Sneutrino dark matter and LHC signatures

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LAPTh

Annecy-le-Vieux

February 27th 2014

Bolshoi simulation, NASA

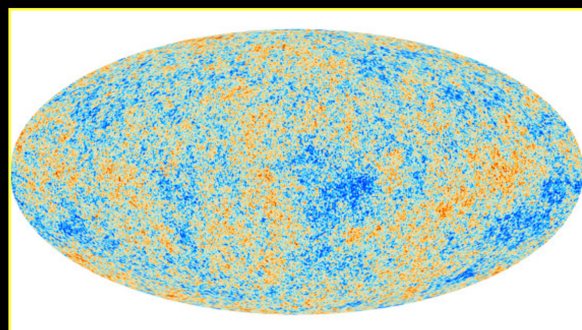
Outline

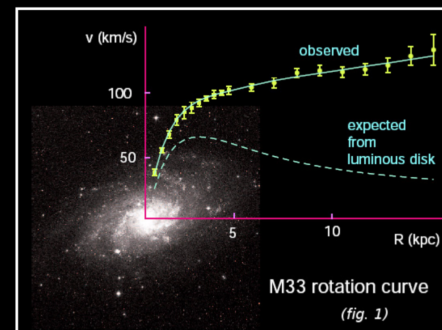
- Theoretical model for sneutrino dark matter
  - (a) Motivated by neutrino mass mechanisms
  - (b) Extension of the MSSM

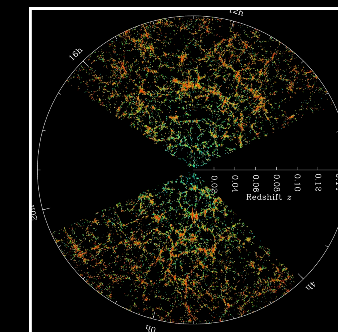
C.A. and M. E. Cabrera, arXiv: 1311.6549 [hep-ph], submitted to JHEP

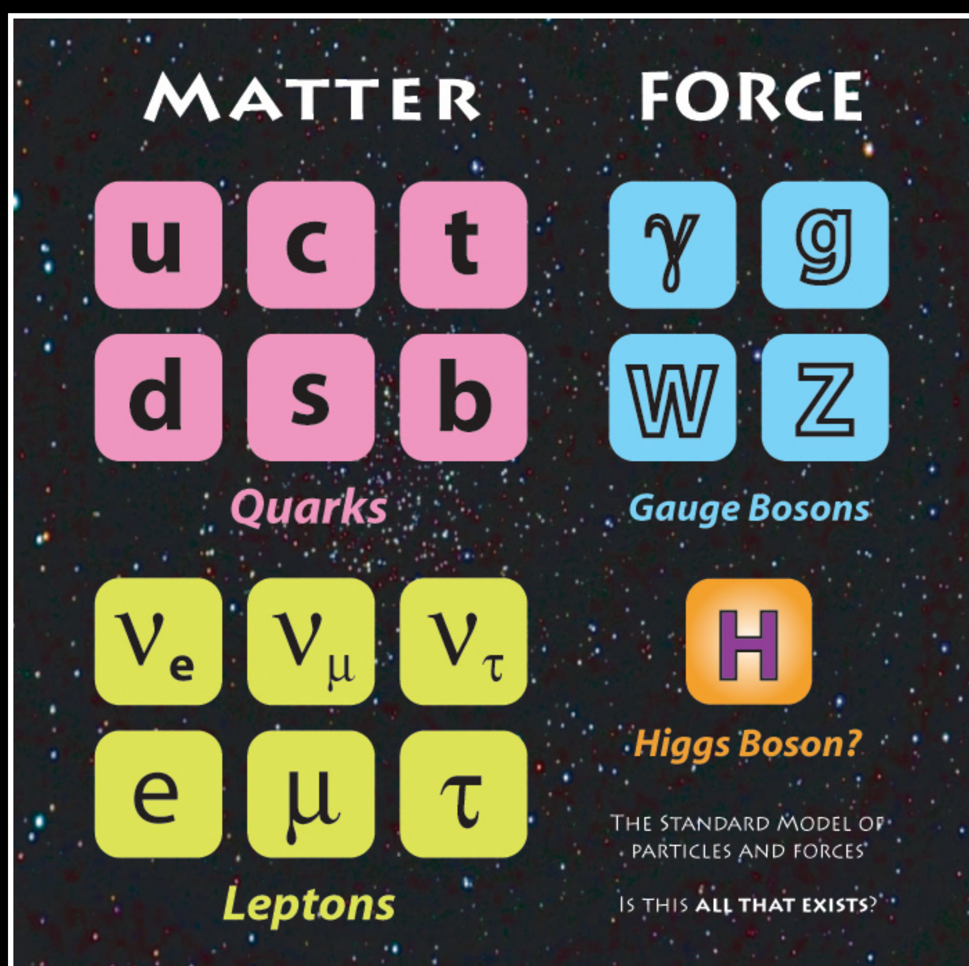
- Method used in the analysis
  - (a) Sampling method
  - (b) Likelihood with observables and constraints
- Results
- Predictions for signatures at LHC
- Conclusions

Dark matter exists (in 1 slide)









Among the candidates for Cold Dark Matter beyond the SM there are the

WIMPs

Weakly Interacting Massive Particles

Neutral and Stable at least on cosmological scales

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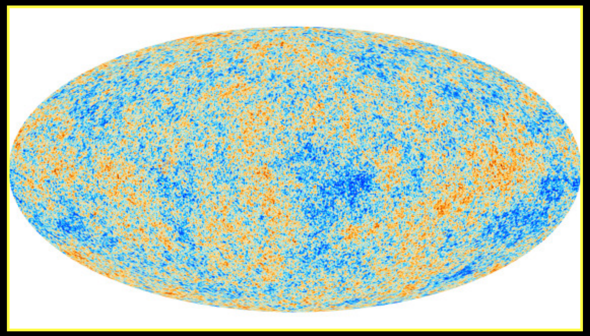

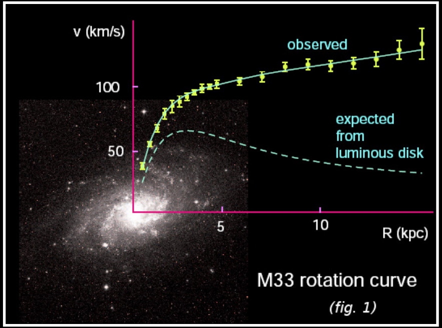

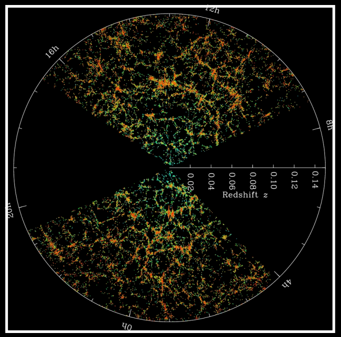

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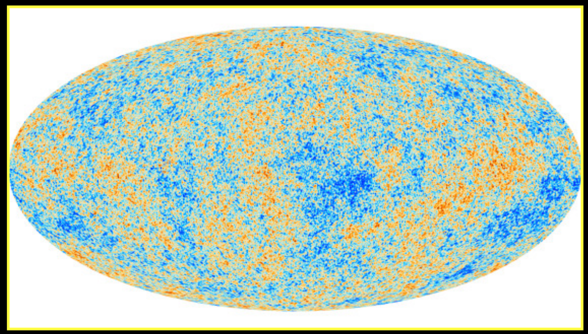

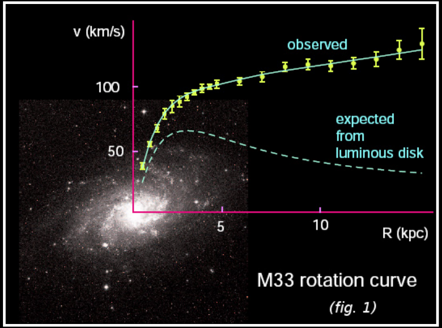

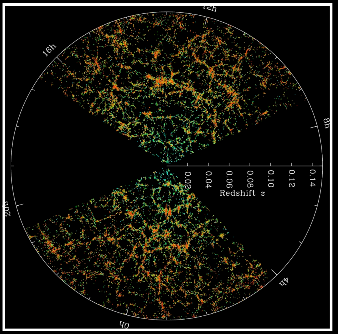

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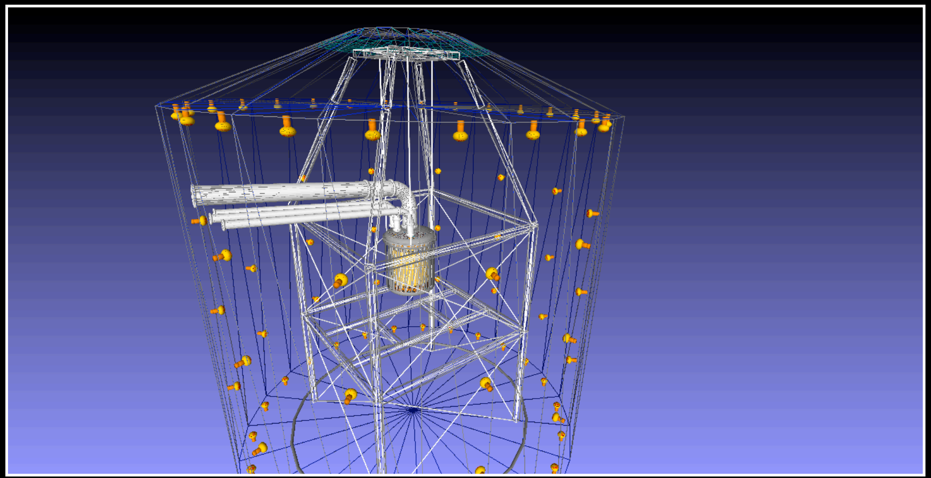
Why WIMPs ?

- Achieve naturally the correct relic density via the freeze-out

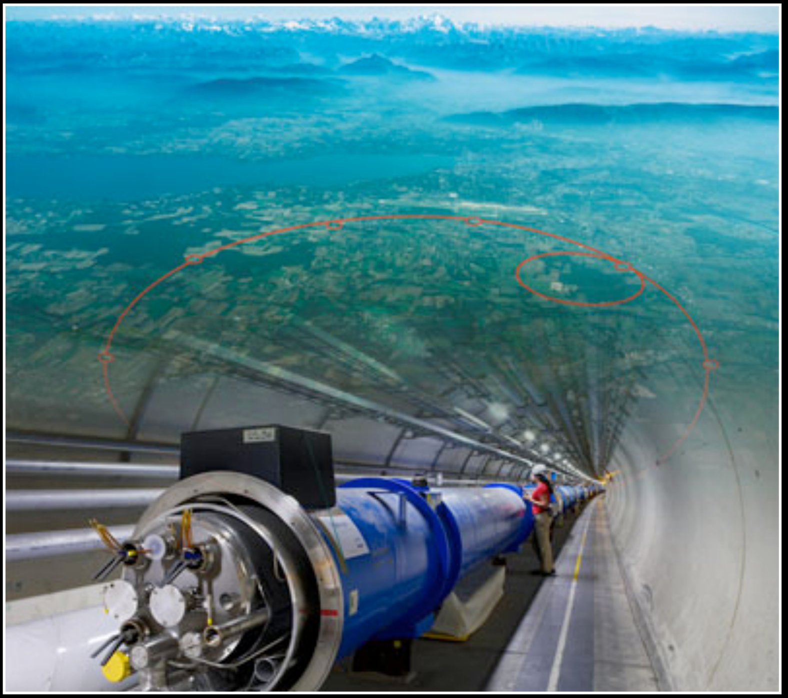
$$\Omega_{\rm DM}{\rm h}^2 \sim 0.3\left(\frac{10^{-26}{\rm cm}^3{\rm s}^{-1}}{<\sigma_A v>}\right)$$

$$<\sigma_A v>\sim \frac{g^2}{m_\chi^2} \sim \frac{0.01^2}{(100\ {\rm GeV})^2} \sim 8\times 10^{-25}{\rm cm}^3{\rm s}^{-1}$$

- Arise in motivated theoretical extension of the standard model
- WIMPs do not look like so 'DARK' as might produce signals visible in one or more detectors



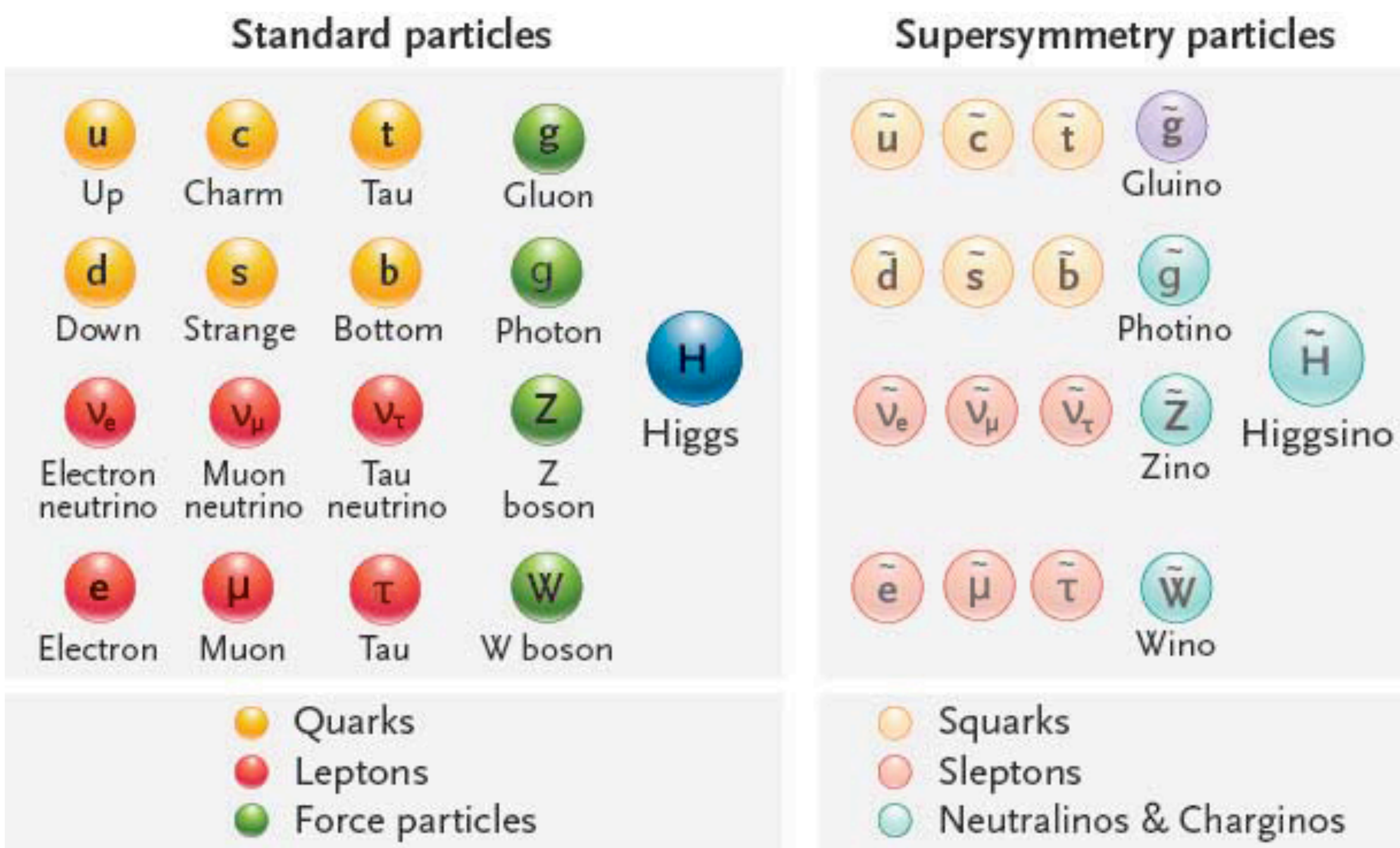
Direct detection



Production at colliders

Indirect detection

Sneutrino can not be 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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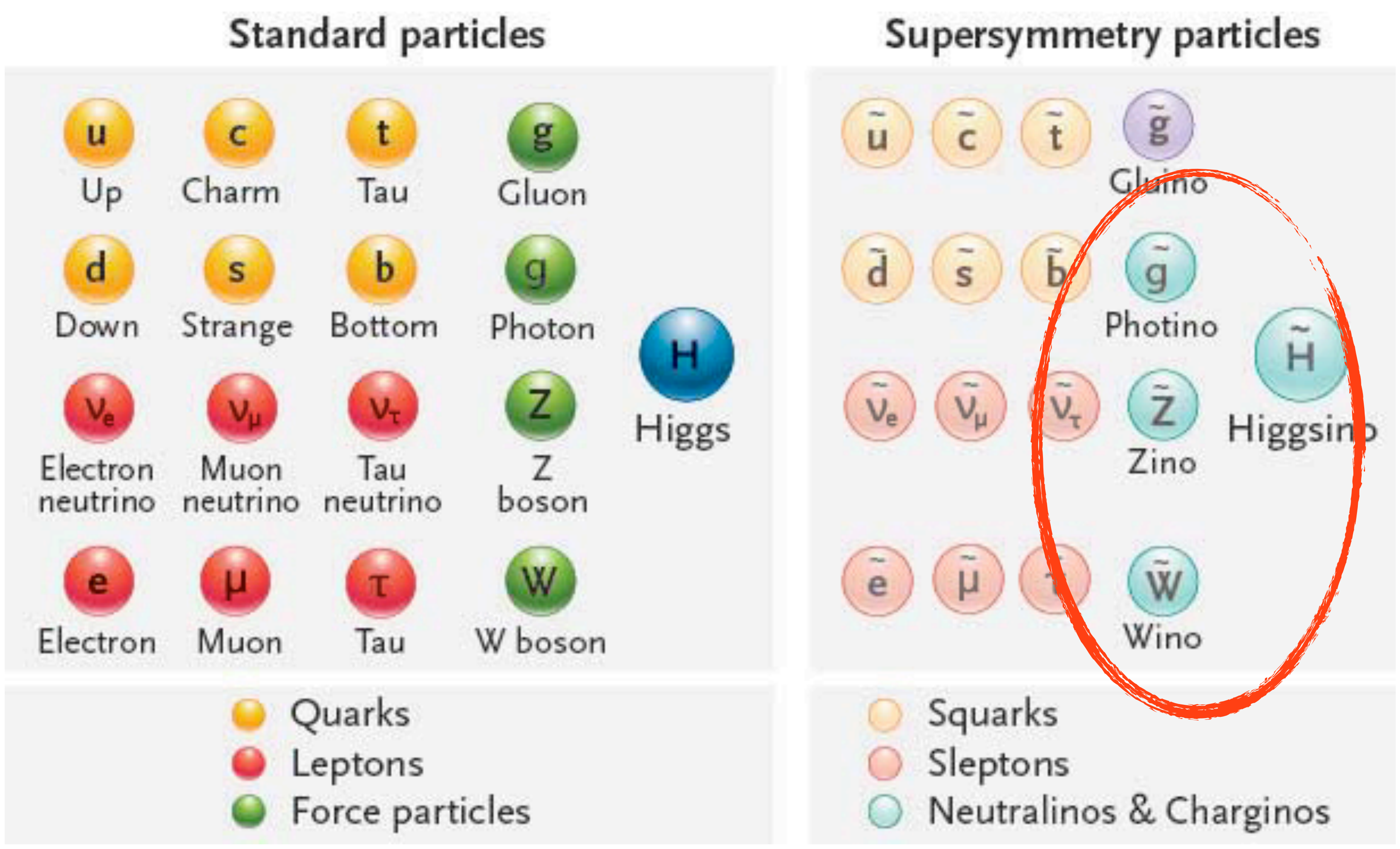

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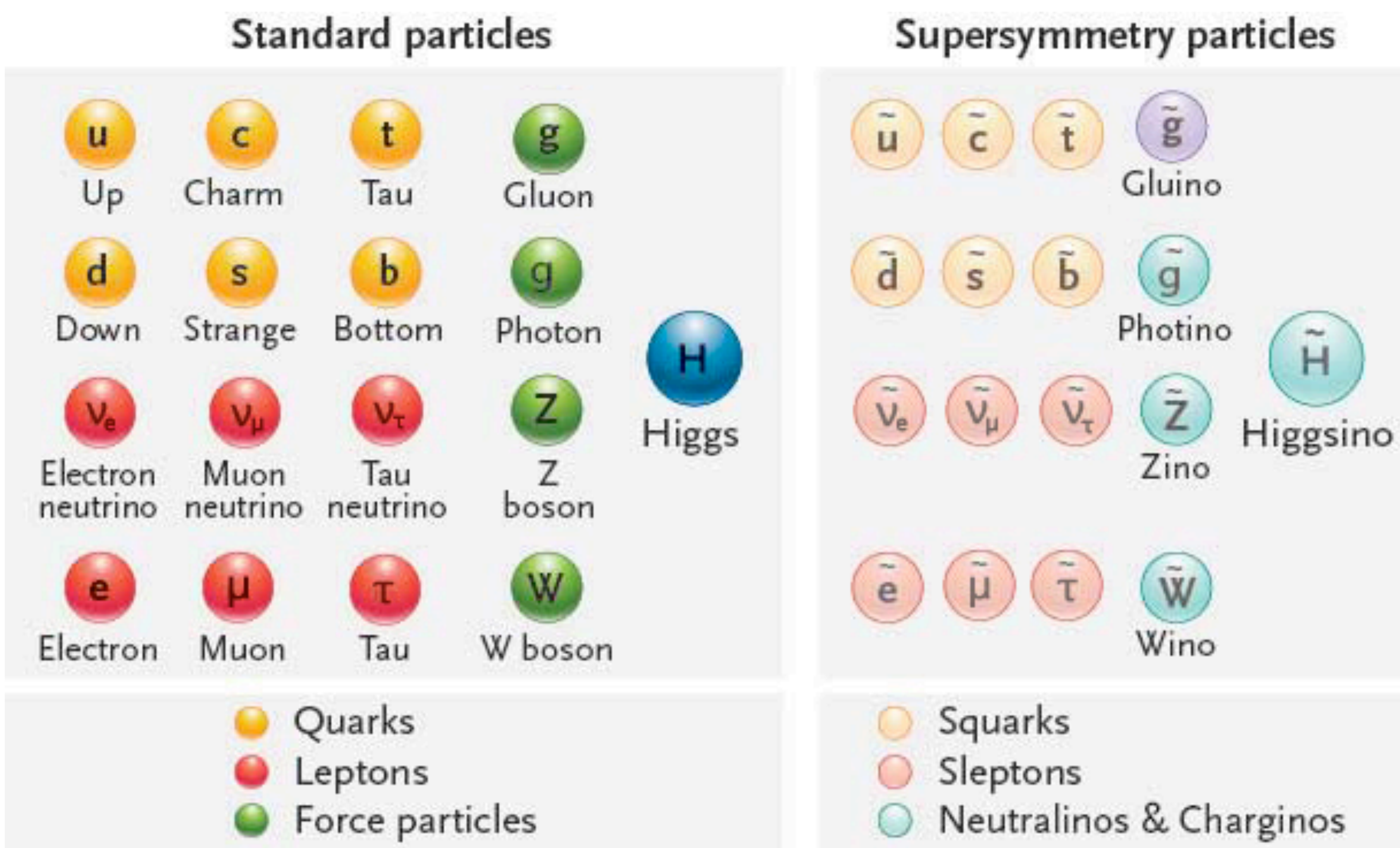

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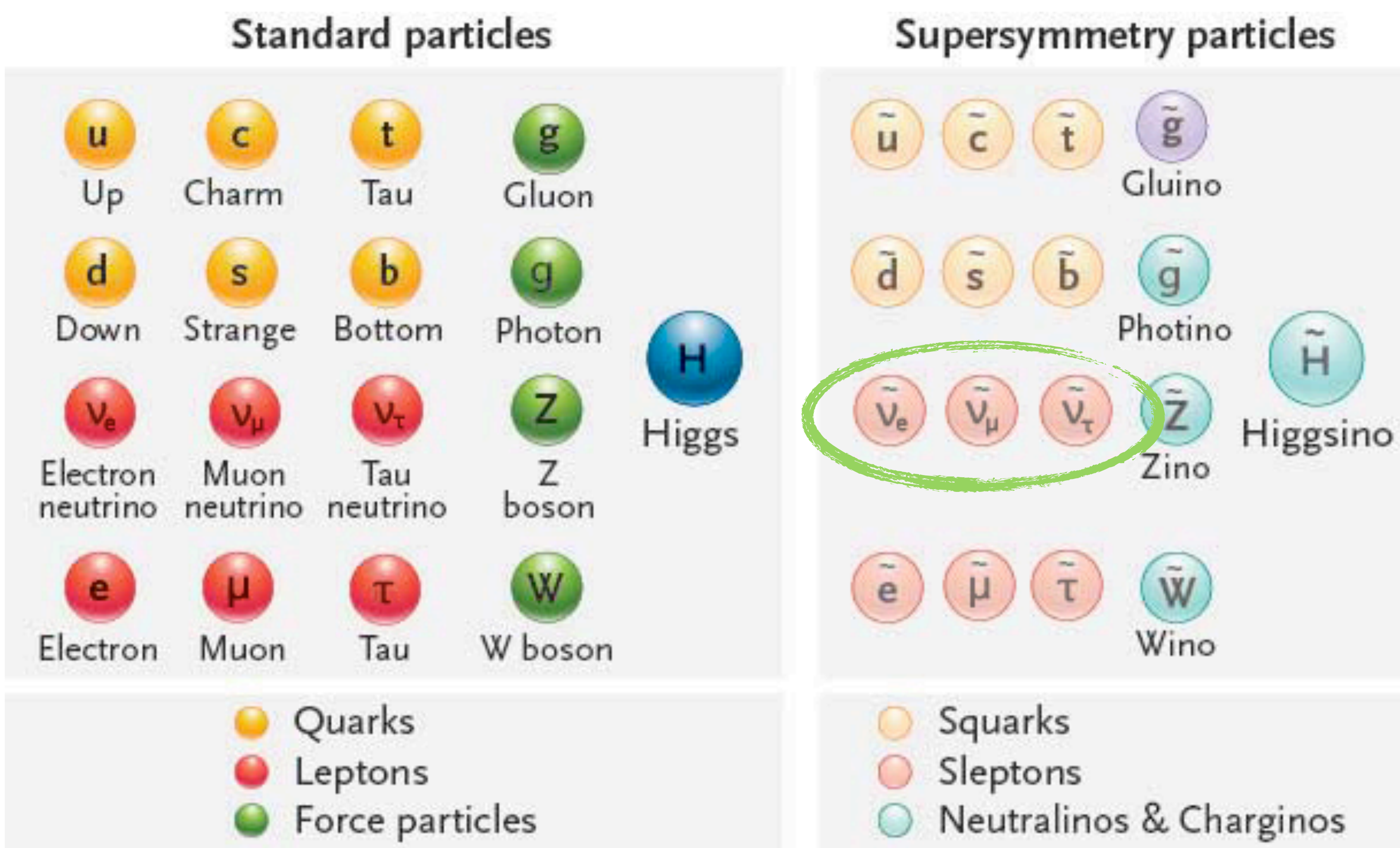

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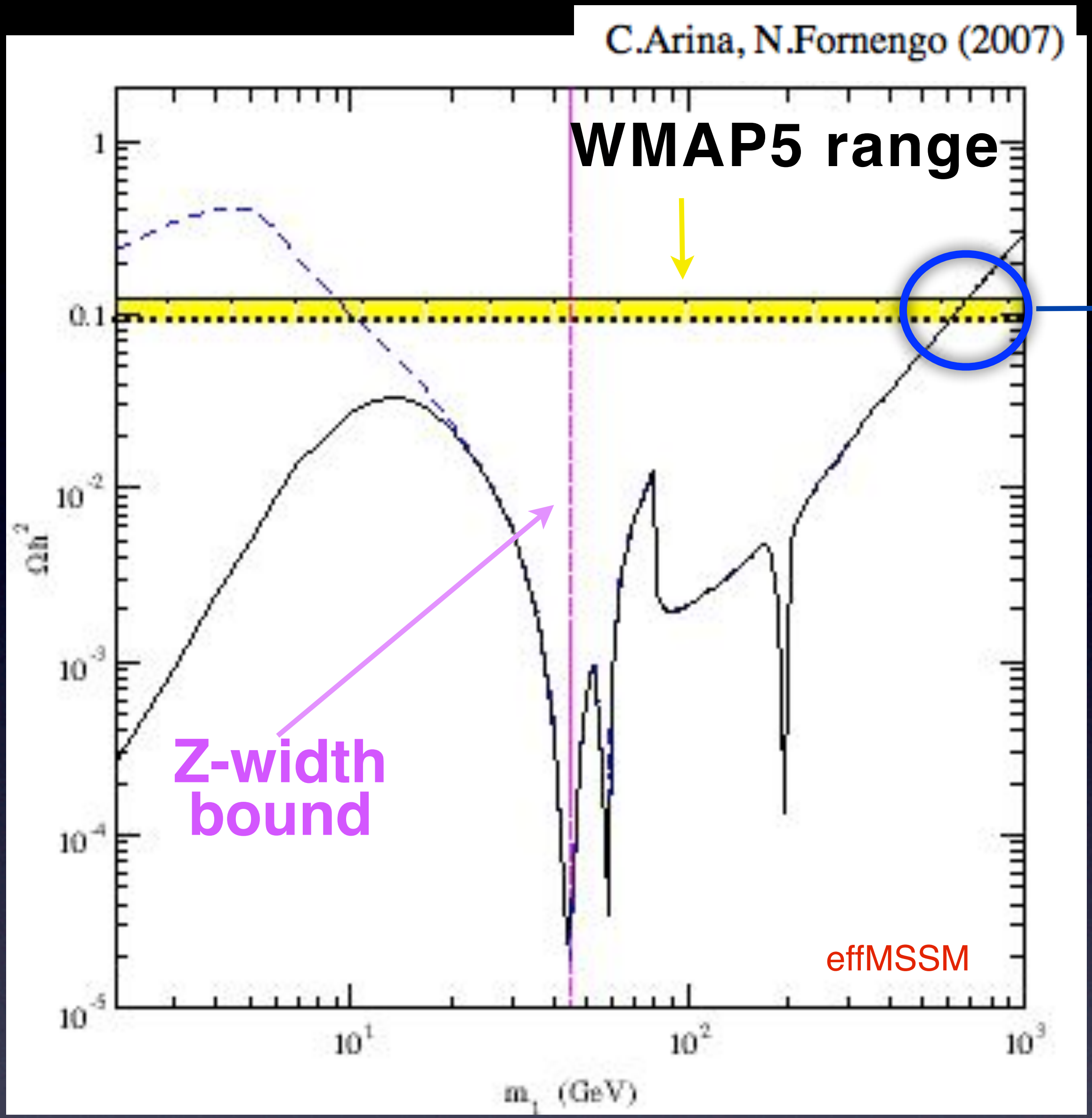
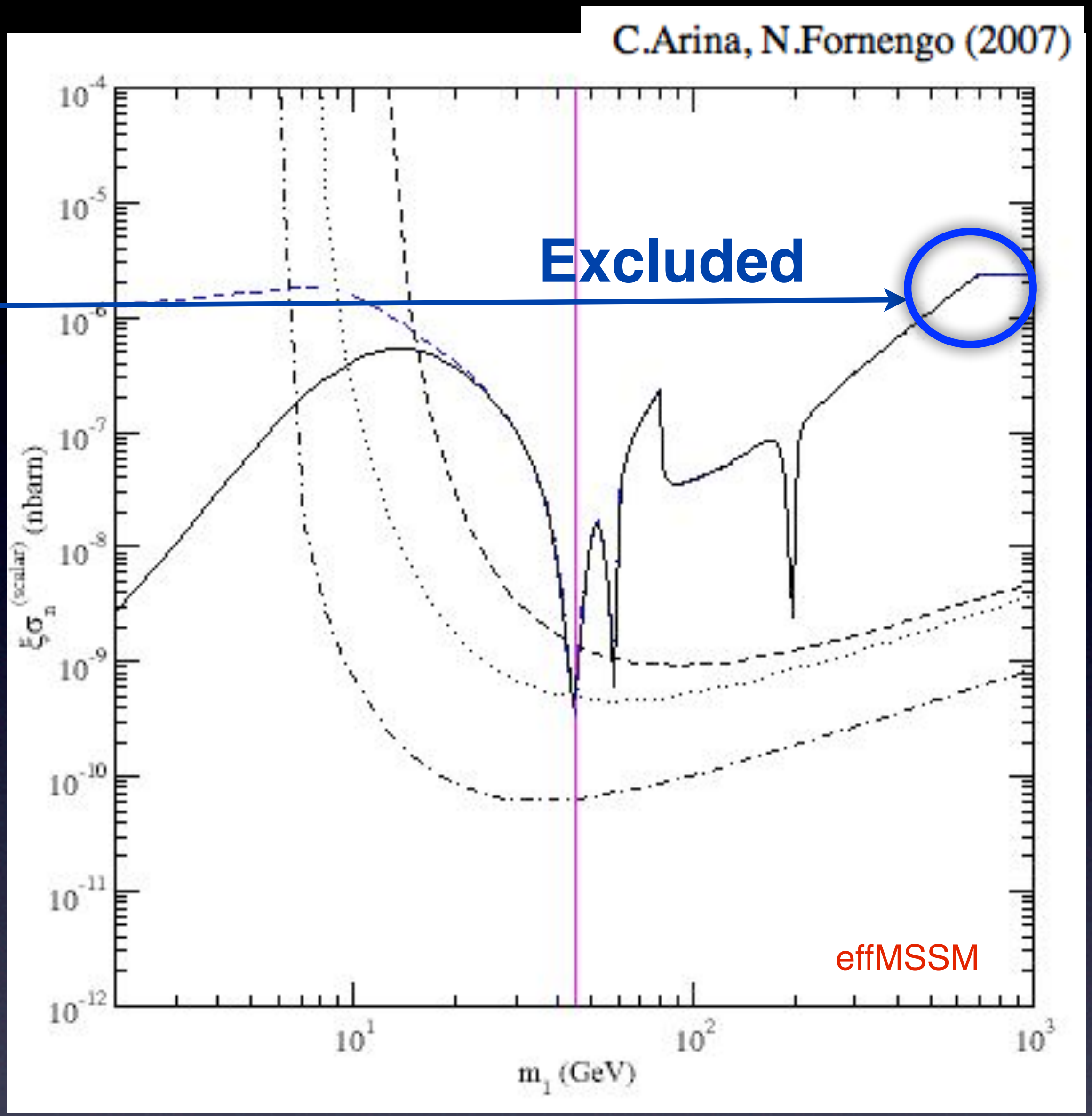
Ωh^2 and $\xi\sigma^{(scalar)}_{nucleon}$ versus the sneutrino mass m_1





- dips $\longrightarrow$ Z and Higgs poles
- sharp drop $\longrightarrow$ WW threshold

$\tilde{\nu} - Z$ coupling is gauge and gives:

- low relic abundance (underabundant)
- large scattering on nucleon (excluded by direct detection exp)

Sneutrinos excluded as CDM except in fine-tuned conditions

Are the Dark Matter and the Neutrino sector related?

