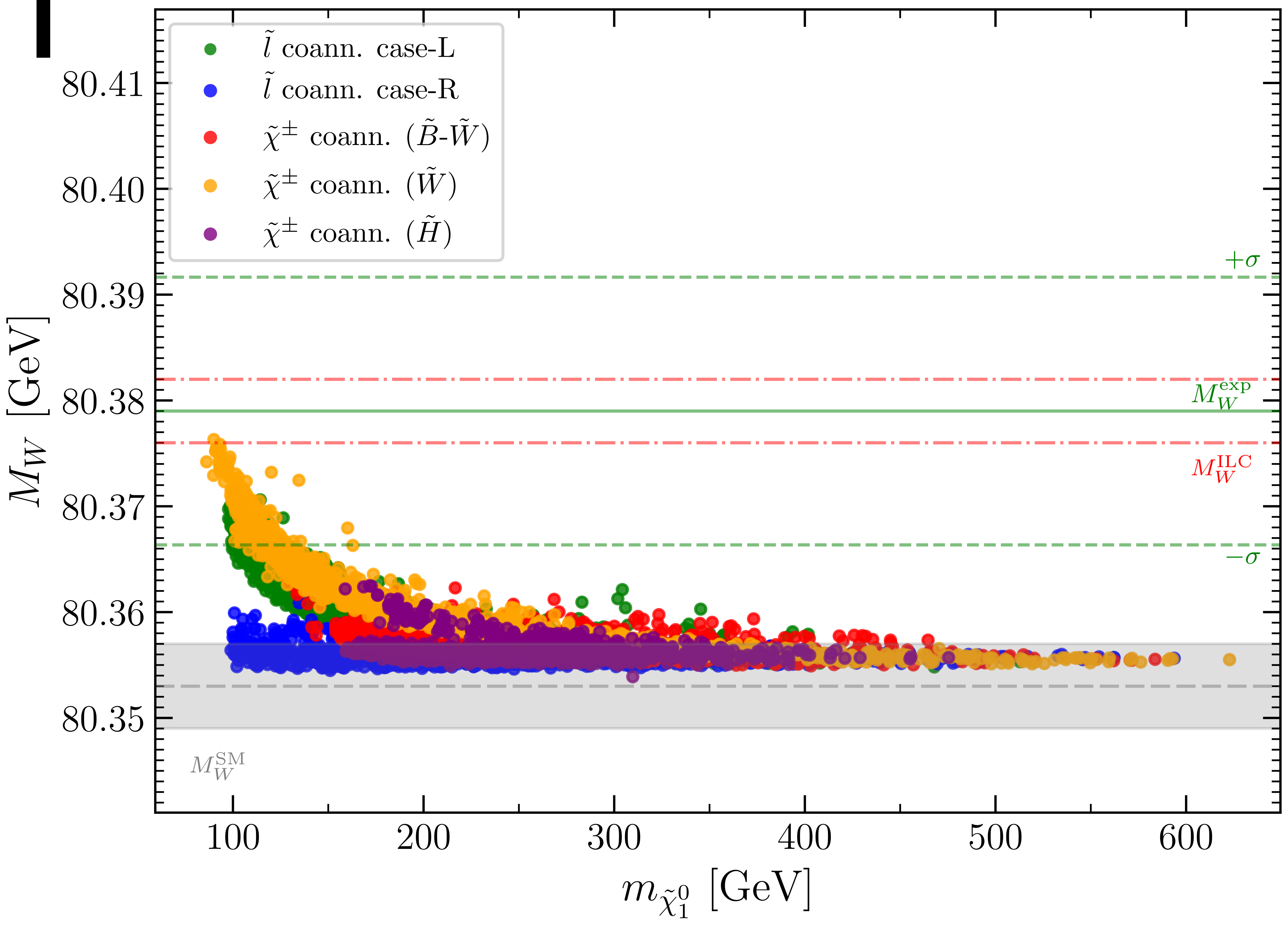
Direct detection SI bounds from XENON1T

Interpretation of muon (g-2) and MW

FeynHiggsv2.18.1

CDF-II = 80.433 +- 0.009



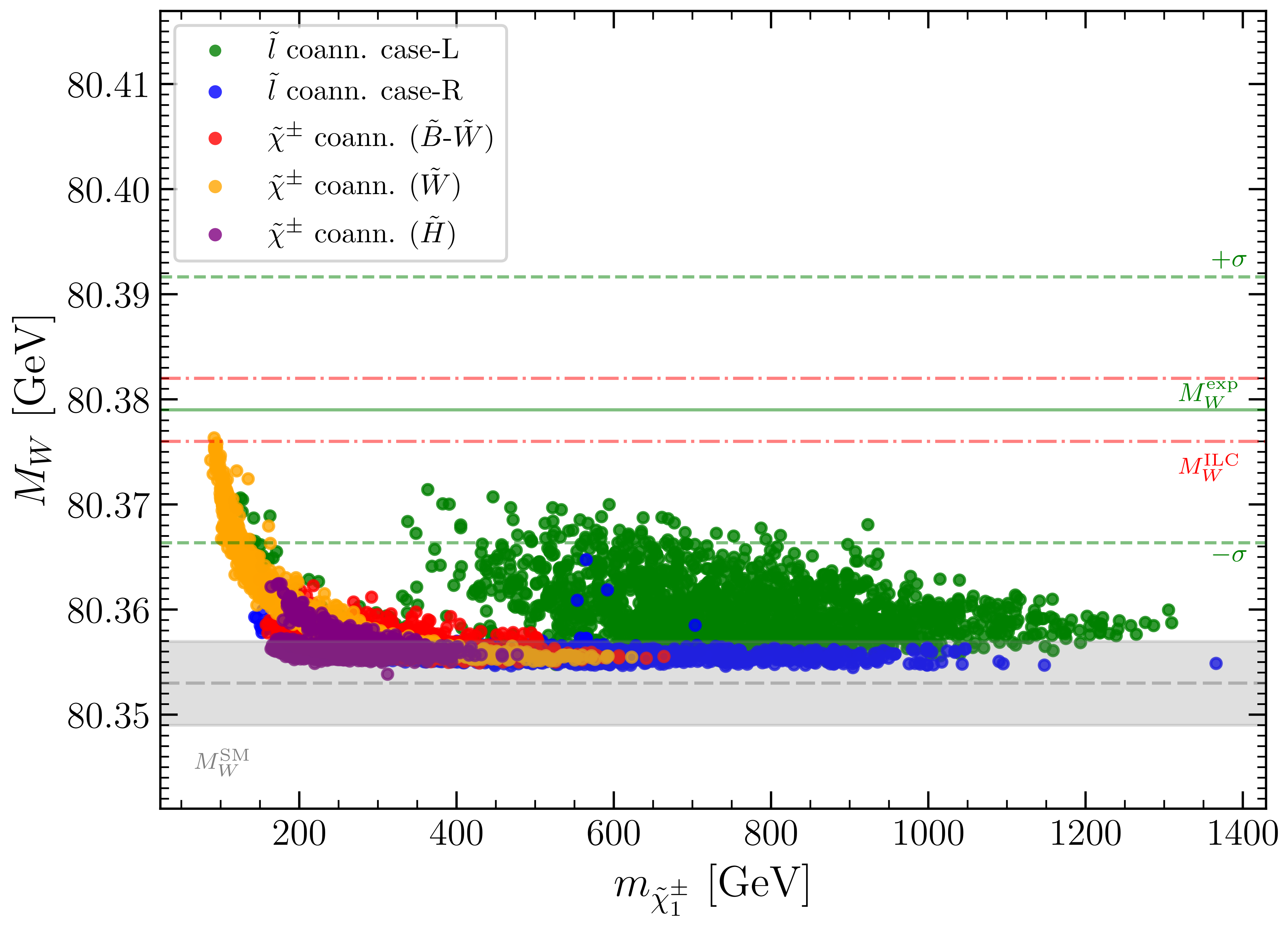


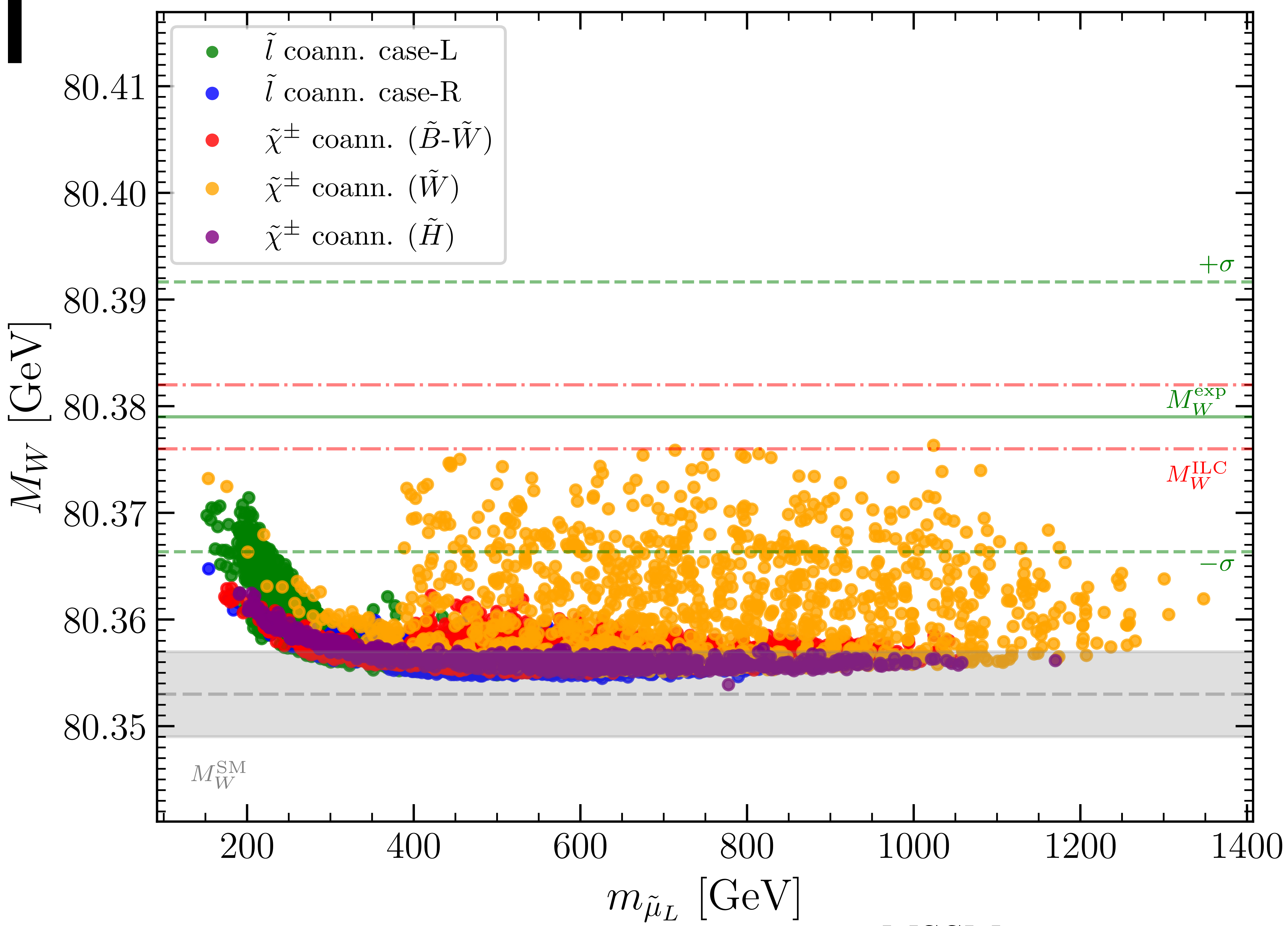
- Heavy EW masses corresponding to low Δa_μ^{MSSM} recovers the SM prediction, the decoupling limit.
- The scenario of Wino DM and slepton co-annihilation (case-L) can give rise to sizable contribution to MW upto 25 and 20 MeV respectively.

Interpretation of muon (g-2) and MW

FeynHiggsv2.18.1

CDF-II = 80.433 +- 0.009





- Lightest chargino of mass $m_{\tilde{\chi}_1^{\pm}} \leq 200$ GeV in Wino DM case give rise to the largest value for M_W^{MSSM} while left-handed smuon less than 250 GeV is favored for slepton co-annihilation in consistent with muon (g-2), DM and LHC searches.

