LHC signatures from sneutrino dark matter

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Rencontre de Physique des Particules

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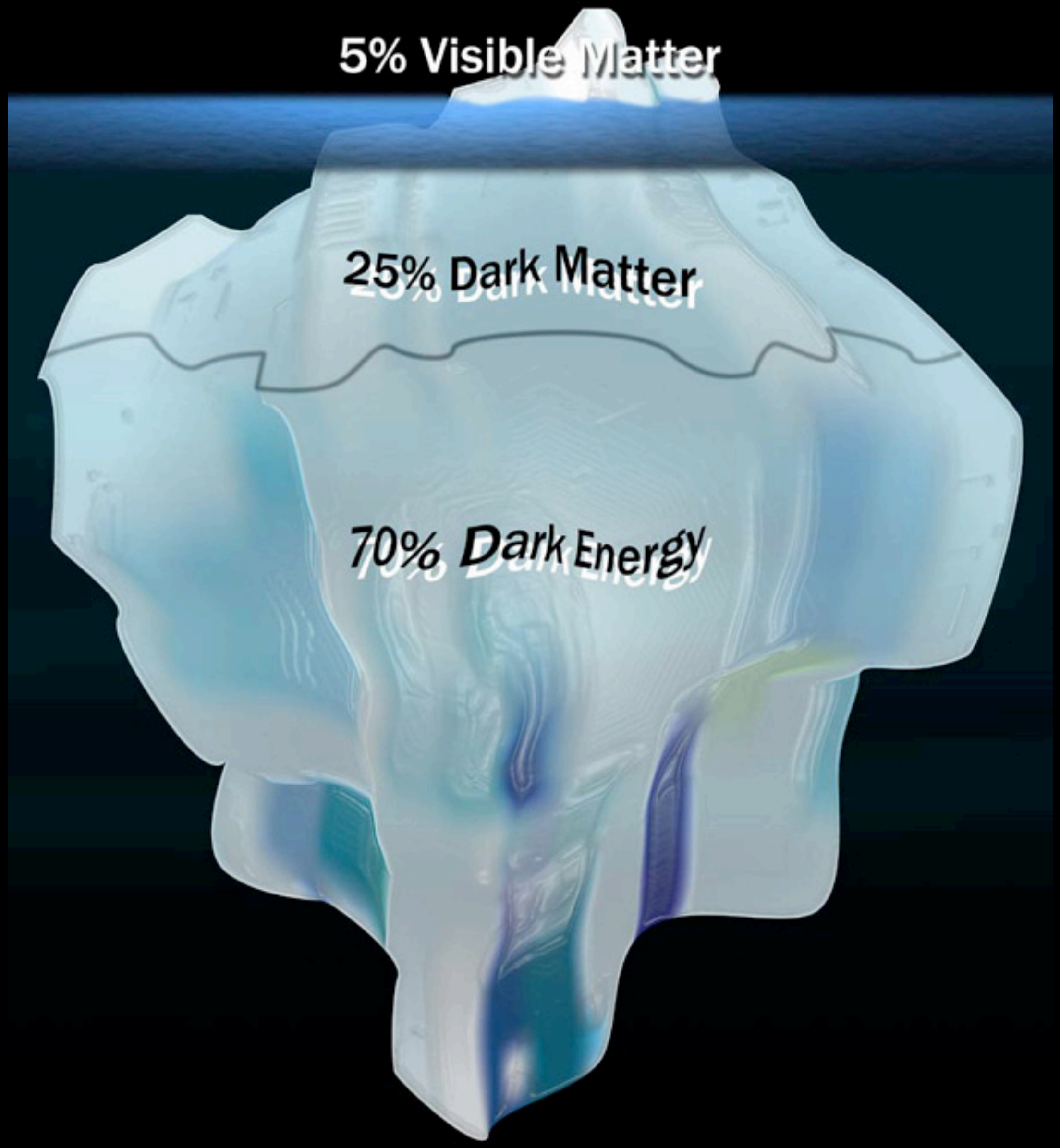
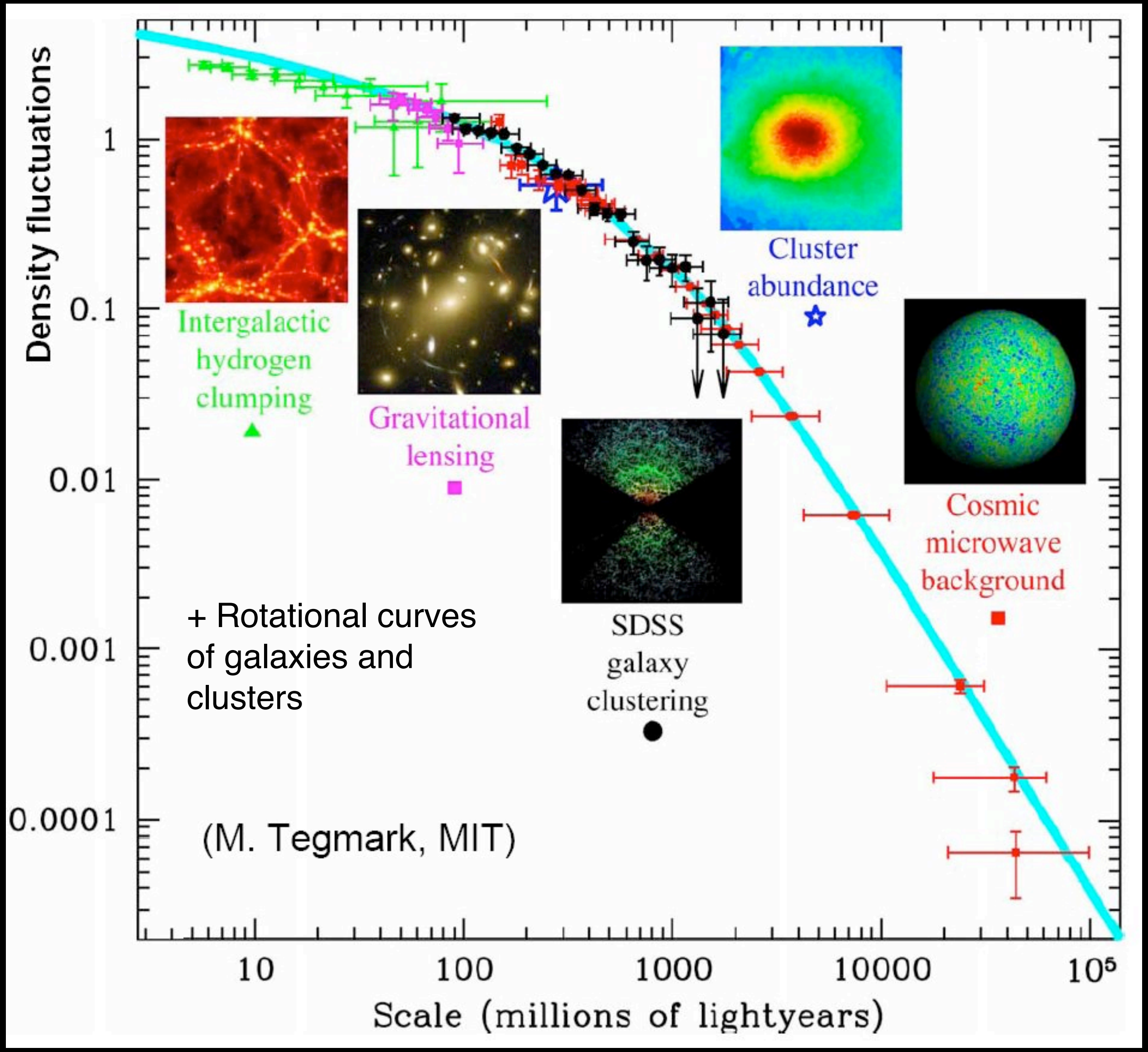
CA and Maria Eugenia Cabrera,
arXiv: 1311.6549 [hep-ph],
submitted to JHEP

Bolshoi simulation, NASA

Standard cosmological model

P.A.R. Ade et al., Planck collaboration 2013





Gravitational hints of Dark Matter (DM) at all scales

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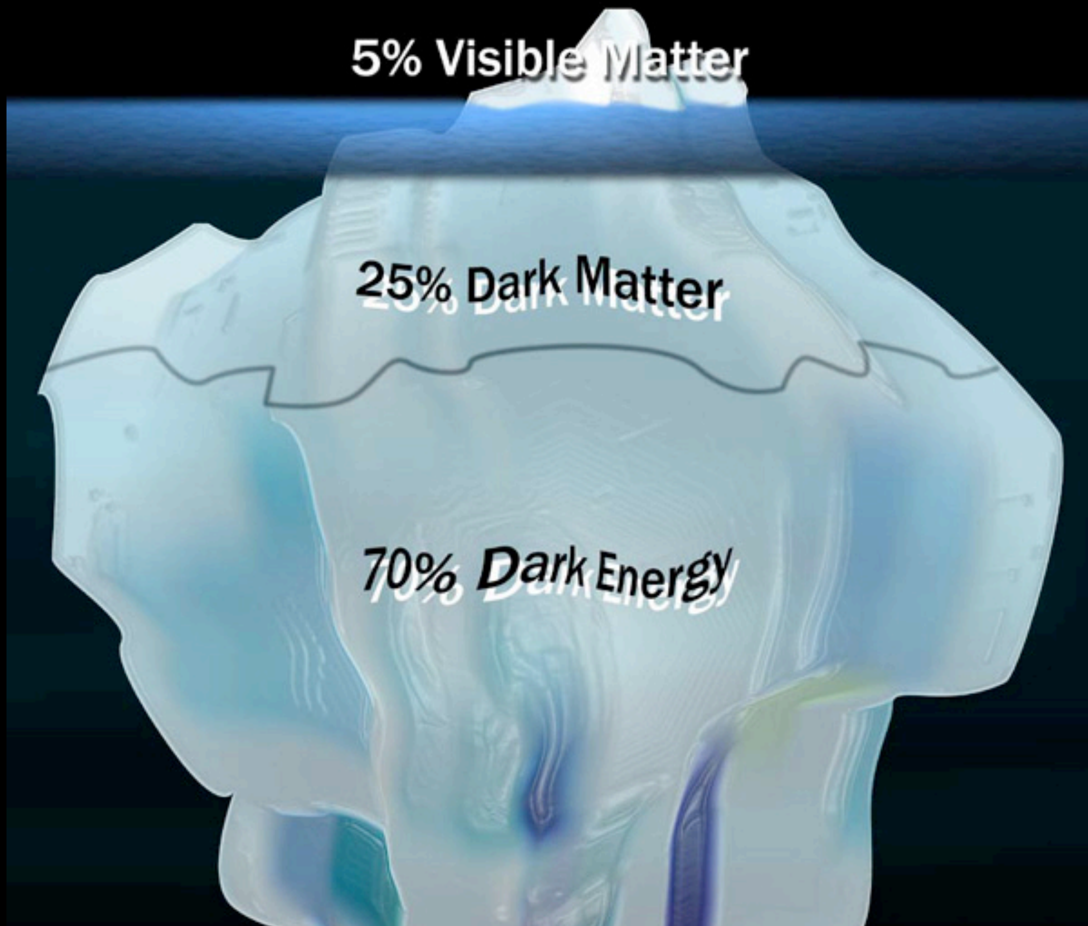
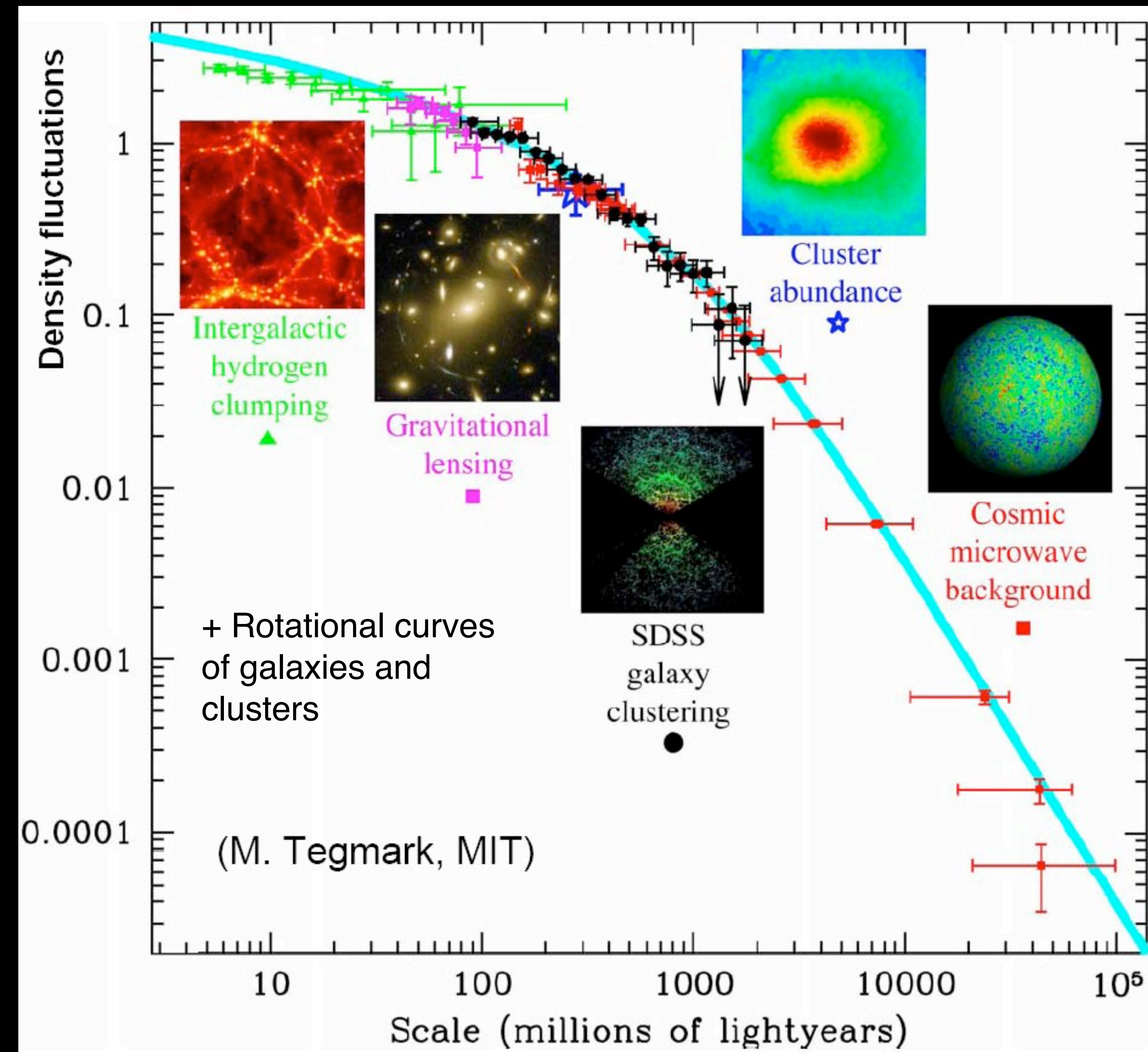


Parameter	*Planck* ("CMB+Lens")	*WMAP* (9-year)
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025
τ	0.089 ± 0.032	0.089 ± 0.014
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11
H_0 (km s^{-1}Mpc^{-1})	67.9 ± 1.5	70.0 ± 2.2
σ_8	0.823 ± 0.018	0.821 ± 0.023
Ω_b	0.0481[b]	0.0463 ± 0.0024
Ω_c	0.257[b]	0.233 ± 0.023



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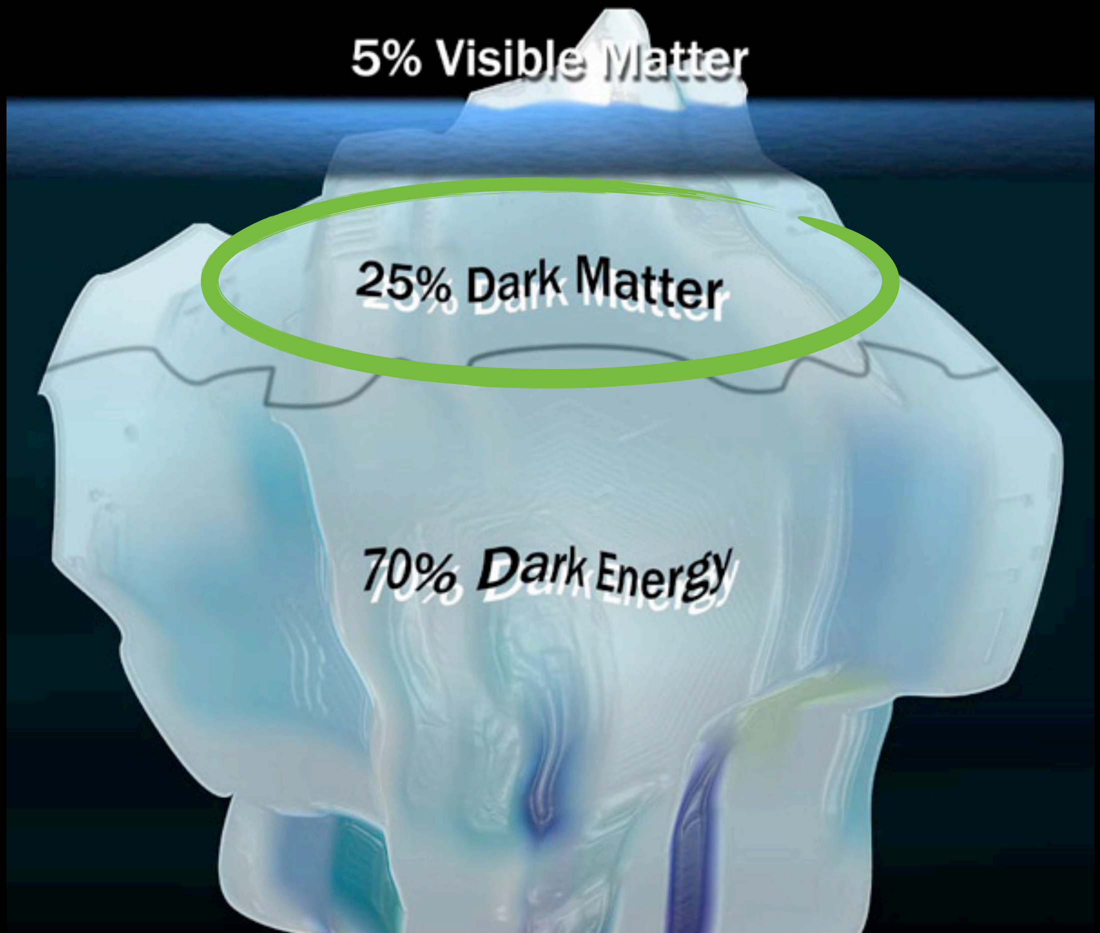

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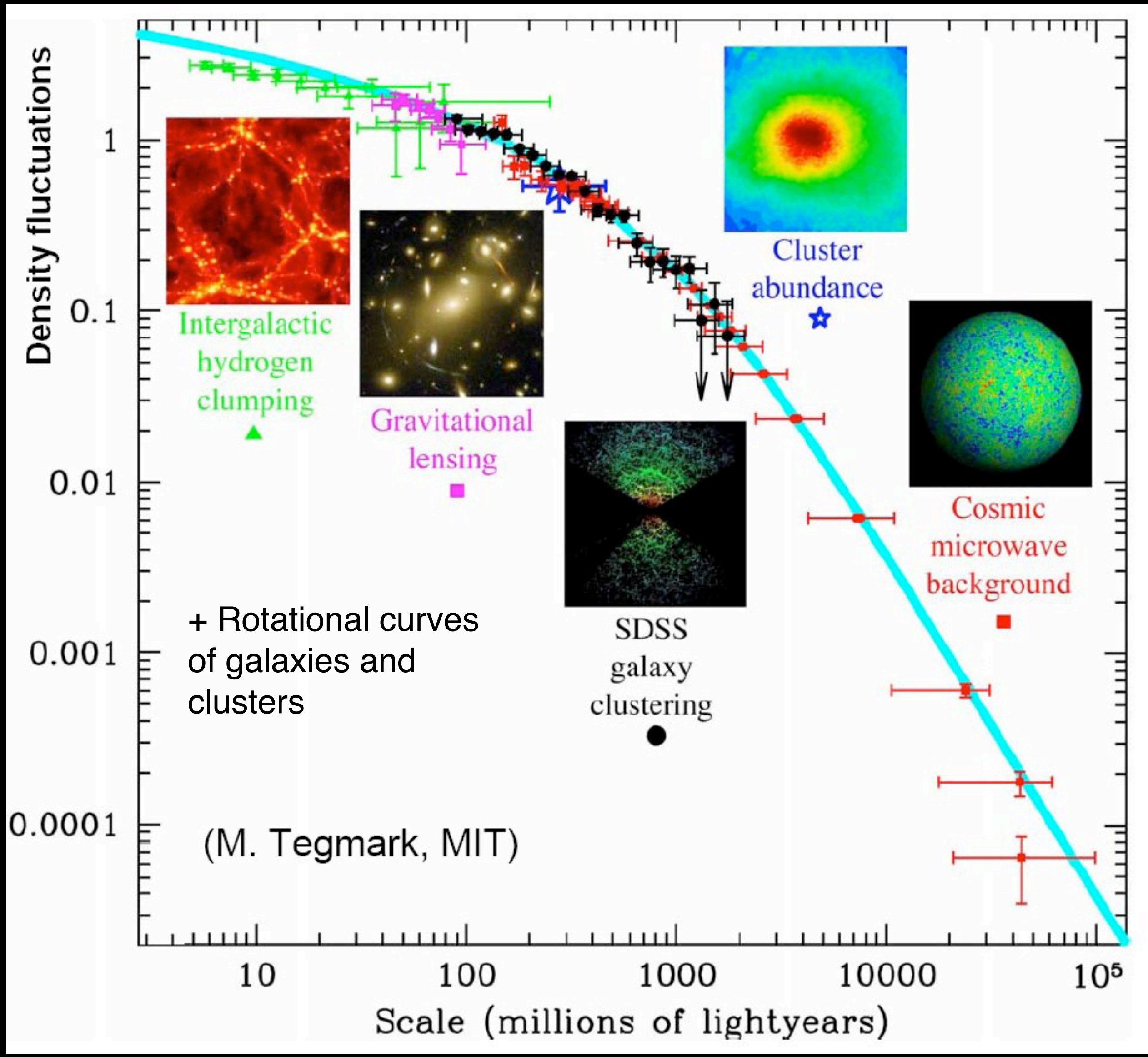
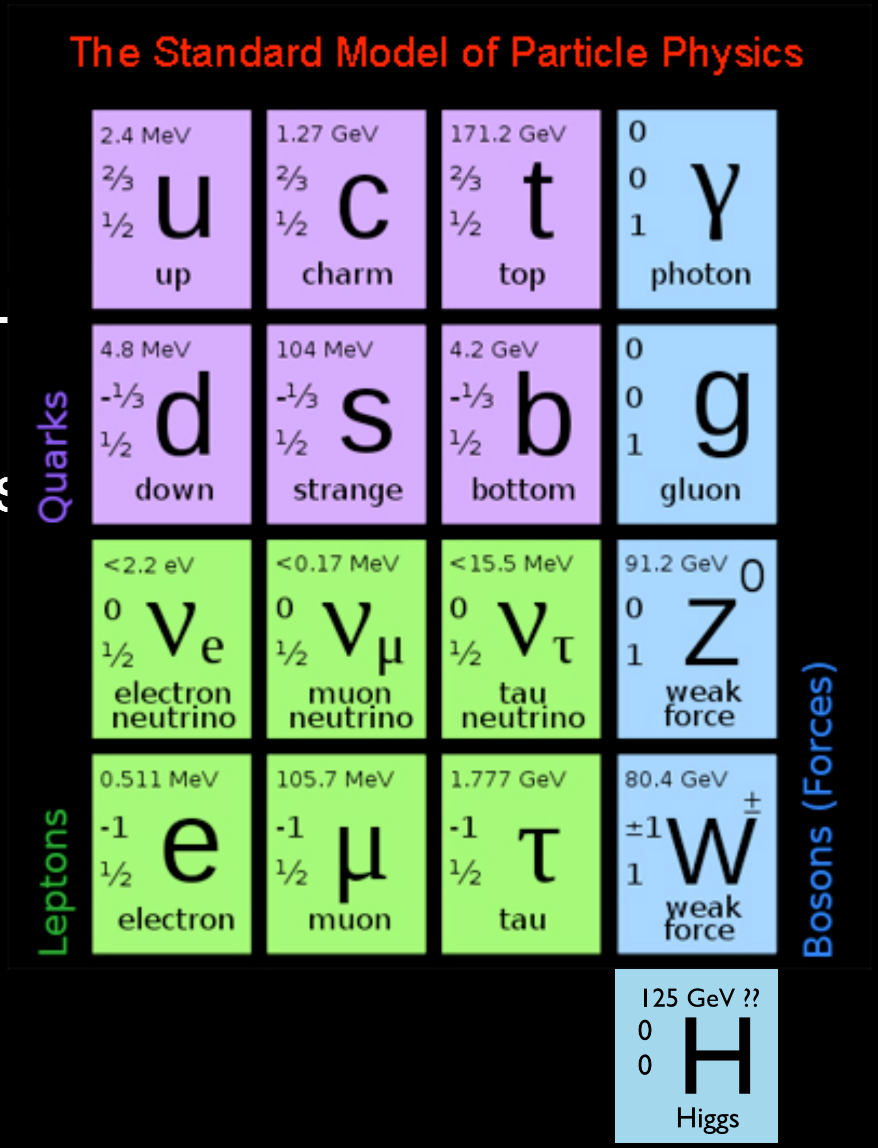


Gravitational hints of Dark Matter (DM) at all scales

What do we know about the dark matter?

