Revisiting the slepton coannihilation model with light higgsino

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in progress

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Dark Matter in SUSY Model

The existence of Dark Matter is inferred from cosmological observations.

$$\Omega_{DM} h^2 = 0.12$$

Supersymmetric (SUSY) model provides some candidates.

Neutralino, Gravitino …

We focus on neutralino dark matter, especially bino $\tilde{B}$.

Since bino is gauge singlet, it is **difficult** to search for Bino by collider experiments and direct detection.

In addition, the bino dark matter annihilation has **very small cross section**.
To achieve the observed relic abundance, we should require other particles.

Slepton Coannihilation

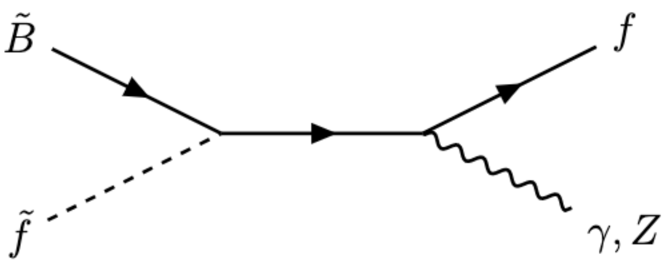
To realize the large annihilation cross section, the well-known mechanism is the coannihilation.

Griest, Seckel (1991)

$$\langle \sigma_{eff} v \rangle = \sum_{i,j} \langle \sigma_{ij} v \rangle \frac{n_i^{eq.}}{n^{eq.}} \frac{n_j^{eq.}}{n^{eq.}}$$

Bino can coannihilate with scalar partner of matter, e.g. slepton, when these particles are degenerate with bino:

$$\delta m \sim m_{bino}/20$$



The effective annihilation cross section are calculated by **micrOMEGAs**.

Slepton Coannihilation

$\mathcal{O}(100\ \mathrm{GeV})$ squarks are severely constrained by collider experiments due to the strong production process.

Slepton coannihilation model is allowed in ~ 100 GeV regions.

e.g. smuon coannihilation

Smuons can be produced at LHC:

$$p\,p \to \tilde{\mu}_{L/R}\,\tilde{\mu}_{L/R} \to \tilde{\chi}^0\mu\,\tilde{\chi}^0\mu,$$

Since smuon and bino are degenerate, the final state muons are soft.
ATLAS analysis (LHC Run 2) gives the constraint by soft lepton search.

ATLAS collaboration, arXiv:1911.12606

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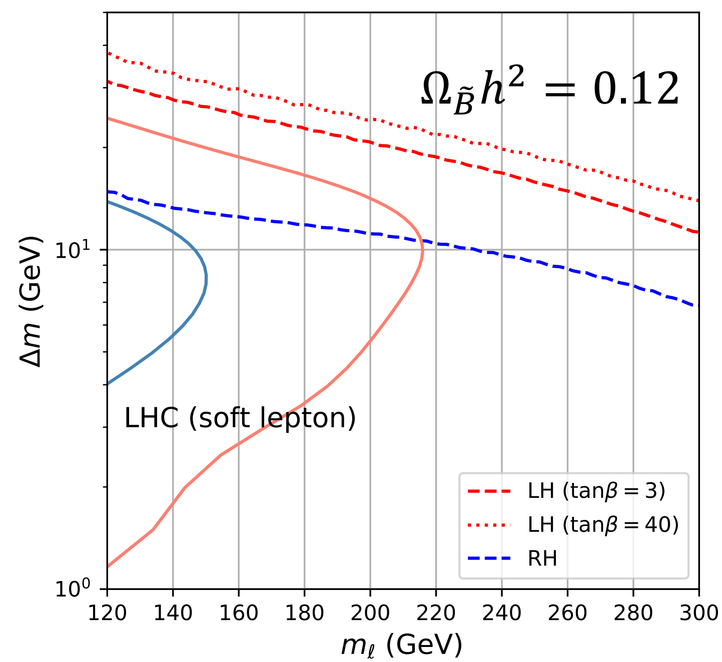
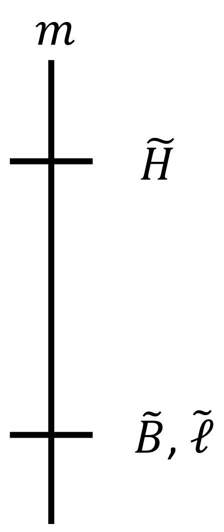


Light Higgsino

In the context of naturalness, higgsino $\tilde{H}$ is also motivated to be $\mathcal{O}(100\ \mathrm{GeV})$.

