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SUSY $(g\text{-}2)_\mu$ With & Without Stable Neutralino

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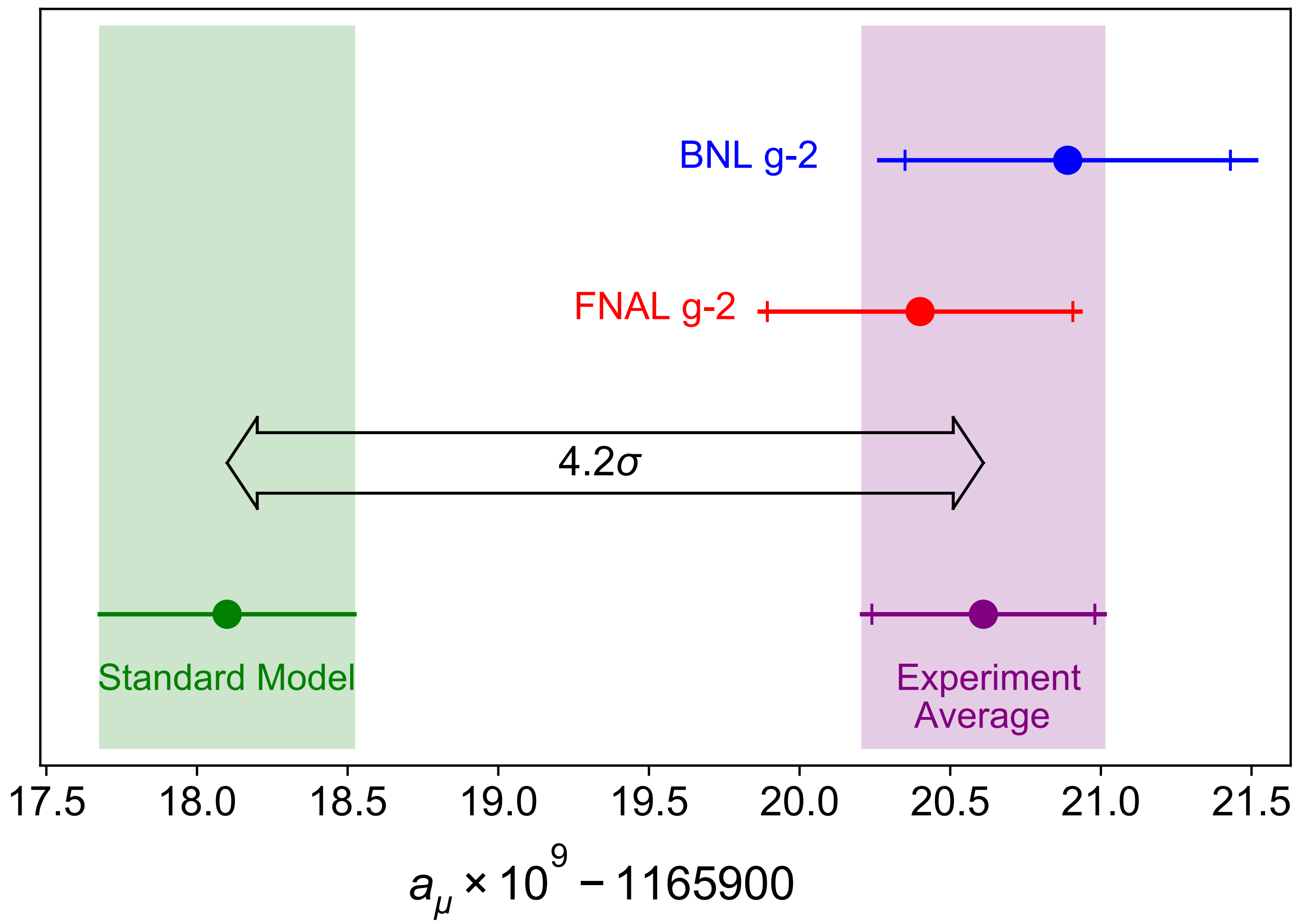
Based on [2202.12928]

30 June 2022 Humboldt Kolleg @ Kitzbühel

$(g-2)_\mu$ anomaly

[Phys. Rev. LeS. 126 (2021) 14, 141801]



$$a_\mu^{\text{theo}} = 0.0011659\,1810\,(43)$$
$$a_\mu^{\text{exp}} = 0.0011659\,2061\,(41)$$

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

Motivation

- There are many BSM scenarios that can explain the $(g-2)_\mu$ anomaly:

  Leptoquarks, Z', VLL, 2HDM, axion, ..

- Supersymmetry is particularly motivated since it offers:

  Coupling Unification, Radiative EWSB, Baryogenesis, DM, …

- There are many studies on SUSY g-2 already:

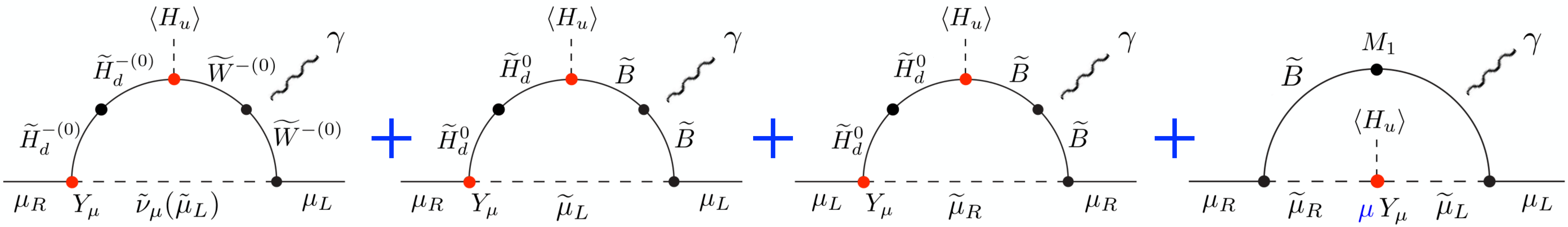
  [Athrona, Balazsa, Jacoba, Kotlarskic, Stockingerc, Stockinger-Kim]; [Chakraborti, Heinemeyer, Saha]; [Endo,Hamaguchi,Iwamoto,Kitahara]; [Cox, Han, Yanagida]; [Baum, Carena, Shah, Wagner]; [Badziak, KS]; [Hagiwara,Ma,Mukhopadhyay'18], …

- Most studies assume the neutralino is the Lightest SUSY Particle (LSP) and stable.

  Q: What happens if neutralino is unstable? (e.g. RPV, Gravitino LSP)

  A: DM constraints go away, but LHC constraints change. **How?**

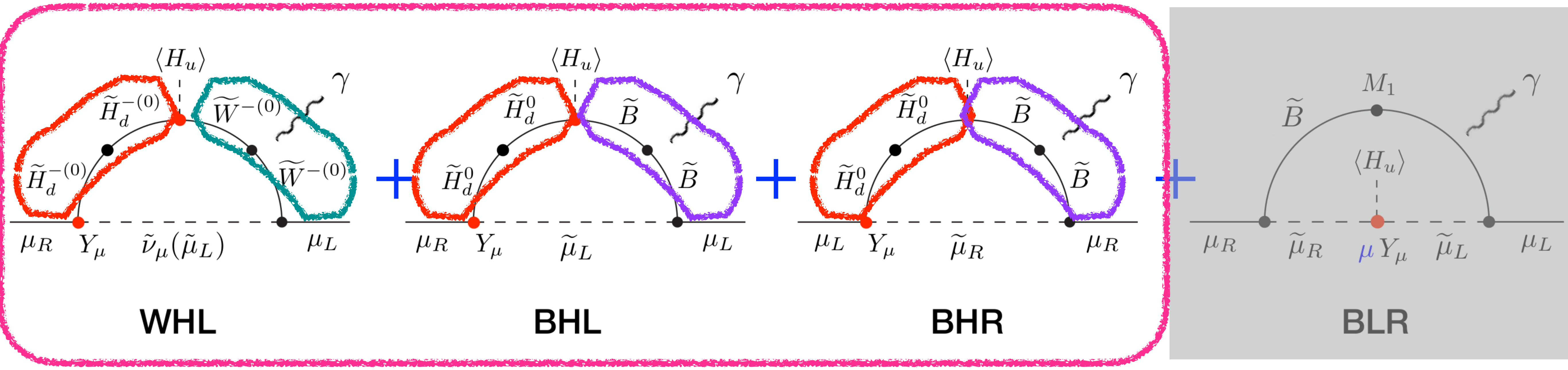
$$\Delta a_\mu^{\text{SUSY}} \simeq$$

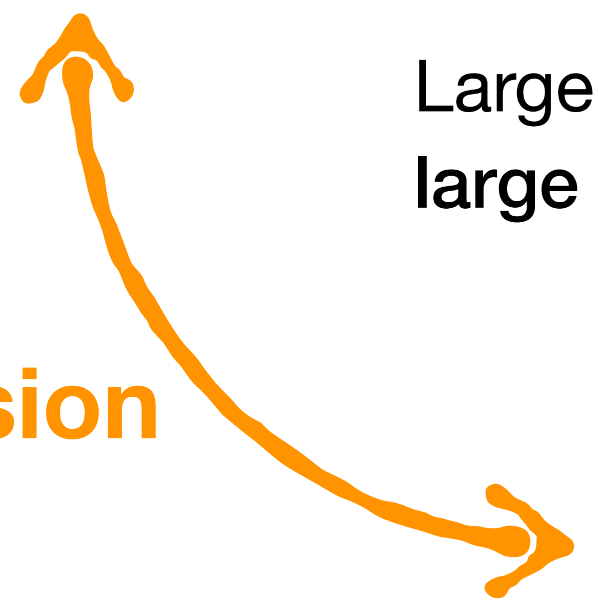


WHL **BHL** **BHR** **BLR**

There are 4 important 1-loop (mass insertion) diagrams in large tanβ regime

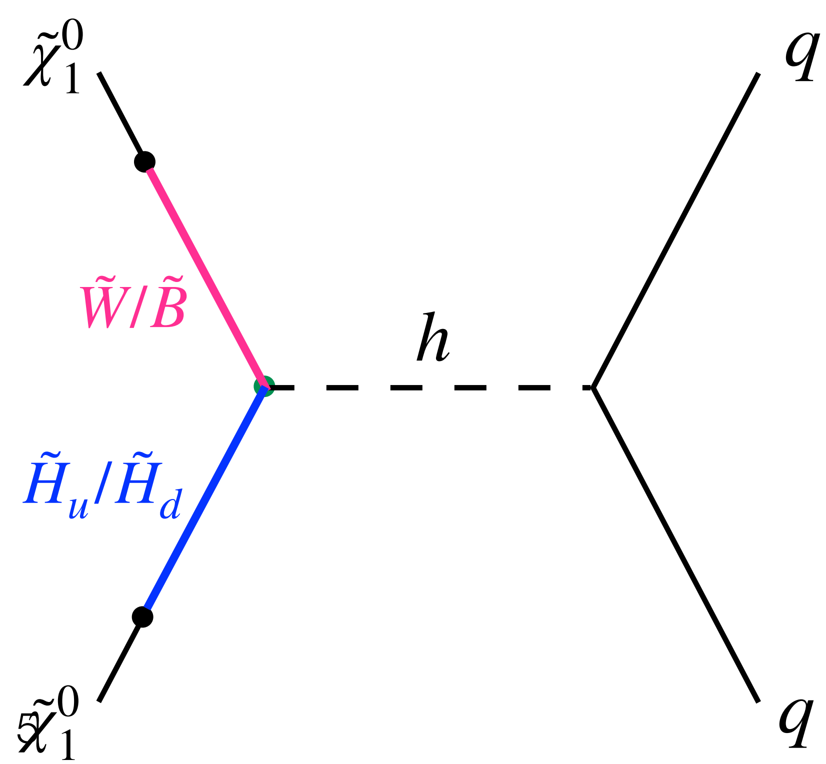
$$\Delta a_\mu^{\text{SUSY}} \simeq$$



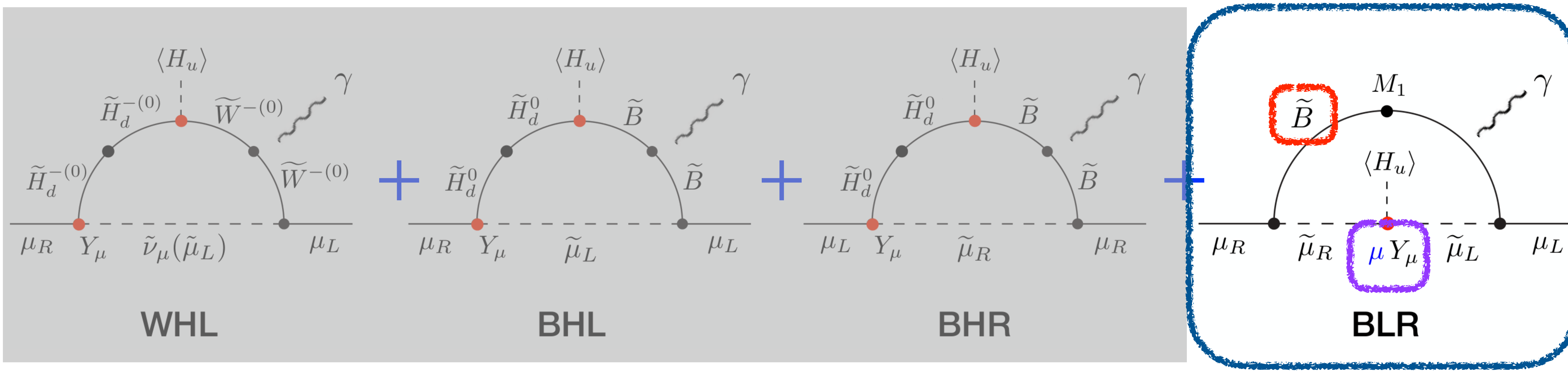


tension

Large gaugino-Higgsino mixing leads to a
large cross-section for DM Direct Detection:



$$\Delta a_\mu^{\rm SUSY} \simeq$$



❖ **Bino** has very small annihilation cross-section

⟹ **Tend to produce too much DM** $\Omega_{\tilde\chi_1^0} > \Omega_{\rm DM}$

tension

❖ Large off-diagonal term in stau mass matrix:

- charge breaking vacuum: $m^2_{\rm stau1} > 0$

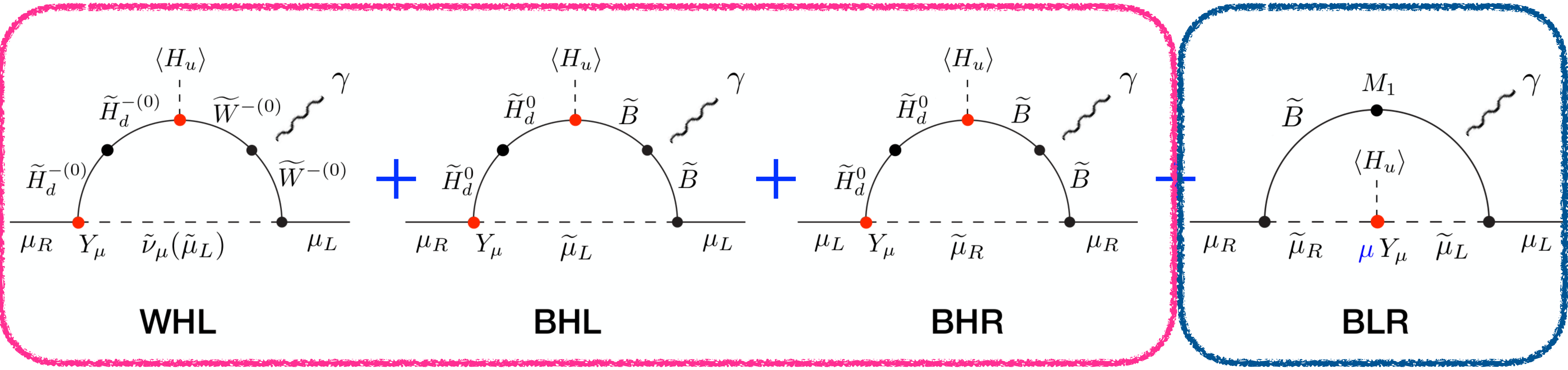
- LEP bound: $m_{\rm stau1} > 81.9$ GeV

- stau LSP: $m_{\rm stau1} > m_{\rm neutralino1}$

- Vacuum (meta-)stability

$$(\tilde\tau \text{ mass matrix}) \sim \begin{pmatrix} m^2_{\tilde\tau_R} & Y_\tau \mu \langle H_u \rangle \\ Y_\tau \mu \langle H_u \rangle & m^2_{\tilde\tau_L} \end{pmatrix}$$

$$\Delta a_\mu^{\rm SUSY} \simeq$$



SUSY g-2 has a tension with:

- DM Direct Detection
- (Bino-like) DM overproduction
- lepton + **large $E_T^{\rm miss}$** @ LHC
- Vacuum stability (for BLR)

} consequence of **stable neutralino**

How the situation improves / deteriorates if **neutralino is unstable**?

Analysis

Model Parameters: (5 masses + tanβ)

M_1 : Bino mass

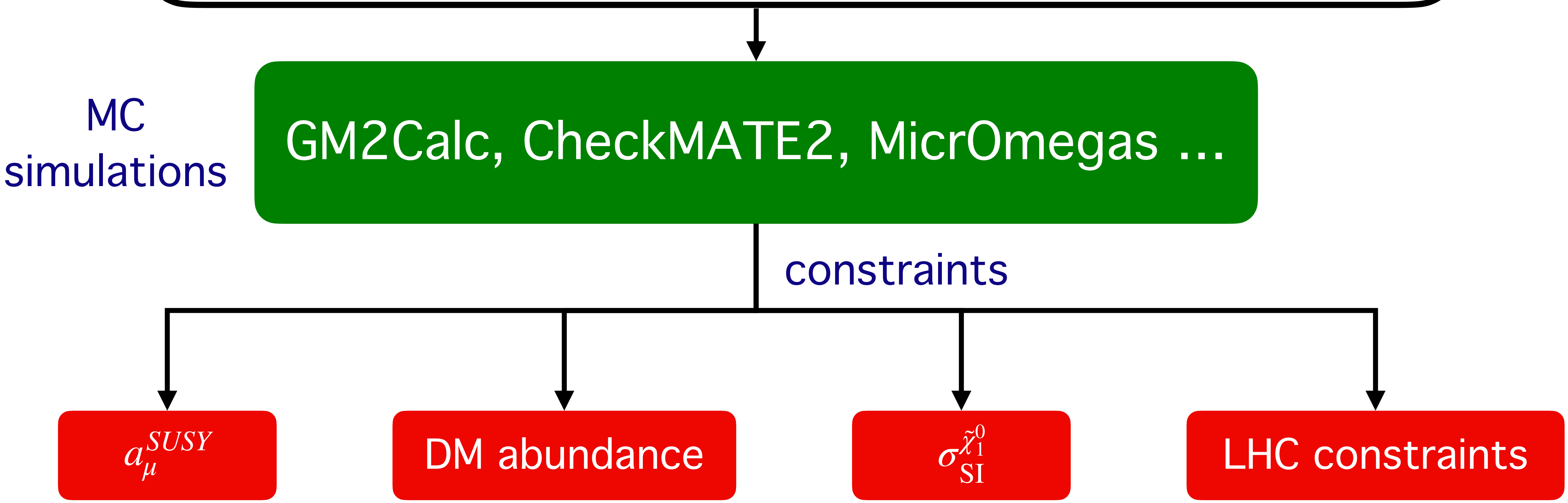
M_2 : Wino mass

μ : Higgsino mass

$$m_{\tilde{l}_R} \equiv \widetilde{m}^2_{\tilde{e}_R} = \widetilde{m}^2_{\tilde{\mu}_R} = \widetilde{m}^2_{\tilde{\tau}_R}$$

$$m_{\tilde{l}_L} \equiv \widetilde{m}_{\tilde{\nu}_e} = \widetilde{m}_{\tilde{\nu}_\mu} = \widetilde{m}_{\tilde{\nu}_\tau} = \widetilde{m}_{\tilde{e}_L} = \widetilde{m}_{\tilde{\mu}_L} = \widetilde{m}_{\tilde{\tau}_L}$$

$$\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$$



List of ATLAS & CMS searches included in our analysis

13 TeV

Name	E/TeV	$\mathcal{L}$/fb^{-1}	Description
atlas_1604_01306	13	3.2	Monophoton
atlas_1605_09318	13	3.3	3 b-jets + 0-1 lepton + MET
atlas_1609_01599	13	36	Monophoton
atlas_1704_03848	13	36	Monophoton
atlas_conf_2015_082	13	3.2	2 leptons (Z) + jets + MET
atlas_conf_2016_013	13	3.2	1 lepton + jets (4 tops, VVL quarks)
atlas_conf_2016_050	13	13.3	1 lepton + (b) jets + MET
atlas_conf_2016_054	13	13.3	1 lepton + (b) jets + MET
atlas_conf_2016_076	13	13.3	2 lepton + jets + MET
atlas_conf_2016_096	13	13.3	Multi-lepton + MET
atlas_conf_2017_060	13	36	Monojet
atlas_conf_2016_066	13	13.3	Photons, jets and MET
atlas_1712_08119	13	36	soft leptons (compressed EWKinos)
atlas_1712_02332	13	36	squarks and gluinos, 0 lepton, 2-6 jets
atlas_1709_04183	13	36	Jets + MET (stops)
atlas_1802_03158	13	36	search for GMSB with photons
atlas_1708_07875	13	36	EWKino search with taus and MET
atlas_1706_03731	13	36	Multilepton + Jets + MET (RPC and RPV)
atlas_1908_08215	13	36	2 leptons + MET (EWKinos)
atlas_1909_08457	13	139	SS lepton + MET (squark, gluino)
atlas_conf_2019_040	13	139	Jets + MET (squark, gluino)
atlas_conf_2019_020	13	139	3 leptons (EWKino)
atlas_1803_02762	13	36	2 or 3 leptons (EWKino)
atlas_conf_2018_041	13	80	Multi-b-jets (stops, sbottoms)
atlas_2101_01629	13	139	1 lepton + jets + MET
atlas_conf_2020_048	13	139	Monojet
atlas_2004_14060	13	139	$t\bar{t}$ + MET
atlas_1908_03122	13	139	Higgs bosons + b-jets + MET
atlas_2103_11684	13	139	4 or more leptons (RPV, GMSB)
atlas_2106_09609	13	139	Multijets + leptons (RPV)
atlas_1911_06660	13	139	Search for Direct Stau Production
cms_pas_sus_15_011	13	2.2	2 leptons + jets + MET
cms_sus_16_039	13	35.9	electrowekinos in multilepton final state
cms_sus_16_025	13	12.9	electroweakino and stop compressed spectra
cms_sus_16_048	13	35.9	two soft opposite sign leptons

