NATIONAL SCIENCE CENTRE
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SUSY $(g-2)_\mu$ With & Without Neutralino Dark Matter

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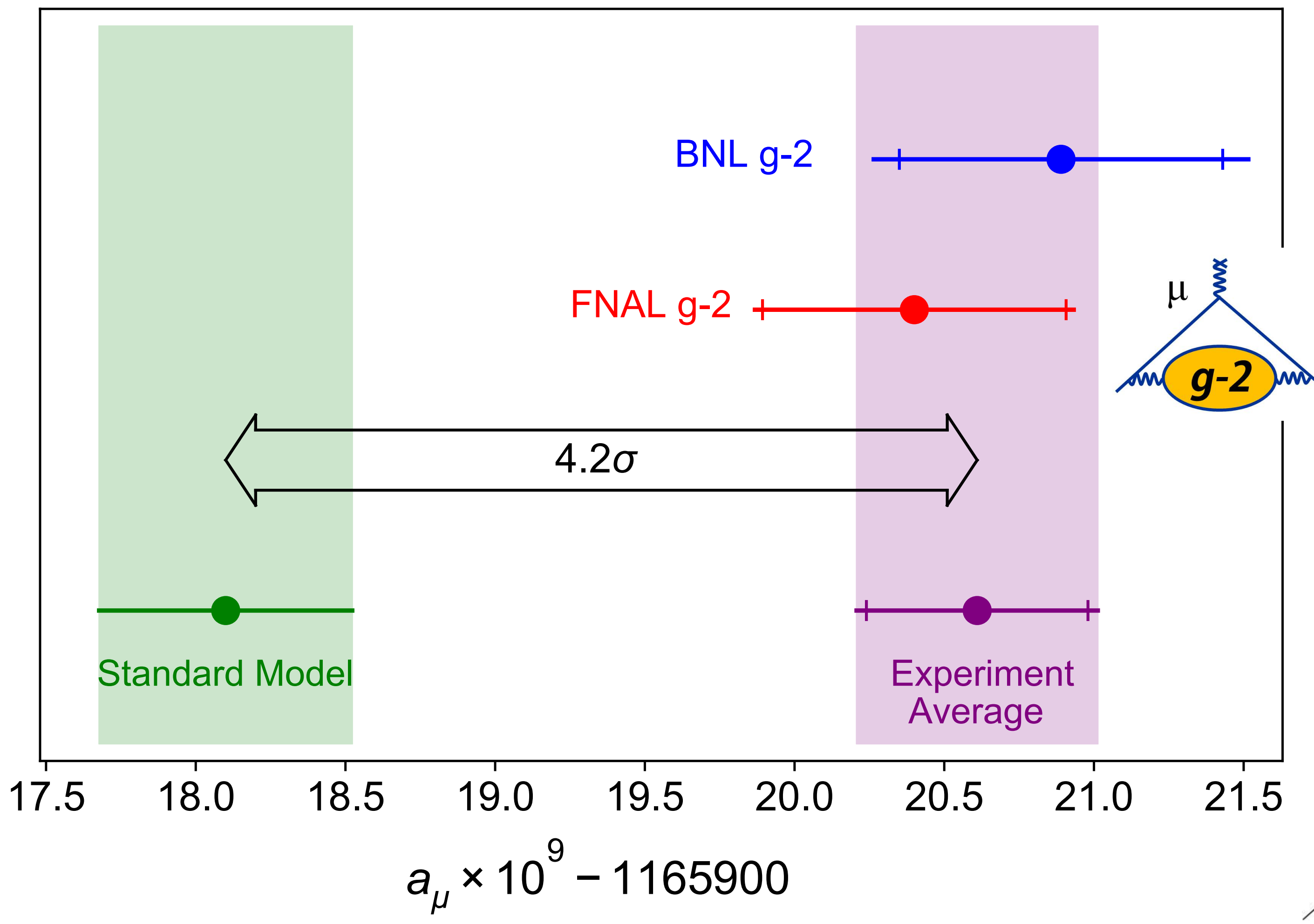
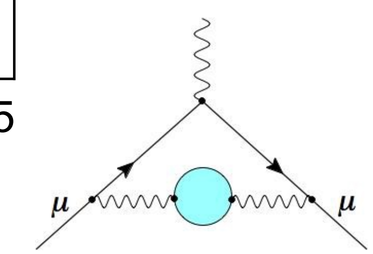
Based on [2202.12928]

1 June 2022 Planck 2022 @ Paris

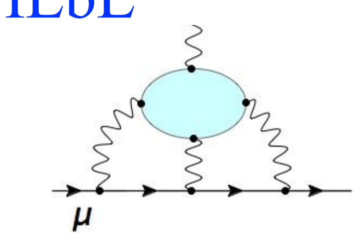
$(g-2)_\mu$ anomaly

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





from HVP, HLbL



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

stat err dominant

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

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:

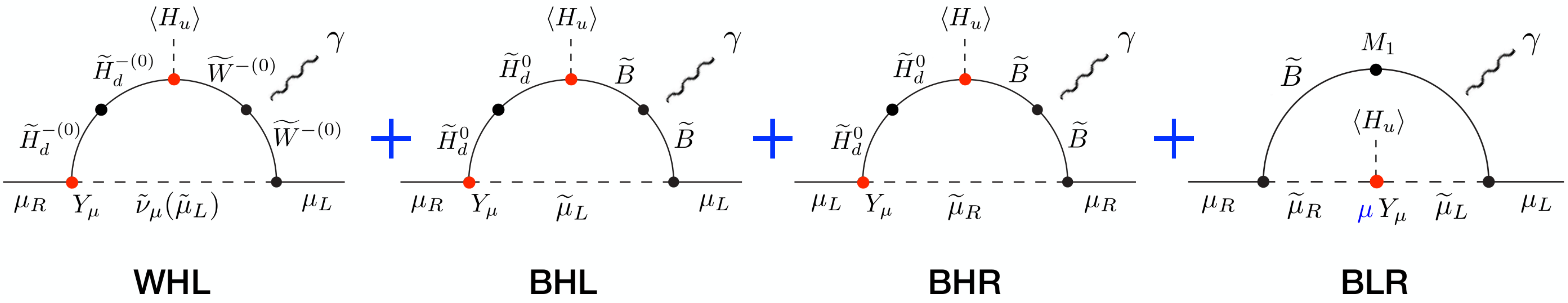
  [Athrona, Balazsa, Jacoba, Kotlarskic, Stockingerc, Stockinger-Kim]; [Chakraborti, Heinemeyer, Saha]; [Endo,Hamaguchi,Iwamoto,Kitahara]; [Cox, Han, Yanagida]; [Baum, Carena, Shah, Wagner]; [Badziak, KS]; [Hagiwara,Ma,Mukhopadhyay'18], …

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

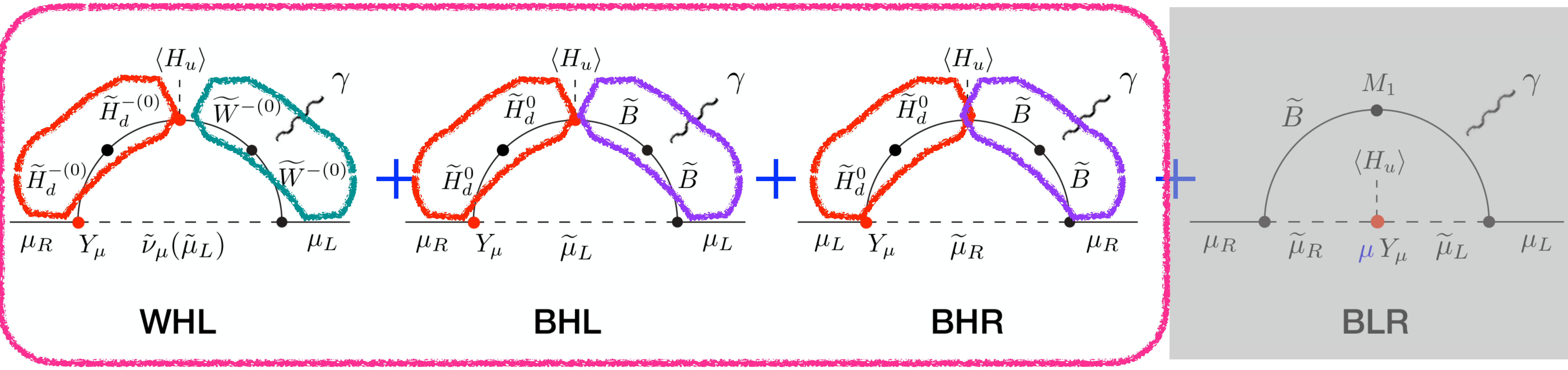
  Q: What happens if neutralino is unstable? (e.g. RPV, Gravitino LSP)

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

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

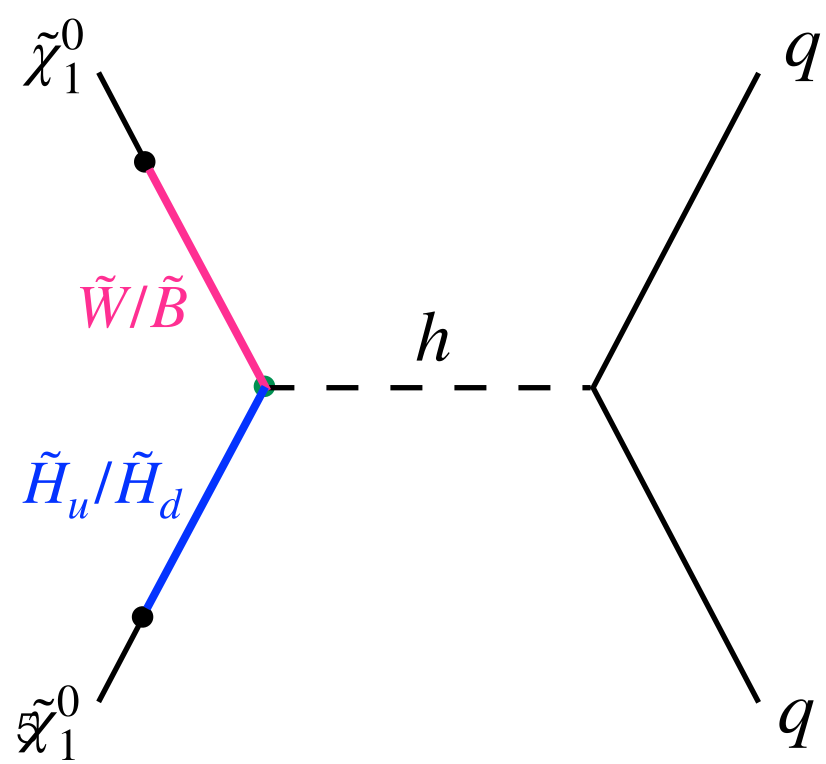


$$\Delta a_\mu^{\rm SUSY} \simeq$$

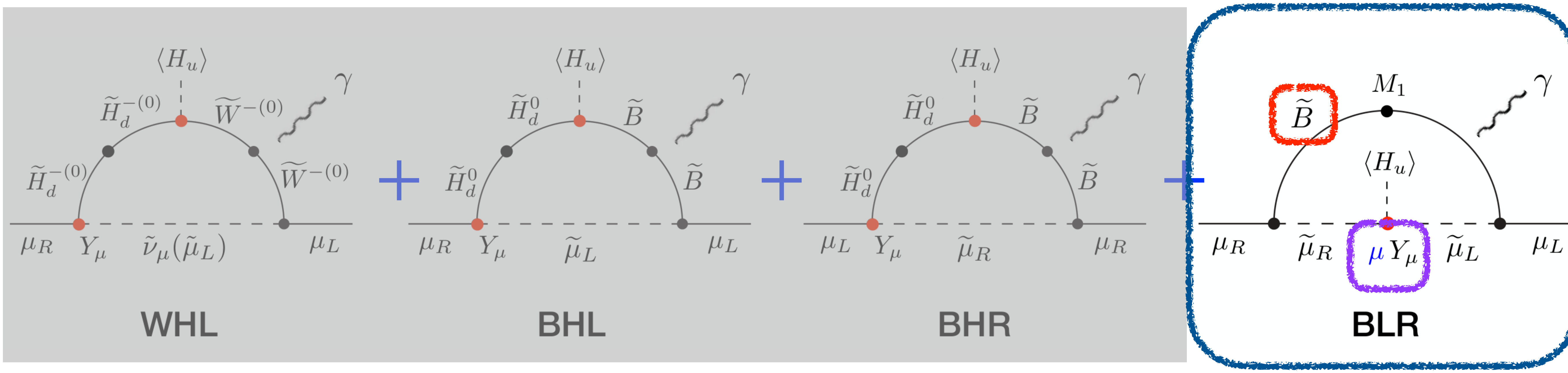


tension

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



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



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

$\Longrightarrow$ **Tend to produce too much DM**

tension

❖ Large off-diagonal term in stau mass matrix:

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

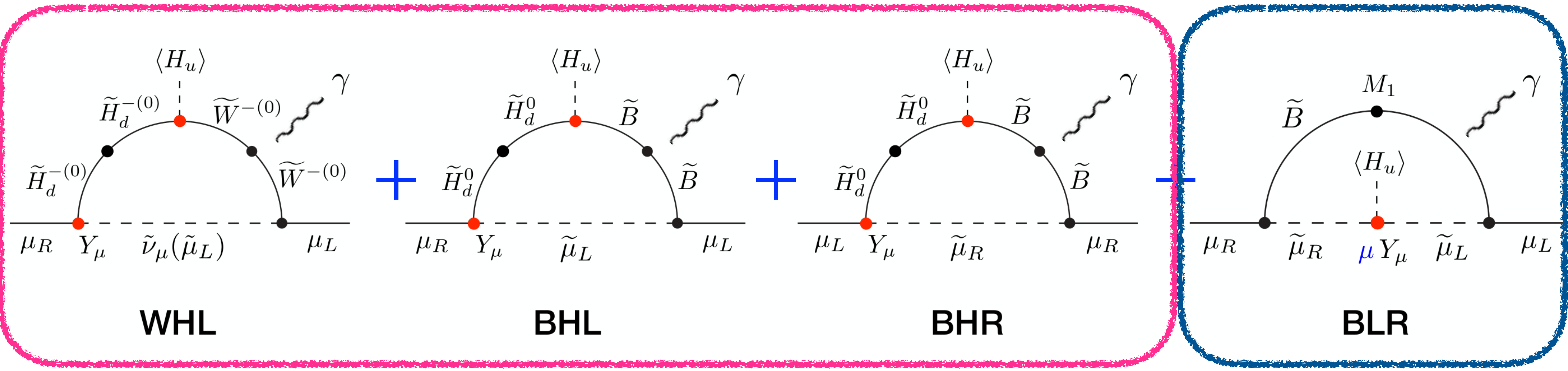
- LEP bound: $m_{\mathrm{stau1}} > 90$ GeV

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

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

M_2 : Wino mass — $m_{\tilde{l}_L} \equiv \widetilde{m}_{\tilde{\nu}_e} = \widetilde{m}_{\tilde{\nu}_\mu} = \widetilde{m}_{\tilde{\nu}_\tau} = \widetilde{m}_{\tilde{e}_L} = \widetilde{m}_{\tilde{\mu}_L} = \widetilde{m}_{\tilde{\tau}_L}$

μ : Higgsino mass — $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$

MC simulations

GM2Calc, CheckMATE2, MicrOmegas ...

constraints

- a_μ^{SUSY}
- DM abundance
- $\sigma_{\mathrm{SI}}^{\tilde{\chi}_1^0}$
- LHC constraints

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

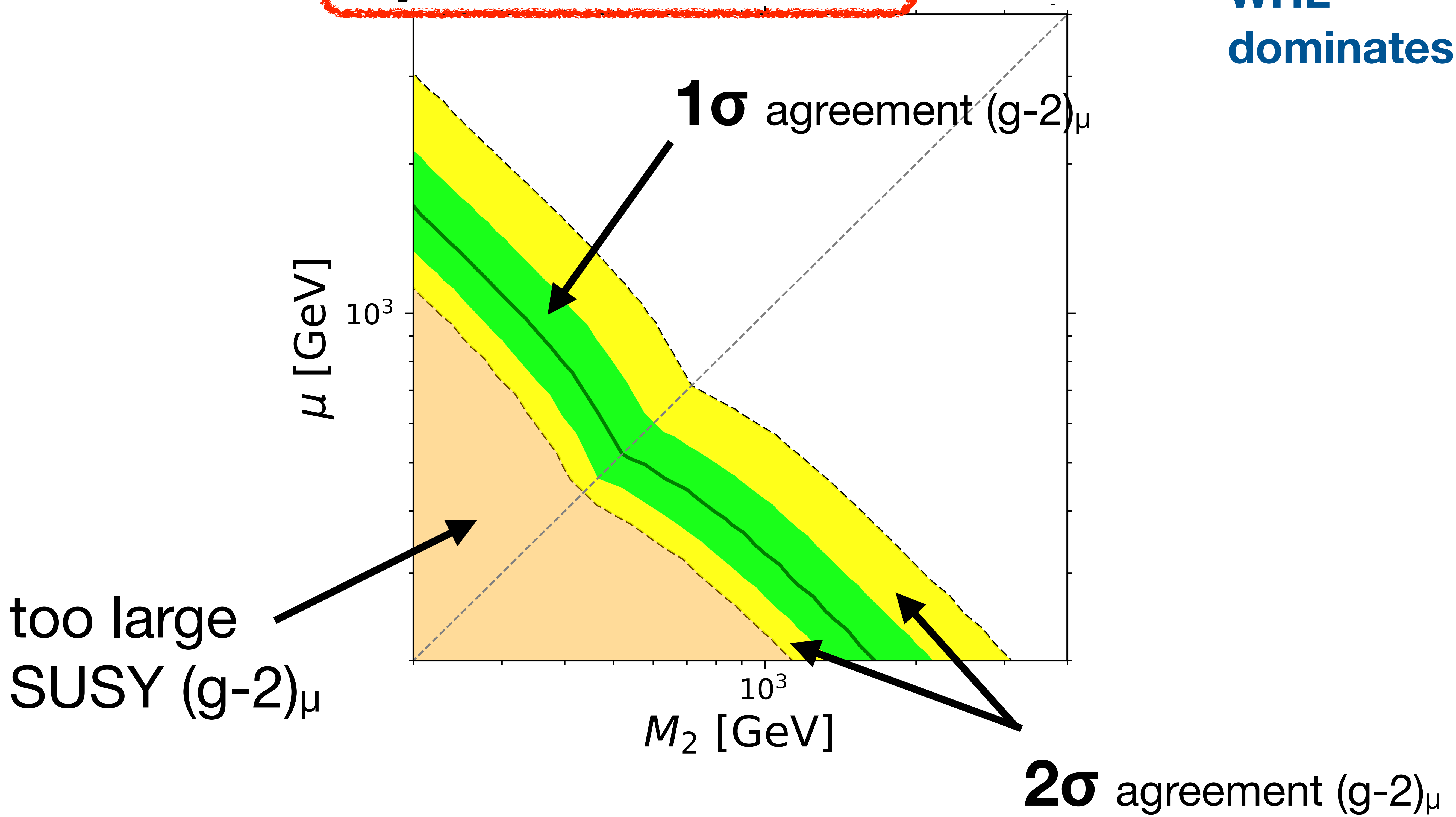
Name	E/TeV	$\mathcal{L}$/fb^{-1}	Description
atlas_1308_1841	8	20.3	0 lepton + $\geq$ 7 jets + MET
atlas_1308_2631	8	20.1	0 leptons + 2 b-jets + MET
atlas_1402_7029	8	20.3	3 leptons + MET (chargino+neutralino)
atlas_1403_4853	8	20.3	2 leptons + MET (direct stop)
atlas_1403_5222	8	20.3	stop production 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

