PICTP program:
New physics beyond the Standard Model
@Fragrant Hill

Testing electroweak SUSY for muon g-2 and dark matter @ LHC and Beyond

Lei Wu

Nanjing Normal University

Collaborators: M. Abdughani, K. Hikasa, J. M. Yang and J. Zhao

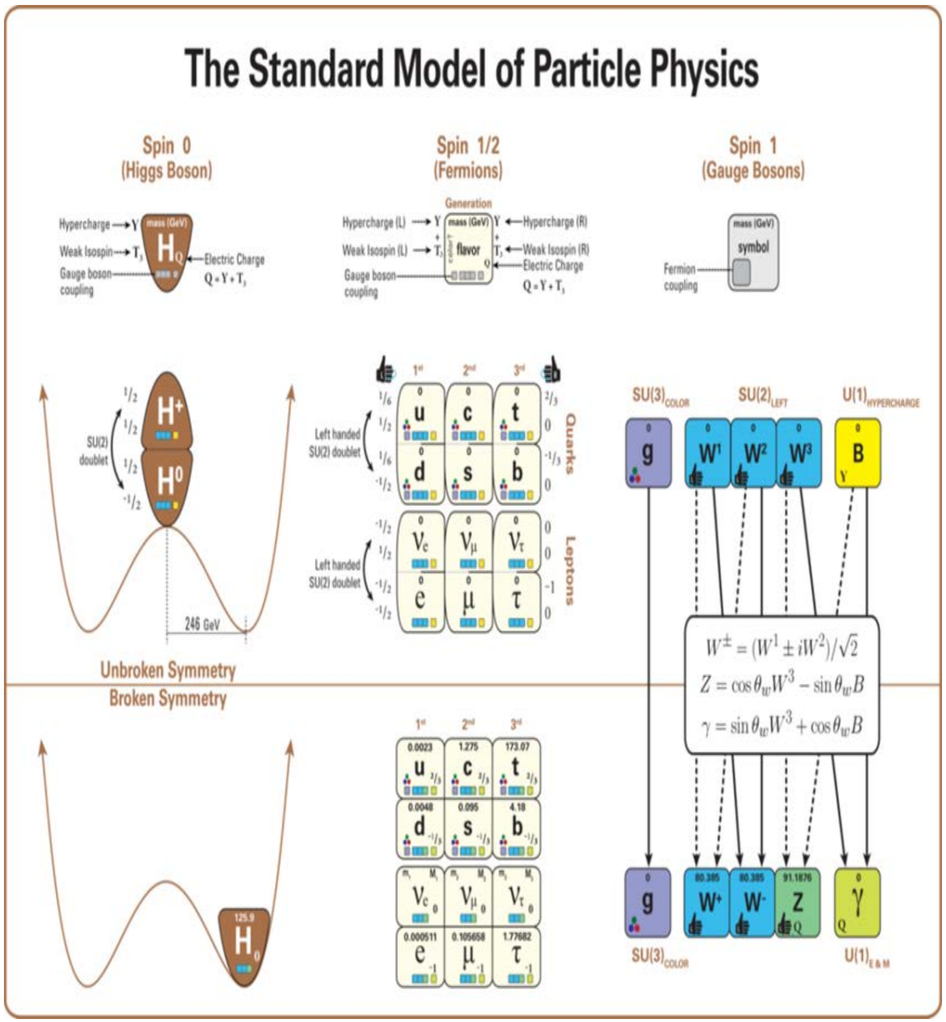
arXiv:1909.07792

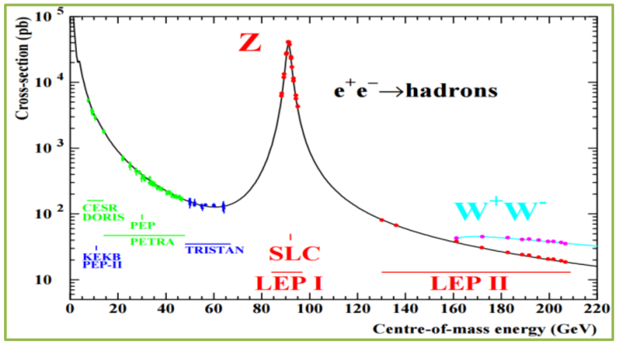
Outline

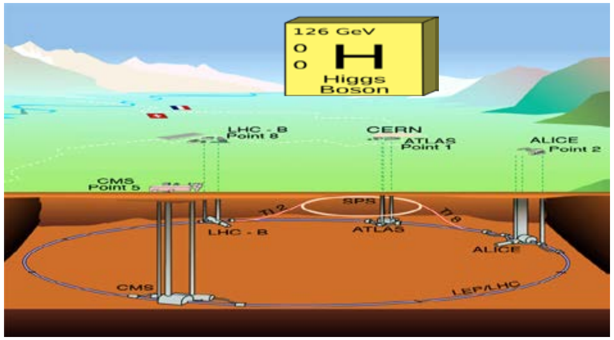
- **Why electroweak SUSY ?**
- **SUSY Muon g-2 and neutralino DM**
- **Implications for EWSUSY and collider tests**
- **Conclusions**

Why EWSUSY?

- **Success of the Standard Model**

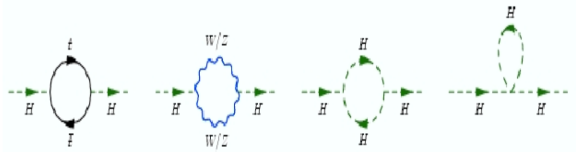






• Problems of the Standard Model

➢ Higgs Naturalness



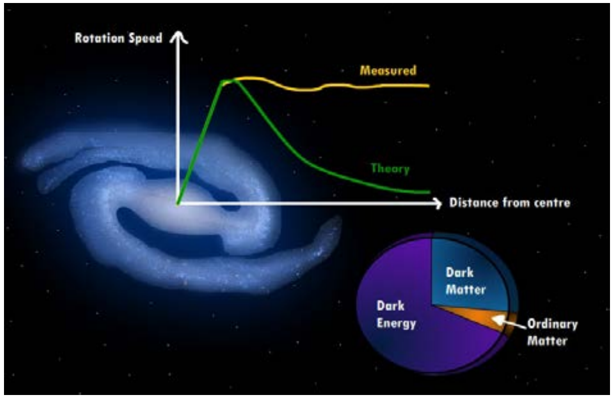
$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2$$

$\approx -(200\ \text{GeV})^2$ for $\Lambda = 10^3$ GeV

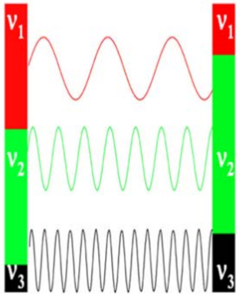
$\approx -(200\ \text{GeV})^2 \cdot 10^{32}$ for $\Lambda = 10^{19}$ GeV

$$m_H^2 = m_{0H}^2 + \delta m_H^2$$

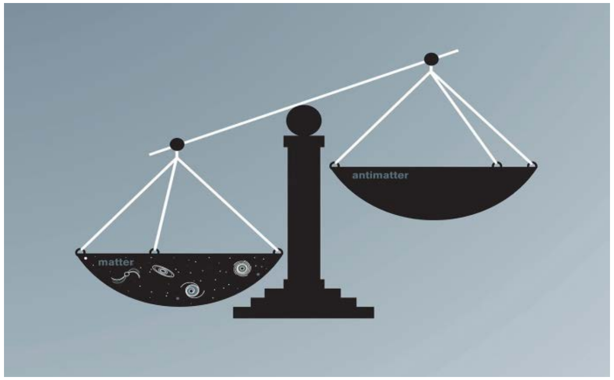
➢ Dark Matter



➢ Neutrino Mass

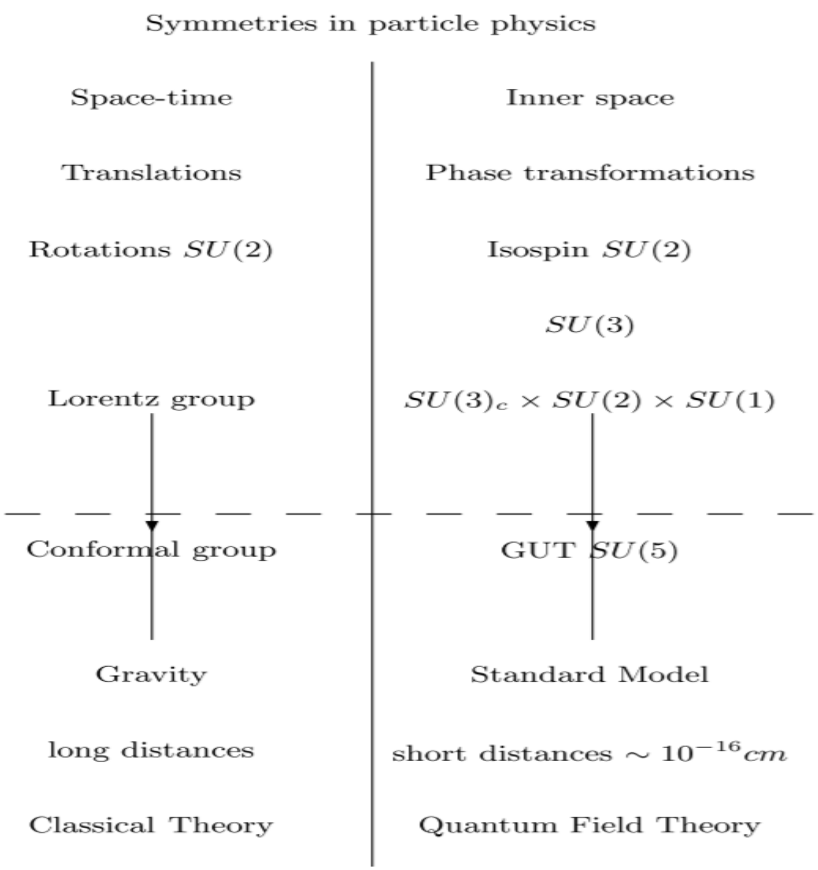
$|\nu_e\rangle =$  $= c_1|\nu_e\rangle + c_2|\nu_\mu\rangle + c_3|\nu_\tau\rangle$

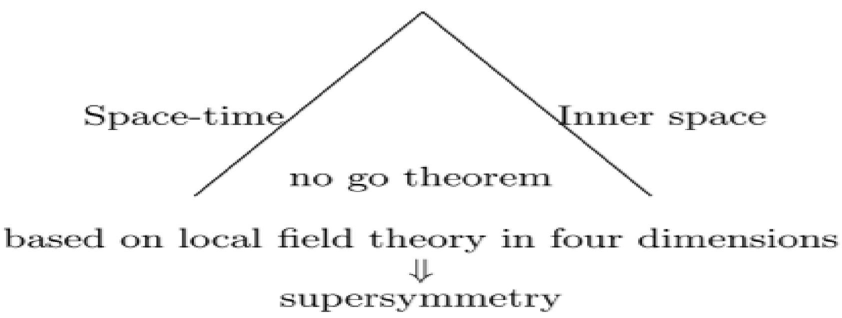
➢ Matter-antimatter asymmetry



• Supersymmetry

- Supersymmetry (SUSY): a symmetry between bosons and fermions.
- Introduced in 1973 as a part of an extension of the special relativity.
- Super Poincare algebra.





