DM with supersymmetric triplets

CA, V.Martín-Lozano and G.Nardini, arXiv:1403.6434

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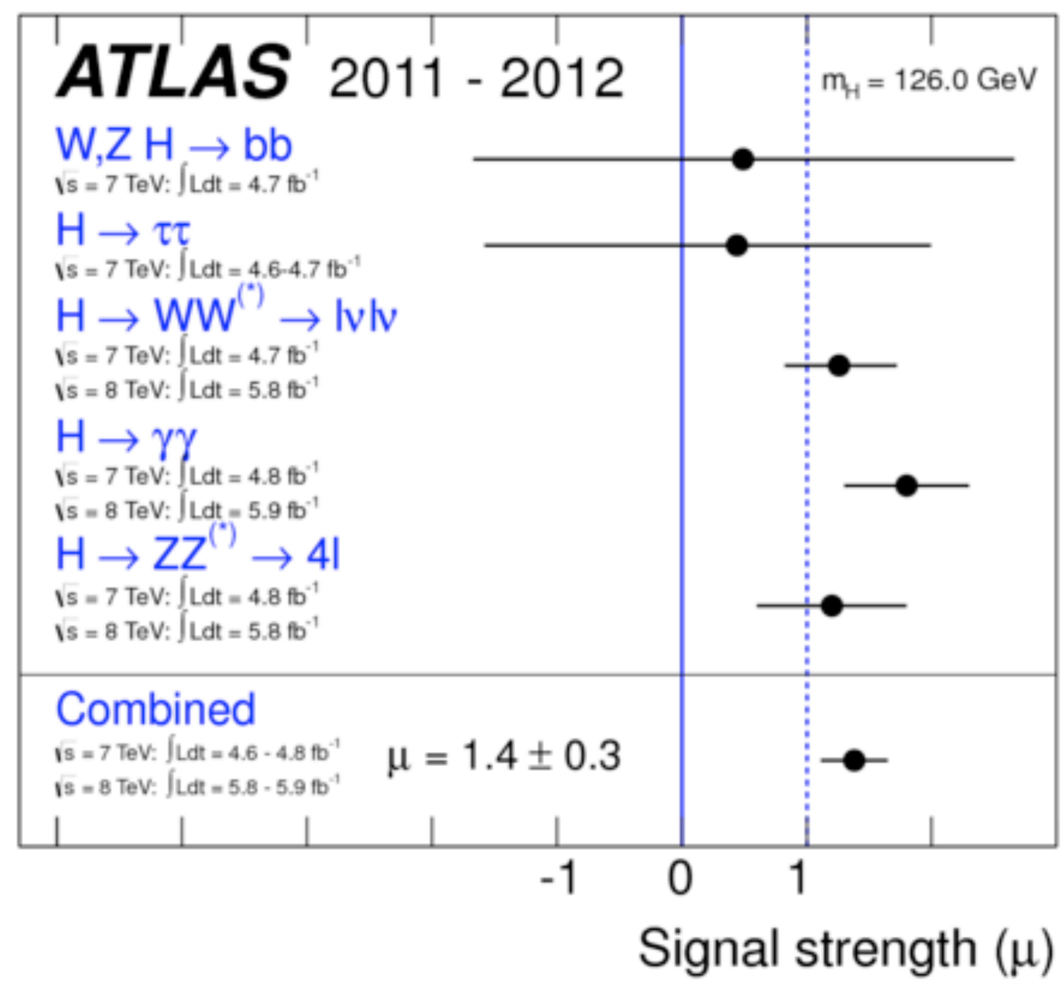
June 4th 2014

Bolshoi simulation, NASA

Why Triplet extension of the MSSM?

- Little hierarchy problem within the MSSM to accommodate m_h= 126 GeV
- Extension of the MSSM with SINGLETS or TRIPLETS mitigates the problem
- Higgs is SM-like except in the loop-suppressed processes
- Triplets are particularly interesting for that



The Triplet extension of the MSSM

$$\Sigma = \begin{pmatrix} \xi^0/\sqrt{2} & -\xi_2^+ \\ \xi_1^- & -\xi^0/\sqrt{2} \end{pmatrix} \qquad Y = 0\ SU(2)_L\text{-triplet superfield}$$

$$W_{\mathrm{TMSSM}} = W_{\mathrm{MSSM}} + \lambda H_1 \cdot \Sigma H_2 + \frac{1}{2}\mu_\Sigma \operatorname{Tr}\Sigma^2$$

$$\begin{aligned}\mathcal{L}_{\mathrm{TMSSM_{SB}}} &= \mathcal{L}_{\mathrm{MSSM_{SB}}} + m_4^2 \operatorname{Tr}(\Sigma^\dagger \Sigma) \\ &+ \left[B_\Sigma \operatorname{Tr}(\Sigma^2) + \lambda A_\lambda H_1 \cdot \Sigma H_2 + \mathrm{h.c.}\right]\end{aligned}$$

A.Delgado, G.Nardini and M.Quiros ’12, ’13

TMSSM considered in a definite configuration to introduce the minimal amount of new parameters and satisfy a SM-like Higgs

TMSSM scalar and Higgs sectors

- Scalar triplet vev is constrained by electroweak parameters $\langle \xi^0 \rangle \lesssim 4\,\mathrm{GeV}$

$$|A_\lambda|, |\mu|, |\mu_\Sigma| \lesssim 10^{-2} \frac{m_\Sigma^2 + \lambda^2 v^2/2}{\lambda v}$$

EW scale

TMSSM scalar and Higgs sectors

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$$m_\Sigma = \; 5\,\mathrm{TeV}$$

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- After electroweak symmetry breaking the CP-even Higgs mass matrix is

$$\mathcal{M}^2_{h,H} = \begin{pmatrix} m_A^2 \cos^2\beta + m_Z^2 \sin^2\beta & (\lambda^2 v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta \\ (\lambda^2 v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta & m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta \end{pmatrix}$$

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- Decoupling limit $m_A \to \infty$
  1. $m^2_{h,tree} = m_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta$
  2. Higgs is SM-like except in loop-induced processes

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λ and μ_Σ

2 free parameters

Electroweak sector

- Triplet ⟶ additional degrees of freedom in the electroweakino sector

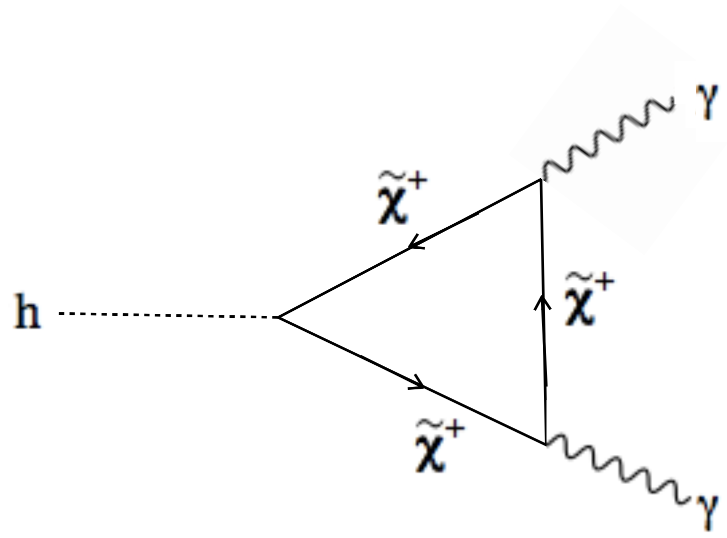
$$\mathcal{M}^{tree}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_1 & \frac{1}{2}g_1 v_2 & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_1 & -\frac{1}{2}g_2 v_2 & 0 \\ -\frac{1}{2}g_1 v_1 & \frac{1}{2}g_2 v_1 & 0 & -\mu & -\frac{1}{2}v_2\lambda \\ \frac{1}{2}g_1 v_1 & -\frac{1}{2}g_2 v_2 & -\mu & 0 & -\frac{1}{2}v_1\lambda \\ 0 & 0 & -\frac{1}{2}v_2\lambda & -\frac{1}{2}v_1\lambda & \mu_\Sigma \end{pmatrix}$$

Neutralino sector relevant for Higgs invisible decay width and for DM

$$\mathcal{M}^{tree}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & g_2 v \sin\beta & 0 \\ g_2 v \cos\beta & \mu & -\lambda v \sin\beta \\ 0 & \lambda v \cos\beta & \mu_\Sigma \end{pmatrix}$$

Chargino sector relevant for $\begin{cases} h \to \gamma\gamma \\ h \to Z\gamma \end{cases}$

Higgs signatures

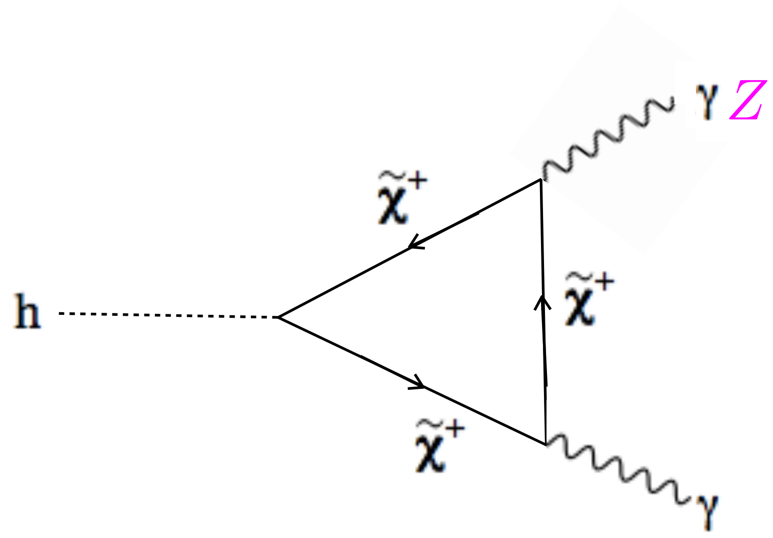


$$R_{\gamma\gamma} = \left| 1 + \frac{A^{\gamma\gamma}_{\widetilde{\chi}^{\pm}_{1,2,3}}}{A^{\gamma\gamma}_{W} + A^{\gamma\gamma}_{t}} \right|^2$$

$$A^{\gamma\gamma}_{\widetilde{\chi}^{\pm}_{1,2,3}} = \sum_{i=1}^{3} \frac{2M_W}{\sqrt{2}\, m_{\widetilde{\chi}^{\pm}_i}} (g^L_{h\widetilde{\chi}^+_i \widetilde{\chi}^-_i} + g^R_{h\widetilde{\chi}^+_i \widetilde{\chi}^-_i}) A_{1/2}(\tau_{\widetilde{\chi}^{\pm}_i})$$

$A^{\gamma\gamma}_{W} = -8.3$ $\qquad$ $A^{\gamma\gamma}_{t} = 1.9$

Higgs signatures



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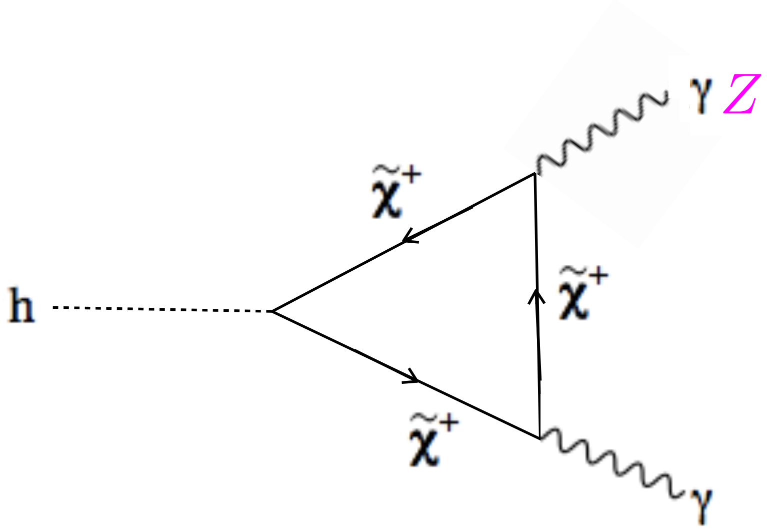

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$A^{\gamma\gamma}_W = -8.3$ $\qquad$ $A^{\gamma\gamma}_t = 1.9$

$$R_{Z\gamma} = \left| 1 + \frac{A^{Z\gamma}_{\tilde{\chi}^{\pm}_{1,2,3}}}{A^{Z\gamma}_W + A^{Z\gamma}_t} \right|^2$$

$$A^{Z\gamma}_{\tilde{\chi}^{\pm}_{1,2,3}} = \sum_{j,k=1}^{3} \frac{g_2\, m_{\tilde{\chi}^{\pm}_j}}{g_1\, m_Z} f\left(m_{\tilde{\chi}^{\pm}_j}, m_{\tilde{\chi}^{\pm}_k}, m_{\tilde{\chi}^{\pm}_k}\right) (g^L_{h\tilde{\chi}^+_j \tilde{\chi}^-_i} + g^R_{h\tilde{\chi}^+_j \tilde{\chi}^-_i})(g^L_{Z\tilde{\chi}^+_j \tilde{\chi}^-_i} + g^R_{Z\tilde{\chi}^+_j \tilde{\chi}^-_i})$$

$A^{Z\gamma}_W = -12$ $\qquad$ $A^{Z\gamma}_t = 0.6$

Set up of the analysis

SUSY Model = TMSSM

SARAH

↓

Supersymmetric mass spectrum

SPheno

(masses computed at full 1-loop + Higgs has 2 loop corrections)

↓

SPheno, CPSuperH

Higgs Physics

Sampling method and free parameters

$$\{\theta_i\} = \{M_1, M_2, M_3, \widetilde{m}, \tan\beta, \mu, \lambda, \mu_\Sigma\}$$

Sampling with the algorithm MultiNest

$$p(\theta_i|d) \propto \mathcal{L}(d|\theta_i)\pi(\theta_i)$$

- Nested sampling
- Sampling scale as n instead of n^2 as for a random scan

NS parameters	Prior range
$\log_{10}(M_1/\mathrm{GeV}), \log_{10}(\mu_\Sigma/\mathrm{GeV})$	$1 \to 3$
$\log_{10}(\mu/\mathrm{GeV}), \log_{10}(M_2/\mathrm{GeV})$	$2 \to 3$
$\widetilde{m}/\mathrm{TeV}$	$0.63 \to 2$
$\log_{10}(\tan\beta)$	$0 \to 1$
λ	$0.5 \to 1.2$

$$m_\Sigma = 5\,\mathrm{TeV}\ , \quad A_t = A_b = 0\ , \quad M_3 = 1.4\,\mathrm{TeV}\ , \quad m_A = 1.5\,\mathrm{TeV}$$

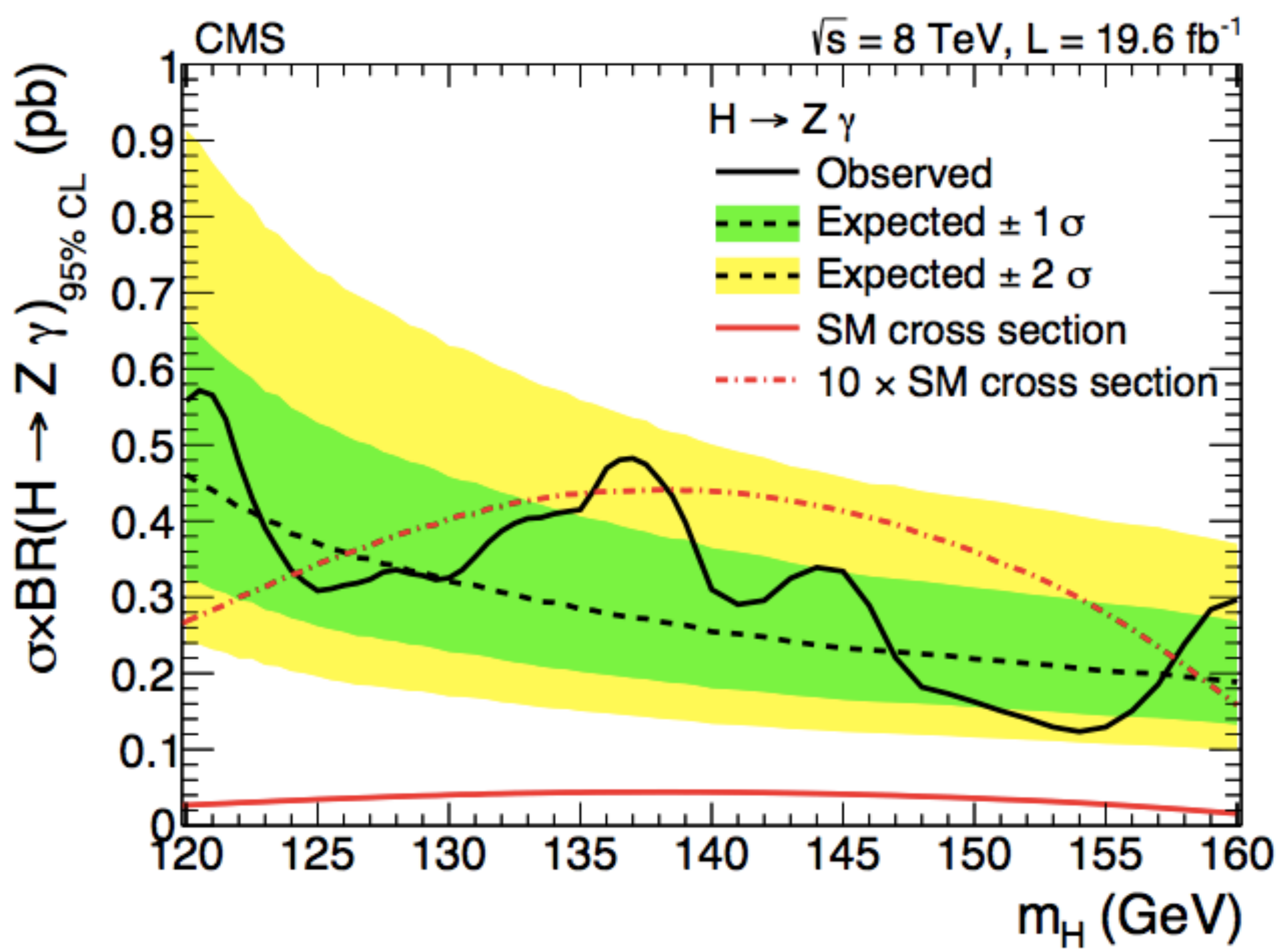
Likelihood and priors

Collider data

m_h	125.85 ± 0.4 GeV (exp) ± 3 GeV (theo)
$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	< 2 MeV
$m_{\tilde{t}_1}$	> 650 GeV (LHC 90% CL)
$m_{\tilde{\chi}_1^+}$	> 101 GeV (LEP 95% CL)