- Evidence that neutrinos are massive
- Neutrino masses are not accounted for in the SM / MSSM
- Several mechanisms to give mass to neutrinos (Dirac masses or seesaw)
- The BSM extension to give masses to neutrino can influence the dark matter phenomenology

CA and N. Fornengo JHEP 2007: TYPE I SEESAW
CA, F. Bazzocchi, N. Fornengo, J. Romao and J. Valle PRL 2008: INVERSE SEESAW

MSSM at GUT scale + inverse seesaw

CA,F.Bazzocchi, N.Fornengo, J.Romao and J.Valle, PRL 2008 arXiV:0806.3225

$$W_{inv} = \epsilon_{ij}(\mu \hat{H}_i^1 \hat{H}_j^2 - Y_l \hat{H}_i^1 \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^2 \hat{L}_j \hat{N}) + M \hat{N} \hat{S} + \frac{1}{2} \mu_S \hat{S} \hat{S}$$

$$V_{\rm soft} = (M_L^2)\, \tilde{L}_i^* \tilde{L}_i + (M_N^2)\, \tilde{N}^* \tilde{N} + (M_S^2)\, \tilde{S}^* \tilde{S} - [B_M \tilde{N} \tilde{S} + \frac{1}{2} B_{\mu_S} \tilde{S} \tilde{S} + \epsilon_{ij}(\Lambda_l H_i^1 \tilde{L}_j \tilde{R} + A_{h_\nu} H_i^2 \tilde{L}_j \tilde{N}) + h.c.]$$

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Neutrino sector

μ_S = 0 L is conserved

Inverse see-saw mechanism

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

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
- Z coupling off-diagonals

$$\Phi^\dagger = (\tilde{\nu}^*_+ \; \tilde{N}^*_+ \; \tilde{S}^*_+ \; \tilde{\nu}^*_- \; \tilde{N}^*_- \; \tilde{S}^*_-)$$

MSSM at GUT scale + inverse seesaw

ıd J.Valle, PRL

$W_{inv} \quad =$

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Neutrino se

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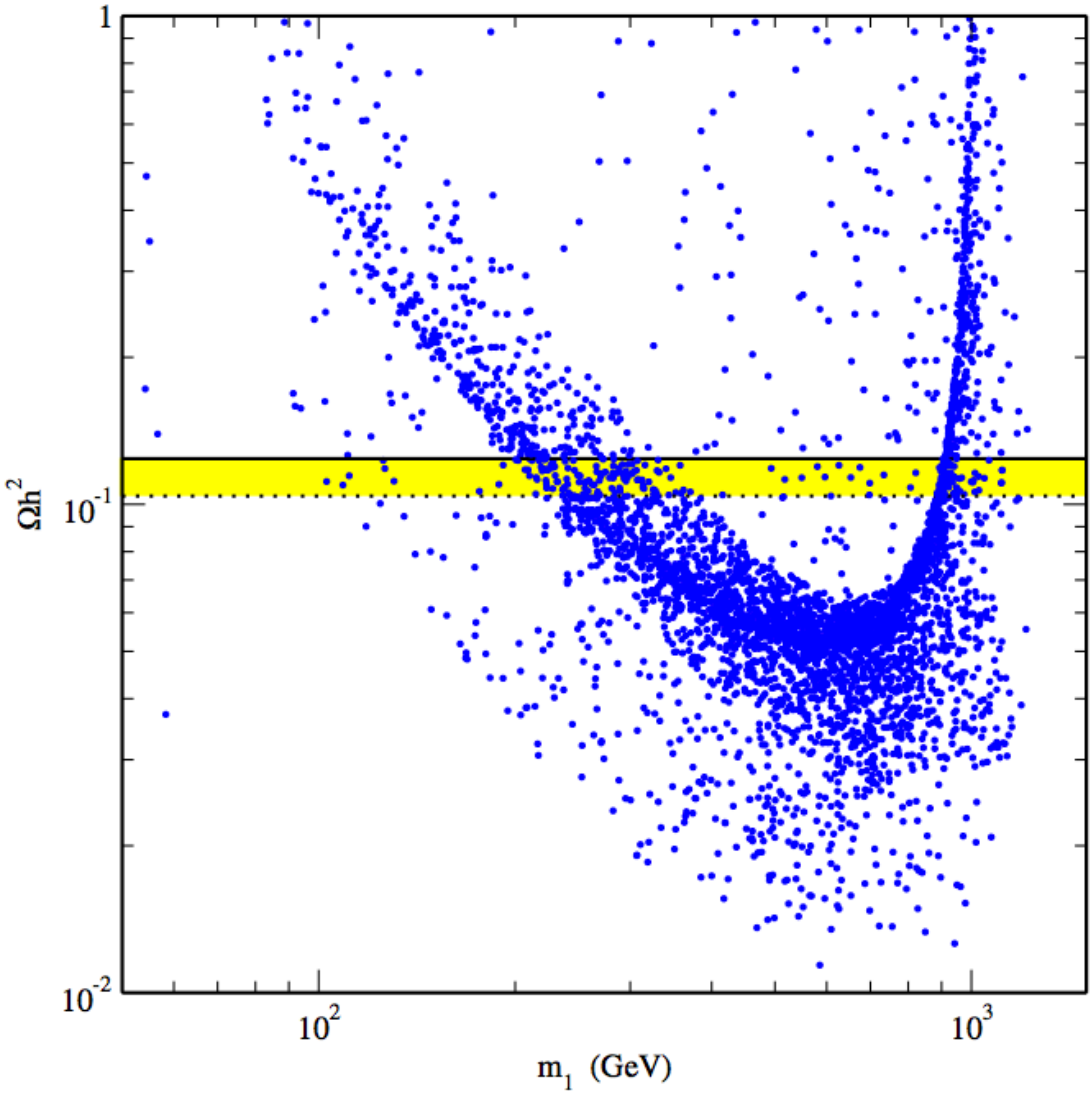


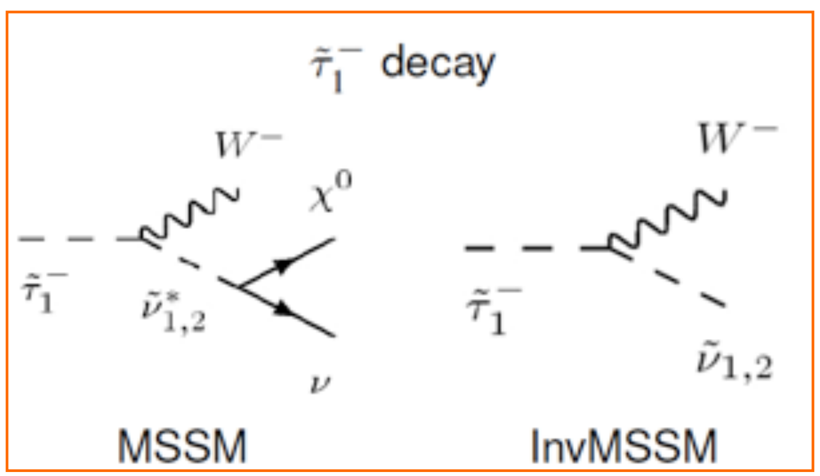
Possible different phenomenology at LHC

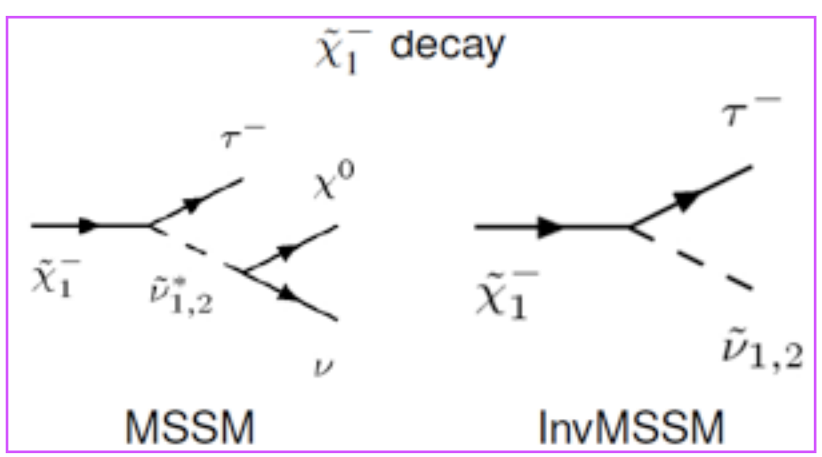
- Heavy SUSY spectrum, in particular sleptons. The NNLSP is the neutralino

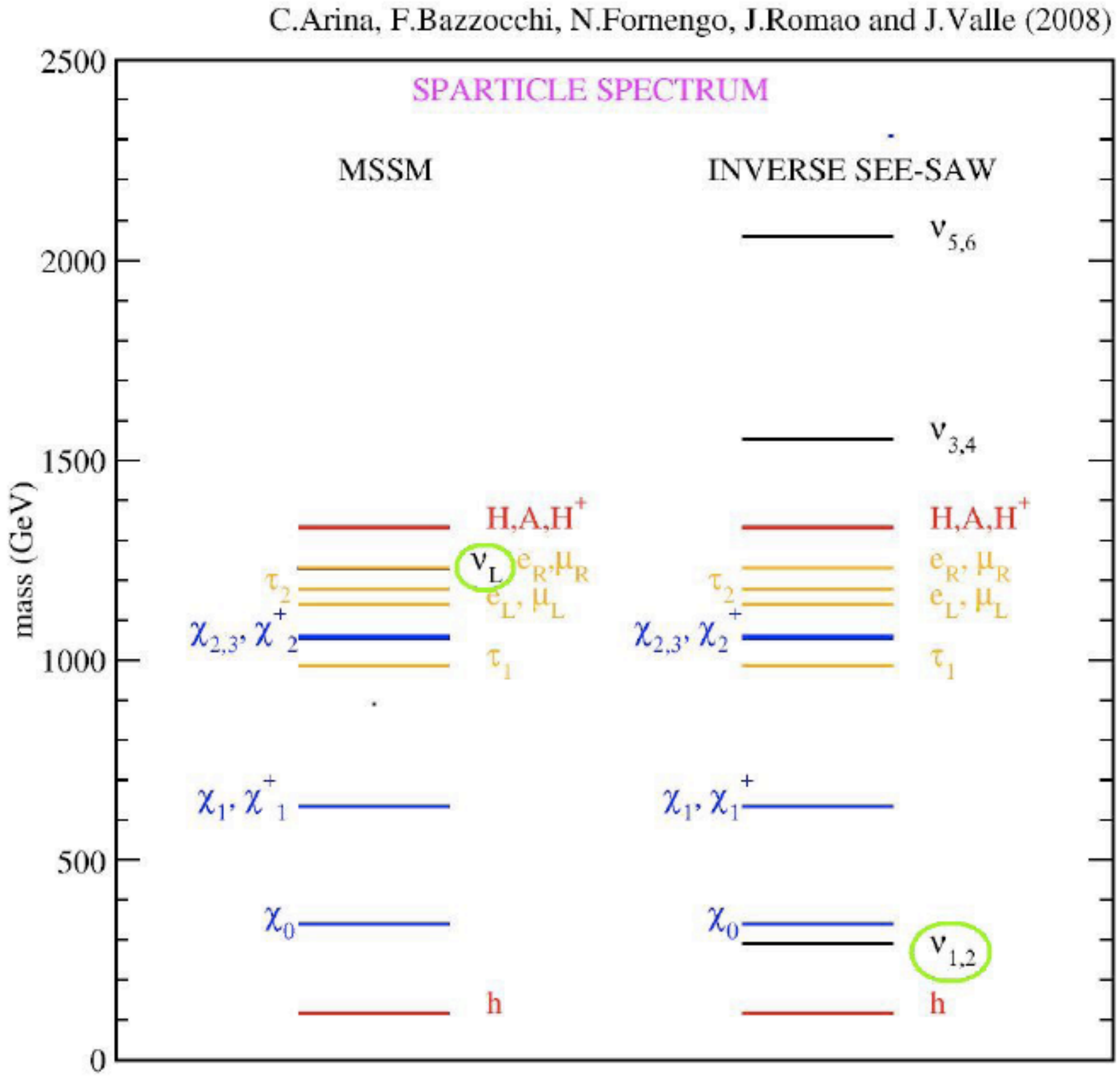
- At LHC expected a similar phenomenology as in the neutralino case, however qualitatively expected more leptons in the final state

$$\tilde{\chi}_1^- \to W^- \chi^0$$

Topologies @ LHC







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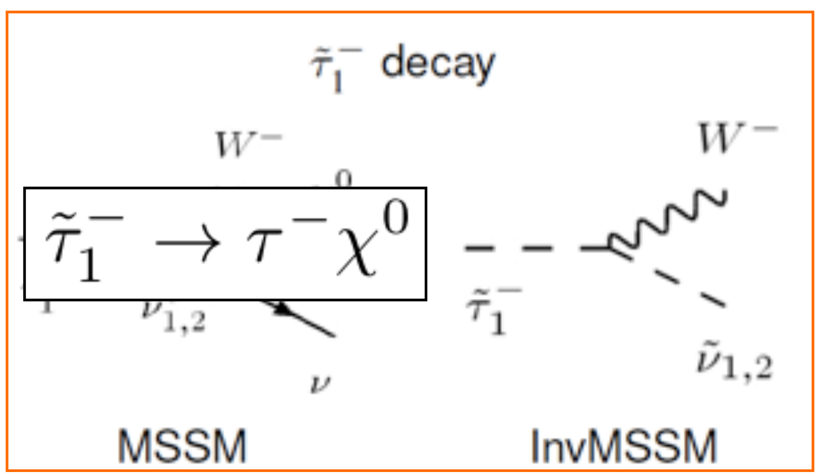
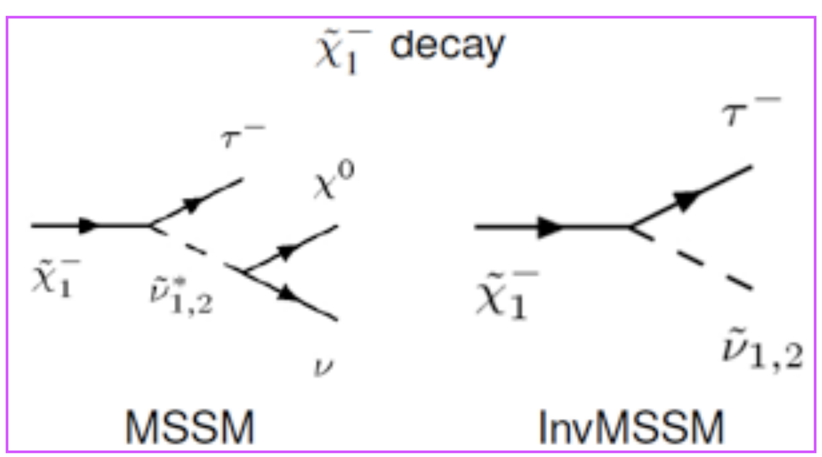
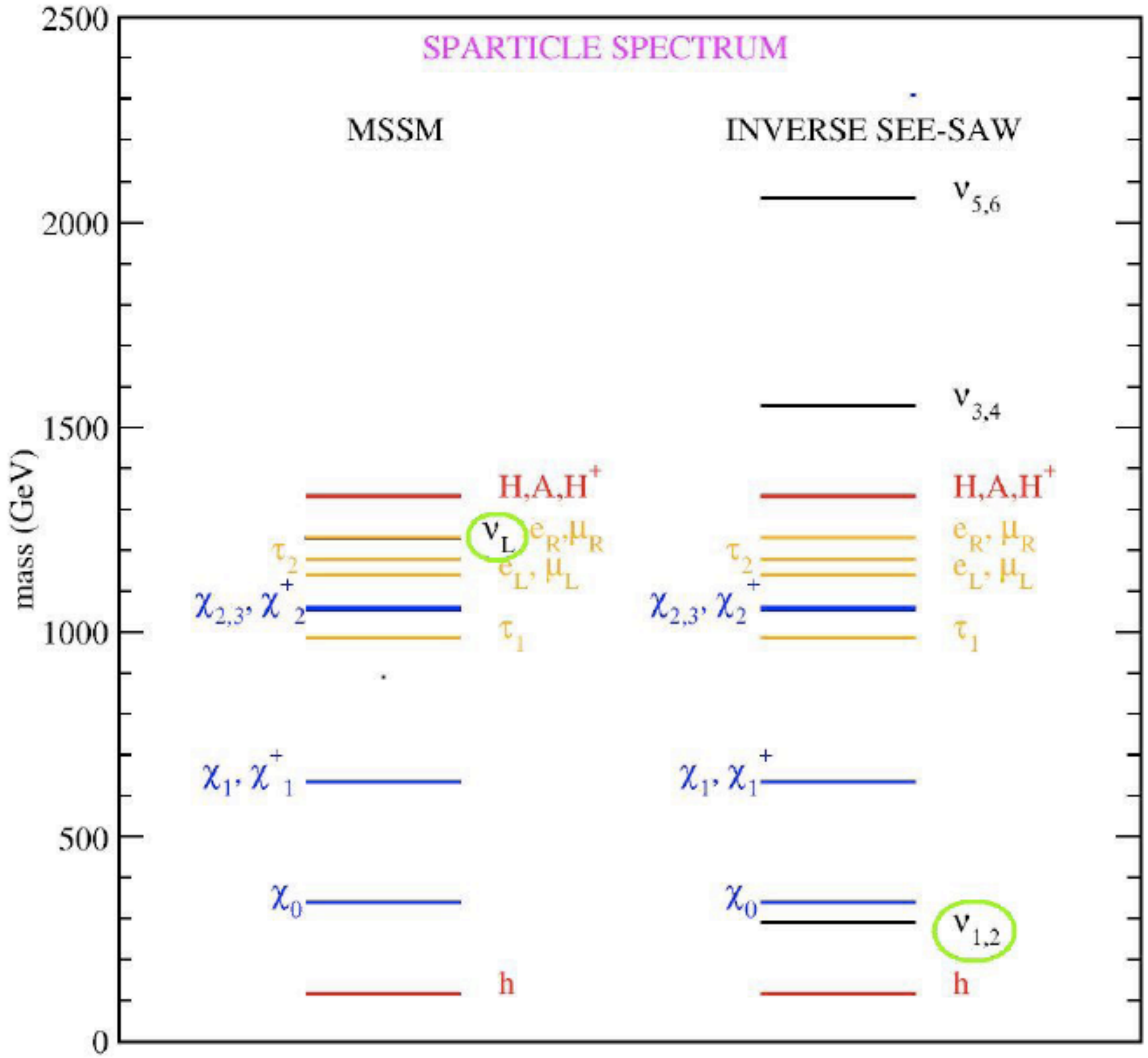




C.Arina, F.Bazzocchi, N.Fornengo, J.Romao and J.Valle (2008)



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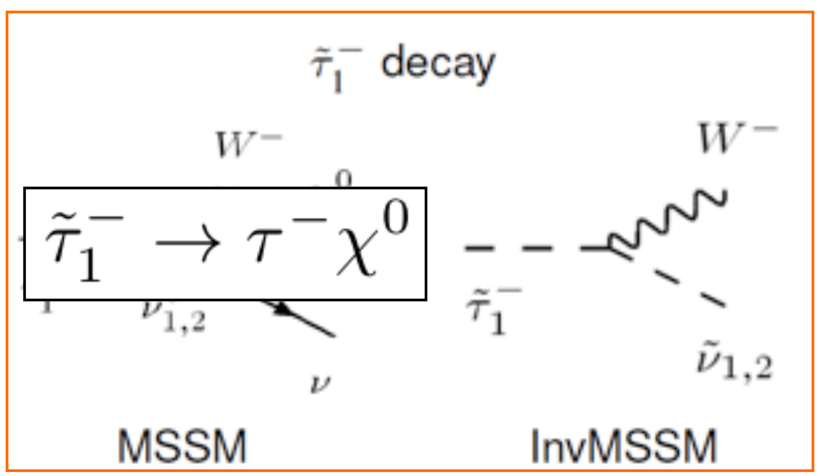

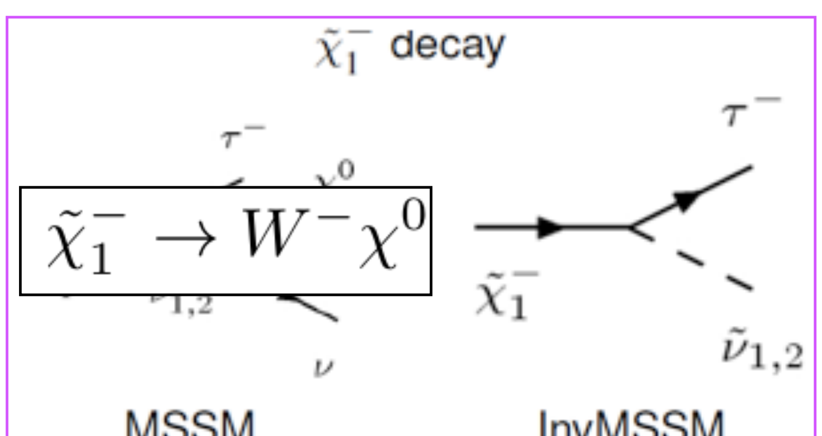

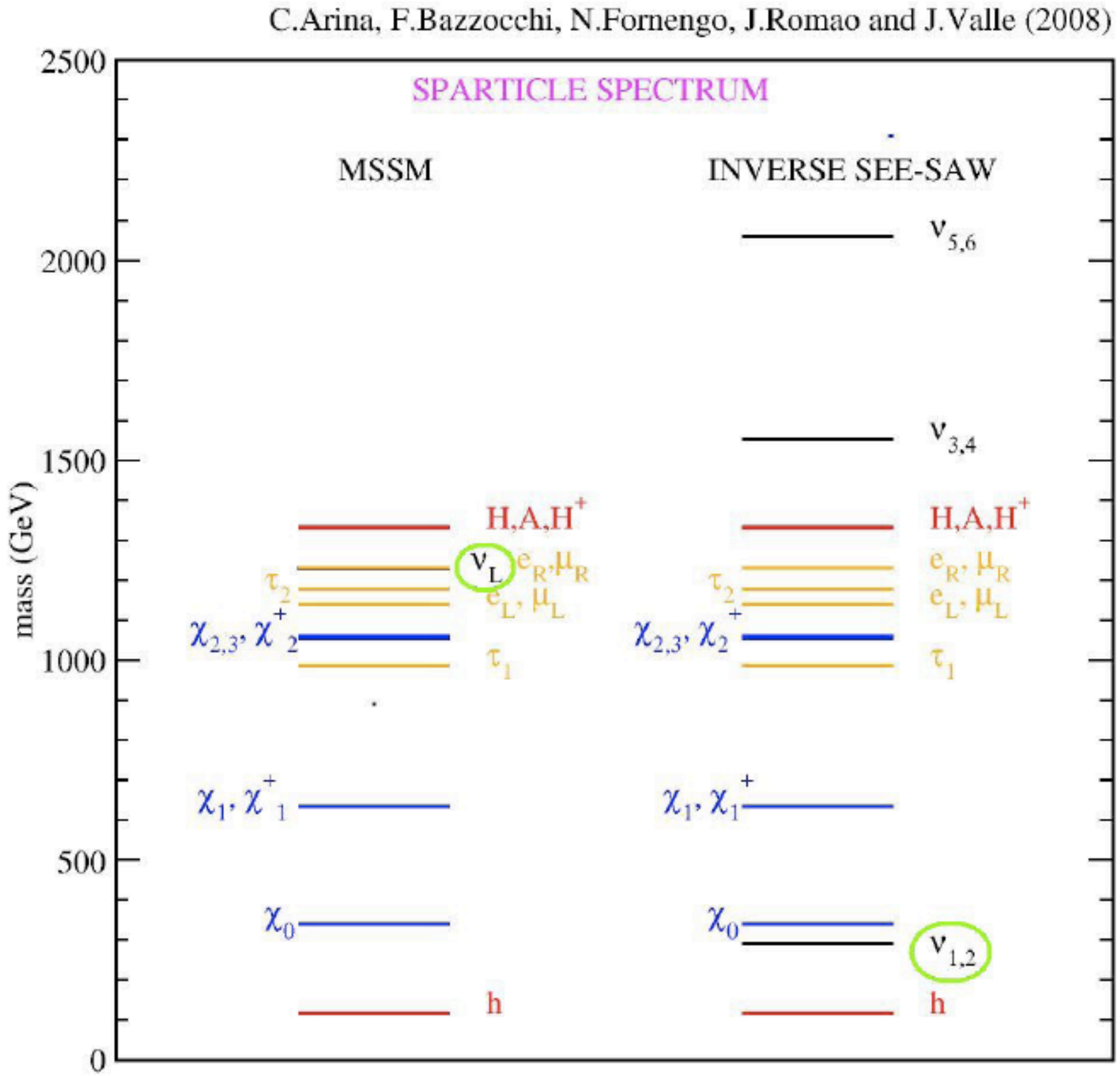

The theoretical model: MSSM+RN

Arkani-Hamed et al. '00, CA and N.Fornengo '07, G.Belanger et al. '10, '12

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Absence of lepton number violating terms

Neutrinos have Dirac masses $\quad m_D = v_u Y_\nu$

Why not considering a seesaw model?

1. The method we set up is technical and requires a lot of effort: test in the simplest model possible
2. Phenomenology with the addition of a right-handed sneutrino field only captures the main sneutrino properties which are interesting for signatures at LHC

Sneutrino mass matrix and mixing

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

Sneutrino left and right component mixes

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

Effect of mixing:

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

(ii) suppressed cross-section for scattering off nucleus

(iii) In the RGEs by considering the yukawa of the tau, the $\tilde{\nu}_{1\tau} \equiv \tilde{\nu}_1$ is the LSP

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Method for the analysis of 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

Sampling method and free parameters

VERY LARGE PARAMETER SPACE: n=13 free parameters

$$\{\theta_i\} = \{M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_L, A_{\tilde{\nu}}, A_Q, B, \mu\}$$

Sampling with the algorithm MultiNest

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

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

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Posterior probability
function = result

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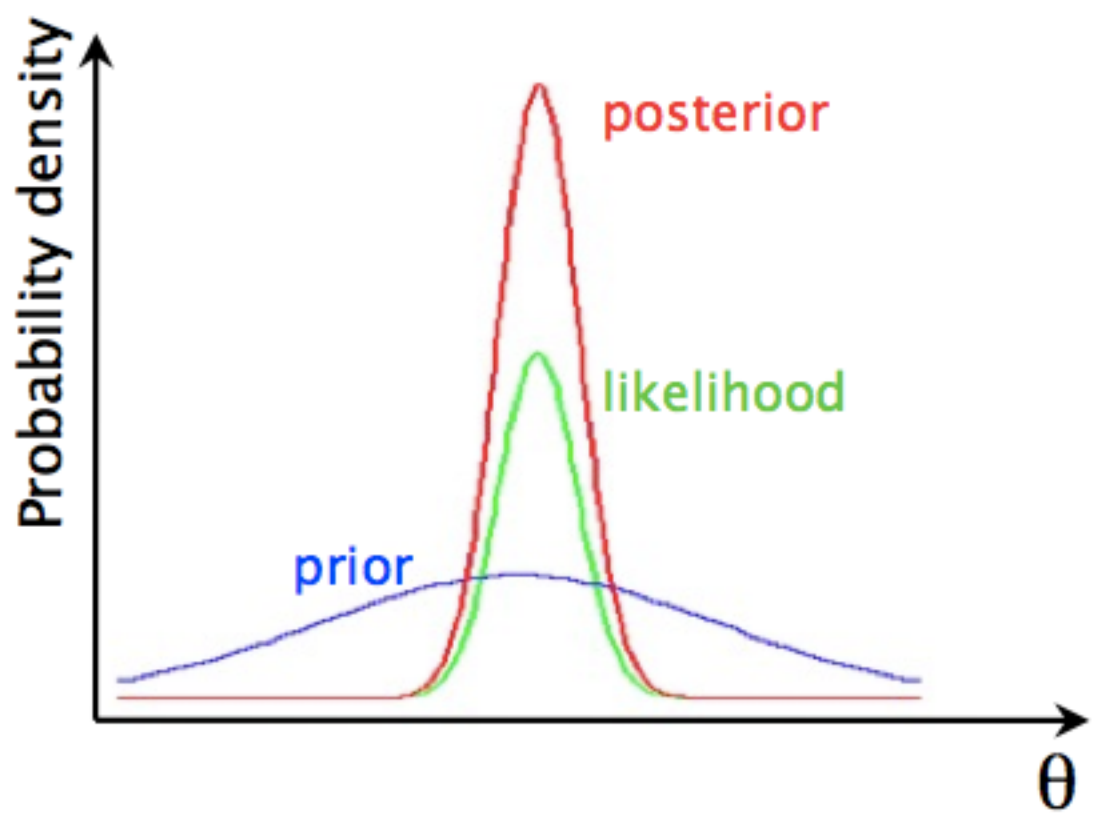
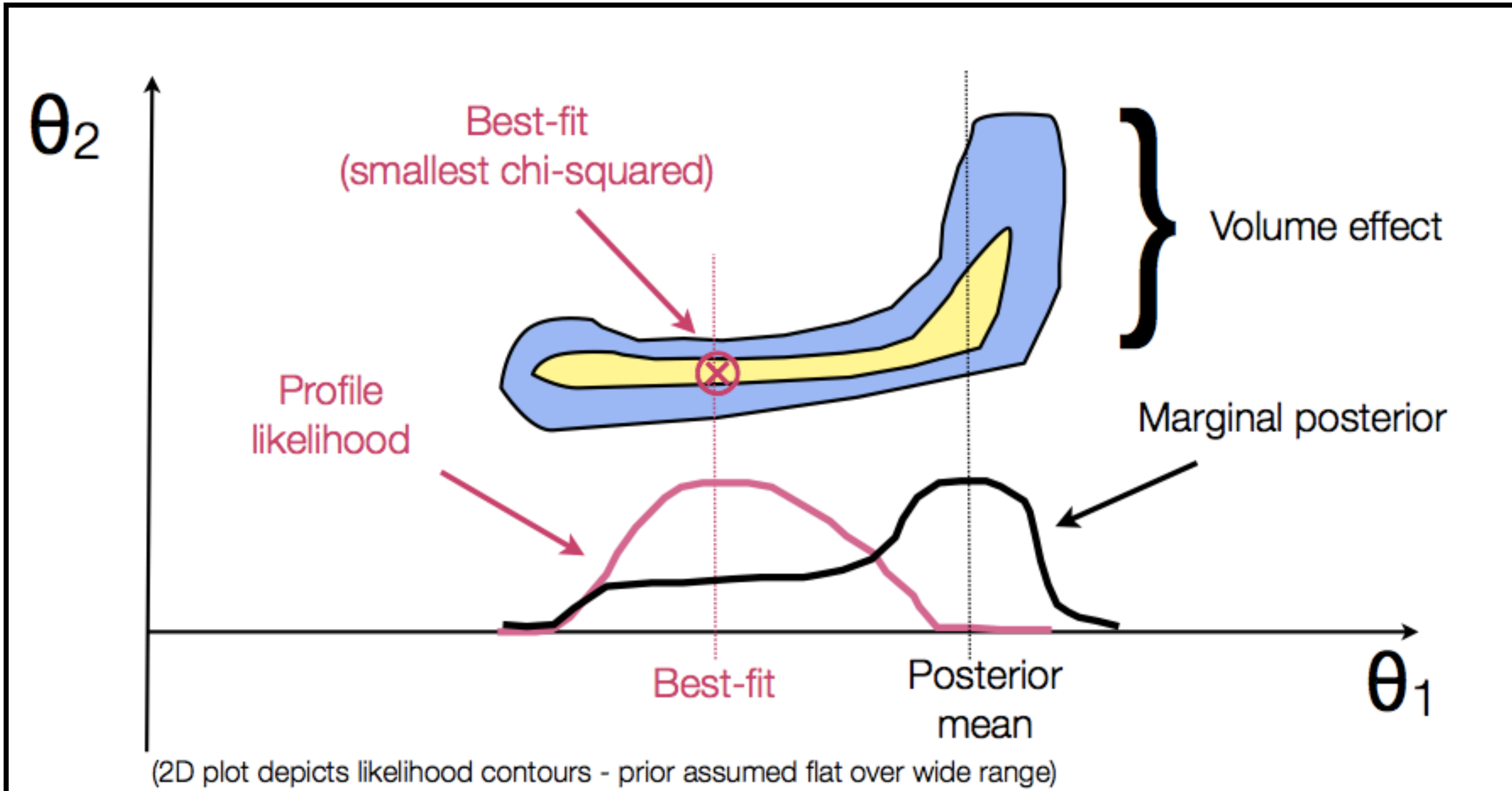


C. Arina (IAP, Paris & GRAPPA Institute, UvA) - LAPTh, February 27th 2014

Posterior pdf versus profile likelihood



credit: R.Trotta

Because of the dimensionality of the parameter space we consider only posterior pdf as equal weighted sample, hence the results will not have statistical meaning!