In summary, the Super–Poincaré algebra is given by the following set of commutators and anticommutators:

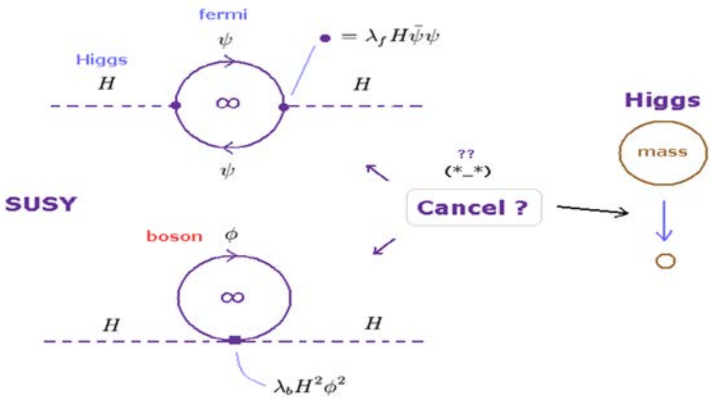
Haag, Lopuczansky and Sohnius

$$
\begin{aligned}
[P_\mu, P_\nu] &= 0, \\
[M_{\mu\nu}, P_\rho] &= -i(\eta_{\mu\rho}P_\nu - \eta_{\nu\rho}P_\mu), \\
[M_{\mu\nu}, M_{\rho\sigma}] &= -i(\eta_{\mu\rho}M_{\nu\sigma} - \eta_{\mu\sigma}M_{\nu\rho} - \eta_{\nu\rho}M_{\mu\sigma} + \eta_{\nu\sigma}M_{\mu\rho}), \\
[P_\mu, Q_a] &= 0, \\
[M_{\mu\nu}, Q_a] &= -(\sigma^4_{\mu\nu})_{ab}Q_b, \\
\{Q_a, \overline{Q}_b\} &= 2(\gamma^\mu)_{ab}P_\mu, \\
\{Q_a, Q_b\} &= -2(\gamma^\mu C)_{ab}P_\mu, \\
\{\overline{Q}_a, \overline{Q}_b\} &= 2(C^{-1}\gamma^\mu)_{ab}P_\mu, \qquad (4.1)
\end{aligned}
$$

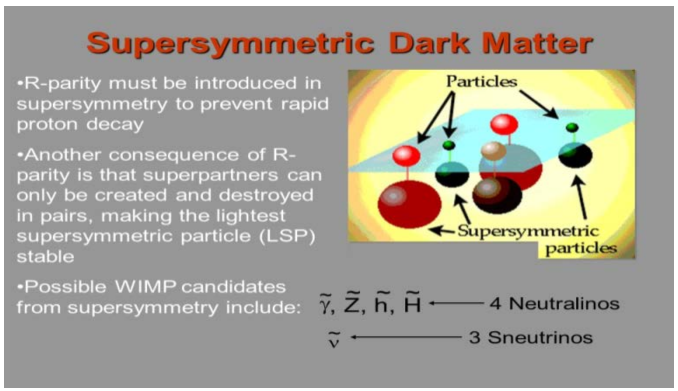
$(a, b = 1, 2, 3, 4)$, where

$$\sigma^4_{\mu\nu} = \frac{i}{4}\left[\gamma_\mu, \gamma_\nu\right].$$

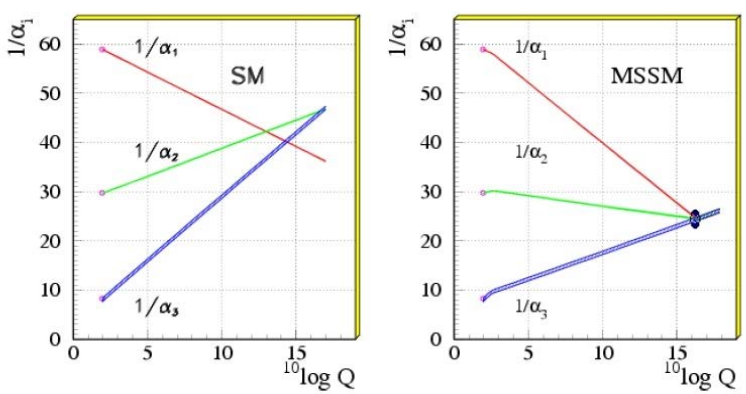
Naturalness



Dark Matter



Unification



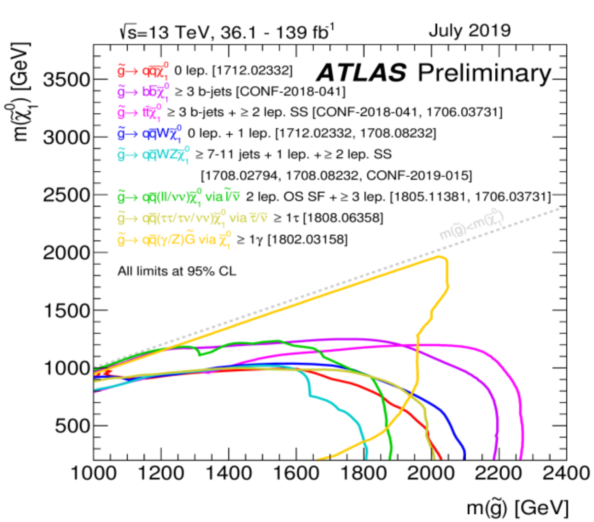
- **1970–74** Several theorists independently develop SUSY
- **1981** Supersymmetric version of the standard model proposed
- **1983** SUSY used to explain dark matter
- **1990** SUSY suggested as a way to unify electroweak and strong forces
- **2000** Large Electron Positron collider (the LHC's predecessor) fails to find evidence of SUSY particles called sleptons
- **2008** Tevatron sets mass limits on supersymmetric quarks (squarks)
- **2011** LHC tightens limits on SUSY masses

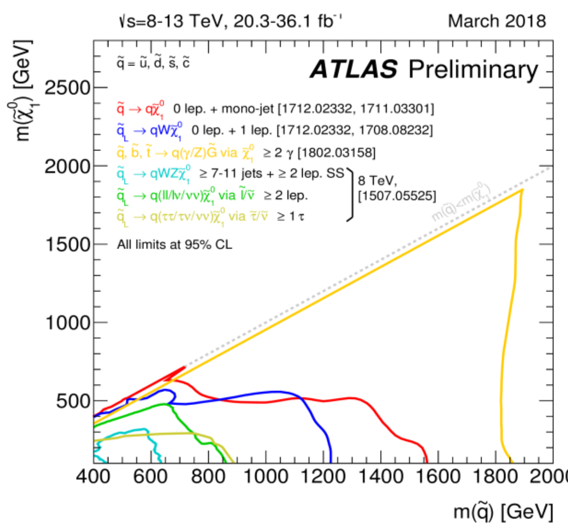
……

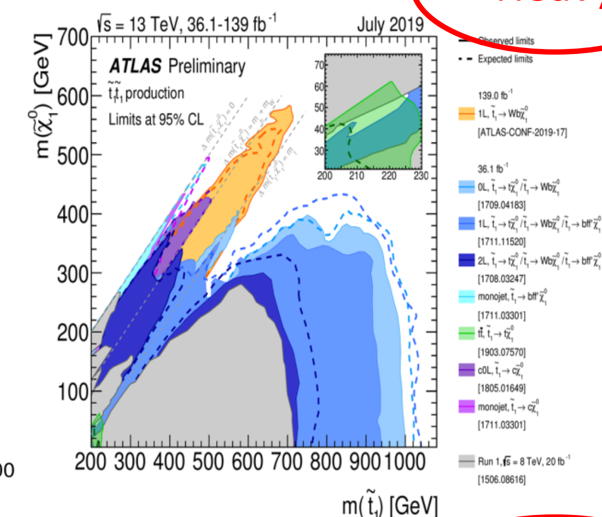
Such a passion will continue, although we haven't seen it.