The light higgsino provides plenty of phenomenologies in several experiments.

- Direct Detection (higgs exchange)
- Muon magnetic dipole moment, g-2 (next page)
- Collider experiment (electroweakino pair production)



Muon g-2

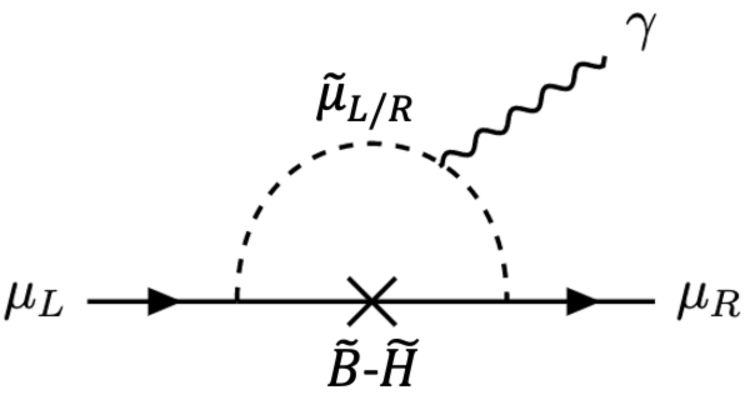
When bino, smuon and higgsino is light, SUSY contribution to muon g-2 is sizable.
These are proportional to tanβ (tanβ enhancement).

Moroi ('95) Carena, Giudice, Wagner ('95)

$\tilde{B}, \tilde{H}, \tilde{\mu}_R$ (BHR model)

$$a_\mu^{\mathrm{BHR}} \approx -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\mu_R}^2}, \frac{\mu^2}{m_{\mu_R}^2}\right)$$

μ should be **negative** to explain the anomaly



$\tilde{B}, \tilde{H}, \tilde{\mu}_L$ (BHL model)

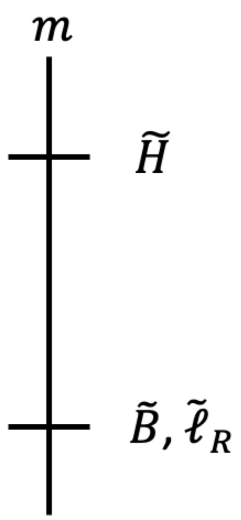
$$a_\mu^{\mathrm{BHL}} \approx \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\mu_L}^2}, \frac{\mu^2}{m_{\mu_L}^2}\right)$$

Model

In this talk, we focus on BHR model.

$$m_{\tilde{\ell}_R}, M_1, \mu$$

is important parameters. We set $\boldsymbol{m_{\tilde{\ell}_R}}$ on (M_1, μ) plane to explain the observed dark matter relic abundance.



To search for this model,

(i) Dark matter direct detection

(ii) Collider experiment

are important. We **update** several experimental constraints on this model with several parameter spaces.

Dark Matter Direct Detection

From bino-higgsino mixing, neutralino interacts with matter via higgs exchange.

If the heavy higgs is also in EW scale, CP-even heavy higgs exchange is also important.

$$\sigma_p^{SI} \sim \left[(F_p^{(d)} + F_u^{(p)})(m + \mu \sin 2\beta)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta (-F_p^{(d)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2} \right]$$

If μ term is negative, heavy higgs contribution is destructive.

Huang, Wagner (2014)

We consider the LZ experiment for the spin-independent cross section constraint.

LHC Constraint

In addition to $\tilde{\ell}\,\tilde{\ell}$ pair production, the model can be probed via electroweakino pair production.

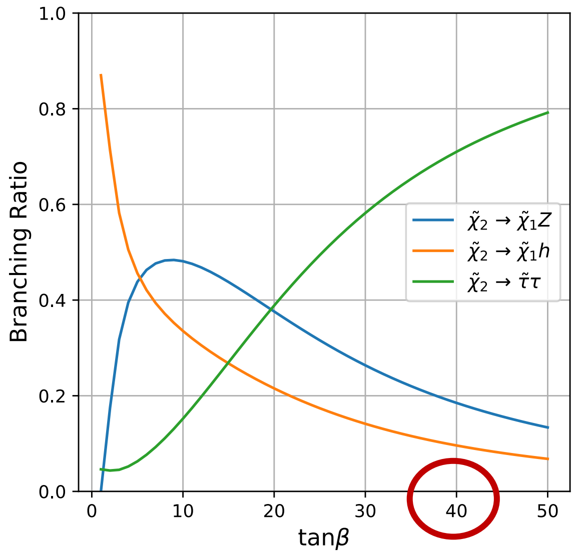
$$pp \longrightarrow \tilde{\chi}_i \tilde{\chi}_j$$

The signal significance depends on the branching ratio of higgsino.