Likelihood: Observables and constraints

The log likelihood is the sum of the likelihood of each observable/bound we consider

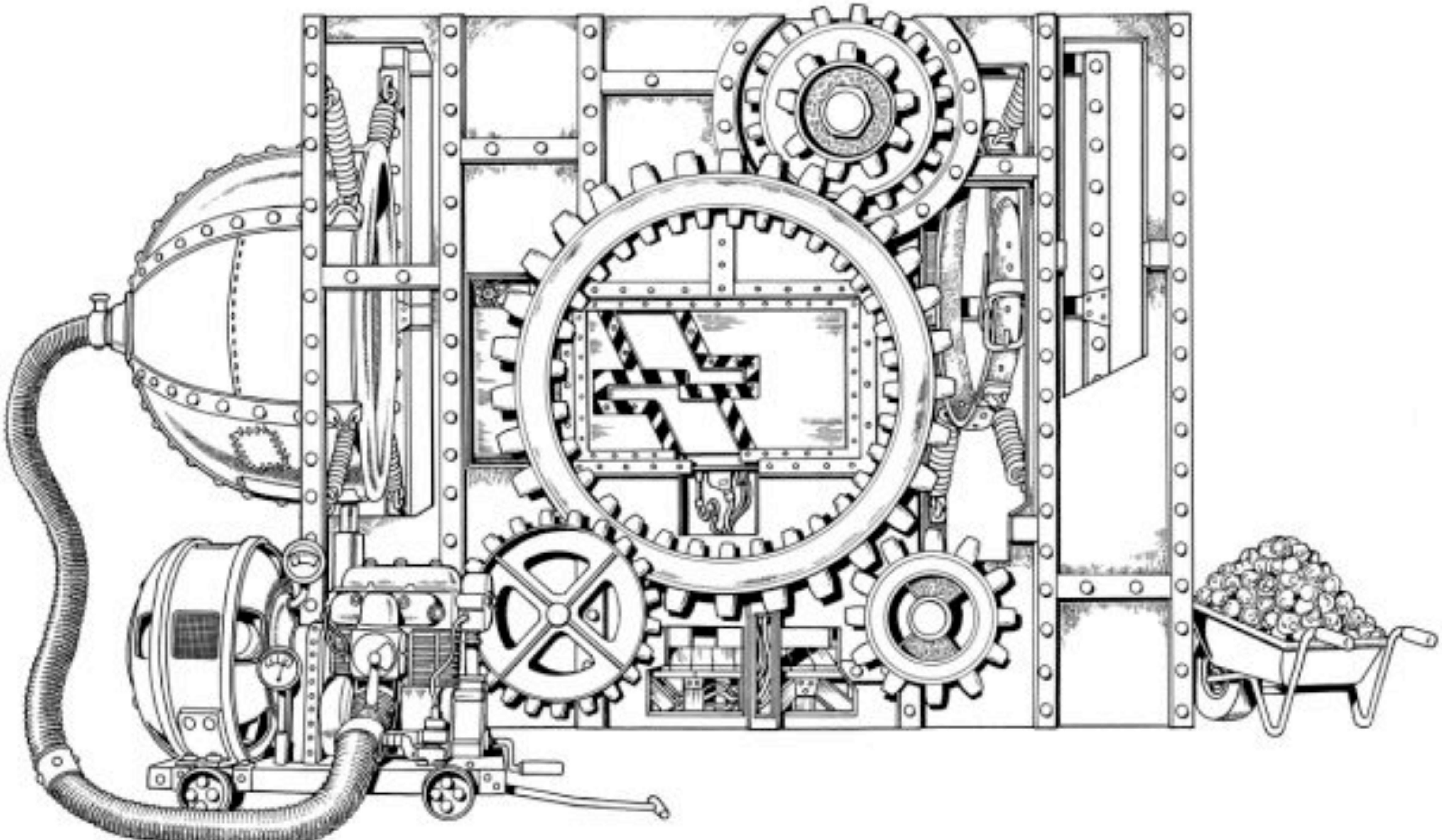
Observable with a measure have a gaussian likelihood:

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:

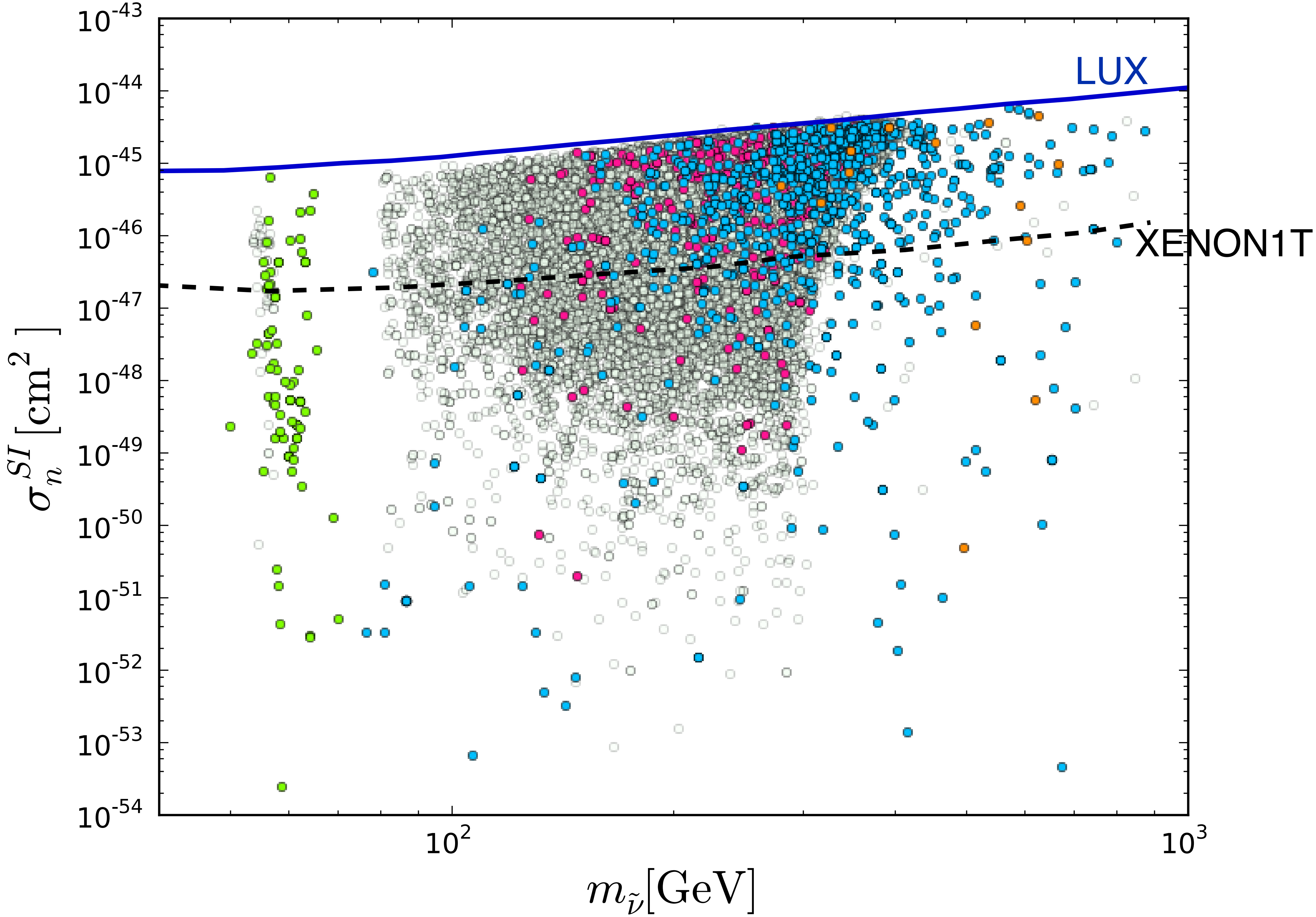
1. Chargino and slepton masses > 101 GeV (95% CL LEP)
2. Stau > 85 GeV (95% CL LEP)
3. LUX bound at 90% CL
4. Higgs invisible decay width (< 60%)

Running the machinery for model testing

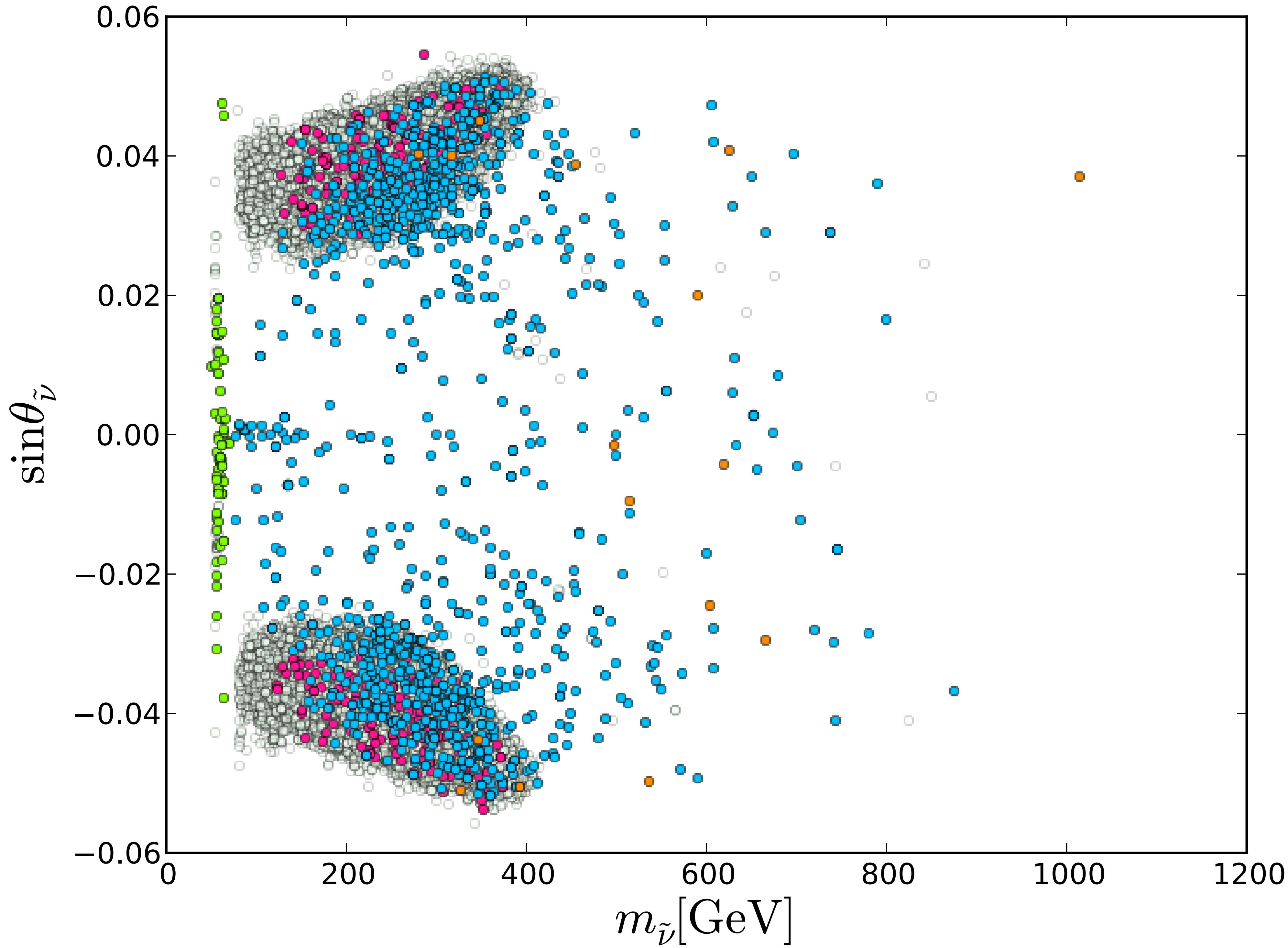


Results: where the sneutrino is a good dark matter candidate in the MSSM+RN

Sneutrino is a good dark matter candidate



Because of LUX the LSP is mostly right-handed

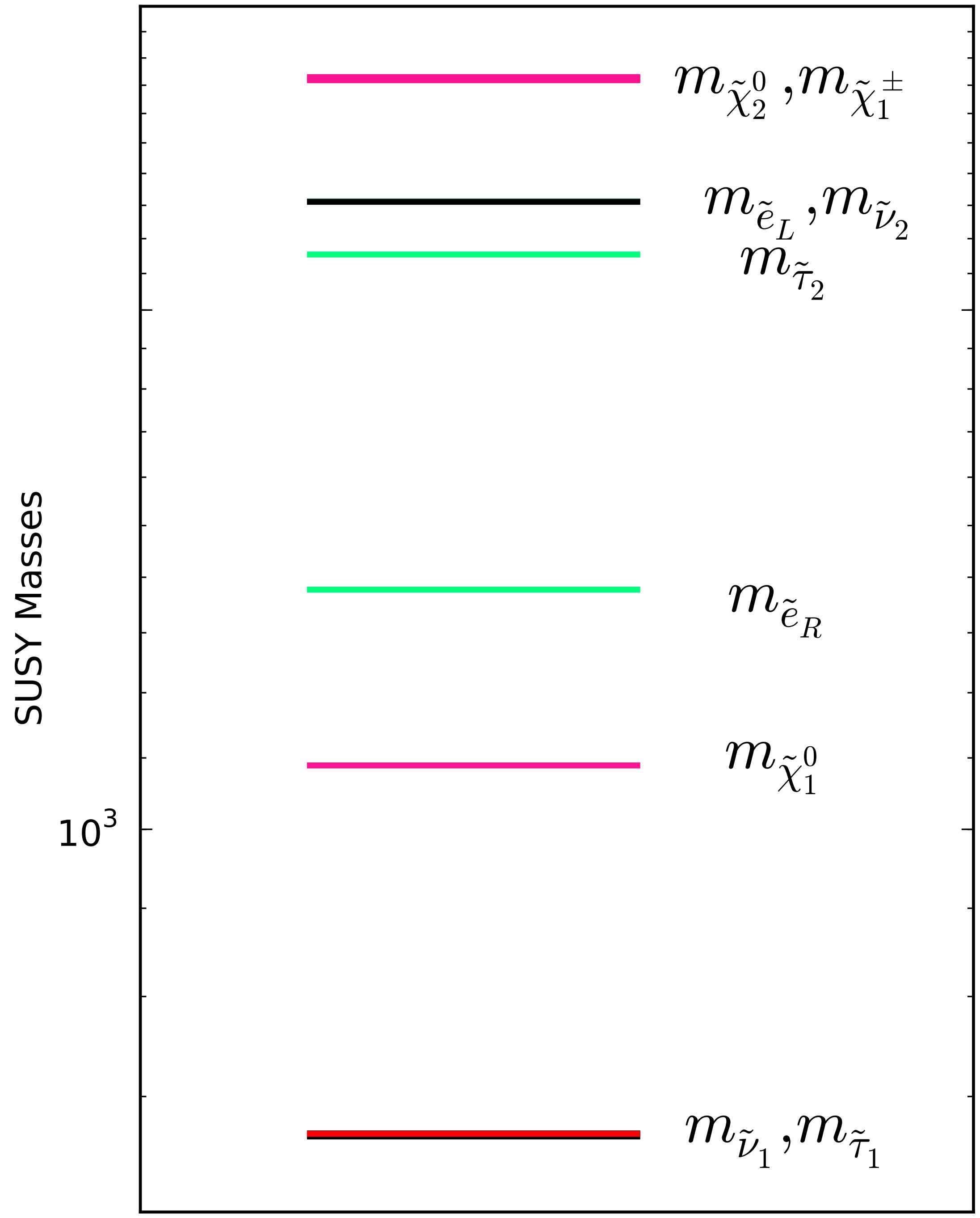


Different colors characterized by a different mass spectrum pattern and different annihilation processes that fix the relic density

Predictions for LHC from sneutrino dark matter

Orange points pattern

Mass spectrum



Relic density is set by

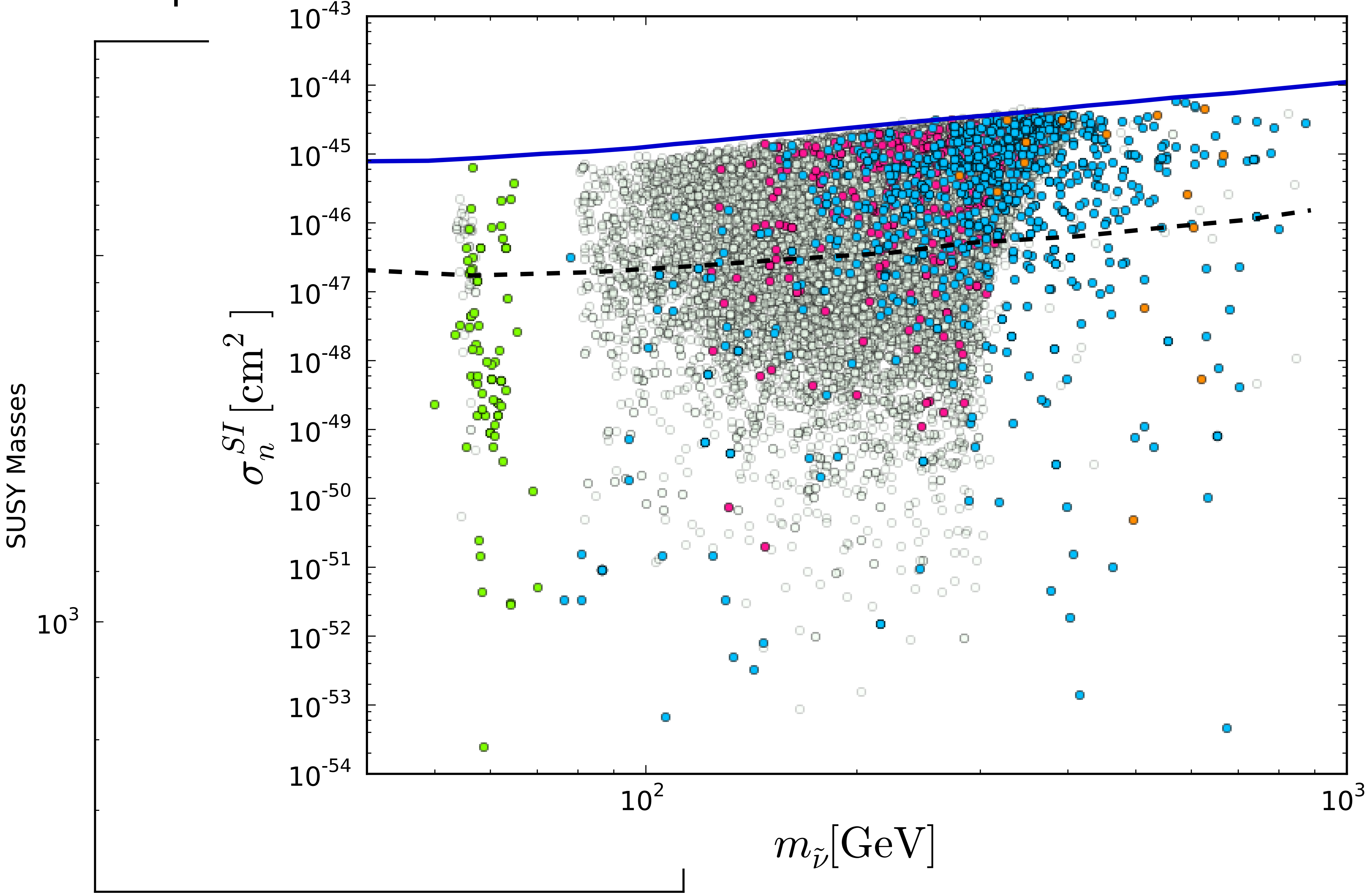
$$\left.\begin{aligned} \tilde{\tau}_1^+\tilde{\tau}_1^- &\to W^+W^-, ZZ, hh, t\bar{t} \\ \tilde{\nu}_1\tilde{\tau}_1^- &\to ZW^-, hW^- \\ \tilde{\nu}_1\tilde{\nu}_1^* &\to W^+W^-, ZZ, hh, t\bar{t} \end{aligned}\right\}$$

Very subdominant

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

Orange points pattern

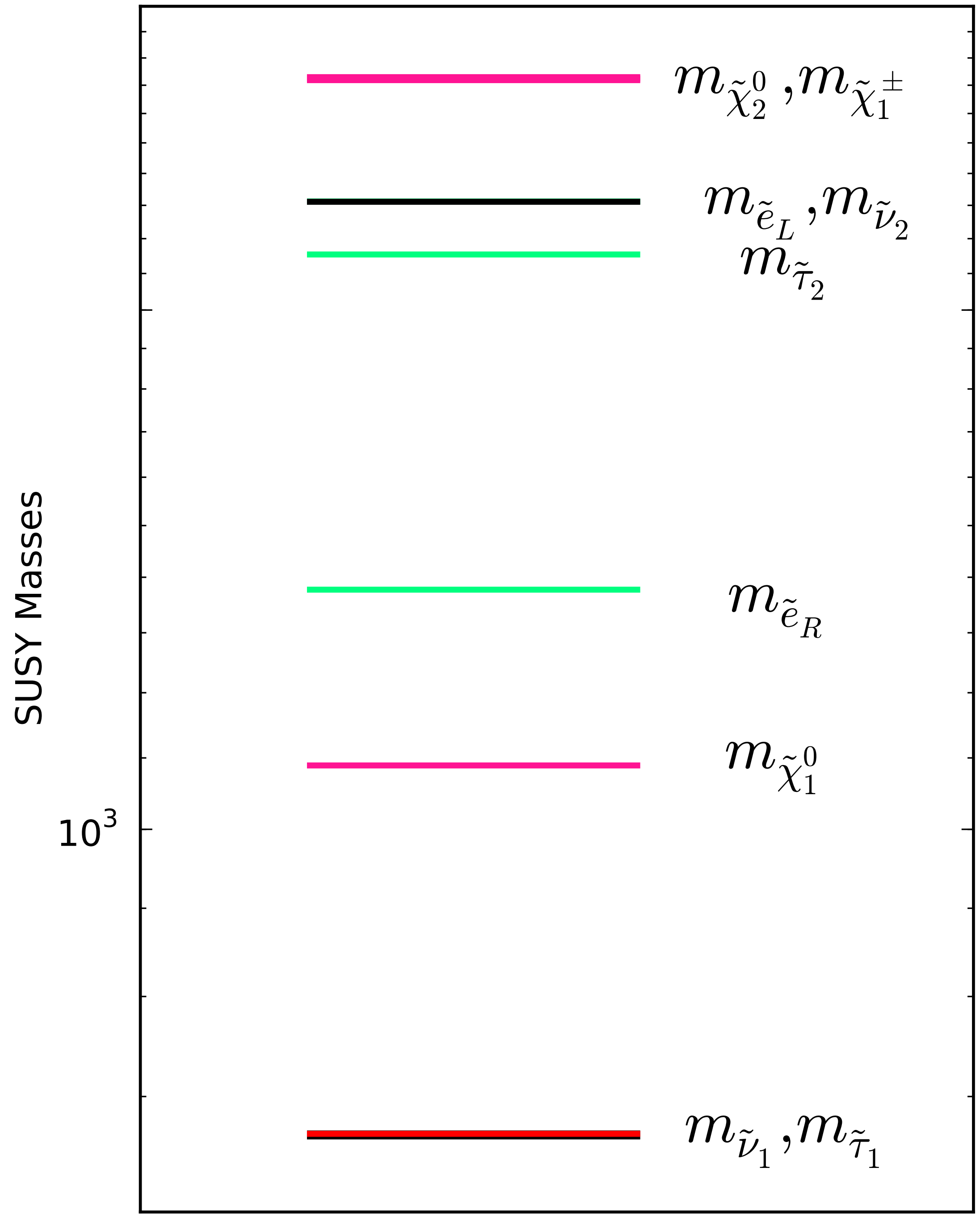
Mass spe



}

Orange points pattern

Mass spectrum



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Very subdominant

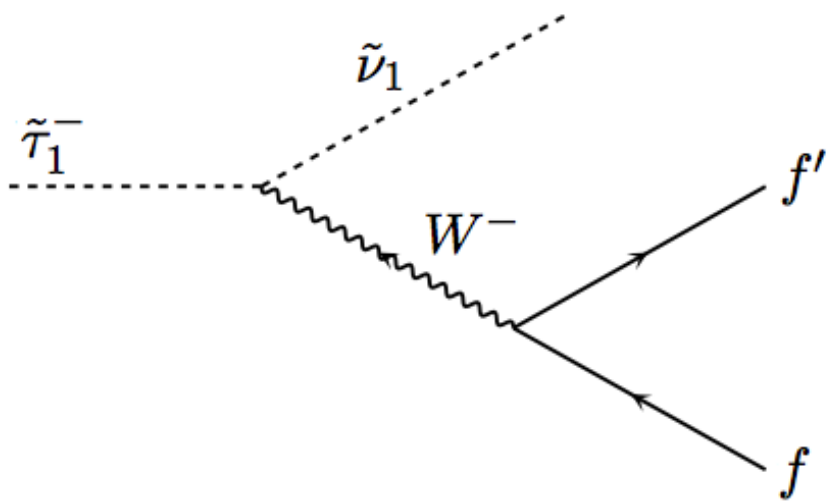
unless $\sin\theta_{\tilde\nu} > 0.02$

Long-lived staus

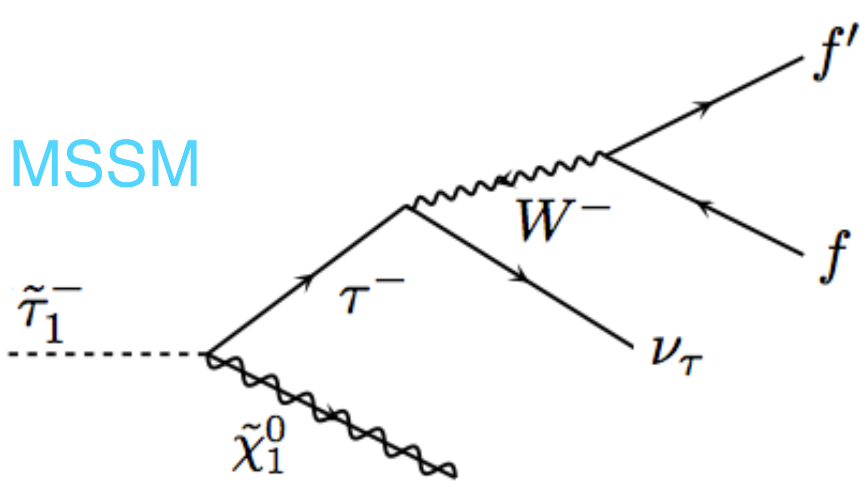
Signature arising when:

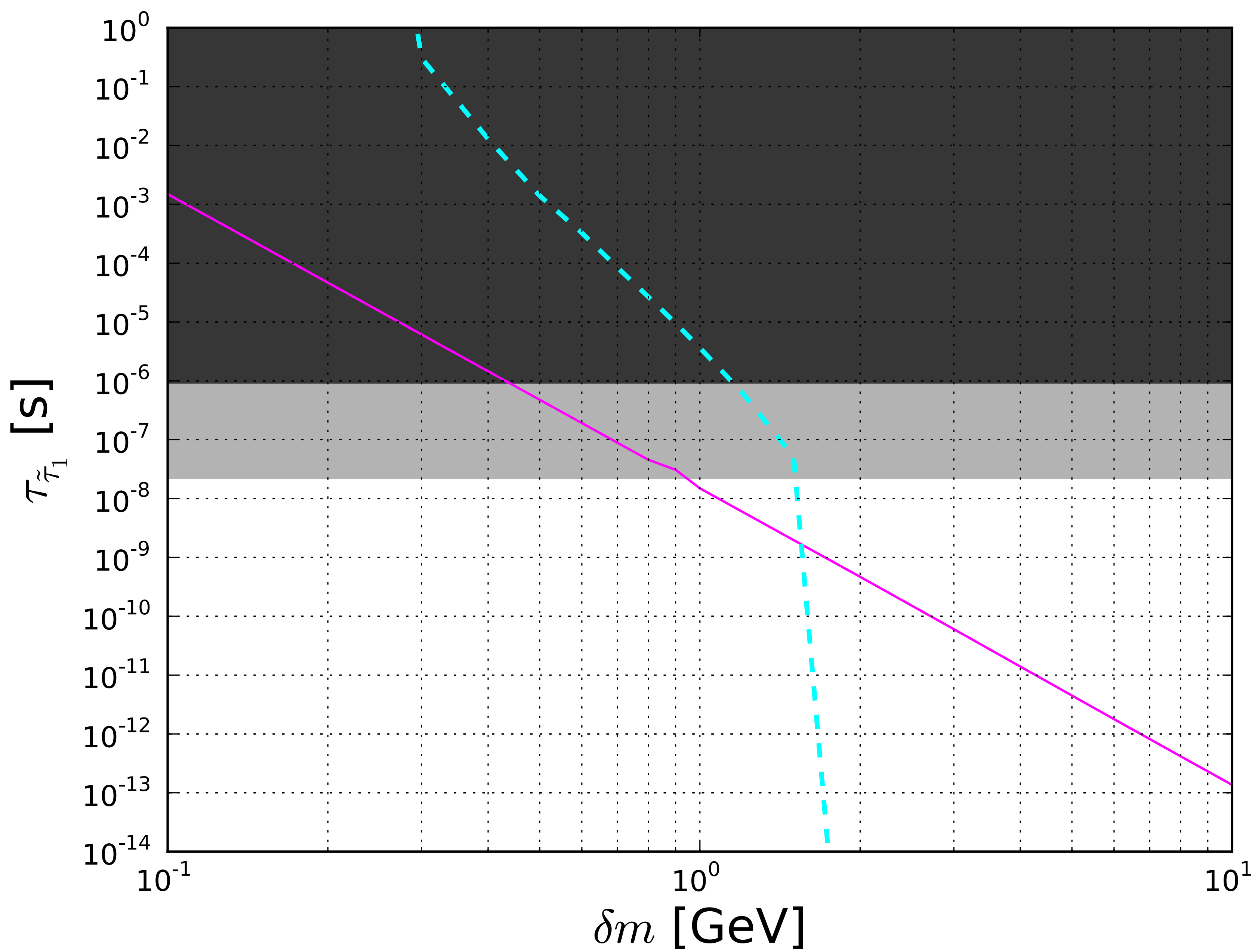
1. Stau is the NSLP
2. small $\delta m \equiv m_{\tilde{\tau}_1^-} - m_{\tilde{\nu}}$

MSSM + RN



MSSM

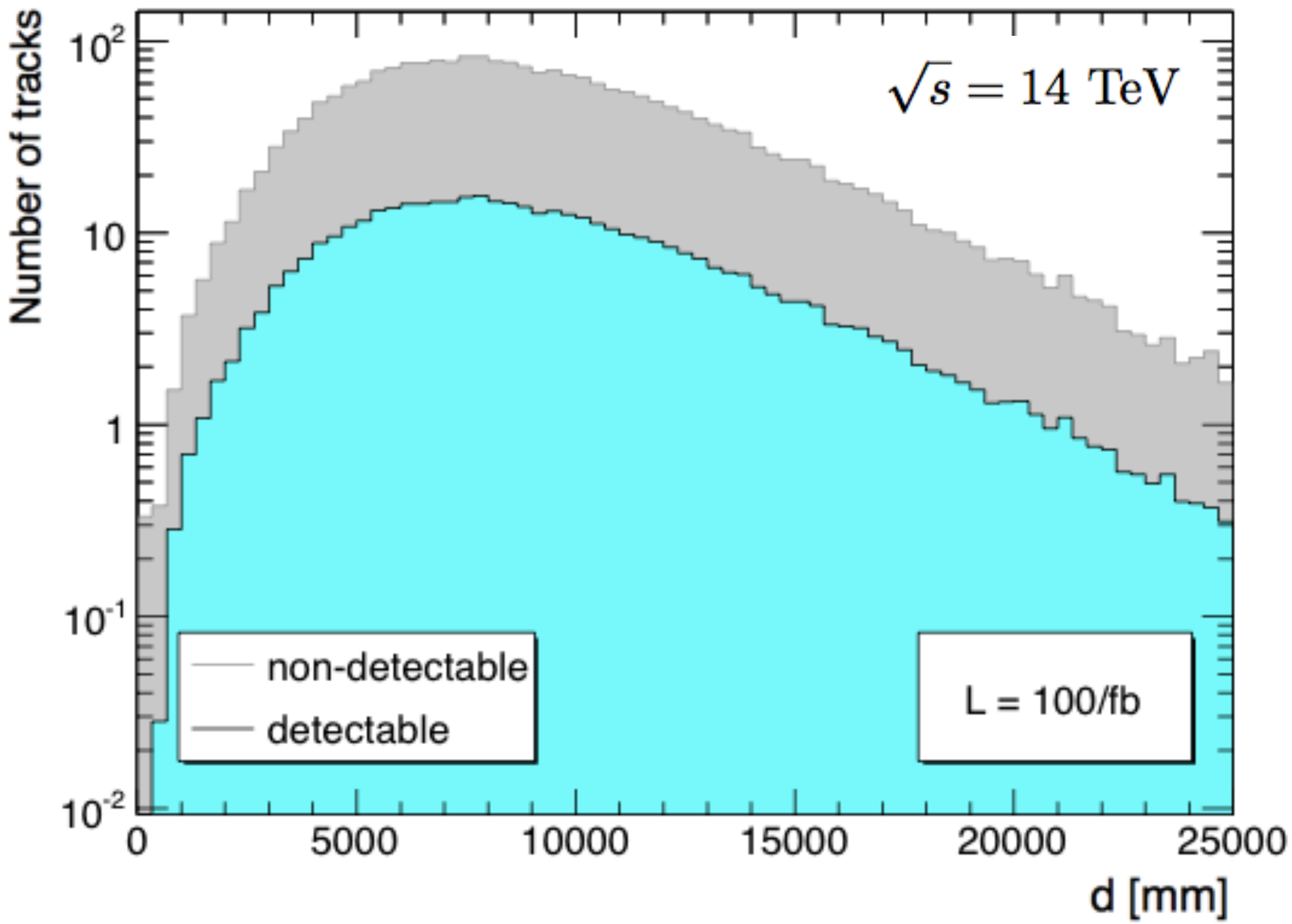




Existing bound: $mass_{llp}$ > 300 GeV allowed (ATLAS-CONF-2013-58)

