

DM Direct Detection and Collider Search Complementarity

BASED ON :

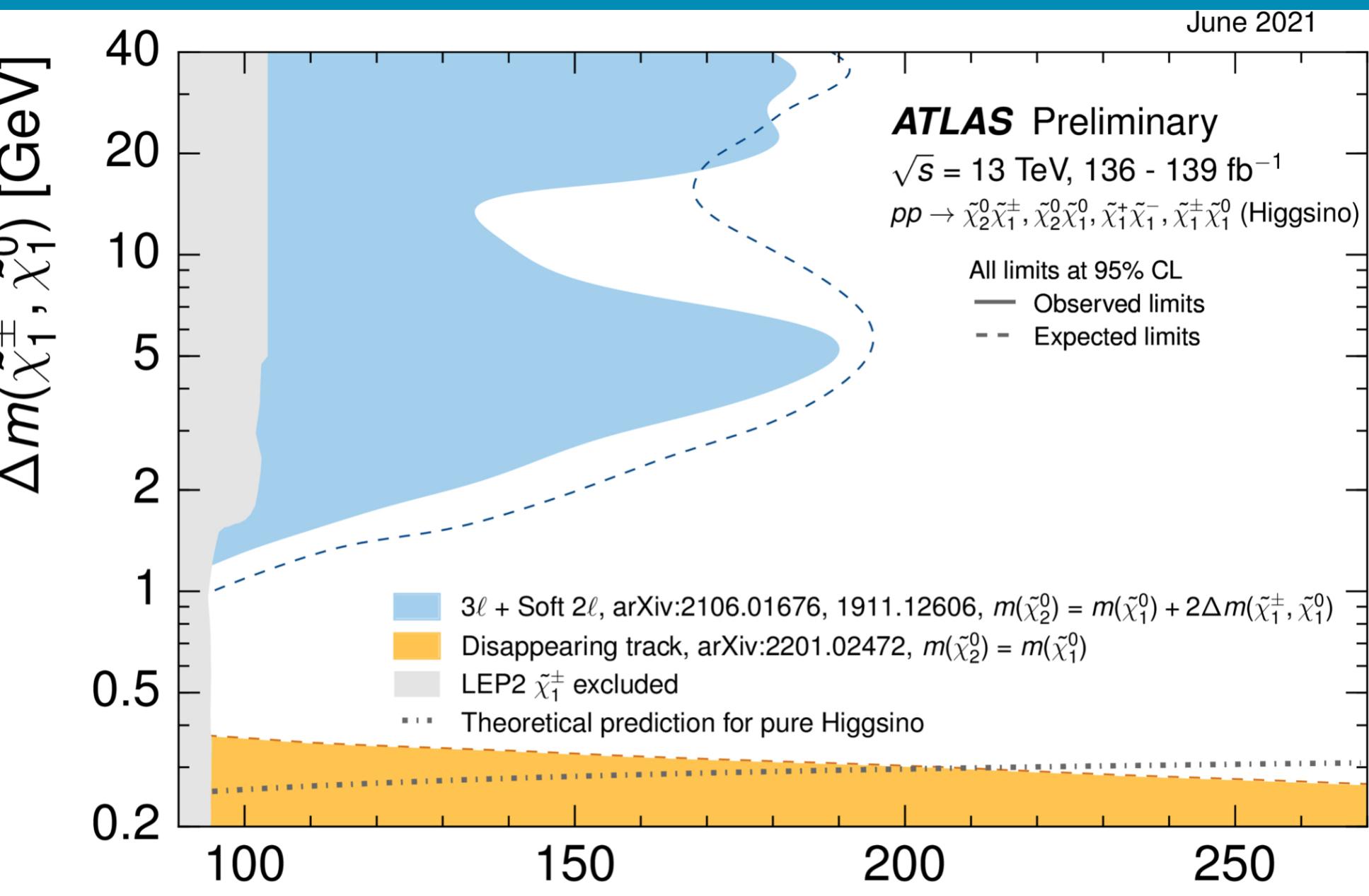
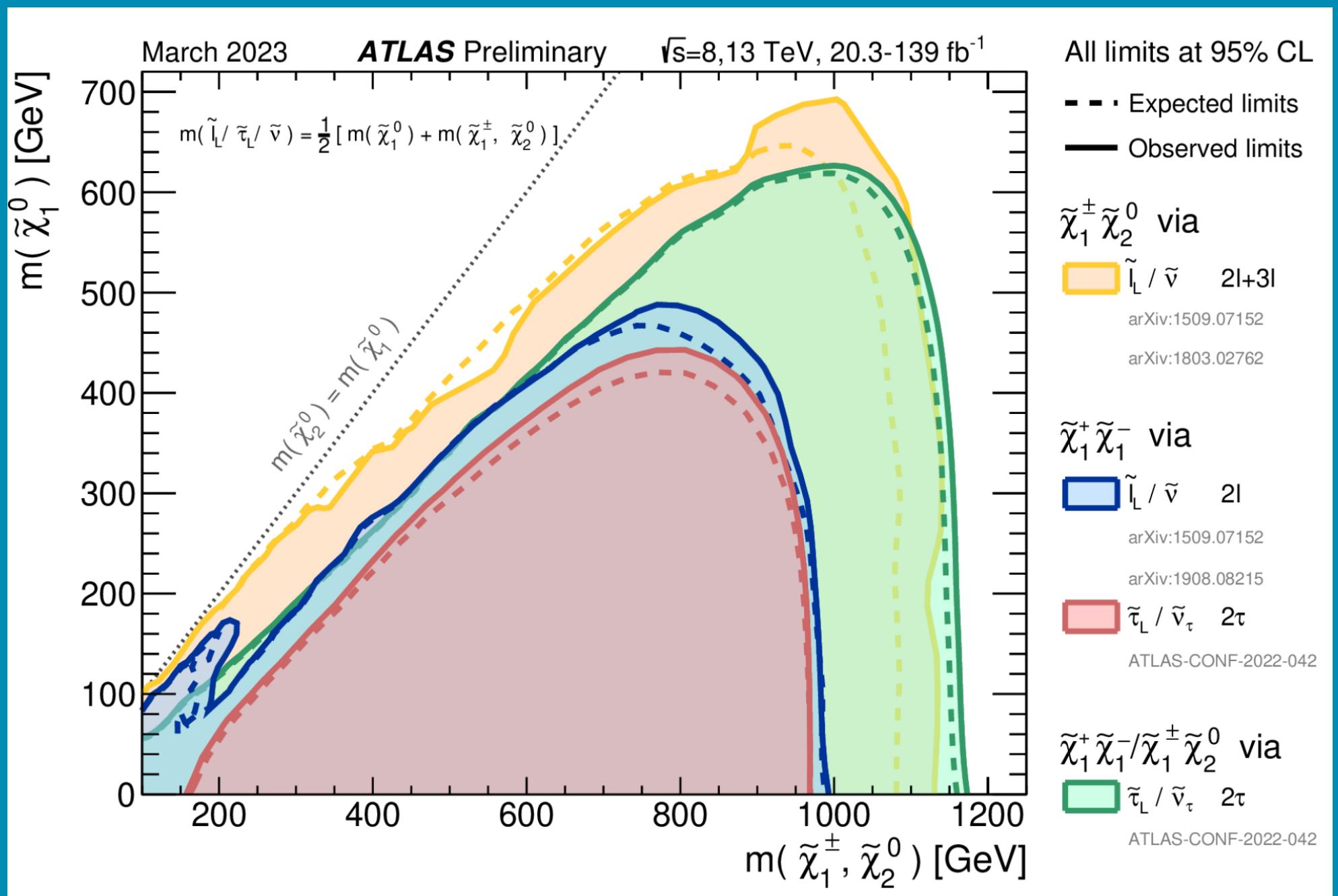
EPJC 81 (2021) 12, 1114, EPJC 82 (2022) 5, 423

WITH S. HEINEMEYER (IFT, MADRID), I. SAHA (U. ALLAHABAD) & C. SCHAPPACHER (KIT, KARLSRUHE)

- MSSM EW sector may be hiding key to new physics

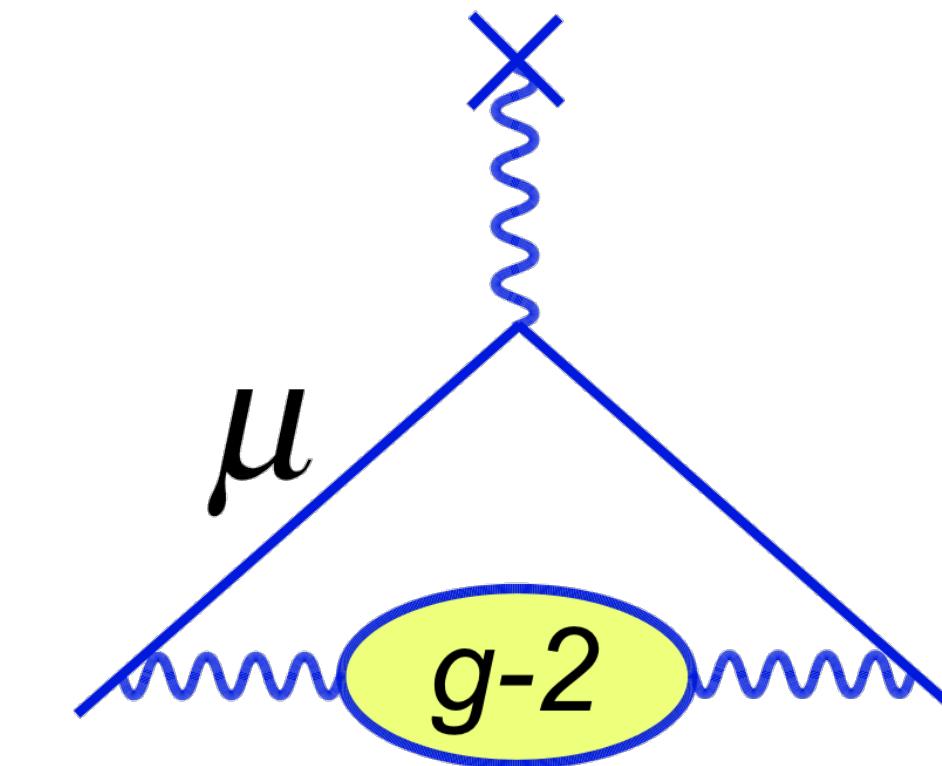
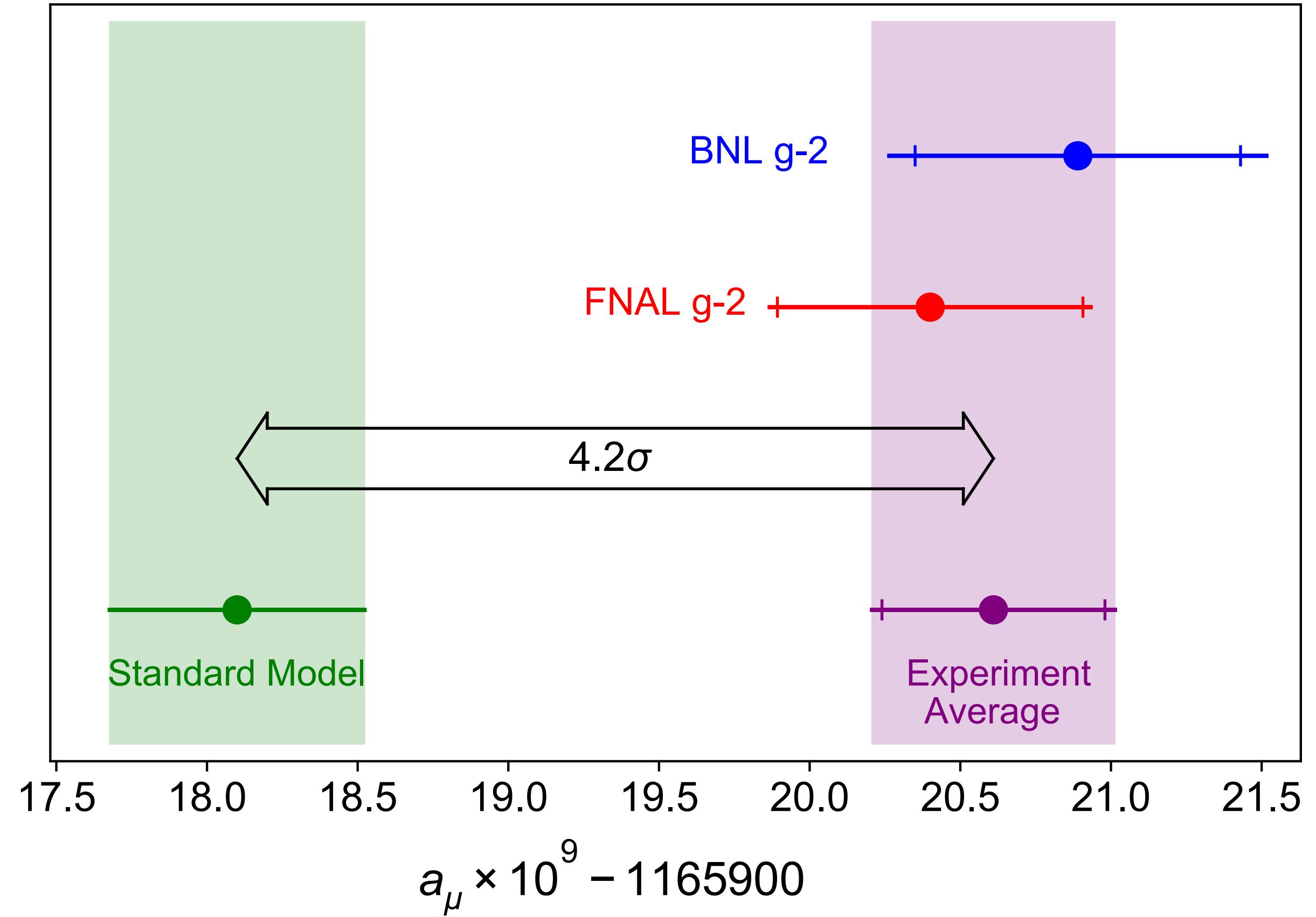
- Modest production cross section, mass bounds from the LHC allows sub-TeV superpartners

- May show up elsewhere : DM experiments, $(g - 2)_\mu$
- New results from Fermilab ‘MUON (g-2)’



Muon (g-2) anomaly

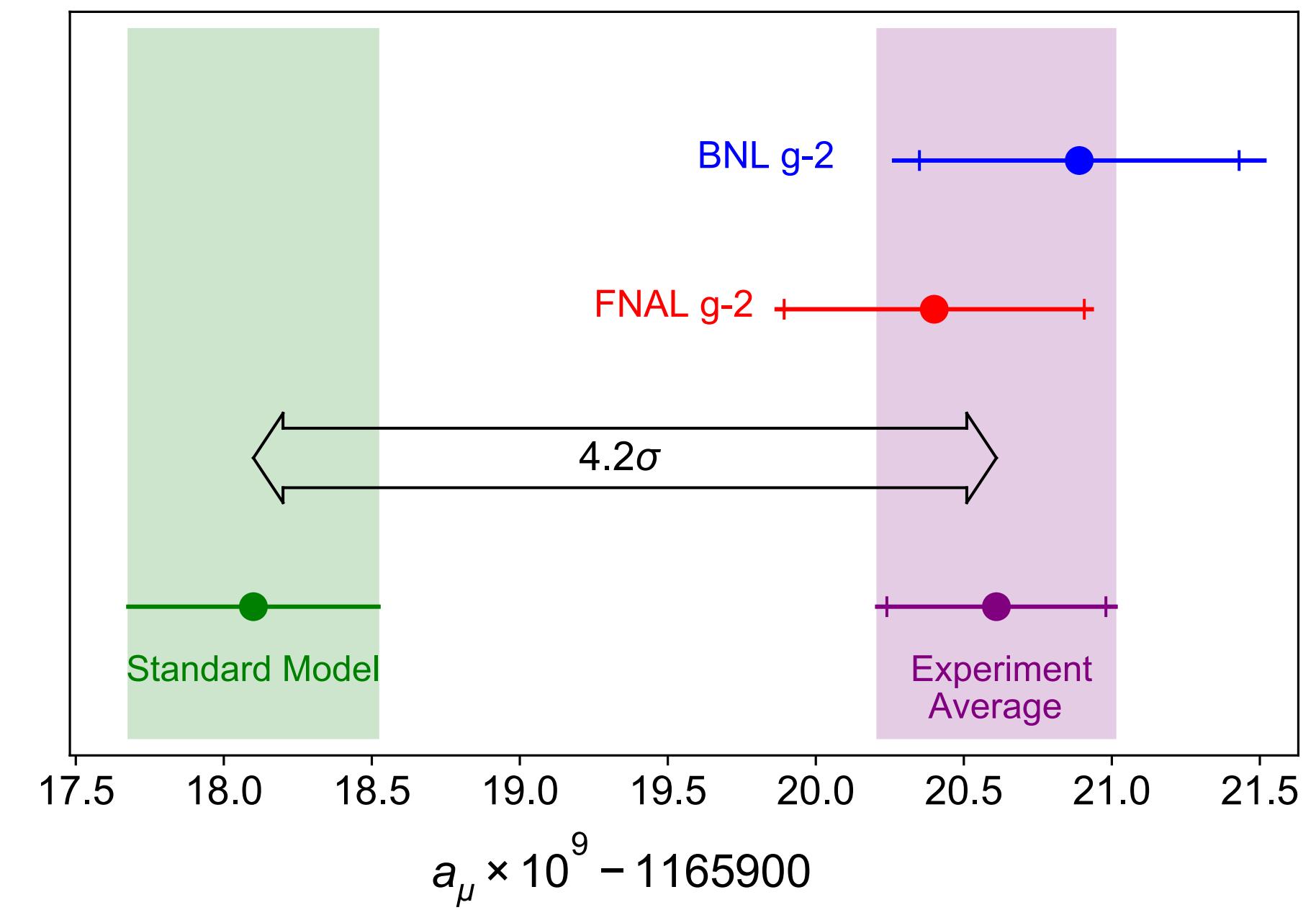
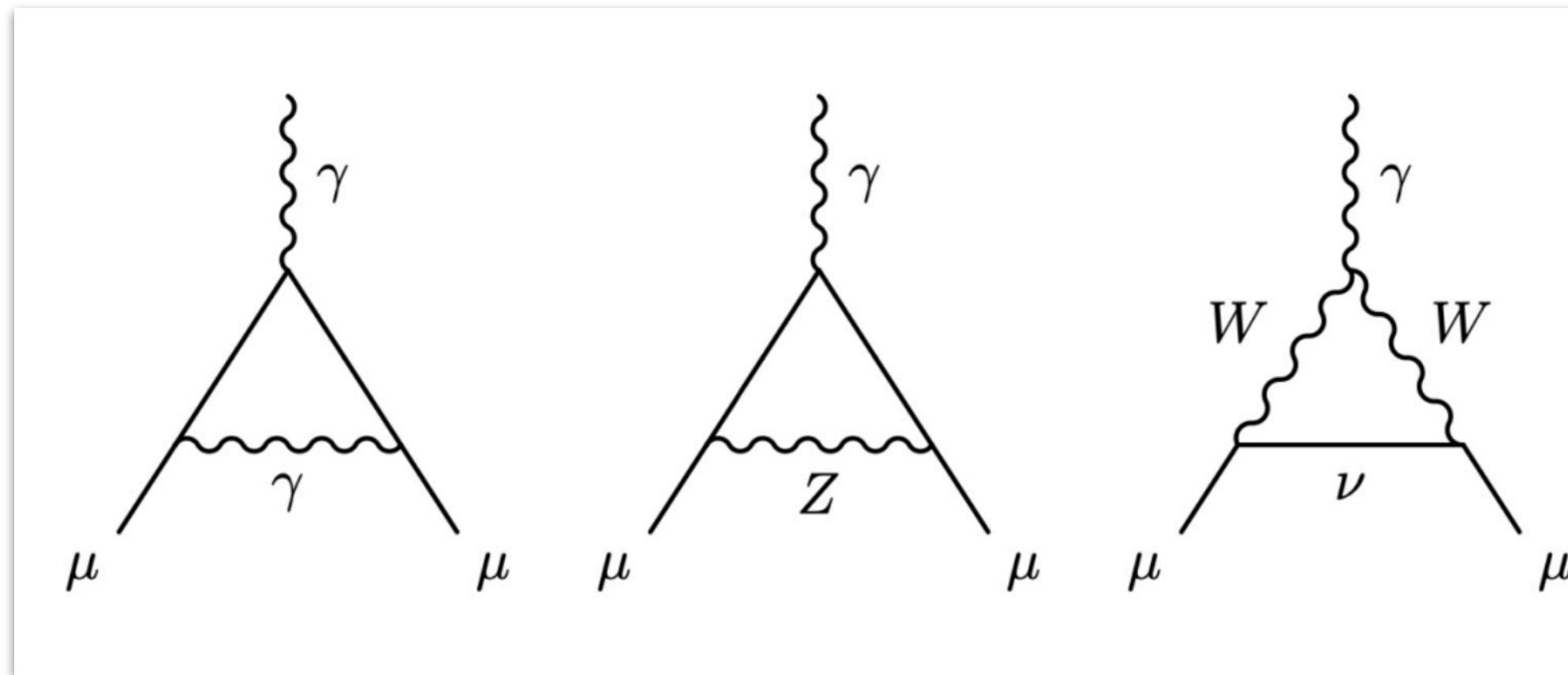
$$a_{\mu}^{exp} - a_{\mu}^{theo,SM} = (25.1 \pm 5.9) \times 10^{-10}$$



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

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

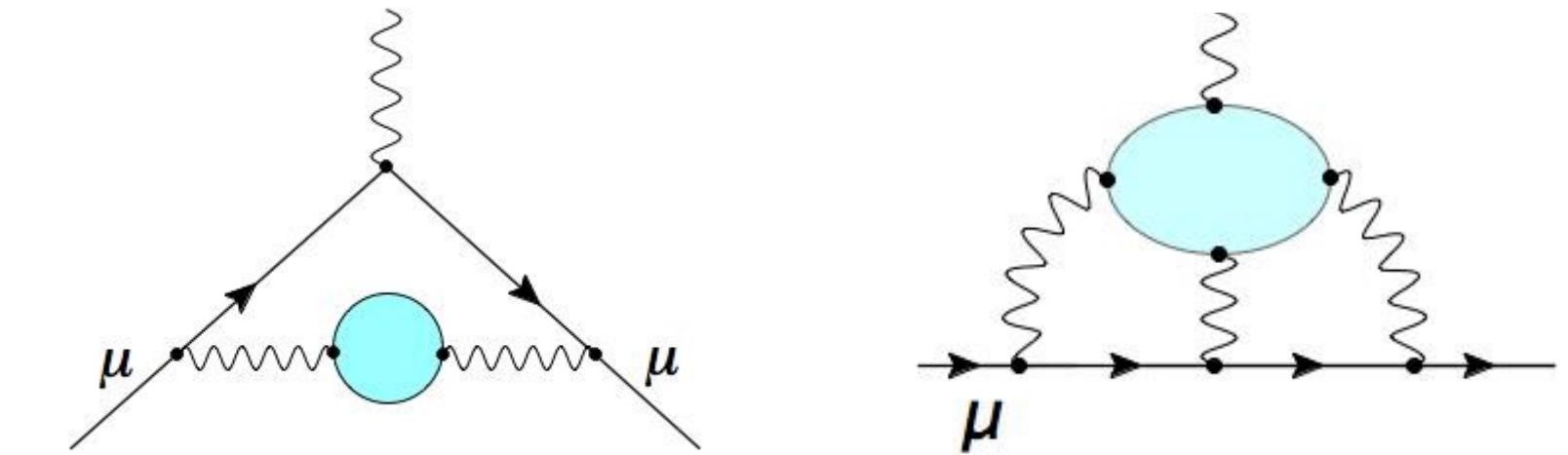
Muon (g-2) anomaly



	QED	HVP	EW	
a_μ^{theo}	0.00	1165	91	810 (43)
a_μ^{exp}	0.00	1165	92	061 (41)

