Impact of non-minimal squark flavour violation on the neutralino relic density

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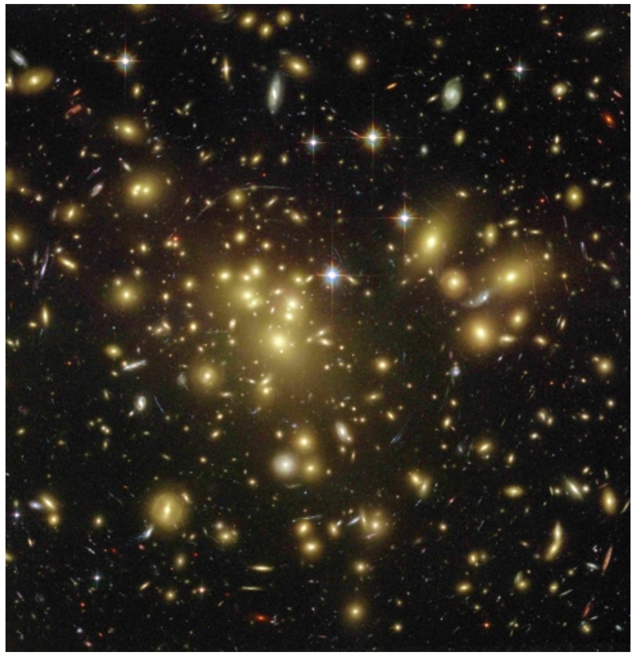
Outline

- Introduction: supersymmetric dark matter
- Neutralino relic density: constraining the cMSSM parameter space
- Phenomenology of non minimal flavour violation
- Numerical results
- Conclusion and perspectives

Introduction : supersymmetric dark matter

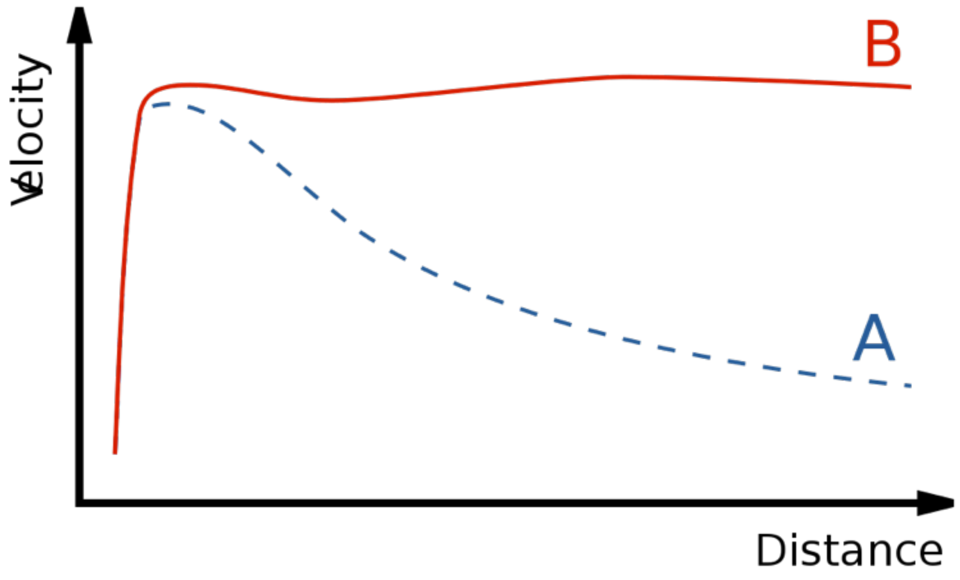
Some dark matter evidences

Gravitational lensing in galaxy clusters

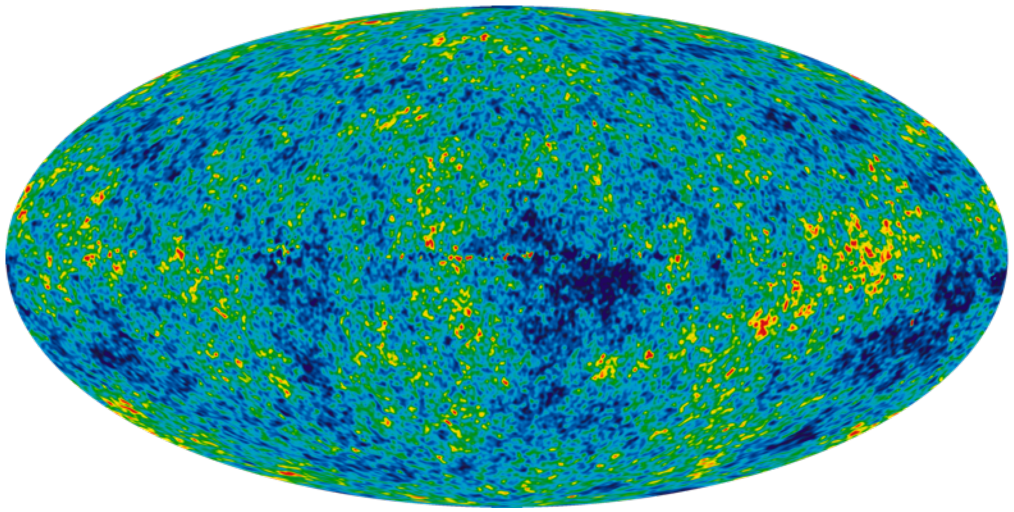


Bullet cluster

Galaxies rotation curves



Cosmic microwave background



SUSY provides WIMP candidates - I

- Best dark matter candidate: Weakly Interacting Massive Particle
- Need to extend the Standard Model
- Supersymmetry relates bosons and fermions
- Here we consider the Minimal Supersymmetric Standard Model (MSSM):

Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name
$\tilde{q}_L$, $\tilde{q}_R$	left and right squark	$\tilde{q}_1$, $\tilde{q}_2$	squark 1 and 2
$\tilde{l}_L$, $\tilde{l}_R$	left and right slepton	$\tilde{l}_1$, $\tilde{l}_2$	slepton 1 and 2
$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
$\tilde{g}$	gluino	$\tilde{g}$	gluino
$\tilde{W}^{\pm}$	charged winos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
$\tilde{H}_1^-$	higgsino $-$		
$\tilde{H}_2^+$	higgsino $+$		
$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
$\tilde{W}^3$	neutral wino		
$\tilde{H}^0_{1,2}$	neutral higgsinos		

SUSY provides WIMP candidates - II

- In MSSM, lightest neutralino is often the Lightest Supersymmetric Partner (LSP)

- Assuming R-parity, the LSP is stable

  → good dark matter candidate !

Constrained MSSM («cMSSM»):

- Supersymmetry breaking mediated by gravitational interaction

- Reduction to 5 parameters at GUT scale: m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}(\mu)$

- Would like to constraint this parameter space from dark matter relic density

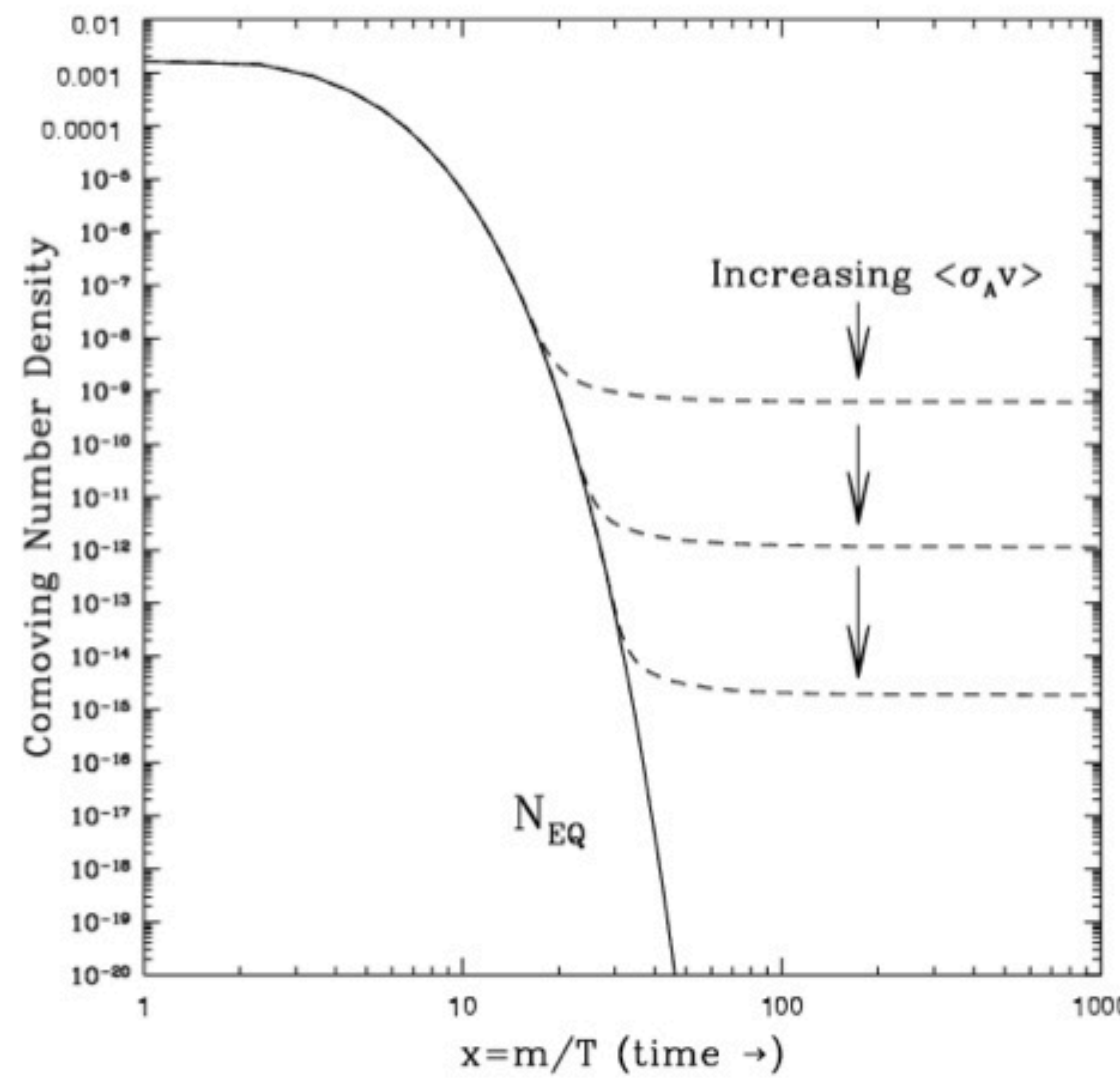
Neutralino relic density: constraining the cMSSM parameter space

Neutralinos (co)annihilation and relic density

- When temperature is high enough, LSP in thermal equilibrium with SM particles

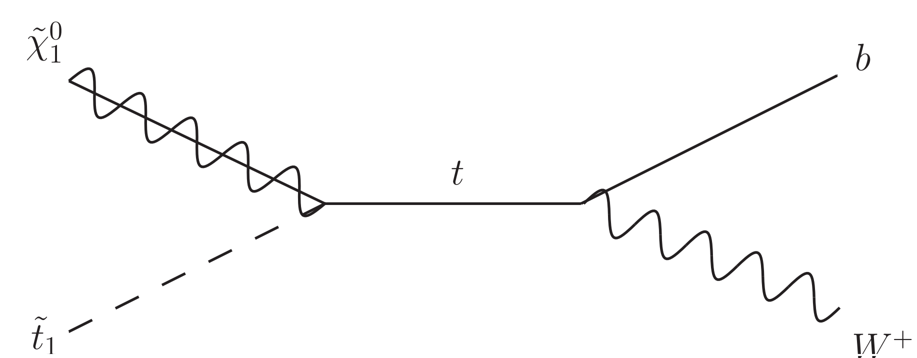
- Universe expands: annihilation lets density decrease

- Annihilation rate lower than expansion rate: freeze-out $\rightarrow \Omega_c h^2 \sim \dfrac{1}{\langle \sigma_{\rm ann} v \rangle}$



- Coannihilation with sfermion also important when $m_{\tilde{\chi}} \sim m_{\tilde{f}}$

- Possible with stop or stau in cMSSM



Phenomenology of relic density

- Generate spectrum and low energy observables with SPheno

  [W. Porod, arXiv:hep-ph/0301101]

- Calculate relic density with MicrOmegas

  [G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, arXiv:hep-ph/1005.4133]

