

Light Singlino in the nMSSM

Collider and Astrophysical Probes

Daniele Barducci

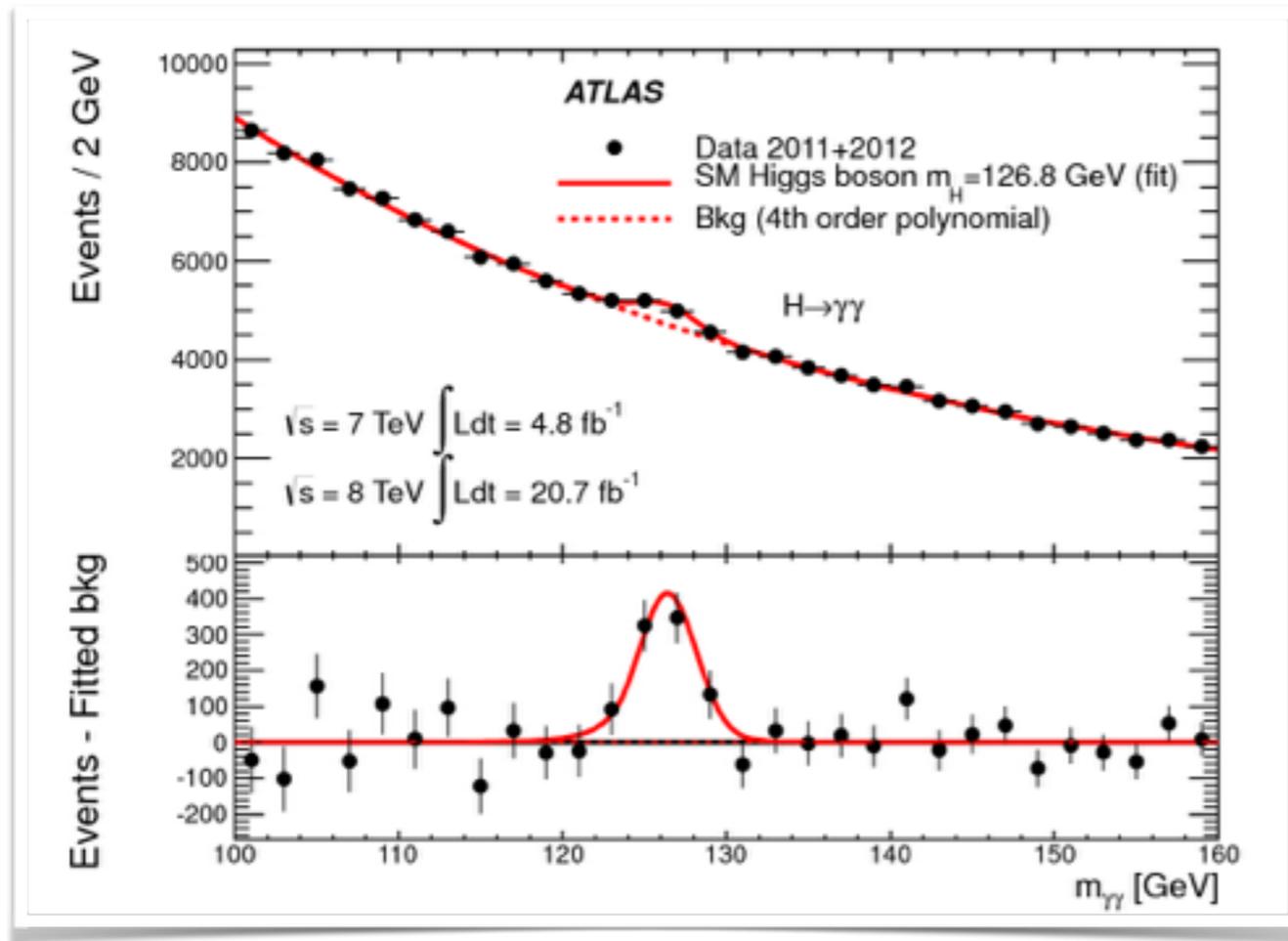
w/ G. Belanger, C. Hugonie and S. Pukhov arXiv:1510.00246

