Sneutrino dark matter and its LHC phenomenology

Chiara Arina

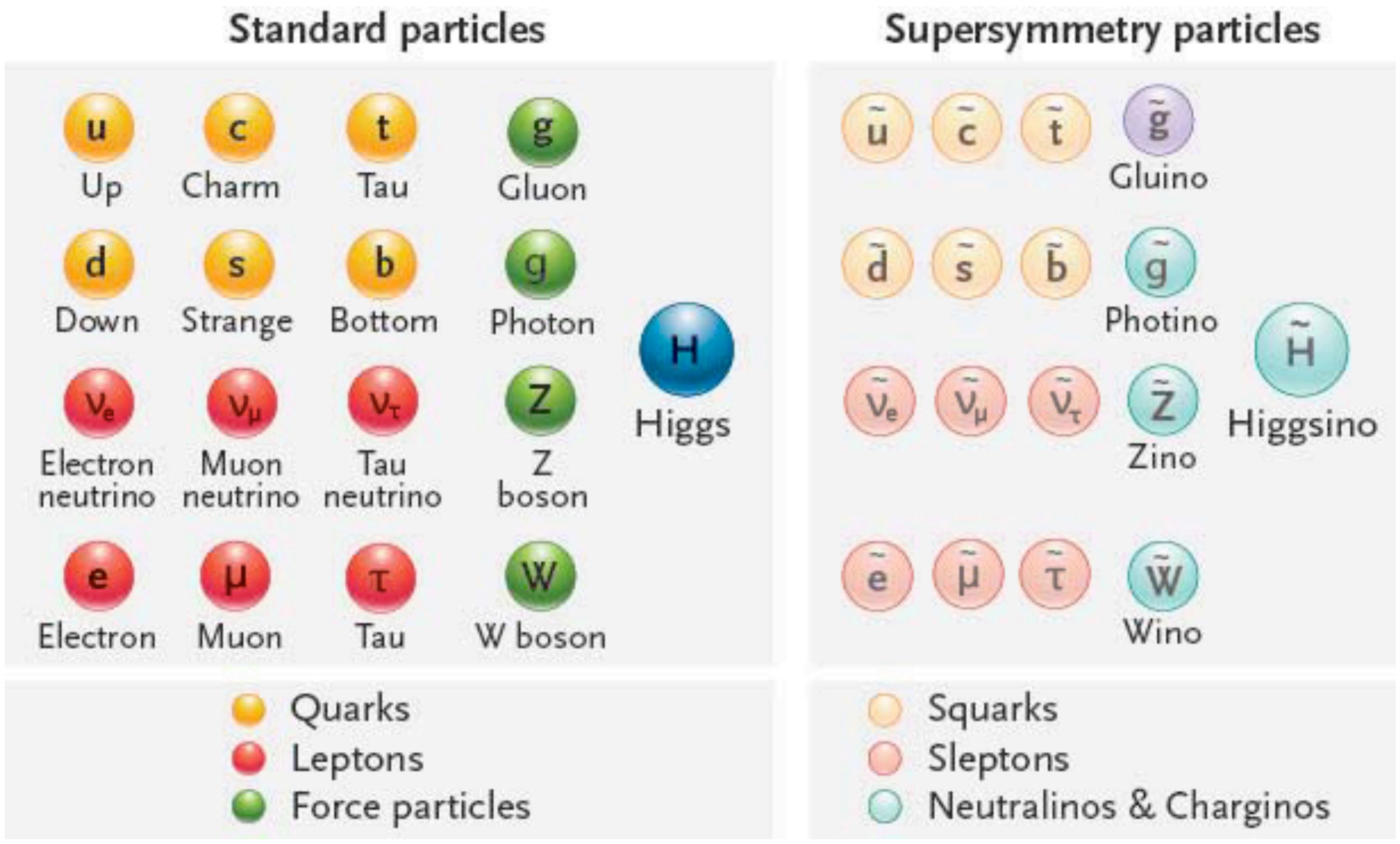
Physics challenges in the face of LHC-14

workshop @ IFT

September 23th 2014

Bolshoi simulation, NASA

Sneutrino dark matter in the MSSM?



Left-handed sneutrino as dark matter: Ibanez ’84, Falk et al ’94.

Sneutrino belongs to the $SU(2)_L$ doublet, it has Y=1 and couples to the Z boson

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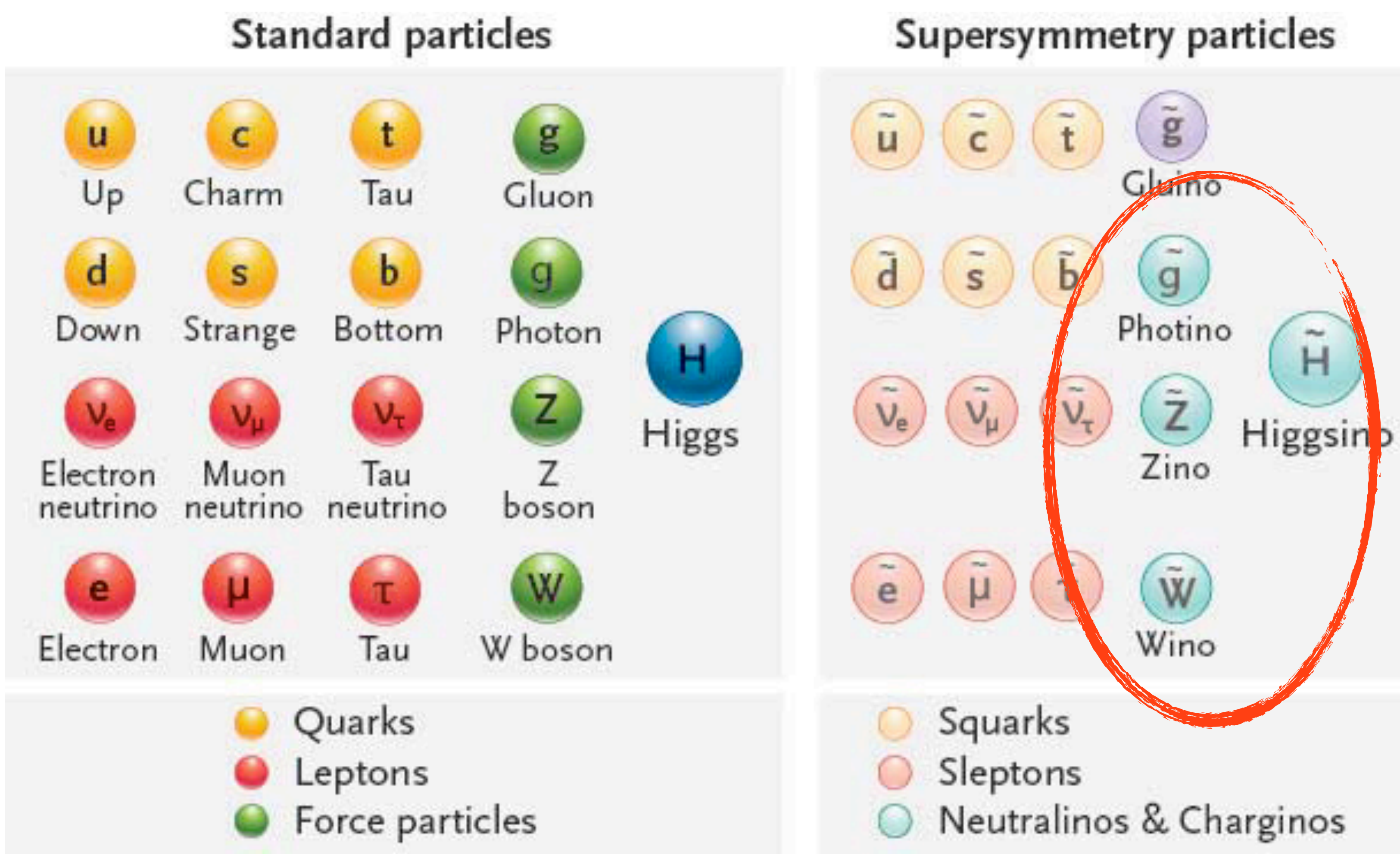

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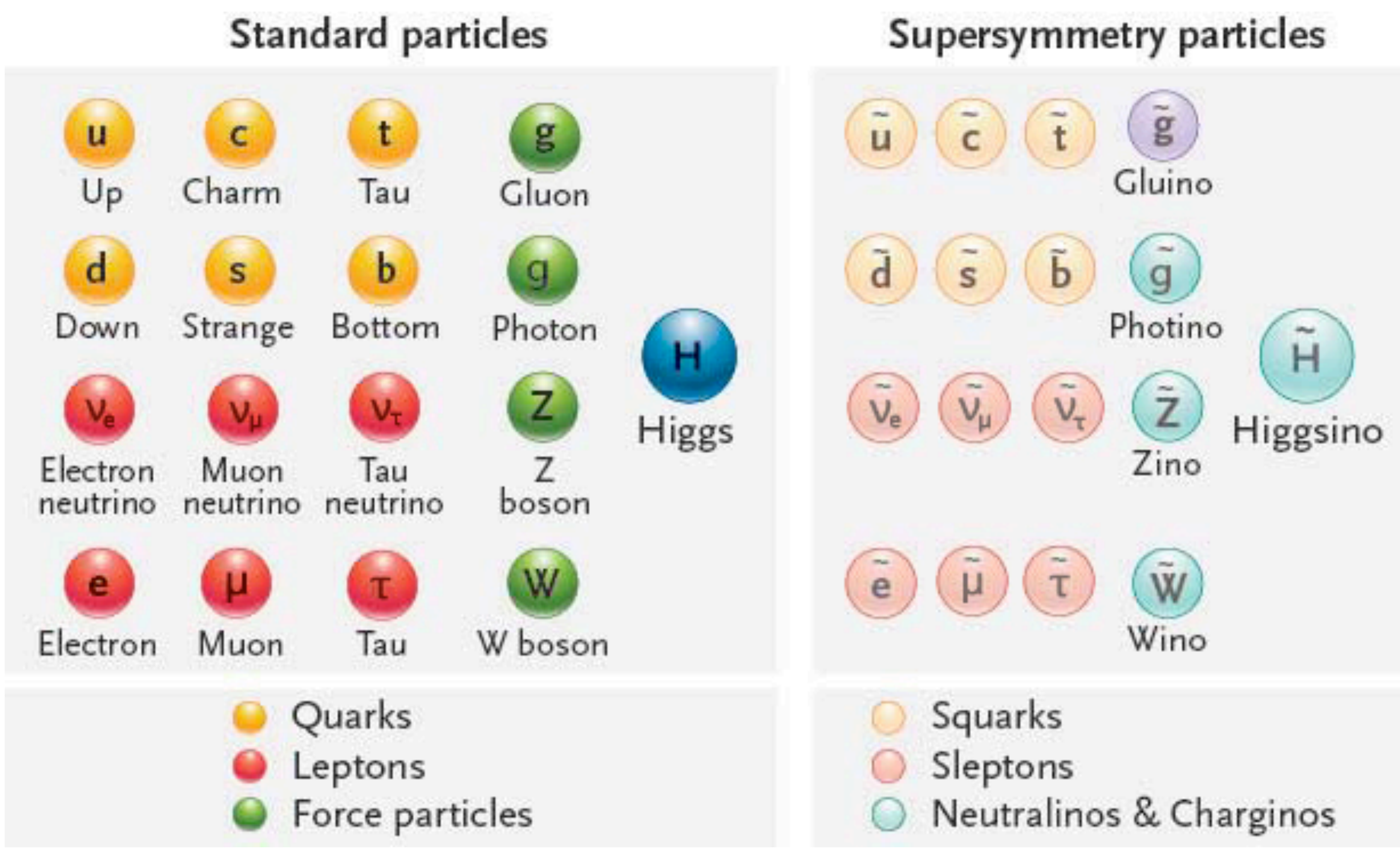

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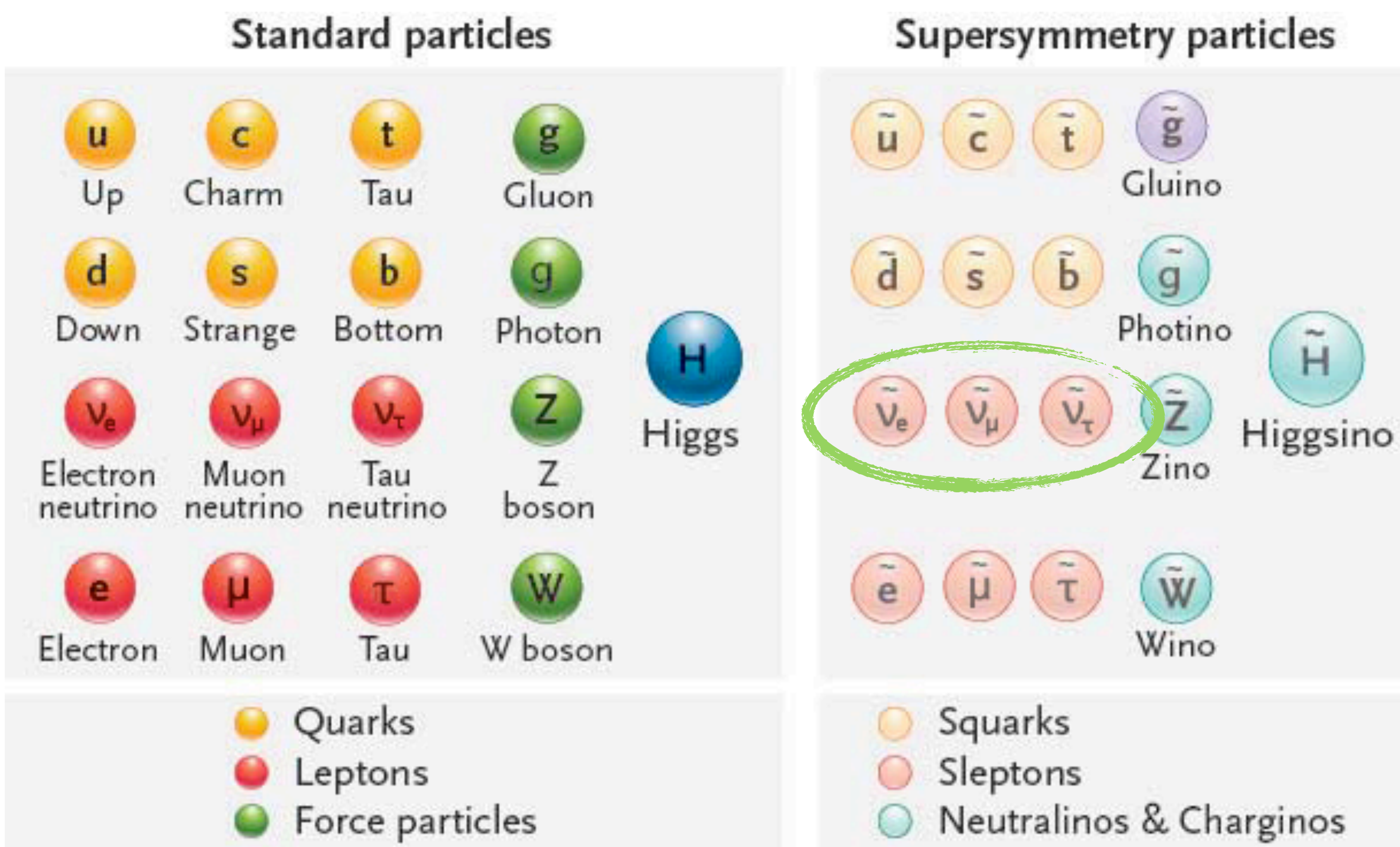

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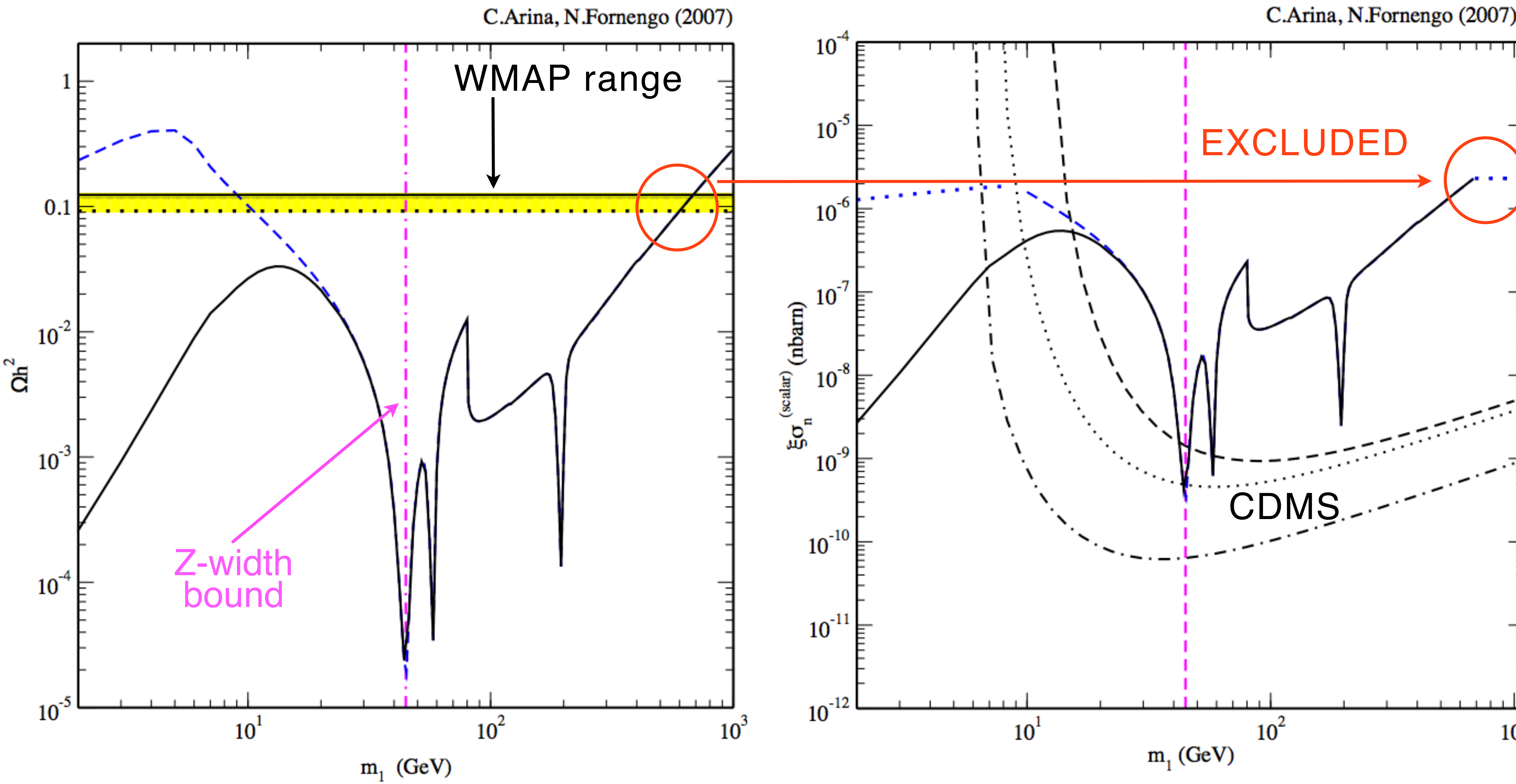
Sneutrino can not be DM in the MSSM



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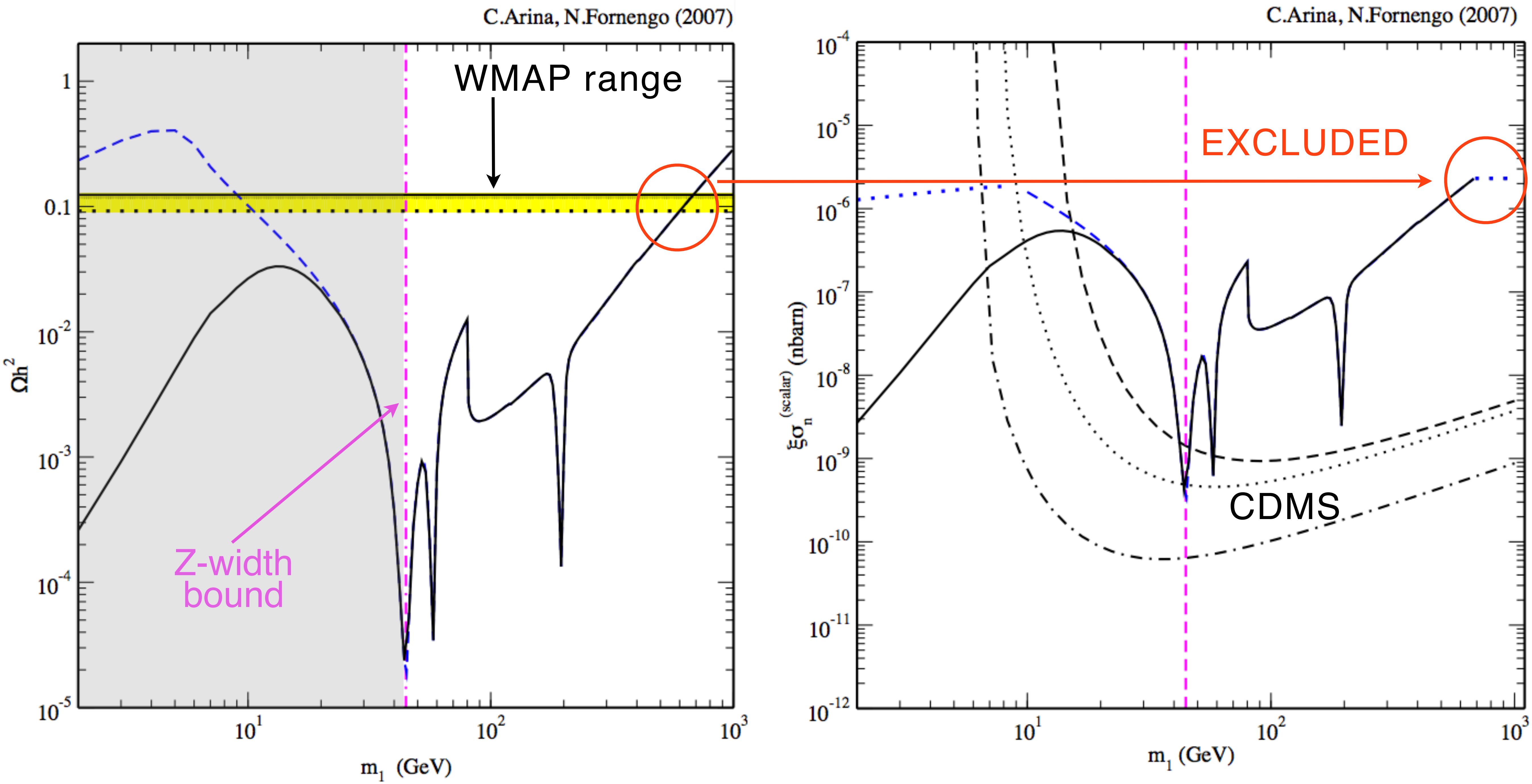

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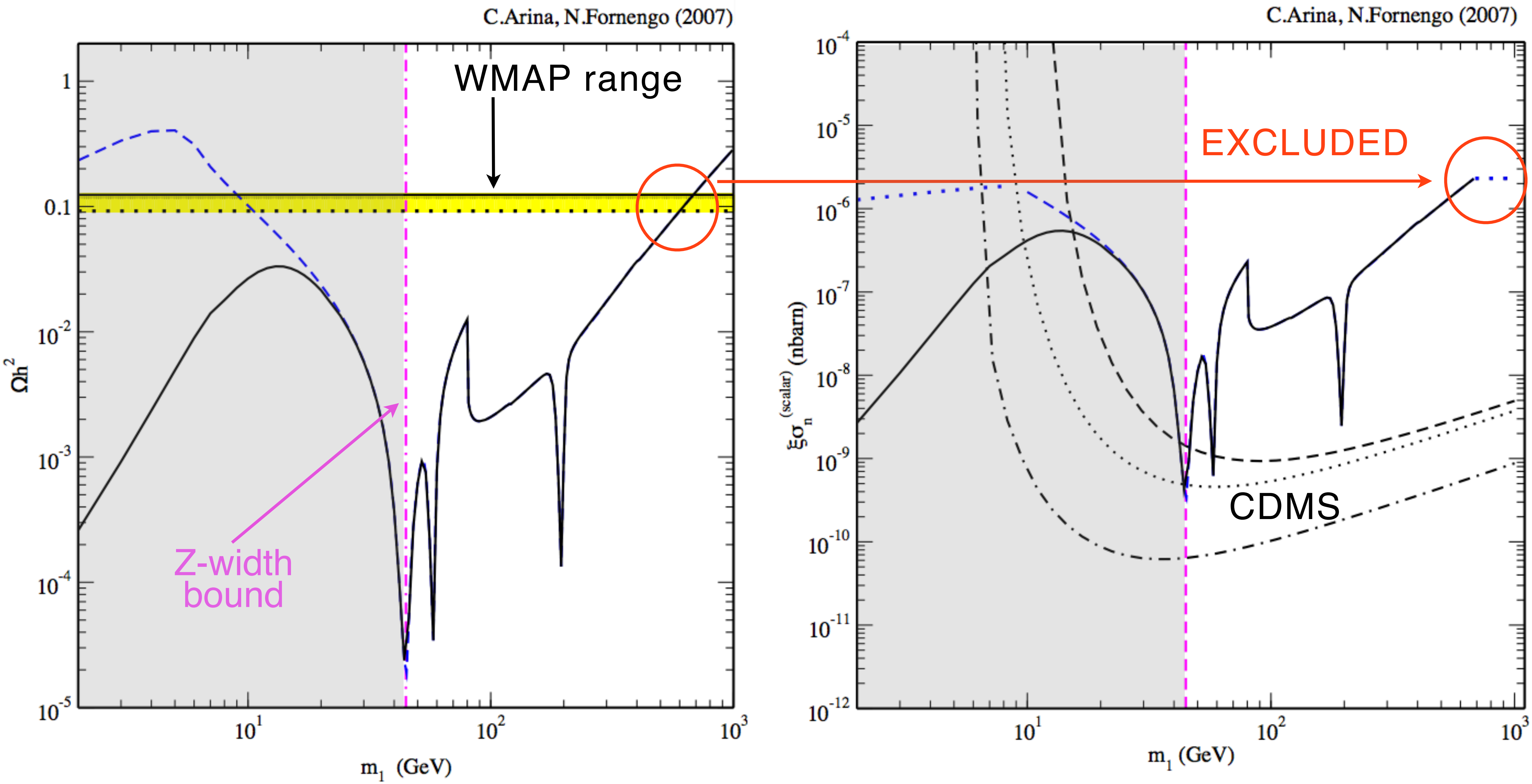

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Are the Dark Matter and the Neutrino sector related?