• Searches for SUSY --- LHC

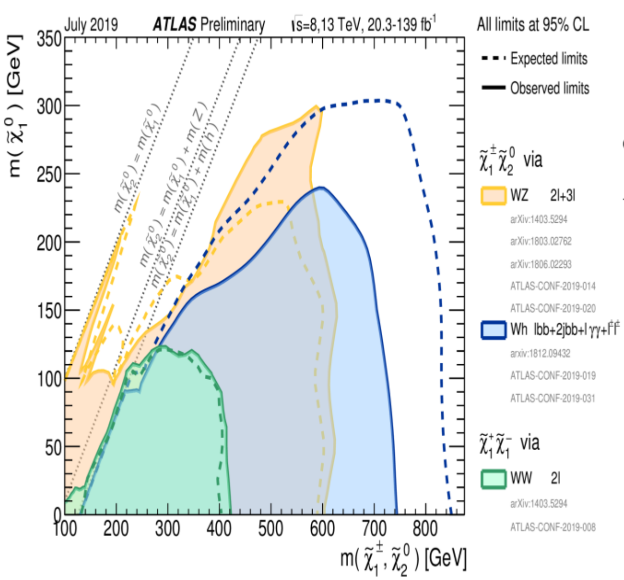
Heavy

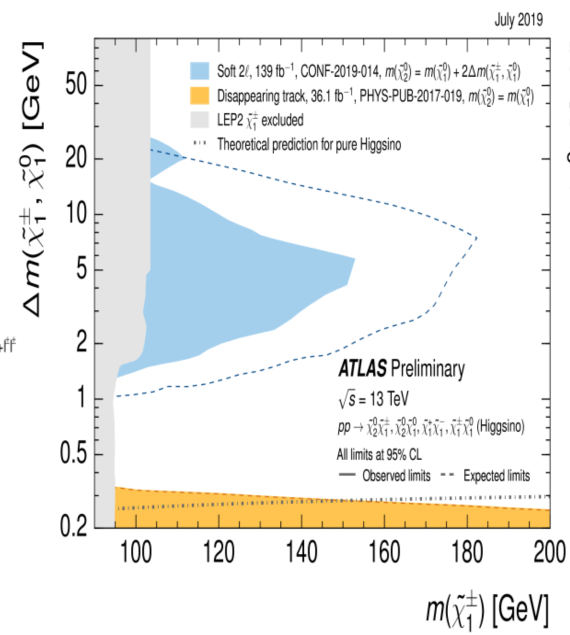


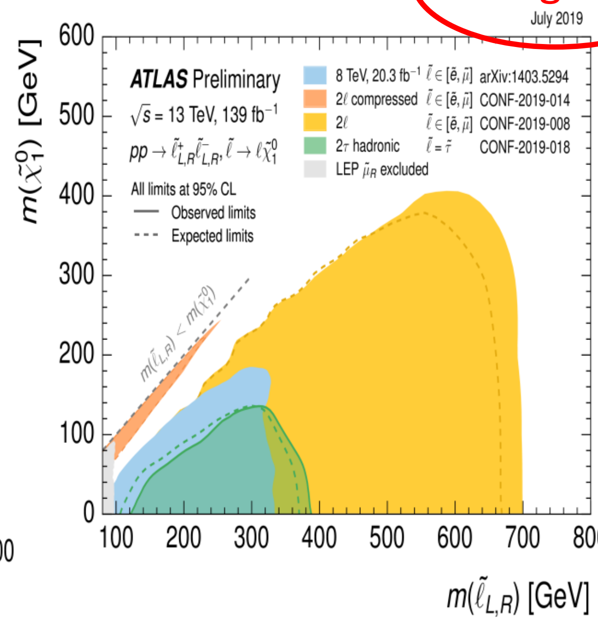




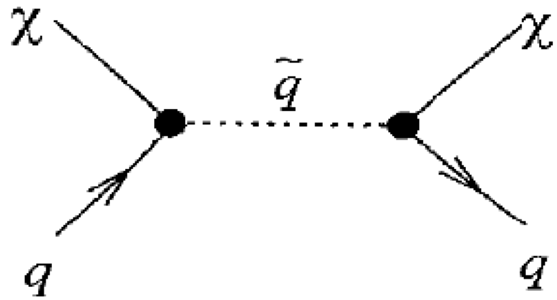
Light

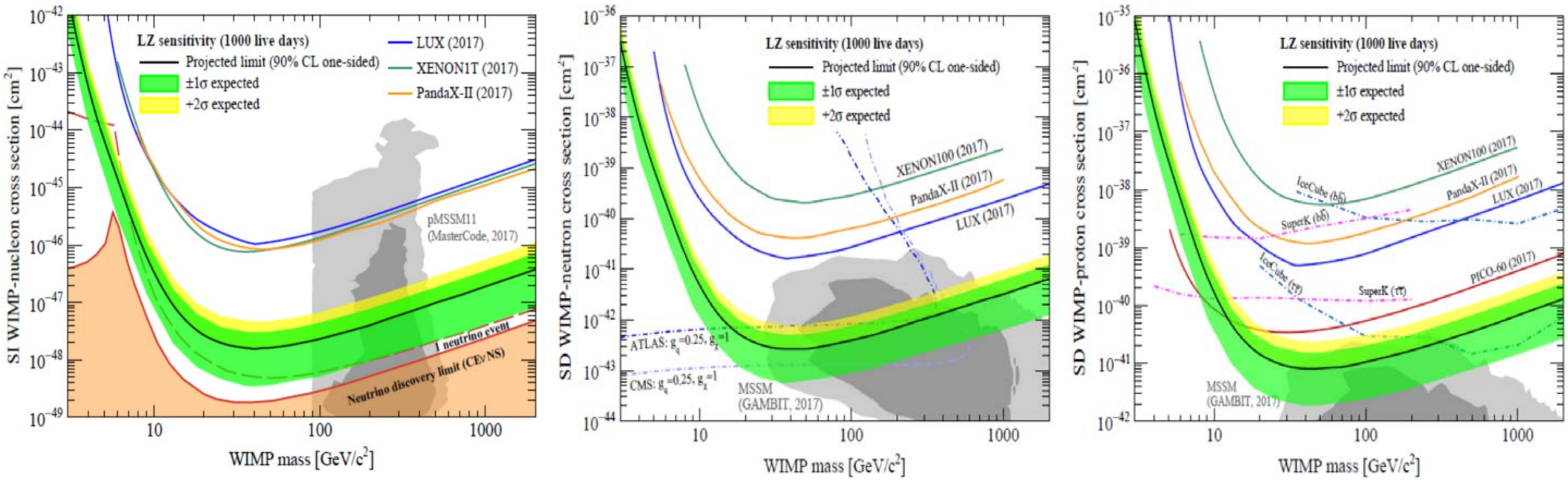






• Searches for SUSY --- Dark Matter

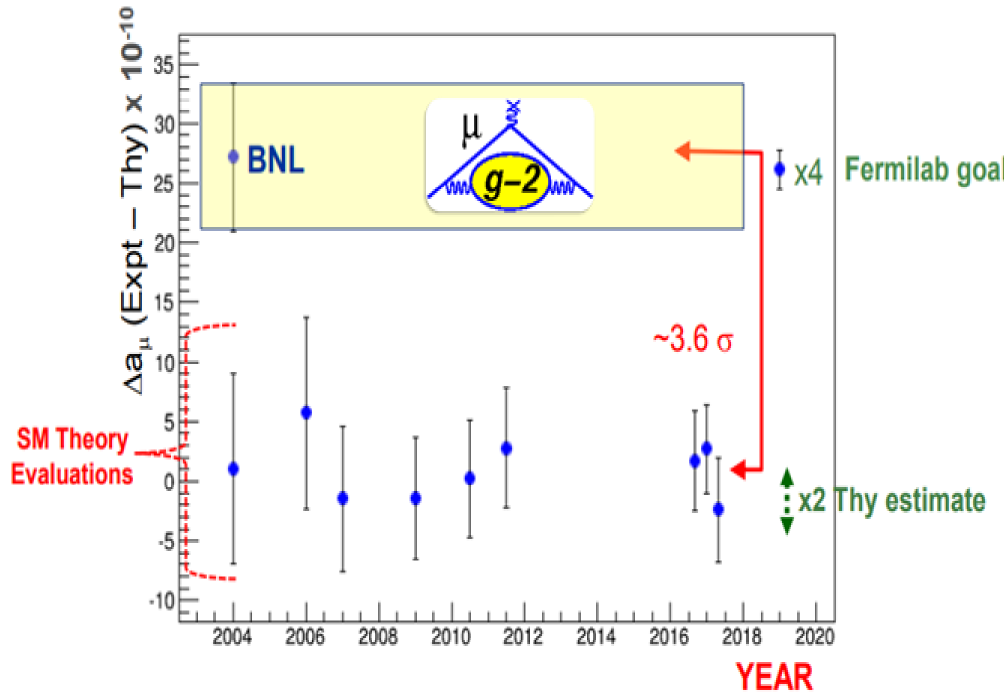




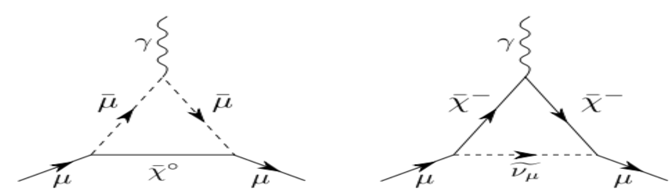
Colored mediators are strongly disfavored,

• Searches for SUSY --- Low energy observables

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0020	-0.4
Γ_Z [GeV]	2.4952 ± 0.0023	2.4942 ± 0.0008	0.4
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7411 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.44 ± 0.04	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.959 ± 0.008	—
σ_{had}[nb]	41.541 ± 0.037	41.481 ± 0.008	1.6
R_e	20.804 ± 0.050	20.737 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.737 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.782 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01618 ± 0.00006	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1030 ± 0.0002	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0001	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23154 ± 0.00003	0.7
	0.23148 ± 0.00033		-0.2
	0.23104 ± 0.00049		-1.0
A_e	0.15138 ± 0.00216	0.1469 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

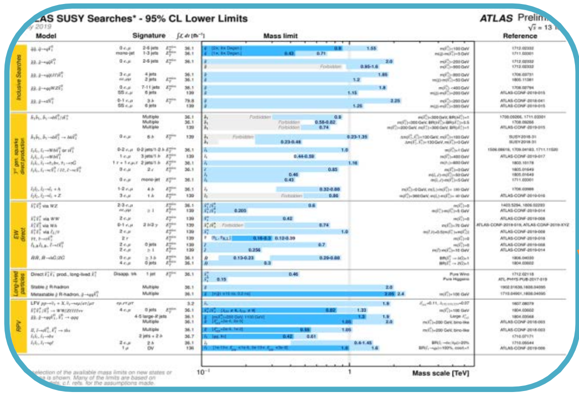


a_μ is now measured to 540 ppb; Goal is 140 ppb

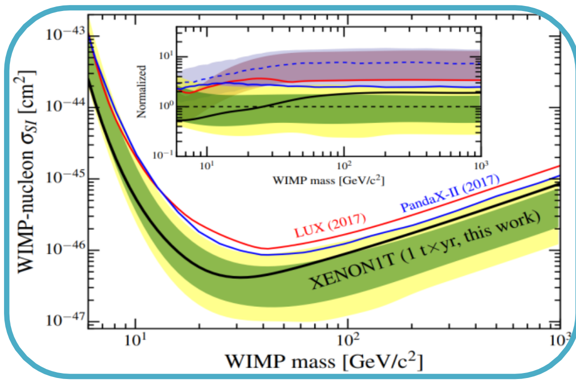


Uncolored sparticles have to be light.

