Gravitino Dark Matter in Split-SUSY

(pheno approach)

Based on [G. Cottin, M. Díaz, M. J. Guzmán, BP: 1406.2368]

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Outlook

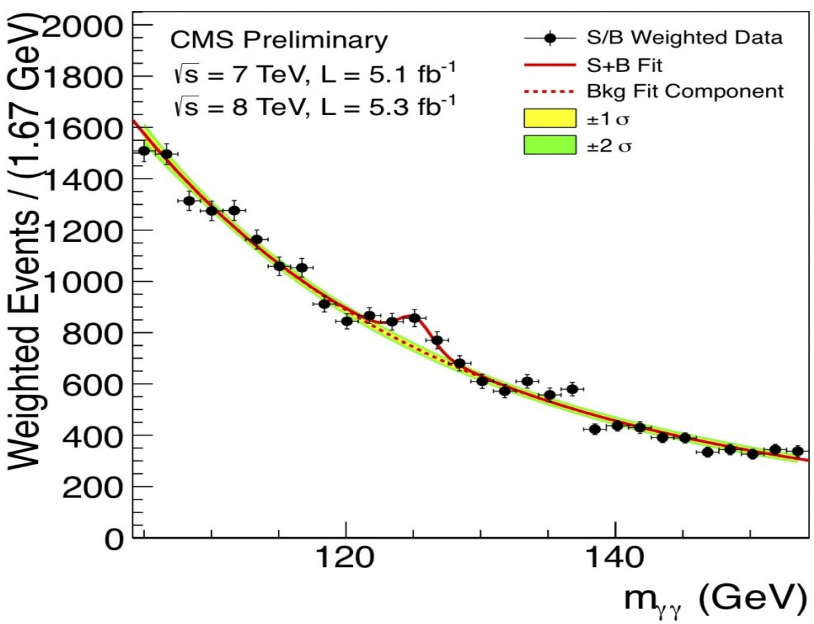
- General motivation and specific approach
- The model: Split-SUSY with BRpV and Gravitino LSP
- Known results in Split-SUSY (Higgs mass and Neutrinos)
- Gravitino Dark Matter (Relic Density and Life-Time)
- Summary

General Motivation

Take into account current experimental information from colliders (LHC and CMS), Neutrinos (Oscillation experiments), Cosmology (Dark Matter), etc., in the context of Supersymmetry phenomenology

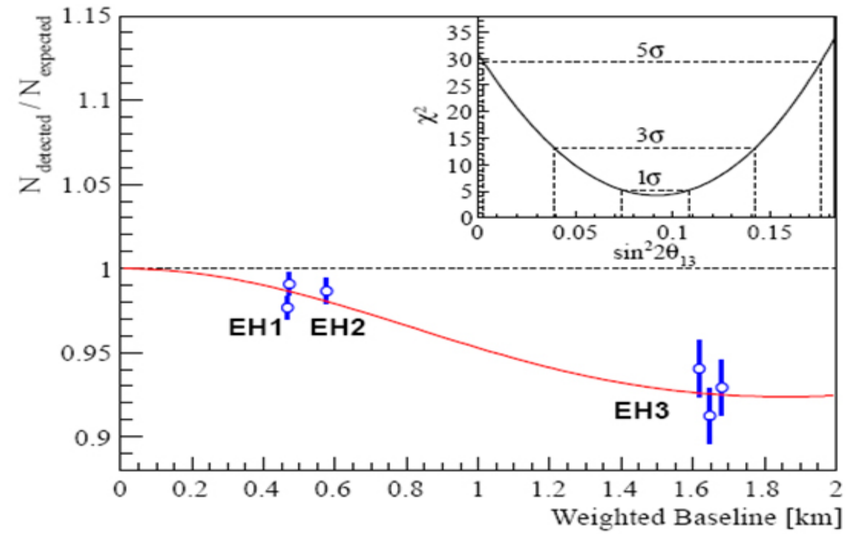
… in particular

SUSY model:
Split Supersymmetry with Bilinear R-Parity Violation and Gravitino LSP