- Within SUSY, all mechanisms giving mass to neutrinos (Dirac masses or seesaw type I, II, III, inverse seesaw...) modify the scalar sector as well
- With modified scalar sector, sneutrino DM is OK
- Sneutrino DM and neutrino masses are naturally related

MSSM + inverse seesaw

CA,F.Bazzocchi, N.Fornengo, J.Romao and J.Valle, PRL '08 2008
V. De Romeri and M.Hirsch, JHEP 2012

$$
\begin{aligned}
W_{inv} &= \epsilon_{ij}(\mu \hat{H}^1_i \hat{H}^2_j - Y_l \hat{H}^1_i \hat{L}_j \hat{R} + Y_\nu \hat{H}^2_i \hat{L}_j \hat{N}) + M \hat{N} \hat{S} + \tfrac{1}{2}\mu_S \hat{S}\hat{S} \\
V_{\rm soft} &= (M^2_L)\, \tilde{L}^*_i \tilde{L}_i + (M^2_N)\, \tilde{N}^* \tilde{N} + (M^2_S)\, \tilde{S}^* \tilde{S} - [B_M \tilde{N}\tilde{S} + \tfrac{1}{2} B_{\mu_S} \tilde{S}\tilde{S} + \epsilon_{ij}(\Lambda_l H^1_i \tilde{L}_j \tilde{R} + A_{h_\nu} H^2_i \tilde{L}_j \tilde{N}) + h.c.]
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μ_S = 0 L is conserved

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$$

Neutrino sector

μ_S = 0 L is conserved

Inverse see-saw mechanism

$$
\begin{aligned}
m_D &= v_2 Y_\nu \\
m_\nu &\simeq \mu_S \frac{m_D^2}{M^2}
\end{aligned}
$$

The smallness of the neutrino mass is given by the smallness of μ_S 0(keV)

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Sneutrino sector

- mixed state of the left-handed sneutrino, the right-handed sneutrino and the singlet scalar field
- sizeable mixing because all soft masses at the same scale

Effect of mixing:

(i) coupling with Z boson reduced by the mixing angle

(ii) suppressed cross-section for scattering off nucleus

MSSM + inverse seesaw

CA,F.Bazzocchi, N.Fornengo, J.Romao and J.Valle, PRL ’08 2008
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W_{inv}

V_{soft} ... $+A_{h_\nu} H_i^2 \tilde{L}_j \tilde{N}) + h.c.]$

Neutr ... or

Inver

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mass ... singlet scalar field
of μ_S ... ft masses at the

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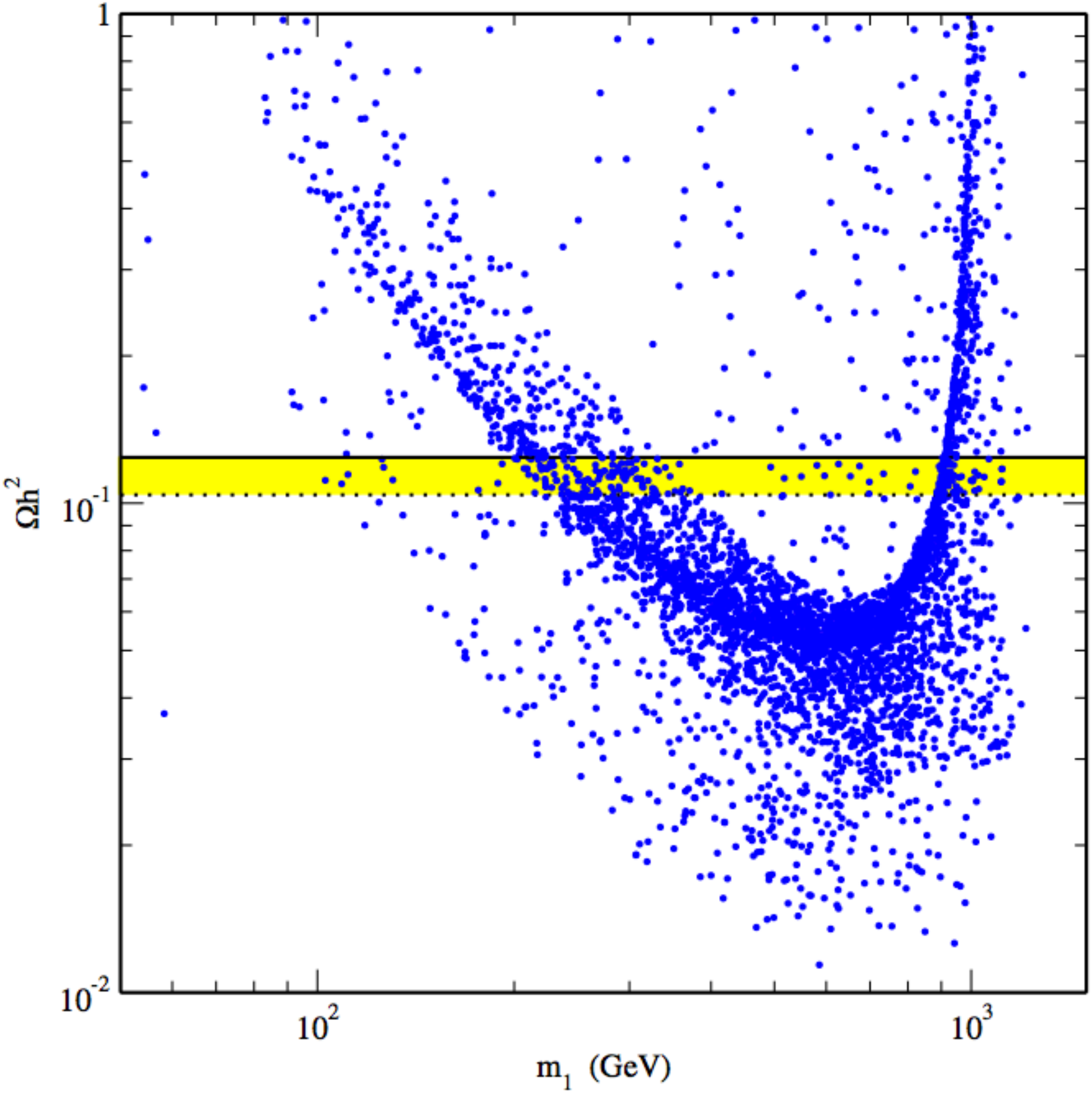
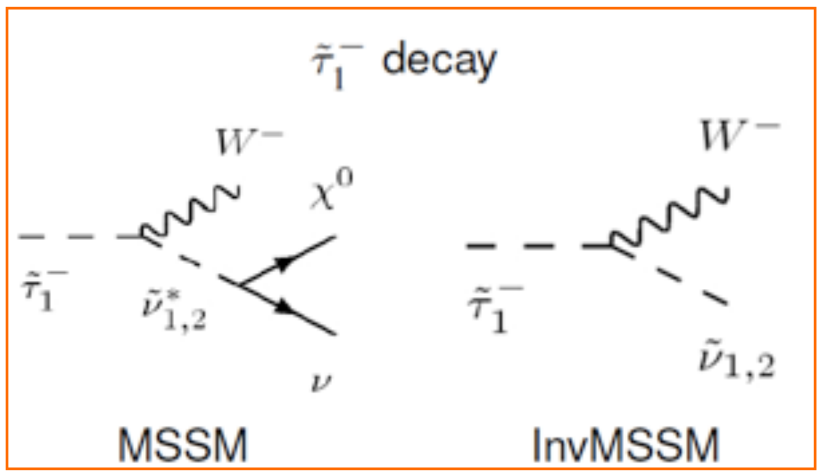
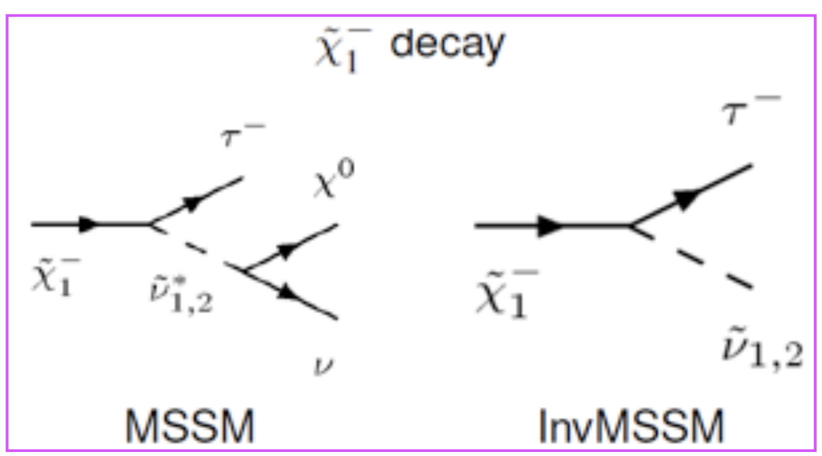


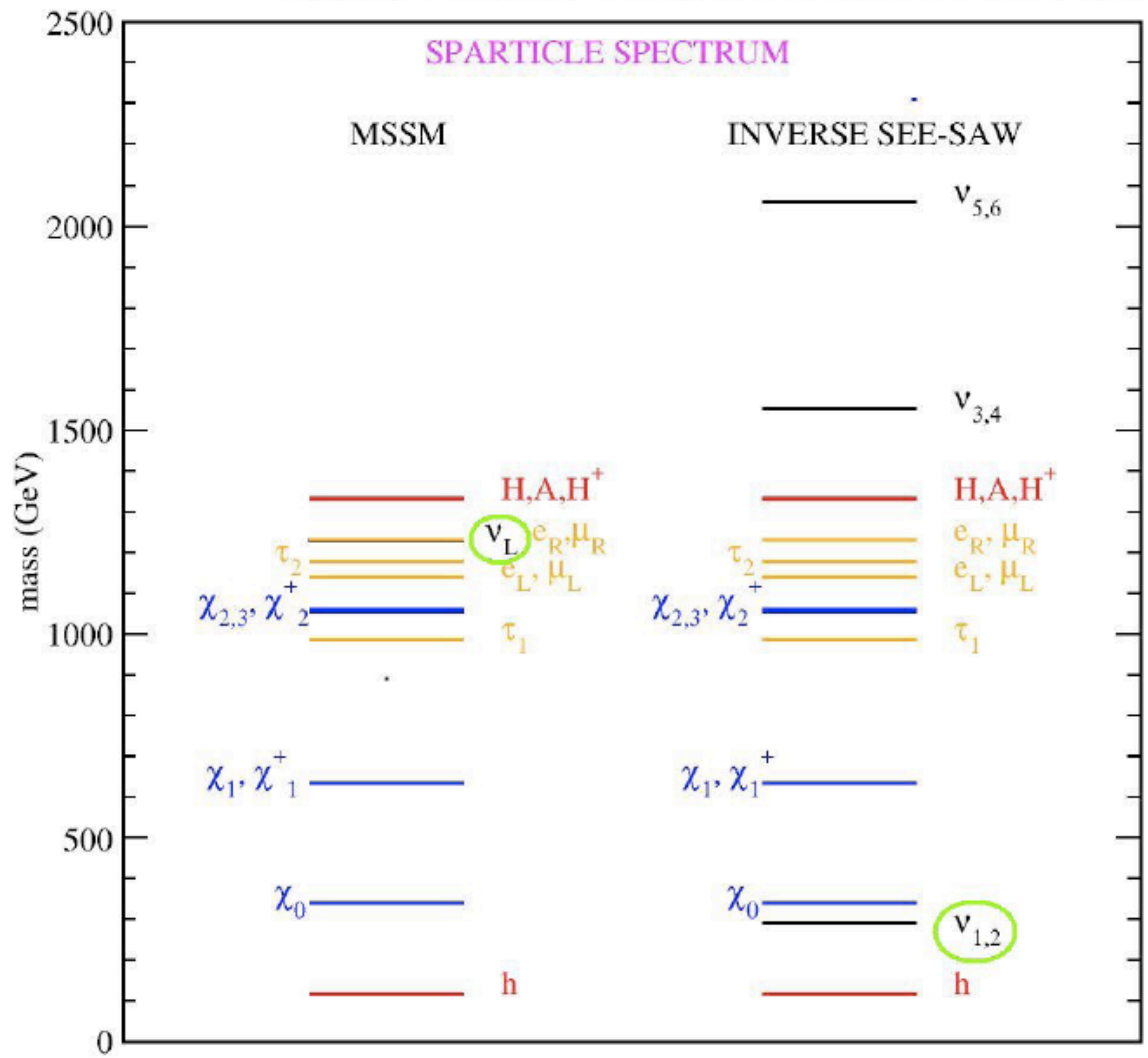
SUSY mass spectrum with sneutrino LSP

Topologies @ LHC are different from MSSM





C.Arina, F.Bazzocchi, N.Fornengo, J.Romao and J.Valle (2008)



Signatures in the simplest scenario: MSSM+RN

Arkani-Hamed et al. ’00,
CA and N.Fornengo ‘07,
G.Belanger et al. ‘10, ‘12
CA and M.E.Cabrera JHEP 04(2104)100

$$W = \epsilon_{ij}(\mu \hat{H}_i^u \hat{H}_j^d - Y_l \hat{H}_i^d \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^u \hat{L}_j \hat{N})$$

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Dirac masses for neutrinos: $m_D = v_u Y_\nu$

Sneutrino left and right component mixes:

$$\mathcal{M}_{LR}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2} m_Z^2 \cos(2\beta) + m_D^2 & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \mathrm{cotg}\beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \mathrm{cotg}\beta & m_N^2 + m_D^2 \end{pmatrix}$$

$$\begin{cases} \tilde{\nu}_1 = -\sin\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \cos\theta_{\tilde{\nu}}\ \tilde{N} \\ \tilde{\nu}_2 = +\cos\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \sin\theta_{\tilde{\nu}}\ \tilde{N} \end{cases}$$

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Free parameters and likelihood constraints

13 free parameters $\{\theta_i\} = \{M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_L, A_{\tilde{\nu}}, A_Q, B, \mu\}$
(GUT scale initial conditions)

Observable with a measure have a gaussian likelihood:

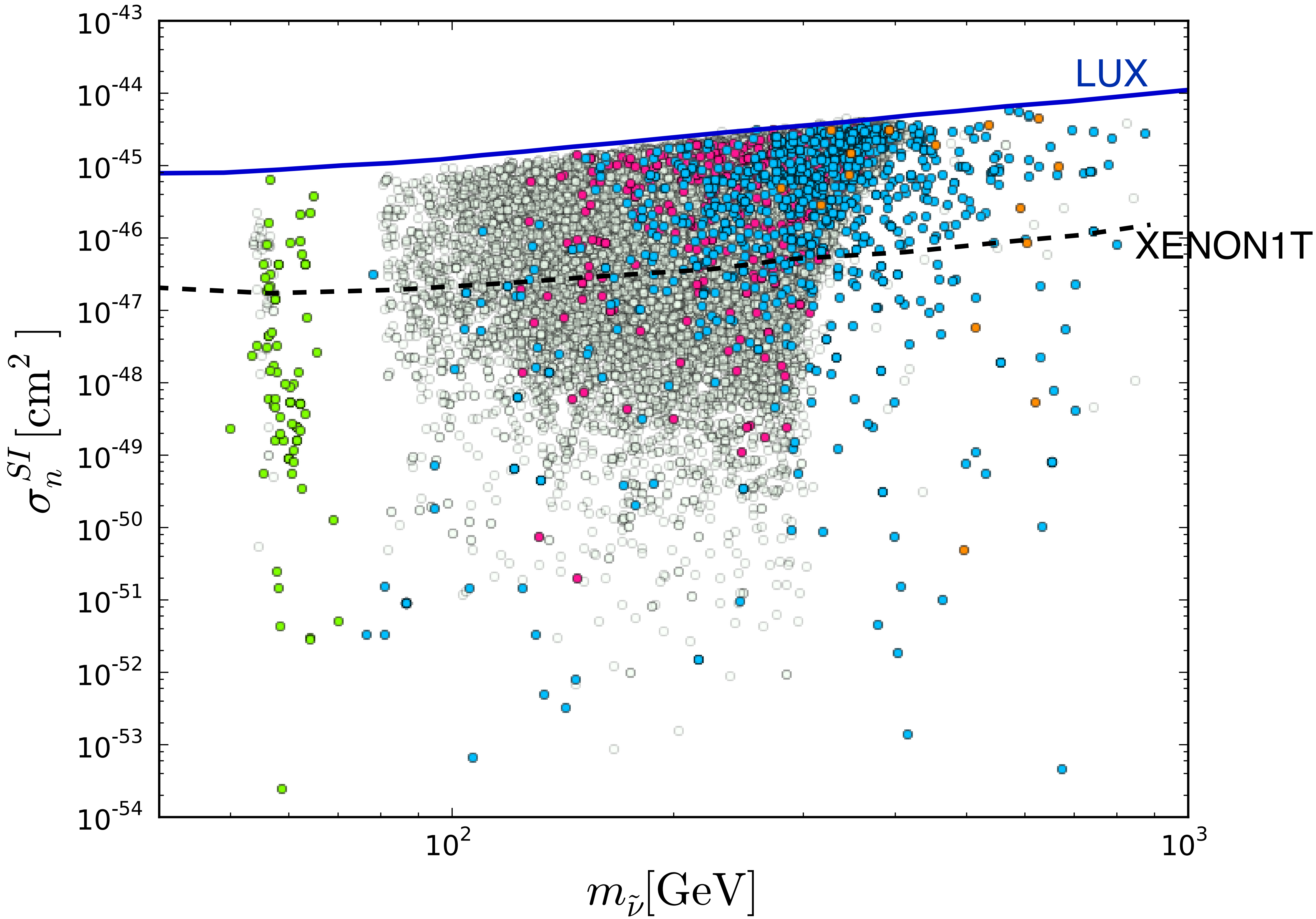
1. Higgs mass
2. $\Omega_{\rm DM} h^2$ from Planck
3. Z invisible decay width

Constraints that have only an lower/upper limits are included with a step likelihood function:

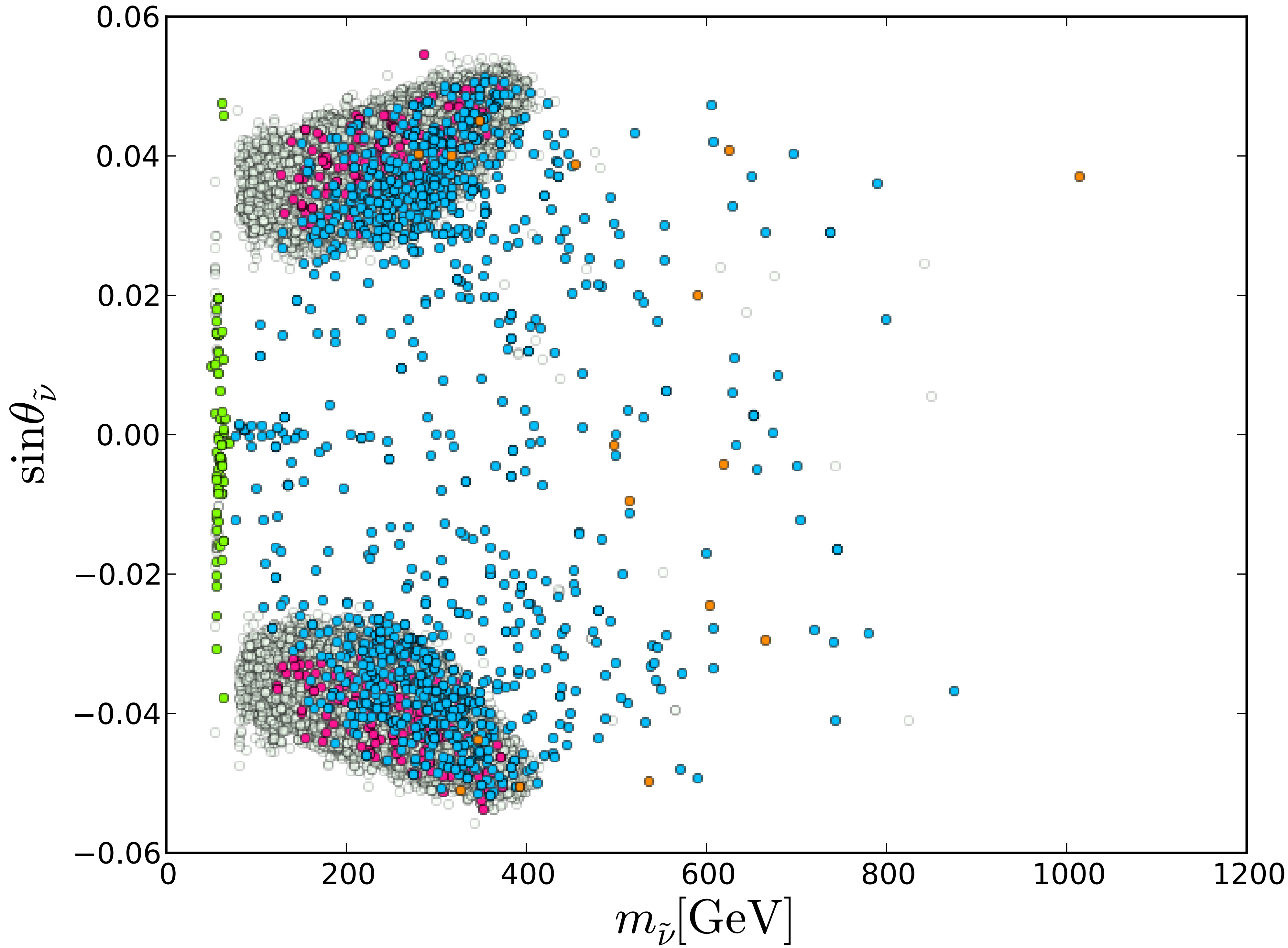
1. Chargino and slepton masses > 101 GeV (95% CL LEP)
2. Stau > 85 GeV (95% CL LEP)
3. LUX bound at 90% CL
4. Higgs invisible decay width (< 60%)

Sampling of the likelihood with the algorithm MultiNest

Sneutrino is a good dark matter candidate

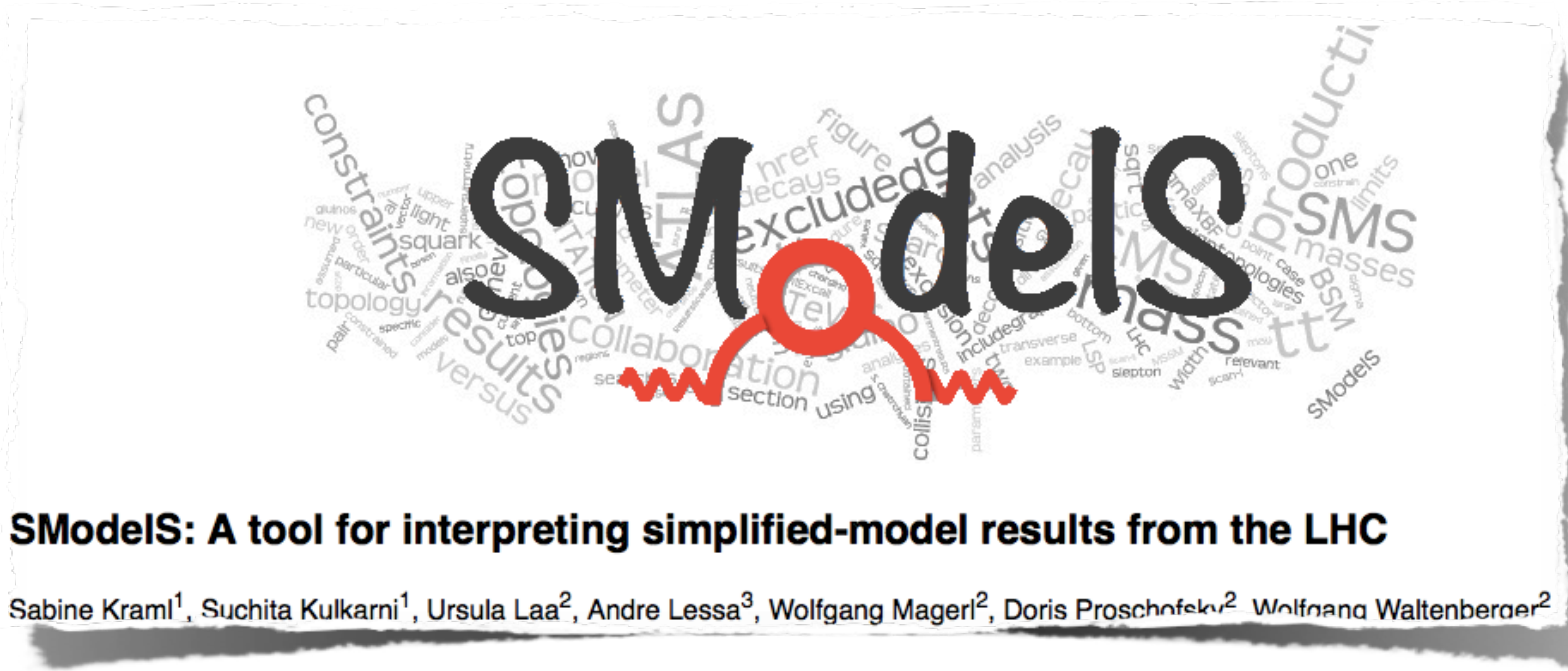


Because of LUX the LSP is mostly right-handed



Different colors characterized by a different mass spectrum pattern and different annihilation processes that fix the relic density

What is the current status of MSSM+RN with respect to LHC searches?



SModelS: A tool for interpreting simplified-model results from the LHC

Sabine Kraml[1], Suchita Kulkarni[1], Ursula Laa[2], Andre Lessa[3], Wolfgang Magerl[2], Doris Proschofsky[2], Wolfgang Waltenberger[2]

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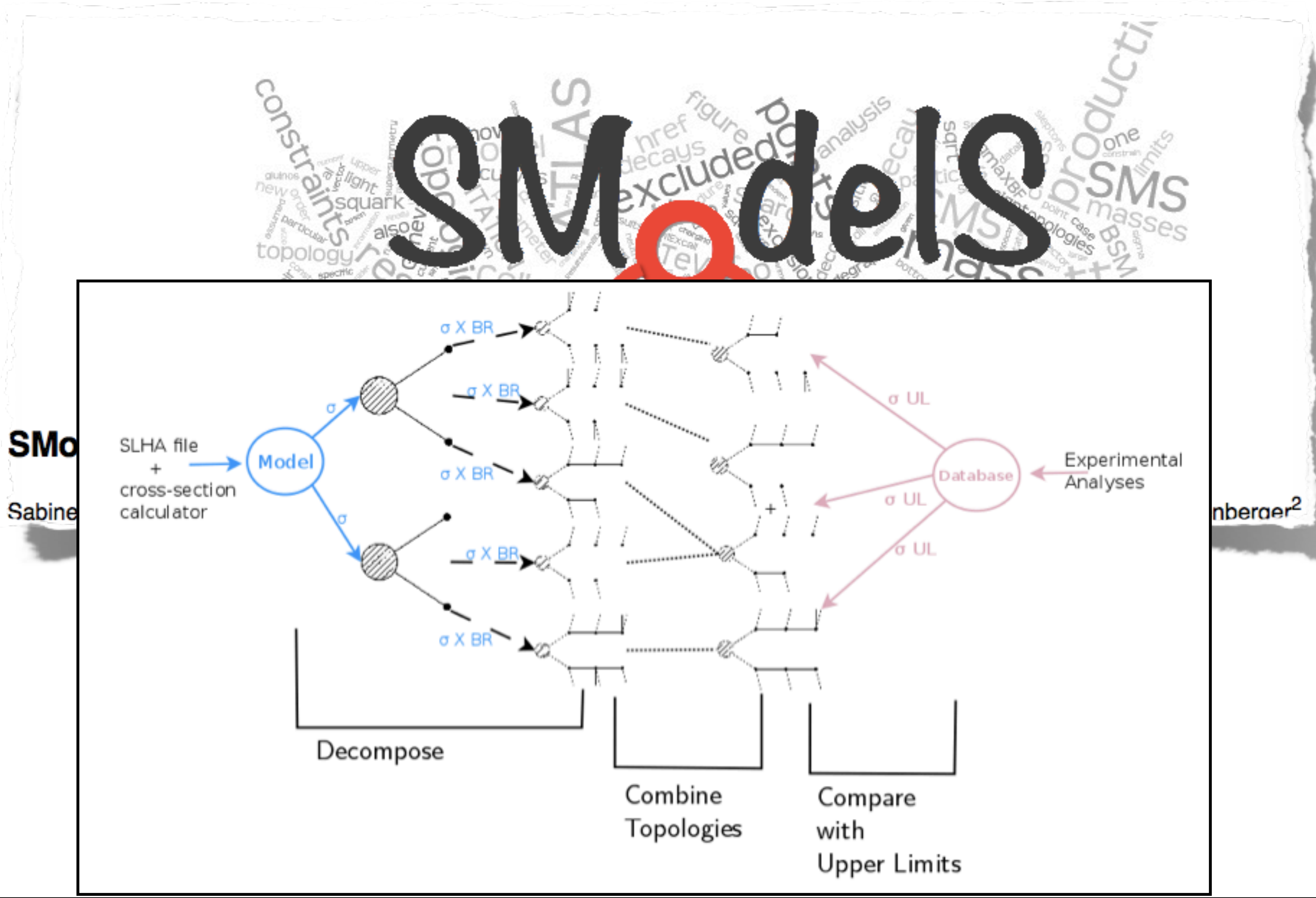
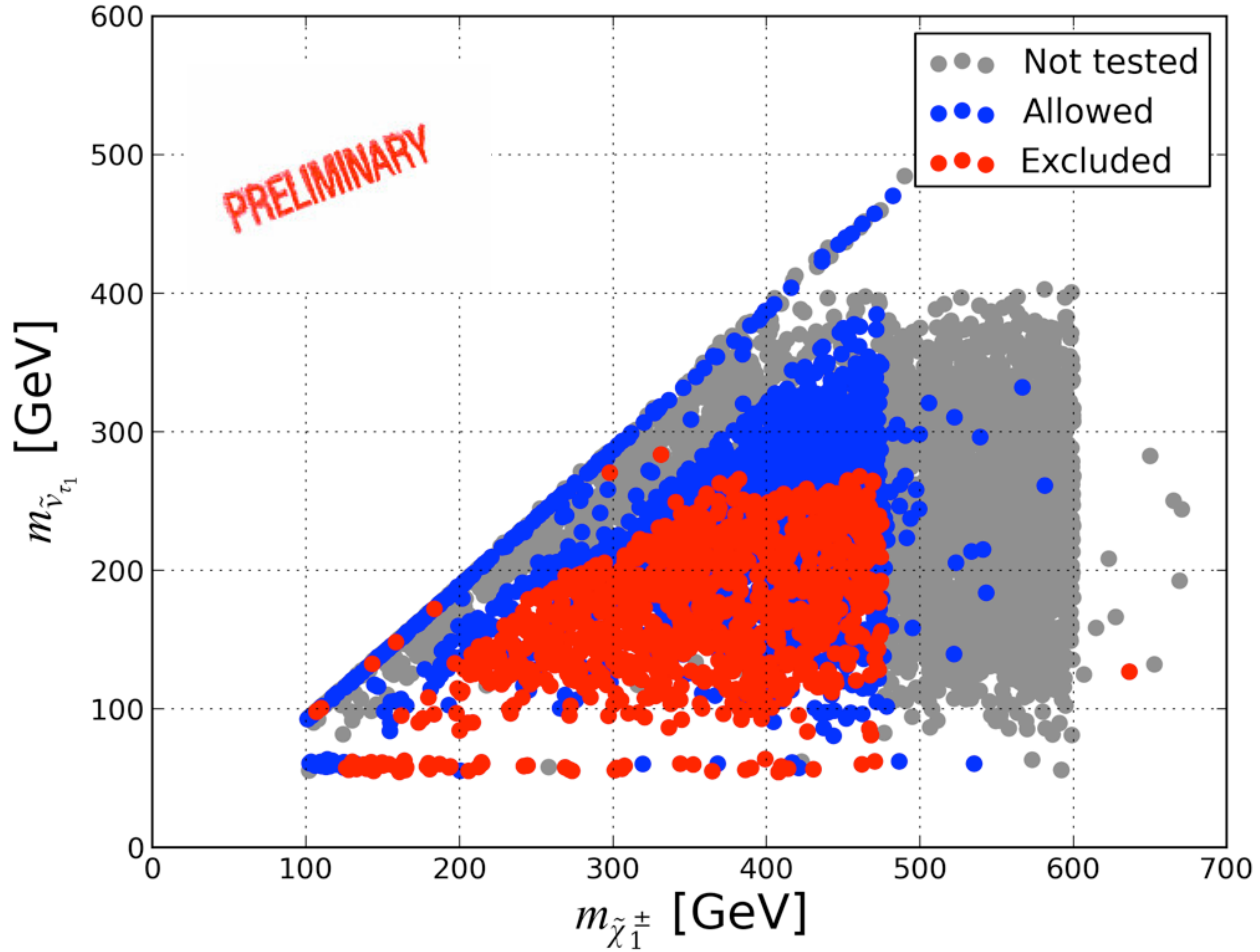


Test electroweak production in the MSSM+RN

Work in progress in collaboration with
CA, M.E.Cabrera, S.Kraml, S.Kulkarni and U.Laa



Notice that the points below are not excluded, except for almost pure wino charginos!