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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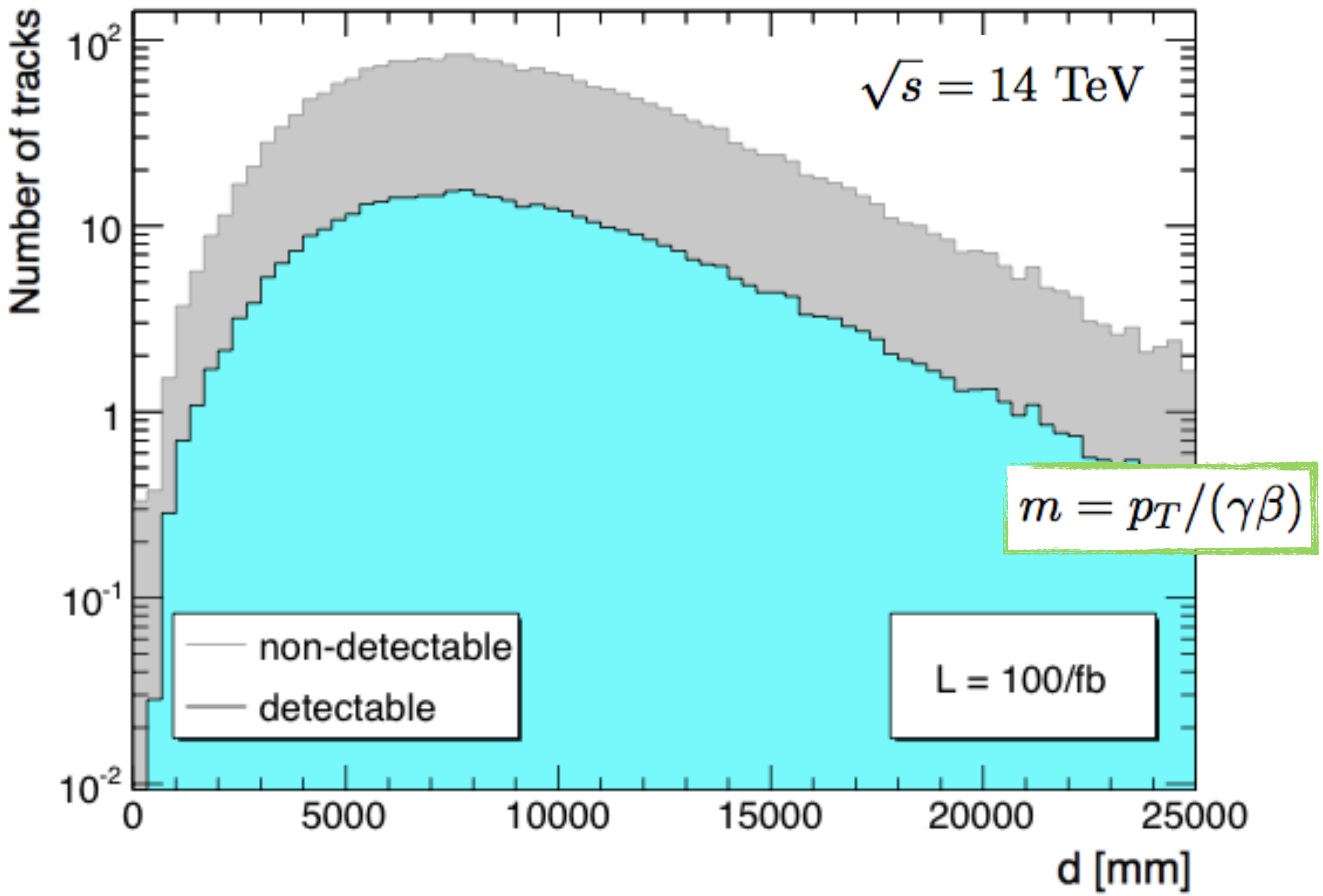
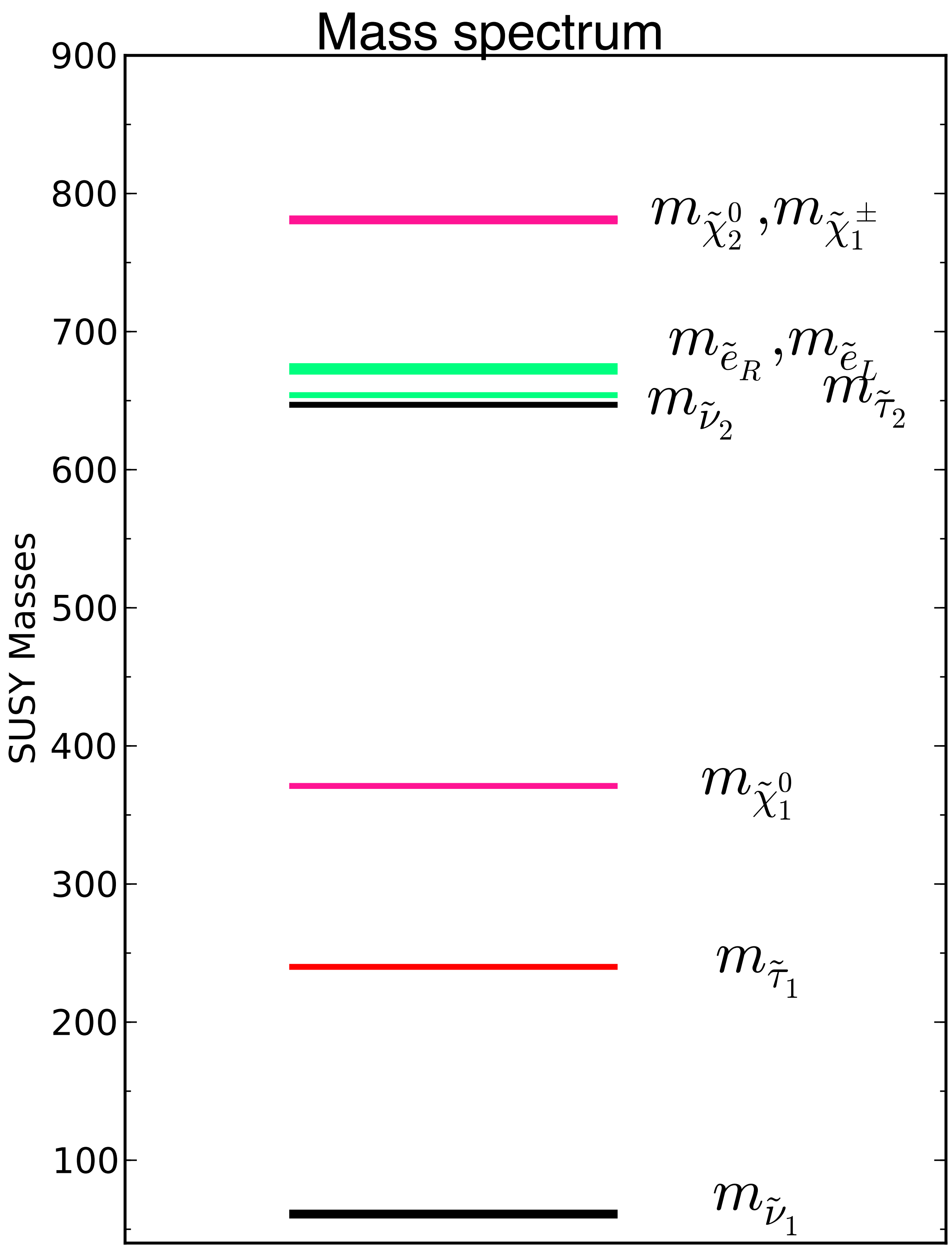


Green points (Higgs pole) pattern



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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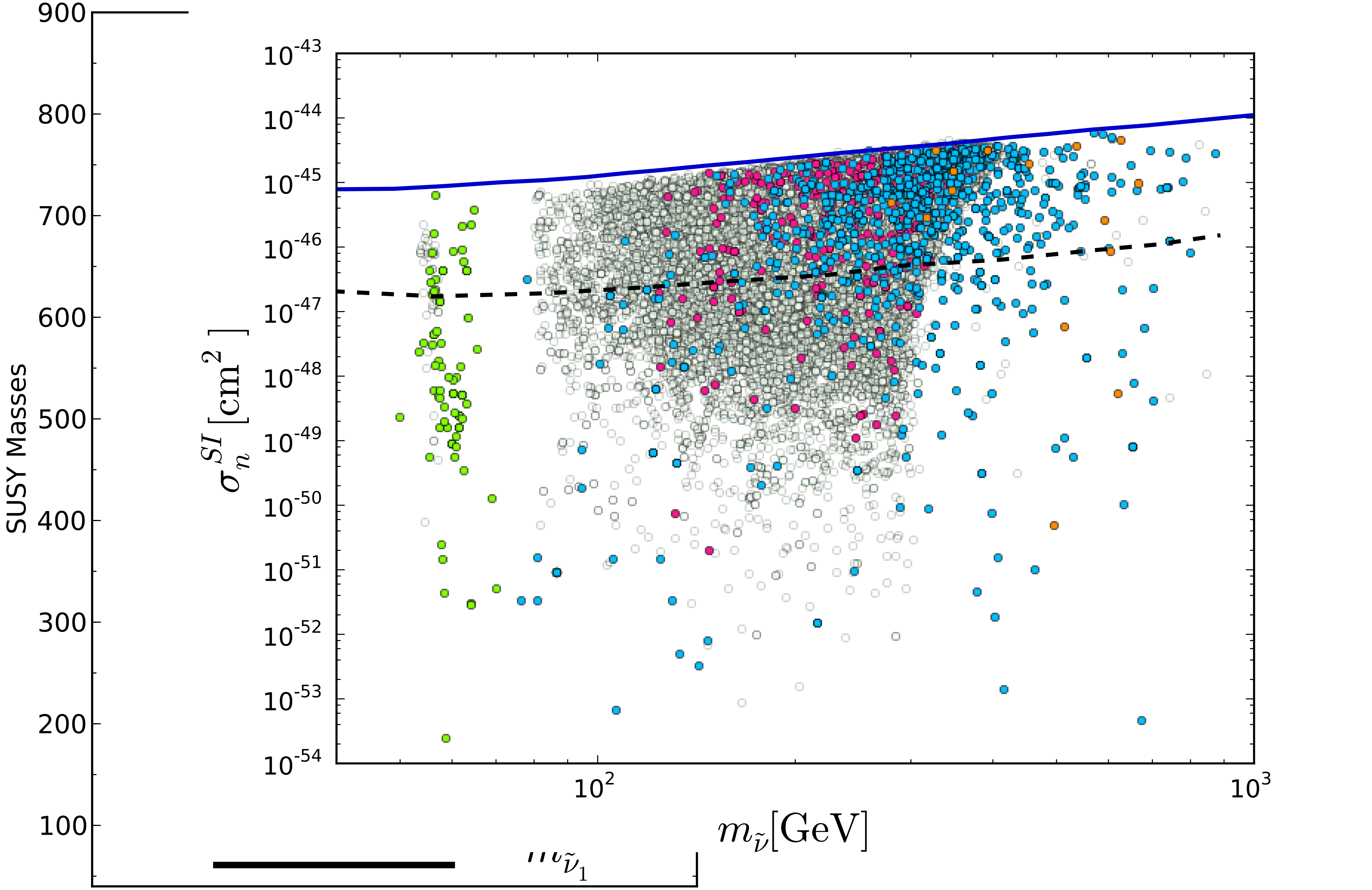

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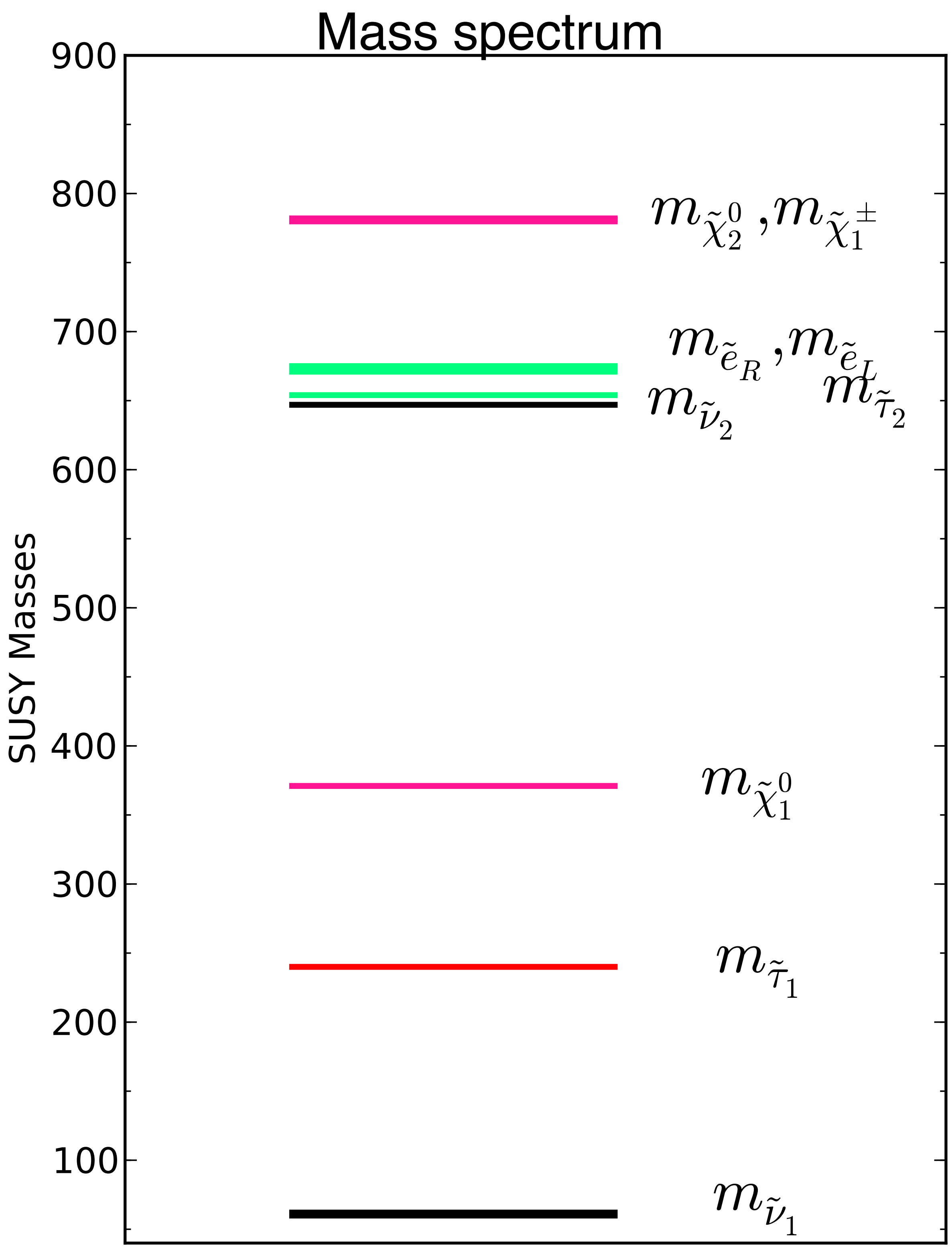

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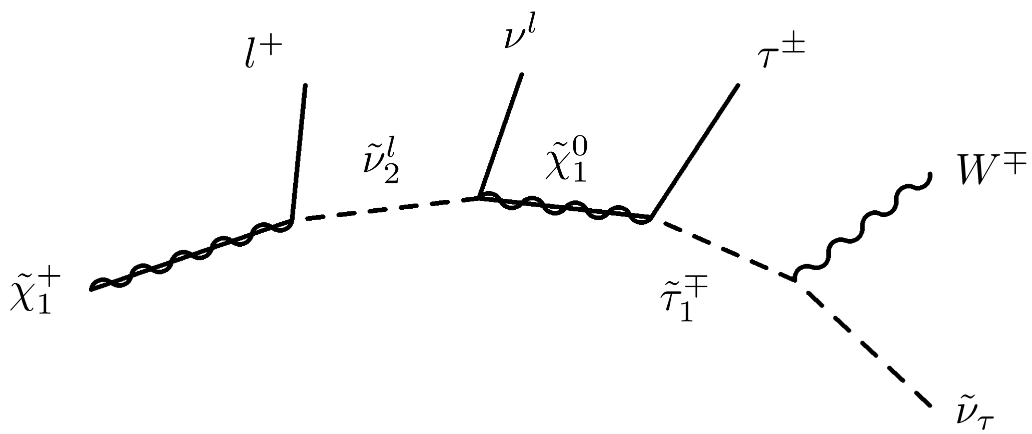
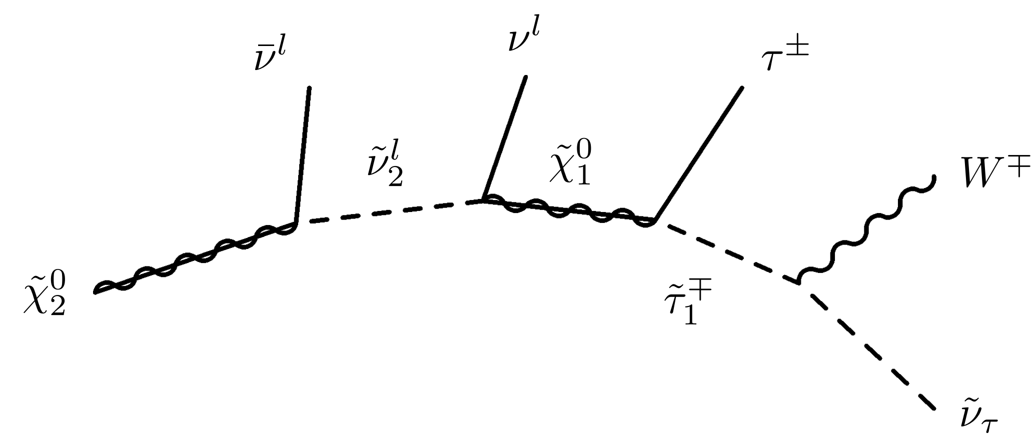
3 uncorrelated leptons



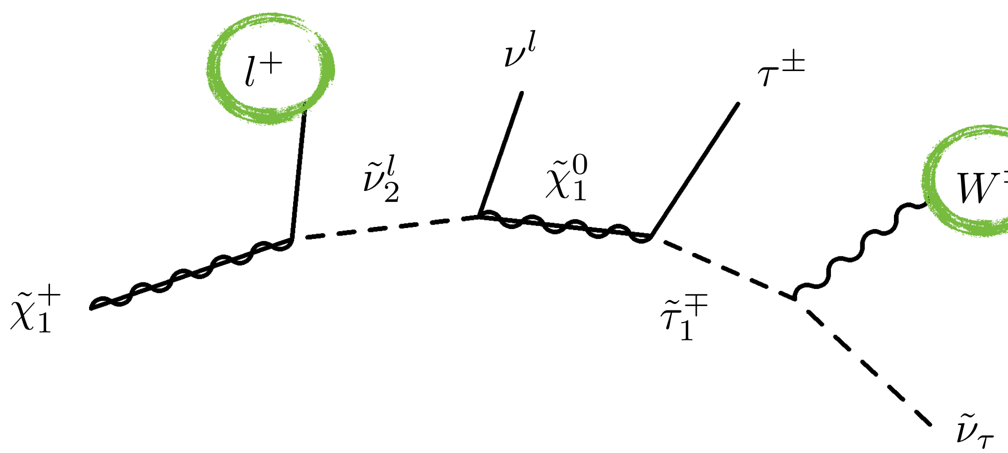


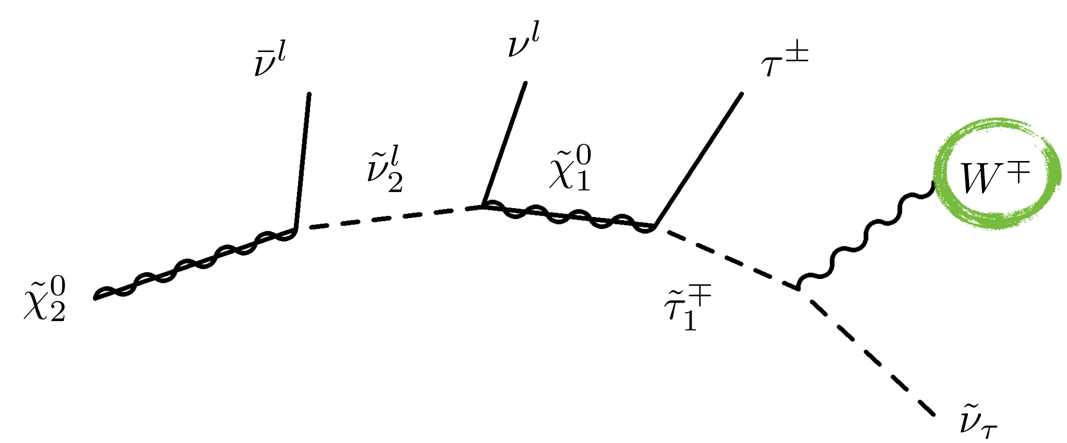
- Feature characteristic of the Higgs pole (LSP very right-handed)
- Sleptons are lighter than charginos and neutralinos (typically stau is the NLSP)
- The two final taus are not tagged due to low efficiency

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





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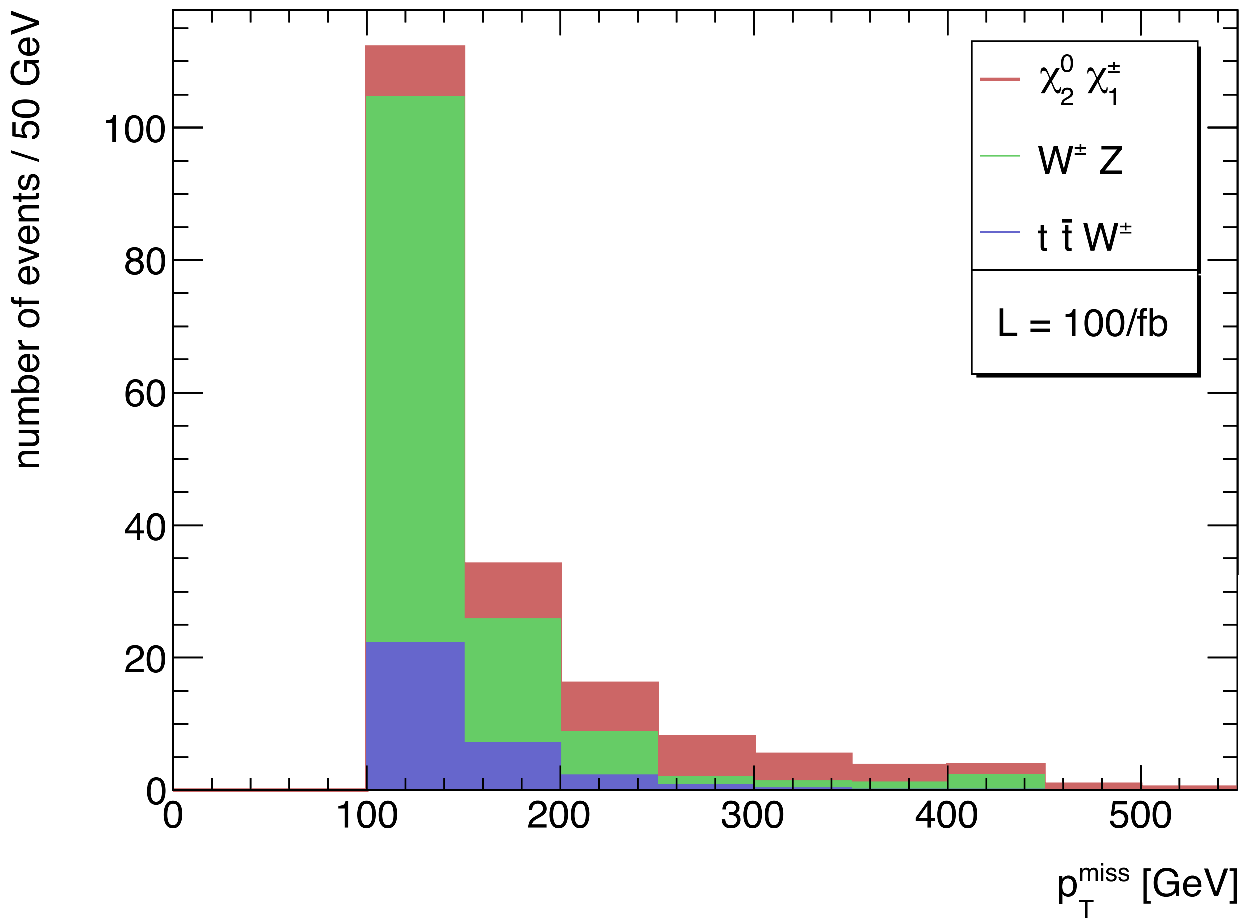
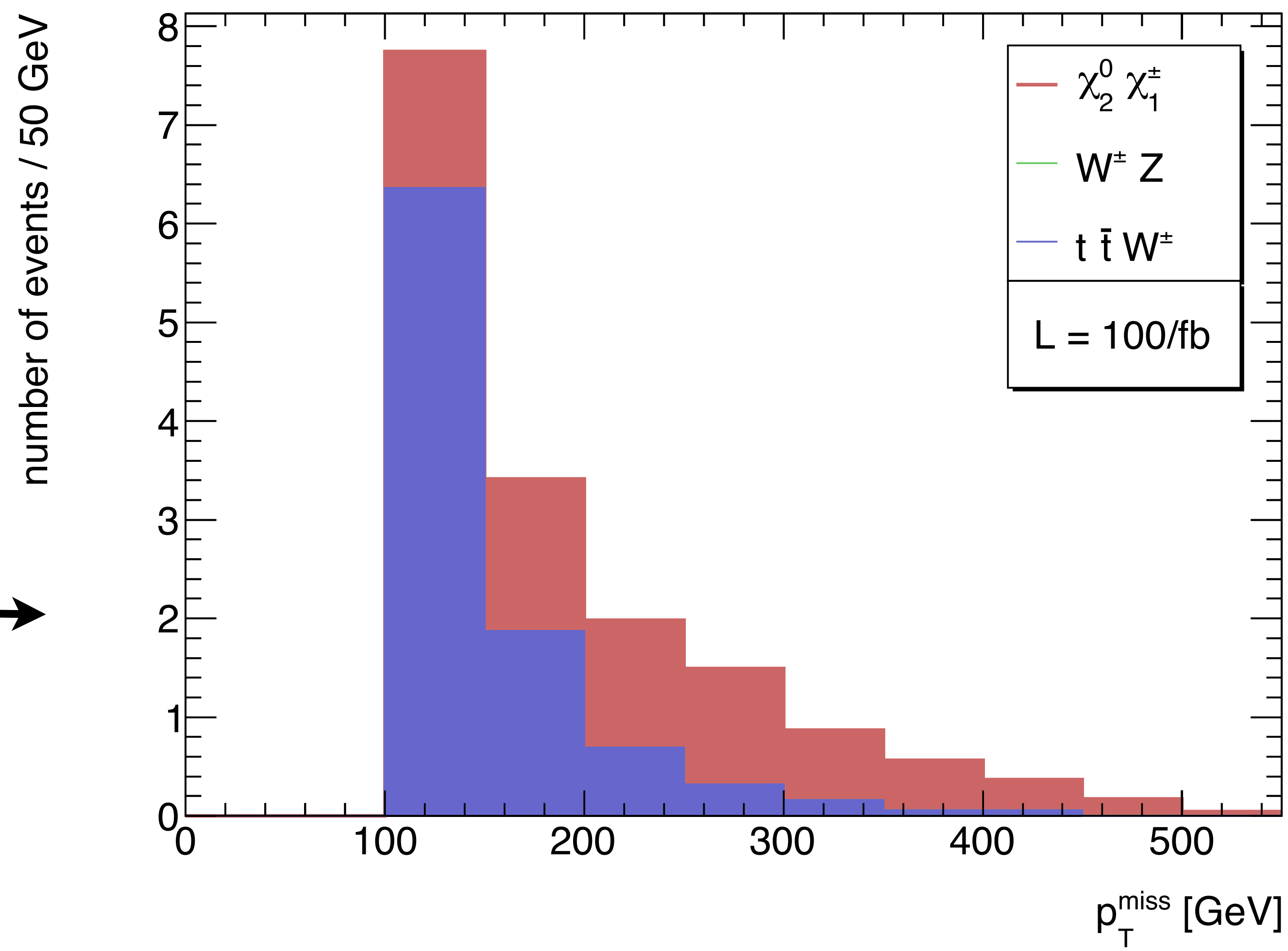
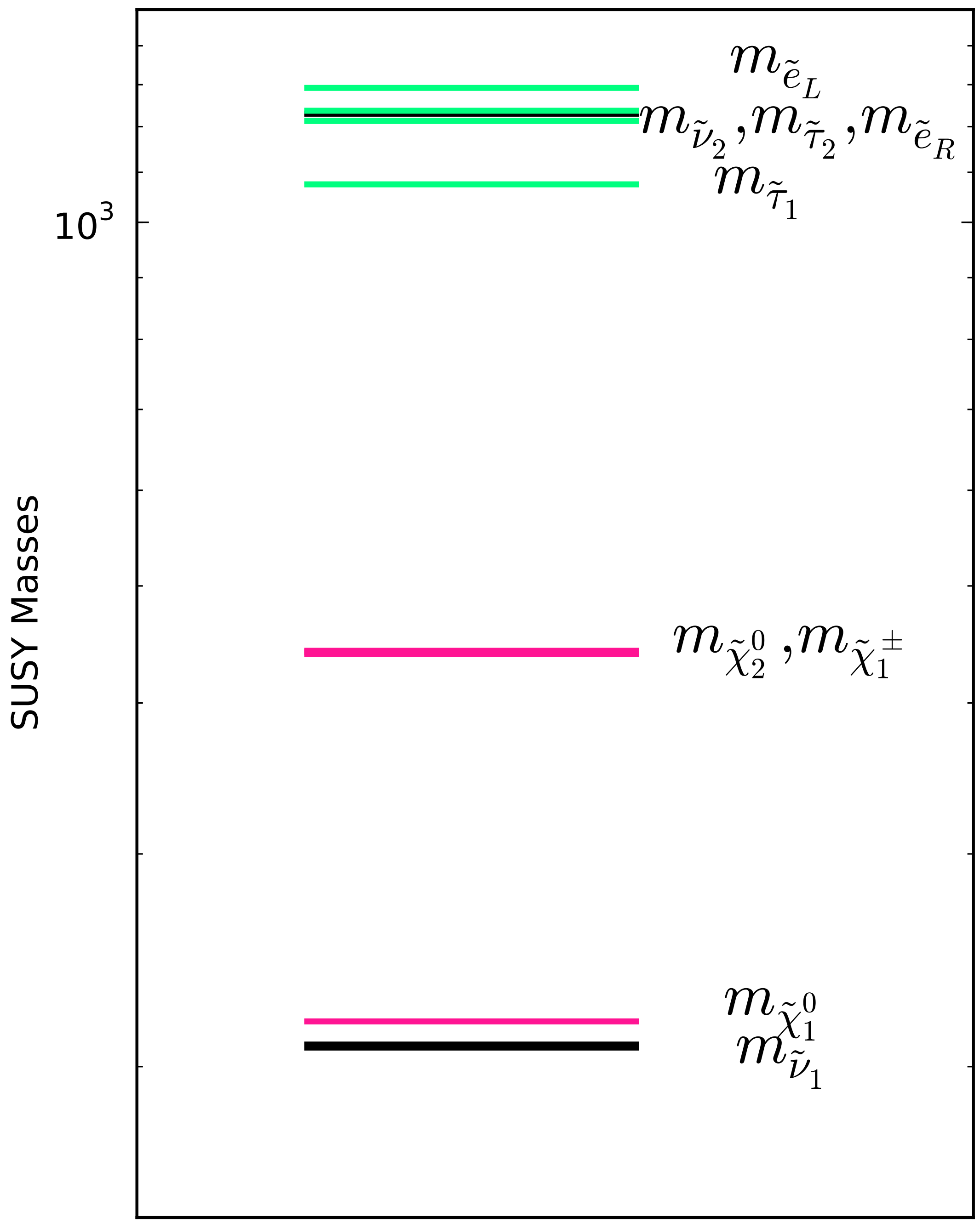


Additional cut forbidding OSSF leptons



Magenta points pattern

Mass spectrum

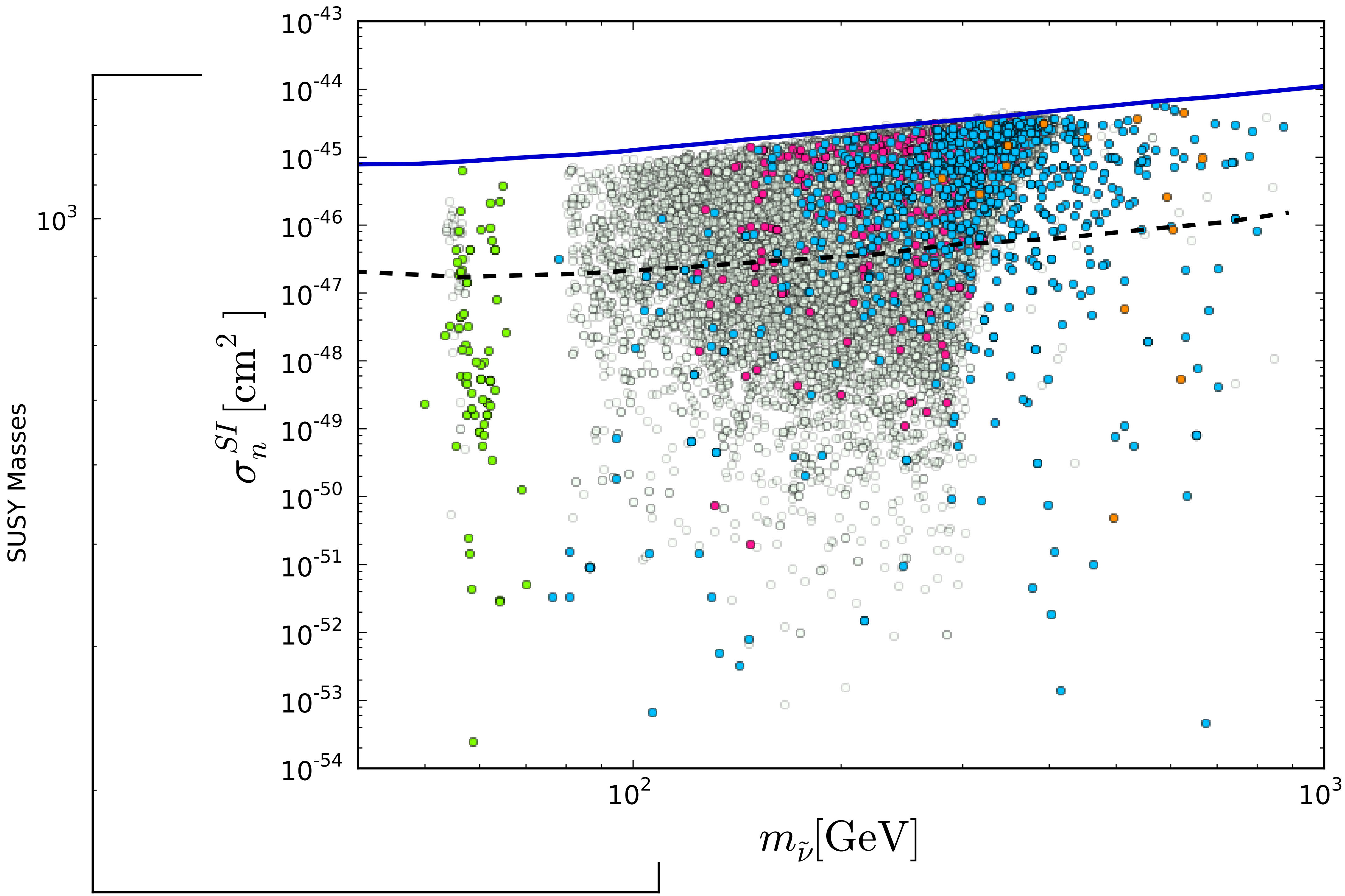


Relic density is set by sneutrino and coannihilation/annihilation with the lightest neutralino

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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Magenta points pattern

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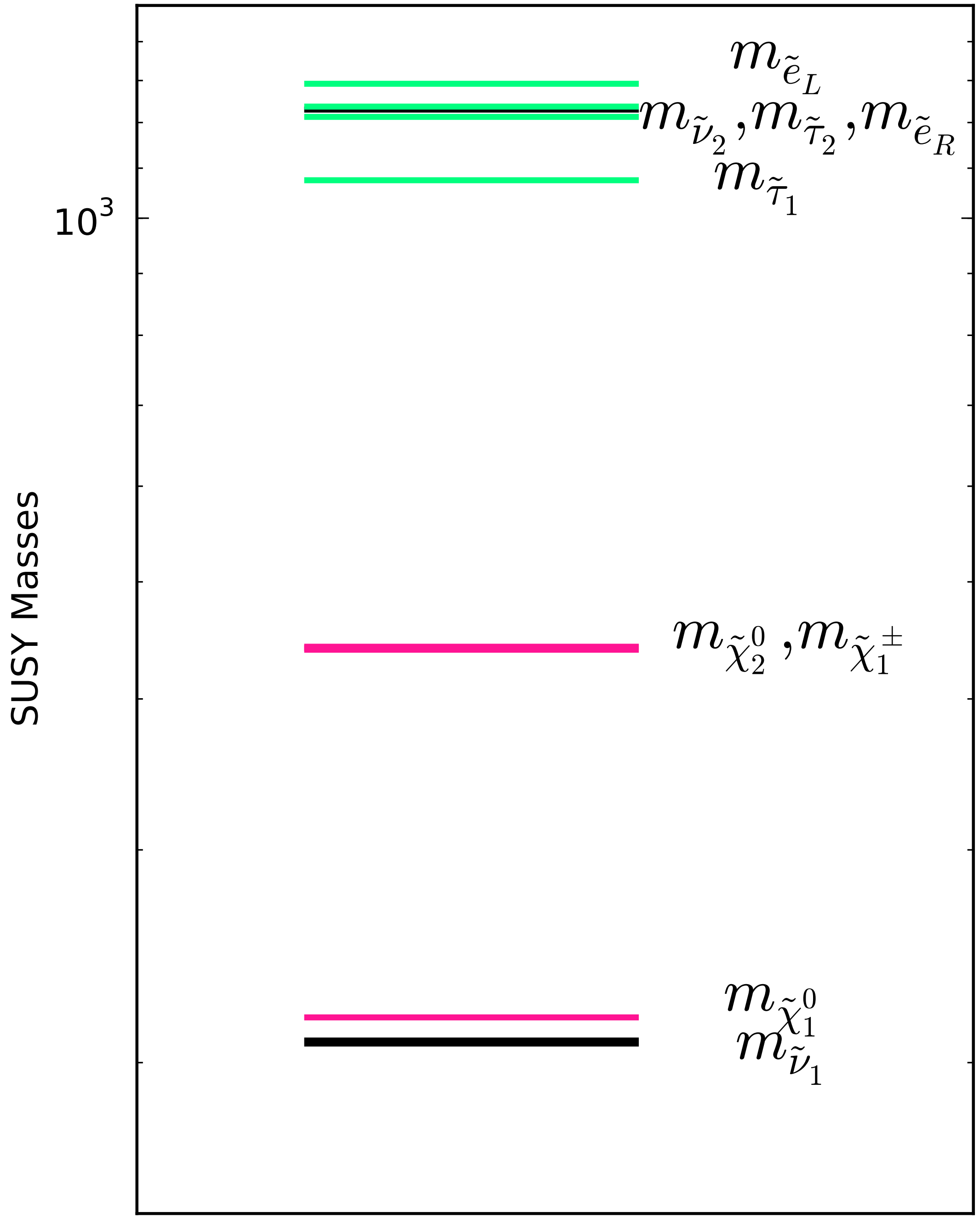