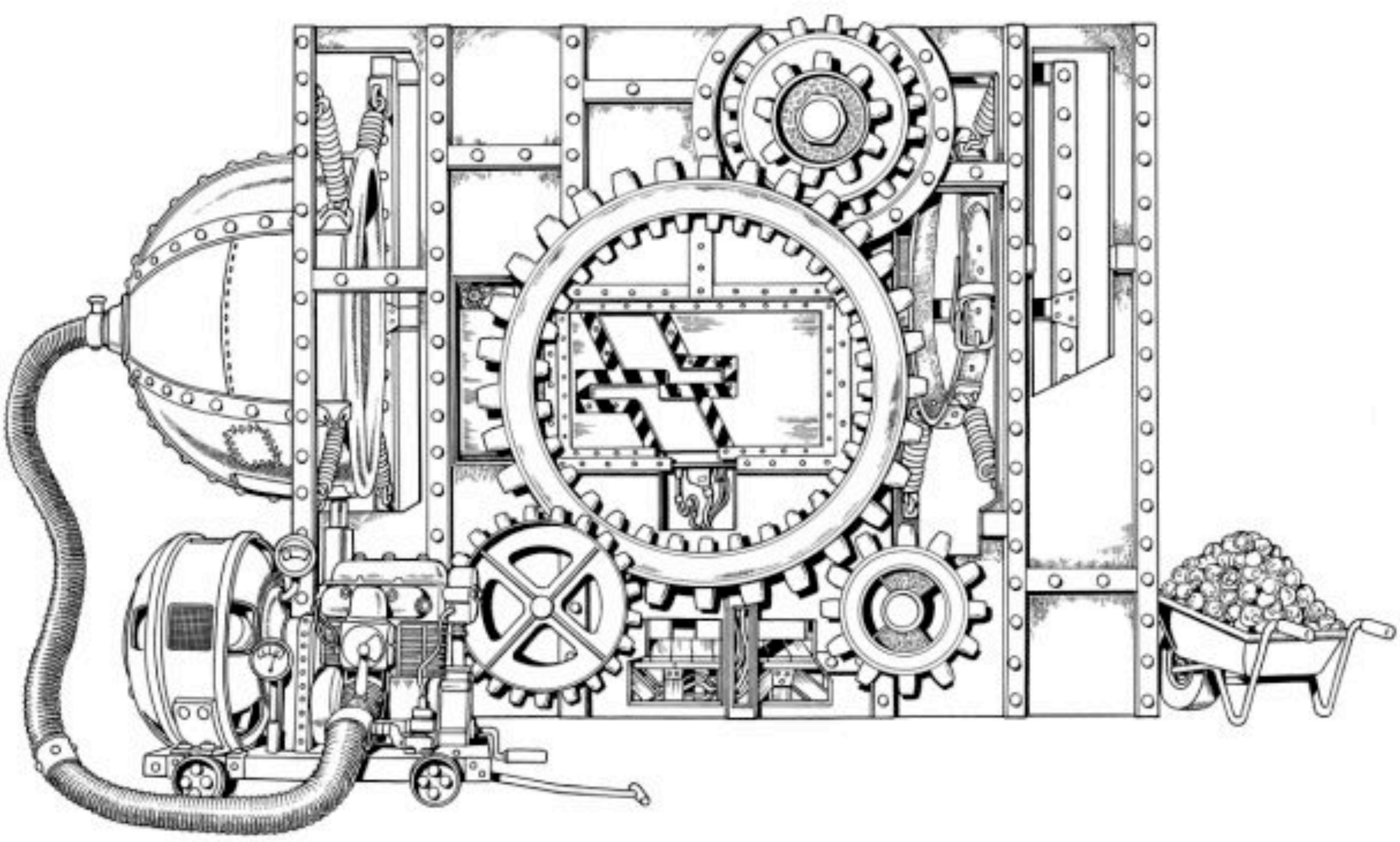
} Gaussian likelihood

} Step function

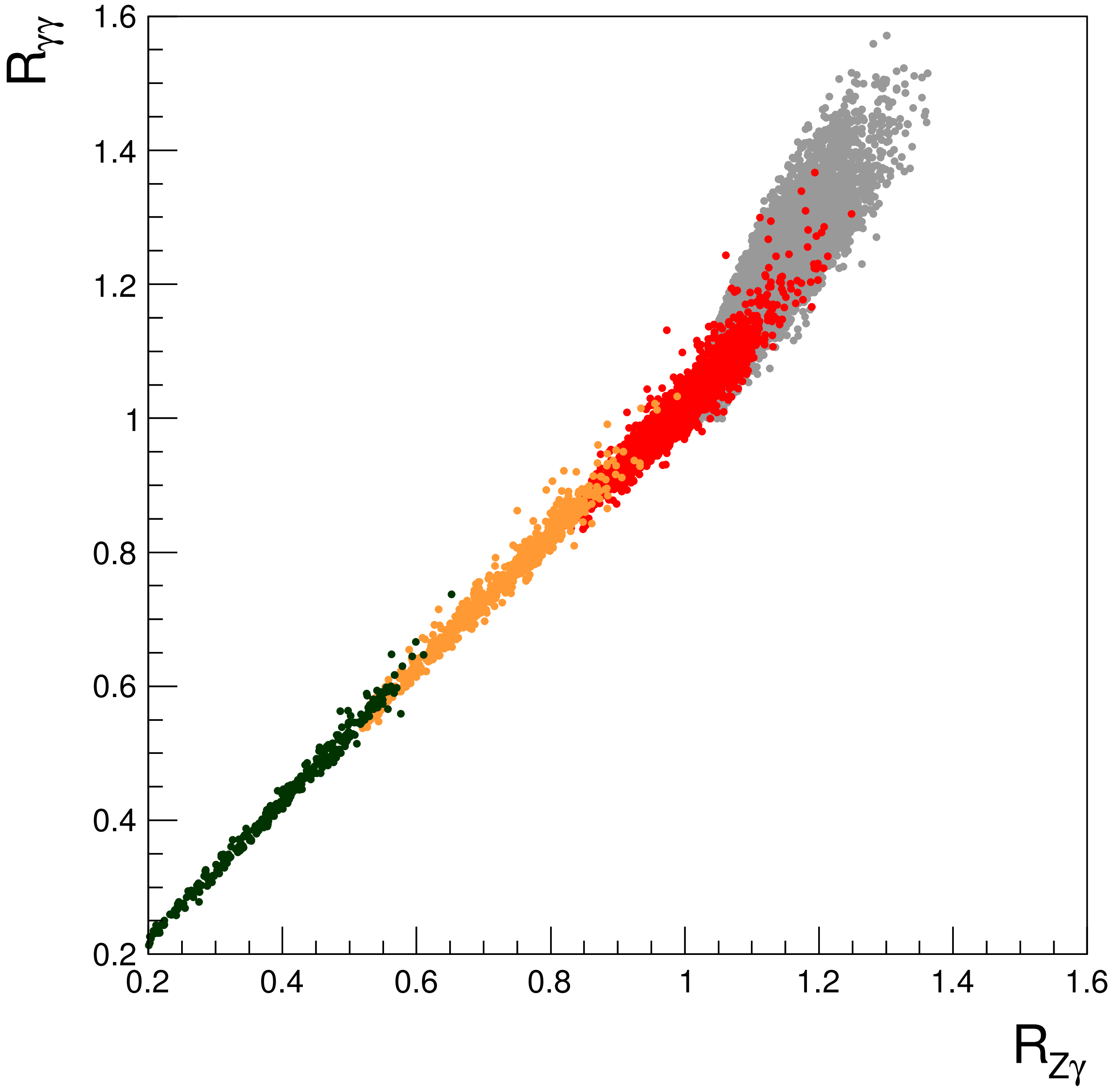


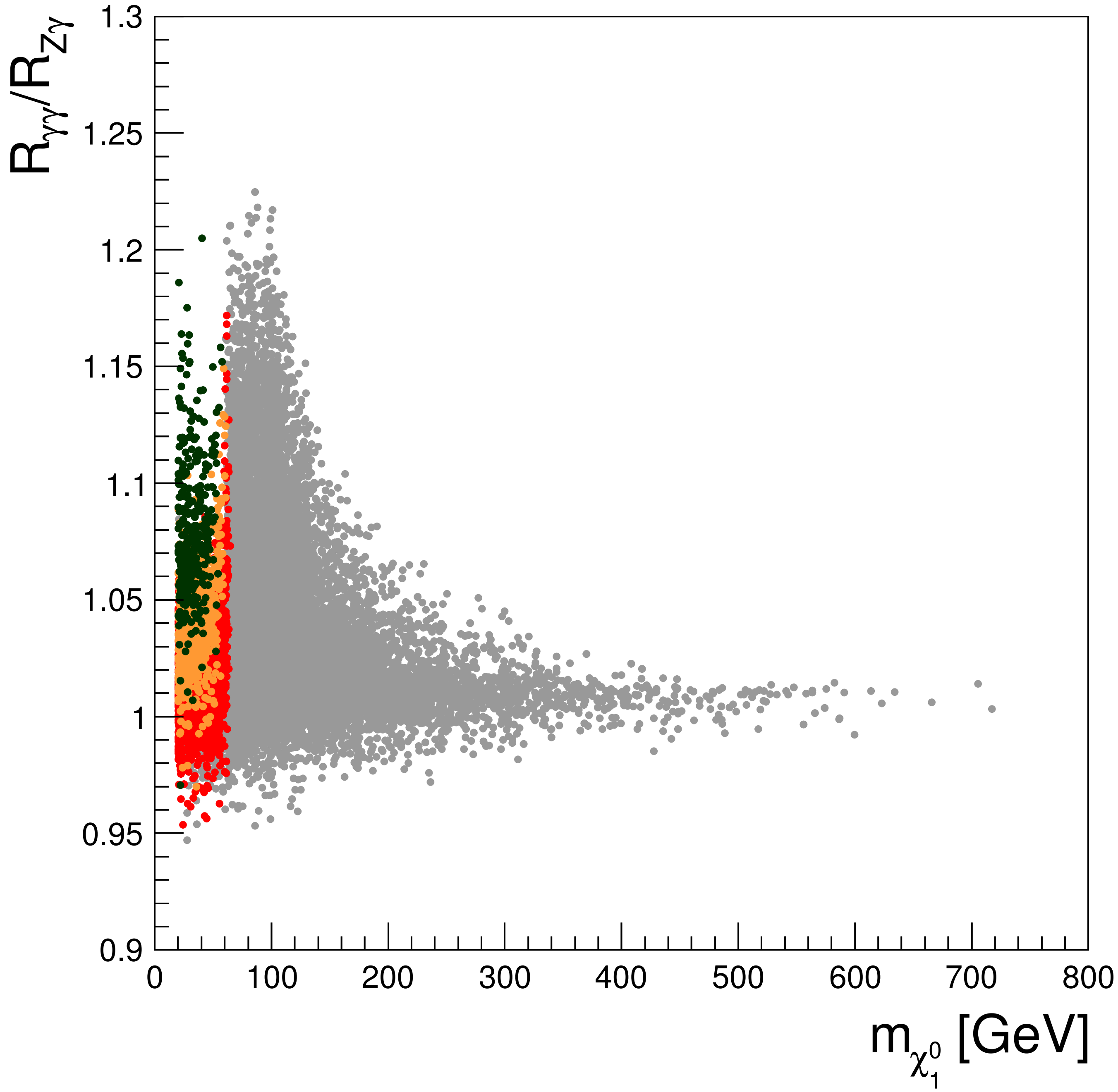
No bounds on loop suppressed processes

Running the machinery for Higgs physics ...



Higgs signal strengths

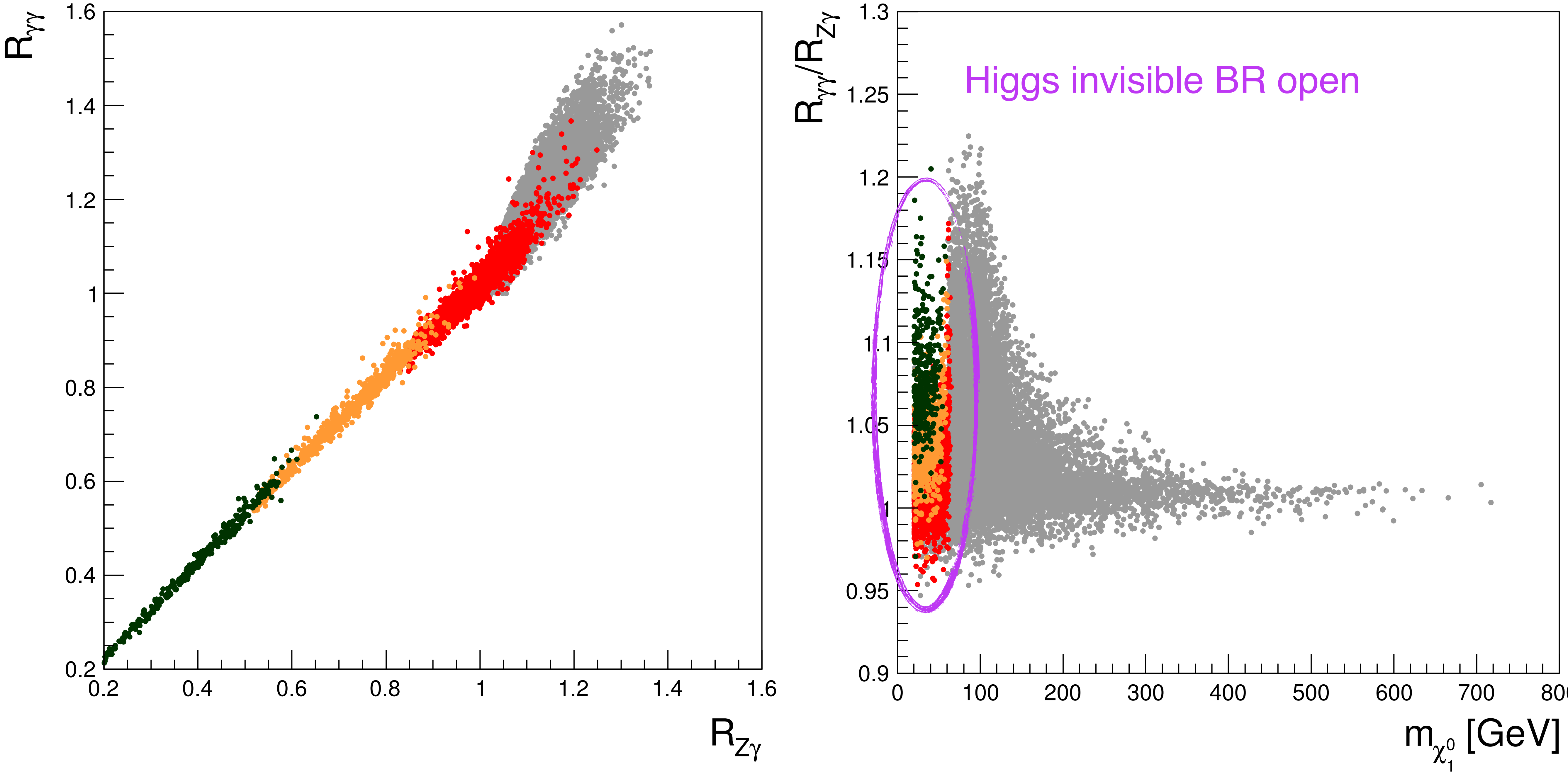




$$R_{XY} \equiv \mathrm{BR}(h \to XY)/\mathrm{BR}_{\mathrm{SM}}(h \to XY) \times (1 - \mathrm{BR}(\mathrm{h} \to \tilde{\chi}^0 \tilde{\chi}^0))$$

Without DM constraints neutralino mass can go down to ~ 20 GeV

Higgs signal strengths



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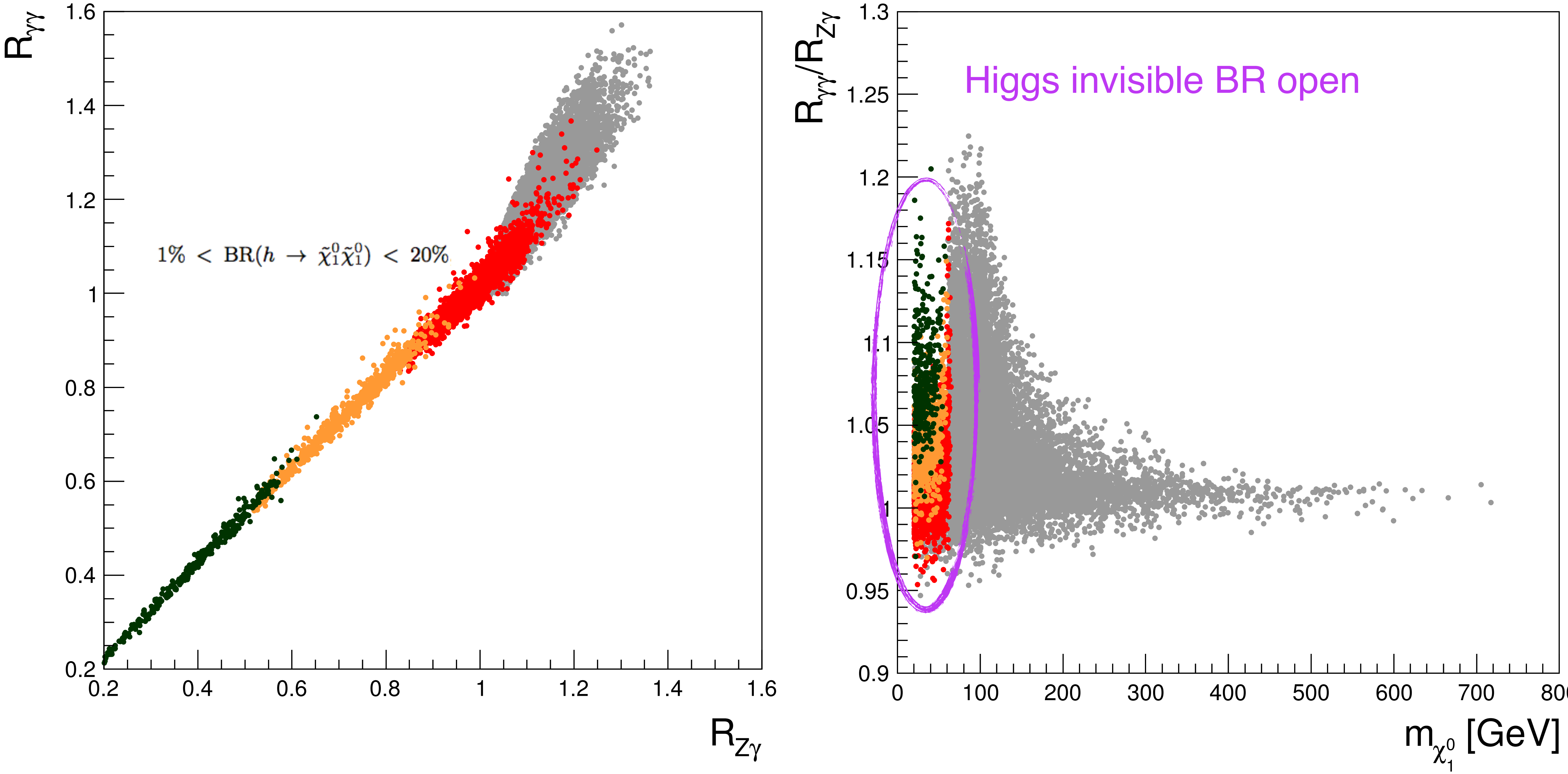