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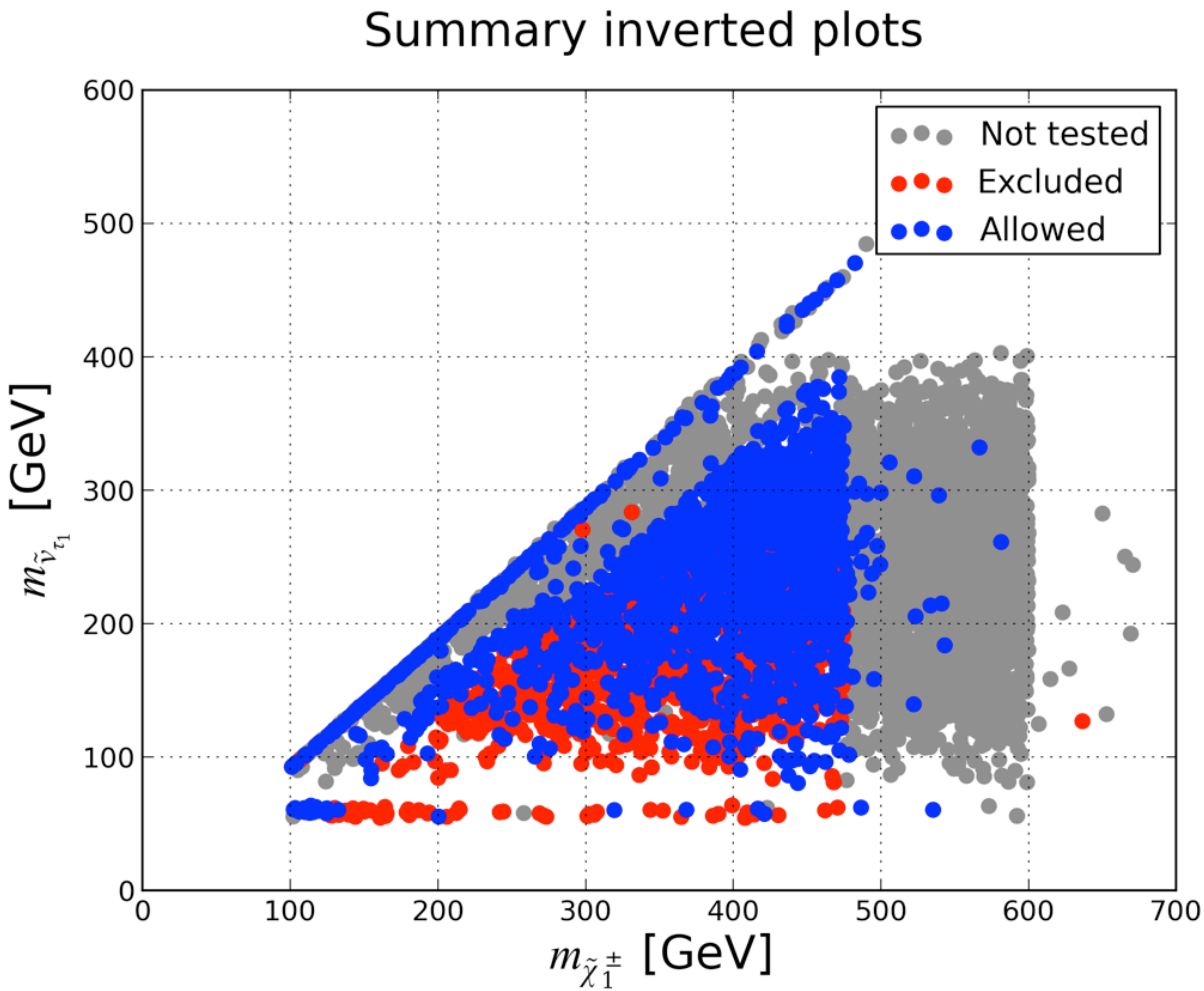

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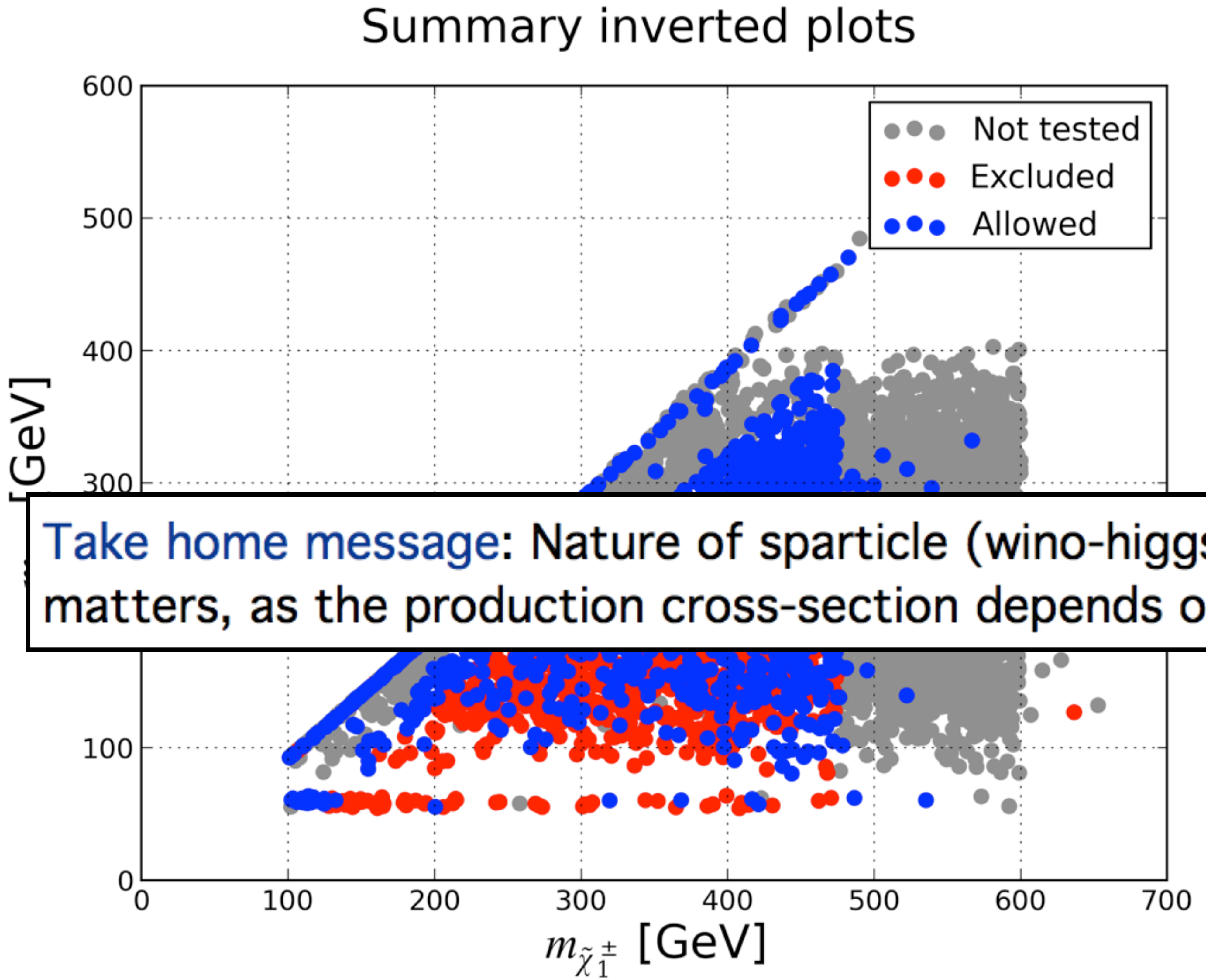

Take home message: Nature of sparticle (wino-higgsino mixing) matters, as the production cross-section depends on it

e wino charginos!

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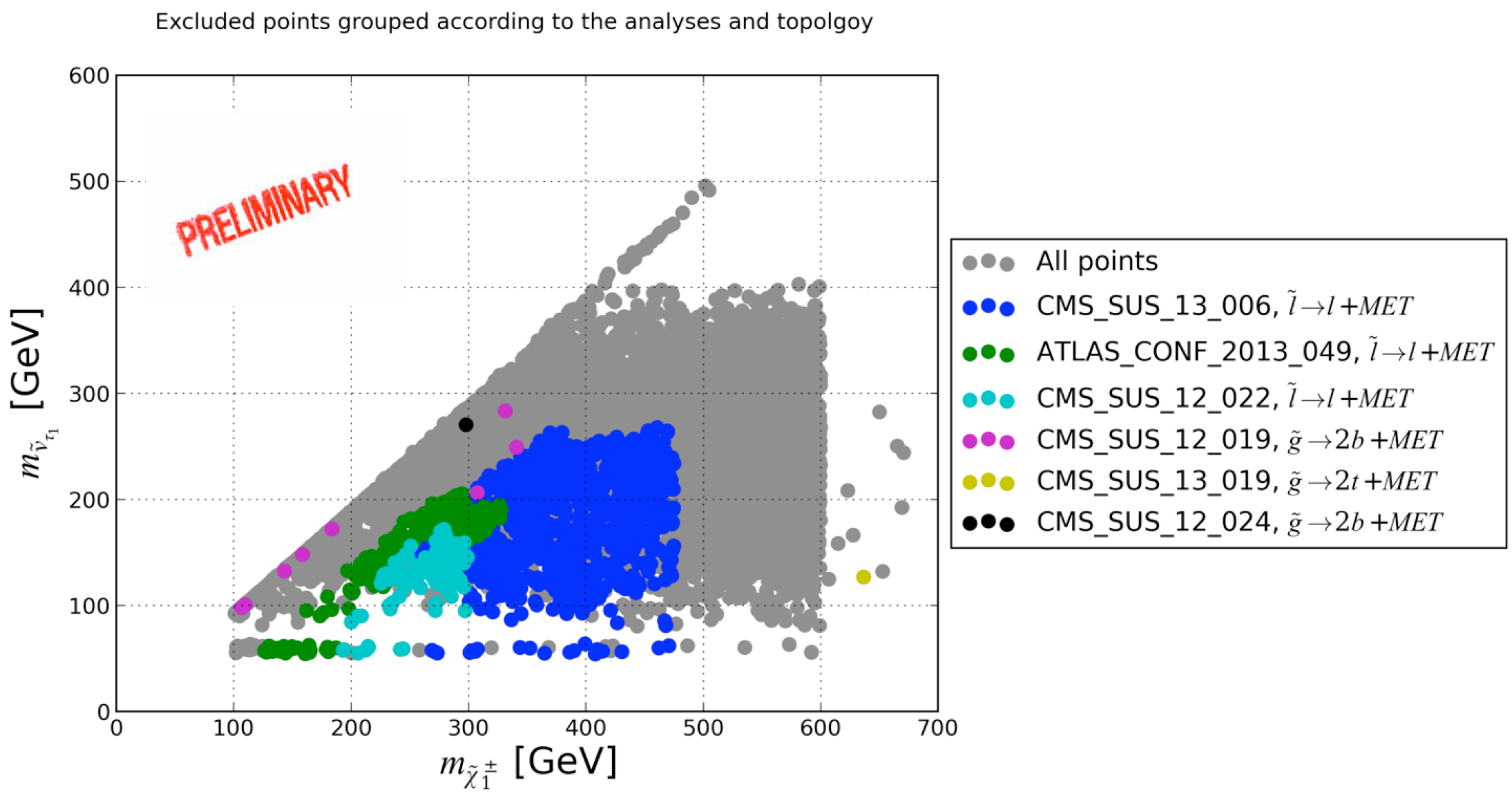

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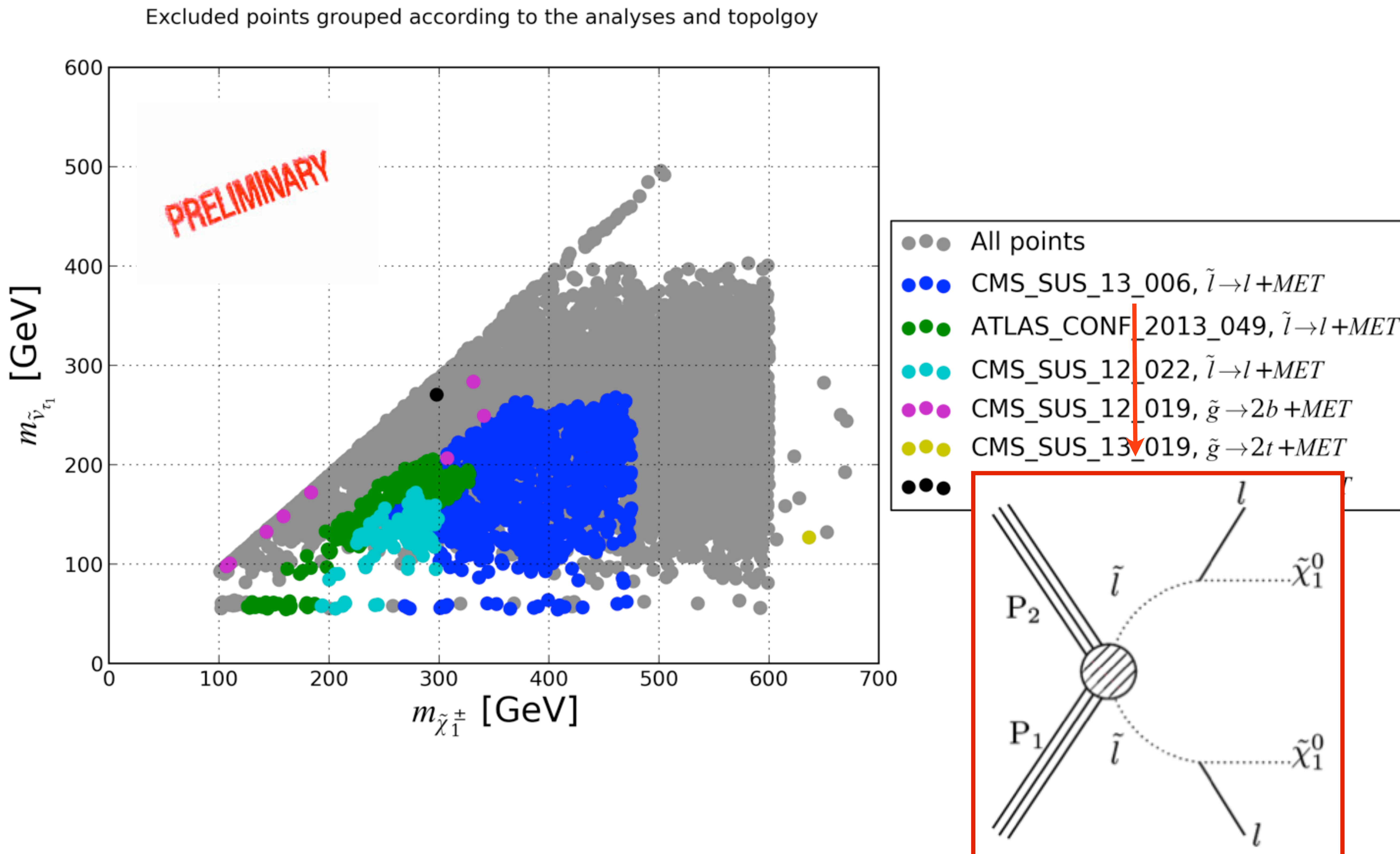
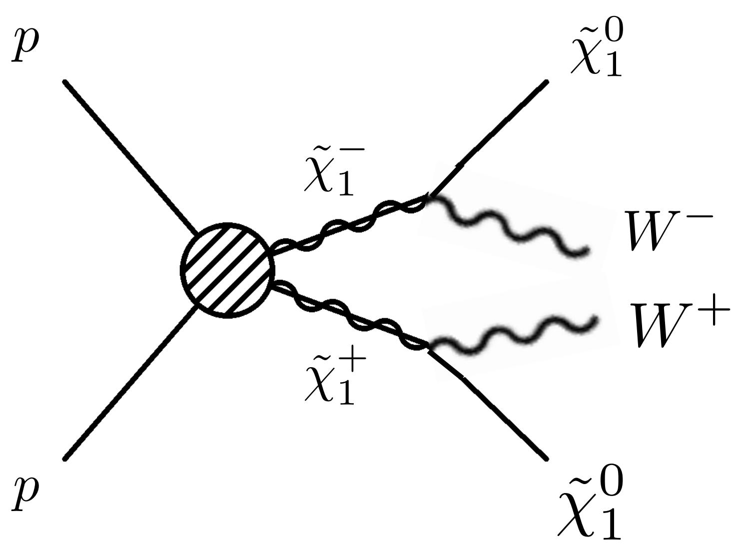


Why slepton production relevant?

MSSM

Chargino production



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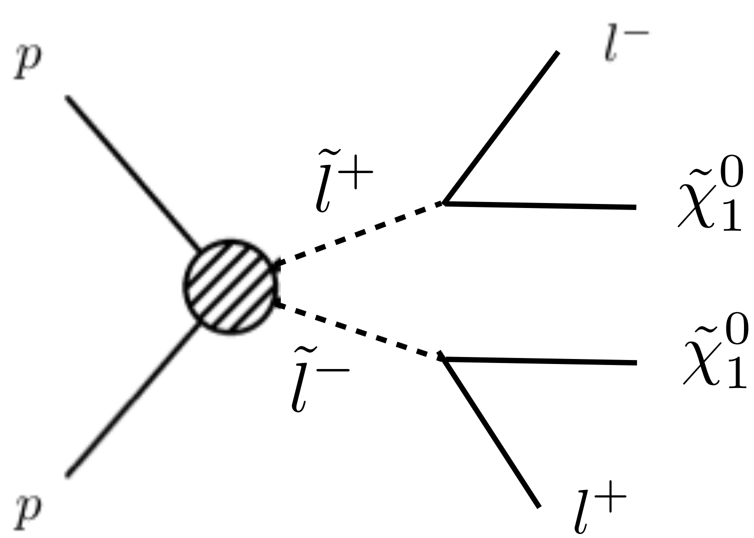
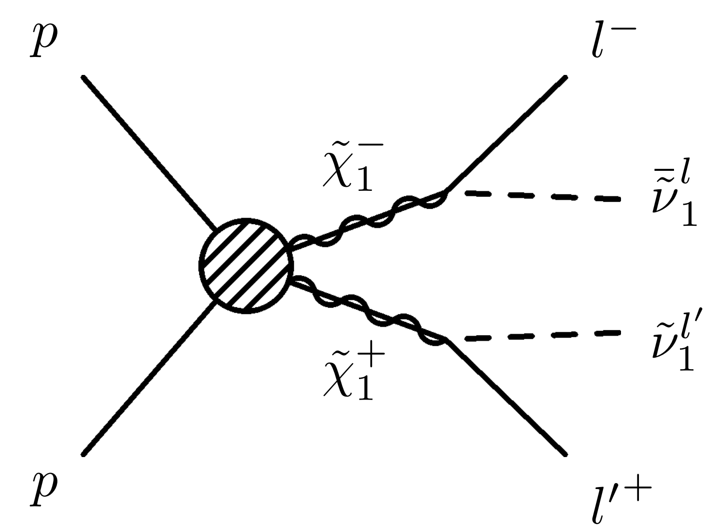


MSSM+RN

Chargino production



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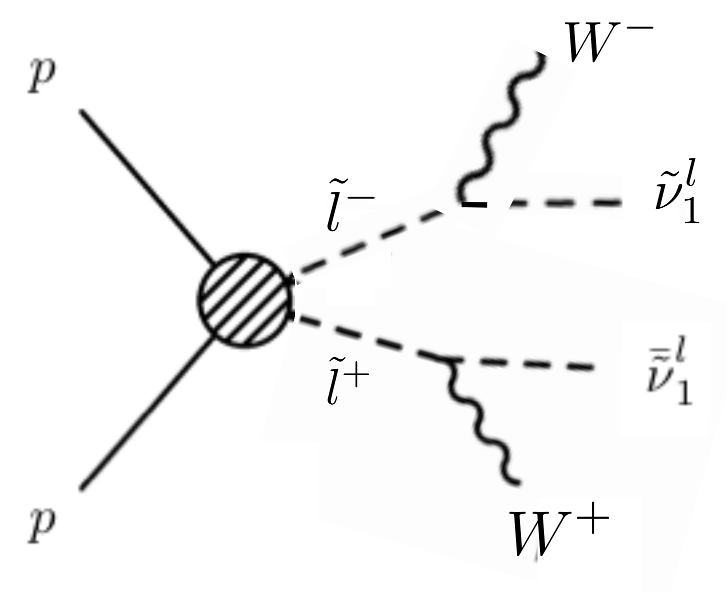
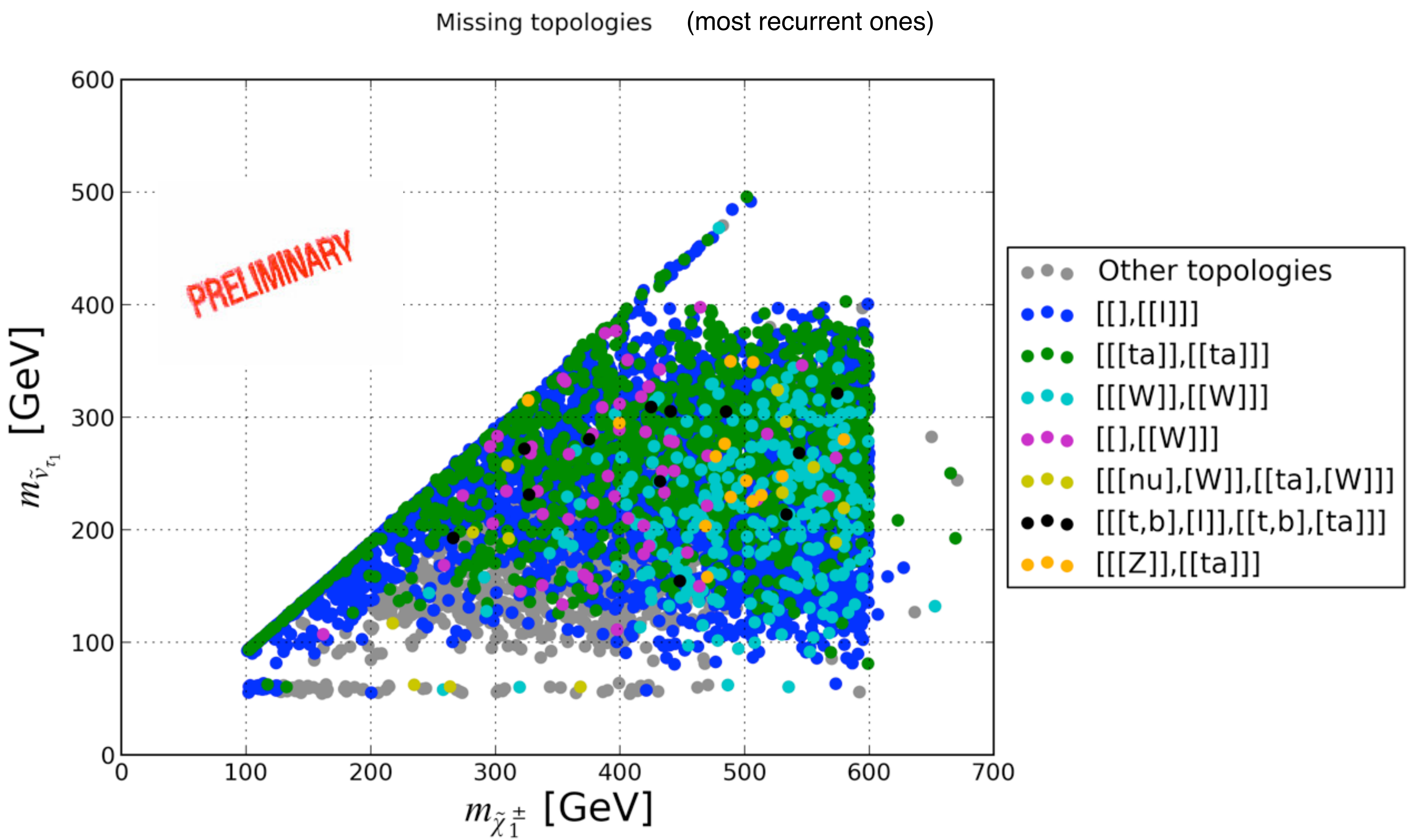


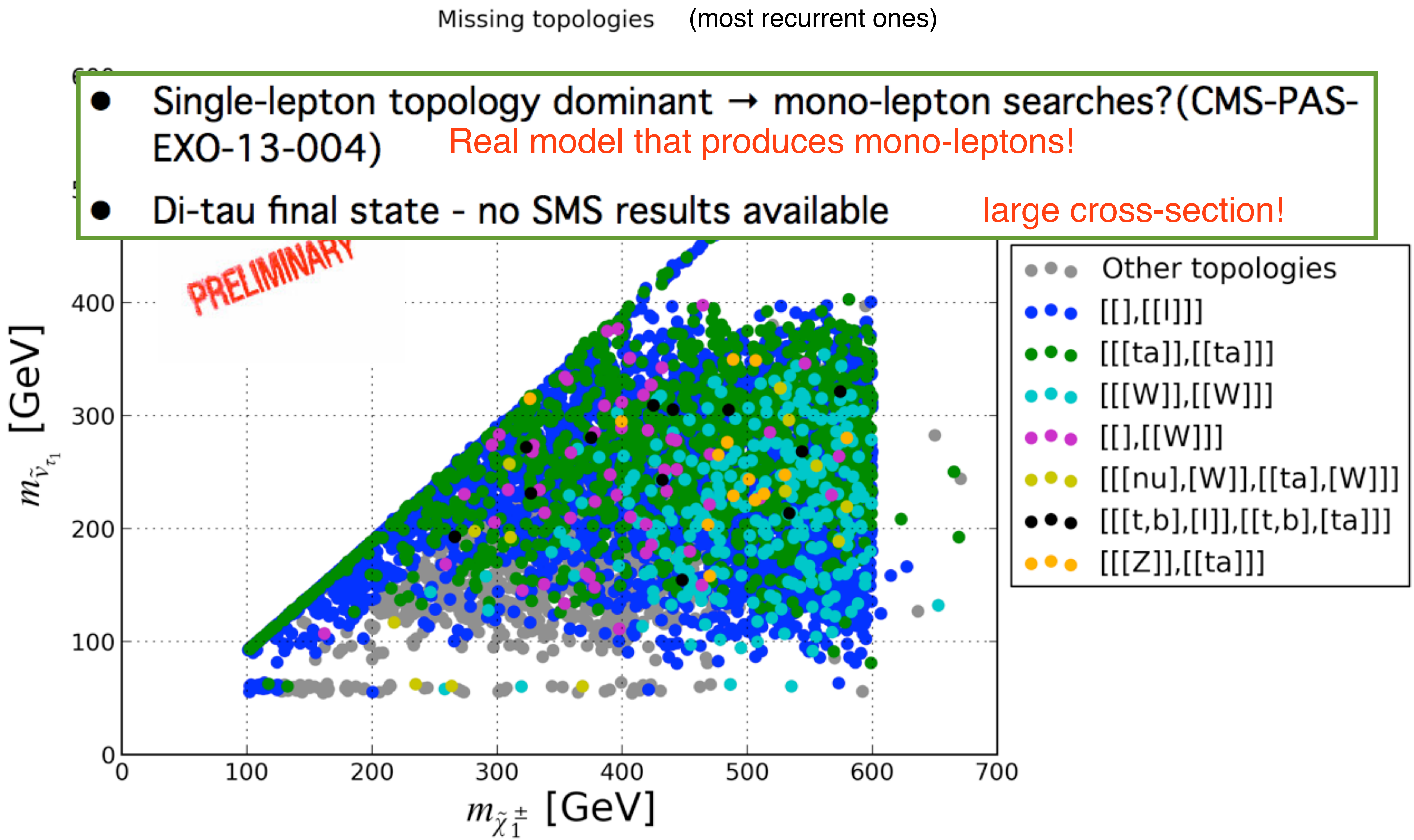
The scalar nature of the sneutrino has the effect of exchange the final state for slepton production with the one for electroweak production of the MSSM!