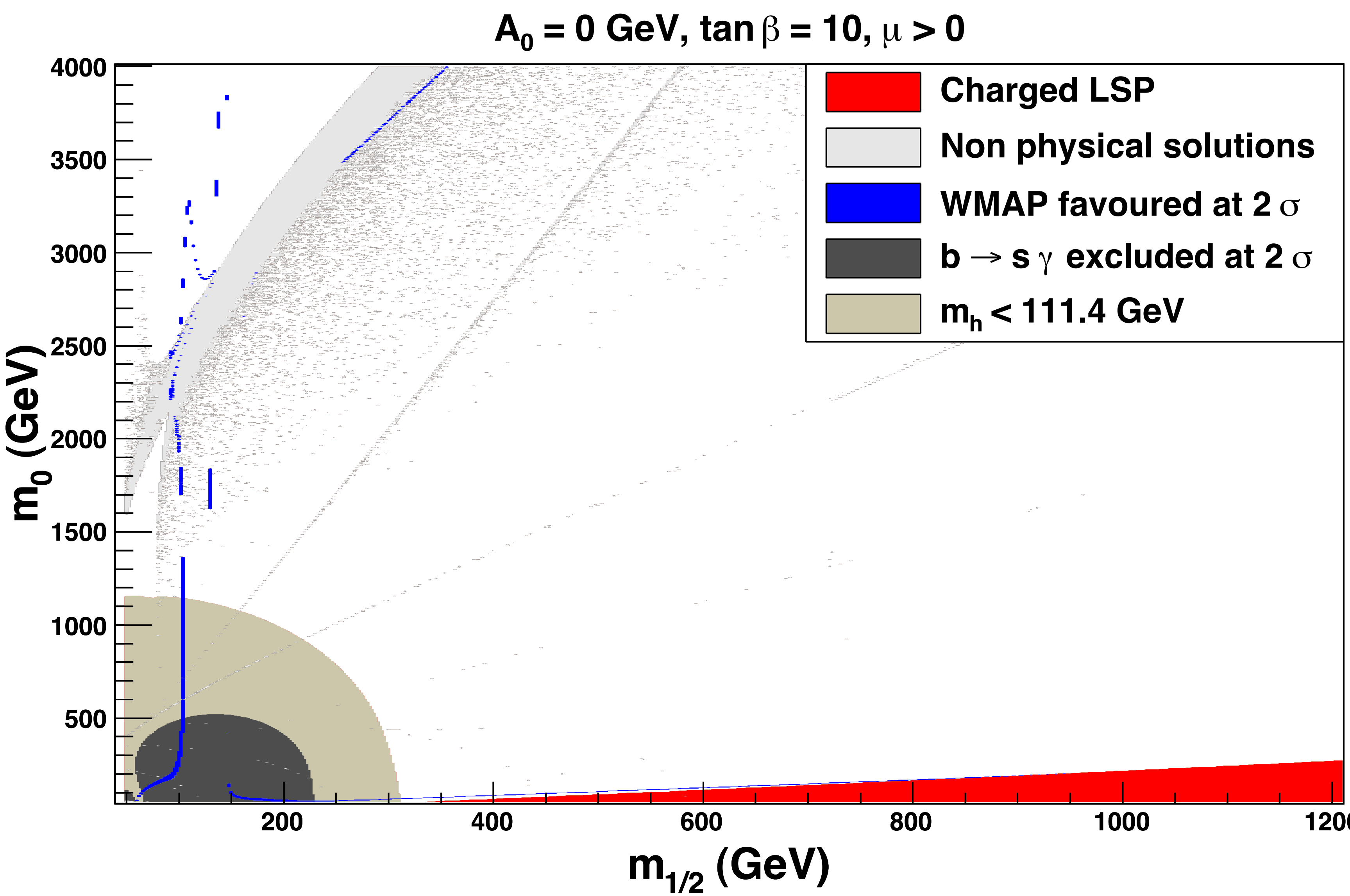
- Apply constraints:

$$\begin{aligned} \Omega.h^2 &= 0.1126 \pm 0.0036 \\ \mathrm{BR}(b \to s\gamma) &= (3.55 \pm 0.26 \pm 0.23).10^{-4} \\ m_h &> (114.4 - 3)\ \mathrm{GeV} \end{aligned}$$

Phenomenology of relic density

Relic density can drop to observed value thanks to several processes:

- annihilation into W pairs via chargino exchange (focus point)
- coannihilation with stau (along the stau-LSP forbidden region)
- annihilation into quark pairs (Z pole resonance)



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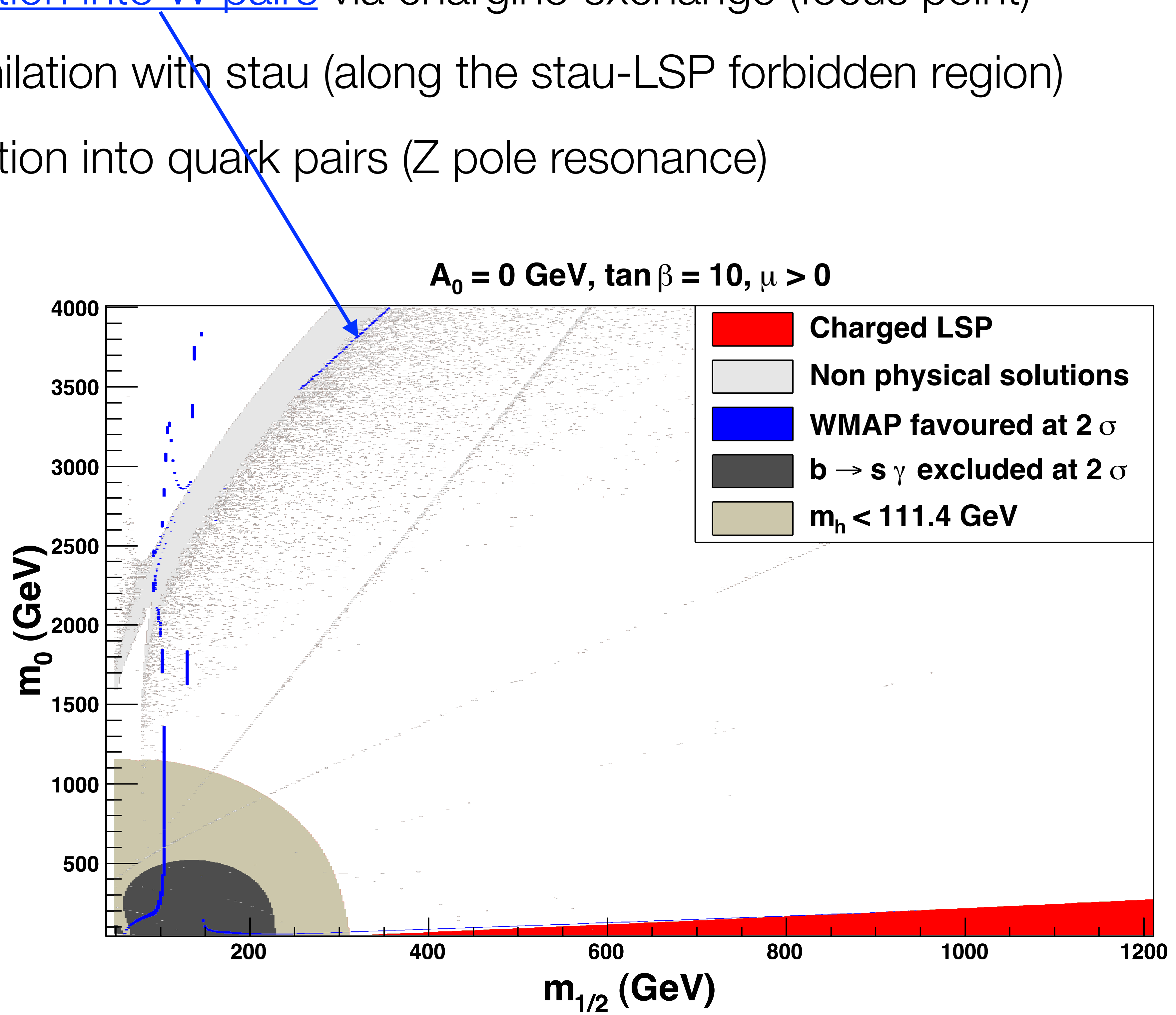

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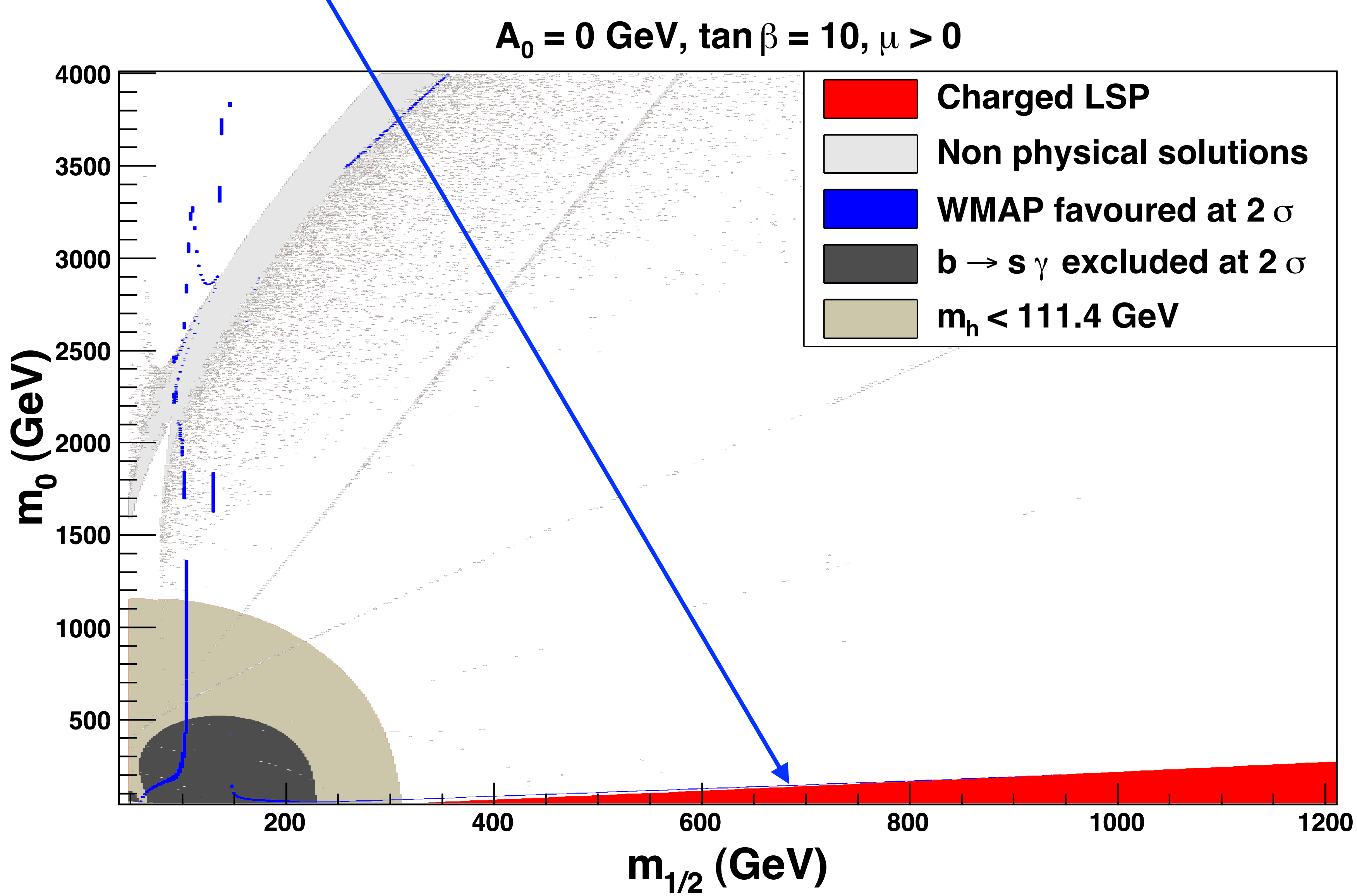