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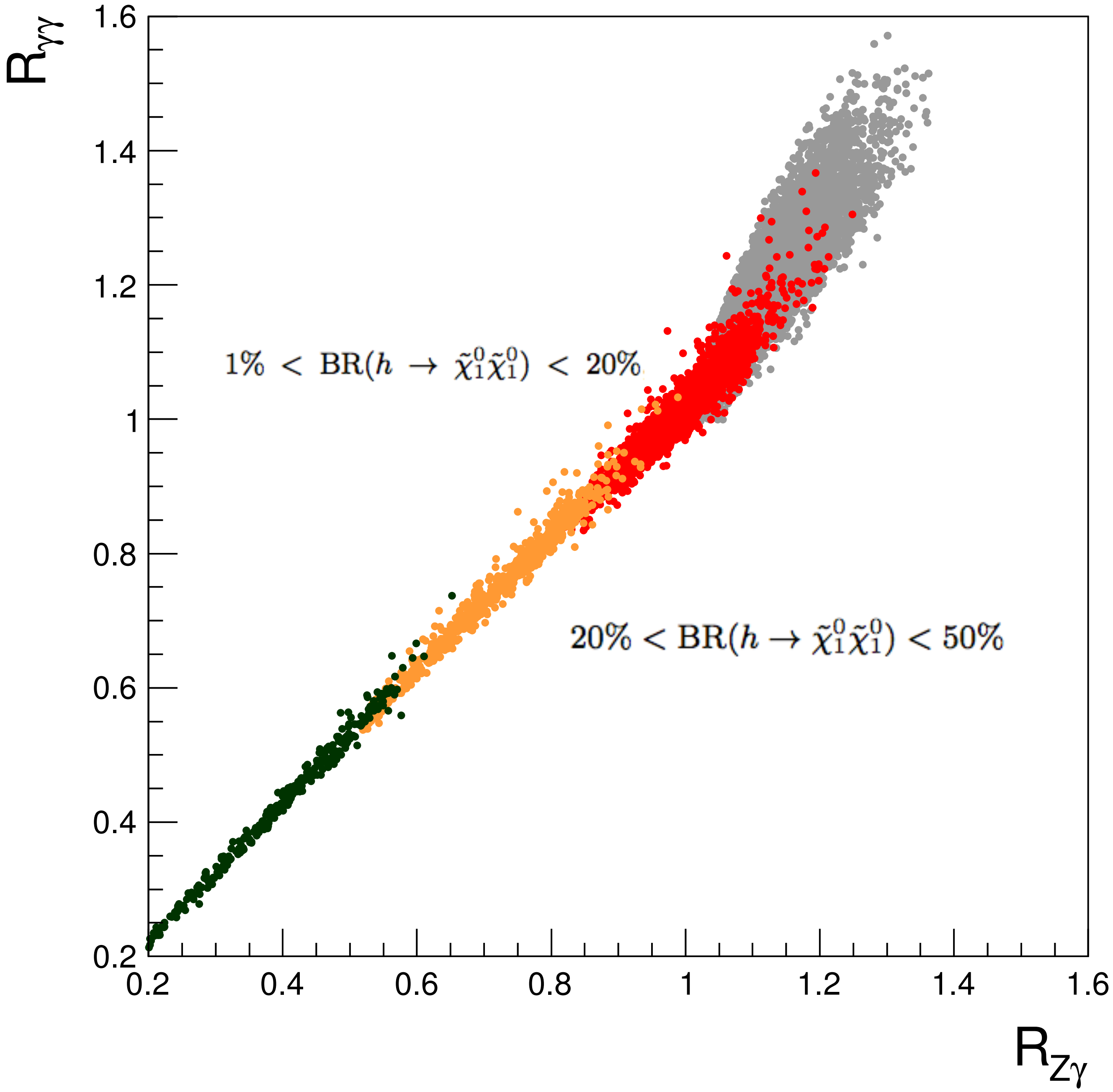

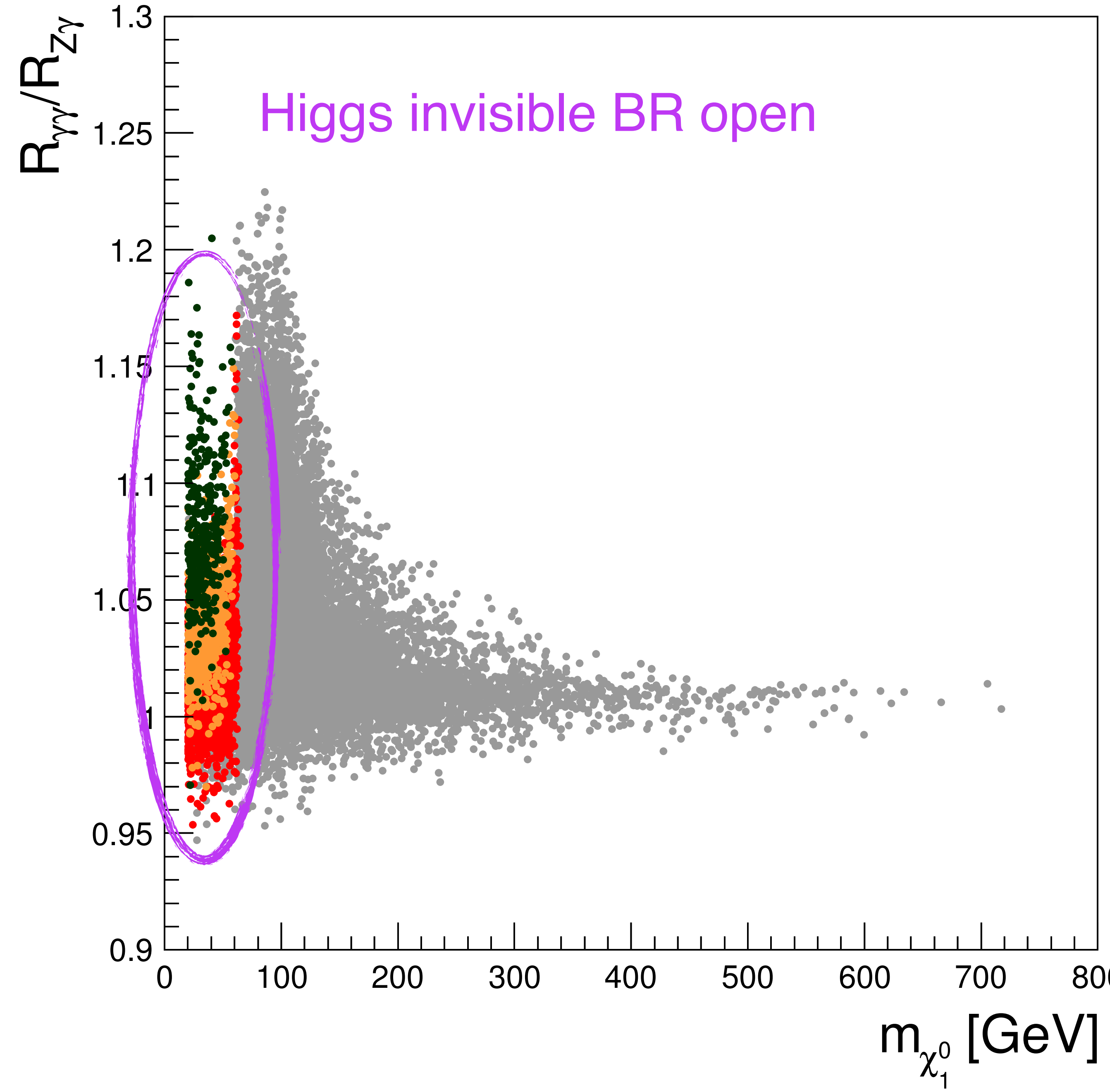

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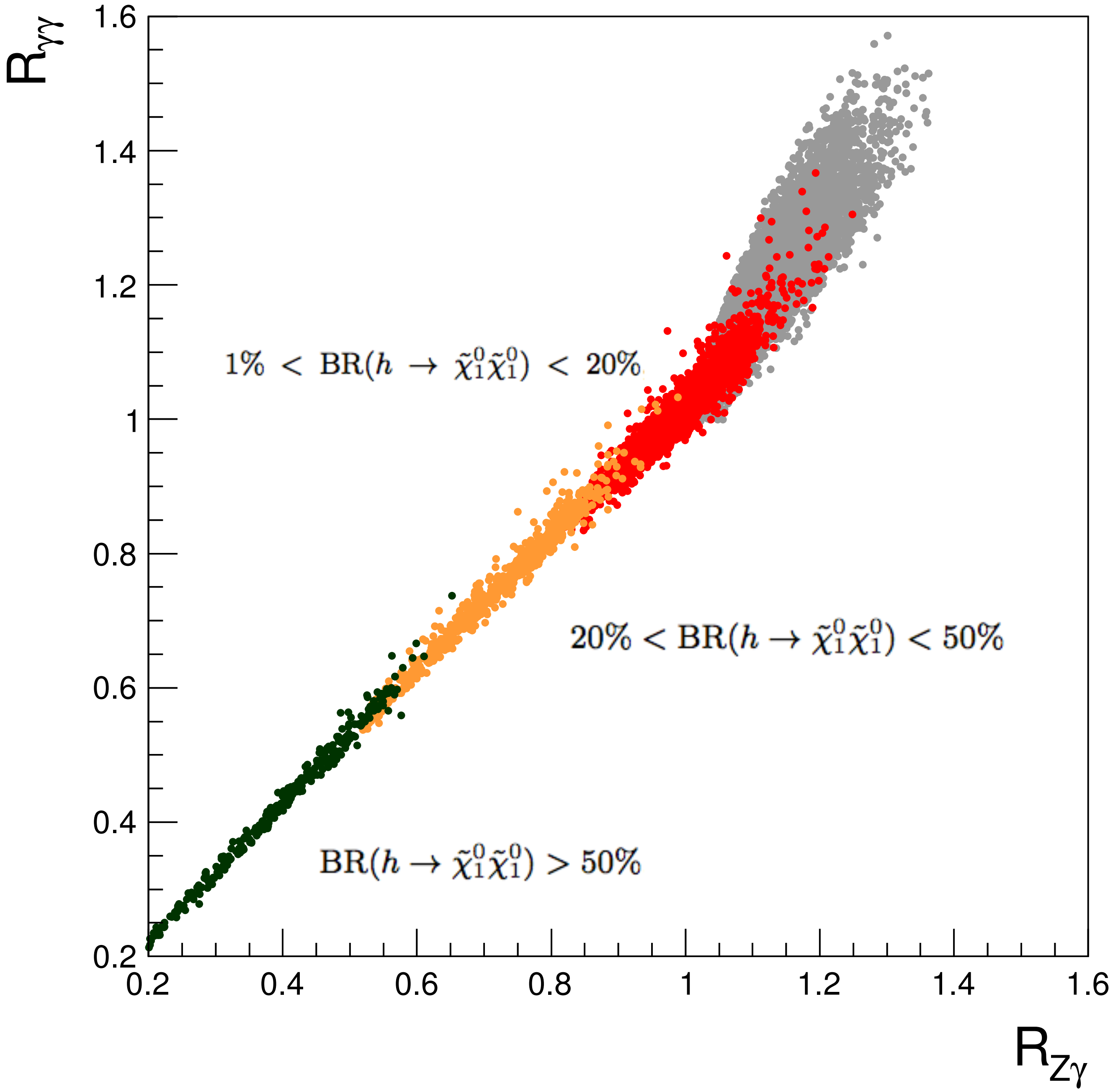

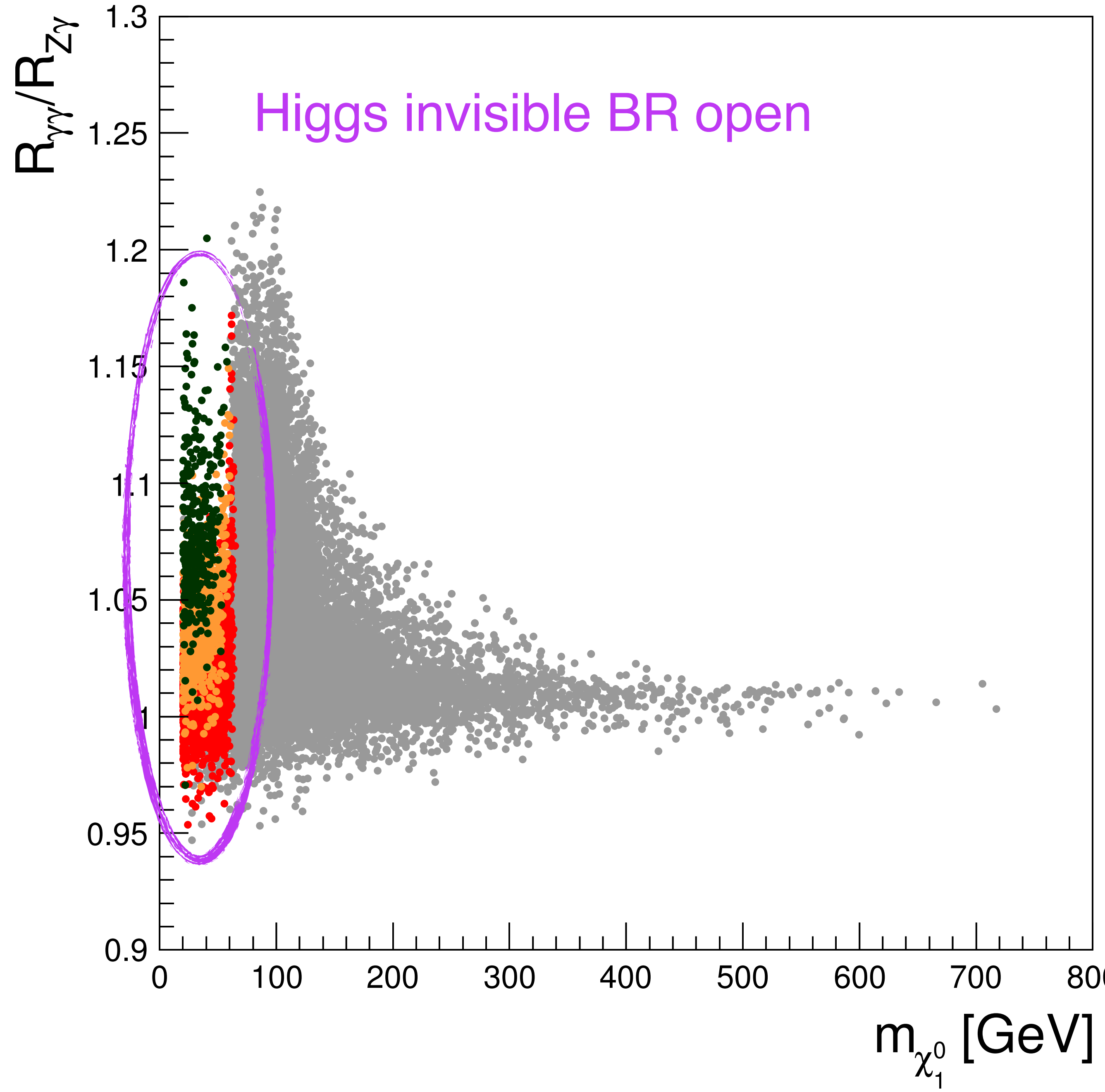

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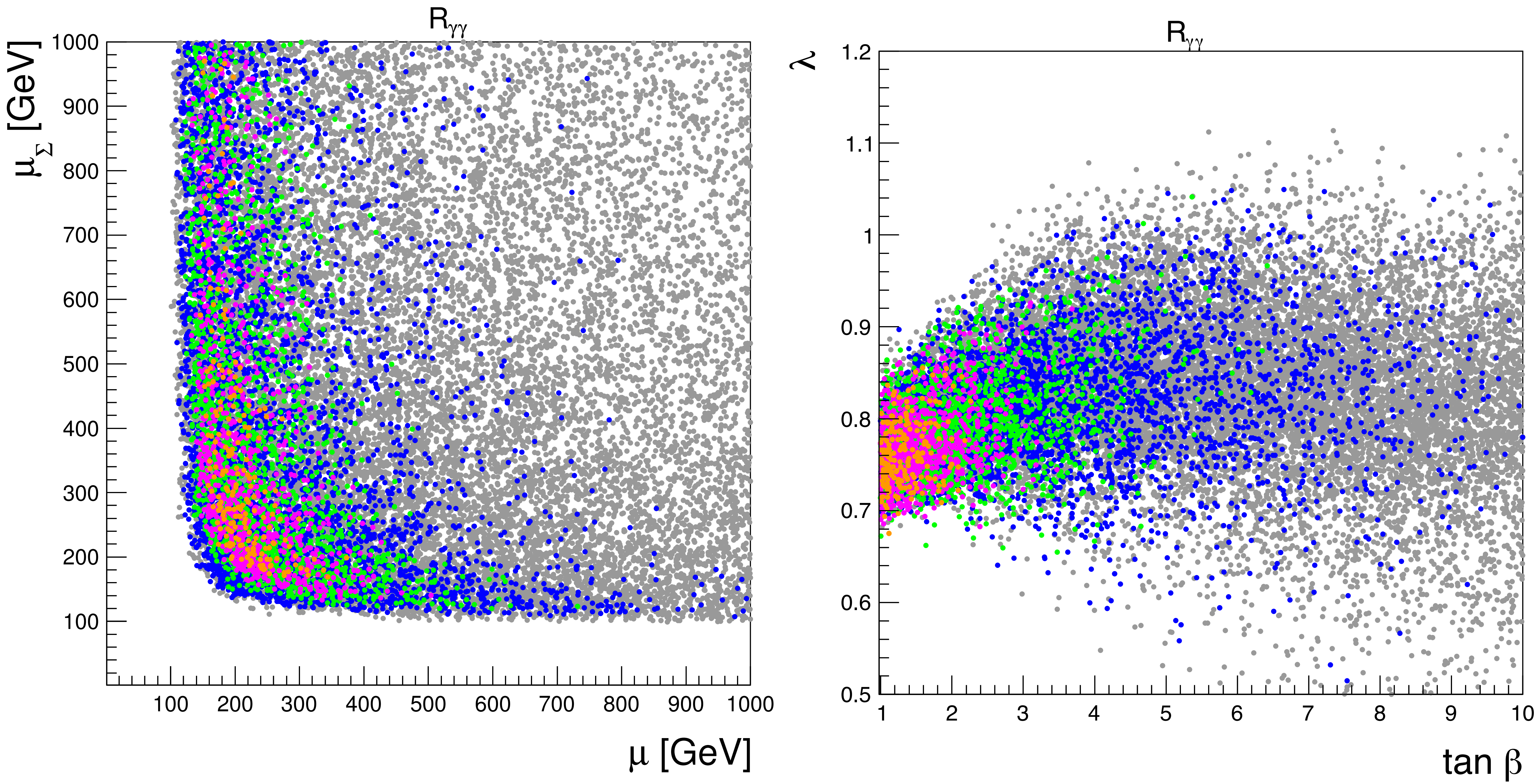