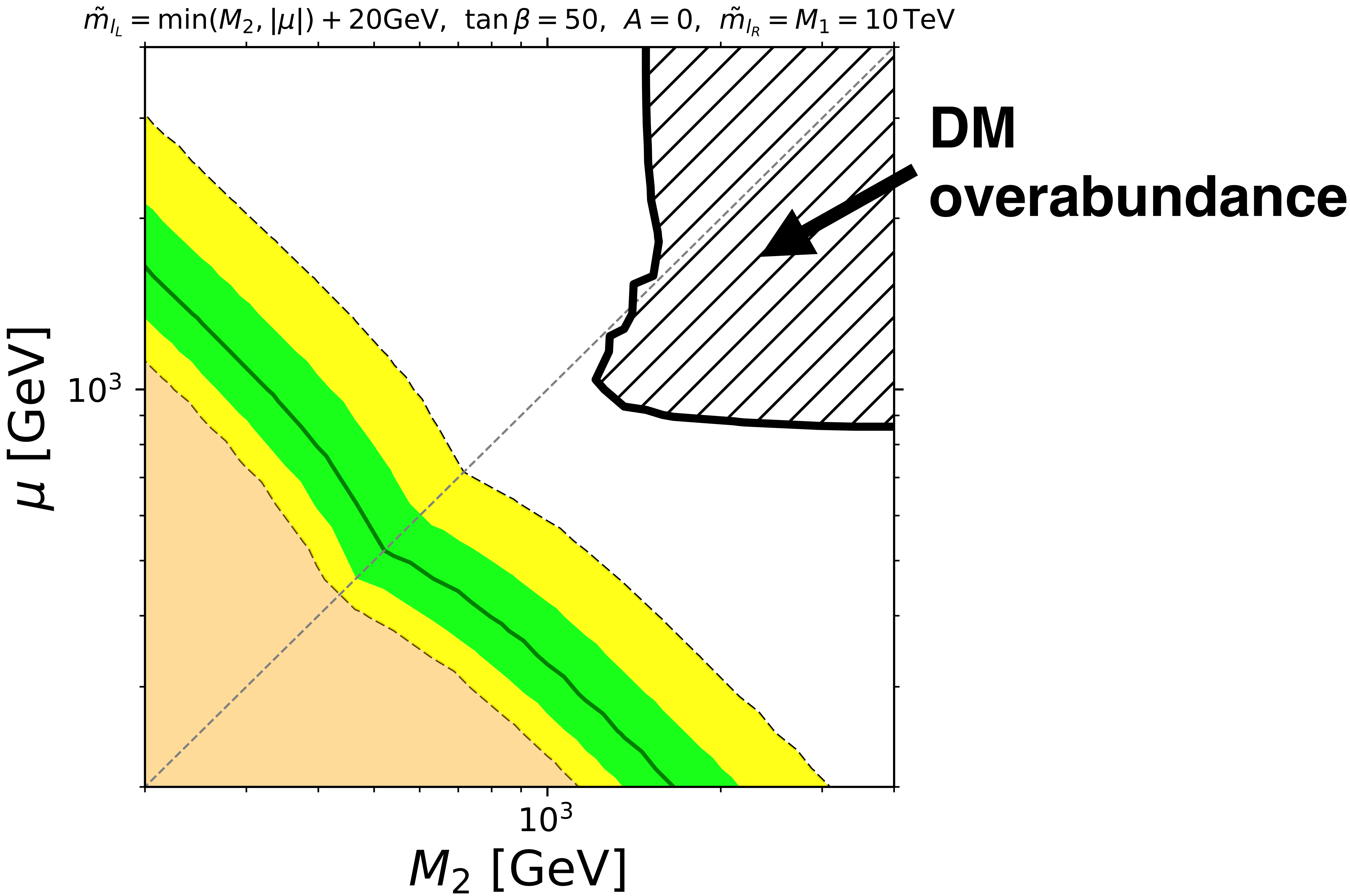
compressed mass spectrum

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

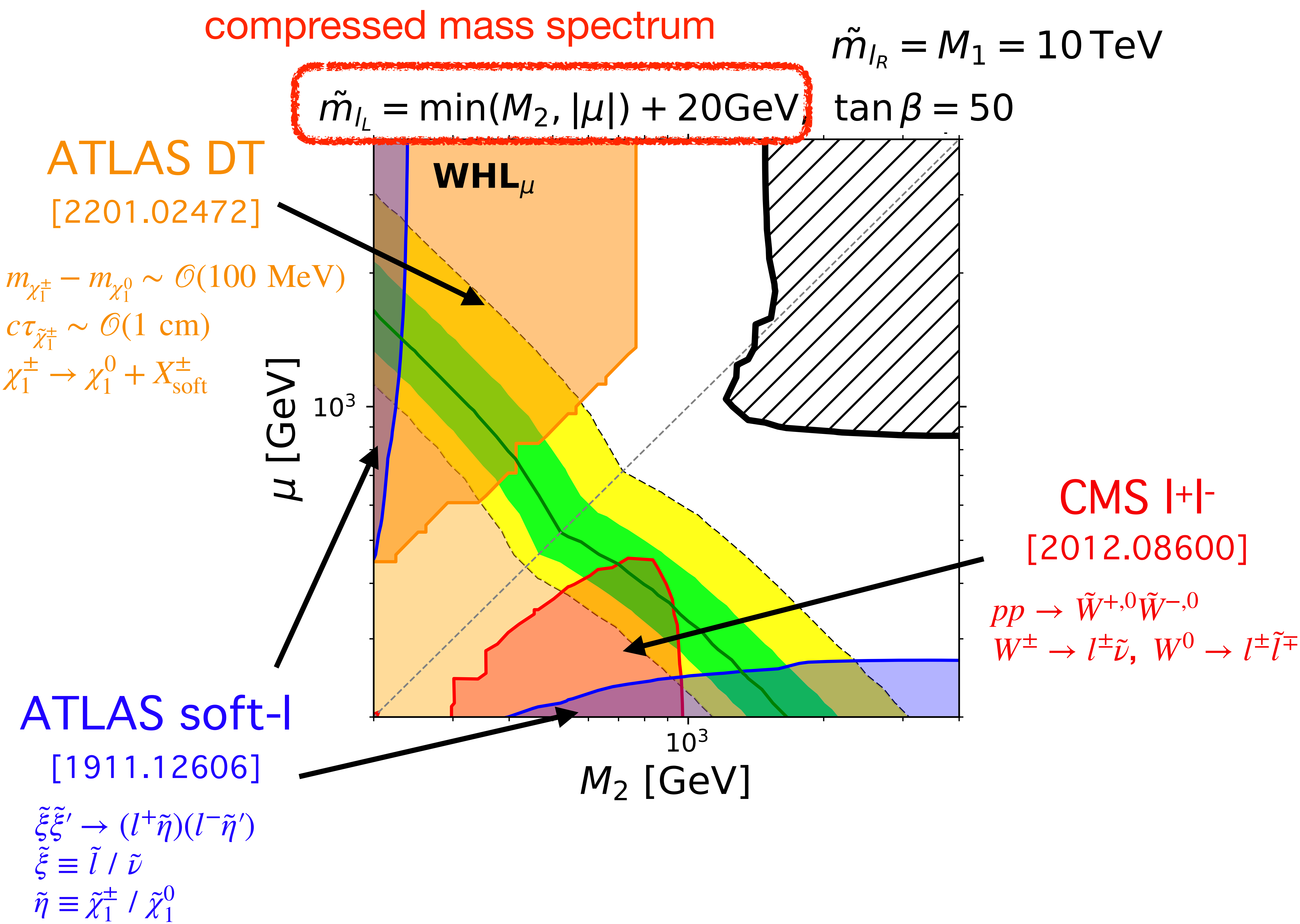
$\tilde{m}_{l_L} = \min(M_2, |\mu|) + 20\text{GeV}$, $\tan\beta = 50$

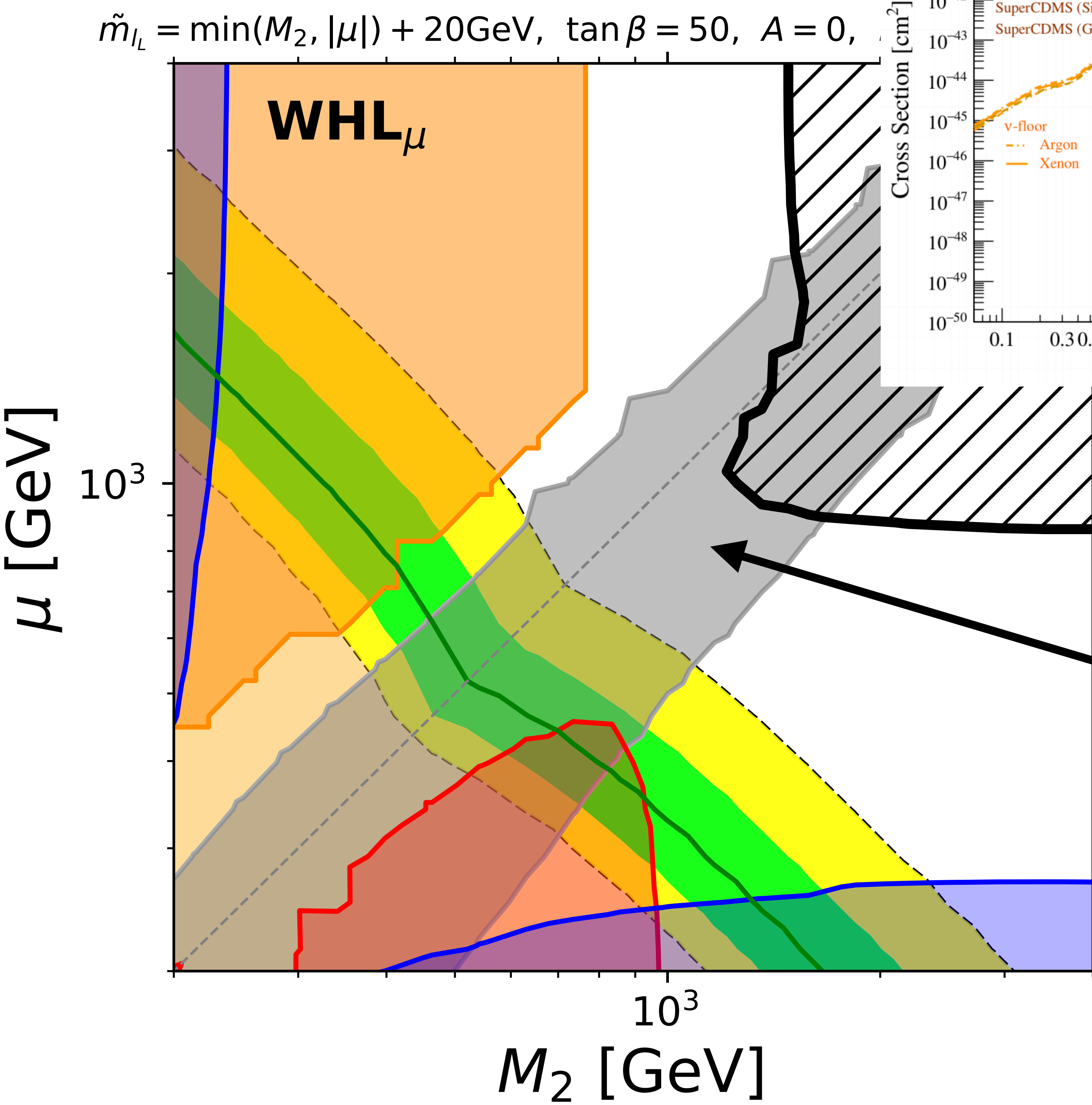
WHL dominates

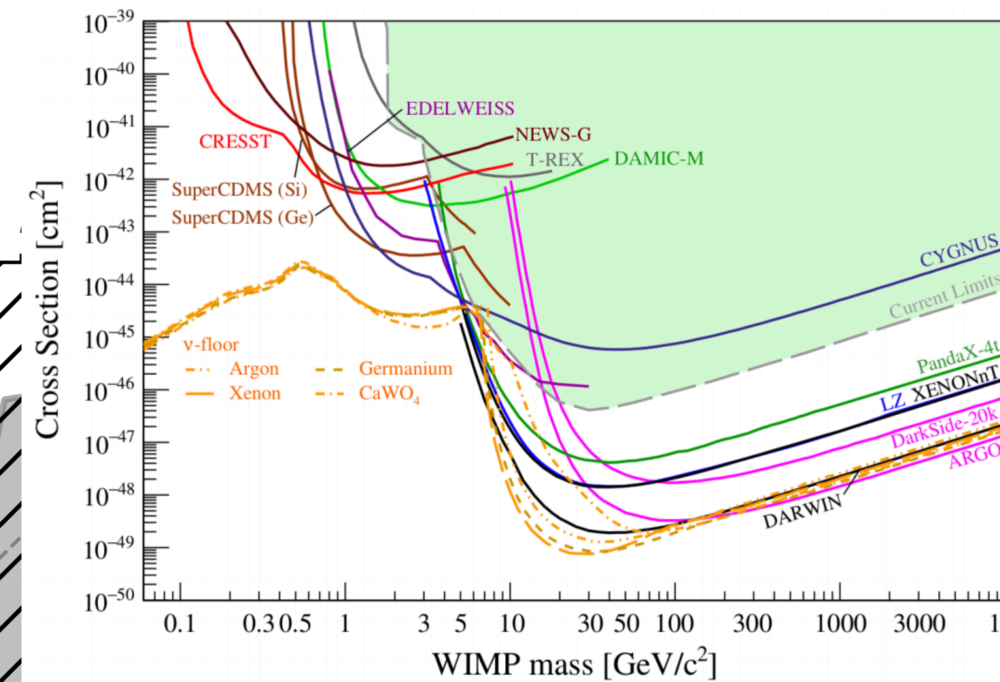




$\tilde{m}_{l_L} = \min(M_2, |\mu|) + 20\text{GeV}$, $\tan\beta = 50$, $A = 0$, $\tilde{m}_{l_R} = M_1 = 10\,\text{TeV}$
10^3
μ [GeV]
10^3
M_2 [GeV]
DM overabundance

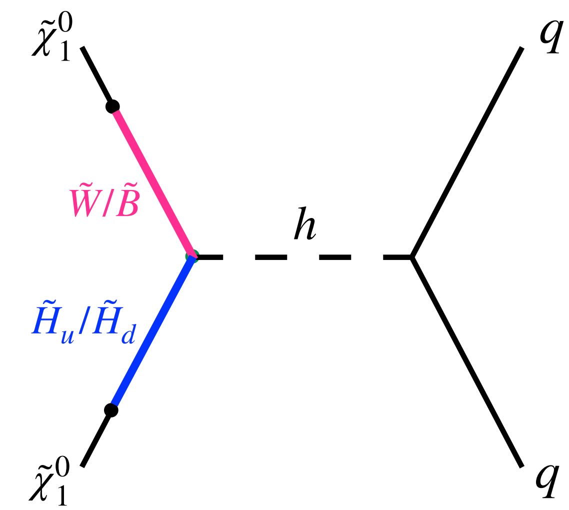

compressed mass spectrum
$\tilde{m}_{l_R} = M_1 = 10\,\mathrm{TeV}$
$\tilde{m}_{l_L} = \min(M_2, |\mu|) + 20\mathrm{GeV}$, $\tan\beta = 50$
ATLAS DT
[2201.02472]
$m_{\chi_1^\pm} - m_{\chi_1^0} \sim \mathcal{O}(100\ \mathrm{MeV})$
$c\tau_{\tilde{\chi}_1^\pm} \sim \mathcal{O}(1\ \mathrm{cm})$
$\chi_1^\pm \to \chi_1^0 + X^\pm_{\mathrm{soft}}$
WHL$_\mu$
μ [GeV]
10^3
M_2 [GeV]
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]
$\tilde{\xi}\tilde{\xi}' \to (l^+\tilde{\eta})(l^-\tilde{\eta}')$
$\tilde{\xi} \equiv \tilde{l}\ /\ \tilde{\nu}$
$\tilde{\eta} \equiv \tilde{\chi}_1^\pm\ /\ \tilde{\chi}_1^0$