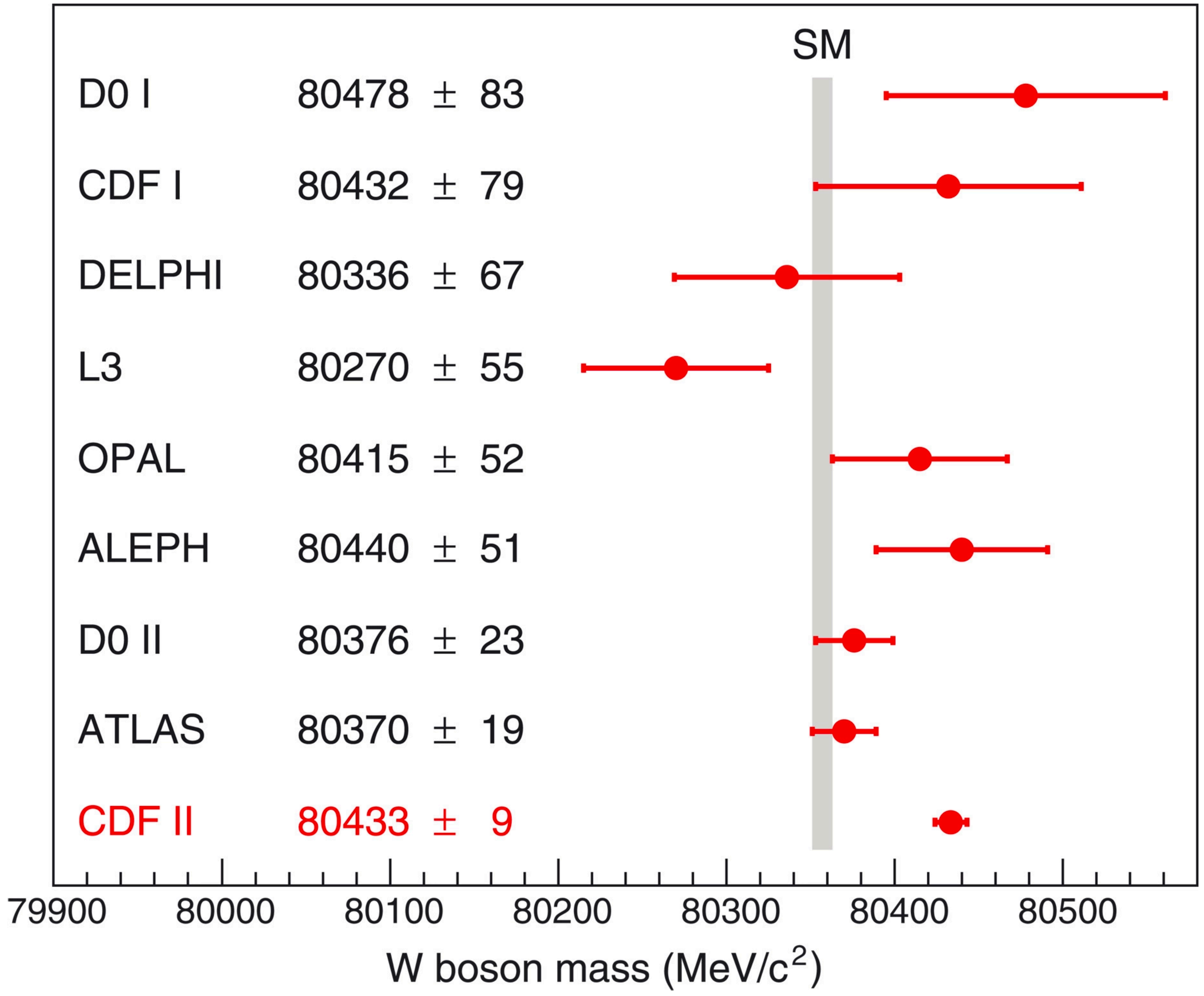
- For wino DM, the vertex and box diagram is important while for the sleptons the self-energy diagrams contributions are relevant.