8 TeV

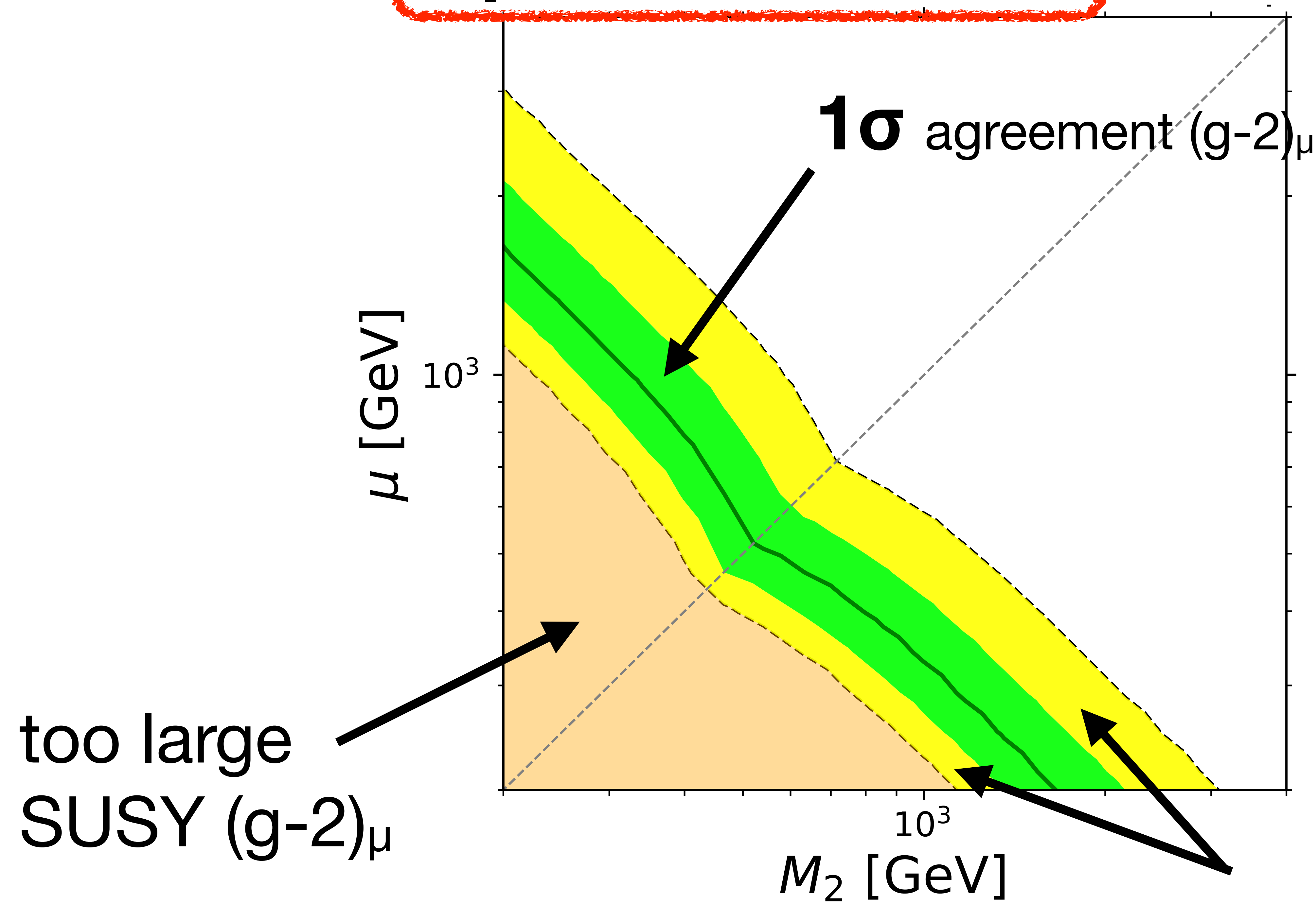
Name	E/TeV	$\mathcal{L}$/fb^{-1}	Description
atlas_1308_1841	8	20.3	0 lepton + $\geq$ 7 jets + MET
atlas_1308_2631	8	20.1	0 leptons + 2 b-jets + MET
atlas_1402_7029	8	20.3	3 leptons + MET (chargino+neutralino)
atlas_1403_4853	8	20.3	2 leptons + MET (direct stop)
atlas_1403_5222	8	20.3	stop production with Z boson and b-jets
atlas_1404_2500	8	20.3	Same sign dilepton or 3 lepton
atlas_1405_7875	8	20.3	0 lepton + 2-6 jets + MET
atlas_1407_0583	8	20.3	ATLAS, 1 lepton + (b-)jets + MET (stop)
atlas_1407_0608	8	20.3	Monojet or charm jet (stop)
atlas_1411_1559	8	20.3	monophoton plus MET
atlas_1501_07110	8	20.3	1 lepton + 125GeV Higgs + MET
atlas_1502_01518	8	20.3	Monojet + MET
atlas_1503_03290	8	20.3	2 leptons + jets + MET
atlas_1506_08616	8	20.3	di-lepton and 2b-jets + lepton
atlas_1507_05493	8	20.3	photonic signatures of gauge-mediated SUSY
atlas_conf_2012_104	8	20.3	1 lepton + $\geq$ 4 jets + MET
atlas_conf_2013_024	8	20.3	0 leptons + 6 (2 b-)jets + MET
atlas_conf_2013_049	8	20.3	2 leptons + MET
atlas_conf_2013_061	8	20.3	0-1 leptons + $\geq$ 3 b-jets + MET
atlas_conf_2013_089	8	20.3	2 leptons (razor)
atlas_conf_2015_004	8	20.3	invisible Higgs decay in VBF
atlas_1403_5294	8	20.3	2 leptons + MET, (SUSY electroweak)
atlas_higg_2013_03	8	20.3	2 leptons + MET, (invisible Higgs)
atlas_1502_05686	8	20.3	search for massive sparticles decaying to many jets
cms_1303_2985	8	11.7	α_T + b-jets
cms_1408_3583	8	19.7	monojet + MET
cms_1502_06031	8	19.4	2 leptons, jets, MET (only on-Z)
cms_1504_03198	8	19.7	1 lepton, $\geq$ 3 jets, $\geq$ 1 b-jet, MET (DM + 2 top)
cms_sus_13_016	8	19.5	OS lepton 3+ b-tags

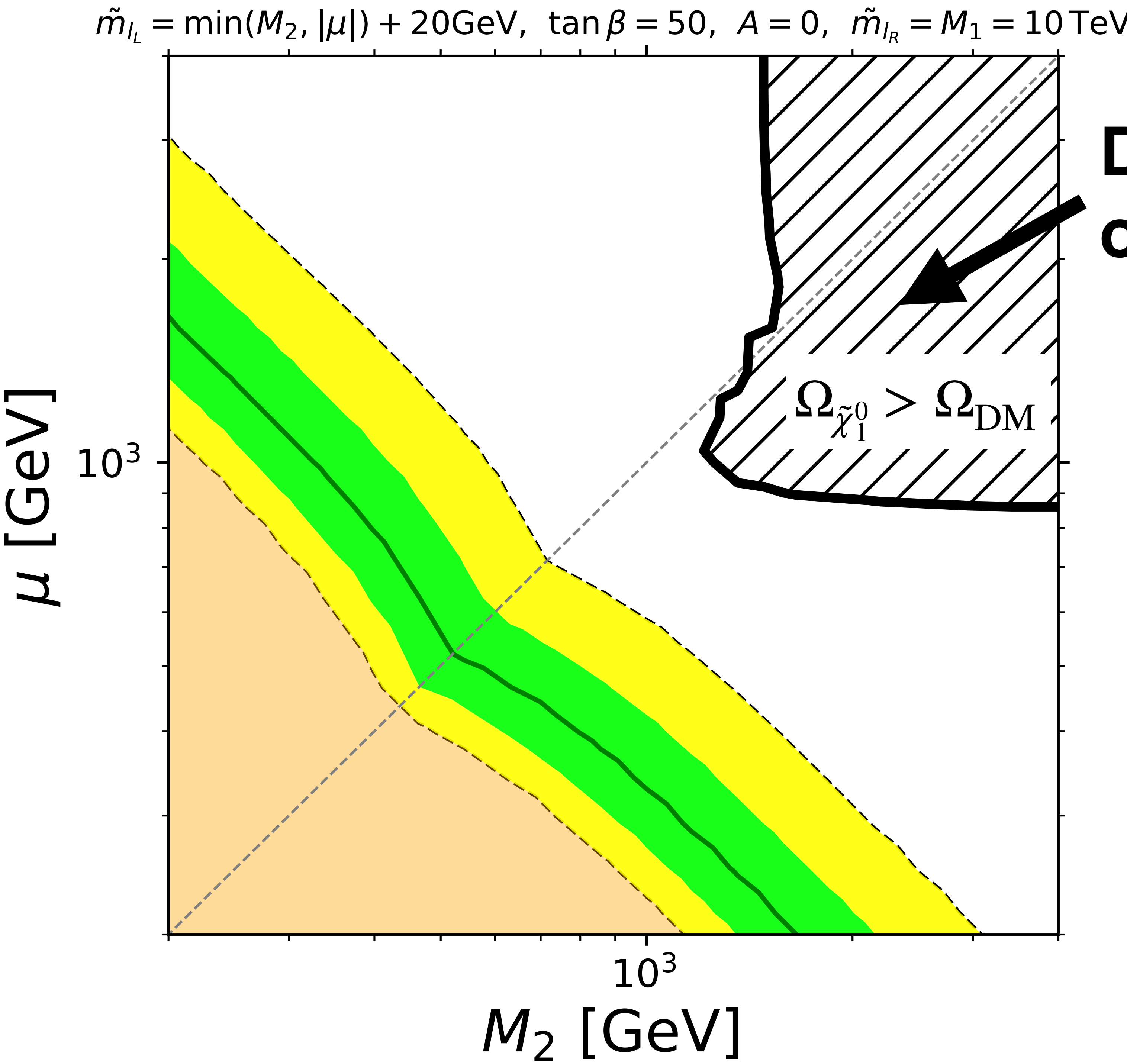
compressed mass spectrum

$\tilde{m}_{l_R} = M_1 = 10\,\mathrm{TeV}$

$\tilde{m}_{l_L} = \min(M_2, |\mu|) + 20\mathrm{GeV}, \tan\beta = 50$

WHL dominates





DM overabundance

compressed mass spectrum

$\tilde{m}_{l_R} = M_1 = 10\,\mathrm{TeV}$

$\tilde{m}_{l_L} = \min(M_2, |\mu|) + 20\mathrm{GeV}$, $\tan\beta = 50$

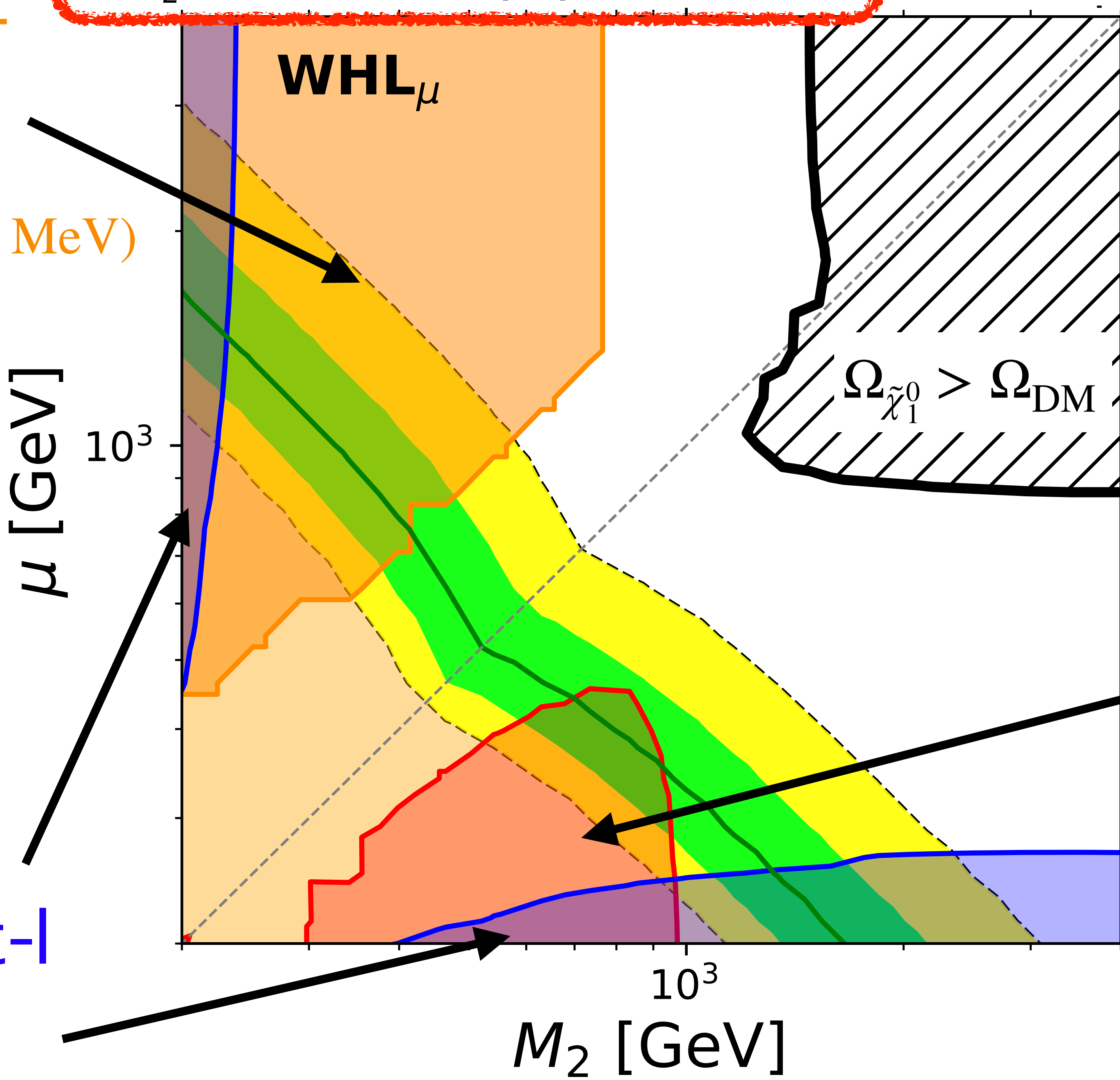
ATLAS DT

[2201.02472]

$m_{\chi_1^\pm} - m_{\chi_1^0} \sim \mathcal{O}(100\ \mathrm{MeV})$

$c\tau_{\tilde{\chi}_1^\pm} \sim \mathcal{O}(1\ \mathrm{cm})$

$\chi_1^\pm \to \chi_1^0 + X_{\mathrm{soft}}^\pm$



CMS l+l-

[2012.08600]

$pp \to \tilde{W}^{+,0}\tilde{W}^{-,0}$

$W^\pm \to l^\pm\tilde{\nu},\ W^0 \to l^\pm\tilde{l}^\mp$

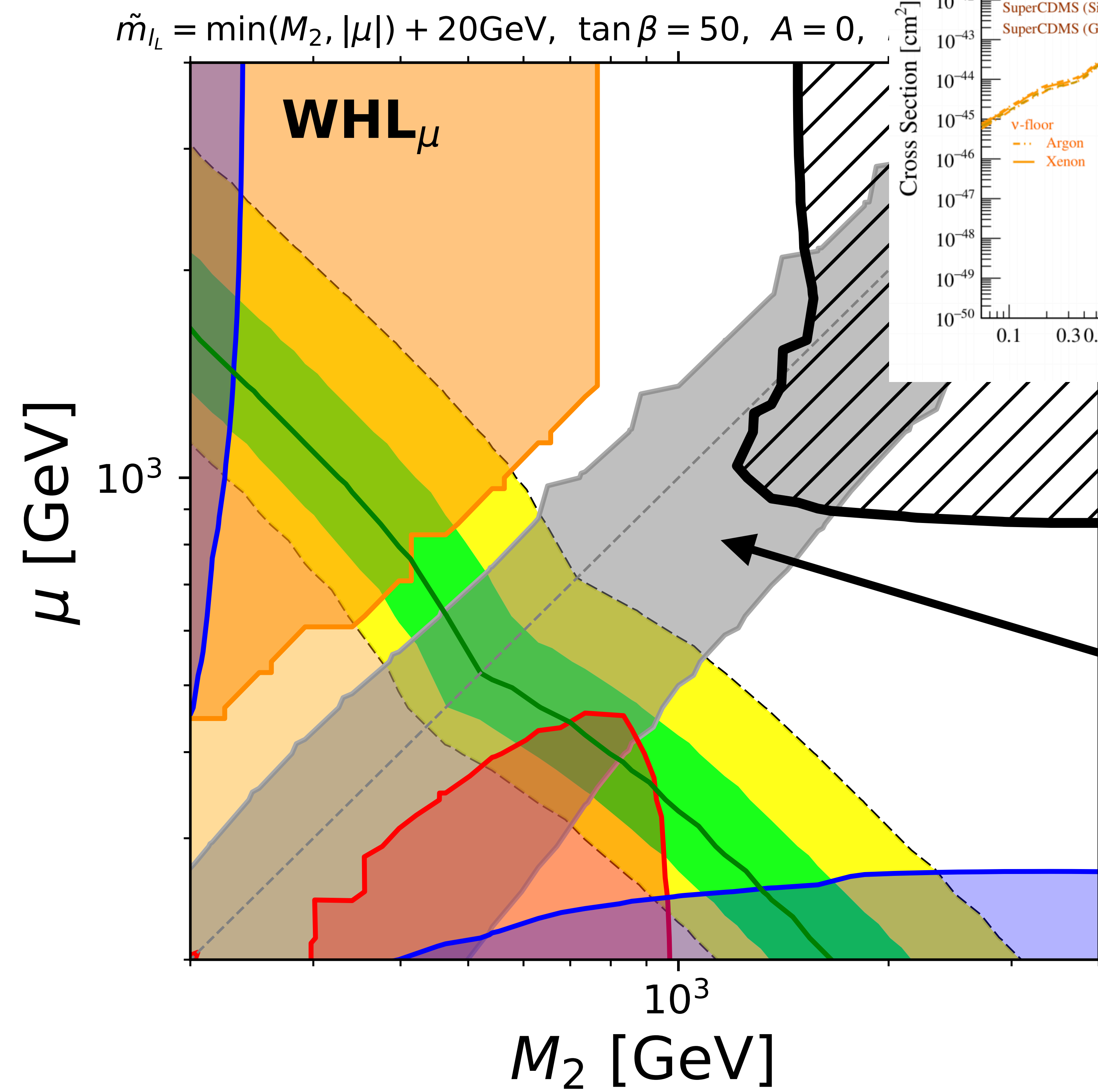
ATLAS soft-l

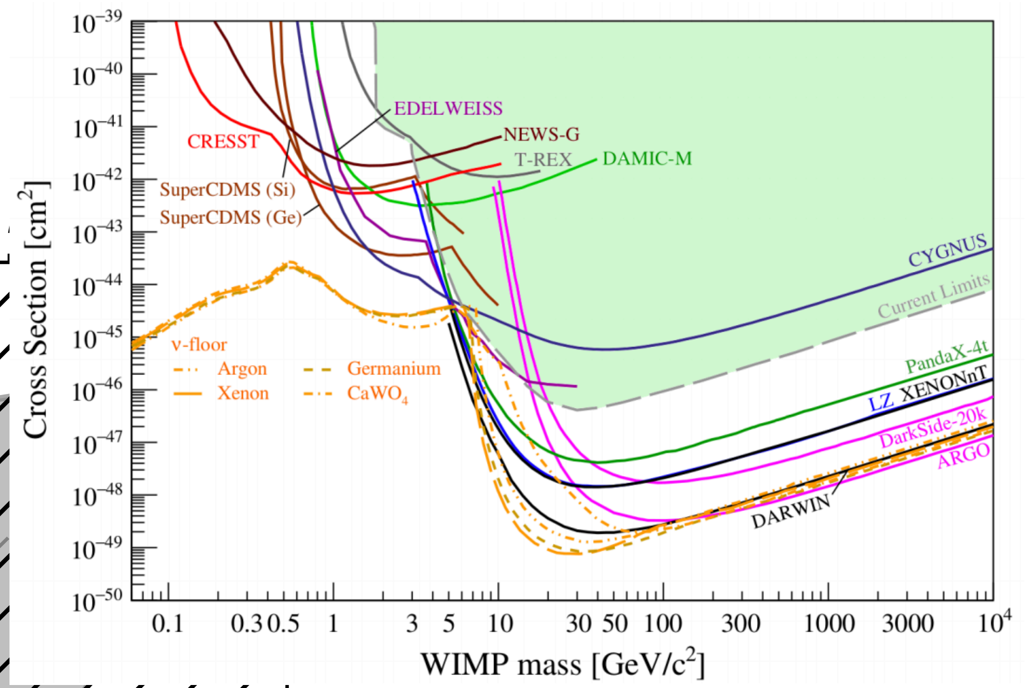
[1911.12606]

$\tilde{\xi}\tilde{\xi}' \to (l^+\tilde{\eta})(l^-\tilde{\eta}')$

$\tilde{\xi} \equiv \tilde{l}\ /\ \tilde{\nu}$

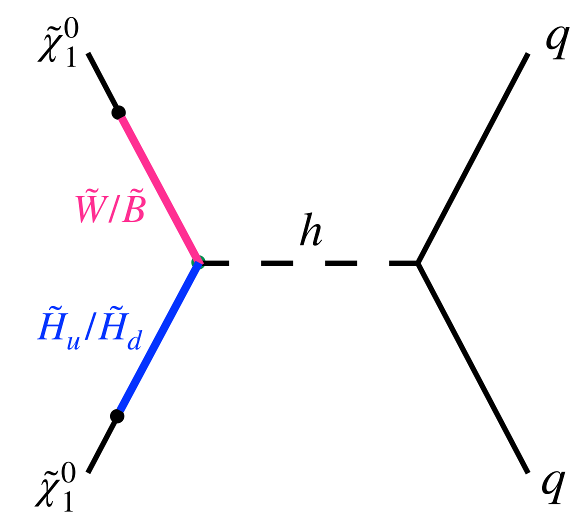
$\tilde{\eta} \equiv \tilde{\chi}_1^\pm\ /\ \tilde{\chi}_1^0$