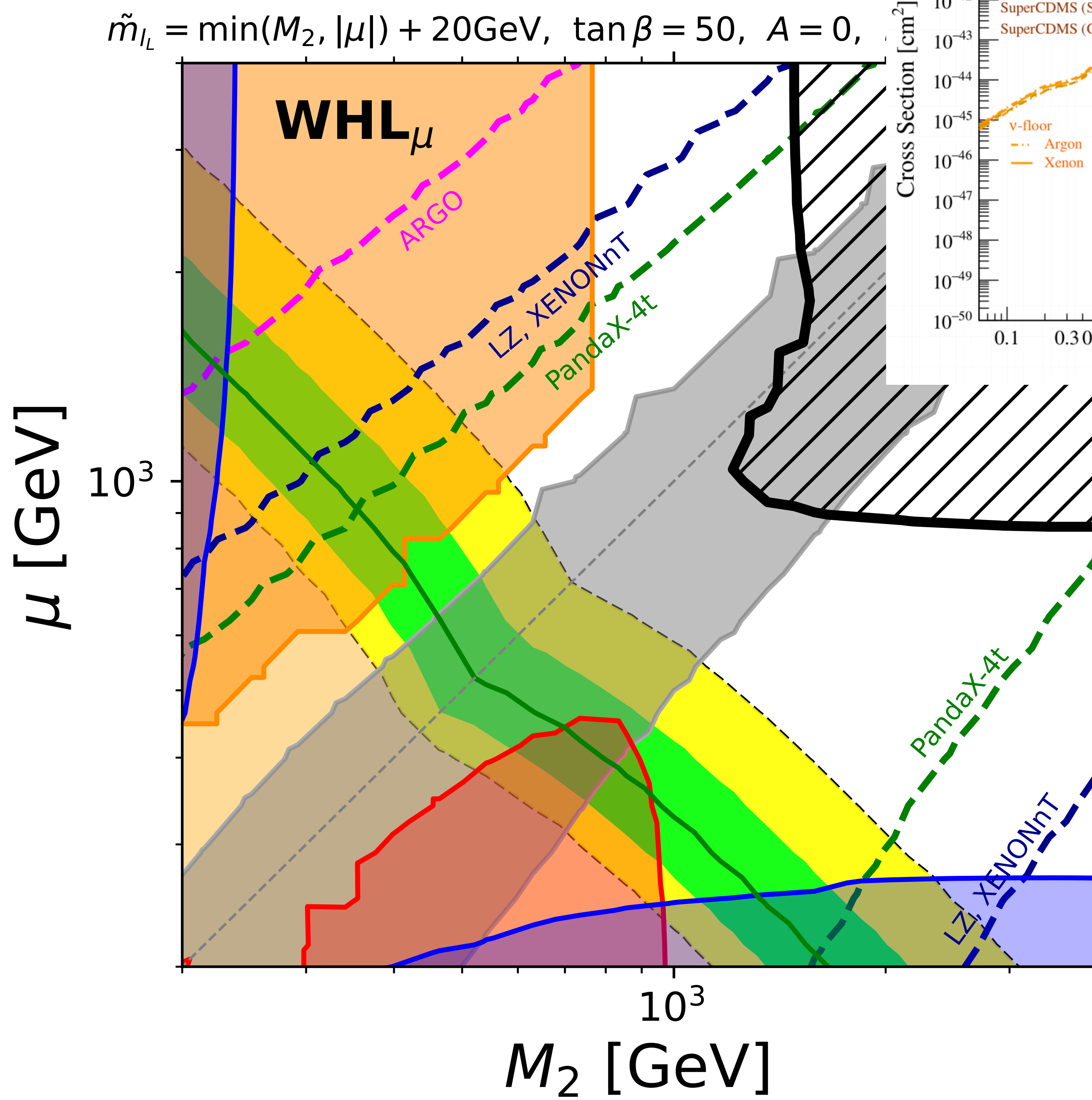


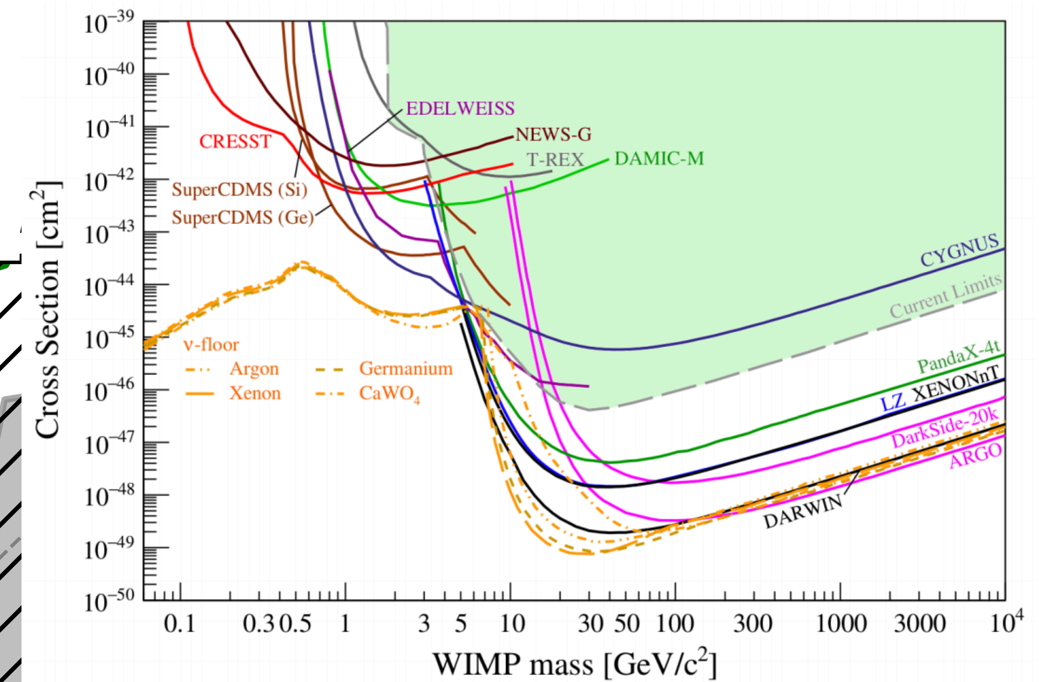


XENON1T

[1805.12562]



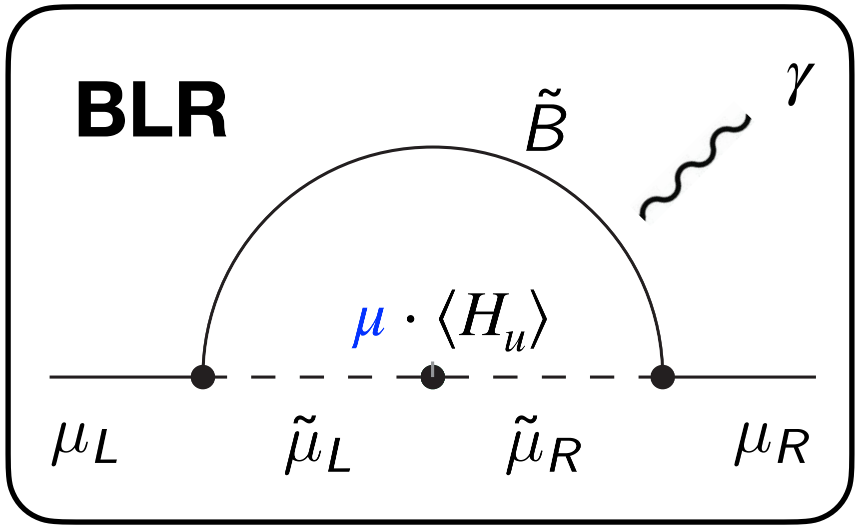


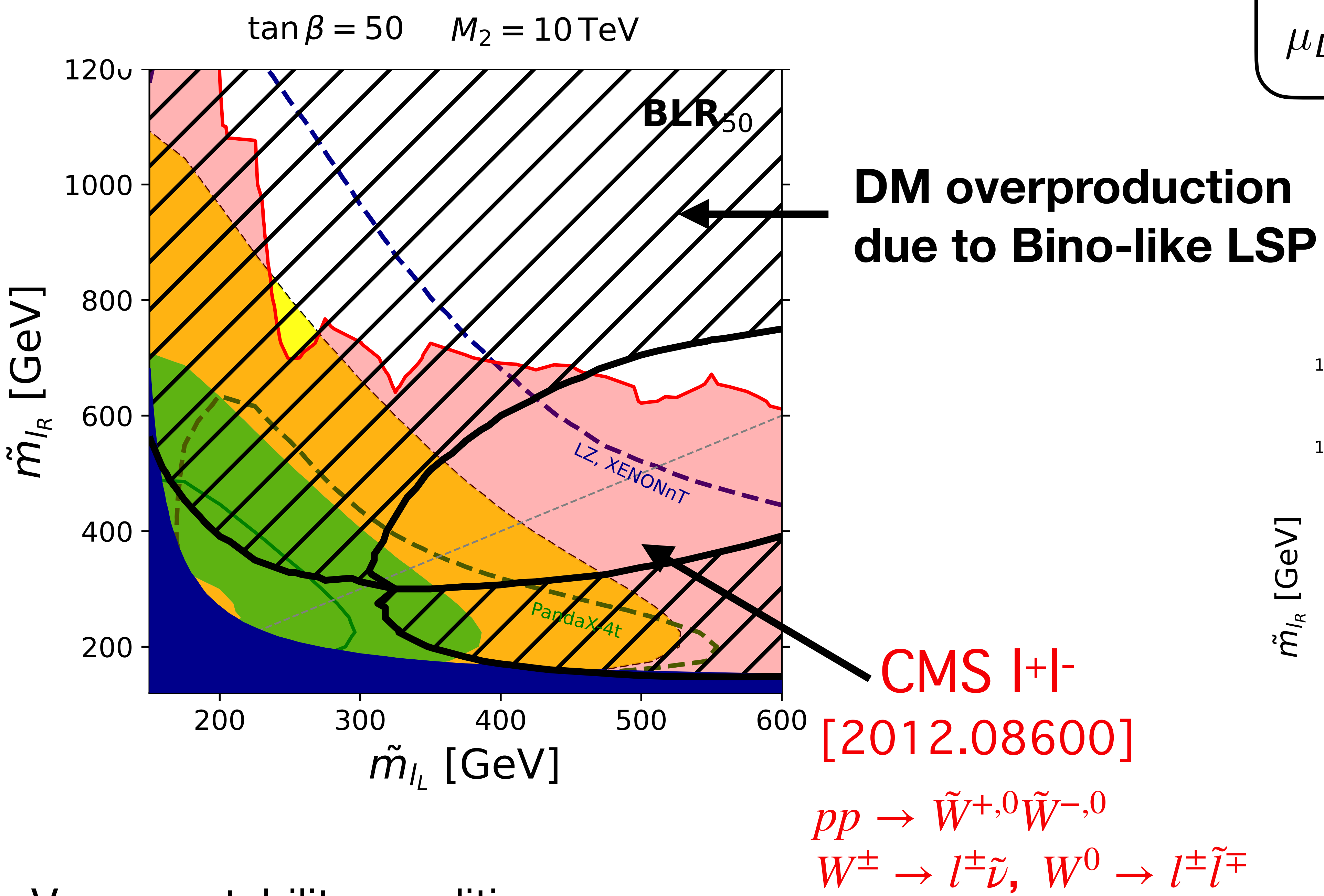


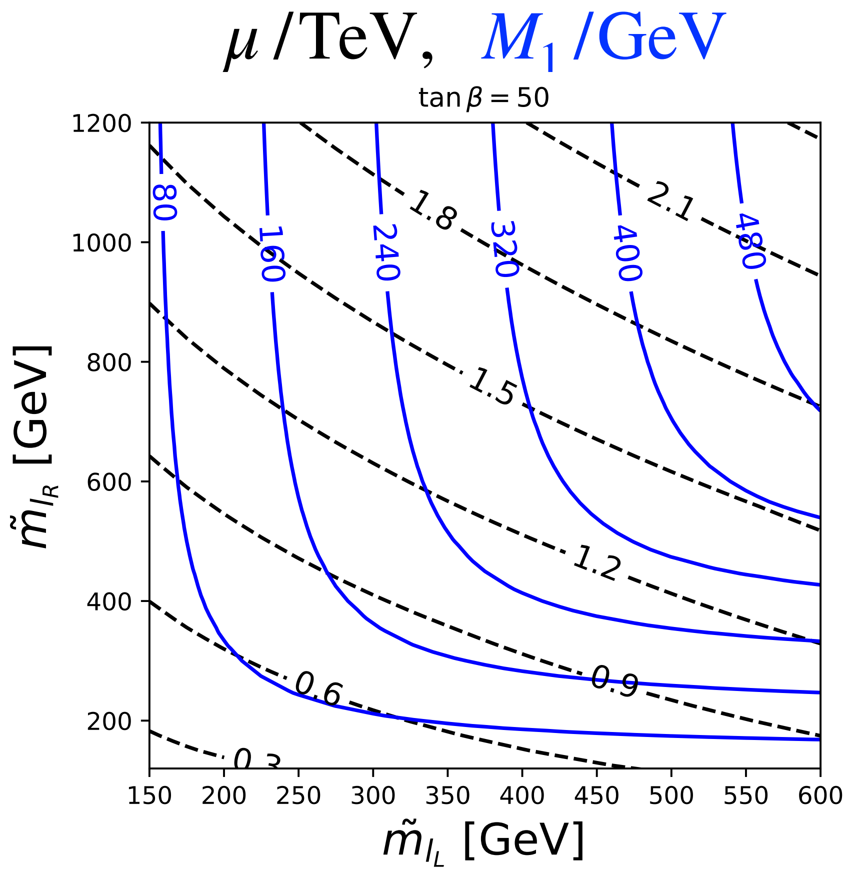
All g-2 region will be probed by the next generation DM-DD experiments

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

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







Vacuum stability condition:

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

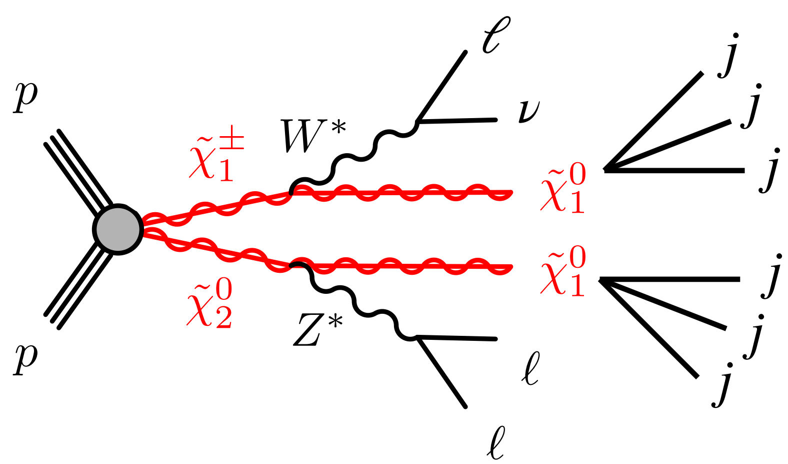
[Kitahara, Yoshinaga 13]; [Endo, Hamaguchi, Kitahara, Yoshinaga 13]

Unstable Neutralino

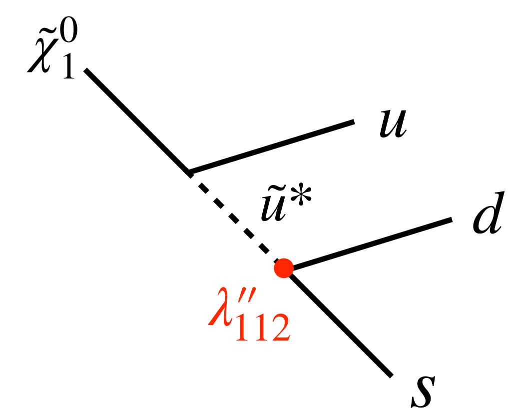
We study **2** example-scenarios with *un*stable neutralino

RPV

(UDD-type)

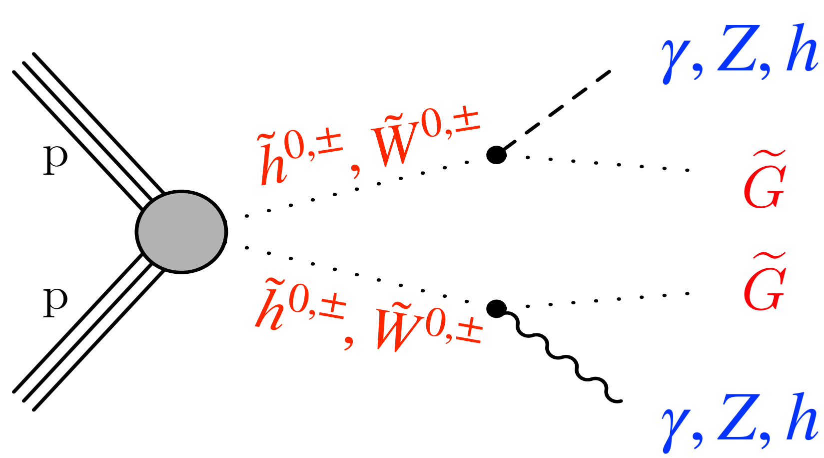


$$W_{\text{RPV}} = \lambda''_{ijk} U^c_i D^c_j D^c_k$$



Gravitino LSP

(general GMSB)



prompt decay into "massless" gravitino

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

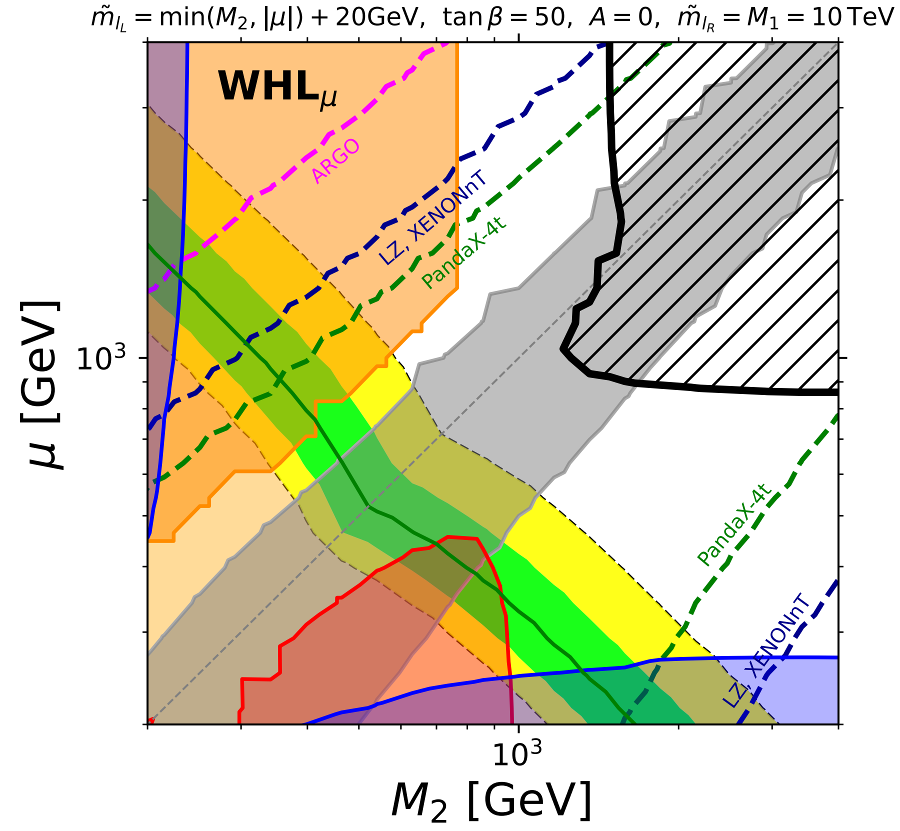
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}Z) = \left(\left|N_{12} c_W - N_{11} s_W\right|^2 + \frac{1}{2}\left|N_{13} c_\beta - N_{14} s_\beta\right|^2\right)\left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A},$$

