A Simplified Dark Matter Model for Muon g-2 with Scalar Lepton Partners at the TeV Scale

Jan Tristram Acuña

International School for Advanced Studies (SISSA) &
Institute for Fundamental Physics of the Universe (IFPU)
Trieste, Italy

- JTA, Patrick Stengel, and Piero Ullio, *arxiv:2109:xxxxx*

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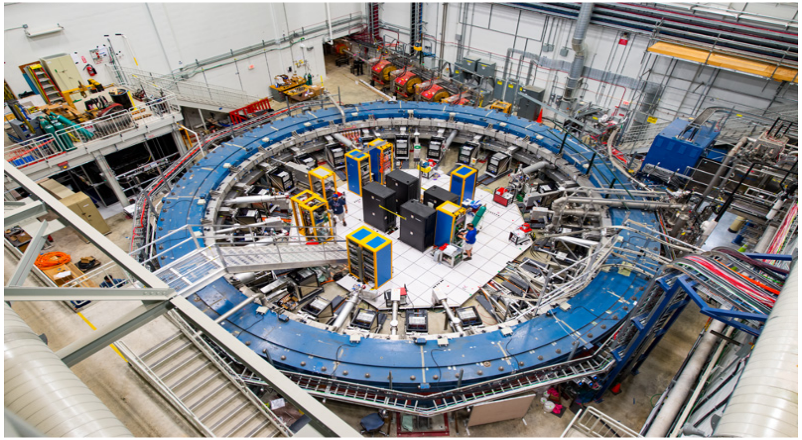
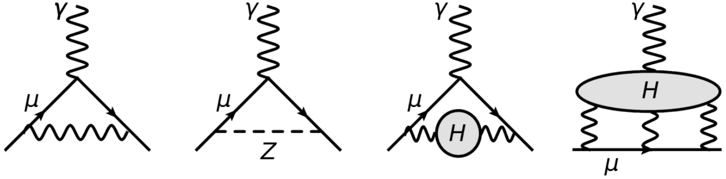
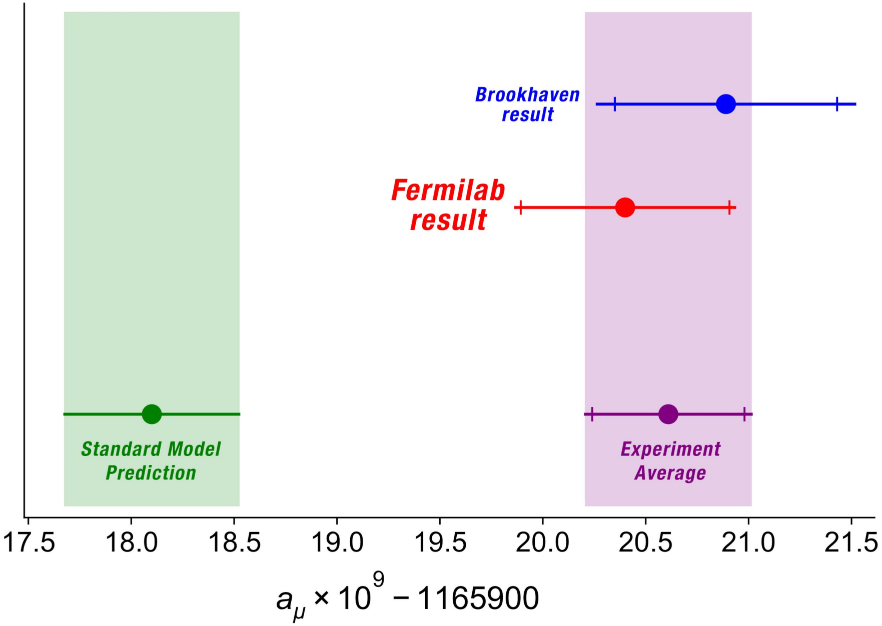
Motivation: FNAL measurement







$$a_\mu(FNAL) = 116592040(54) \times 10^{-11} (0.46\ ppm)$$

$$a_\mu(BNL) = 116592080(54)(33) \times 10^{-11} (0.54\ ppm)$$

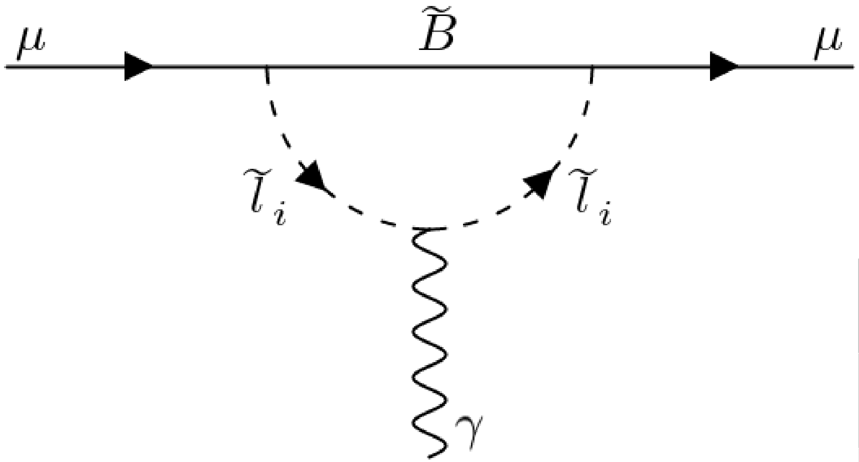
$$a_\mu(\exp) = 116592061(41) \times 10^{-11} (0.35\ ppm)$$

$$a_\mu(SM) = 116591810(43) \times 10^{-11} (0.37\ ppm)$$

$$a_\mu \equiv \frac{g-2}{2}$$

$$\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$$

Assume new physics

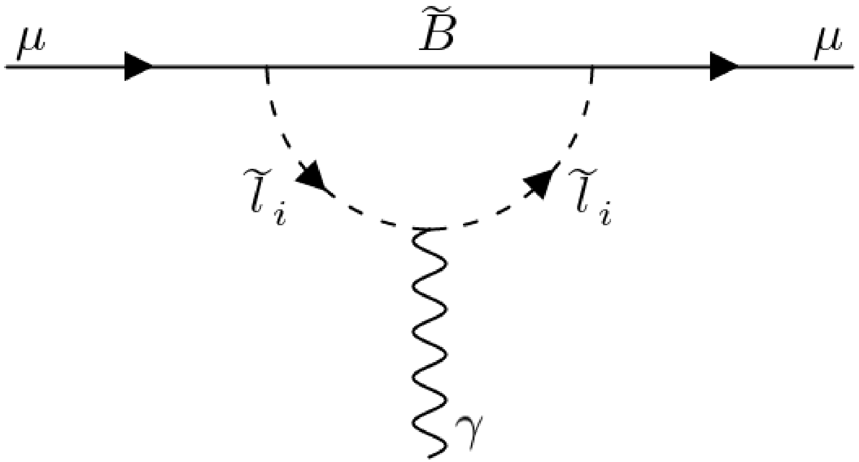


$$\mathcal{L} \supset -\lambda_L \tilde{l}_L^\dagger \bar{B}_R l_L - \lambda_R \tilde{l}_R^\dagger \bar{B}_L \mu_R + \text{h.c.}$$

$$\lambda_{L,R} = \sqrt{2}\, g_Y Y_{L,R}$$

Particle	$SU(2)_L$	$U(1)_Y$	Z_2
$\sim l_L = (\sim\nu_L, \sim\mu_L)$	2	-1/2	-1
$\sim\mu_R$	1	-1	-1
$l_L = (\nu_L, \mu_L)$	2	-1/2	1
μ_R	1	-1	1
$\sim B$	1	1	-1