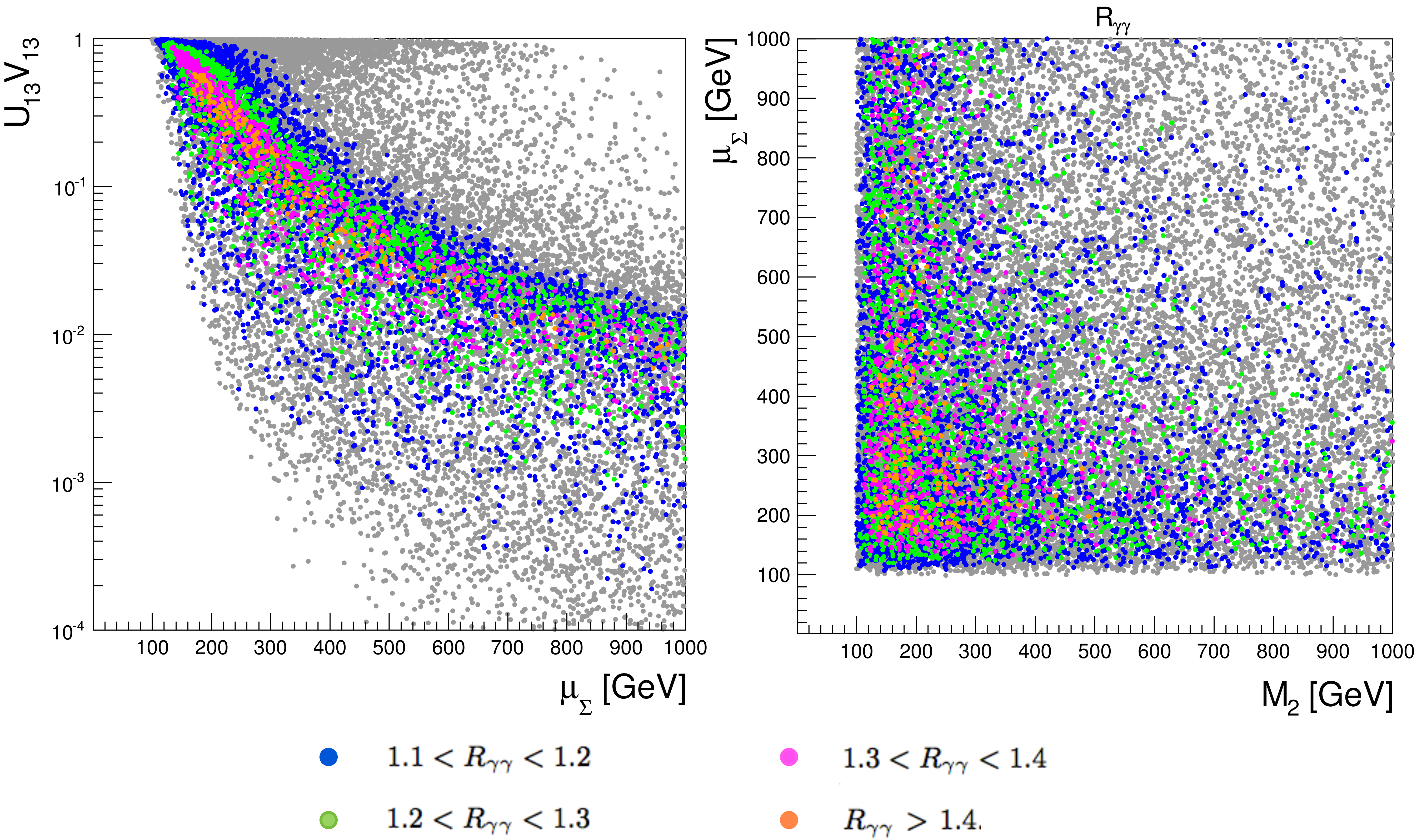
● $1.1 < R_{\gamma\gamma} < 1.2$

● $1.2 < R_{\gamma\gamma} < 1.3$

● $1.3 < R_{\gamma\gamma} < 1.4$

● $R_{\gamma\gamma} > 1.4.$

Higgs signal strengths



Set up of the analysis

SUSY Model = TMSSM

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Supersymmetric mass spectrum

SPheno

(masses computed at full 1-loop + Higgs has 2 loop corrections)

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↙ ↘

micrOMEGAs

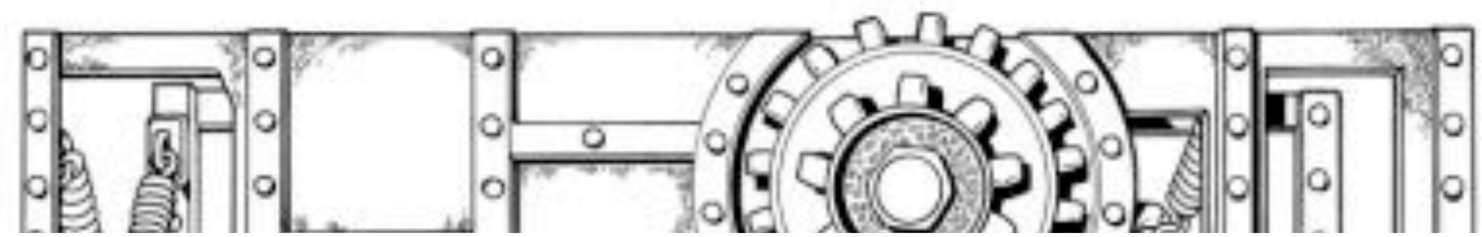
Relic Abundance $\Omega_{\rm DM}h^2$

+ dark matter direct detection predictions

SPheno, CPSuperH

Higgs Physics

Running the machinery with DM constraints ...

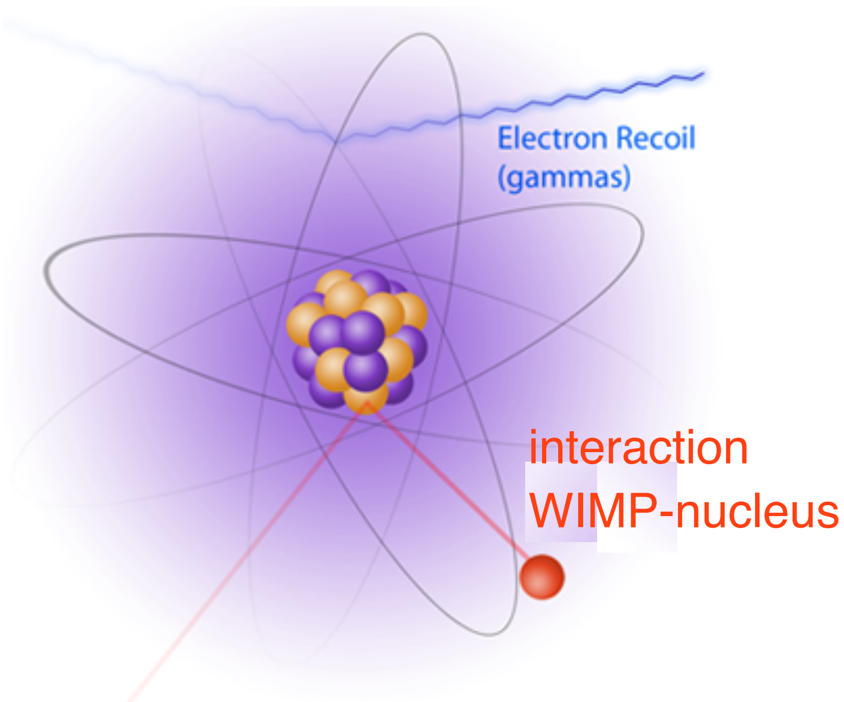


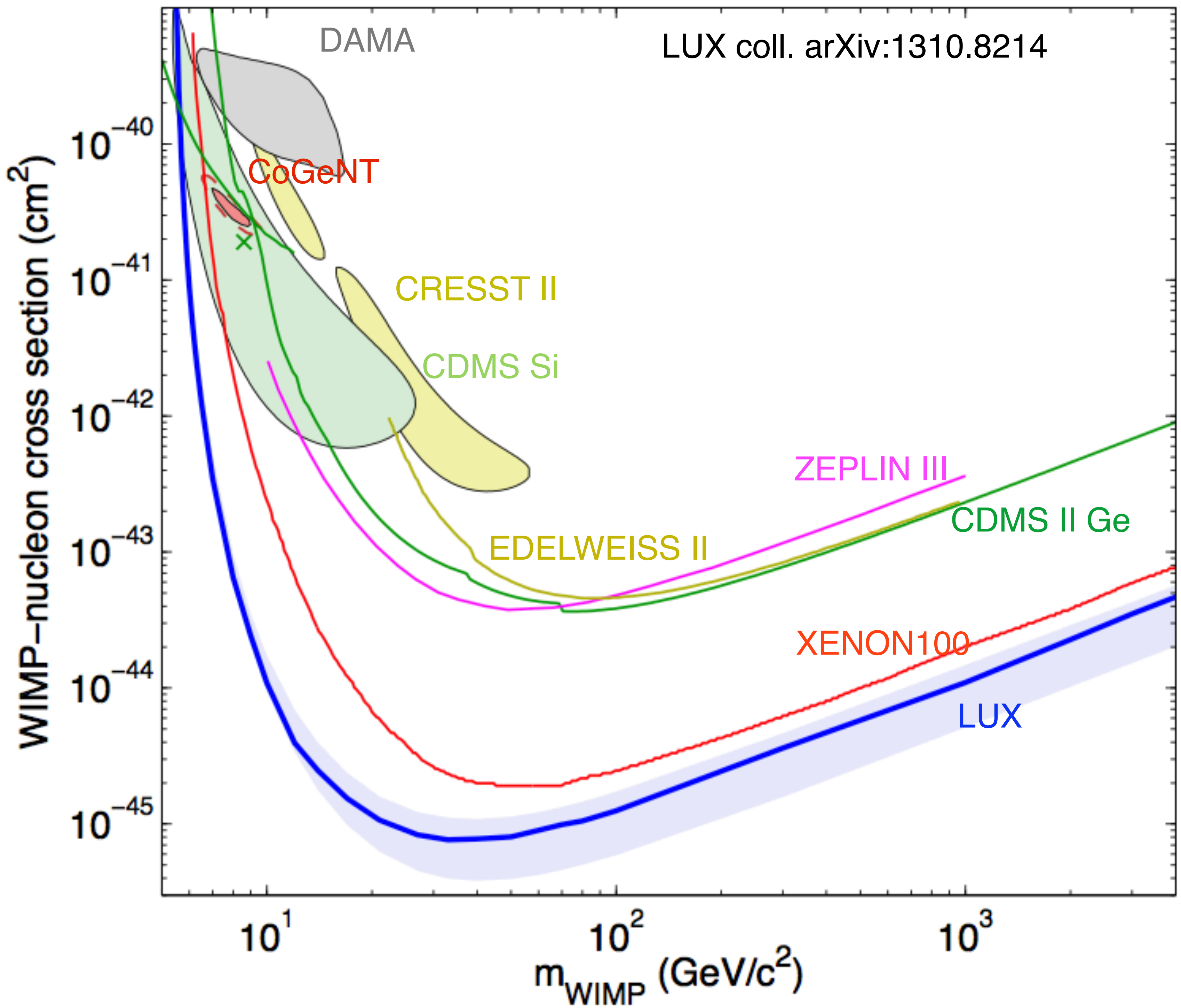
Type	Observable	Measurement/Limit
Collider data	m_h	125.85 ± 0.4 GeV (exp) ± 3 GeV (theo)
	$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	< 2 MeV
	$m_{\tilde{t}_1}$	> 650 GeV (LHC 90% CL)
	$m_{\tilde{\chi}_1^+}$	> 101 GeV (LEP 95% CL)
DM data	$\Omega_{\rm DM} h^2$	0.1186 ± 0.0031 (exp) $\pm 20\%$ (theo)
	$\sigma_{\rm Xe}^{SI}$	LUX (90% CL)

TMSSM DM candidate:

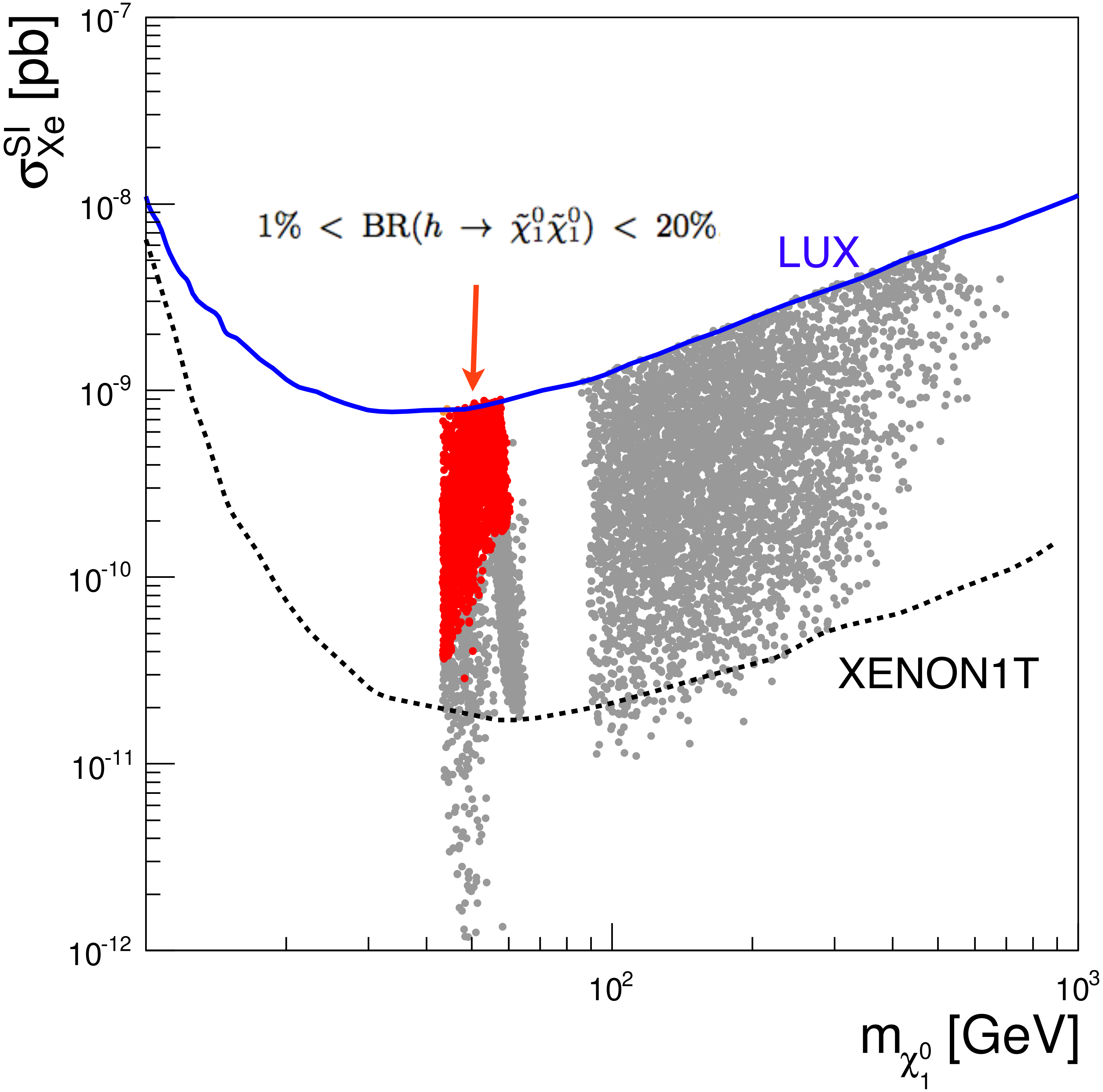
Neutralino (with triplino component)