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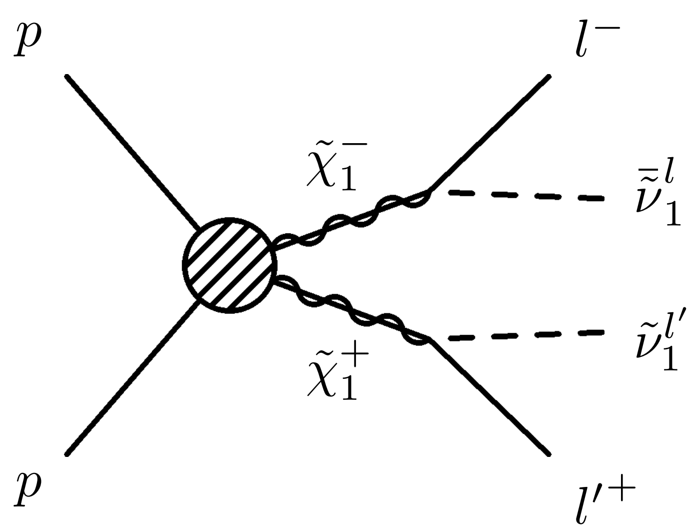
Chargino production

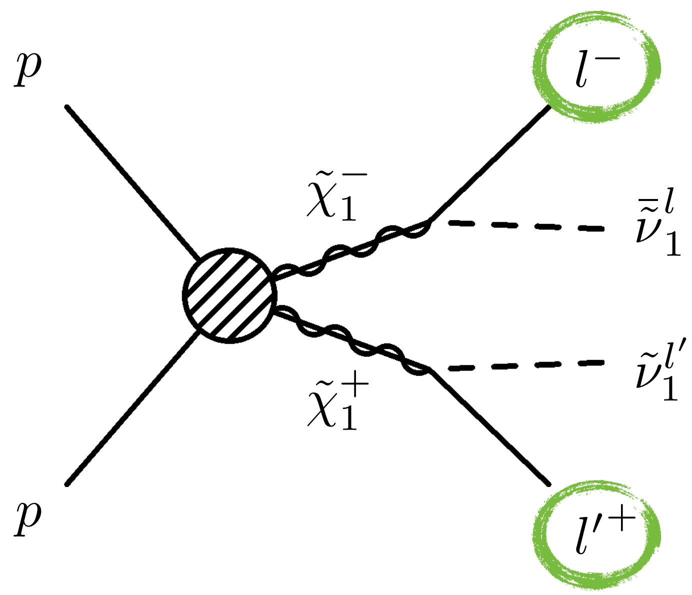


- When chargino is ligther than sleptons
- Decay 2-body into the LSP (MSSM is 3-body)

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

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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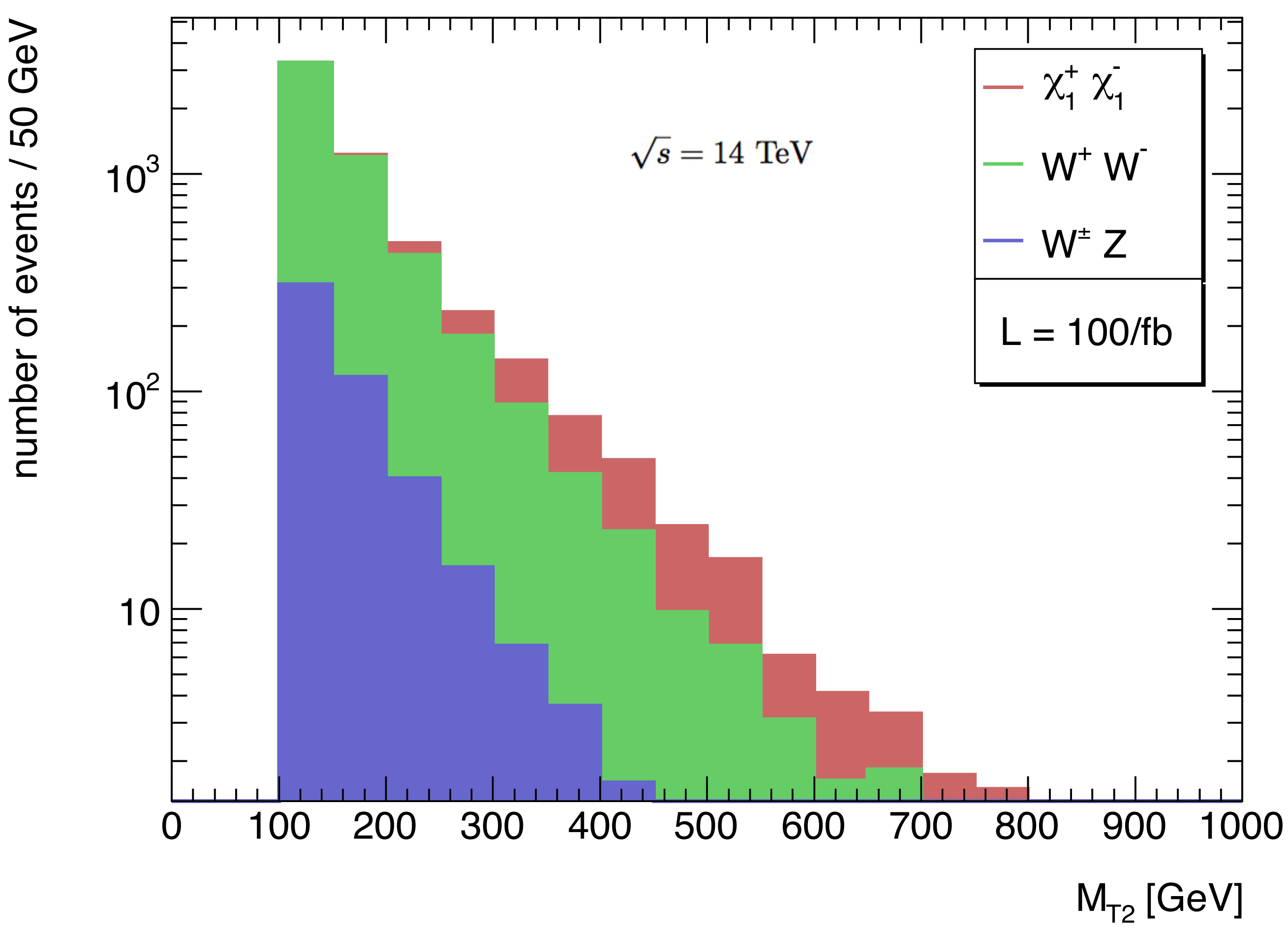
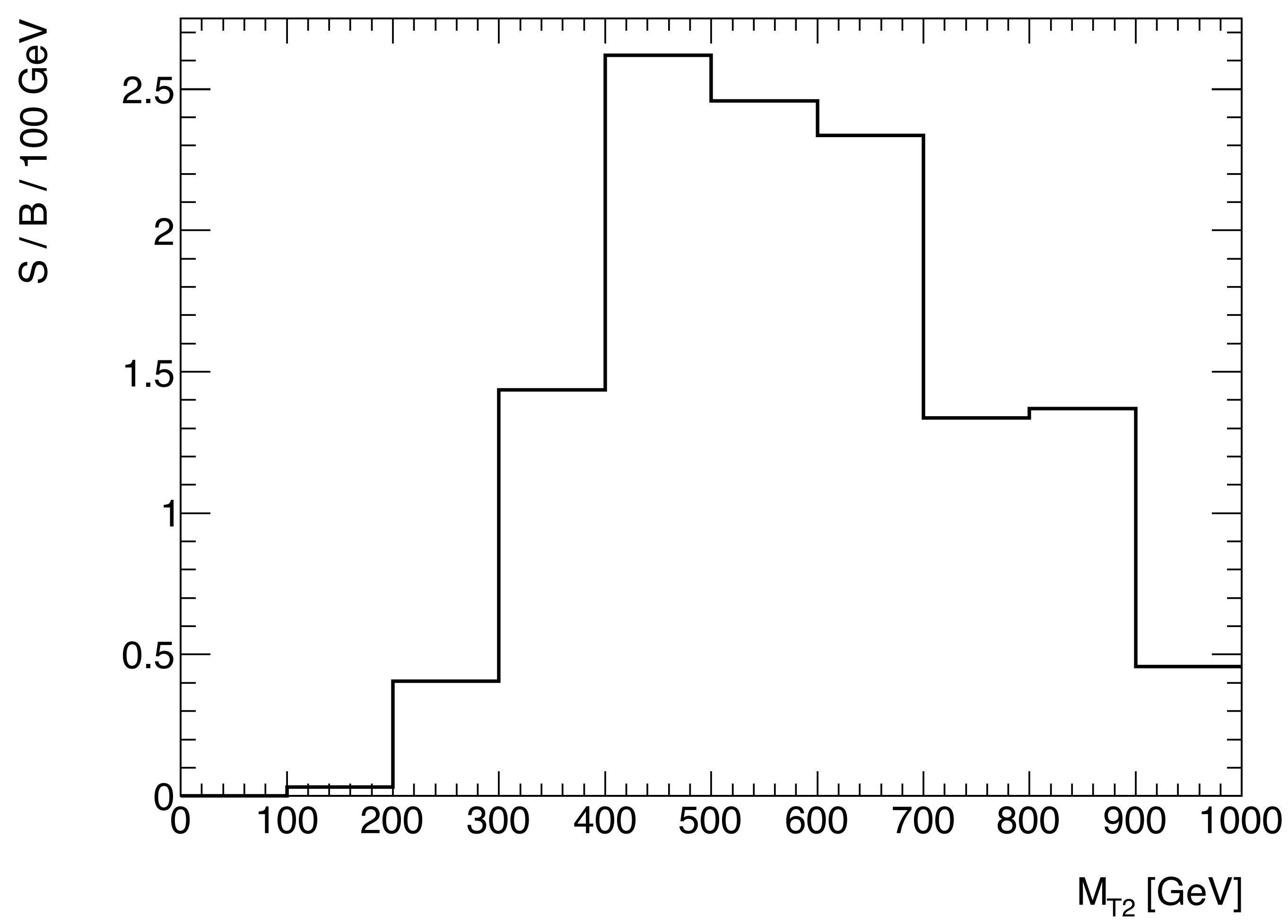
Signal: 2 leptons with opposite sign and uncorrelated flavor

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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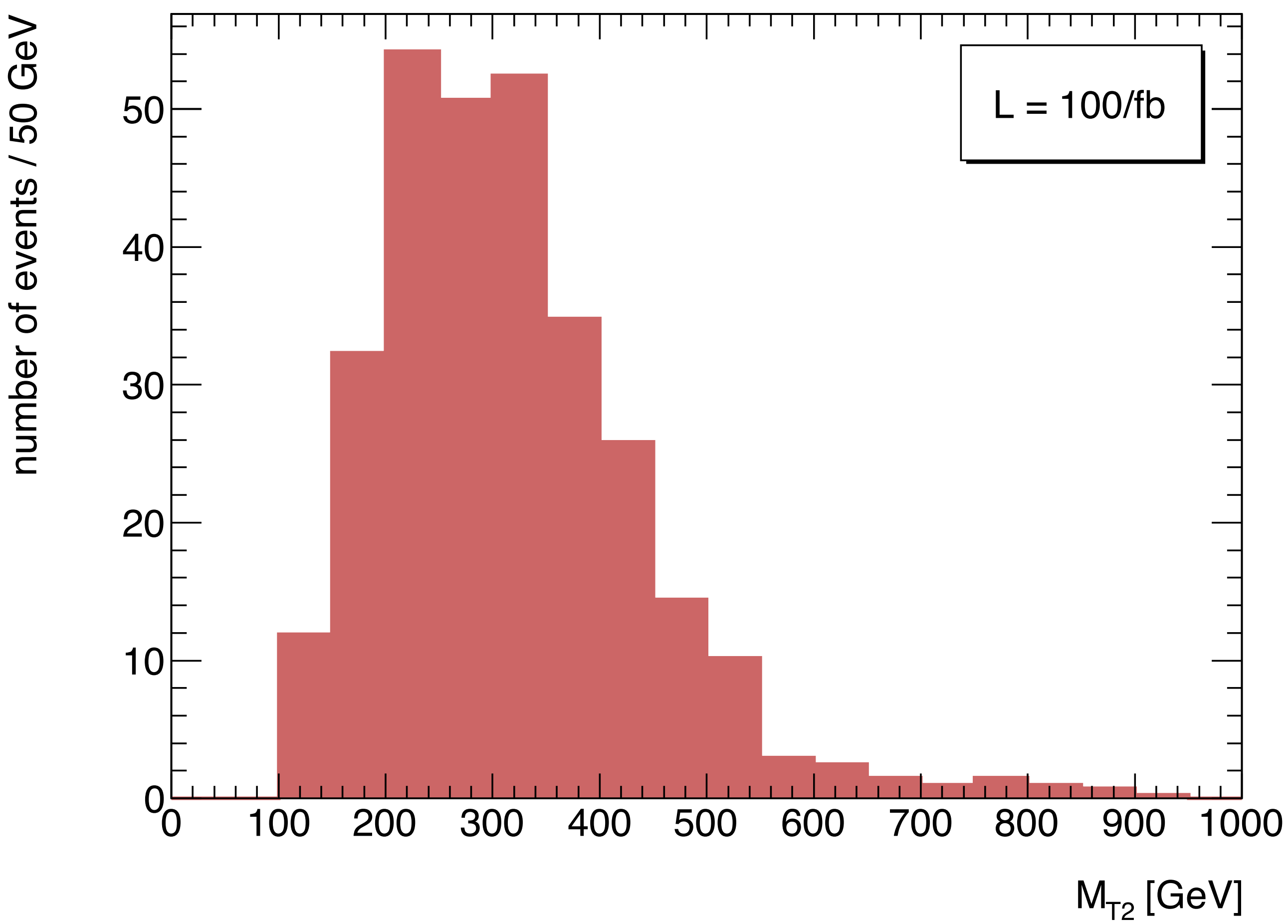
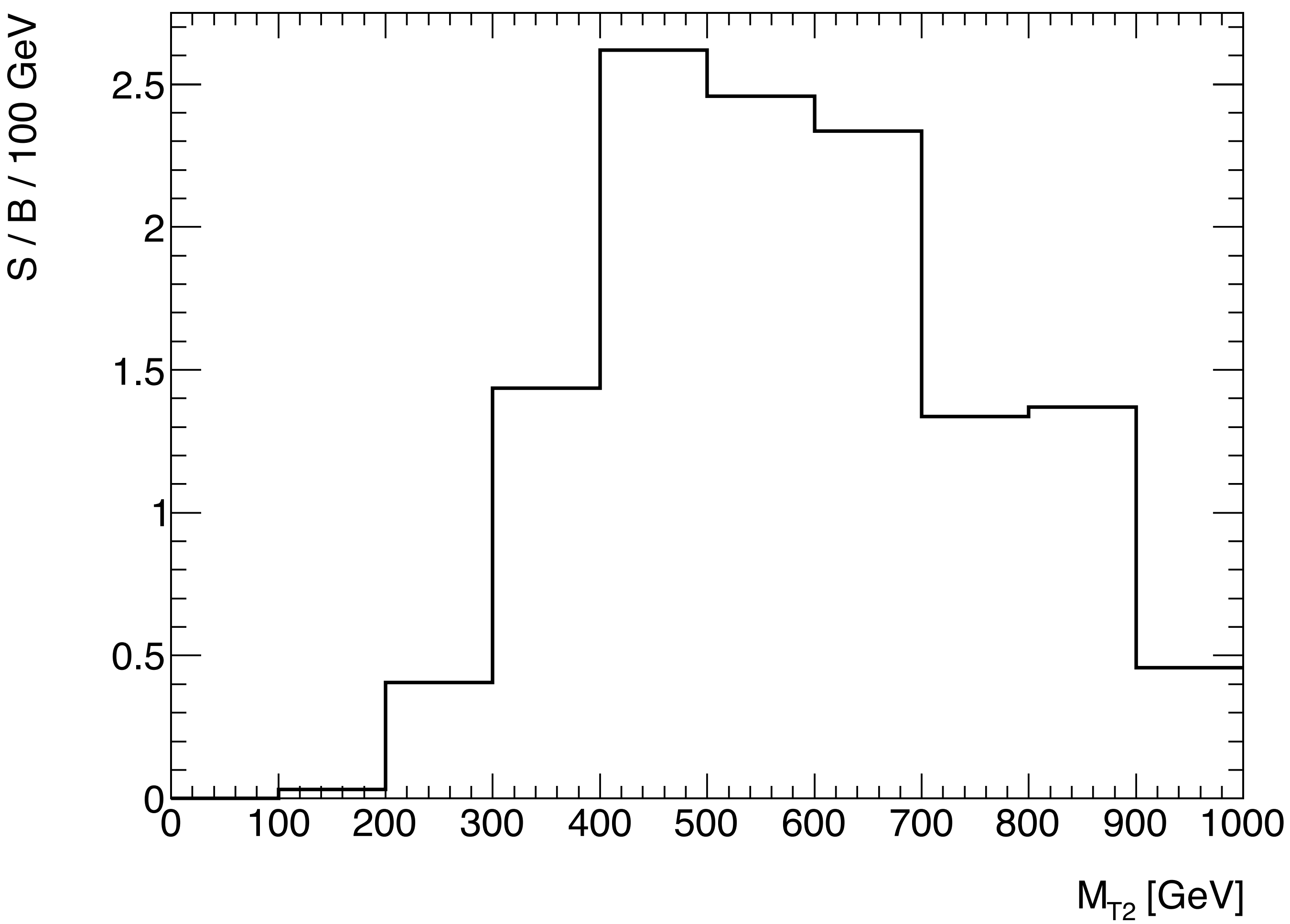




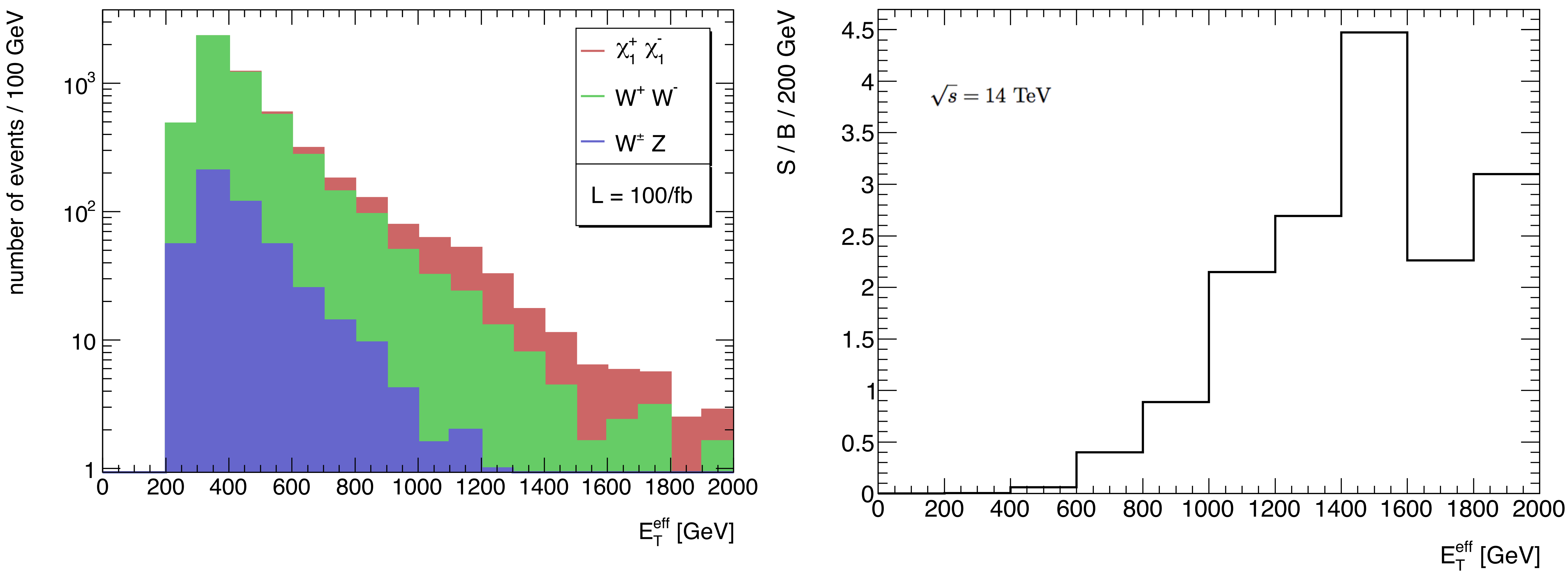
Chargino production

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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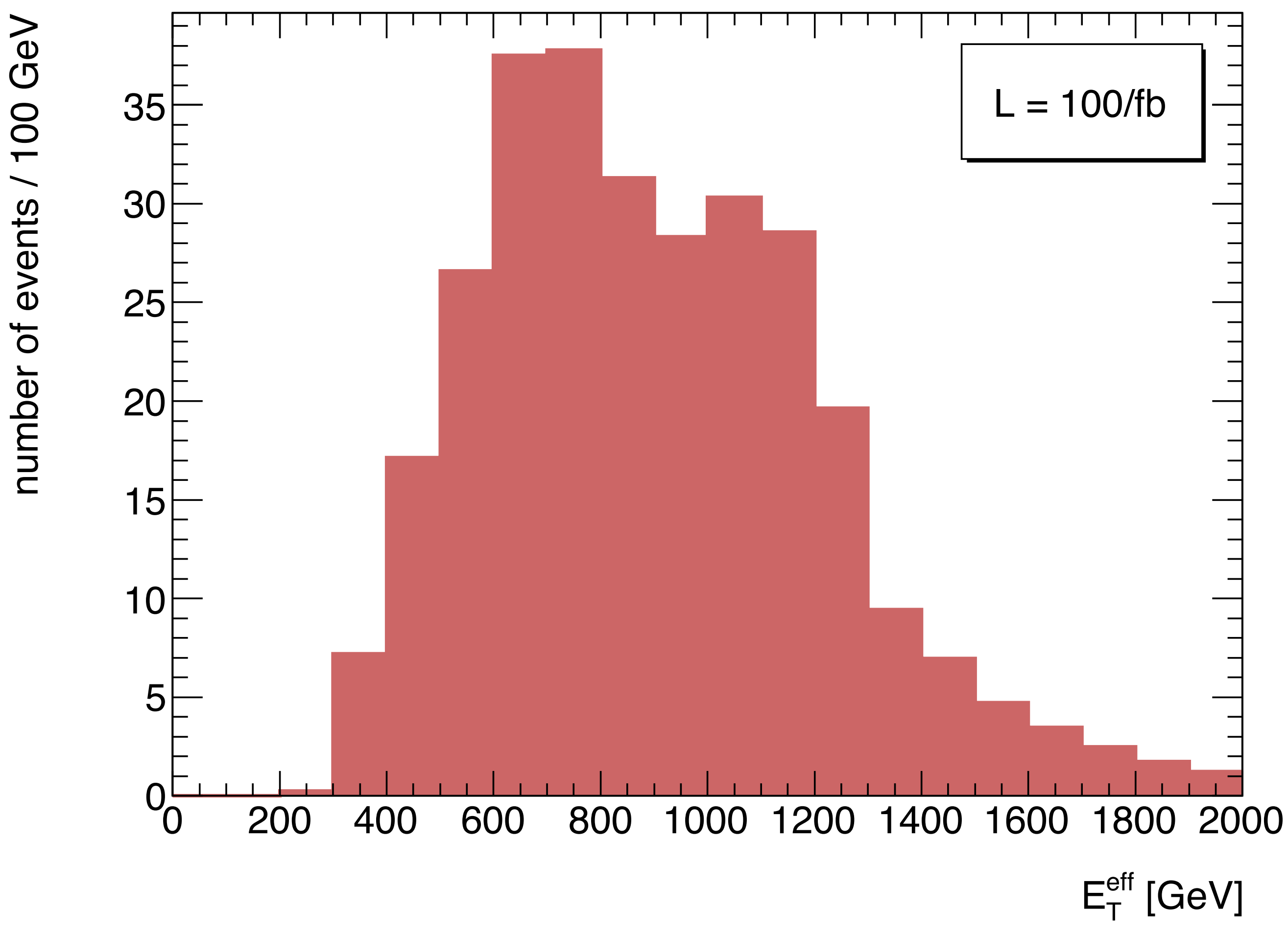
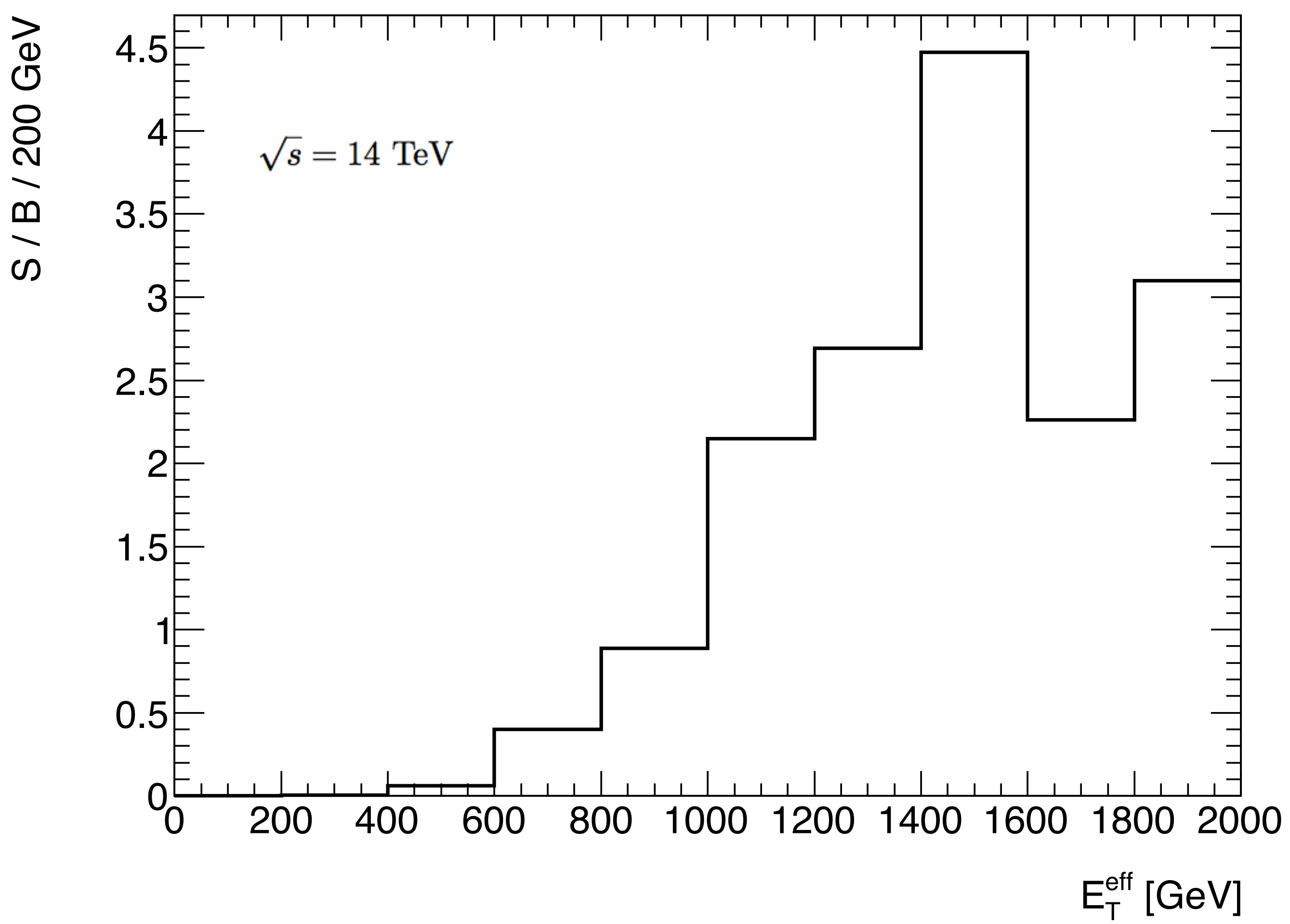
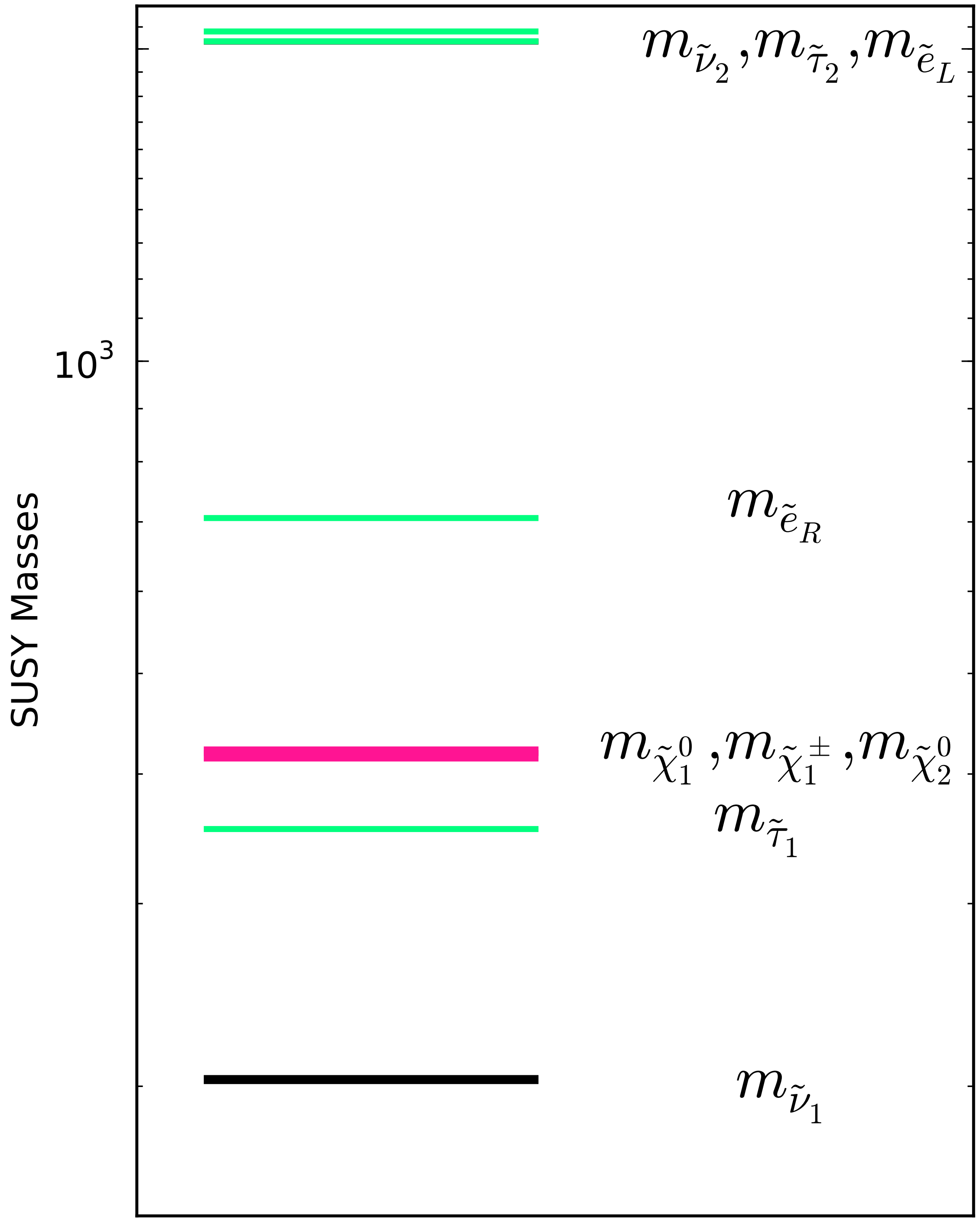




Gray points pattern

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

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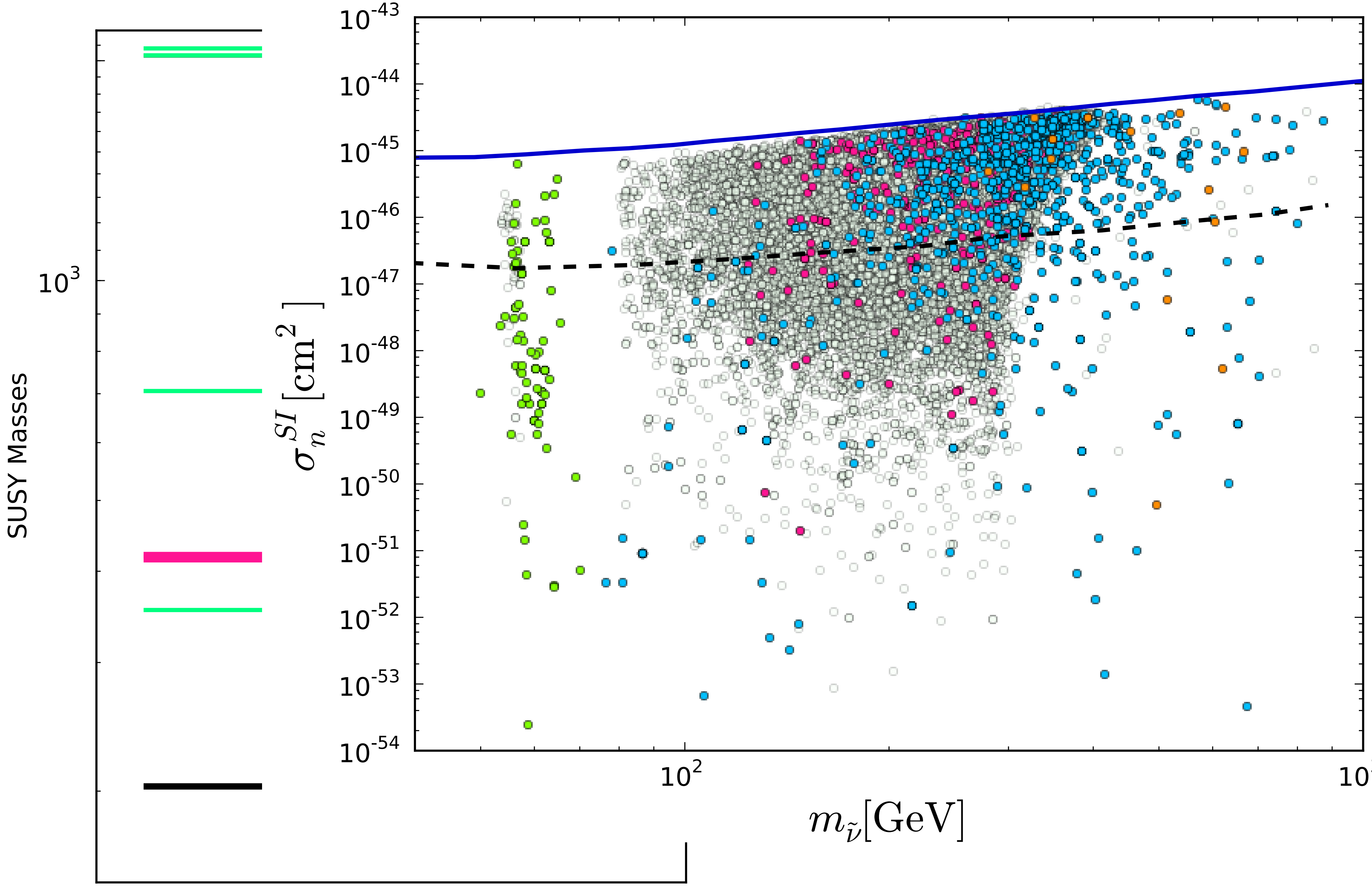