Higgs mass: 1207.7214 & 1303.4571

Rough estimation of lower bounds on SUSY spectrum: ATLAS and CMS collaborarion

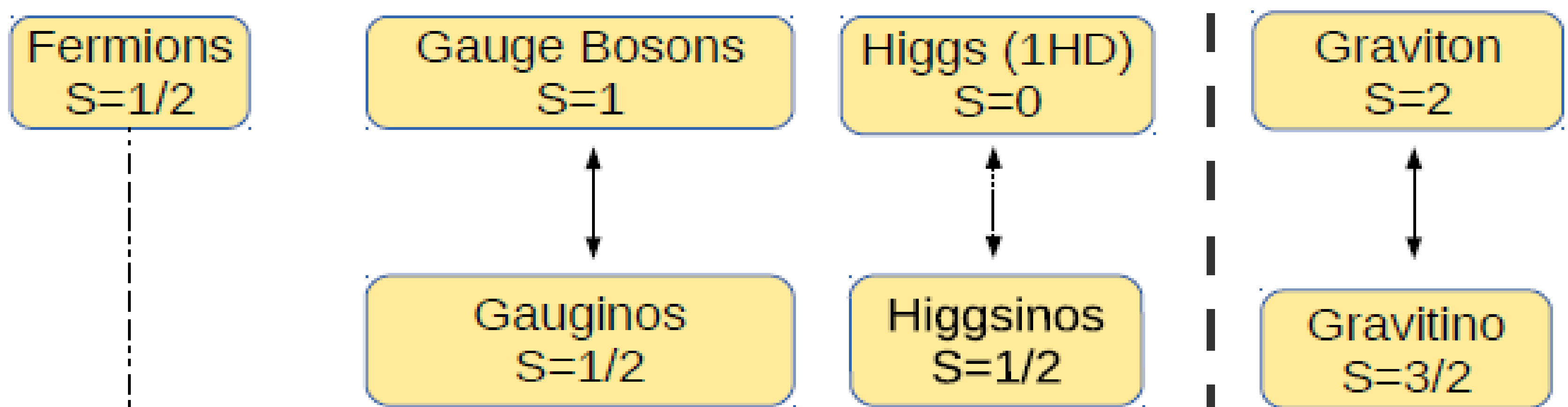


3-Flavor global fits: 1405.7540

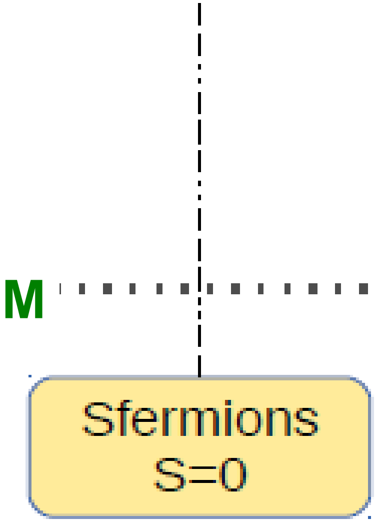
Density: 1303.5076
Life-time lower bounds: 1106.0308

Split-SUSY with BRpV

Motivations and original idea in hep-th/0405159 and hep-ph/0406088. In practice, we make use of the freedom that we have to choose the soft parameters. Thus, we play an aggressive game and decouple the scalar sector from the EW scale.



- Unification of gauge couplings is hold it
- Higgs mass has to be fine-tuned
- Neutrino physics is half solved with BRpV



- Above the scale **M** we have the MSSM again
- Matching conditions at **M**

Free parameters of the model

- Gaugino masses and mu parameter: Mino = $M1$, $M2$, $M3$, μ
- Split-SUSY scale M and $\tan\beta$ (gauge and quartic effective couplings)
- Reheating Temperature T_R (or mG)
- Effective BRpV parameters $\lambda 1$, $\lambda 2$, $\lambda 3$
- Effective mass parameter μ_g

** We assume negligible trilinear couplings, A = 0*

Higgs and Neutrinos in Split-SUSY

Higgs mass

- Several technical details in hep-th/0405159, 0705.1496, 1211.1000, 1312.5743
- The low energy Higgs potential of Split-SUSY is SM like