Additional terms



$$\mathcal{L} \supset -\begin{pmatrix}\tilde{\mu}_L^\dagger & \tilde{\mu}_R^\dagger\end{pmatrix}\begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{LR}^2 & m_{RR}^2\end{pmatrix}\begin{pmatrix}\tilde{\mu}_L \\ \tilde{\mu}_R\end{pmatrix} - m_{LL}^2 \tilde{\nu}_L^\dagger \tilde{\nu}_L$$

$$\mathcal{L} \supset -m_{LL,soft}^2 \tilde{l}_L^\dagger \tilde{l}_L - m_{RR,soft}^2 \tilde{\mu}_R^\dagger \tilde{\mu}_R$$

$$\mathcal{L}_D = -\frac{g_Y^2}{2}\left|\sum_i Y_i \mathcal{S}_i^\dagger \mathcal{S}_i\right|^2 - \frac{g^2}{4}\left[\mathrm{tr}\left\{M^2\right\} - \frac{1}{2}\left(\mathrm{tr}\left\{M\right\}\right)^2\right]$$

$$M_{AB} \equiv \sum_i \mathcal{S}_{iA}\mathcal{S}_{iB}^\dagger$$

$$\begin{aligned} m_{LL}^2 &= m_1^2 c_\theta^2 + m_2^2 s_\theta^2 \\ m_{RR}^2 &= m_1^2 s_\theta^2 + m_2^2 c_\theta^2 \\ m_{LR}^2 &= |m_2^2 - m_1^2||c_\theta s_\theta| \end{aligned}$$

$$\tilde{\mu}_1 = \tilde{\mu}_L c_\theta - \tilde{\mu}_R s_\theta, \quad \tilde{\mu}_2 = \tilde{\mu}_L s_\theta + \tilde{\mu}_R c_\theta$$

Model parameters:

M_B, m_1, m_2, θ

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Contribution to g-2

$$\Delta a_\mu = -\frac{1}{32\pi^2}\lambda_L\lambda_R \sin(2\theta)\ \frac{m_\mu}{M_B}\left[L(x_1) - L(x_2)\right]$$

$$L(x) \equiv \frac{x}{(1-x)^2}\left[1 + x + \frac{2x\ln x}{(1-x)}\right], \quad x_i \equiv \frac{M_B^2}{m_i^2}$$

$$r \equiv \frac{m_1 - M_B}{M_B}, \quad y \equiv \frac{m_2^2 - m_1^2}{4m_W^2}|\sin(2\theta)|$$

(M_B, r, y, θ)

$$\begin{aligned} m_{LL}^2 &= m_1^2 c_\theta^2 + m_2^2 s_\theta^2 \\ m_{RR}^2 &= m_1^2 s_\theta^2 + m_2^2 c_\theta^2 \\ m_{LR}^2 &= |m_2^2 - m_1^2||c_\theta s_\theta| \end{aligned}$$

$$m_{\tilde\nu}^2 = m_1^2 + \left(m_2^2 - m_1^2\right) s_\theta^2 - m_W^2$$

$$\tilde\mu_1 = \tilde\mu_L c_\theta - \tilde\mu_R s_\theta, \quad \tilde\mu_2 = \tilde\mu_L s_\theta + \tilde\mu_R c_\theta$$

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Left handed branch (LHB)
[$M_B < m_1 \leq m_\nu << m_2$]
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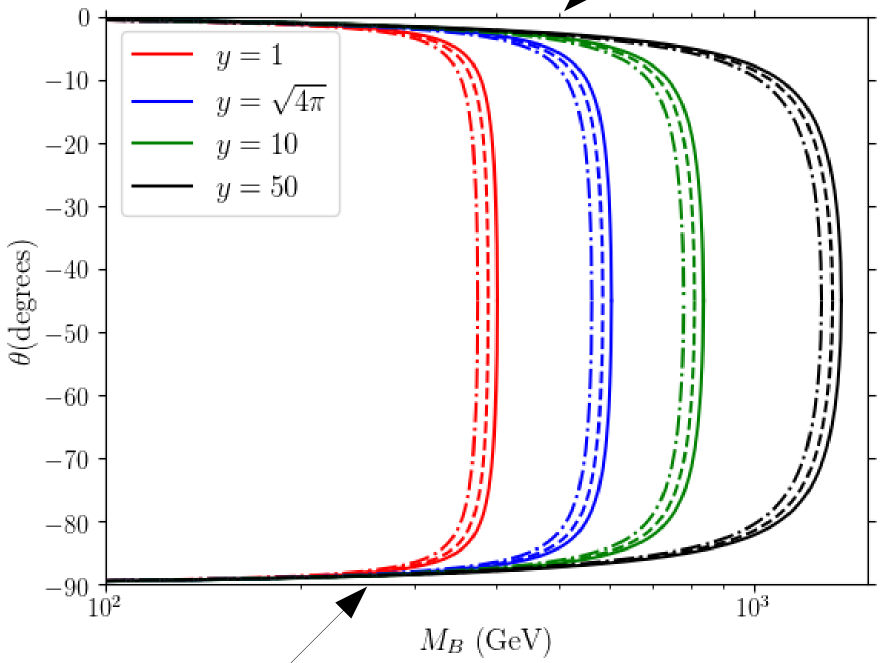

Right handed branch (RHB)
[$M_B < m_1 << m_\nu \leq m_2$]