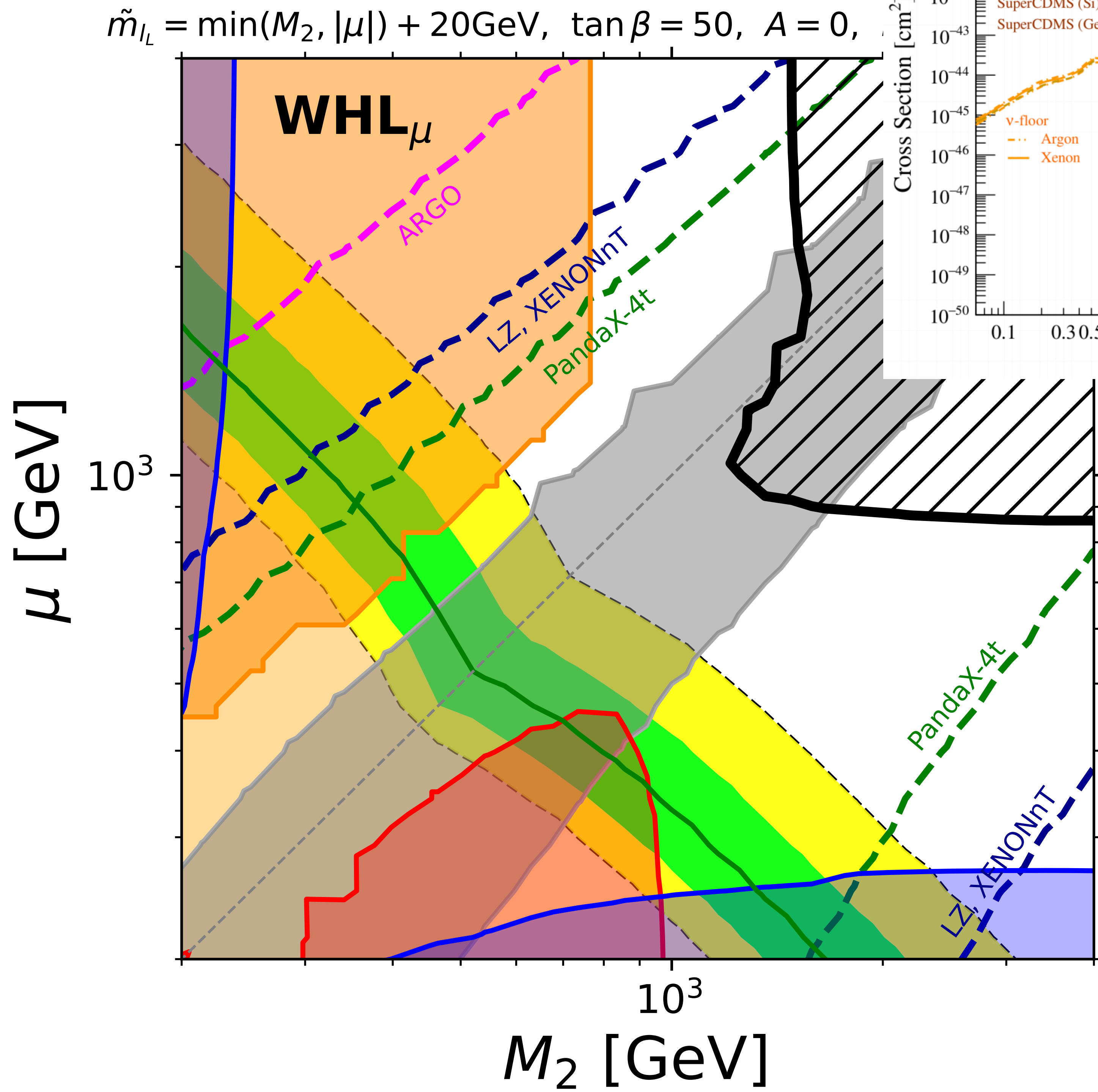


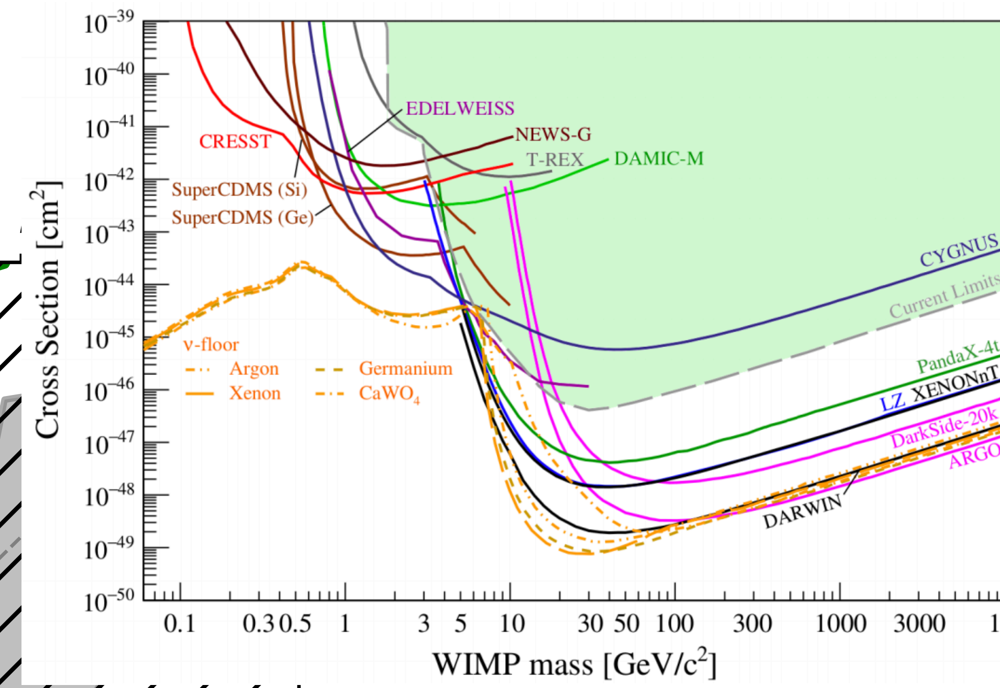
XENON1T

[1805.12562]



$$\sigma^{\mathrm{SI}}_{N-\chi_1^0} \cdot \frac{\Omega_{\tilde{\chi}_1^0}}{\Omega_{\mathrm{DM}}} > \sigma^{\mathrm{SI}}_{\mathrm{XENON}}$$

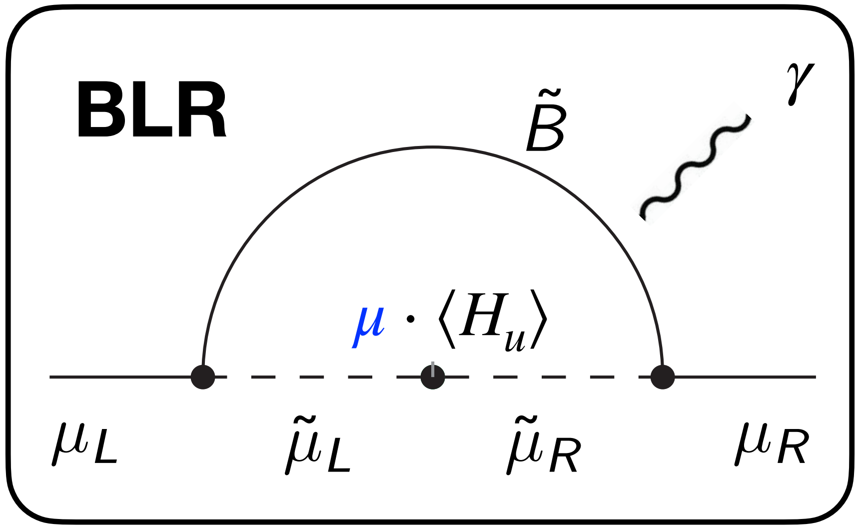


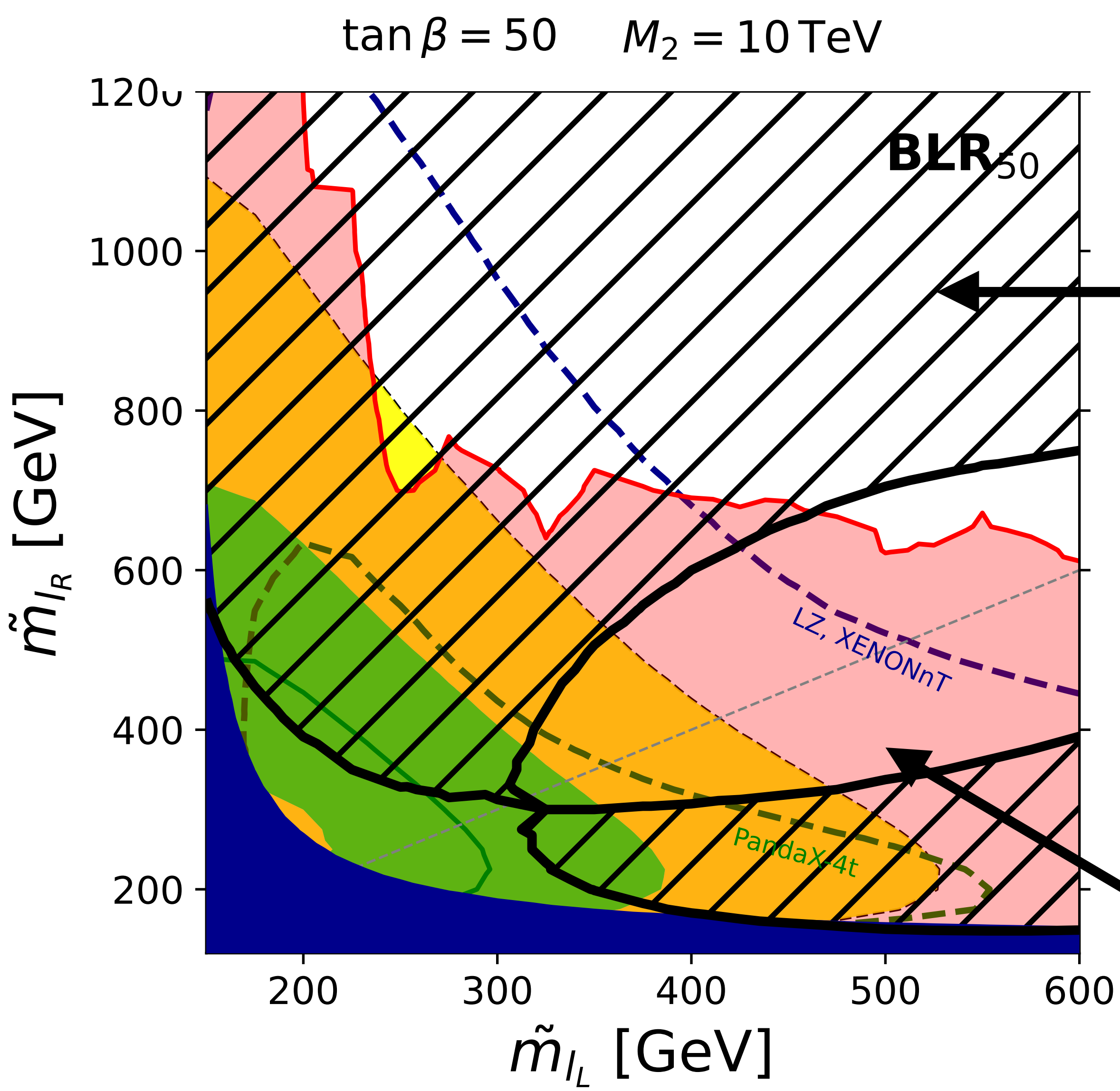


The entire SUSY g-2 region will be probed by the next generation DM-DD experiments

$M_1 = m_{\tilde{\tau}_1} - 20\,\mathrm{GeV}$, ➡ compressed spectrum

$\mu = \mu_{\max}$ ➡ vacuum stability upper limit



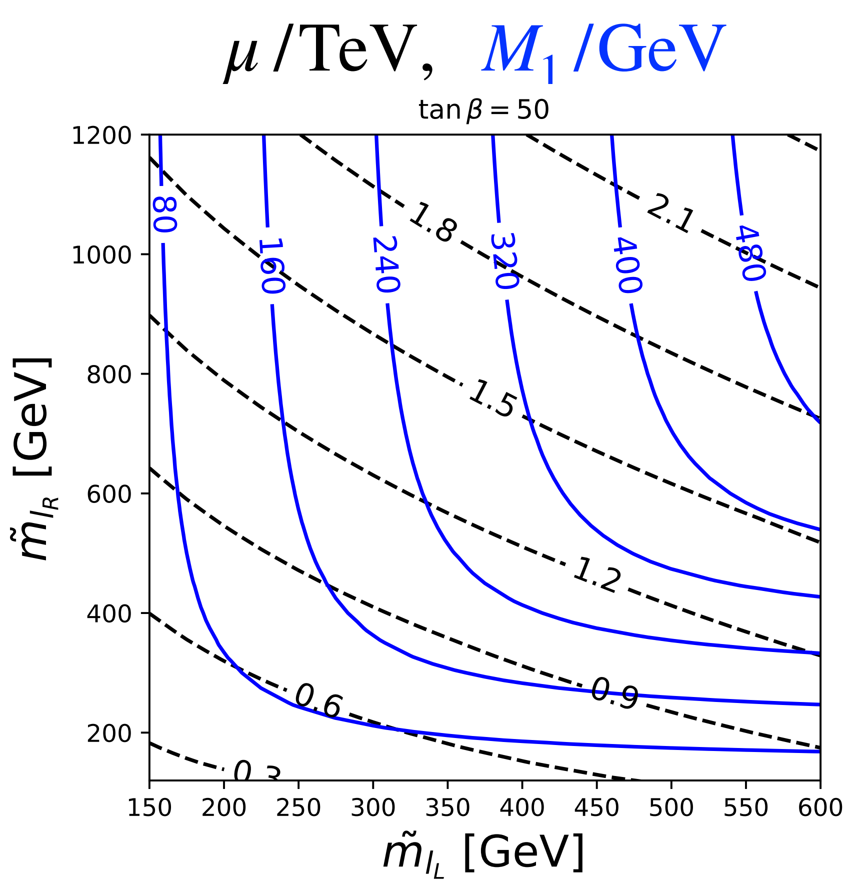


DM overproduction due to Bino-like LSP

CMS l^+l^- [2012.08600]

$pp \to \tilde{W}^{+,0}\tilde{W}^{-,0}$

$W^{\pm} \to l^{\pm}\tilde{\nu},\ W^0 \to l^{\pm}\tilde{l}^{\mp}$



Vacuum stability condition:

$$\left|m^2_{\tilde{\ell}_{LR}}\right| \le \left[1.01\times 10^2\,\mathrm{GeV}\sqrt{m_{\tilde{\ell}_L} m_{\tilde{\ell}_R}} + 1.01\times 10^2\,\mathrm{GeV}(m_{\tilde{\ell}_L} + 1.03 m_{\tilde{\ell}_R}) - 2.27\times 10^4\,\mathrm{GeV}^2 + \frac{2.97\times 10^6\,\mathrm{GeV}^3}{m_{\tilde{\ell}_L} + m_{\tilde{\ell}_R}} - 1.14\times 10^8\,\mathrm{GeV}^4\left(\frac{1}{m^2_{\tilde{\ell}_L}} + \frac{0.983}{m^2_{\tilde{\ell}_R}}\right)\right]$$

[Kitahara, Yoshinaga 13]; [Endo, Hamaguchi, Kitahara, Yoshinaga 13]

SUSY g-2 solution is tightly constrained if the neutralno is stable, by DM and the missing energy signature at the LHC.

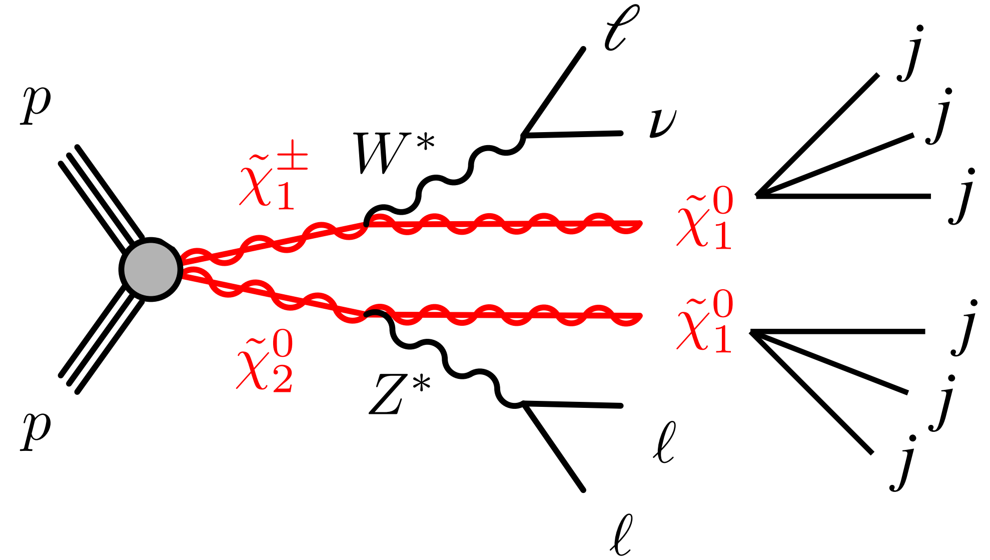
How the situation changes if the neutralino is **unstable?**

We study **two** such examples:

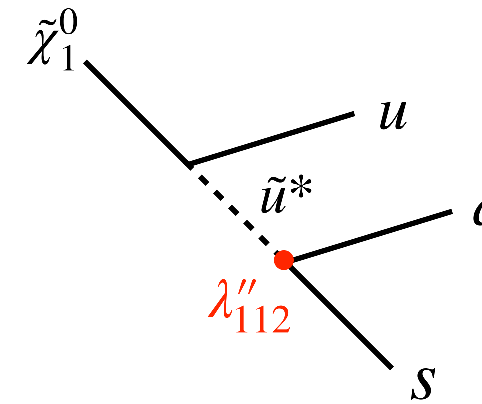
- **R-parity violation (RPV)**
- **Gravitino LSP**

RPV

(UDD-type)