$$\mathcal{L} \supset m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2$$

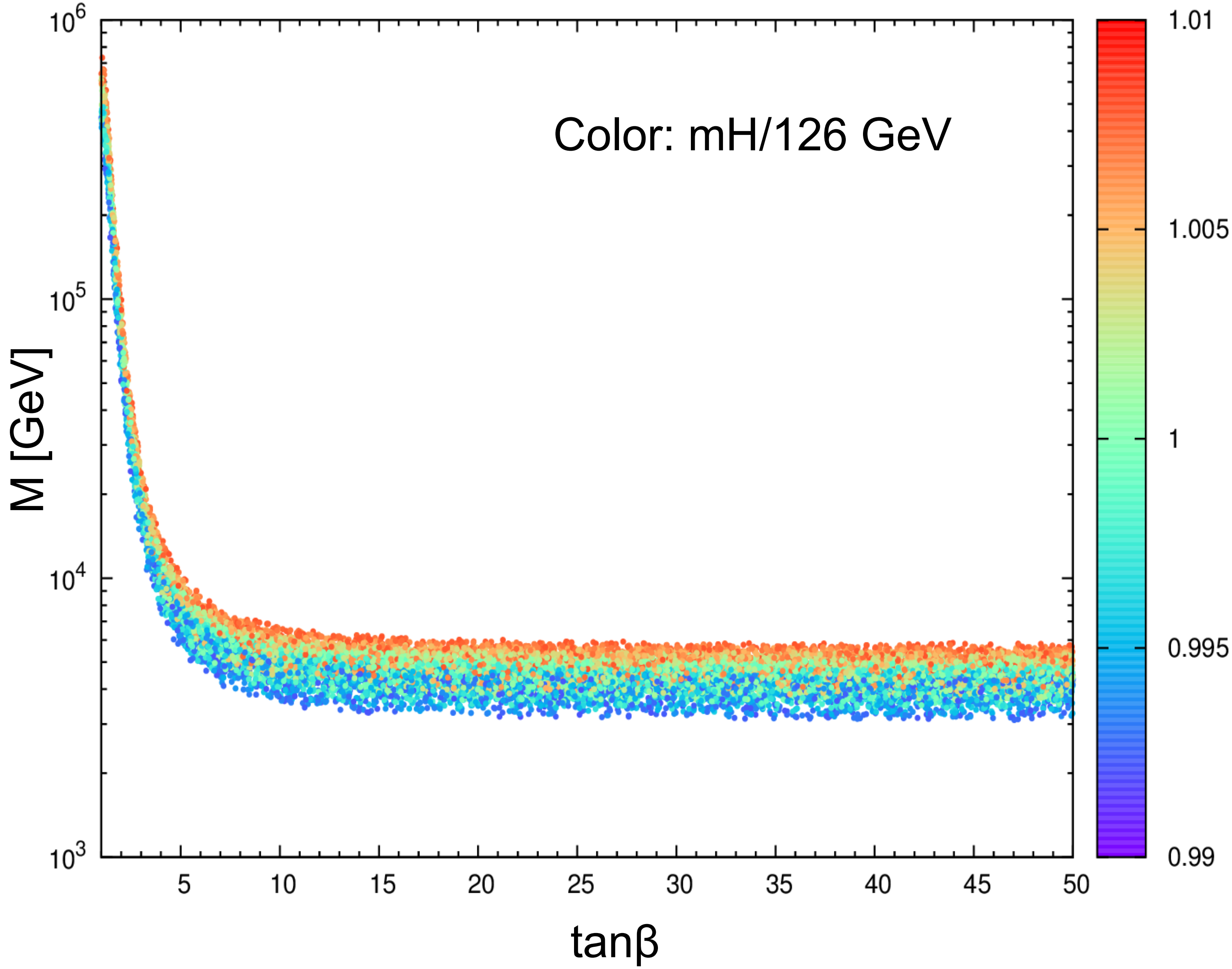
- In order to compute the Higgs mass we run down the quartic coupling from M to the EW scale by using LL RGEs. The BC at M is given by

$$\lambda(\mathrm{M}) = \frac{1}{4}\left[g^2(\mathrm{M}) + g'^2(\mathrm{M})\right]\cos^2 2\beta$$

- After considering 1-loop quantum corrections it is obtained that

$$M_H = \sqrt{\frac{\lambda(Q)}{\sqrt{2}\,G_F}}\,\left[1 + \delta^{\mathrm{SM}}(Q) + \delta^{\chi}(Q)\right]$$

Higgs mass



For tanβ below 1 the behavior is symmetric

Neutralino-Neutrino sector

$$\mathcal{L} \ni \epsilon_i \tilde{\mathrm{H}}_u^\dagger i\sigma_2 L_i$$ - BRpV

$$- \frac{1}{\sqrt{2}} a_i \mathrm{H}^\mathrm{T} i\sigma_2 (-\tilde{g}_d \sigma \tilde{W} + \tilde{g}'_d \tilde{B}) L_i$$ - Sneutrino part of H

$$+ \frac{1}{\sqrt{2}} \mathrm{H}^\dagger (\tilde{g}_u \sigma \tilde{W} + \tilde{g}'_u \tilde{B}) \tilde{\mathrm{H}}_u$$ - Higgs-up part of H

$$+ \frac{1}{\sqrt{2}} \mathrm{H}^\mathrm{T} i\sigma_2 (-\tilde{g}_d \sigma \tilde{W} + \tilde{g}'_d \tilde{B}) \tilde{\mathrm{H}}_d$$ - Higgs-down part of H

$$+ \frac{M_1}{2} \tilde{B}\tilde{B} + \frac{M_2}{2} \tilde{W}\tilde{W} + \mu \tilde{\mathrm{H}}_u^\dagger i\sigma_2 \tilde{\mathrm{H}}_d$$ - Soft mass terms