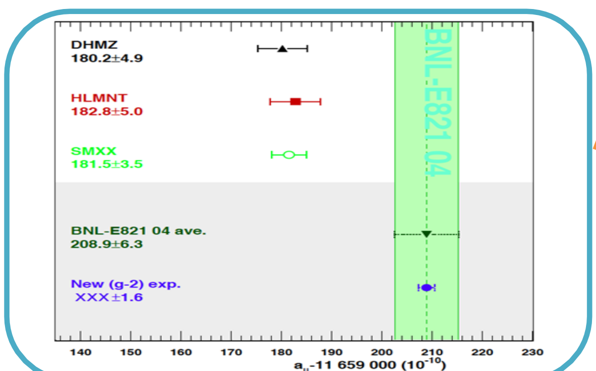
• EWSUSY (bottom-up)



LHC

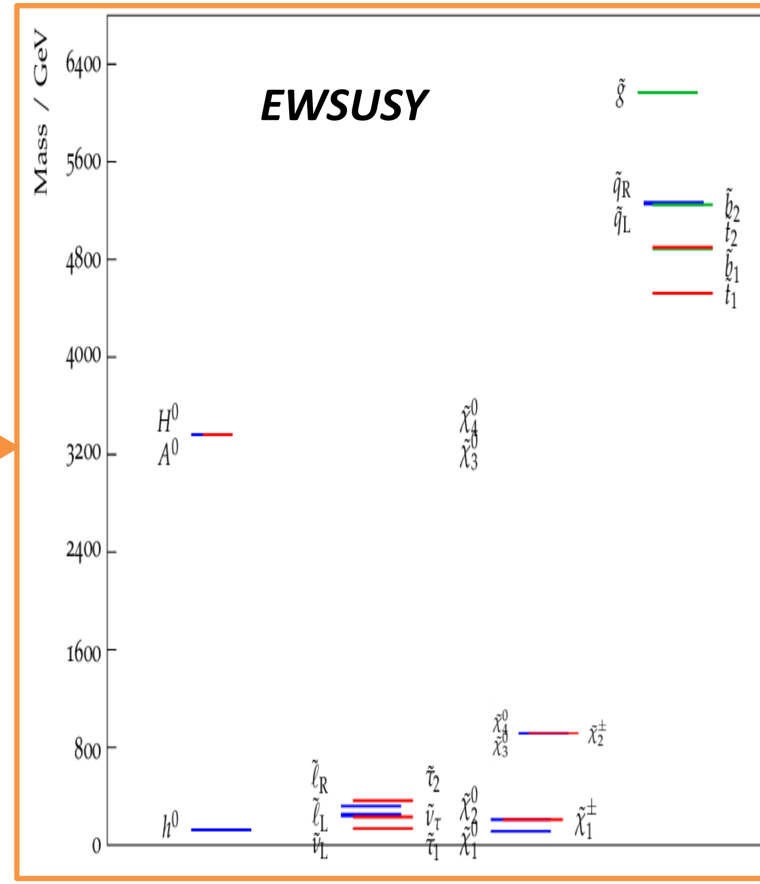


DM



Muon g-2

ElectroWeak SUSY



• EWSUSY (top-down)

Gaugino mediation scenarios for muon $g-2$ and dark matter

Peter Cox, Chengcheng Han (Tokyo U., IPMU), Tsutomu T. Yanagida (Tokyo U., IPMU & Shanghai Jiaotong U.), Norimi Yokozaki (Tohoku U.)

Nov 30, 2018 - 17 pages

JHEP 1908 (2019) 097
(2019-08-20)
DOI: 10.1007/JHEP08(2019)097
IPMU18-0193, TU-1077
e-Print: arXiv:1811.12699 [hep-ph] | PDF

Reconciling the muon g−2 , a 125 GeV Higgs boson, and dark matter in gauge mediation models

Ilia Gogoladze, Qaisar Shafi (Delaware U. & Delaware U., Bartol Inst.), Cem Salih Ün (Uludag U.)

Sep 25, 2015 - 13 pages

Phys.Rev. D92 (2015) no.11, 115014
(2015-12-17)
DOI: 10.1103/PhysRevD.92.115014
e-Print: arXiv:1509.07906 [hep-ph] | PDF

Reconcile muon g-2 anomaly with LHC data in SUGRA with generalized gravity mediation

Fei Wang (Zhengzhou U. & Beijing, Inst. Theor. Phys.), Wenyu Wang (Beijing U. of Tech.), Jin Min Yang (Beijing, Inst. Theor. Phys.)

Apr 2, 2015 - 13 pages

JHEP 1506 (2015) 079
(2015-06-12)
DOI: 10.1007/JHEP06(2015)079
e-Print: arXiv:1504.00505 [hep-ph] | PDF

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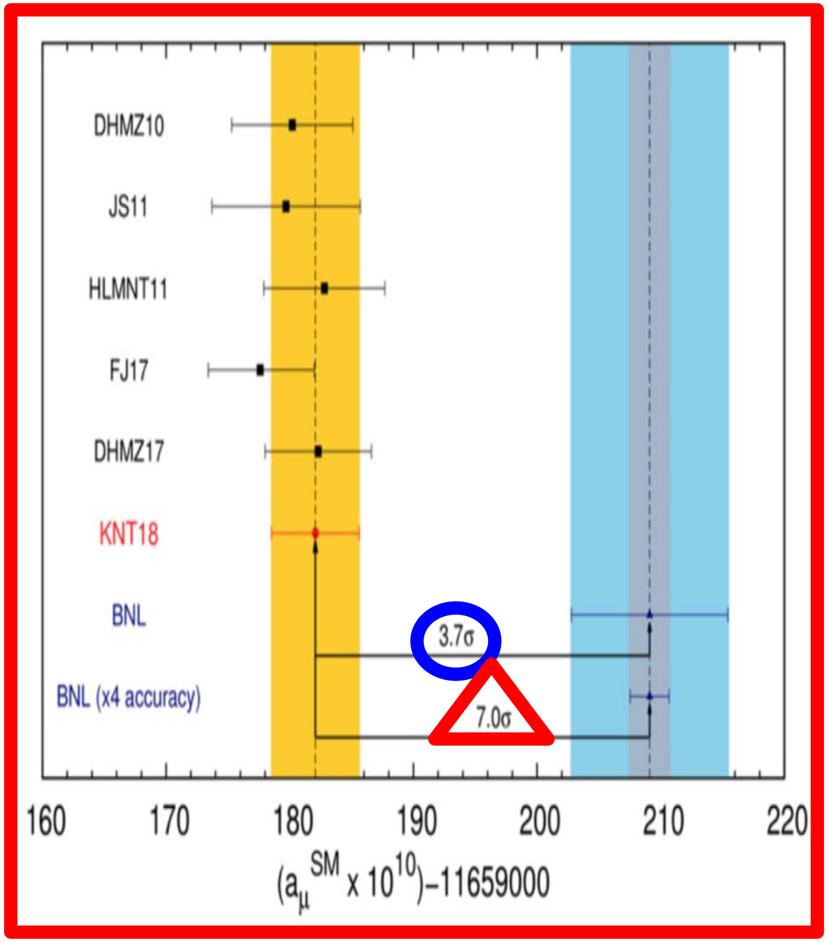
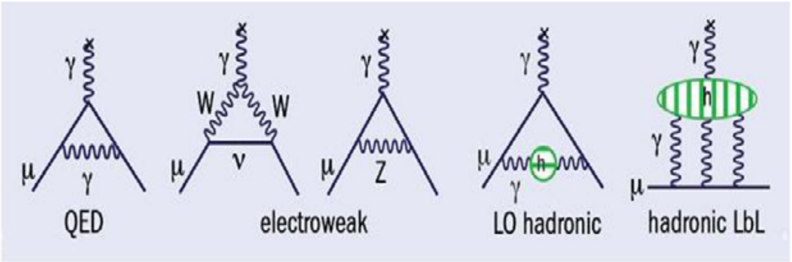
sorry for missing your papers

SUSY muon g-2 and DM

- **SM muon g-2**



Contributions to the SM:



a_μ $\sim 10^{-3}$ $\sim 10^{-7}$ $\sim 10^{-9}$

- Main theoretical uncertainty comes from LO Hadronic loop contributions (quarks and gluons)

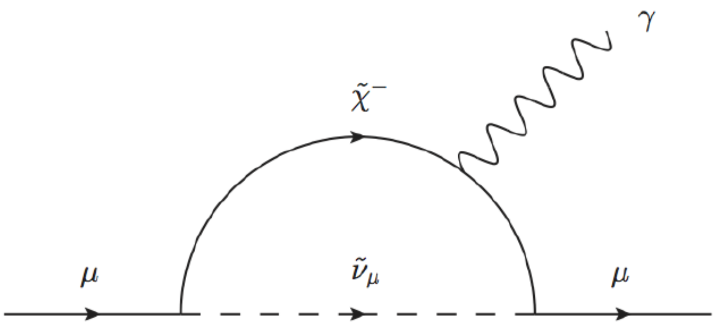
$$20.6 \times 10^{-10} < \Delta a_\mu < 36.6 \times 10^{-10} \quad (1\sigma)$$
$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$

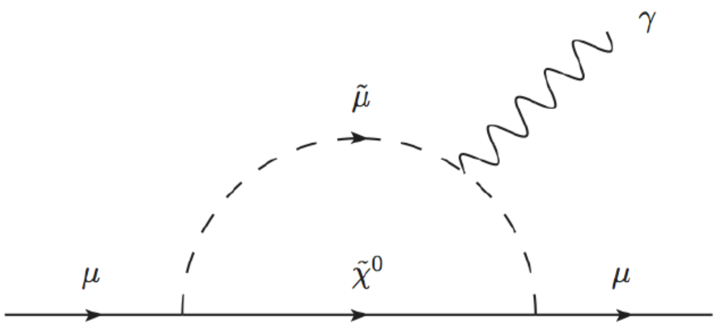
where

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$$

• SUSY muon g-2 @ 1 loop

One-loop contributions come from the following diagrams:





$$a_\mu^{\rm SUSY}\left(\widetilde{\chi}^\pm,\widetilde{\nu}_\mu\right) \approx \frac{g_2^2}{(4\pi)^2}\frac{m_\mu^2}{m_{\rm soft}^2}\,{\rm sgn}(\mu)\tan\beta.$$