DM implications

Particle	$SU(2)_L$	$U(1)_Y$	Z_2
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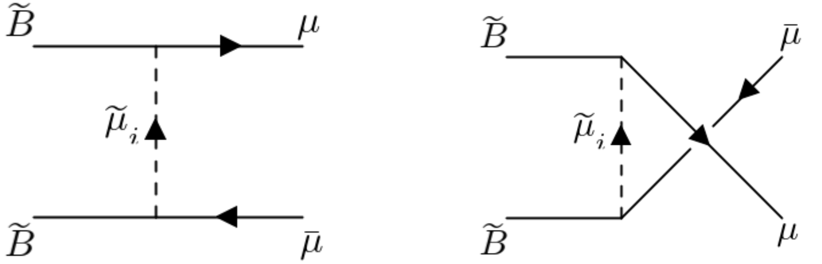


$$\langle \sigma v \rangle_0 = \frac{M_B^2}{32\pi} \left[\lambda_L \lambda_R \sin(2\theta)\right]^2 \left(\frac{1}{m_1^2 + M_B^2} - \frac{1}{m_2^2 + M_B^2} \right)^2$$

$$\begin{aligned} \langle \sigma v \rangle_0 &= \frac{32\pi^3}{m_\mu^2} (\Delta a_\mu)^2 \mathcal{F} \\ &= (2.25 \times 10^{-4}\,\mathrm{pb}) \left(\frac{\Delta a_\mu}{25 \times 10^{-10}} \right)^2 \mathcal{F}, \end{aligned}$$

$$\Omega h^2 \sim 0.1 \left(\frac{1\,\mathrm{pb}}{\langle \sigma v \rangle (T_f)} \right)$$

$$\mathcal{F} \equiv \frac{1}{\left[L(M_B^2/m_1^2) - L(M_B^2/m_2^2)\right]^2} \left(\frac{1}{1 + m_1^2/M_B^2} - \frac{1}{1 + m_2^2/M_B^2} \right)^2$$

Fukushima, K., Kelso, C., Kumar, J., Sandick, P., & Yamamoto, T. (2014).
MSSM dark matter and a light slepton sector: The incredible bulk. Physical Review D, 90(9), 095007.

Coannihilations

Initial states	Final states
$\tilde{B}\tilde{B}$	$\mu^-\mu^+,\, \nu_\mu\bar{\nu}_\mu$
$\tilde{\mu}_i\tilde{\mu}_j^*$	$f\bar{f},\, \gamma\gamma,\, W^+W^-,\, ZZ,\, hh,\, Z\gamma,\, h\gamma,\, hZ$
$\tilde{\mu}_i\tilde{\mu}_j$	$\mu^-\mu^-$
$\tilde{\nu}_\mu\tilde{\nu}_\mu^*$	$f\bar{f},\, \nu_\mu\bar{\nu}_\mu,\, \nu_\mu\nu_\mu,\, W^+W^-,\, ZZ,\, hh,\, hZ$
$\tilde{B}\tilde{\mu}_i$	$\mu^-\gamma,\, \mu^-Z,\, \mu^-h,\, \nu_\mu W^-$
$\tilde{B}\tilde{\nu}_\mu$	$\nu_\mu Z,\, \nu_\mu h,\, \mu^-W^+$
$\tilde{\mu}_i^*\tilde{\nu}_\mu$	$\mu^+\nu_\mu,\, W^+Z,\, W^+\gamma,\, W^+h,\, f_u\bar{f}_d$
$\tilde{\mu}_i\tilde{\nu}_\mu$	$\mu^-\nu_\mu$

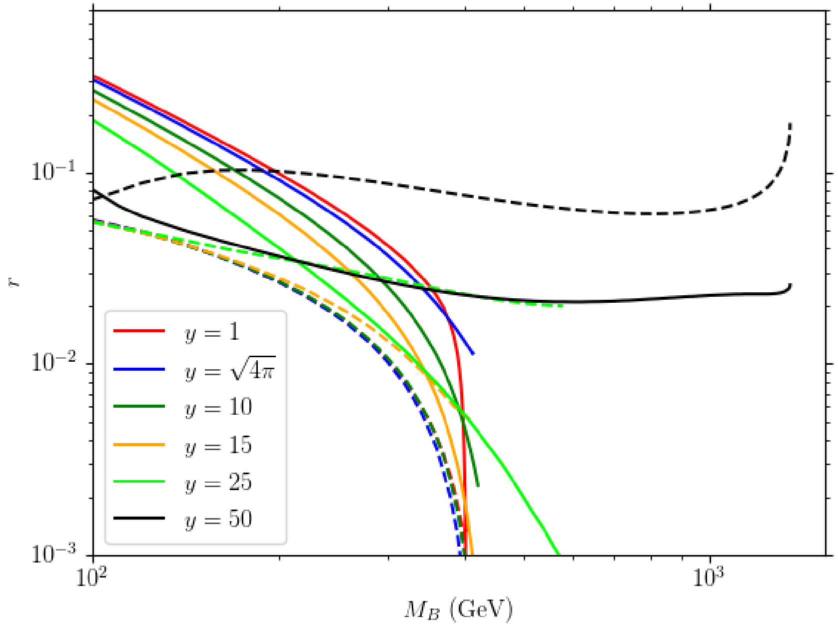
$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle_{eff}\left(n^2 - n_{eq}^2\right)$$

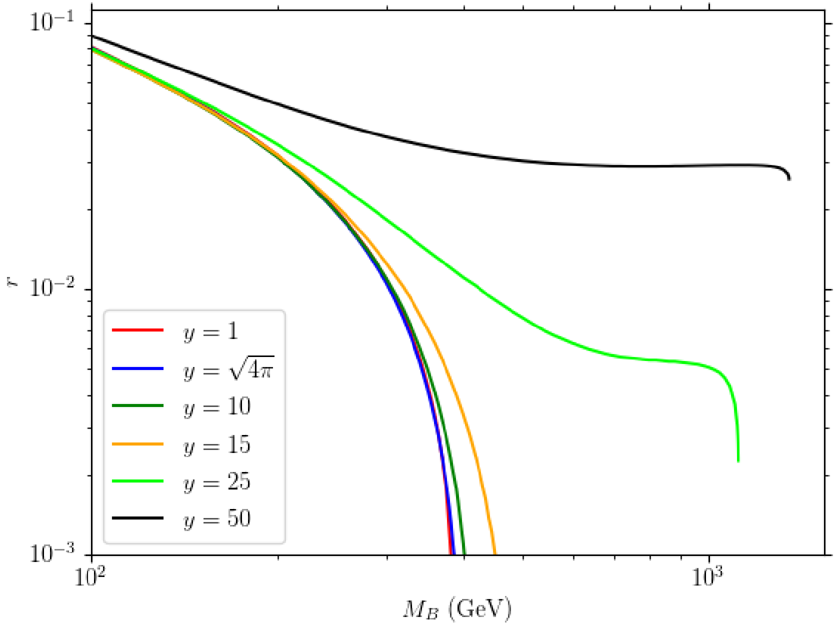
$$\langle\sigma v\rangle_{eff} = \sum_{ij}\langle\sigma v\rangle_{ij} r_i r_j,$$

$$r_i \equiv \frac{\frac{g_i}{g_{\rm LSP}}\left(1+\Delta_i\right)^{3/2}\exp\left(-x\Delta_i\right)}{1+\sum_{k\neq {\rm LSP}}\frac{g_k}{g_{\rm LSP}}\left(1+\Delta_k\right)\exp\left(-x\Delta_k\right)}$$

$$\Delta_i \equiv \frac{m_i - m_{LSP}}{m_{LSP}}, \quad x \equiv \frac{m_{LSP}}{T}$$

Coannihilations





LHB
(dashed curve: sneutrino-bino rel. mass split.)