Direct detection constraint on spin-independent scattering





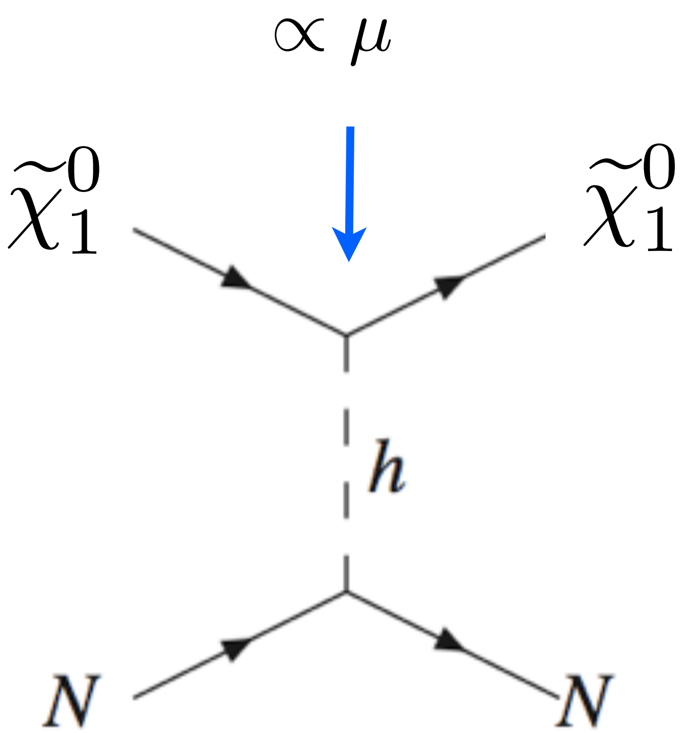
Neutralino as DM



- The LSP is good DM in the Higgs pole and in the well-tempered region

$$m_{\tilde{\chi}^0_1} > 40 \text{ GeV}$$

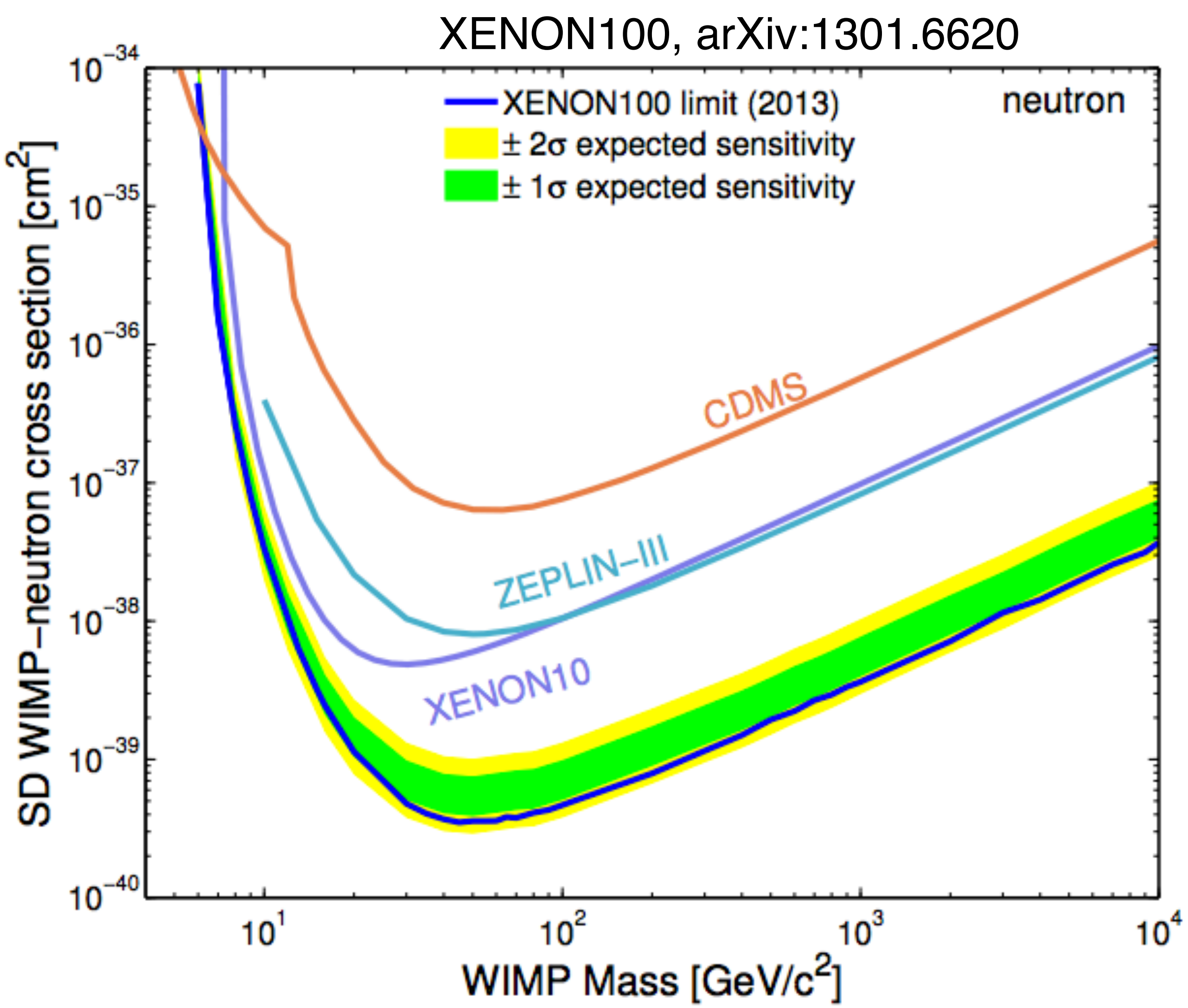
- Dominant channel for SI scattering depends on the higgsino component

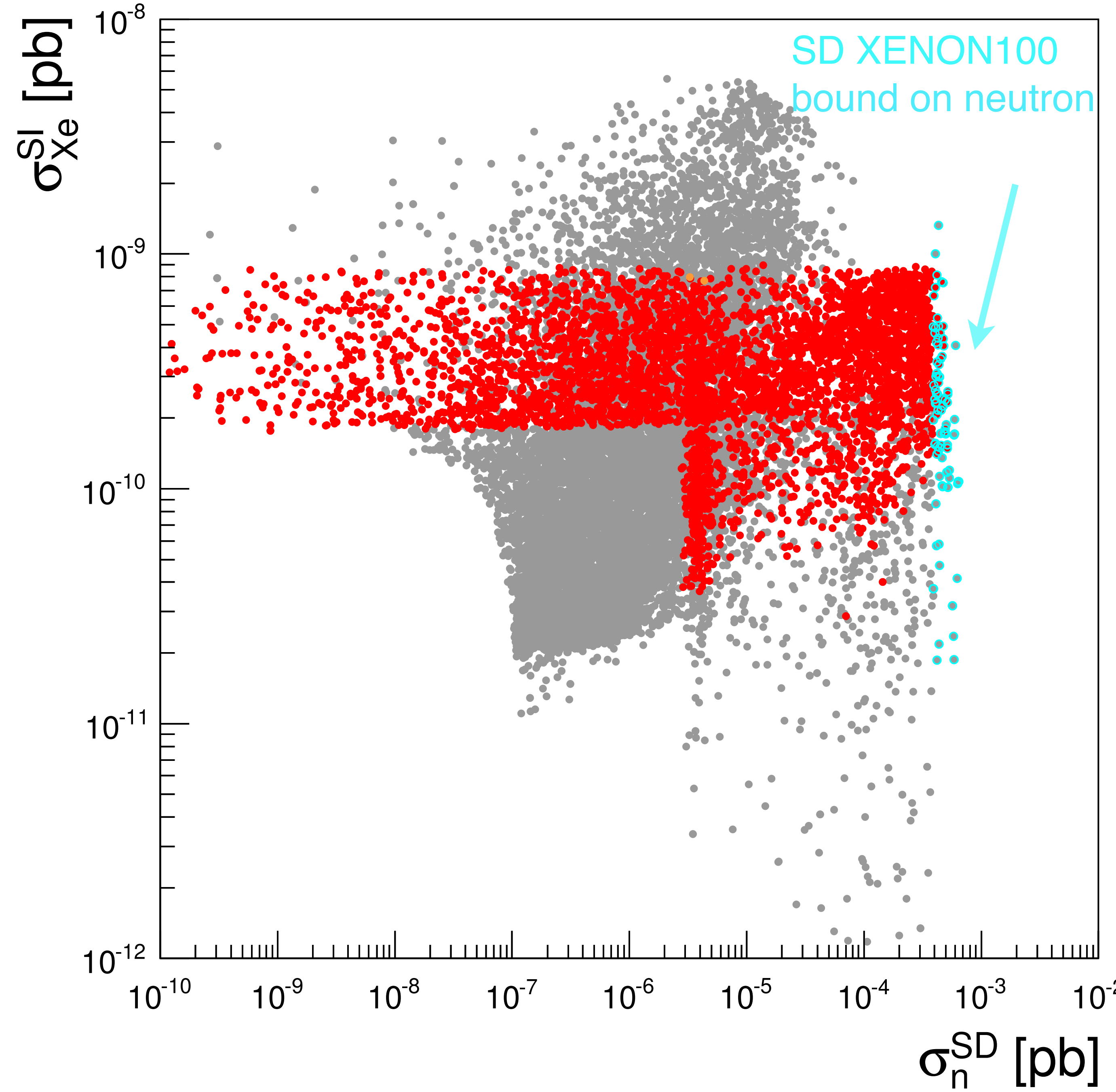


Complementarity between DM direct detection and colliders

Neutralino spin-dependent interaction

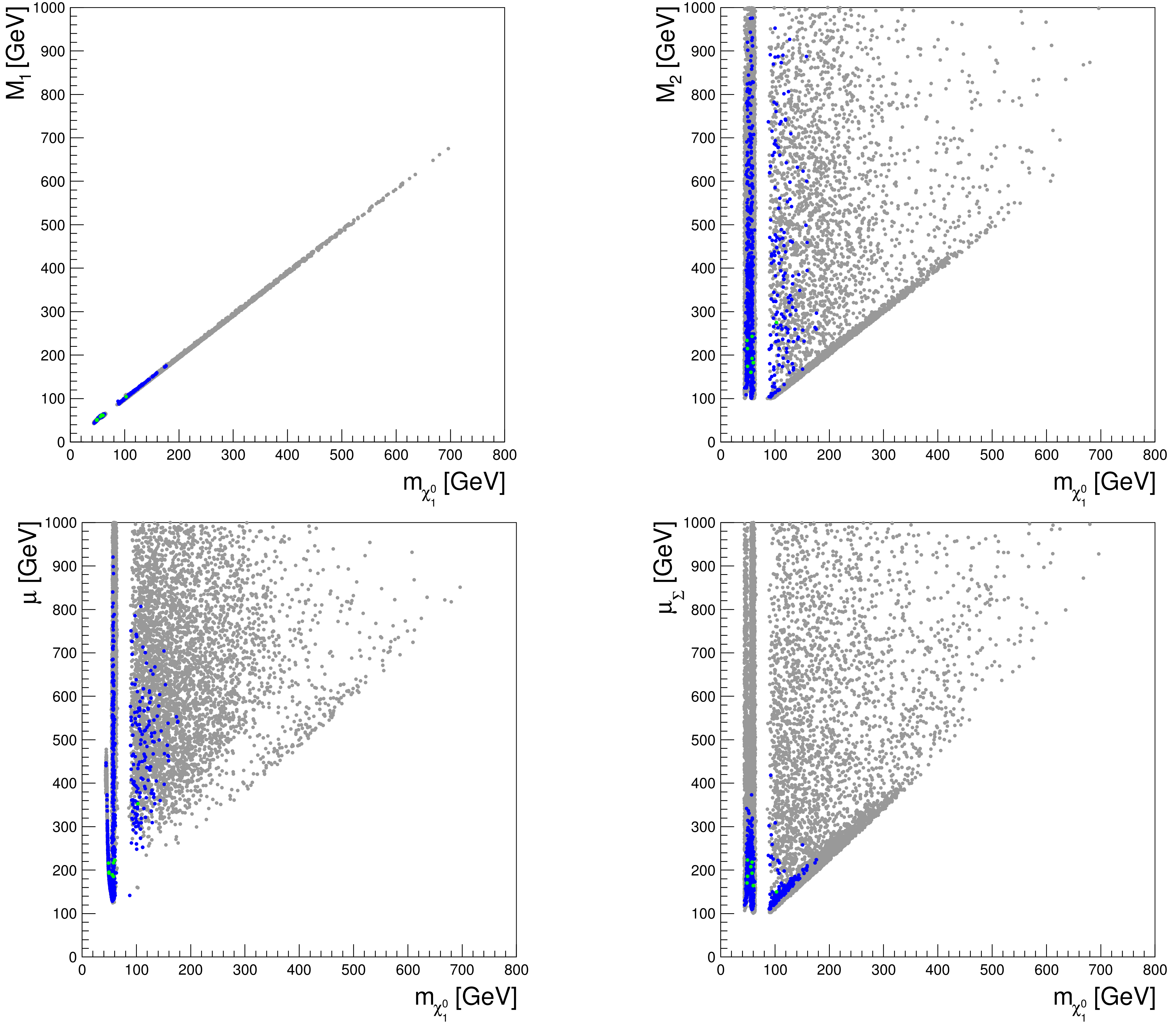
$$\frac{d\sigma}{dE} = \frac{d\sigma}{dE}\bigg|_{SI} + \frac{d\sigma}{dE}\bigg|_{SD}$$





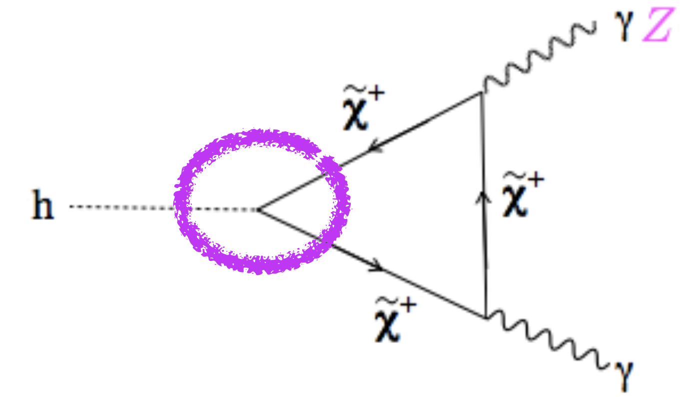
- Xenon100 more sensitive to scattering on neutron
- Spin-dependent scattering on proton is one order of magnitude lower
- Large uncertainties on the nuclear form factors