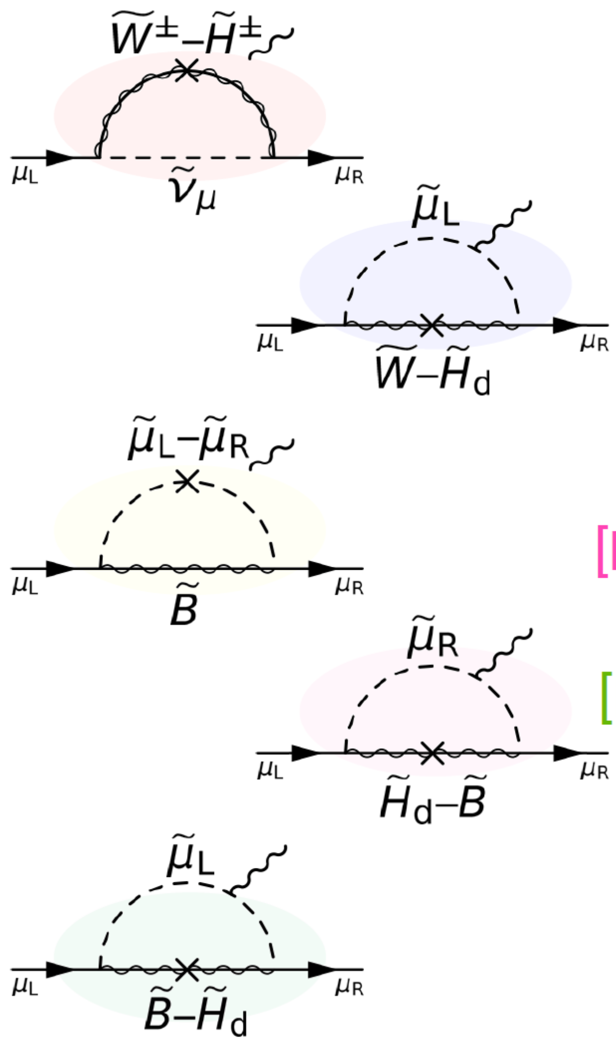
$$a_\mu^{\rm SUSY}\left(\widetilde{\chi}^0,\widetilde{\mu}\right) \approx \frac{g_Y^2}{(4\pi)^2}\frac{m_\mu^2}{m_{\rm soft}^2}\,{\rm sgn}(\mu)\tan\beta + \cdots,$$

Sneutrino-chargino diagram

- Typically dominant contribution
- Needs light charginos/sneutrinos

Smuon-neutralino diagram

- Bino-smuon loop can be dominant with light binos and large $\tilde{\mu}_{L,R}$ mixing



[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$

[B] $$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_\mathrm{L}}}{M_1},\frac{m_{\tilde{\mu}_\mathrm{R}}}{M_1}\right)$$

[BHR] $$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_\mathrm{R}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_\mathrm{R}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{R}}}\right)$$

[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$

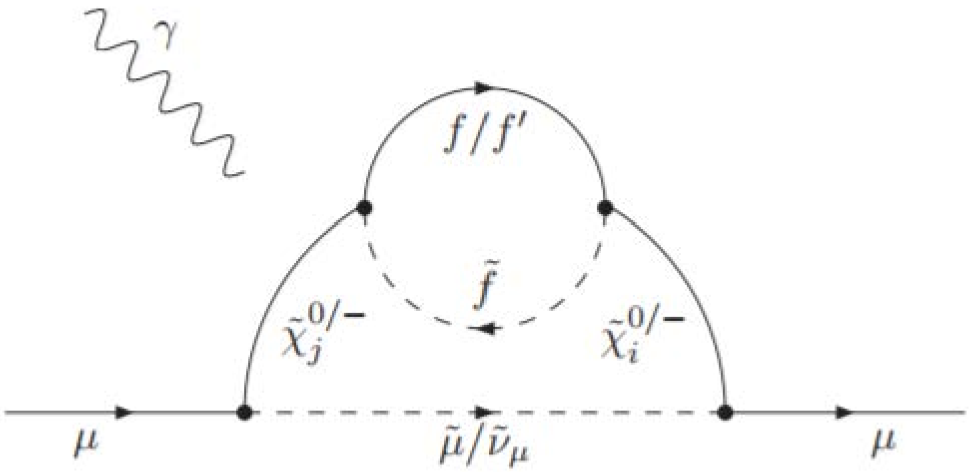
F_a, F_b are loop functions and positive.

$$F_a(x,y)=\frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2},\qquad F_b(x,y)=-\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

From Iwamoto

- **SUSY muon g-2 @ 2 loop**

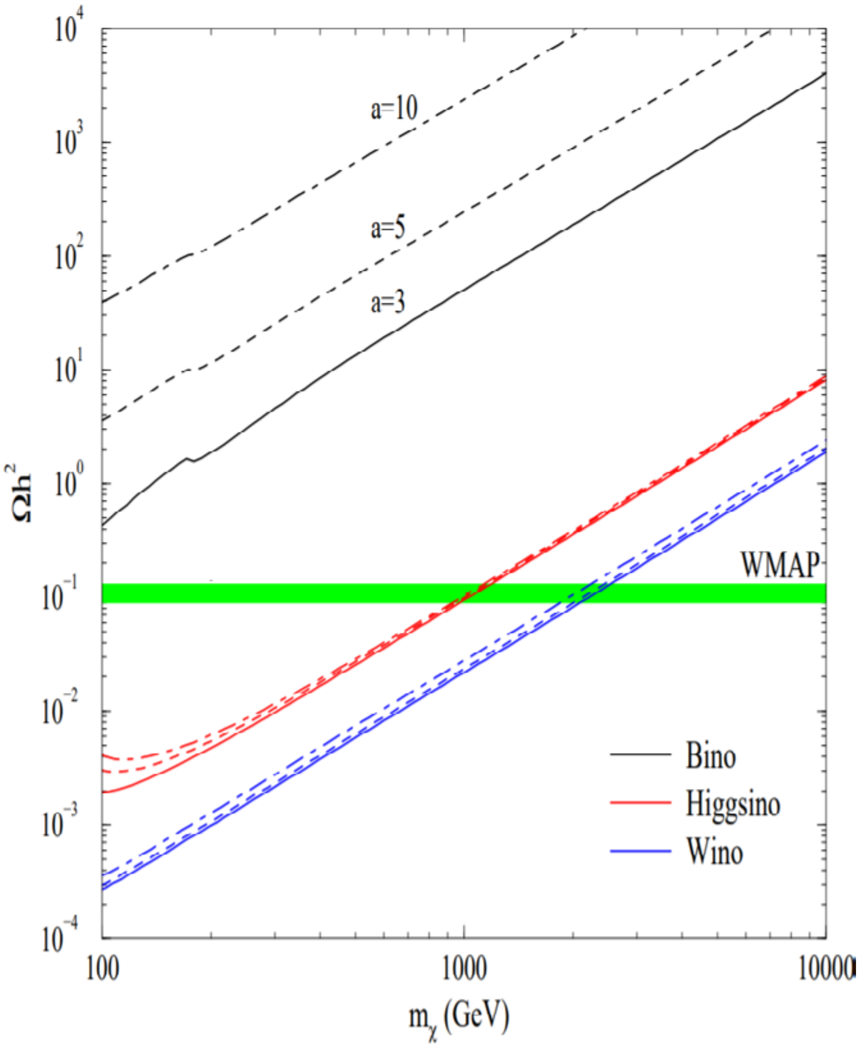


These corrections are also significant and even logarithmically enhanced for heavy squark, about 10%.

- lighter SUSY-particles
- larger tan β

$\Rightarrow$ larger a_μ^{SUSY}

• DM relic density and Direct detections



For a wino/higgsino-like neutralino DM,it is too heavy to produce the required g-2.

For a bino-like neutralino DM,

1. **Co-annihilating with stop/stau/wino…**
2. **Mixed with Higgsinos(+Wino)**
3. **Resonant annihilation via Z, h, A, H**

Implications for EWSUSY and Collider Tests

- **Possible scenarios of EWSUSY for both g-2 and DM**

Bino-Higgsino-Slepton (BHL)

Bino-Wino-Slepton (BWL)

Bino-Higgsino-Wino-Slepton (BHWL)

- **Parameter scan**

Scan ranges

$$\text{BWL}: \quad 0\ \text{TeV} \le M_1, M_2 \le 3\ \text{TeV}, \quad 3\ \text{TeV} \le \mu \le 5\ \text{TeV}$$

$$\text{BHL}: \quad 0\ \text{TeV} \le M_1, \mu \le 3\ \text{TeV}, \quad 3\ \text{TeV} \le M_2 \le 5\ \text{TeV}$$

Other SUSY parameters in both scenarios are taken as

$$100\ \text{GeV} \le M_{L_{1,2}} = M_{E_{1,2}} \le 3\ \text{TeV} \quad 1 \le \tan\beta \le 50$$

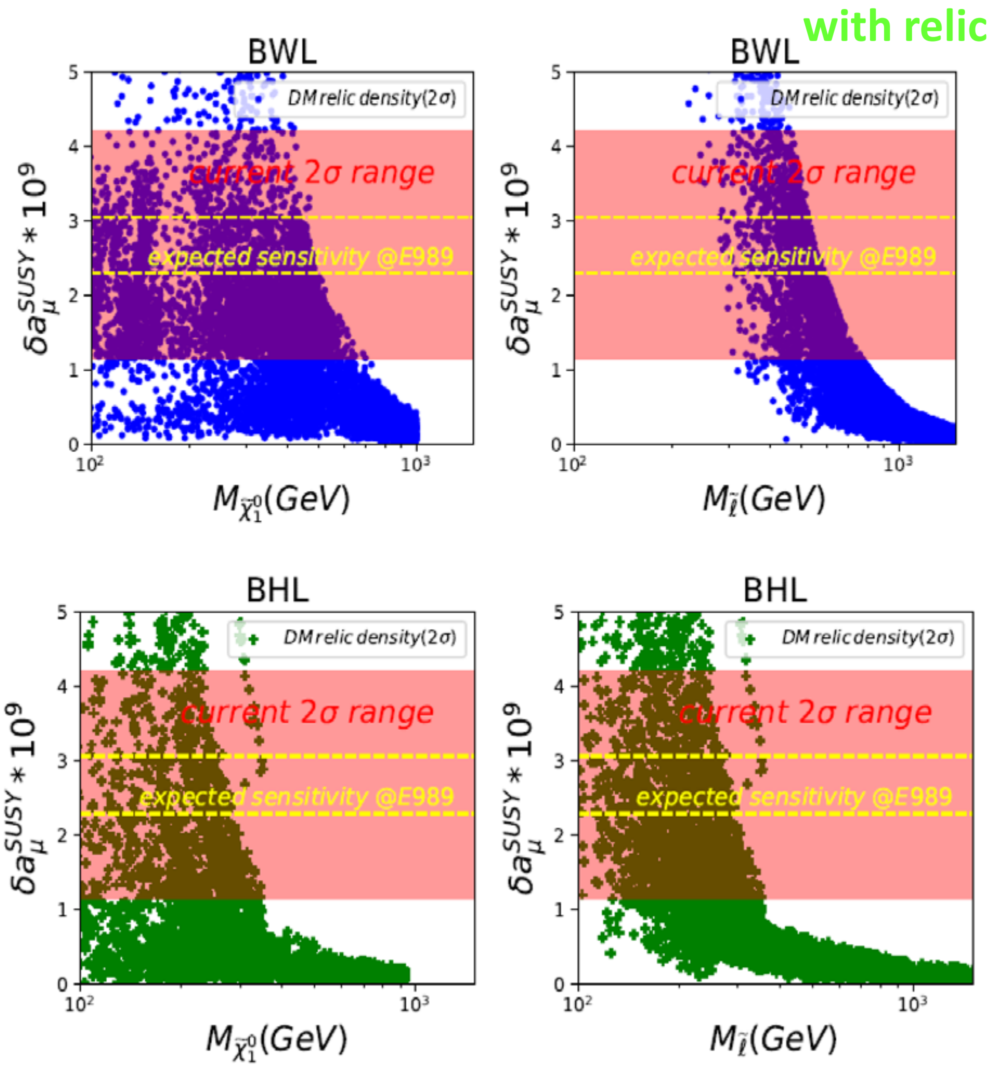
$$3\ \text{TeV} \le M_{\tilde{t}_R} \le 5\ \text{TeV} \quad -5\ \text{TeV} \le A_t = A_b = A_\tau \le 5\ \text{TeV}$$

$$M_{L_3} = M_{E_3} = M_3 = 5\ \text{TeV} \quad A_u = A_d = A_e = 0$$

Constraints

- Higgs mass
- Vacuum stability
- LEP and LHC
- Muon g-2
- DM Relic density and direct detection