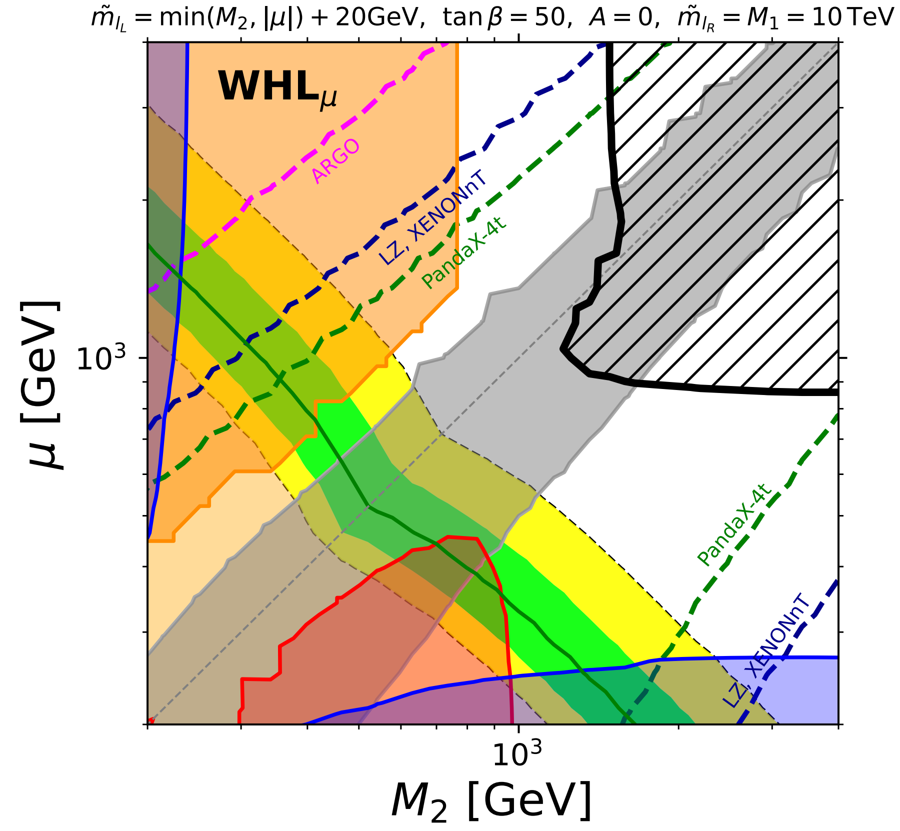


$$W_{\mathrm{RPV}} = \lambda''_{ijk} U_i^c D_j^c D_k^c$$

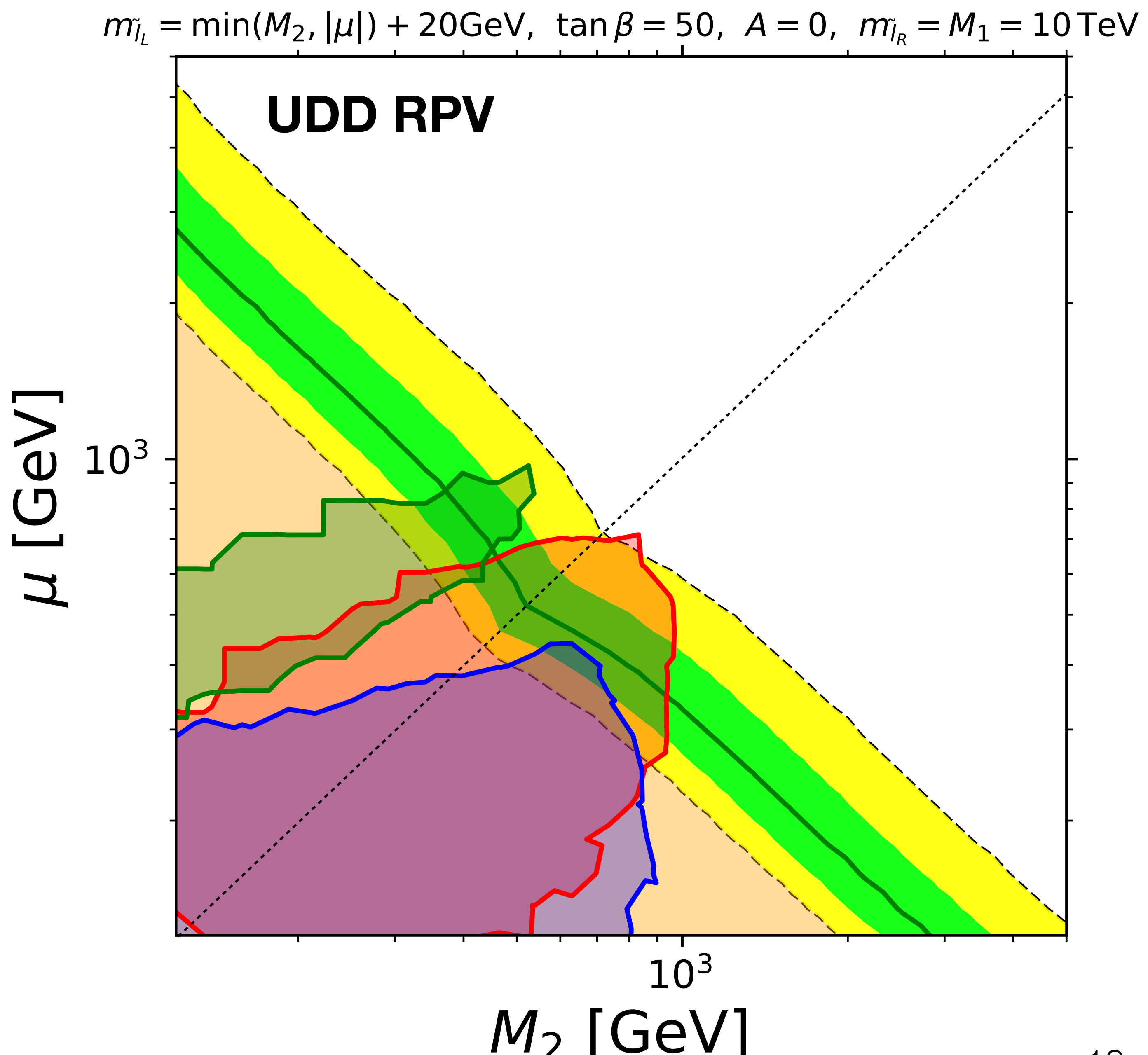


UDD RPV

stable neutralino



WHL dominated plane



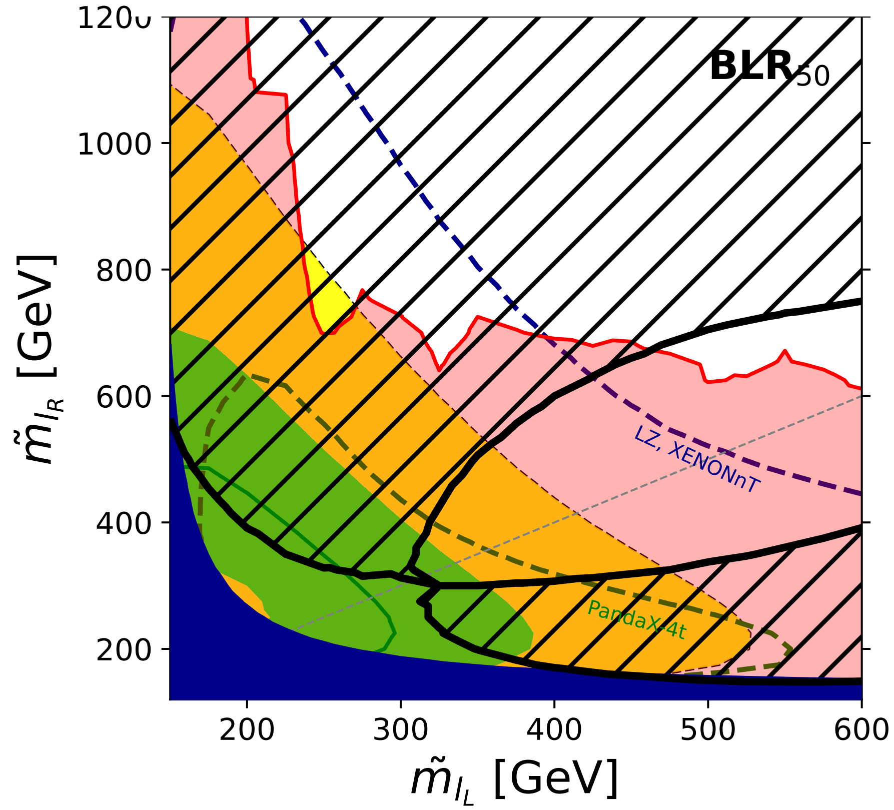
ATLAS multijet+l
[2106.09609]

CMS multilepton
[1709.05406]

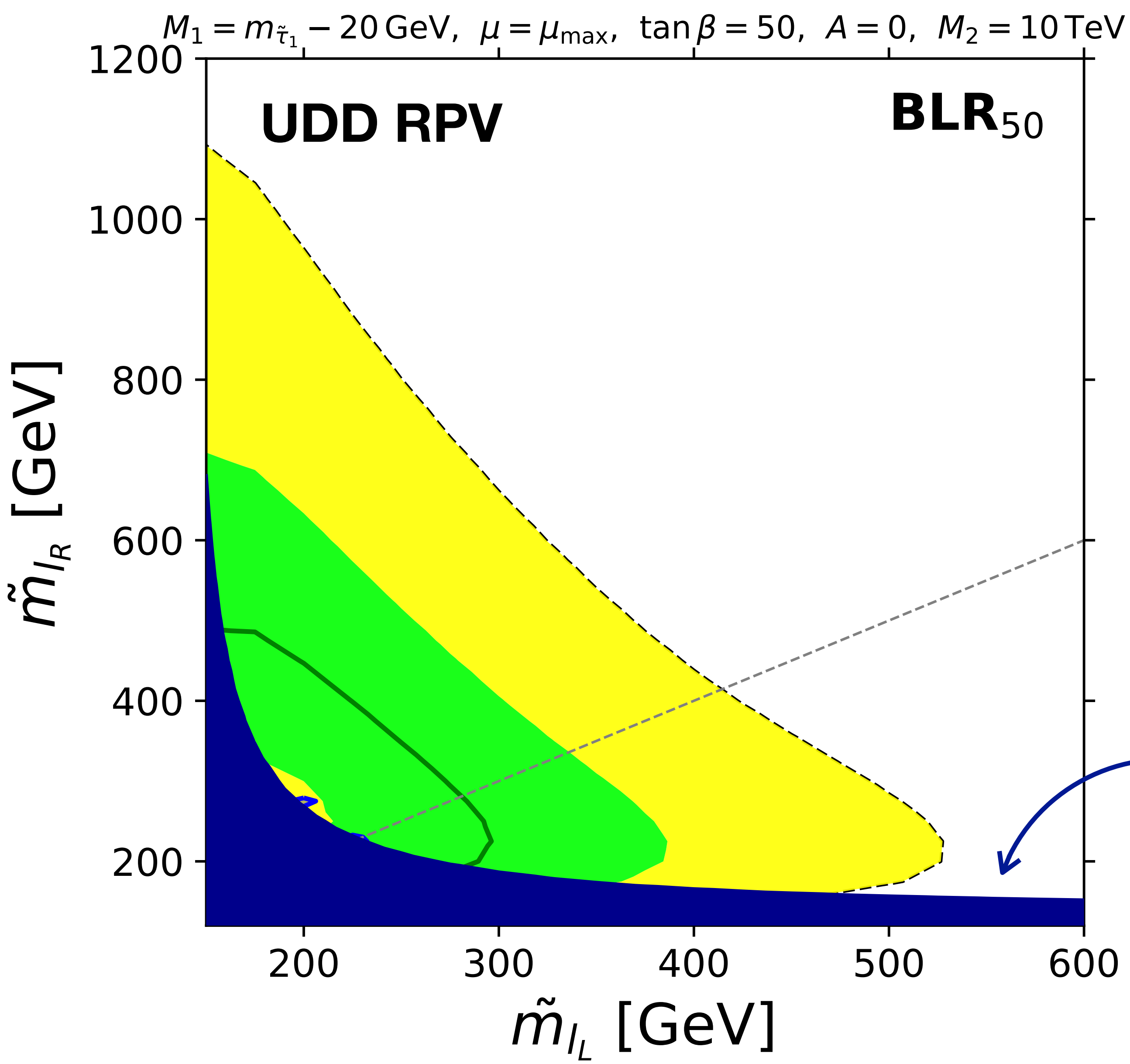
ATLAS jets +E_T^{miss}
[ATLAS-CONF-2019-040]

UDD RPV

stable neutralino



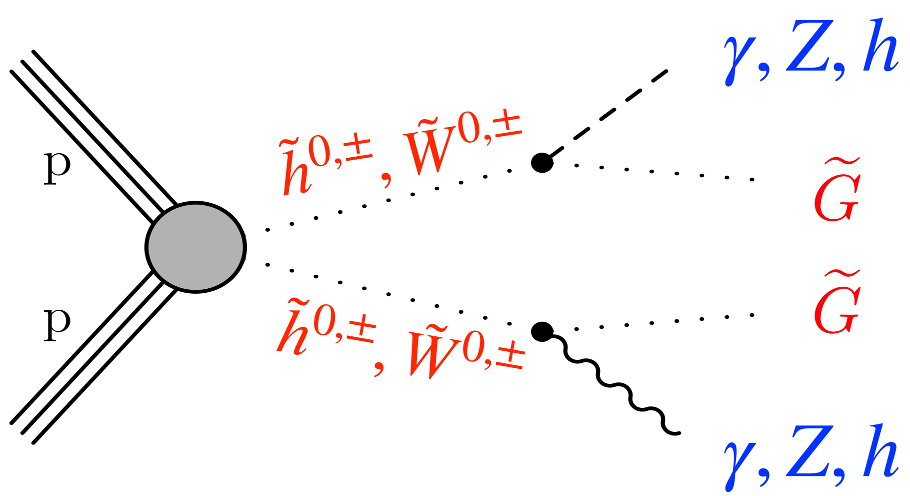
BLR dominated plane



stau LEP limit

Gravitino LSP

(general GMSB)



prompt decay into "massless" gravitino

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) = \left|N_{11}c_W + N_{12}s_W\right|^2 \mathcal{A}\,,$$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}Z) = \left(\left|N_{12}c_W - N_{11}s_W\right|^2 + \frac{1}{2}\left|N_{13}c_\beta - N_{14}s_\beta\right|^2\right)\left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}\,,$$

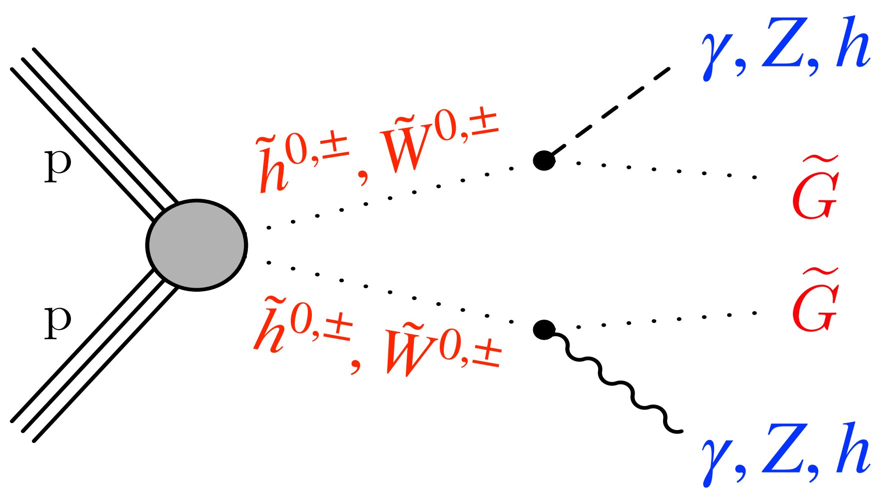
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}h) = \frac{1}{2}\left|N_{13}c_\beta + N_{14}s_\beta\right|^2\left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}\,,$$

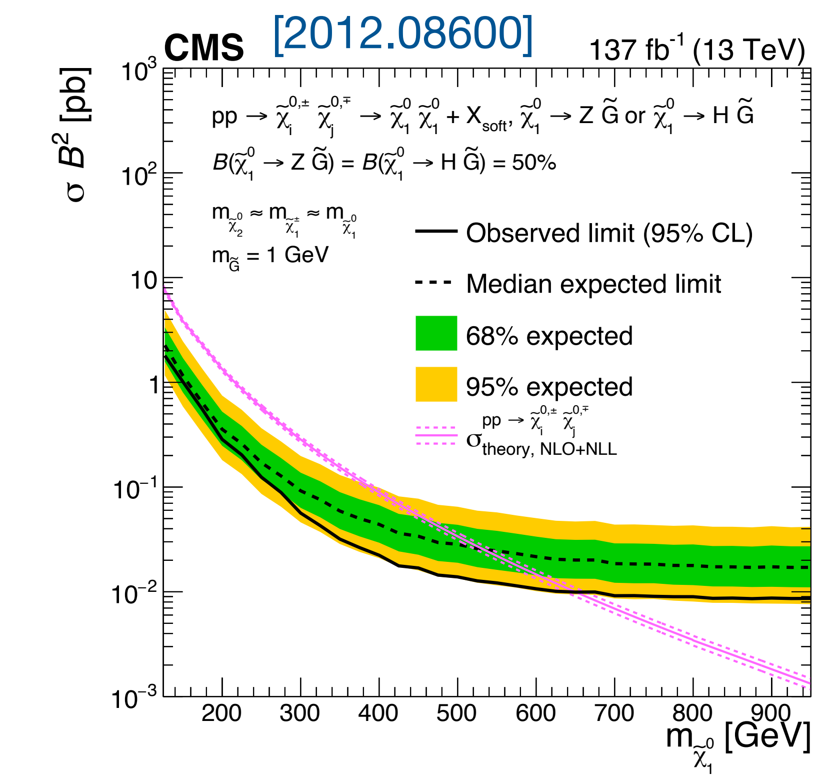
$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi m_{3/2}^2 M_{\rm pl}^2} \sim \frac{1}{0.3\,\text{mm}}\left(\frac{m_{\tilde{\chi}_1^0}}{100\,\text{GeV}}\right)^5\left(\frac{m_{3/2}}{10\,\text{eV}}\right)^{-2}$$

Gravitino LSP

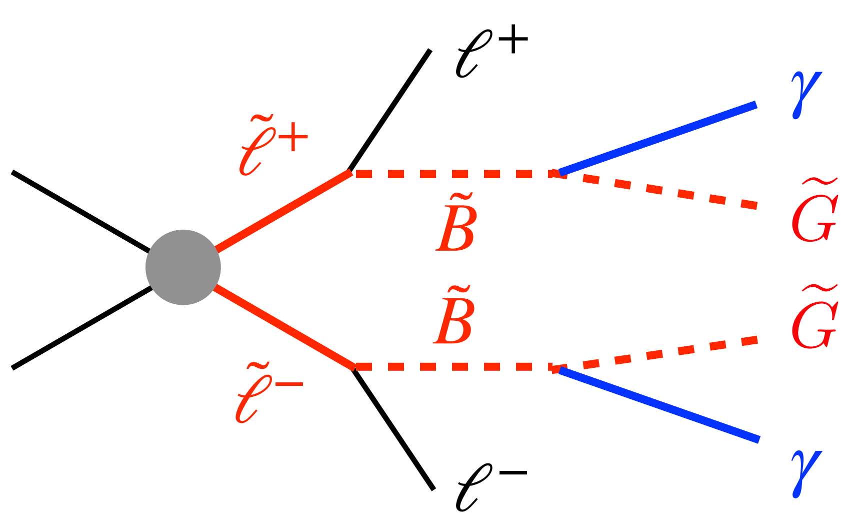
We assume a **massless** gravitino (m < 1GeV) and **prompt** neutralino decay.

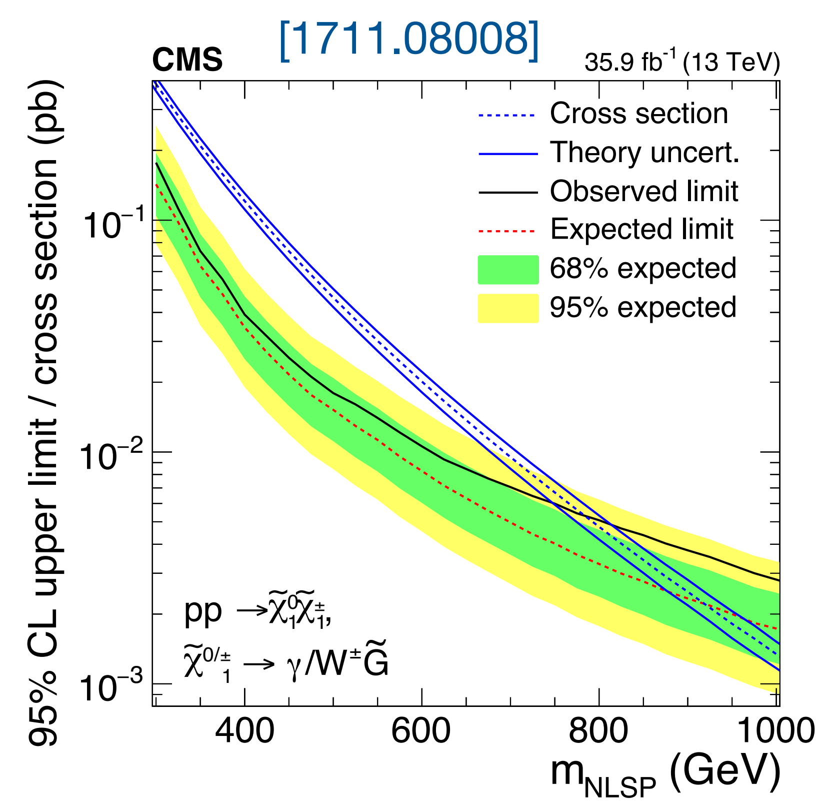
Wino, Higgsino LSP



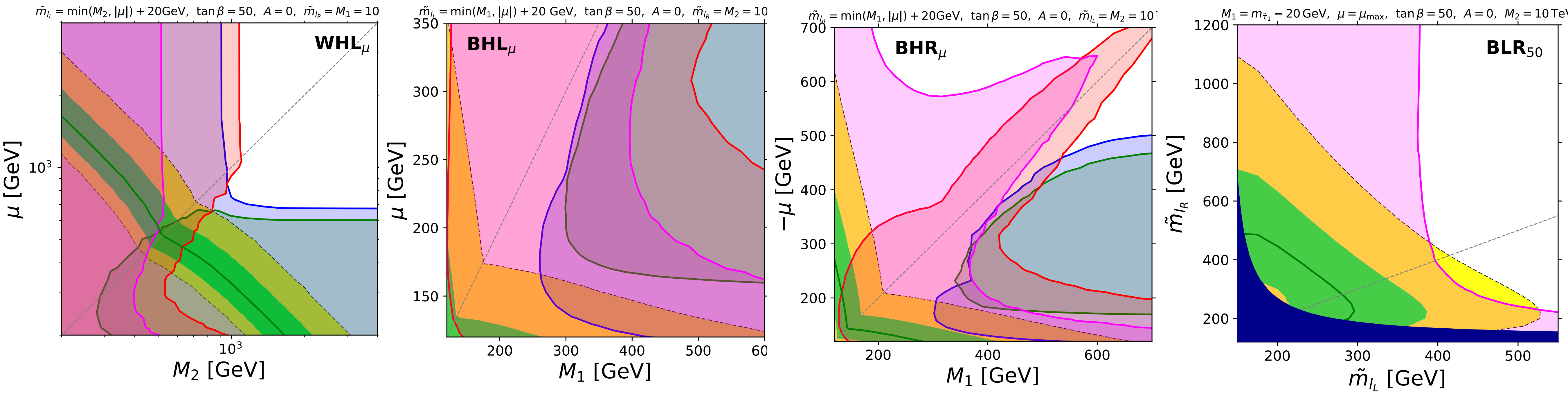


Bino LSP





Gravitino LSP



$[\gamma\widetilde{G}][\gamma\widetilde{G}]$ CMS $\gamma + \not{E}_T$ [1711.08008]

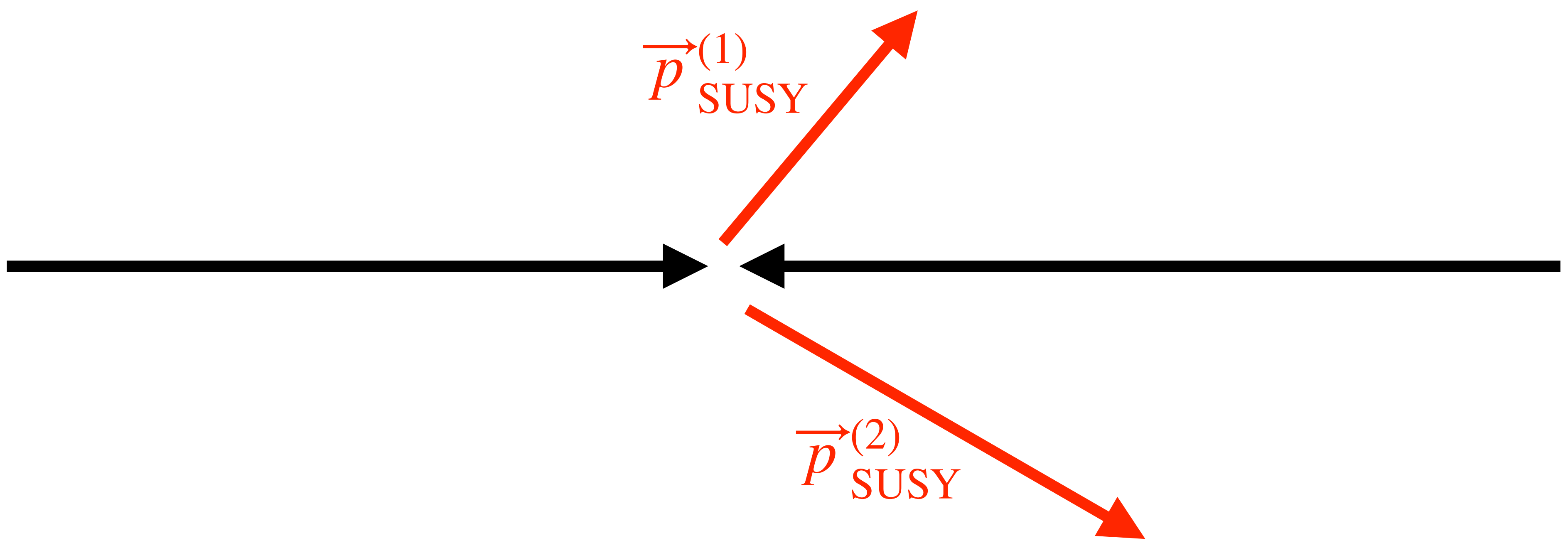
$[\gamma\widetilde{G}][Z(h)\widetilde{G}]$ CMS $\gamma + \not{E}_T$ [1711.08008]