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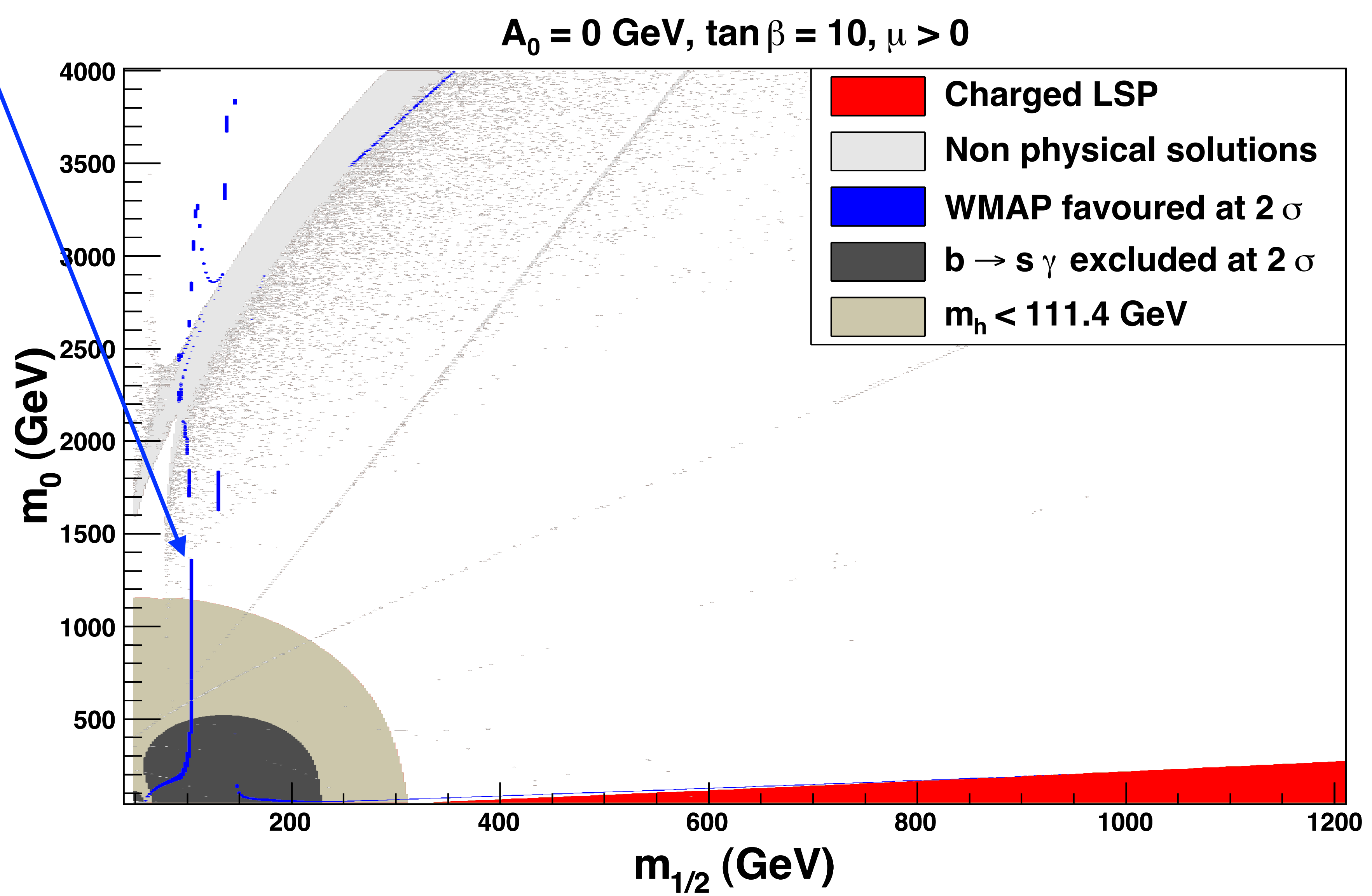
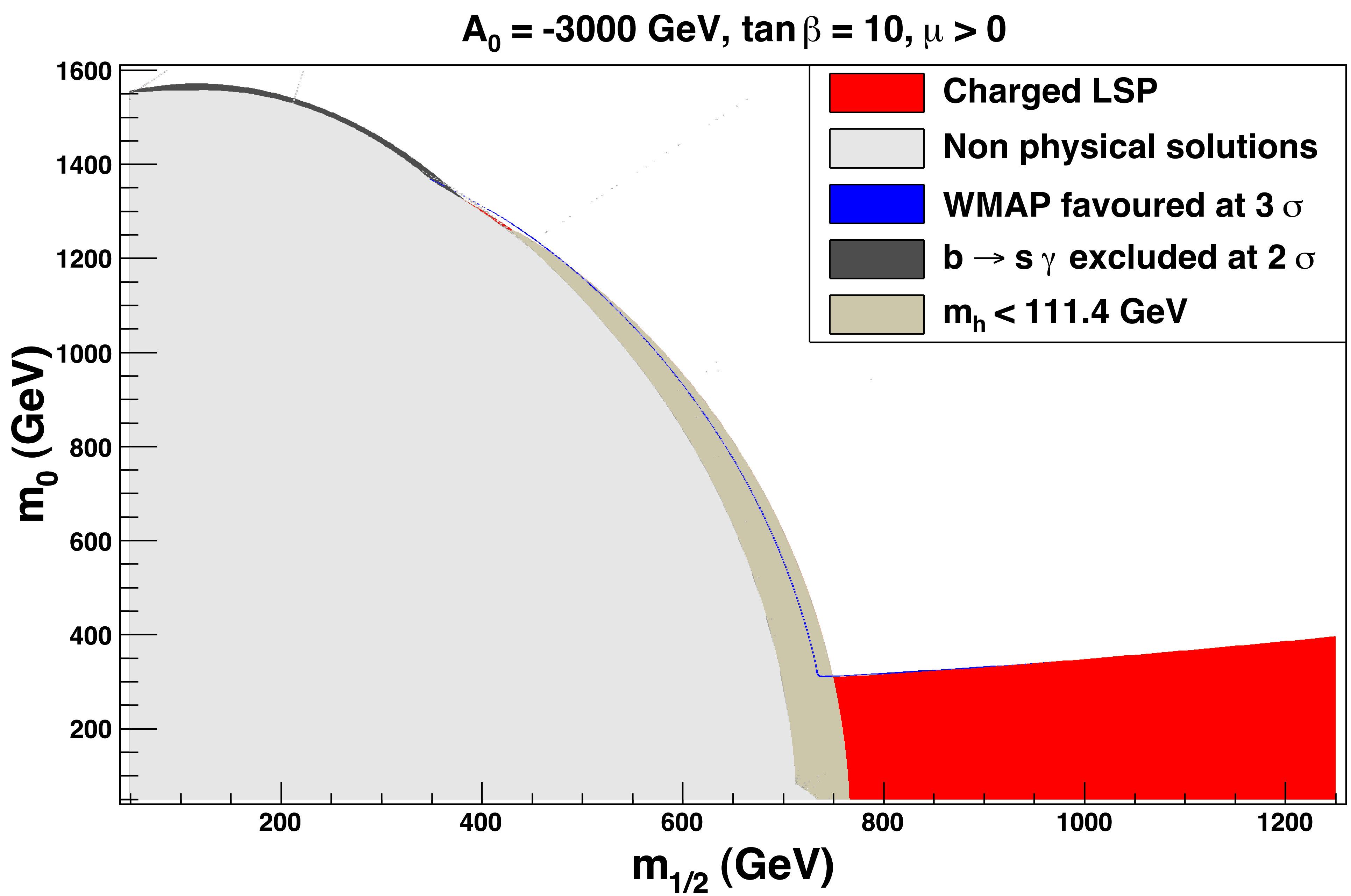


Phenomenology of relic density

Larger $|A_0|$ → larger splitting → lighter stop → coannihilation



Phenomenology of non minimal flavour violation

Constrained Minimal Flavour Violation

In cMFV, all flavour violation sources related to CKM matrix:

$$\mathcal{M}^2_{\tilde{U}} = \begin{pmatrix} V_{\rm CKM}\, m^2_{\tilde{Q}}\, V^\dagger_{\rm CKM} + m^2_U + \Delta_L & m_U(A_{\tilde{U}} - \mu\cot\beta) \\ m_U(A_{\tilde{U}} - \mu\cot\beta) & m^2_{\tilde{U}} + m^2_U + \Delta_R \end{pmatrix}$$

$$\Delta_L = (T^3_q - e_q \sin^2\theta_W)\cos(2\beta)\, m^2_Z\, \mathbb{1}_{3\times 3}$$

$$\Delta_R = e_q \sin^2\theta_W \cos(2\beta)\, m^2_Z\, \mathbb{1}_{3\times 3}$$

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Soft breaking mass matrices

$$m^2_{\tilde{U}} = \begin{pmatrix} m^2_{\tilde{U}_u} & 0 & 0 \\ 0 & m^2_{\tilde{U}_c} & 0 \\ 0 & 0 & m^2_{\tilde{U}_t} \end{pmatrix},\; m^2_{\tilde{Q}} = \begin{pmatrix} m^2_{\tilde{Q}_{u,d}} & 0 & 0 \\ 0 & m^2_{\tilde{Q}_{c,s}} & 0 \\ 0 & 0 & m^2_{\tilde{Q}_{t,b}} \end{pmatrix}$$

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$$\Delta_R = e_q \sin^2\theta_W \cos(2\beta)\, m^2_Z\, \mathbb{1}_{3\times 3}$$

Trilinear couplings

$$m_U A_{\tilde{U}} = \begin{pmatrix} m_u A_{\tilde{u}} & 0 & 0 \\ 0 & m_c A_{\tilde{c}} & 0 \\ 0 & 0 & m_t A_{\tilde{t}} \end{pmatrix}$$

Beyond minimal flavour violation - I

- Squark and quark mass matrices renormalizations are different

- New flavour violation sources can appears when embedding SUSY in GUT

$\longrightarrow$ off-diagonal terms in the susy breaking masses and trilinear couplings matrices

$$m^2_{\tilde{U}} = \begin{pmatrix} m^2_{\tilde{U}_u} & \Delta^{uc}_{RR} & \Delta^{ut}_{RR} \\ \Delta^{cu}_{RR} & m^2_{\tilde{U}_c} & \Delta^{ct}_{RR} \\ \Delta^{tu}_{RR} & \Delta^{tc}_{RR} & m^2_{\tilde{U}_t} \end{pmatrix}, \; m^2_{\tilde{Q}} = \begin{pmatrix} m^2_{\tilde{Q}_{u,d}} & \Delta^{uc,ds}_{LL} & \Delta^{ut,db}_{LL} \\ \Delta^{cu,sd}_{LL} & m^2_{\tilde{Q}_{c,s}} & \Delta^{ct,sb}_{LL} \\ \Delta^{tu,bd}_{LL} & \Delta^{tc,bs}_{LL} & m^2_{\tilde{Q}_{t,b}} \end{pmatrix}$$

$$m_U A_{\tilde{U}} = \begin{pmatrix} m_u A_{\tilde{u}} & \Delta^{uc}_{LR,RL} & \Delta^{ut}_{LR,RL} \\ \Delta^{cu}_{LR,RL} & m_c A_{\tilde{c}} & \Delta^{ct}_{LR,RL} \\ \Delta^{tu}_{LR,RL} & \Delta^{tc}_{LR,RL} & m_t A_{\tilde{t}} \end{pmatrix}$$

Then, diagonalization leads to 6 mass eigenstates $\tilde{u}_i$ $(m_{\tilde{u}_1} < ... < m_{\tilde{u}_6})$

Beyond minimal flavour violation - II

$$m^2_{\tilde{U}} = \begin{pmatrix} m^2_{\tilde{U}_u} & \Delta^{uc}_{RR} & \Delta^{ut}_{RR} \\ \Delta^{cu}_{RR} & m^2_{\tilde{U}_c} & \Delta^{ct}_{RR} \\ \Delta^{tu}_{RR} & \Delta^{tc}_{RR} & m^2_{\tilde{U}_t} \end{pmatrix}, \; m^2_{\tilde{Q}} = \begin{pmatrix} m^2_{\tilde{Q}_{u,d}} & \Delta^{uc,ds}_{LL} & \Delta^{ut,db}_{LL} \\ \Delta^{cu,sd}_{LL} & m^2_{\tilde{Q}_{c,s}} & \Delta^{ct,sb}_{LL} \\ \Delta^{tu,bd}_{LL} & \Delta^{tc,bs}_{LL} & m^2_{\tilde{Q}_{t,b}} \end{pmatrix}$$

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Dimensionless parametrization:

$$\begin{aligned} \Delta^{qq'}_{RR} &= \delta^{qq'}_{RR} m_{\tilde{U}_q} m_{\tilde{U}_{q'}} \\ \Delta^{qq'}_{LL} &= \delta^{qq'}_{LL} m_{\tilde{Q}_q} m_{\tilde{Q}_{q'}} \\ \Delta^{qq'}_{LR} &= \delta^{qq'}_{LR} m_{\tilde{Q}_q} m_{\tilde{U}_{q'}} \\ \Delta^{qq'}_{RL} &= \delta^{qq'}_{RL} m_{\tilde{U}_q} m_{\tilde{Q}_{q'}} \end{aligned}$$