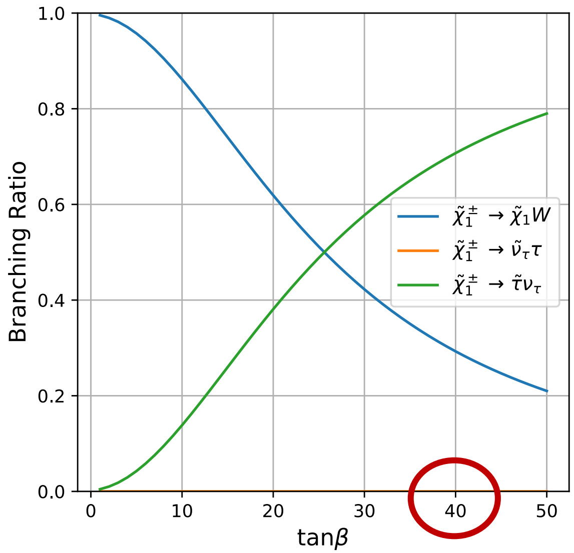
In case of large $\tan\beta$, neutralino/chargino

decay into $\tilde{\tau}$ or $\tilde{\nu}_\tau$ dominantly.

$\tilde{\chi}_2^0$



$\tilde{\chi}_1^\pm$



LHC Reinterpretation

ATLAS papers provide **the upper limit of the cross section** in the simplified model (*e.g.* wino production with **100%** branching ratio).

These upper limits can be **reinterpreted** as the limits to the specified model. Then the parameter space is **excluded** if the following condition is satisfied:

$$\sigma(pp \to \tilde{\chi}\tilde{\chi}) \times Br(\tilde{\chi} \to \tilde{\chi}_1^0 X) Br(\tilde{\chi} \to \tilde{\chi}_1^0 X) \ > \ \sigma_{LHC},$$

Production cross section | Branching ratio | LHC upper limit in simplified model

For example, the constraint from WZ channel is obtained by the following inequality:

$$\sigma\left(pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm\right) \times Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z) Br\left(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W\right) \ > \ \sigma_{LHC}$$

Result ($\tan\beta = 40$)

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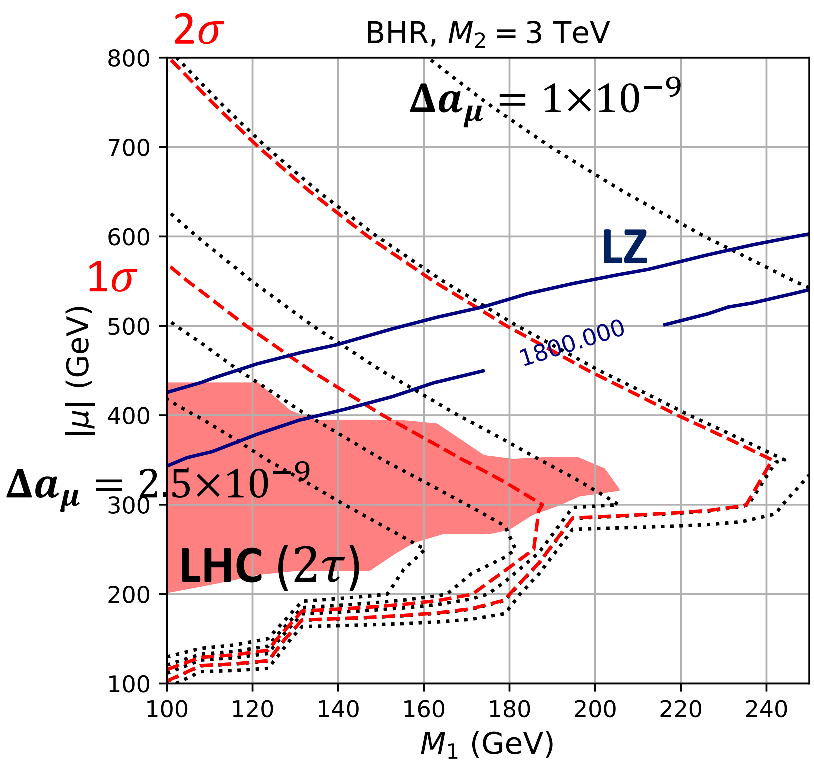


*This is preliminary result.
Δa_μ is calculated by using approximated formula.