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

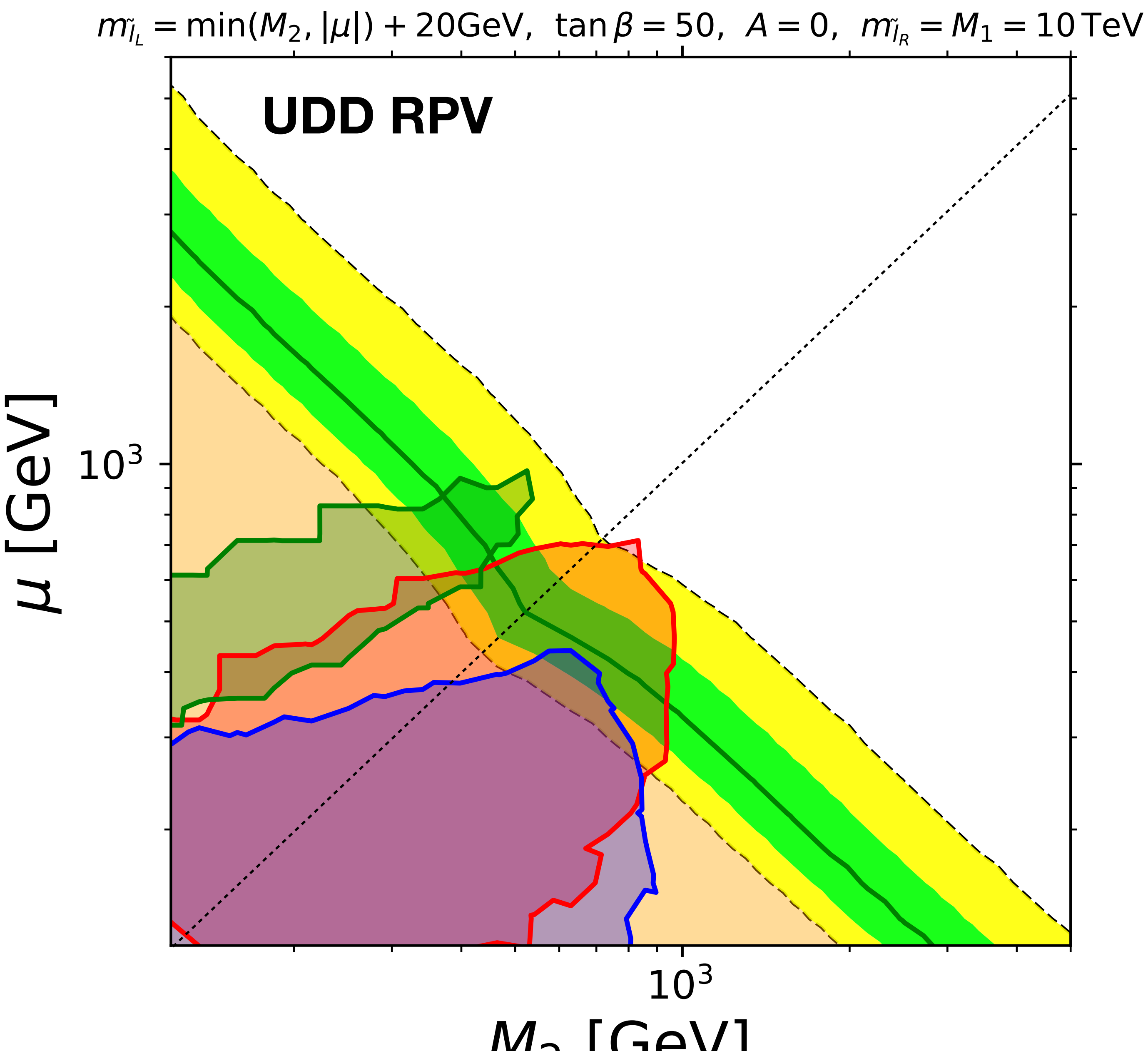
$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi m_{3/2}^2 M_{\text{pl}}^2} \sim \frac{1}{0.3\,\text{mm}} \left(\frac{m_{\tilde{\chi}_1^0}}{100\,\text{GeV}}\right)^5 \left(\frac{m_{3/2}}{10\,\text{eV}}\right)^{-2}$$

UDD RPV

stable neutralino



WHL dominated plane



ATLAS multijet+l

[2106.09609]

CMS multilepton

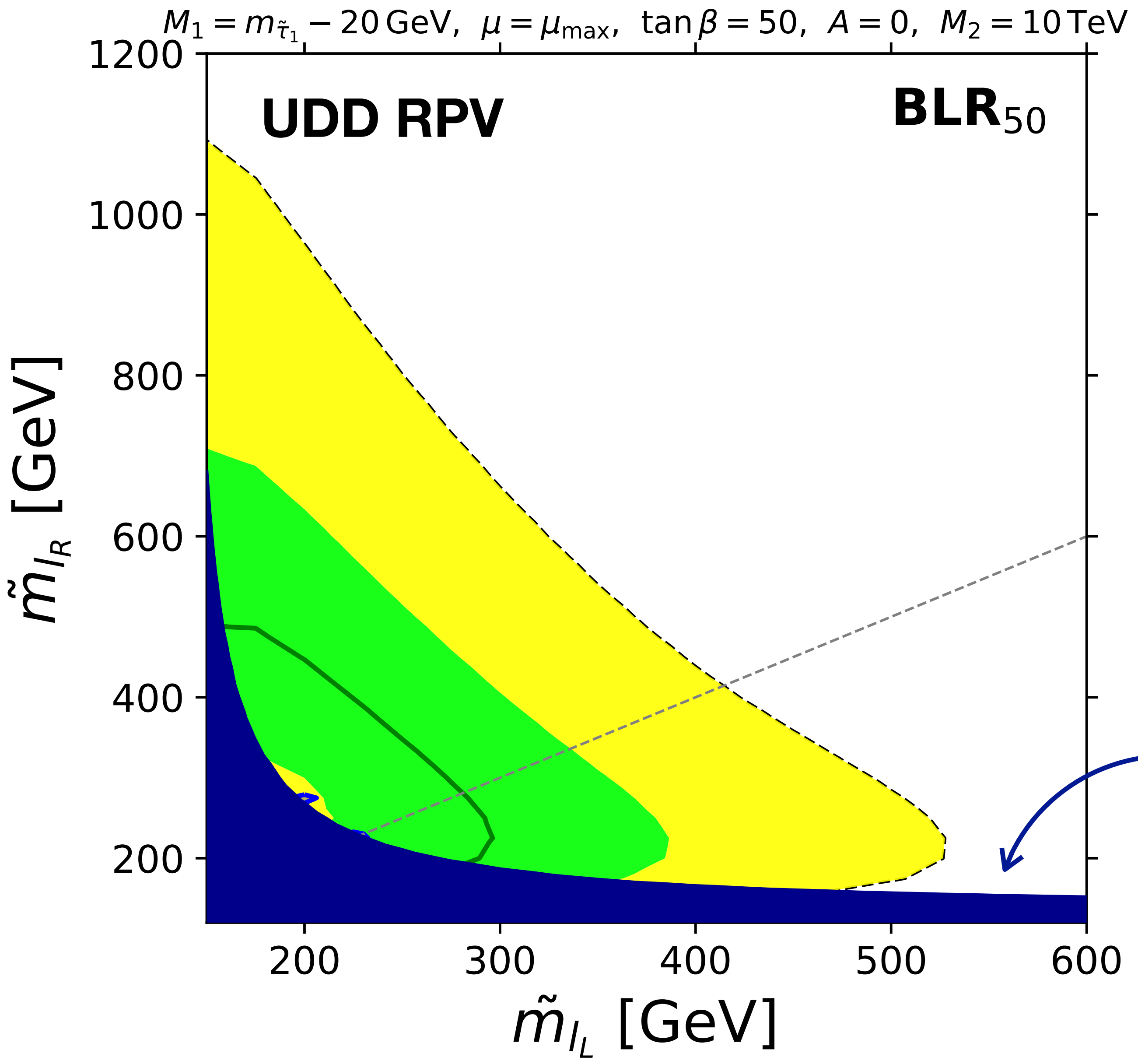
[1709.05406]

ATLAS jets $+E_T^{miss}$

[ATLAS-CONF-2019-040]

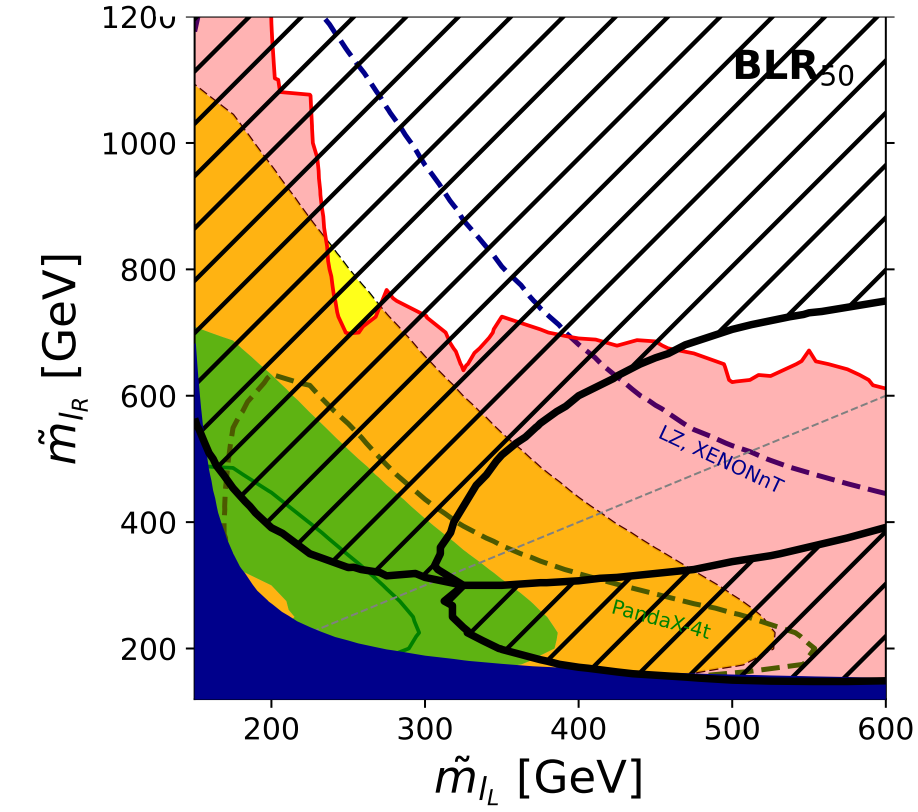
UDD RPV

BLR dominated plane



stau LEP limit

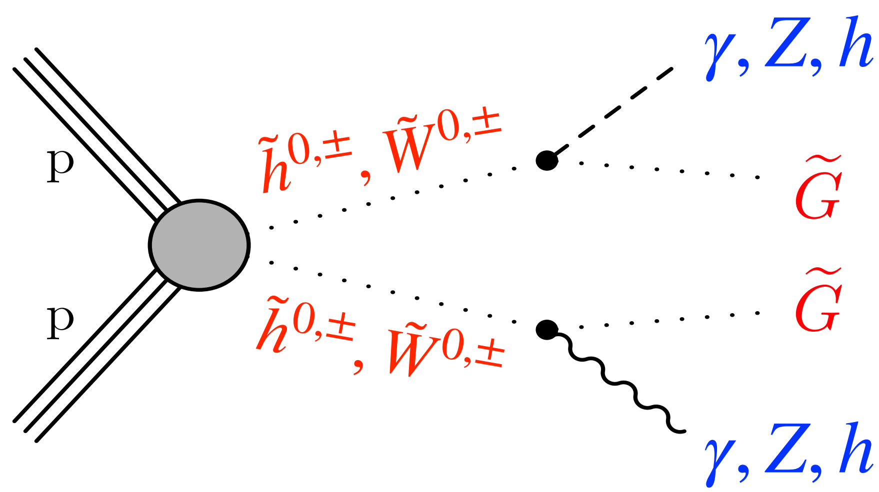
stable neutralino

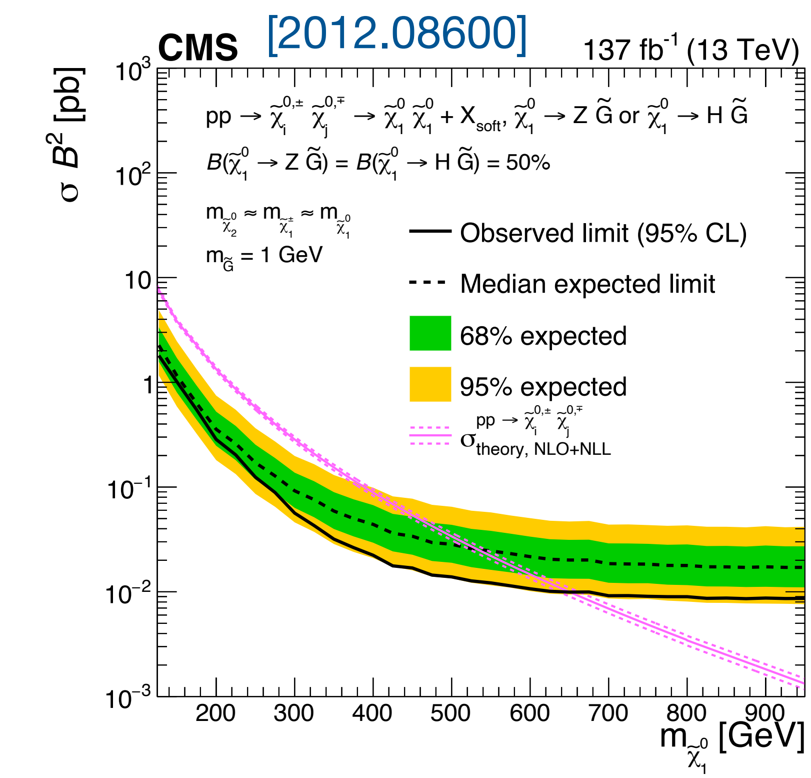


Gravitino LSP

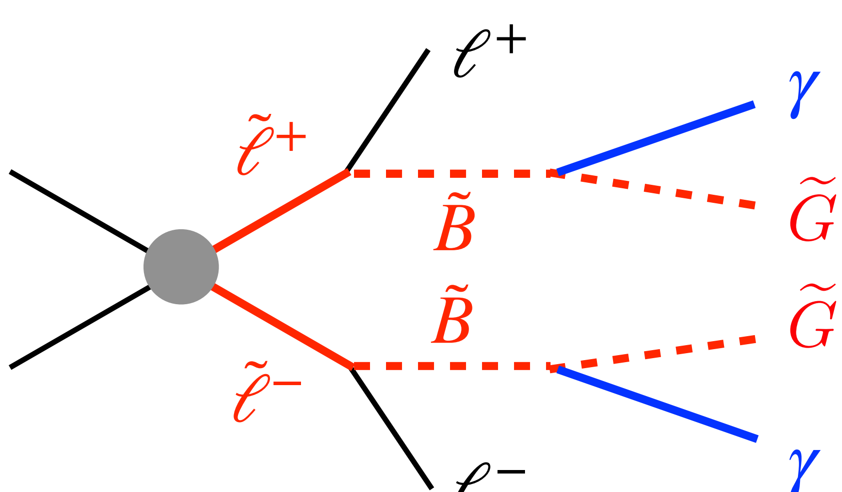
We assume a **massless** gravitino (m < 1GeV) and **prompt** neutralino decay.