from HVP, HLbL

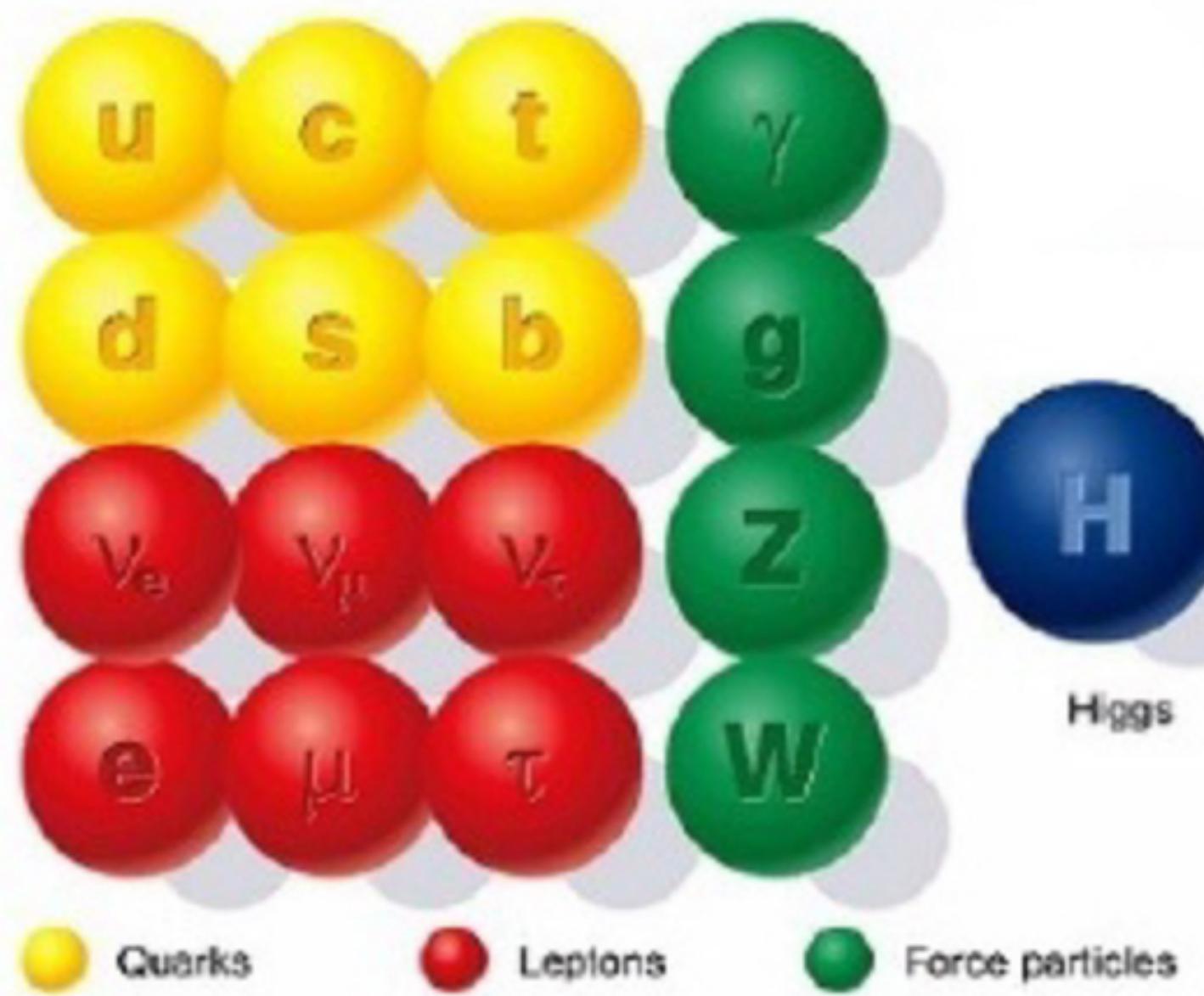
stat err dominant



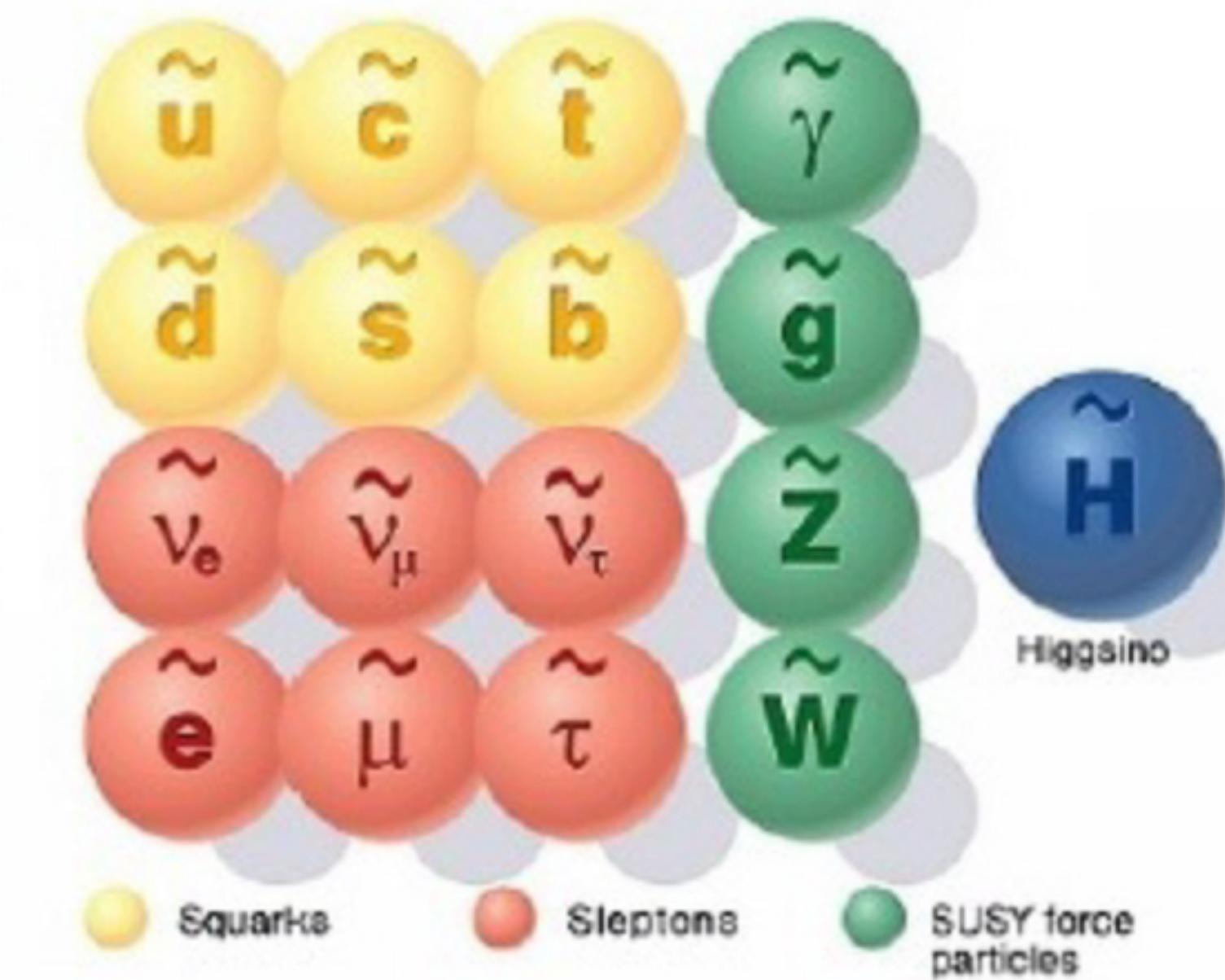
$$a_\mu^{\text{exp}} - a_\mu^{\text{theo}} \simeq (25 \pm 6) \times 10^{-10} \simeq \Delta a_\mu^{\text{BSM}} ?$$

MSSM particle content

SUPERSYMMETRY



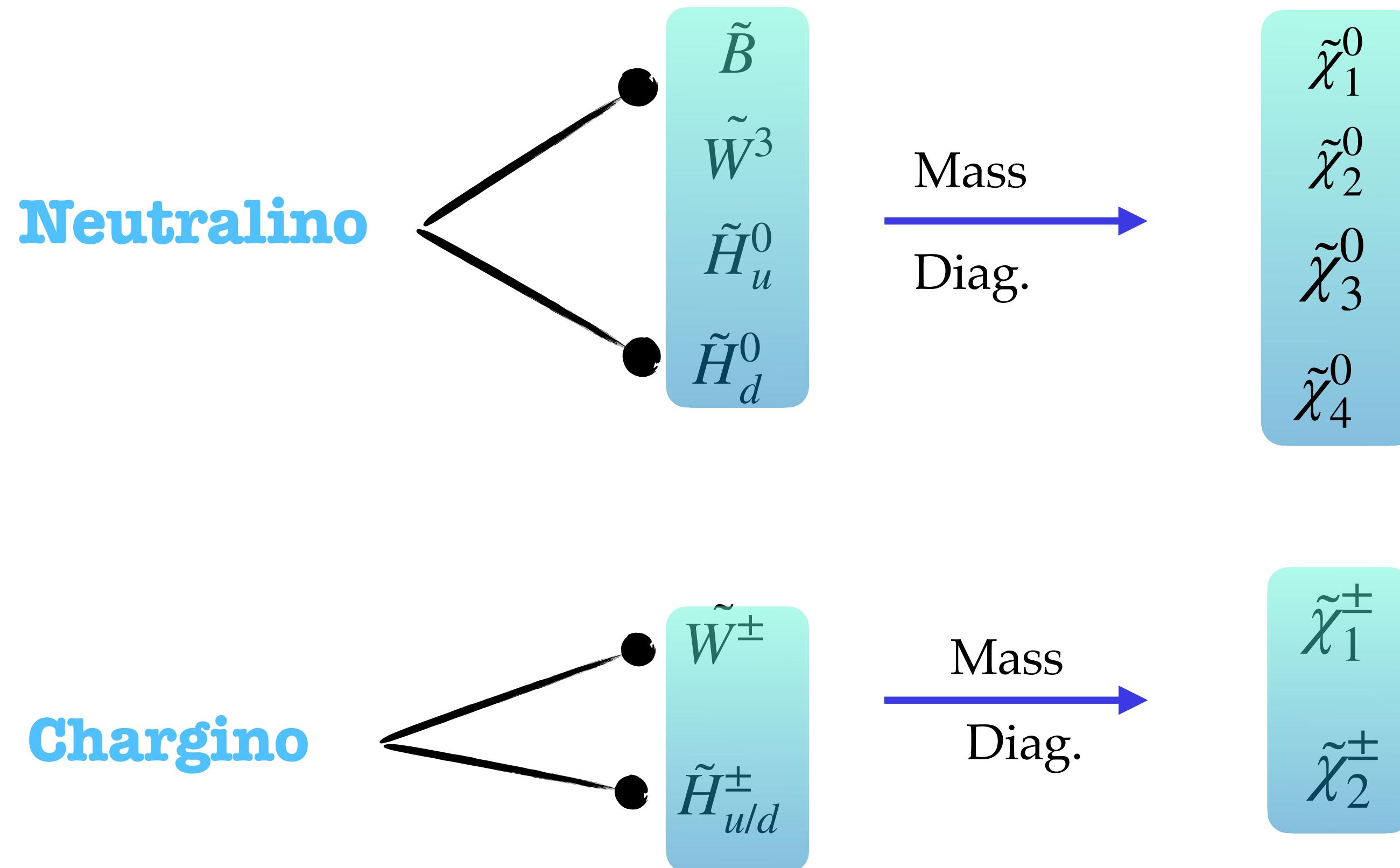
Standard particles



SUSY particles

EW Gauginos

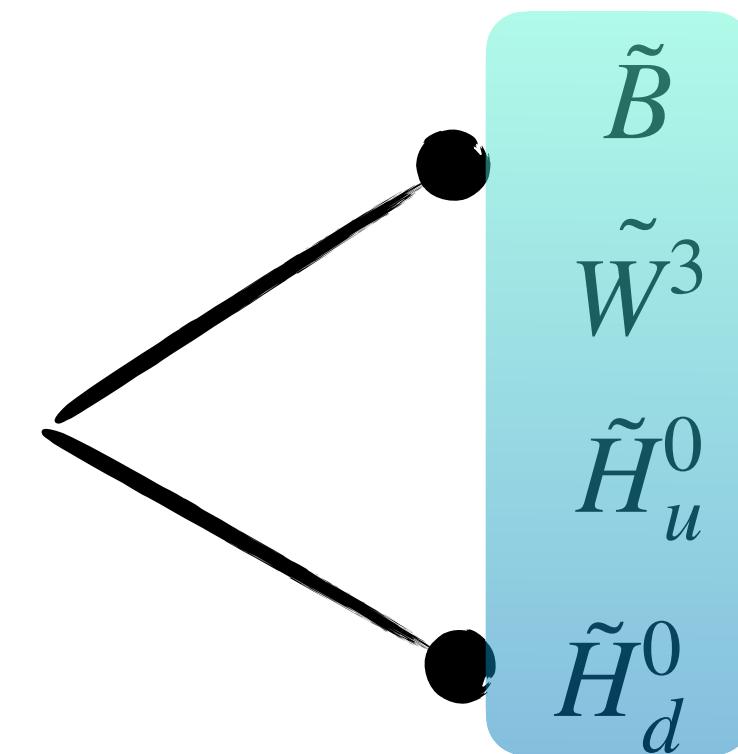
Masses and mixing are determined by U(1) and SU(2) gaugino masses M_1, M_2 and Higgsino mass parameter μ .



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



Neutralino Mass Matrix

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

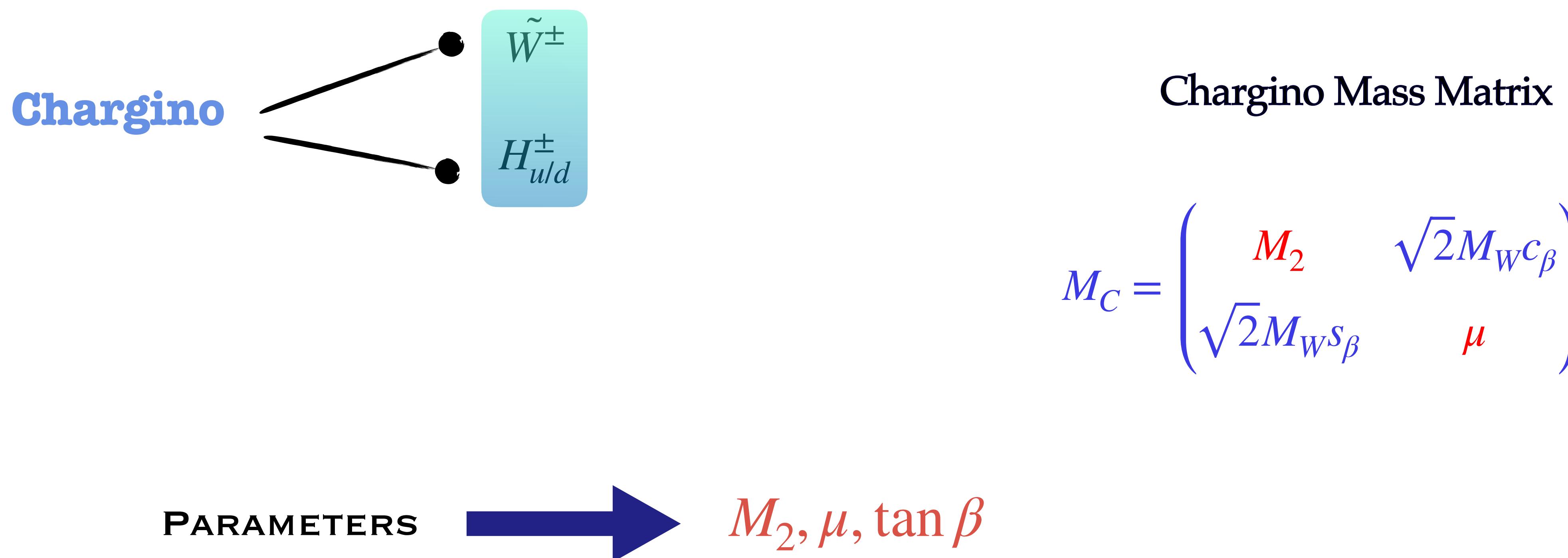
FOUR PARAMETERS



$M_1, M_2, \mu, \tan \beta$

EW Gauginos

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



Sleptons

Slepton Mass Matrix

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

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

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

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

PARAMETERS



$m_{\tilde{L}}, m_{\tilde{R}}, \mu, \tan \beta$

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

Muon (g-2) in MSSM

$$\mathcal{L}_{\text{eff}} \ni i\tilde{a}_\mu \cdot \bar{\psi}_{\textcolor{red}{L}} \sigma^{\mu\nu} \psi_{\textcolor{blue}{R}} F_{\mu\nu}$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo}} \simeq (25 \pm 6) \times 10^{-10} \sim \mathcal{O}(\Delta a_\mu^{\text{SM,EW}})$$

We need **very light BSM particles** OR **enhancement from couplings**

$$\Delta a_\mu^{\text{BSM}} \sim \Delta a_\mu^{\text{SM,EW}} \cdot \left(\frac{m_W^2}{m_{\text{BSM}}^2} \right) \cdot \left(\frac{g_{\text{BSM}}}{g_{\text{SM}}} \right)$$

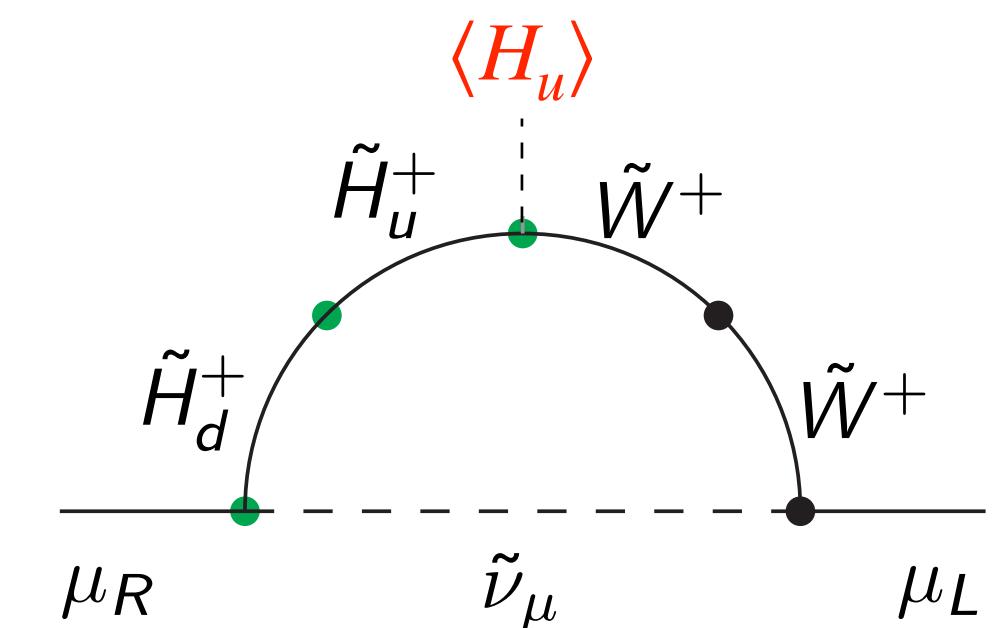
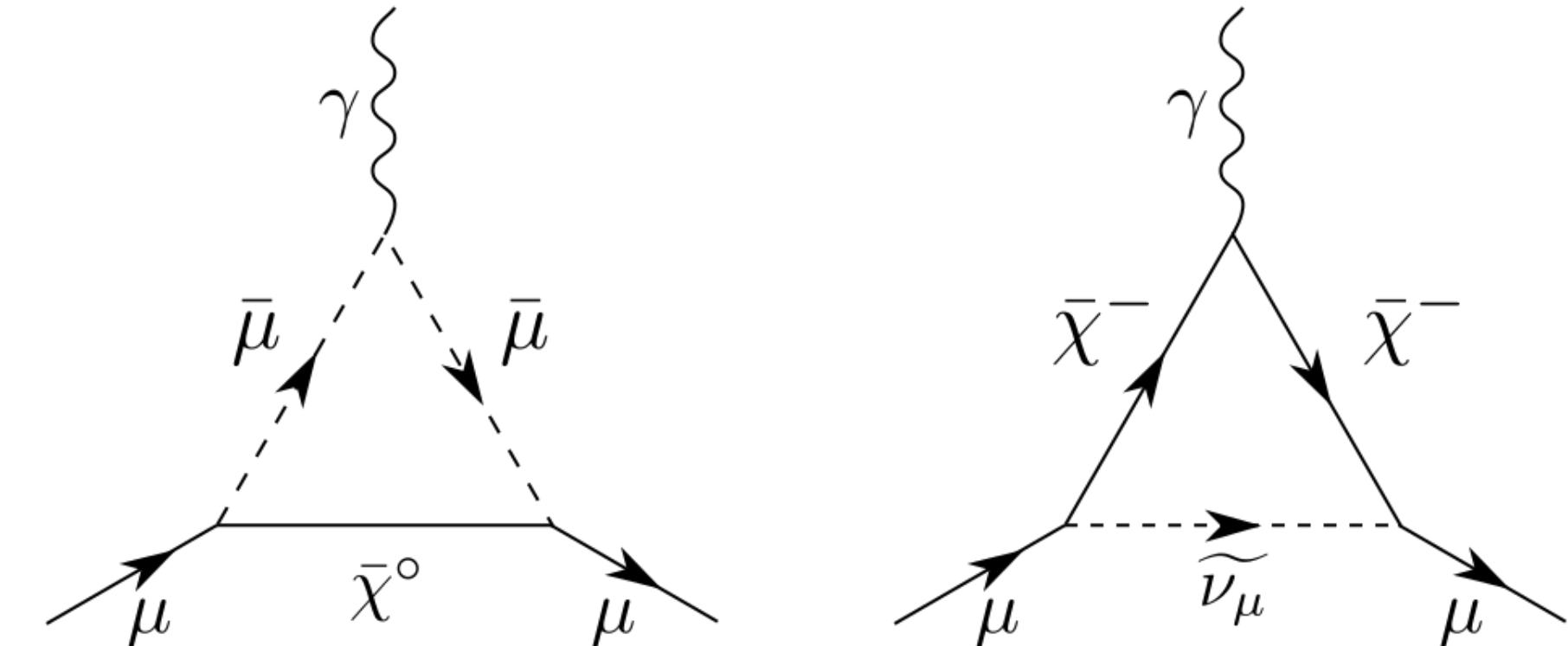
$$\text{SM EW 1 loop : } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}.$$

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

SUSY can easily explain anomaly !

$$\tan\beta \in [5 - 60] \rightarrow$$

$$m_{\text{SUSY}} \in [200 - 600] \text{ GeV}$$



Constraints

Direct Searches at LHC

LHC searches restricted to simplified models

Proper recasting is important

checkMATE

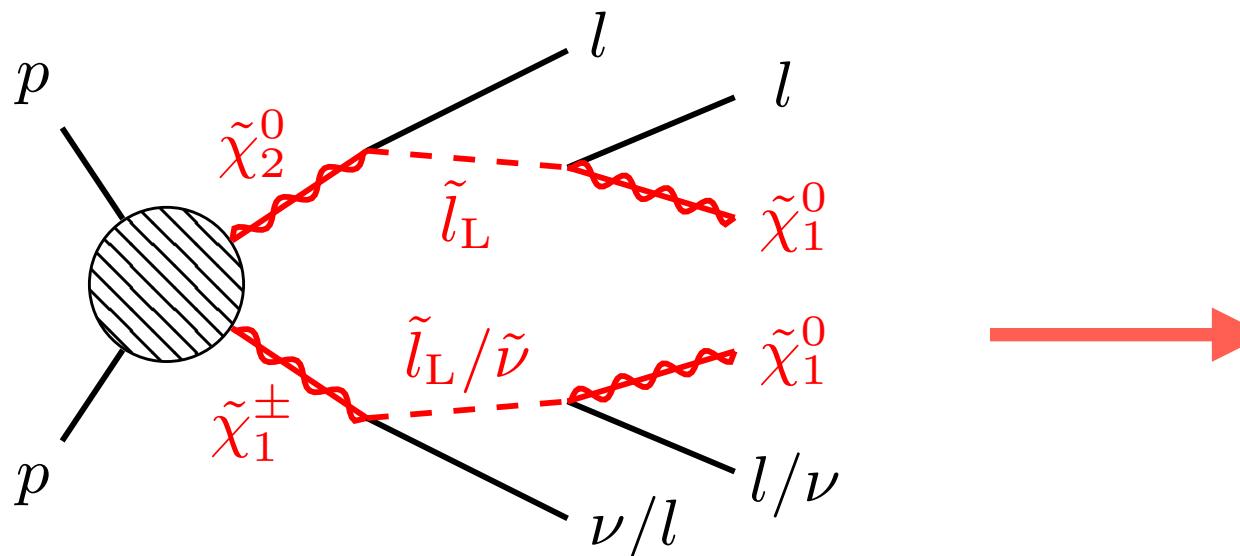
Indirect Constraints

- Muon ($g-2$).
- WMAP/PLANCK relic density.
- Spin independent direct detection data from XENON/LUX.