Constraints on non minimal flavour violation

- FCNC measurements highly constrains mixing with the first generation

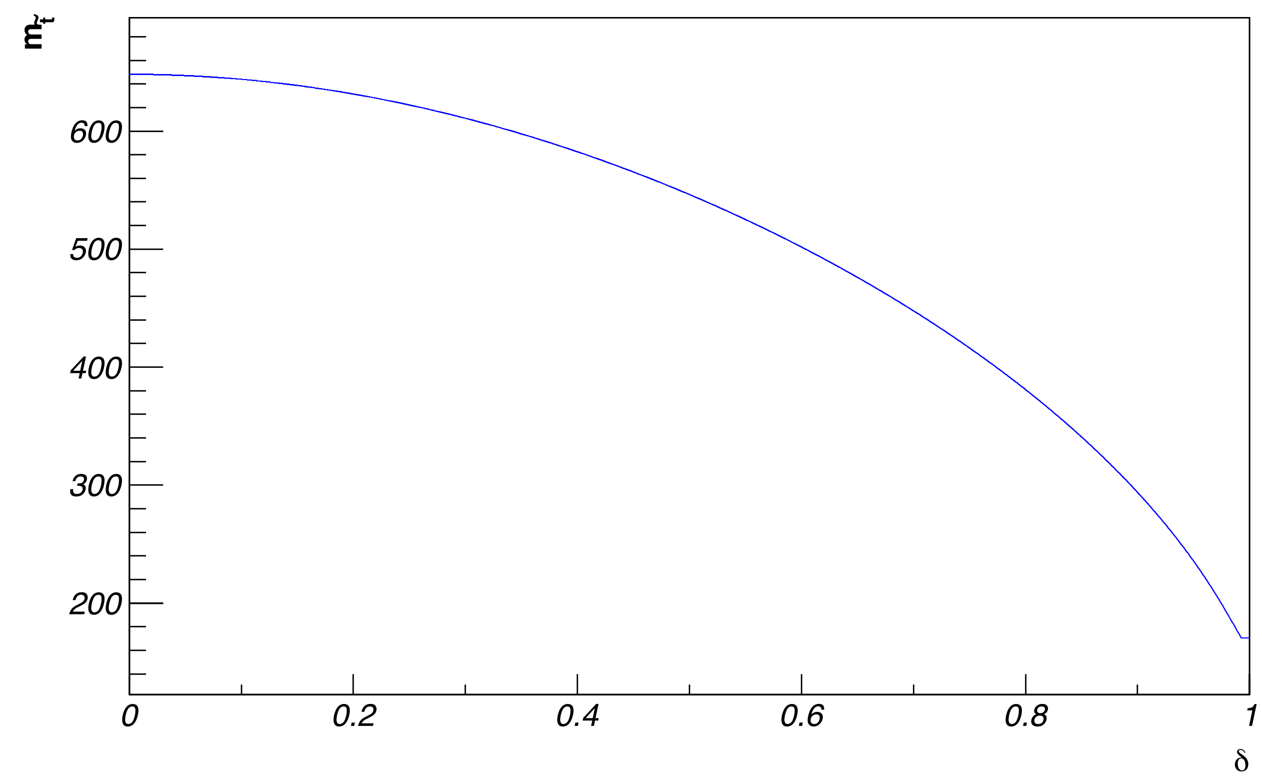
- Mixing between generations 2 and 3 less constrained

- Mixing in the right-right sector also less constrained

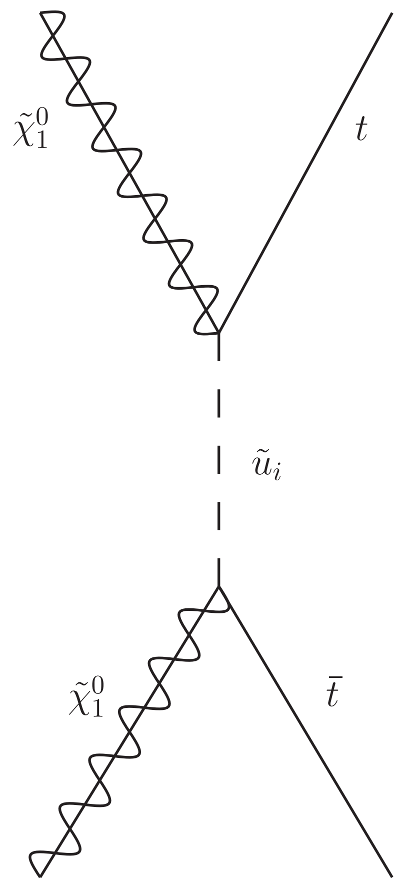
$\rightarrow \delta_{RR}^{ct} = \delta_{RR}^{tc} = \delta_{RR}^{23} \equiv \delta$ considered here

- Use the strongest flavour constraint here: $\mathrm{BR}(b \rightarrow s\gamma)$

Phenomenological effects: annihilation - I



Larger mixing leads to lighter squark after diagonalization...

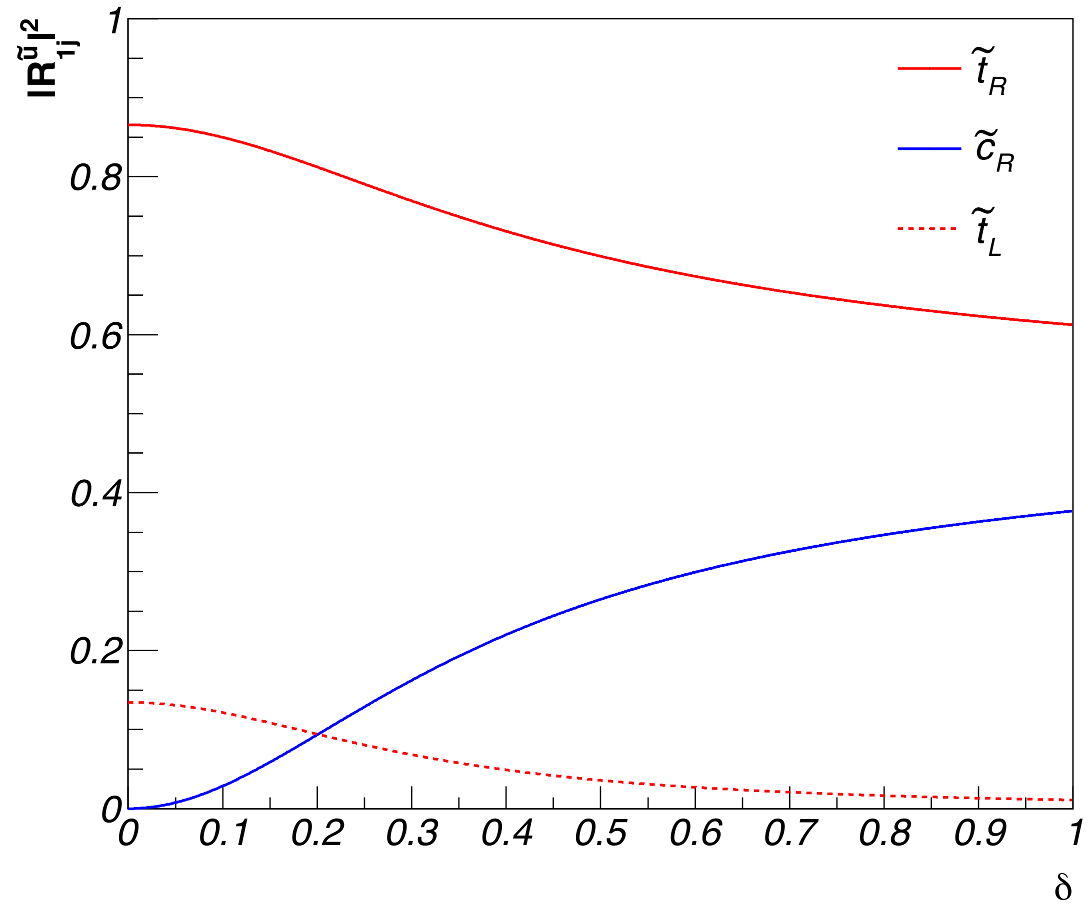


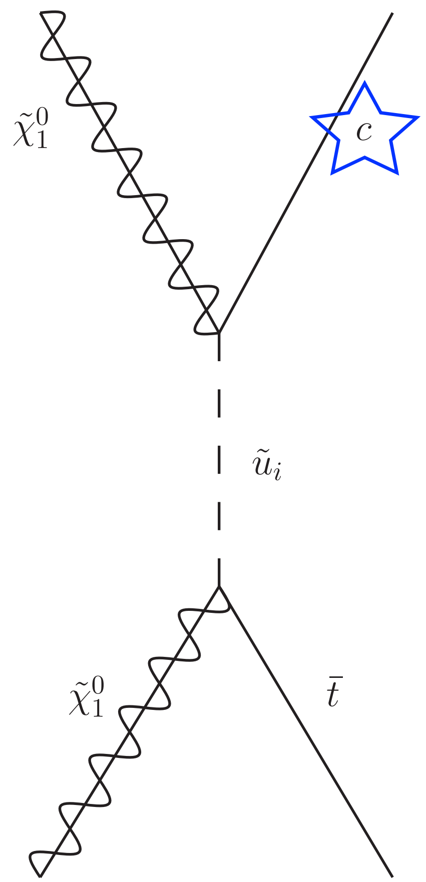
...which can enhances Neutralino annihilation into quark pairs via squark exchange

Phenomenological effects: annihilation - II

Modification of the squark content

$\longrightarrow$ new couplings and channels





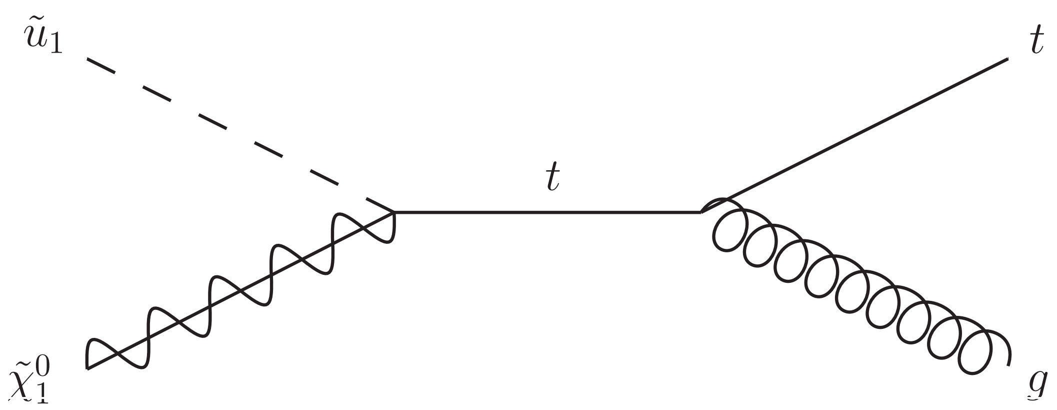
$$\sim \sum_{i=1}^{6} \frac{1}{t - m_{\tilde u_i}} R_{\tilde u_i, \tilde c_{L/R}} R^*_{\tilde u_i, \tilde t_{L/R}}$$

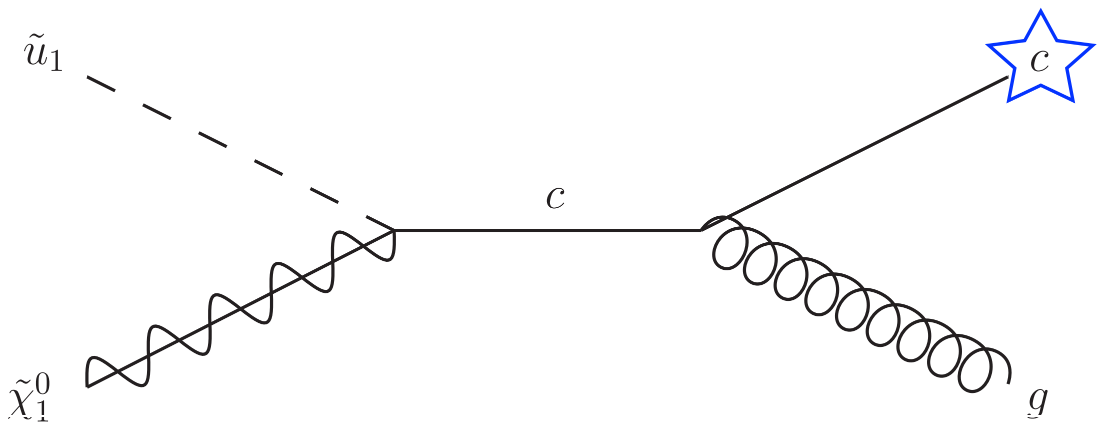
$\longrightarrow$ 0 in cMFV
$\longrightarrow$ in NMFV, channel allowed...
$\longrightarrow$ ...and kinematically favoured !

Phenomenological effects - coannihilation

- Decreasing LSP-NLSP mass difference increases exponentially the coannihilation contribution → Coannihilation extremely sensitive to the stop mass !