Properties derived from Cosmology and astrophysics:

- Neutral
- Massive enough to account for large scale structures
- Stable at least on cosmological scale
- Thermally (or non-thermally) produced: $\Omega_{\rm DM}$ = 0.227 +- 0.014
- Cluster to account for large scale structures and form halos



New Physics beyond the Standard Model to account for non baryonic candidate

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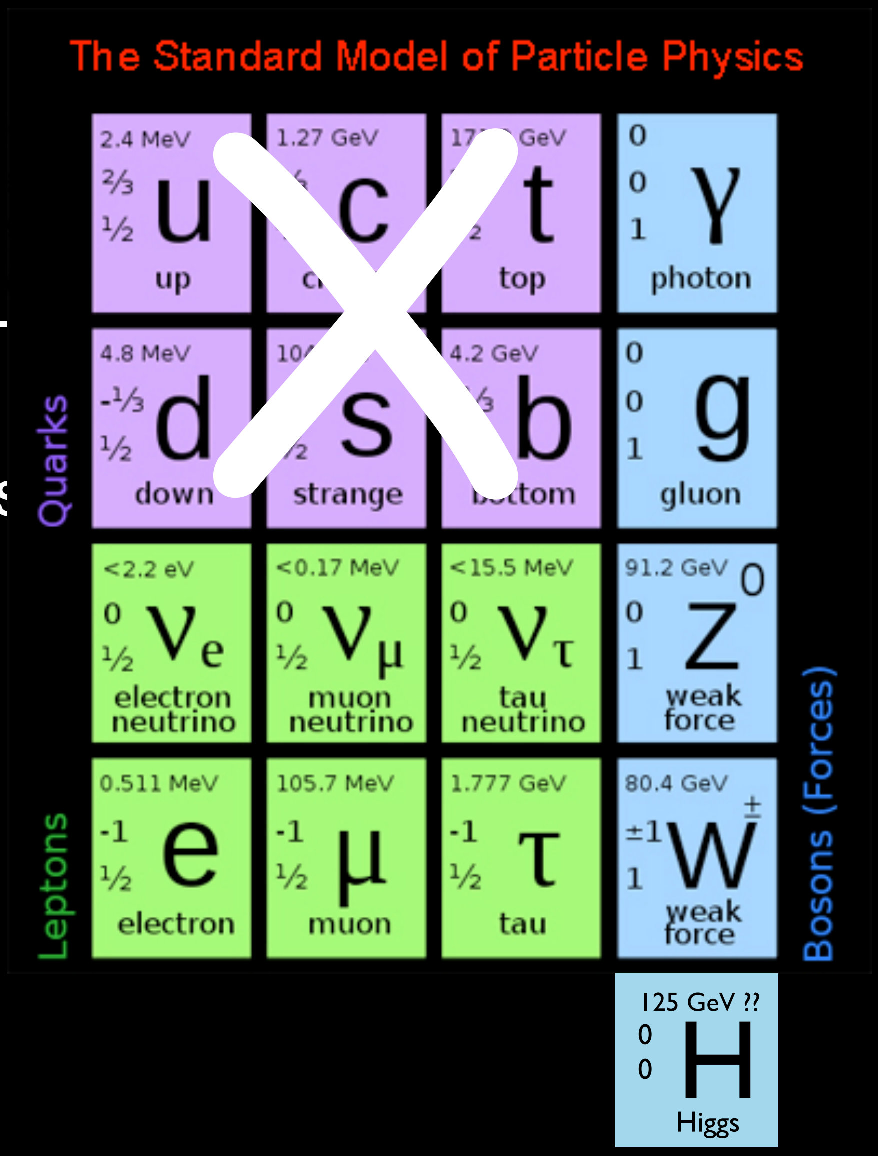

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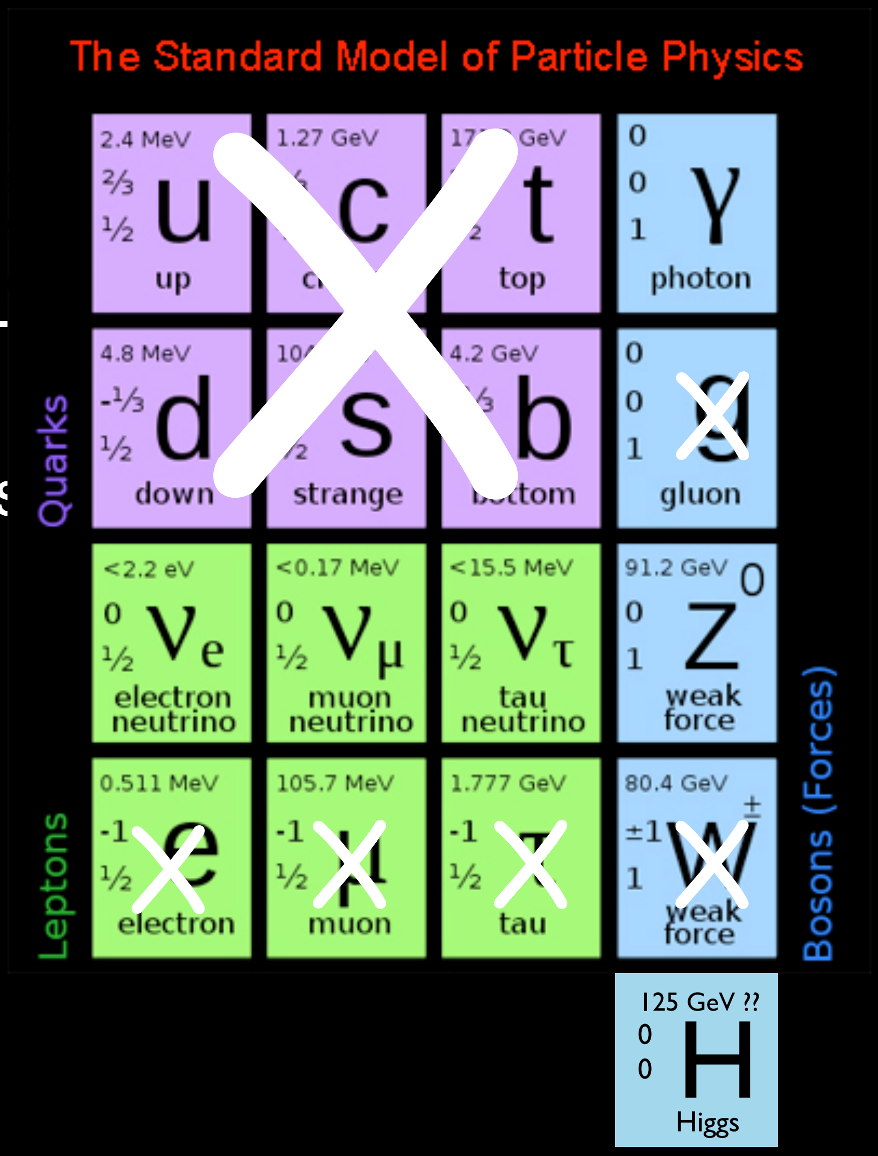

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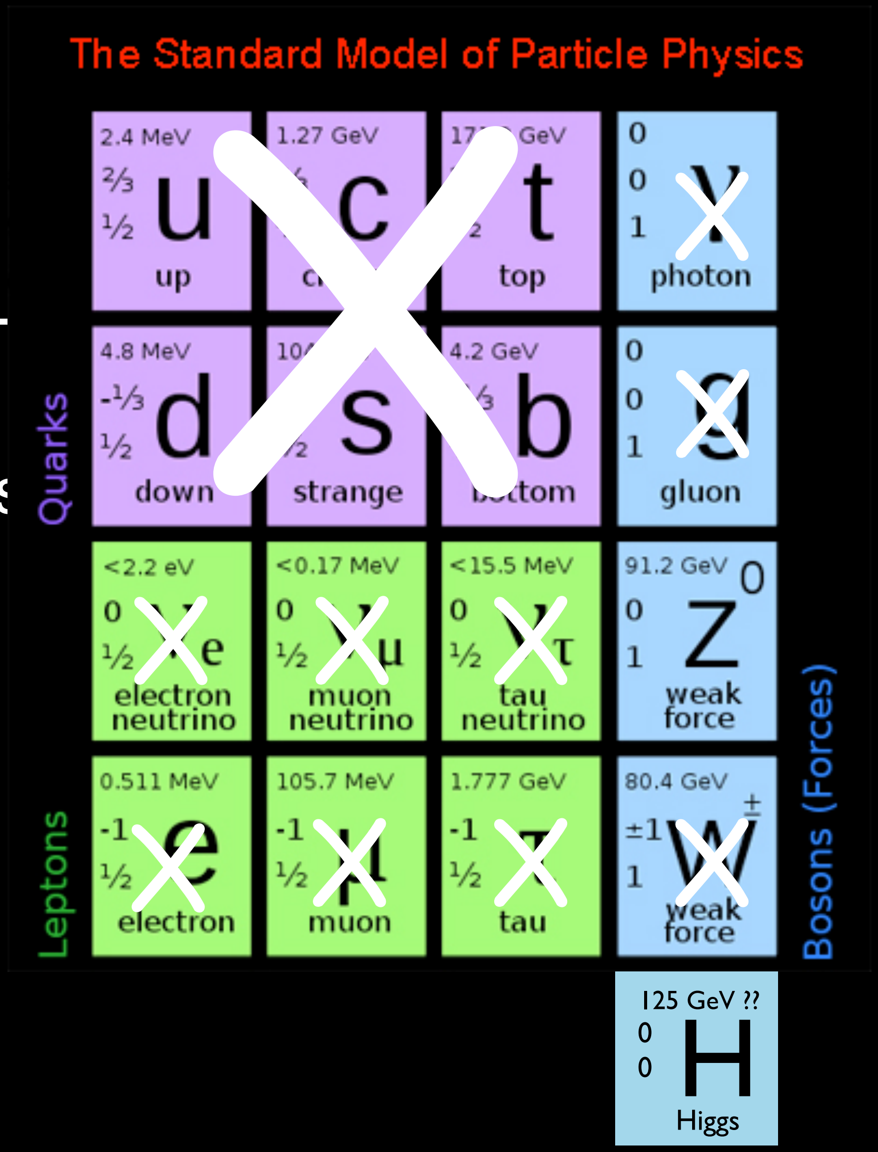

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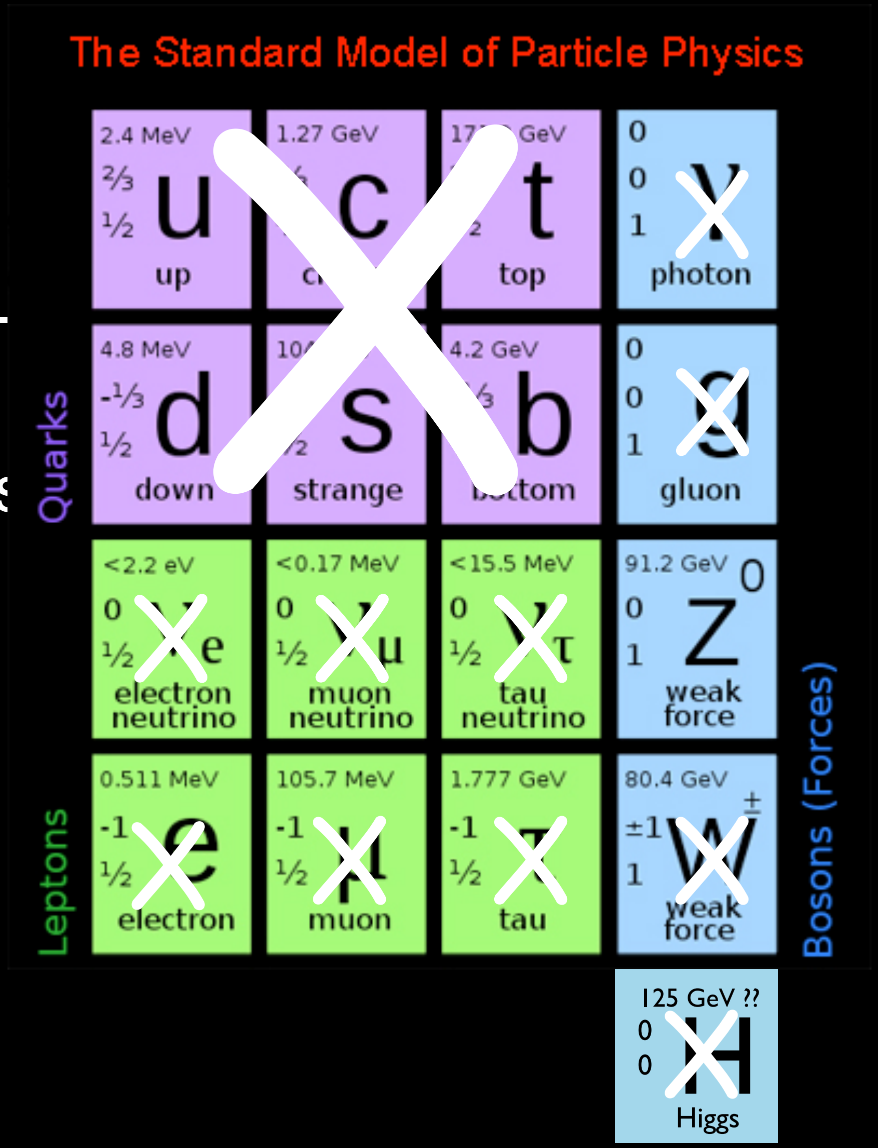

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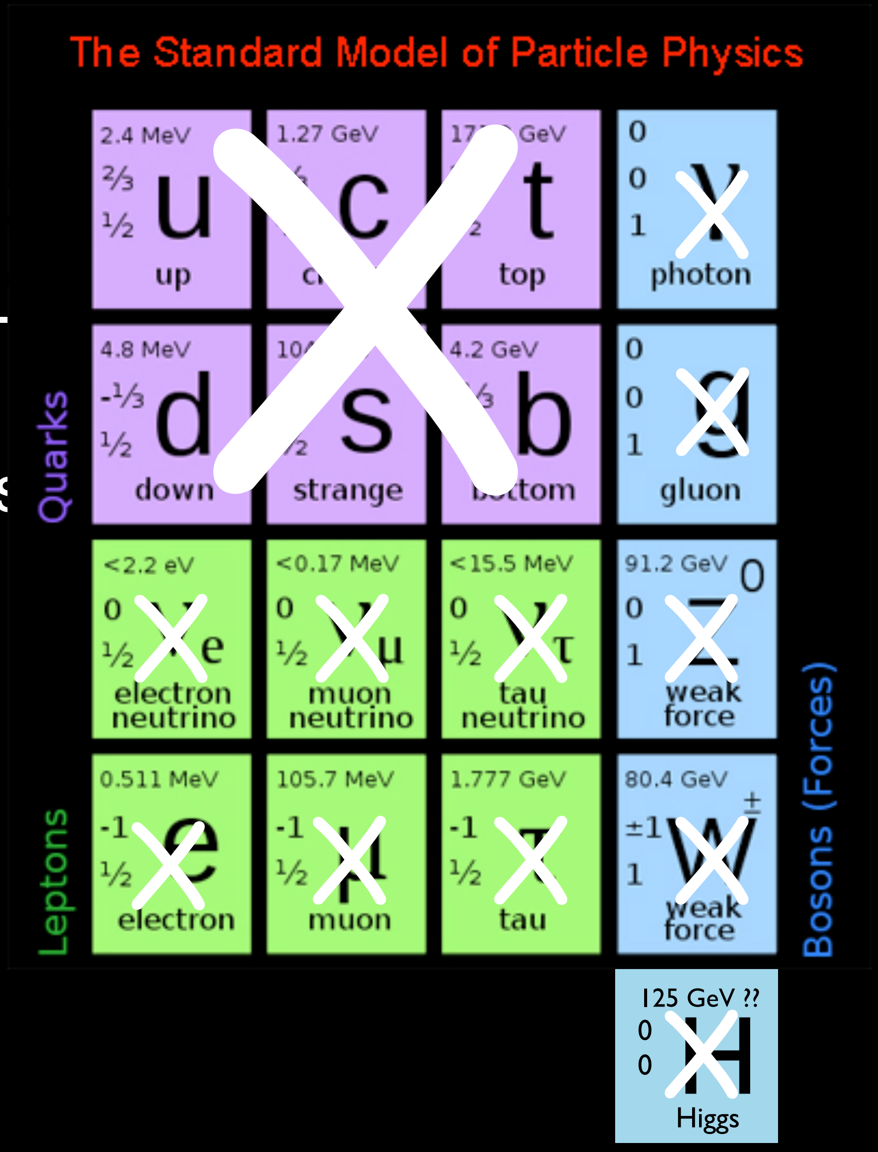
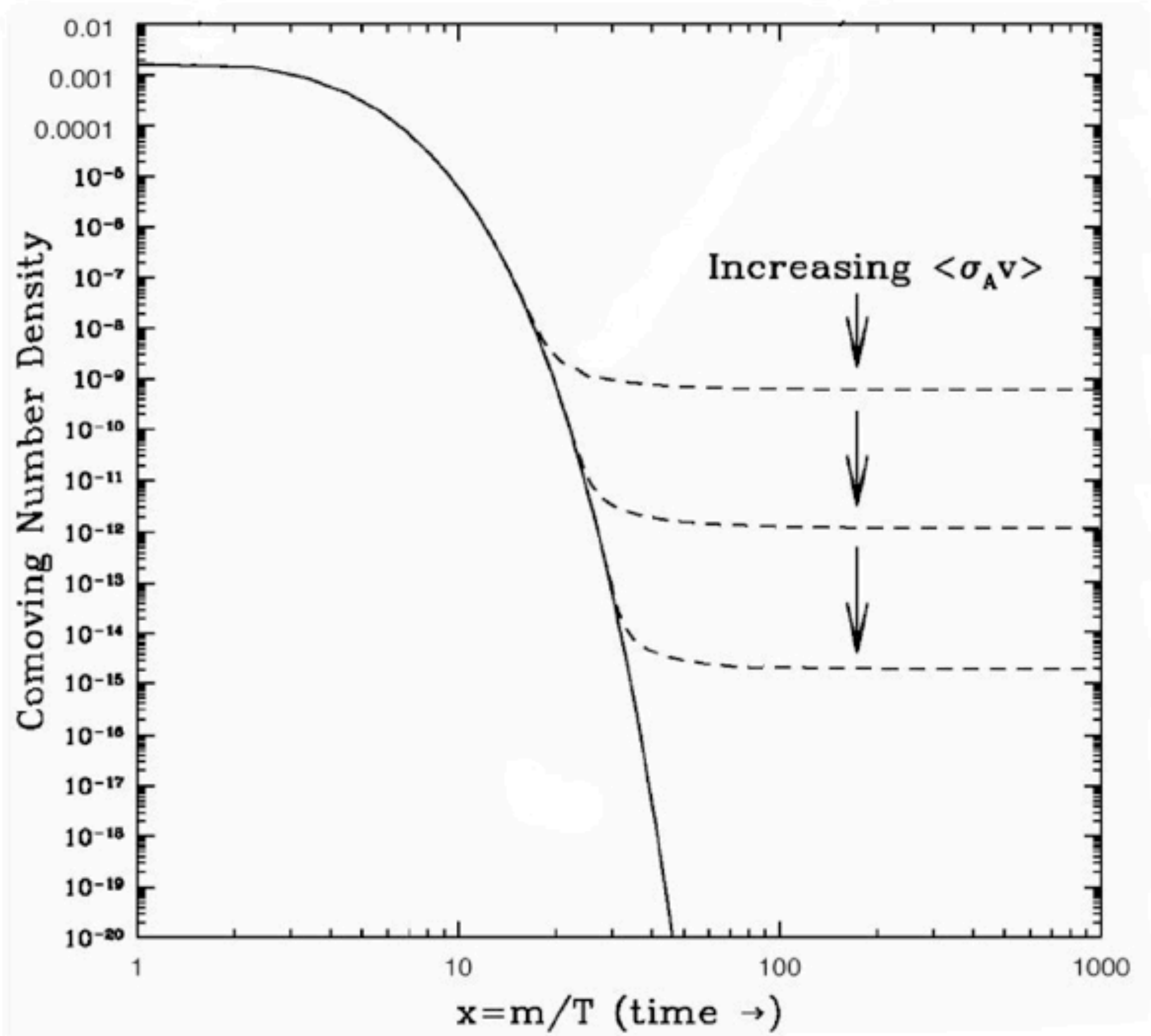


New Physics beyond the Standard Model to account for non baryonic candidate

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

Sneutrino in the MSSM

SM Symbol	Particles/Fields Name	SUSY Partners: Interaction eigenstates	SUSY Partners: Name	SUSY Partners: Mass eigenstates	Supermultiplets Symbol
q	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	$\hat{Q}, \hat{U}, \hat{D}$
l	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	$\hat{L}, \hat{R}$
ν	neutrino	$\tilde{\nu}_L$	sneutrino	$\tilde{\nu}_L$	$\hat{L}$
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	$\hat{g}$
$W^\pm$	W boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}_i^\pm$	$\hat{W}$
H^-	H boson	$\tilde{H}_1^-$	higgsino	chargino	$(\hat{H}_1^0, \hat{H}_1^-)$
H^+	H boson	$\tilde{H}_2^+$	higgsino	$i = 1, 2$	$(\hat{H}_2^+, \hat{H}_2^0)$
B	B field	$\tilde{B}$	bino	$\tilde{\chi}_i^0$	$\hat{B}$
W^3	W^3 field	$\tilde{W}^3$	wino	neutralino	$\hat{W}$
H_1^0	H boson	$\tilde{H}_1^0$	higgsino	$i = 0, 1, 2, 3$	$(\hat{H}_1^0, \hat{H}_1^-)$
H_2^0	H boson	$\tilde{H}_2^0$	higgsino		$(\hat{H}_2^+, \hat{H}_2^0)$
H_3^0	H boson				

- Sneutrino belongs to the $SU(2)_L$ doublet, it has Y=1 and couples to the Z boson
- Excluded below the Z pole
- Annihilates very efficiently: subdominant dark matter candidate
- $\xi \equiv \min(\Omega_{DM} h^2, \Omega_{\tilde{\nu}} h^2)$
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Discussion on left-handed sneutrino as dark matter: Ibanez '84, Falk et al '94.
Discussion on DM with Y not 0, see e.g. Minimal Dark Matter, M.Cirelli et al. '05.