LHC searches

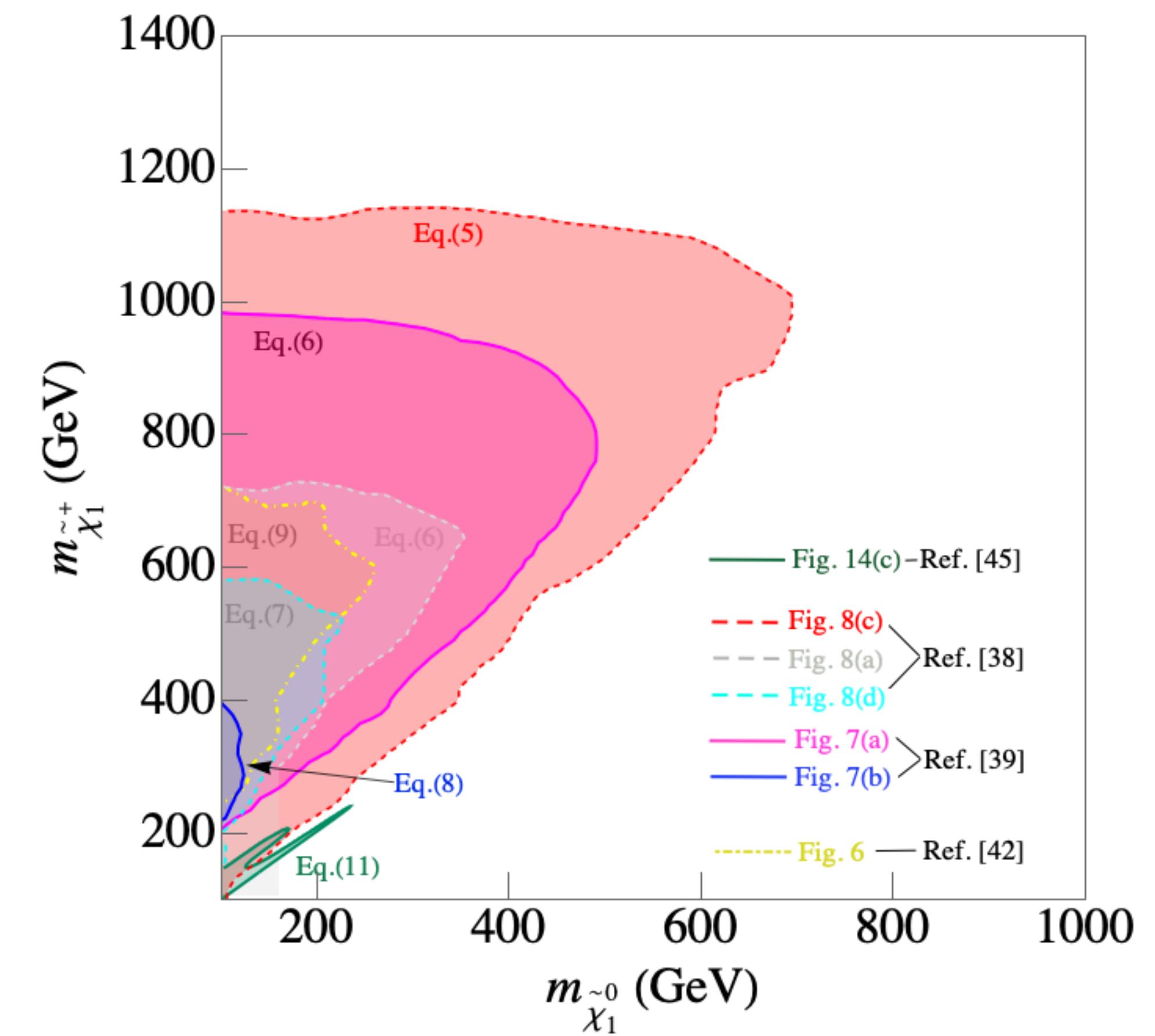
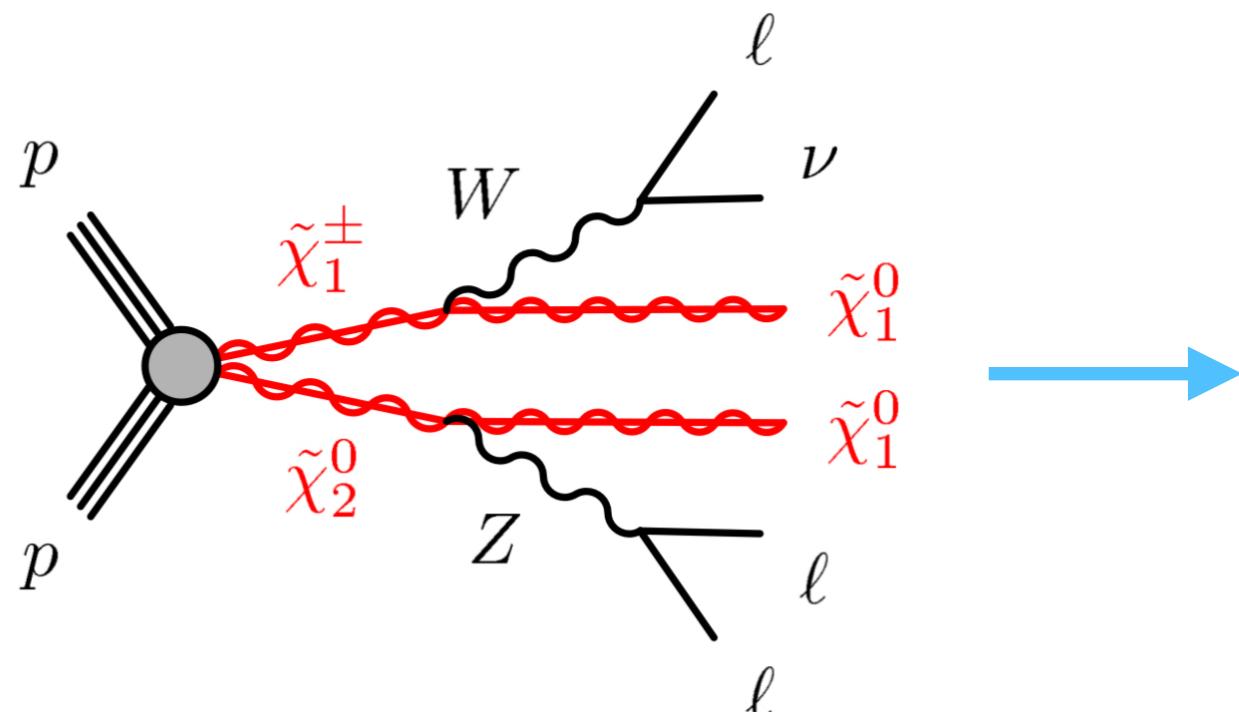
Trilepton searches

ATLAS [1803.02762]
13 TeV, 36 fb^{-1}



- Pure wino-bino scenario
- 100% BR
- $m_{\tilde{l}_L} = \frac{1}{2}(m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})$
- $m_{\tilde{l}_L} = m_{\tilde{\nu}}$
- $(\tilde{e}, \tilde{\mu}, \tilde{\tau})_L$ degenerate

Simplified models



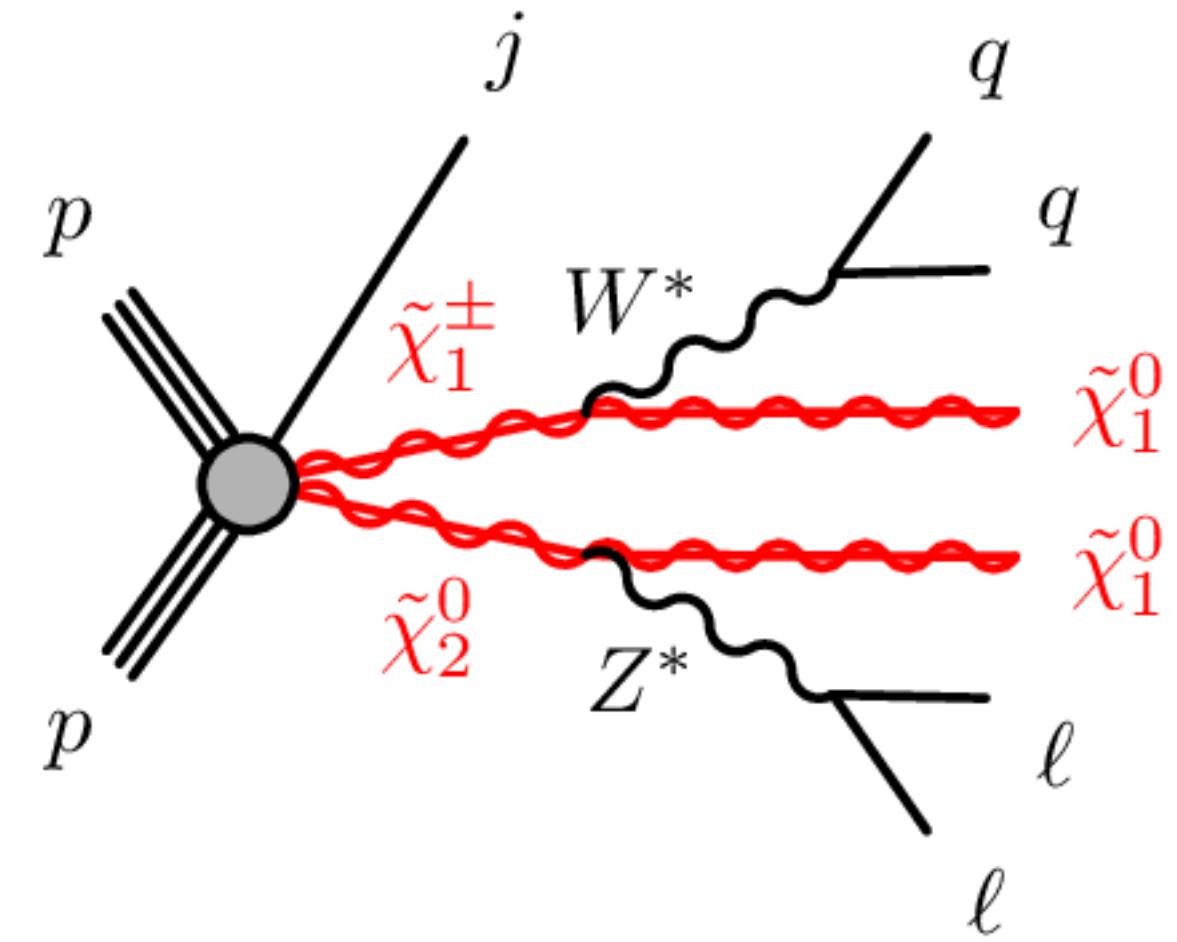
Proper recasting is important → [checkMATE](#)

LHC searches

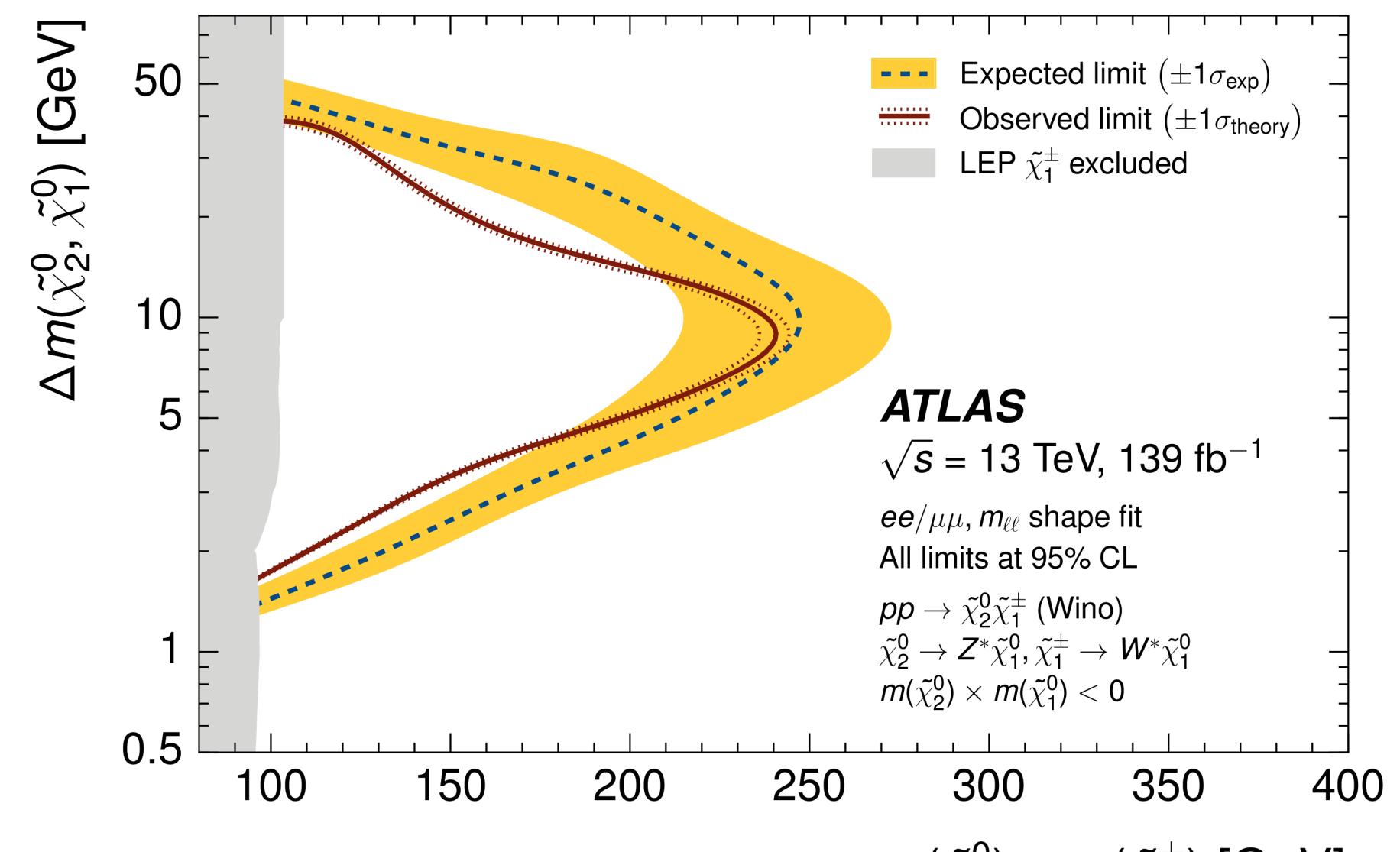
Compressed spectra searches

ATLAS 1911.12606

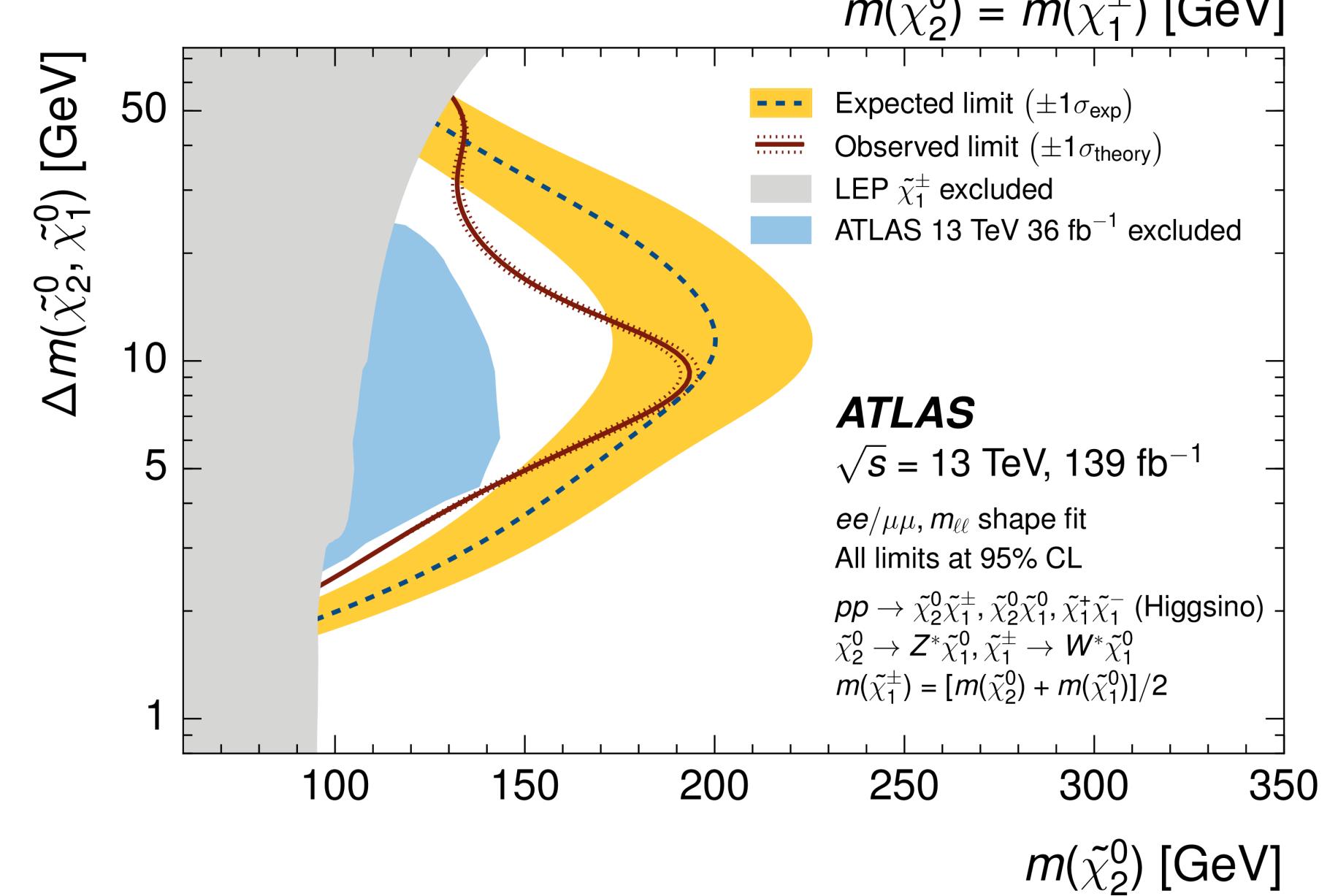
Soft leptons : ISR jet required
to give boost



Wino



Higgsino

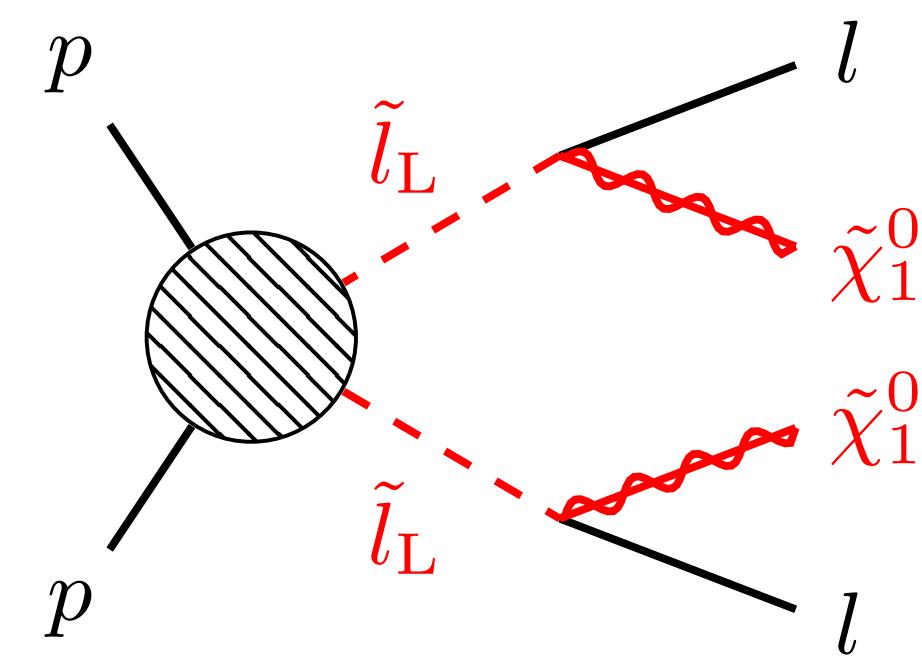


LHC searches

Slepton pair production

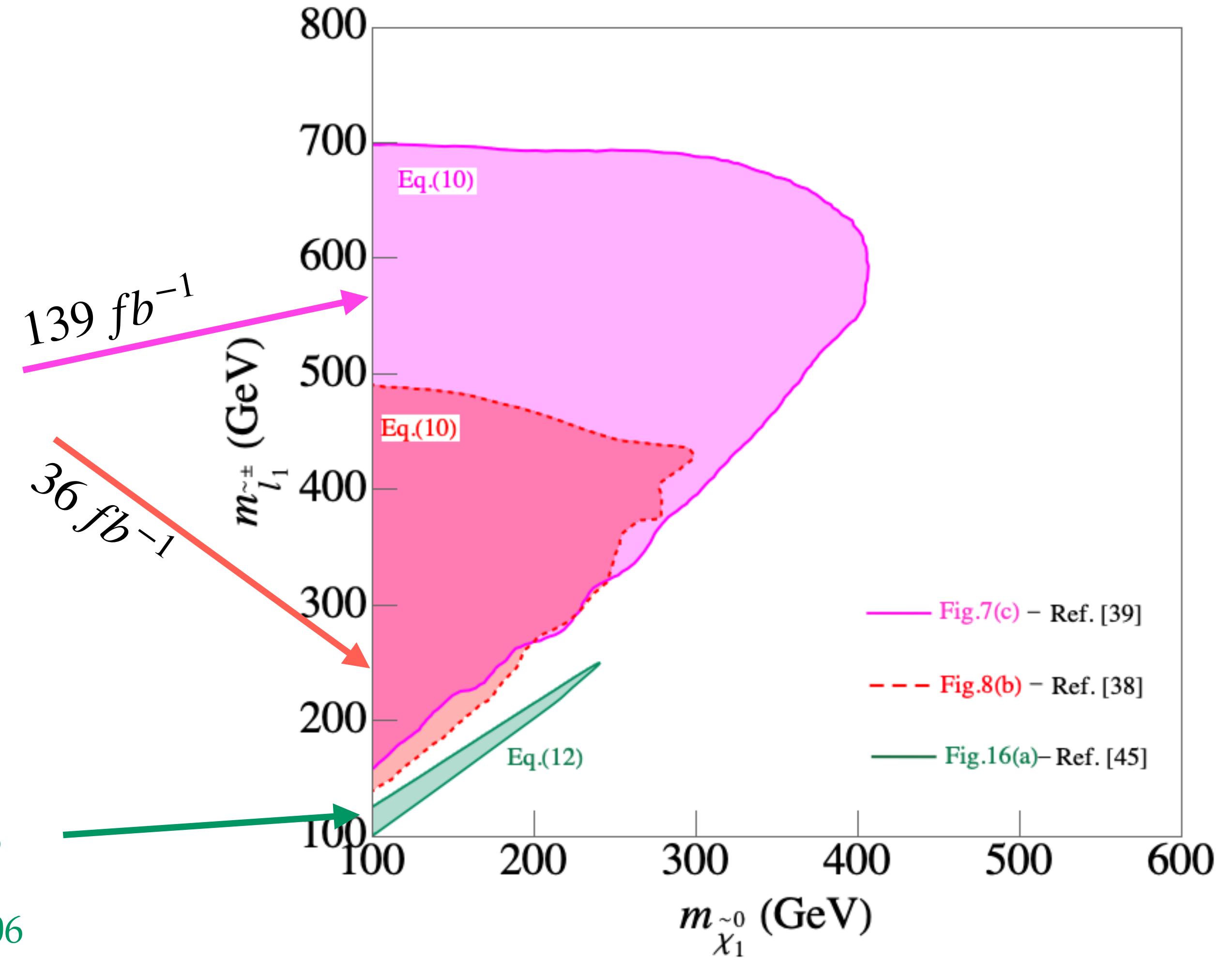
ATLAS [1908.08215]