BHR model (right-handed smuon)
μ term is negative sign.

- Direct detection constraint from the LZ experiment (navy lines) for each value of heavy higgs. Heavy higgs is constrained by LHC, $\boldsymbol{m_H < 1800}$ **GeV** for $\tan\beta = 40$.
  ATLAS collaboration, arXiv: 2002.12223
- LHC constraint from the 2τ search (red filled region).
- Muon g-2 contours (black dotted lines). The discrepancy (BNL+FNAL) is $\Delta a_\mu = (2.51 \pm 0.59)\times10^{-9}$

Summary

- Slepton coannihilation model with light higgsino can be probed by direct detection, collider experiment and muon g-2.
- We update the experimental results on these models. In this talk, BHR model with large $\tan\beta$ is considered.
- We found that there remains some regions where muon g-2 contribution is not small. These regions will be probed by future collider experiment, like ILC.

Backup

Mass Spectrum

In our consideration, M_1, μ, and $m_{\tilde{\ell}_{L,R}}$ (left- and right-handed slepton mass) is phenomenologically important.

The smuon mass eigenvalue can be approximated as soft mass + hyperfine splitting caused by EW breaking

$$\mathrm{BR}: m_{\tilde{\ell},R}^2 = M_R^2 - \sin^2\theta_W \cos(2\beta) m_Z^2 \ ,$$

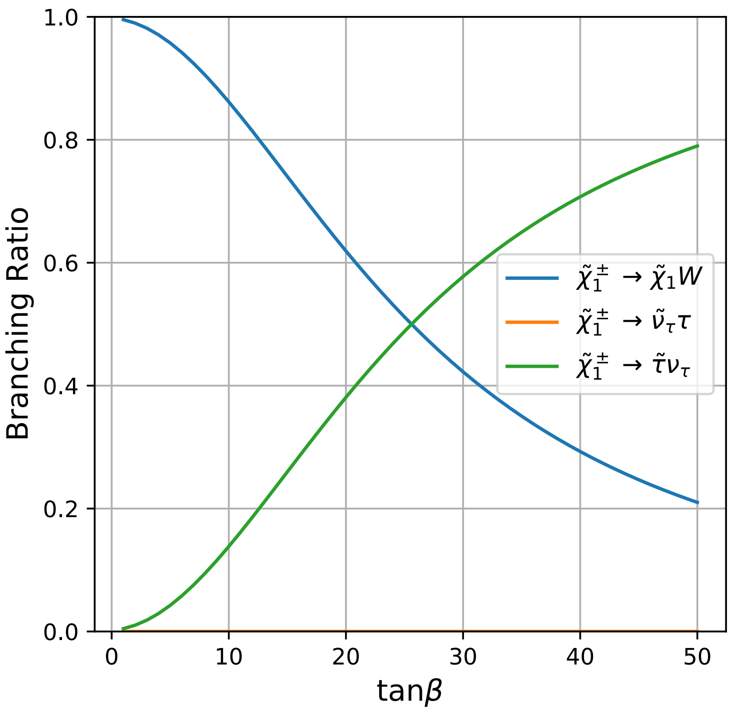
$$\mathrm{BL}: \begin{cases} m_{\tilde{\ell},L}^2 = M_L^2 + \left(-\frac{1}{2} + \sin^2\theta_W\right)\cos(2\beta) m_Z^2 \ , \\ m_{\tilde{\nu},L}^2 = M_L^2 + \frac{1}{2}\cos(2\beta) m_Z^2 \ , \end{cases}$$

For left-handed slepton, **sneutrino is lighter than smuon**. Bino coannihilates with sneutrino, not smuon.