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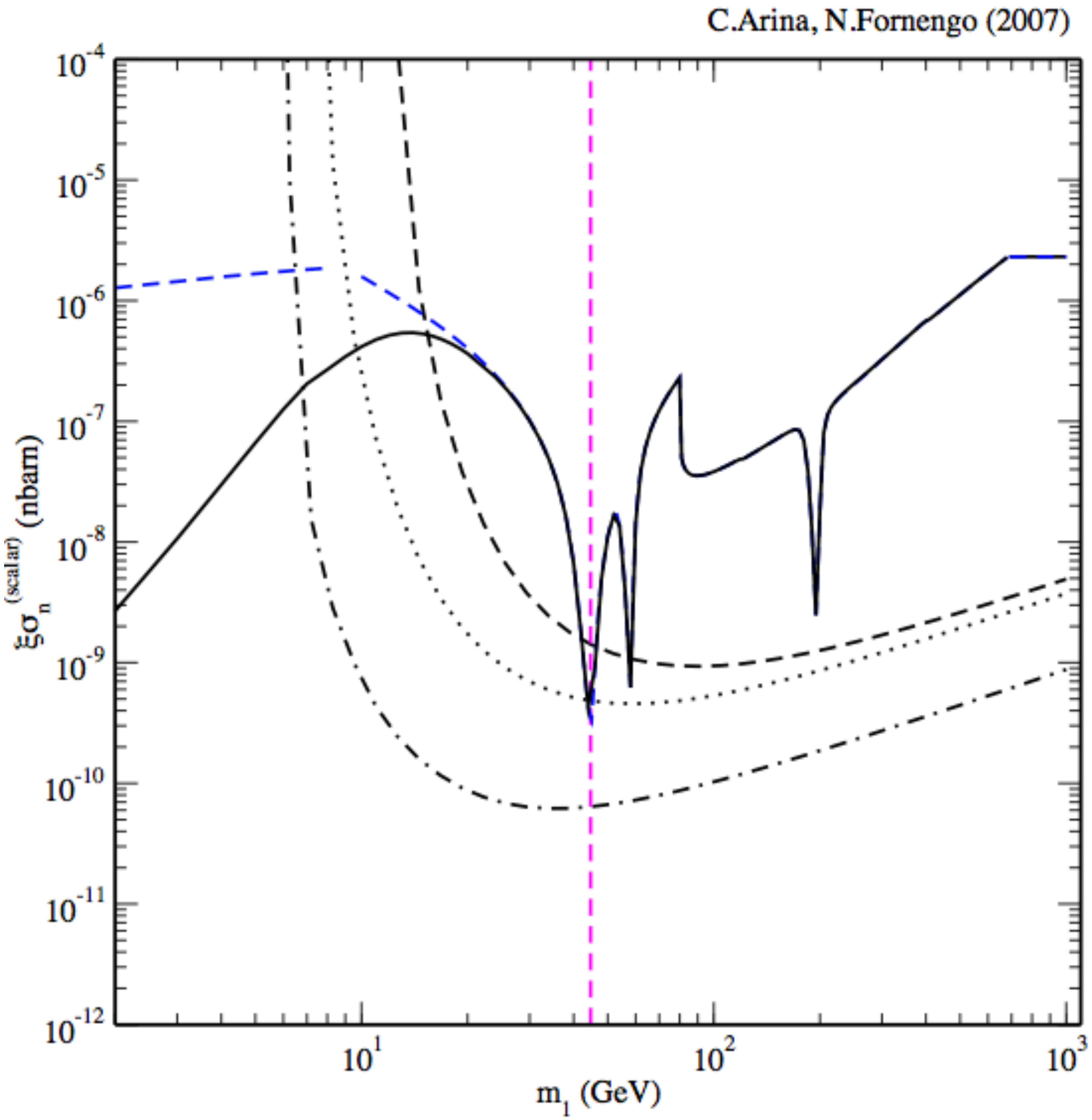

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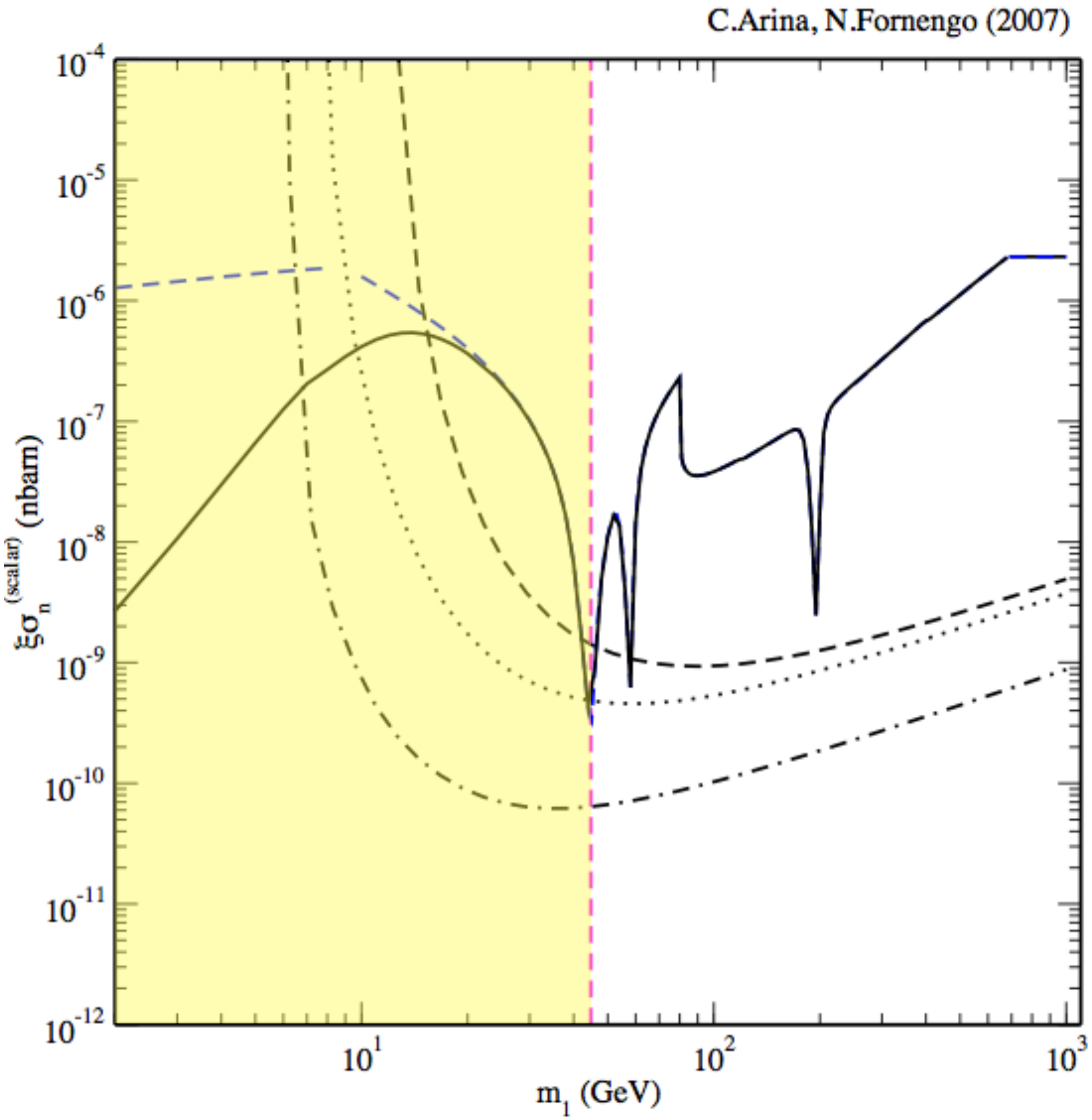

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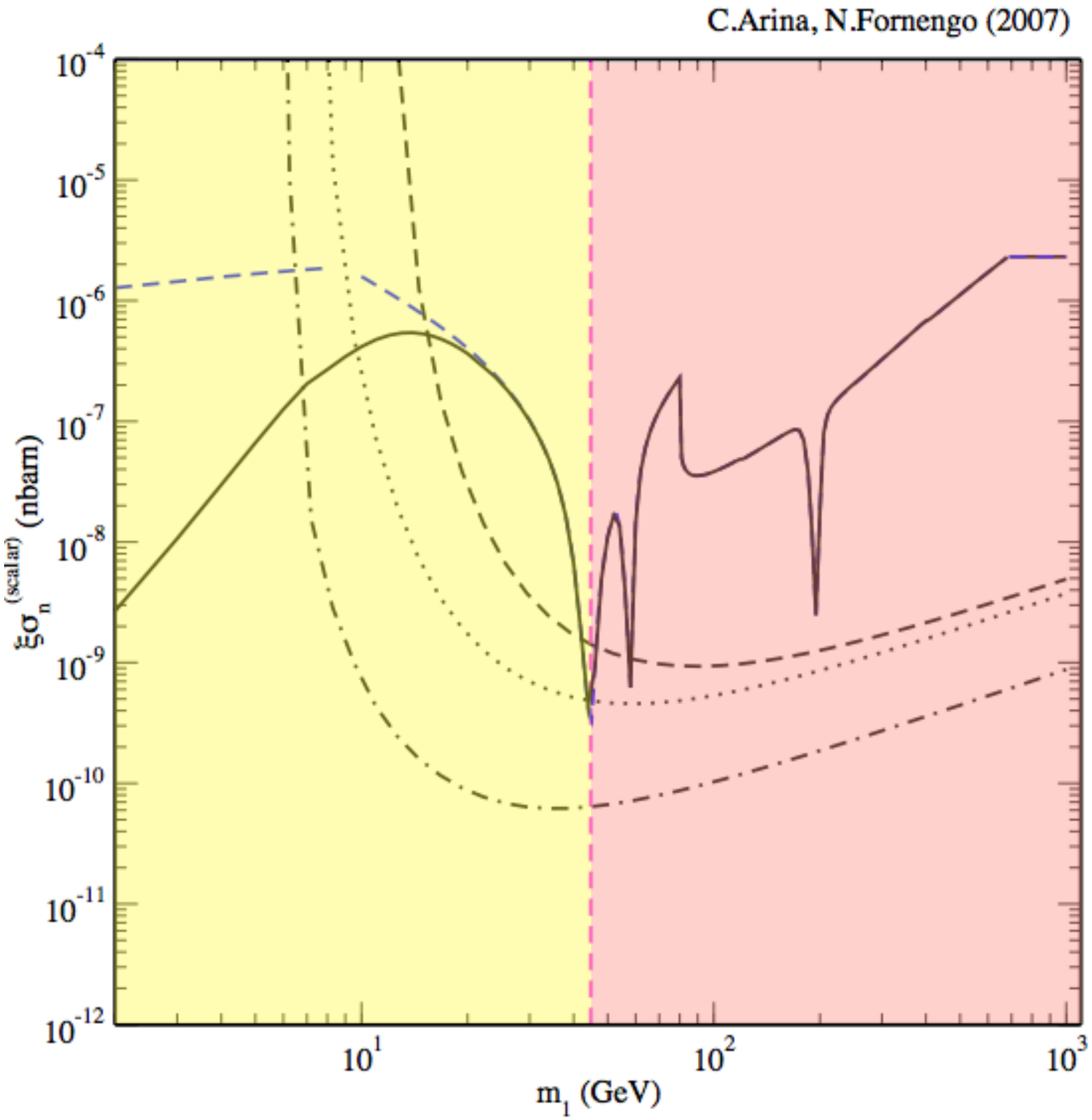

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Sneutrino as LSP and dark matter in the MSSM + RN

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

No letpon violating terms
(dirac masses for neutrinos)

$$V_{\text{soft}} = M_L^2\, \tilde{L}_i^* \tilde{L}_i + M_N^2\, \tilde{N}^* \tilde{N} - [\epsilon_{ij}(\Lambda_l H_i^d \tilde{L}_j \tilde{R} + \Lambda_\nu H_i^u \tilde{L}_j \tilde{N}) + \text{h.c.}]$$

LSP

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 snu$_{\text{tau}}$ is the LSP

Set up of the numerical analysis

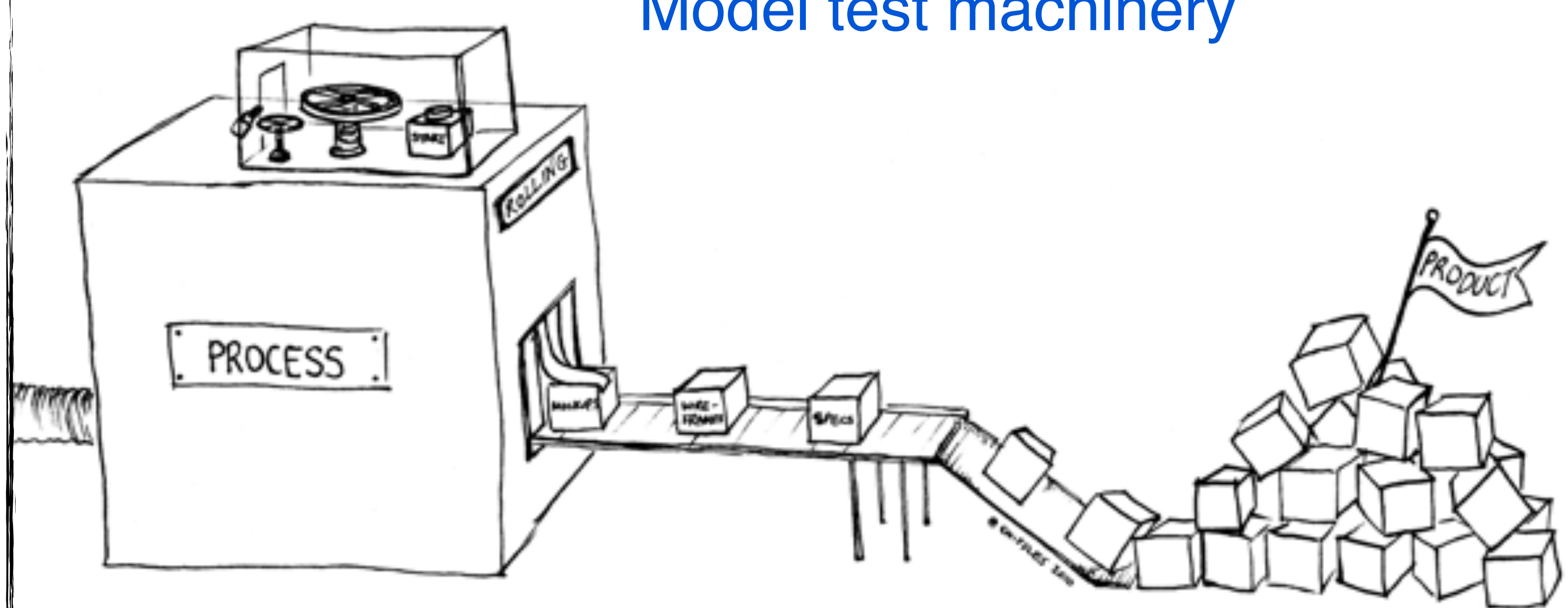
Model implementation with `FeynRules`
SUSY spectrum with `SoftSusy`
Dark matter predictions with `micrOMEGAs`
MonteCarlo simulations with `MadGraph5, Pythia, Delphes`
Sampling with nested sampler `MultiNest`

\+

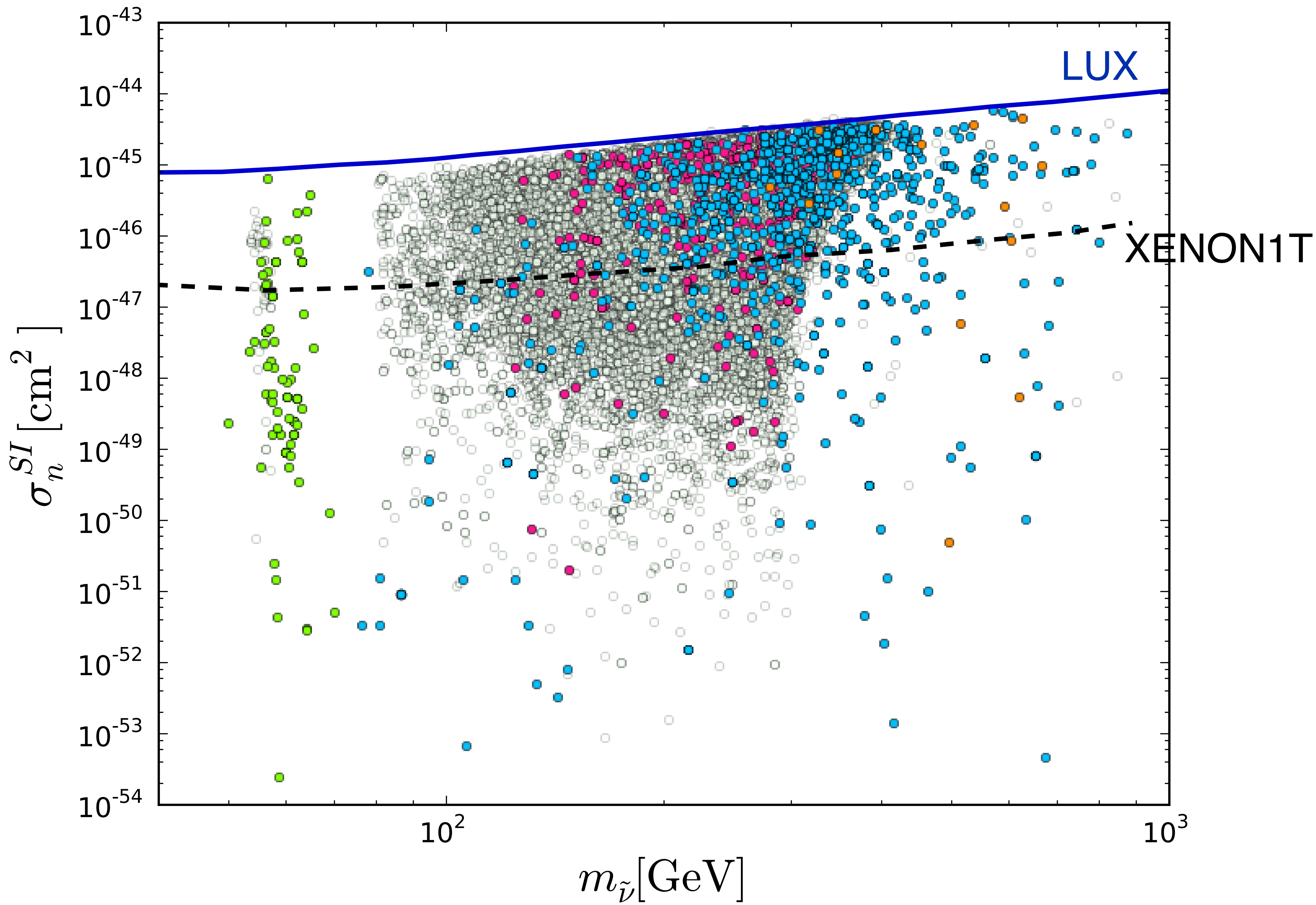
Observational constraints:

1. Higgs mass
2. $\Omega_{\rm DM} h^2$ from Planck
3. Z invisible decay width
4. Higgs invisible decay width
5. LUX bound for direct detection
6. bounds on SUSY masses

Model test machinery



Sneutrino is a good dark matter candidate



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

- Boundary conditions are changed, here they are fixed at GUT scale
- Update with the Higgs mass and LUX bound

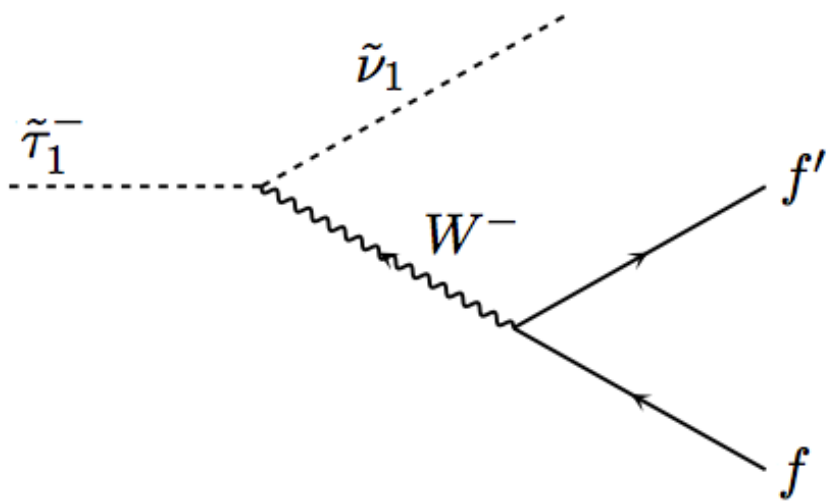
Long-lived staus

Signature arising when:

(orange points)