Details in: hep-ph/0605285

… effective neutrino mass matrix

$$\mathbf{M}_\nu^{eff} = \frac{v^2}{4\det M_{\chi^0}^{SS}} \left(M_1 \tilde{g}_d^2 + M_2 \tilde{g}_d'^2\right) \begin{bmatrix} \lambda_1^2 & \lambda_1\lambda_2 & \lambda_1\lambda_3 \\ \lambda_2\lambda_1 & \lambda_2^2 & \lambda_2\lambda_3 \\ \lambda_3\lambda_1 & \lambda_3\lambda_2 & \lambda_3^2 \end{bmatrix}$$

with $\lambda_i \equiv a_i \mu + \epsilon_i$

- At tree-level only one mass different from zero is generated
- At 1-loop the texture of the matrix is the same
- In order to generate the second mass, we consider the contribution of a dimension-5 operator with a democratic texture: 0902.1720

$$M_g^{\nu ij} = A\lambda^i\lambda^j + \mu_g$$

- In this approach the atmospheric mass is given by

$$\boxed{\Delta m^2_{\rm atm} \simeq A^2|\lambda|^4}$$

Gravitino Dark Matter

Gravitino interactions derived from Supergravity

- In “minimal” supergravity we have

$$\begin{aligned}\mathcal{L} \ni & -\frac{i}{\sqrt{2}M_P}\left[(D_\mu^* \phi^{i*})\bar{\psi}_\nu \gamma^\mu \gamma^\nu P_L \chi\right. \\ & \left. -(D_\mu \phi^i)\bar{\chi}^i P_R \gamma^\nu \gamma^\mu \psi_\nu\right] \\ & -\frac{i}{8M_P}\bar{\psi}_\mu [\gamma^\nu, \gamma^\rho]\gamma^\mu \lambda^{(\alpha)a} F_{\nu\rho}^{(\alpha)a}\end{aligned}$$

- Using these interactions we are able to compute the gravitino relic density (hep-ph/0701104, 0708.2786)

- Without BRpV terms, the gravitino is stable. However, after including BRpV terms, as we showed before, the gravitino aquires a finite life-time

Gravitino relic density

- We consider that after the inflationary period, the density of gravitinos is negligible in comparison to their thermal equilibrium density

- Then, the relic density of gravitinos is mostly generated right after reheating from the scattering and decay of relativistic particles

$$Y_{3/2}(T') = \frac{n_{3/2}(T')}{s(T')} = -\int_{T_R}^{T'} dT \frac{C_{3/2}(T)}{s(T)H(T)T}$$

- From Higgs mass we obtain that M takes moderated values

- In general, the reheating temperature T_R is required to be quite high

- Therefore, it is reasonable to assume that T_R >> M. Then, the particle content and interactions that determine the gravitino relic density are dictated by the MSSM model → Standard formulas with Split-SUSY RGEs

Gravitino relic density

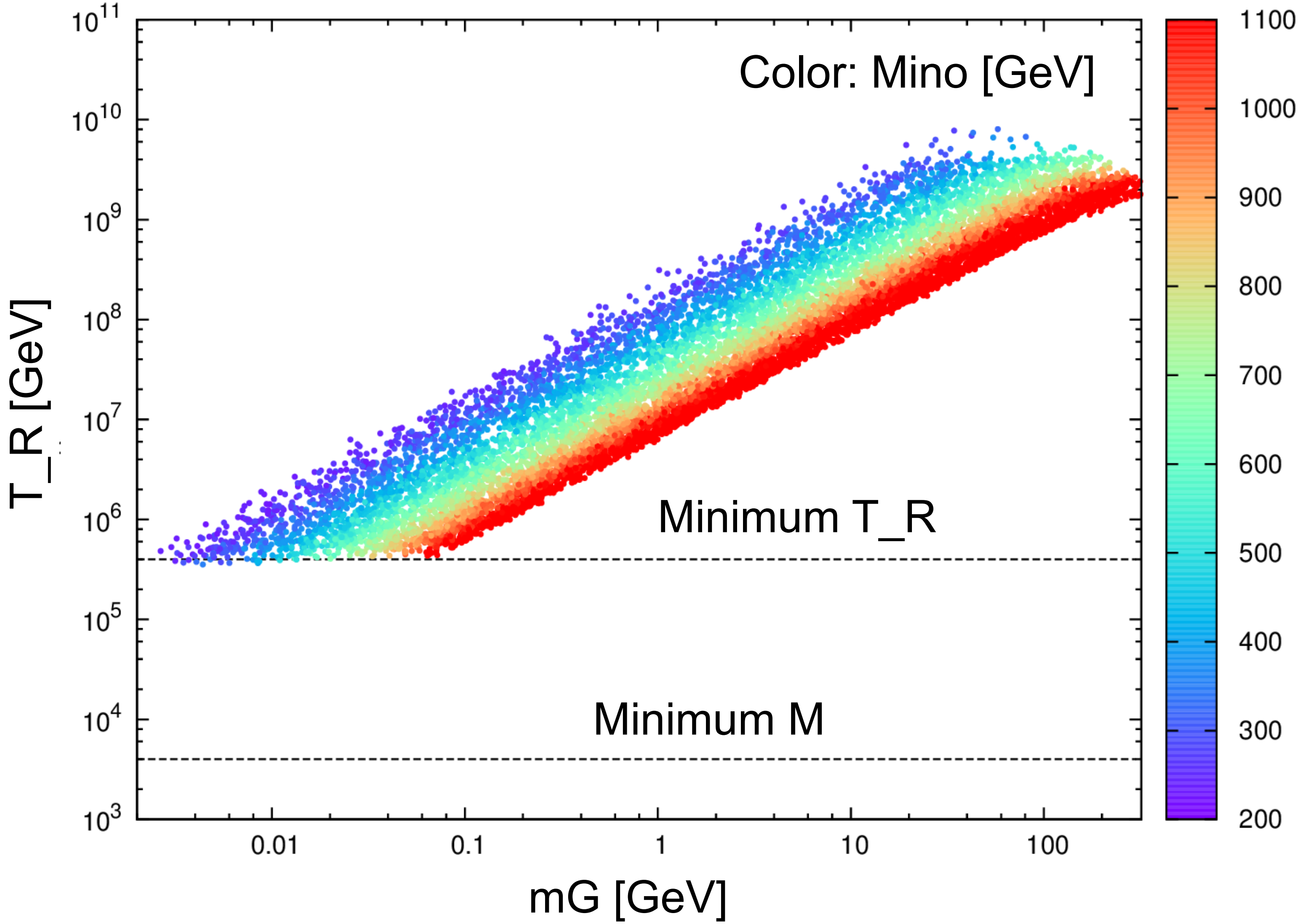
- As we are interested on values of T_R as low as 10^5 GeV (g_s(Q) ~1), we compute the relic density using the formulas derived in hep-ph/0701104