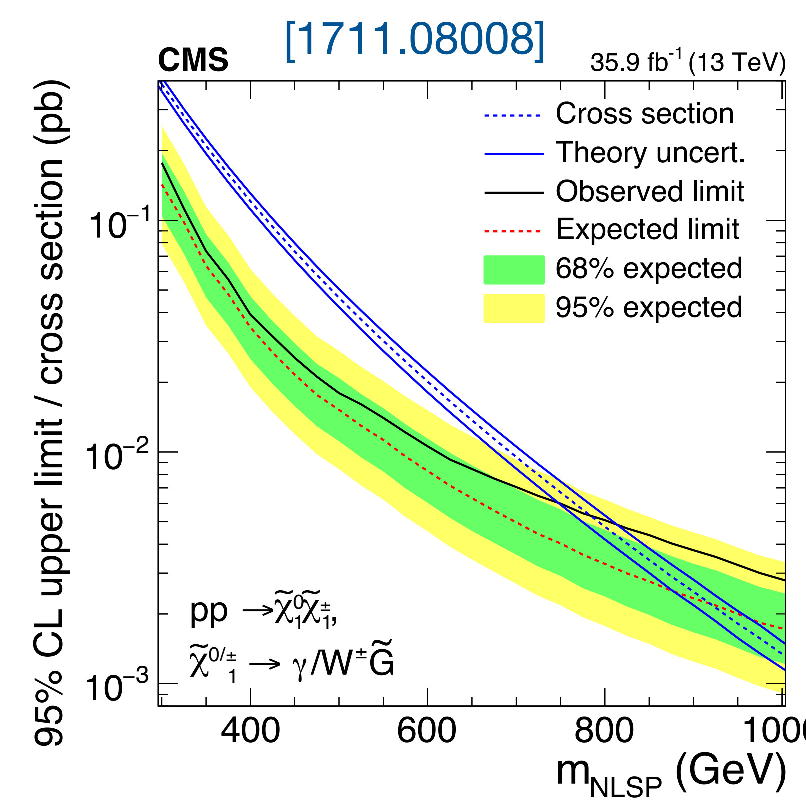
Wino, Higgsino LSP



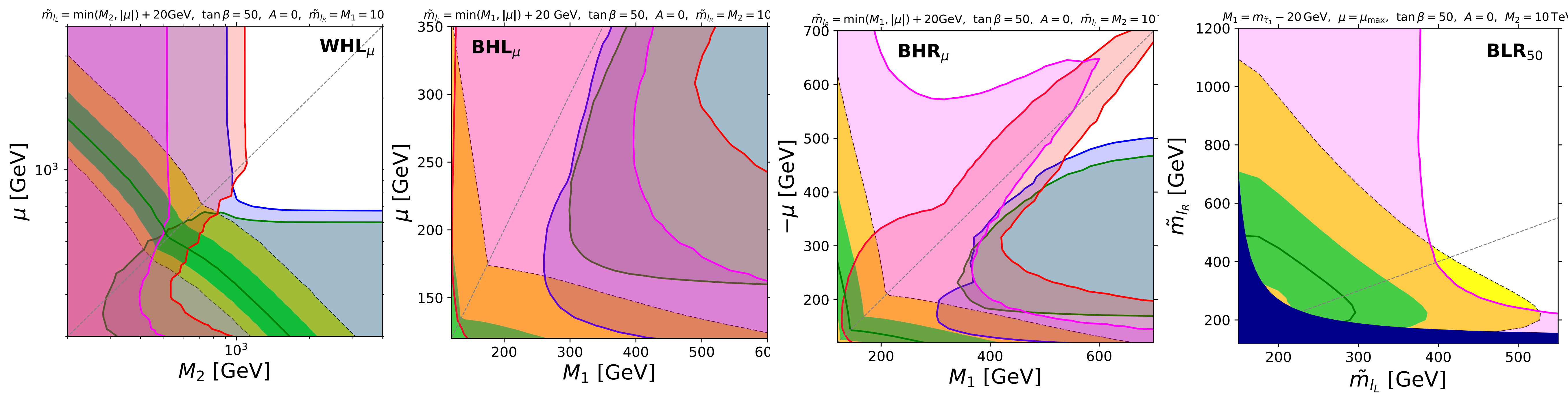


Bino LSP





Gravitino LSP



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

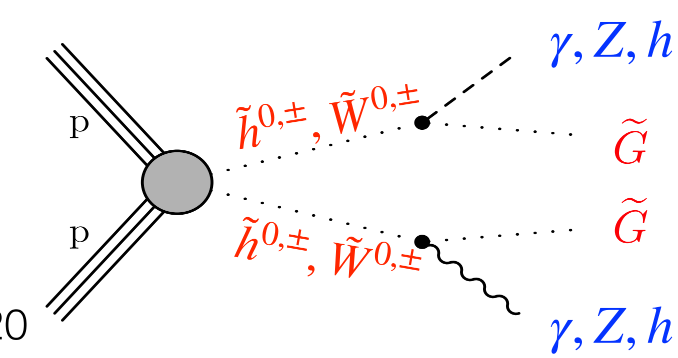
$[\gamma\widetilde{G}][Z(h)\widetilde{G}]$ CMS $\gamma + \not{E}_T$ [1711.08008]

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

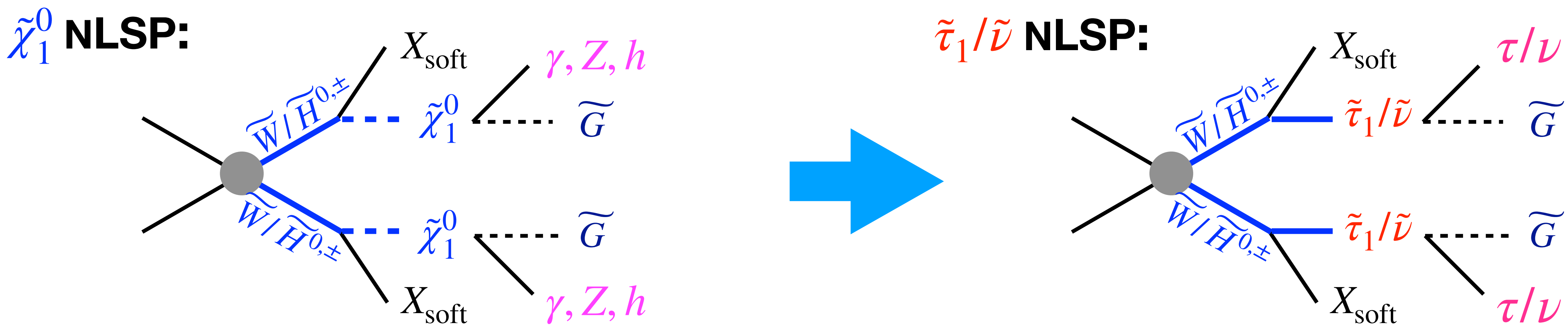
$[h\widetilde{G}][Z\widetilde{G}]$ CMS $\ell^+\ell^-$ [2012.08600]

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

Unlike MSSM, in gravitino LSP, one cannot hide high pT decay products and E_T^{miss} by making mass spectrum compressed.



Gravitino LSP with slepton NLSP



WHL plane:

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

BHL plane:

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

} $\tilde{\nu}_L$ **NLSP**

BHR plane:

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

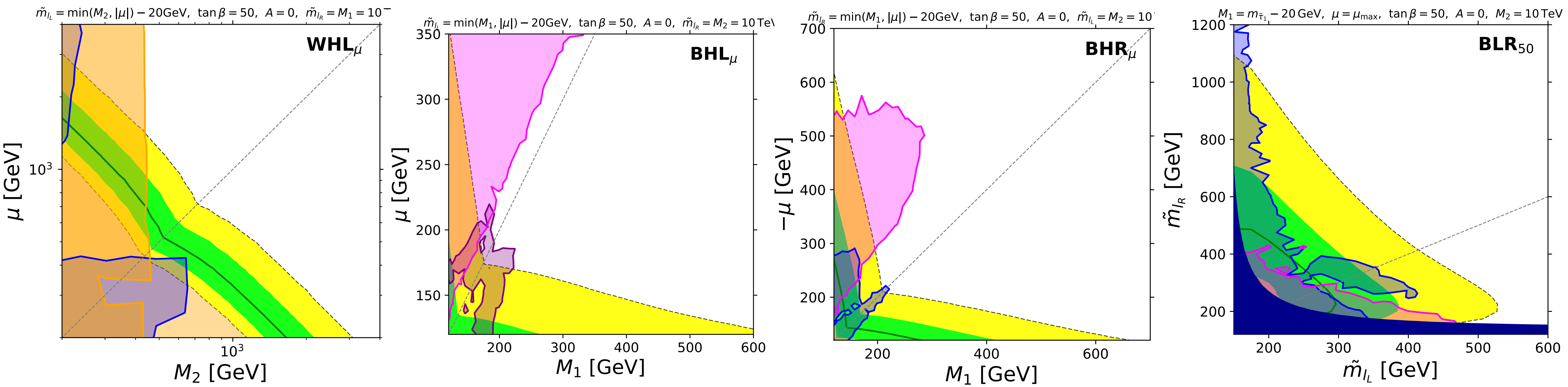
} $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ **NLSP**

BLR plane:

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

} $\tilde{\tau}_1$ **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]

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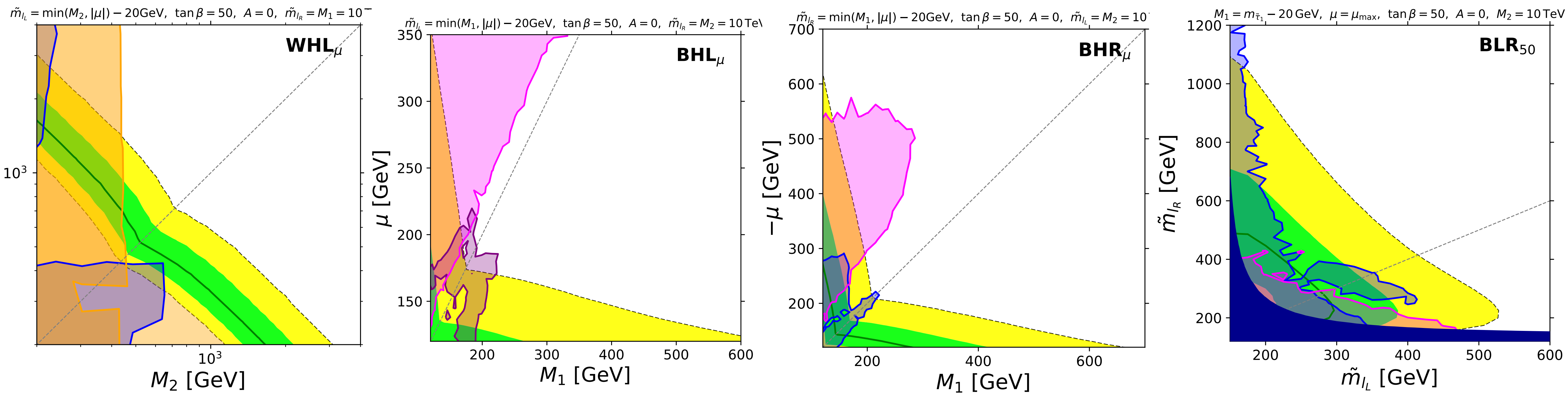

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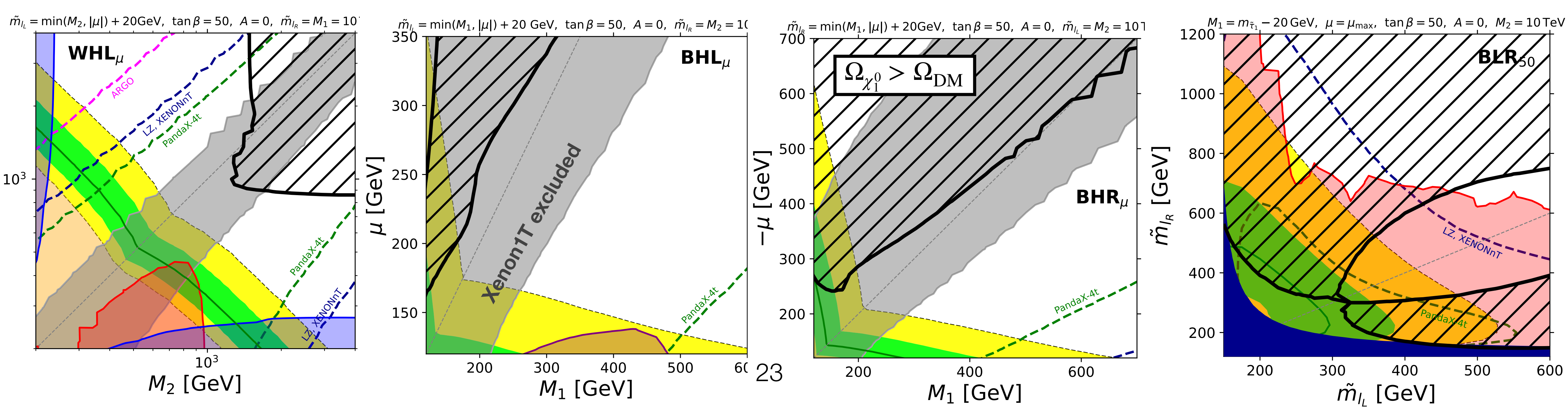
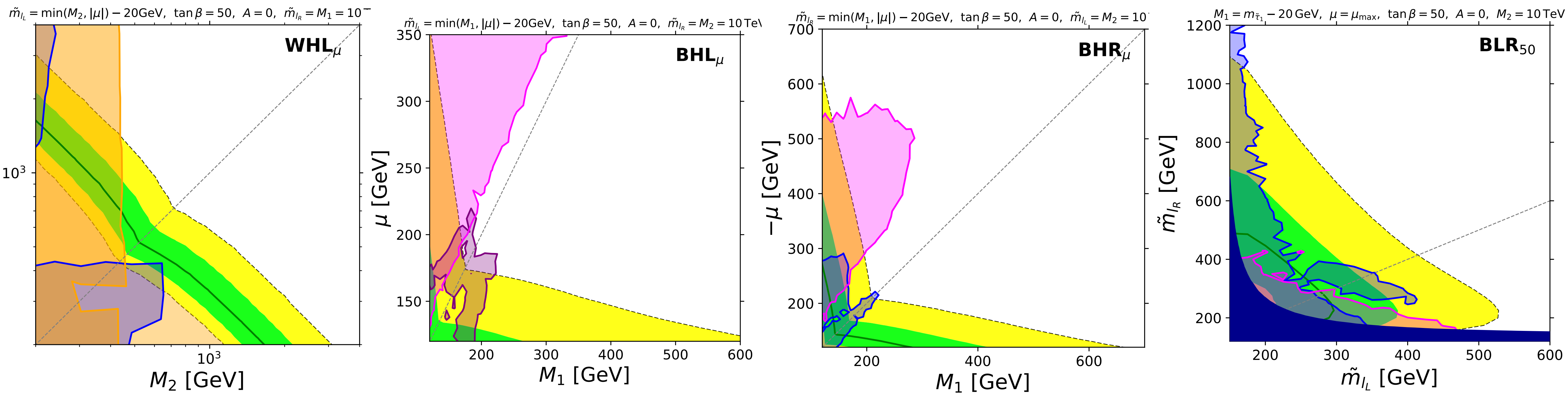
MSSM with stable neutralino:



Gravitino LSP with slepton NLSP



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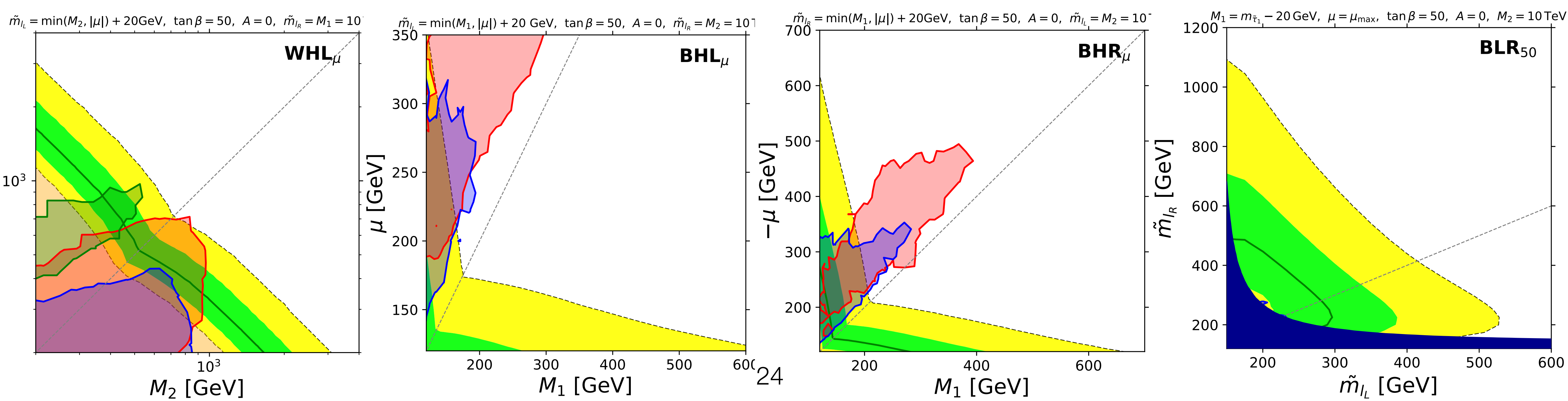
UDD RPV :



Summary

- SUSY might be a solution to the $(g-2)_\mu$ anomaly
  - stable LSP $\tilde{\chi}_1^0$ $\Longrightarrow$ LHC constraints from large $\not{E}_T$ search
  - slepton-gaugino-Higgsino are light $\Longrightarrow$ stringent constraint from DM-DD detection
  - LR slepton and Bino are light $\Longrightarrow$ Bino overproduction

- If $\tilde{\chi}_1^0$ is not stable LSP, DM constraints go away, and LHC signature changes.
  - ① RPV with UDD $\Longrightarrow$ LHC constraints from multijet + lepton
  - ② Gravitino LSP with $\tilde{\chi}_1^0$ NLSP $\Longrightarrow$ $(g-2)_\mu$ region excluded by $\gamma + \not{E}_T$ channel
  - ③ Gravitino LSP with ***non*** $\tilde{\chi}_1^0$ NLSP $\Longrightarrow$ LHC constraints from soft lepton/tau

Explanation for $(g-2)_\mu$ anomaly is possible for the scenarios ① and ③

Norway grants

NATIONAL SCIENCE CENTRE POLAND

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

Table 1: The parameter planes and choices of the other parameters. $\mu_{\rm max}$ 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.