RHB

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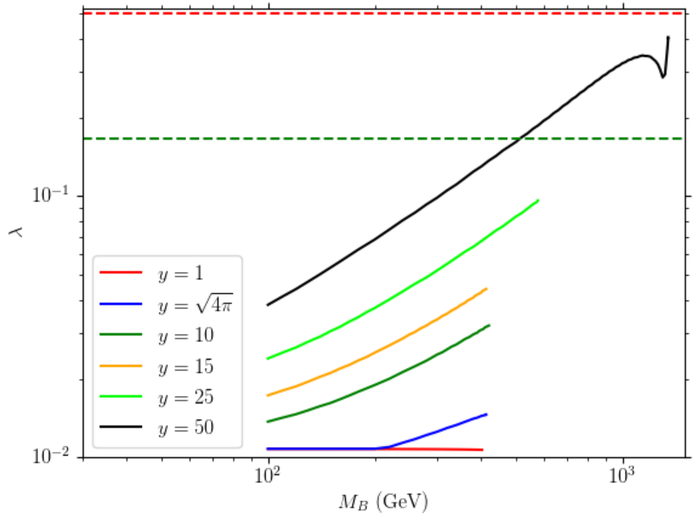
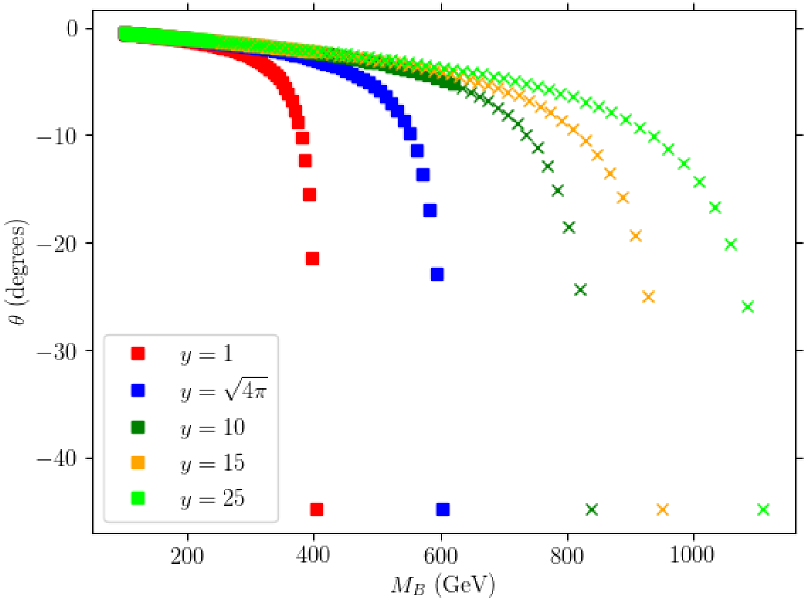
Theoretical constraints

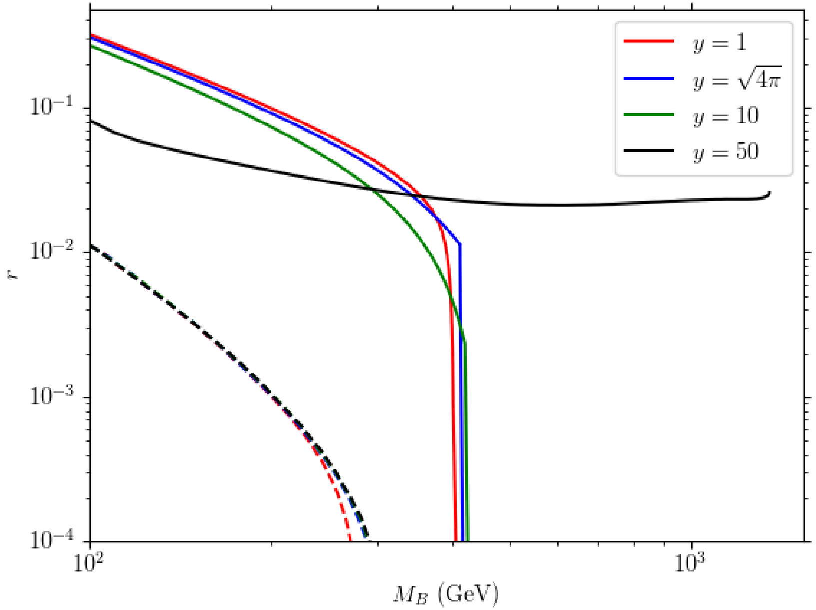
- Perturbative unitarity



- Vacuum stability



Direct detection

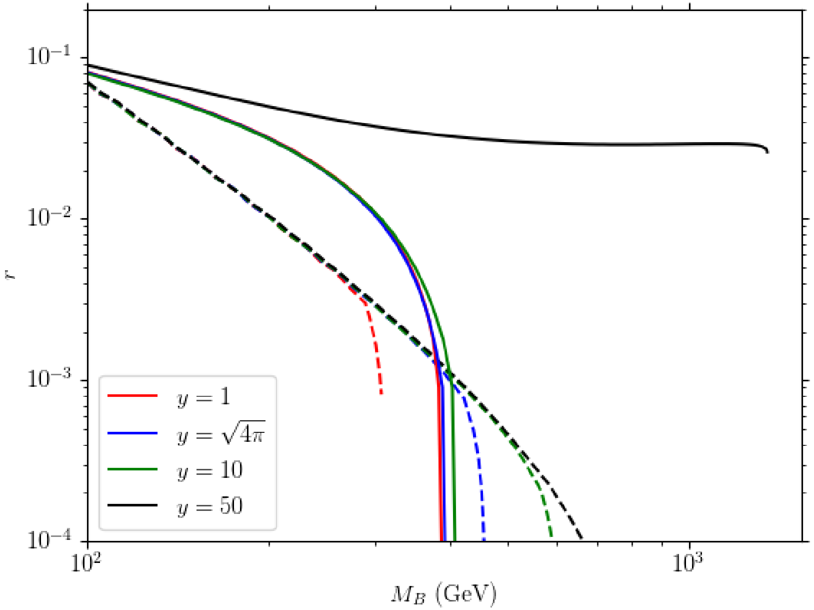


$$\mathcal{L}_{BN} = \sum_{N=p,n}\sum_{q=u,d}\left[c_q^{(0)}\bar{B}B\; m_N f_{q,N}^{(0)}\bar{N}N + c_q^{(1)}\bar{B}\gamma_\mu\gamma^5 B\; f_{q,N}^{(1)}\bar{N}\gamma^\mu\gamma^5 N\right] + e c_A(q^2)\bar{B}\gamma_\mu\gamma^5 B\; \bar{p}\gamma^\mu p$$

$$\mathcal{A} \approx \frac{e}{48\pi^2}\sum_{i=1,2}\alpha_\mu^{(i)}\beta_\mu^{(i)}\int_0^1 dx\,\frac{3x-2}{x+(1-x)t_i - x(1-x)\eta_i}$$

$$t_i \equiv m_\mu^2/m_i^2$$

$$\eta_i \equiv M_B^2/m_i^2$$



Summary

- Pheno constraints
  - g-2+relic density, can reach as high as TeV
  - Direct detection
- Theoretical constraints
  - Perturbative unitarity
  - Vacuum stability

Grazie per la vostra attenzione!