- New channels also present :

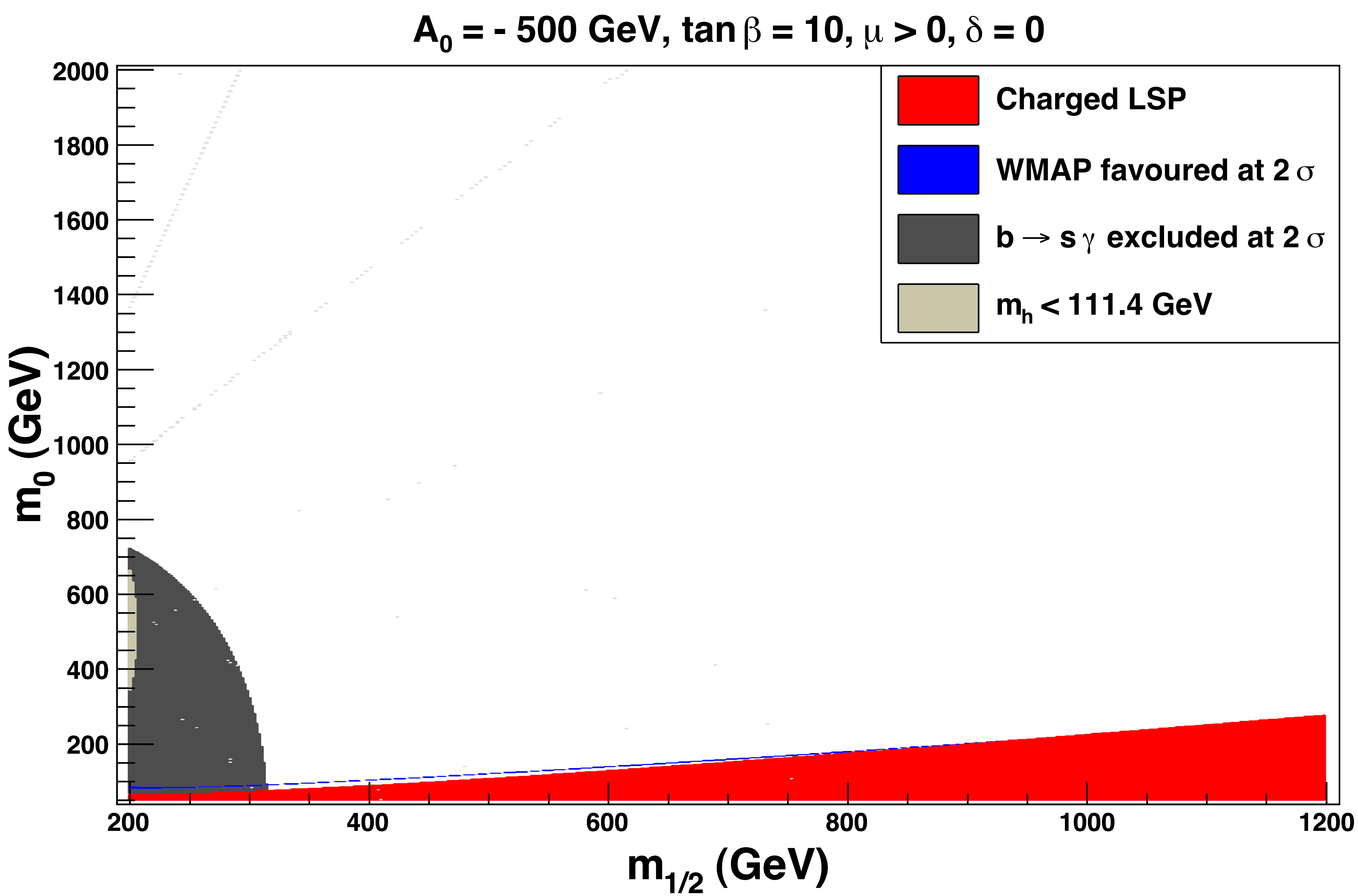




Numerical results

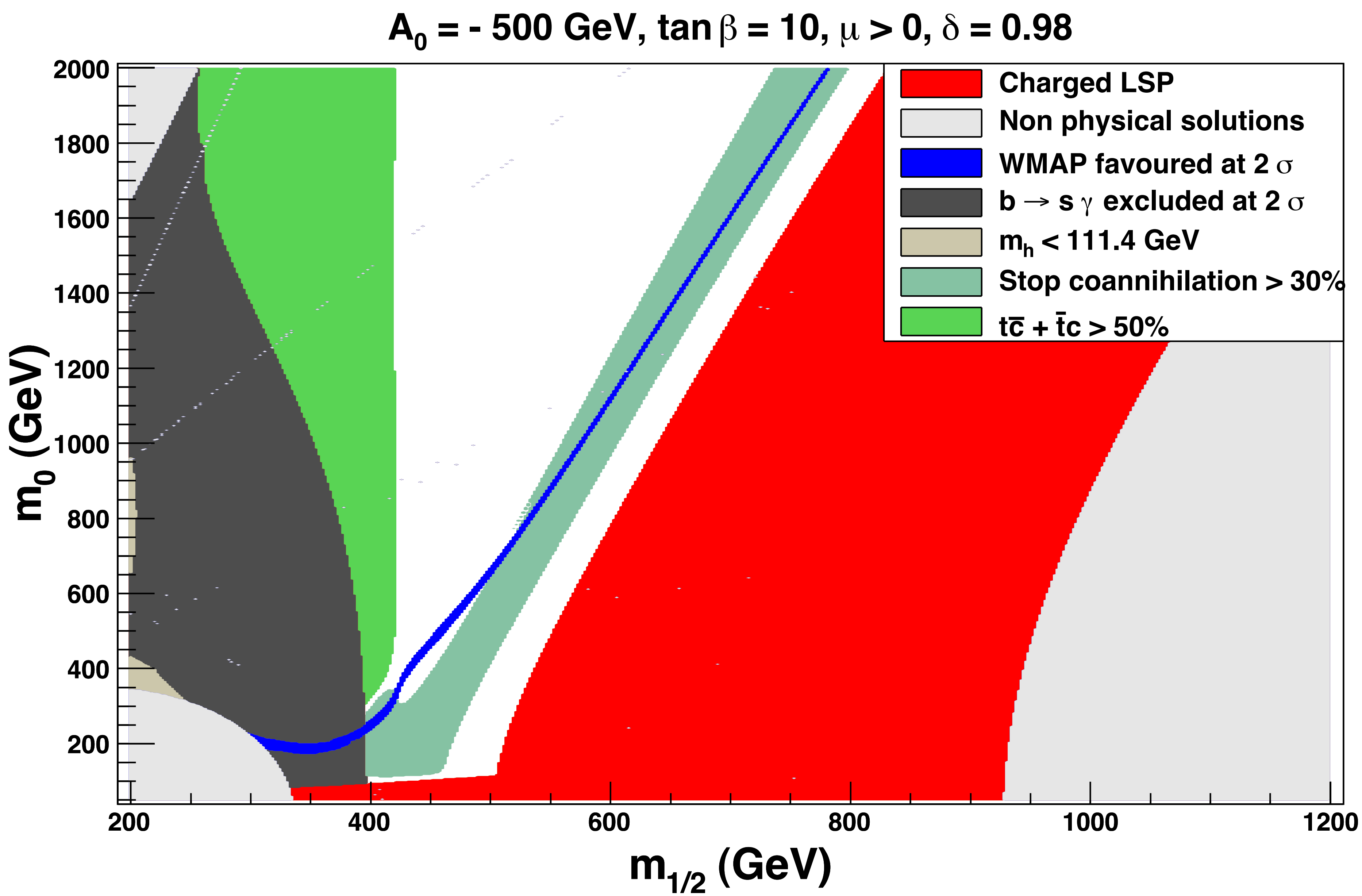
Numerical results

- Generate NMFV model with SARAH [F. Staub, arXiv:hep-ph/0806.0538]
- CalcHEP model [A. Pukhov, arXiv:hep-ph/0412191]
- Implemented in MicrOmegas



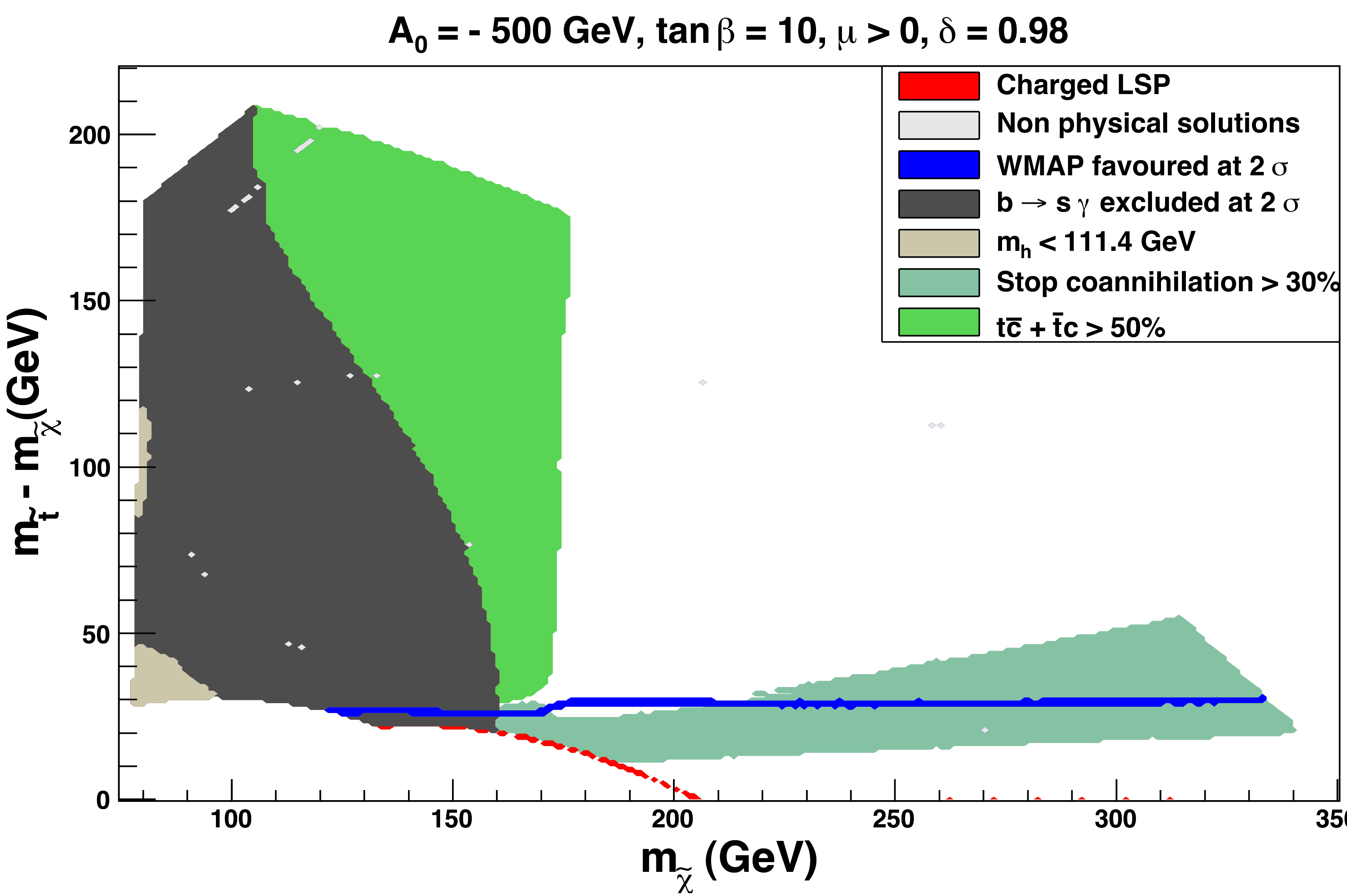
Numerical results

- Large off-diagonal elements → new allowed regions
- New contributions: stop coannihilation and neutralino annihilation into $c\bar{t}$
- Most of this new region not excluded by $\mathrm{BR}(b \to s\gamma)$