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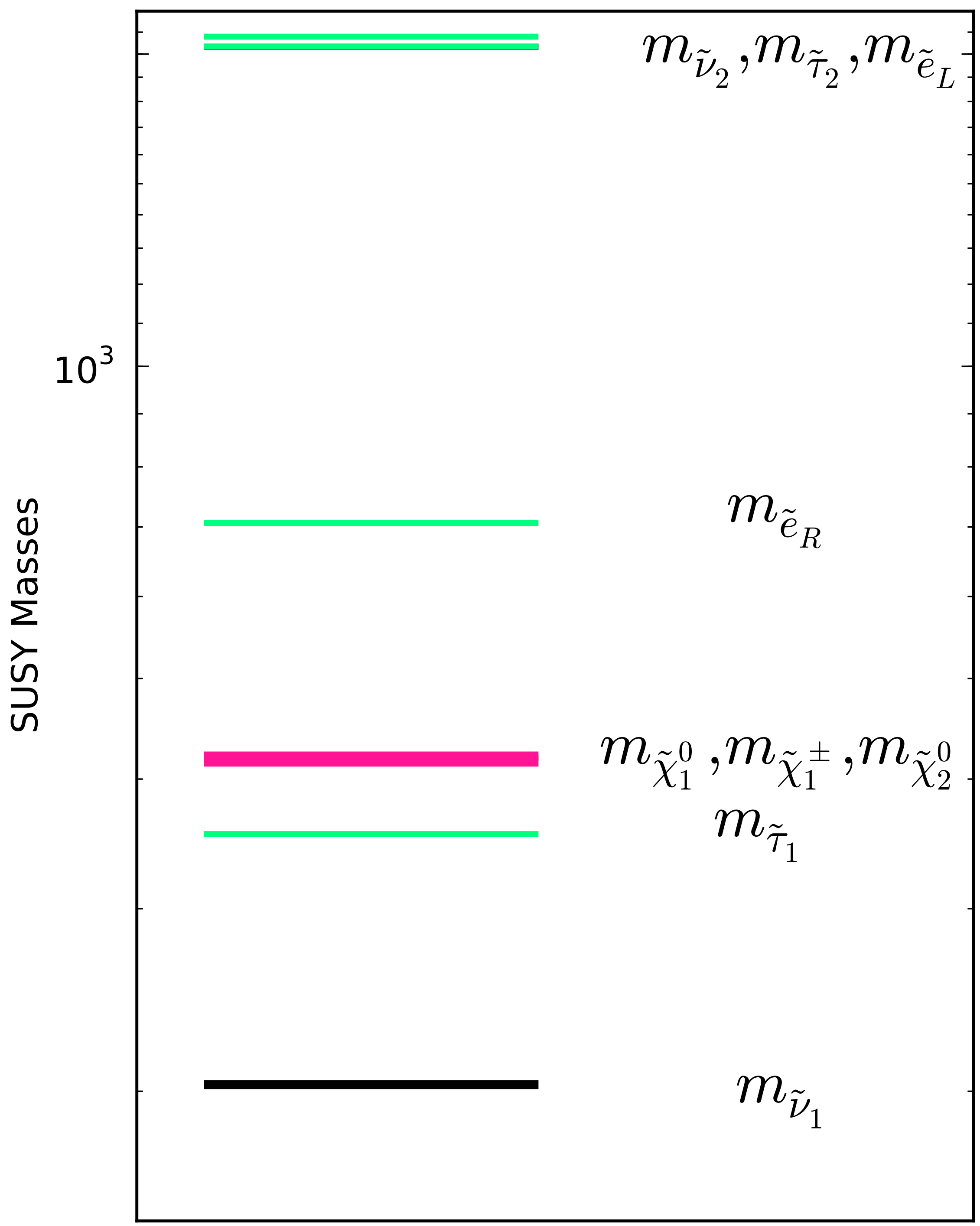

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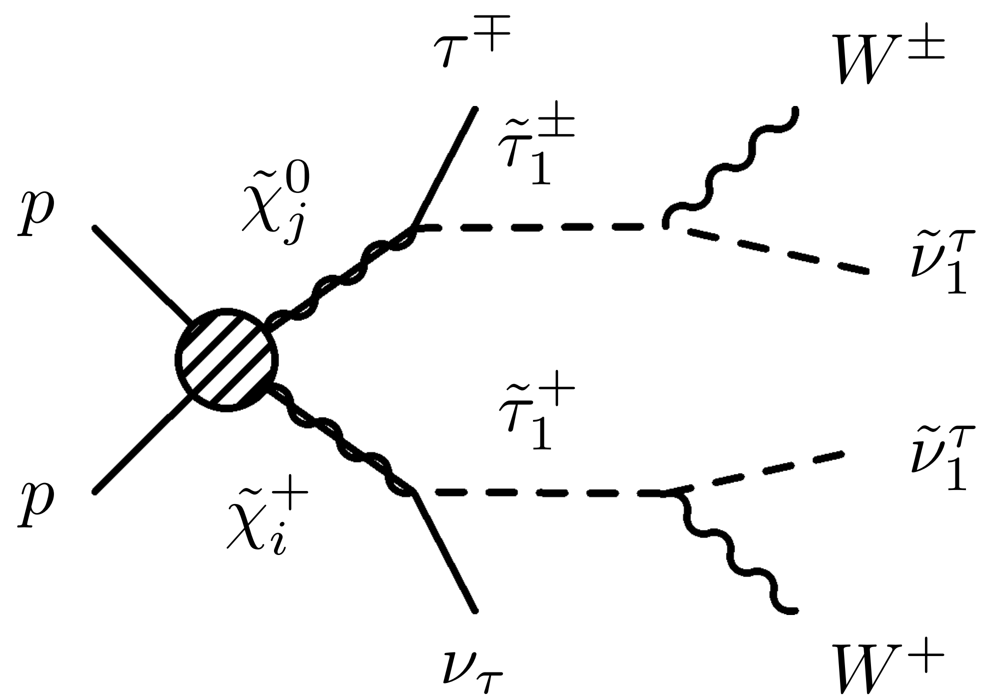
2 Same sign leptons, uncorrelated flavor



- 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%
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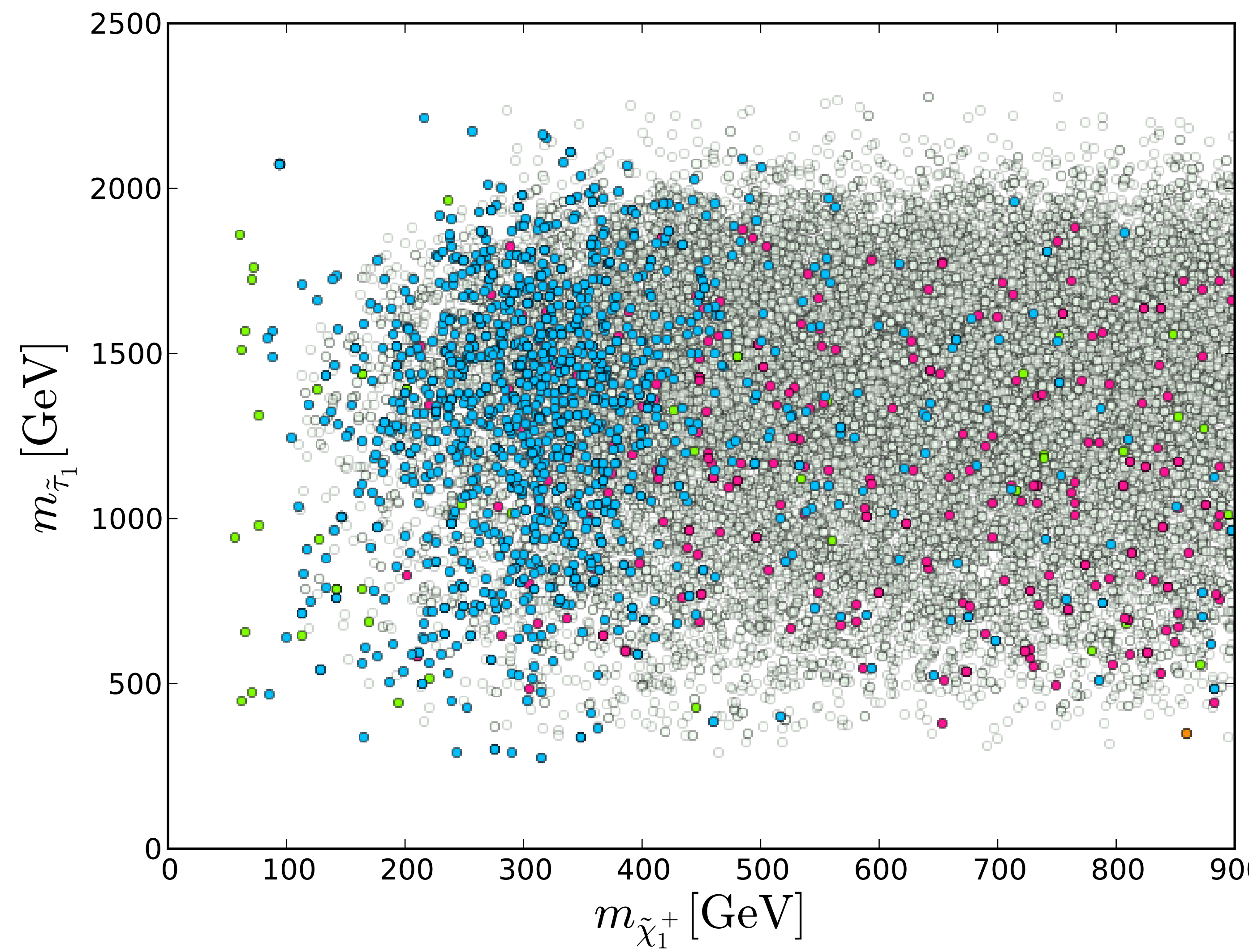
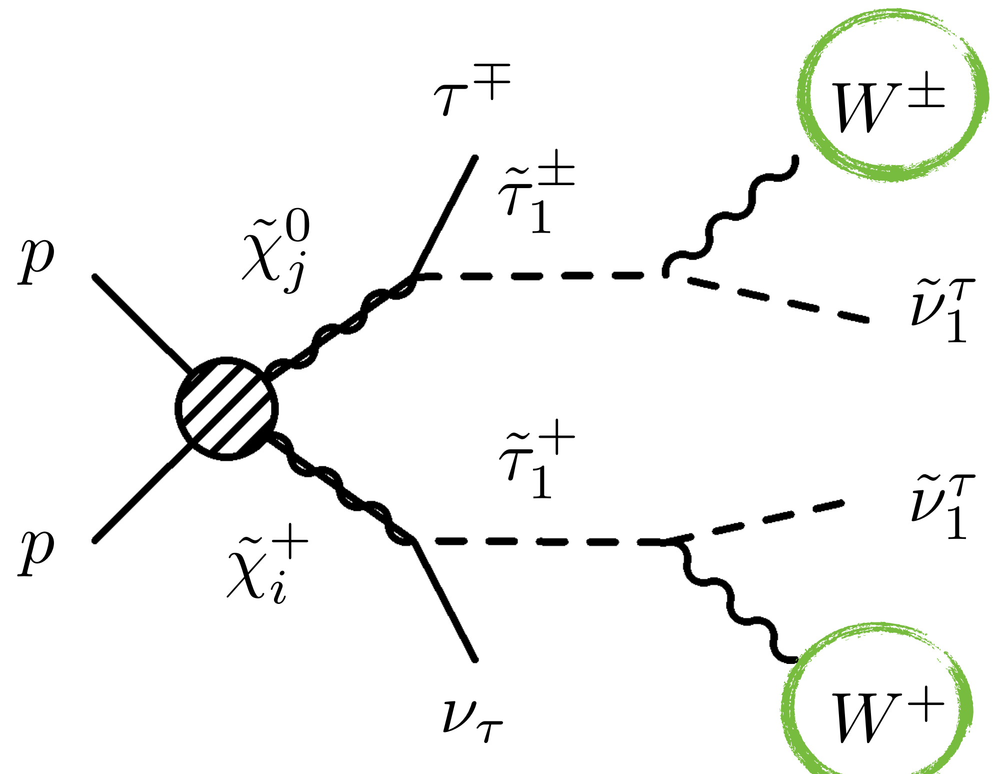


2 Same sign leptons, uncorrelated flavor



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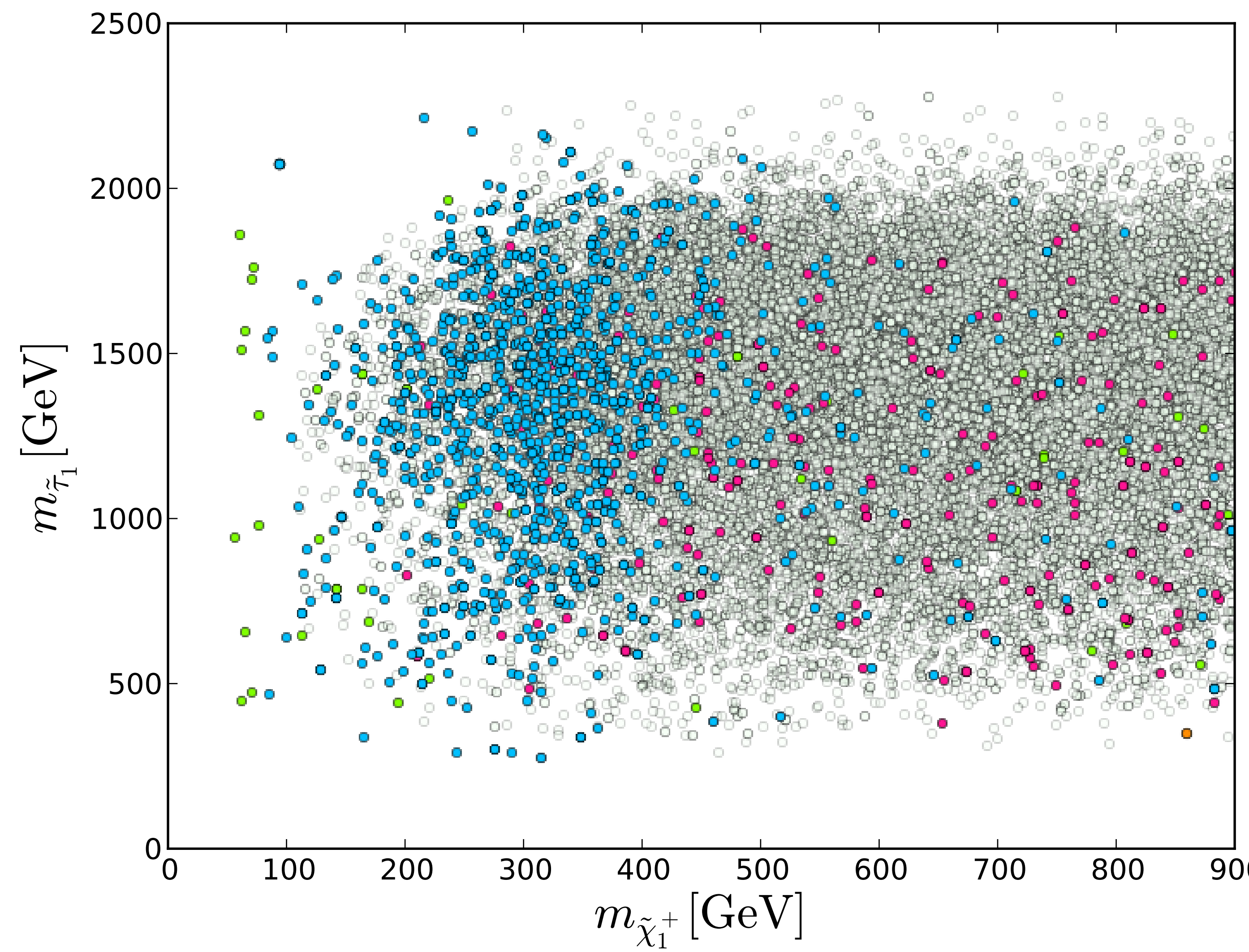

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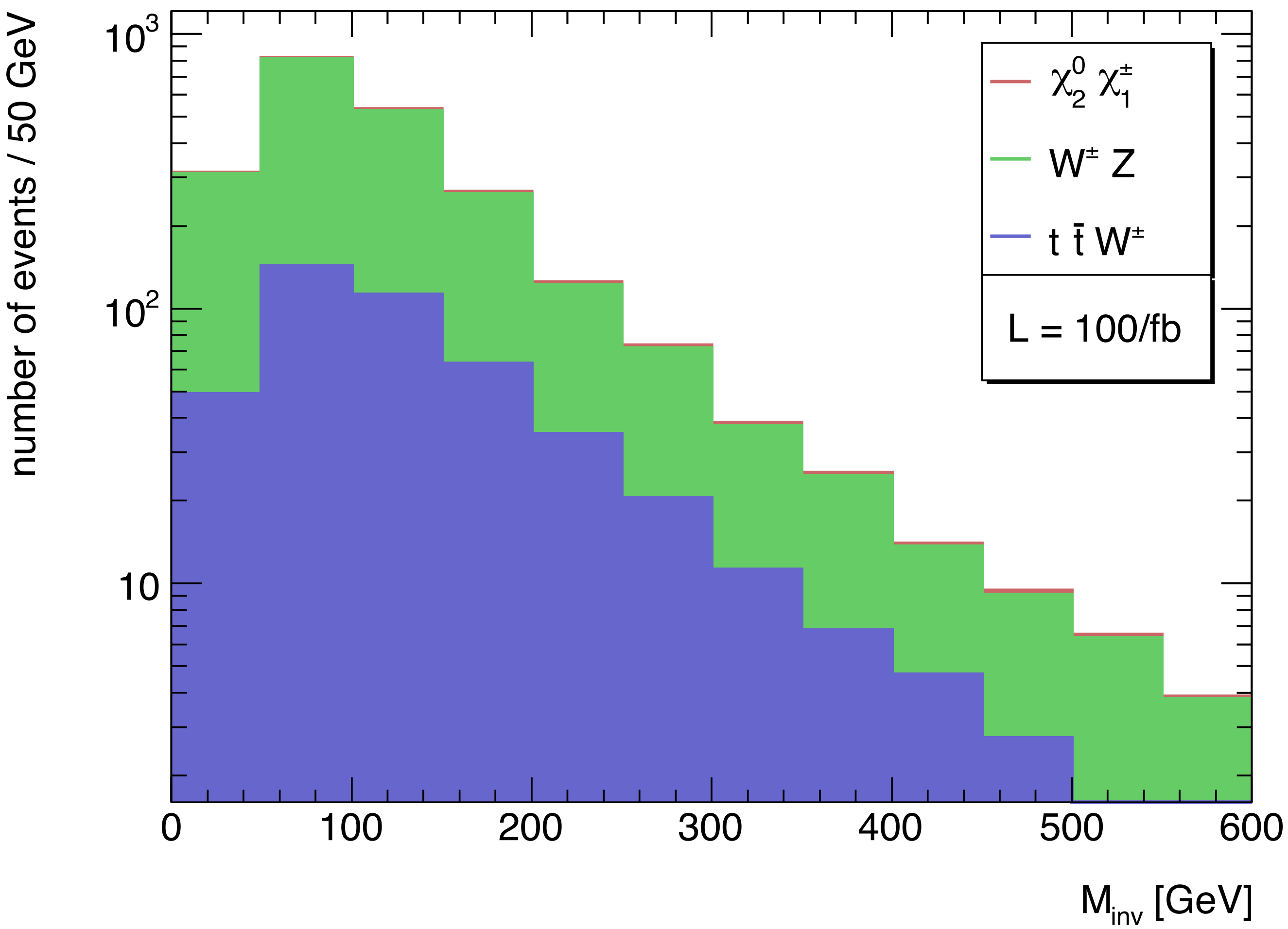
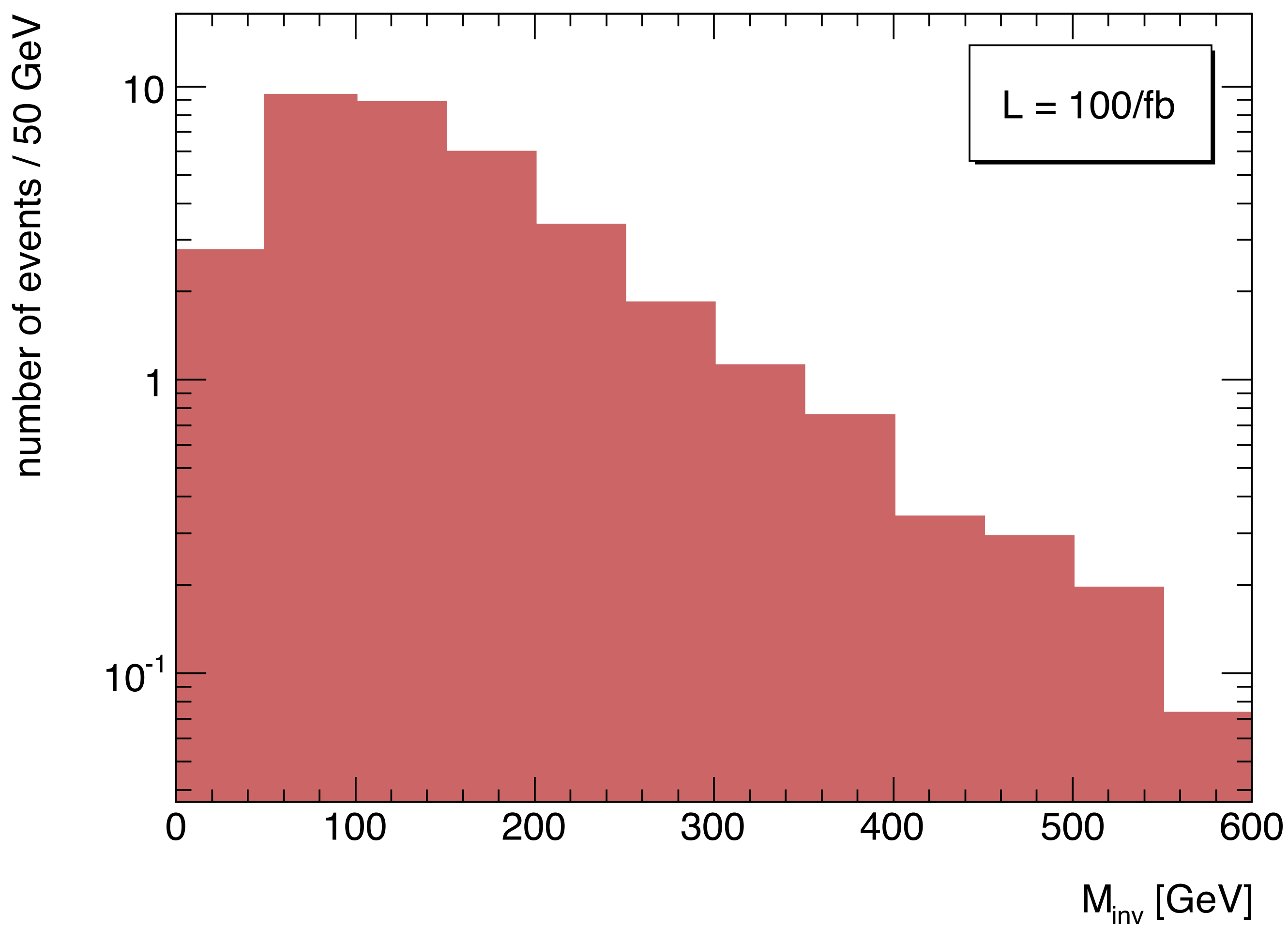
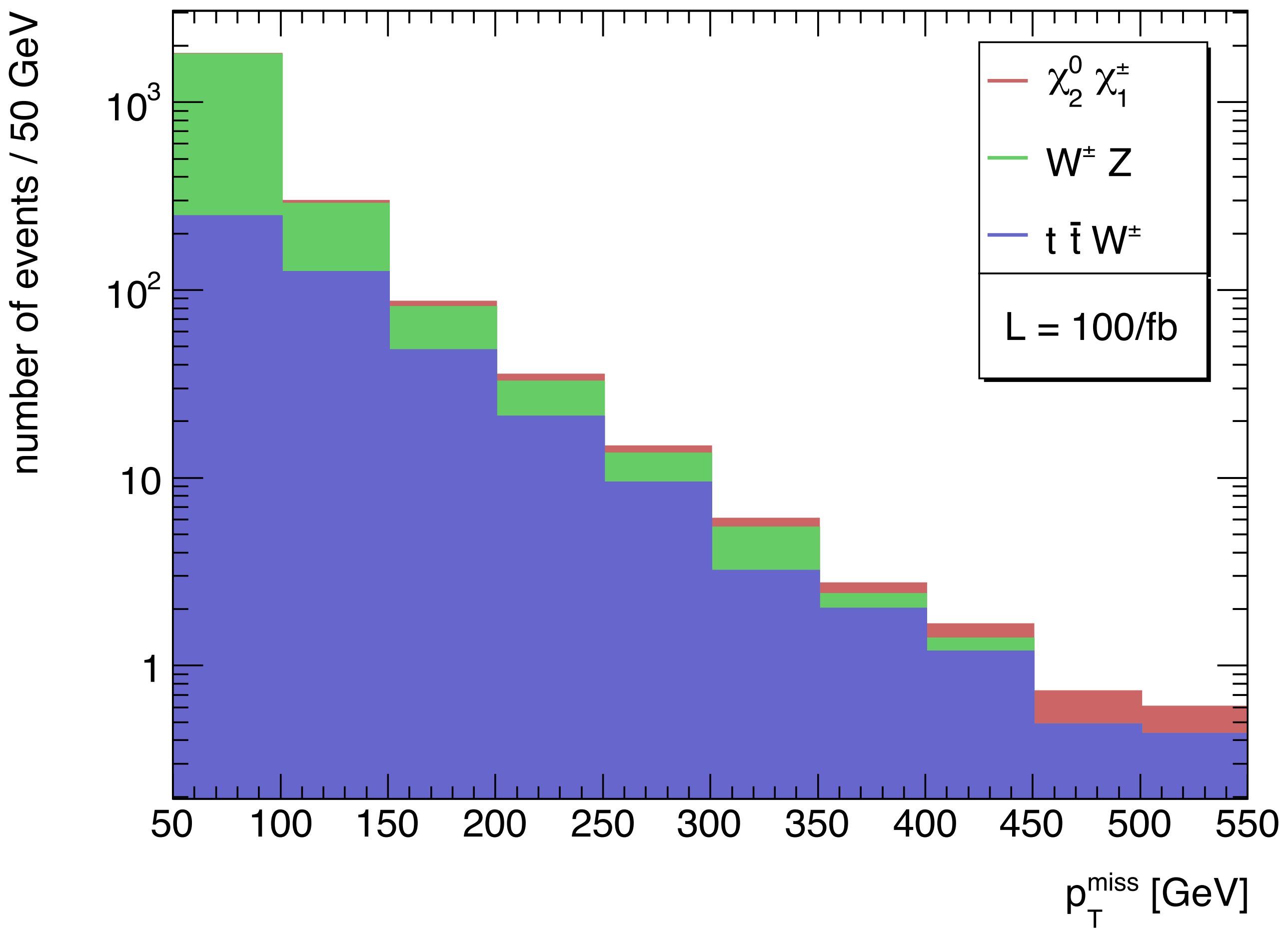
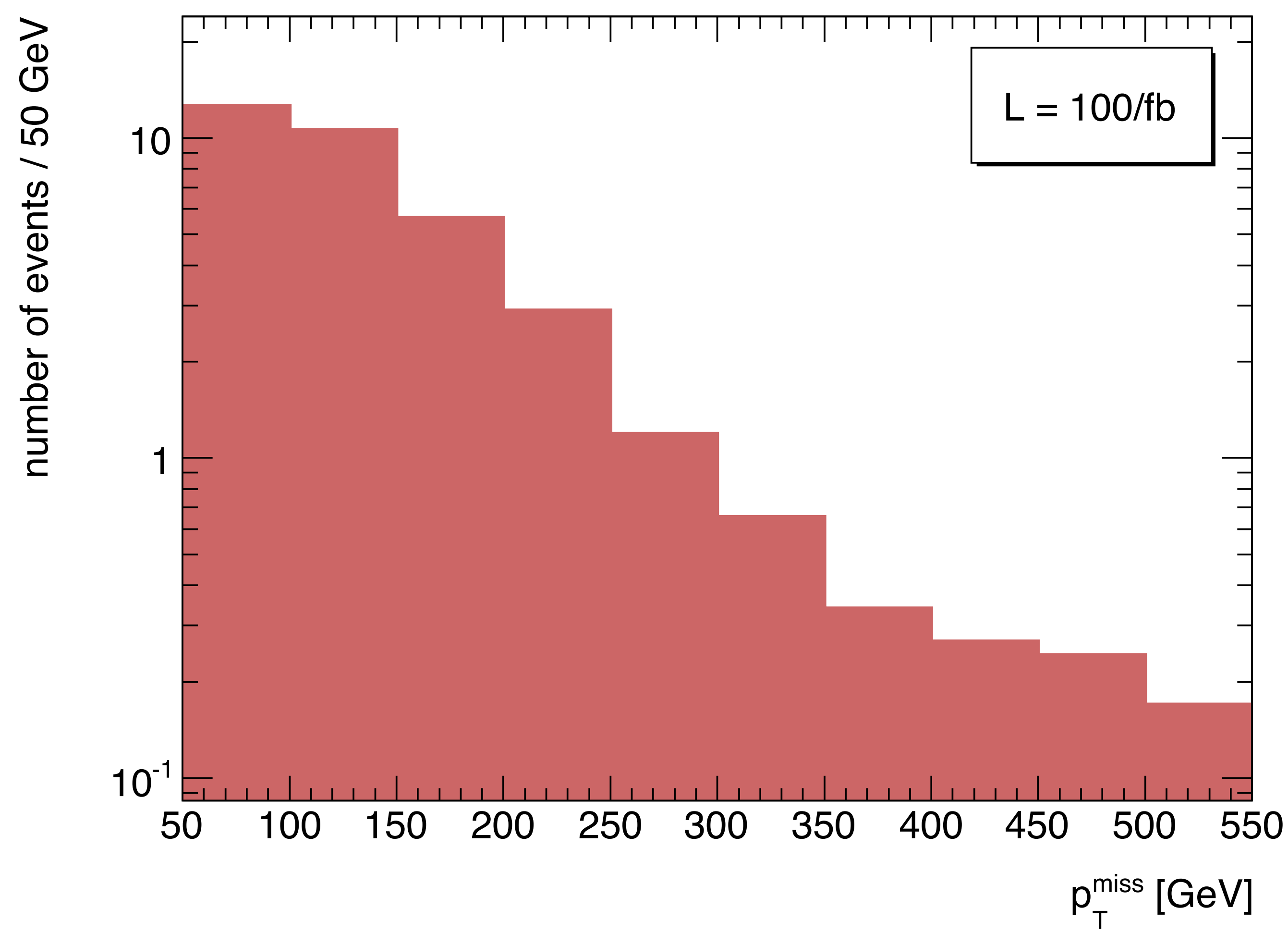




The signal is hidden at low p_T and M_{inv} values, where the background is maximal

2 Same sign leptons, uncorrelated flavor





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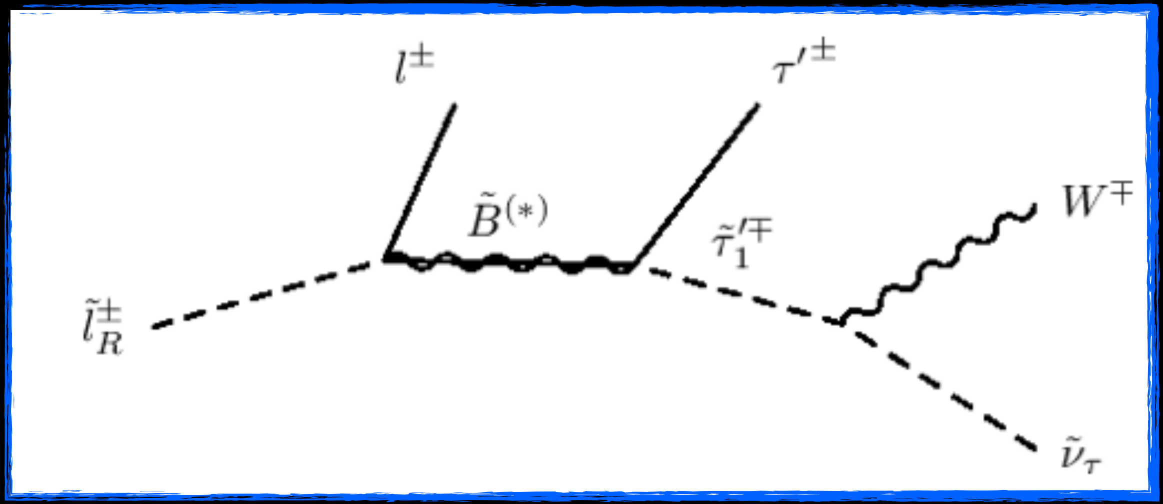
Conclusions

· In the LHC era it is important to consider alternative scenarios to neutralino DM for searches and constraints

· Dark matter in connection with neutrino masses can provide signatures into leptons which are different from the standard MSSM



· Sneutrino dark matter can be tested by future XENON1T detector, however it can hide as well below this bound ... those points might be tested by next LHC = complementarity of DM searches

Prospects and future developments

- For sneutrino dark matter in particular:

  (a) extend the analysis to seesaw models, in particular to inverse seesaw

  (b) relevant constraints from flavor physics

  (c) sneutrino can be inelastic dark matter and hence can develop a whole pheno different from standard WIMP (asymmetric, connected with leptogenesis)

CA et al. PRL 2008; CA, N.Sahu, R.Mohapatra Phys Lett B 2013.