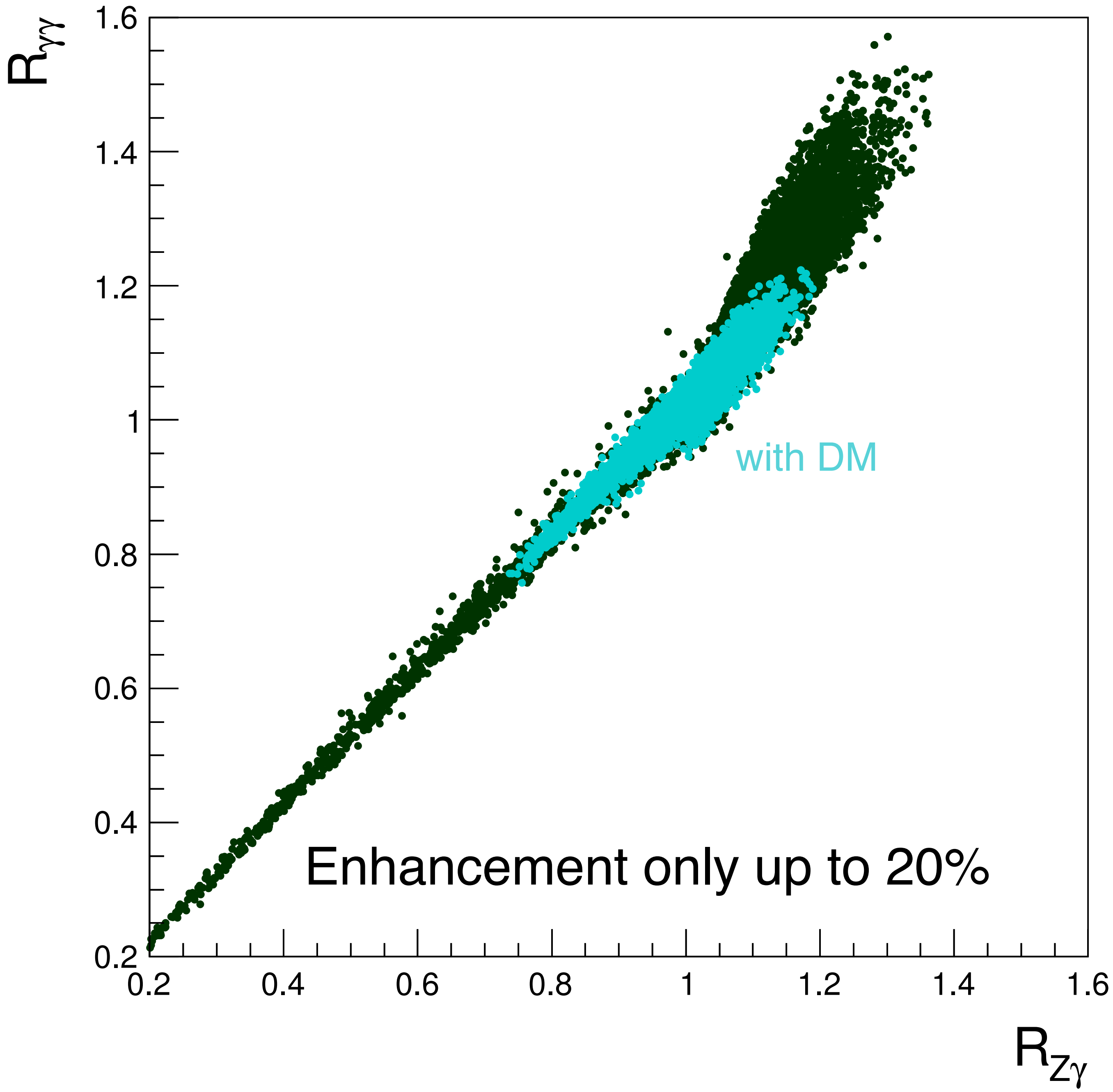
Composition of the neutralino

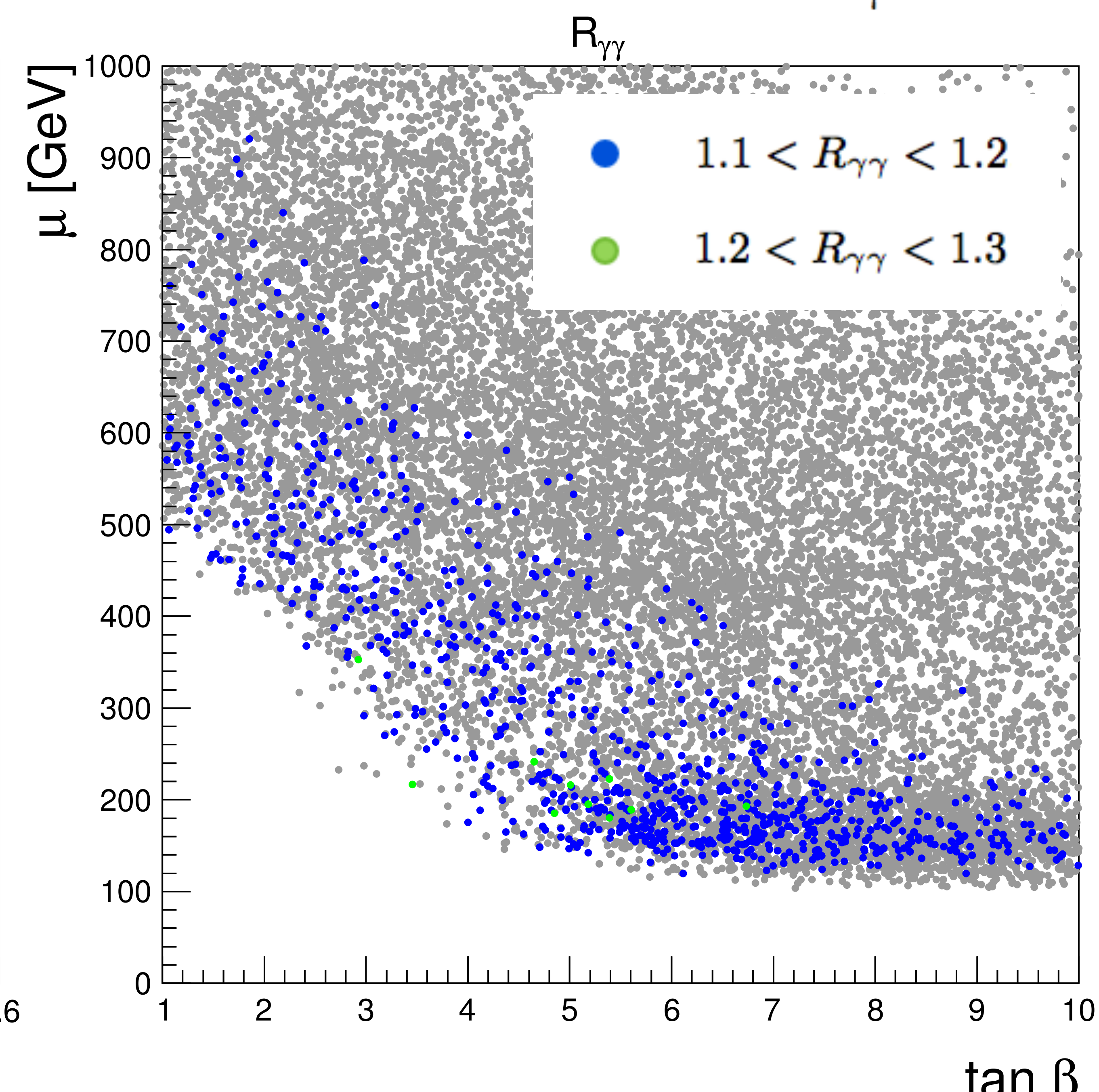


Impact of DM on Higgs pheno

μ constrained by LUX impacts Higgs loop-processes







Conclusions

Triplet extension of the MSSM has some adgvantages

(a) Reduces fine-tuning in the Higgs mass (new contribution at tree level)

(b) Higgs phenomenology is SM-like

(c) Only loop-induced processes deviate from SM behavior (extra charginos)

$$\Gamma(h \to \gamma\gamma) < 60\%$$
$$\Gamma(h \to \gamma Z) < 40\%$$

loop-induced processes are correlated

If the lightest neutralino is the DM candidate

(a) Compatible with DM constraints on the Higgs pole or co-annihilation regions

(b) Strong impact on the loop-induces processes because of DD constraints

$$\Gamma(h \to \gamma\gamma), \Gamma(h \to \gamma Z) < 20\%$$

Back up slides

More on the Higgs sector

Minimization conditions for electroweak symmetry breaking:

$$m_3^2 = m_A^2 \sin\beta\cos\beta \ ,$$
$$m_Z^2 = \frac{m_2^2 - m_1^2}{\cos 2\beta} - m_A^2 + \lambda^2 v^2/2 \ ,$$
$$m_A^2 = m_1^2 + m_2^2 + 2|\mu|^2 + \lambda^2 v^2/2 \ ,$$
$$m_H^{\pm} = m_A^2 + m_W^2 + \lambda^2 v^2/2 \ ,$$

$$\frac{1}{2}(h_2, h_1, x)\,\widehat{\mathcal{M}}^2 \begin{pmatrix} h_2 \\ h_1 \\ x \end{pmatrix}$$

$$H_i^0 = v_i + (h_i + i\chi_i)/\sqrt{2}$$

$$x = \mathrm{Re}\,\xi^0/\sqrt{2}$$

$$\mathcal{O}(\lambda\hat{\mu}v)$$

$$\widehat{\mathcal{M}}^2 = \begin{pmatrix} \mathcal{M}^2 & \begin{matrix} \cdot \\ \cdot \end{matrix} \\ \cdot \quad \cdot & m_\Sigma^2 + \frac{\lambda^2}{2} v^2 \end{pmatrix}$$

$$\hat{\mu} = \max\{|\mu|, |\mu_\Sigma|, |A_\lambda|\}$$

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \cos^2\beta + m_Z^2 \sin^2\beta & (\lambda^2 v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta \\ (\lambda^2 v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta & m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta \end{pmatrix}$$

More on the Higgs sector

Higgs mass has full 2 loop corrections from RGEs resummation + full one loop mass spectrum + corrections of the order

$$\mathcal{O}(h_t^2 g_3^2)$$

$$\mathcal{O}(h_t^4)$$

$$\Gamma(Z \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0) = \frac{1}{12\pi} \frac{G_F}{\sqrt{2}} m_Z^3 \left(1 - \frac{4m_{\widetilde{\chi}_1^0}^2}{m_Z^2}\right)^{3/2} \left(|N_{13}|^2 - |N_{14}|^2\right)^2$$

$$\Gamma(h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0) = \frac{G_F m_W^2}{2\sqrt{2}\pi} m_h \left(1 - \frac{4m_{\widetilde{\chi}_1^0}^2}{m_h^2}\right)^{3/2} g_{h\chi_1^0\chi_1^0}^2$$

$$g_{h\chi_1^0\chi_1^0} = (N_{12} - \frac{g_1}{g_2} N_{11})(\sin\beta N_{14} - \cos\beta N_{13}) + \frac{\lambda}{g_2} N_{15}(N_{14}\sin\beta + N_{13}\cos\beta)$$

$$m_\Sigma^2 \equiv m_4^2 + \mu_\Sigma^2 + B_\Sigma \mu_\Sigma$$

Details on diphoton etc..

$A_W^{\gamma\gamma}$ = -8.3

$A_t^{\gamma\gamma}$ = 1.9

$$A_W^{Z\gamma} = -12$$

$$A_t^{Z\gamma} = 0.6$$

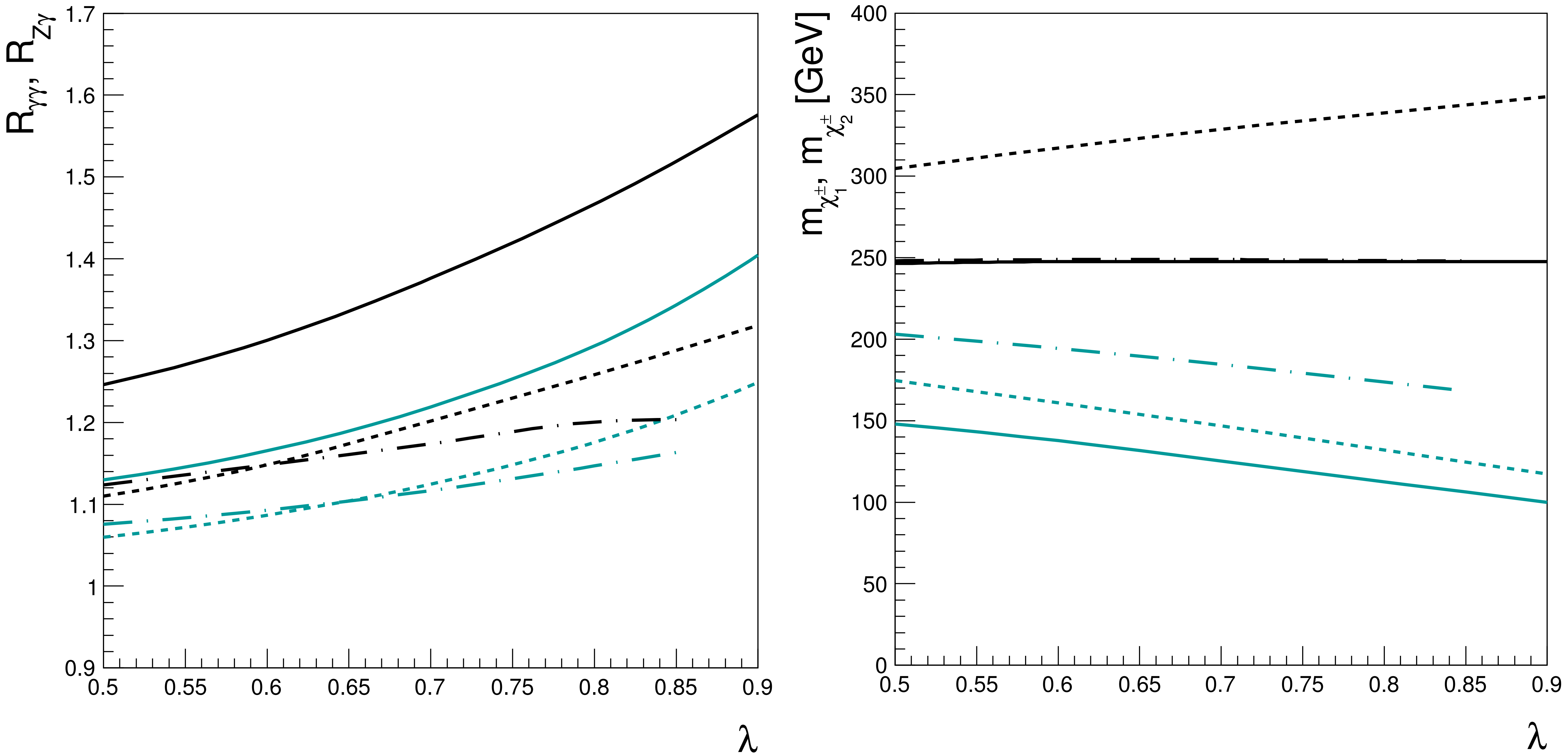
$$g^L_{Z\chi_j^+\chi_k^-} = -\left(V_{i1}V_{j1}^* + \frac{1}{2}V_{i2}V_{j2}^* + V_{i3}V_{j3}^* - \delta_{ij}s_W^2\right)$$

$$g^R_{Z\chi_j^+\chi_k^-} = -\left(U_{i1}U_{j1}^* + \frac{1}{2}U_{i2}U_{j2}^* + U_{i3}U_{j3}^* - \delta_{ij}s_W^2\right)$$

$$g^L_{h\tilde{\chi}_i^+\tilde{\chi}_j^-} = \frac{1}{\sqrt{2}}\left[\left(U_{j1}V_{i2} - \frac{\lambda}{g_2}U_{j2}V_{i3}\right)\sin\beta + \left(U_{j2}V_{i1} + \frac{\lambda}{g_2}U_{j3}V_{i2}\right)\cos\beta\right]$$

$$g^R_{h\tilde{\chi}_i^+\tilde{\chi}_j^-} = \frac{1}{\sqrt{2}}\left[\left(U_{i1}V_{j2} - \frac{\lambda}{g_2}U_{i2}V_{j3}\right)\sin\beta + \left(U_{i2}V_{j1} + \frac{\lambda}{g_2}U_{i3}V_{j2}\right)\cos\beta\right]$$