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

- 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:

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

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

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

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

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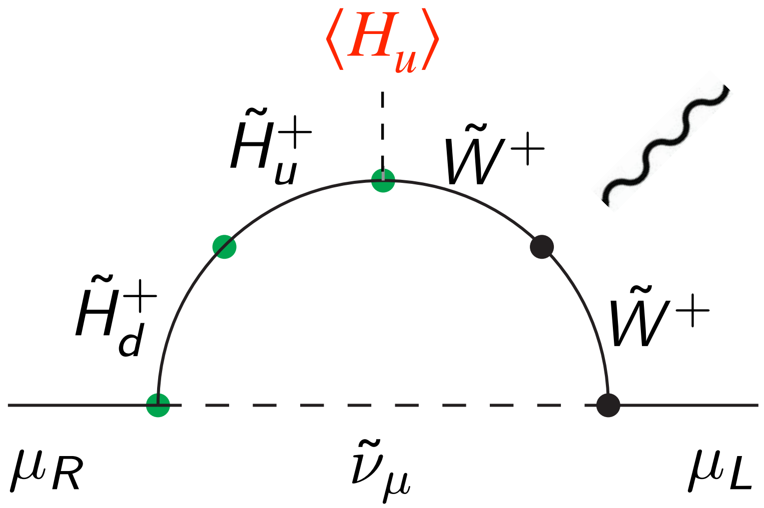
SUSY: $\Delta\tilde{a}_\mu^{\text{SUSY}} \propto Y_\mu \langle H_u \rangle = m_\mu \cdot \tan\beta$

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



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

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

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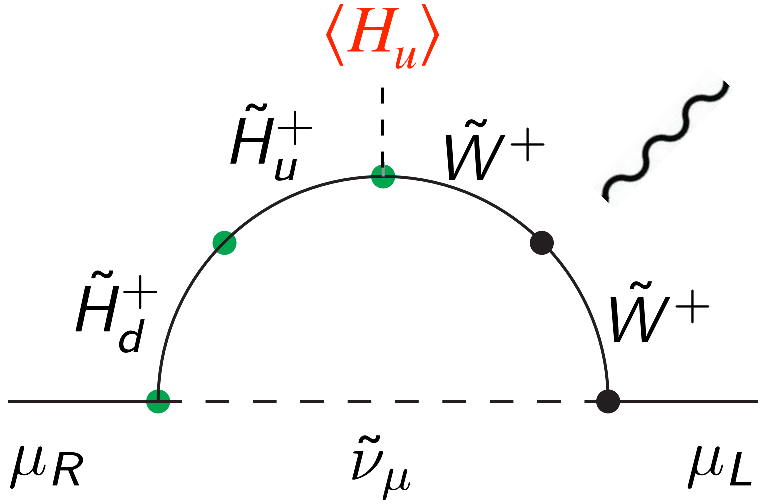


$$\langle H_u \rangle^2 + \langle H_d \rangle^2 = \langle H \rangle^2$$

$\langle H \rangle^2$ ↑ $(246\ \text{GeV})^2$

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

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

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

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

M_1 : Bino mass

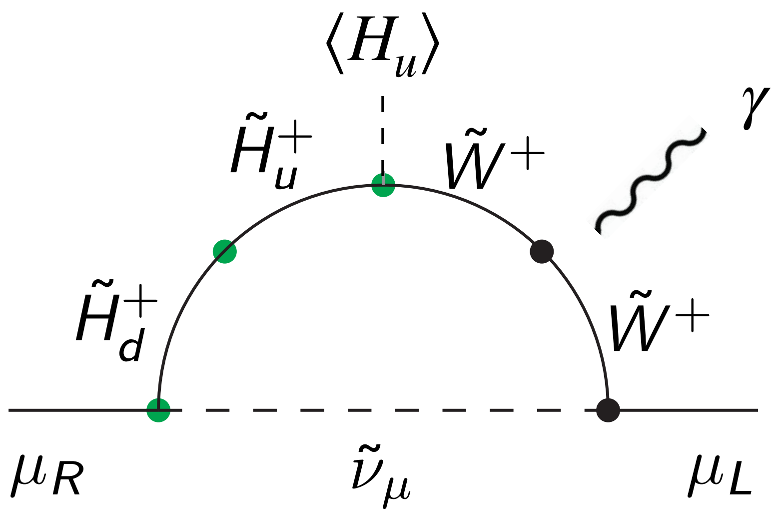
M_2 : Wino mass

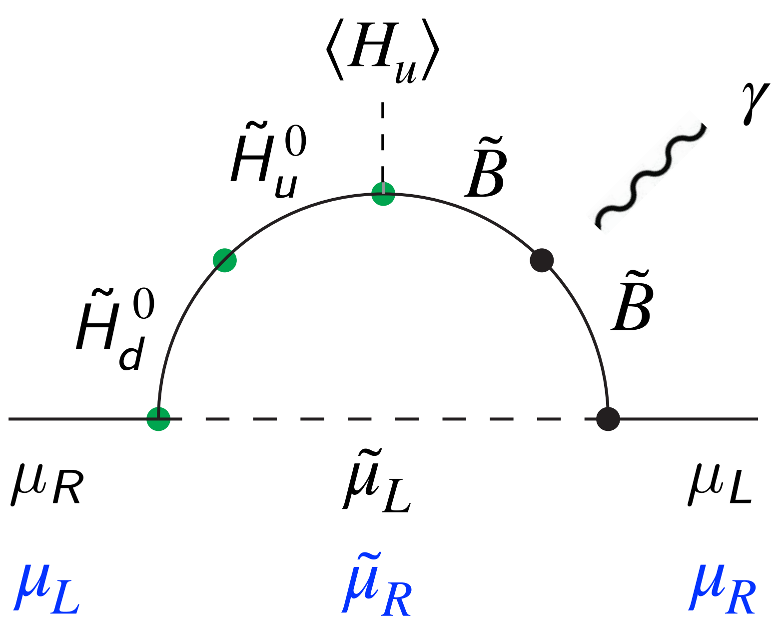
μ : Higgsino mass

$$\begin{cases} m_{\tilde{l}_R} \equiv \widetilde{m}^2_{\tilde{e}_R} = \widetilde{m}^2_{\tilde{\mu}_R} = \widetilde{m}^2_{\tilde{\tau}_R} \\ m_{\tilde{l}_L} \equiv \widetilde{m}_{\tilde{\nu}_e} = \widetilde{m}_{\tilde{\nu}_\mu} = \widetilde{m}_{\tilde{\nu}_\tau} = \widetilde{m}_{\tilde{e}_L} = \widetilde{m}_{\tilde{\mu}_L} = \widetilde{m}_{\tilde{\tau}_L} \\ \tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle \end{cases}$$

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

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



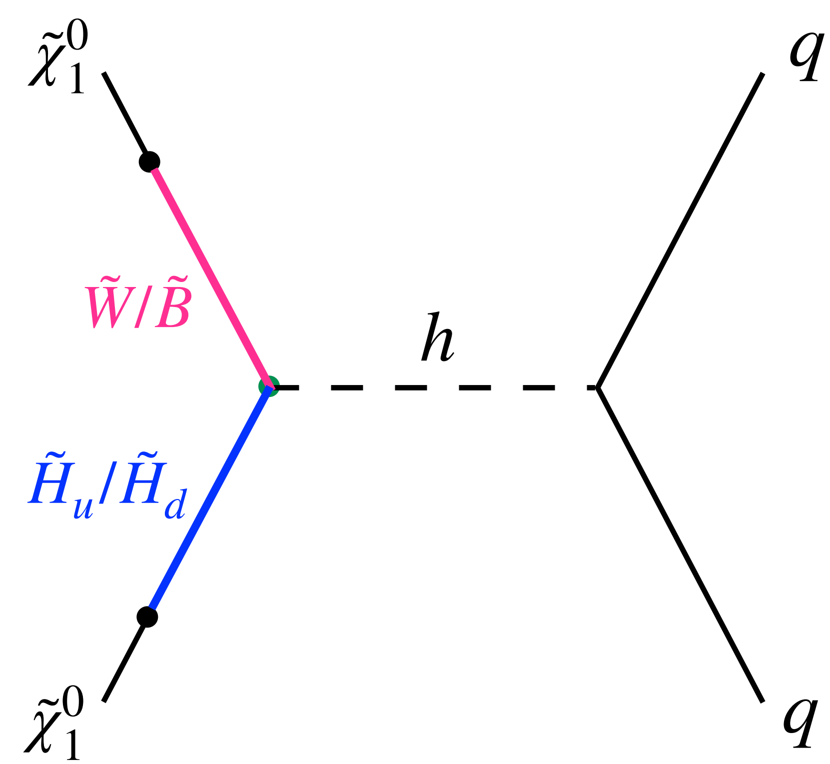


$$\Delta a_\mu^{\rm WHL}(M_2, \mu, m_{\tilde{l}_L}) = \frac{\alpha_W}{8\pi} \frac{m_\mu^2}{M_2 \mu} \tan\beta \cdot f_{\rm W}(\{\mathbf{m}\})$$

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

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

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

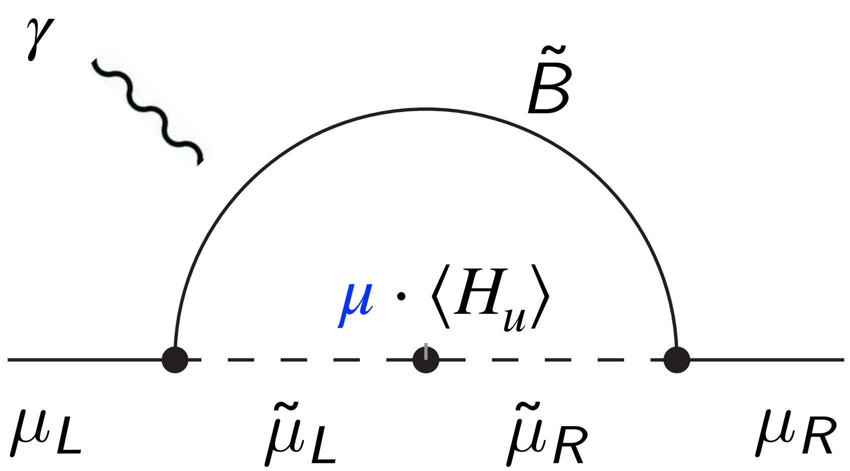


M_1 : Bino ($\tilde{B}$) mass

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:**

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

[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)

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

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

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

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

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**~~

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

↑ large

Bino and both L and R sleptons must be light:

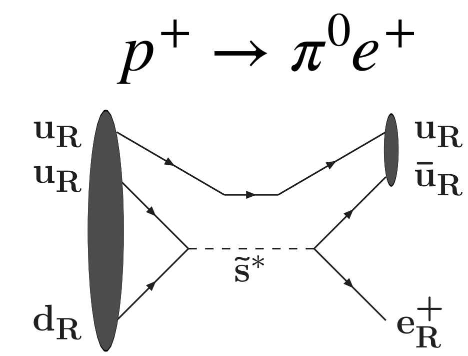
$\Longrightarrow$ **LHC constraint with large $\not{E}_T$** ← **Modified**

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

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

R-Parity Violation; UDD

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



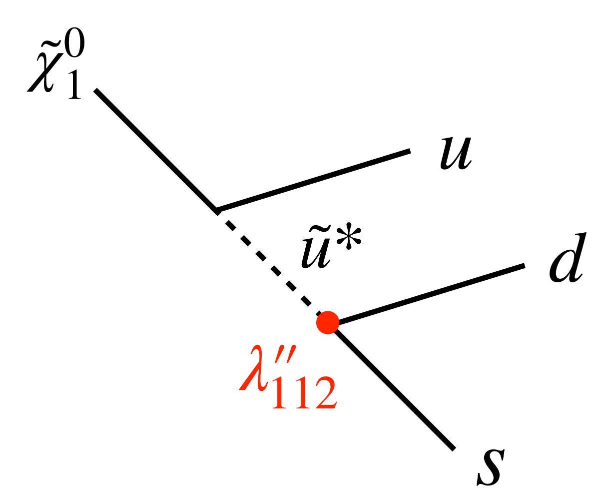
- Allowing both **B** and **L** violation leads to a rapid proton decay:
- We introduce only the **UDD** operator with: $\lambda''_{112} \neq 0$

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

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

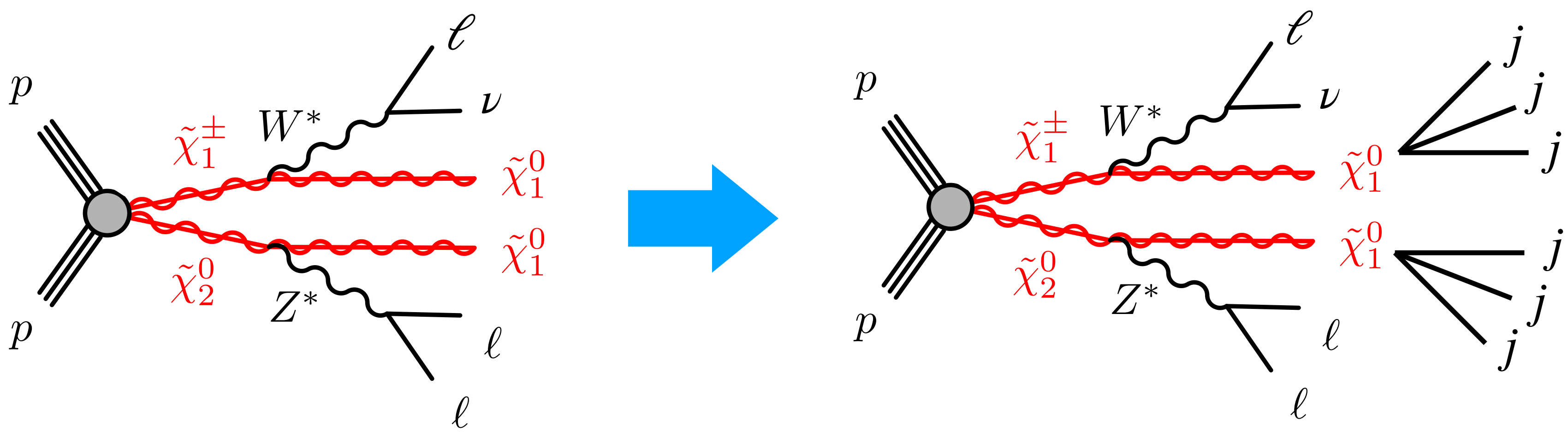
[1810.08228]

- **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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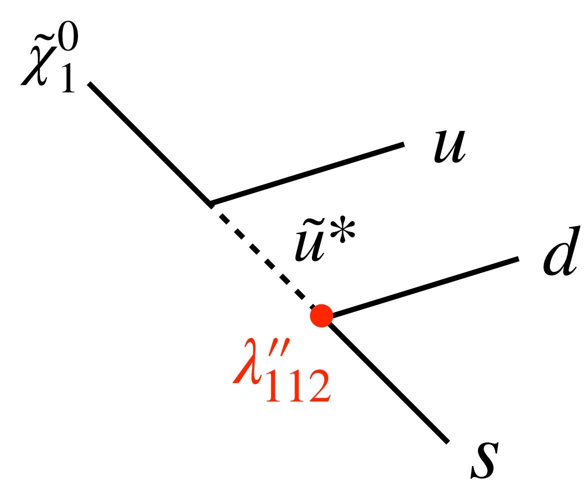
  no leptons, no b-jets in the neutralino decay



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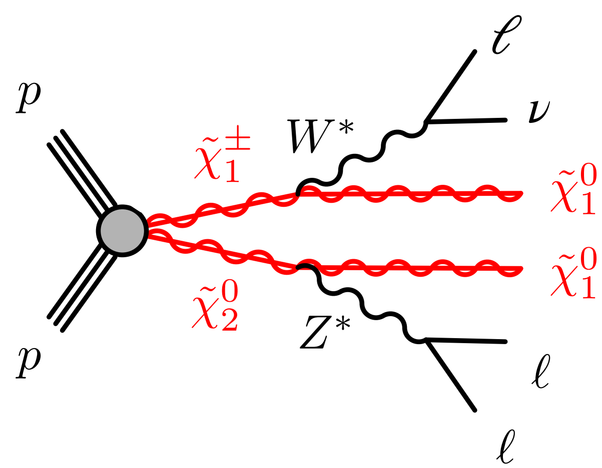
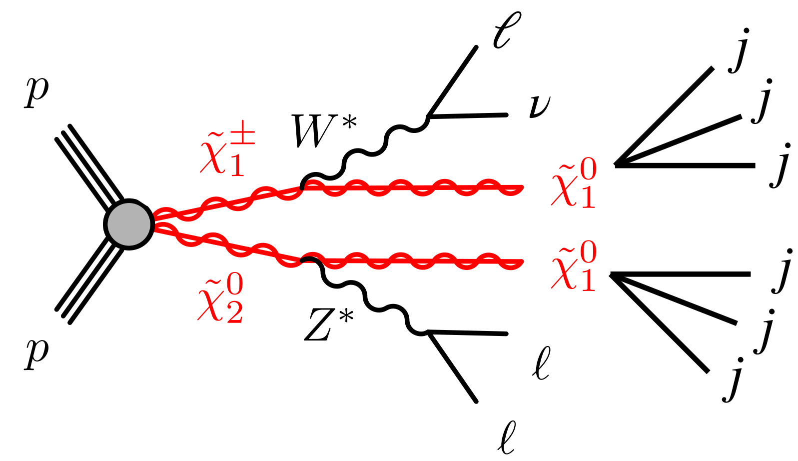


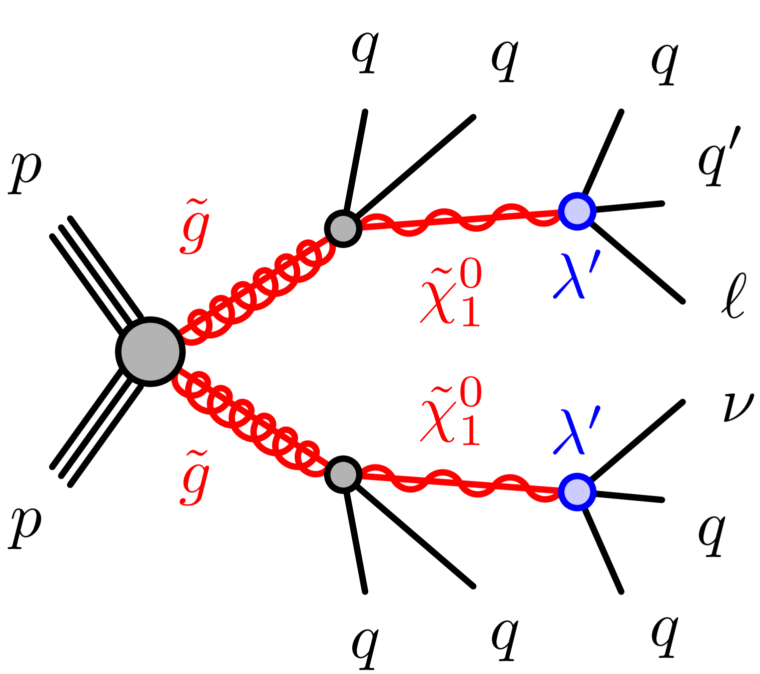


RPV (UDD-type)

No missing energy, but multi-jet

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

ATLAS [2106.09609]



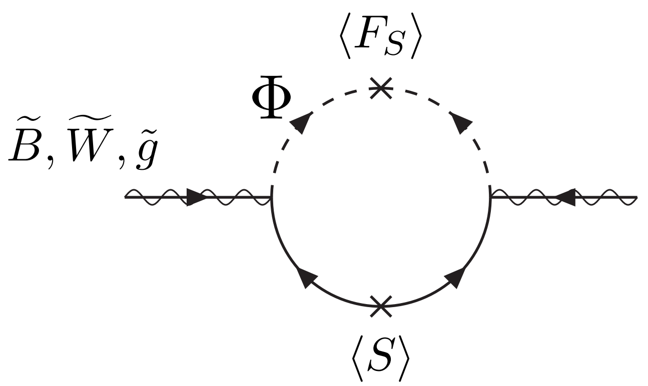
CMS [1709.05406]

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:

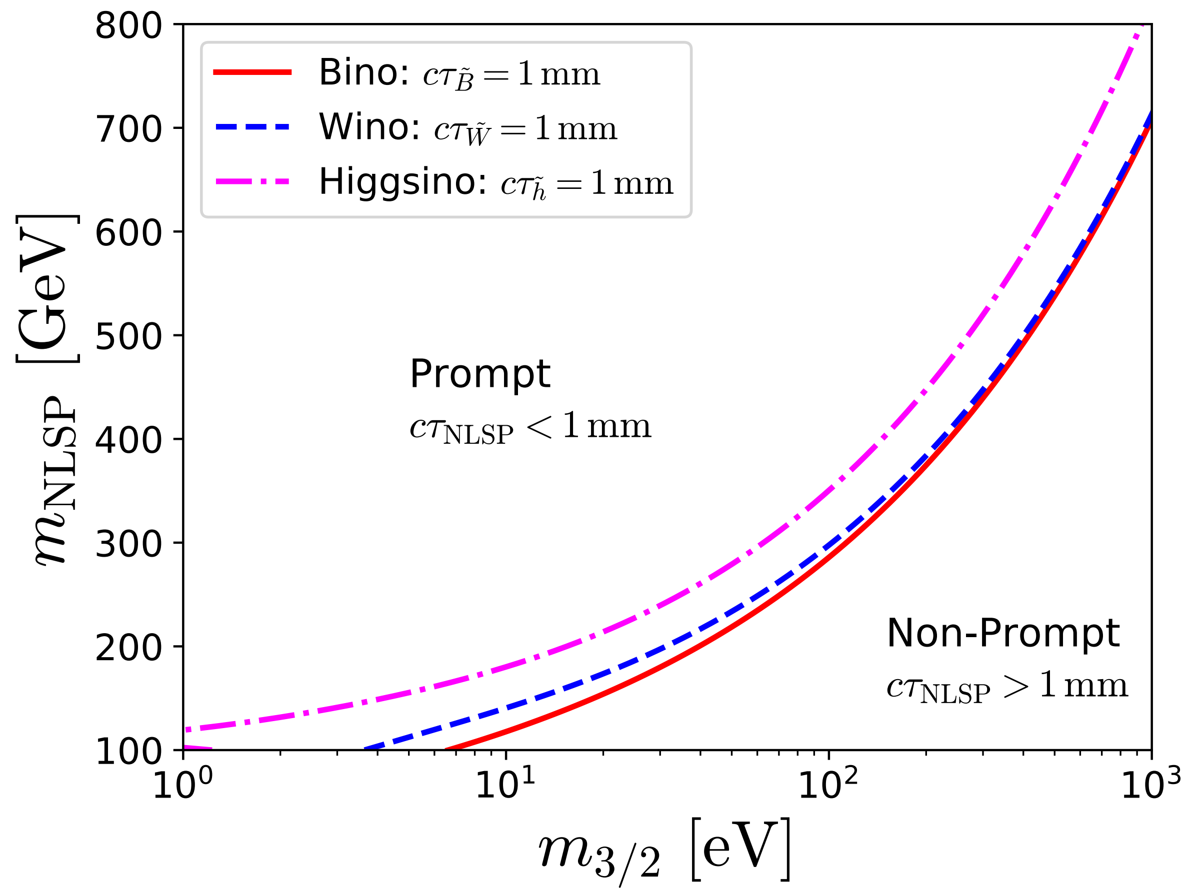
$$\delta m_h^2 \propto m_{SUSY}^2 \ln\left(\frac{\Lambda_{\rm mess}}{M_{\rm PL}}\right) \qquad m_{3/2} = \frac{4\pi}{\sqrt{3}\alpha_W} M_2 \frac{\Lambda_{\rm mess}}{M_{\rm PL}}$$



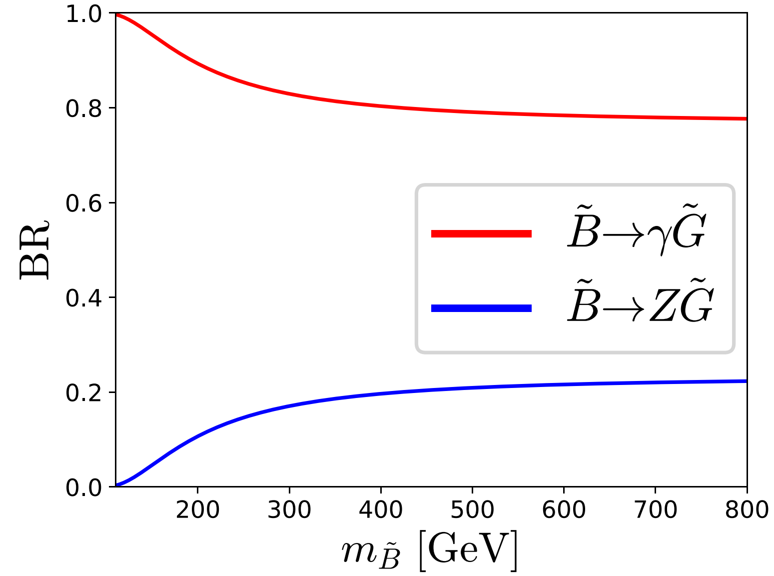
- The decay rate of the NLSP neutralino into the gravitino can be calculated. For light gravitinos (< 10-100 eV), the neutralino decays are prompt.

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

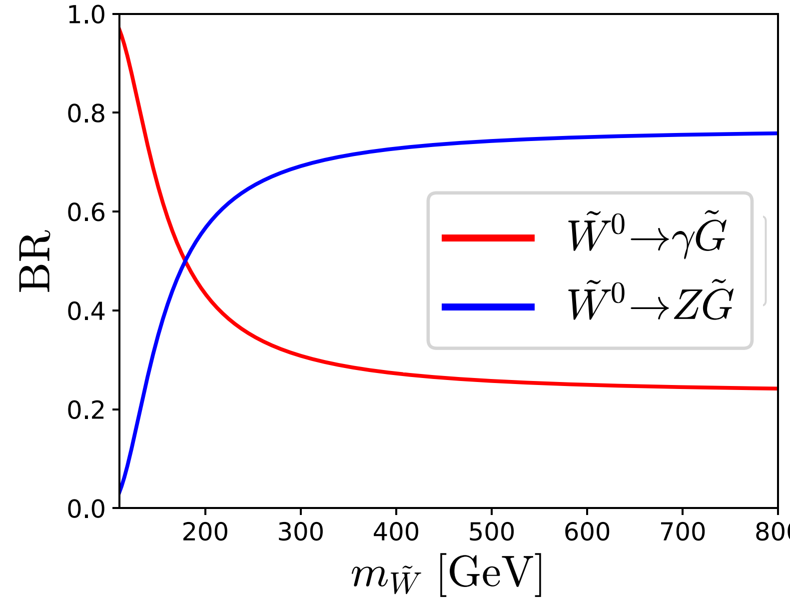
$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi m_{3/2}^2 M_{\rm pl}^2} \sim \frac{1}{0.3\,\mathrm{mm}}\left(\frac{m_{\tilde{\chi}_1^0}}{100\,\mathrm{GeV}}\right)^5\left(\frac{m_{3/2}}{10\,\mathrm{eV}}\right)^{-2}$$



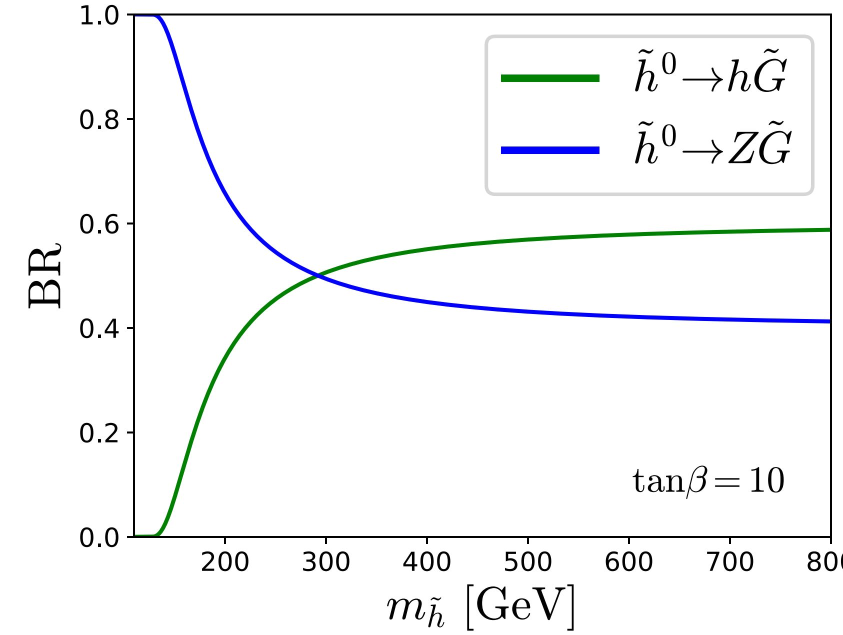
Bino-like

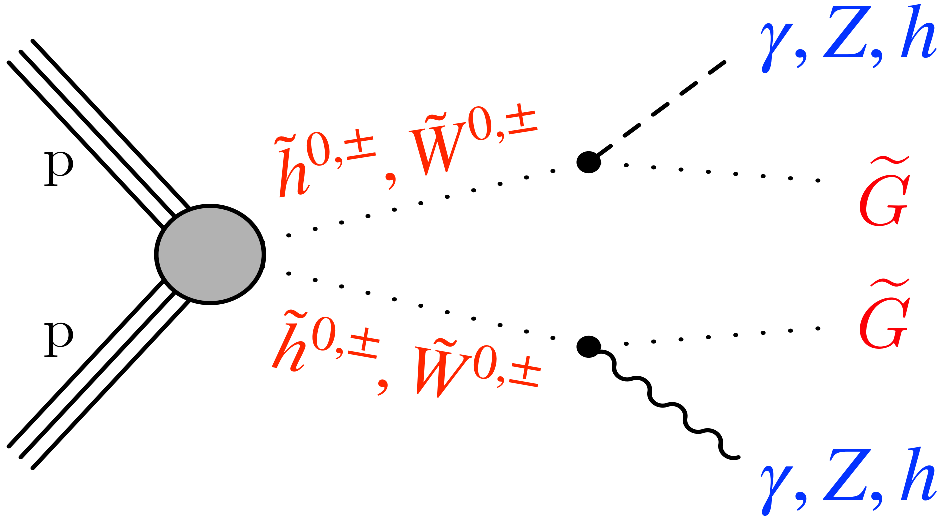


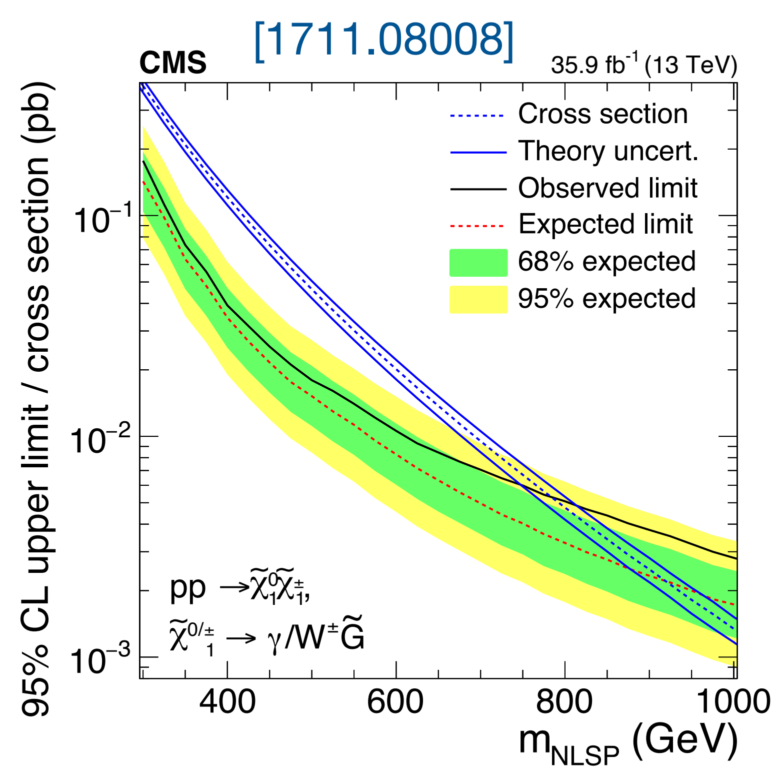
Wino-like

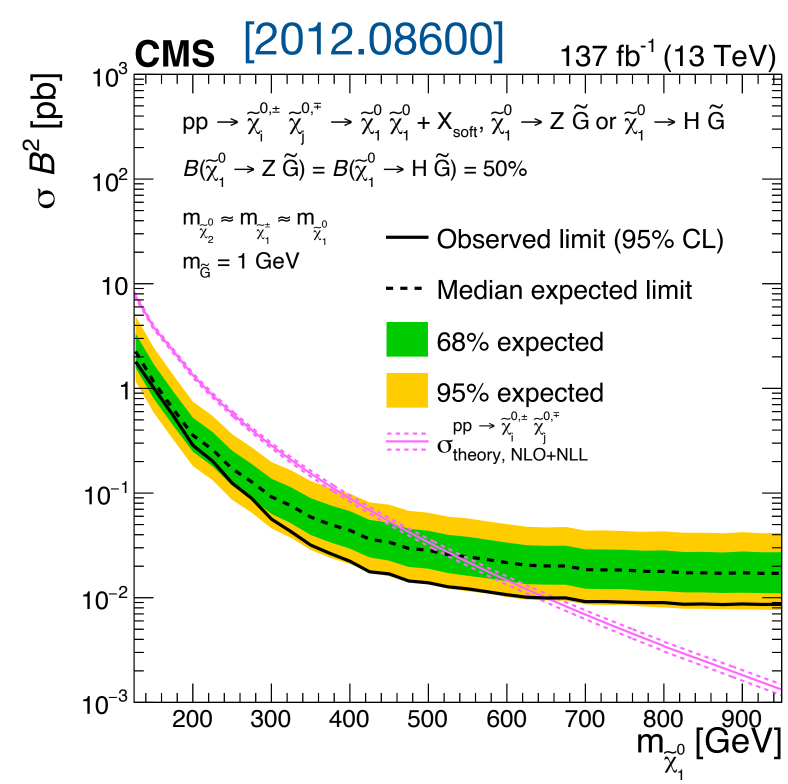


Higgsino-like









- 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]

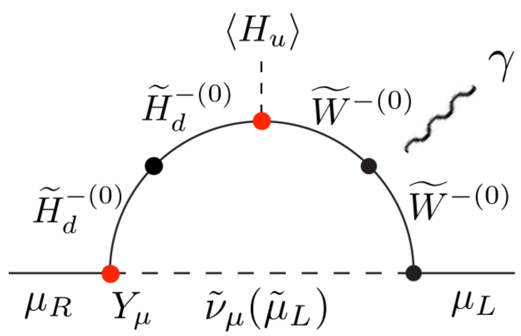
Neutralino abundance, Direct Detection: MicrOMEGAs [2003.08621]

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

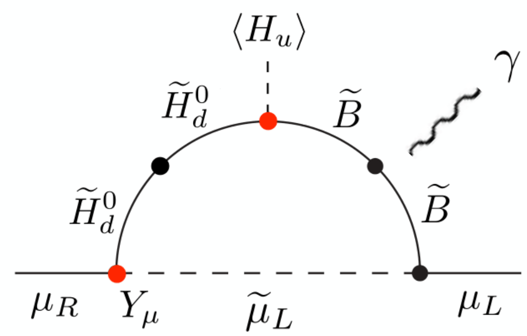
LHC constraints:

- **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

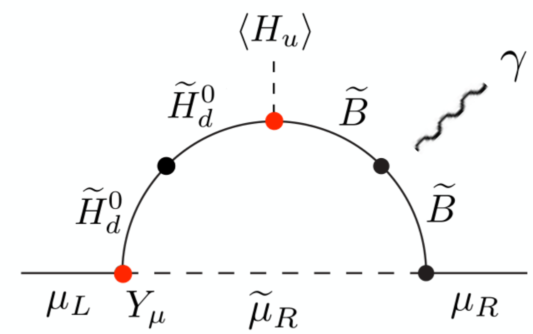
Parameter planes



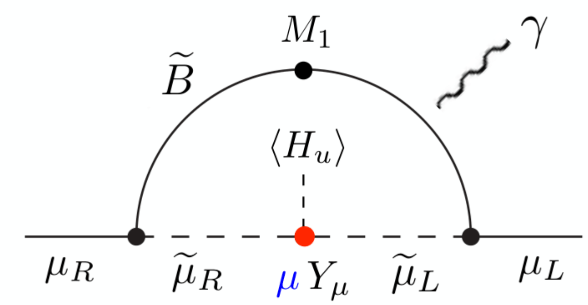
$\Delta a_\mu^{\mathrm{WHL}}(M_2, \mu, m_{\tilde{l}_L})$



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



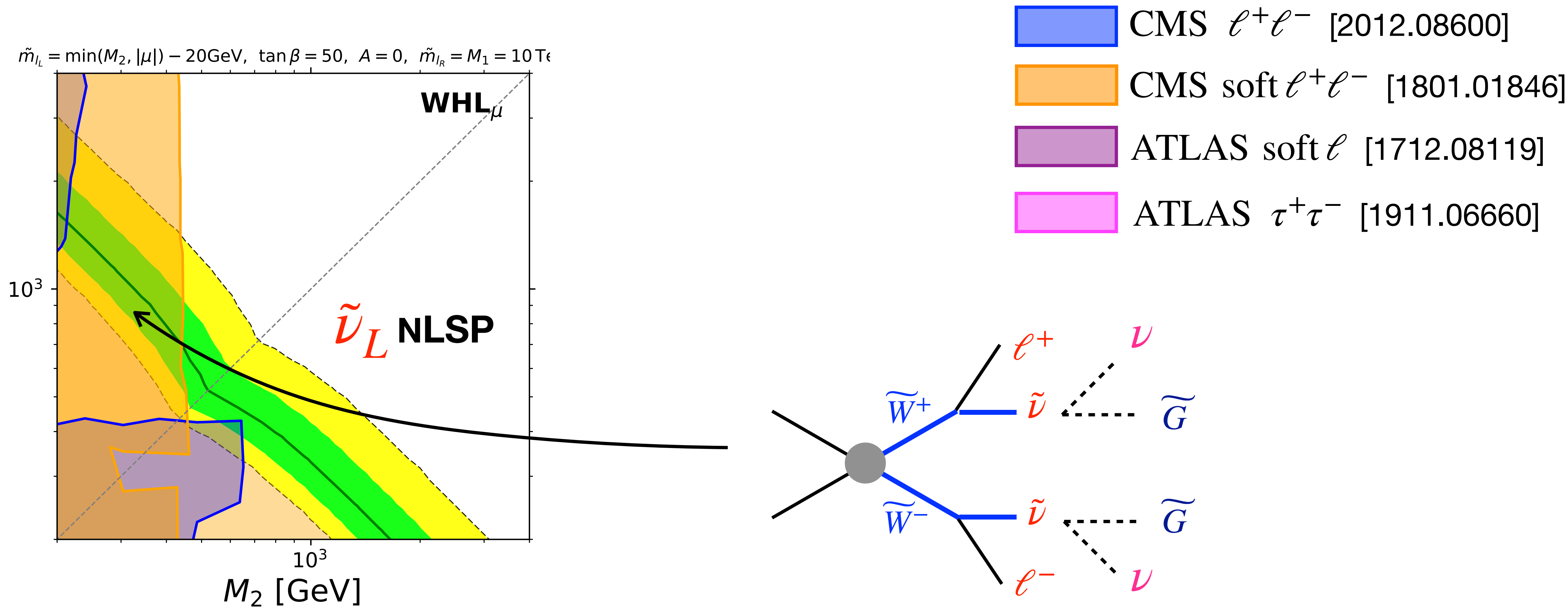
$\Delta a_\mu^{\mathrm{BHR}}(M_1, \mu, m_{\tilde{l}_R})$