Test electroweak production in the MSSM+RN



Test electroweak production in the MSSM+RN

- Single-lepton topology dominant → mono-lepton searches?(CMS-PAS-EXO-13-004) Real model that produces mono-leptons!
- Di-tau final state - no SMS results available large cross-section!



Test electroweak production in the MSSM+RN

Missing topologies (most recurrent ones)

- Single-lepton topology dominant → mono-lepton searches?(CMS-PAS-EXO-13-004) Real model that produces mono-leptons!
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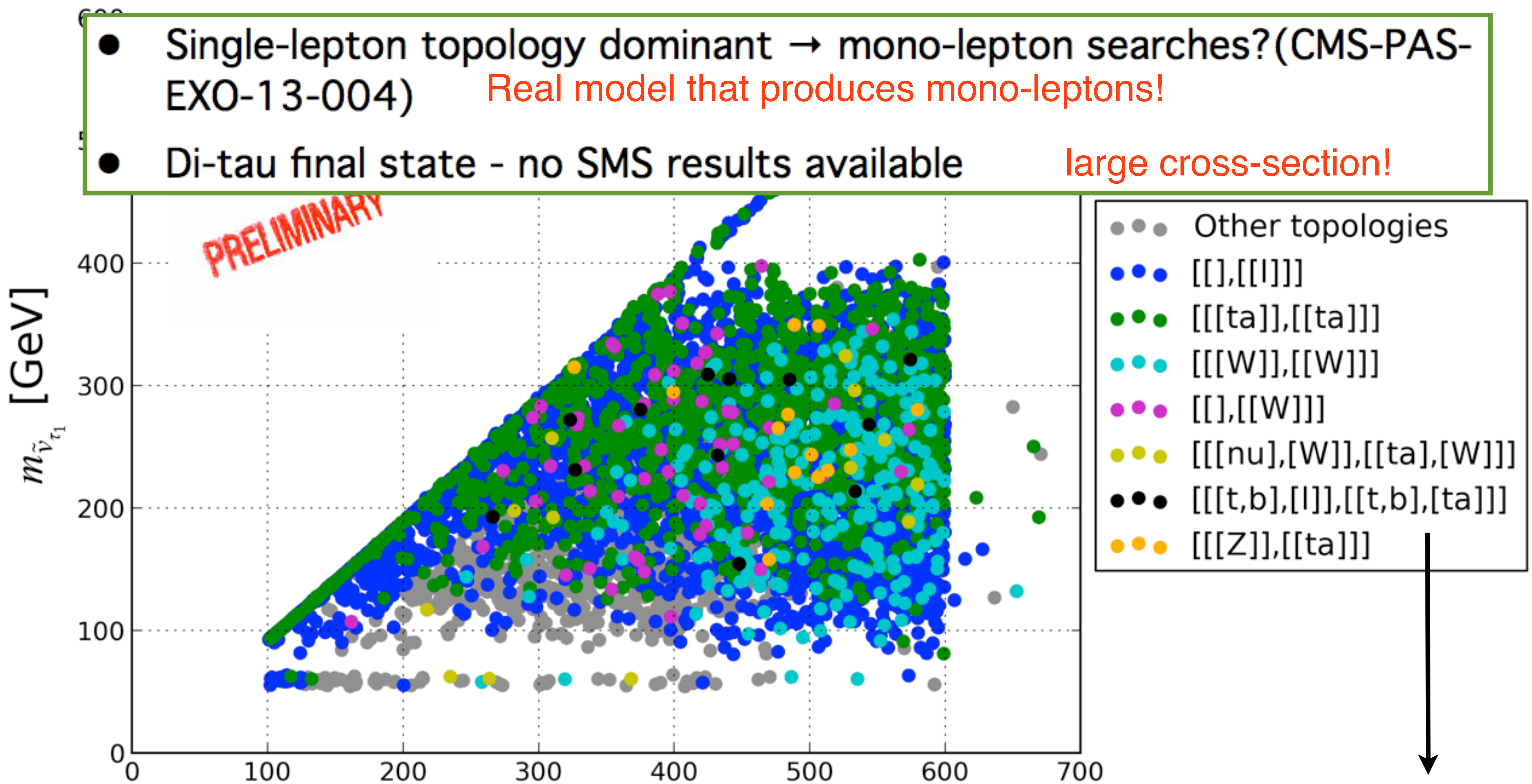
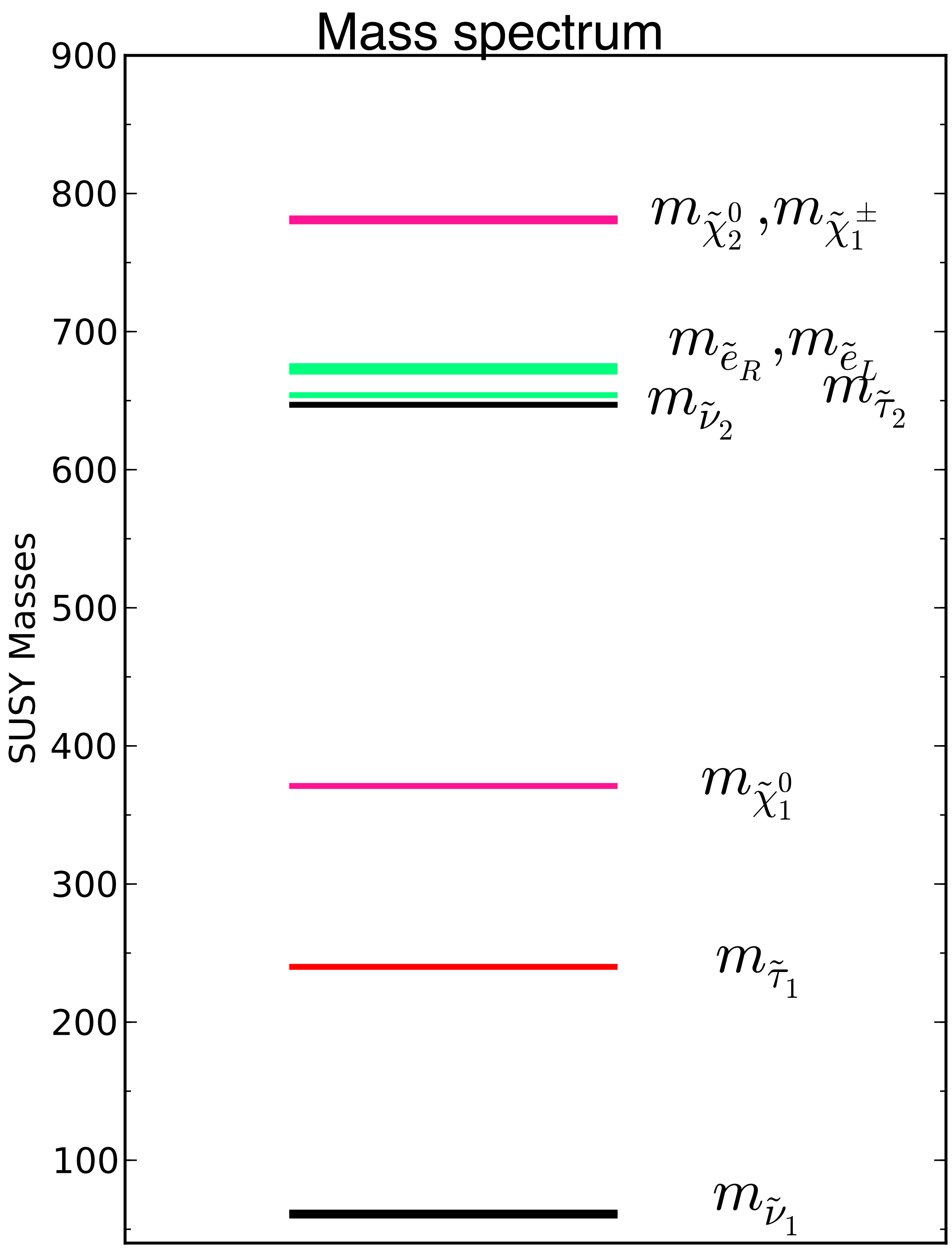


Take home message: not all relevant SMS topologies are indeed considered in the experimental results

Future predictions: Green points (Higgs pole) pattern

CA and M.E.Cabrera, JHEP 04(2104)100



Relic density is set by

$$\tilde{\nu}_1 \tilde{\nu}_1^* \to f \bar{f}$$

Via s-channel Higgs exchange
by definition of Higgs pole

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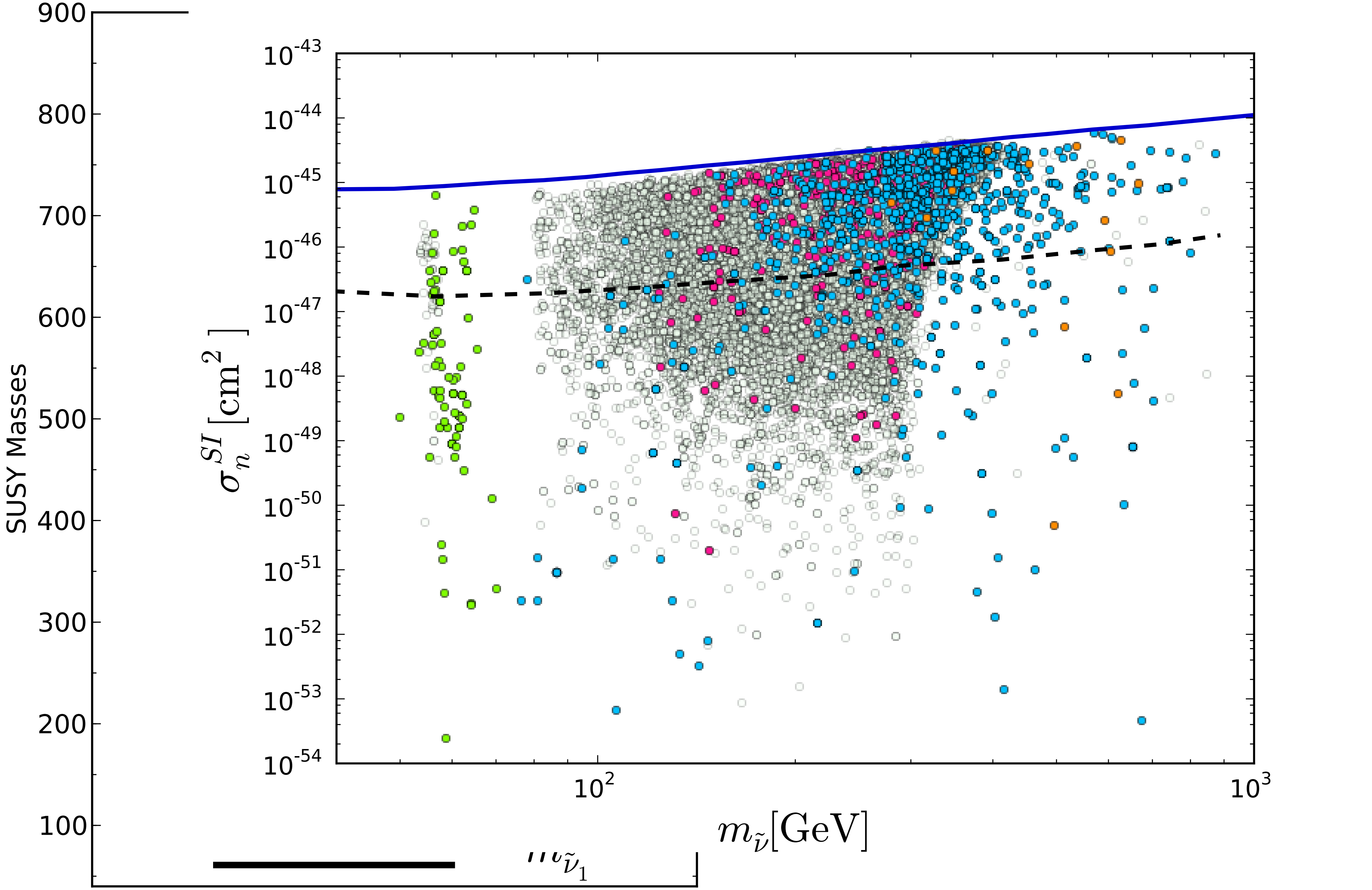

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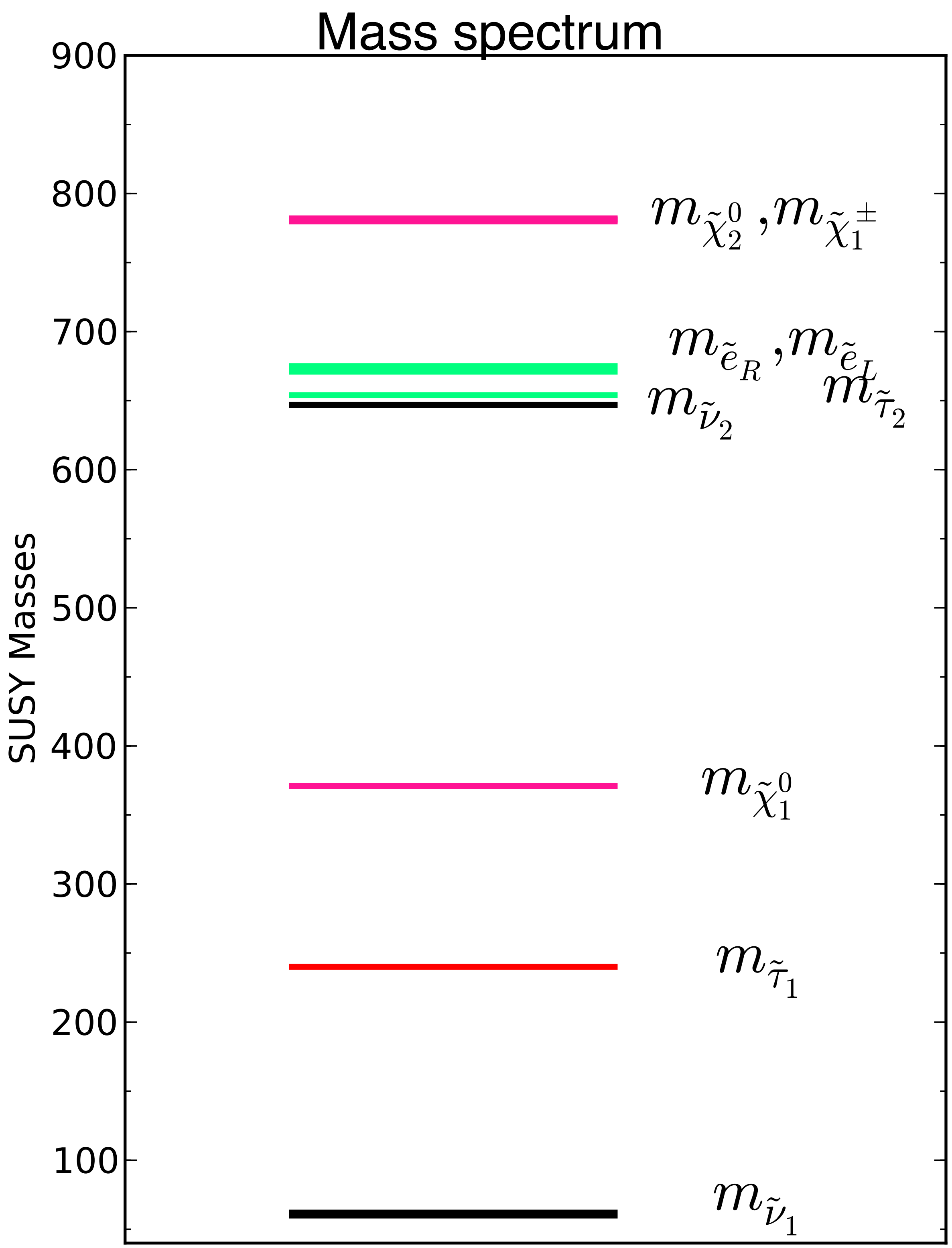

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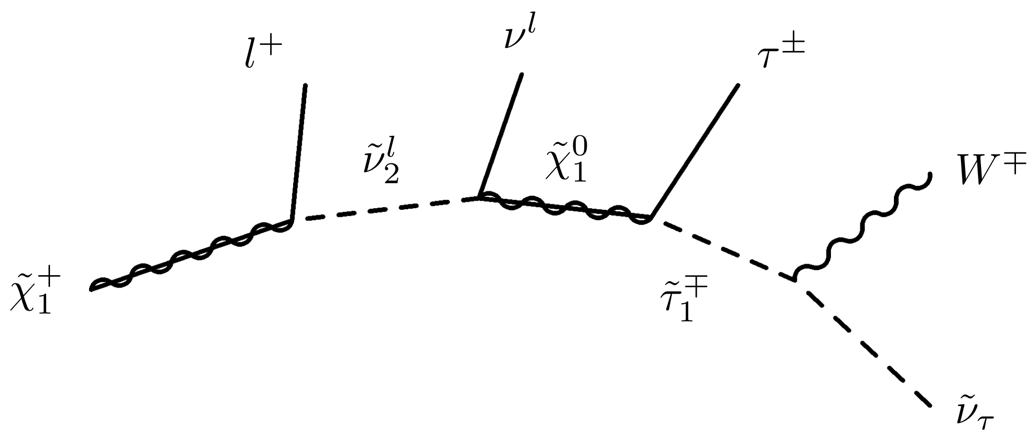
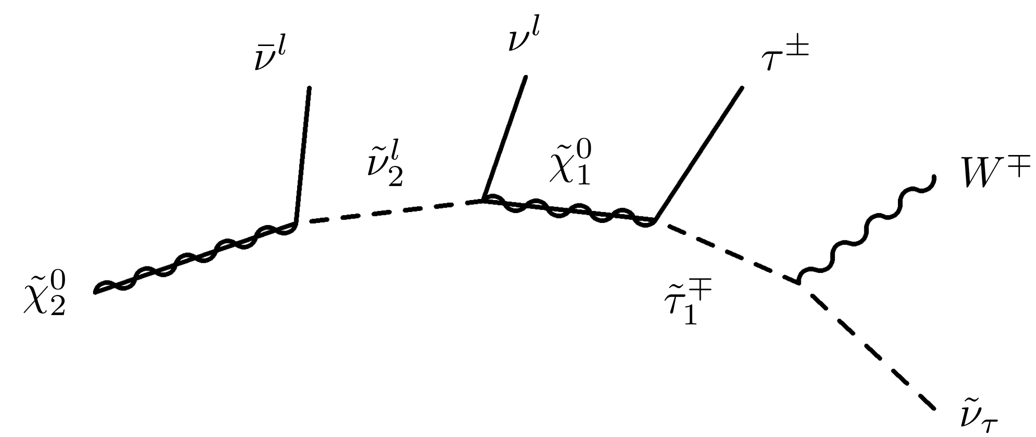
3 uncorrelated leptons



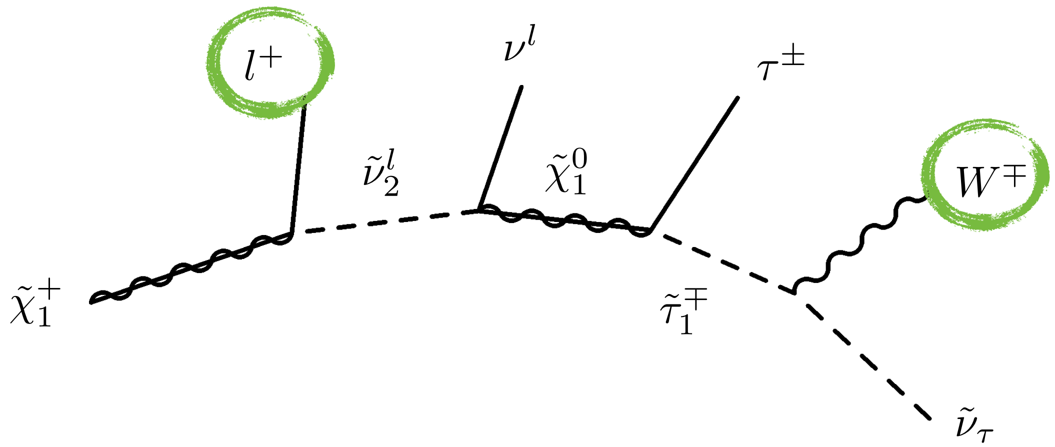


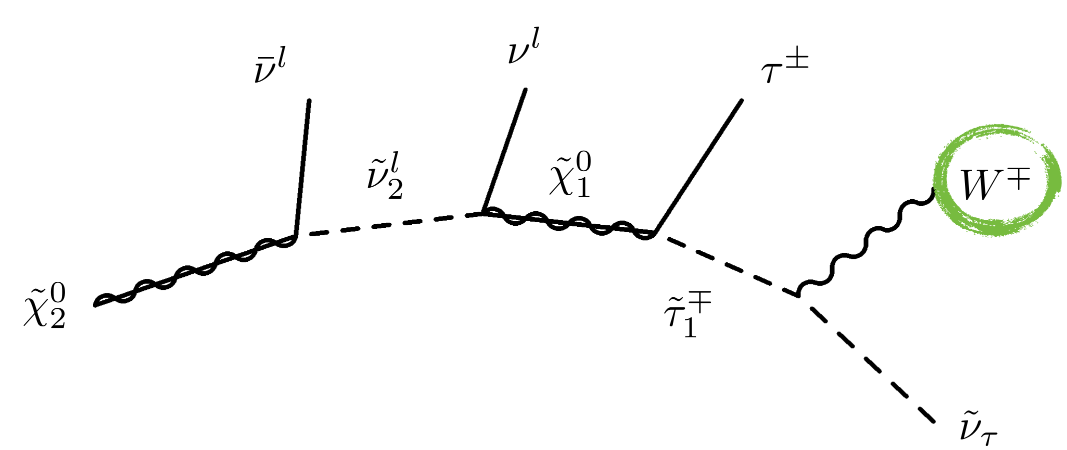
- Feature characteristic of the Higgs pole (LSP very right-handed)
- Sleptons are lighter than charginos and neutralinos (typically stau is the NLSP)
- The two final taus are not tagged due to low efficiency

Process			BR
$\tilde{\chi}_1^+$	$\rightarrow$	$e^+\ \tilde{\nu}_2$	15%
		$\mu^+\tilde{\nu}_2$	15%
		$\tau^+\tilde{\nu}_2$	21%
$\tilde{\chi}_1^0$	$\rightarrow$	$\tau^+\tilde{\tau}_1^-$	90%
$\tilde{\tau}_1^\pm$	$\rightarrow$	$W^\pm\ \tilde{\nu}_1$	100%

Process			BR
$\tilde{\chi}_2^0$	$\rightarrow$	$\nu\ \tilde{\nu}_2$	48%
		$\tilde{l}_L\ l$	28%
$\tilde{\nu}_2$	$\rightarrow$	$\tilde{\chi}_1^0\ \nu$	98%

3 uncorrelated leptons



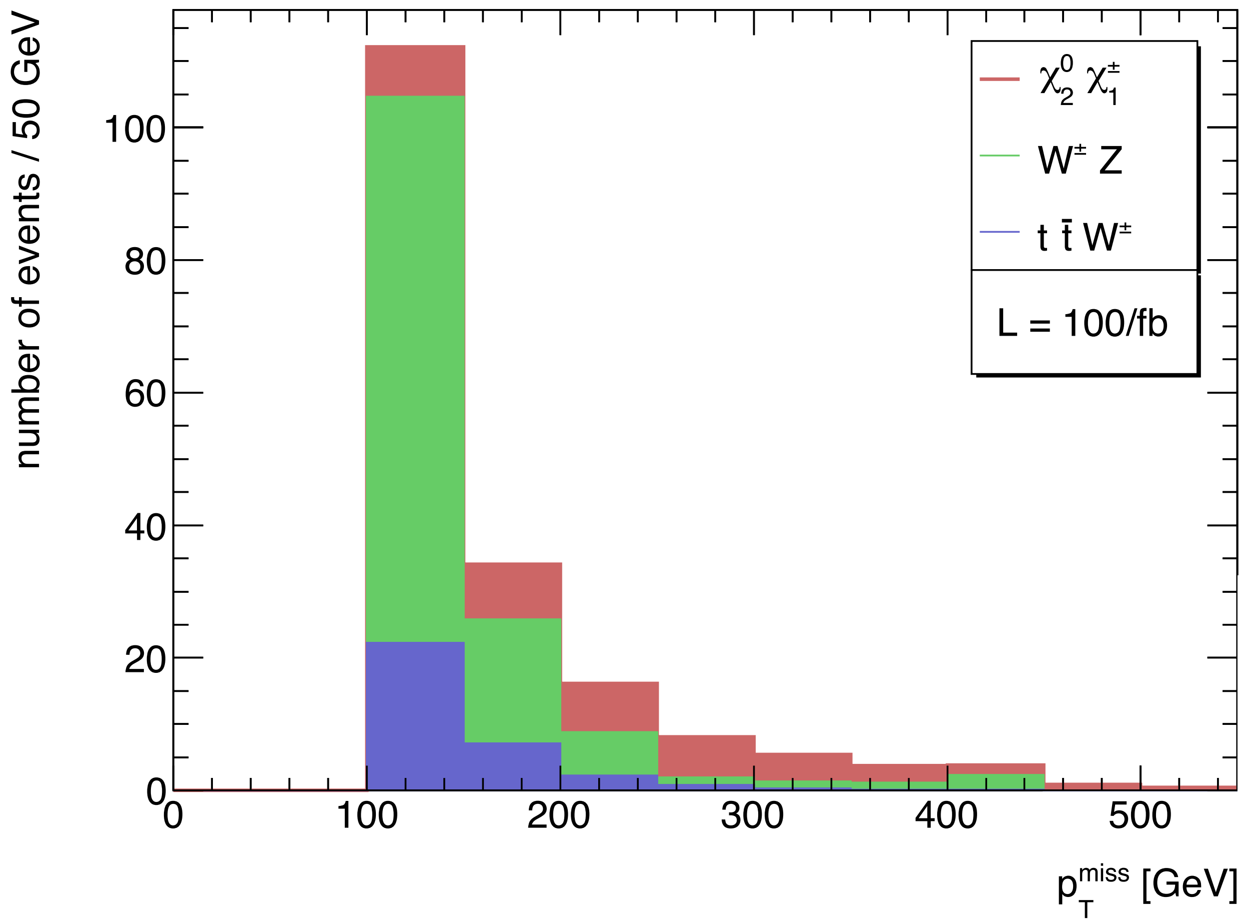


- Feature characteristic of the Higgs pole (LSP very right-handed)
- Sleptons are lighter than charginos and neutralinos (typically stau is the NLSP)
- The two final taus are not tagged due to low efficiency