- Tools developing for model testing:

  (d) Several tools for theoretical predictions which are more or less easily combined

  (e) Likelihood to confront the model with experimental data is a challenging part of model testing business (if possible it is a better way to go than to use the x% CL)

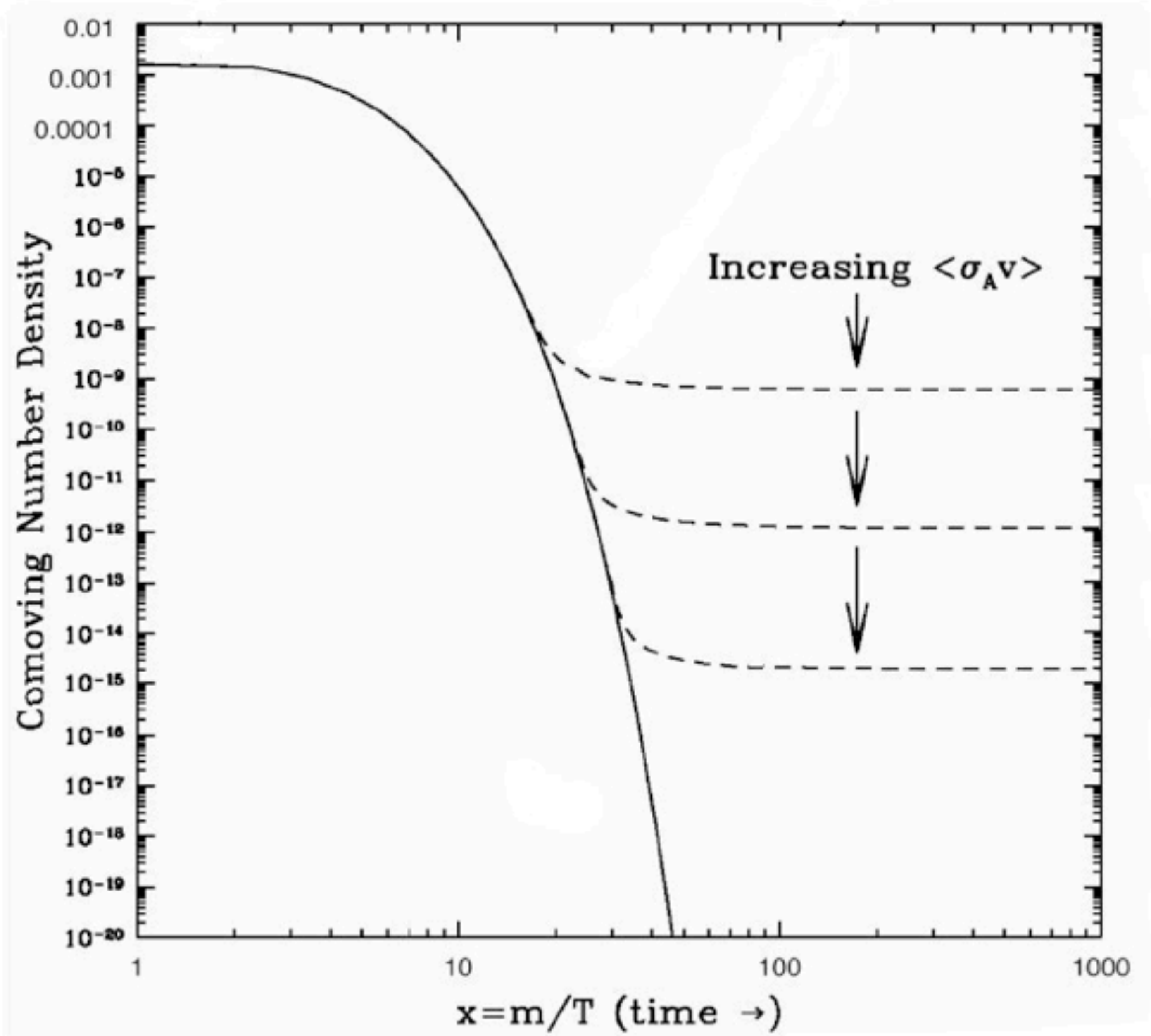
  (f) We are doing effort for direct detection experiments to have likelihood codes (i.e. XENON100 or IceCube) that include uncertainties

CA, Phys Rev D 2013; CA, J.Hamann, R.Trotta, Y.Wong JCAP 2011, JCAP 2012.

Back up slides

WIMPs: weakly interacting massive particles

Lee & Weinberg '77, Gunn et al. '78, Steigman et al. '78, Kolb & Turner '81, Ellis et al. '84, Scherrer & Turner '85, Griest & Seckel '91



$$\chi + \overline{\chi} \leftrightarrow \mathrm{SM} + \overline{\mathrm{SM}}$$

Freeze-out (chemical decoupling):

$$\Gamma = n < \sigma_A v > \sim \mathrm{H}$$

$$\Omega_{\mathrm{DM}} \mathrm{h}^2 \sim 0.3 \left(\frac{10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{< \sigma_A v >} \right)$$

$$< \sigma_A v > \sim \frac{g^2}{m_\chi^2} \sim \frac{0.01^2}{(100\ \mathrm{GeV})^2} \sim 8 \times 10^{-25} \mathrm{cm}^3 \mathrm{s}^{-1}$$

GeV ⟶ TeV scale DM candidates with weak scale interaction: e.g. from SUSY

Details on 2 SSDF leptons

- Benchmark point

$$m_{\tilde{\chi}_1^\pm} = 419.3 \text{ GeV}, \quad m_{\tilde{\chi}_2^0} = 421.2 \text{ GeV}$$

$$m_{\tilde{\nu}_1^\tau} = 202.6 \text{ GeV}, \quad \sin\theta_{\tilde{\nu}} = -0.031$$

$$m_{\tilde{\tau}_1} = 354.2 \text{ GeV}, \quad \sin\theta_{\tilde{\tau}} = -0.00013$$

- Backgrounds

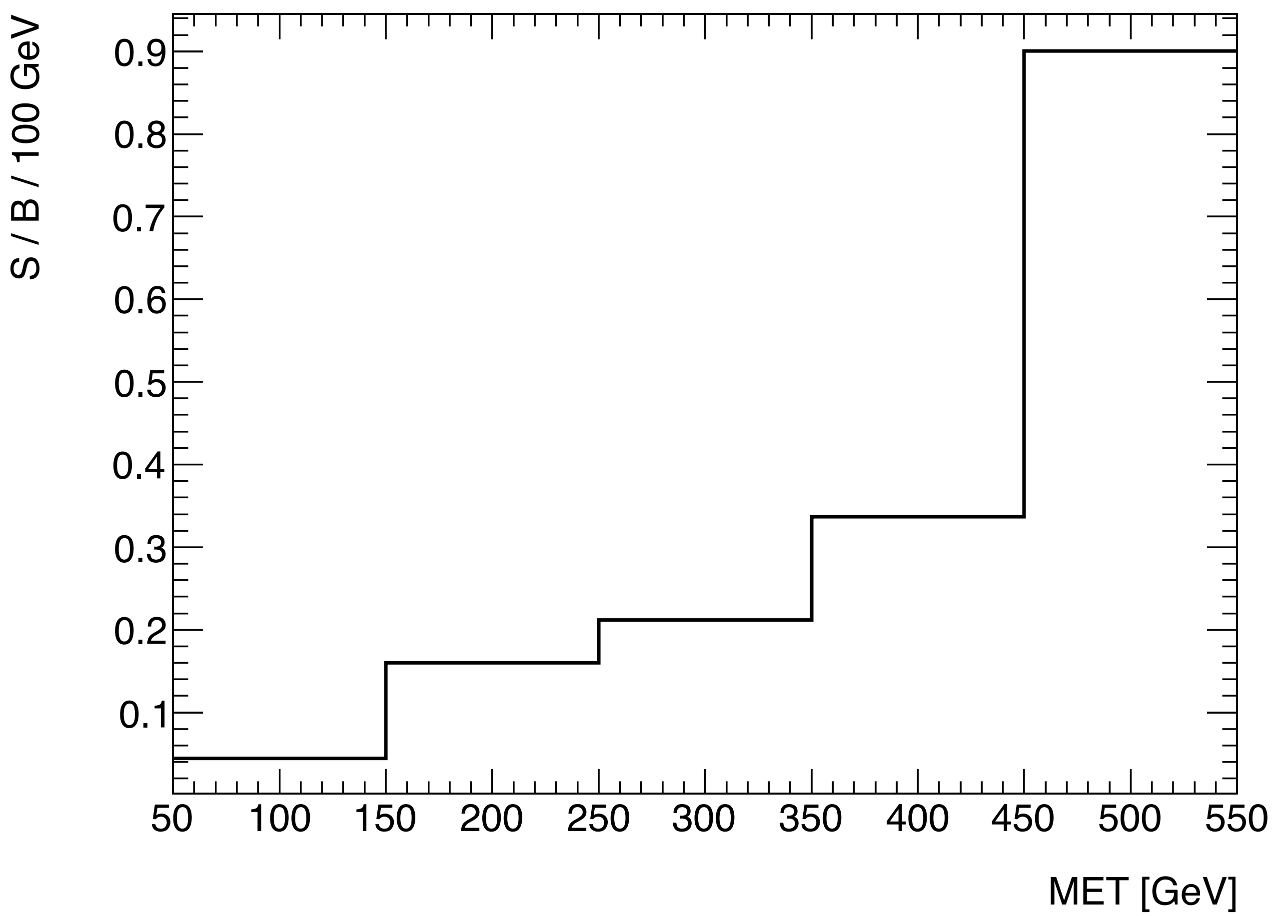
(i) $WZ \to W\ l^+\ l^-$ with MG5 and Pythia 8

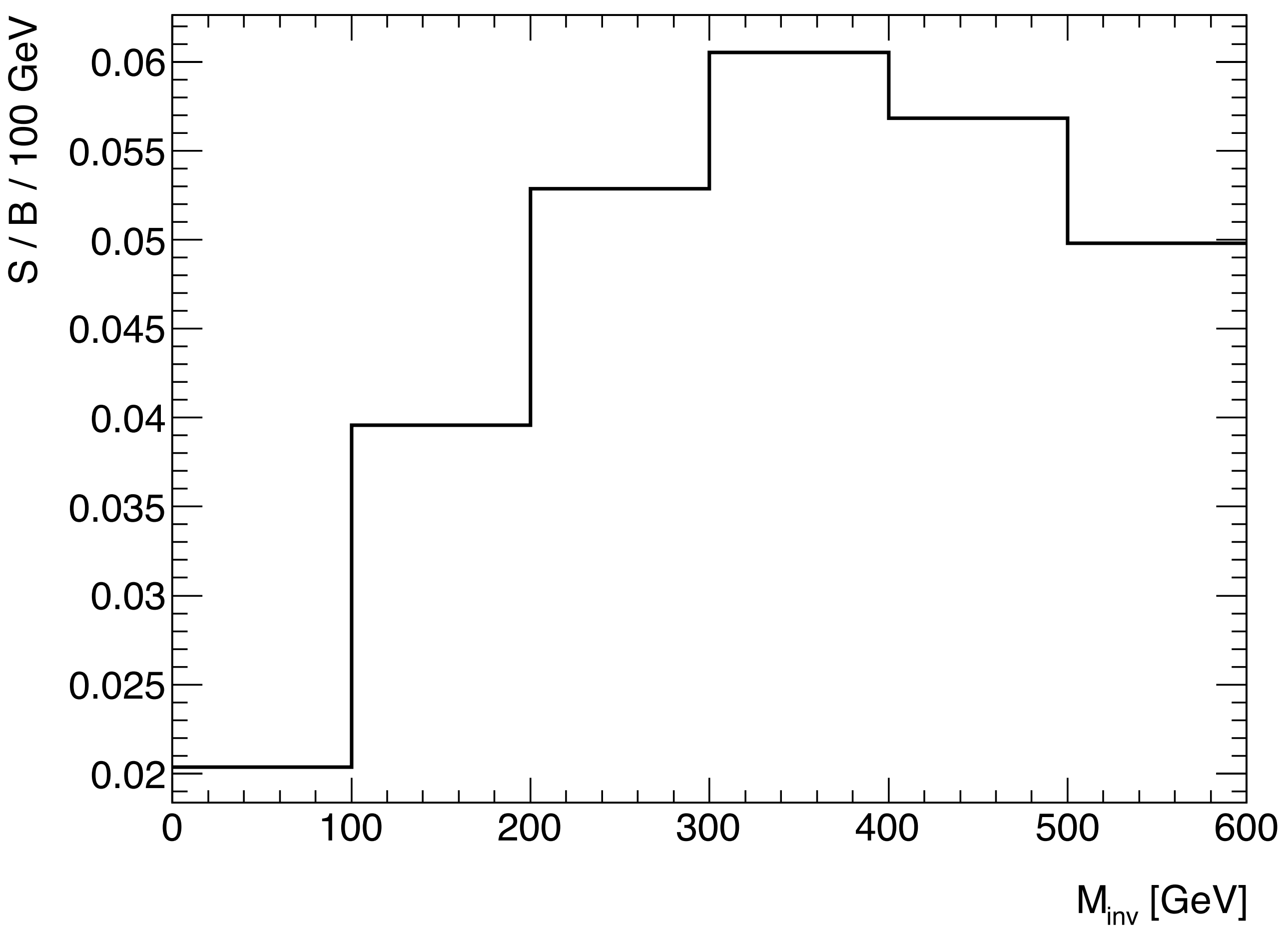
(ii) $t\bar{t}W$ with MG5 and Pythia 6

- Cuts for the analysis:

1. Two same sign, different flavor leptons with $p_T > 20$ GeV and $\eta < 2.5$
2. At least one lepton with $p_T > 25$ GeV
3. $p_T^{\text{miss}} > 50$ GeV

Details on 2 SSDF leptons





Details on 3 uncorrelated leptons

- Benchmark point

$$m_{\tilde{\chi}_1^\pm} = 781.1 \text{ GeV}, \quad m_{\tilde{\chi}_2^0} = 780.02 \text{ GeV}$$
$$m_{\tilde{\nu}_2^{l(\tau)}} = 671.1(647.3) \text{ GeV}, \quad \sin\theta_{\tilde{\nu}^{l(\tau)}} = 0.007$$
$$m_{\tilde{\tau}_1} = 240.3 \text{ GeV}, \quad \sin\theta_{\tilde{\tau}} = -0.09$$

- Backgrounds

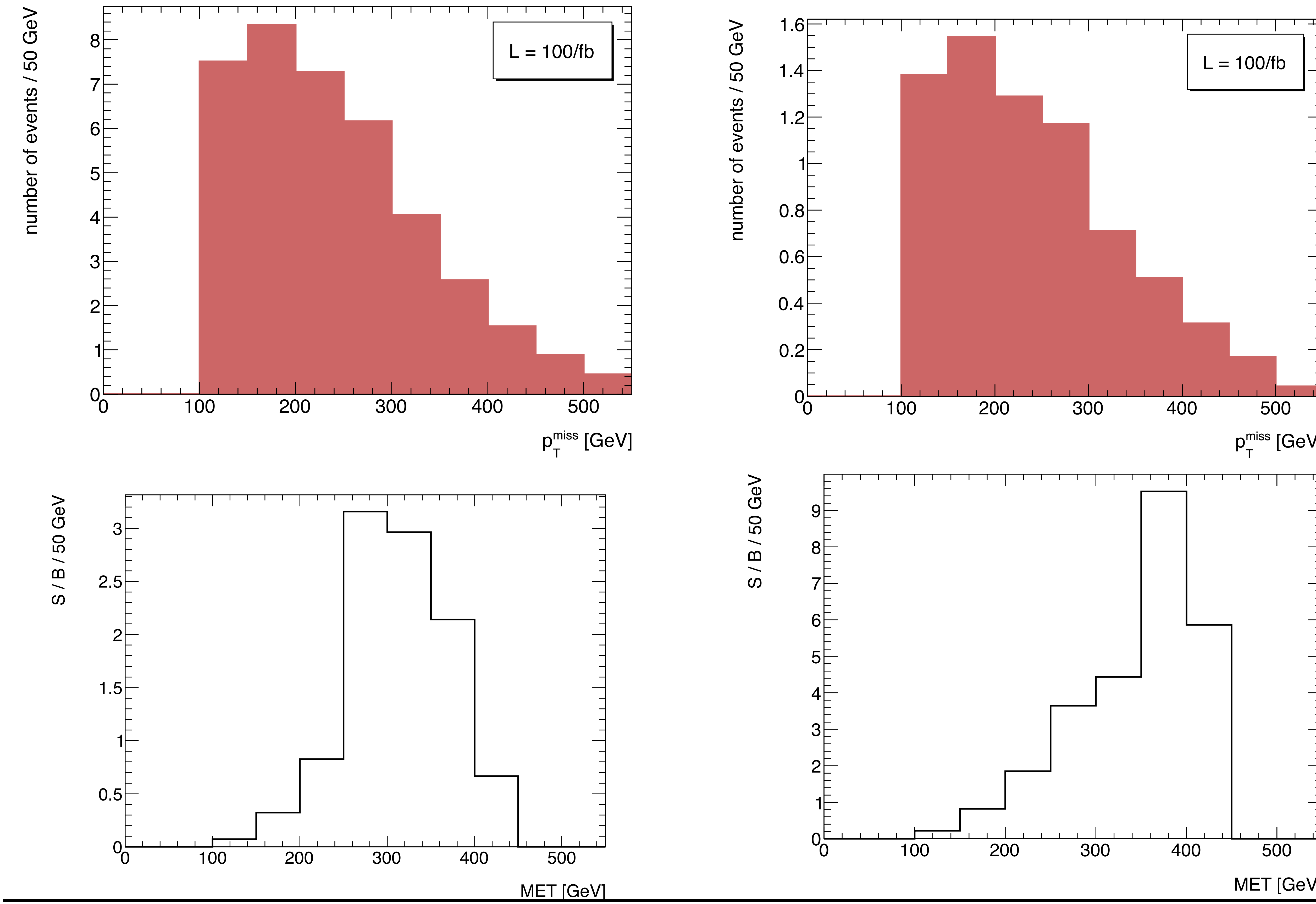
(i) $WZ \to W\ l^+\ l^-$ with MG5 and Pythia 8

(ii) $t\bar{t}W$ with MG5 and Pythia 6

- Cuts for the analysis:

1. Three leptons with $p_T > 20$ GeV and $\eta < 2.5$
2. At least one lepton with $p_T > 25$ GeV
3. $E_T^{\text{miss}} > 100$ GeV
4. Events with opposite sign same flavor (OSSF) are forbidden or Z veto

Details on 3 uncorrelated leptons



Details on analysis of long-lived staus

- Benchmark point

$$m_{\tilde{\tau}_1^-} = 666.3\,\text{GeV}\,, \quad \sin\theta_{\tilde{\tau}} = 0.99$$

$$m_{\tilde{\nu}} = 665.5\,\text{GeV}\,, \quad \sin\theta_{\tilde{\nu}} = -0.029$$

$$\Gamma_{\tilde{\tau}} = 7.33 \times 10^{-18}\,\text{GeV}\,, \quad \tau_{\tilde{\tau}} = 8.98 \times 10^{-8}\,\text{s}$$

$$\sigma = 8.23 \times 10^{-5}\ \text{pb}$$

- Backgrounds

(i) for particle leaving the detector volume: high p_T muons with mis-measured velocity (data driven)

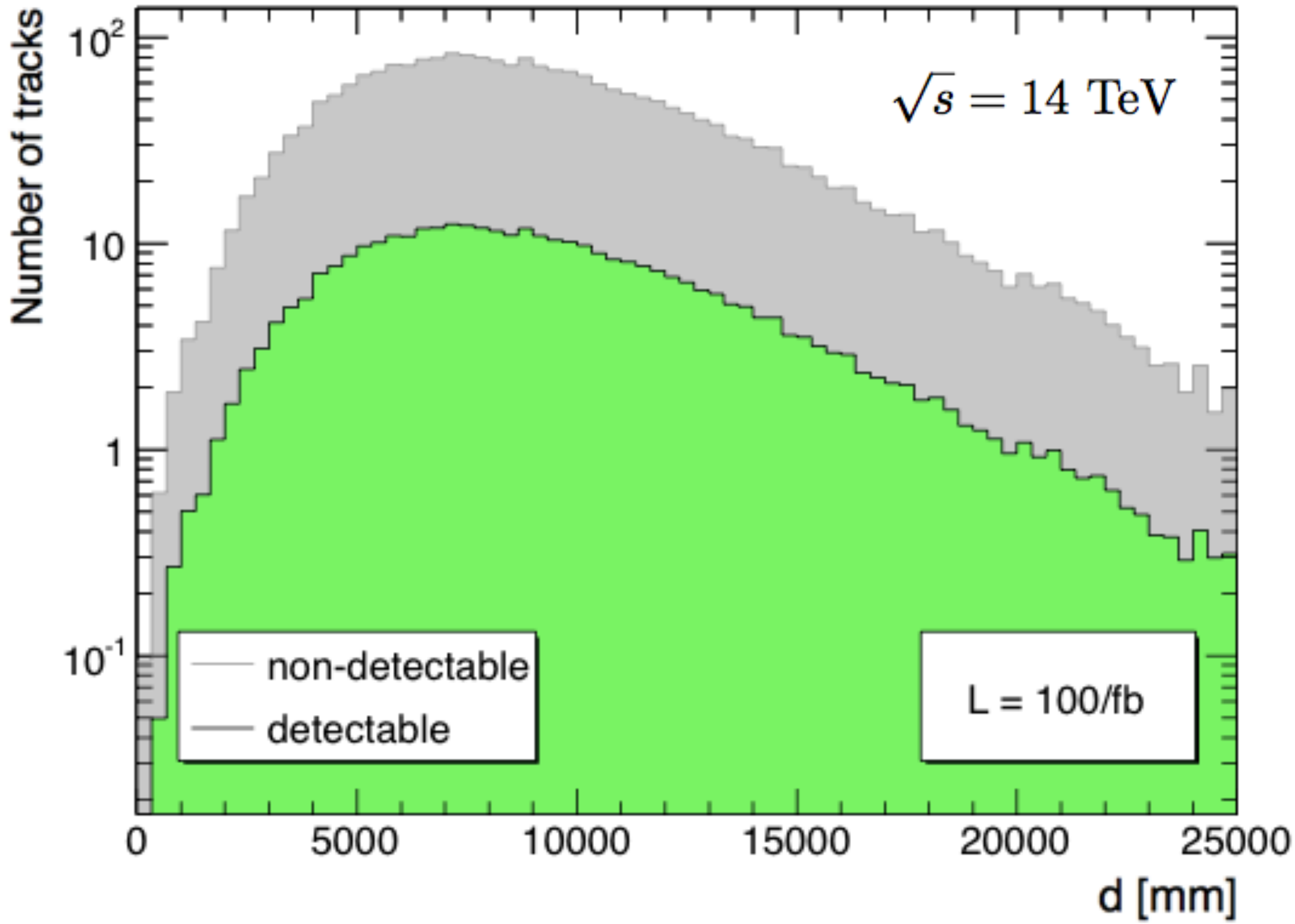
(ii) in the hadronic calorimeter: hadrons or low p_T changed particles, whose p_T is badly measured

- Cuts for the analysis:

1. No other tracks with $p_T > 0.5\ \text{GeV}$ within a cone of radius $\Delta R = 0.05$
2. Should travel at least 514 mm to decay into the hadronic calorimeter

Long-lives staus I

- Staus produced in pair directly
- Assumed observation of only 1 charged track from the hadronic calorimeter to escaping charged particles (ATLAS efficiency $\epsilon = 0.15$)



Detail on chargino production

- Benchmark point

$$m_{\tilde{\chi}_1^\pm} = 440.8\ \text{GeV},\ m_{\tilde{\nu}_1^{l(\tau)}} = 125.6(124.1)\ \text{GeV},\ \sin\theta_{\tilde{\nu}_{l(\tau)}} = 0.038(0.042)$$

- Backgrounds

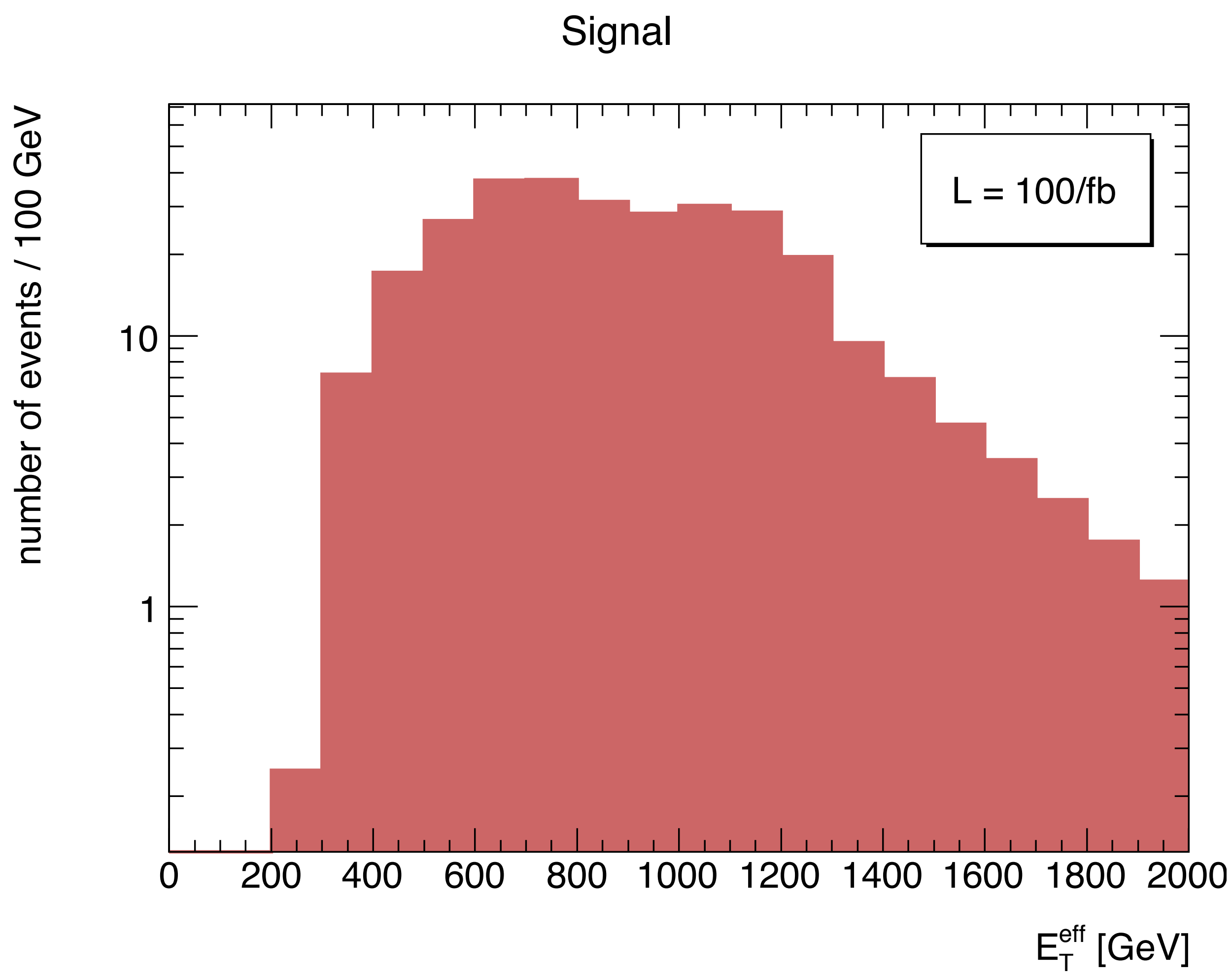
(i) W^+W^- and WZ

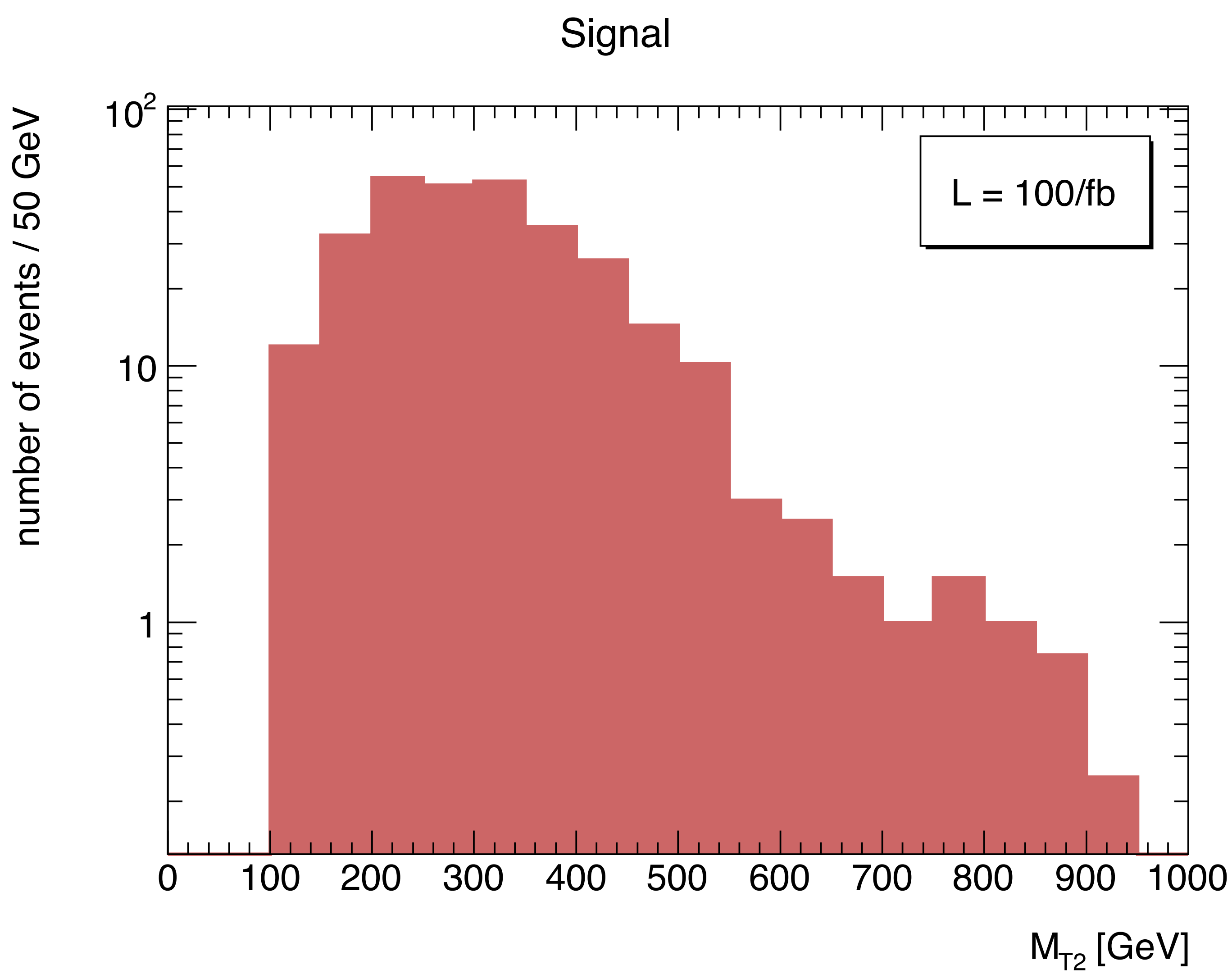
(ii) Computed with MG5 and Pythia 8 at LO (detector simulation delphes)

- Cuts for the analysis:

1. Two opposite sign leptons
2. Z veto $|m_{ll} - m_Z| > 10\ \text{GeV}$
3. Second hardest jet with $p_T < 50\ \text{GeV}$
4. $m_{T2} > 110\ \text{GeV}$
5. $p_T^{\text{miss}} > 40\ \text{GeV}$

Detail on chargino production





Details on MSSM+RN

The inclusion of the right-handed neutrino superfield produces a mixing between left and right-component of the sneutrino

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

$$\sin 2\theta_{\tilde{\nu}} = \sqrt{2} A_{\tilde{\nu}} v \sin\beta / \left(m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1} \right)$$

$$m_D = v_u Y_\nu$$

$$\Delta\Gamma_Z = \sin^4\theta_{\tilde{\nu}} \frac{\Gamma_\nu}{2} \left[1 - \left(\frac{2 m_{\tilde{\nu}_1}}{m_Z} \right)^2 \right]^{3/2} \theta(m_Z - 2\, m_{\tilde{\nu}_1})$$

$$\xi \sigma_n^{SI} = \xi \frac{4\mu_n^2}{\pi} \frac{(Z f_p + (A - Z) f_n)^2}{A^2}$$

Details on RGEs

The inclusion of the right-handed neutrino superfield modifies the RGEs as follows:

$$\frac{\mathrm{d}m_N^2}{\mathrm{d}\ln\mu} = \frac{4}{16\pi^2}\left(A_{\tilde\nu}\right)^2$$

$$\frac{\mathrm{d}m_L^2}{\mathrm{d}\ln\mu} = (\text{MSSM terms}) + \frac{2}{16\pi^2}\left(A_{\tilde\nu}\right)^2$$

$$\frac{\mathrm{d}A_{\tilde\nu}}{\mathrm{d}\ln\mu} = \frac{2}{16\pi^2}\left(-\frac{3}{2}g_2^2 - \frac{3}{10}g_1^2 + \frac{3}{2}Y_t^2 + \frac{1}{2}Y_\tau^2\right)A_{\tilde\nu}$$

$$\frac{\mathrm{d}m_{H_u}^2}{\mathrm{d}\ln\mu} = (\text{MSSM terms}) + \sum_k \frac{2}{16\pi^2}\left(A_{\tilde\nu}^k\right)^2$$

Bayesian Inference framework

X data

$\theta = \{\theta_1, ..., \theta_n, \psi_a, ..., \psi_z\}$

θ_i theoretical model parameters

ψ_k nuisance parameters = astrophysics and systematics

$$\mathcal{P}(\theta|X)\mathrm{d}\theta \propto \mathcal{L}(X|\theta)\cdot\pi(\theta)\mathrm{d}\theta$$

Posterior probability function (PDF)

Likelihood (proper of each EXP)

Prior

Common prior choices that do not favour any parameter region

$$\pi_{\log}(\log\theta)\ \mathrm{d}\log\theta = \begin{cases} \mathrm{d}\log\theta, & \text{if } \theta_{\min} \leq \theta \leq \theta_{\max}, \\ 0, & \text{otherwise,} \end{cases}$$

$$\pi_{\mathrm{flat}}(\theta)\mathrm{d}\theta \propto \begin{cases} \mathrm{d}\theta, & \text{if } \theta_{\min} \leq \theta \leq \theta_{\max}, \\ 0, & \text{otherwise,} \end{cases}$$

Posterior sampled with nested sampling techniques (MultiNest) given the likelihood and the prior and marginalized over nuisance parameters

$$\mathcal{P}_{\mathrm{mar}}(\theta_1, ..., \theta_n|X) \propto \int \mathrm{d}\psi_1...\mathrm{d}\psi_m\ \mathcal{P}(\theta_1, ..., \theta_n, \psi_1..., \psi_m|X)$$