13 TeV, 139 fb^{-1}



COMPRESSED

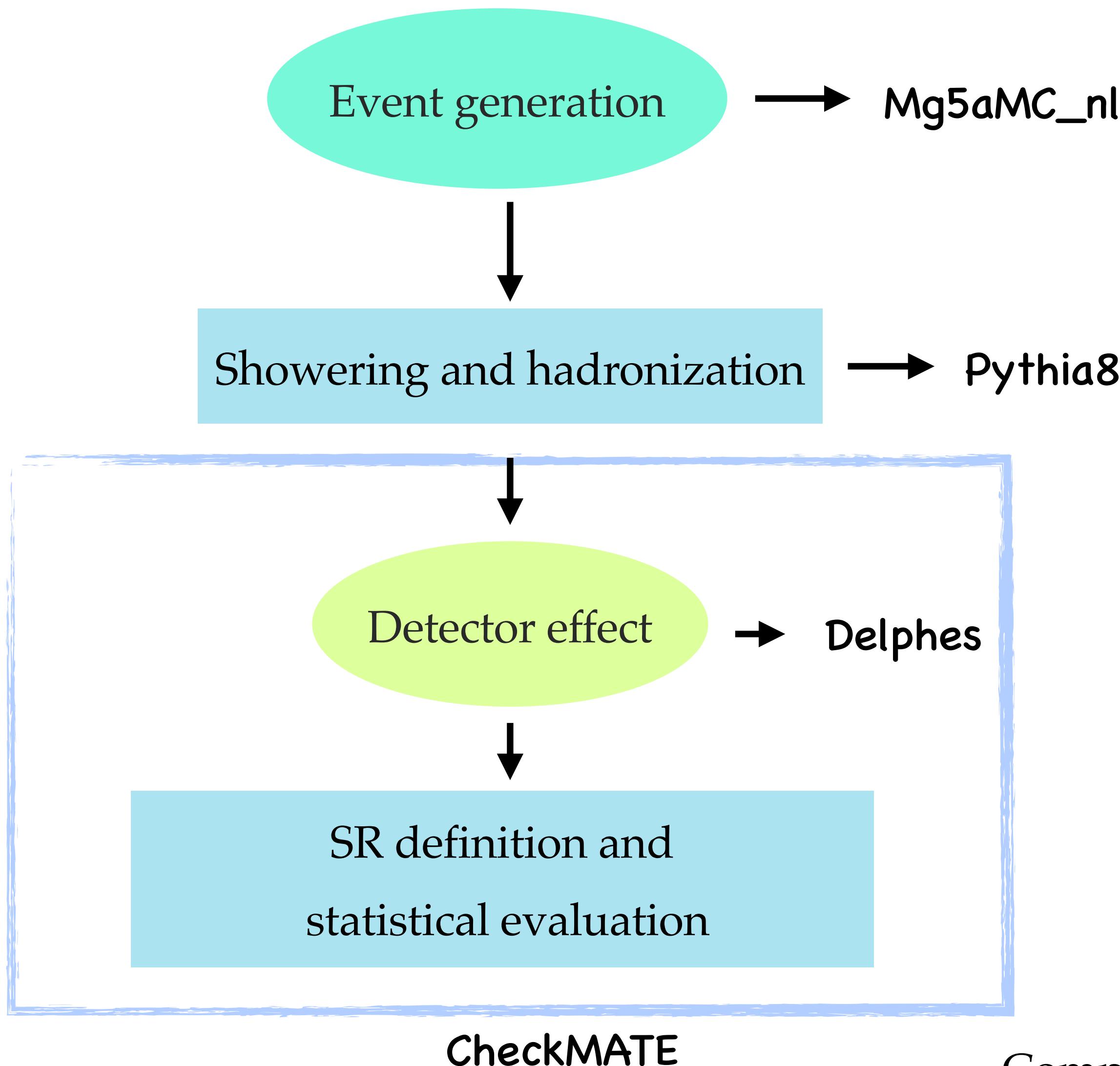
ATLAS 1911.12606



Proper recasting is important → **checkMATE**

Recasting with CM

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



Most relevant in our case

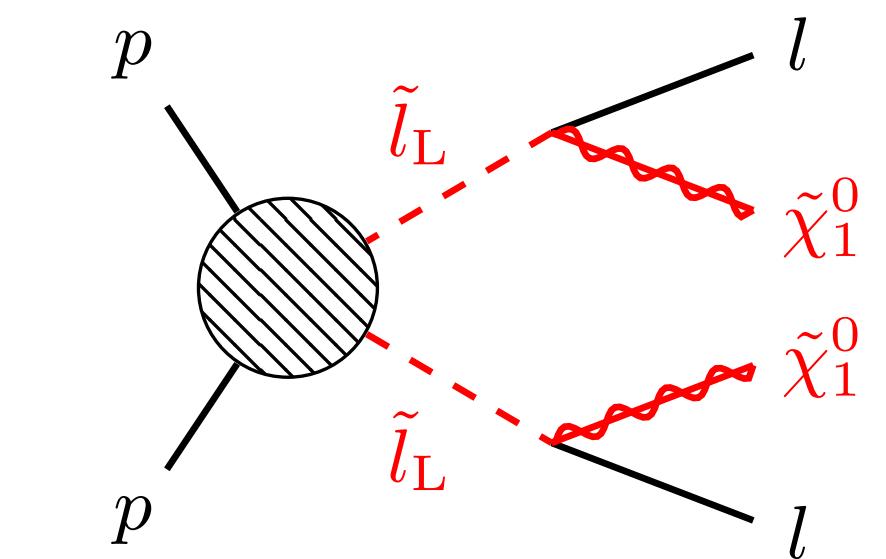
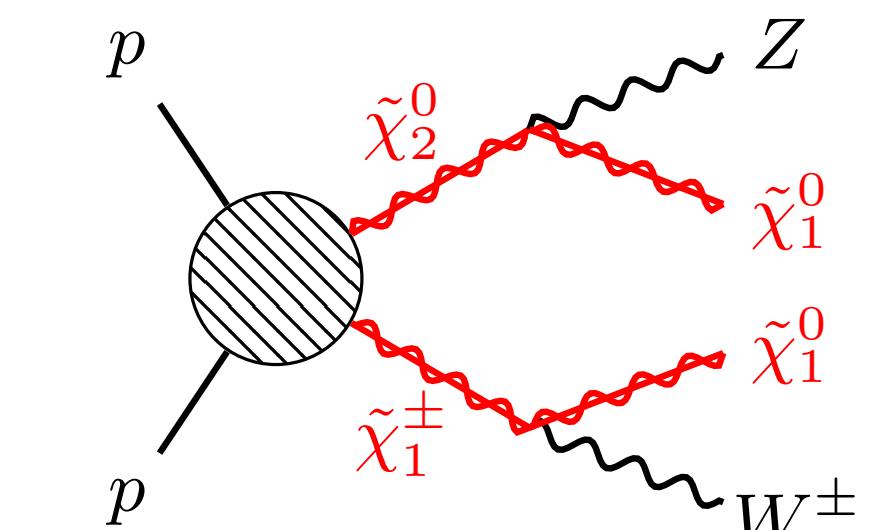
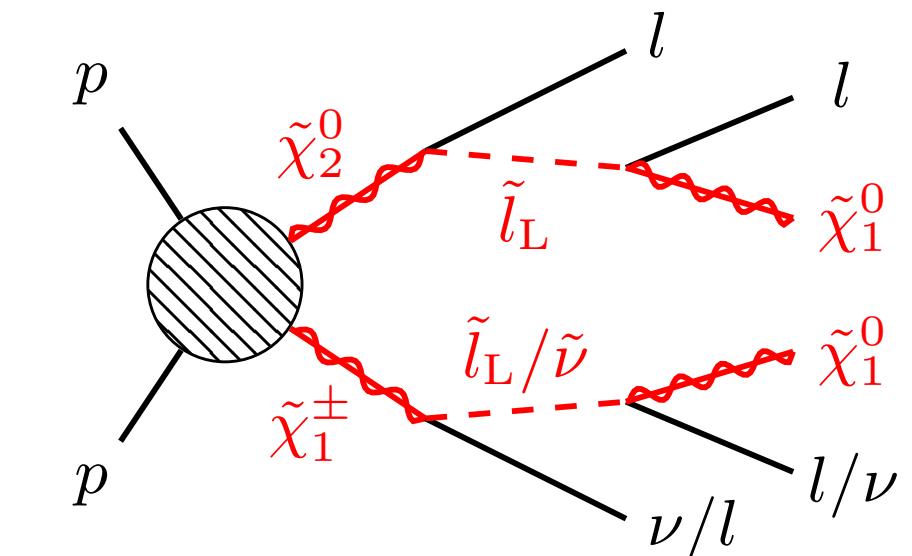
- ATLAS [1803.02762]

13 TeV, 36fb^{-1}

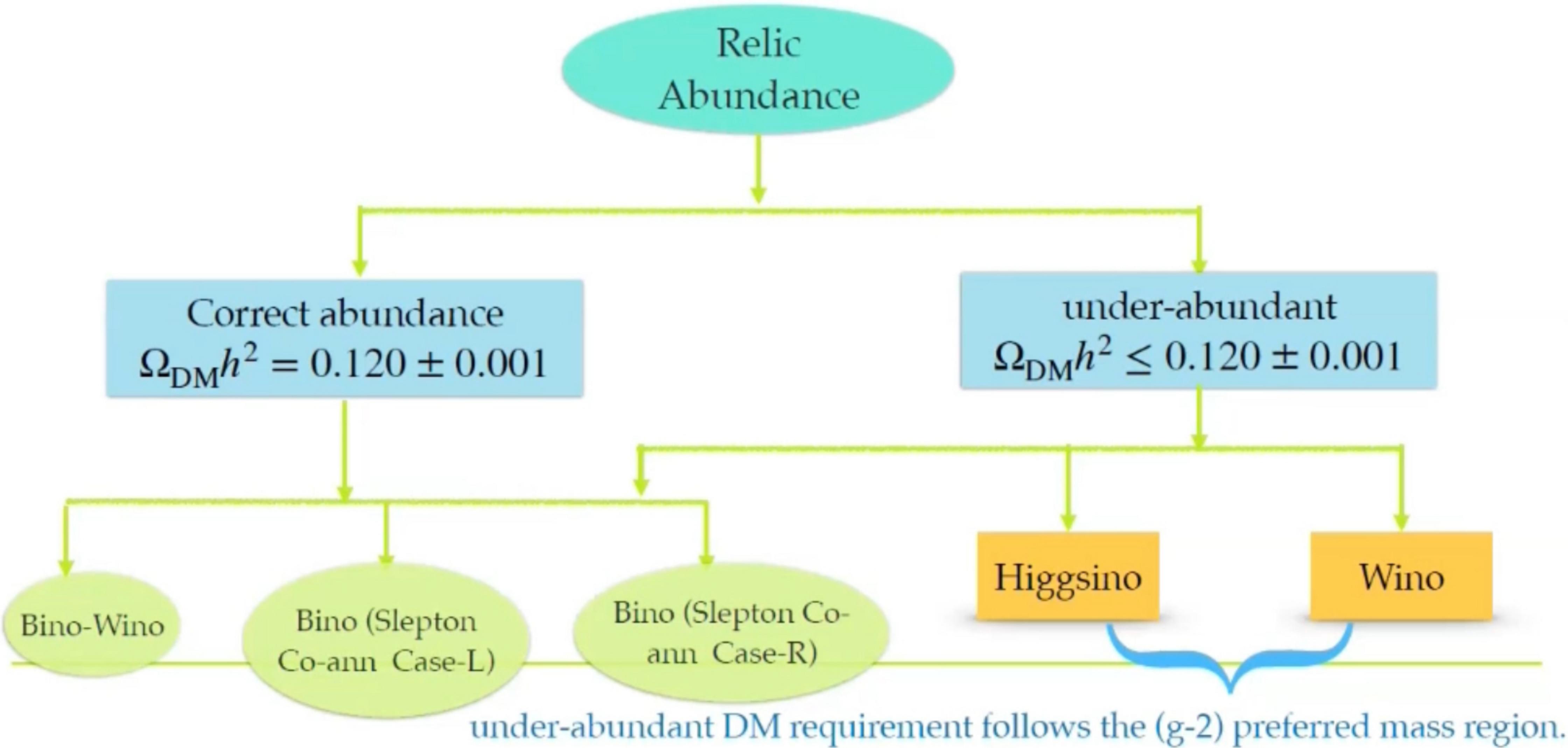
- ATLAS [1908.08215]

13 TeV, 139fb^{-1}

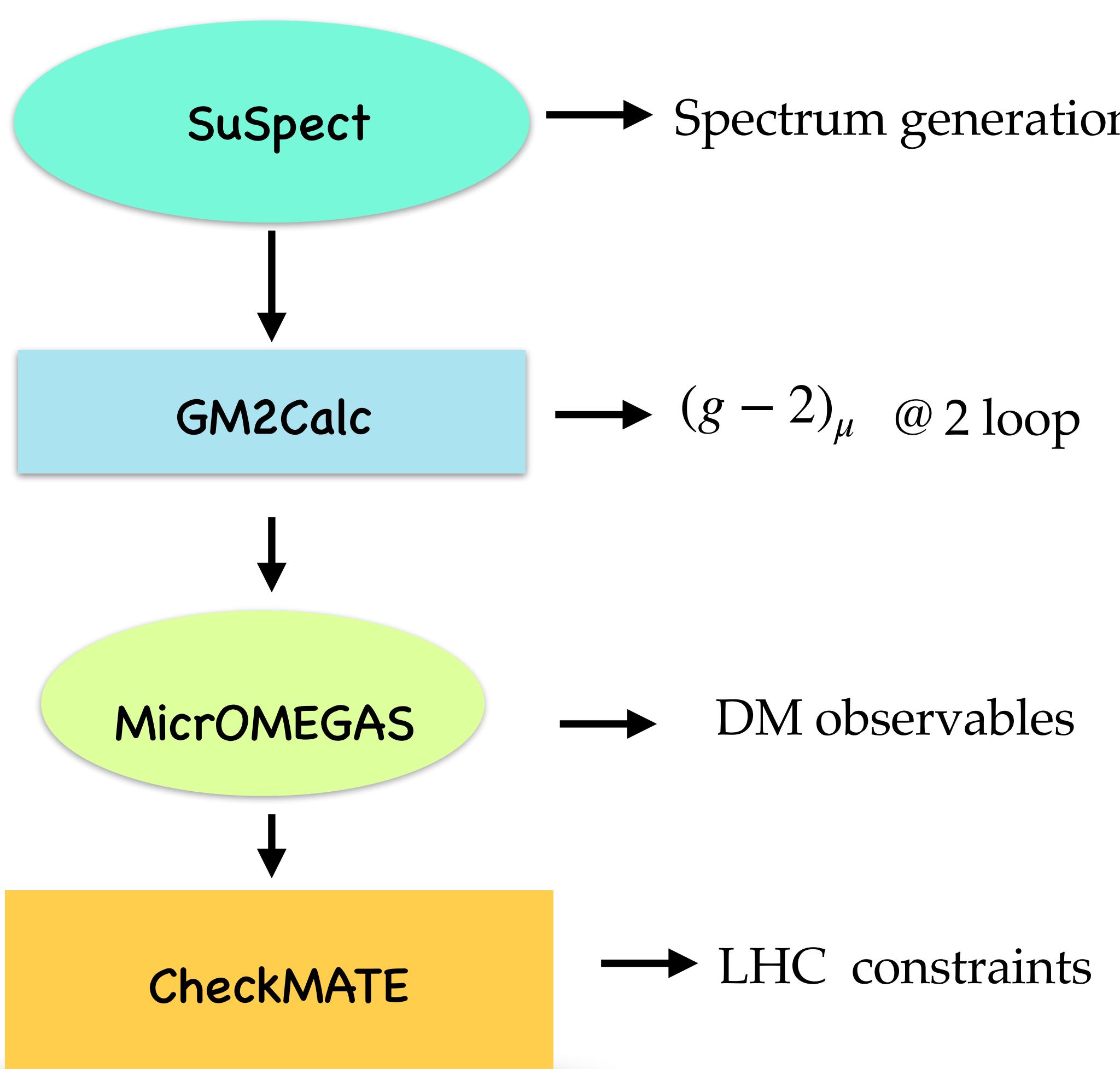
Compressed spectra searches applied directly



Classification based on DM nature

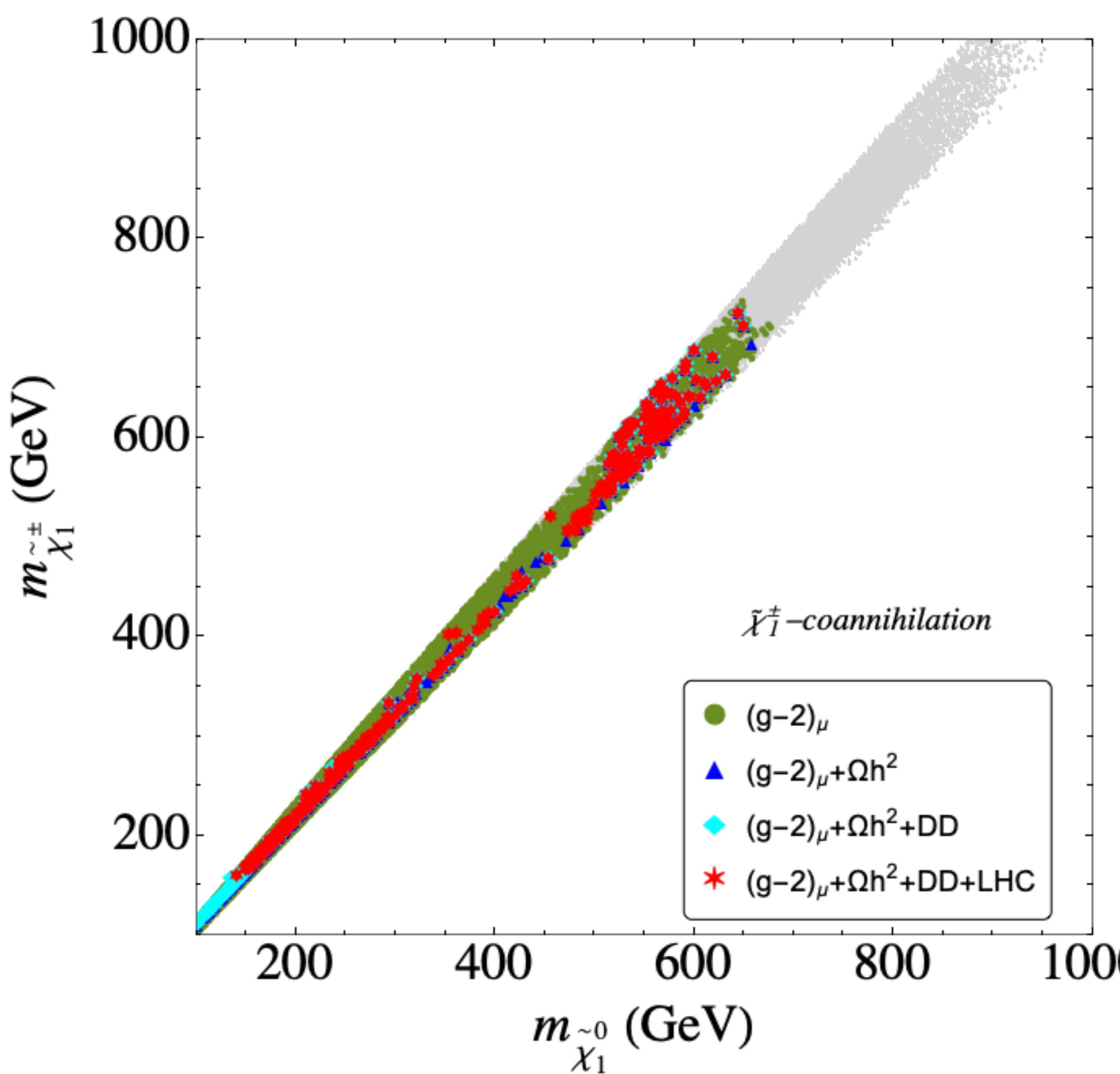


Analysis flow



- $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$
- $\Omega_{CDM} h^2 = 0.120 \pm 0.001$
- Direct detection SI bounds from XENON1T

Chargino Co-annihilation



Green: $(g - 2)_\mu$ but not DM, LHC

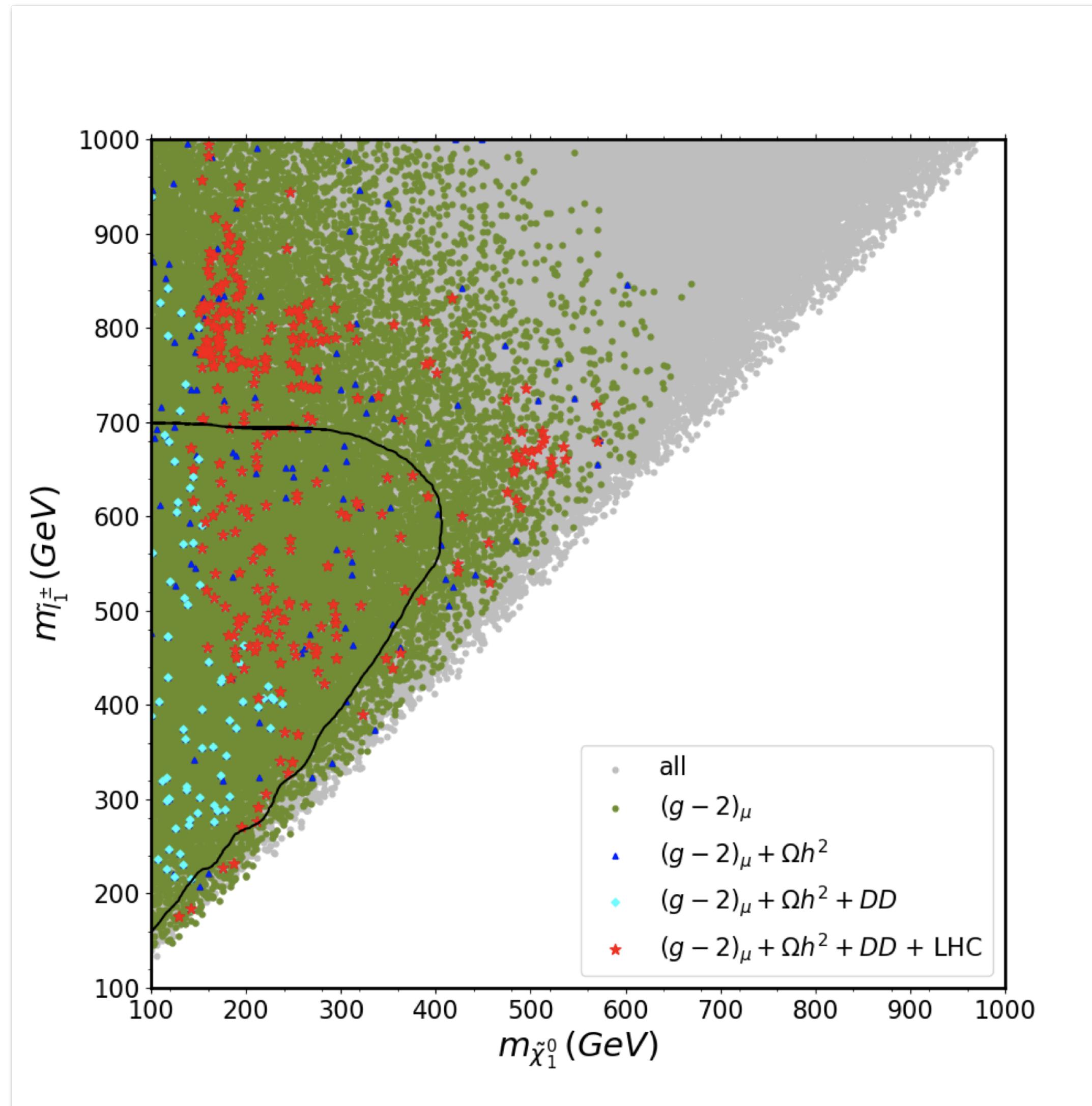
Blue: $(g - 2)_\mu + \text{DM}$, but not LHC

Red: all

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

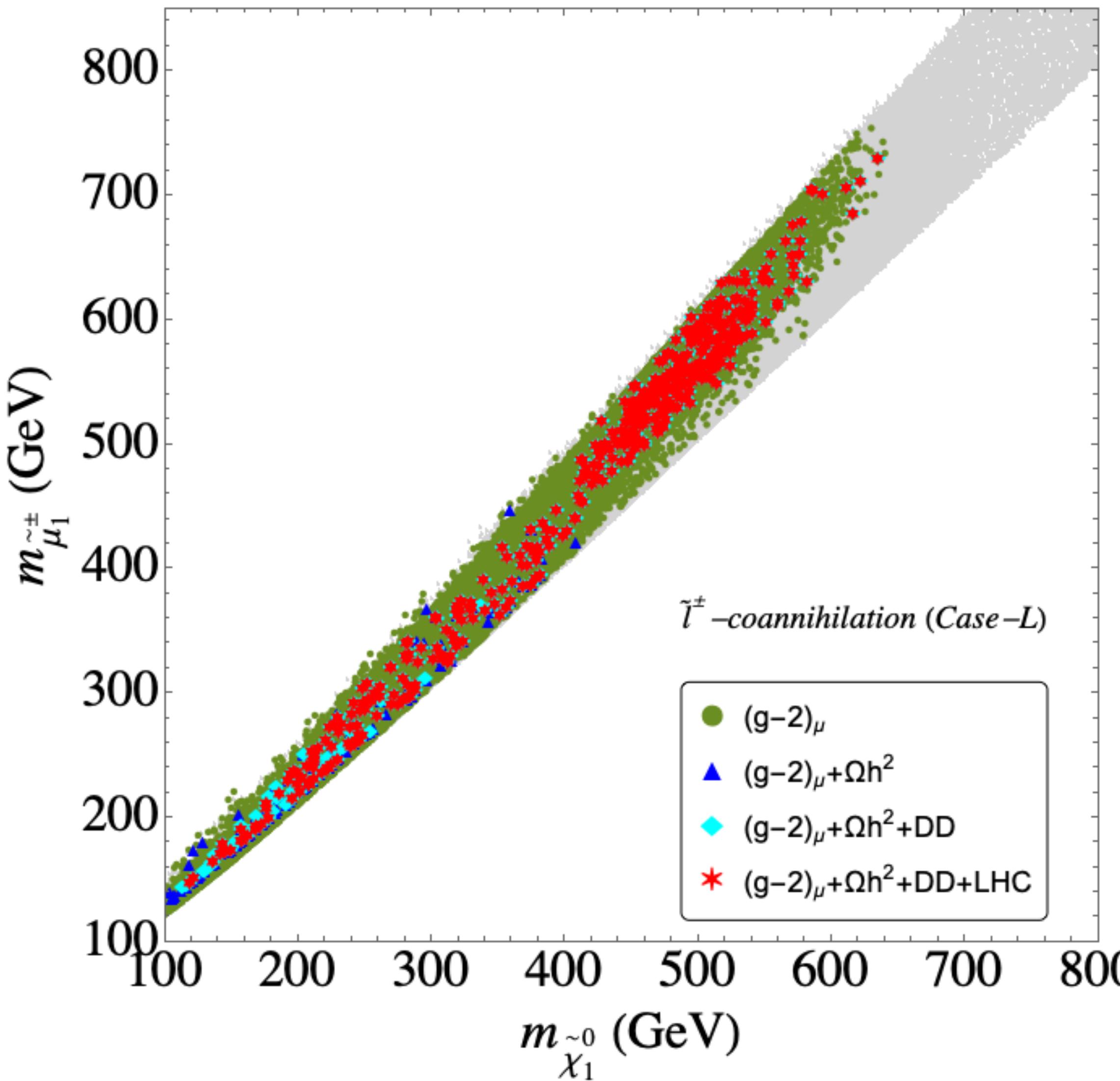
Upper and lower bounds from $(g - 2)_\mu$ and
LHC searches (for compressed spectrum)

Chargino Co-annihilation



- Green: $(g - 2)_\mu$ but not DM, LHC
 - Blue: $(g - 2)_\mu + \Omega h^2$, but not LHC
 - Red: all
- Slepton-pair production $\rightarrow (2l + \text{missing } E_T)$ provides important search channel.
- Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^+ \nu_e(\nu_\mu)$
- ATLAS: $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^0 e(\mu)$
- Less no. of signal leptons.