$$\Omega_{3/2}(T_0)h^2 = m_{3/2}Y_{3/2}(T_0)\frac{s(T_0)h^2}{\rho_c(T_0)}$$

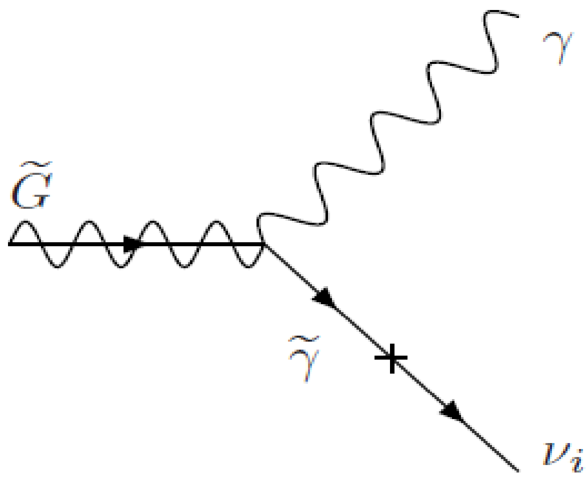
$$= 0.167\left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{T_\mathrm{R}}{10^{10}\,\mathrm{GeV}}\right)\left[\frac{1.30}{2\pi^5}9\lambda_t^2(T_R) + \sum_{N=1}^{3}\left(1+\frac{M_N^2(T_R)}{3m_{3/2}^2}\right)\left(\frac{n_N f_N(\alpha_N g_N(T_R))}{2(2\pi)^3} + \frac{1.29}{8\pi^5}g_N^2(T_R)(C_N' - C_N)\right)\right]$$

- See details in hep-ph/0701104,1406.2368

Gravitino relic density



Gravitino decay



$$\Gamma(\tilde{G} \to \gamma\nu) = \frac{m_{3/2}^3}{32\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2$$

$$U_{\tilde{\gamma}\nu_i} \simeq \frac{\mu}{2(\det M_{\chi^0})} (\tilde{g}_d M_1 s_W - \tilde{g}'_d M_2 c_W) \lambda_i v$$