Extra slides

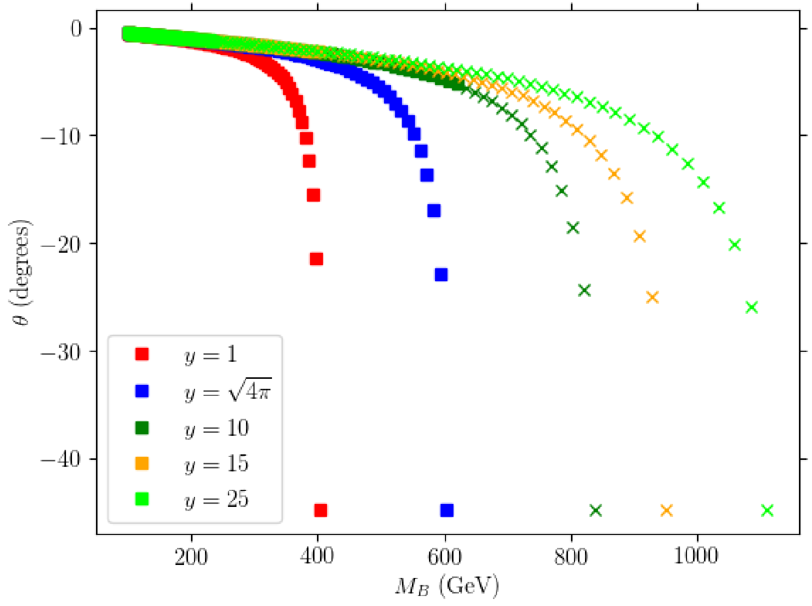
Vacuum stability

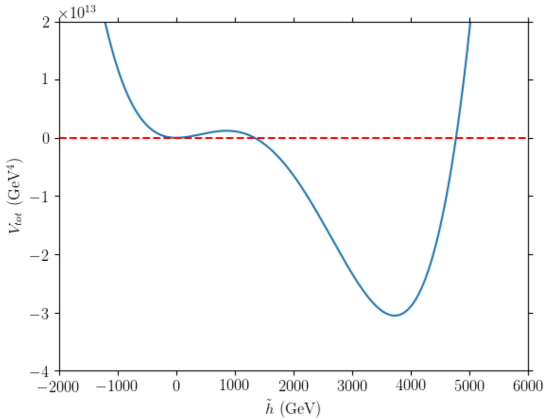
$$h = v + \tilde{h} \qquad \tilde{X} \equiv \frac{X}{\tilde{h}}, \quad \tilde{Y} \equiv \frac{Y}{\tilde{h}}, \quad \tilde{Z} \equiv \frac{Z}{\tilde{h}}.$$

$$V_{tot}(\tilde{X},\tilde{Y},\tilde{Z},\tilde{h}) = m^2(\tilde{X},\tilde{Y},\tilde{Z})\tilde{h}^2 - A(\tilde{X},\tilde{Y},\tilde{Z})\tilde{h}^3 + \lambda(\tilde{X},\tilde{Y},\tilde{Z})\tilde{h}^4$$

$$A(\tilde{X},\tilde{Y},\tilde{Z}) \equiv \frac{(g^2+g_Y^2)\,v}{8}\tilde{X}^2 + \frac{(-g^2+g_Y^2)\,v}{8}\tilde{Y}^2 - \frac{k_s}{\sqrt{2}}\tilde{Y}\tilde{Z} - \frac{g_Y^2 v Y_R}{4}\tilde{Z}^2 - \frac{(g^2+g_Y^2)\,v}{8},$$

$$k_s = \frac{\sqrt{2}m_{LR}^2}{v}$$





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Vacuum stability

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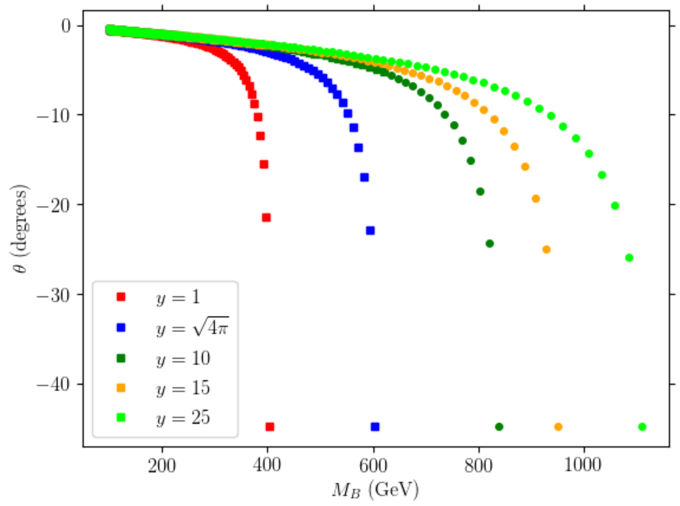
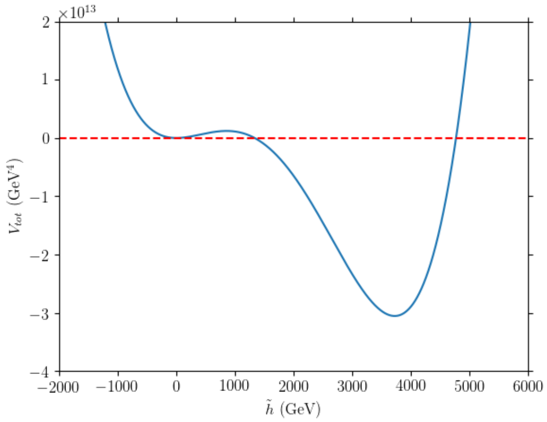
$$A(\tilde{X},\tilde{Y},\tilde{Z}) \equiv \frac{(g^2+g_Y^2)\,v}{8}\tilde{X}^2 + \frac{(-g^2+g_Y^2)\,v}{8}\tilde{Y}^2 - \frac{k_s}{\sqrt{2}}\tilde{Y}\tilde{Z} - \frac{g_Y^2 v Y_R}{4}\tilde{Z}^2 - \frac{(g^2+g_Y^2)\,v}{8},$$

$$k_s = \frac{\sqrt{2}m_{LR}^2}{v}$$





Vacuum stability

$$V_H = \frac{\mu^2}{2}h^2, \quad V_{mix} = \frac{k_s}{\sqrt{2}}hYZ$$

$$V_D^{(1)} = \frac{g_Y^2}{32}\left[h^2 - \left(X^2 + Y^2\right) + 2Y_R Z^2\right]^2$$

$$V_2 = \frac{m_{LL}^2}{2}\left(X^2 + Y^2\right) + \frac{m_{RR}^2}{2}Z^2$$

$$V_D^{(2)} = \frac{g^2}{32}\left[h^4 - 2h^2\left(X^2 - Y^2\right) + \left(X^2 + Y^2\right)^2\right]$$

$$k_s = \frac{\sqrt{2}m_{LR}^2}{v}$$

$$h = v + \tilde{h} \qquad \tilde{X} \equiv \frac{X}{\tilde{h}}, \quad \tilde{Y} \equiv \frac{Y}{\tilde{h}}, \quad \tilde{Z} \equiv \frac{Z}{\tilde{h}}.$$