Slepton Co-annihilation: Case-L



Case-L: SU(2) doublet

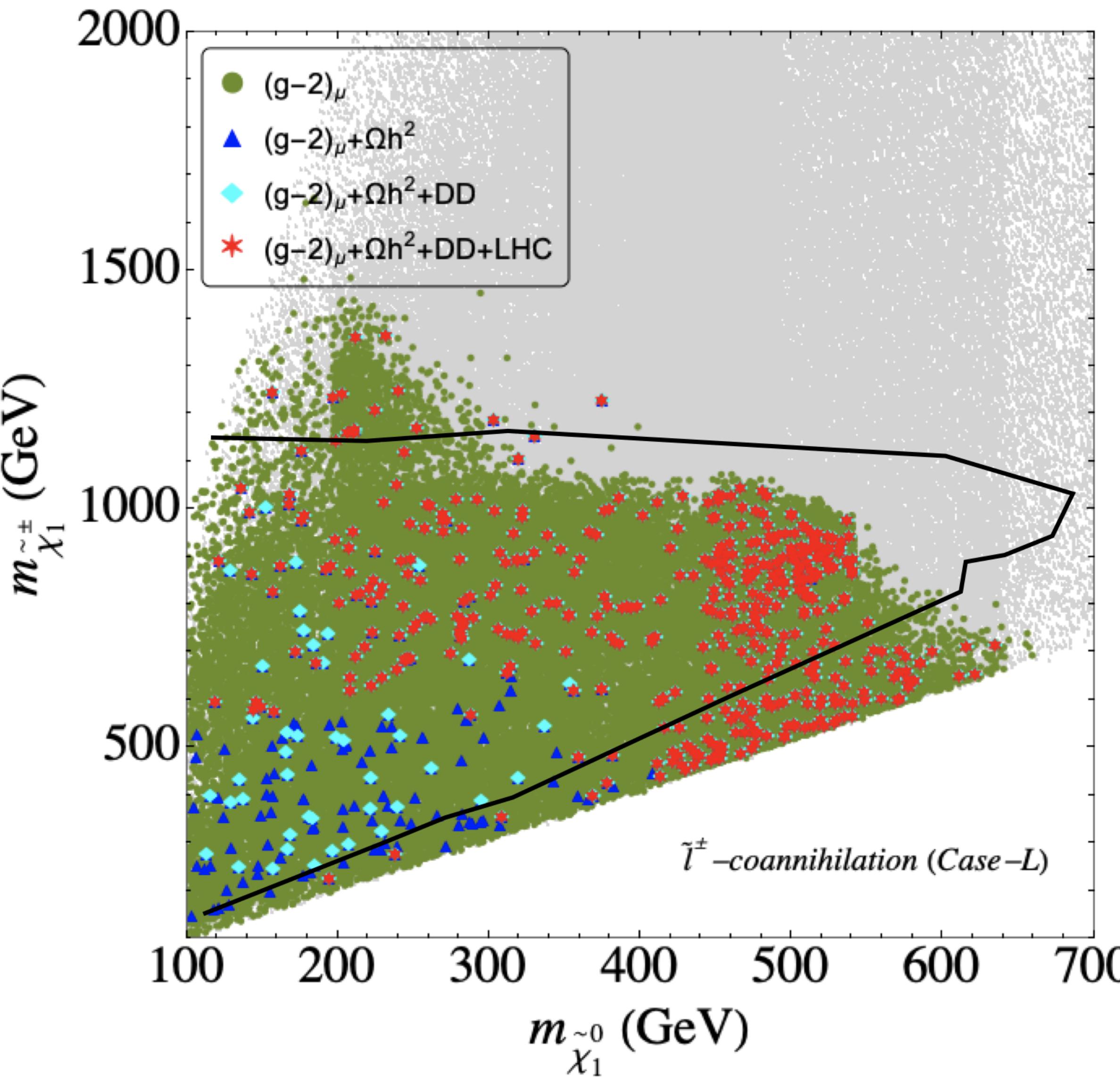
Green: $(g - 2)_\mu$ but not DM, LHC

Blue: $(g - 2)_\mu + \Omega h^2$, but not LHC

Red: all

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

Slepton Co-annihilation: Case-L



Green: $(g - 2)_\mu$ but not DM, LHC

Blue: $(g - 2)_\mu + \text{DM}$, but not LHC

Red: all

(3l + missing E_T) exclusion limit gets relaxed!

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1 \nu_\tau$$

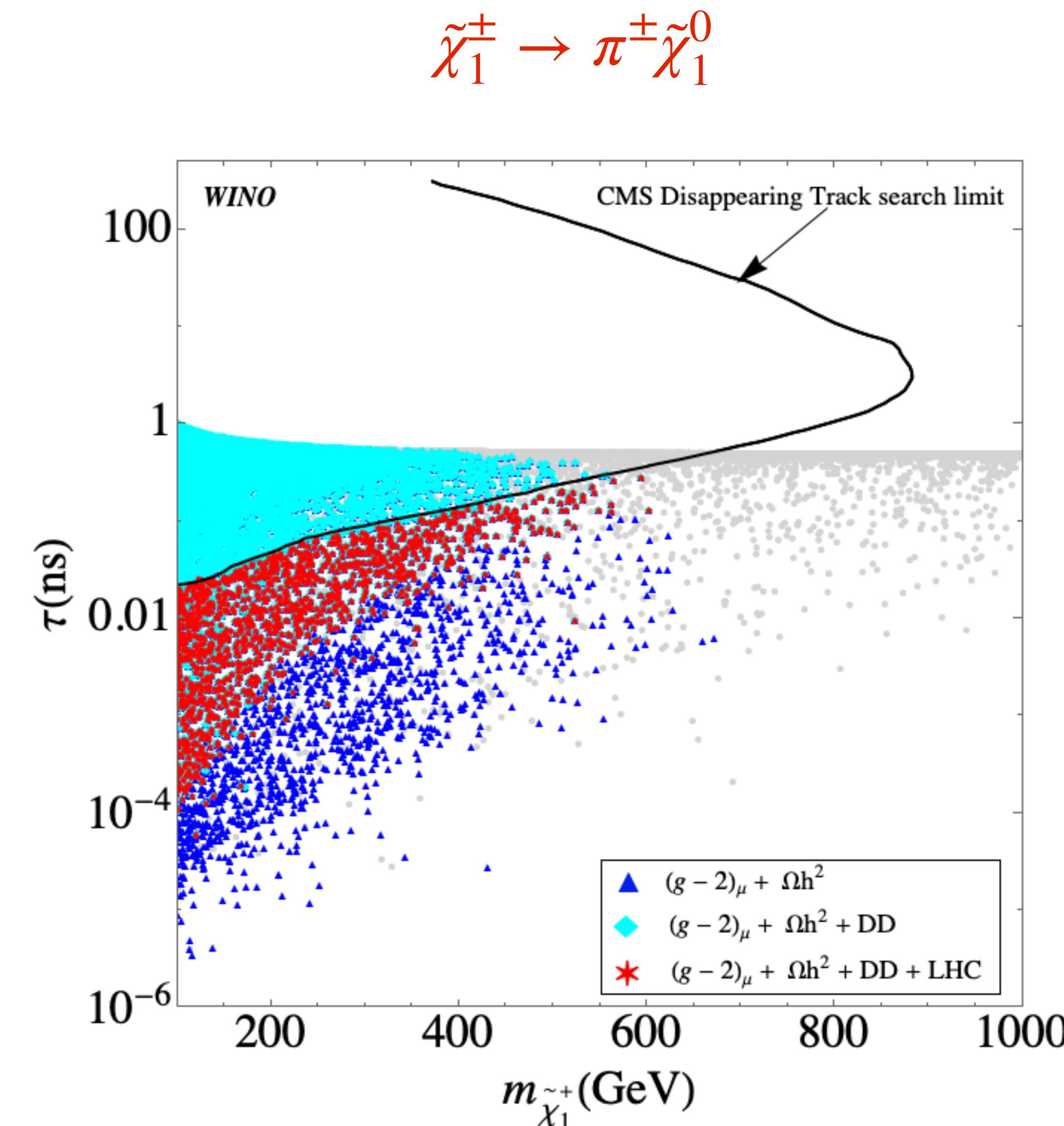
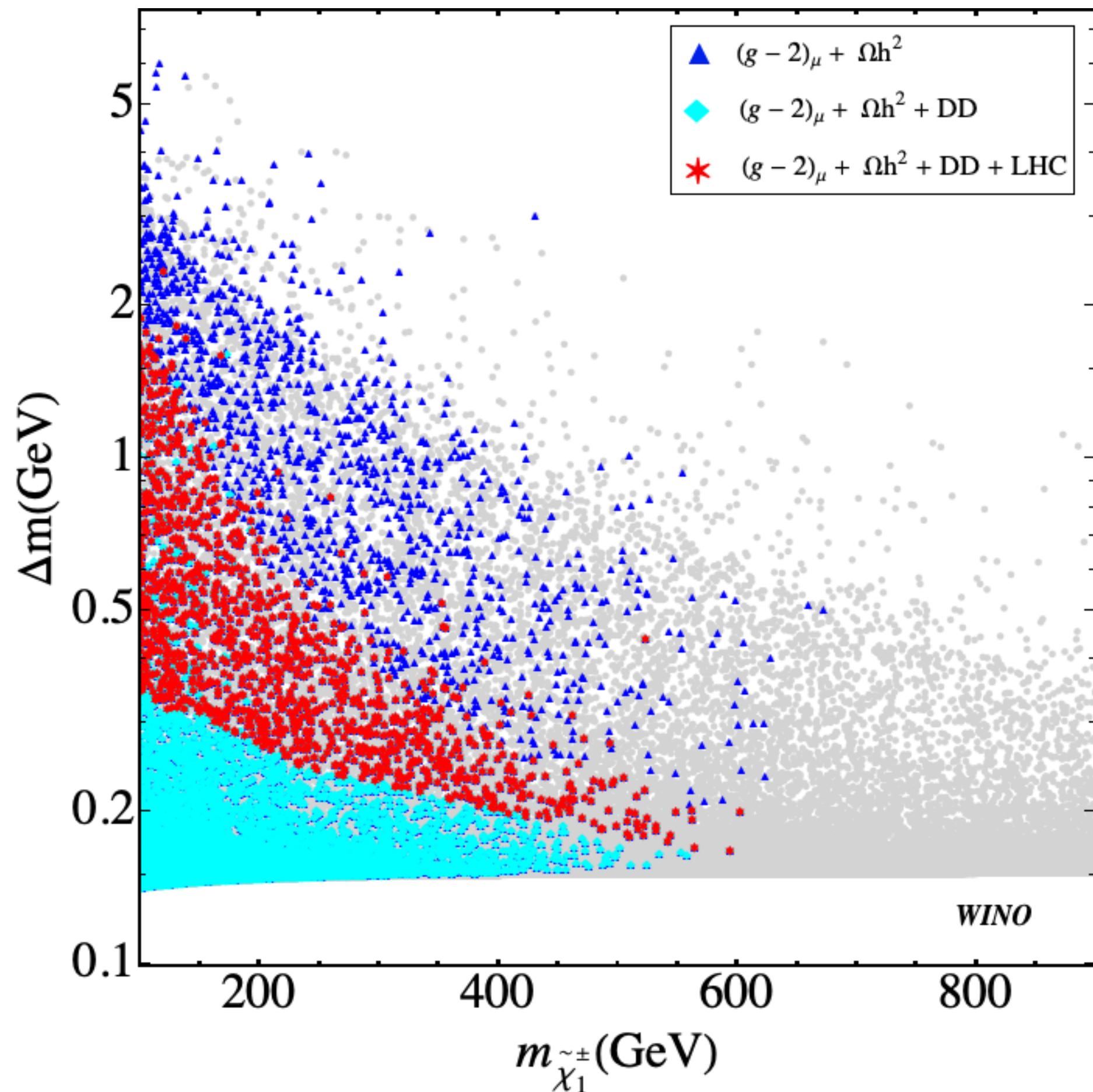
$$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\nu} \nu$$

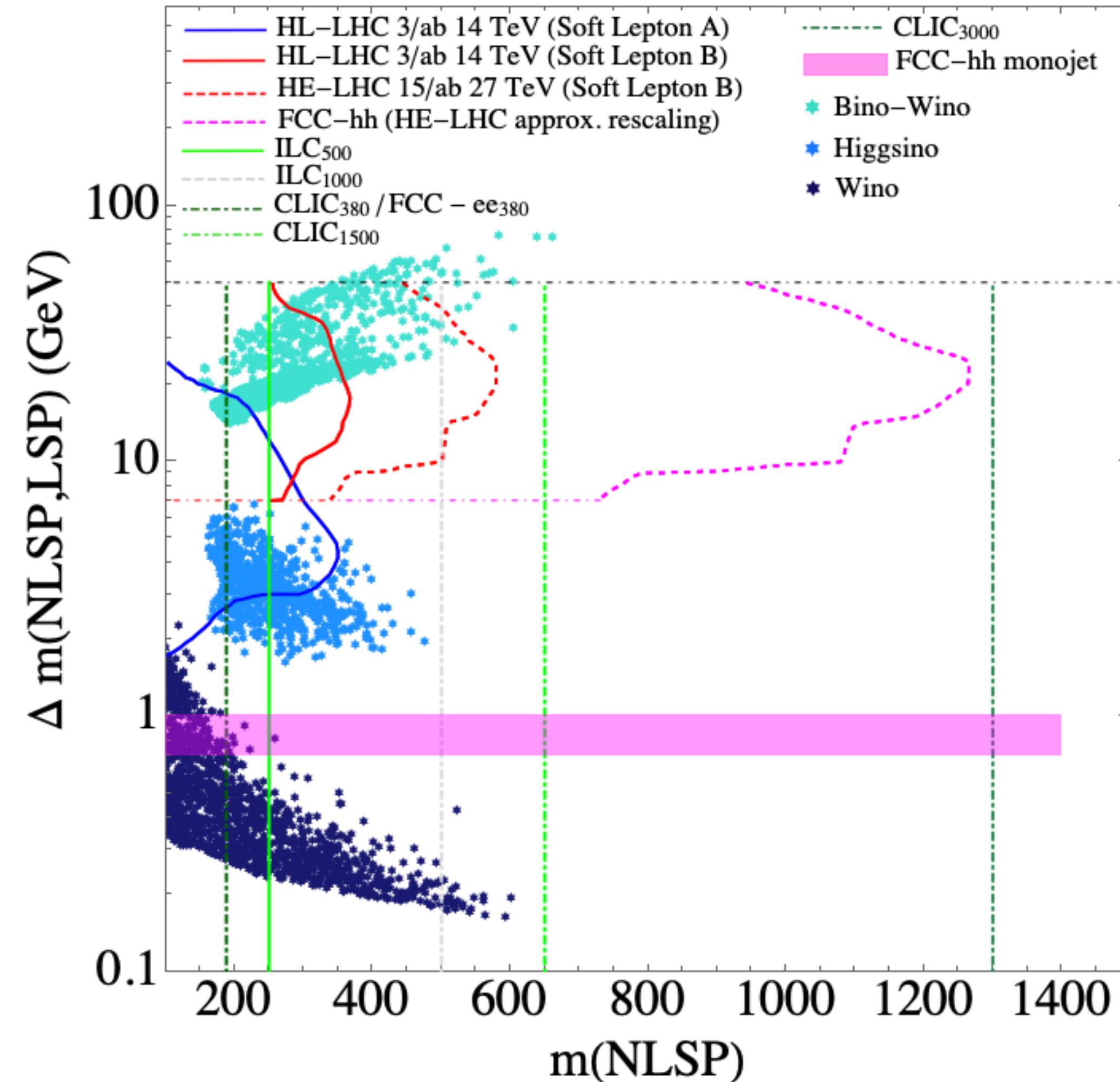
Wino LSP

$$\Omega_{CDM} h^2 \leq 0.122$$

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

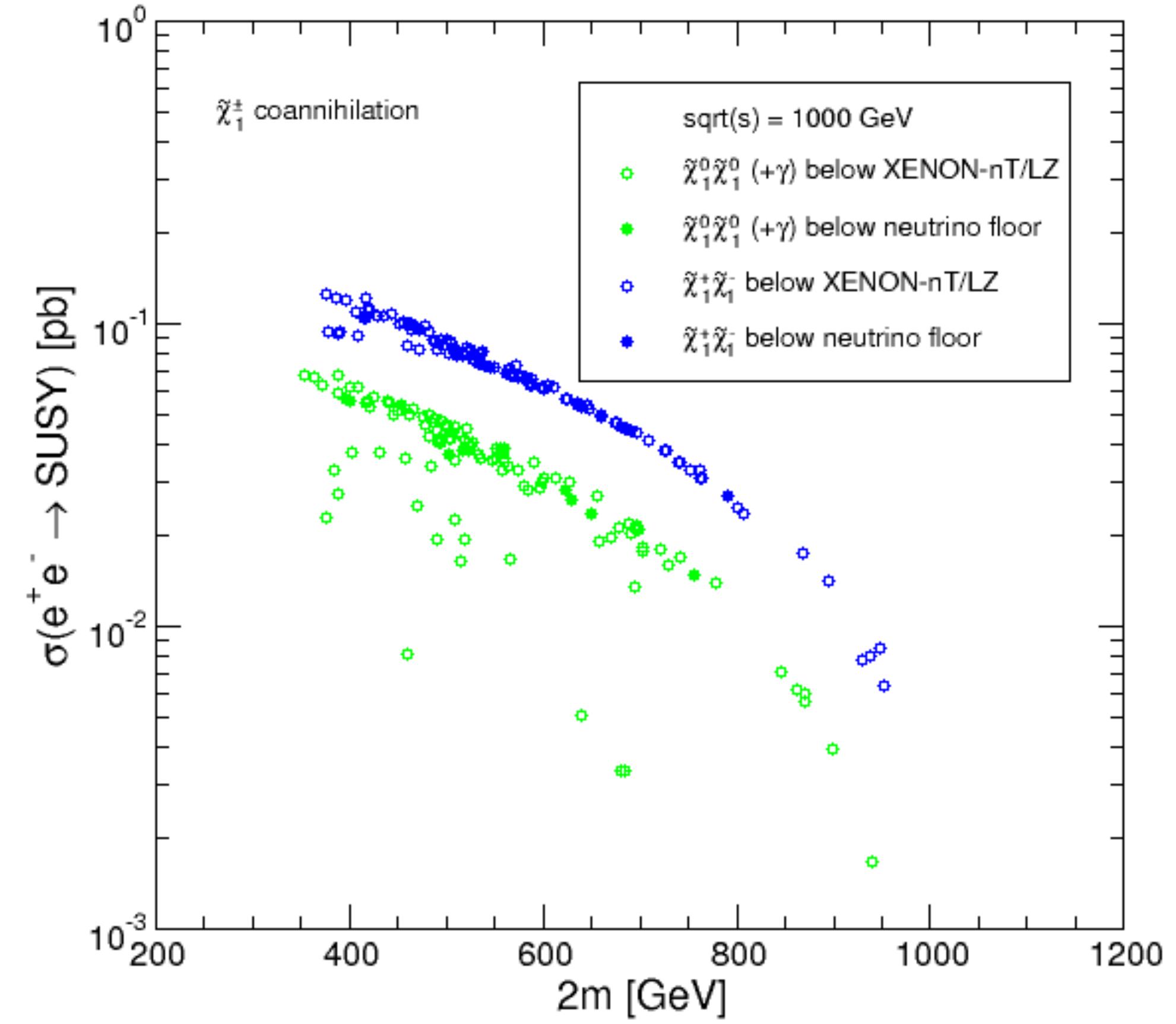
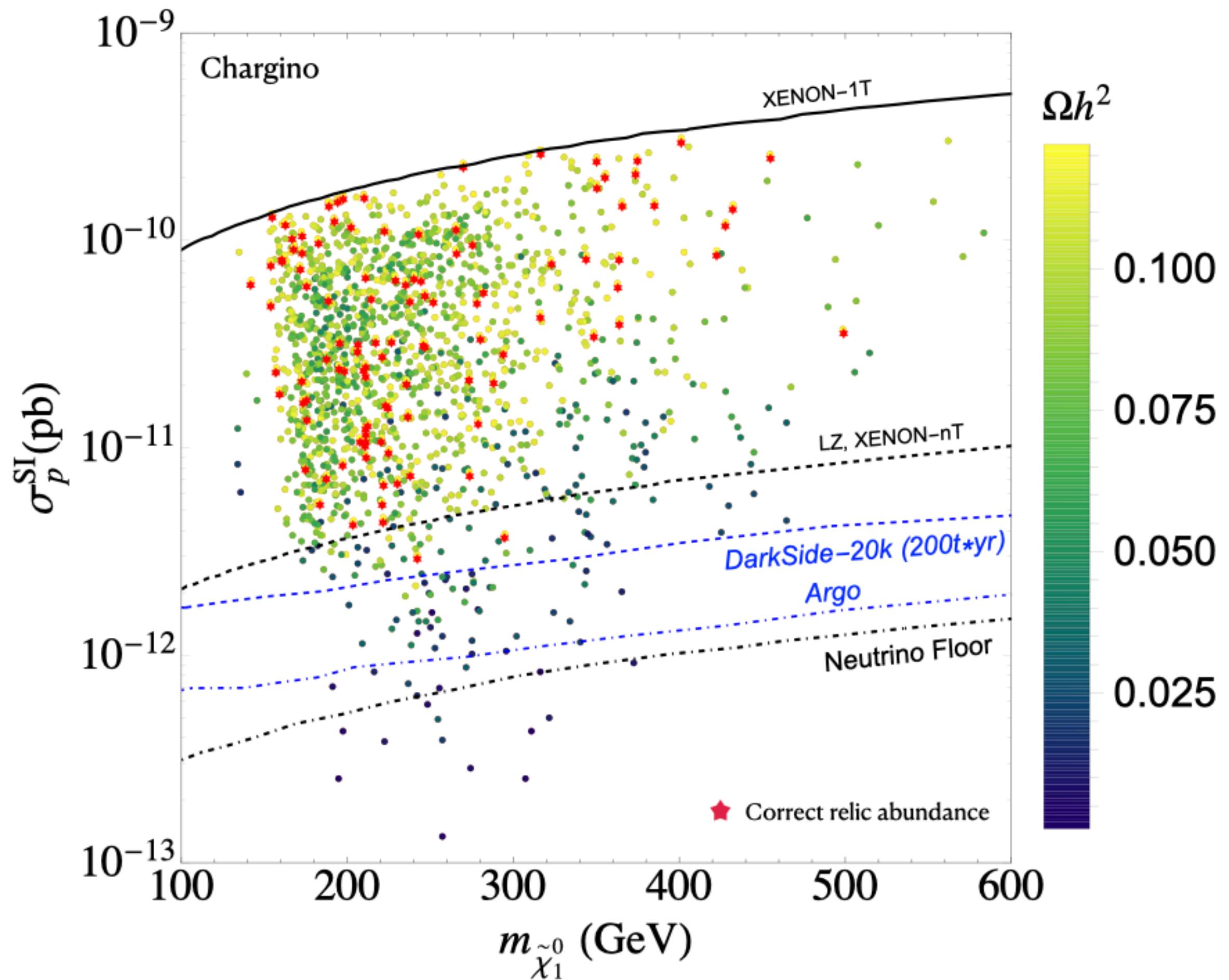


Future collider prospects



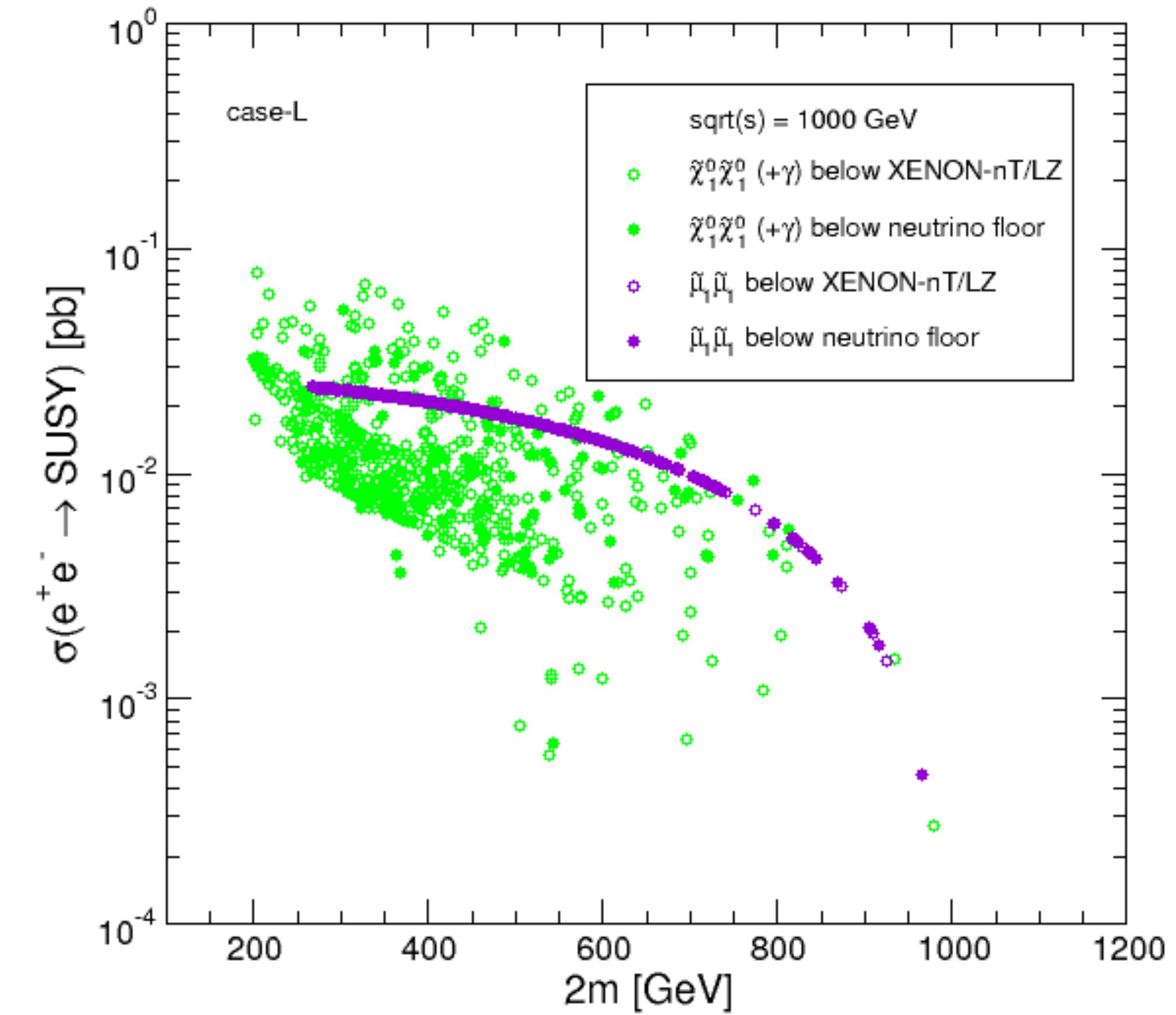
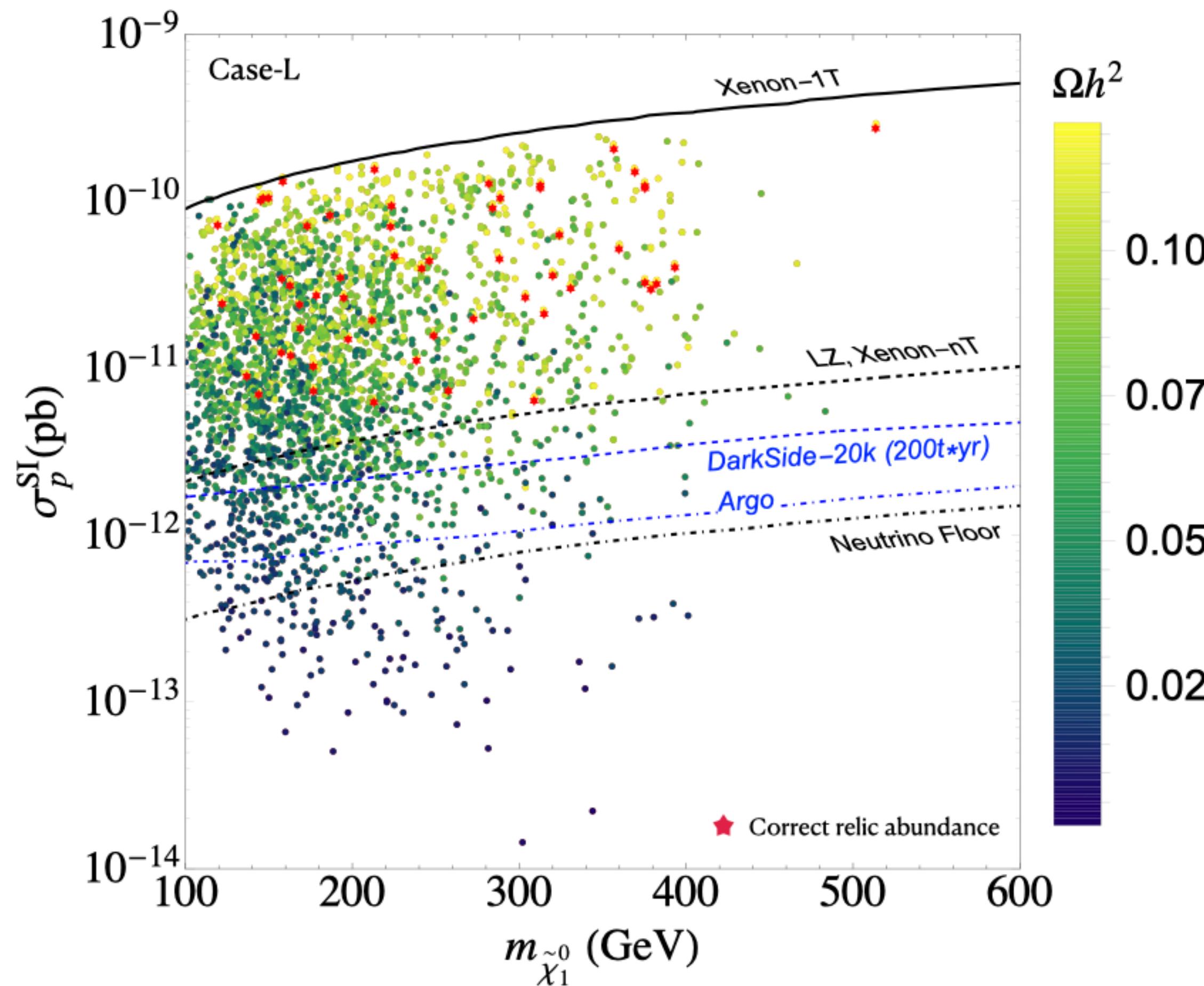
DD - ILC complementarity