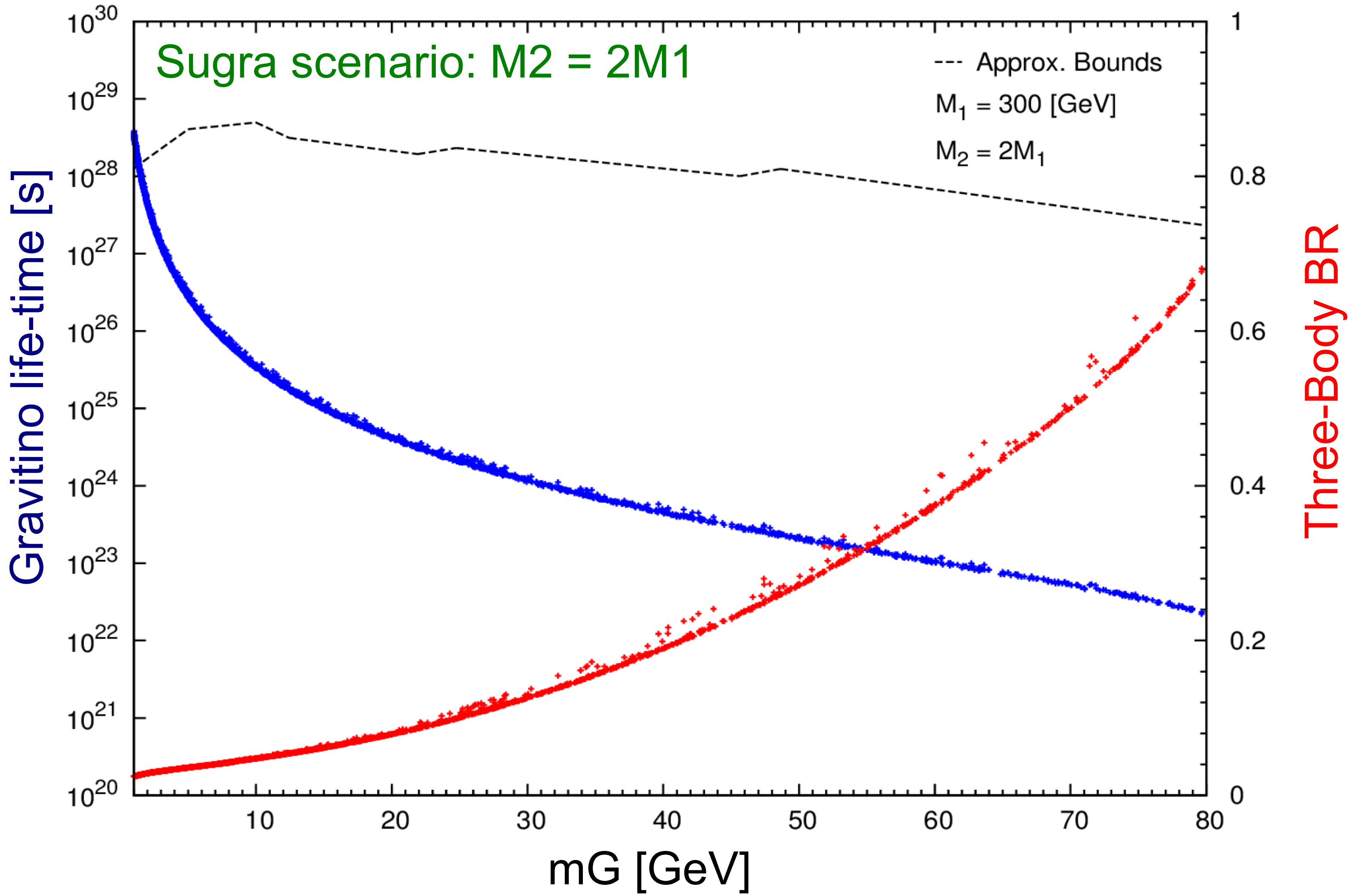
Plus several three body contributions !!

- Every contribution is proportional to $|\lambda|^2$

- Then, we can replace back the atmospheric mass in order to get