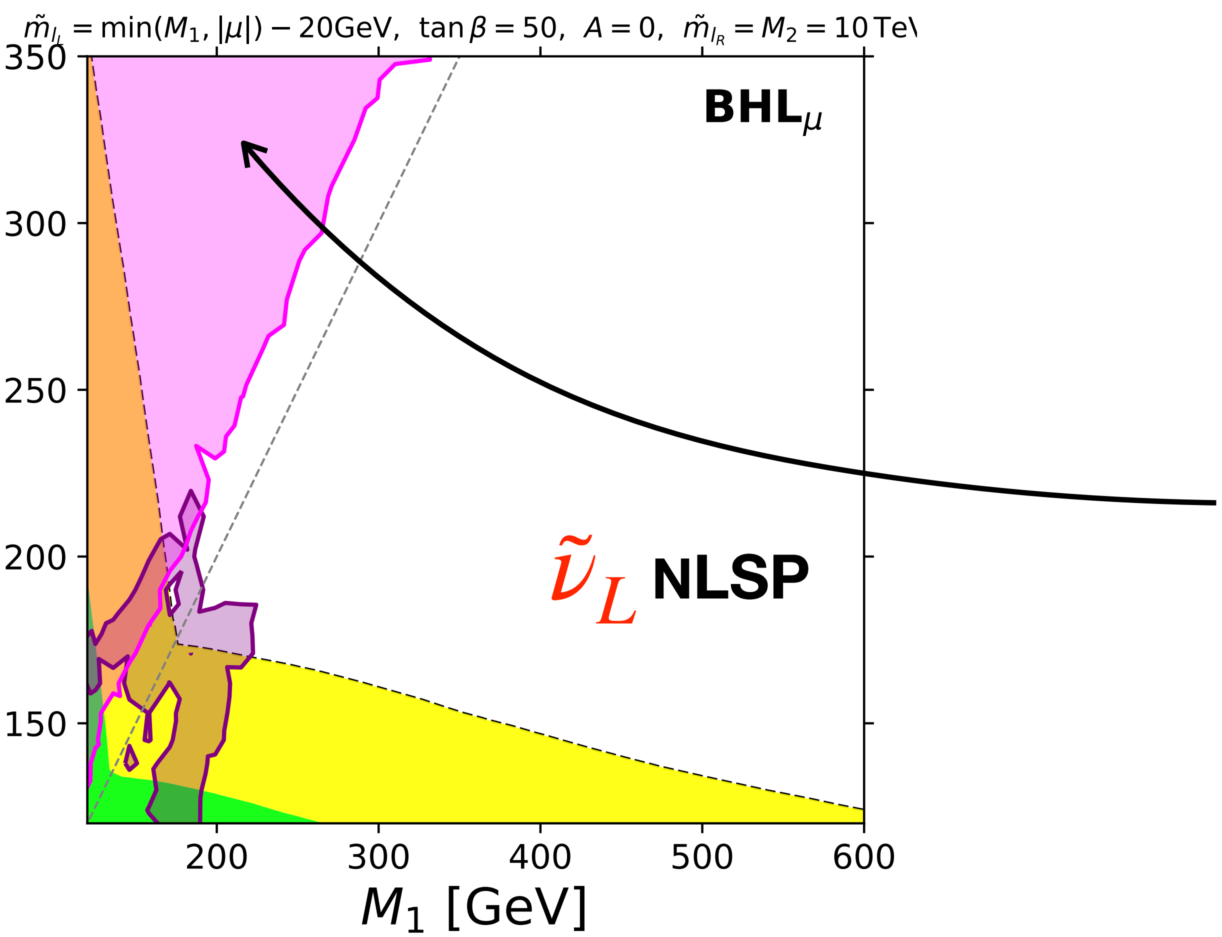


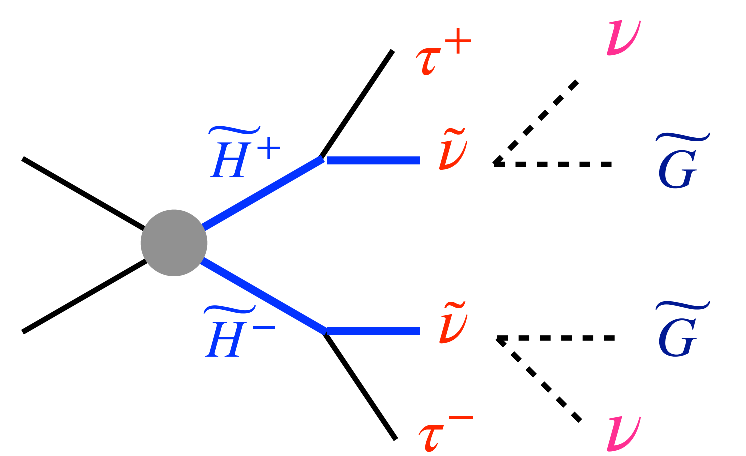
$\Delta a_\mu^{\mathrm{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R}\,;\, \mu)$

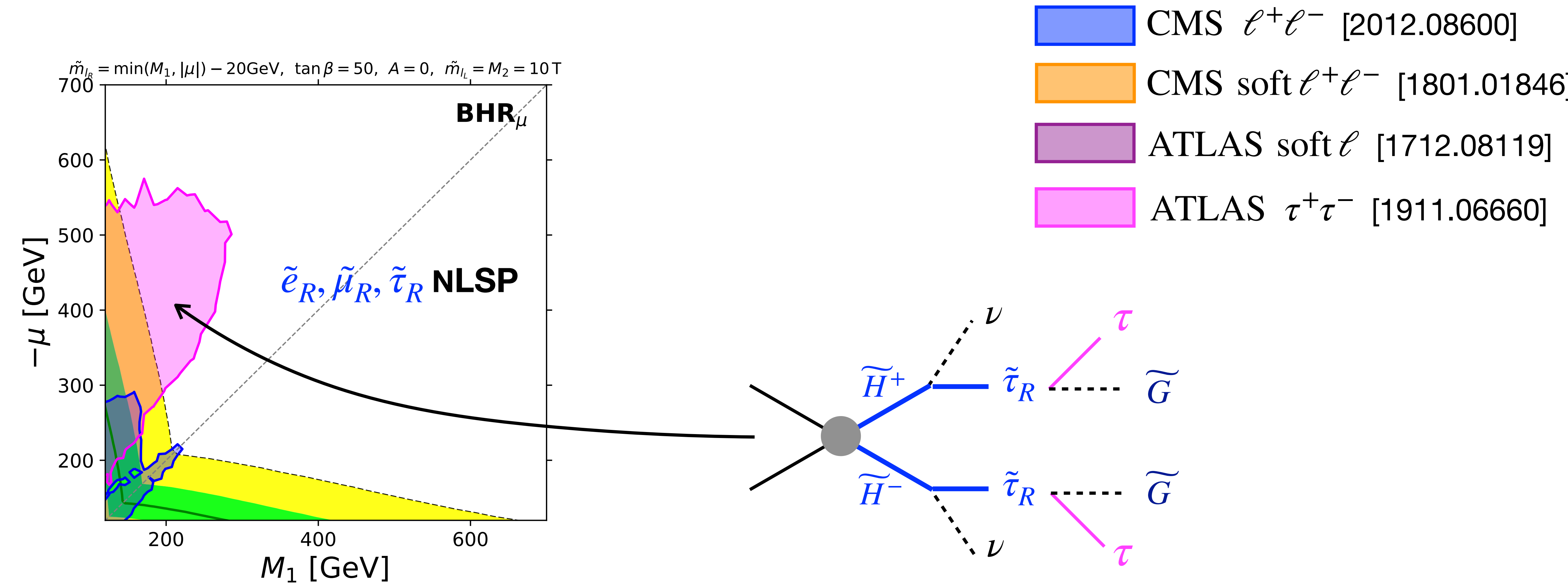
2D planes

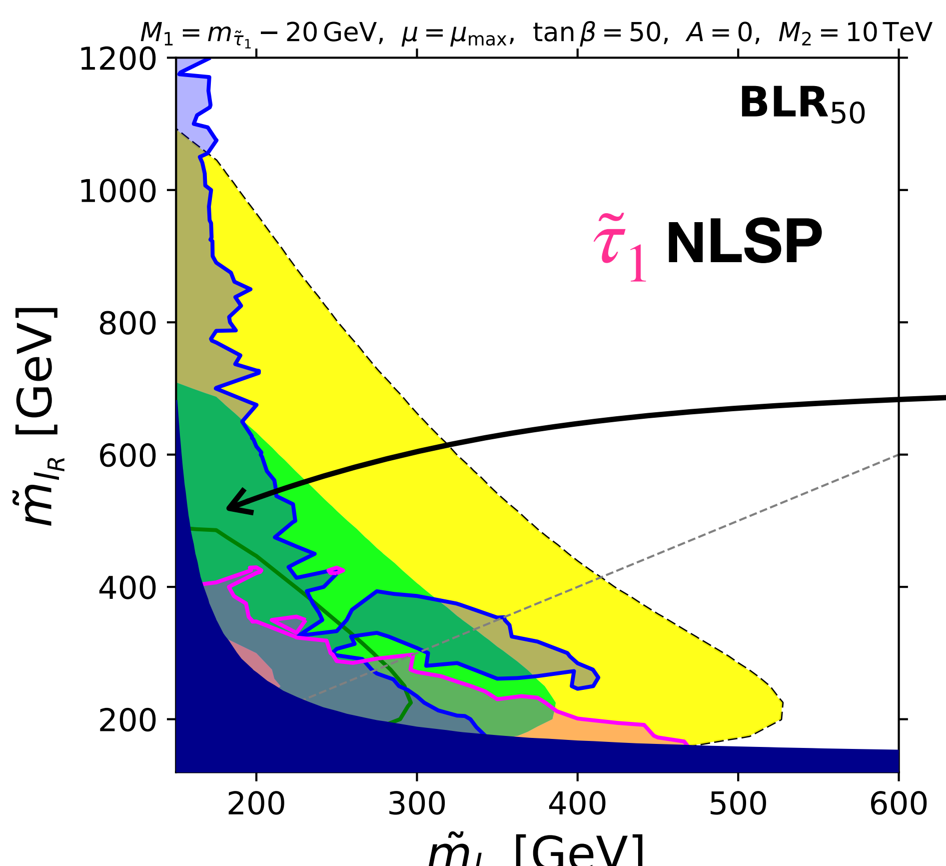
name	axes	other parameters	$\tan\beta$
WHL	(M_2, μ)	$\tilde{m}_{l_\mathrm{L}} = \min(M_2, \mu) + 20\,\mathrm{GeV}, \quad M_1 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$	50
BHL	(M_1, μ)	$\tilde{m}_{l_\mathrm{L}} = \min(M_1, \mu) + 20\,\mathrm{GeV}, \quad M_2 = \tilde{m}_{l_\mathrm{R}} = 10\,\mathrm{TeV}$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

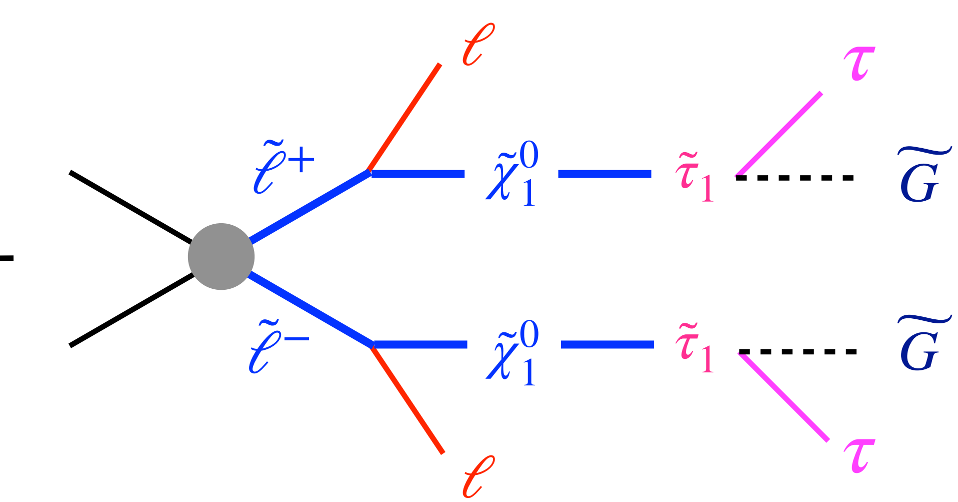

CMS $\ell^+\ell^-$ [2012.08600]
CMS soft $\ell^+\ell^-$ [1801.01846]
ATLAS soft ℓ [1712.08119]
ATLAS $\tau^+\tau^-$ [1911.06660]
$\tilde{m}_{l_L} = \min(M_2, |\mu|) - 20\text{GeV}$, $\tan\beta = 50$, $A = 0$, $\tilde{m}_{l_R} = M_1 = 10$ Te
WHL$_\mu$
$\tilde{\nu}_L$ NLSP
μ [GeV]
M_2 [GeV]
10^3
$\widetilde{W}^+$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


$\tilde{m}_{l_L} = \min(M_1, |\mu|) - 20\text{GeV}$, $\tan\beta = 50$, $A = 0$, $\tilde{m}_{l_R} = M_2 = 10$ TeV
BHL$_\mu$
$\tilde{\nu}_L$ NLSP
μ [GeV]
M_1 [GeV]
350
300
250
200
150
200
300
400
500
600

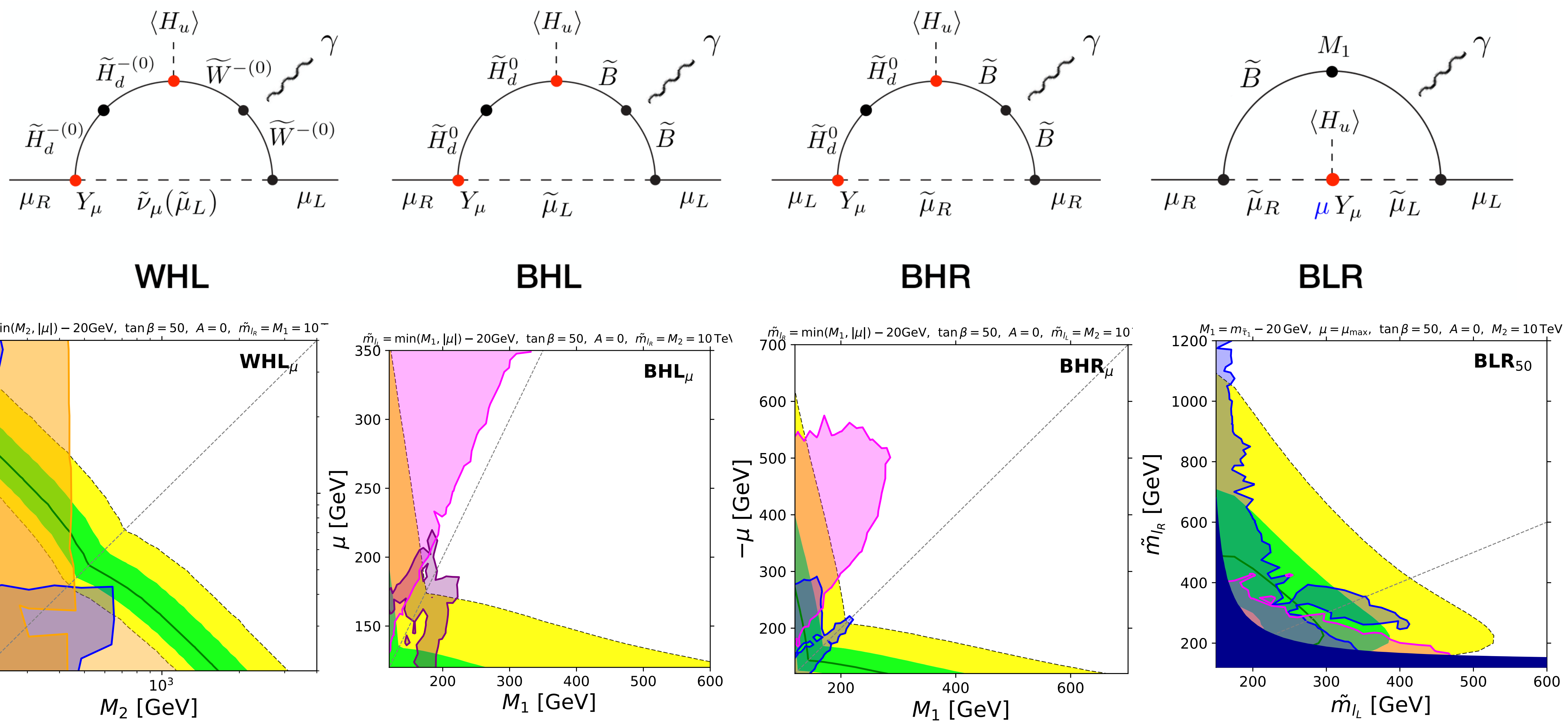

$\widetilde{H}^+$
$\widetilde{H}^-$
τ^+
τ^-
$\tilde{\nu}$
ν
$\widetilde{G}$


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


$M_1 = m_{\tilde{\tau}_1} - 20$ GeV, $\mu = \mu_{\max}$, $\tan\beta = 50$, $A = 0$, $M_2 = 10$ 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)



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