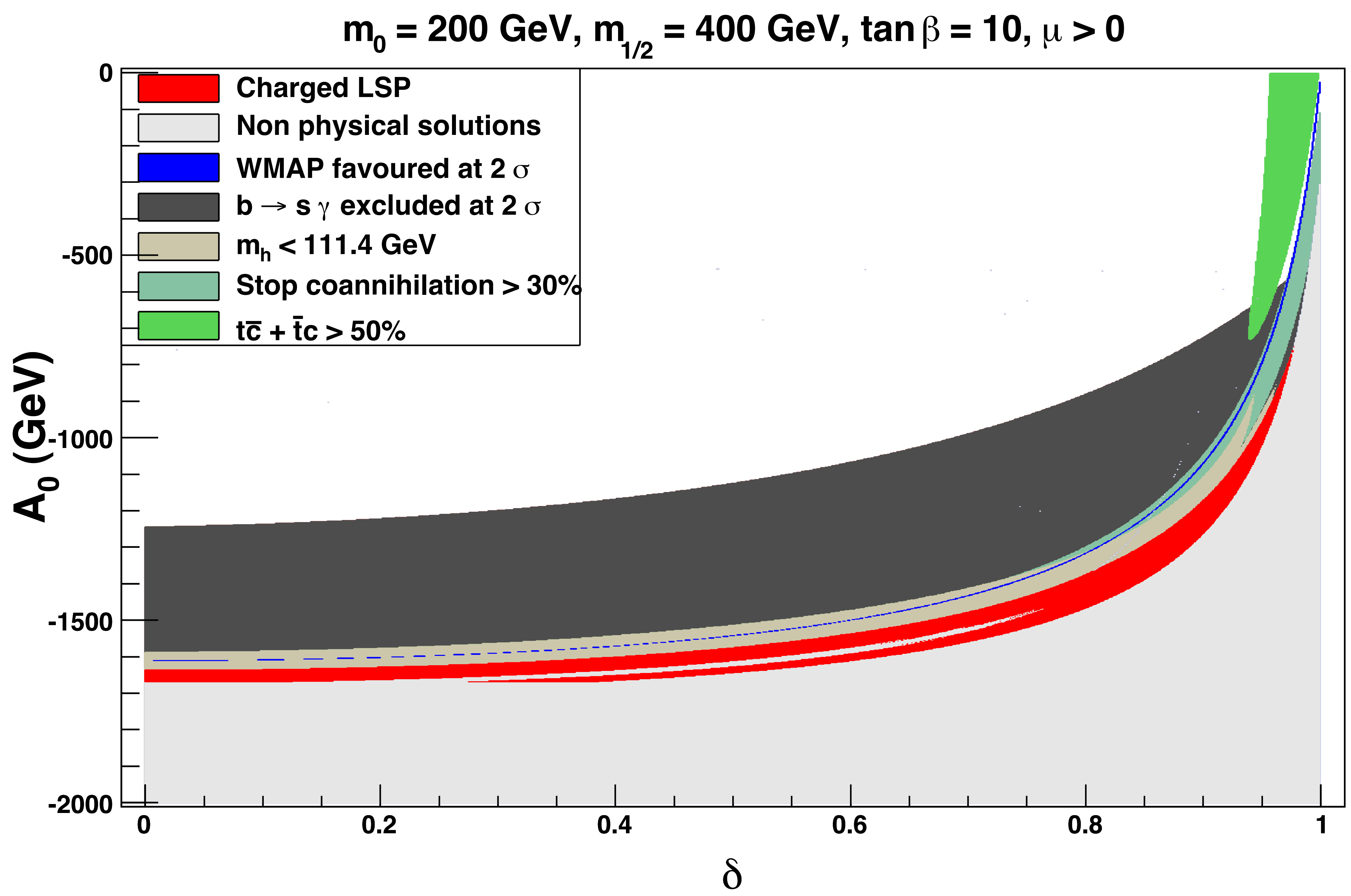
Numerical results

- Coannihilation lies in a fixed mass difference range
- Annihilation in $c\bar{t}$ become less important when top pairs can be produced



Numerical results

- Needs a very large flavour violating term to escape $\mathrm{BR}(b \to s\gamma)$ constraint
- Coannihilation either present for large A_0 or very large δ
- Annihilation in $c\bar{t}$ present only for very large δ



Conclusion and perspectives

Conclusion and perspectives

- NMFV can significantly modify relic density in the parameter space

- Opens new regions compatible with relic density and $\mathrm{BR}(b \to s\gamma)$ constraints

Some perspectives:

- Use additional constraints: $\Delta M_{B_s}, \Delta\rho$

- Study Non Universal Higgs / Gaugino Masses

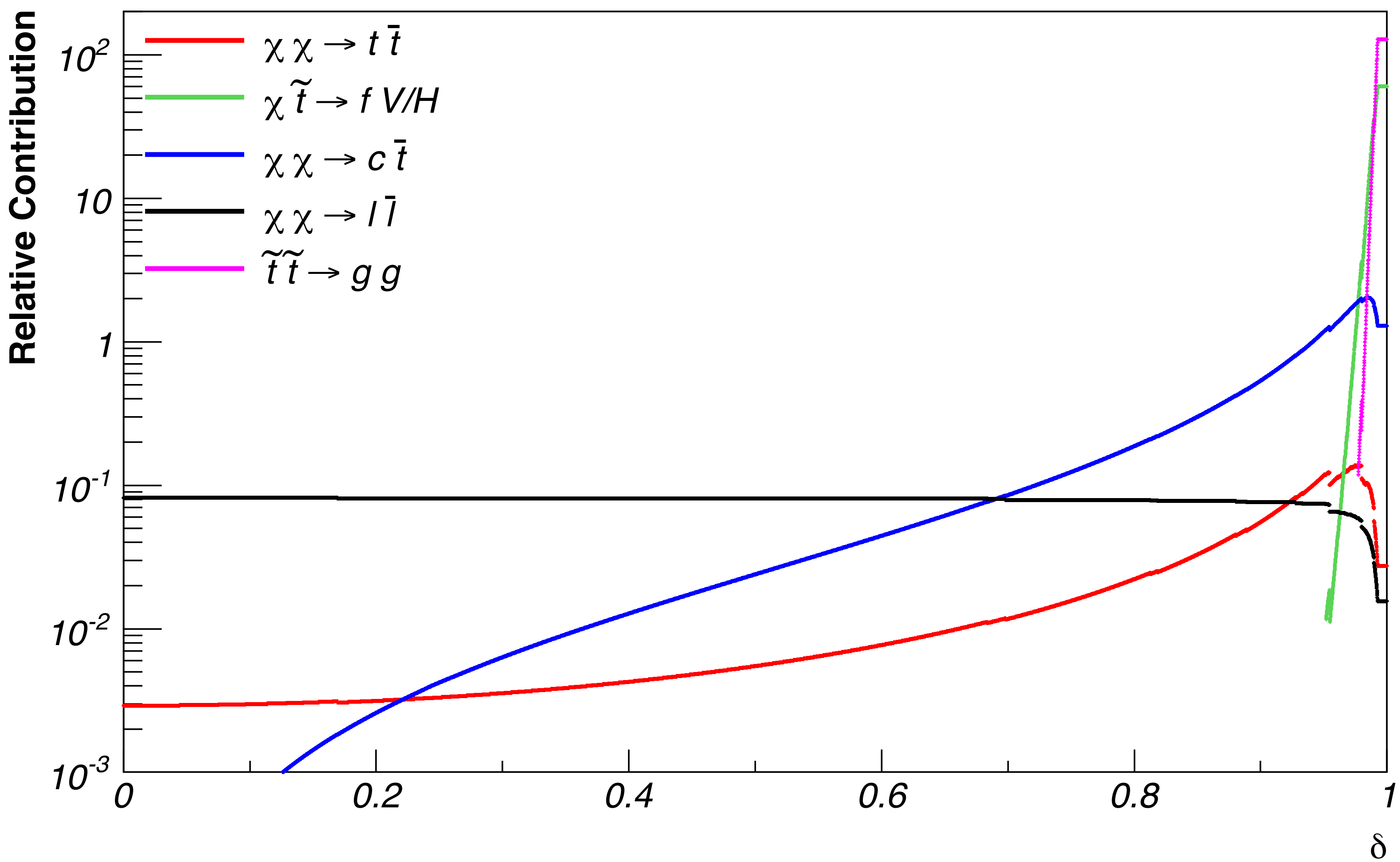
- Study NMFV in the leptonic sector - stau coannihilation

Thank you for your attention !

Backup slides

Phenomenological effects - coannihilation

Decreasing LSP-NLSP mass difference increases exponentially the coannihilation contribution → Coannihilation extremely sensitive to the stop mass !