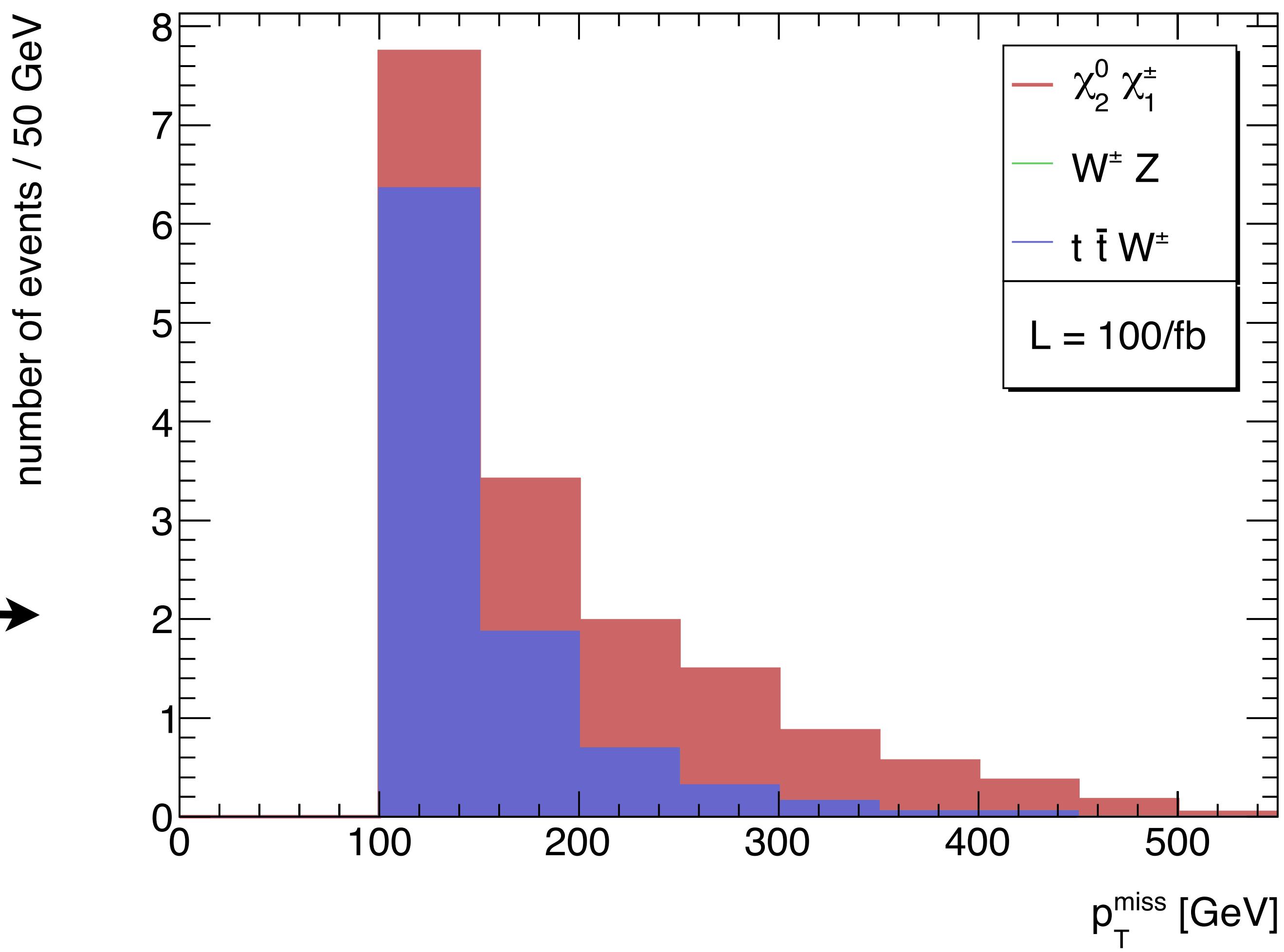
Process			BR
$\tilde{\chi}_1^+$	$\rightarrow$	$e^+\ \tilde{\nu}_2$	15%
		$\mu^+\tilde{\nu}_2$	15%
		$\tau^+\tilde{\nu}_2$	21%
$\tilde{\chi}_1^0$	$\rightarrow$	$\tau^+\tilde{\tau}_1^-$	90%
$\tilde{\tau}_1^\pm$	$\rightarrow$	$W^\pm\ \tilde{\nu}_1$	100%

Process			BR
$\tilde{\chi}_2^0$	$\rightarrow$	$\nu\ \tilde{\nu}_2$	48%
		$\tilde{l}_L\ l$	28%
$\tilde{\nu}_2$	$\rightarrow$	$\tilde{\chi}_1^0\ \nu$	98%

3 uncorrelated leptons



Additional cut forbidding OSSF leptons

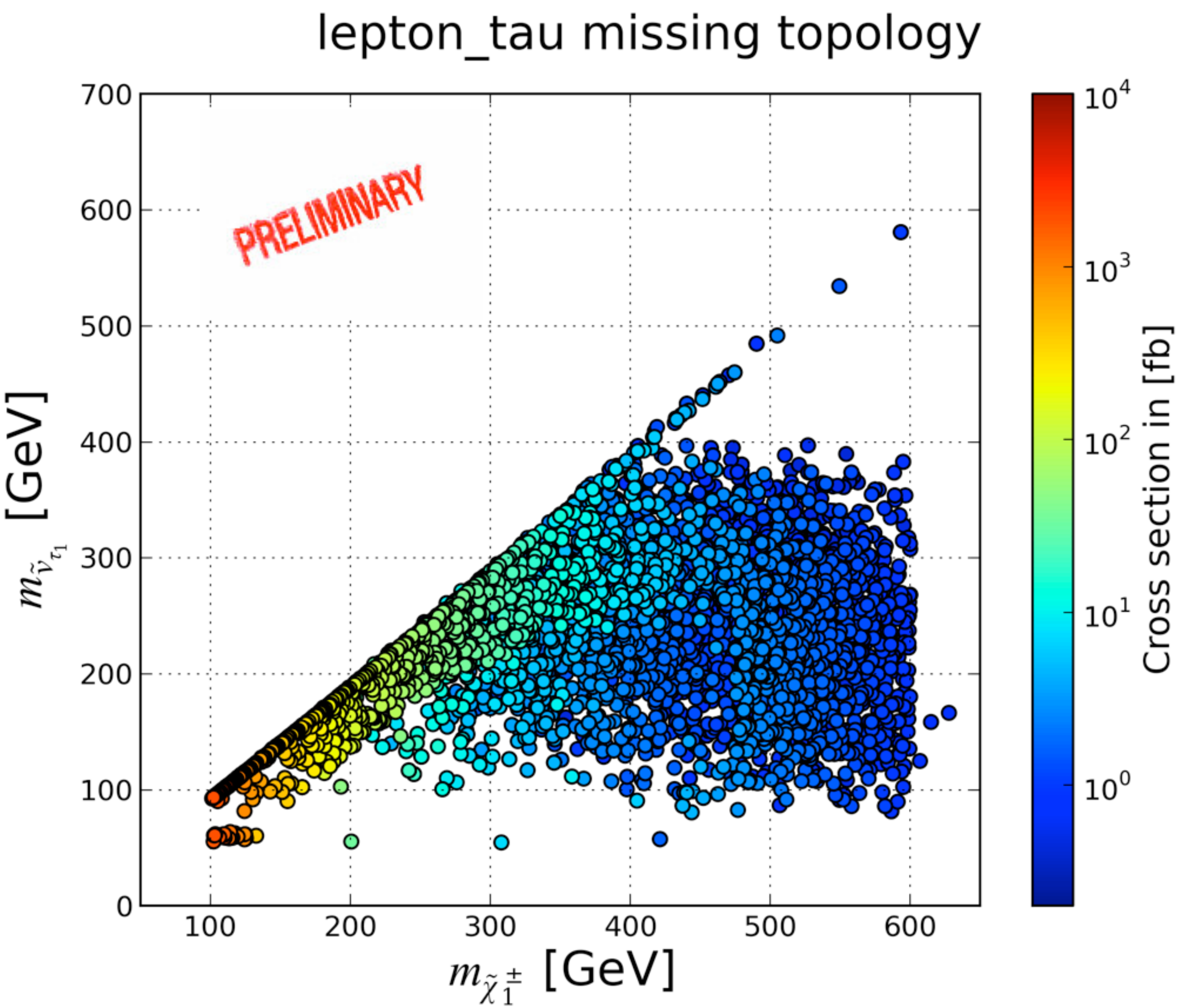


Conclusions and work in progress

- Dark matter in connection with neutrino masses can provide signatures into leptons which are different from the standard MSSM
- Study of kinematics proper to sneutrinos for SModelS
- Application of SModelS to light squark sector as well
- Complementarity of searches among LHC and XENON1T
- What about seesaw models?

Backup slides
Predictions for LHC from sneutrino dark matter

Test electroweak production in the MSSM+RN



Set up of the analysis

WIMP Model = MSSM+RN

FeynRules

↓

Supersymmetric mass spectrum

↓

SoftSUSY

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

+ dark matter direct detection predictions

micrOMEGAs

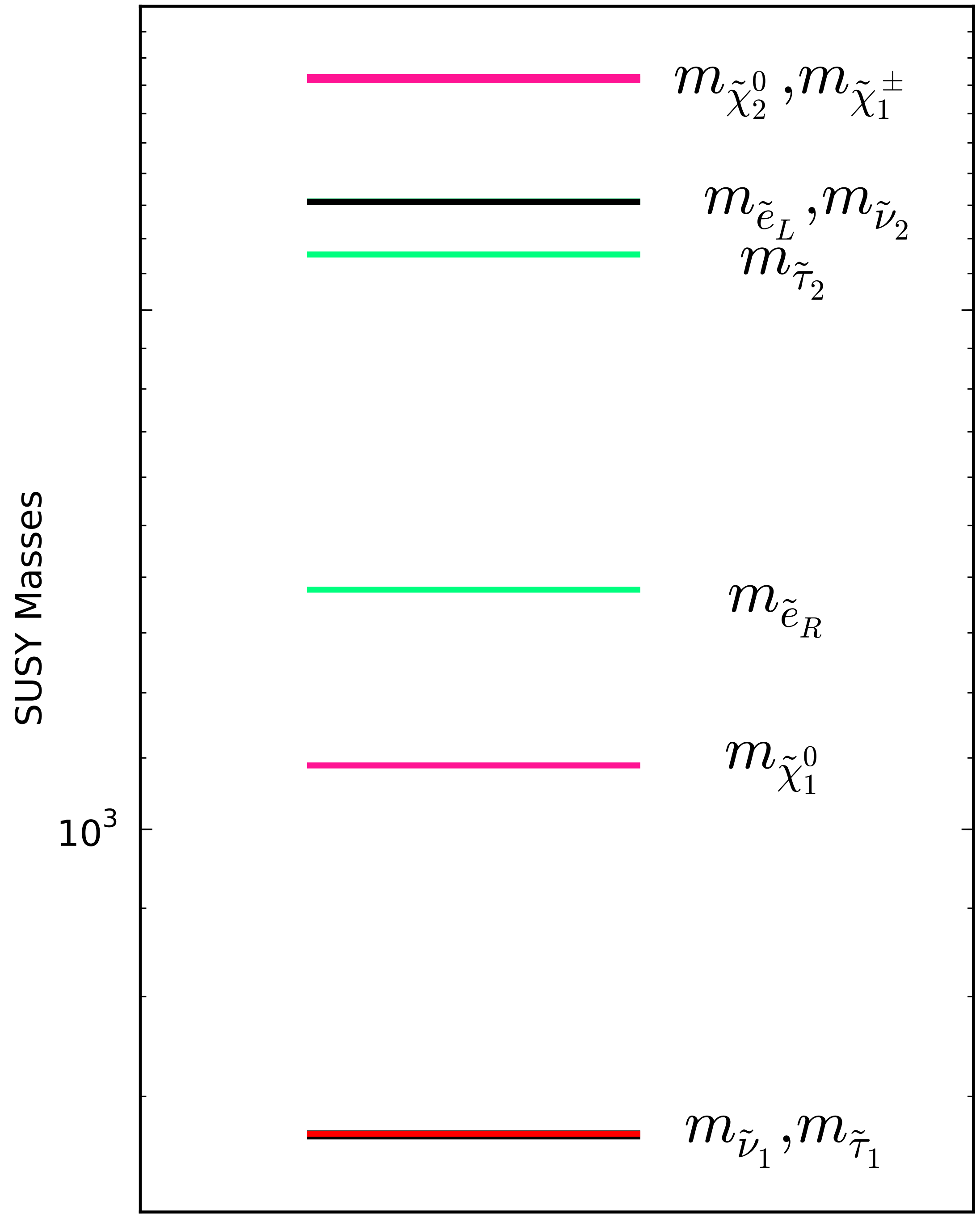
↓

Predictions at LHC

MadGraph5, Pythia, Delphes

Orange points pattern

Mass spectrum



Relic density is set by

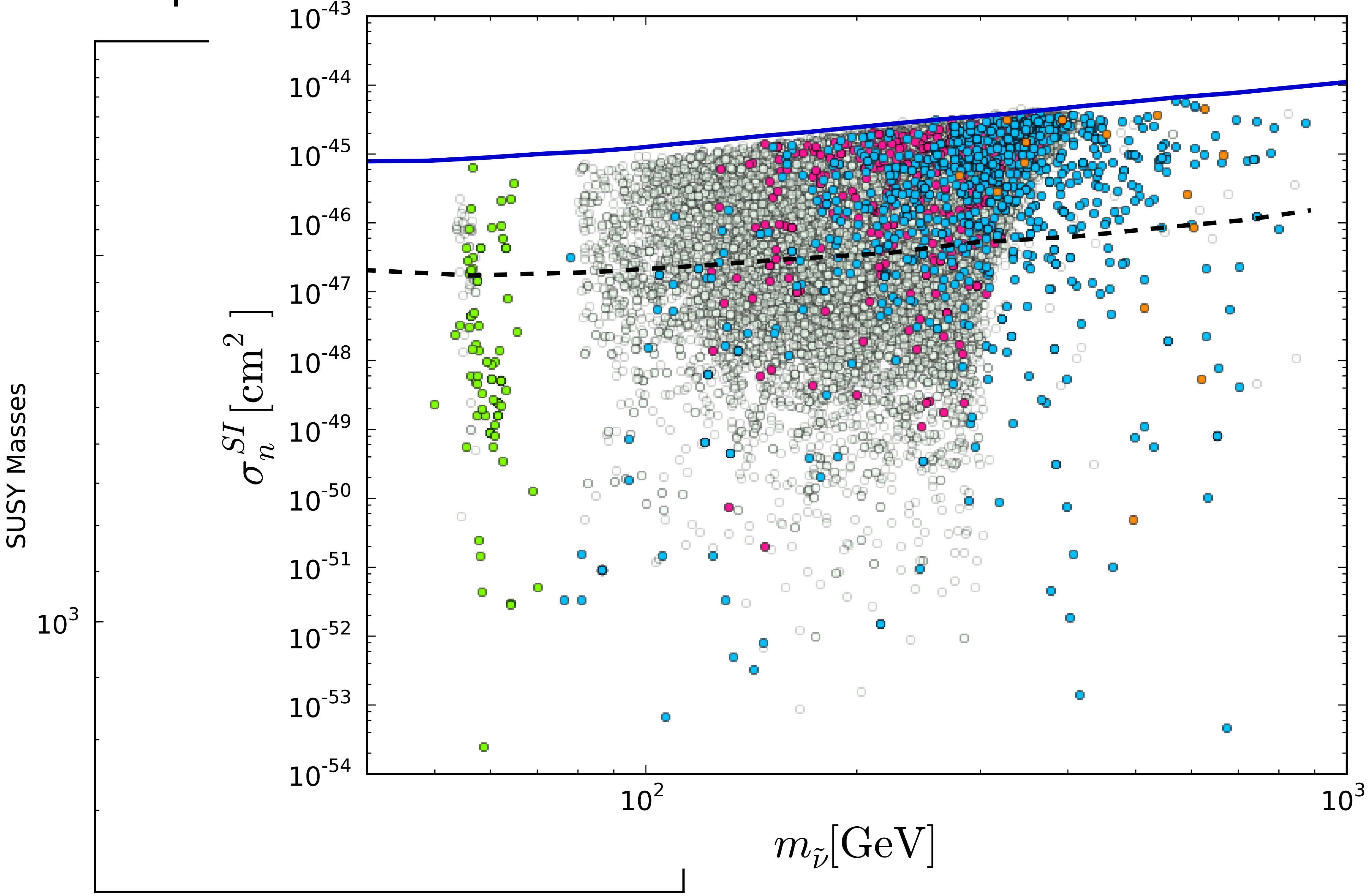
$$\left.\begin{array}{ll} \tilde{\tau}_1^+\tilde{\tau}_1^- & \to W^+W^-, ZZ, hh, t\bar{t} \\ \tilde{\nu}_1\tilde{\tau}_1^- & \to ZW^-, hW^- \\ \tilde{\nu}_1\tilde{\nu}_1^* & \to W^+W^-, ZZ, hh, t\bar{t} \end{array}\right\}$$

Very subdominant

unless $\sin\theta_{\tilde{\nu}} > 0.02$

Orange points pattern

Mass spe



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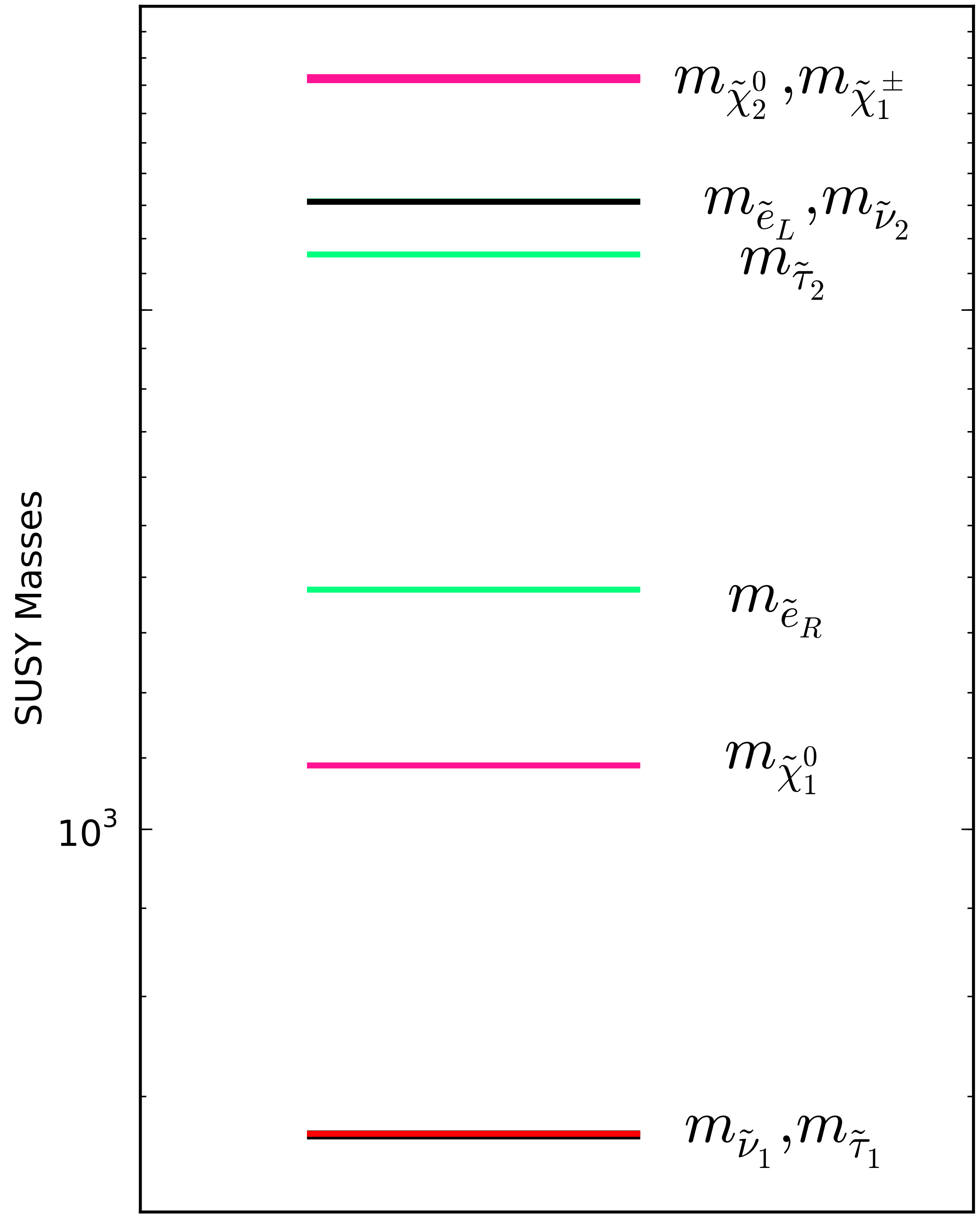

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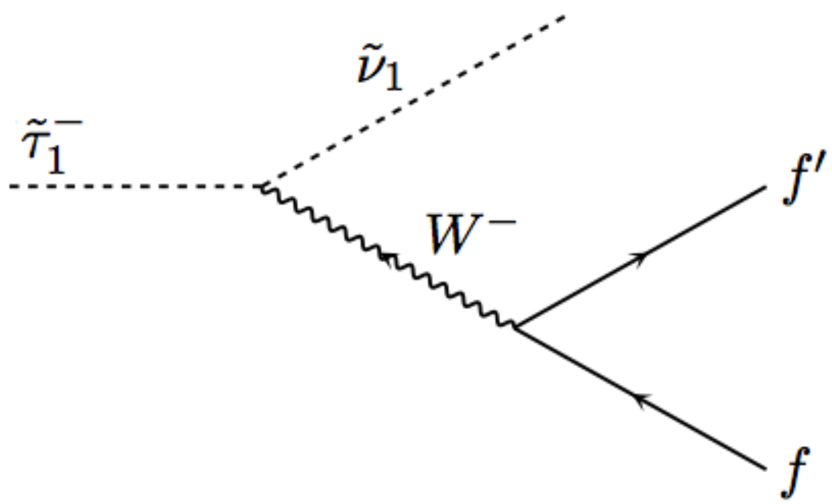
Long-lived staus

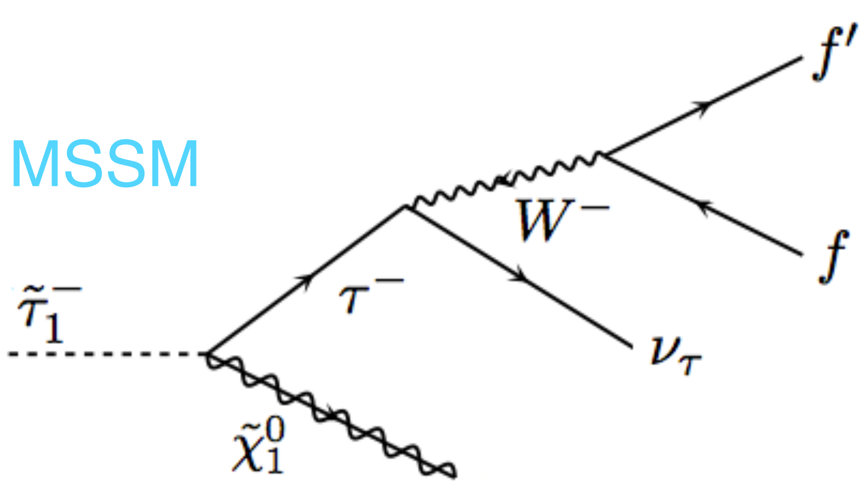
Signature arising when:

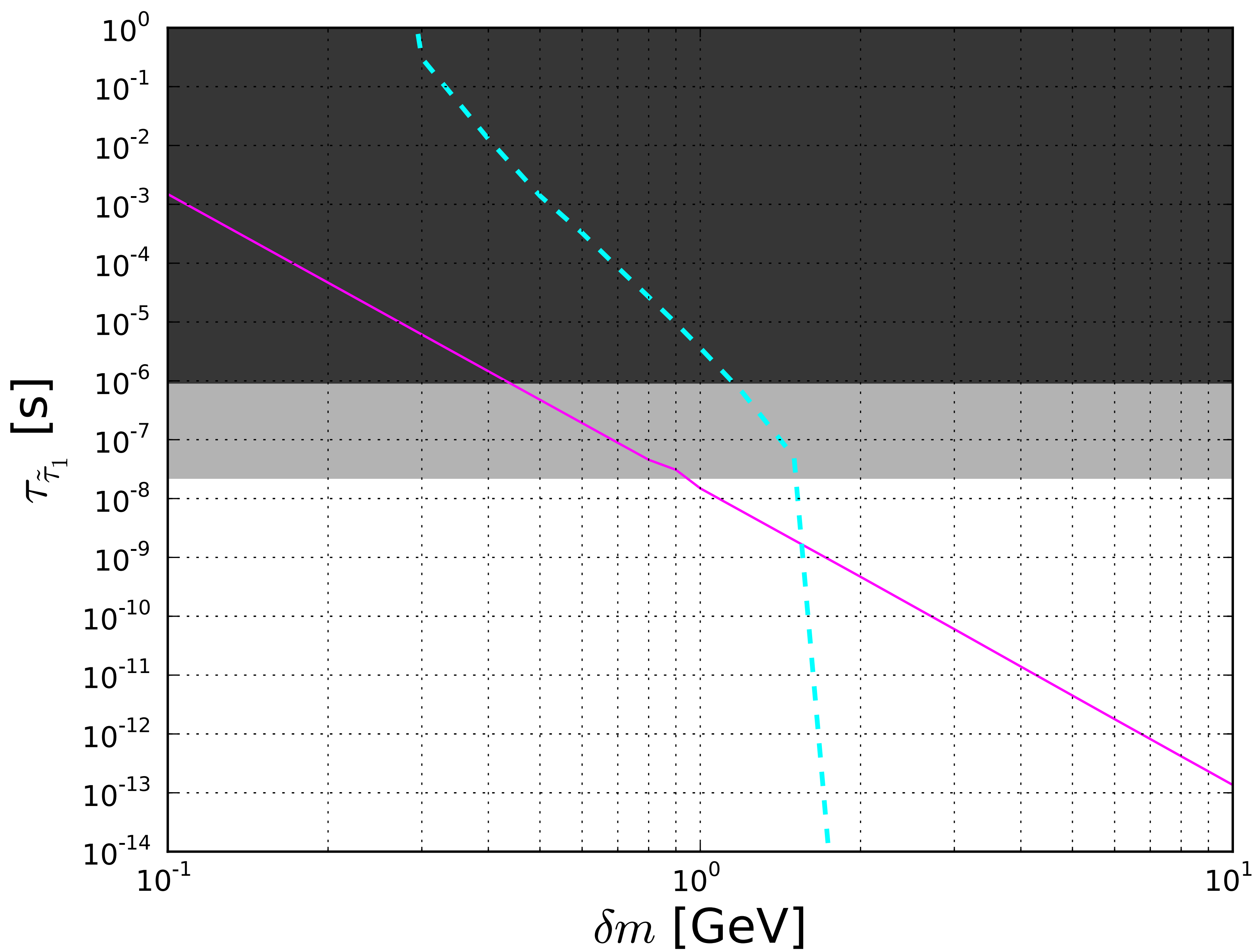
1. Stau is the NSLP
2. small $\delta m \equiv m_{\tilde{\tau}_1^-} - m_{\tilde{\nu}}$

MSSM + RN



MSSM

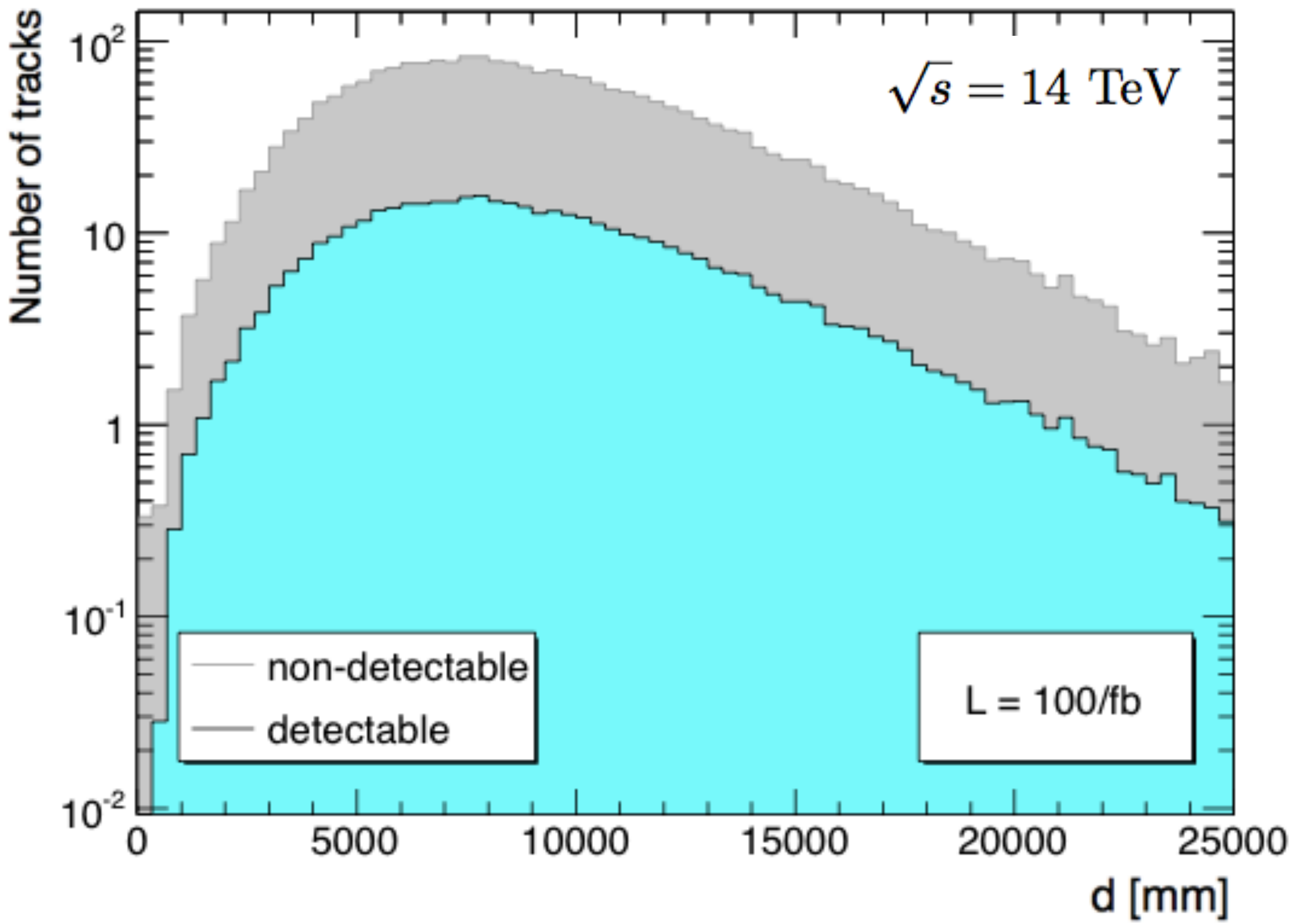




Existing bound: mass$_{llp}$ > 300 GeV allowed (ATLAS-CONF-2013-58)