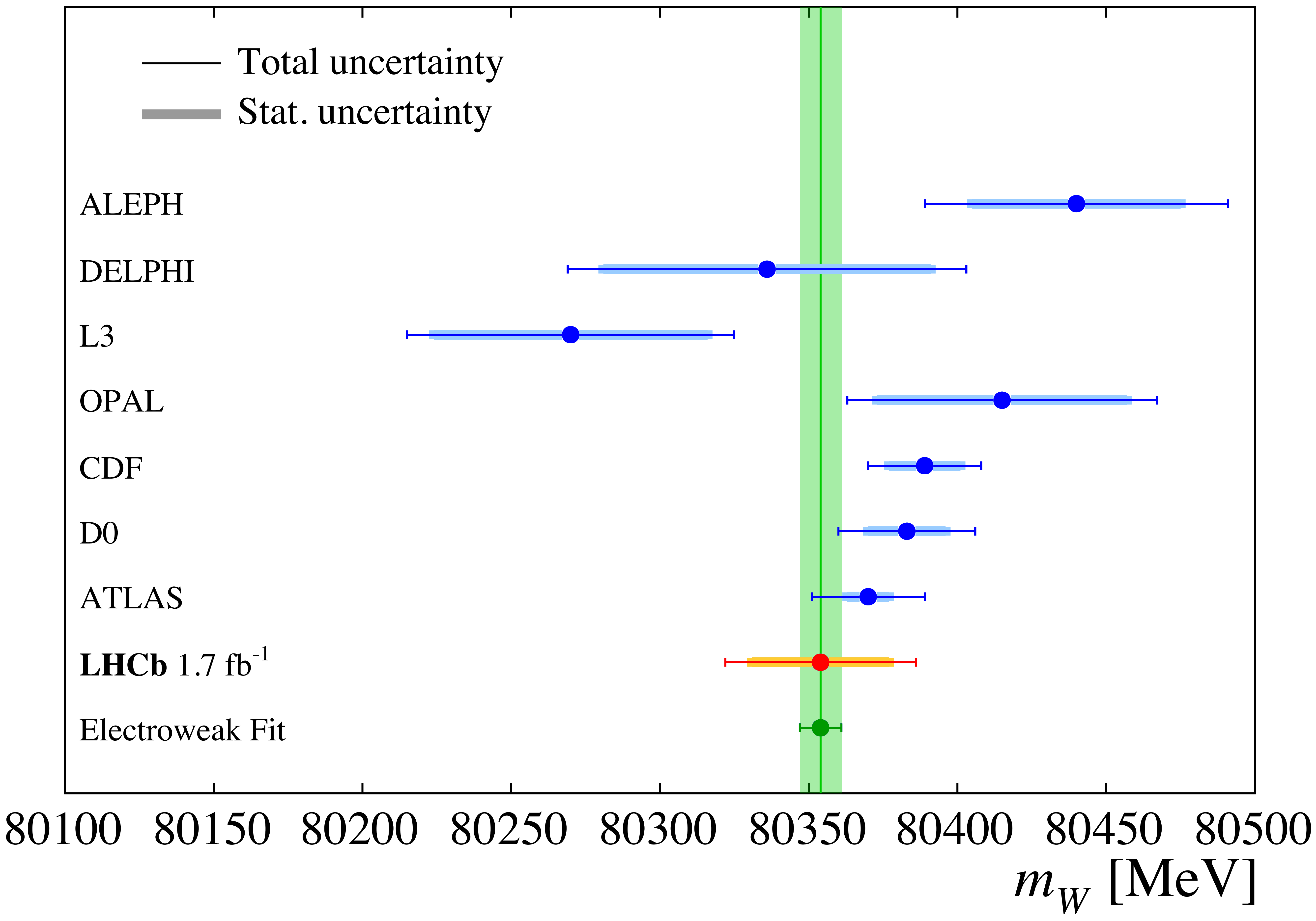
Conclusions

- It is possible to constrain the EW MSSM with the help of indirect constraints along with the direct collider limits.
- DM and muon (g-2) constraint put effective upper limit on EW SUSY NLSP masses while LHC limits restrict the mass ranges from below.
- LHC exclusion bound strongly depends on EW gaugino composition. Proper recasting of ATLAS/CMS analysis relaxes the existing bound.
- Searches at future lepton colliders i.e. ILC (1 TeV) will be conclusive.
- The light EW sector consistent with muon (g-2), DM and LHC can contribute to the W-mass up to maximum 25 MeV. The slepton coannihilation (case-L) and Wino DM scenario give the largest contribution to MW.
- If the W-mass anomaly persists in future with a substantially large deviation from the current PDG value, an analysis including the light stop/sbottom sector will be necessary.

THANK YOU!