Profile Likelihood is prior independent (comparison with frequentist approach)

$$\mathcal{L}_{\mathrm{prof}}(X|\theta_1, ..., \theta_n) \propto \max_{\psi_1...\psi_m} \mathcal{L}(X|\theta_1, ..., \theta_n, \psi_1..., \psi_m)$$

$$\Delta\chi^2_{\mathrm{eff}}(m_{\mathrm{DM}}, \sigma_n^{\mathrm{SI}}) \equiv -2\ln\mathcal{L}_{\mathrm{prof}}(m_{\mathrm{DM}}, \sigma_n^{\mathrm{SI}})$$

Details on MSSM+RN sampling

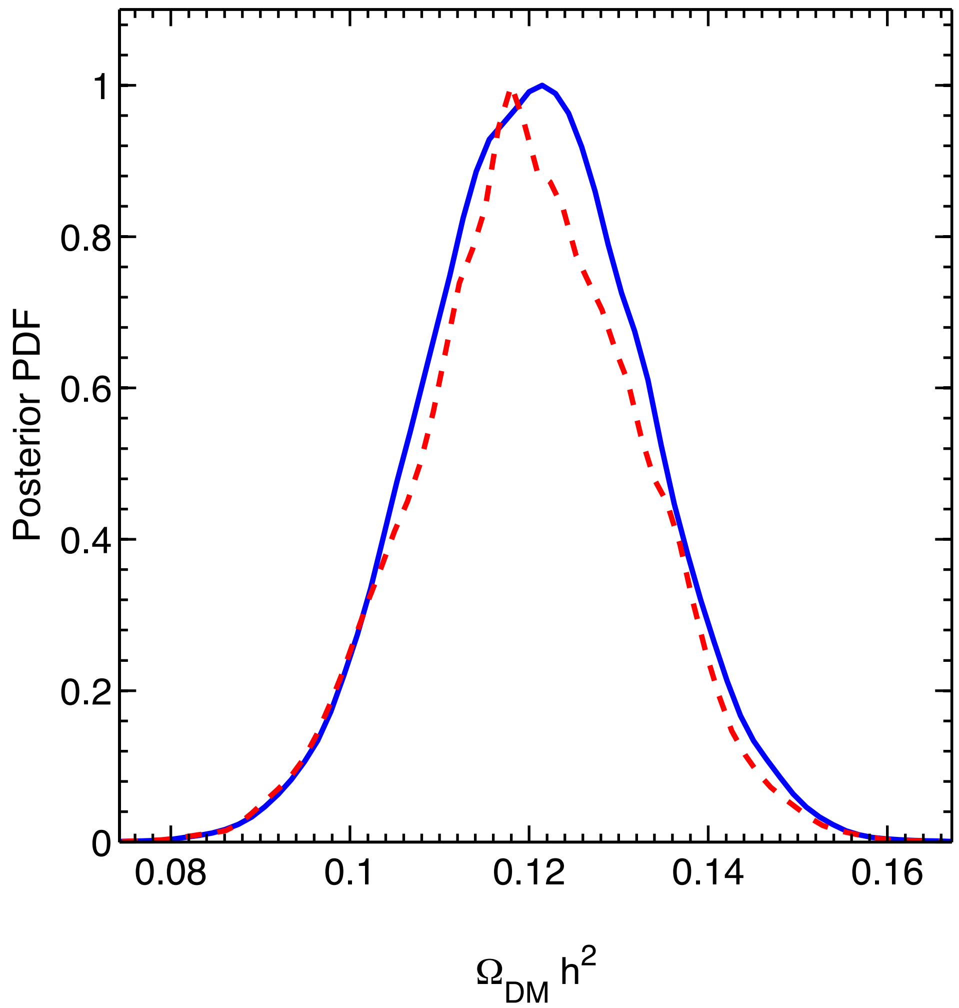
Parameters $\{\theta_i\} = \{M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_L, A_{\tilde{\nu}}, A_Q, B, \mu\}$

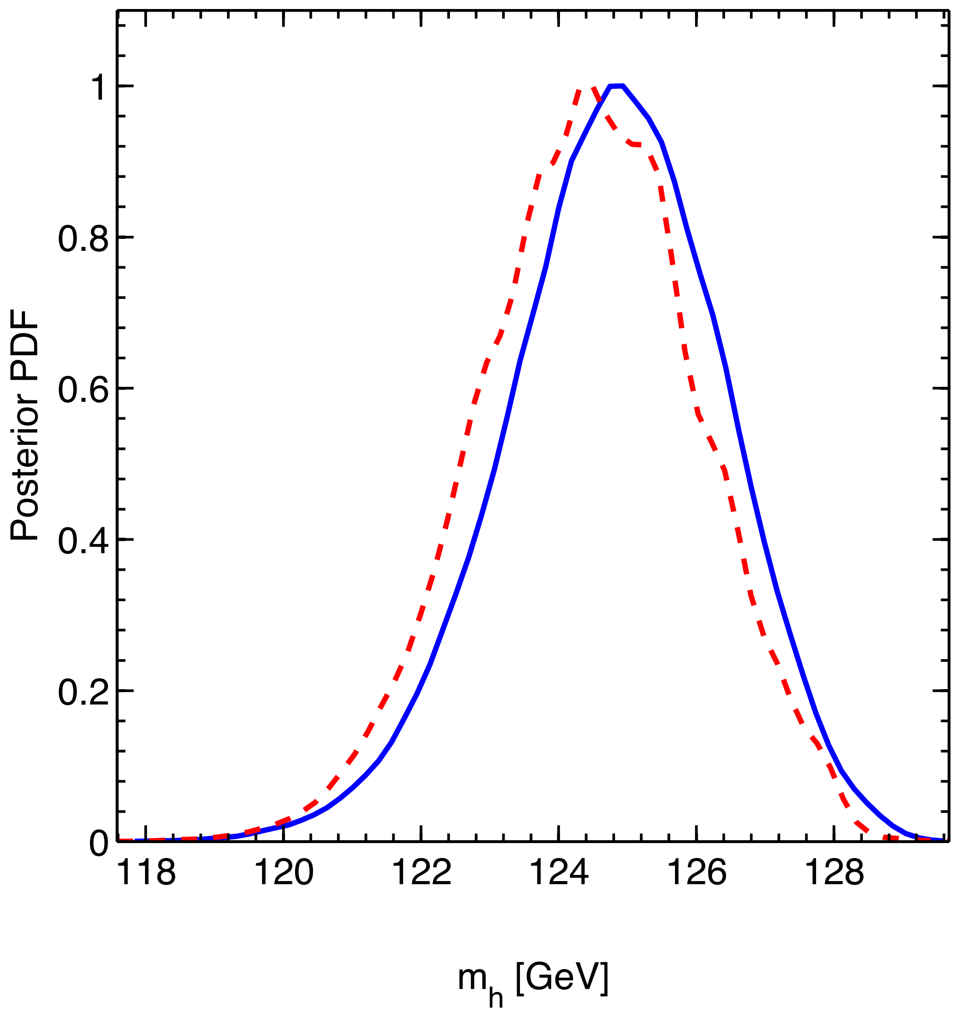
M_1, M_2	$-4000 \to 4000$ GeV
$\log_{10}(M_3/\text{GeV})$	$-4 \to 4$
$\log_{10}(m_Q/\text{GeV})$	$2 \to 5$
m_L, m_R	$1 \to 2000$ GeV
m_N	$1 \to 2000$ GeV
$\log_{10}(A_Q/\text{GeV})$	$-5 \to 5$
A_L	$-4000 \to 4000$ GeV
$A_{\tilde{\nu}}$	$-1000 \to 1000$ GeV
$\log_{10}(m_H/\text{GeV})$	$1 \to 5$
$\tan\beta$	$3 \to 50$

Data for constraints

Observable	Measured	Observable	Limit
		$\xi\sigma_n^{SI}$	LUX (90% CL)
$\Omega_{\rm DM}h^2$	$0.1186 \pm 0.0031(\text{exp}) \pm 20\%(\text{theo})$	$m_{\tilde{e},\tilde{\mu}}$	> 100 GeV (LEP 95% CL)
m_h	125.85 ± 0.4 GeV (exp) ± 4 GeV(theo)	$m_{\tilde{\tau}_1^-}$	> 85 GeV (LEP 95% CL)
$\Gamma_Z^{\rm invisible}$	166 ± 2 MeV	$m_{\tilde{\chi}_1^+}$	> 100 GeV (LEP 95% CL)
		$\Gamma_h^{\rm invisible}$	$> 65\%$ (LHC 95% CL)

Details on the 1D posterior pdfs





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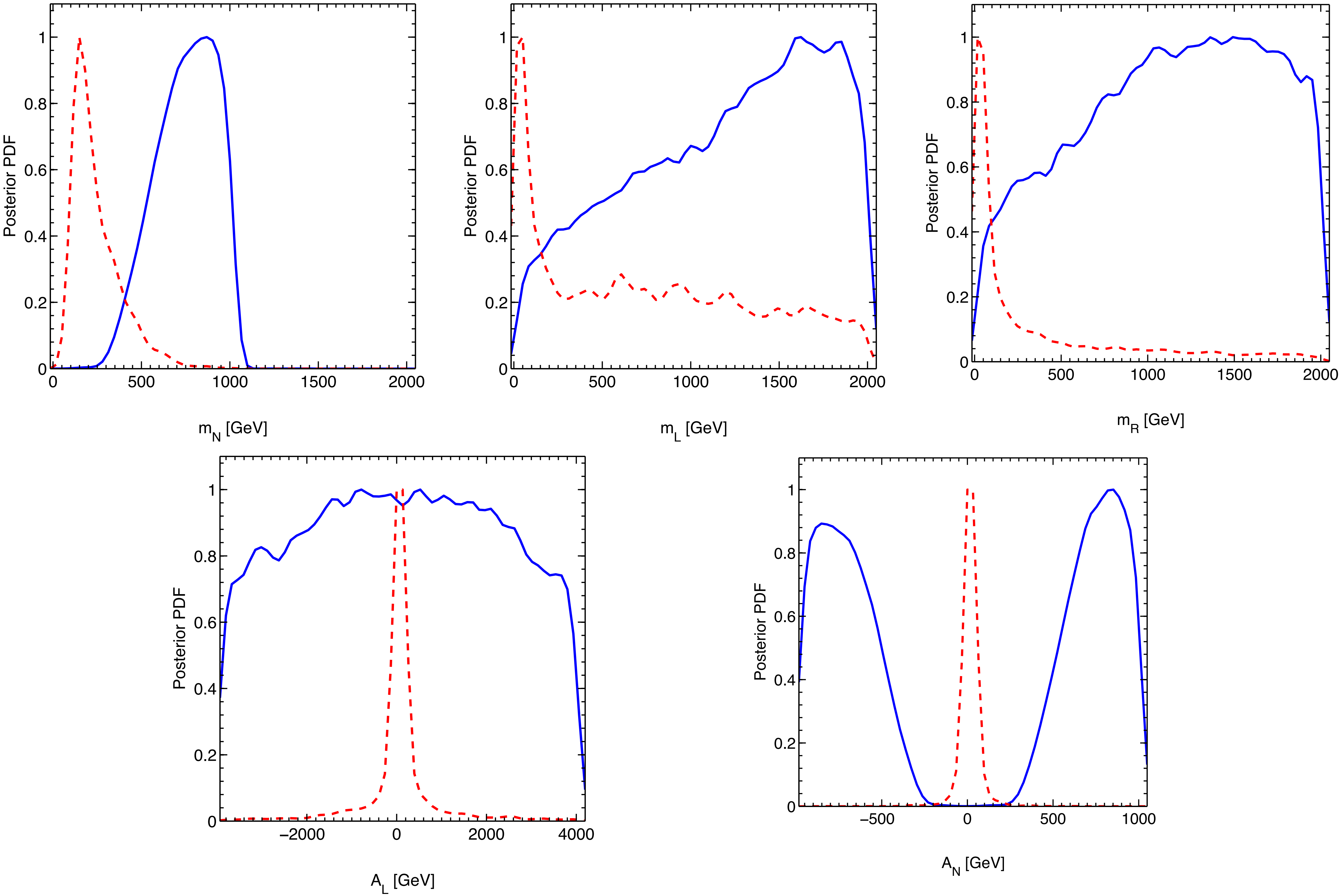

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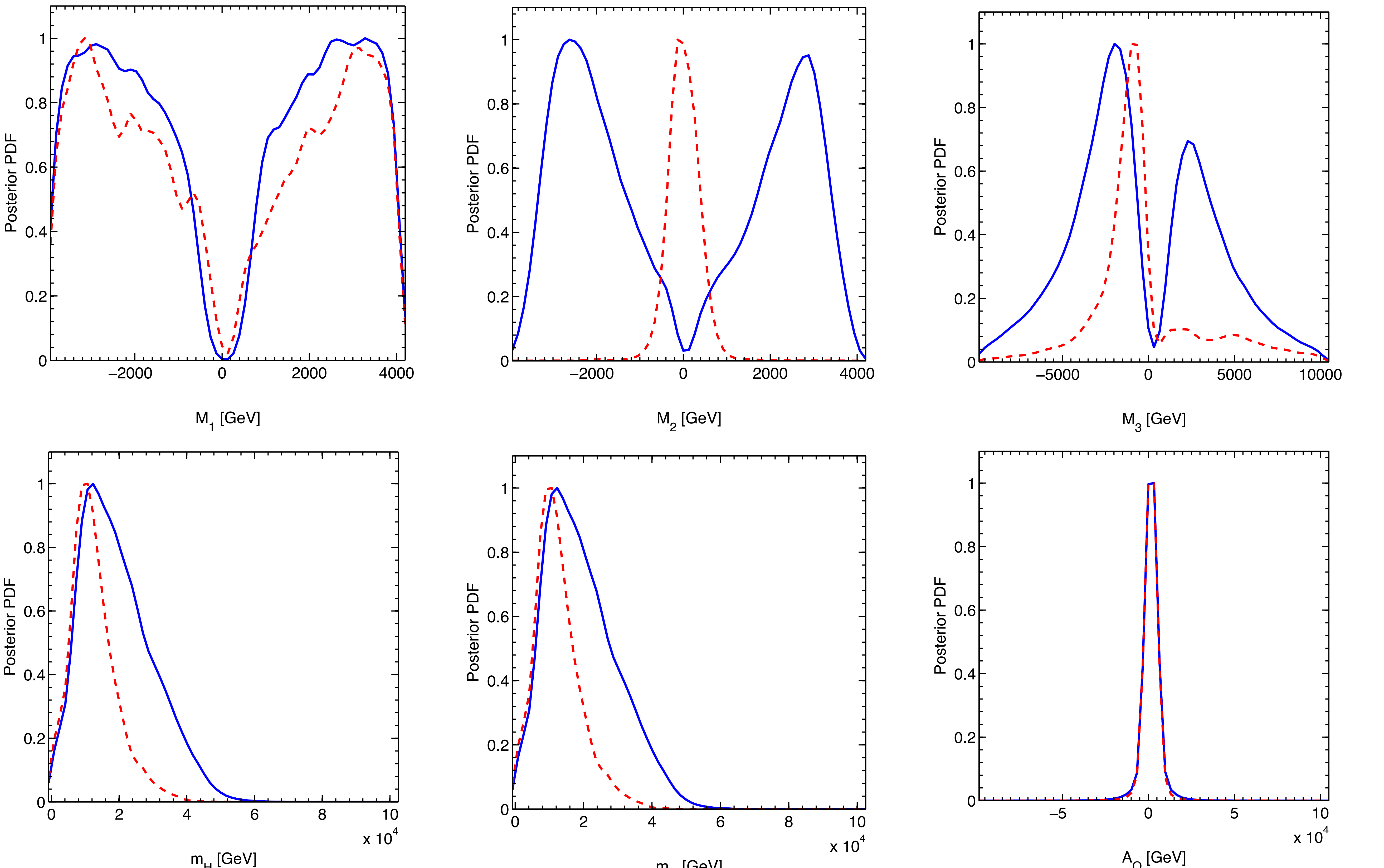

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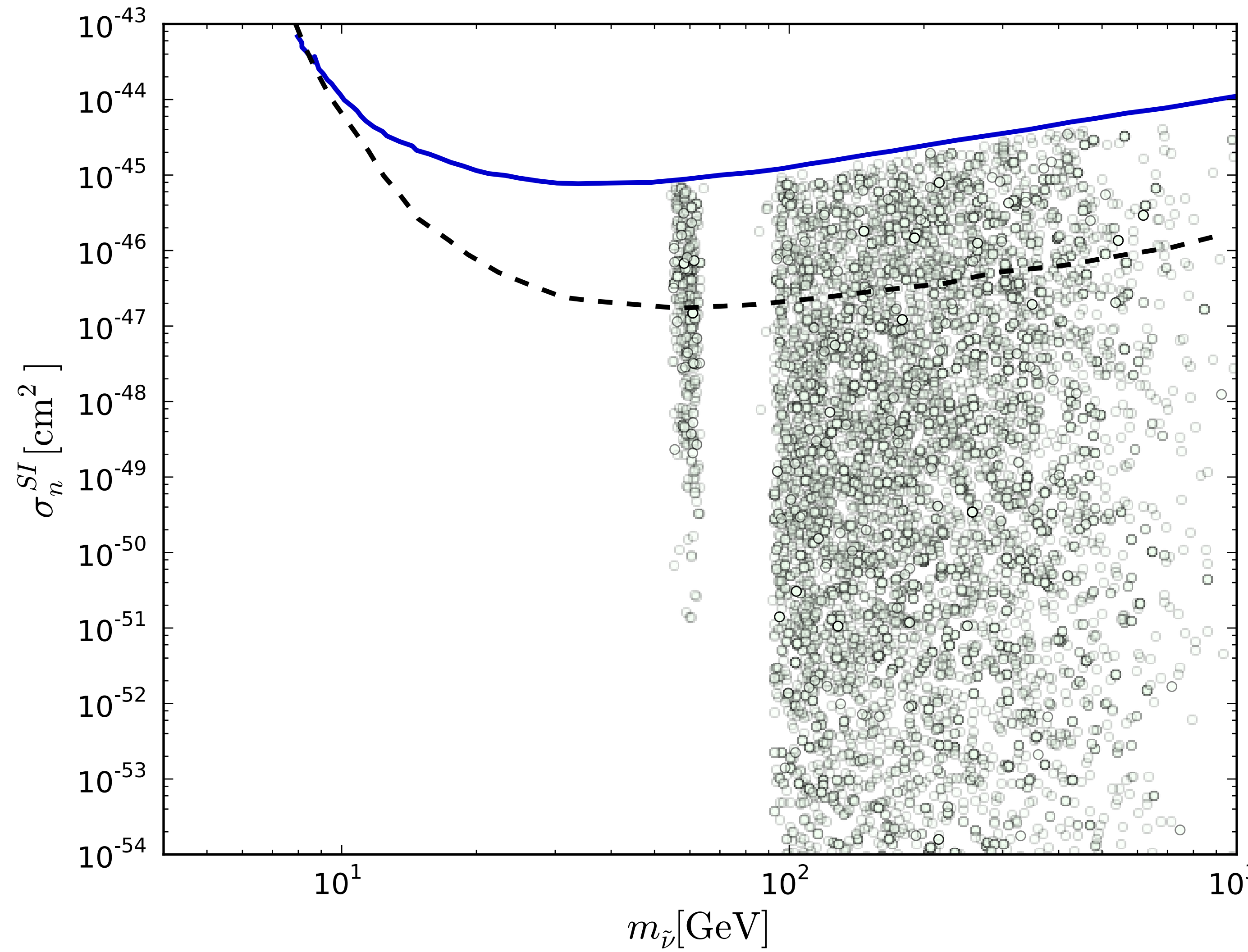
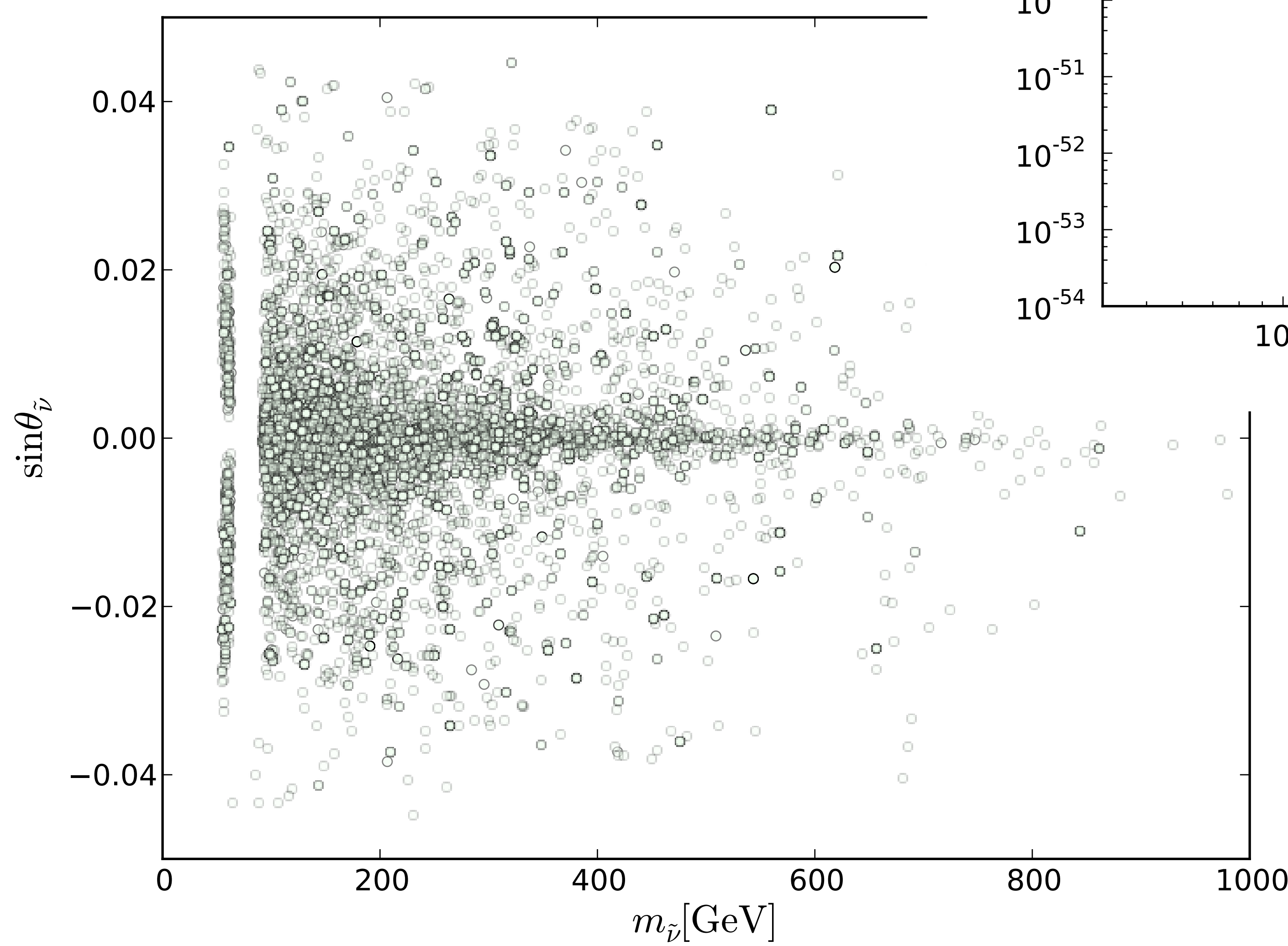
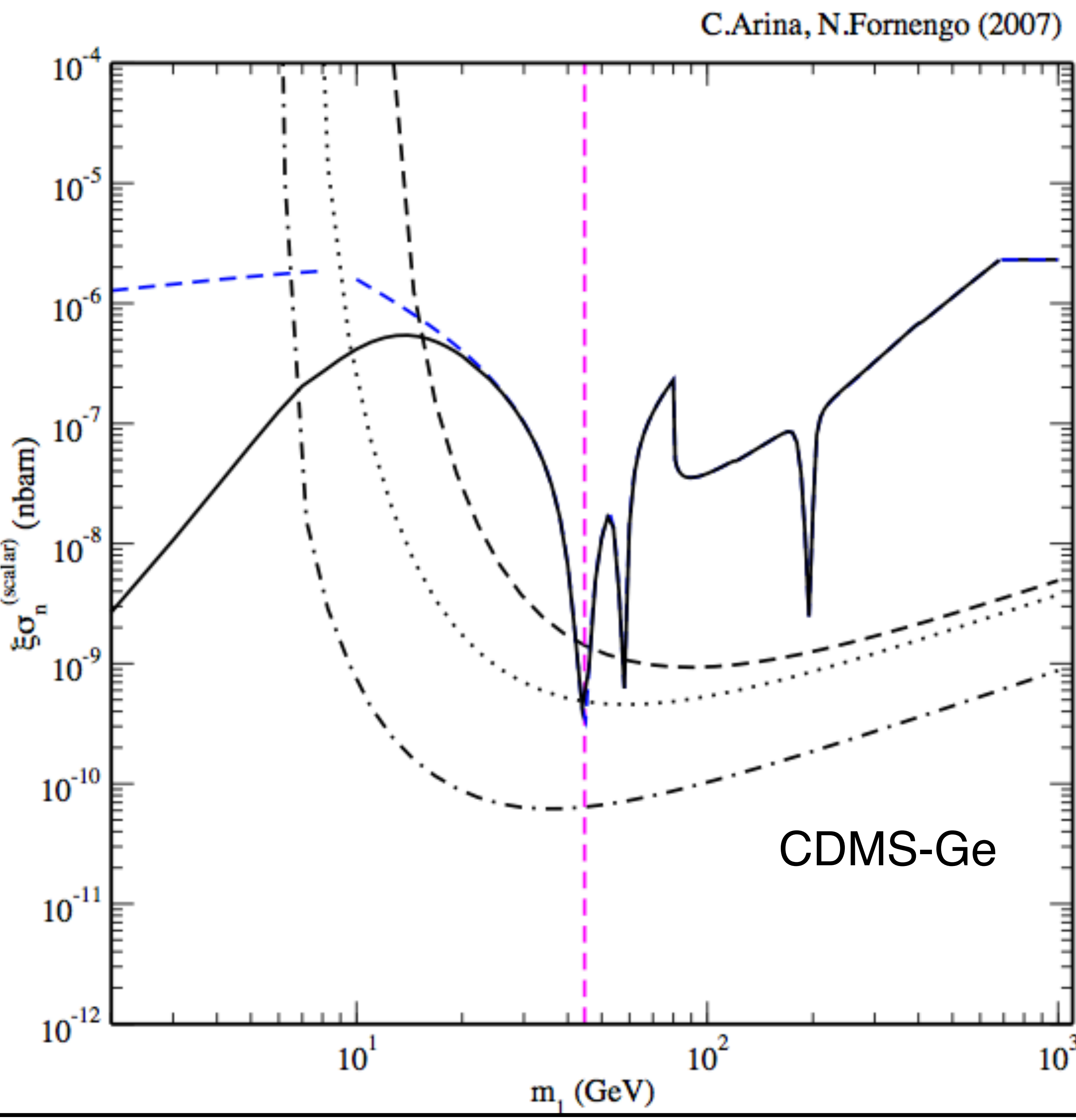




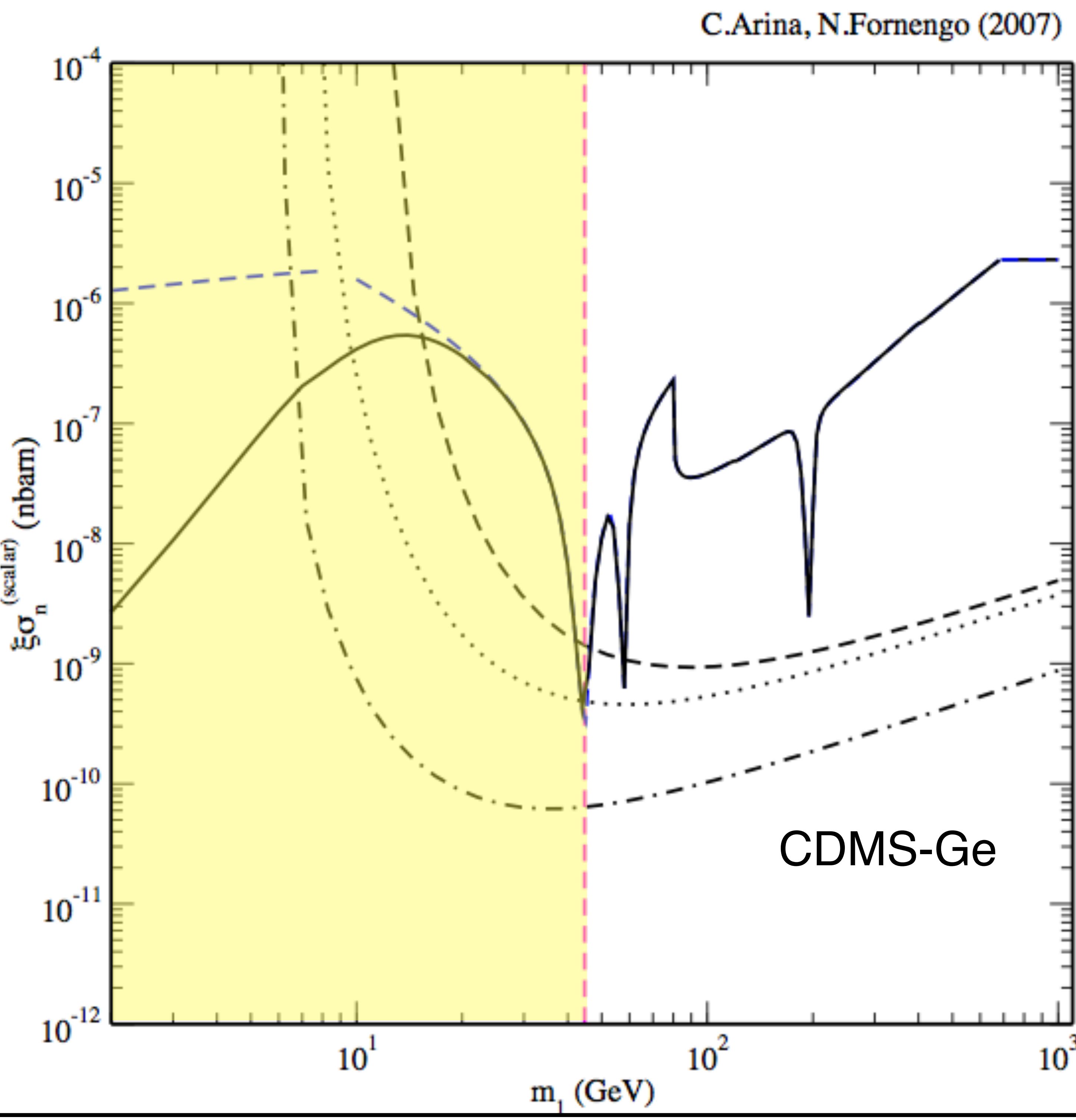
Sneutrino dark matter excluded in the MSSM



$$\xi \equiv \min(\Omega_{DM}h^2, \Omega_{\tilde{\nu}}h^2)$$

- Excluded below the Z pole
- Annihilates very efficiently: subdominant dark matter candidate
- Excluded by direct detection above the Z pole

Sneutrino dark matter excluded in the MSSM



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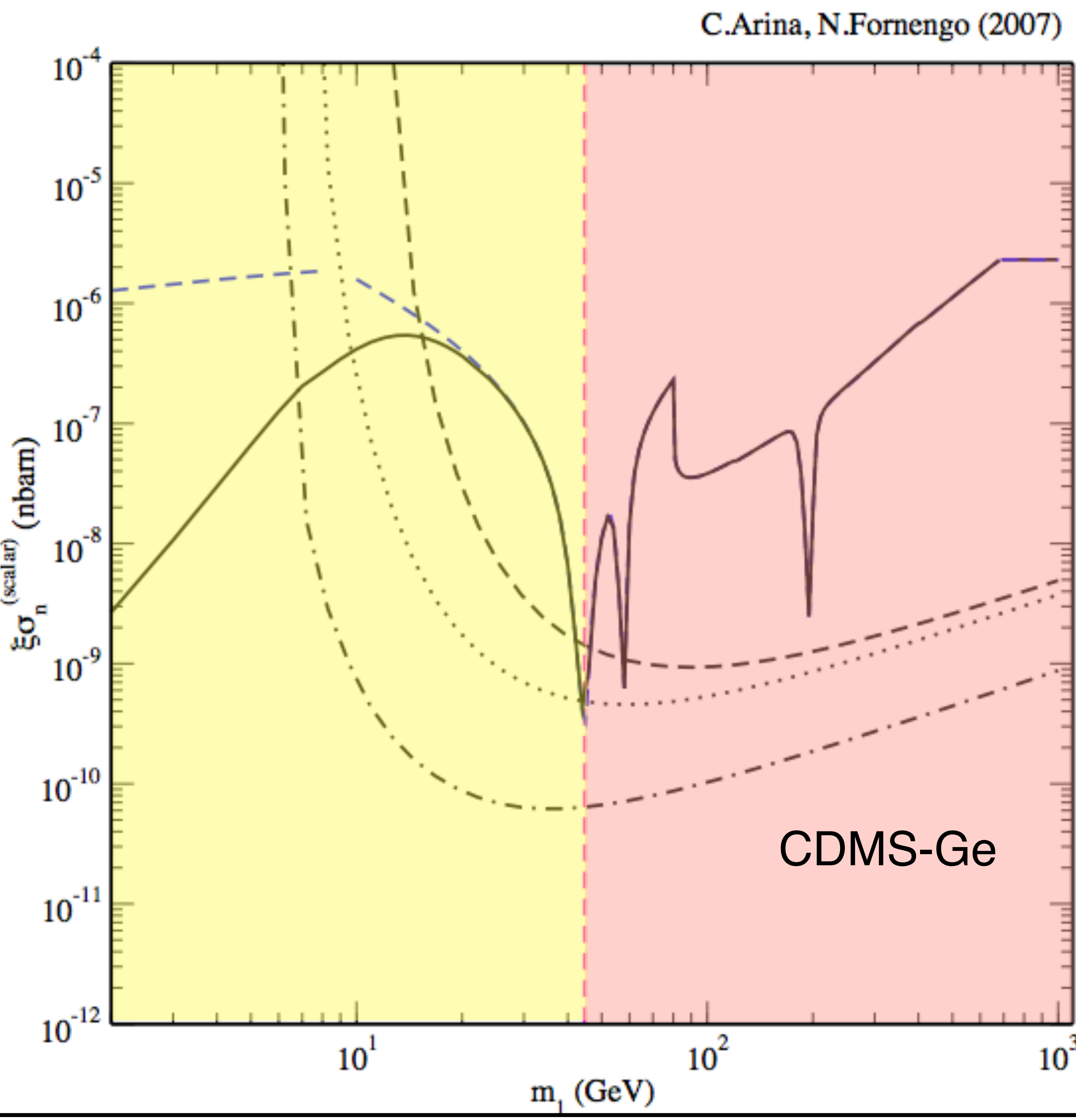

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