Long-lived staus

- Staus produced in pair directly
- Assumed observation of both charged tracks from the hadronic calorimeter to escaping charged particles (ATLAS efficiency $\epsilon = 0.2$)



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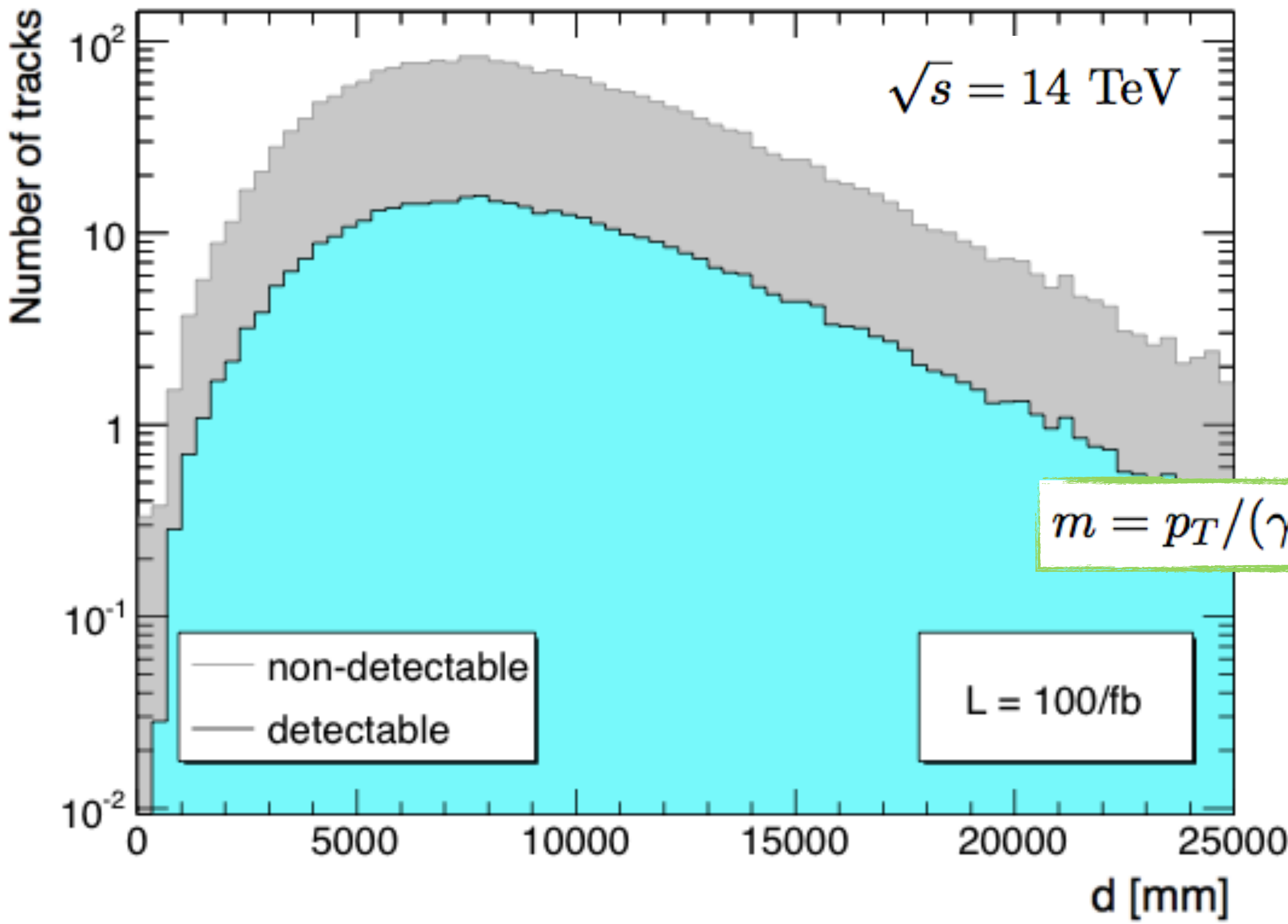
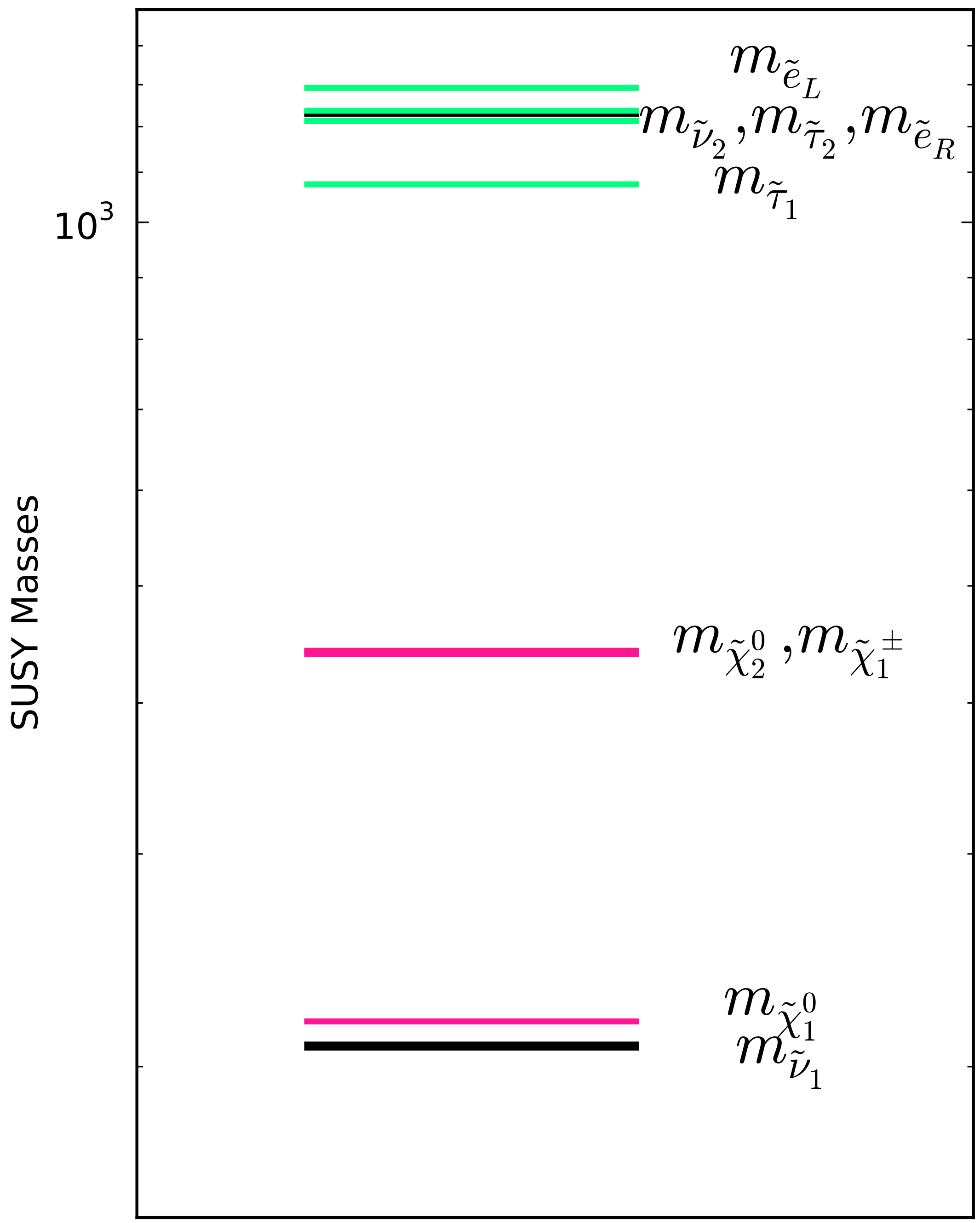


$m = p_T/(\gamma\beta)$

Magenta points pattern

Mass spectrum

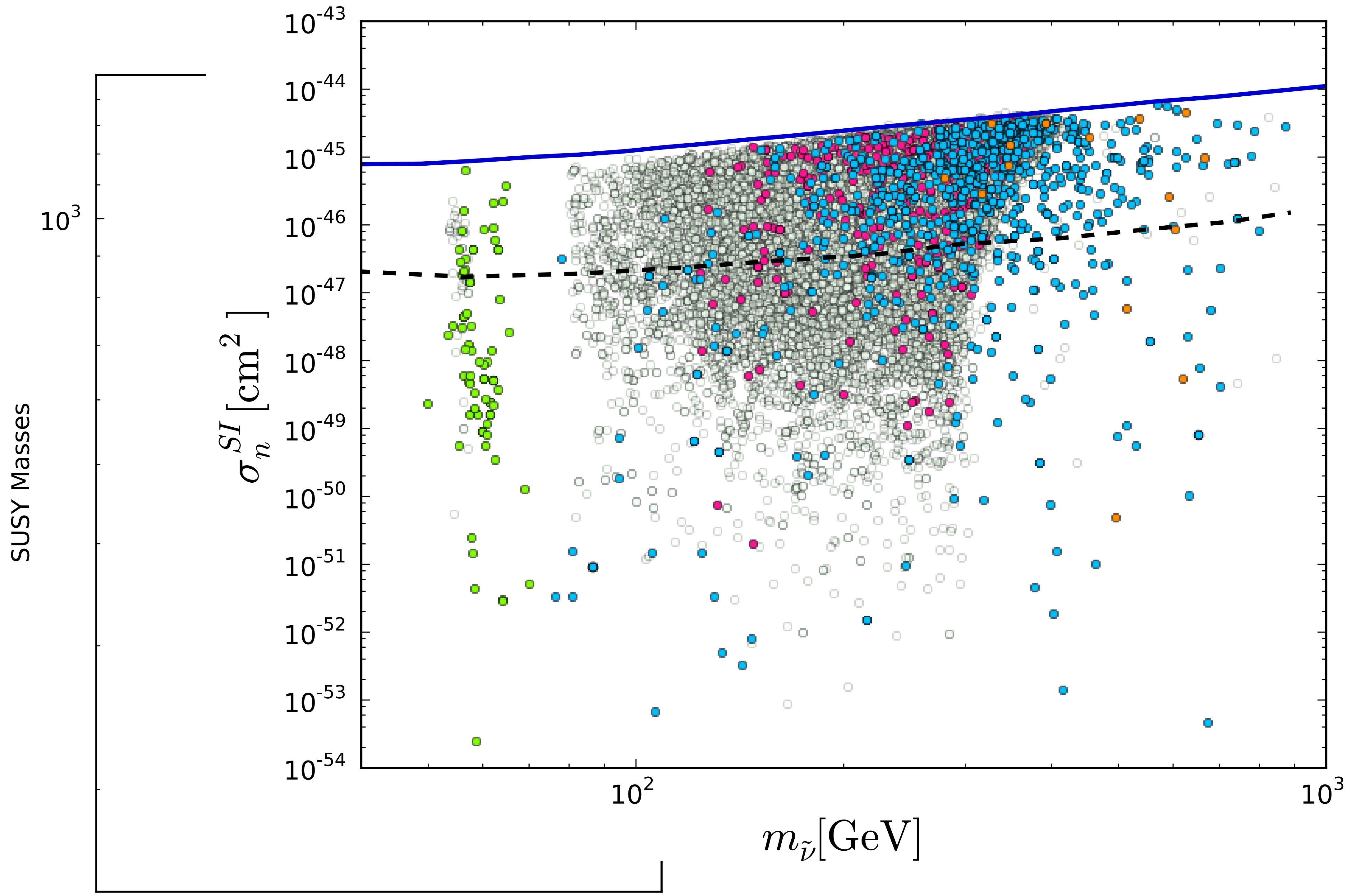


Relic density is set by sneutrino and coannihilation/annihilation with the lightest neutralino

Blue points have chargino degenerate as well, relic density set by neutralino/gaugino sectors and LSP very sterile: hard to distinguish from MSSM

Magenta points pattern

Mass spe



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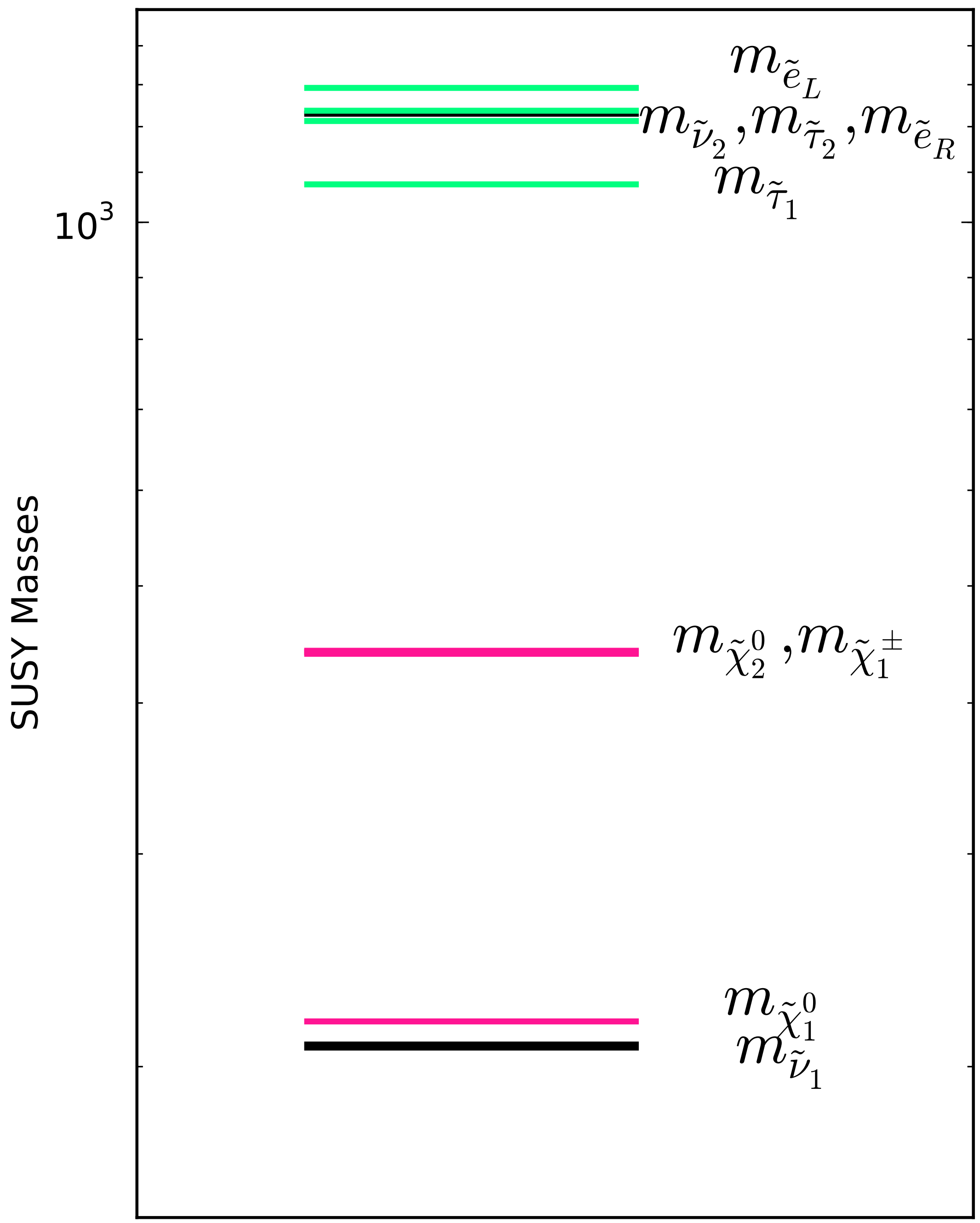

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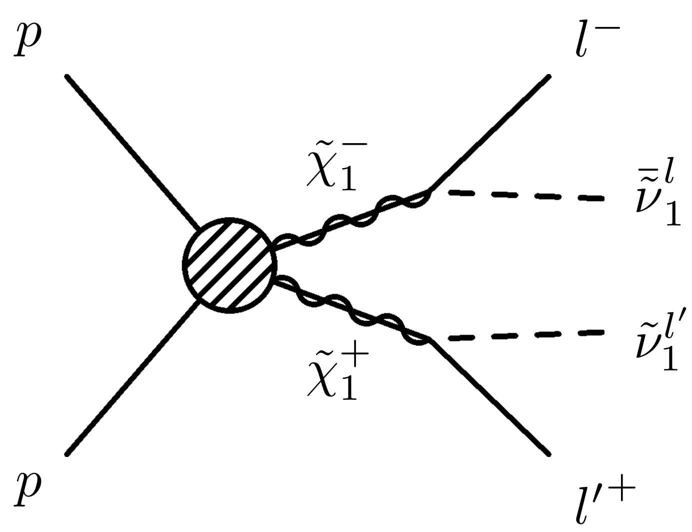
Chargino production

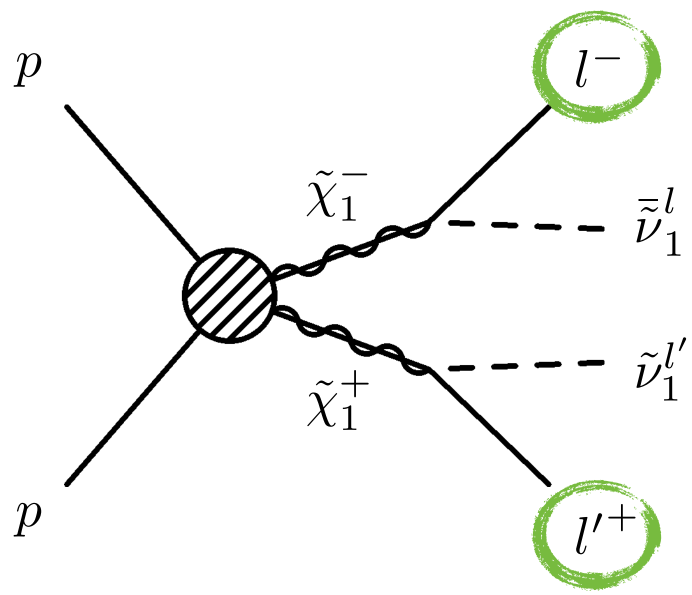


- When chargino is ligther than sleptons
- Decay 2-body into the LSP (MSSM is 3-body)

$$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to f' \, \bar{f}\tilde{\chi}_1^0$$

Process			BR
$\tilde{\chi}_1^+$	$\to$	$W^+ \ \tilde{\chi}_1^0$	18.1%
		$e^+ \ \tilde{\nu}_1^e$	25.4%
		$\mu^+ \ \tilde{\nu}_1^{\mu}$	25.4%
		$\tau^+ \ \tilde{\nu}_1^{\tau}$	31.1%

Chargino production



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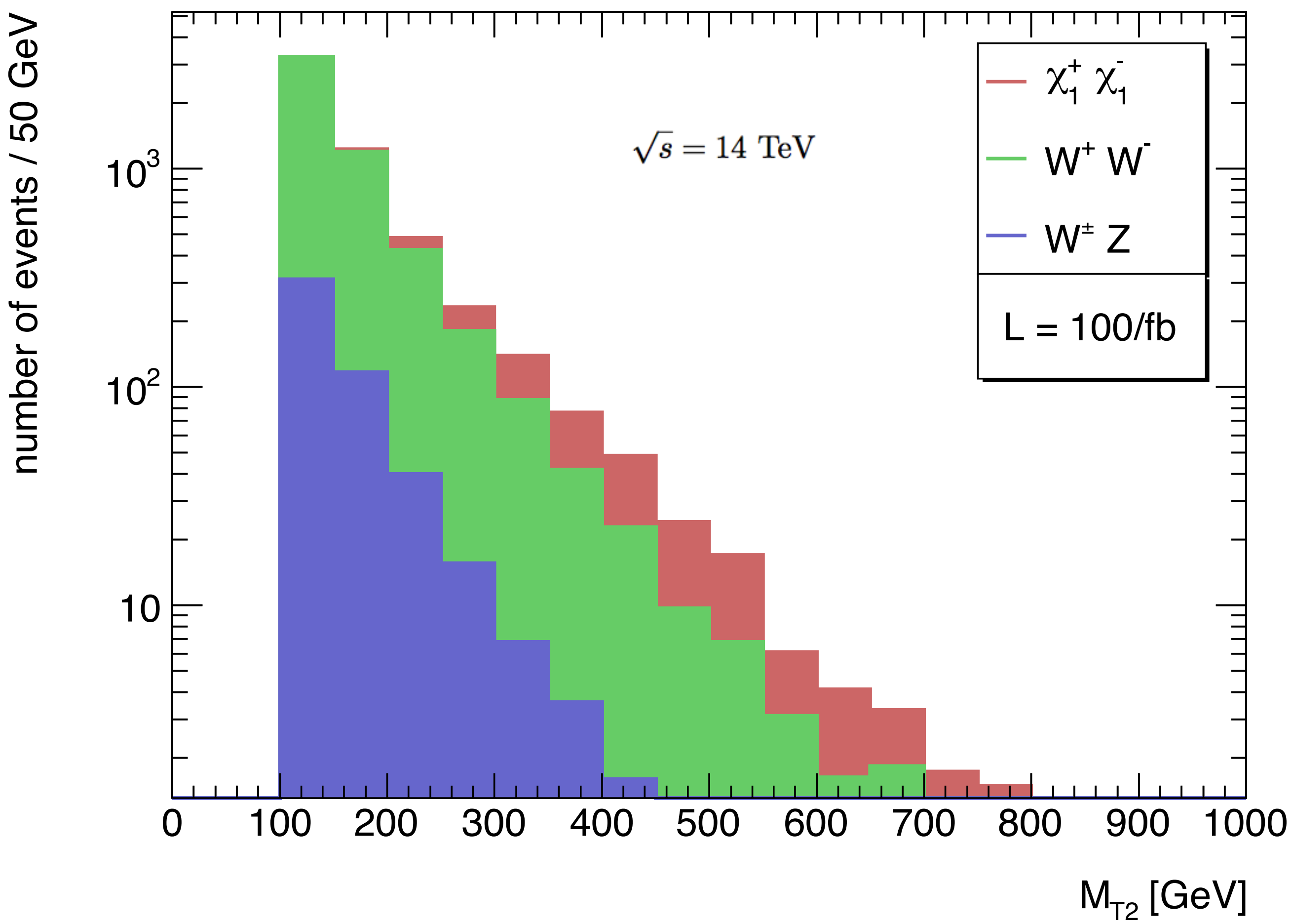
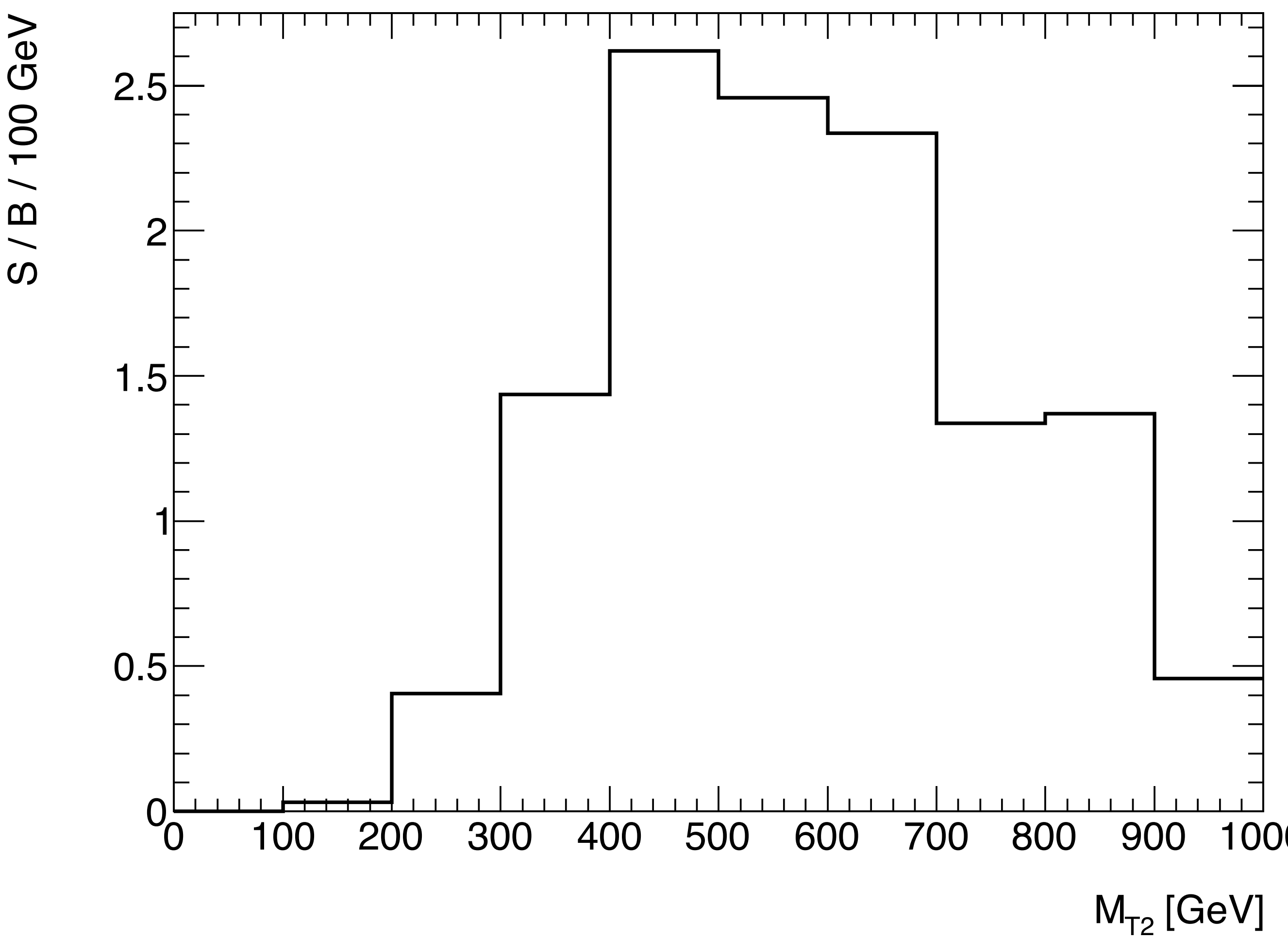
Signal: 2 leptons with opposite sign and uncorrelated flavor

Chargino production

`Transverse-mass‘ (from A.Barr,C.Lester,P.Stephens ’03)

$$m_{T2} = \min_{p_1+p_2=p_T^{\rm miss}} \{\max[M_T(p_{l_1},p_1), M_T(p_{l_2},p_2)]\}$$