$[Z\widetilde{G}][Z\widetilde{G}]$ CMS $\ell^+\ell^-$ [2012.08600]

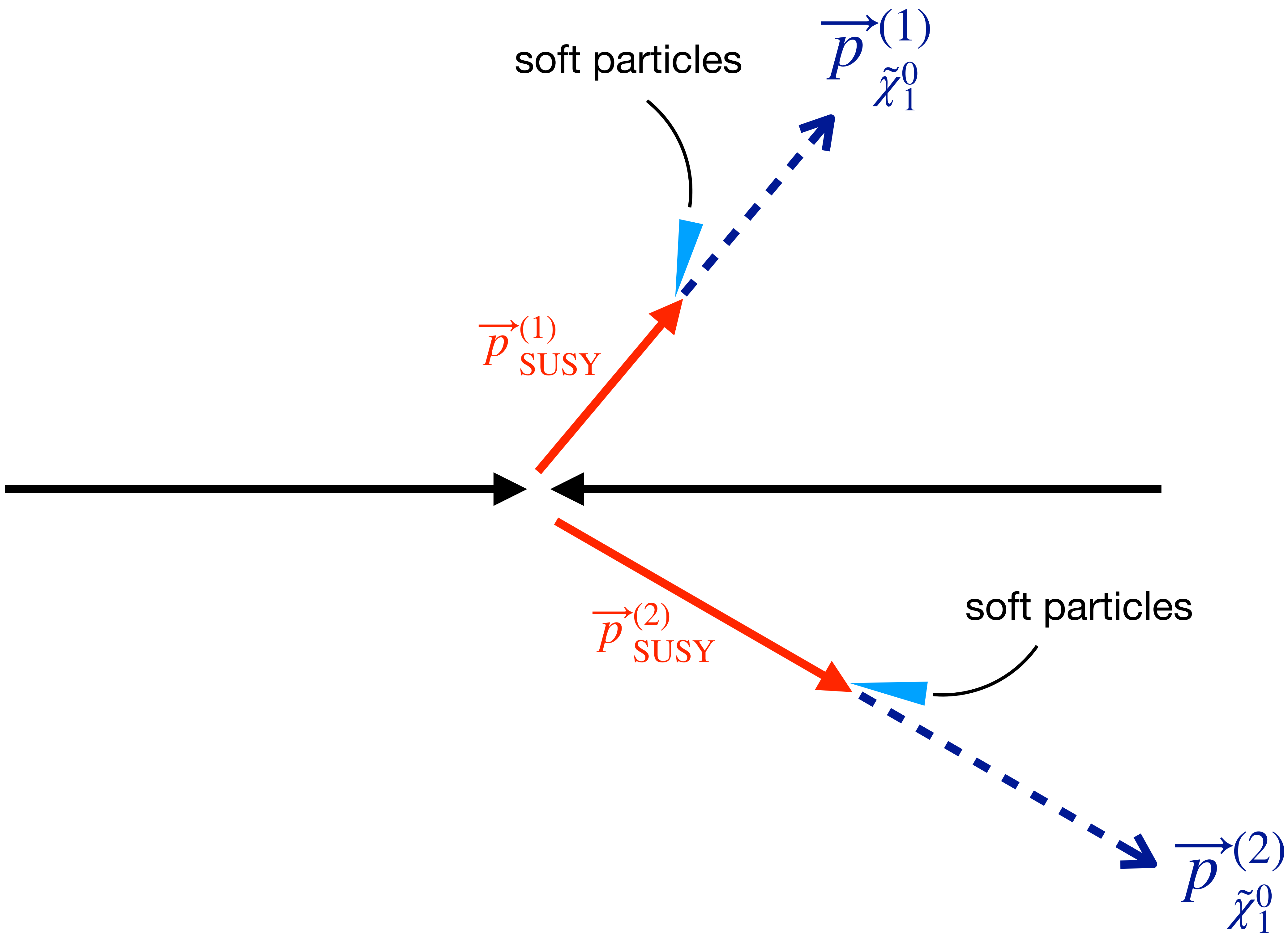
$[h\widetilde{G}][Z\widetilde{G}]$ CMS $\ell^+\ell^-$ [2012.08600]

[(massless) gravitino LSP + neutralino NLSP] cannot explain muon g-2

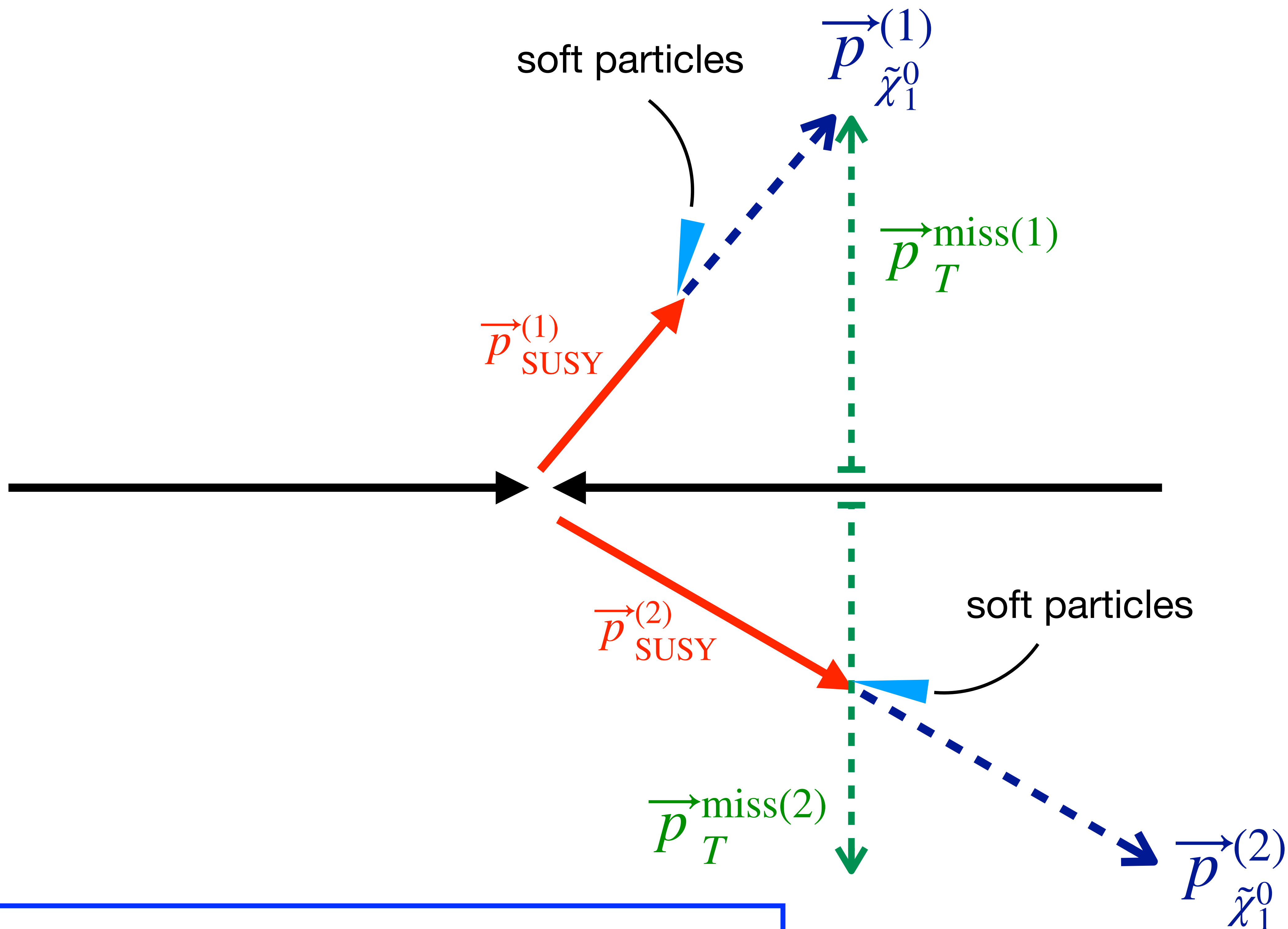
MSSM: compressed spectrum



MSSM: compressed spectrum



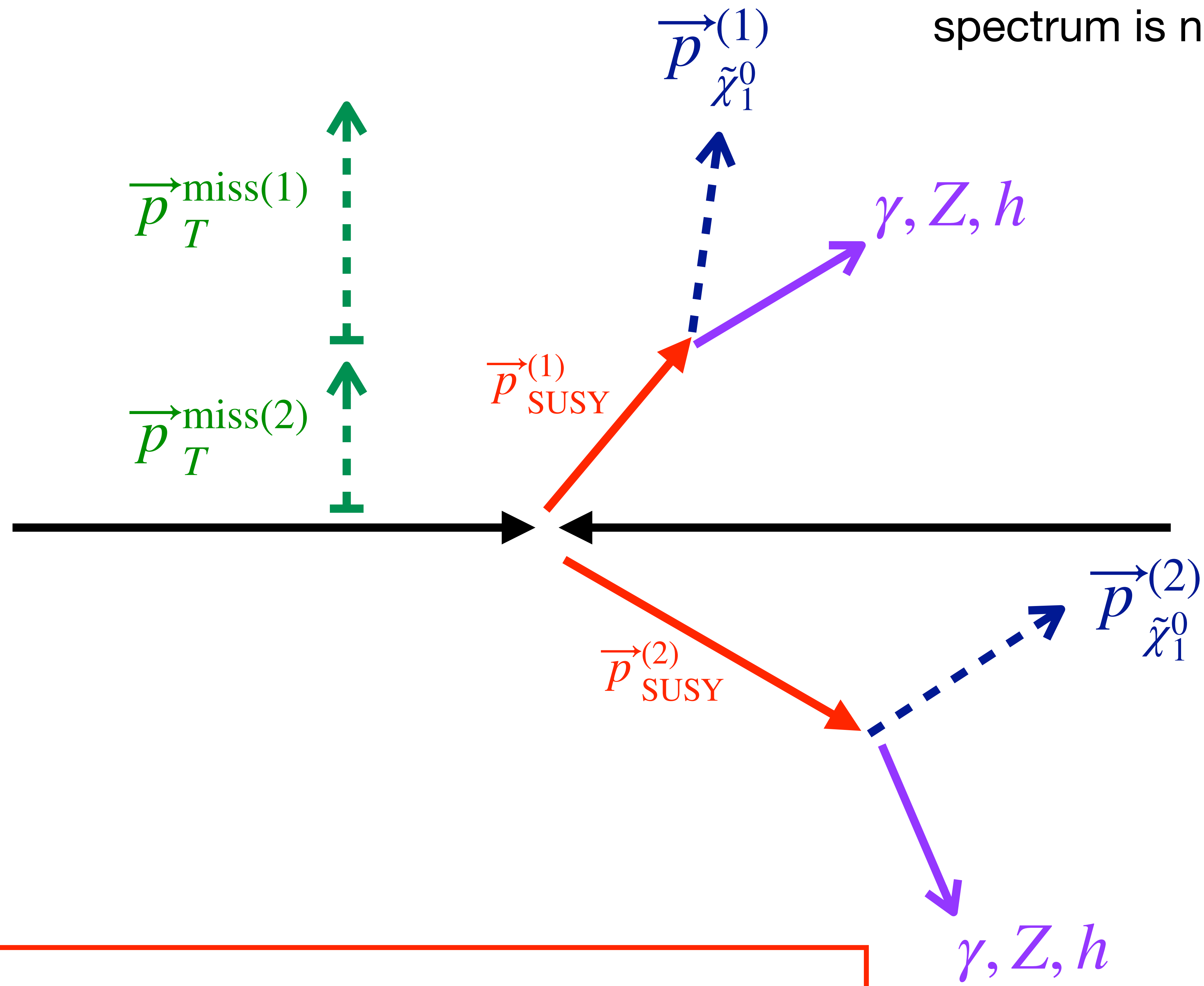
MSSM: compressed spectrum



$$\vec{p}_T^{\,\mathrm{miss}} = \vec{p}_T^{\,\mathrm{miss}(1)} + \vec{p}_T^{\,\mathrm{miss}(2)} \simeq 0$$

Gravitino LSP

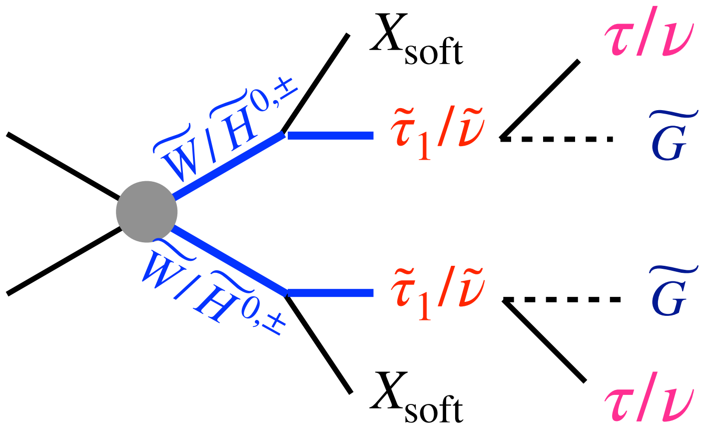
Gravitino is almost massless ➡ compressed spectrum is not possible



$$\vec{p}_T^{\,\text{miss}} = \vec{p}_T^{\,\text{miss}(1)} + \vec{p}_T^{\,\text{miss}(2)} \quad \text{is large}$$

Gravitino LSP with slepton NLSP

$\tilde{\tau}_1/\tilde{\nu}$ **NLSP:**



$(M_2 \text{ vs } \mu)$ with $\tilde{m}_{l_L} = \min(M_2, \mu) + 20\,\text{GeV} \implies m_{l_L} = \min(M_2, \mu) - 20\,\text{GeV}$

BHL plane: $\quad\Big\}\ \tilde{\nu}_L$ **NLSP**

$(M_1 \text{ vs } \mu)$ with $\tilde{m}_{l_L} = \min(M_1, \mu) + 20\,\text{GeV} \implies m_{l_L} = \min(M_2, \mu) - 20\,\text{GeV}$

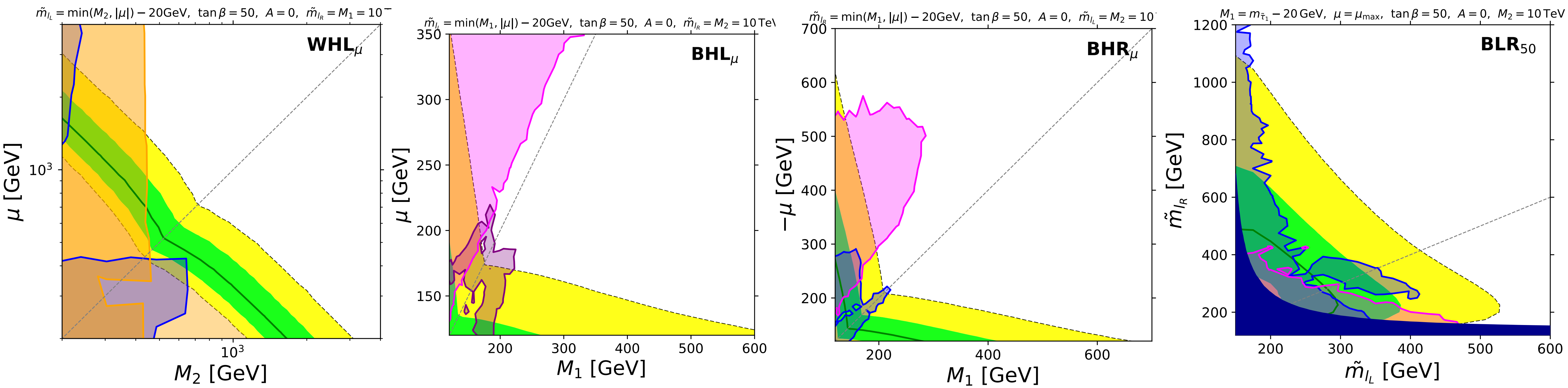
BHR plane:

$(M_1 \text{ vs } \mu)$ with $\tilde{m}_{l_R} = \min(M_1, |\mu|) + 20\,\text{GeV} \implies m_{l_R} = \min(M_1, \mu) - 20\,\text{GeV}$ $\Big\}\ \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ **NLSP**

BLR plane:

$(\tilde{m}_{l_L} \text{ vs } \tilde{m}_{l_R})$ with $M_1 = m_{\tilde{\tau}_1} - 20\,\text{GeV} \implies M_1 = m_{\tilde{\tau}_1} + 20\,\text{GeV}$ $\Big\}\ \tilde{\tau}_1$ **NLSP**

Gravitino LSP with slepton NLSP



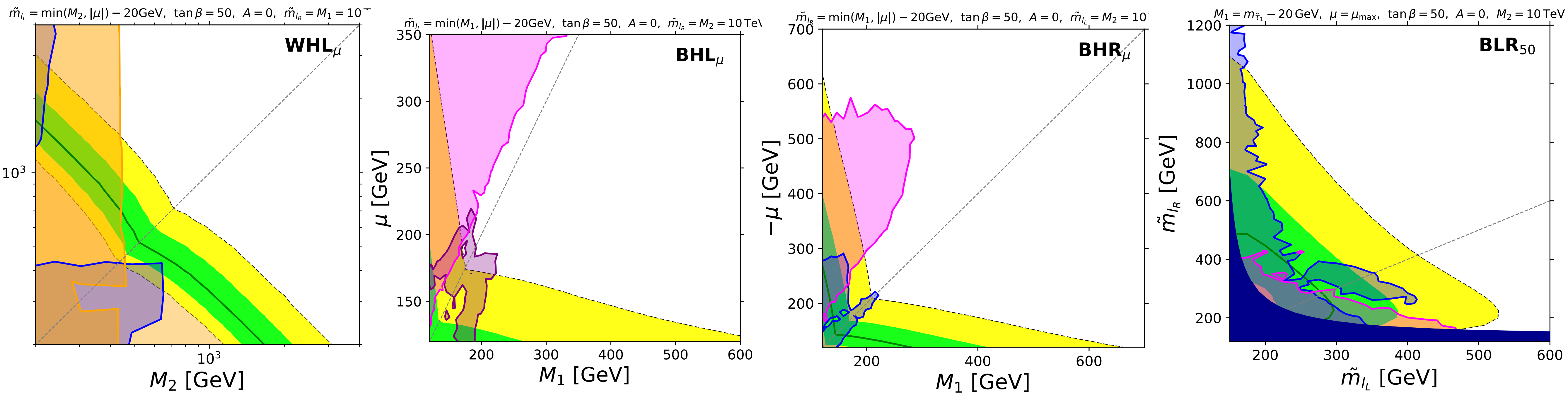
CMS soft l^+l^-
[1801.01846]

CMS multilepton
[1709.05406]

ATLAS soft-l
[1712.08119]

ATLAS $\tau^+\tau^-$
[1911.06660]

Gravitino LSP with slepton NLSP



CMS soft l+l-
[1801.01846]

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[1712.08119]

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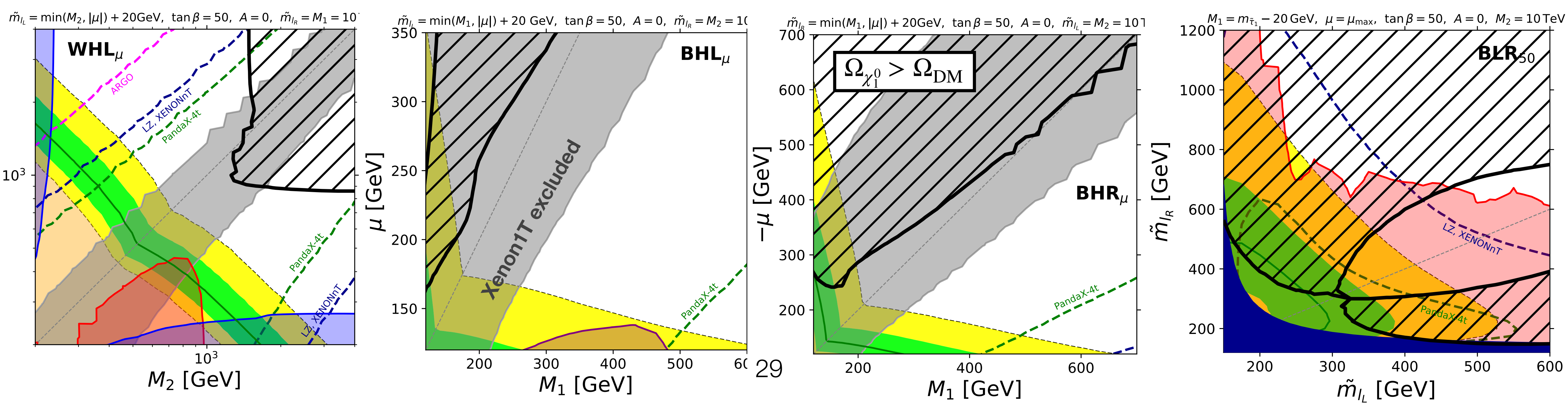
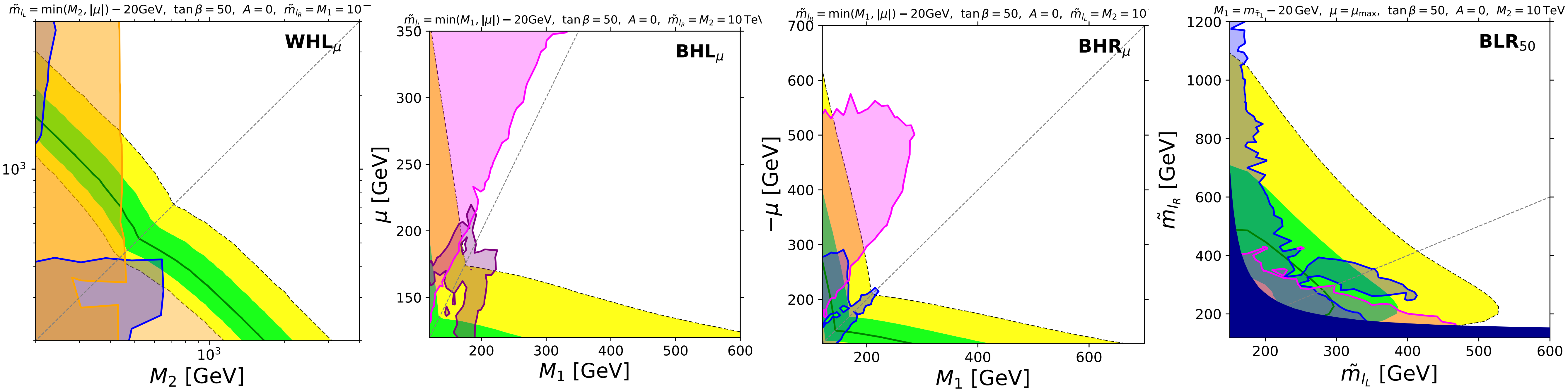
MSSM with stable neutralino:



Gravitino LSP with slepton NLSP



CMS soft l^+l^- [1801.01846]

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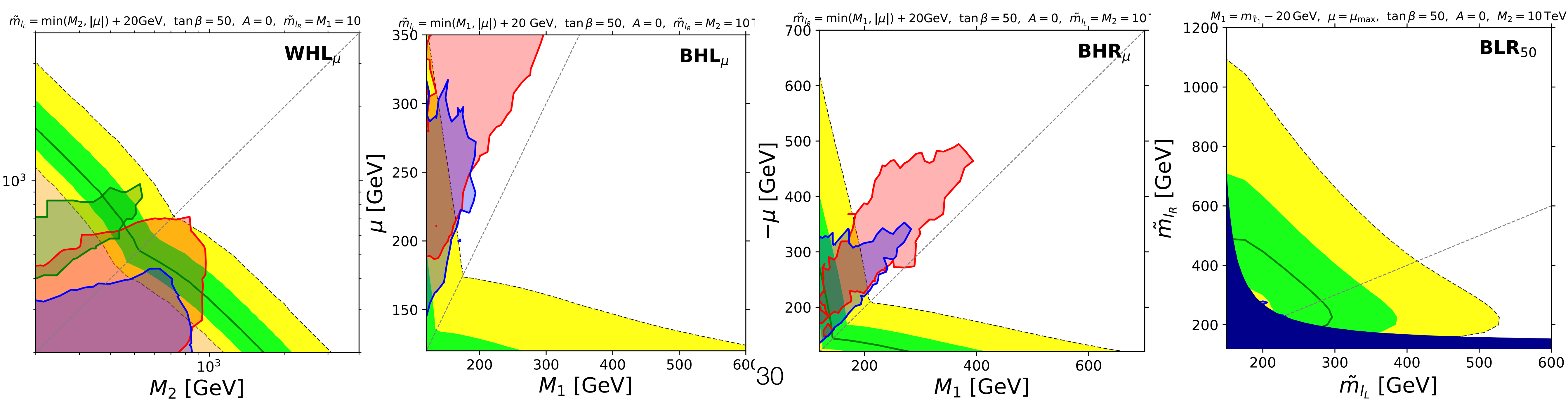
UDD RPV :



Summary

- SUSY $(g\text{-}2)_\mu$ solution requires either:

1. a large Wino(Bino)-Higgsino mixing or
2. a Bino-like LSP with large chirality flip in the slepton sector

These options are strongly constrained by the DM-DD and LHC due to large missing energy signature

- Those constraints are there because neutralino is stable.

- By decaying neutralino into 3-quarks via UDD RPV, the allowed parameter region opens up.

- Making neutralino decay into a massless gravitino **doesn't help**, because it becomes even more difficult to hide the missing energy signature at LHC.

- Gravitino LSP with slepton/stau NLSP is less constrained.

Norway grants

NATIONAL SCIENCE CENTRE
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Understanding the Early Universe:
interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen

Parameter planes definition

name	axes	range [TeV]	other parameters	$\tan\beta$
$\mathbf{WHL}_\mu$	(M_2, μ)	([0.2, 4], [0.2, 4])	$\tilde{m}_{l_\mathrm{L}} = \min(M_2, \mu) + 20\,\mathrm{GeV}, \quad M_1 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
$\mathbf{WHL}_L$	$(M_2, \tilde{m}_{l_\mathrm{L}})$	([0.2, 4], [0.2, 2])	$\mu = \min(M_2, \tilde{m}_{l_\mathrm{L}}) - 20\,\mathrm{GeV}, \quad M_1 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
$\mathbf{BHL}_\mu$	(M_1, μ)	([0.12, 0.6], [0.12, 0.35])	$\tilde{m}_{l_\mathrm{L}} = \min(M_1, \mu) + 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
$\mathbf{BHL}_L$	$(M_1, \tilde{m}_{l_\mathrm{L}})$	([0.12, 0.8], [0.14, 0.22])	$\mu = \min(M_1, \tilde{m}_{l_\mathrm{L}}) - 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
$\mathbf{BHR}_\mu$	$(M_1, \lvert\mu\rvert)$	([0.12, 0.7], [0.12, 0.7])	$\tilde{m}_{l_\mathrm{R}} = \min(M_1, \lvert\mu\rvert) + 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{L}} = 10\,\mathrm{TeV}$	50
$\mathbf{BHR}_L$	$(M_1, \tilde{m}_{l_\mathrm{R}})$	([0.12, 0.8], [0.14, 0.25])	$-\mu = \min(M_1, \tilde{m}_{l_\mathrm{R}}) - 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{L}} = 10\,\mathrm{TeV}$	50
$\mathbf{BLR}_{50}$	$(\tilde{m}_{l_\mathrm{L}}, \tilde{m}_{l_\mathrm{R}})$	([0.15, 0.6], [0.12, 1.2])	$M_1 = m_{\tilde{\tau}_1} - 20\,\mathrm{GeV}, \quad \mu = \mu_\mathrm{max}, \quad M_2 = 10\,\mathrm{TeV}$	50
$\mathbf{BLR}_{10}$	$(\tilde{m}_{l_\mathrm{L}}, \tilde{m}_{l_\mathrm{R}})$	([0.15, 0.6], [0.12, 1.2])	$M_1 = m_{\tilde{\tau}_1} - 20\,\mathrm{GeV}, \quad \mu = \mu_\mathrm{max}, \quad M_2 = 10\,\mathrm{TeV}$	10

Table 1: The parameter planes and choices of the other parameters. μ_max is defined as the maximum value allowed by the vacuum stability constraint.

For GMSB we modify the planes to ensure that slepton/stau/sneutrino is the NLSP.

$$\begin{array}{lcccccc} & & & \text{QED} & \text{HVP} & \text{EW} & \\ a_\mu^{\text{theo}} & = & 0.00 & 1165 & 91 & 810 & (43) \\ a_\mu^{\text{exp}} & = & 0.00 & 1165 & 92 & 061 & (41) \end{array}$$

- The deviation is size of the EW correction in SM:

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

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

$$\Delta a_\mu^{\text{BSM}} \sim \Delta a^{\text{SM,EW}} \cdot \underbrace{\left(\frac{m_W^2}{m_{\text{BSM}}^2}\right) \cdot \left(\frac{g_{\text{BSM}}}{g_{\text{SM}}}\right)}_{\mathcal{O}(1)}$$

Chiral (tanβ) enhancement in SUSY

- (g-2) operator requires chirality flip:

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

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

$$\mathscr{L}_{\rm eff} \ni i\widetilde{a}_\mu \cdot \bar{\psi}_L \sigma^{\mu\nu} \psi_R F_{\mu\nu}$$

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

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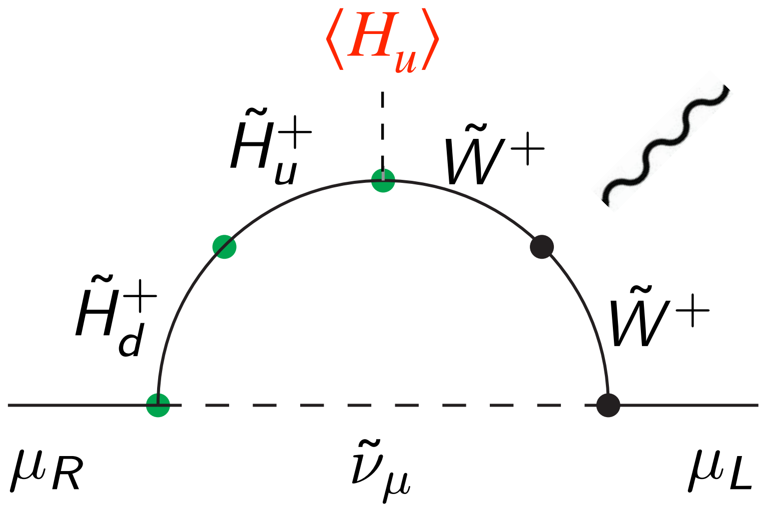
SM: $\tilde{a}_\mu^{\rm SM} \propto Y_\mu \langle H \rangle = m_\mu$

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

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



$$\langle H_u \rangle^2 + \langle H_d \rangle^2 = \langle H \rangle^2$$

$(246\,{\rm GeV})^2$

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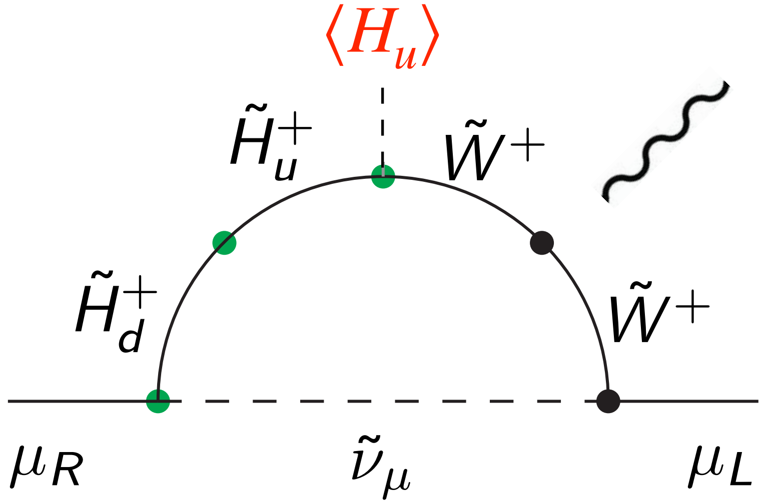


$\langle H_u \rangle^2 + \langle H_d \rangle^2 = \langle H \rangle^2$

$(246\ {\rm GeV})^2$

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

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

- Due to strong LHC constraints, we *decouple coloured SUSY particles* (they do not contribute to $(g\text{-}2)_\mu$ anyway).

- a_μ^{SUSY} depends on 5 mass parameters and $\tan\beta$:

M_1 : Bino mass

M_2 : Wino mass

μ : Higgsino mass

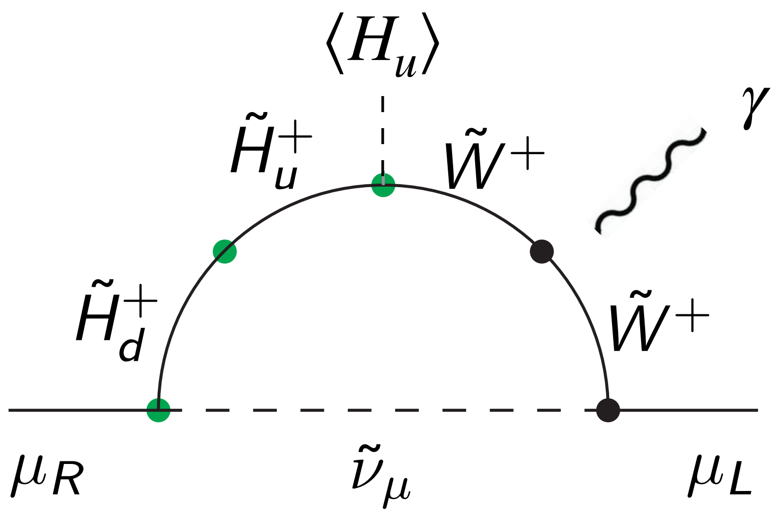
$$m_{\tilde{l}_R} \equiv \widetilde{m}^2_{\tilde{e}_R} = \widetilde{m}^2_{\tilde{\mu}_R} = \widetilde{m}^2_{\tilde{\tau}_R}$$

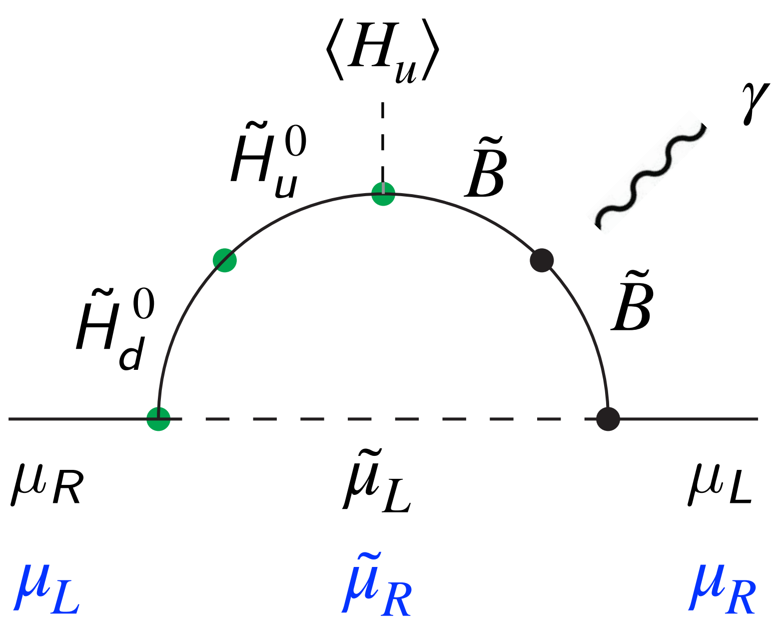
$$m_{\tilde{l}_L} \equiv \widetilde{m}_{\tilde{\nu}_e} = \widetilde{m}_{\tilde{\nu}_\mu} = \widetilde{m}_{\tilde{\nu}_\tau} = \widetilde{m}_{\tilde{e}_L} = \widetilde{m}_{\tilde{\mu}_L} = \widetilde{m}_{\tilde{\tau}_L}$$

$$\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$$

no LFV due to universal soft masses: avoid strong constraint from $\mu \to e\,\gamma$

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



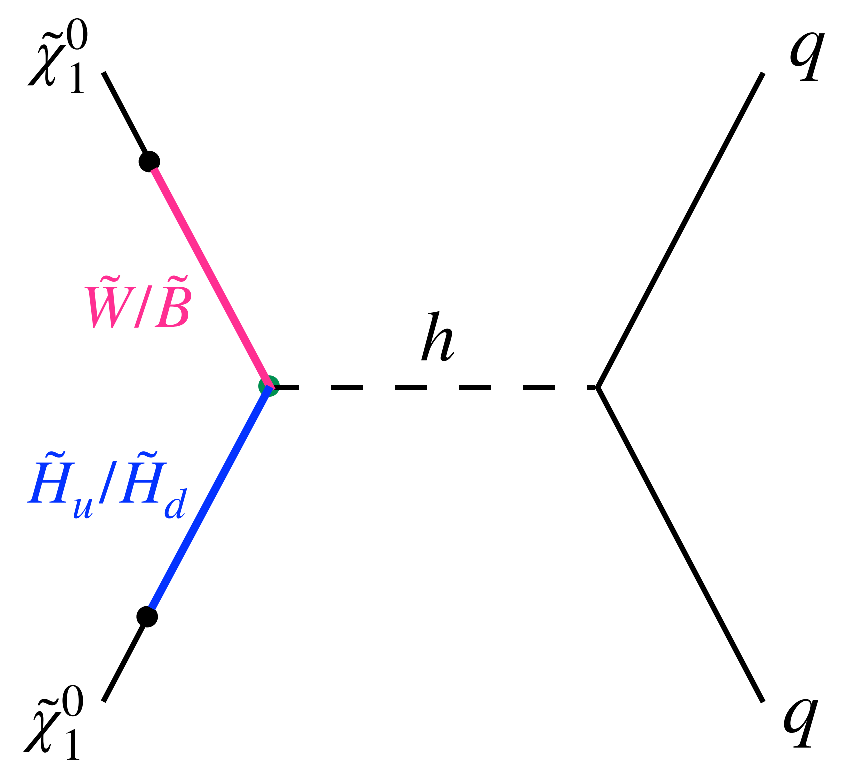


$$\Delta a_\mu^{\rm WHL}(M_2, \mu, m_{\tilde{l}_L}) = \frac{\alpha_W}{8\pi} \frac{m_\mu^2}{M_2 \mu} \tan\beta \cdot f_{\rm W}(\{\mathbf{m}\})$$

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

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

Large gaugino-Higgsino mixing leads to a
large cross-section for DM Direct Detection:

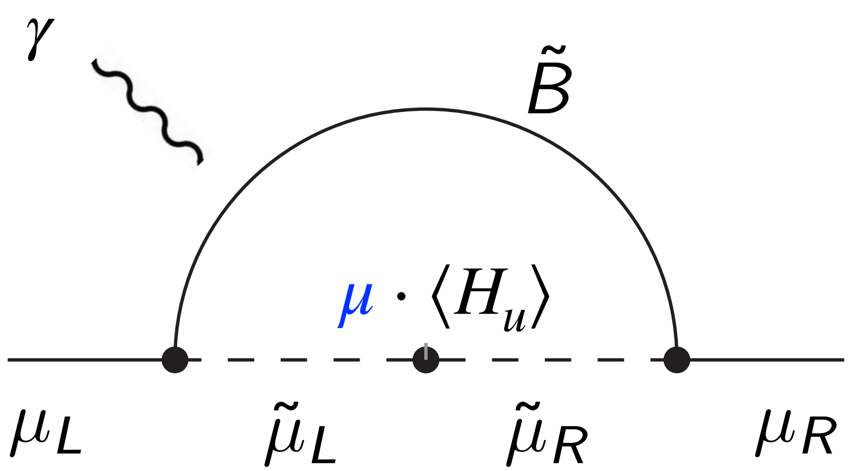


M_1 : Bino ($\tilde{B}$) mass

M_2 : Wino ($\tilde{W}$) mass

μ : Higgsino ($\tilde{H}_u, \tilde{H}_d$) mass

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



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

↑ large μ needed

Constraints:

❖ Stau mass² becomes negative or too small!

$$(\tilde{\tau}\ \text{mass matrix}) \sim \begin{pmatrix} m_{\tilde{\tau}_R}^2 & Y_\tau \mu \langle H_u \rangle \\ Y_\tau \mu \langle H_u \rangle & m_{\tilde{\tau}_L}^2 \end{pmatrix}$$

- charge breaking vacuum: $m^2_{\rm stau1} > 0$
- LEP bound: $m_{\rm stau1} > 90$ GeV
- stau LSP: $m_{\rm stau1} > m_{\rm neutralino1}$
- **Vacuum (meta-)stability:**

$$\left|m_{\tilde{\ell}_{LR}}^2\right| \le \left[1.01\times10^2\,{\rm GeV}\sqrt{m_{\tilde{\ell}_L} m_{\tilde{\ell}_R}} + 1.01\times10^2\,{\rm GeV}(m_{\tilde{\ell}_L} + 1.03 m_{\tilde{\ell}_R}) - 2.27\times10^4\,{\rm GeV}^2 + \frac{2.97\times10^6\,{\rm GeV}^3}{m_{\tilde{\ell}_L} + m_{\tilde{\ell}_R}} - 1.14\times10^8\,{\rm GeV}^4\left(\frac{1}{m_{\tilde{\ell}_L}^2} + \frac{0.983}{m_{\tilde{\ell}_R}^2}\right)\right]$$

[Kitahara, Yoshinaga 13]; [Endo, Hamaguchi, Kitahara, Yoshinaga 13]

❖ **Overproduction of Bino-like neutralinos** in the early universe: $\Omega_{\tilde{\chi}_1^0} < \Omega_{\rm DM}$

slepton-coannihilation needed ⟹ $m_{\rm slepton} \sim m_{\rm Bino}$

Unstable Neutralino (Gravitino, RPV)

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

$\Delta a_\mu^{\text{WHL}}(M_2, \mu, m_{\tilde{l}_L})$

$\Delta a_\mu^{\text{BHL}}(M_1, \mu, m_{\tilde{l}_L})$

$\Delta a_\mu^{\text{BHR}}(M_1, \mu, m_{\tilde{l}_R})$

Higgsino, one gaugino, one slepton all must be light:

$\Longrightarrow$ **LHC constraint with large $\not{E}_T$** **← Modified**

gaugino-Higgsino mixing $\Longrightarrow$ ~~**DM direct detection**~~

$\Delta a_\mu^{\text{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R};\ \mu)$

↑ large

Bino and both L and R sleptons must be light:

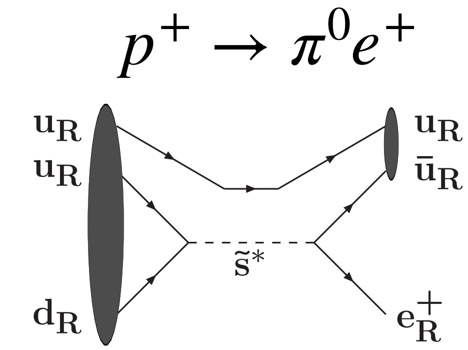
$\Longrightarrow$ **LHC constraint with large $\not{E}_T$** **← Modified**