• Result-1: Muon g-2



In the BWL,

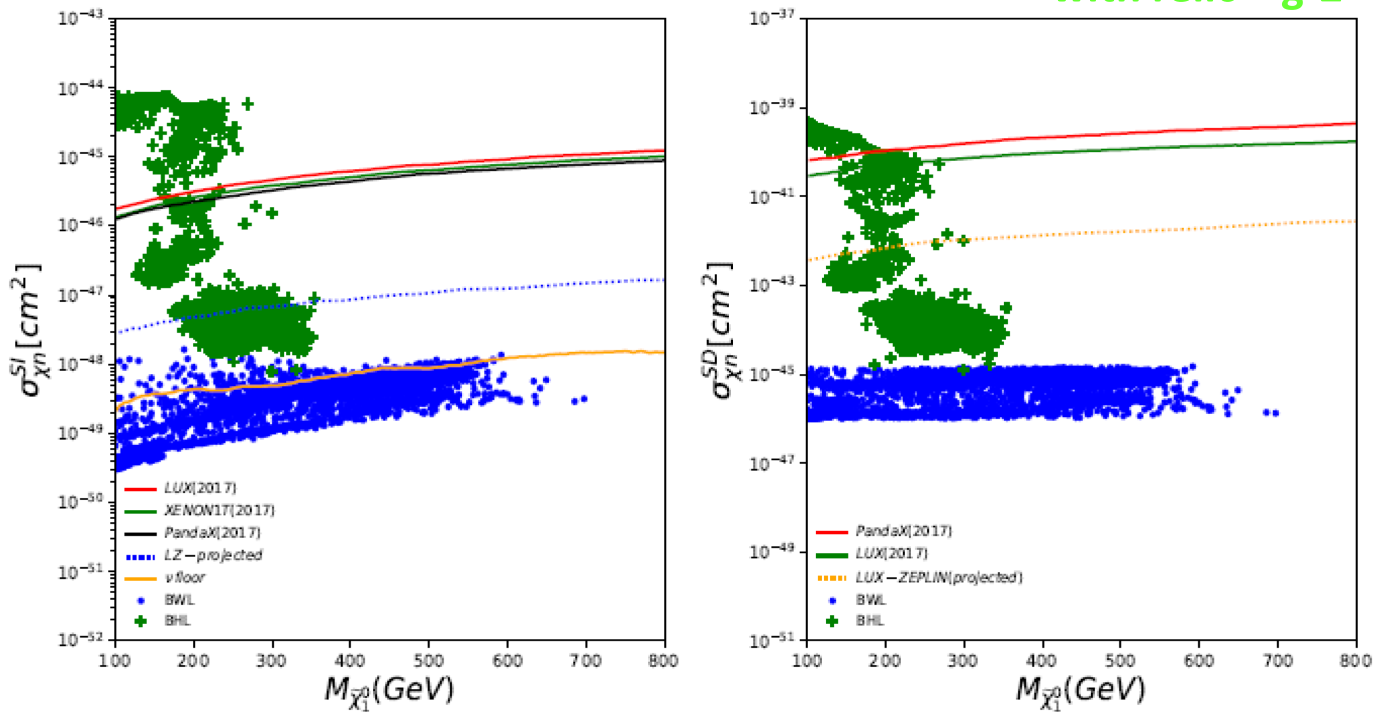
1. **LSP and slepton are lighter than about 700 GeV and 800 GeV, respectively.**
2. **Bino-wino coannihilation (dominant)+ bino-slepton coannihilation.**

In the BHL,

1. **LSP and slepton are lighter than about 350 GeV.**
2. **Bino-slepton coannihilation.**

• Result-2: DM direct detection

with relic + g-2



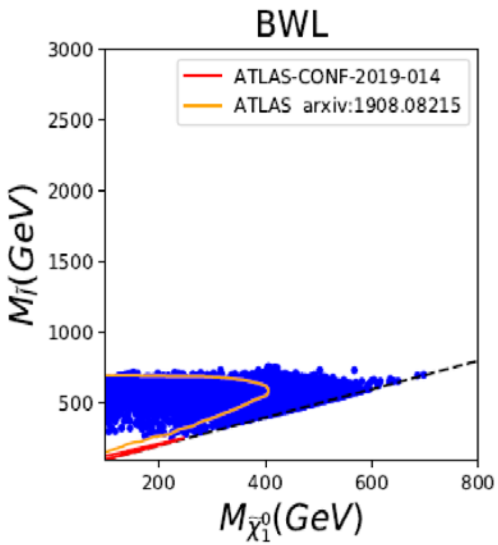
1. In the BWL, the LSP is extremely bino-like, and thus the SI and SD cross sections are very small, which can be much below the LZ-projected sensitivities.

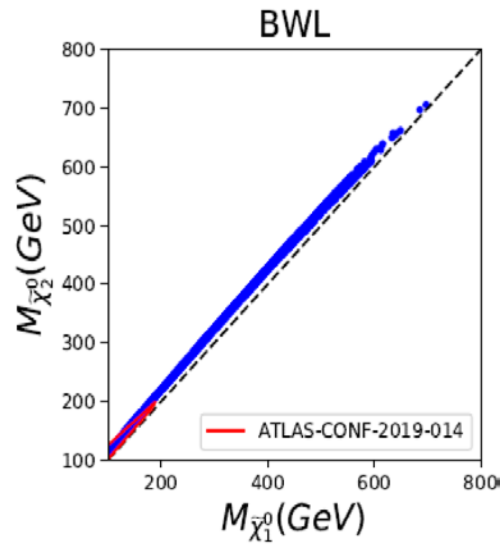
2. In the BHL, the LSP has certain higgsino component so that it can scatter with the nucleons sizably and are tightly constrained by current direct detection limits.

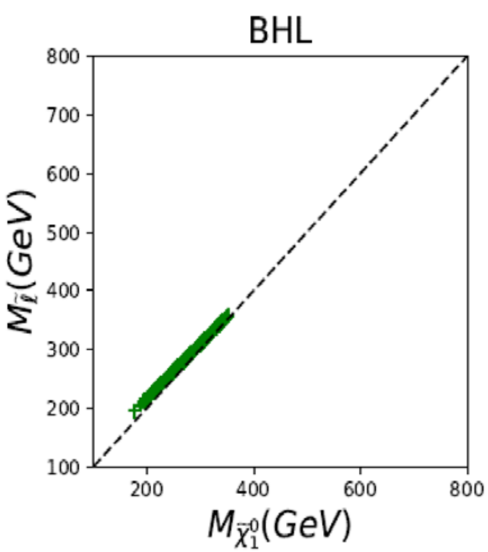
3. Sneutrino DM is excluded by direct detection.

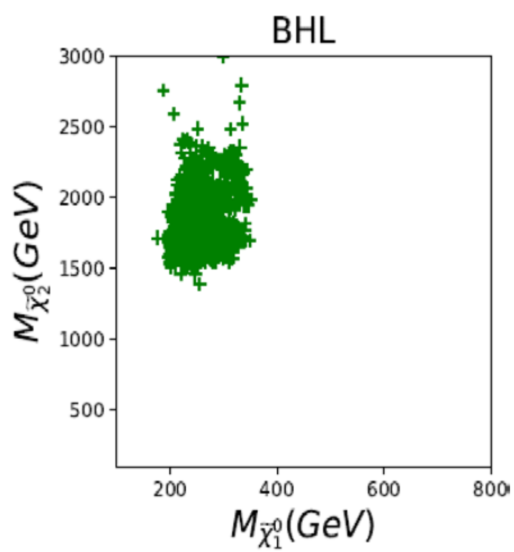
• Result-3 LHC

with relic+g-2+DD









In the BWL,

1. **Samples with sizable mass splitting of slepton and the LSP have been largely excluded by the LHC search for 2lepton+MET events.**

2. **Besides, the light wino-like neutralino in the co-annihilation region are not allowed.**

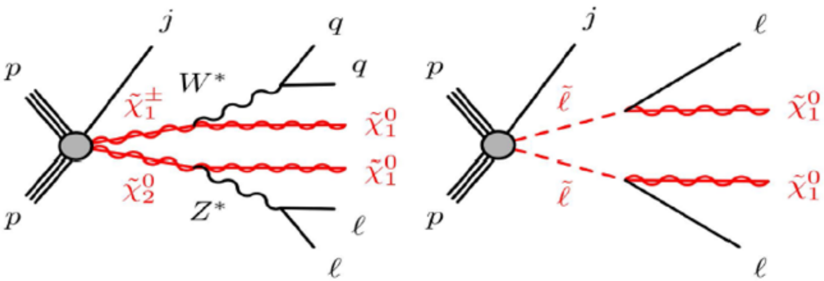
In the BHL,

There is still no LHC bound because:

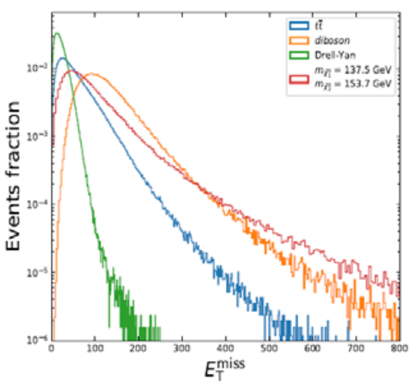
1. **Samples have heavy higgsino-like neutralino**