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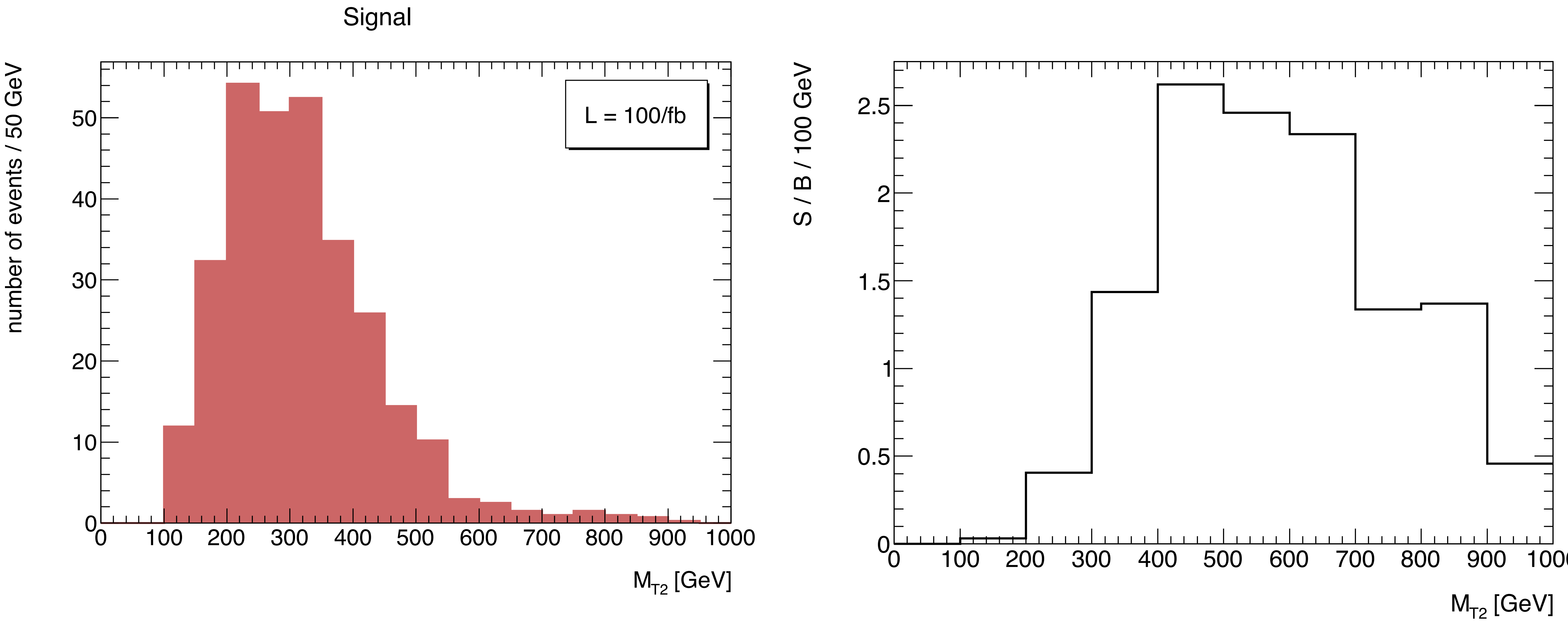


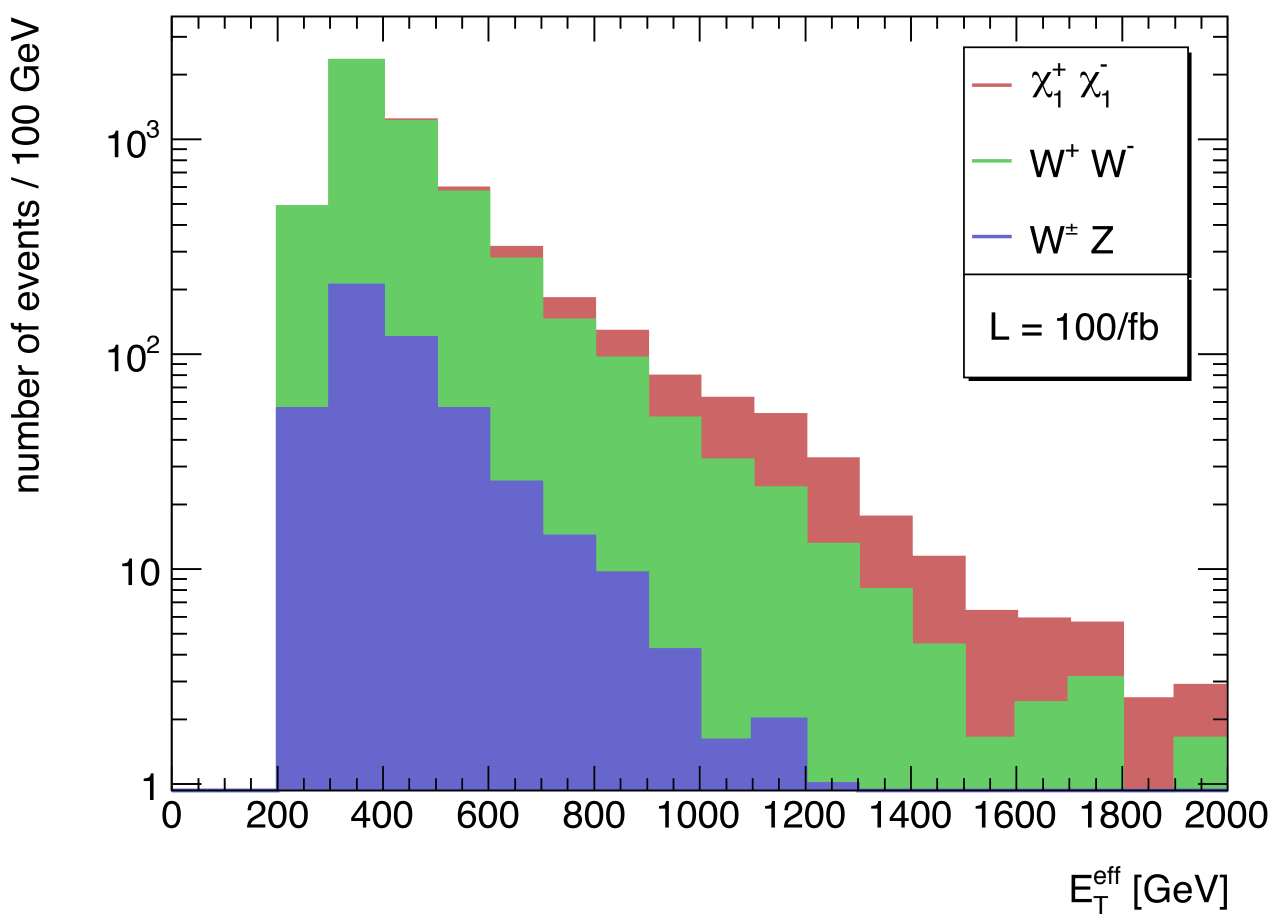
Chargino production

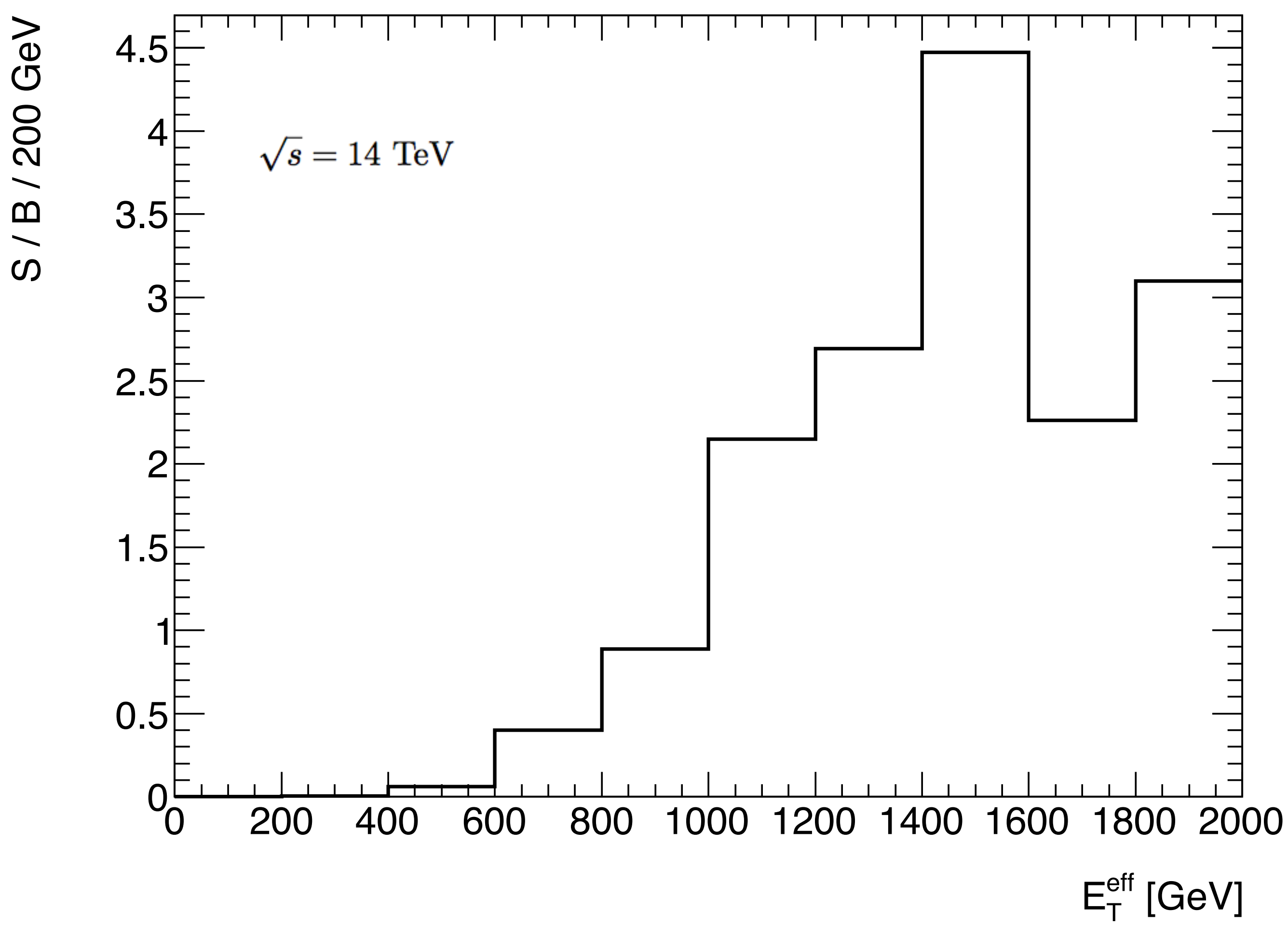
Effective transverse energy (from M.E.Cabrera, A.Casas '12)

$$\mathcal{E}_T^{\rm eff} = \sqrt{(M_{\rm inv}^{ll})^2 + (p_T^{ll})^2} + 2|p_T^{\rm miss}|$$

$M_{\rm inv}^{ll}$ invariant mass of the pair of leptons

p_T^{ll} transverse momentum of the pair of leptons





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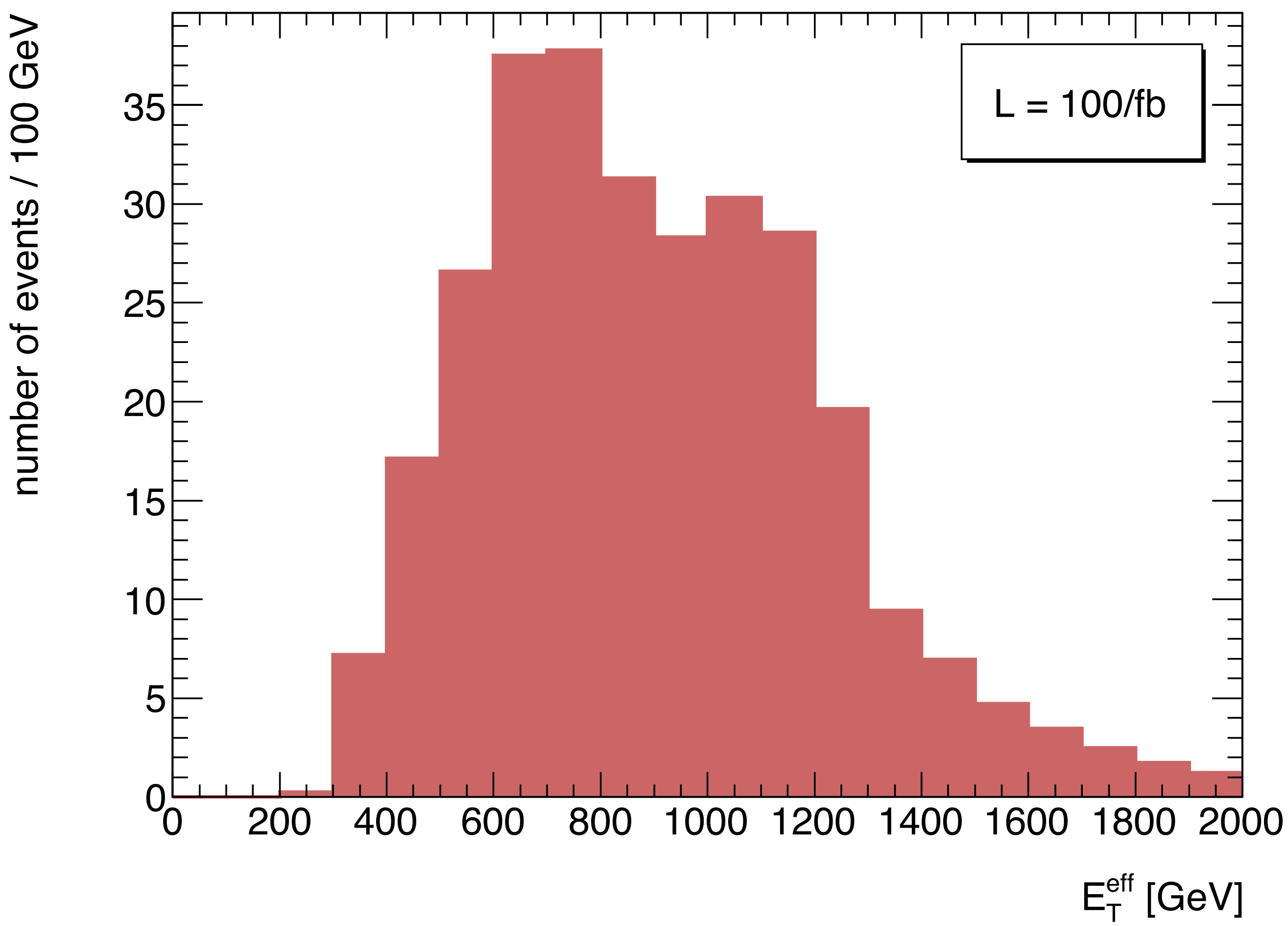
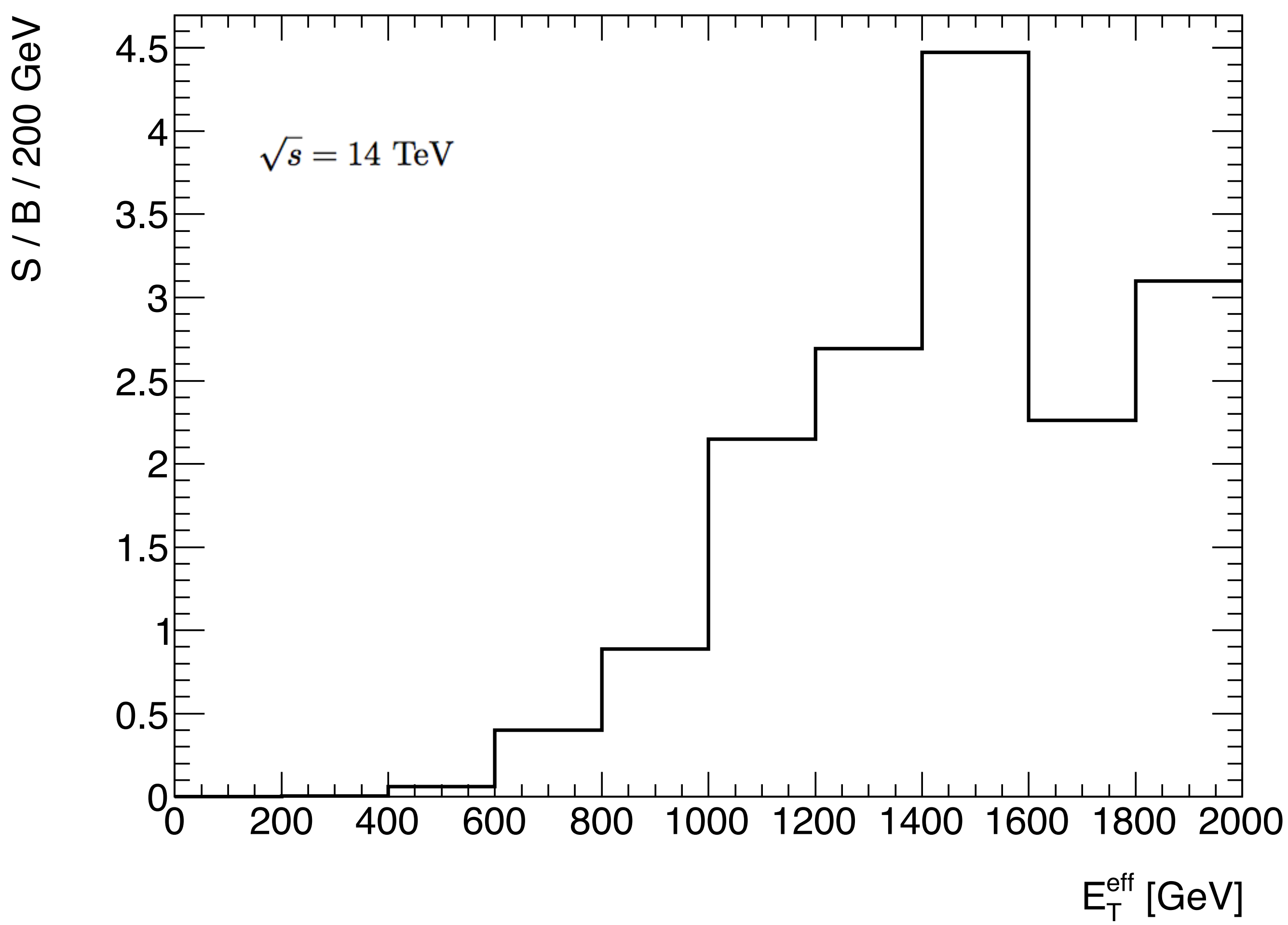
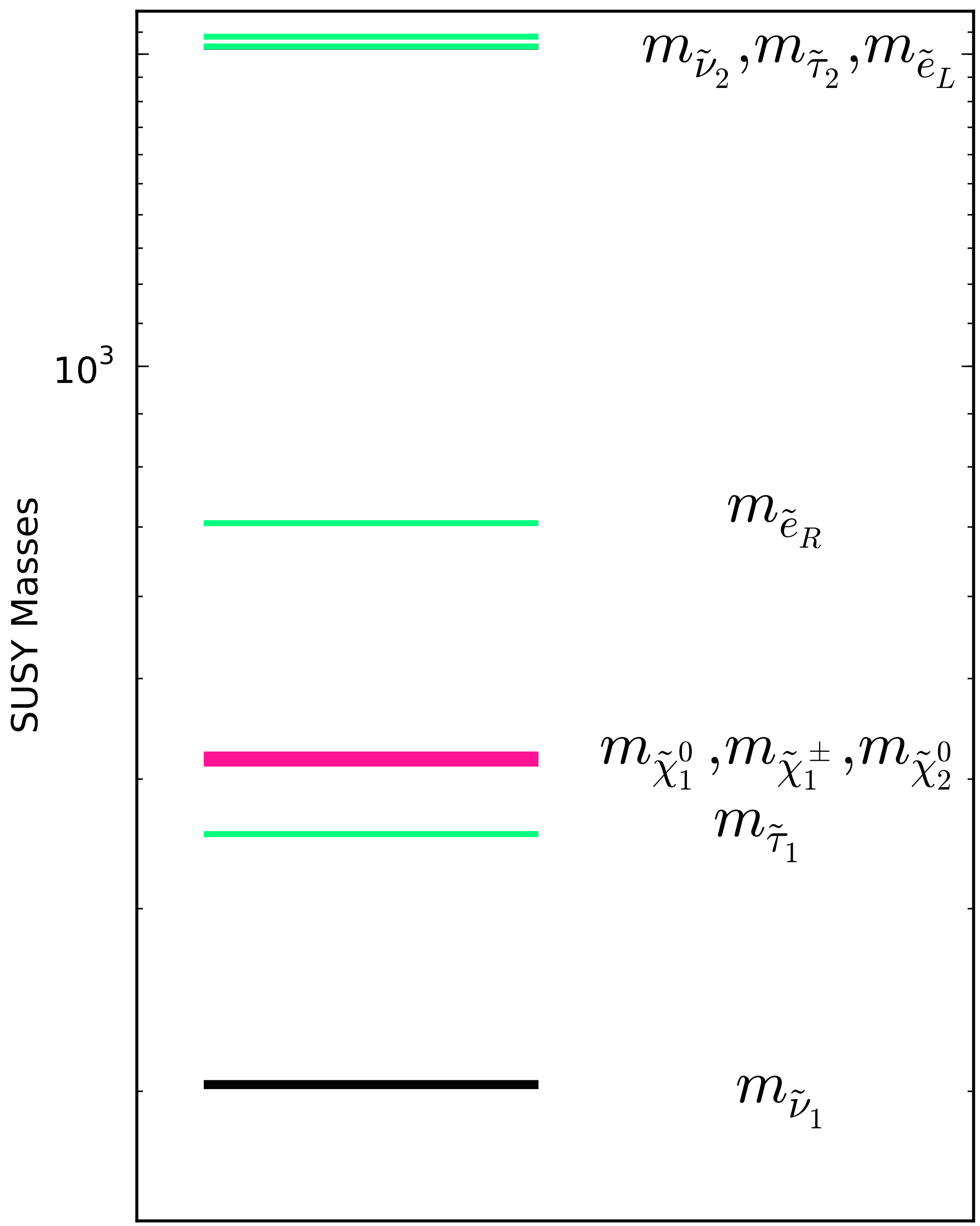




Gray points pattern

Mass spectrum



Relic density is set by sneutrino itself

$$\tilde{\nu}_1 \tilde{\nu}_1^* \to W^+ W^-, f \bar{f}$$

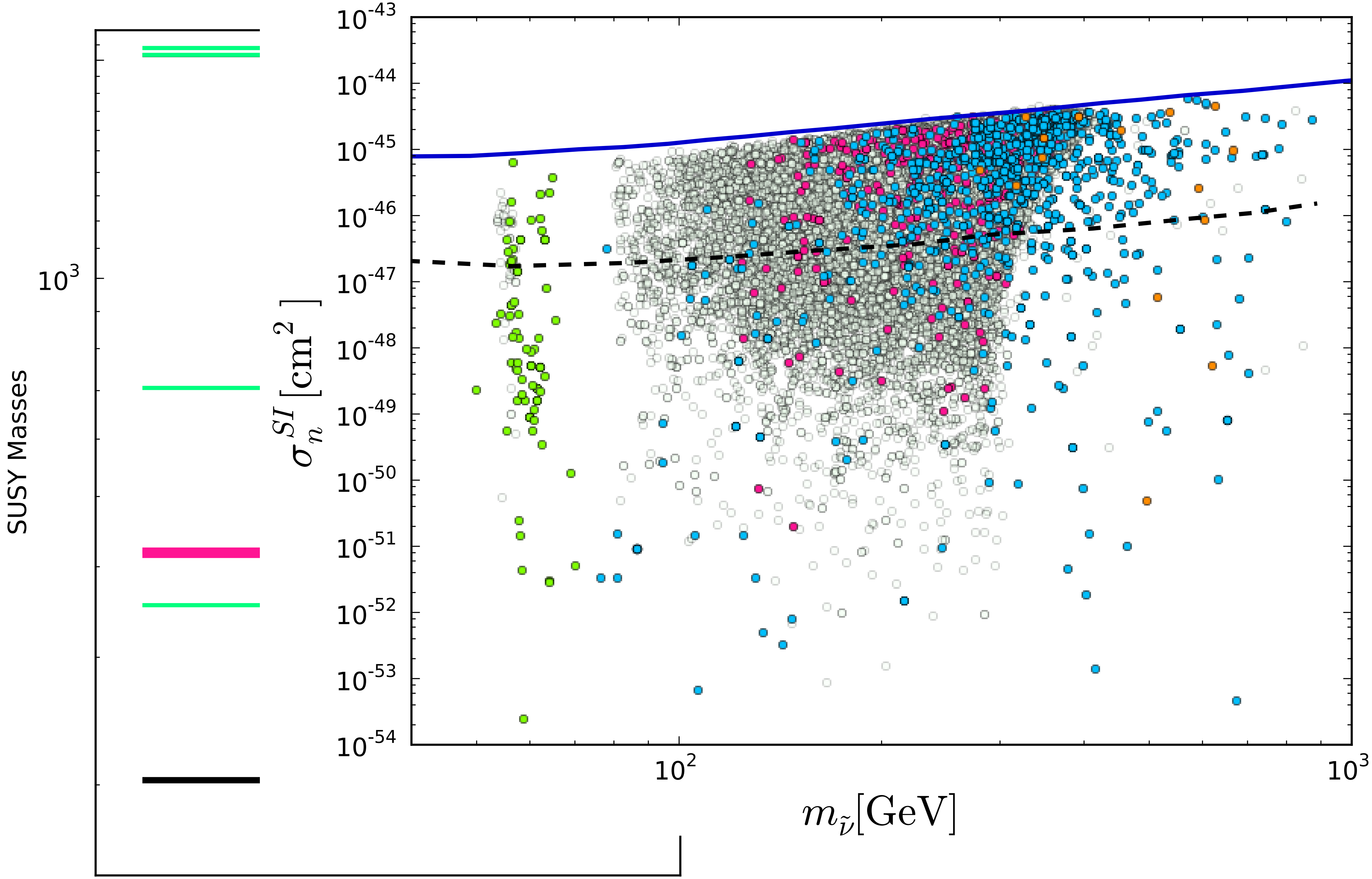
$$\tilde{\nu}_1 \tilde{\nu}_1^* \to \nu \bar{\nu}$$

Via s-channel Z exchange or t-channel neutralino exchange

Gray points pattern

N

lf



nel

Gray points pattern

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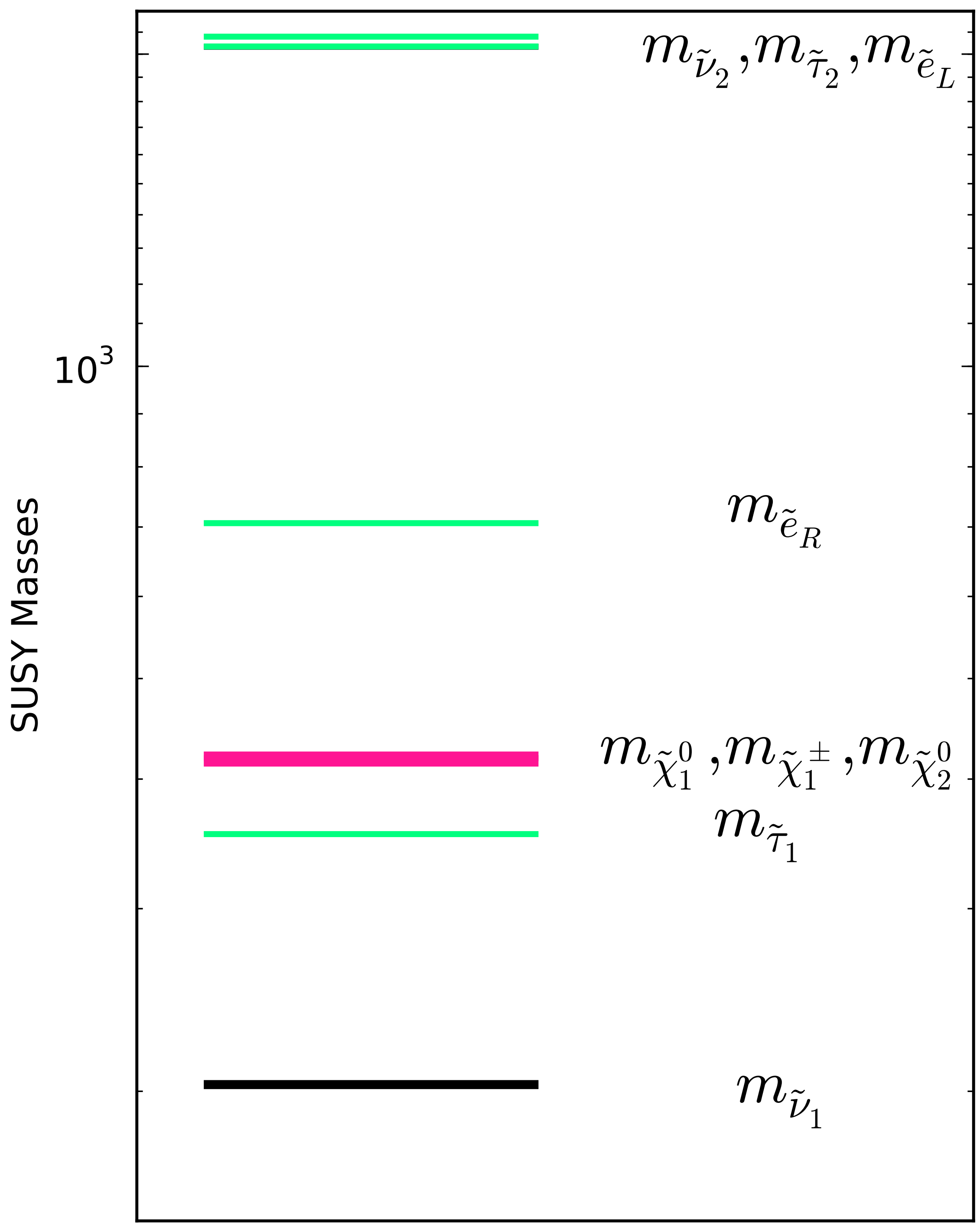