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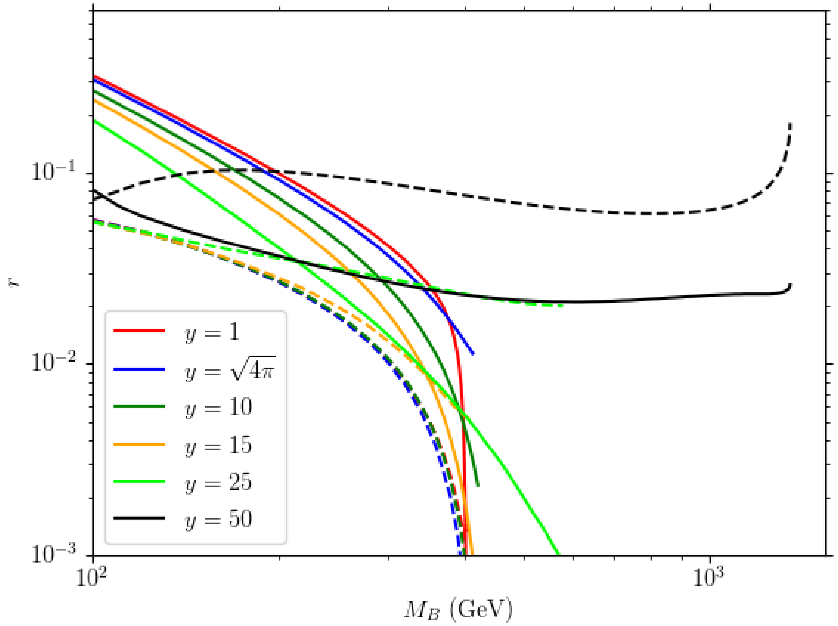
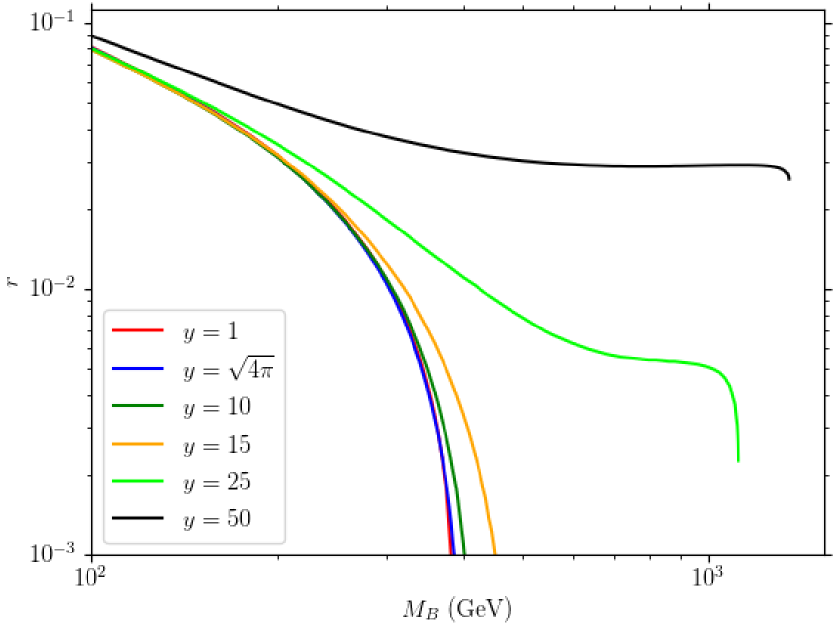
Coannihilations



LHB
(dashed curve: sneutrino-bino rel. mass split.)



RHB

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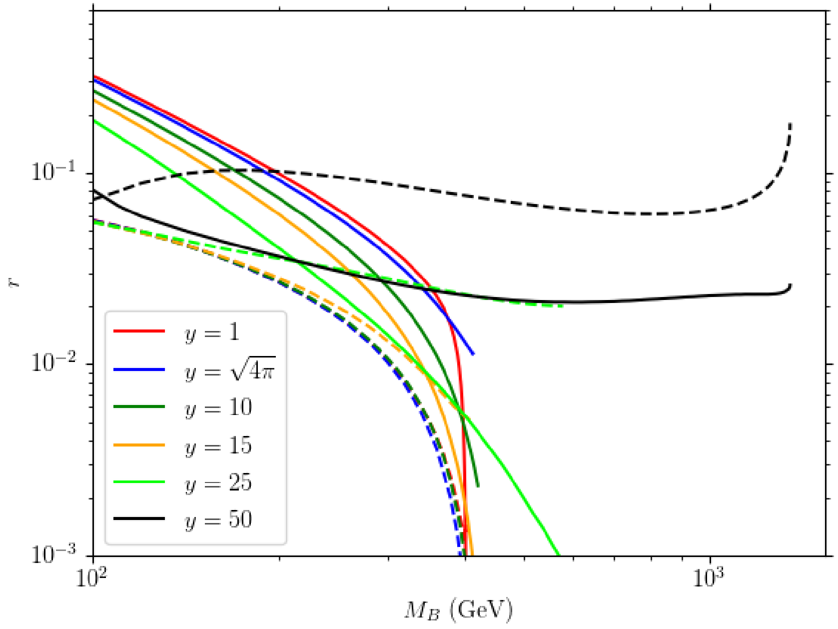
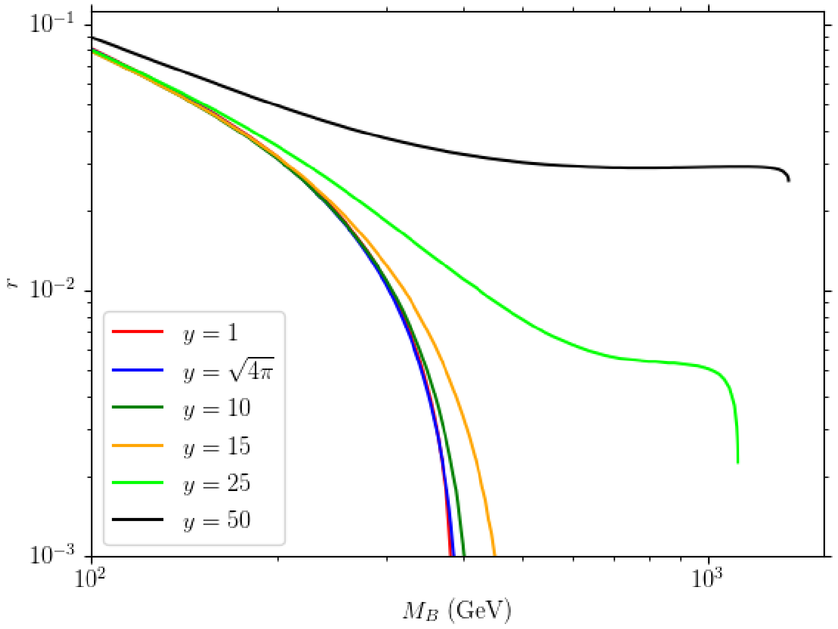
Coannihilations





LHB
(dashed curve: sneutrino-bino rel. mass split.)