Chargino Co-annihilation



DD - ILC complementarity

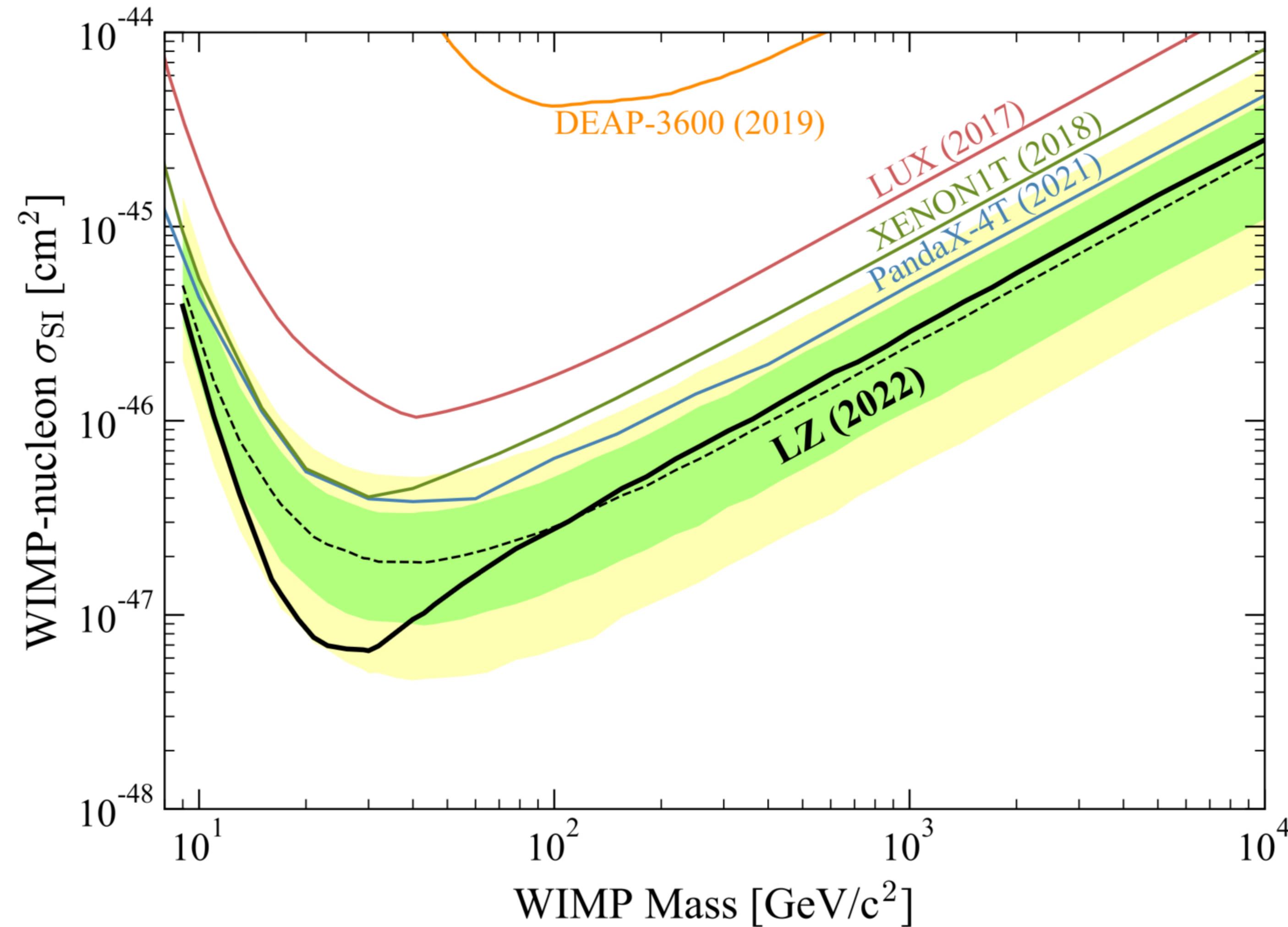
Slepton-L Co-annihilation



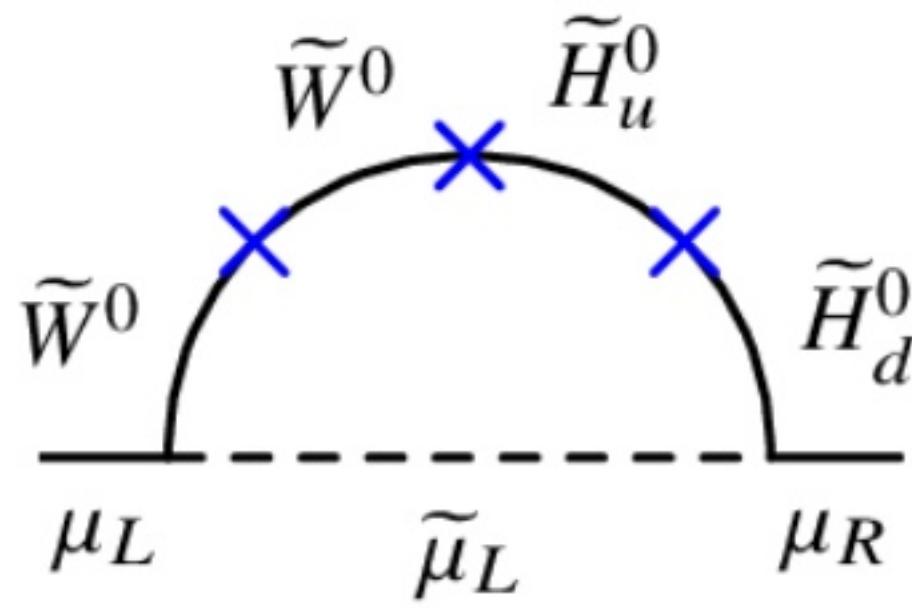
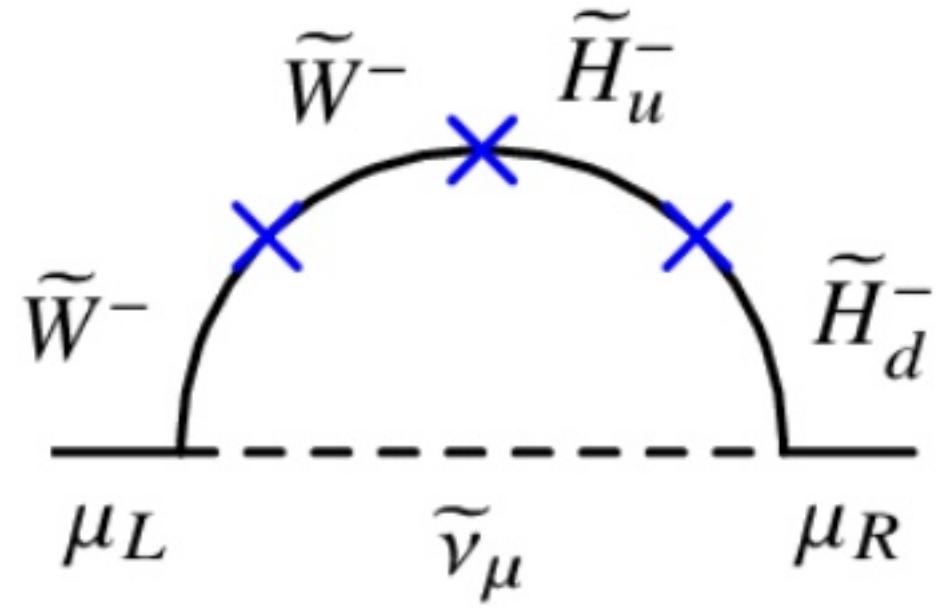
Summary

- DM and muon ($g-2$) constraints put effective upper limit on EW SUSY masses.
- LHC limits restrict the mass ranges from below.
- Proper recasting of ATLAS/CMS analyses important !
- Future collider searches and DD experiments can provide complementary constraints and can be conclusive.
- New results for $(g - 2)_\mu$ from Fermilab, J-PARC, MuonE ... **STAY TUNED!!!**

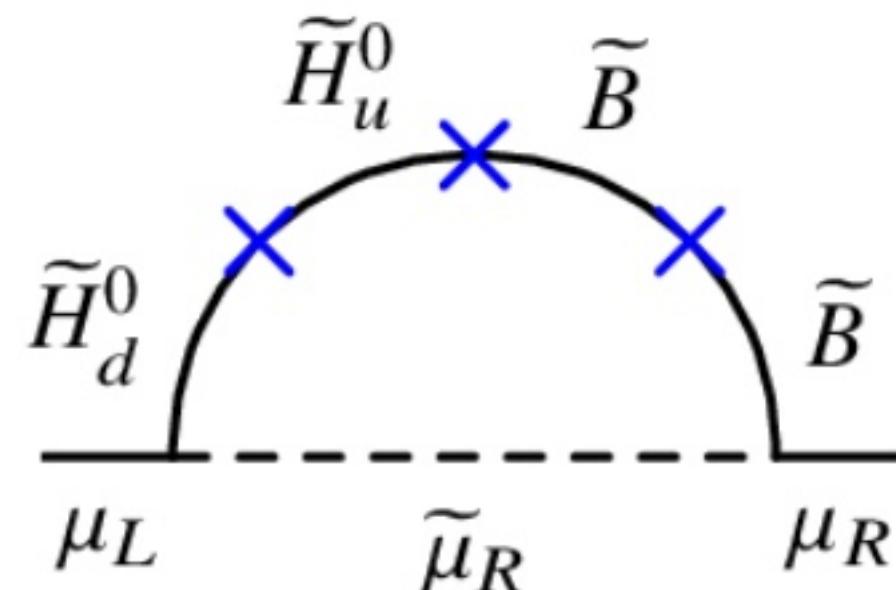
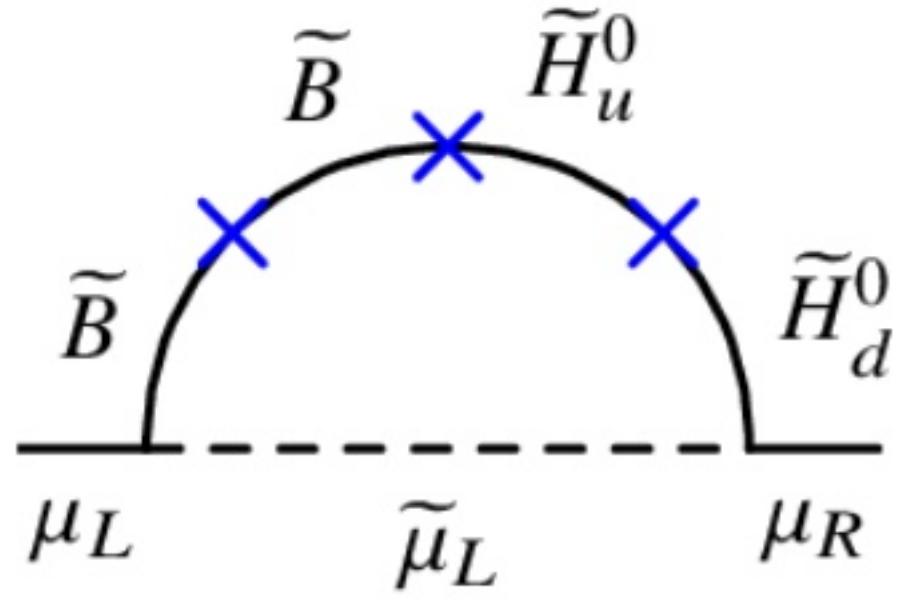
Thank You!



$$\Delta a_\mu^{\text{SUSY}} = \Delta a_\mu^{\text{WHL}} + \Delta a_\mu^{\text{BHL}} + \Delta a_\mu^{\text{BHR}} + \Delta a_\mu^{\text{BLR}}$$

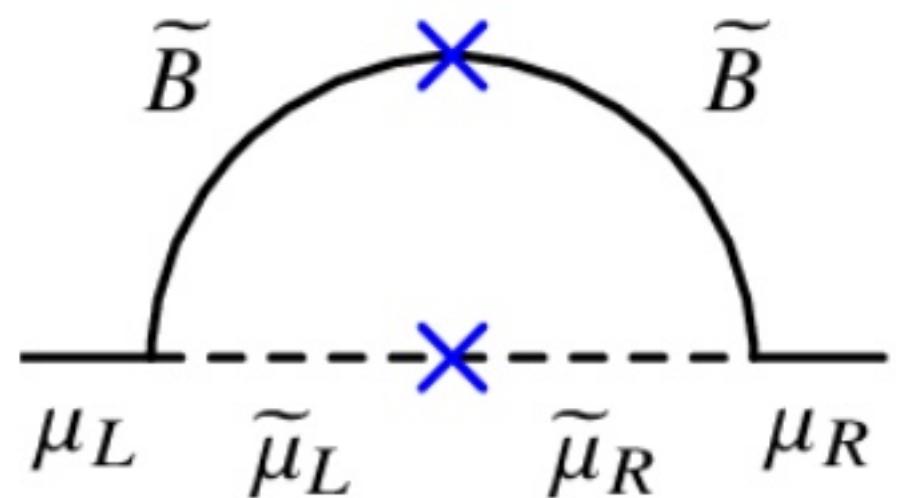


$$\Delta a_\mu^{\text{WHL}}(M_2, \mu, m_{\tilde{l}_L}) = \frac{\alpha_W}{8\pi} \frac{m_\mu^2}{M_2 \mu} \tan \beta \cdot f_{\text{W}}(\{\mathbf{m}\})$$



$$\Delta a_\mu^{\text{BHL}}(M_1, \mu, m_{\tilde{l}_L}) = \frac{\alpha_Y}{8\pi} \frac{m_\mu^2}{M_1 \mu} \tan \beta \cdot f_{\text{N}}(\{\mathbf{m}\})$$

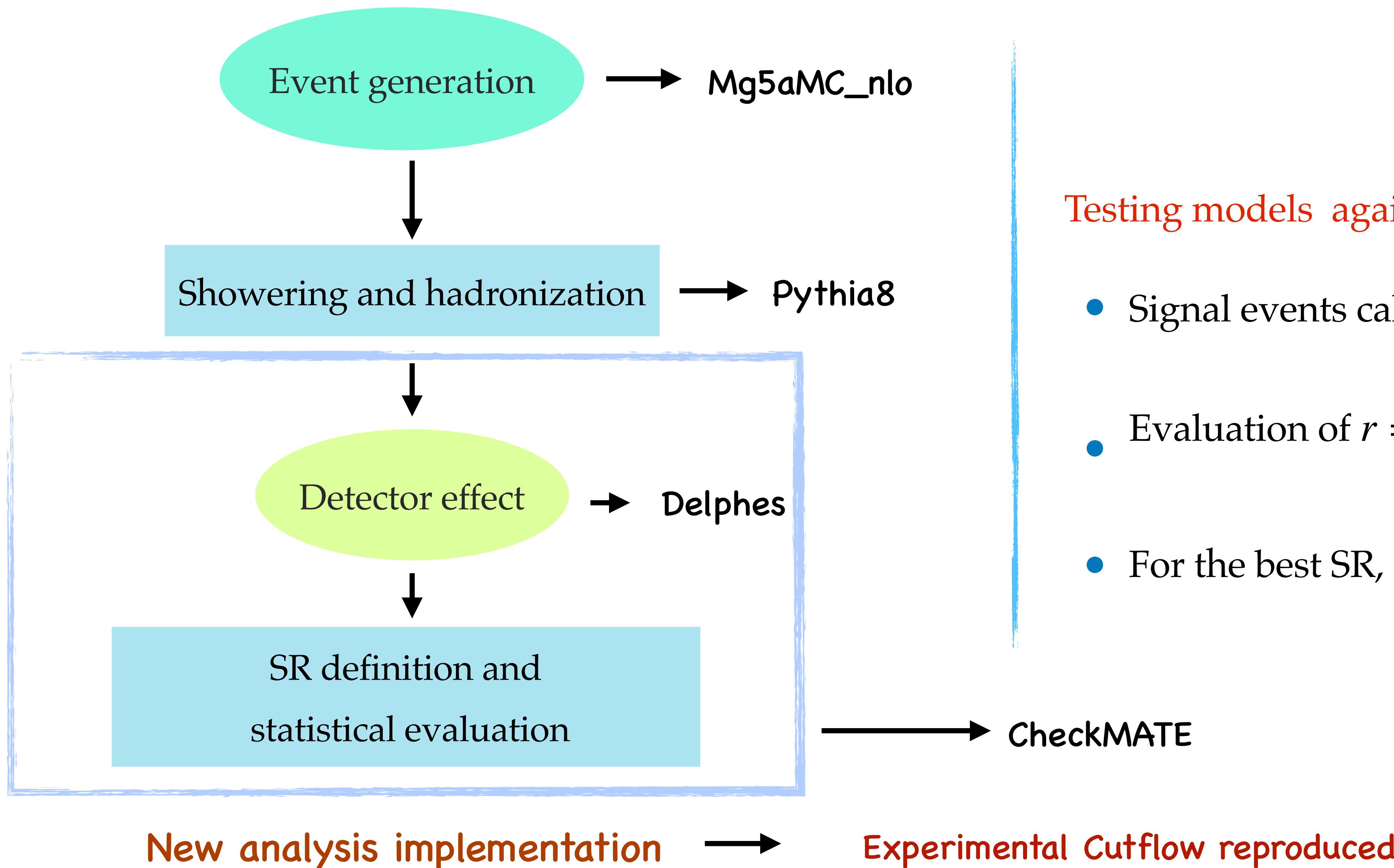
$$\Delta a_\mu^{\text{BHR}}(M_1, \mu, m_{\tilde{l}_R}) = - \frac{\alpha_Y}{8\pi} \frac{m_\mu^2}{M_1 \mu} \tan \beta \cdot f_{\text{N}}(\{\mathbf{m}\})$$



$$\Delta a_\mu^{\text{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R}; \mu) = \frac{\alpha_Y}{4\pi} \frac{m_\mu^2 M_1 \mu}{m_{\mu_L}^2 m_{\mu_R}^2} \tan \beta \cdot f_{\text{BLR}}(\{\mathbf{m}\})$$

Recasting with CM

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Kim, Schmeier, Tattersall, Rolbiecki '15
Dercks, Desai, Kim, Rolbiecki, Tattersall '16

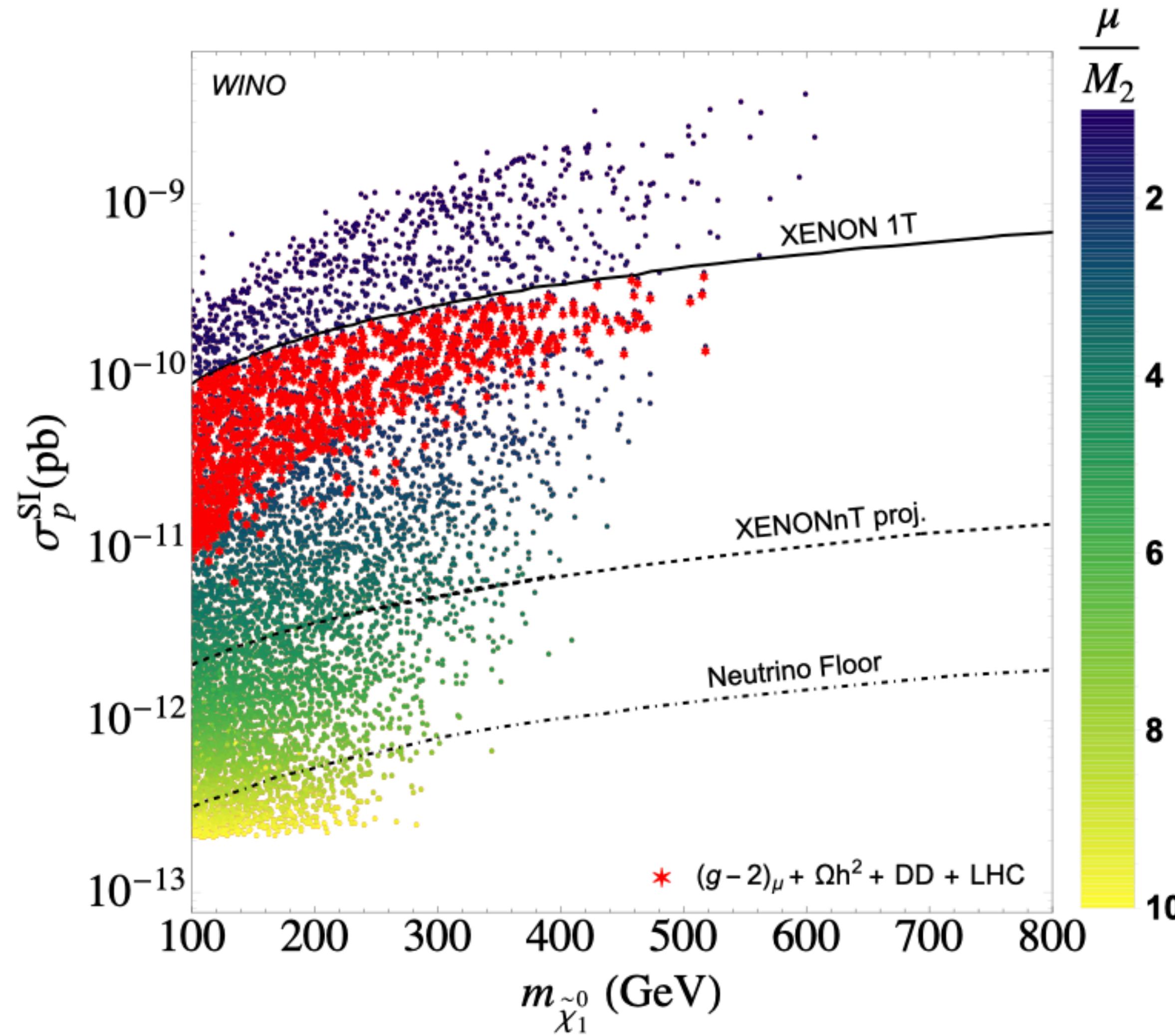


Testing models against LHC analyses

- Signal events calculated for each SR
- Evaluation of $r = \frac{S - 1.96 \times \Delta S}{S_{exp}^{95}}$
- For the best SR, $r > 1 \rightarrow \text{excluded!}$