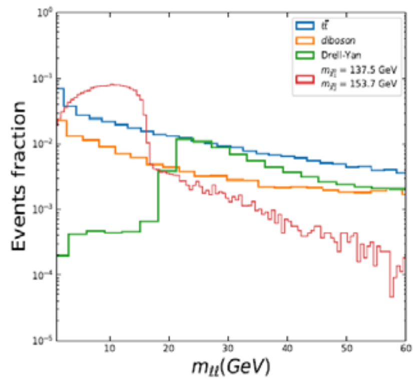
2. **Heavy compressed slepton and LSP**

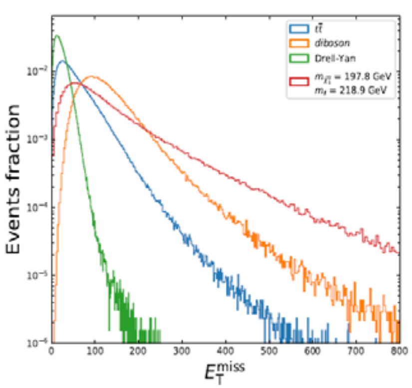
• Result-4: HL-LHC, HE-LHC



soft lepton pair plus missing energy events







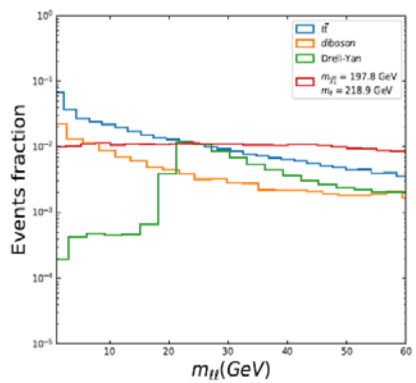


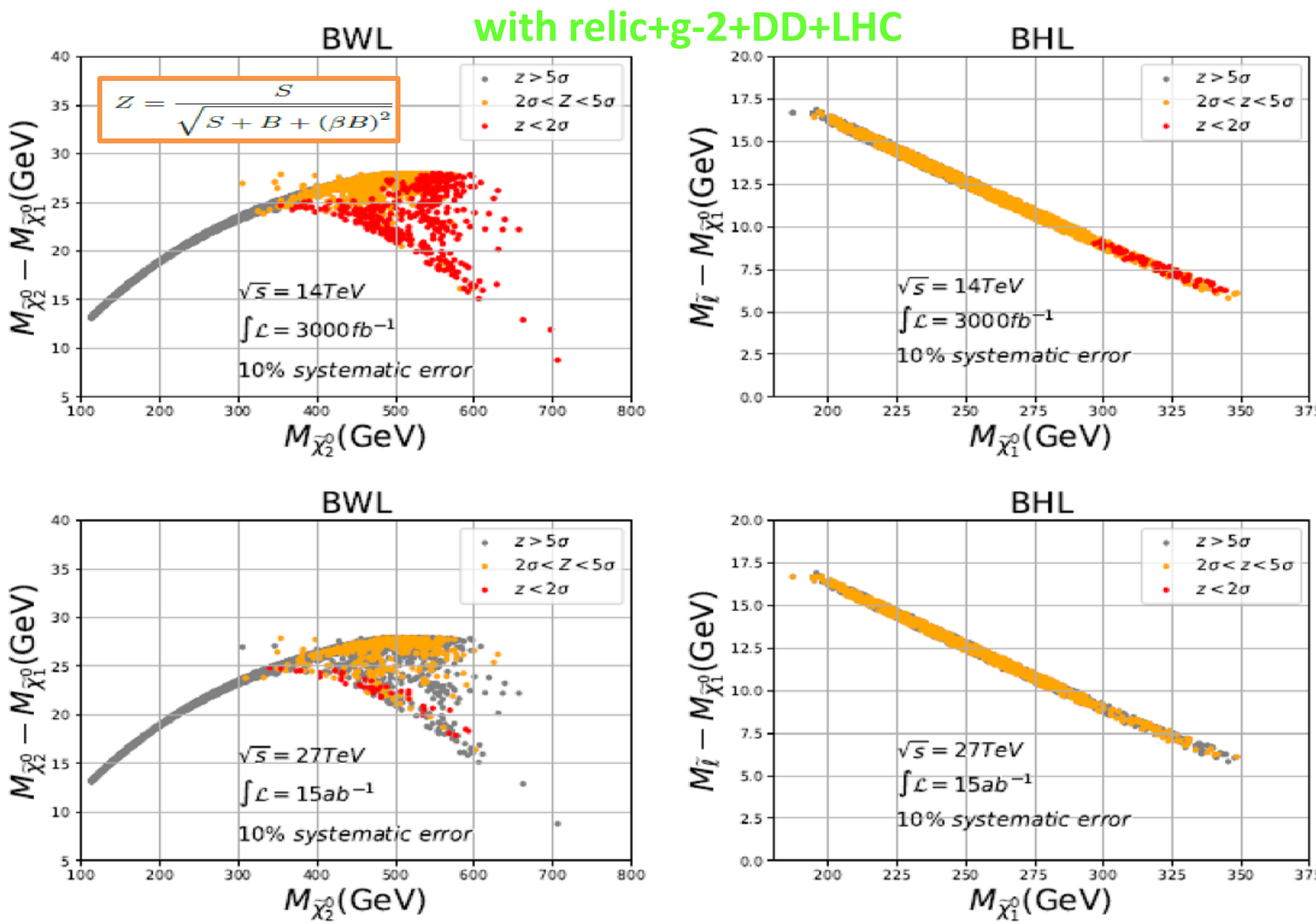
TABLE I. The cut flow for the cross sections of the signal and backgrounds at the 27 TeV HE-LHC for the BWL benchmark point $m_{\tilde{\chi}_1^0} = 137.4$ GeV, $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 153.7$ GeV, $\tan\beta = 50$. The cross sections are in units of fb.

Cuts	$t\bar{t}$	diboson	Drell-Yan	BWL
$\not{E}_T > 200$ GeV	37512.99	1721.53	246.54	618.83
$N(\ell) = 2$, OSSF, $p_T(\ell_1) > 5$ GeV, $p_T(\ell_2) > 4$ GeV	956.16	38.536	15.60	51.03
$N(j) \geq 1$, $N(b) = 0$, $p_T(j_1) > 100$ GeV, $\Delta\phi(j_1, P_T^{miss}) > 2$, $\Delta\phi(j, P_T^{miss}) > 0.4$	74.16	16.43	9.36	34.53
$m_{\tau\tau} \notin [0, 160)$ GeV, 1 GeV $< m_{\ell\ell} <$ 60 GeV, $m_{\ell\ell} \notin (3, 3.2)$ GeV, $\Delta R_{\ell\ell} > 0.05$	23.84	3.64	3.12	27.68
$\not{E}_T/H_T^{lep} > \max(5, 15 - 2m_{\ell\ell})$	7.94	2.26	3.12	24.22
$\Delta R_{\ell\ell} < 2$	2.65	1.38	3.12	20.15

TABLE II. The cut flow for the cross sections of the signal and backgrounds at the 27 TeV HE-LHC for the BHL benchmark point $m_{\tilde{\chi}_1^0} = 197.8$ GeV, $m_{\tilde{\ell}} = 218.9$ GeV, $\tan\beta = 17.5$. The cross sections are in units of fb.

Cuts	$t\bar{t}$	diboson	Drell-Yan	BHL
$\not{E}_T > 200$ GeV	37512.99	1721.53	246.54	69.97
$N(\ell) = 2$, OSSF, $p_T(\ell_1) > 5$ GeV, $p_T(\ell_2) > 4$ GeV	956.16	38.54	15.60	7.21
$N(j) \geq 1$, $N(b) = 0$, $p_T(j_1) > 100$ GeV, $\Delta\phi(j_1, P_T^{miss}) > 2$, $\Delta\phi(j, P_T^{miss}) > 0.4$	74.16	16.43	9.36	4.71
$m_{\tau\tau} \notin [0, 160)$ GeV, 1 GeV $< m_{\ell\ell} <$ 60 GeV, $m_{\ell\ell} \notin (3, 3.2)$ GeV, $\Delta R_{\ell\ell} > 0.05$	23.84	3.64	3.12	2.18
$\not{E}_T/H_T^{lep} > \max[3, 15 - 2[m_{T_2}^{100}/(1\text{GeV}) - 100]]$	13.24	3.15	3.12	1.73