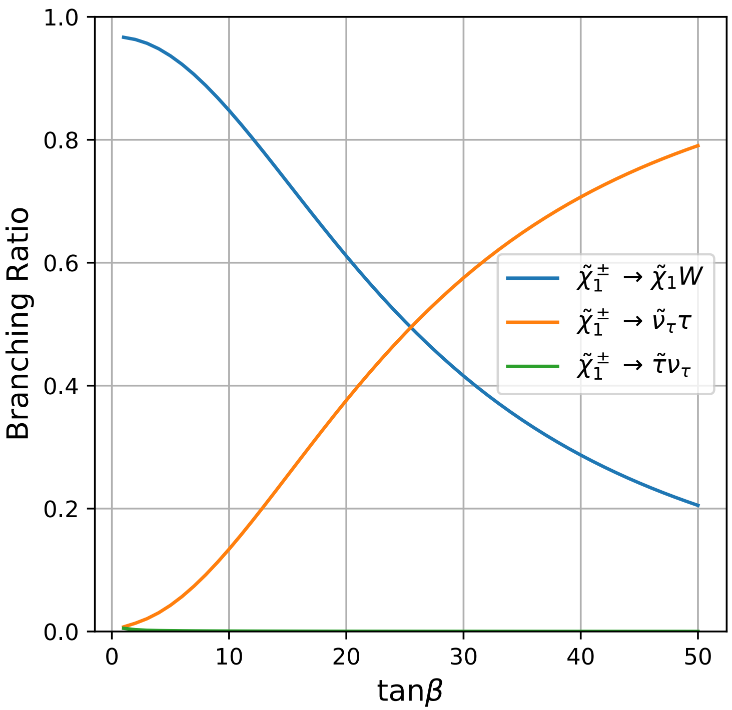
Branching Ratio

- Chargino branching ratio

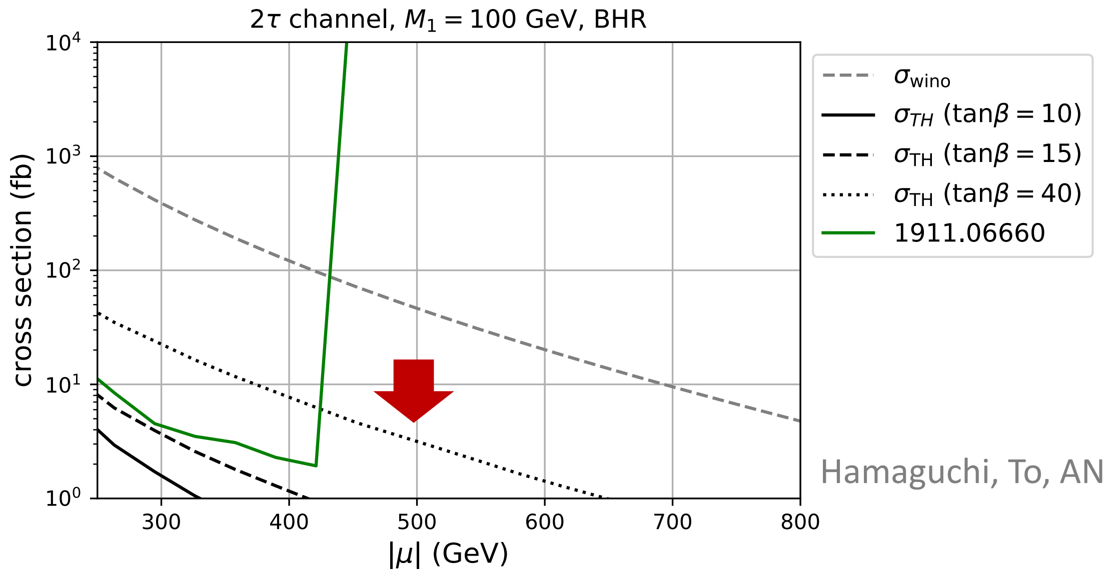
$\mu < 0$



$\mu > 0$



LHC Constraint



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<u>$\tau\tau$ channel</u>

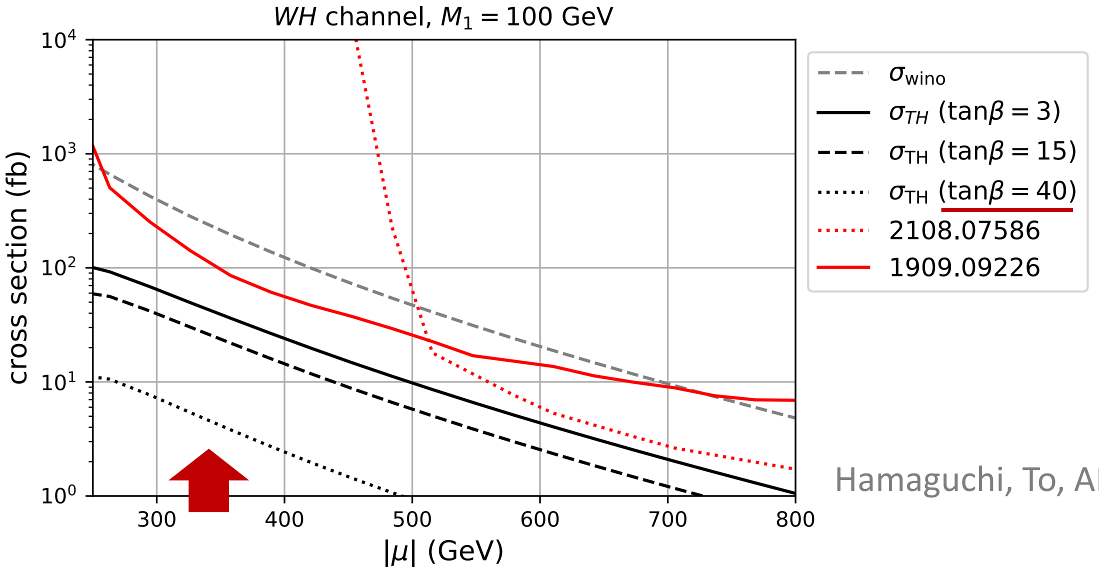
modes $\tilde{\chi} \to \tilde{\nu}(\tilde{\tau})\ \tau$ is enhanced by large $\tan\beta$.

In case of large $\tan\beta$, **the most stringent LHC constraint** comes from 2τ channel.

cf. Endo et. al. (2017)

*Branching ratio also depends on sign of μ term.