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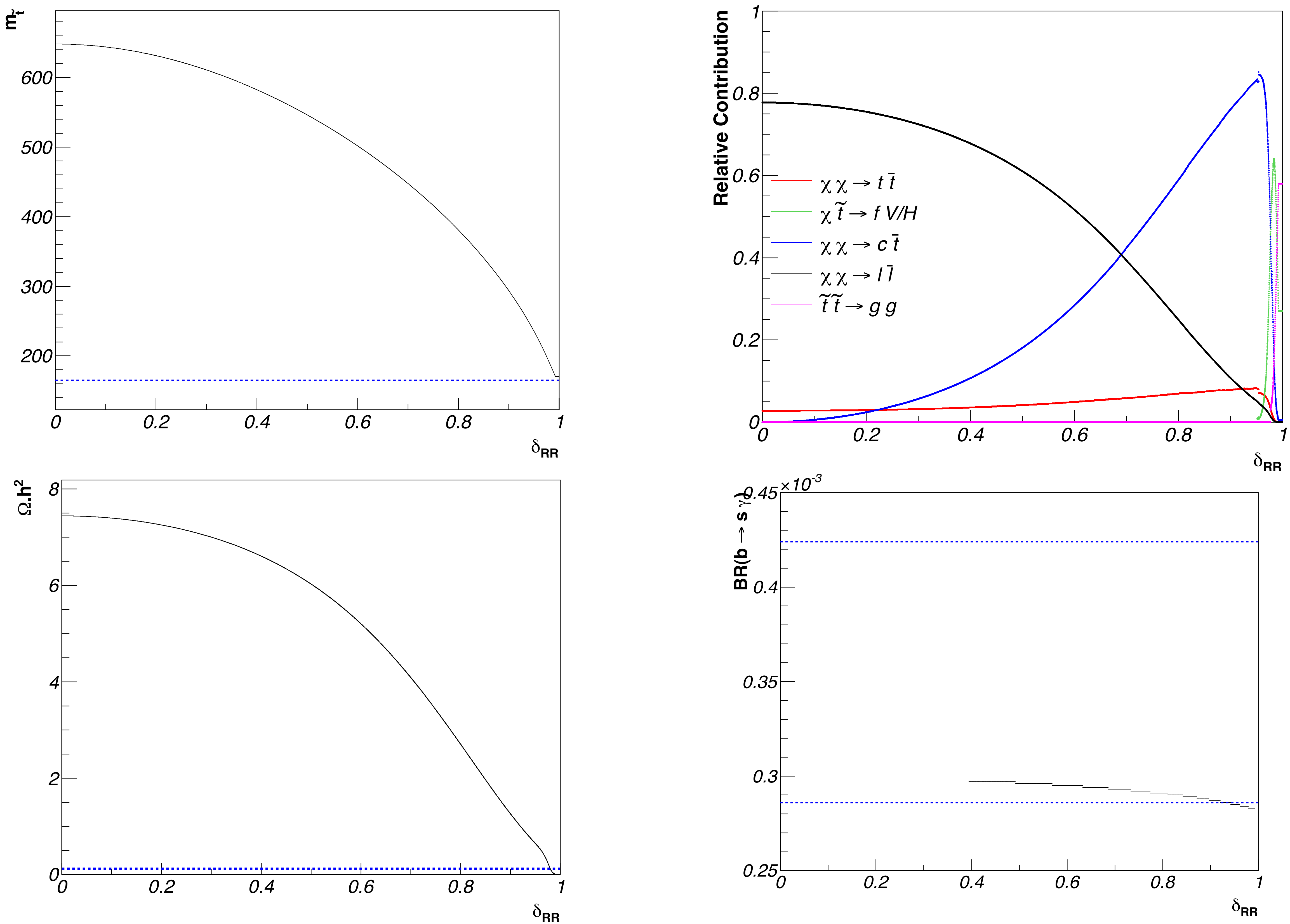
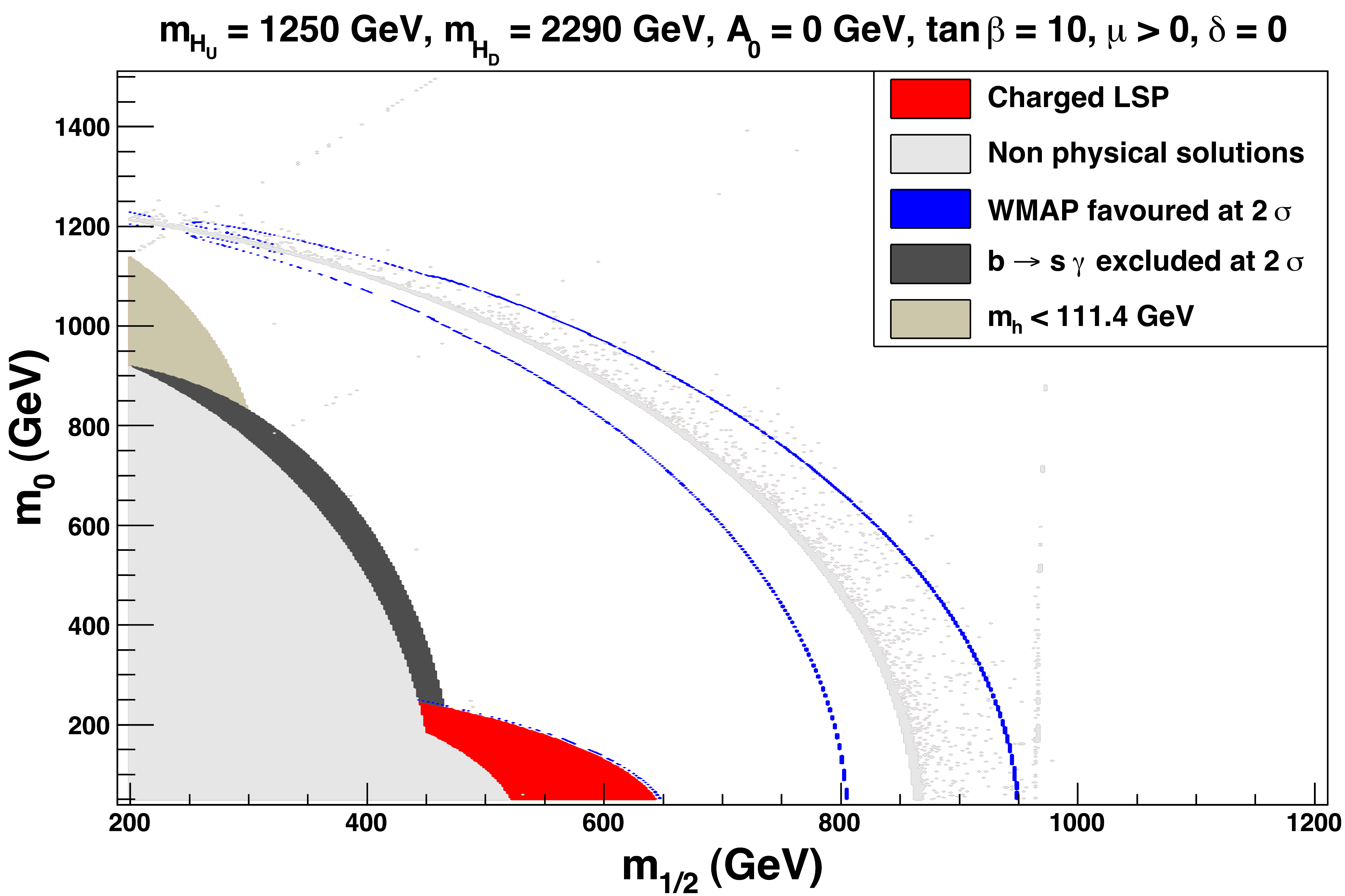
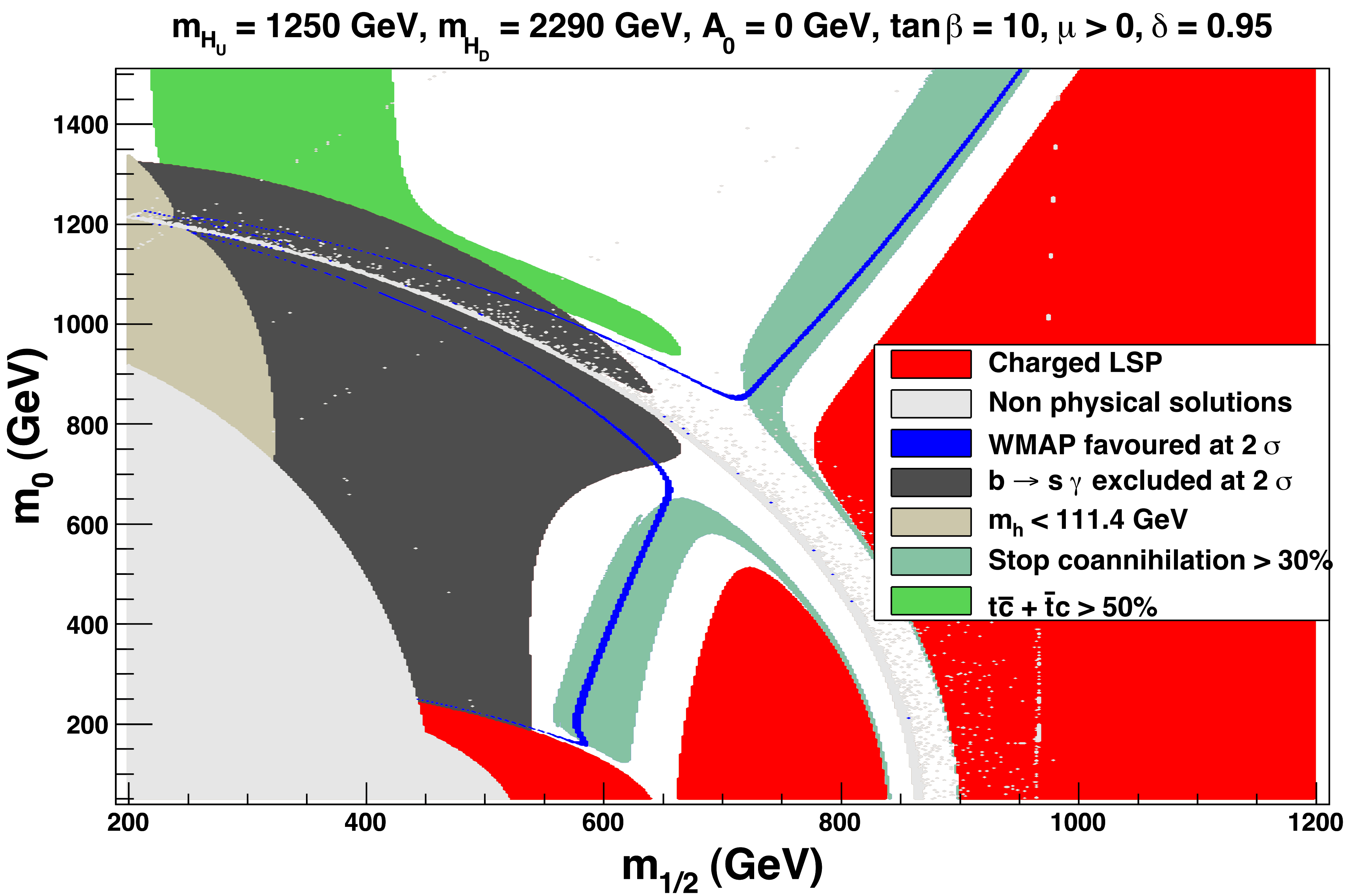


Non minimal flavour violation and NUHM - I

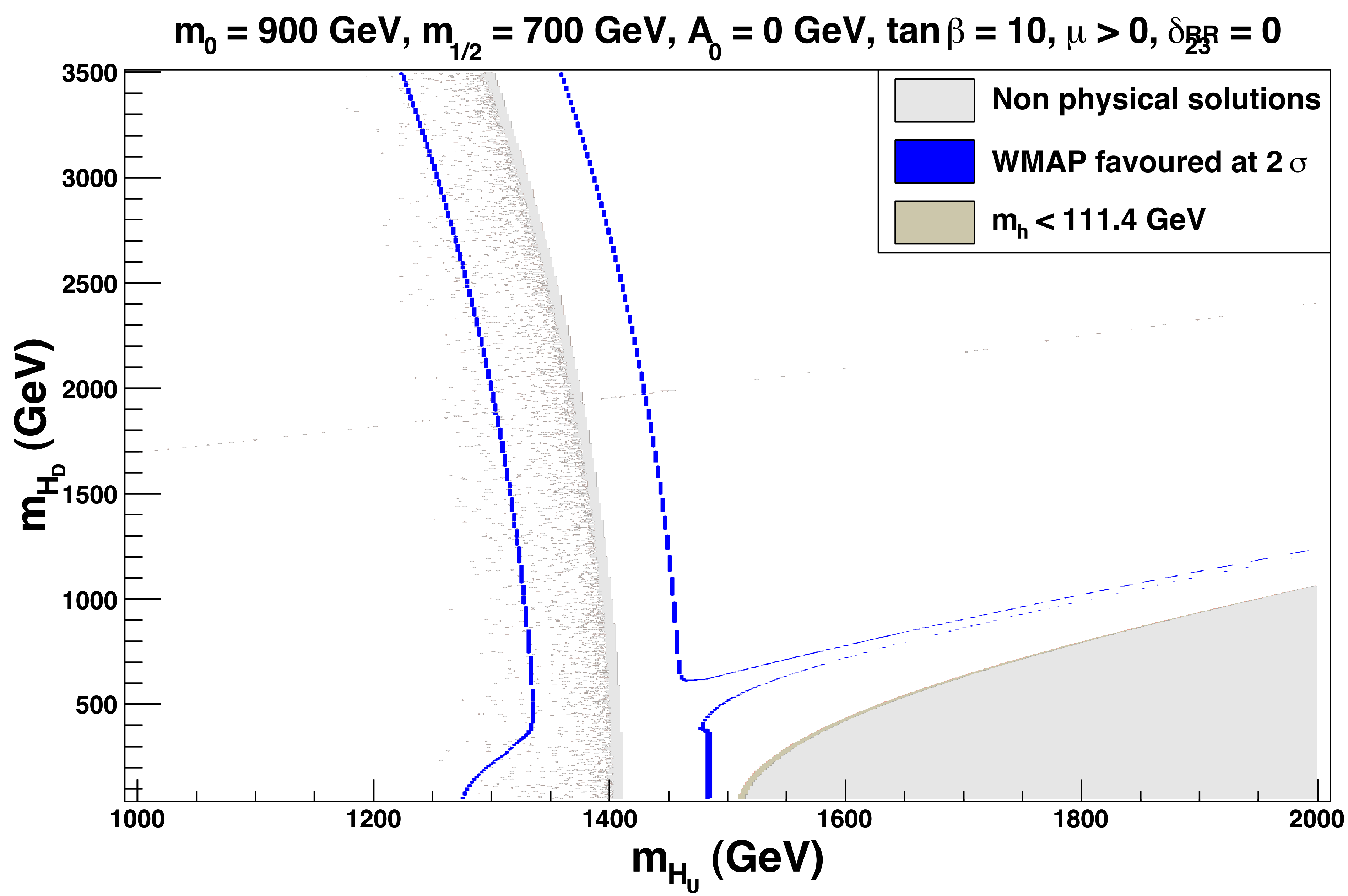
Non Universal Higgs Masses : $m_{H_U} \neq m_{H_D} \neq m_0$



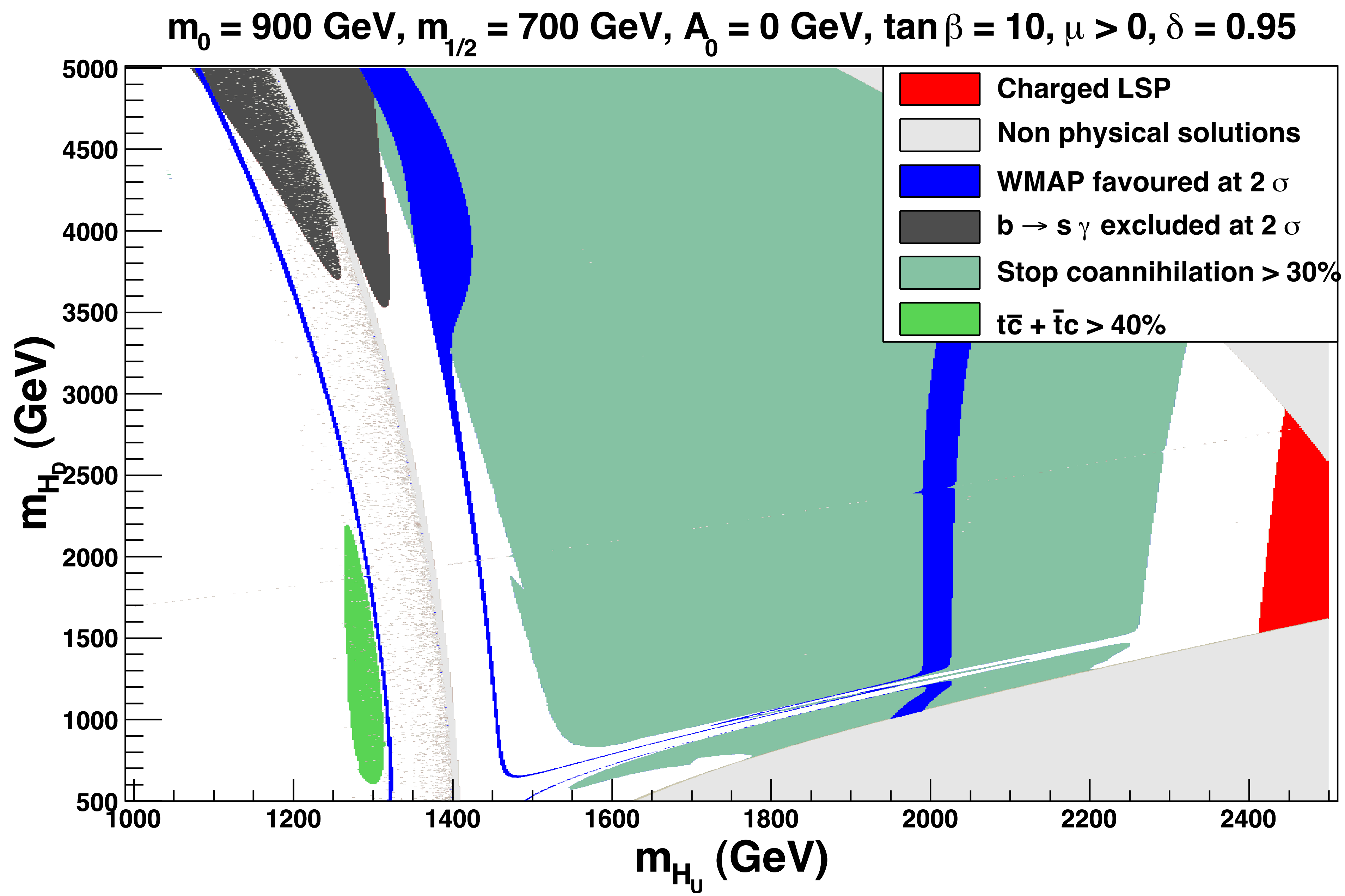
Non minimal flavour violation and NUHM - II