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

MSSM + RN



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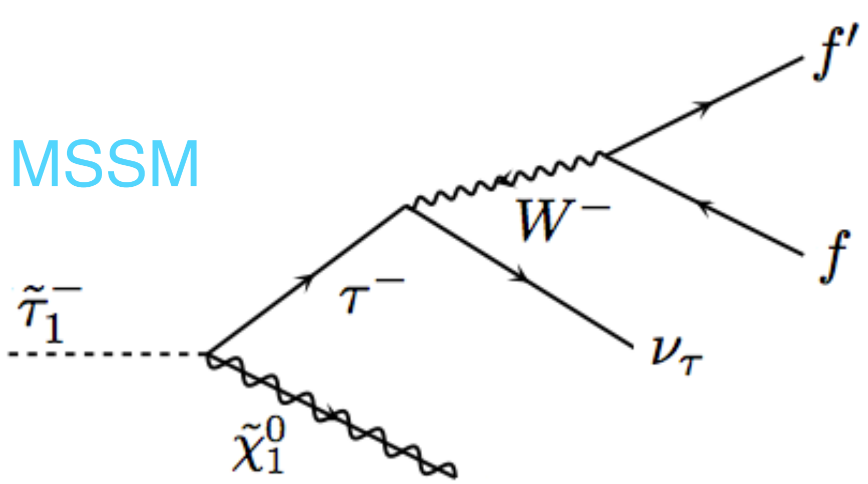
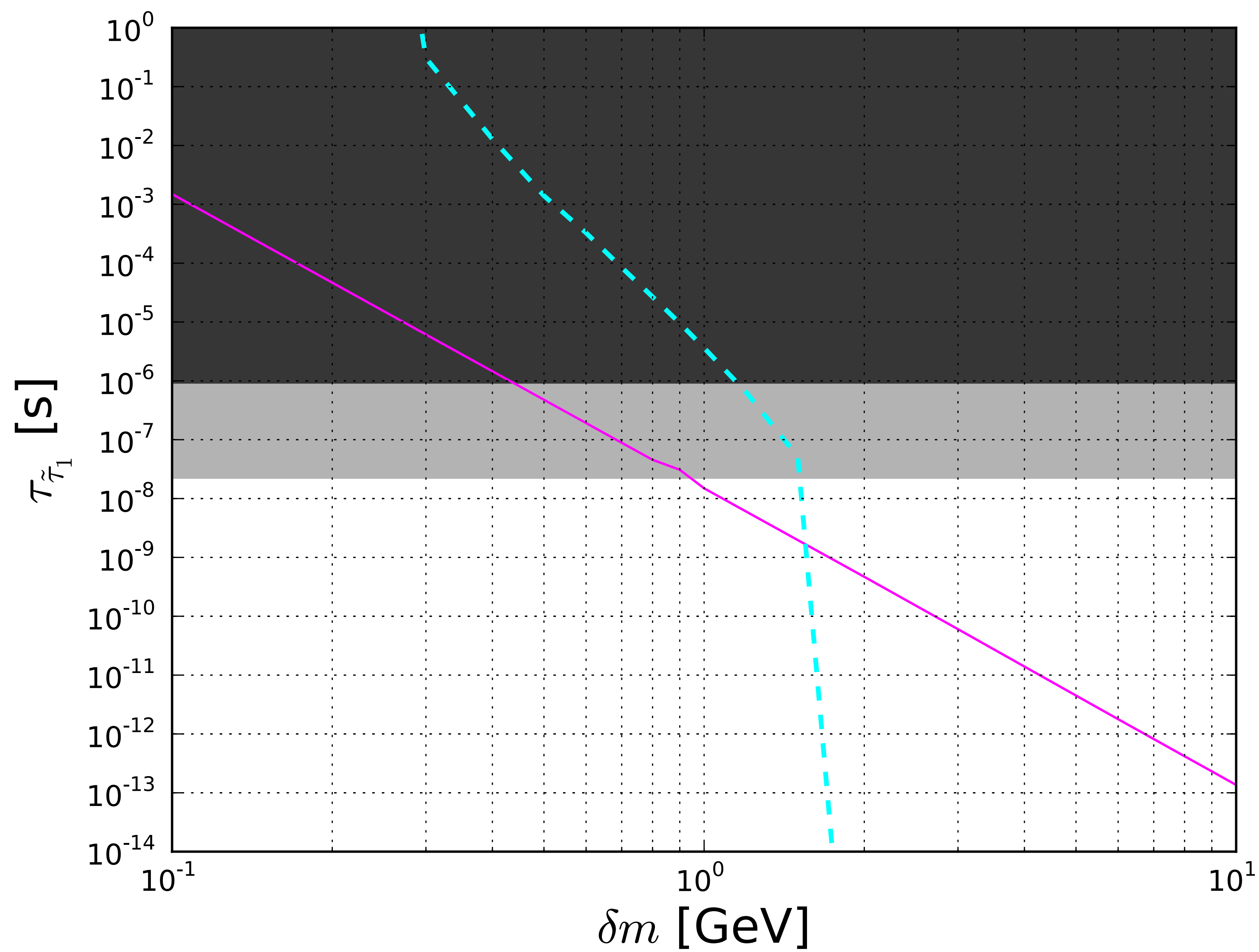
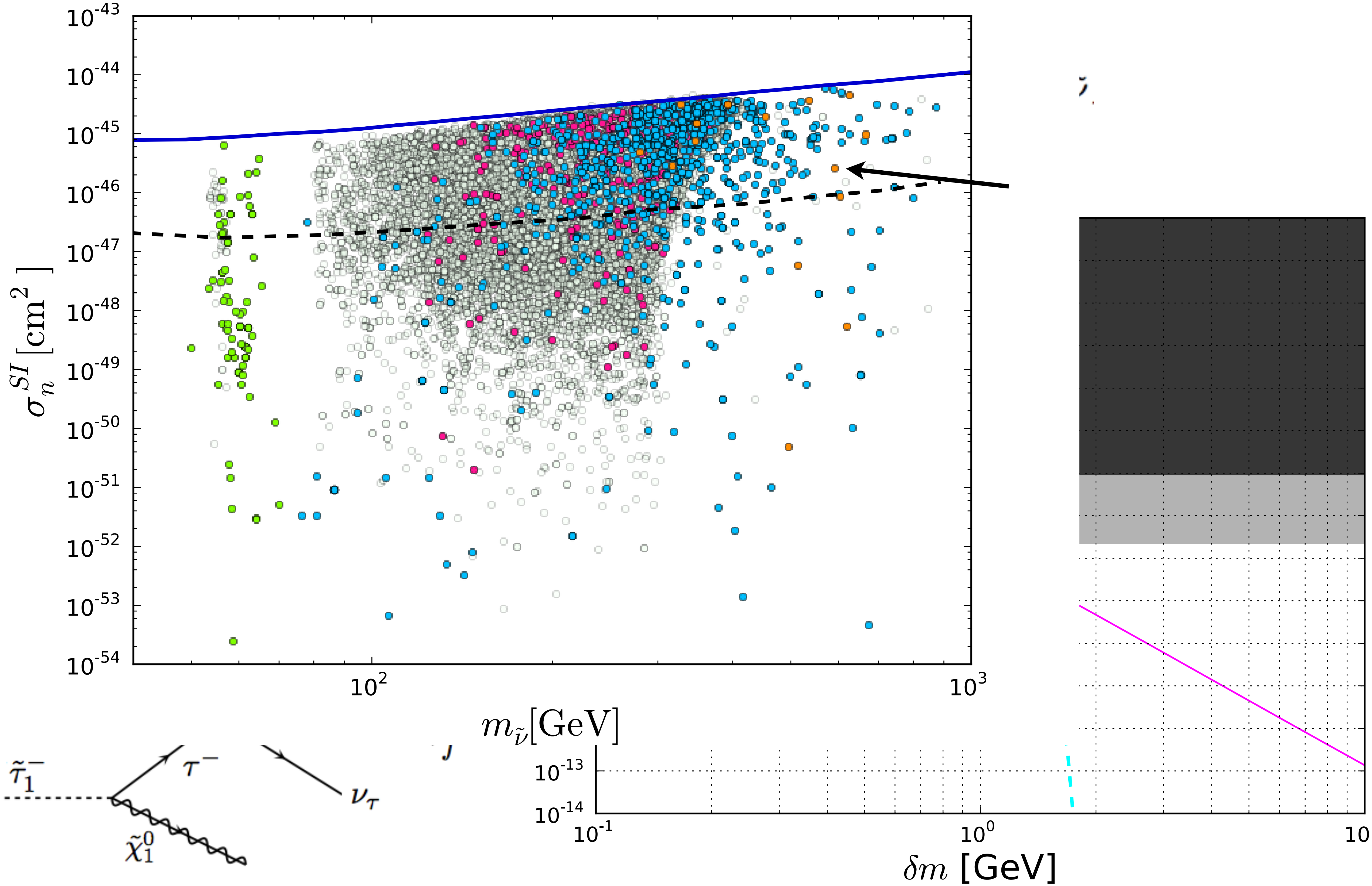




Existing bound: $mass_{llp}$ > 300 GeV allowed (ATLAS-CONF-2013-58)



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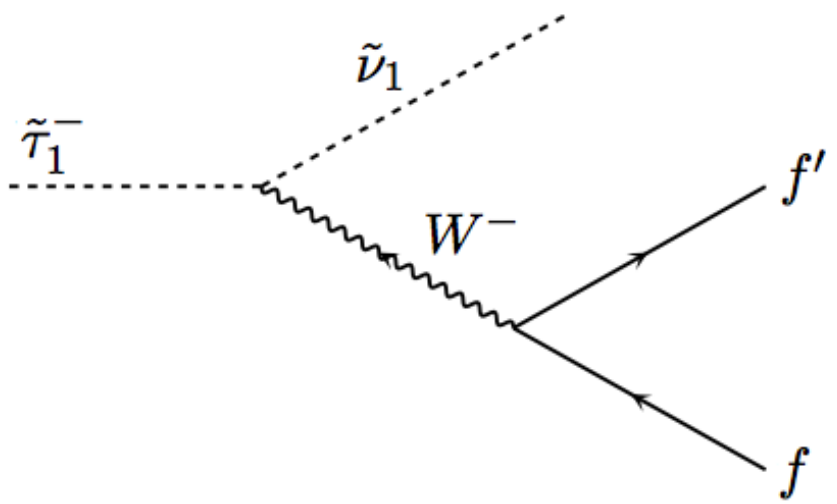

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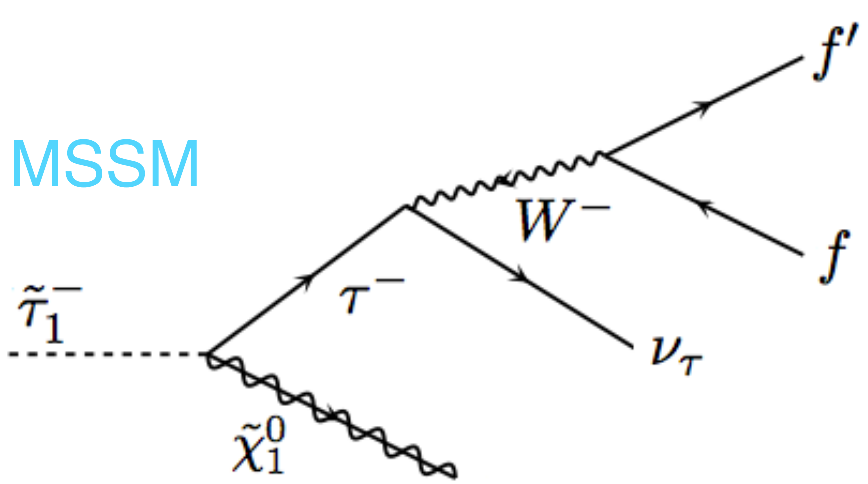

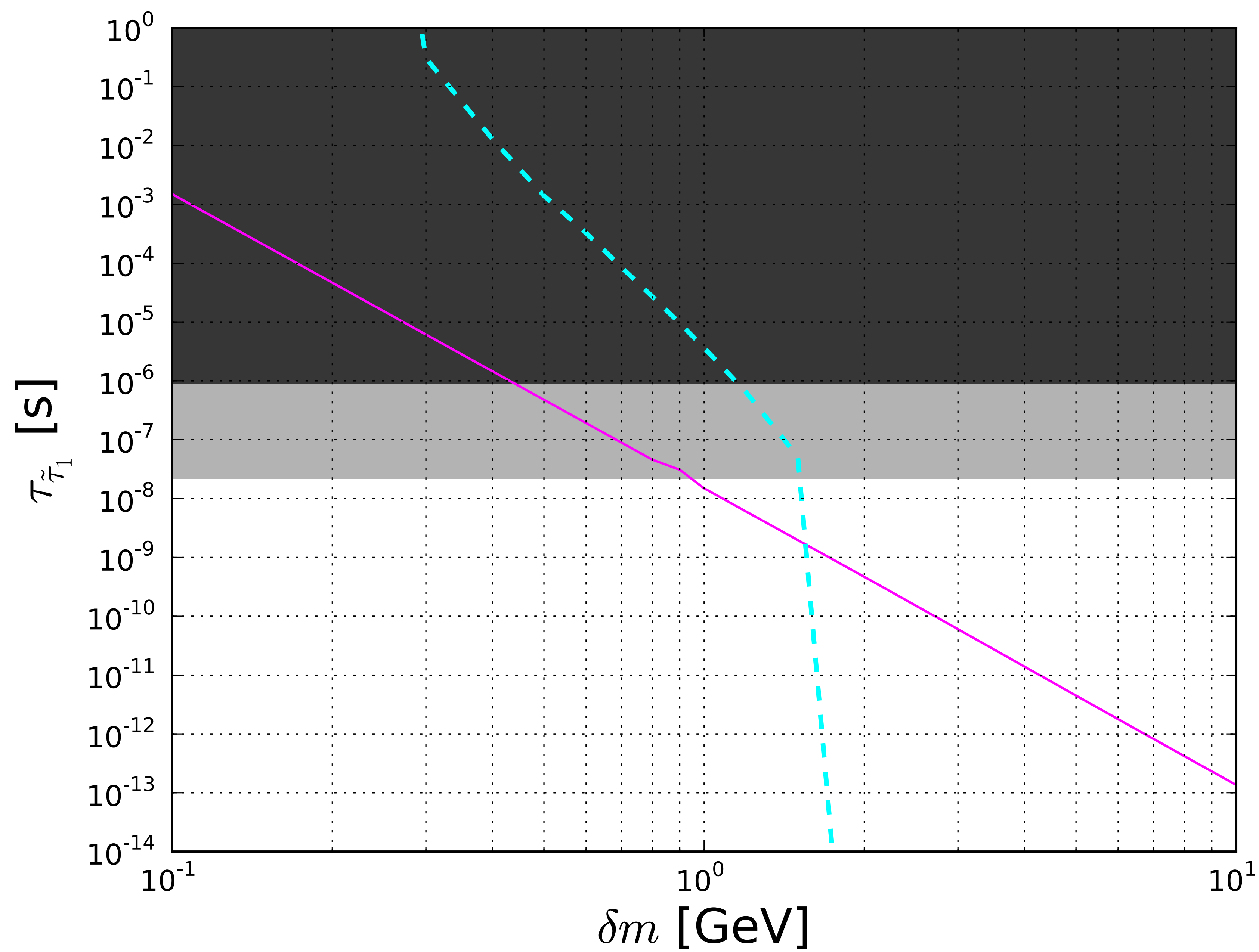

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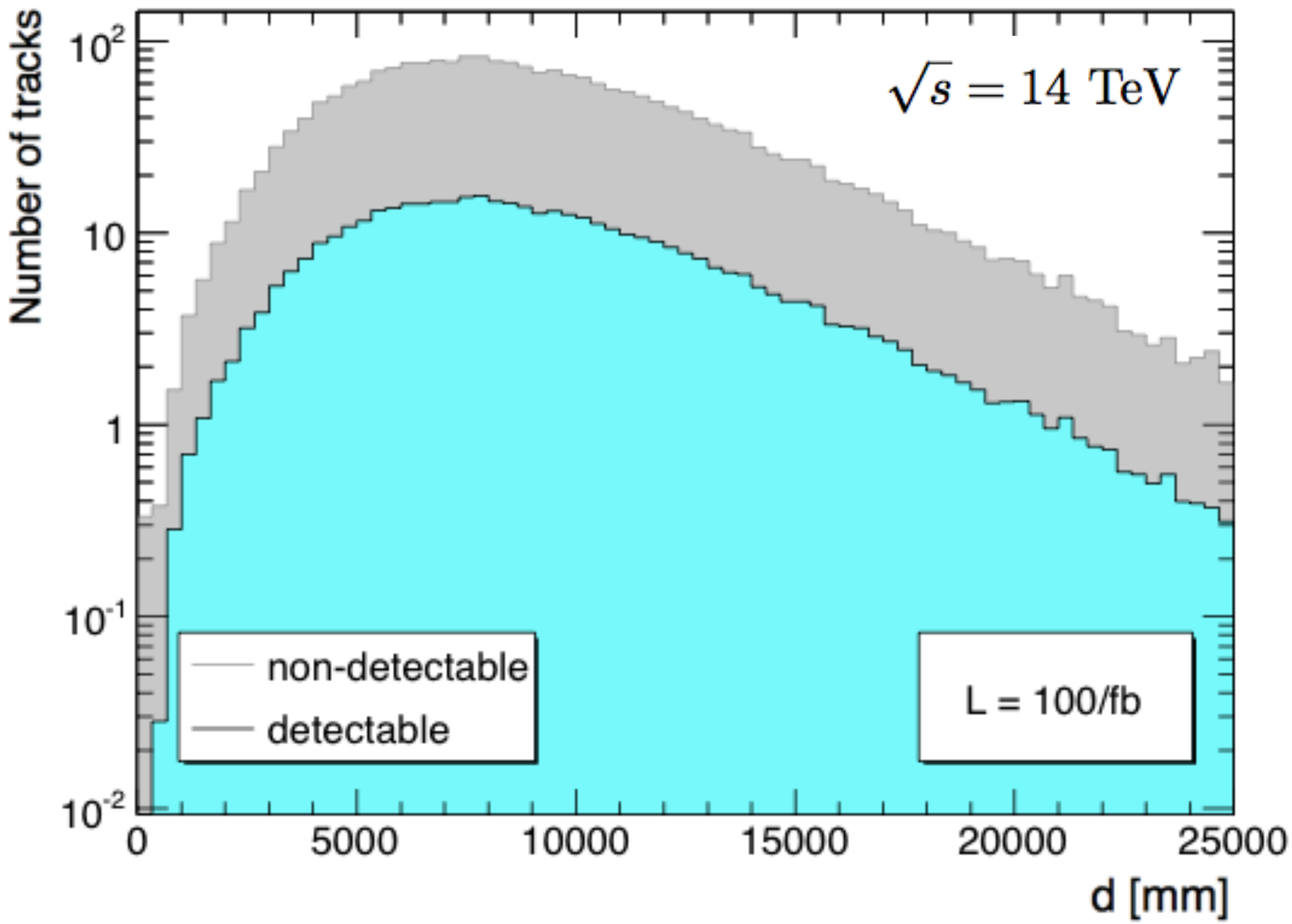
- Staus produced in pair directly
- Assumed observation of both charged tracks from the hadronic calorimeter to escaping charged particles (ATLAS efficiency $\epsilon = 0.2$)



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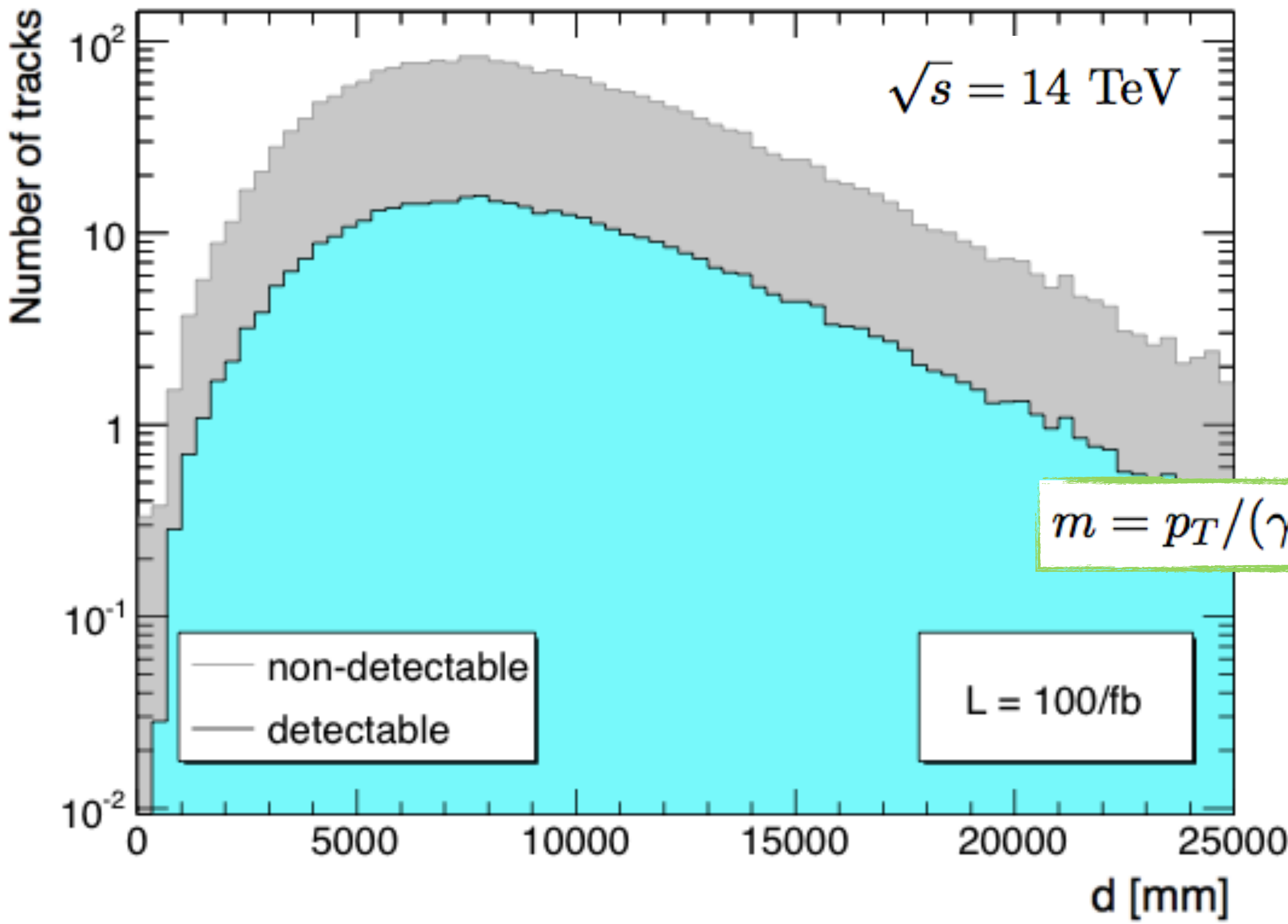
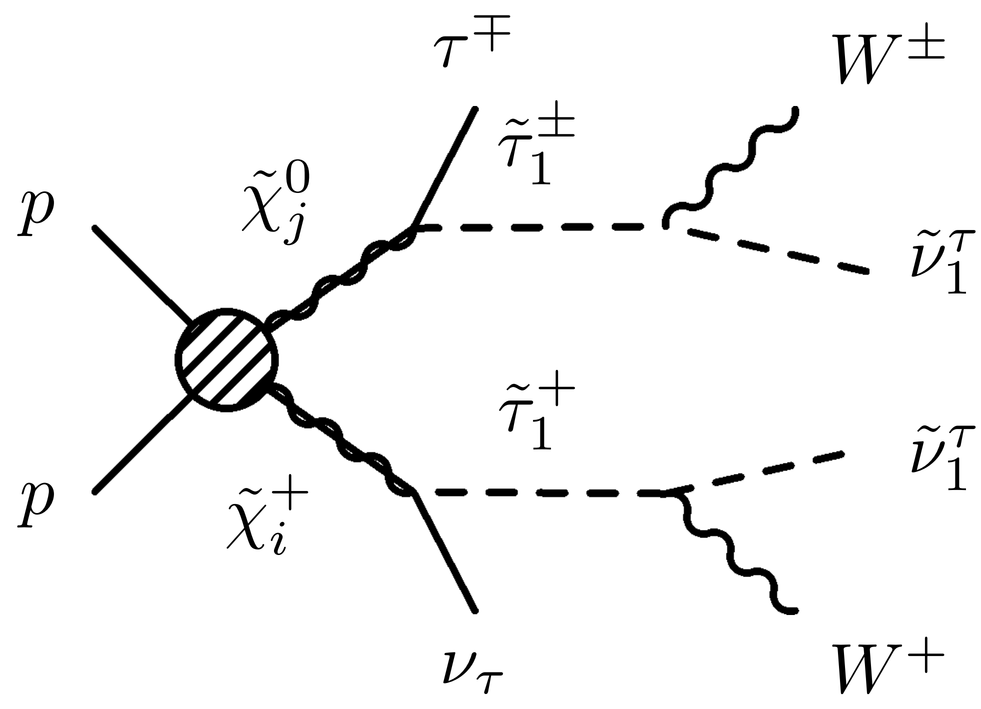