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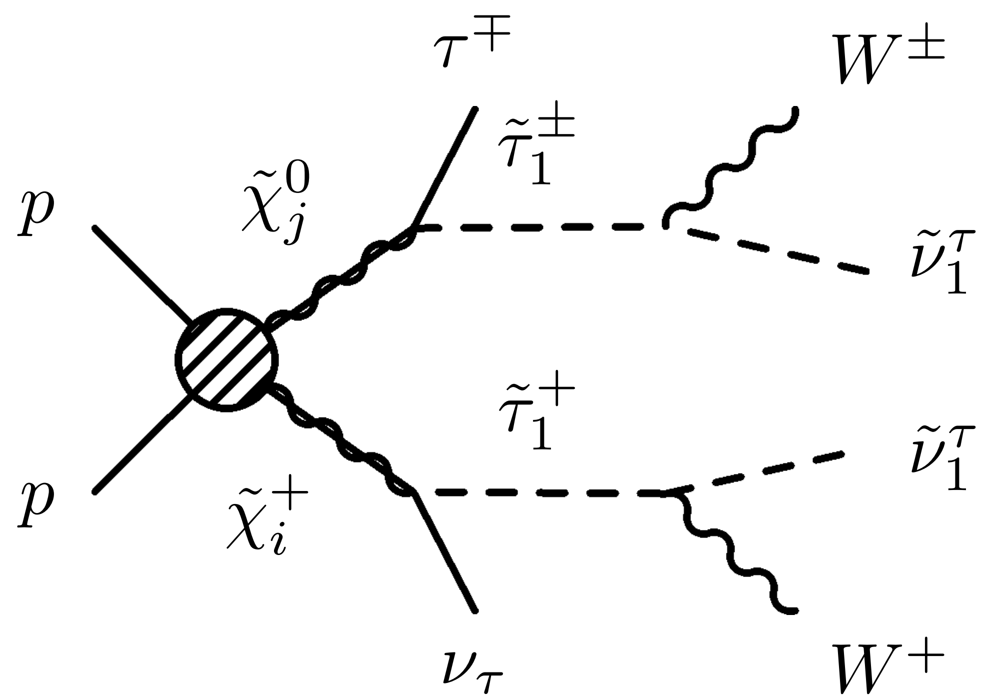
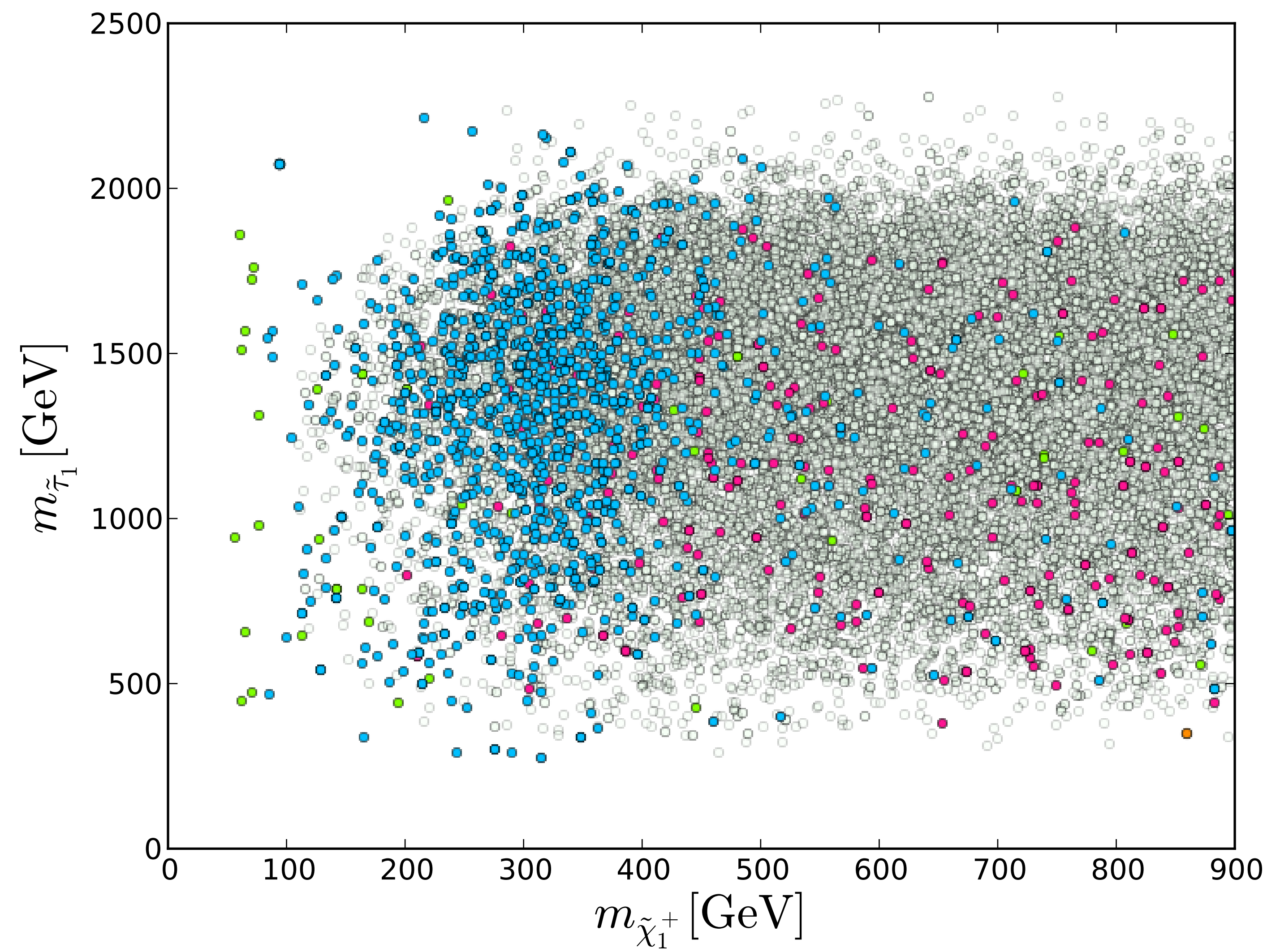
2 Same sign leptons, uncorrelated flavor

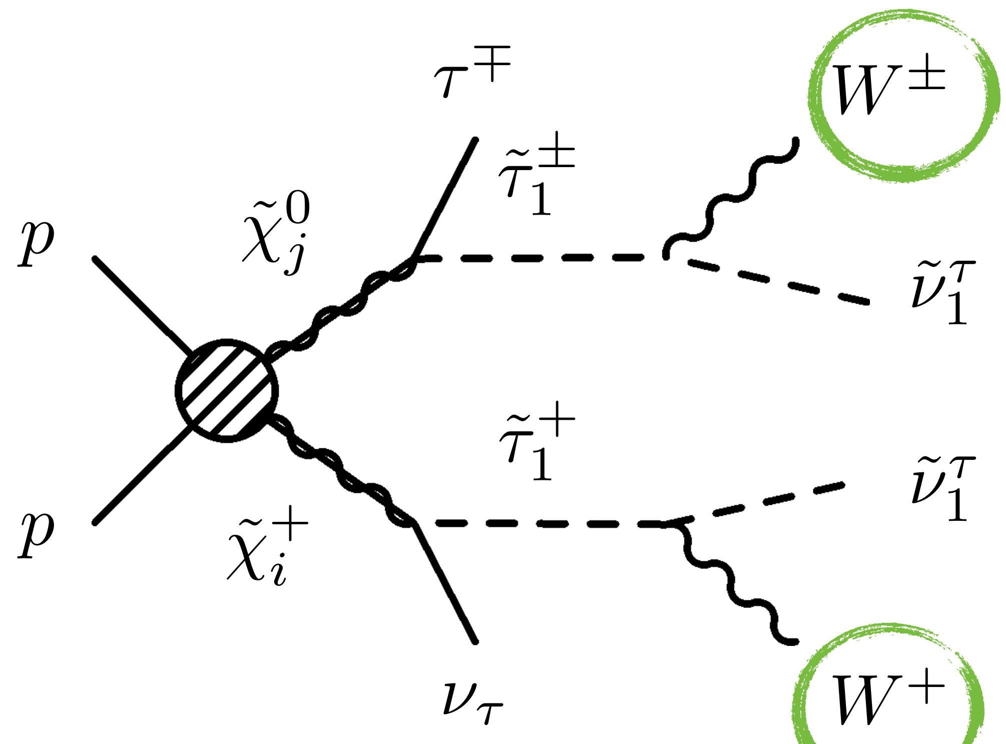


- Arises when the stau is the NLSP
- Different from MSSM where the OS leptons should have the same flavor

Process			BR
$\tilde{\chi}_1^+$	$\rightarrow$	$\nu_\tau\ \tilde{\tau}_1$	99.20%
		$\tau^+\tilde{\nu}_1$	0.72%
$\tilde{\chi}_2^0$	$\rightarrow$	$\tau^\pm\ \tilde{\tau}_1^\mp$	99.99%



2 Same sign leptons, uncorrelated flavor



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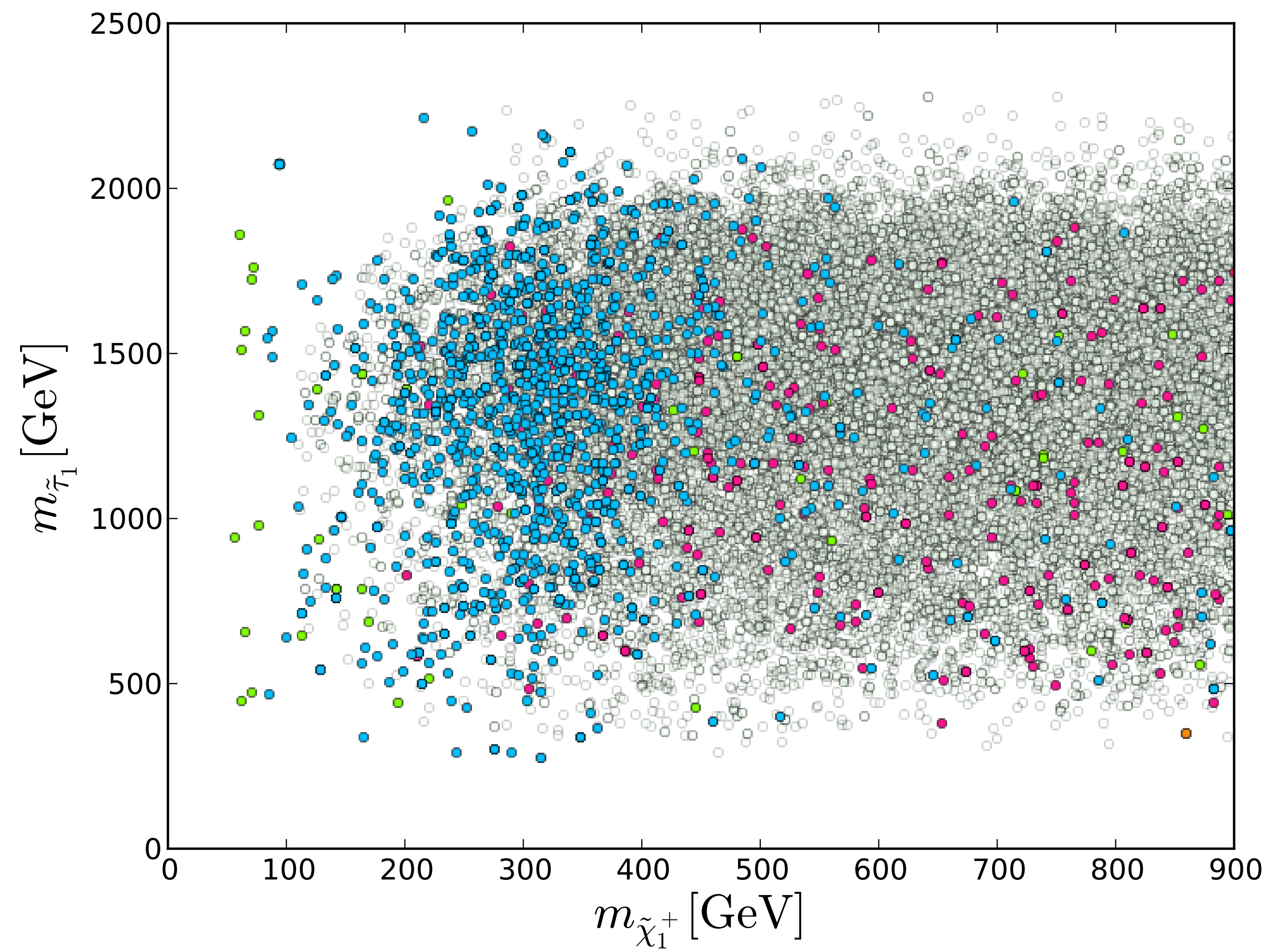

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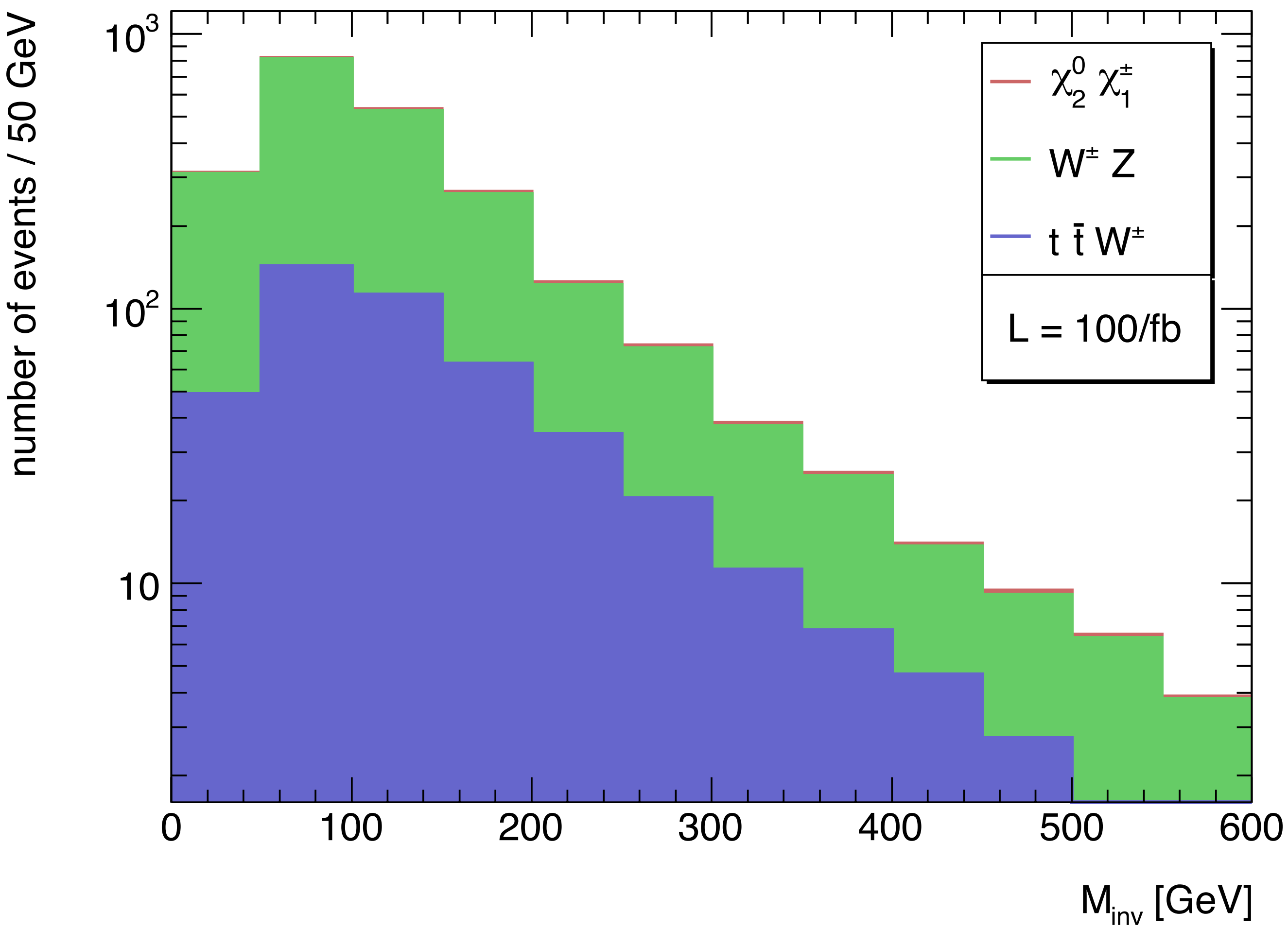

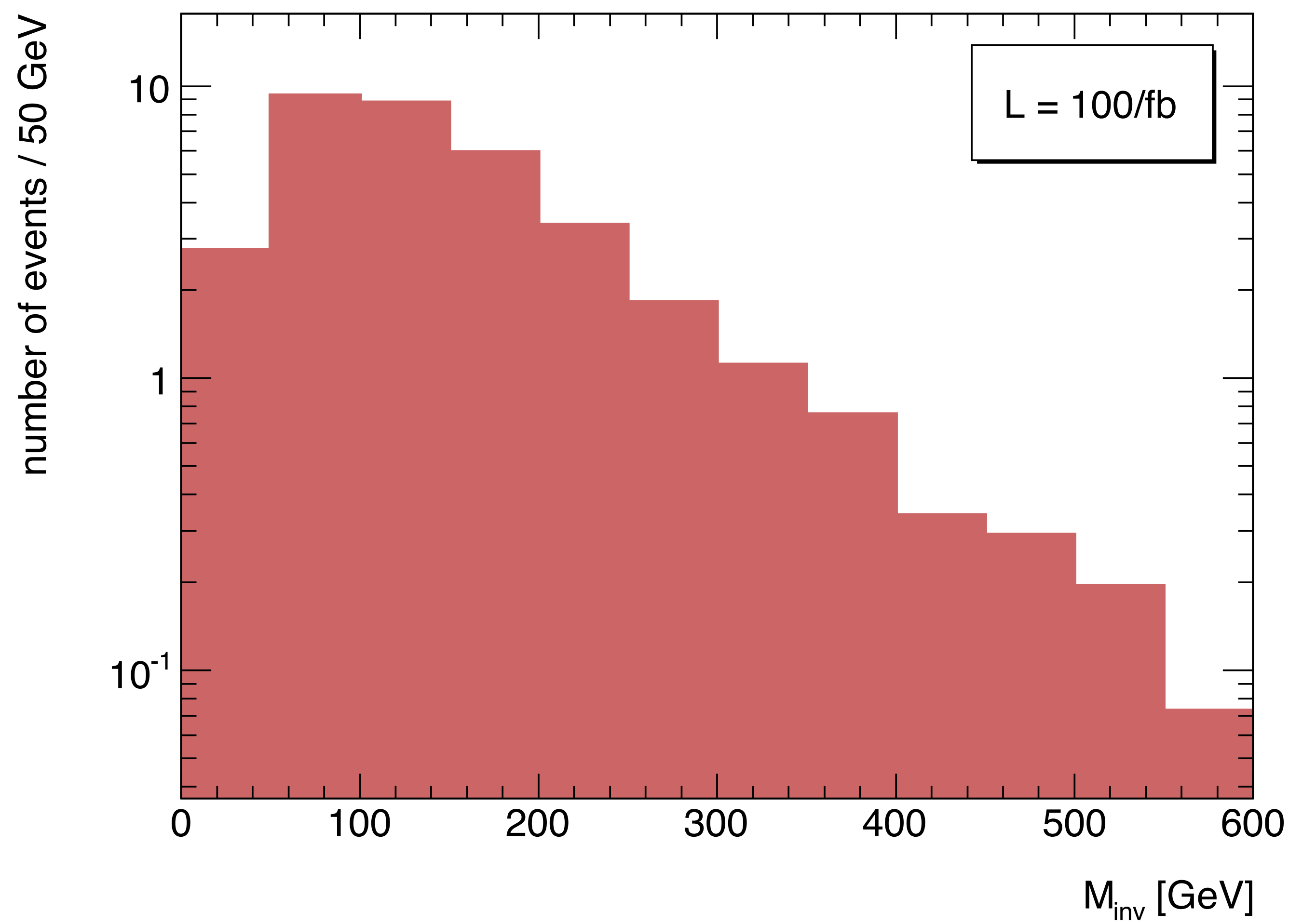

The signal is hidden at low p_T and M_{inv} values, where the background is maximal

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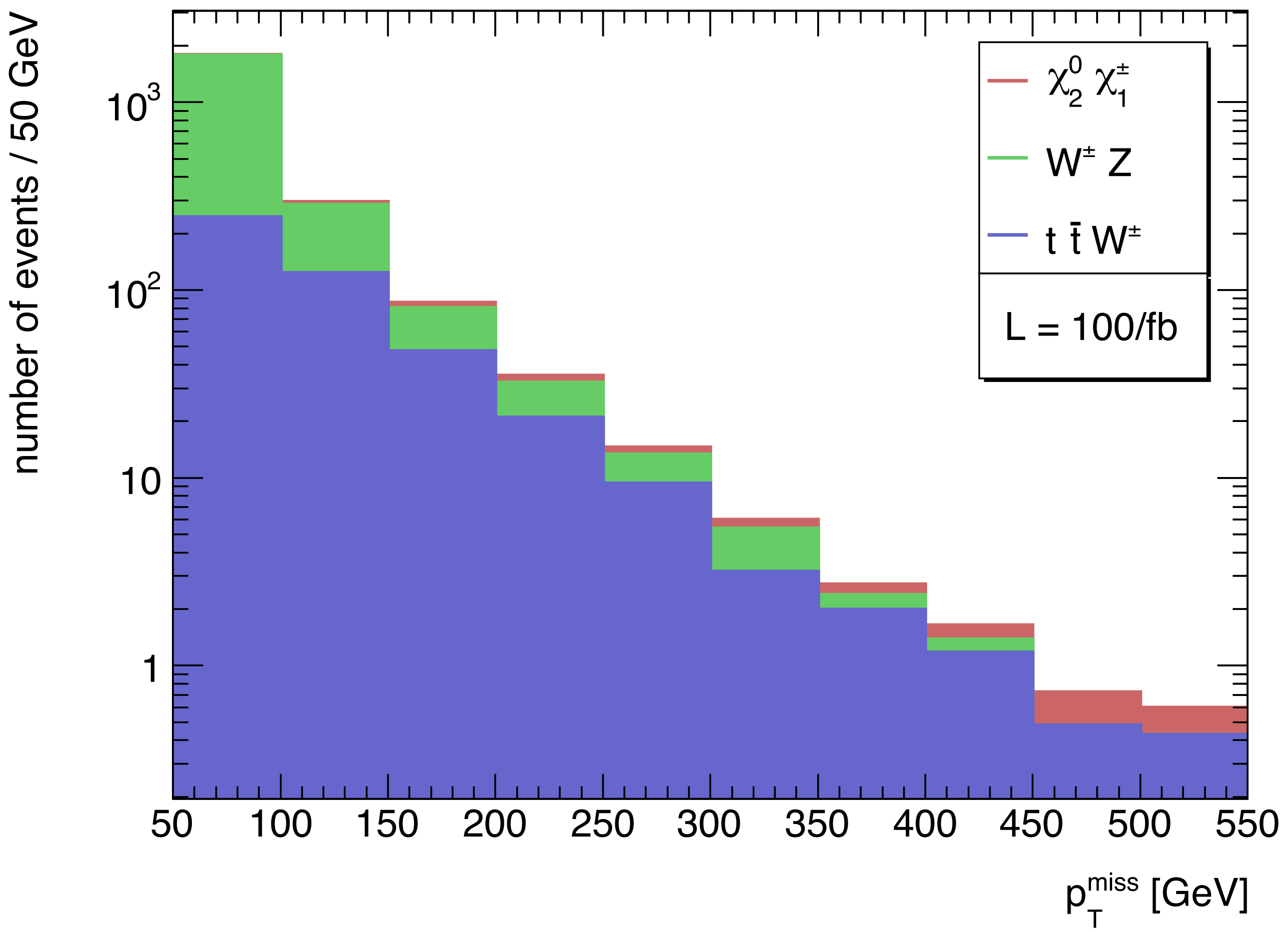

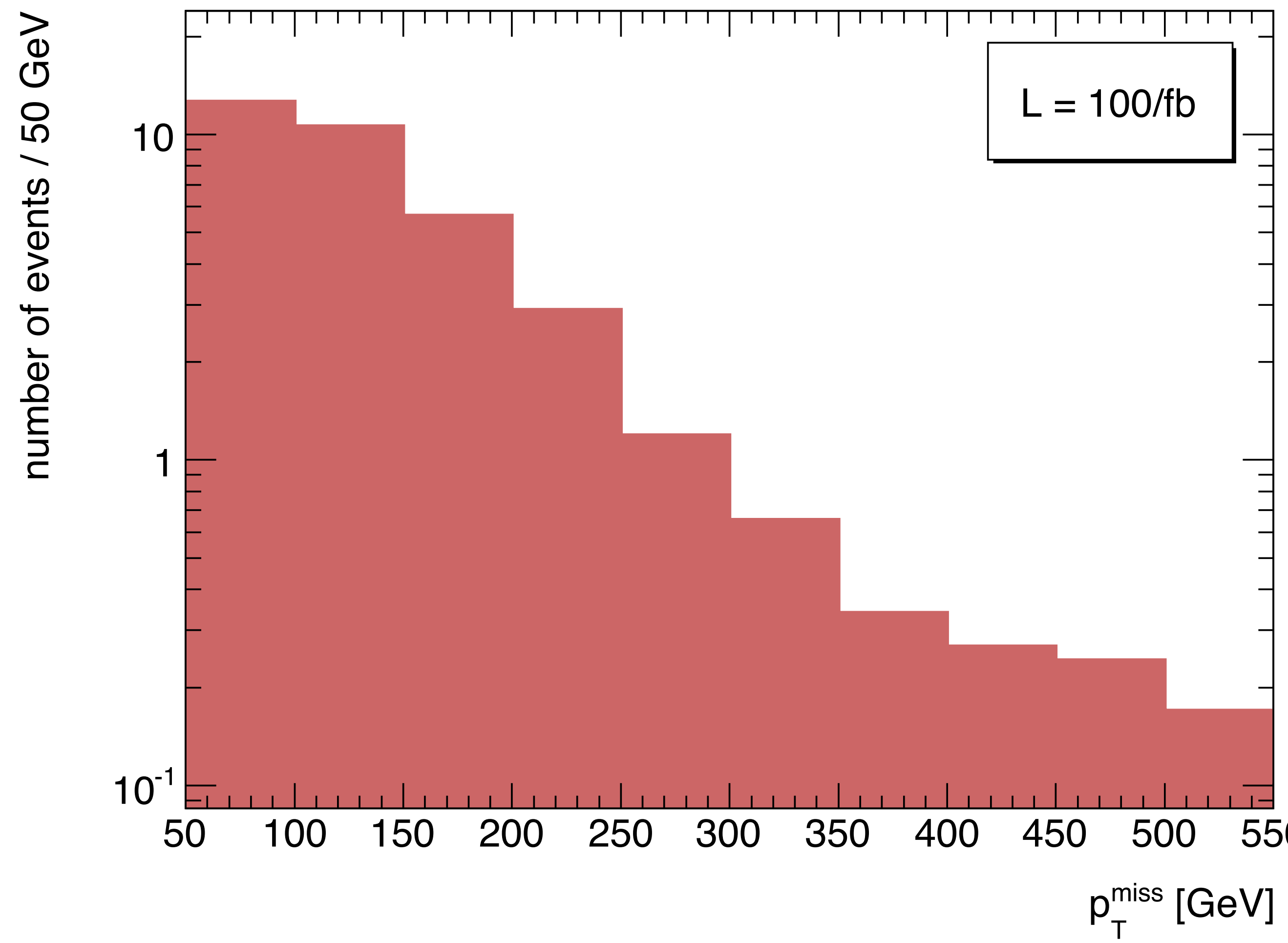

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