$\Longrightarrow$ ~~**Bino abundance** $\Omega_{\chi_1^0} < \Omega_{\text{DM}}$~~

$\Longrightarrow$ **Charged LSP, Vacuum stability**

R-Parity Violation; UDD

$$W_{\rm RPV} = \underbrace{\lambda''_{ijk} U_i^c D_j^c D_k^c}_{\not B} + \underbrace{\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \kappa_i L_i H_u}_{\not L}$$



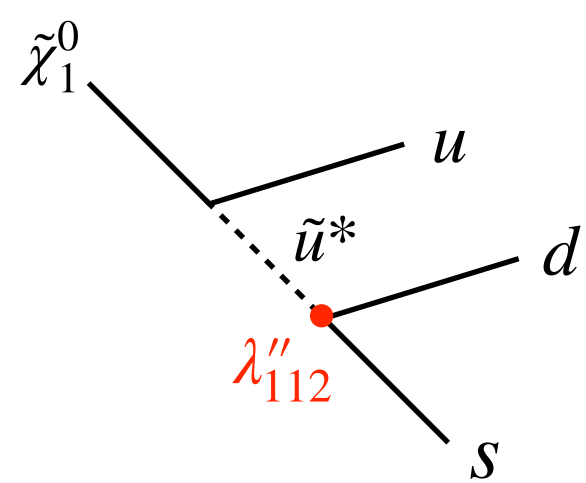
- Allowing both **B** and **L** violation leads to a rapid proton decay:
- We introduce only the **UDD** operator with: $\lambda''_{112} \neq 0$

  - Constraint from K0-K0bar mixing can easily be satisfied:

$$|\lambda''_{112}\lambda''_{123}| \lesssim 2.8 \times 10^{-2} \left(\frac{m_{\tilde{s}_R,\tilde{u}_R}}{1\,\mathrm{TeV}}\right)$$
$$|\lambda''_{112}\lambda''_{113}| \lesssim 1.2 \times 10^{-1} \left(\frac{m_{\tilde{d}_R,\tilde{u}_R}}{1\,\mathrm{TeV}}\right)$$

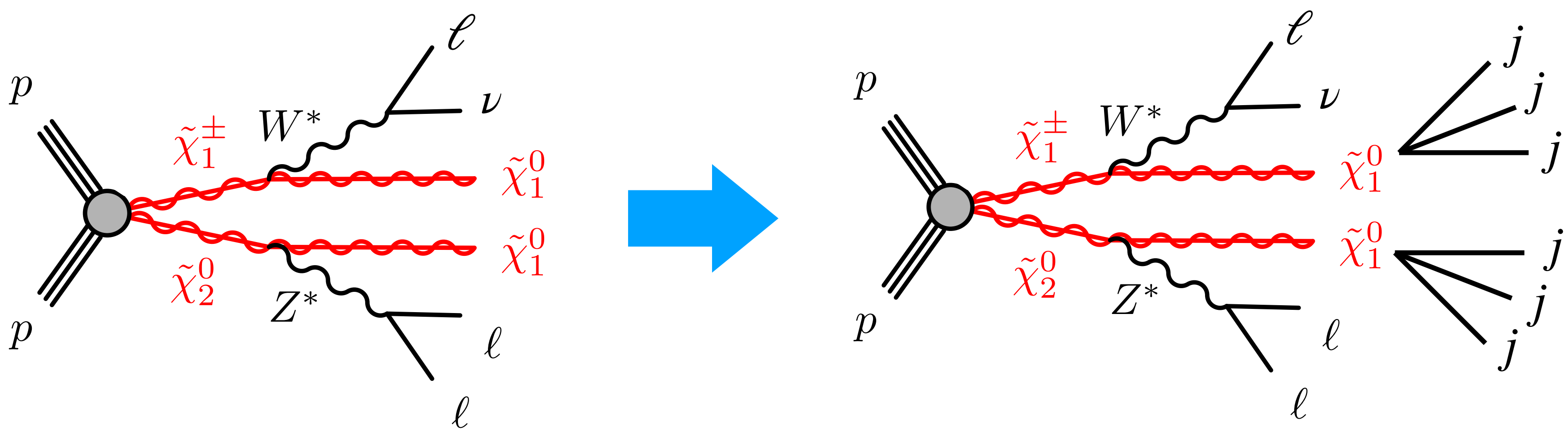
[1810.08228]

  - **LHC signature is the most challenging:**
    no leptons, no b-jets in the neutralino decay



R-Parity Violation; UDD

neutralino LSP



RPV (UDD-type)

No missing energy, but multi-jet

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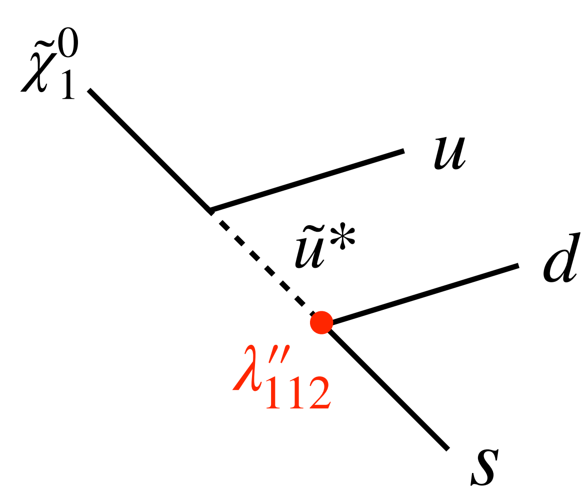

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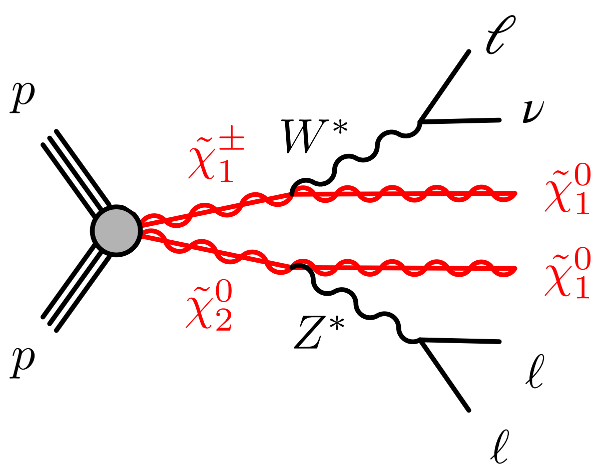
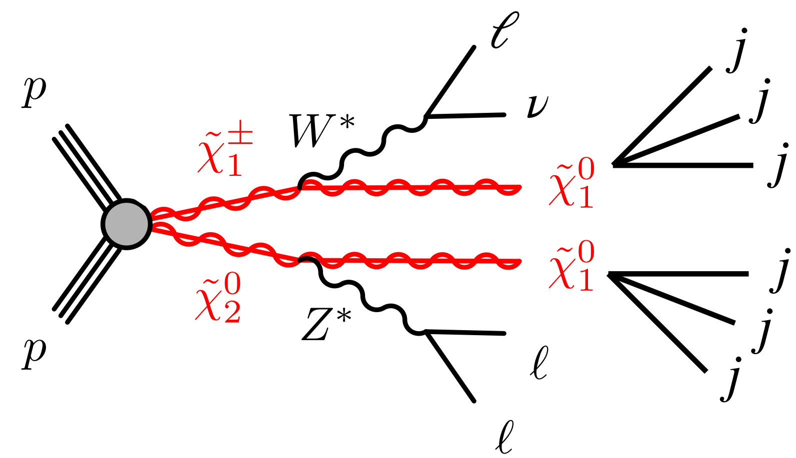


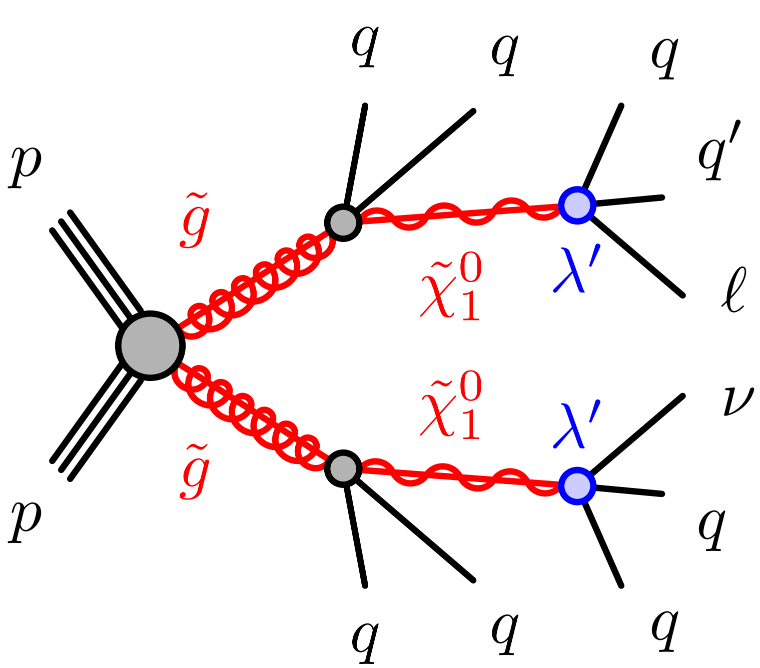


RPV (UDD-type)

No missing energy, but multi-jet

- There exist ATLAS and CMS analyses sensitive to such final states:

ATLAS [2106.09609]



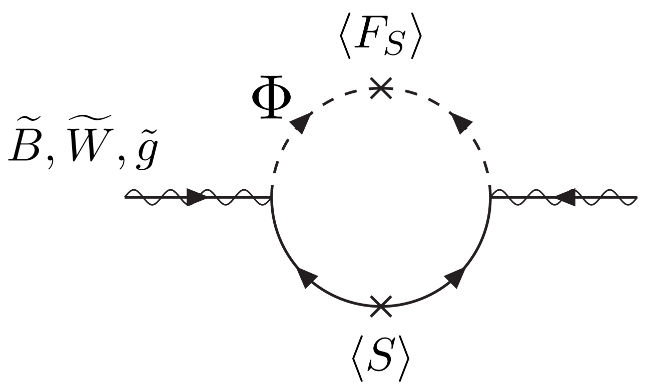
CMS [1709.05406]

Bin	Final state	Definition
1	2 SS leptons	0 jets, $M_T > 100$ GeV and $p_T^{miss} > 140$ GeV
2	2 SS leptons	1 jet , $M_T < 100$ GeV, $p_T^{\ell\ell} < 100$ GeV and $p_T^{miss} > 200$ GeV
3	3 light leptons	$M_T > 120$ GeV and $p_T^{miss} > 200$ GeV
4	3 light leptons	$p_T^{miss} > 250$ GeV
5	2 light leptons and 1 tau	$M_{T2}(\ell_1, \tau) > 50$ GeV and $p_T^{miss} > 200$ GeV
6	1 light lepton and 2 taus	$M_{T2}(\ell, \tau_1) > 50$ GeV and $p_T^{miss} > 200$ GeV
7	1 light lepton and 2 taus	$p_T^{miss} > 75$ GeV
8	more than 3 leptons	$p_T^{miss} > 200$ GeV

Gravitino LSP

- In the gauge-mediated SUSY breaking (GMSB) scenario, light gravitino is motivated by naturalness:

$$\delta m_h^2 \propto m_{SUSY}^2 \ln\left(\frac{\Lambda_{\rm mess}}{M_{\rm PL}}\right) \qquad m_{3/2} = \frac{4\pi}{\sqrt{3}\alpha_W} M_2 \frac{\Lambda_{\rm mess}}{M_{\rm PL}}$$



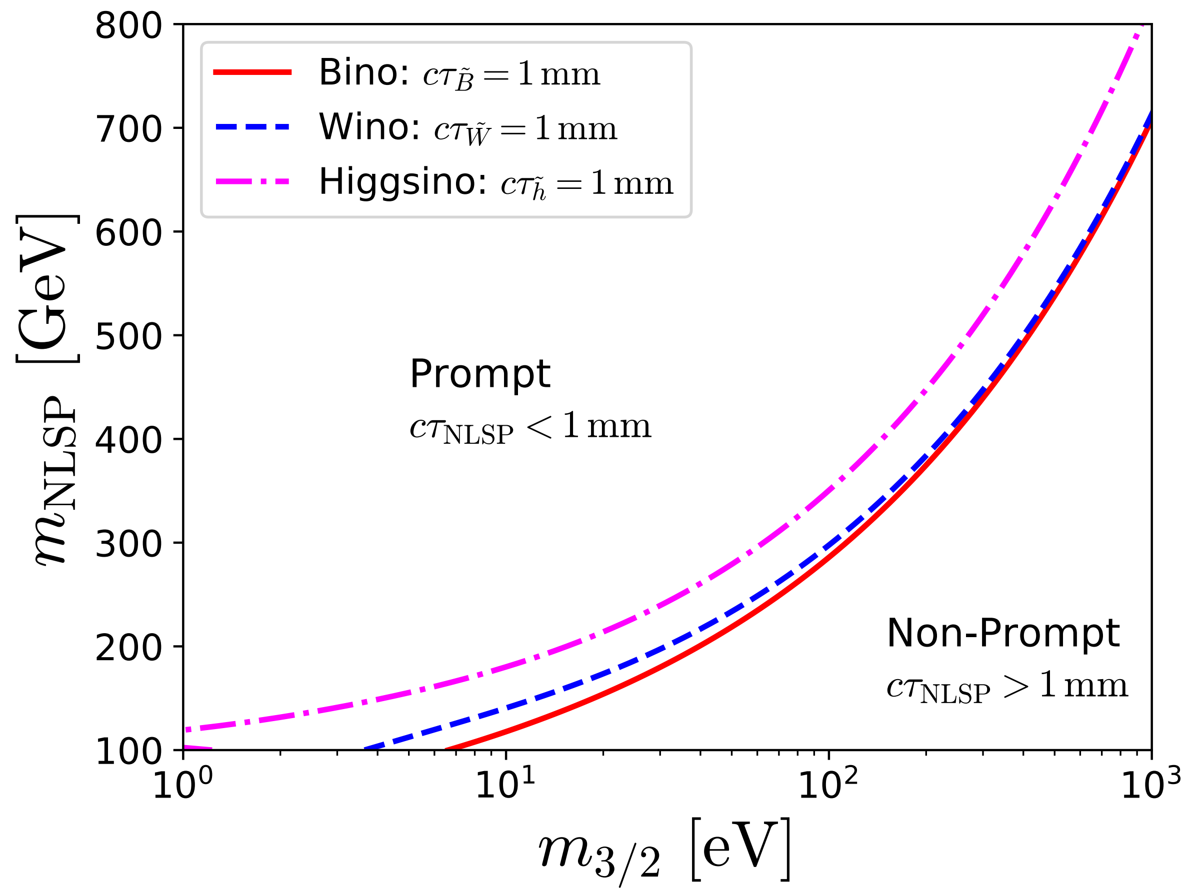
- The decay rate of the NLSP neutralino into the gravitino can be calculated. For light gravitinos (< 10-100 eV), the neutralino decays are prompt.

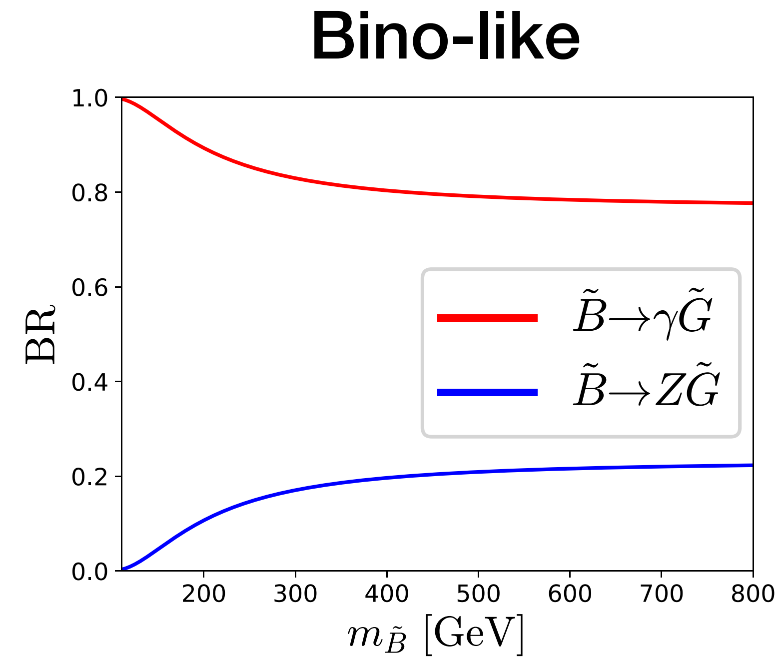
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) = \left|N_{11}c_W + N_{12}s_W\right|^2 \mathcal{A},$$

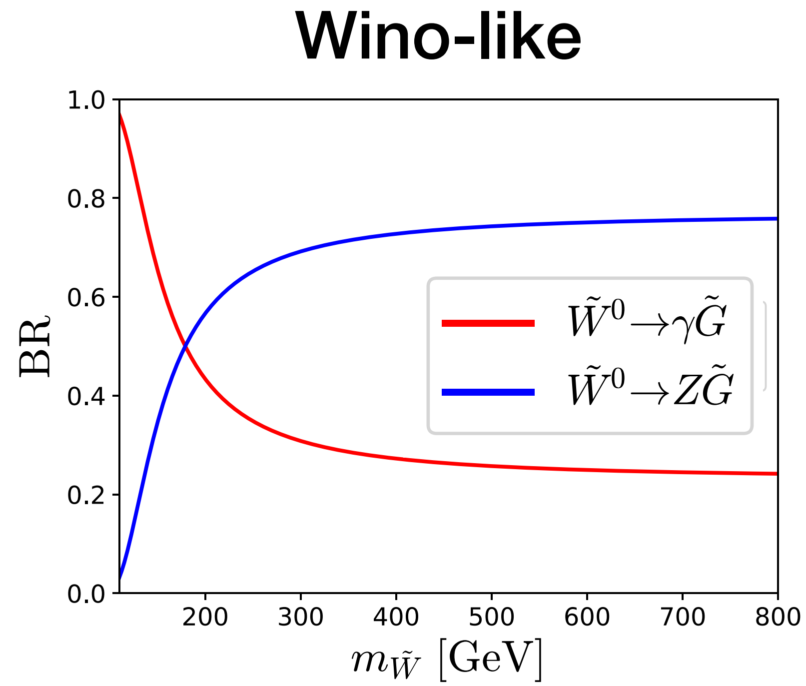
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}Z) = \left(\left|N_{12}c_W - N_{11}s_W\right|^2 + \frac{1}{2}\left|N_{13}c_\beta - N_{14}s_\beta\right|^2\right)\left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A},$$

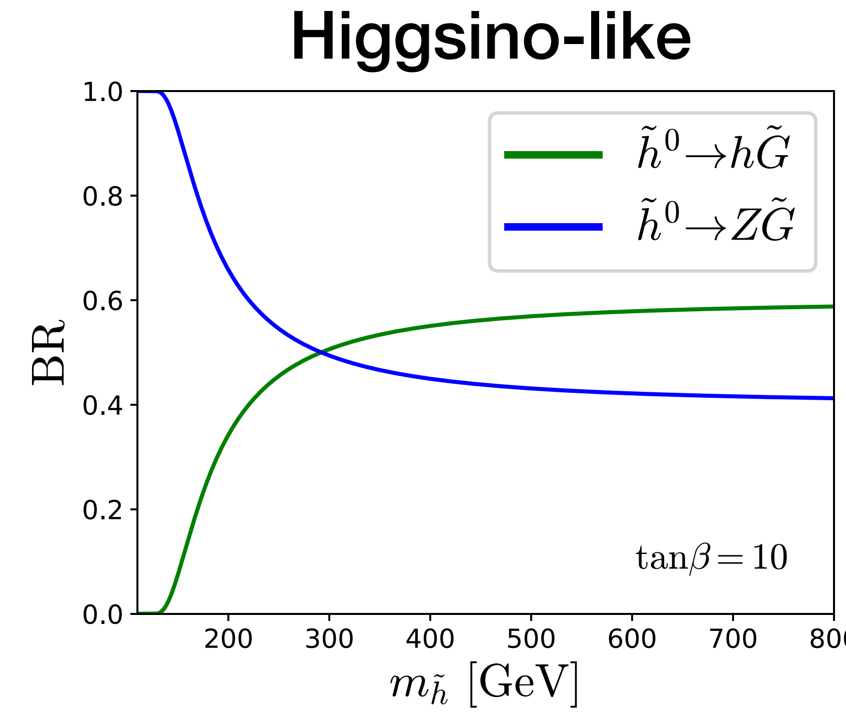
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}h) = \frac{1}{2}\left|N_{13}c_\beta + N_{14}s_\beta\right|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A},$$

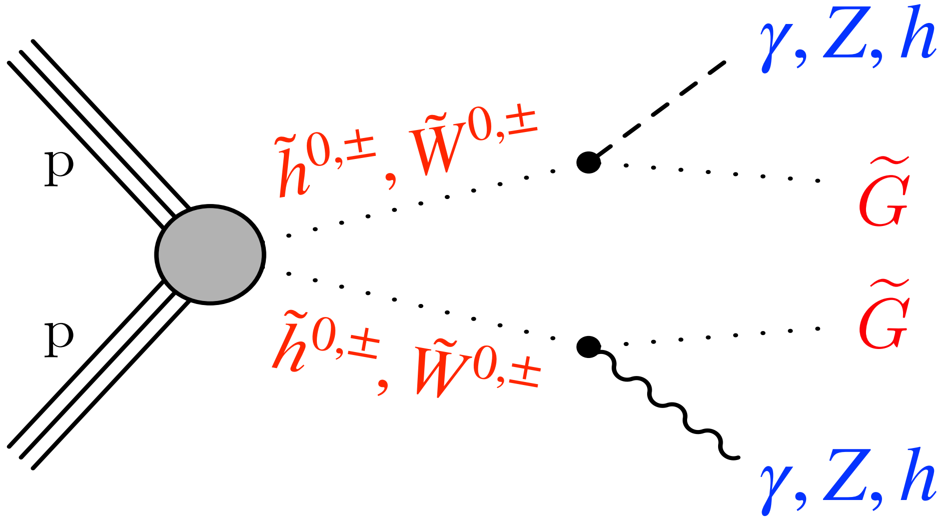
$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi m_{3/2}^2 M_{\rm pl}^2} \sim \frac{1}{0.3\,{\rm mm}}\left(\frac{m_{\tilde{\chi}_1^0}}{100\,{\rm GeV}}\right)^5 \left(\frac{m_{3/2}}{10\,{\rm eV}}\right)^{-2}$$