Higgs signal strengths

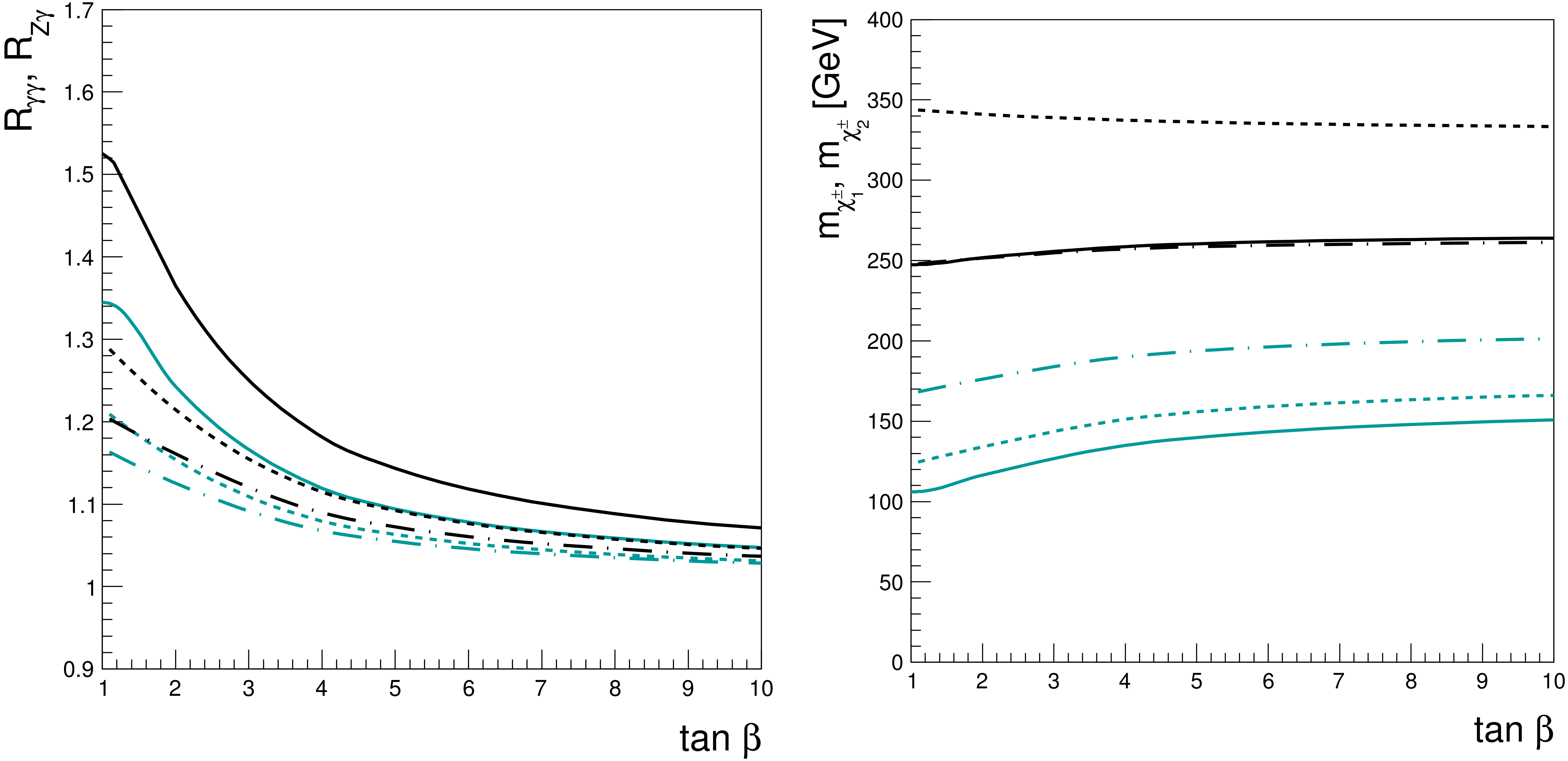


$\mu = \mu_\Sigma = M_2 = 230\,\mathrm{GeV}$

$\mu = \mu_\Sigma = 230\,\mathrm{GeV},\, M_2 = 1\,\mathrm{TeV}$

$\mu_\Sigma = M_2 = 230\,\mathrm{GeV},\, \mu = 400\,\mathrm{GeV}$

Higgs signal strengths

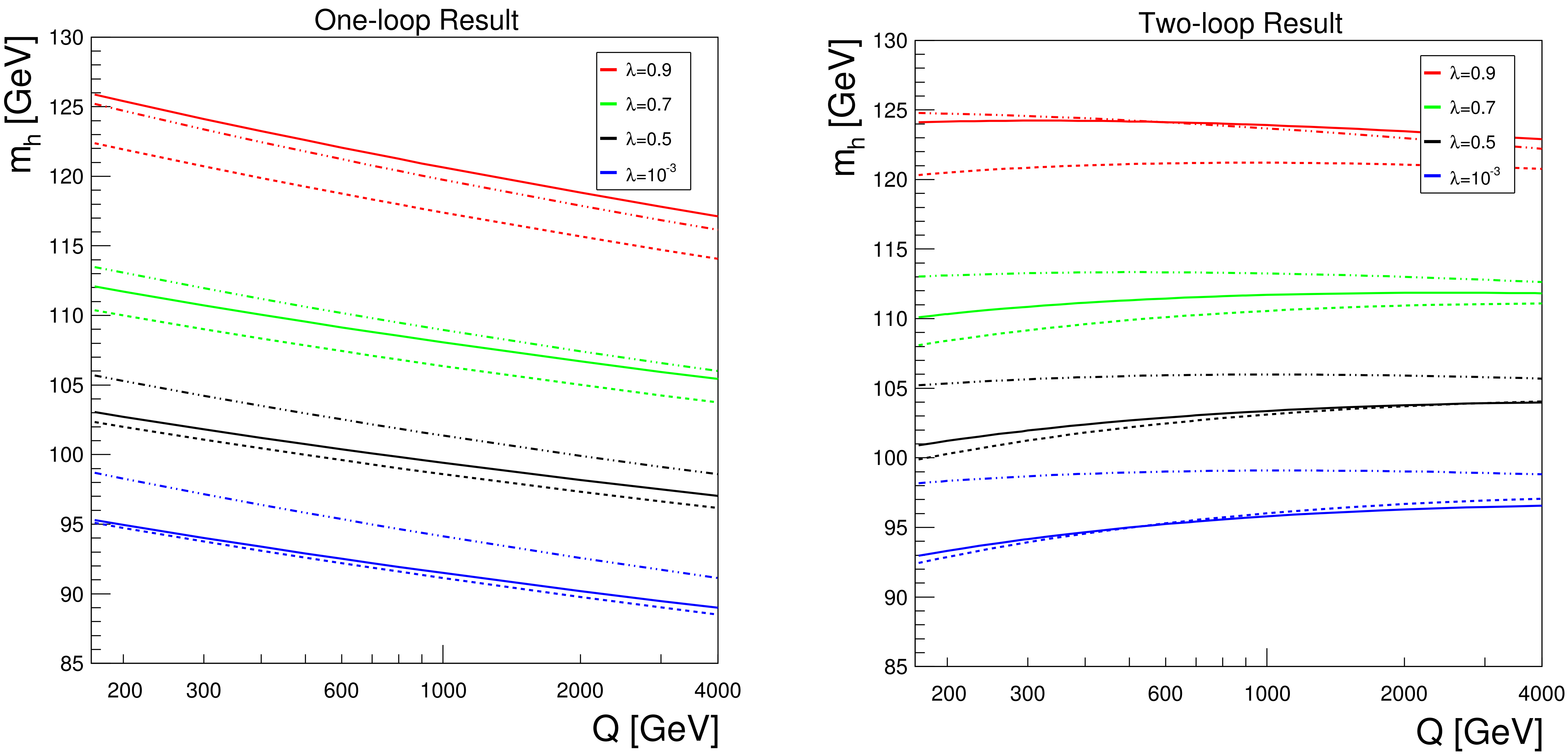


$\mu = \mu_\Sigma = M_2 = 230\,\mathrm{GeV}$

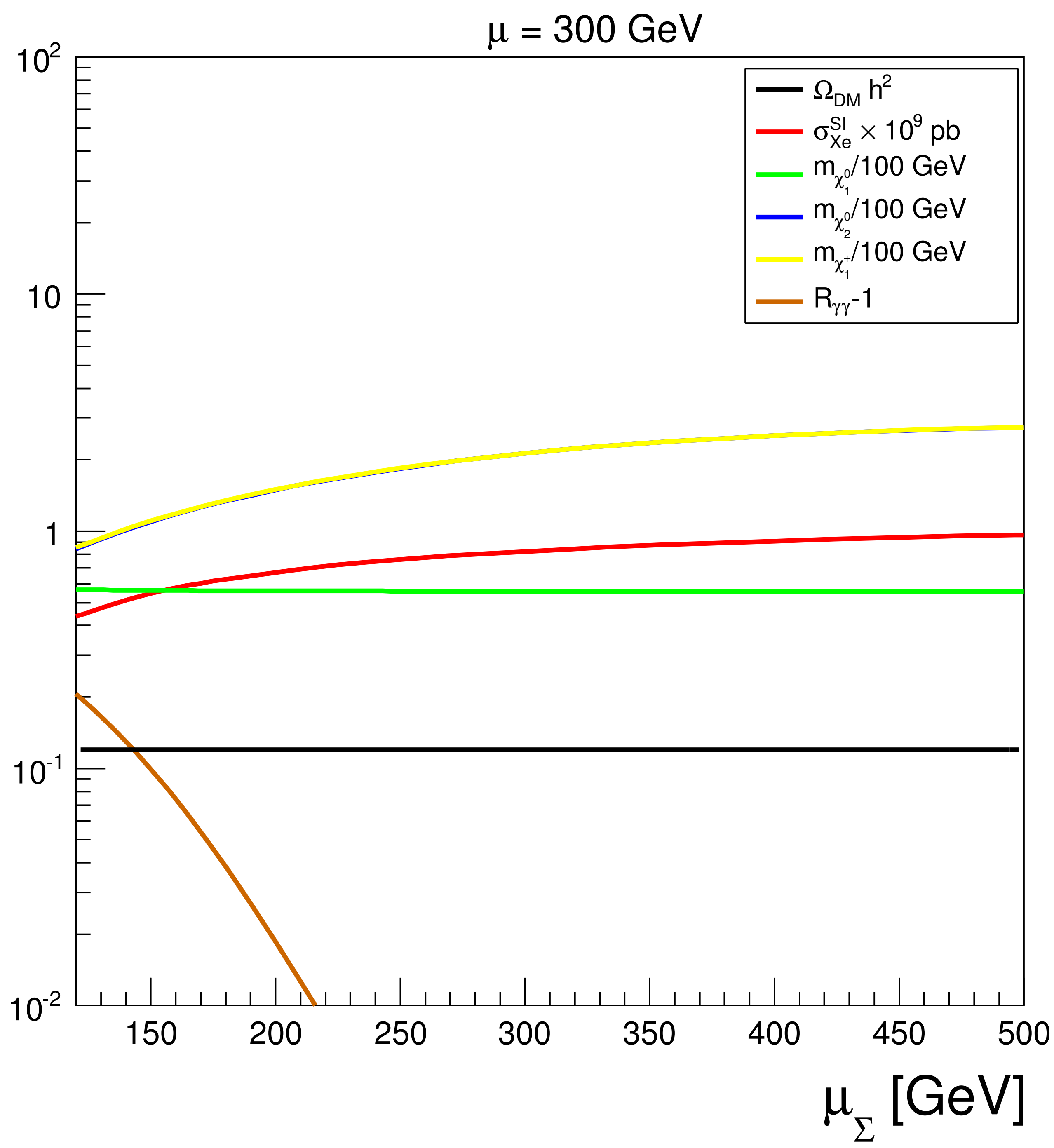
$\mu = \mu_\Sigma = 230\,\mathrm{GeV},\, M_2 = 1\,\mathrm{TeV}$

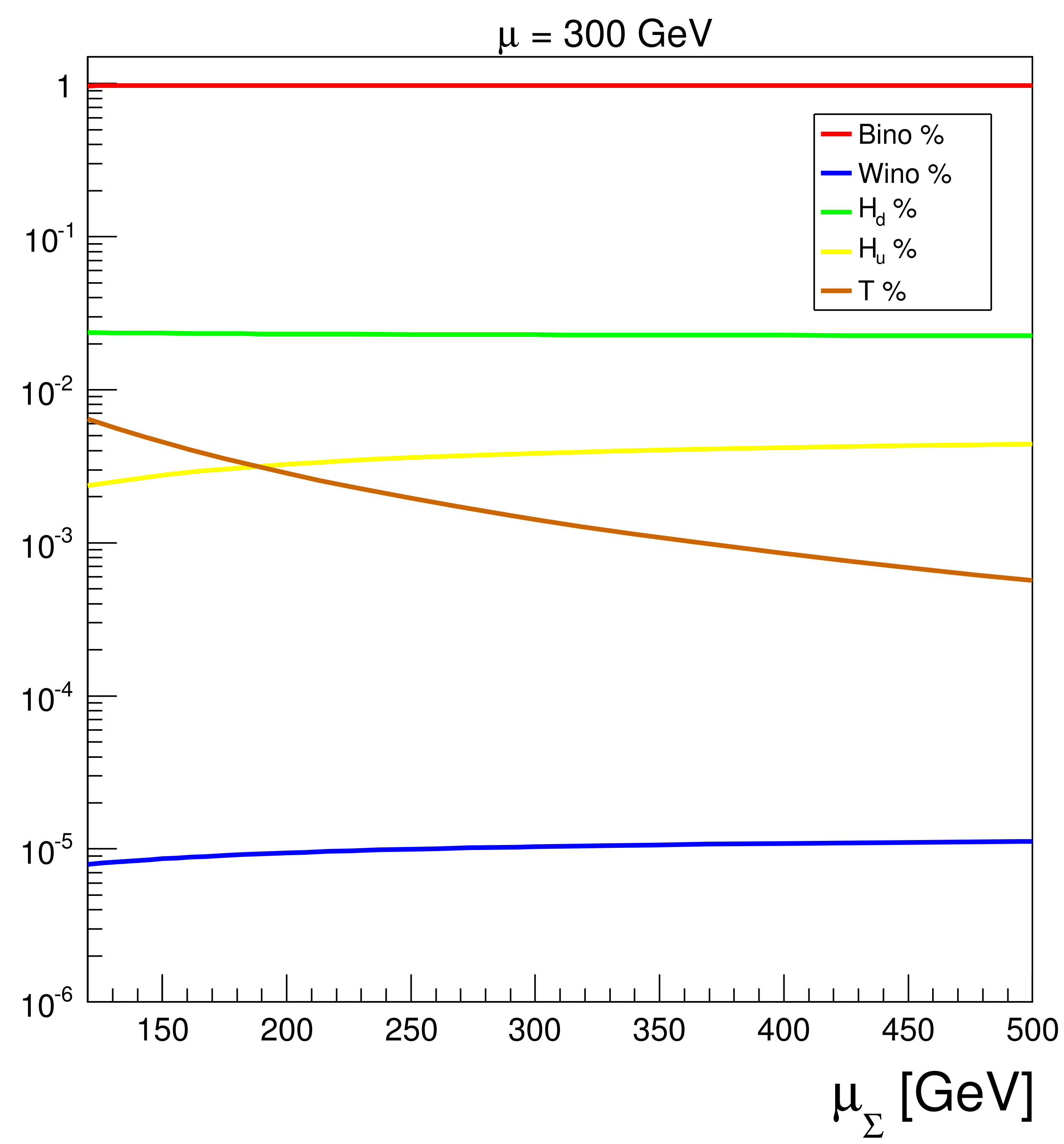
$\mu_\Sigma = M_2 = 230\,\mathrm{GeV},\, \mu = 400\,\mathrm{GeV}$

Higgs mass

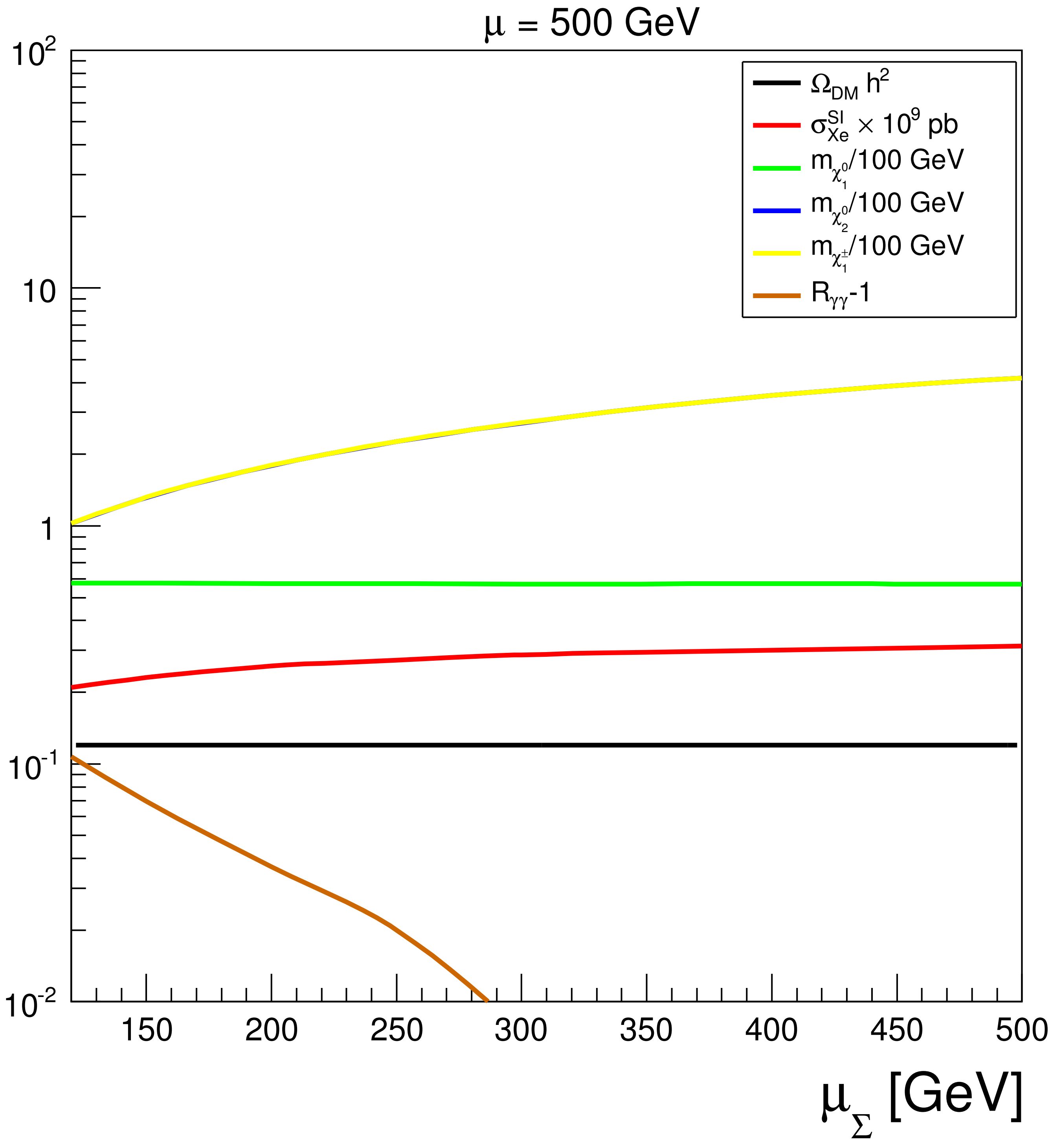

One-loop Result
Two-loop Result
m_h [GeV]
Q [GeV]
λ=0.9
λ=0.7
λ=0.5
λ=10^-3
130
125
120
115
110
105
100
95
90
85
200
300
600
1000
2000
4000