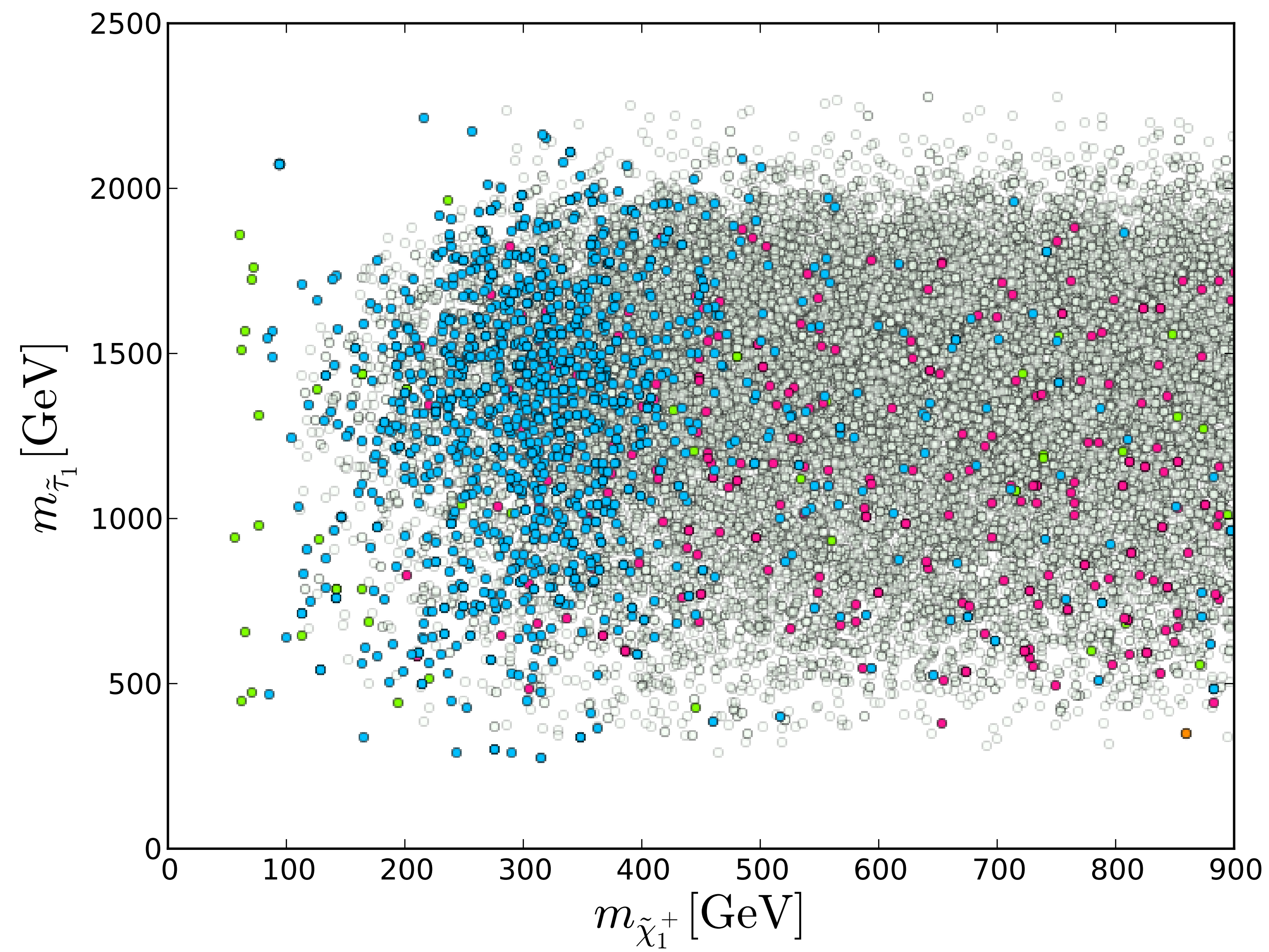
$m = p_T/(\gamma\beta)$

2 Same sign leptons, uncorrelated flavor



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

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%



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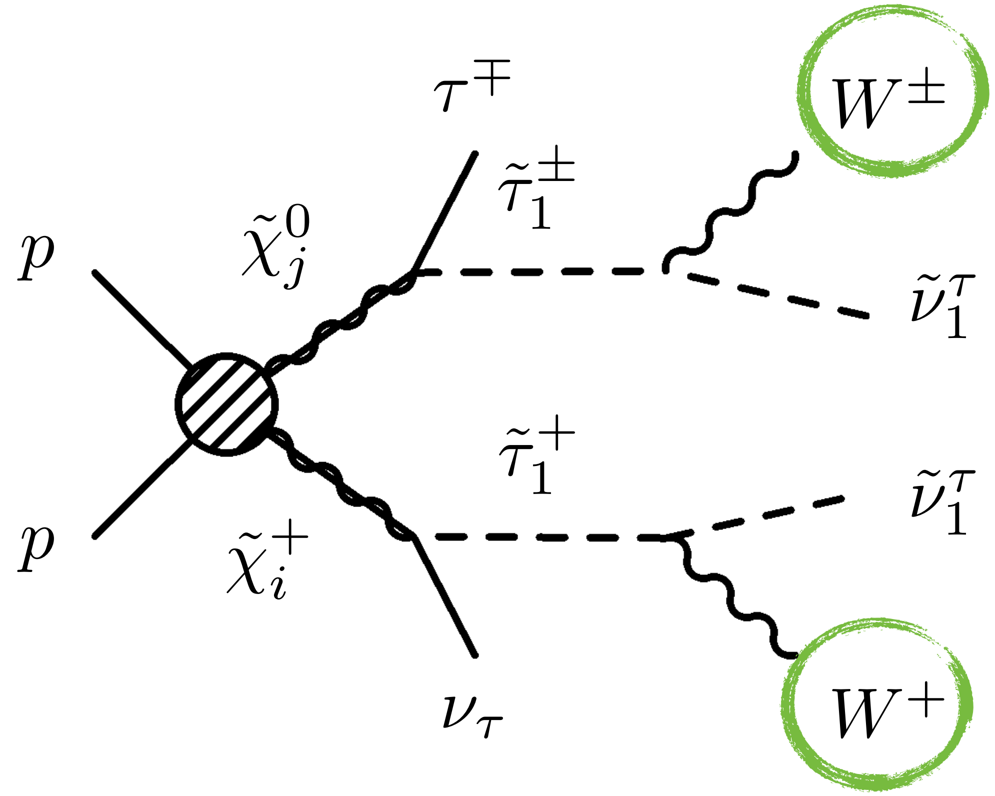
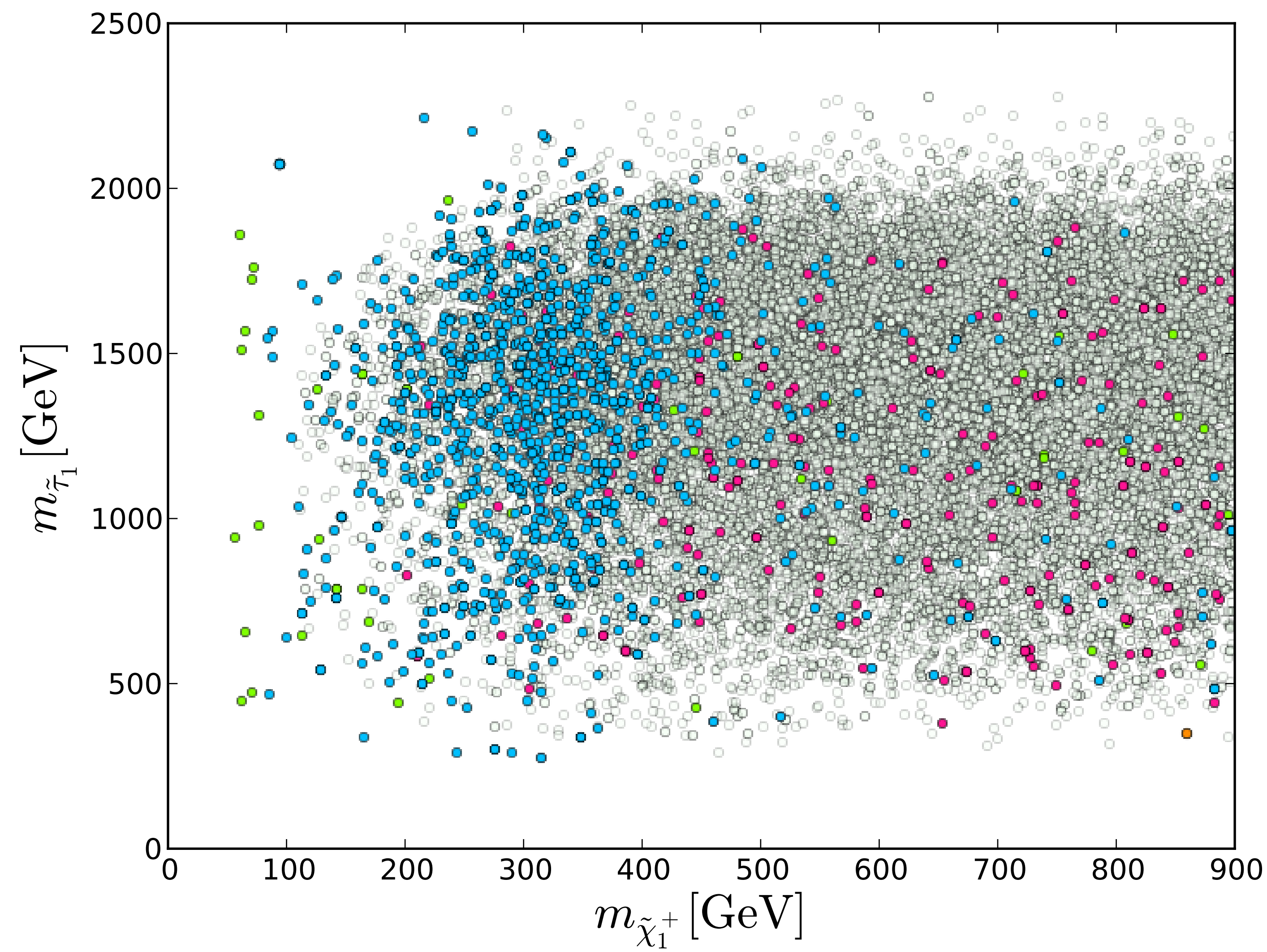


- Arises when the stau is the NLSP
- Different from MSSM where the OS leptons should have the same sign

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%



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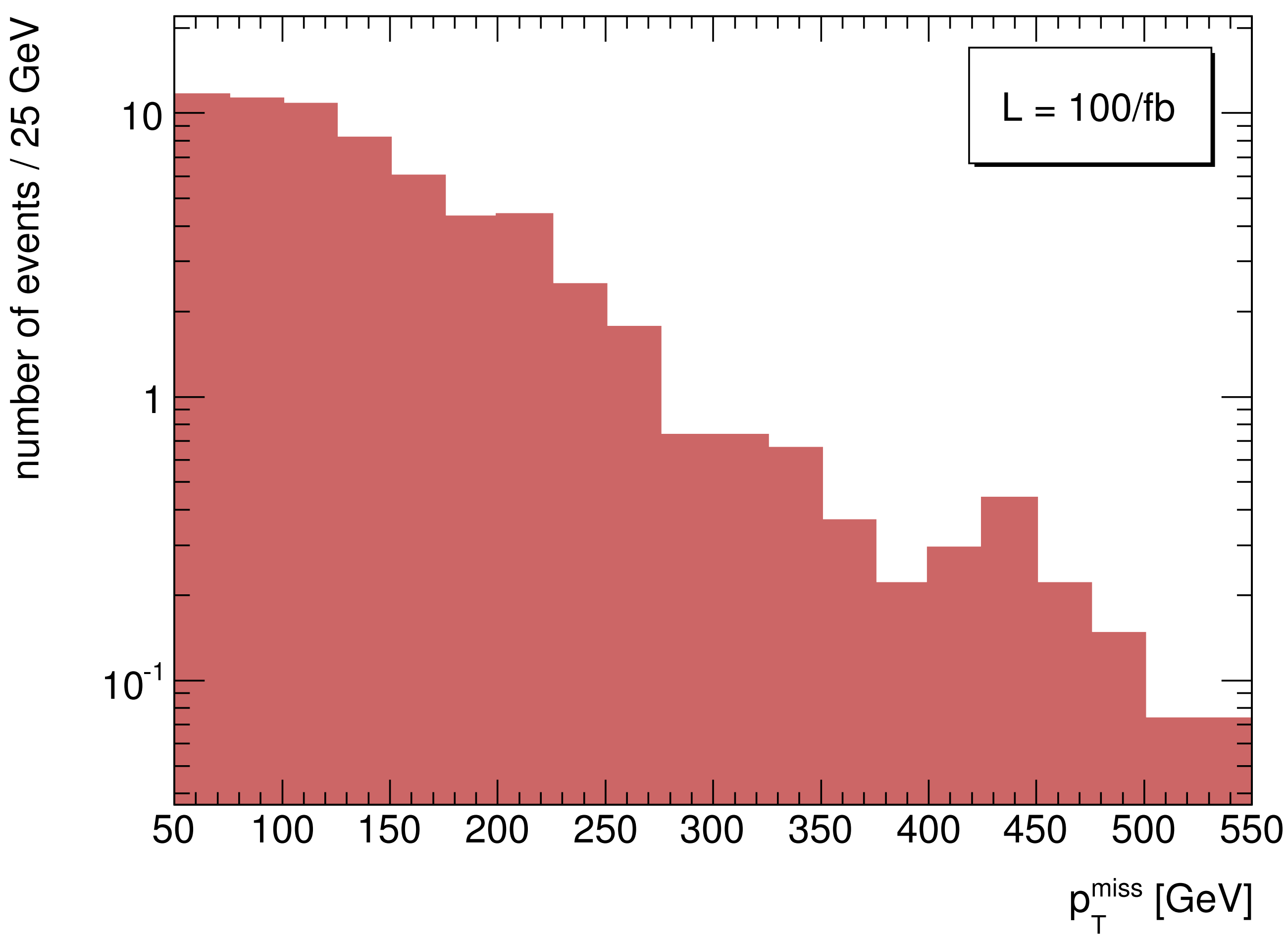

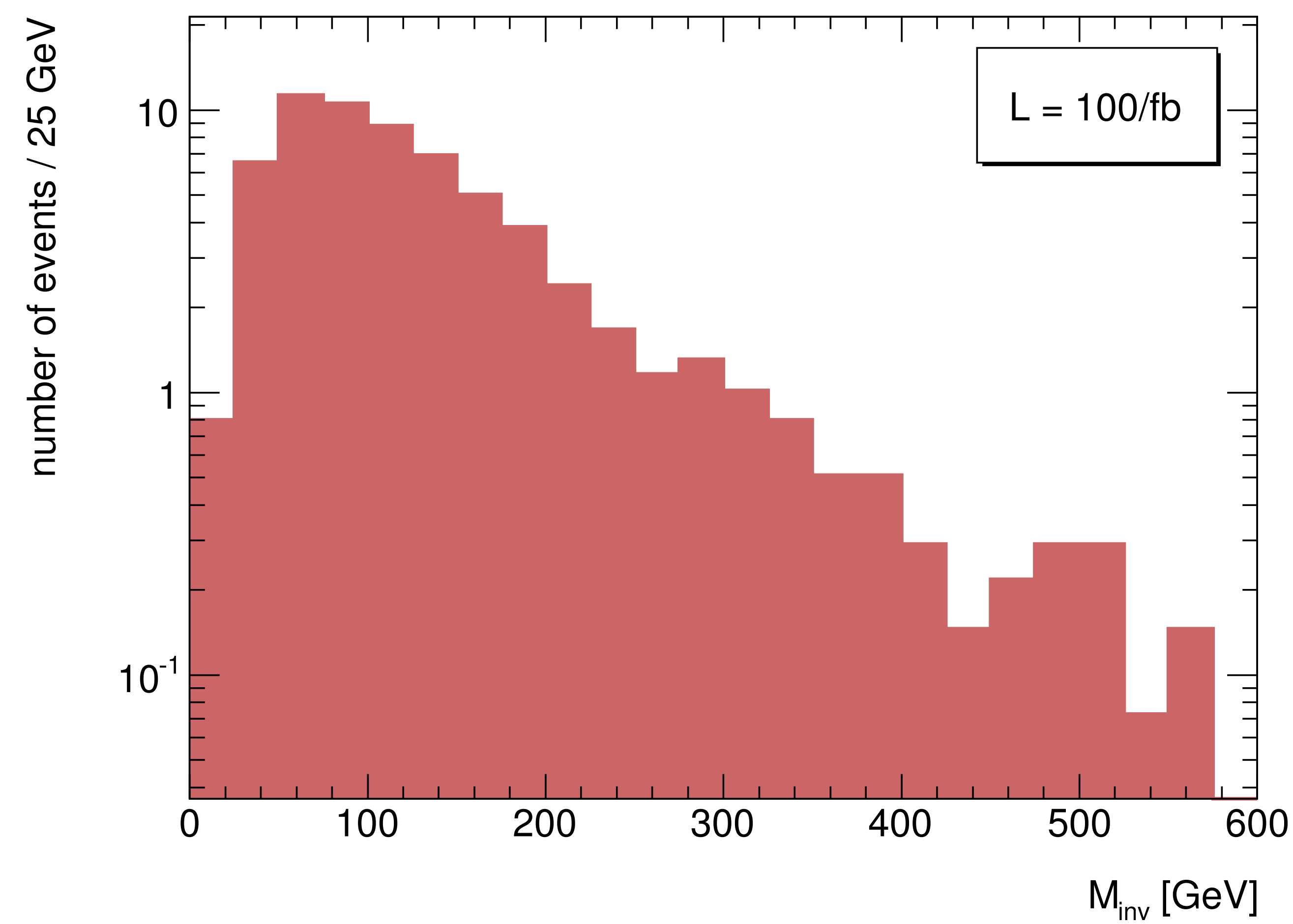

The signal is hidden at low p_T and M_{inv} values, where the background is maximal

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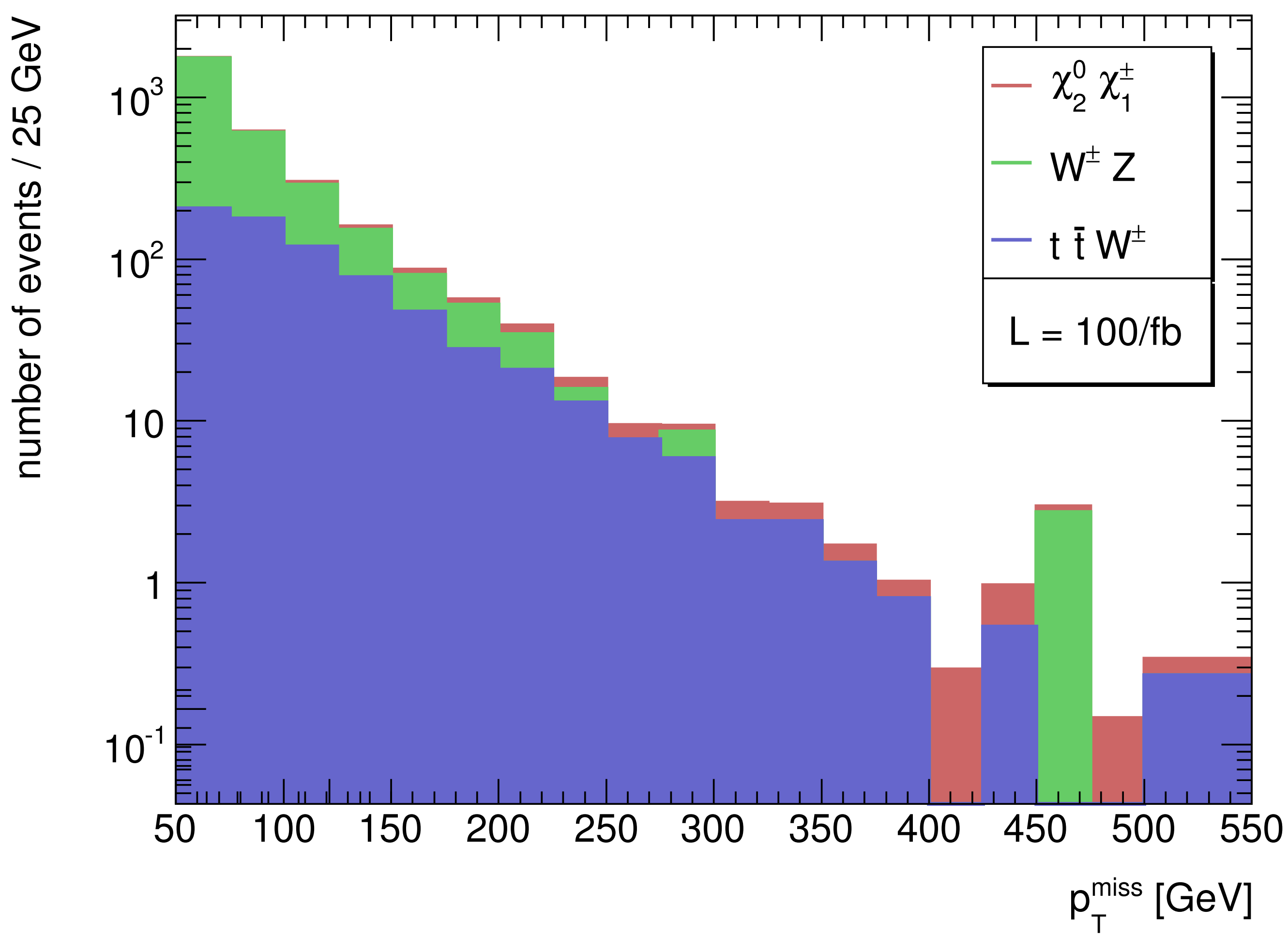