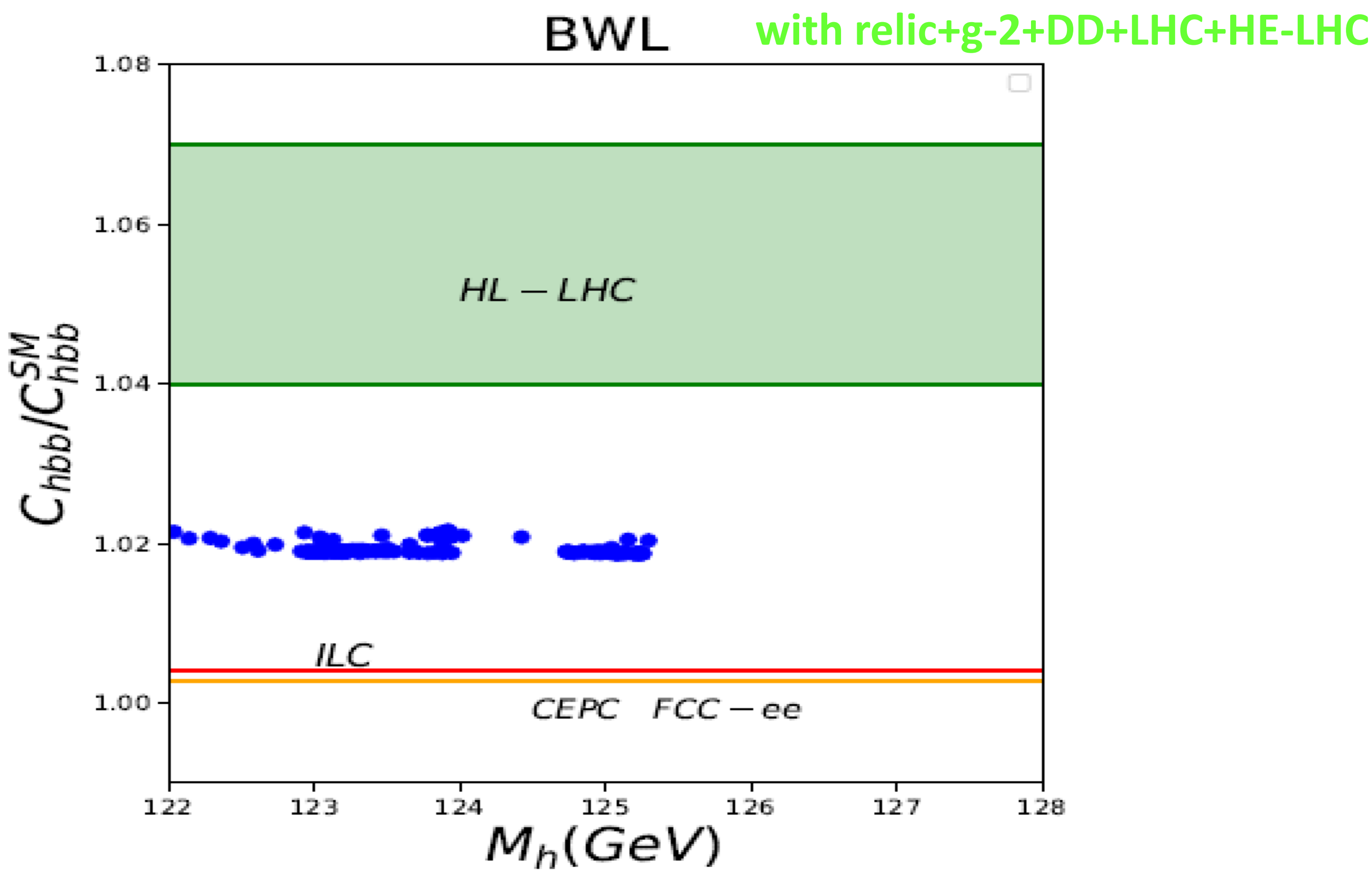
• Result-4: HL-LHC, HE-LHC



1. A large portion of the samples in both scenarios will be excluded by HL-LHC.

2. Future HE-LHC can exclude the whole BHL and most part of BWL scenarios.

• Result-5: CEPC

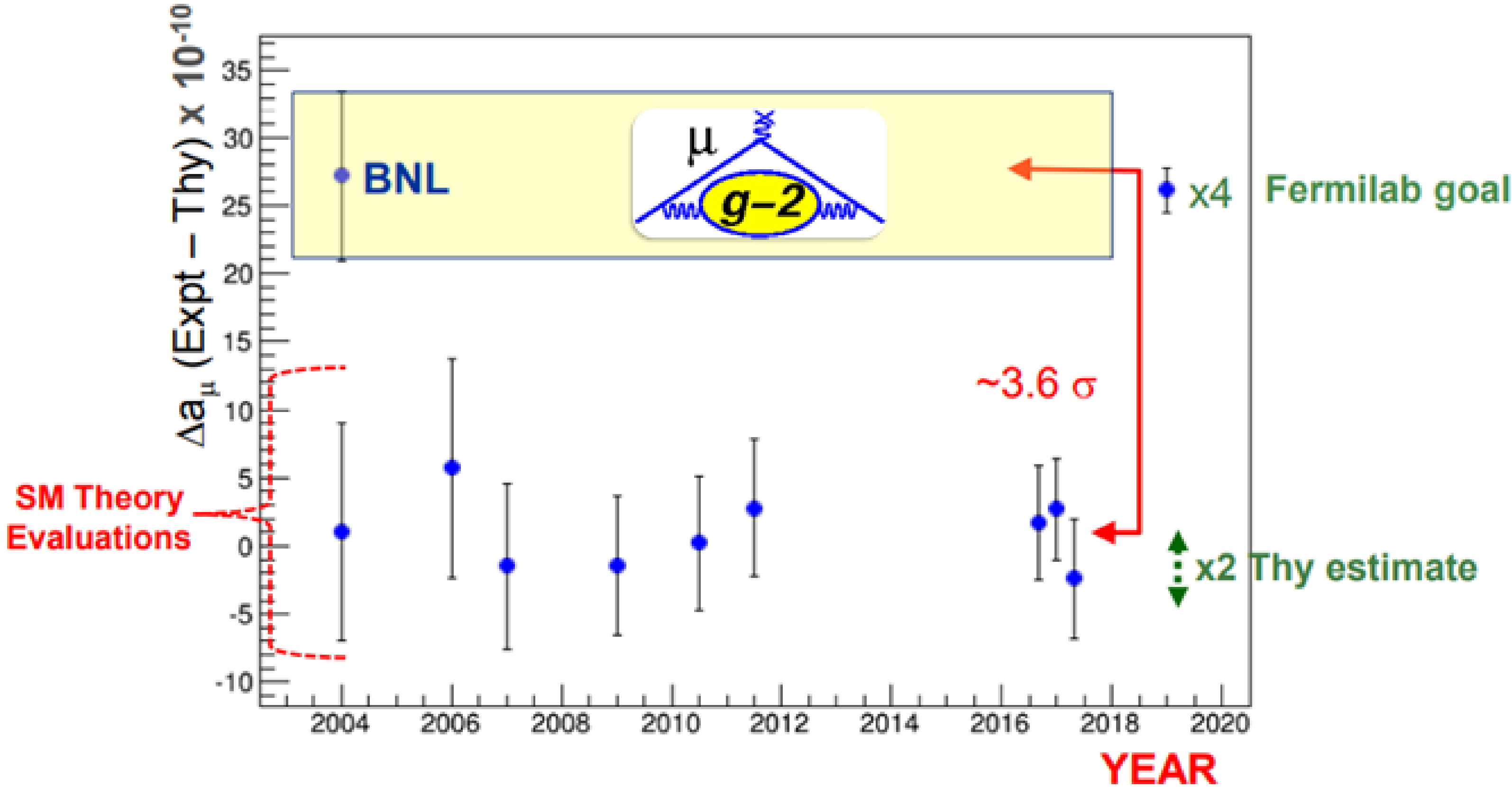


Due to EW corrections and large tanb enhancement, the Higgs-bottom coupling can still be increased by about 2%, which is below the HL-LHC sensitivity but can be readily covered by the Higgs factory ILC, FCC-ee, or CEPC.

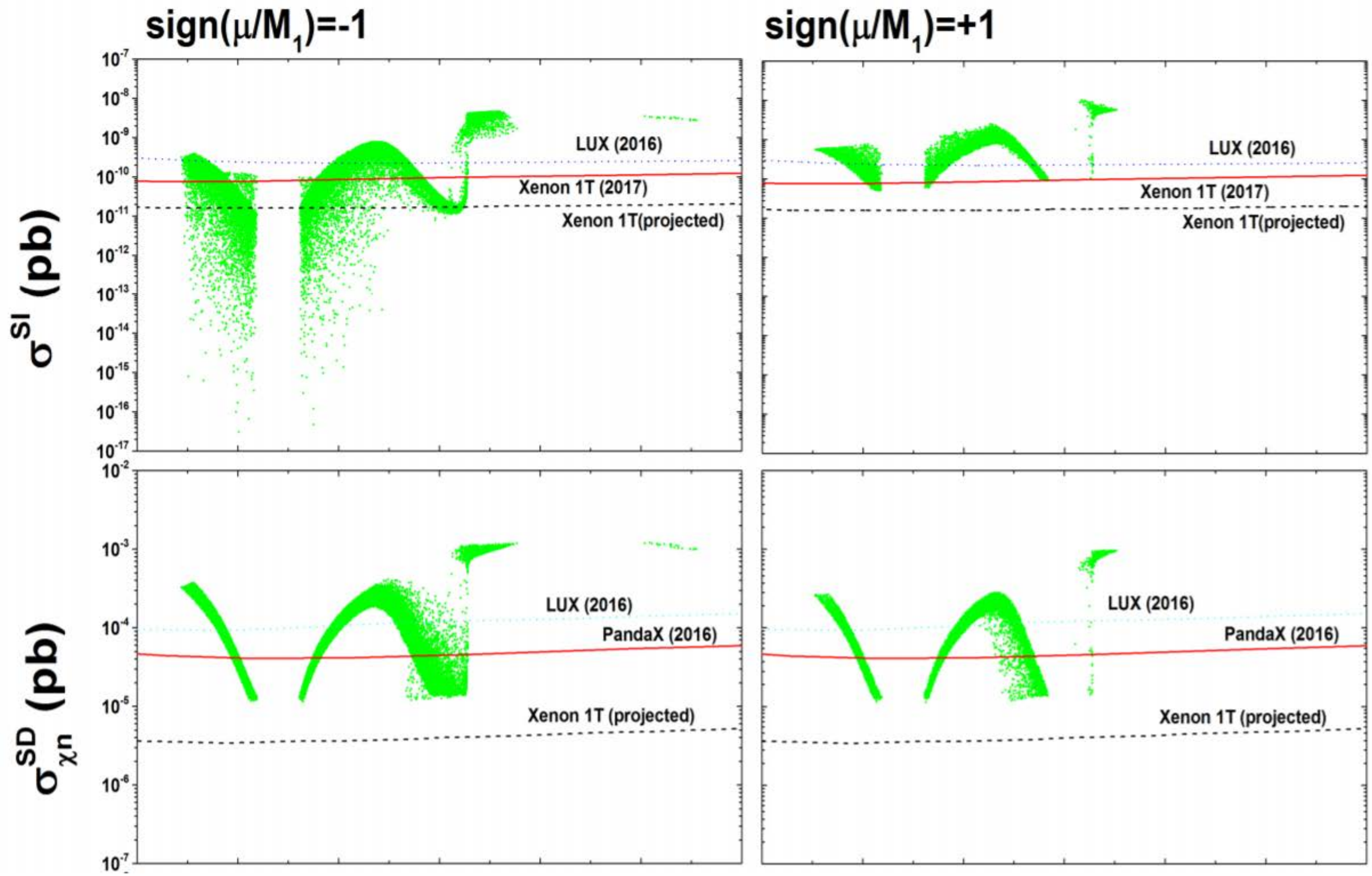
Conclusions

- **EWSUSY is the one of the most favored scenarios by current data. It has been becoming a competitive study at the LHC.**
- **Muon g-2 and DM experiments produce strong bounds for EWSUSY.**
- **Future HE-LHC and CEPC can cover the full parameter space of EWSUSY for muon g-2 and DM.**

Thank you!



a_μ is now measured to 540 ppb; Goal is 140 ppb



Resonant annihilation and Mixture of bino-higgsino are tightly constrained