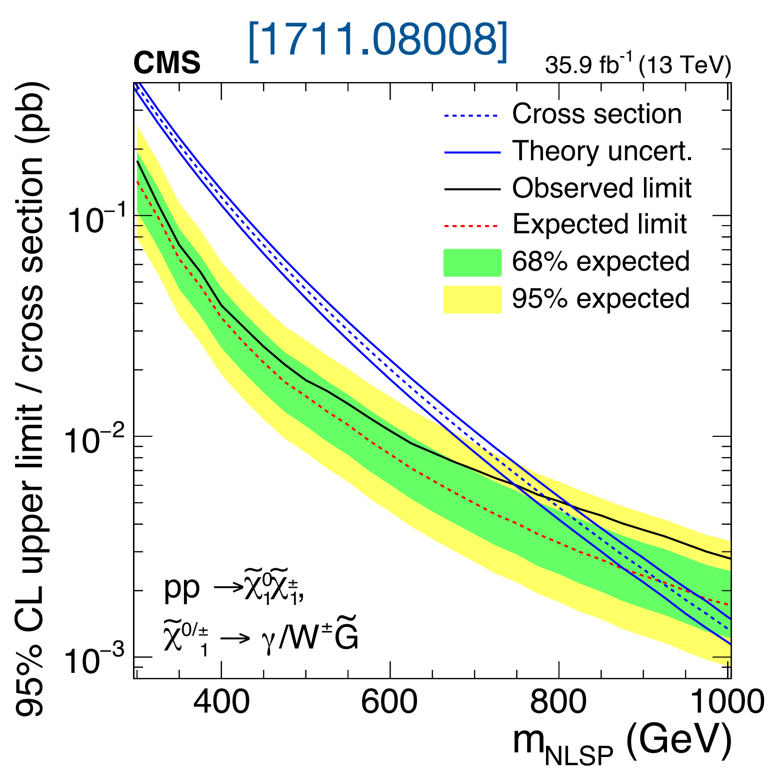


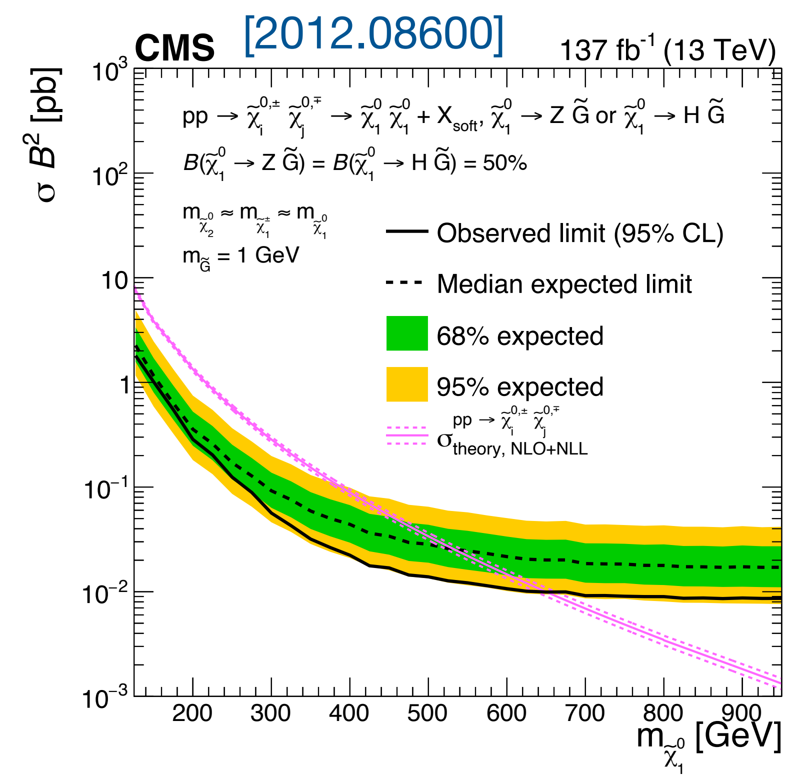












- Higgsino, Wino direct production excluded up to ~ 700GeV
- SUSY g-2 requires Higgsino or Wino with m < 600 GeV

SUSY $(g-2)_\mu$ incompatible with LHC

Analysis Framework

SUSY g-2: 1-loop + leading 2-loop GM2Calc [Eur.Phys.J. C76 (2016) no.2, 62]

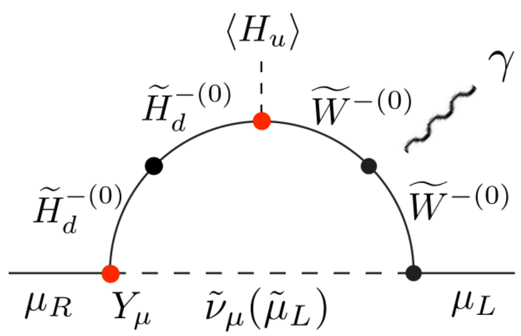
Neutralino abundance, Direct Detection: MicrOMEGAs [2003.08621]

Decay of SUSY particles: SUSY-HIT [hep-ph/0609292]

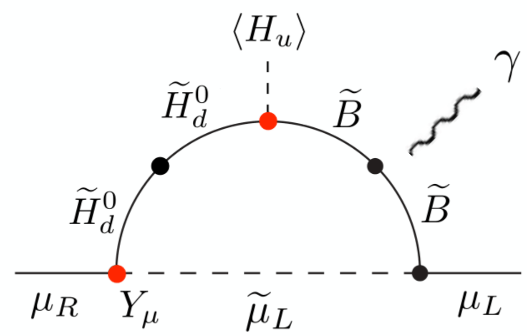
LHC constraints:

- **MSSM:** ① Mapping simplified model limits to the model point (σ BR)
- **RPV:** ② Pythia 8 + CheckMATE 2 [1907.09874], [1611.09856]
- **Gravitino LSP:** Both ① and ②

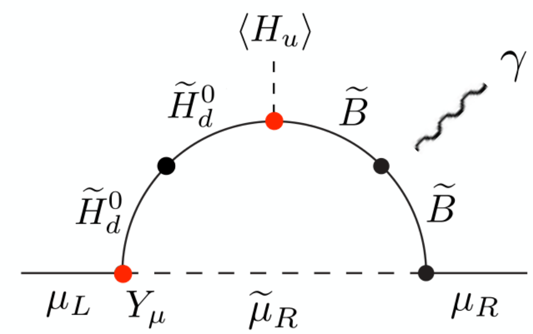
Parameter planes



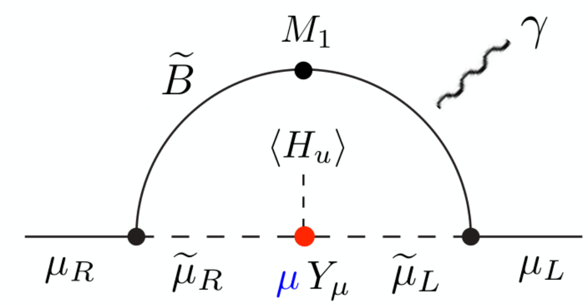
$\Delta a_\mu^{\mathrm{WHL}}(M_2, \mu, m_{\tilde{l}_L})$



$\Delta a_\mu^{\mathrm{BHL}}(M_1, \mu, m_{\tilde{l}_L})$



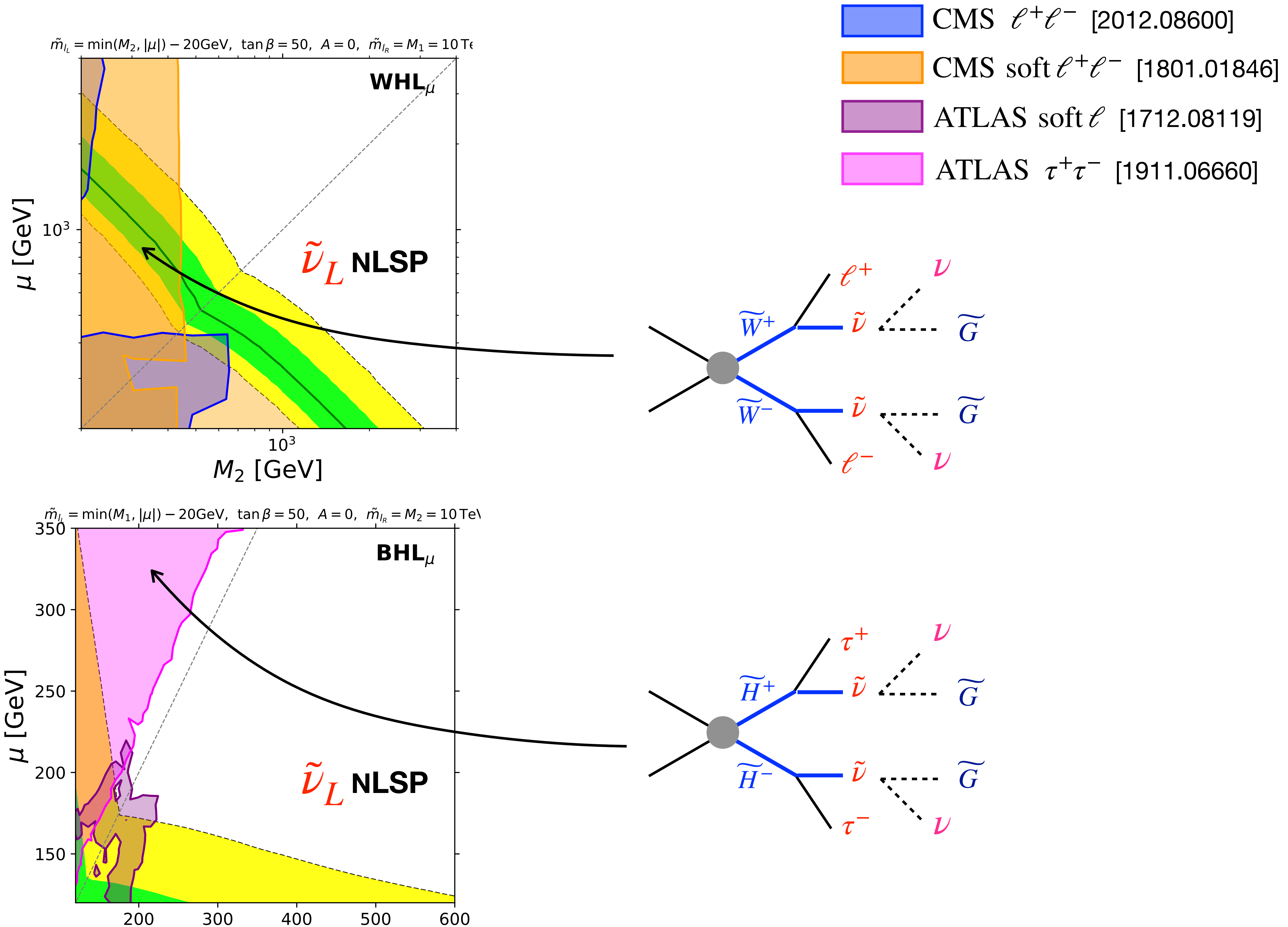
$\Delta a_\mu^{\mathrm{BHR}}(M_1, \mu, m_{\tilde{l}_R})$



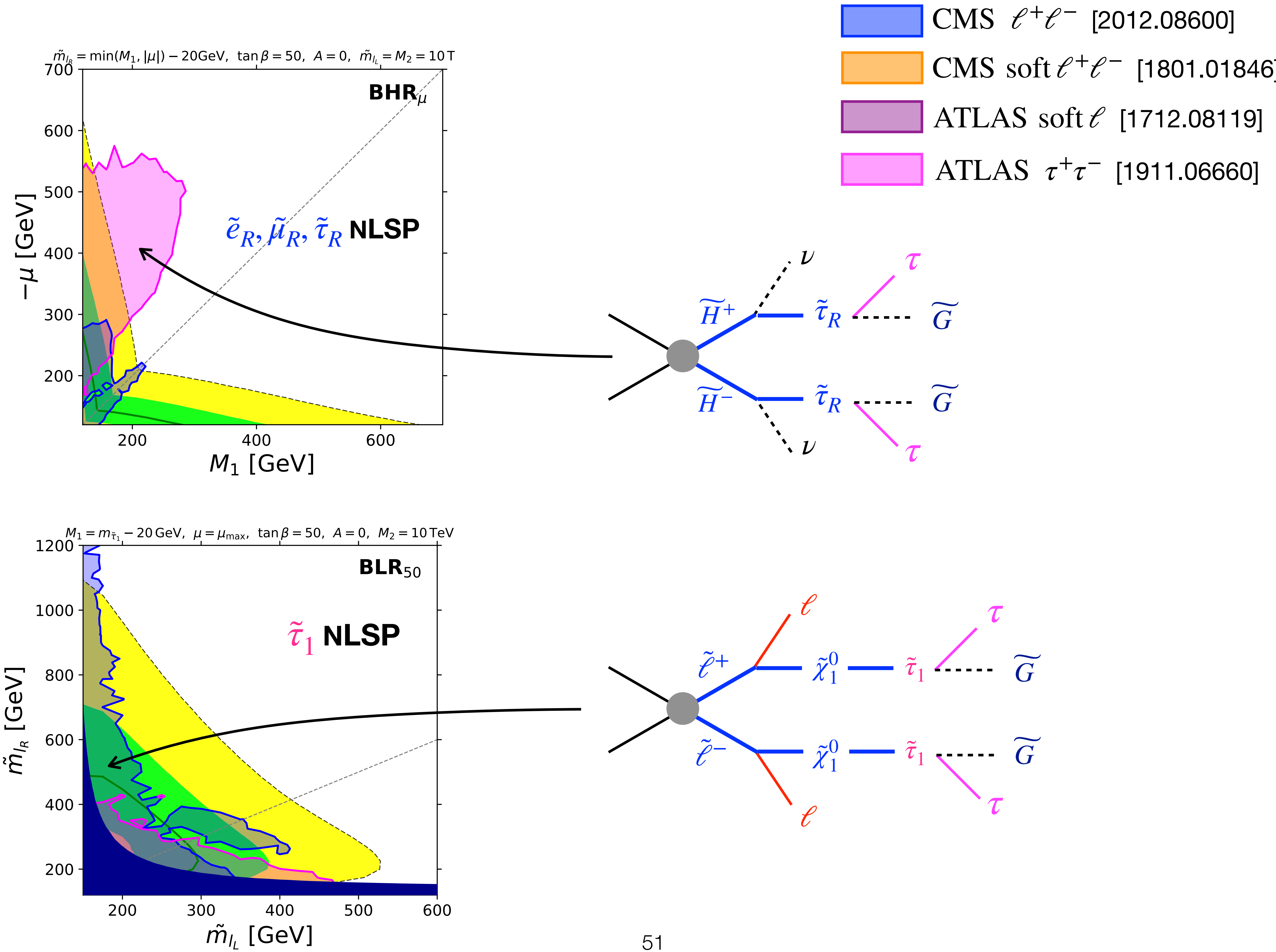
$\Delta a_\mu^{\mathrm{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R}\ ;\ \mu)$

2D planes ↓ (axes)

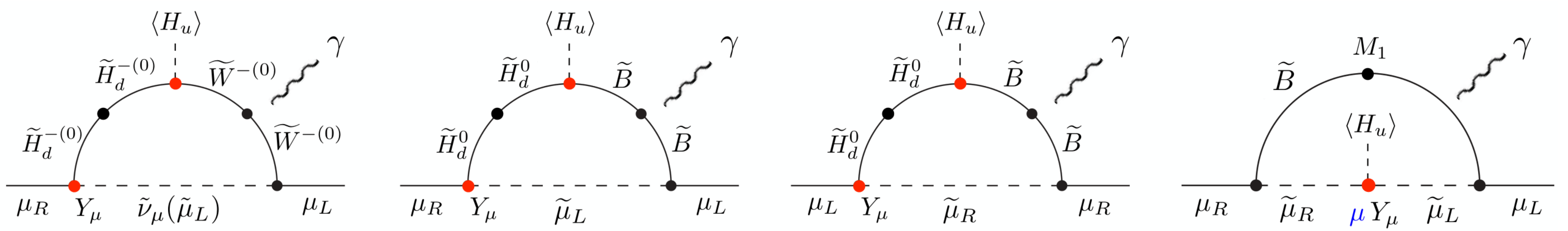
name	axes	other parameters	$\tan\beta$
WHL	(M_2, μ)	$\tilde{m}_{l_\mathrm{L}} = \min(M_2, \mu) + 20\,\mathrm{GeV}, \quad M_1 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
BHL	(M_1, μ)	$\tilde{m}_{l_\mathrm{L}} = \min(M_1, \mu) + 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
BHR	$(M_1, \lvert\mu\rvert)$	$\tilde{m}_{l_\mathrm{R}} = \min(M_1, \lvert\mu\rvert) + 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{L}} = 10\,\mathrm{TeV}$	50
BLR	$(\tilde{m}_{l_\mathrm{L}}, \tilde{m}_{l_\mathrm{R}})$	$M_1 = m_{\tilde{\tau}_1} - 20\,\mathrm{GeV}, \quad \mu = \mu_{\mathrm{max}}, \quad M_2 = 10\,\mathrm{TeV}$	50



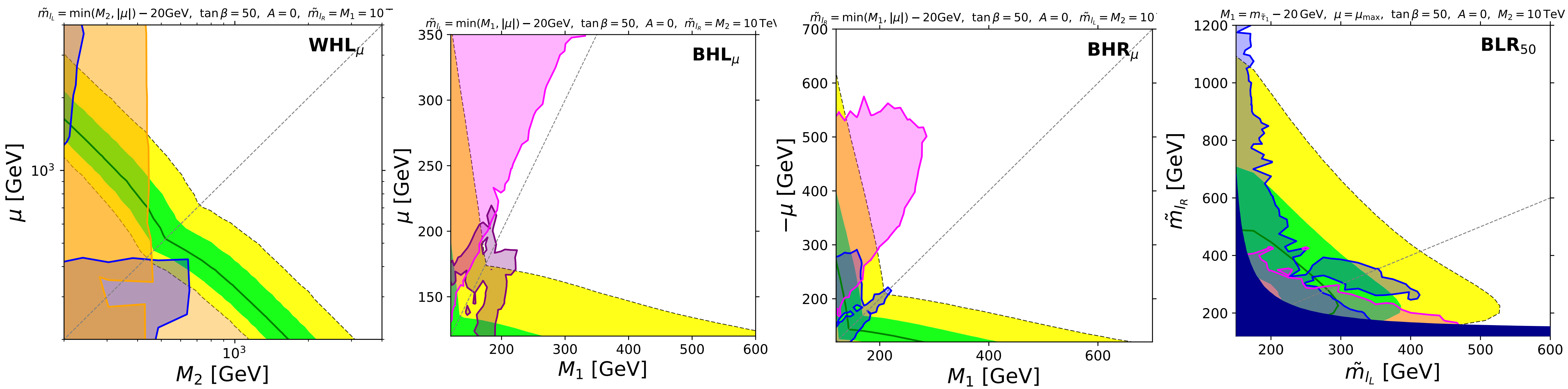
CMS $\ell^+\ell^-$ [2012.08600]
CMS soft $\ell^+\ell^-$ [1801.01846]
ATLAS soft ℓ [1712.08119]
ATLAS $\tau^+\tau^-$ [1911.06660]
$\tilde{m}_{l_L} = \min(M_2, |\mu|) - 20\text{GeV}, \tan\beta = 50, A = 0, \tilde{m}_{l_R} = M_1 = 10\,\text{Te}$
WHL$_\mu$
$\tilde{\nu}_L$ NLSP
μ [GeV]
10^3
M_2 [GeV]
$\widetilde{W}^+$
$\widetilde{W}^-$
ℓ^+
ℓ^-
$\tilde{\nu}$
ν
$\widetilde{G}$
$\tilde{m}_{l_L} = \min(M_1, |\mu|) - 20\text{GeV}, \tan\beta = 50, A = 0, \tilde{m}_{l_R} = M_2 = 10\,\text{Te}$
BHL$_\mu$
$\tilde{\nu}_L$ NLSP
350
300
250
200
150
200
300
400
500
600
M_1 [GeV]
$\widetilde{H}^+$
$\widetilde{H}^-$
τ^+
τ^-


CMS $\ell^+\ell^-$ [2012.08600]
CMS soft $\ell^+\ell^-$ [1801.01846]
ATLAS soft ℓ [1712.08119]
ATLAS $\tau^+\tau^-$ [1911.06660]
$\tilde{m}_{l_R} = \min(M_1, |\mu|) - 20\,\mathrm{GeV}$, $\tan\beta = 50$, $A = 0$, $\tilde{m}_{l_L} = M_2 = 10\,\mathrm{T}$
BHR$_\mu$
$\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ NLSP
$-\mu$ [GeV]
M_1 [GeV]
$\widetilde{H}^+$
$\widetilde{H}^-$
ν
$\tilde{\tau}_R$
τ
$\widetilde{G}$
$M_1 = m_{\tilde{\tau}_1} - 20\,\mathrm{GeV}$, $\mu = \mu_{\max}$, $\tan\beta = 50$, $A = 0$, $M_2 = 10\,\mathrm{TeV}$
BLR$_{50}$
$\tilde{\tau}_1$ NLSP
$\tilde{m}_{l_R}$ [GeV]
$\tilde{m}_{l_L}$ [GeV]
$\tilde{\ell}^+$
$\tilde{\ell}^-$
ℓ
$\tilde{\chi}_1^0$
$\tilde{\tau}_1$
τ
$\widetilde{G}$

Non $\tilde{\chi}_1^0$ NLSP (Short Summary)



WHL **BHL** **BHR** **BLR**



- small $|\mu|$ region is compatible with $(g\text{-}2)_\mu$