Non minimal flavour violation and NUHM - III

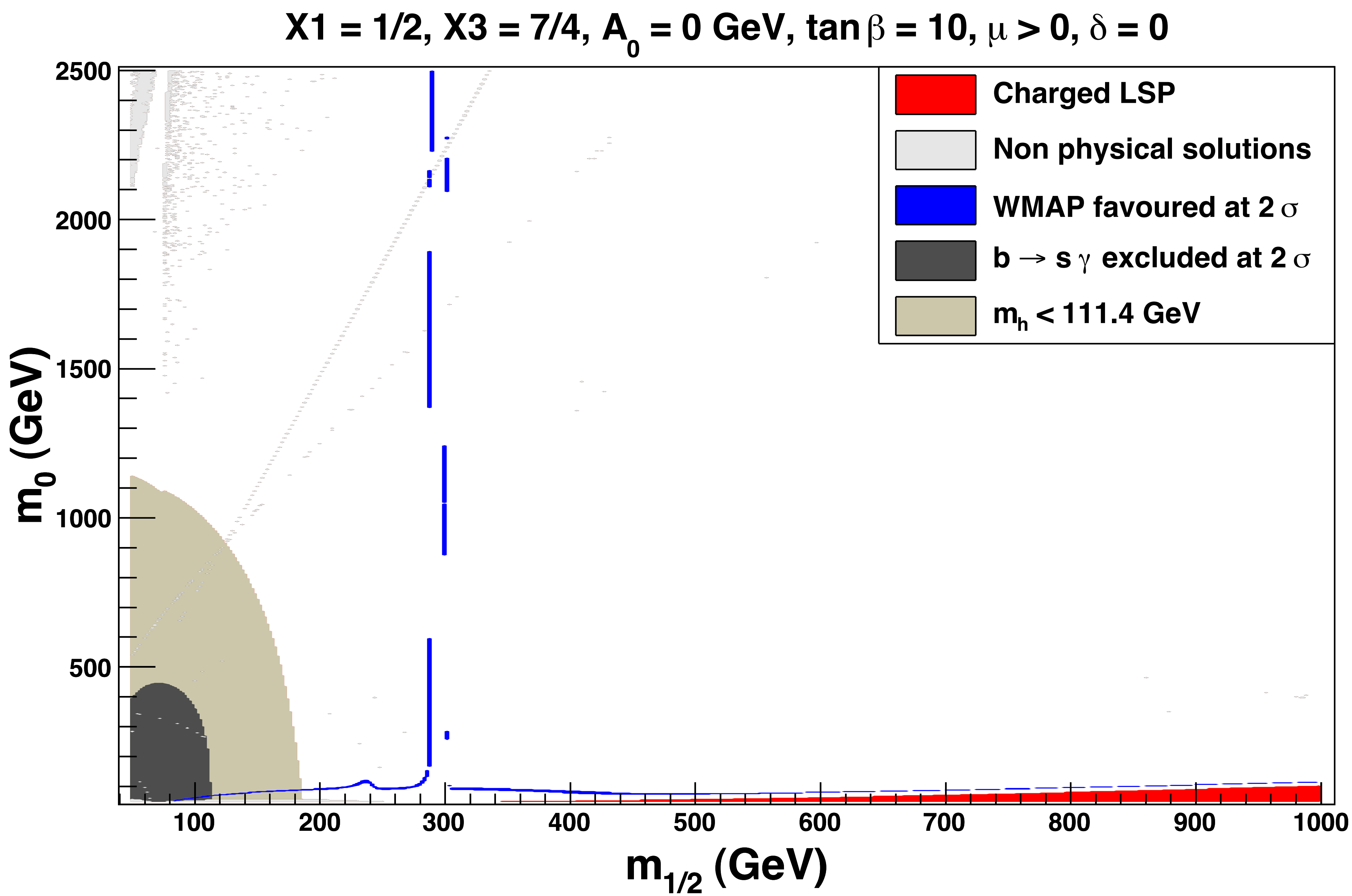


Non minimal flavour violation and NUHM - IV

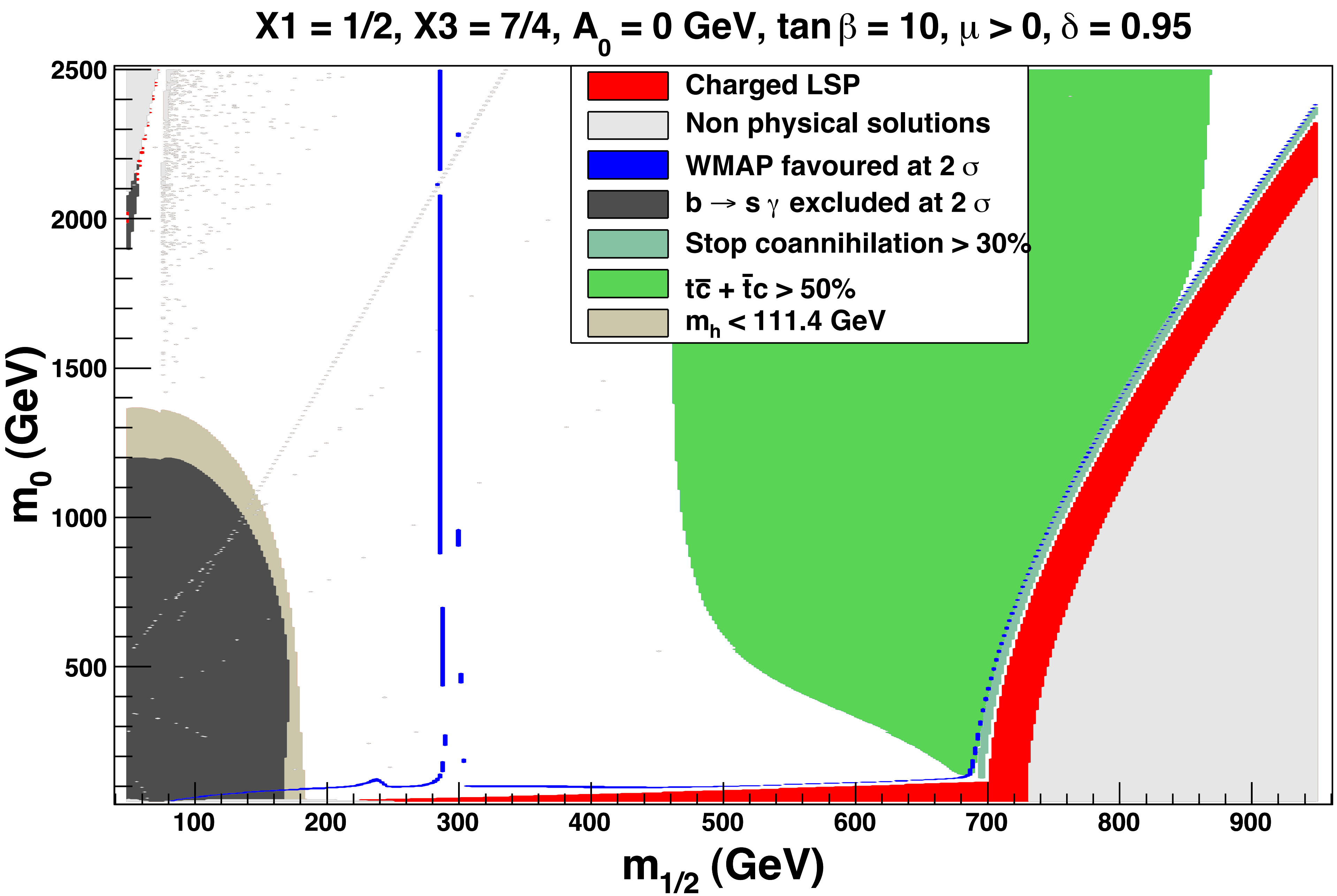


Non minimal flavour violation in NUGM - I

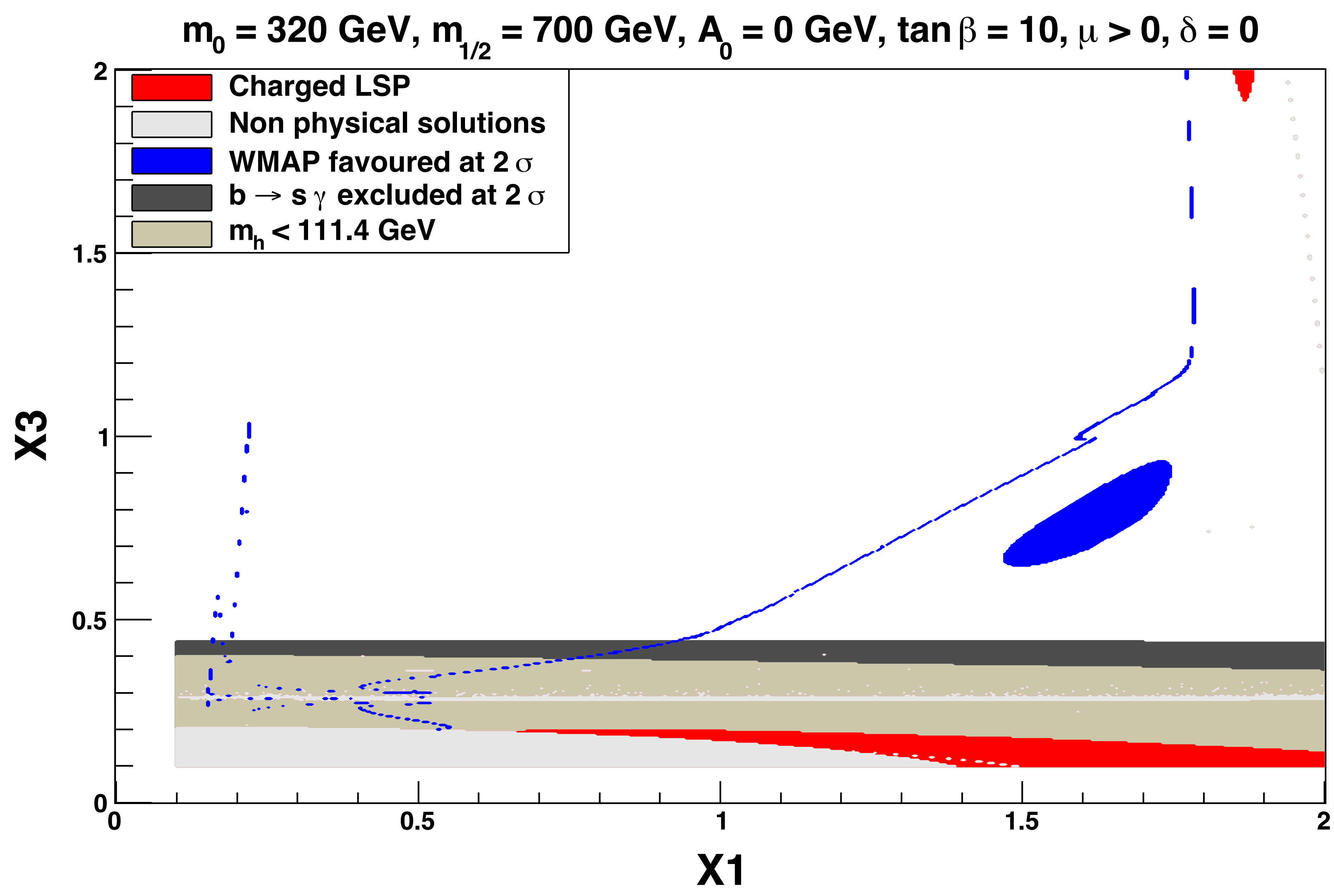
Non Universal Gaugino Masses: $M1 \neq M2 \neq M3 \rightarrow X1 = M1/M2,\ X3 = M3/M2$



Non minimal flavour violation in NUGM - II



Non minimal flavour violation in NUGM - III



Non minimal flavour violation in NUGM - IV