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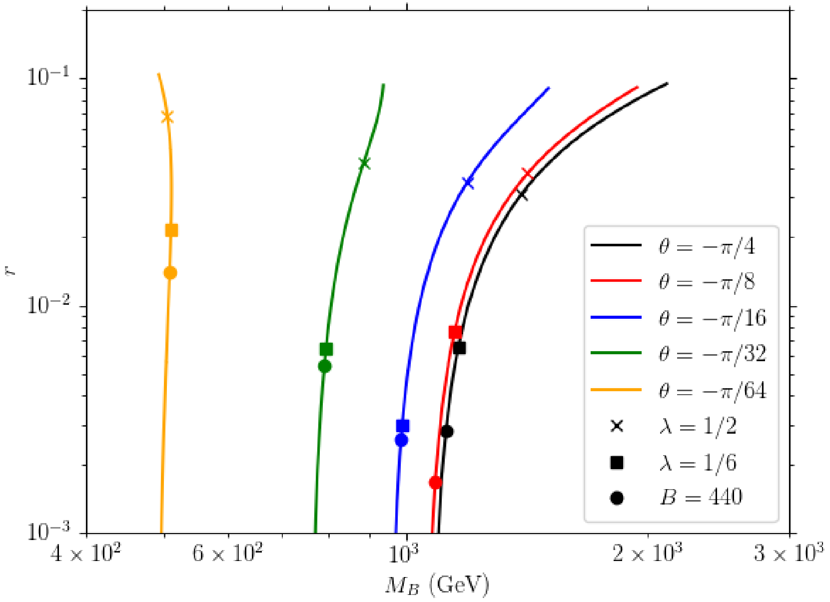
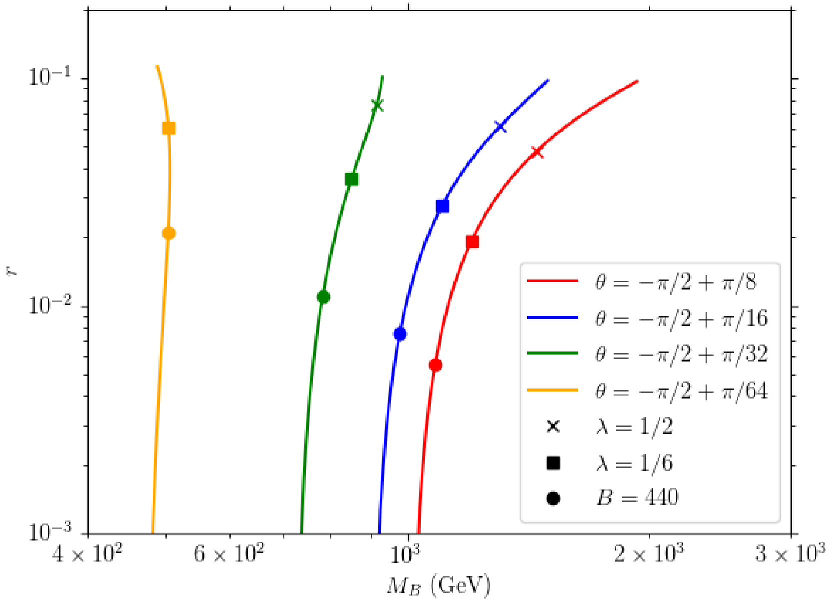
Coannihilations





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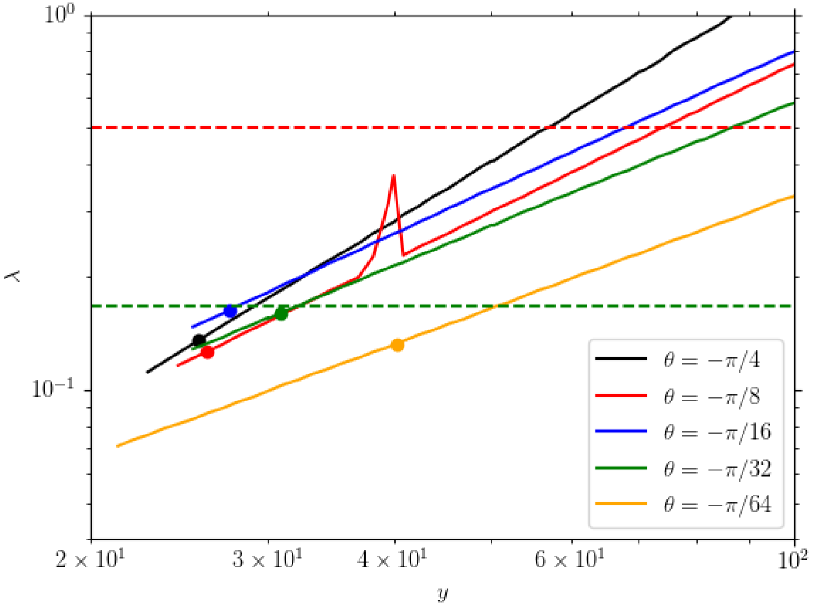
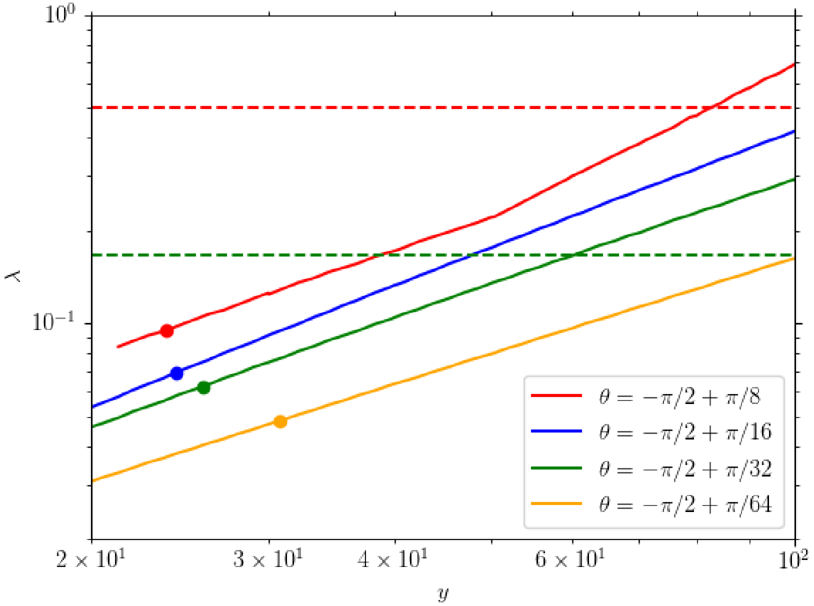
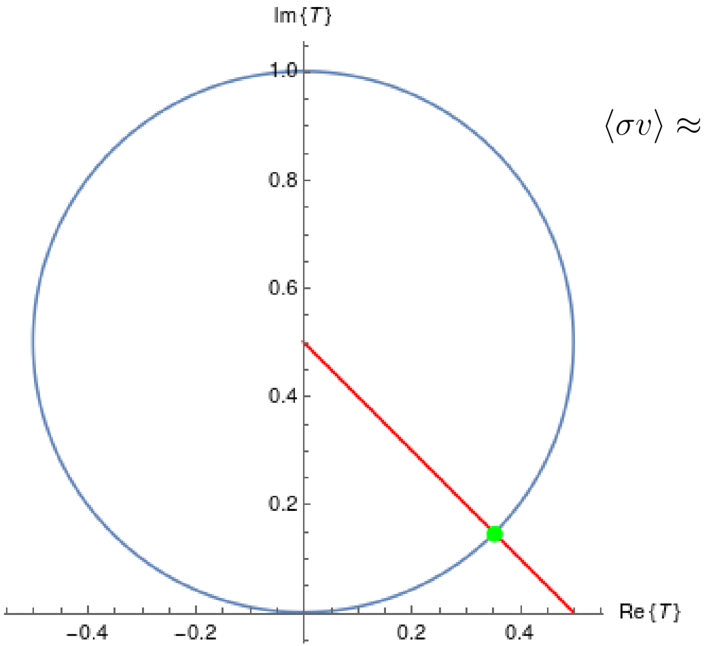