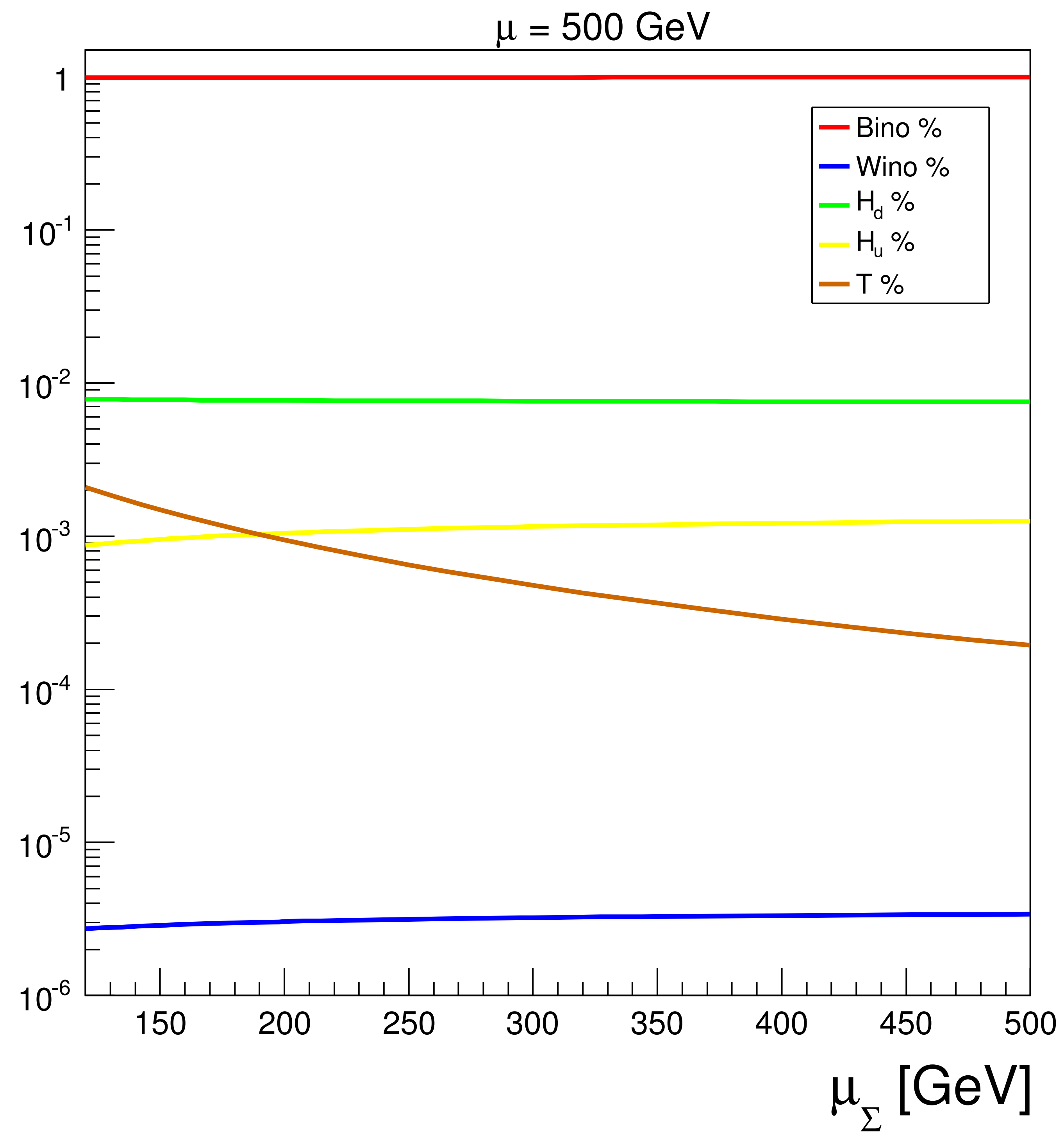
Neutralino as DM in the Higgs pole



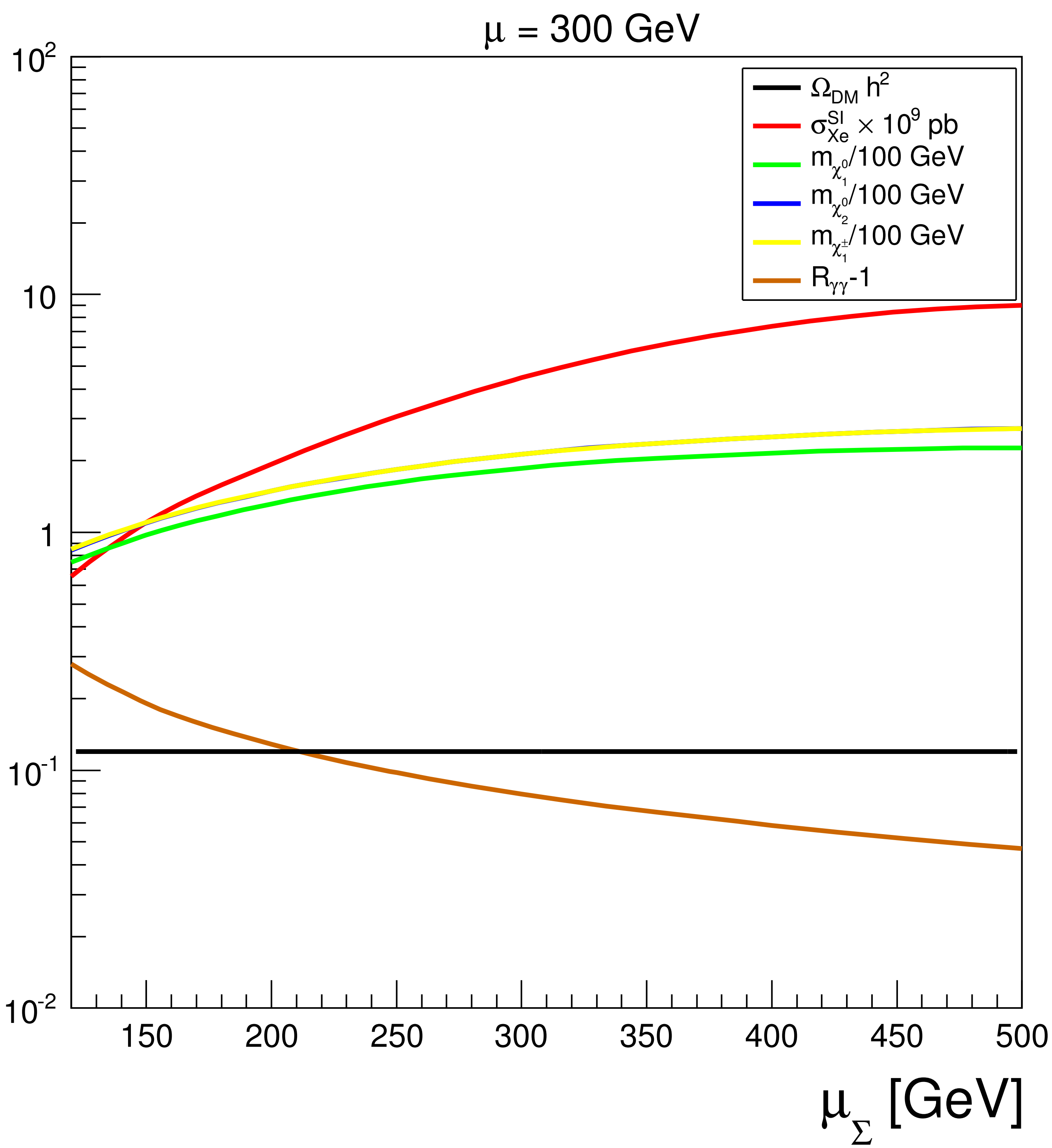


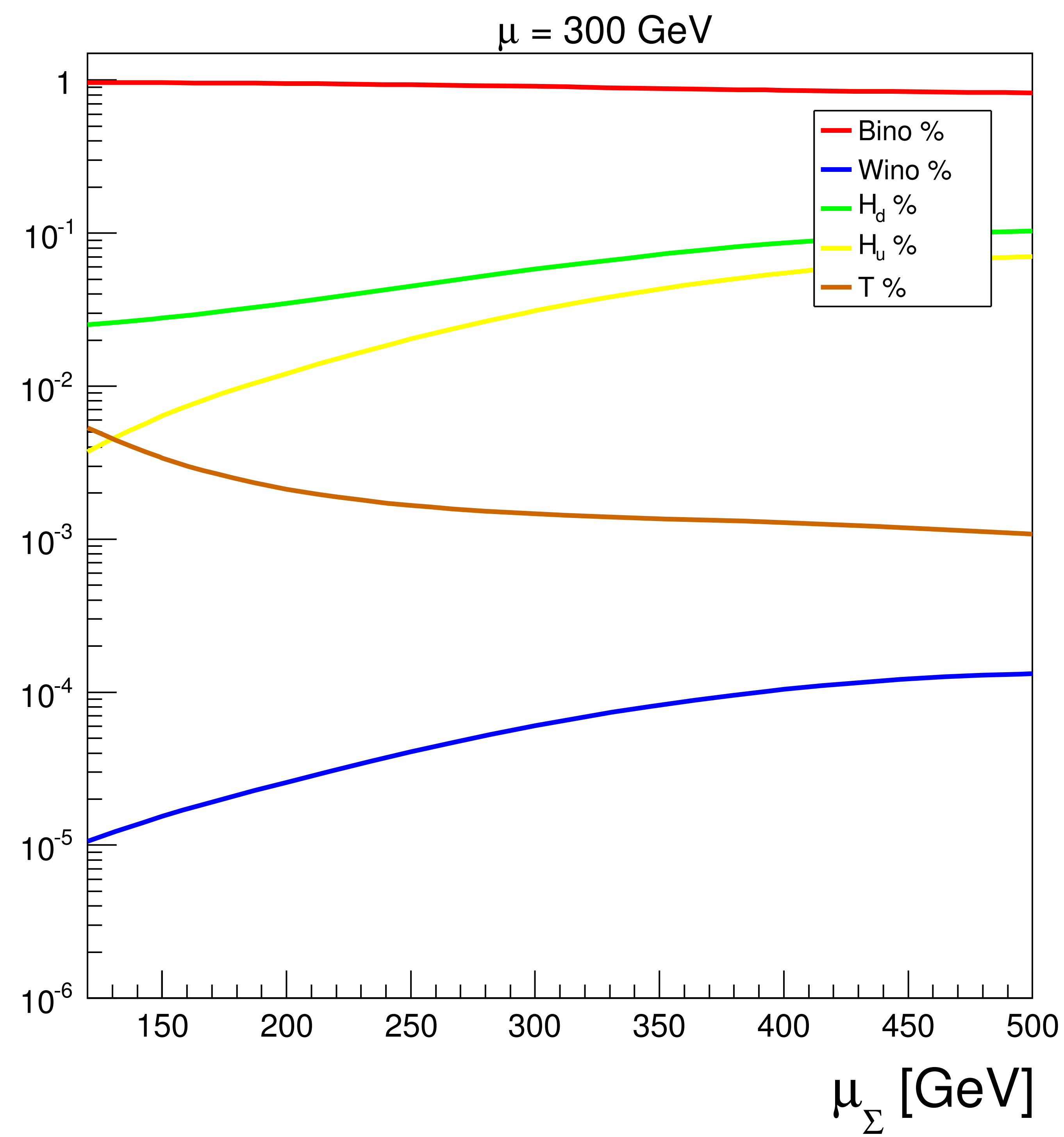
Neutralino as DM in the Higgs pole



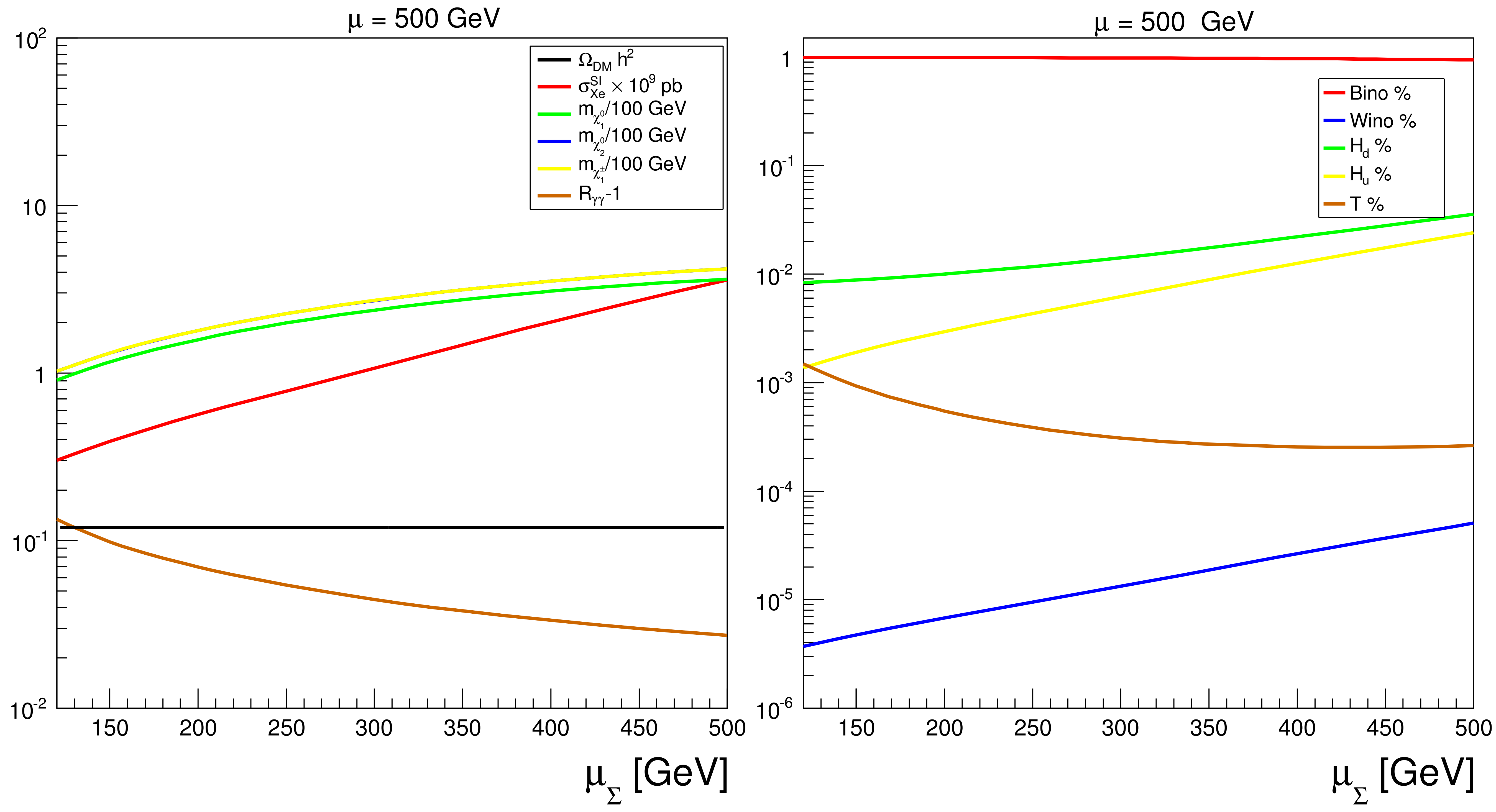


Well tempered neutralino

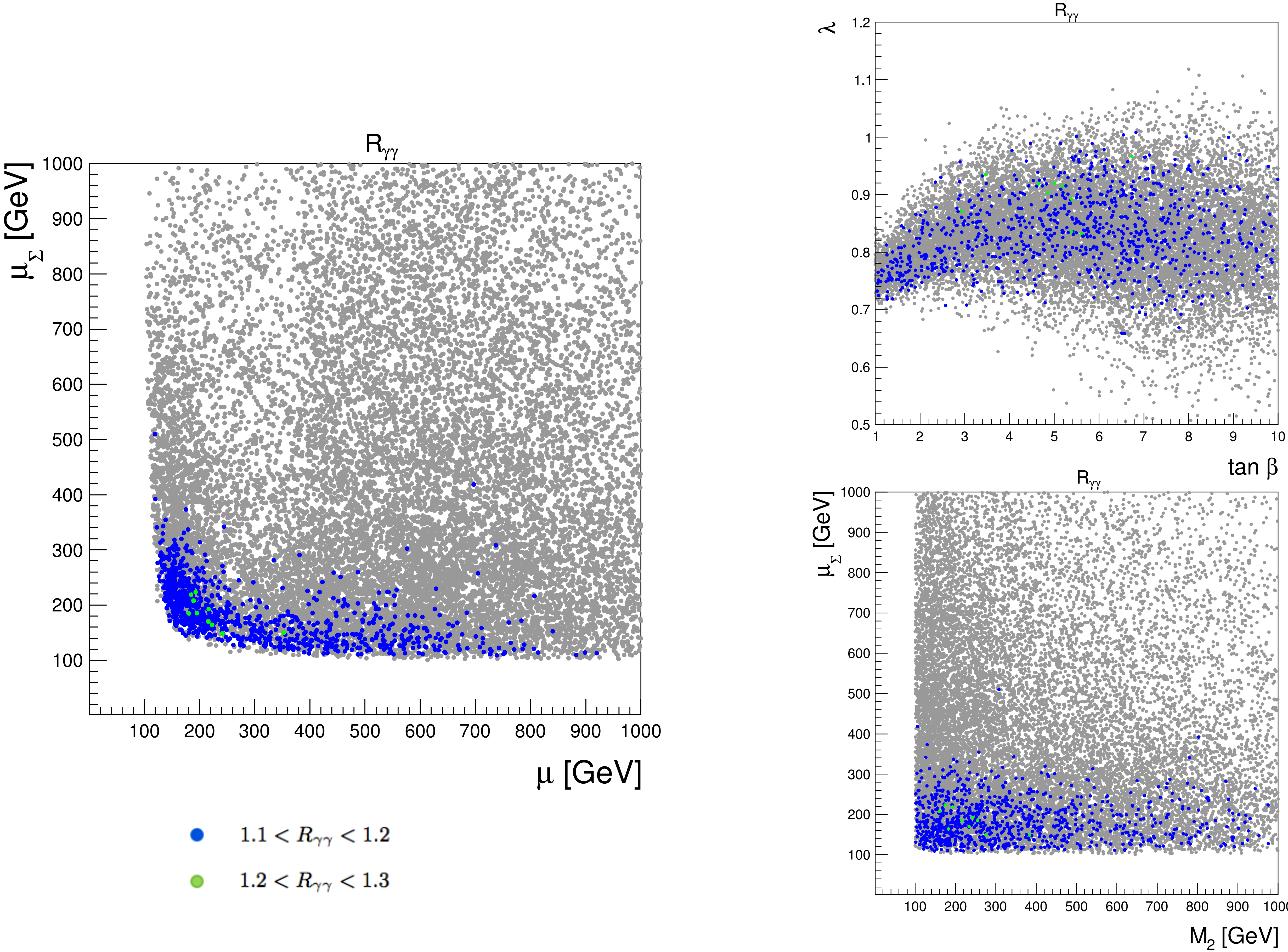




Well tempered neutralino



Neutralino as DM and Higgs



- $1.1 < R_{\gamma\gamma} < 1.2$
- $1.2 < R_{\gamma\gamma} < 1.3$

Sampling method and free parameters

PARAMETER SPACE with 7 free parameters

$$\{\theta_i\} = \{M_1, M_2, M_3, \widetilde{m}, \tan\beta, \mu, \lambda, \mu_\Sigma\}$$

Sampling with the algorithm MultiNest

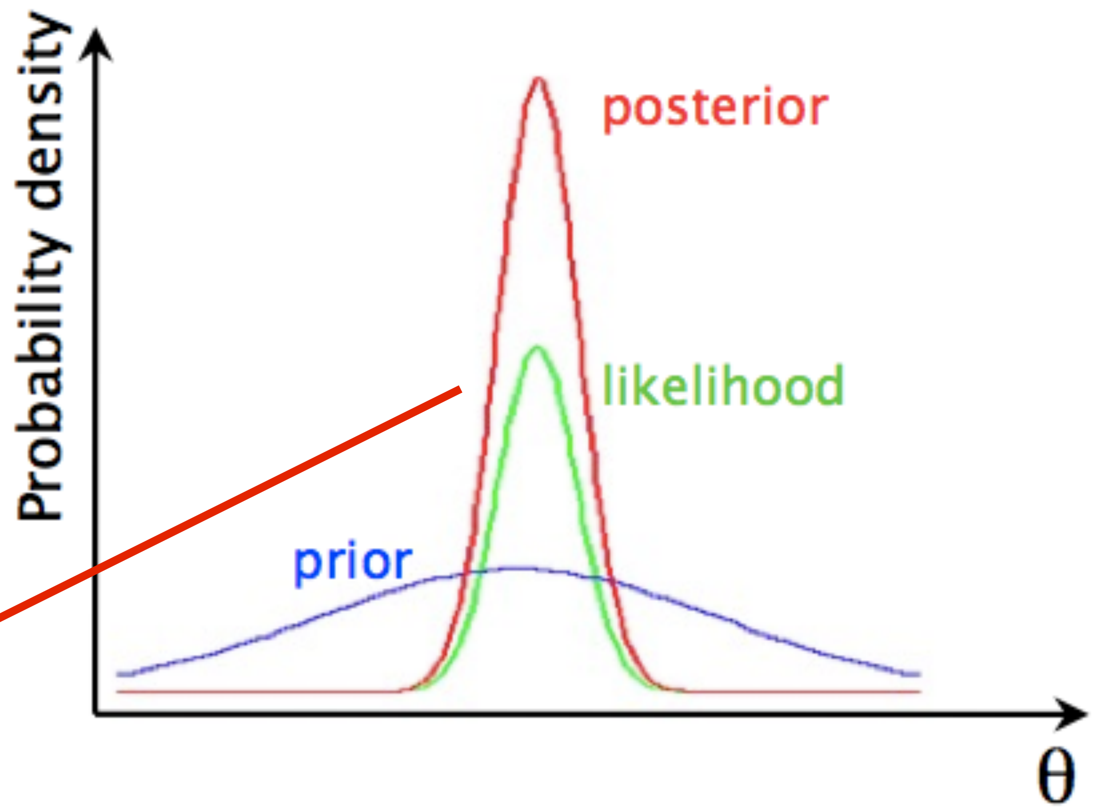
- Nested sampling
- Sampling scale as n instead of n^2 as for a random scan
- Based on Bayes theorem

Likelihood for the theoretical model given the data d

$$p(\theta_i|d) \propto \mathcal{L}(d|\theta_i)\pi(\theta_i)$$

Posterior probability function = result

Priors on the theoretical model



For the results used a sample extracted randomly from the pdf distribution, no statistical meaning