w/ R. Aggleton, N-E. Bomark, S. Moretti and C. Themistocleous arXiv:1609.06089

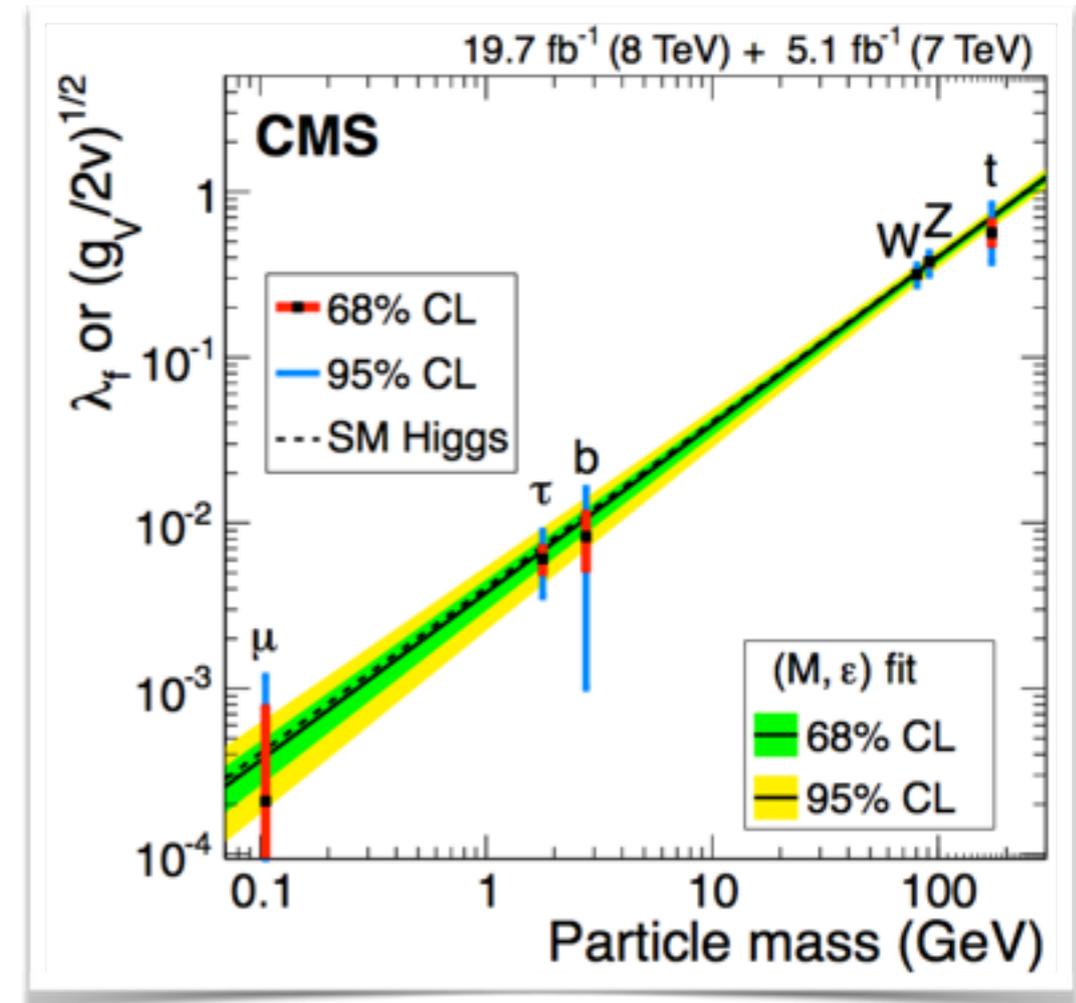


Two solid results from the LHC

The Higgs has been discovered and it has SM-like properties