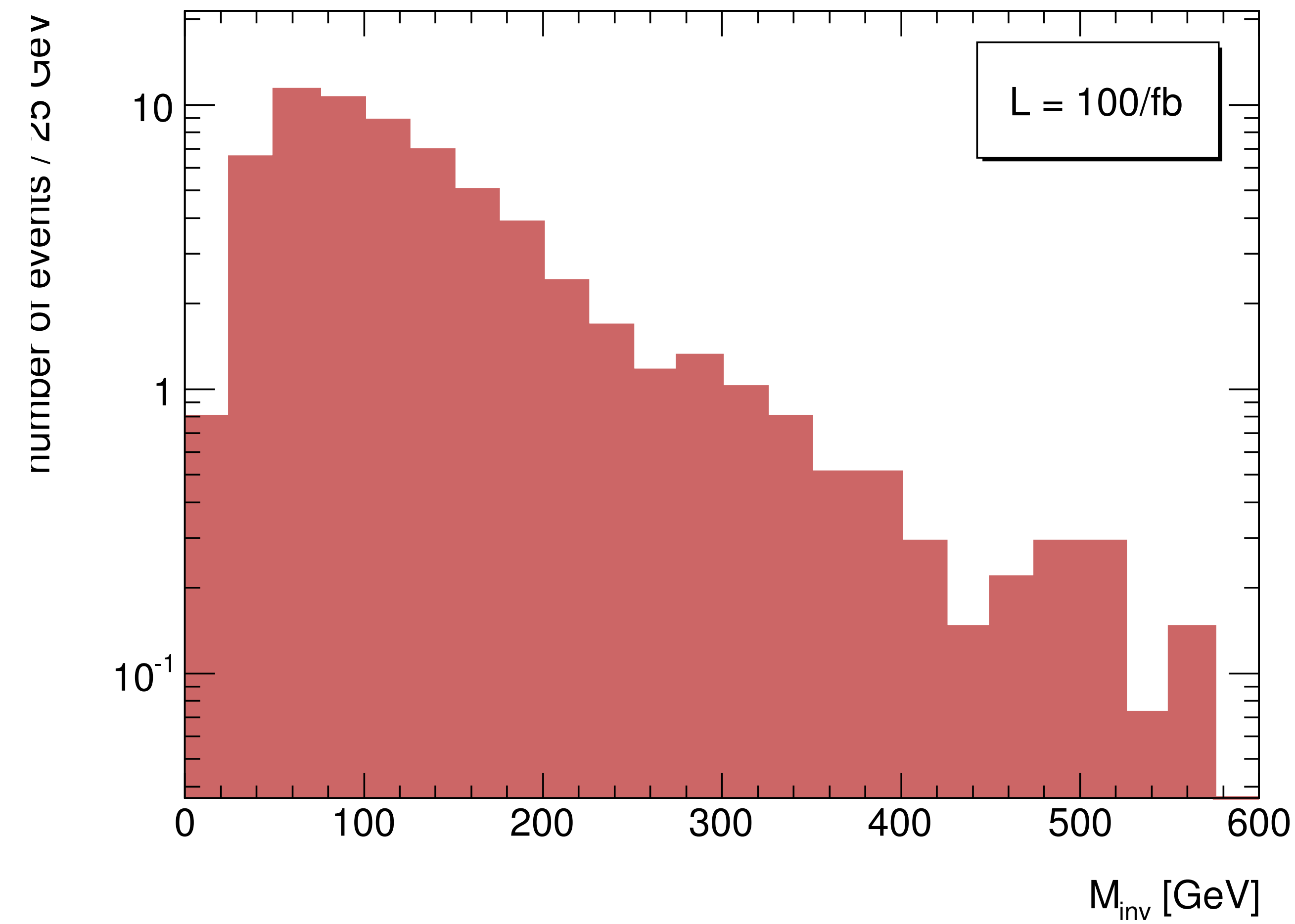

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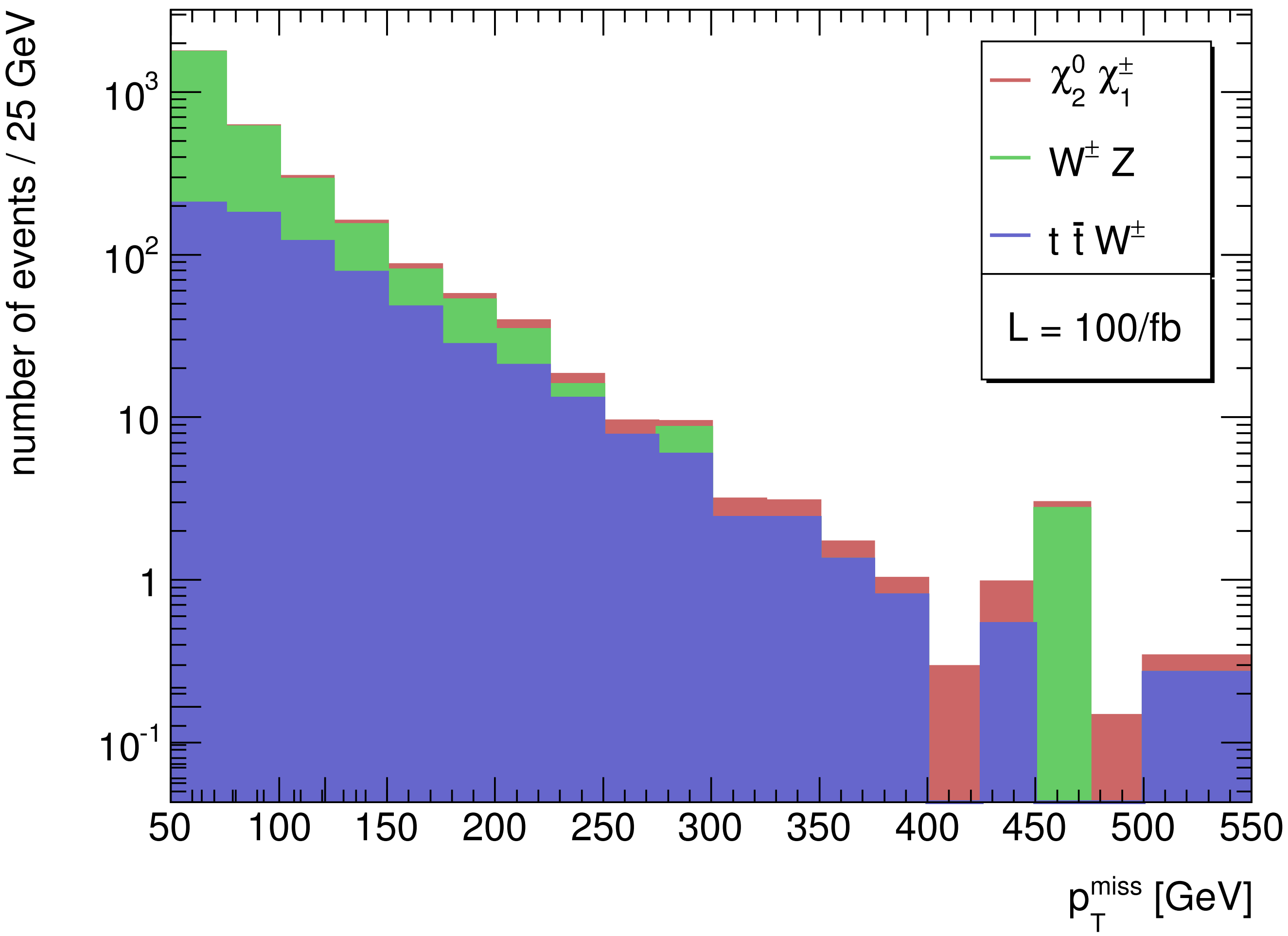

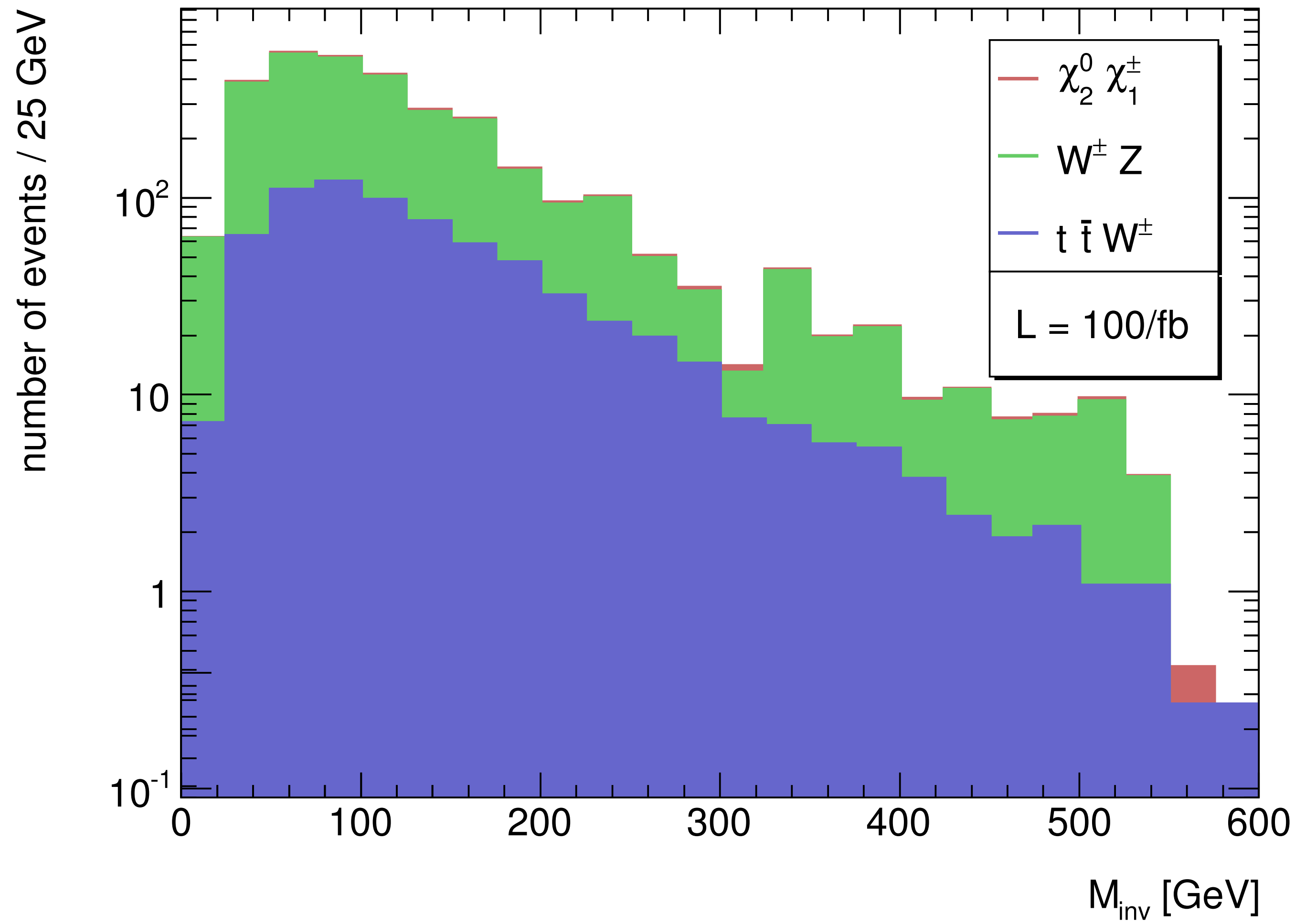

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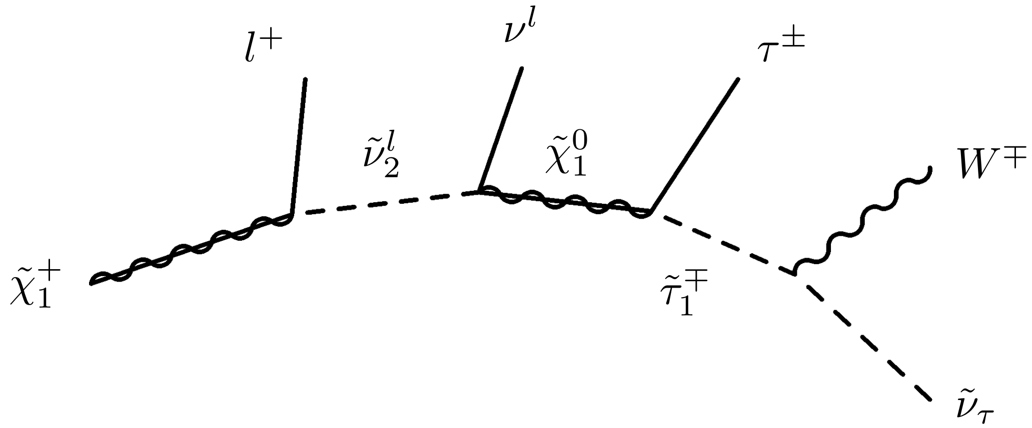
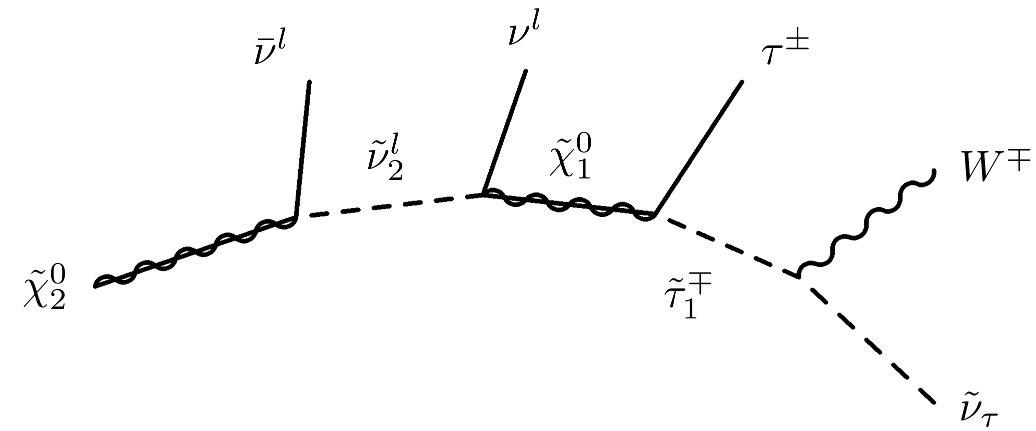
3 uncorrelated leptons



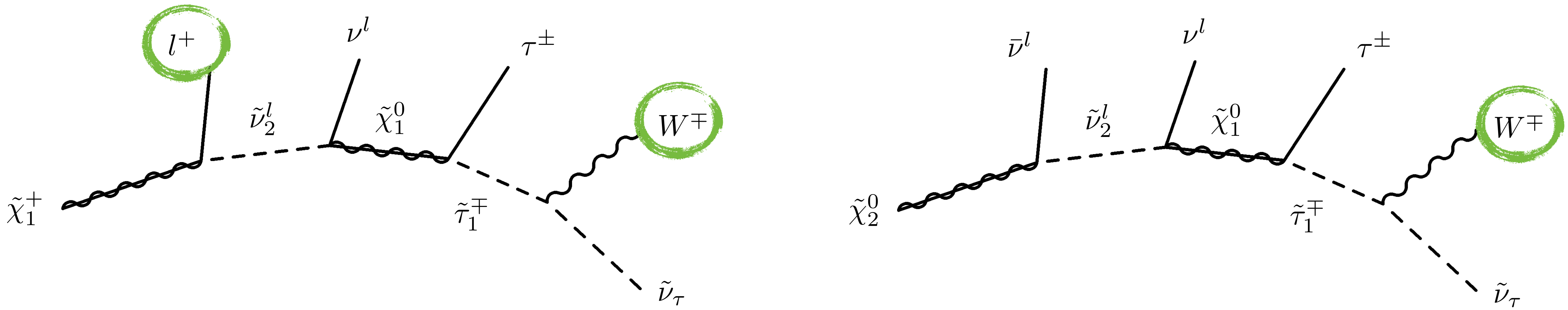


- Feature characteristic of the Higgs pole (LSP very right-handed)
- Sleptons are lighter than charginos and neutralinos (typically stau is the NLSP)
- The two final taus are not tagged due to low efficiency

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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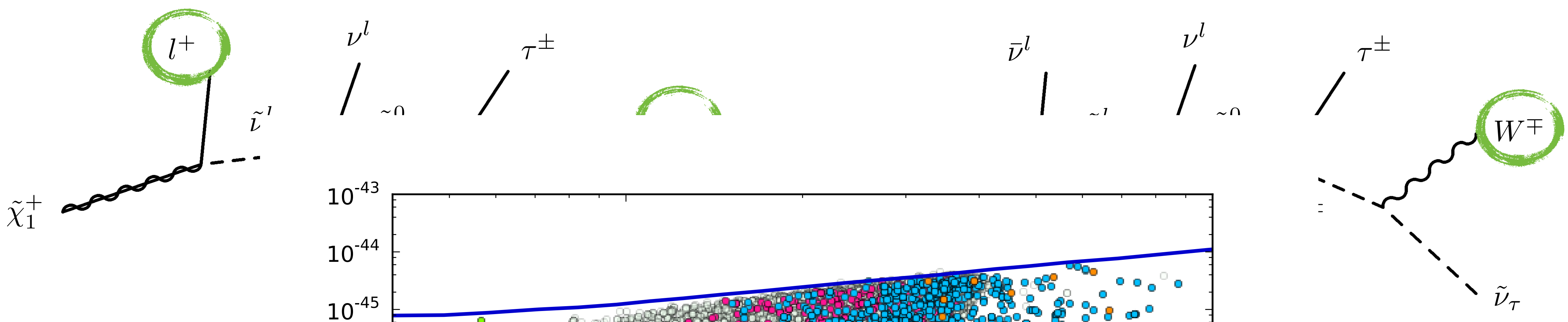

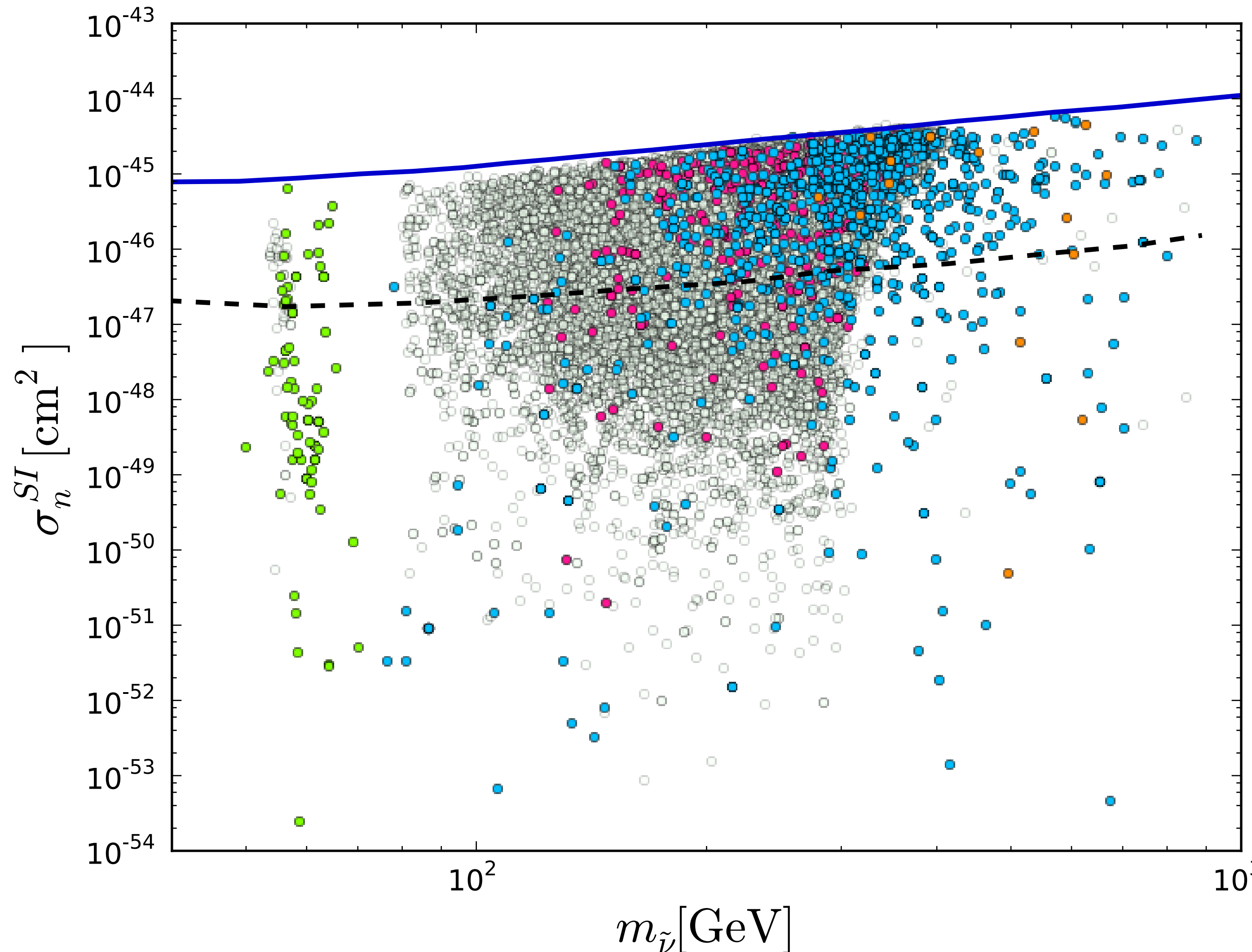

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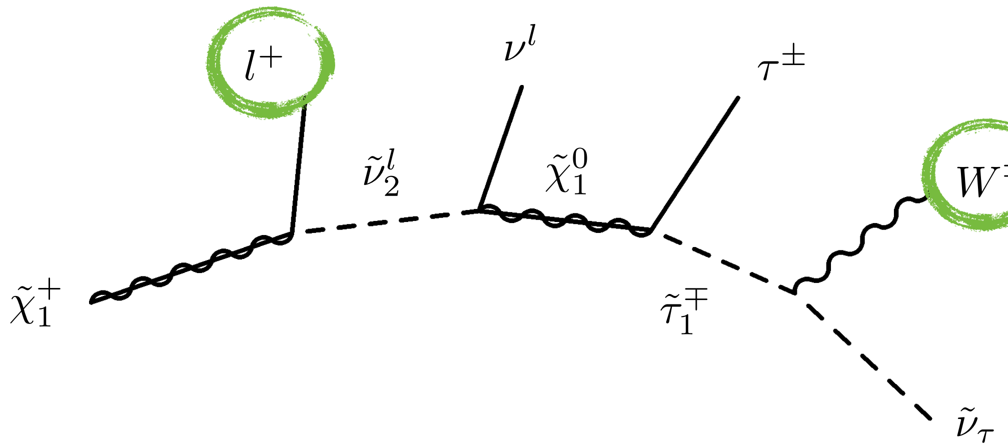