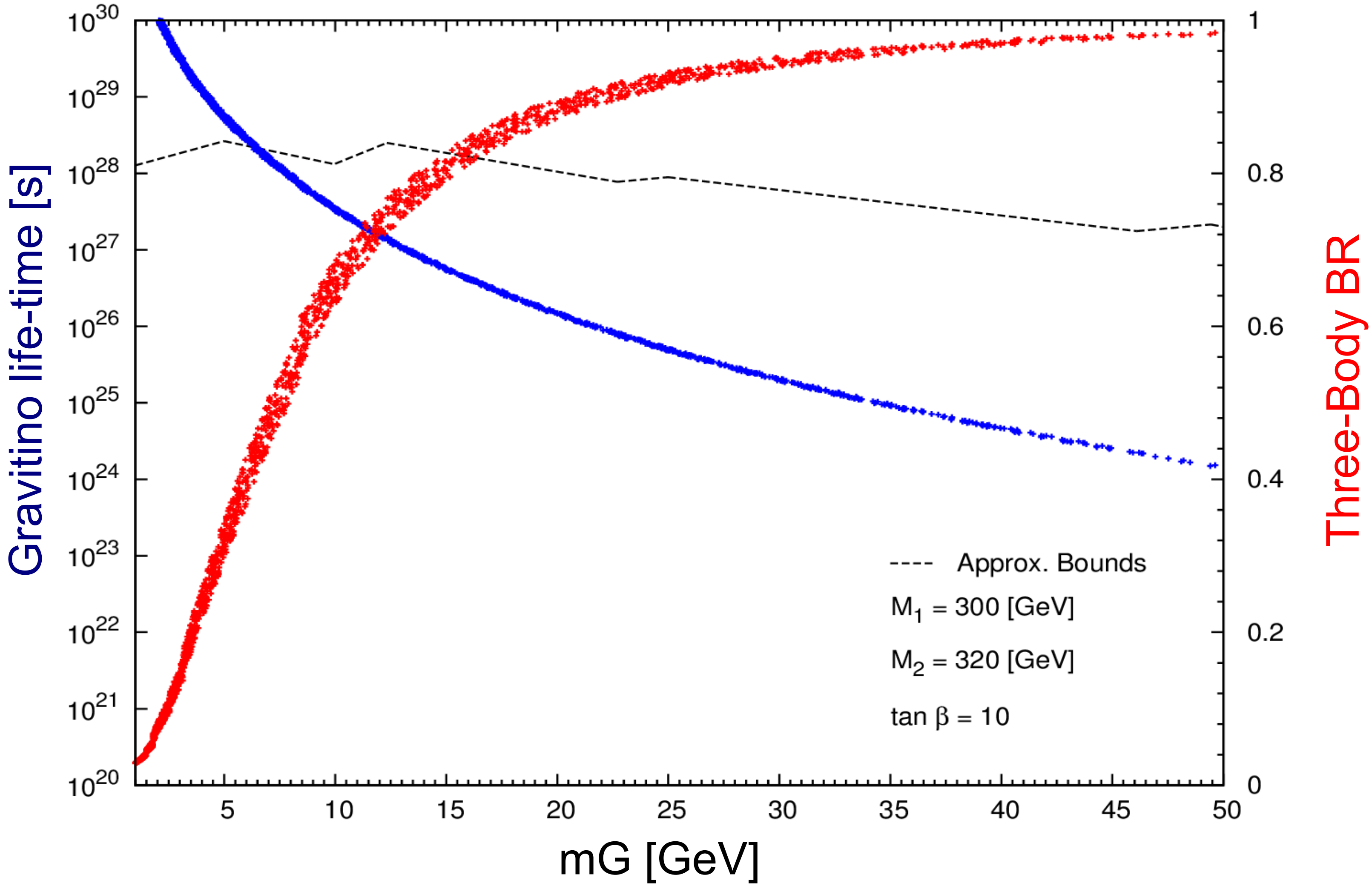
$$\Gamma^{\rm tot}(m_{\tilde{G}}) = \sum_i f_i(m_{\tilde{G}}, \tilde{g}, M_1, M_2) \sqrt{\Delta m^2_{\rm atm}}$$