W-Mass and CDF-II Anomaly





Science 376, 170–176 (2022)

JHEP 01 (2022) 036

SUSY contributions to $(g-2)_\mu$

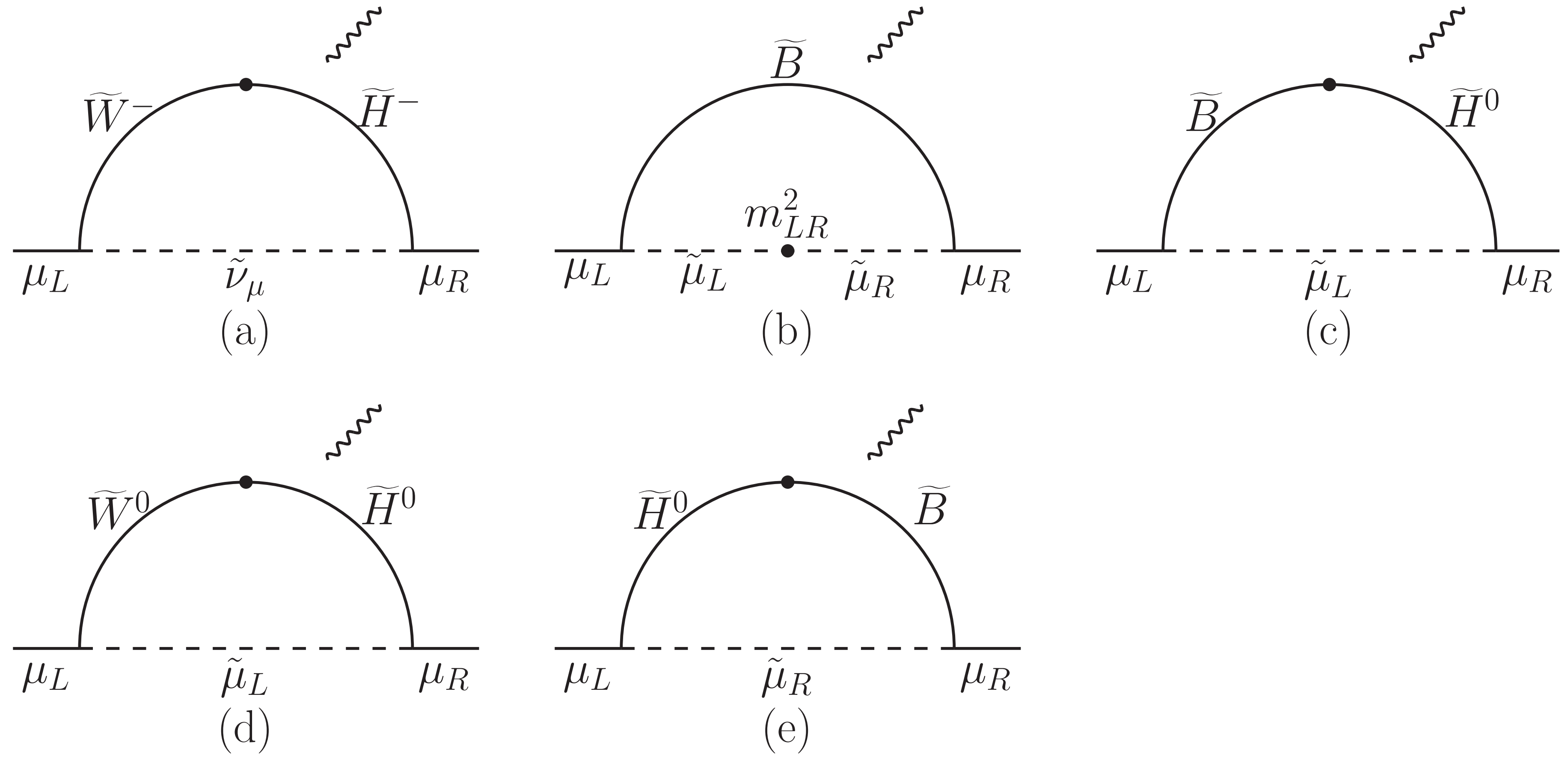
$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\nu}_\mu) \simeq \quad 15 \quad \times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\mu}_L) \simeq -2.5 \quad \times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_L) \simeq \quad 0.76 \times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_R) \simeq -1.5 \quad \times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L,\tilde{\mu}_R,\tilde{B}) \simeq \quad 1.5 \quad \times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2/M_1\mu}\right)\left(\frac{f_N}{1/6}\right).$$



Endo, Hamaguchi, Iwamoto, Yoshinaga'13

Lattice result