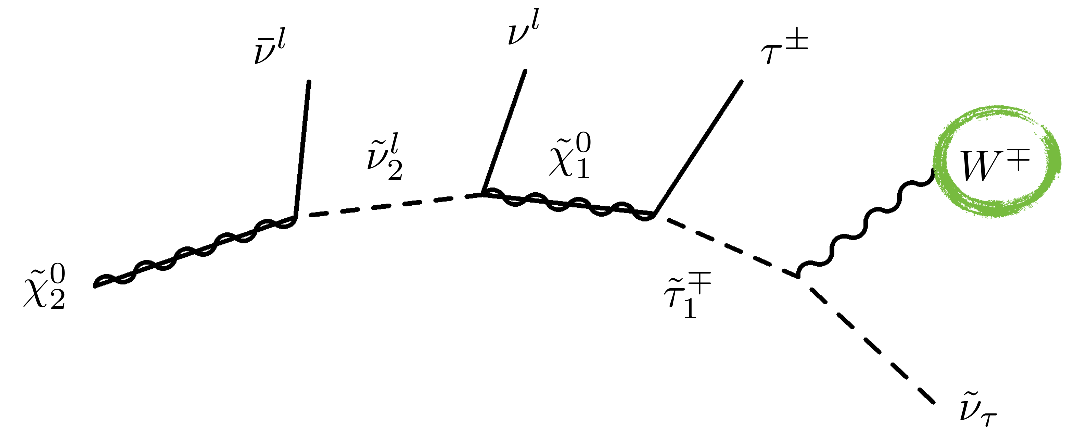

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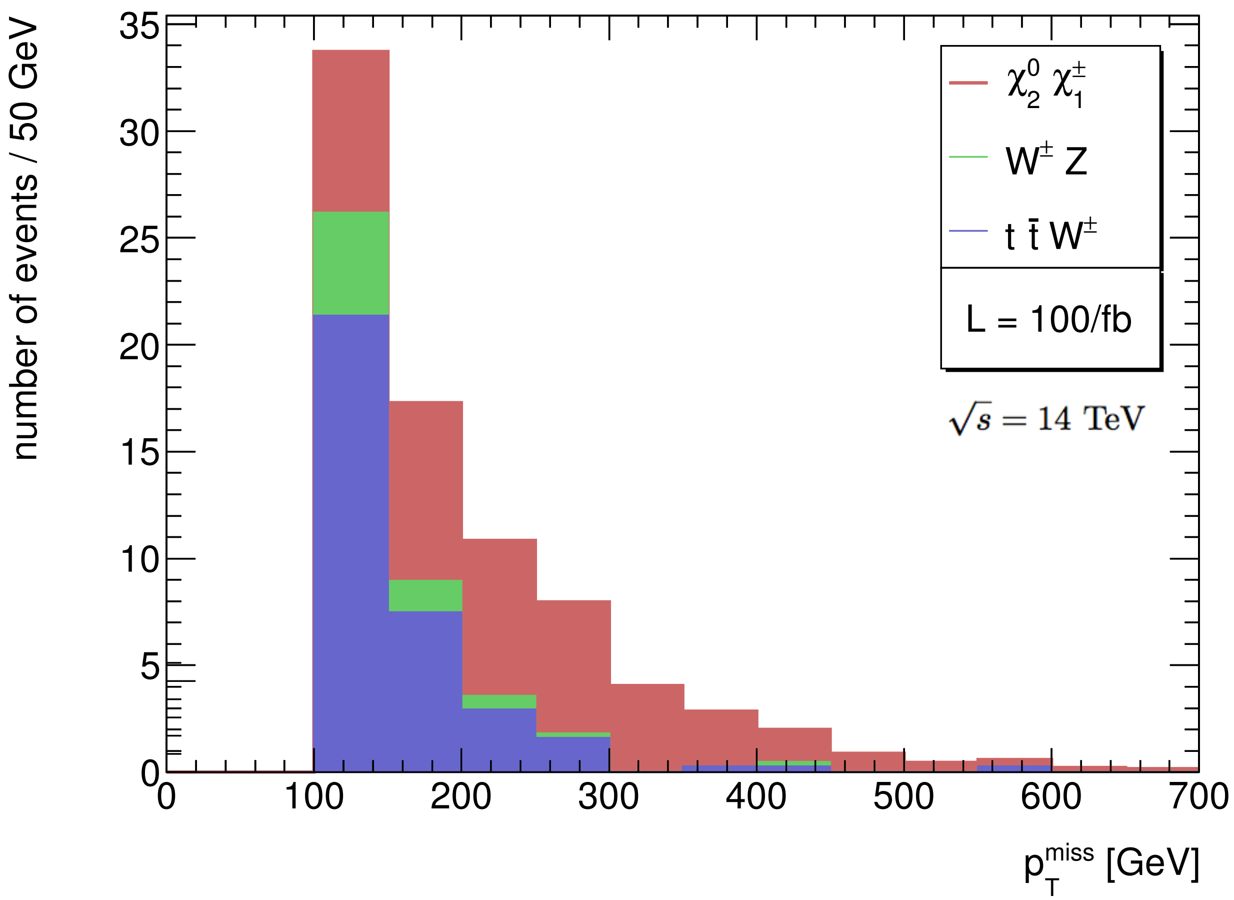
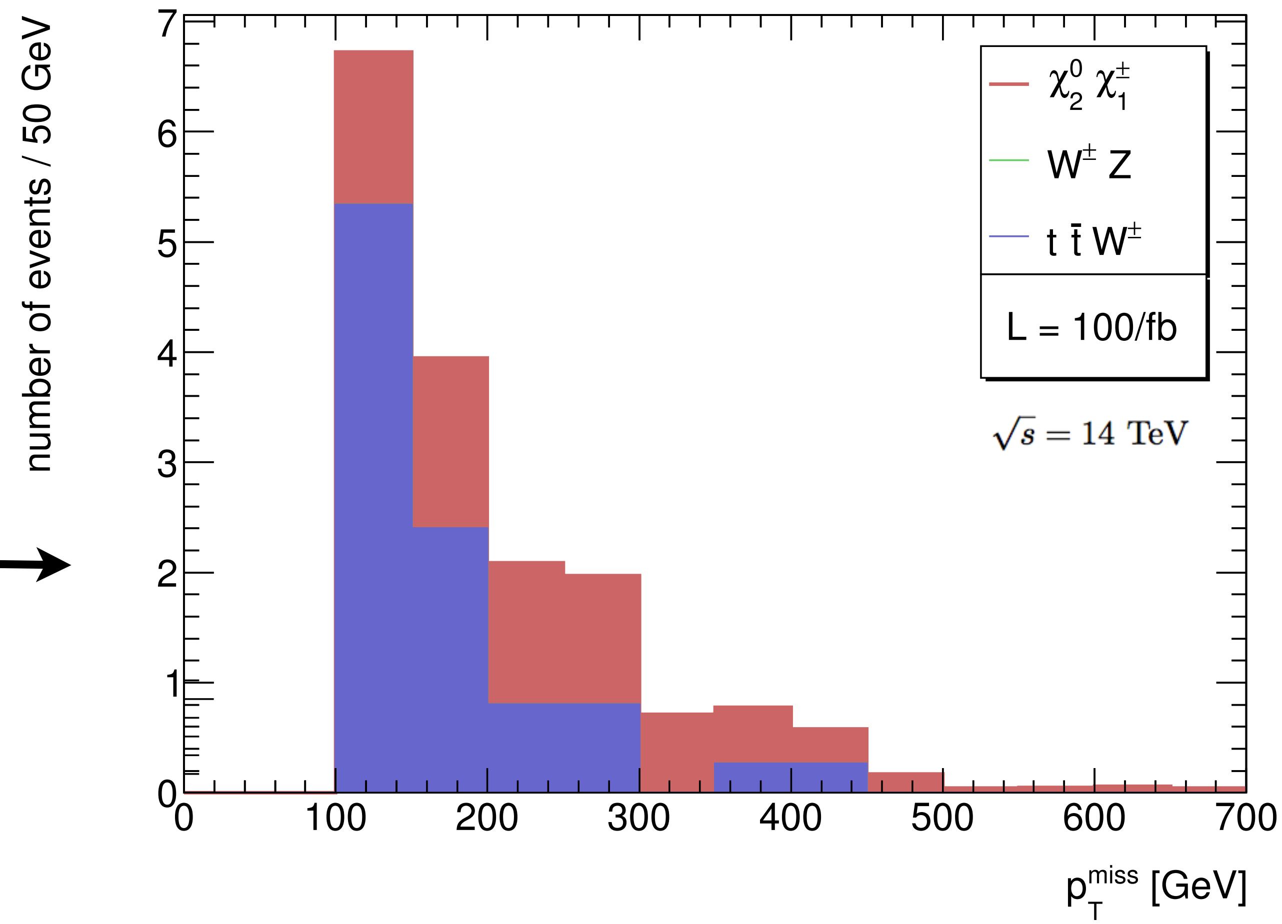
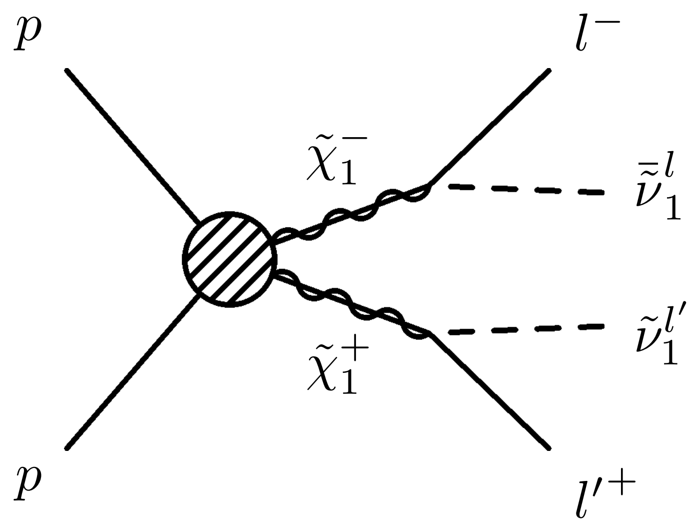


Additional cut of forbidding OSSF leptons



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%

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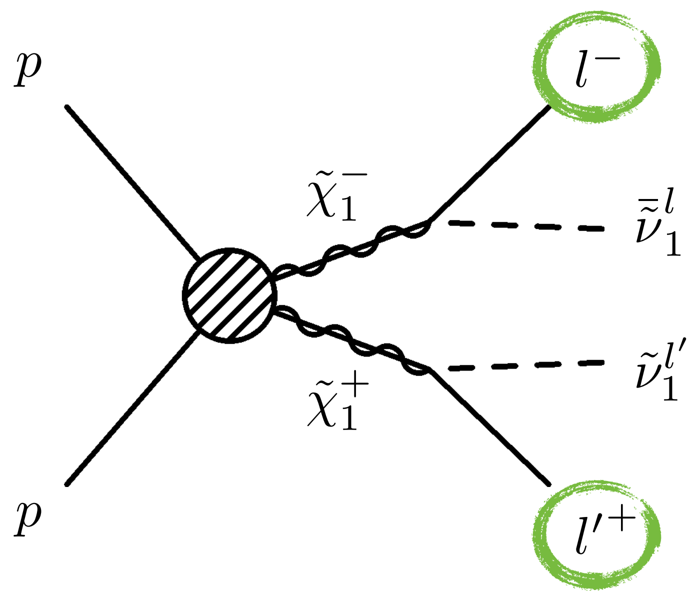

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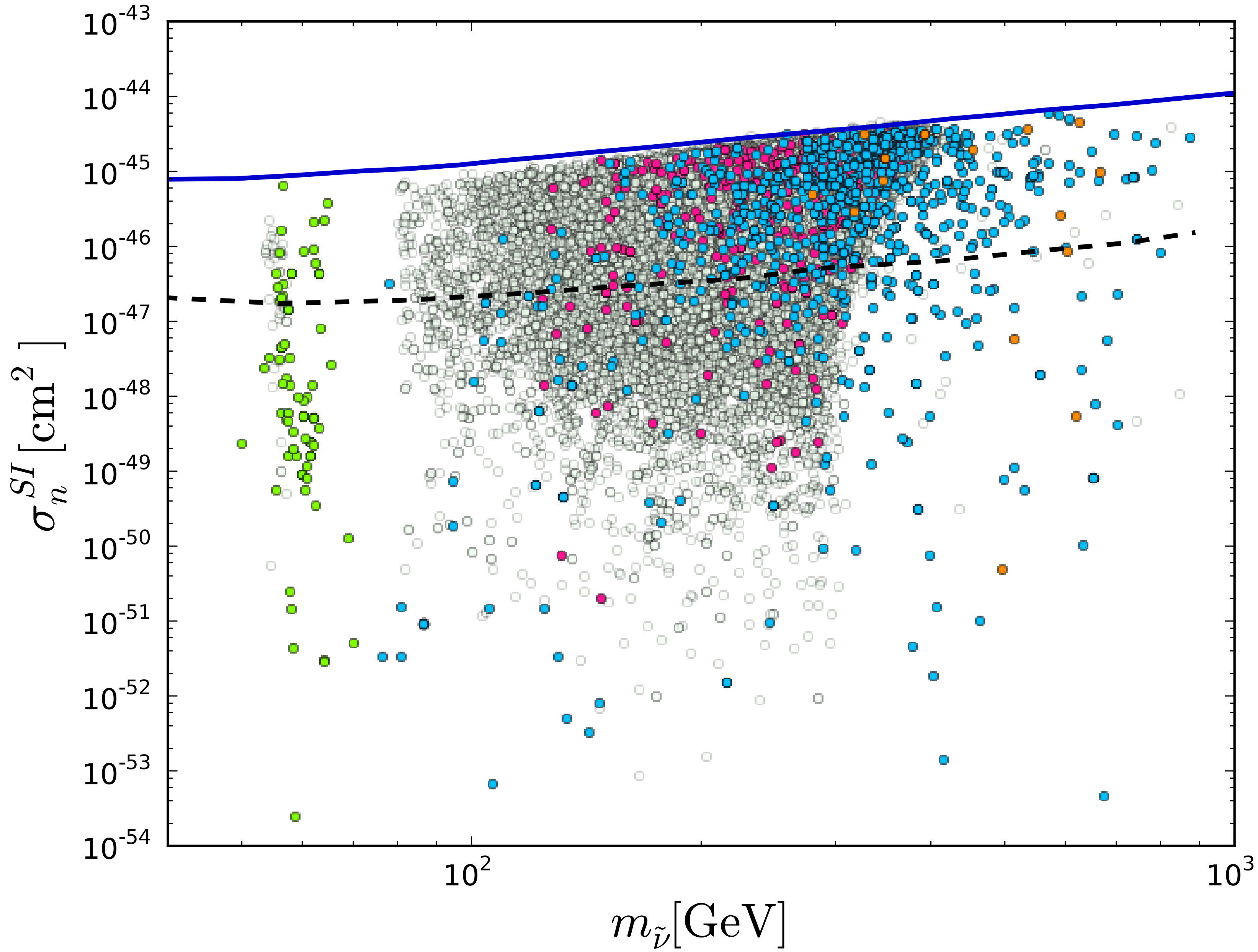
Signal: 2 leptons with opposite sign and uncorrelated flavor

Chargino production



$\tilde{\chi}$

ı sleptons

ʌSSM is 3-body)

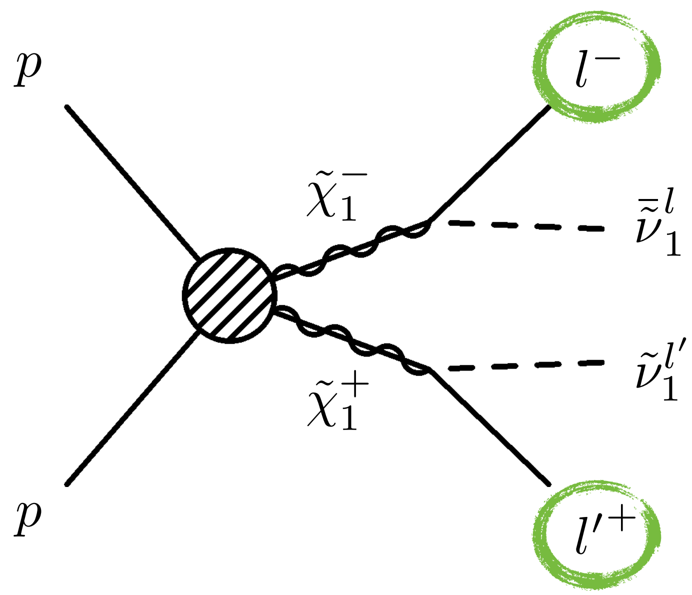
$V^{\pm}\tilde{\chi}_1^0 \to f' \, \bar{f}\tilde{\chi}_1^0$

ptons

te sign

related

Chargino production



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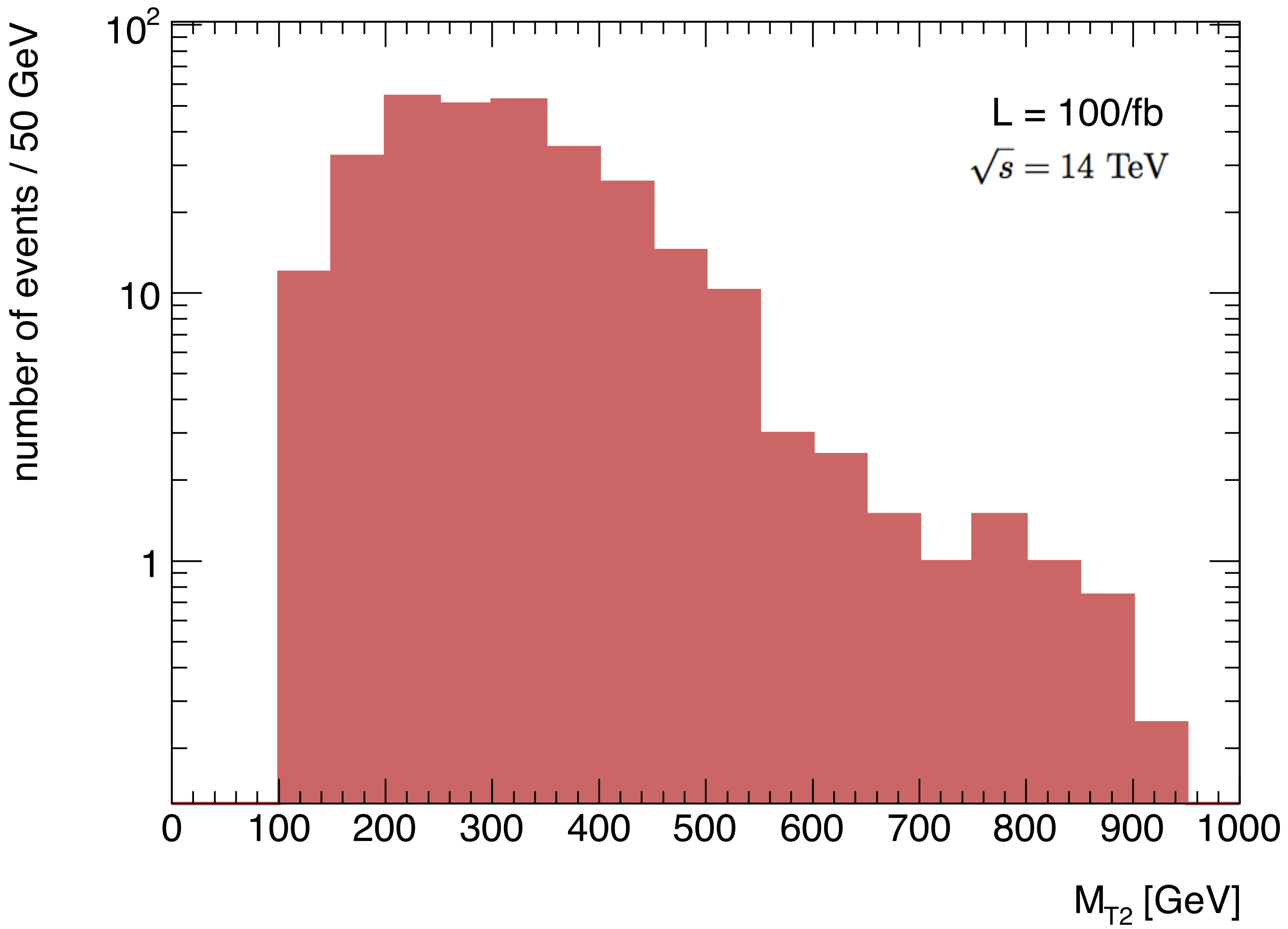
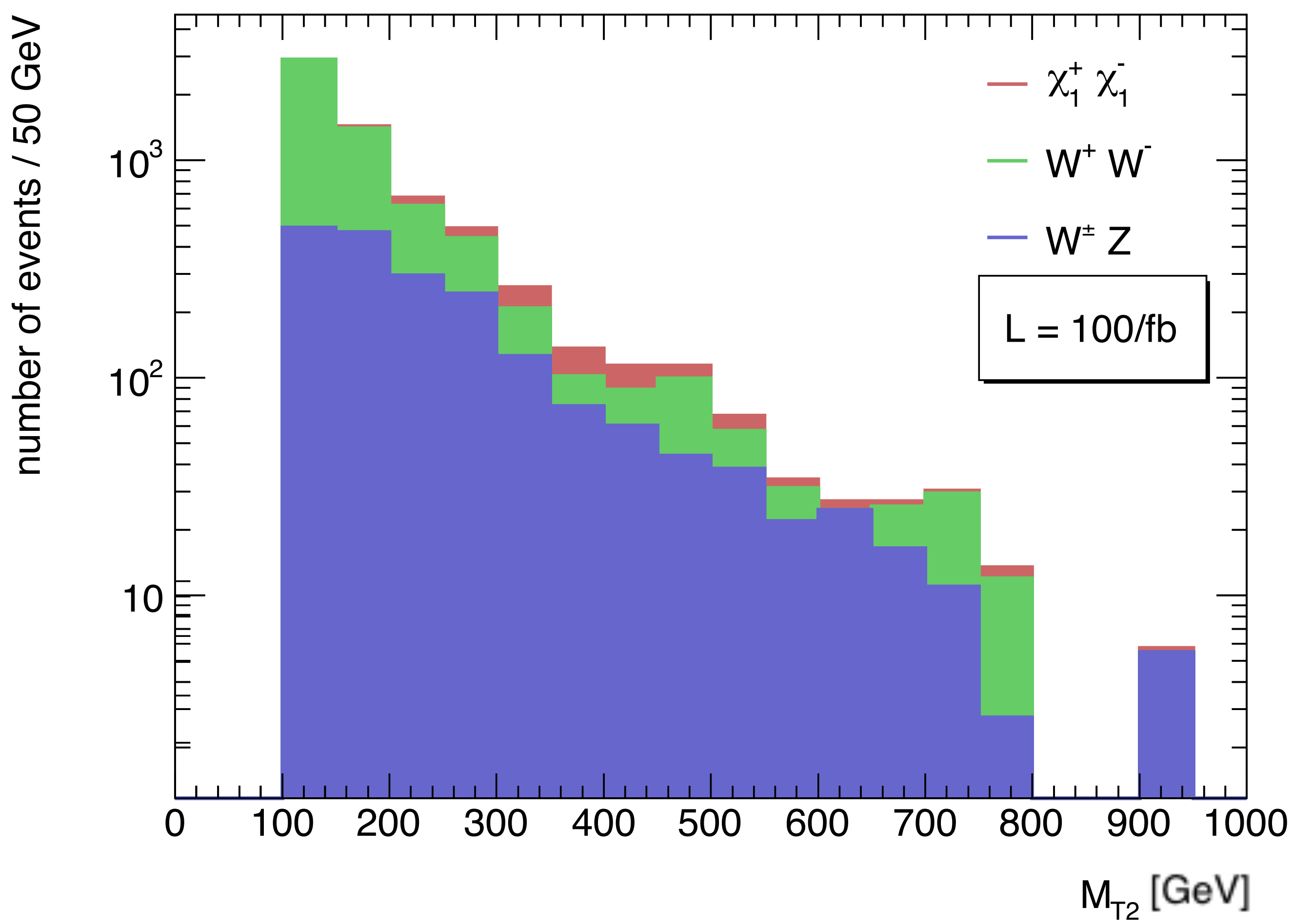
Chargino production