life-time v/s mass



---------- Constraints from gamma ray searches (lines and continuous):
Adapted from 1406.3430, 1007.1728v2

life-time v/s mass



Compressed spectrum: M2 = M1. It is necessary to fix tanβ in order to recover a smooth blue and red lines

Summary

- We have shown that in Split Supersymmetry it is possible to solve the Higgs mass, 3-family neutrino observables and dark matter density and life-time

- The requirement of the Higgs mass suggests a relatively low Split-SUSY scale. This can be used in order to obtain the gravitino relic density from standard approaches, which consider the MSSM particle content as relativistic around the reheating temperature

- The tight constraints in the atmospheric neutrino sector allow us to write the gravitino life-time in terms of few parameters (M1, M2, $\tan\beta$, mG). Which is confirmed numerically

- From a rough analysis of DM indirect searches we obtain that gravitinos with mG > 1 GeV are highly disfavored

Backup Slides

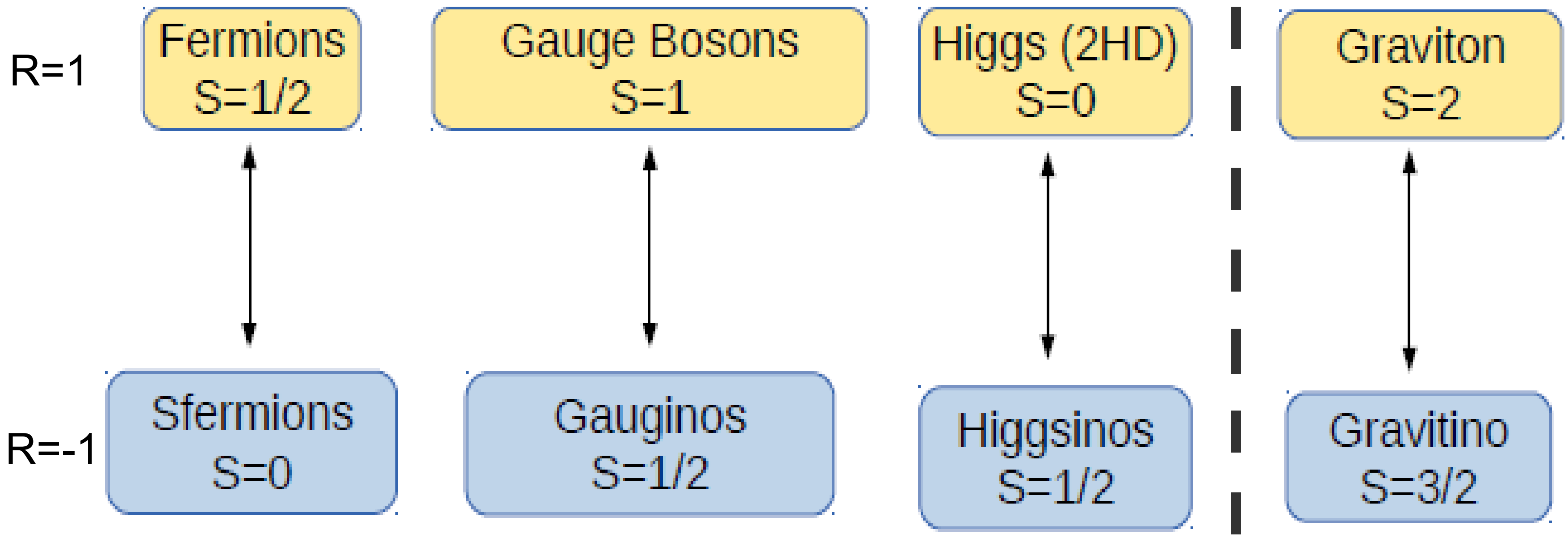
Prospects

- Continue the study of analyitical solutions for the maximum life-time of the gravitino

- Explore systematically the experimental constraints from collider physics and gamma ray searches, specially in the low gravitino mass region

Supersymmetry

- Extension of the SM that incorporate a symmetry between fermion and boson degrees of freedom, i.e. in Supersymmetry n_b = n_f. The simplest phenomenologically viable realization is the MSSM hep-ph/9709356



- Supersymmetry is broken, and the easiest way to parametrize this situation is by introducing soft terms in the SUSY Lagrangian. M_susy ~ 1 TeV in order to explain the hierarchy problem and unification of gauge couplings

Parameters of the numerical scan

Parameter	Description	Range
$M_{\rm ino}$	Common EW-scale for gaugino soft masses	$[200\,{\rm GeV}\,, 1100\,{\rm GeV}]$
M_1	Bino mass	$M_{\rm ino}$
M_2	Wino mass	$M_{\rm ino} + [10\,{\rm GeV}\,, 100\,{\rm GeV}]$
M_3	Gluino mass	$M_2 + [10\,{\rm GeV}\,, 200\,{\rm GeV}]$
μ	mu parameter	$M_{\rm ino} + [10\,{\rm GeV}\,, 100\,{\rm GeV}]$
$\tilde{m}$	Split-SUSY scale	$[10^4\,{\rm GeV}, 10^{10}\,{\rm GeV}]$
$\tan\beta$	Ratio of Higgs expectation values at $\tilde{m}$	$[1, 50]$
T_R	Reheating temperature	$\tilde{m} \times [10^2\,{\rm GeV}, 10^6\,{\rm GeV}]$
μ_g	Effective gravitational mass parameter	$[2 \times 10^{-3}{\rm eV}\,, 4 \times 10^{-3}{\rm eV}]$
λ_1	Effective BRpV parameter	$(\bar{A}/A) \times [10^{-4}\,{\rm GeV}, 10^{-3}\,{\rm GeV}]$
λ_2	-	$(\bar{A}/A) \times [10^{-3}\,{\rm GeV}, 10^{-2}\,{\rm GeV}]$
λ_3	-	$(\bar{A}/A) \times [10^{-3}\,{\rm GeV}, 10^{-2}\,{\rm GeV}]$

Neutrino probability for Daya Bay Experiment

$$P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$

-Neutralino-Neutrino mass matrix

$$\mathcal{M}_N^{SS} = \begin{bmatrix} \mathrm{M}_{\chi^0}^{SS} & (m^{SS})^T \\ m^{SS} & 0 \end{bmatrix}$$

- After diagonalization by blocks of this matrix we can obtain the effective neutrino mass matrix

- Furthermore, and very important for the last part of the work, we can compute the rotation matrix N which mixes the Neutralino and Neutrino sector. In particular we have that the relation between the photino and neutrinos

$$U_{\tilde{\gamma}\nu_i} = \mathcal{N}_{i1} c_W + \mathcal{N}_{i2} s_W$$

Neutralino-Neutrino mass matrix in Split-SUSY +BRpV

$$m^{SS} = \begin{bmatrix} -\frac{1}{2}\tilde{g}'_d a_1 v & \frac{1}{2}\tilde{g}_d a_1 v & 0 & \epsilon_1 \\ -\frac{1}{2}\tilde{g}'_d a_2 v & \frac{1}{2}\tilde{g}_d a_2 v & 0 & \epsilon_2 \\ -\frac{1}{2}\tilde{g}'_d a_3 v & \frac{1}{2}\tilde{g}_d a_3 v & 0 & \epsilon_3 \end{bmatrix}$$

$$\mathbf{M}^{SS}_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}\tilde{g}'_d v & \frac{1}{2}\tilde{g}'_u v \\ 0 & M_2 & \frac{1}{2}\tilde{g}_d v & -\frac{1}{2}\tilde{g}_u v \\ -\frac{1}{2}\tilde{g}'_d v & \frac{1}{2}\tilde{g}_d v & 0 & -\mu \\ \frac{1}{2}\tilde{g}'_u v & -\frac{1}{2}\tilde{g}_u v & -\mu & 0 \end{bmatrix}$$