Wino LSP : Direct detection

Current $(g - 2)_\mu$ limit



- DD coupling

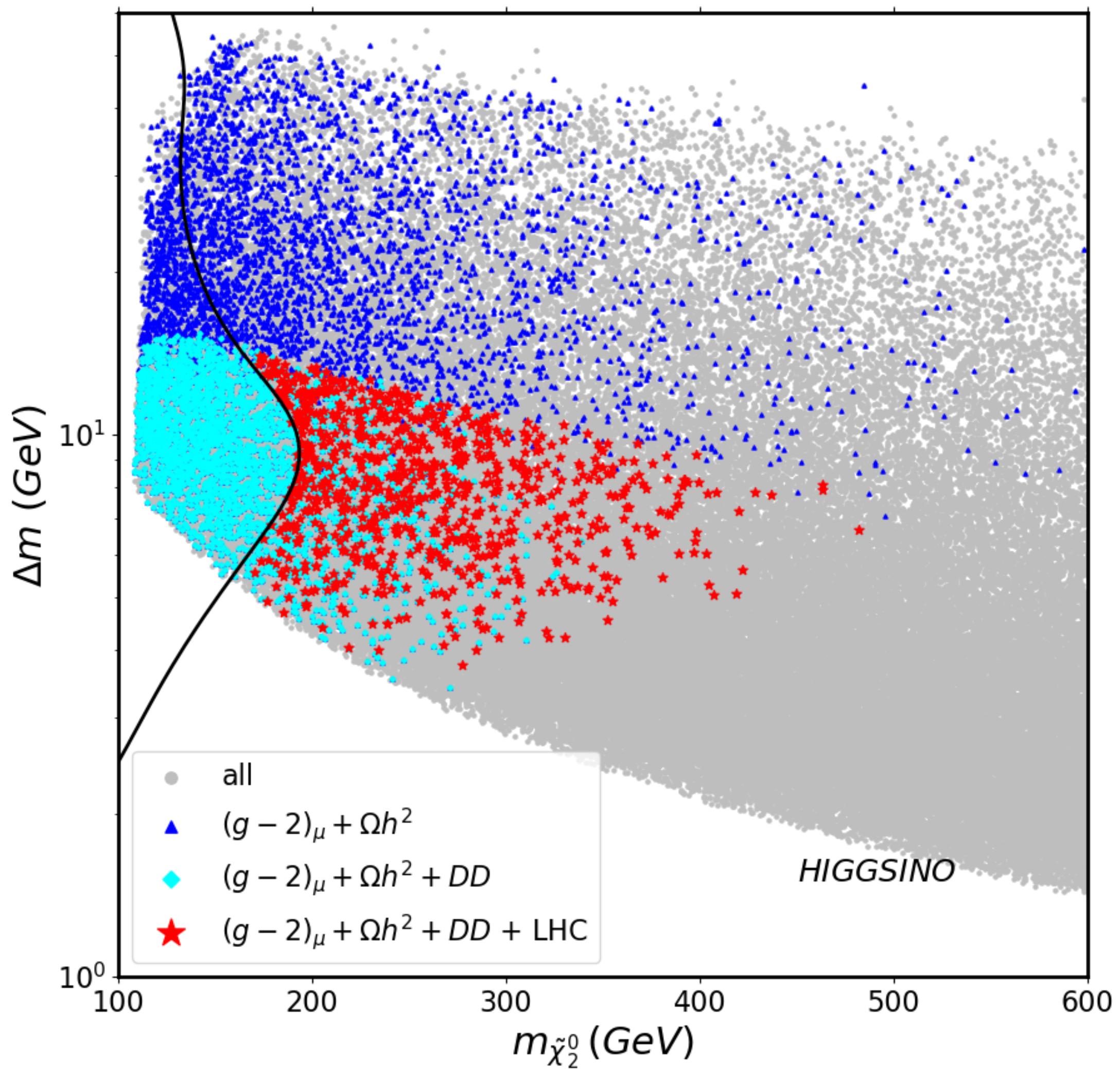
$$c_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq \frac{M_W}{M_2^2 - \mu^2} (M_2 + \mu \sin 2\beta),$$

- All allowed points to be checked by XENONnT

Higgsino LSP

$$\Omega_{CDM} h^2 \leq 0.122$$

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



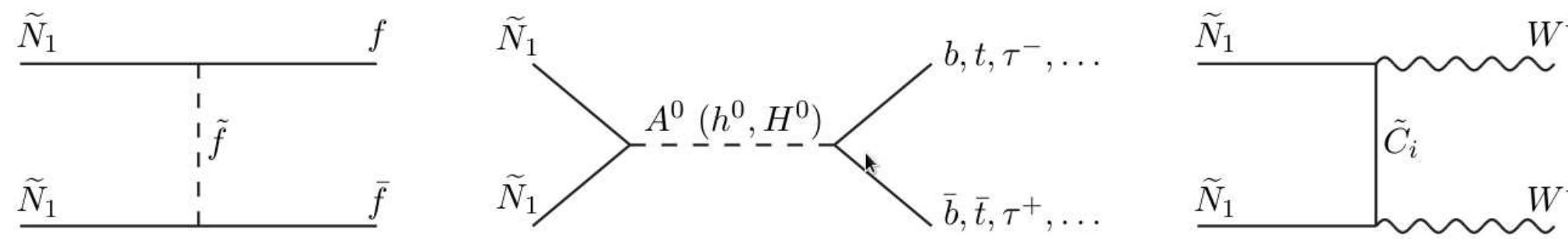
- Compressed spectra searches most important.
- Slepton pair production searches also relevant
- $\Delta m \sim \mathcal{O}(10)$ GeV \rightarrow Disappearing track searches not sensitive

$$c\tau \simeq 0.7 \text{ cm} \times \left[\left(\frac{\Delta m_+}{340 \text{ MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m_+^2}} \right]^{-1}$$

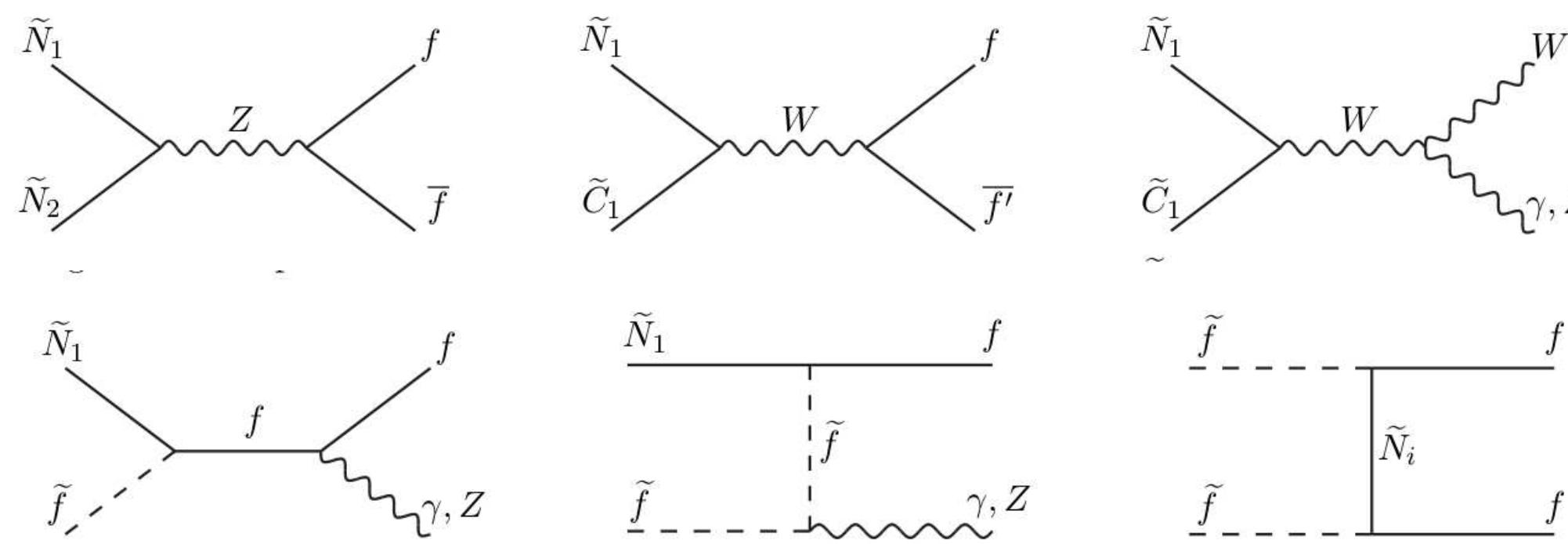
DM Constraints

Relic Density

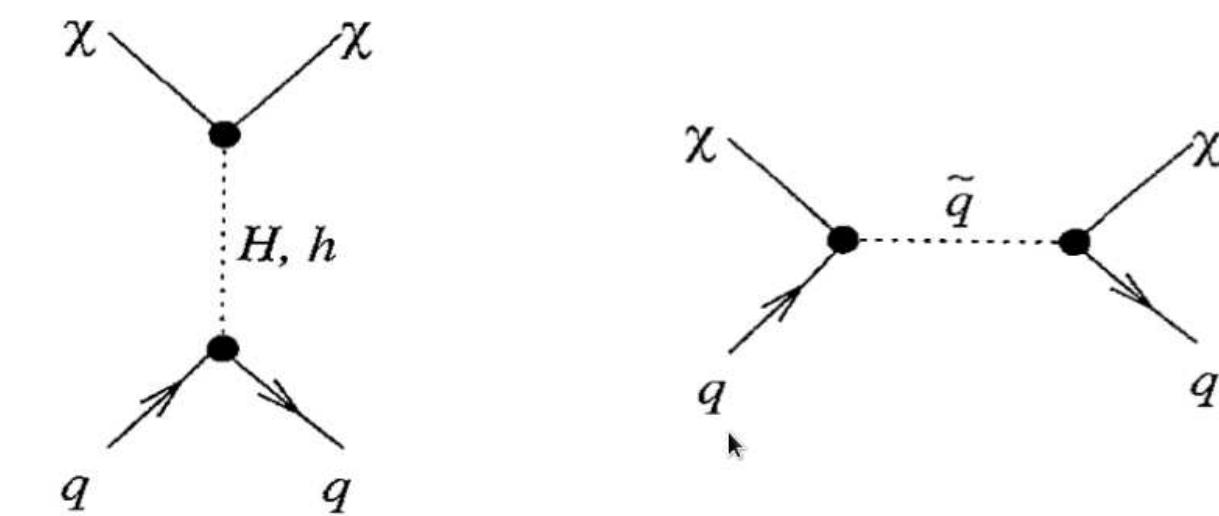
Some annihilation channels that could give right relic density :



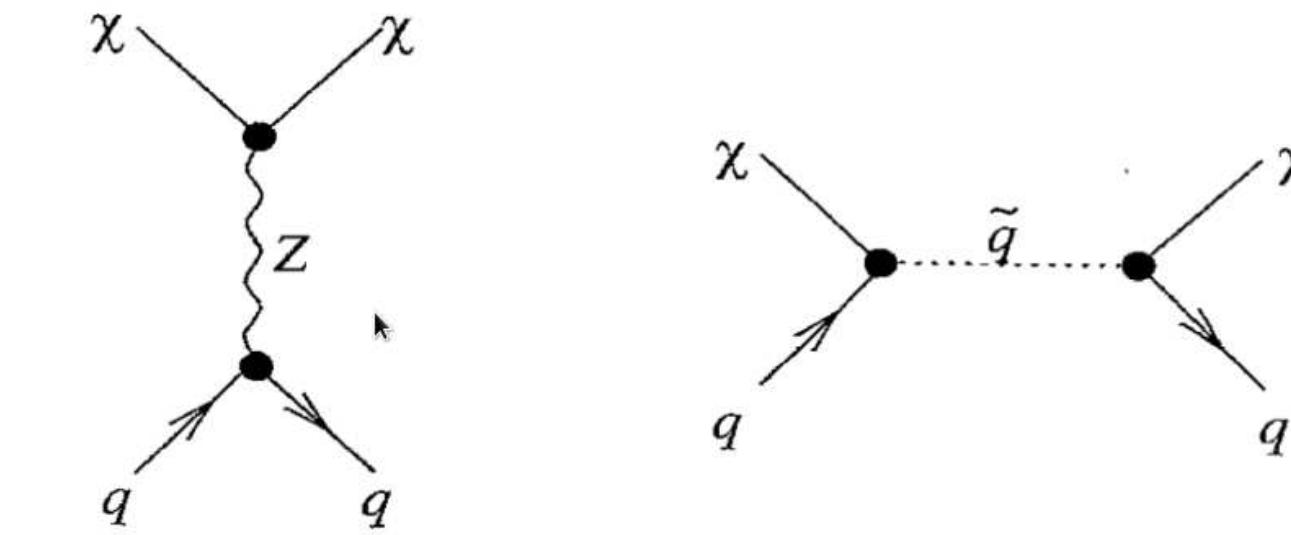
There can be coannihilations with sparticles of slightly heavier masses:



Direct Detection



Diagrams contributing to SI interactions



Diagrams contributing to SD interactions

A well-tempered **bino-wino** or **bino-higgsino** LSP → Chargino coannihilation

Bino - dominated LSP → Slepton coannihilation

LHC searches

- Disappearing track searches

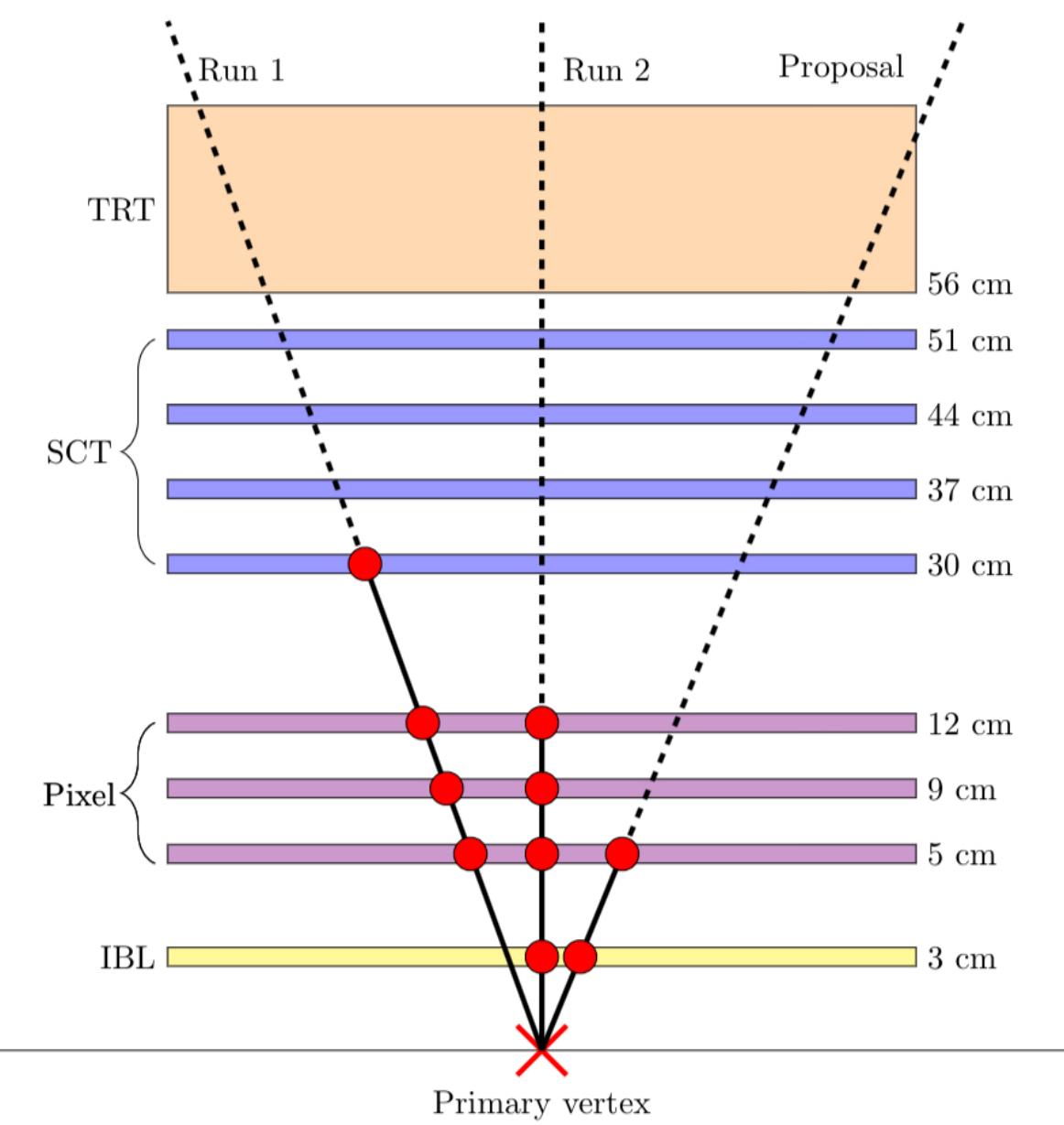


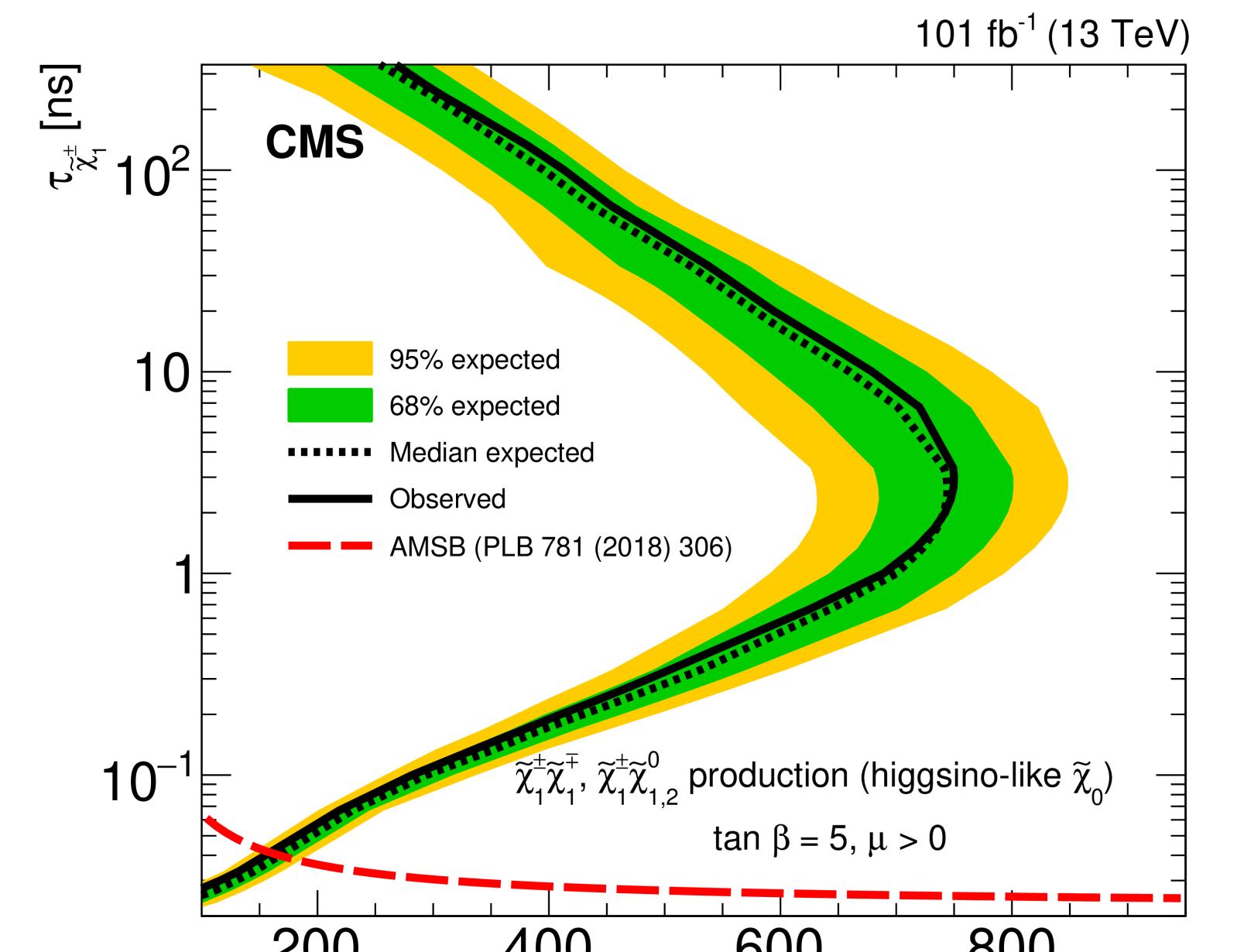
FIG. 1: Required number of hits in the ATLAS inner tracker for the analyses of Run-1&2 and ours.

$$\Delta m \sim 100 \text{ MeV}$$

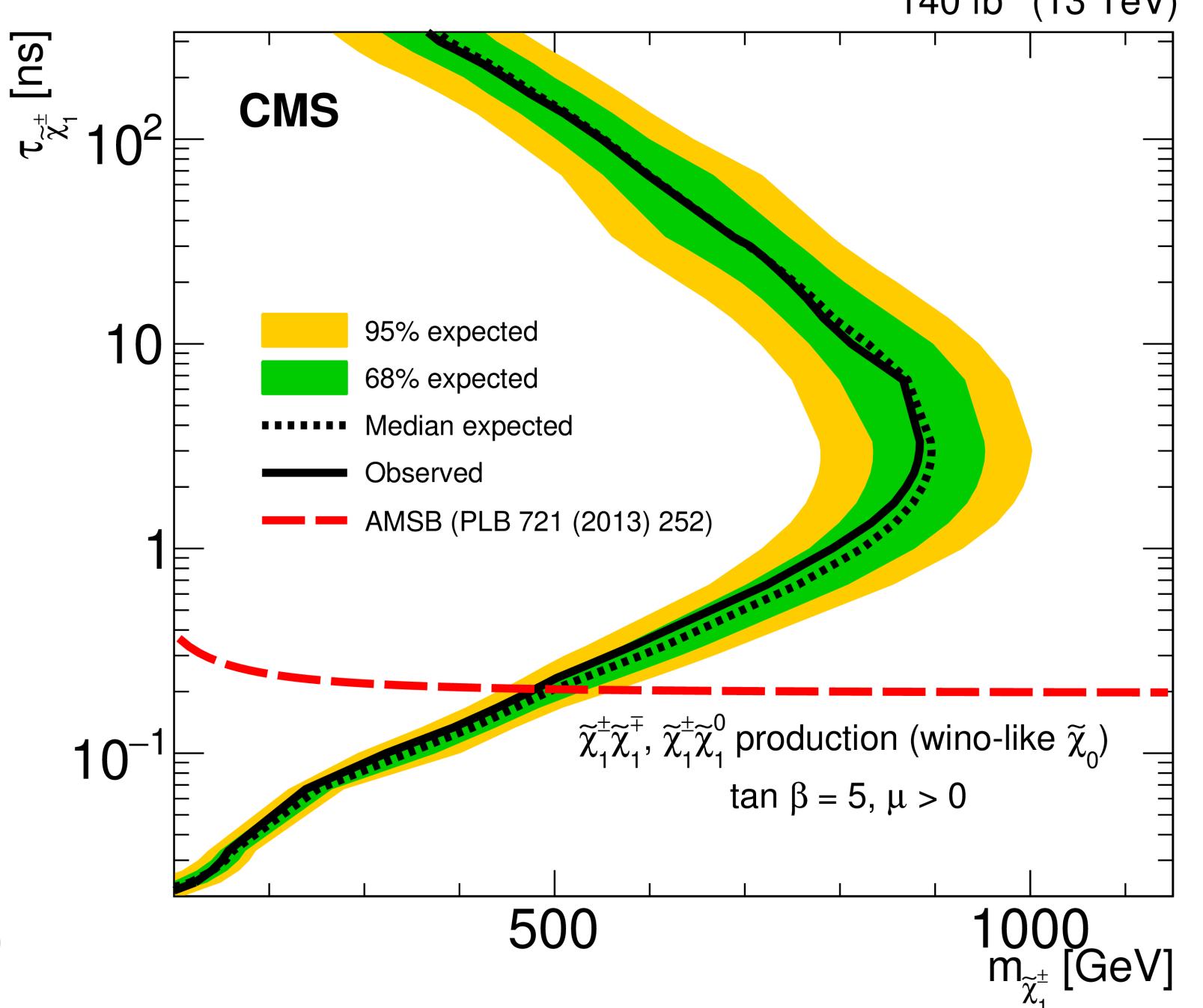
$$\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$$

Finite lifetime, decay
within detector

Higgsino



Wino



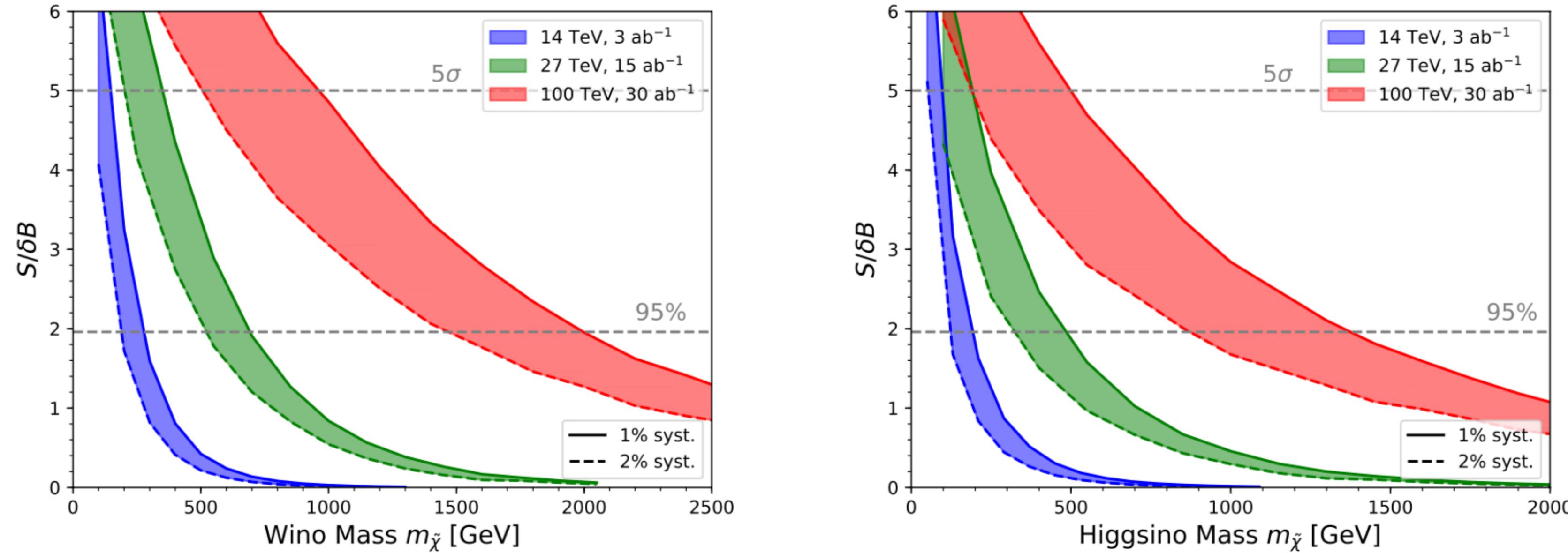


Figure 3: Comparative reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the mono-jet channel for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to optimistic values of the systematic uncertainties on the background estimate of 1% and 2% respectively, which might be achievable using data-driven methods with the accumulation of large statistics.