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

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





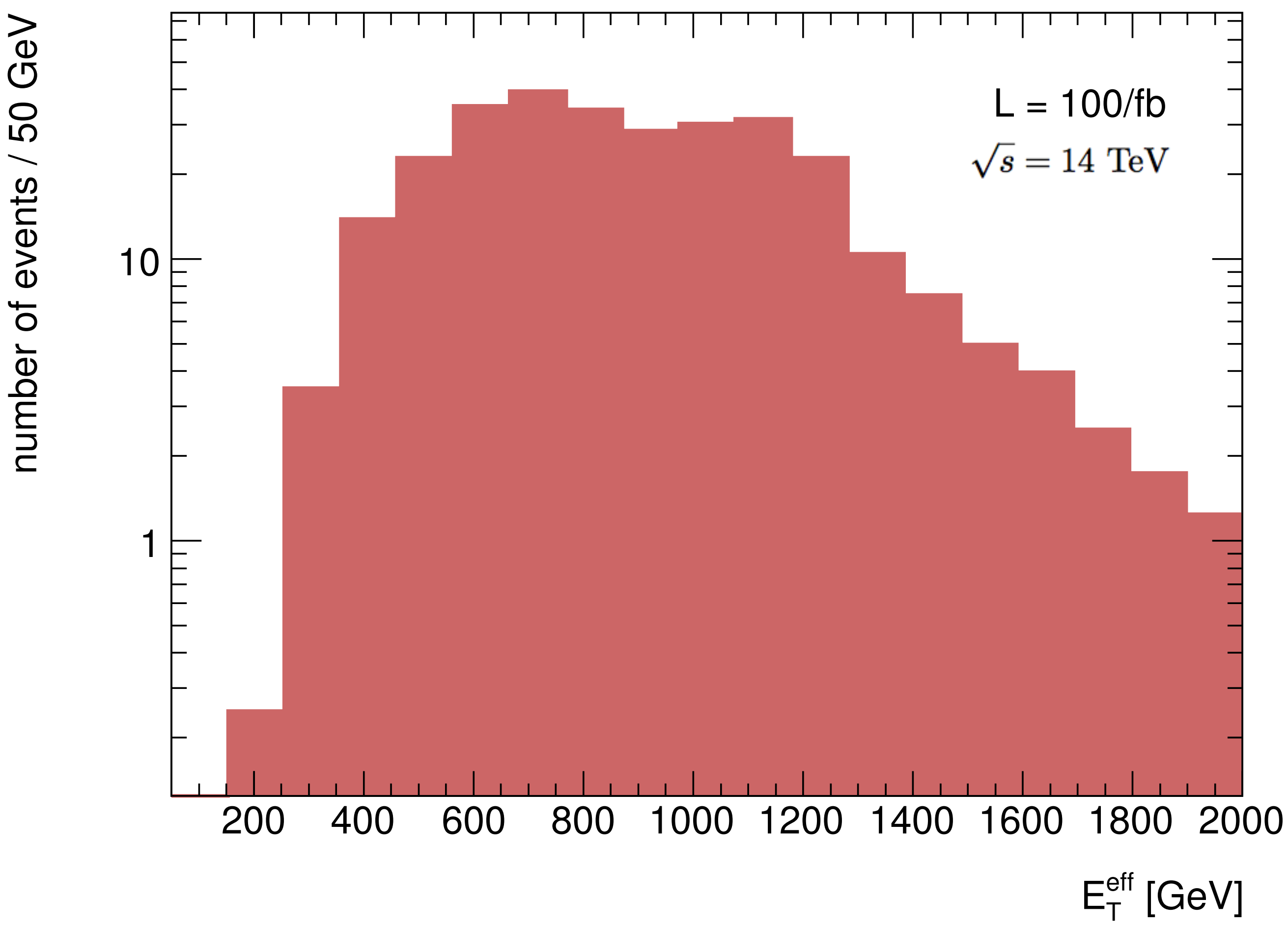
Chargino production

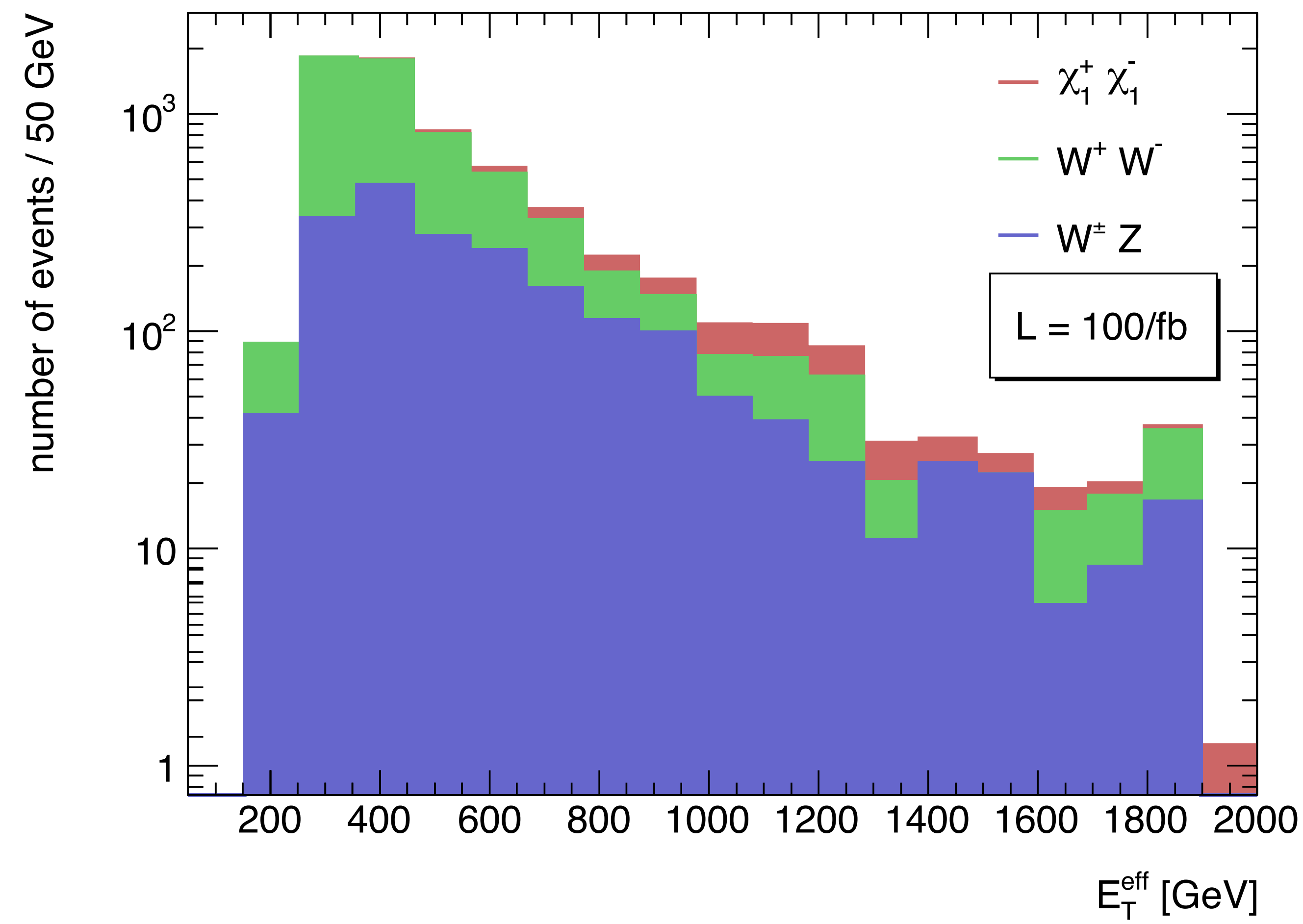
Effective transverse energy (from M.E.Cabrera,A.Casas '12)

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

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

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





Summary

- Sneutrino is a good dark matter candidate in the MSSM+RN with conditions at GUT scale

  (a) Dominant dark matter and compatible with LUX bound for $m_{LSP} > 60$ GeV

  (b) Large portion of the parameter space can be probed by XENON1T

  (c) The annihilation processes that fix the relic density determine the SUSY spectrum

- Characteristic LHC signatures

  (a) Long-lived staus

  (b) Two leptons with same sign, different flavor: difficult to disentangle as it peaks at the background maximum

  (c) Three uncorrelated leptons: clean signature with low background

  (d) Chargino production and decay into two opposite sign uncorrelated flavor leptons

- More from slepton-right decay: 3 uncorrelated leptons per decay but in our samples the slepton right are much heavier than 700 GeV; interesting when associated with colored sparticle productions

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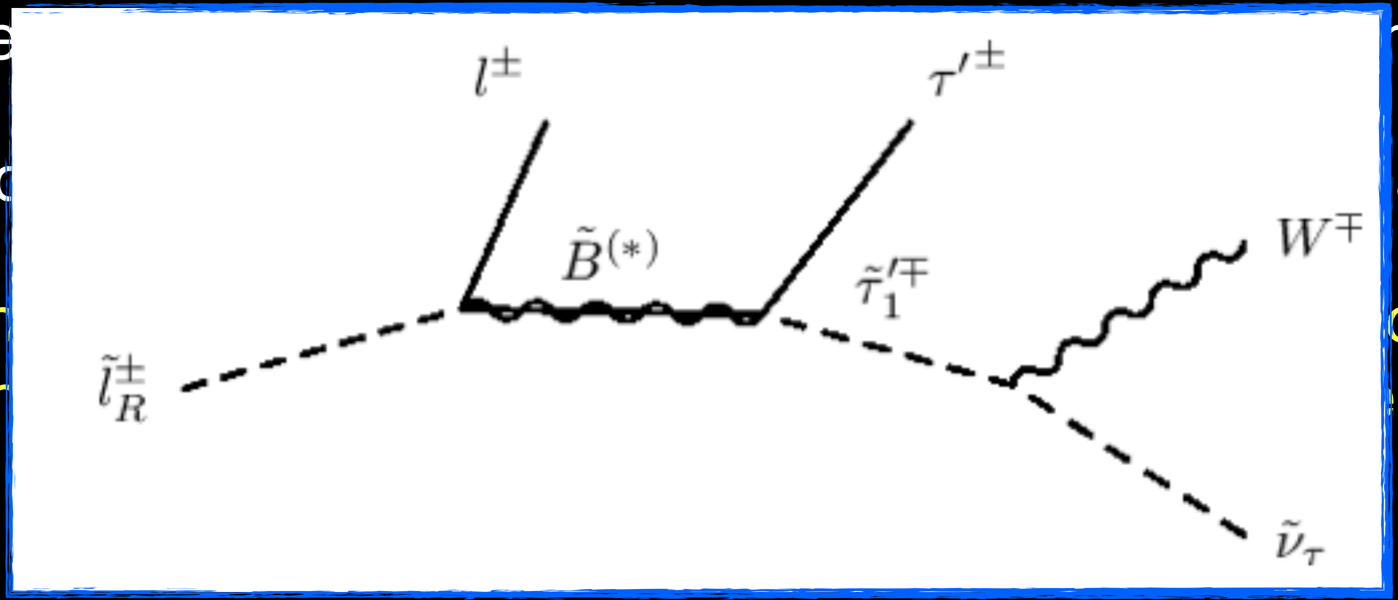

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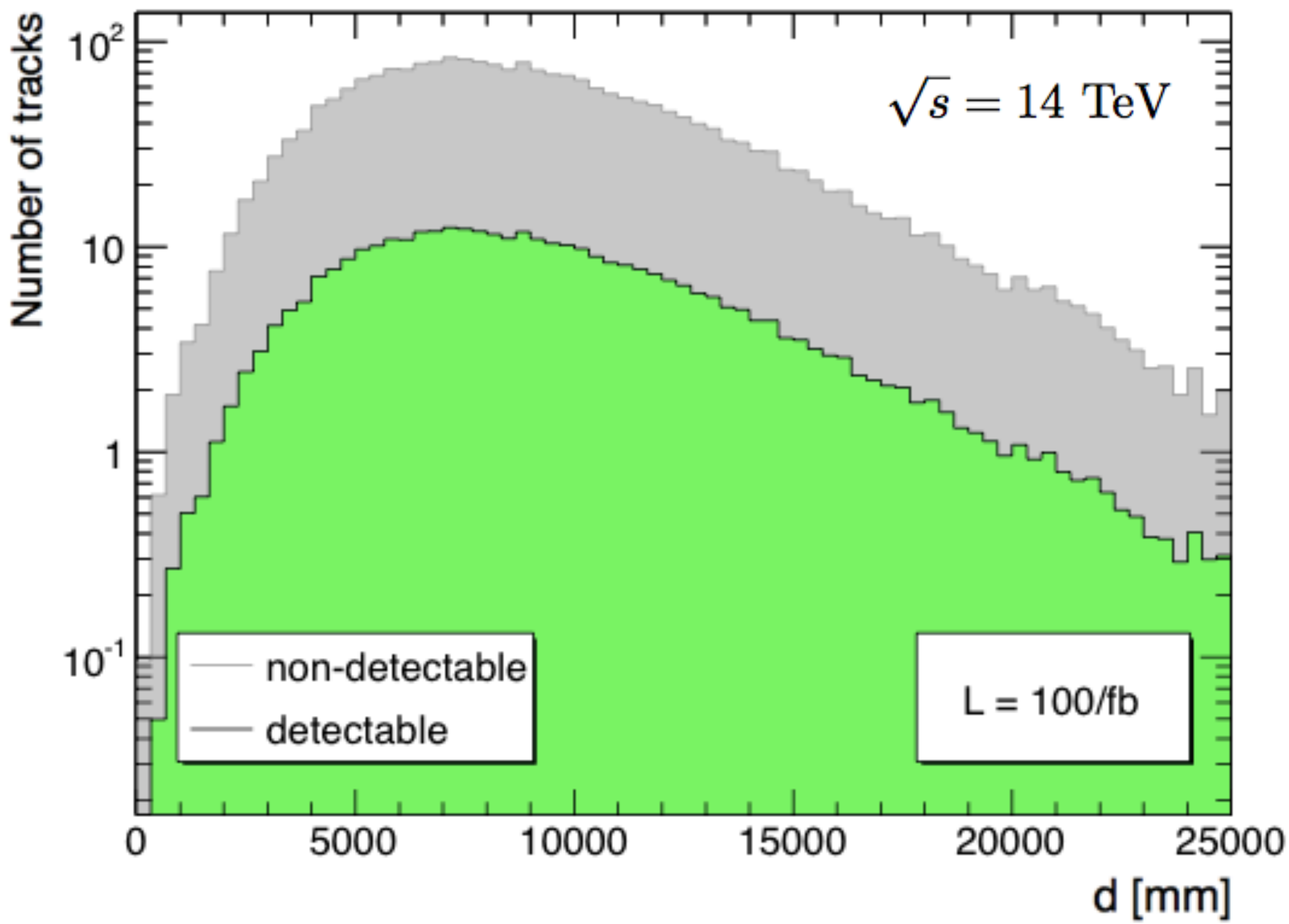
THANKS!

Back up slides

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 $\epsilon = 0.15$)



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 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

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- 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 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

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. $p_T^{\text{miss}} > 40\ \text{GeV}$

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:

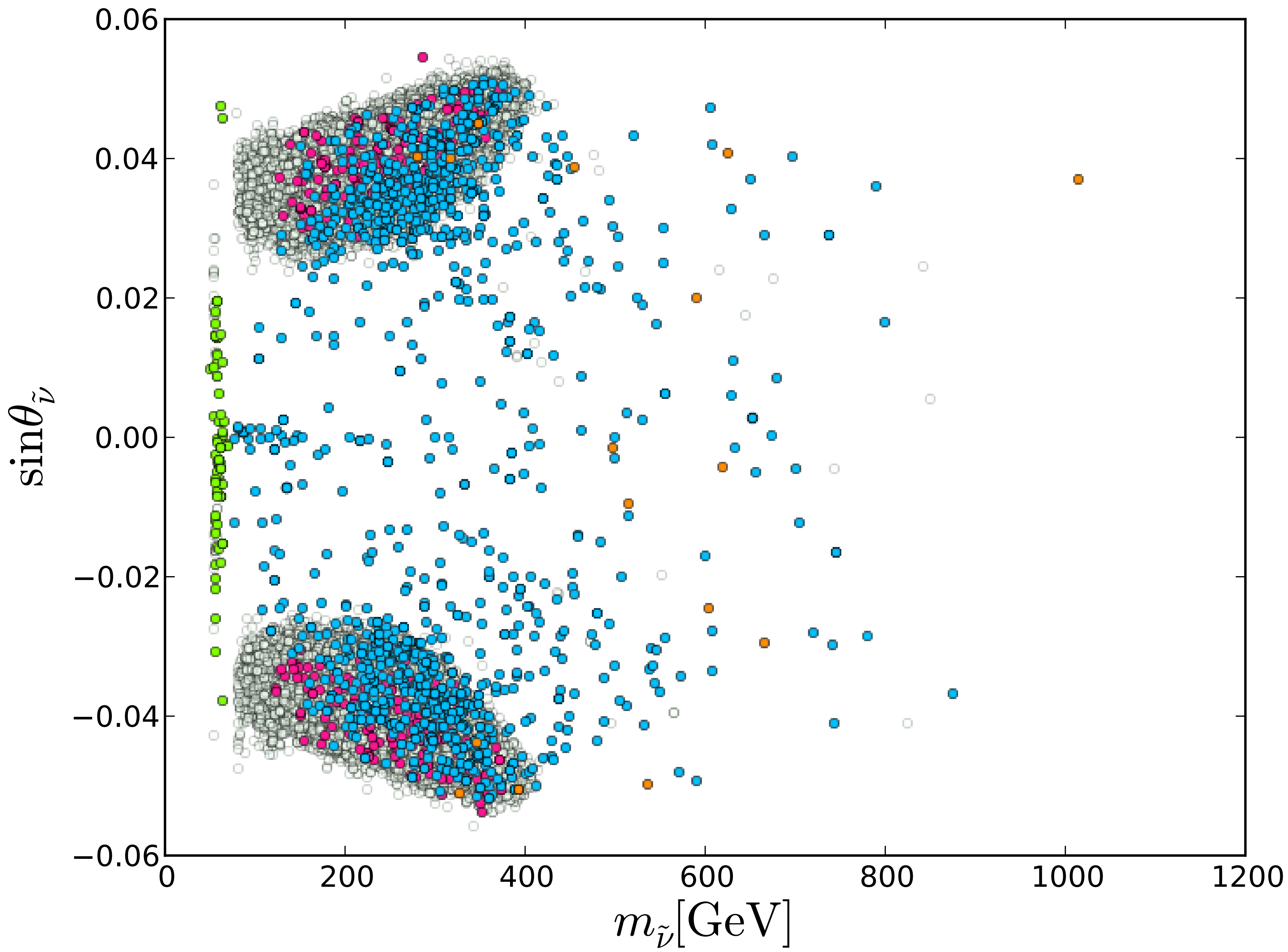
$$\frac{\mathrm{d}m_N^2}{\mathrm{d}\ln\mu} = \frac{4}{16\pi^2}\left(A_{\tilde{\nu}}\right)^2$$

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

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

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

Details on MSSM+RN



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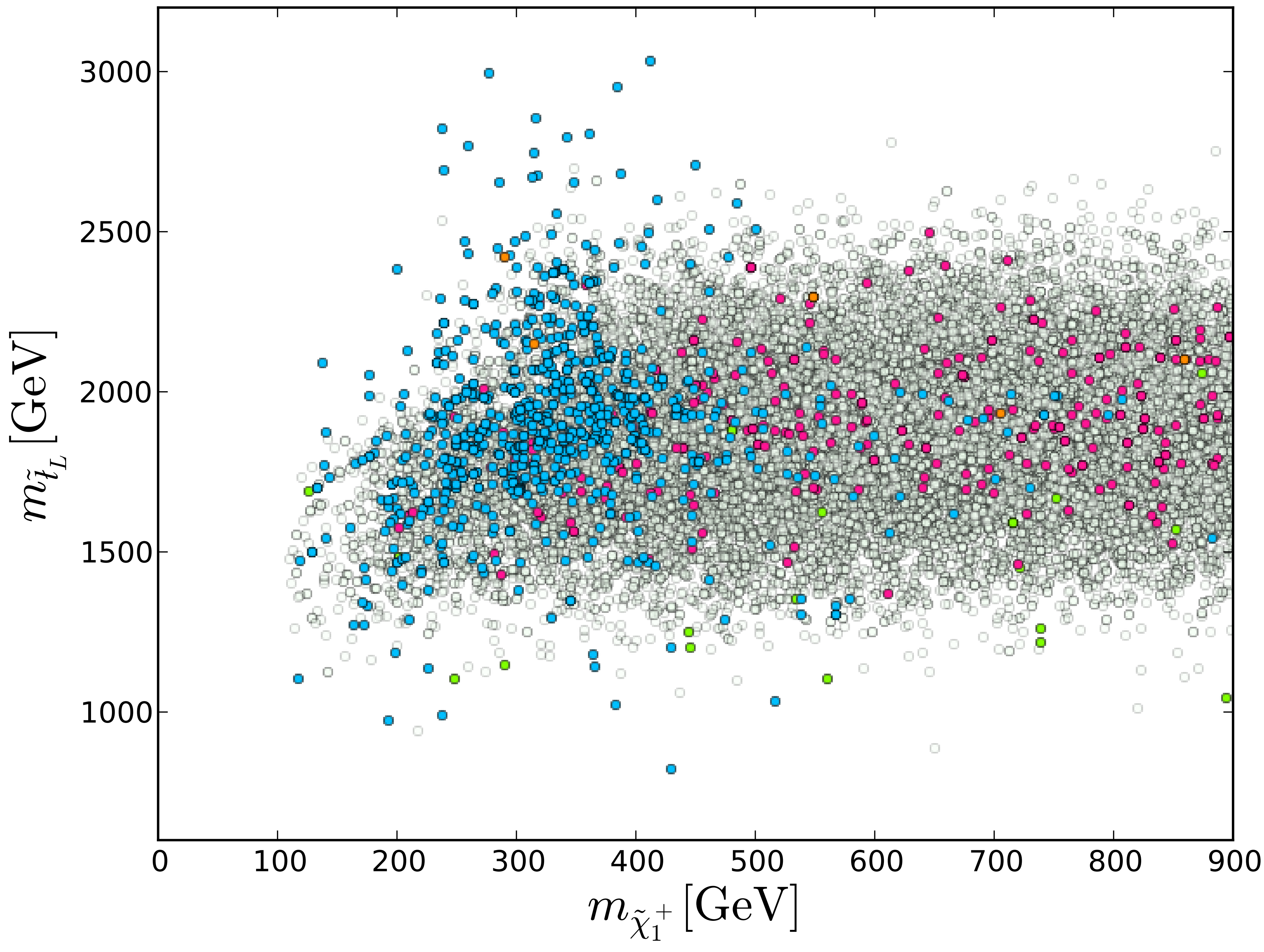

Details on MSSM+RN sampling

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

Data for constraints

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

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

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

- $\mathcal{P}(\theta|X)\mathrm{d}\theta$ → Posterior probability function (PDF)
- $\mathcal{L}(X|\theta)$ → Likelihood (proper of each EXP)
- $\pi(\theta)\mathrm{d}\theta$ → Prior

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Posterior probability function (PDF)

Likelihood (proper of each EXP)

Prior

Common prior choices that do not favour any parameter region

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

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

Observable	Prior
WIMP mass (θ_1)	$\log(m_{\mathrm{DM}}/\mathrm{GeV}):\ 0 \to 3$
SI cross-section (θ_2)	$\log(\sigma_n^{\mathrm{SI}}/\mathrm{cm}^2):\ -44(-46) \to -38$

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

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

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

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Profile Likelihood is prior independent (comparison with frequentist approach)

$$\mathcal{L}_{\rm prof}(X|\theta_1, ..., \theta_n) \propto \max_{\psi_1...\psi_m} \mathcal{L}(X|\theta_1, ..., \theta_n, \psi_1..., \psi_m) \qquad \Delta\chi^2_{\rm eff}(m_{\rm DM}, \sigma_n^{\rm SI}) \equiv -2\ln \mathcal{L}_{\rm prof}(m_{\rm DM}, \sigma_n^{\rm SI})$$