Perturbative unitarity



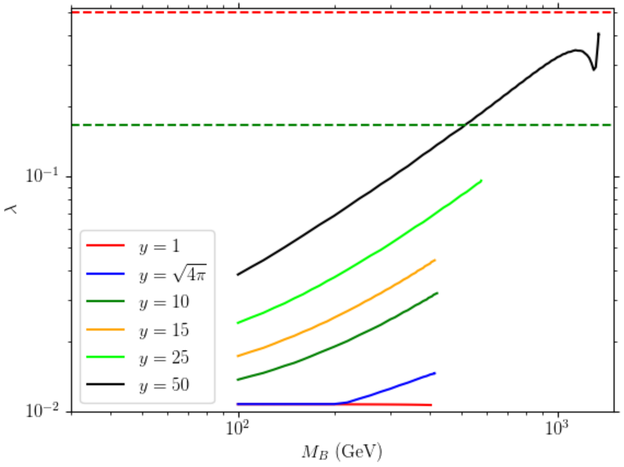
$$\langle \sigma v \rangle \approx \left(2.5 \times 10^{-9}\,\mathrm{GeV}^{-2}\right) \left(\frac{\alpha_\chi}{0.5 \times 10^{-2}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m}\right)^2$$

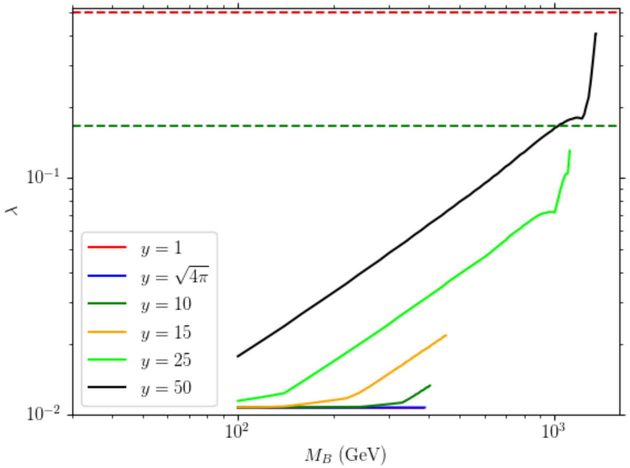
WIMP unitarity limit: < 20 TeV

$$\left(\mathrm{Re}\,\{\hat{T}_i(s)\}\right)^2 + \left(\mathrm{Im}\,\{\hat{T}_i(s)\} - \frac{1}{2}\right)^2 = \frac{1}{4}$$

$$\mathrm{Im}\,\{\hat{T}_i(s)\} = |\hat{T}_i(s)|^2$$

$\mathrm{Re}\{T_i\} \leq 1/6,\ 1/2$





Vacuum stability

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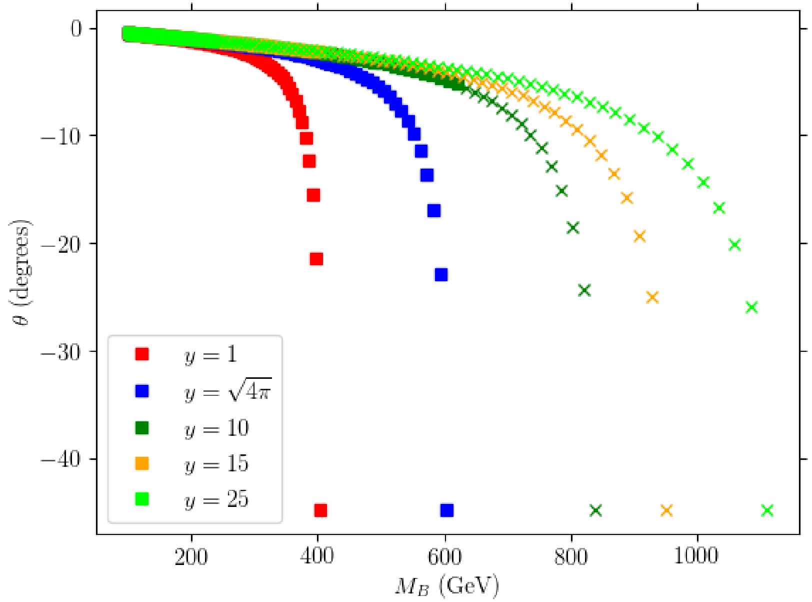

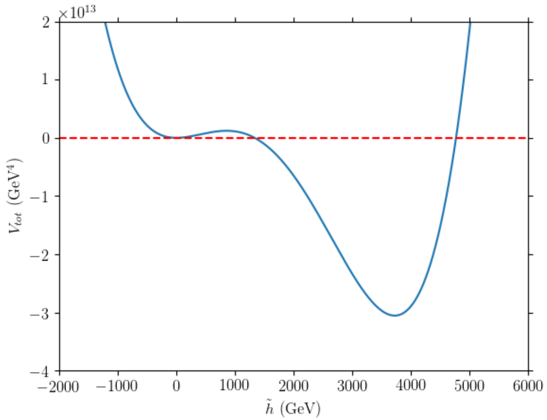

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