When $\text{sgn}(\mu) < 0$, the dominant decay mode of chargino is $\tilde{\chi}^+ \to \tilde{\tau}\ \nu$, not $\tilde{\chi}^+ \to \tilde{\nu}\ \tau$.
Then the relevant process of 2τ channel is <u>only</u> $pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$ in BHR model.

LHC Constraint



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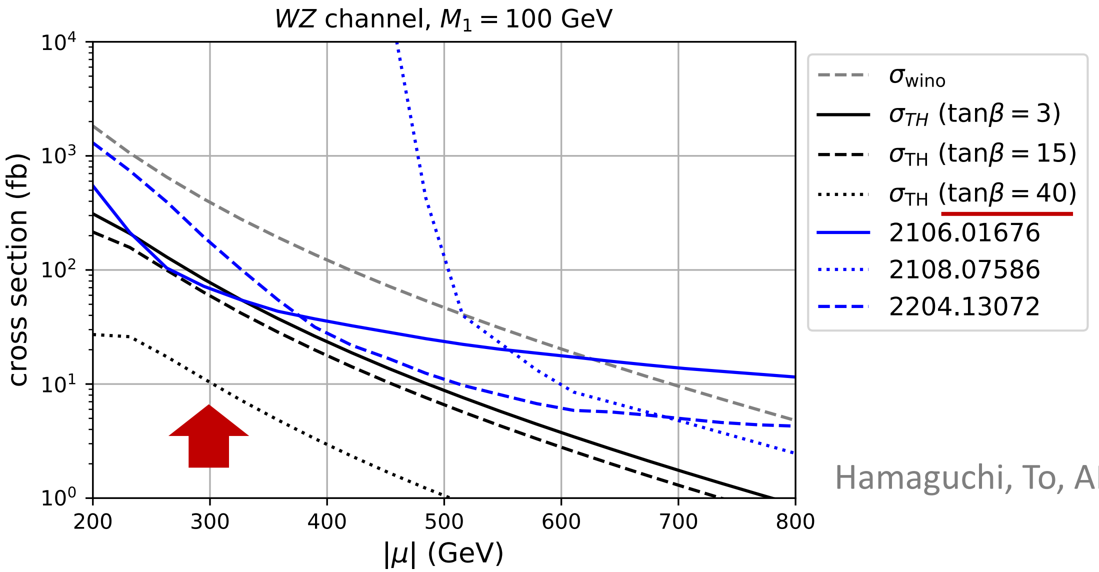

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WZ, Wh channels

modes $\tilde{\chi} \to \tilde{\chi}_1^0\, W/Z/h$ is suppressed for large $\tan\beta$.

In case of large $\tan\beta$, LHC Run 2 results do not constrain the model with WZ/h channels.