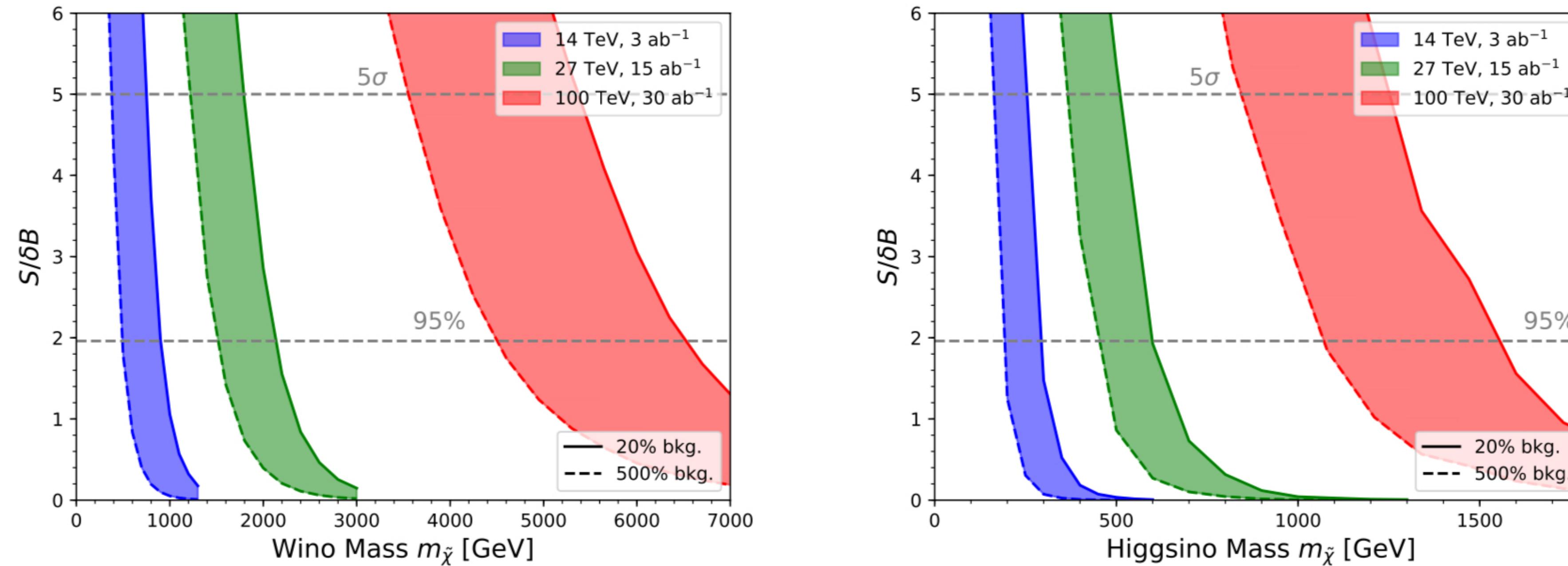


Figure 4: Comparative reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the disappearing charged track analysis for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to modifying the central value of the background estimate by a factor of five, i.e., 20% and 500% of that obtained through the fit function in Eq. 2.9.

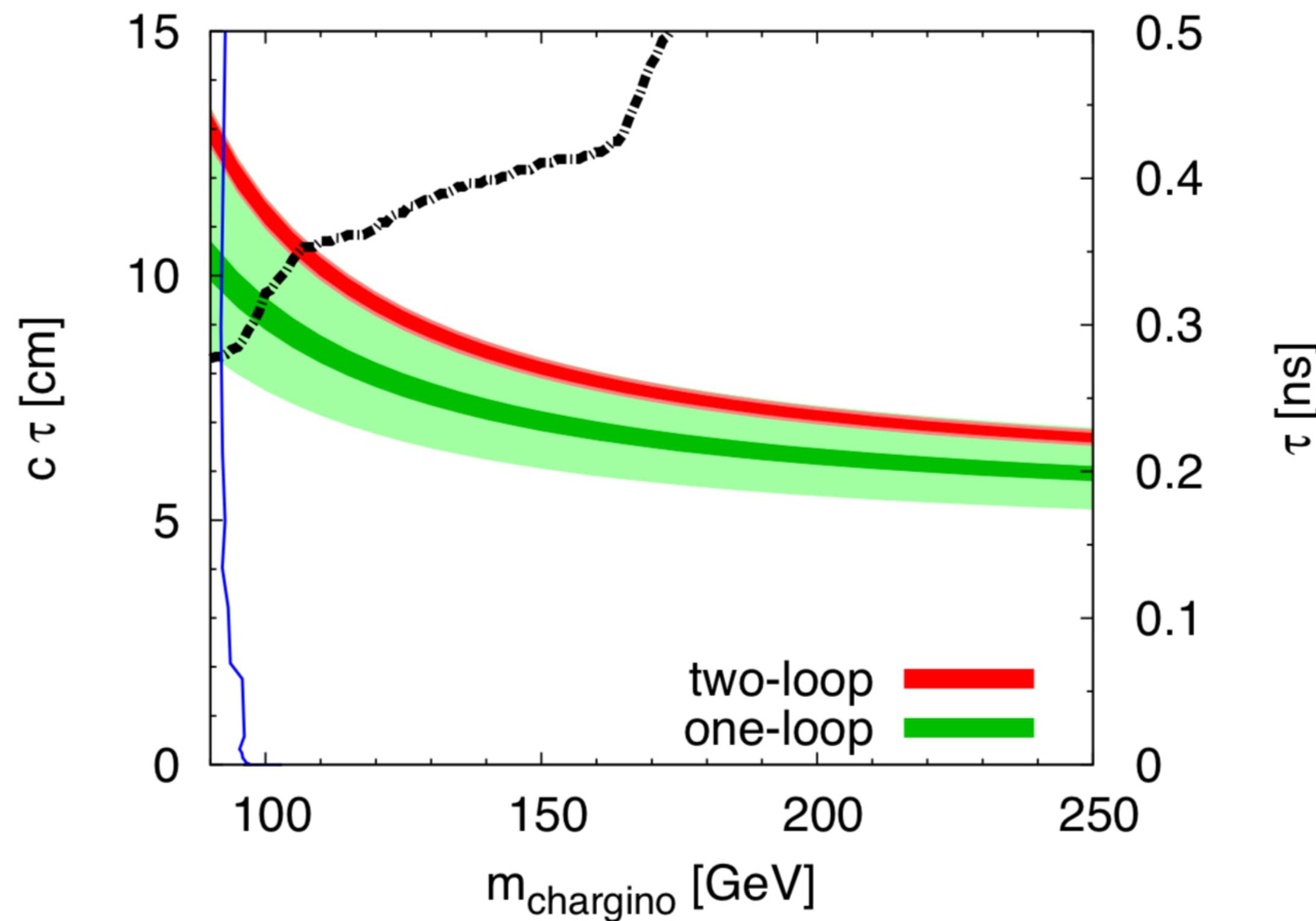
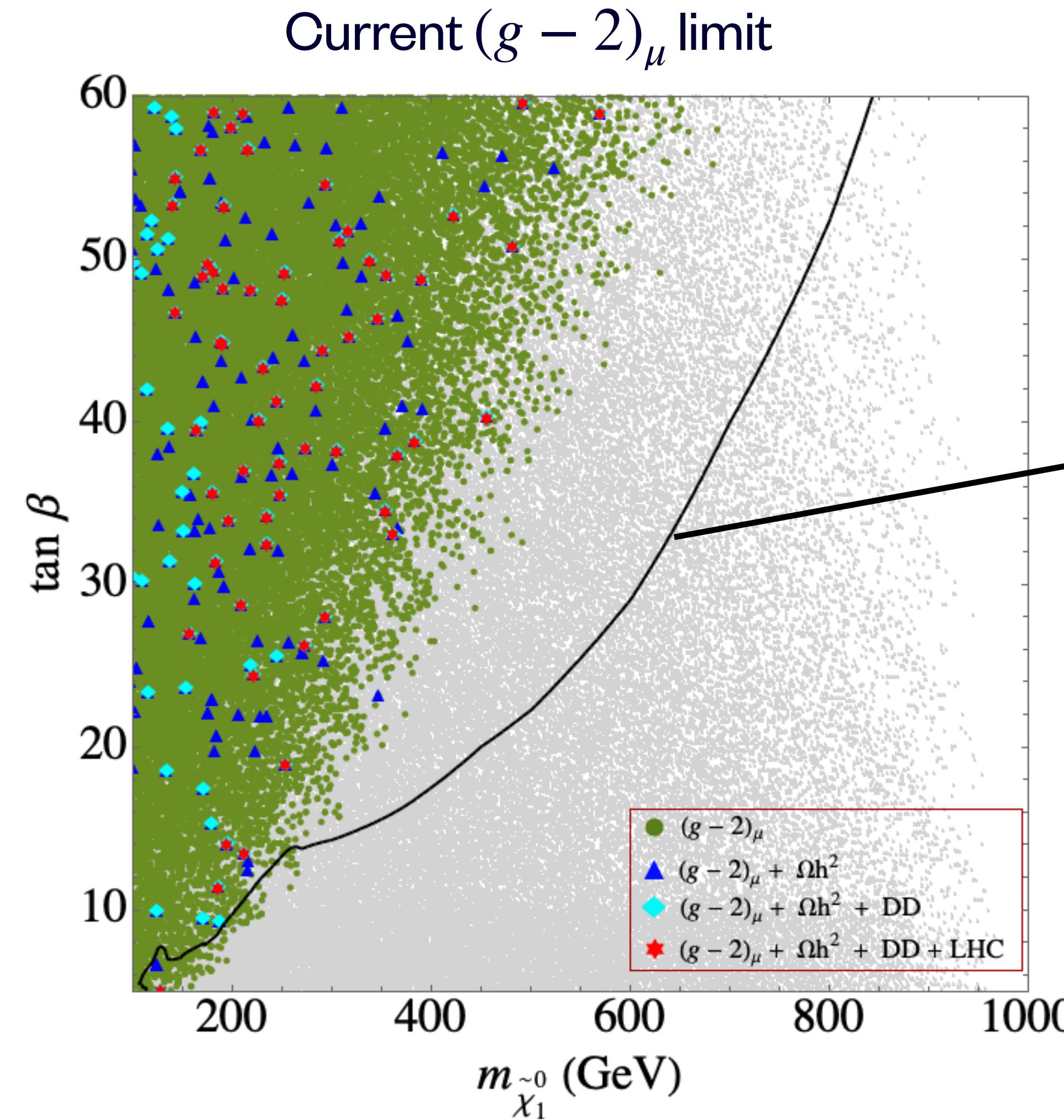


Figure 6: The lifetime of charged wino evaluated by using δm at the one-loop (green band) and two-loop (red band). We neglected the next-to-leading order corrections to the lifetime of the charged wino estimated in terms of the pion decay rate, which is expected to be a few percent correction. The black chain line is the upper limit on the lifetime for a given chargino mass by the ATLAS collaboration at 95 % CL ($\sqrt{s} = 7 \text{ TeV}$, $\mathcal{L} = 4.7 \text{ fb}^{-1}$) [28]. The blue line shows the constraints which are given by the LEP2 constraints [30]–[33].

Possibility of A-pole annihilation

$$a_\mu \sim \frac{\tan \beta}{m_{EW}^2}$$



$$m_{\tilde{\chi}_1^0} = \frac{M_A}{2}$$

$M_h^{125}(\tilde{\chi})$ Benchmark scenario

Bagnaschi et al. '18

Black contour : simplified application of $H/A \rightarrow \tau^+\tau^-$ → A-pole annihilation strongly constrained

MSSM Superpotential

$$W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Soft Breaking Terms

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + c.c) \\ & - \left(\tilde{\bar{u}} \mathbf{a_u} \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a_d} \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a_e} \tilde{L} H_d + c.c \right) \\ & - \tilde{Q}^\dagger \mathbf{m_Q^2} \tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2} \tilde{L} - \tilde{\bar{u}} \mathbf{m_{\bar{u}}^2} \tilde{\bar{u}}^\dagger - \tilde{\bar{d}} \mathbf{m_{\bar{d}}^2} \tilde{\bar{d}}^\dagger - \tilde{\bar{e}} \mathbf{m_{\bar{e}}^2} \tilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + c.c)\end{aligned}$$

Highest mass points

Current $(g - 2)_\mu$ limit

Coannihilation	$\tilde{\chi}_1^\pm$	\tilde{l}^\pm (Case-L)	\tilde{l}^\pm (Case-R)
$m_{\tilde{\chi}_1^0}$	570	533	518
$m_{\tilde{\chi}_2^0}$	605	816	685
$m_{\tilde{\chi}_3^0}$	1087	1370	1098
$m_{\tilde{\chi}_1^\pm}$	605	816	685
$m_{\tilde{e}_1, \tilde{\mu}_1}$	680	549	696
$m_{\tilde{e}_2, \tilde{\mu}_2}$	680	1279	592
$m_{\tilde{\tau}_1}$	582	534	747
$m_{\tilde{\tau}_2}$	765	1286	526
$m_{\tilde{\nu}}$	675	544	692

Anticipated future $(g - 2)_\mu$ limit

Coannihilation	$\tilde{\chi}_1^\pm$	\tilde{l}^\pm (Case-L)	\tilde{l}^\pm (Case-R)
$m_{\tilde{\chi}_1^0}$	423	499	402
$m_{\tilde{\chi}_2^0}$	464	535	448
$m_{\tilde{\chi}_3^0}$	1032	1019	830
$m_{\tilde{\chi}_1^\pm}$	464	535	448
$m_{\tilde{e}_1, \tilde{\mu}_1}$	542	511	795
$m_{\tilde{e}_2, \tilde{\mu}_2}$	541	2349	428
$m_{\tilde{\tau}_1}$	437	509	807
$m_{\tilde{\tau}_2}$	629	2350	406
$m_{\tilde{\nu}}$	536	505	792

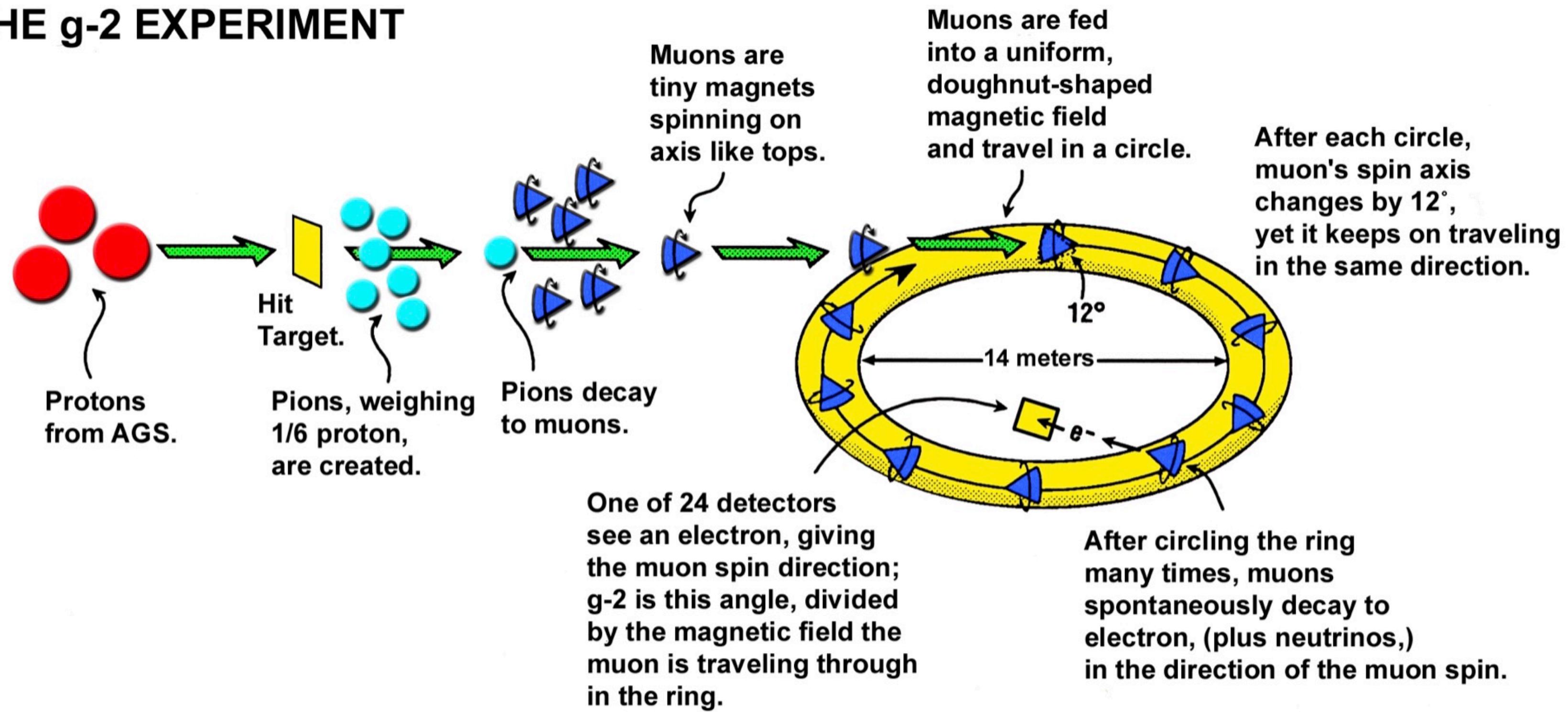
Points satisfying $(g - 2)_\mu$, DM and LHC constraints, masses in GeV.

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

$$\begin{aligned}\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) &\simeq 15 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{(100 \text{ GeV})^2}{M_2 \mu} \right) \left(\frac{f_C}{1/2} \right), \\ \Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) &\simeq -2.5 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{(100 \text{ GeV})^2}{M_2 \mu} \right) \left(\frac{f_N}{1/6} \right), \\ \Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) &\simeq 0.76 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{(100 \text{ GeV})^2}{M_1 \mu} \right) \left(\frac{f_N}{1/6} \right), \\ \Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) &\simeq -1.5 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{(100 \text{ GeV})^2}{M_1 \mu} \right) \left(\frac{f_N}{1/6} \right), \\ \Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) &\simeq 1.5 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{(100 \text{ GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / M_1 \mu} \right) \left(\frac{f_N}{1/6} \right).\end{aligned}$$

Endo, Hamaguchi, Iwamoto, Yoshinaga'13

LIFE OF A MUON: THE g-2 EXPERIMENT



$$\vec{\mu} = g_\mu \frac{e}{2m} \vec{s}$$

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

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

$$a_\mu = \frac{g_\mu - 2}{2}$$

$(g - 2)_\mu$

- Large discrepancy from the SM (more than 3σ):

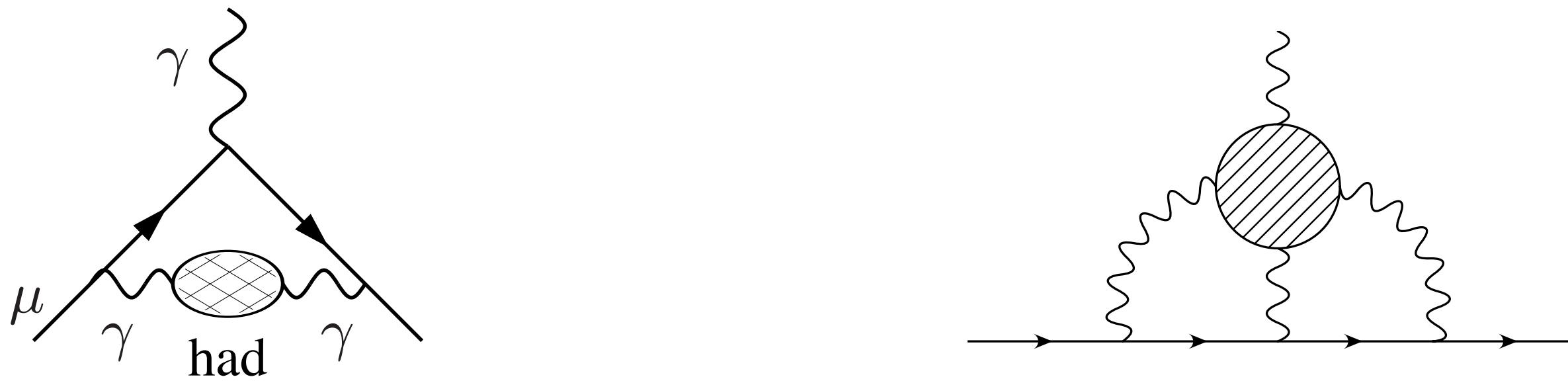
$$a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10}.$$

Keshavarzi, Nomura, Teubner '19

- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.
- QED : complete calculation upto 5 loops. EW : two loops.

Aoyama, Hayakawa, Kinoshita, Nio '17, Ishikawa, Nakazawa, Yasu '18,
Heinemeyer, Stöckinger, Weiglein '04

- Uncertainty dominated by non-perturbative, hadronic sector.



$\tan\beta$ enhancement in SUSY

$$\mathcal{L}_{\text{eff}} \ni i\tilde{a}_\mu \cdot \bar{\psi}_{\textcolor{red}{L}} \sigma^{\mu\nu} \psi_{\textcolor{blue}{R}} F_{\mu\nu}$$

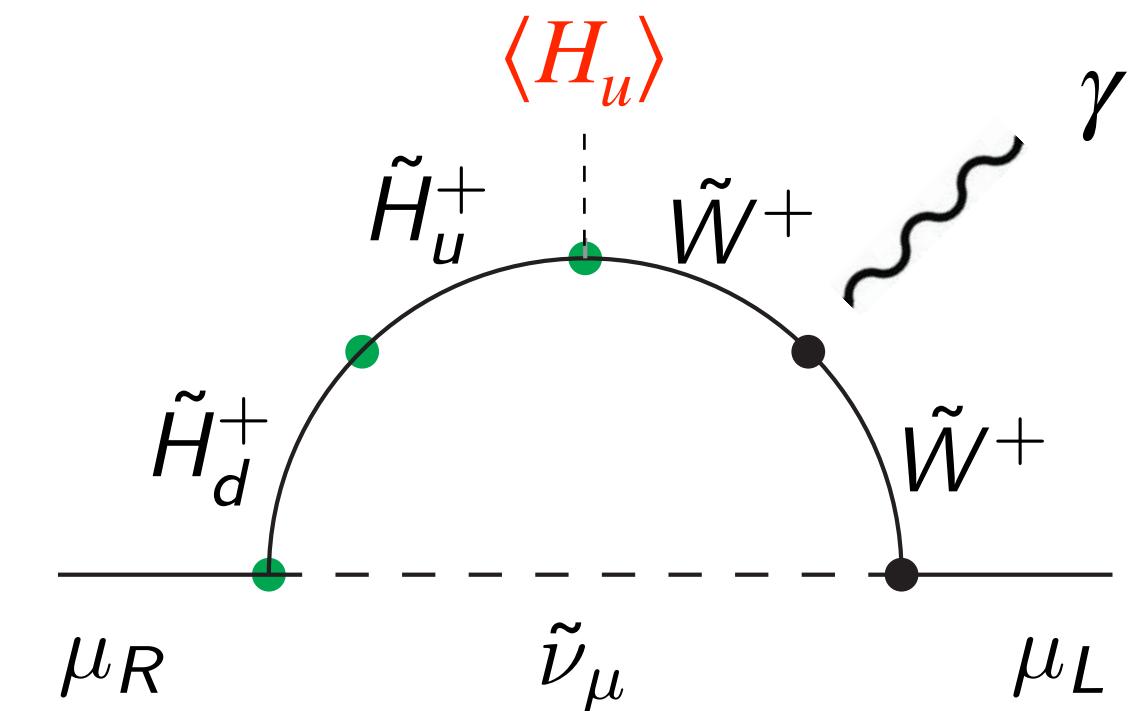
$$\vec{\mu} = g \left(\frac{e}{2m} \right) \vec{s}$$

$$a_\mu = \frac{(g-2)}{2} \equiv m_\mu \tilde{a}_\mu$$

SM: $\tilde{a}_\mu^{\text{SM}} \propto Y_\mu \langle H \rangle = m_\mu$

SUSY: $\Delta \tilde{a}_\mu^{\text{SUSY}} \propto Y_\mu \langle H_u \rangle = m_\mu \cdot \tan\beta$

$$m_\mu = Y_\mu \langle H_d \rangle \quad \tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$



$$\Delta a_\mu^{\text{BSM}} \sim \Delta a^{\text{SM,EW}} \cdot \left(\frac{m_W^2}{m_{\text{SUSY}}^2} \right) \cdot \tan\beta$$

$$\tan\beta \in [5 - 60] \rightarrow m_{\text{SUSY}} \in [200 - 600] \text{ GeV}$$