$$m_H \sim 125 \text{ GeV}$$

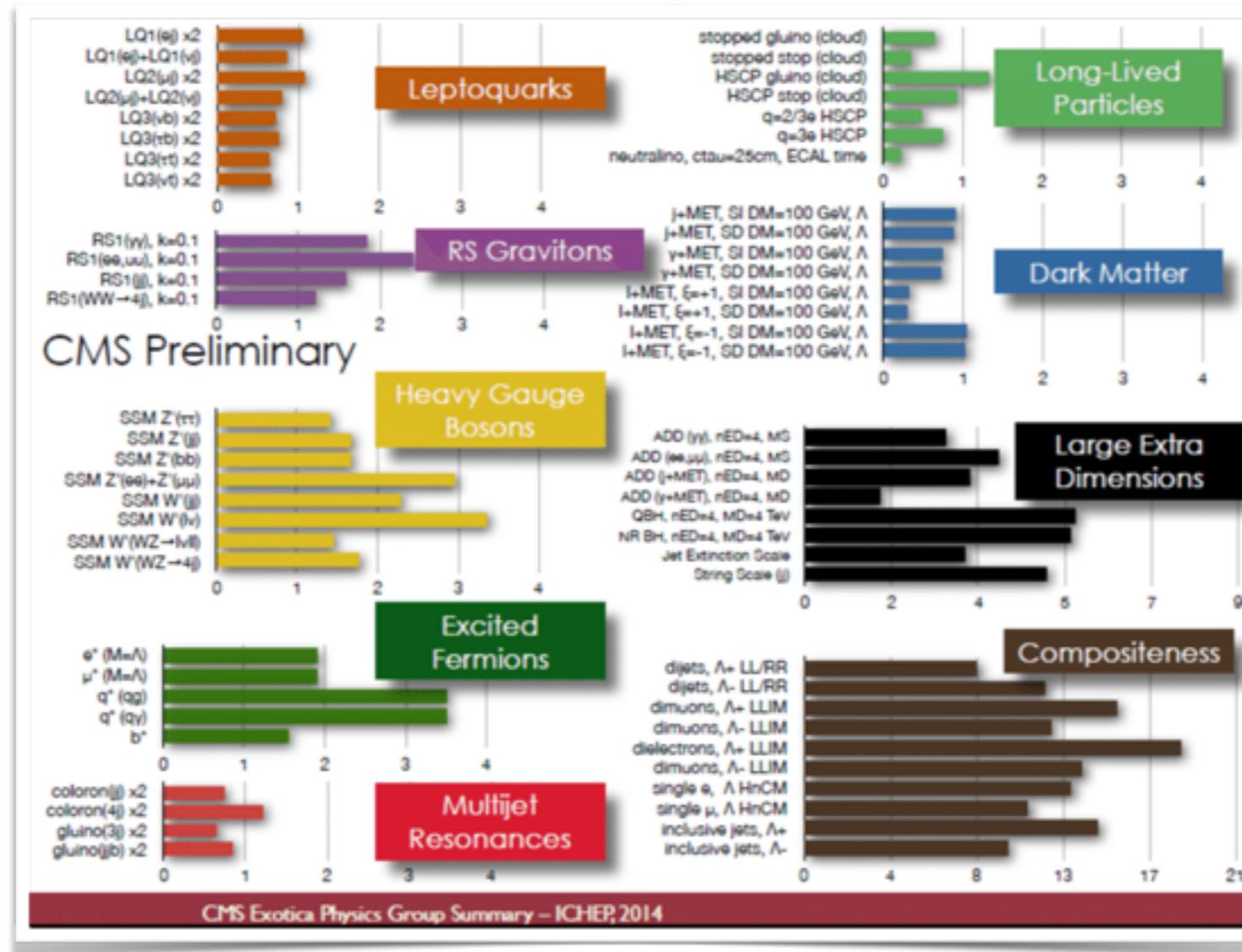


$$\delta g/g \sim 10\%$$

Trilinear and quartic (?) self-coupling to be tested at future colliders

Two solid results from the LHC

Beyond the SM physics has not been found

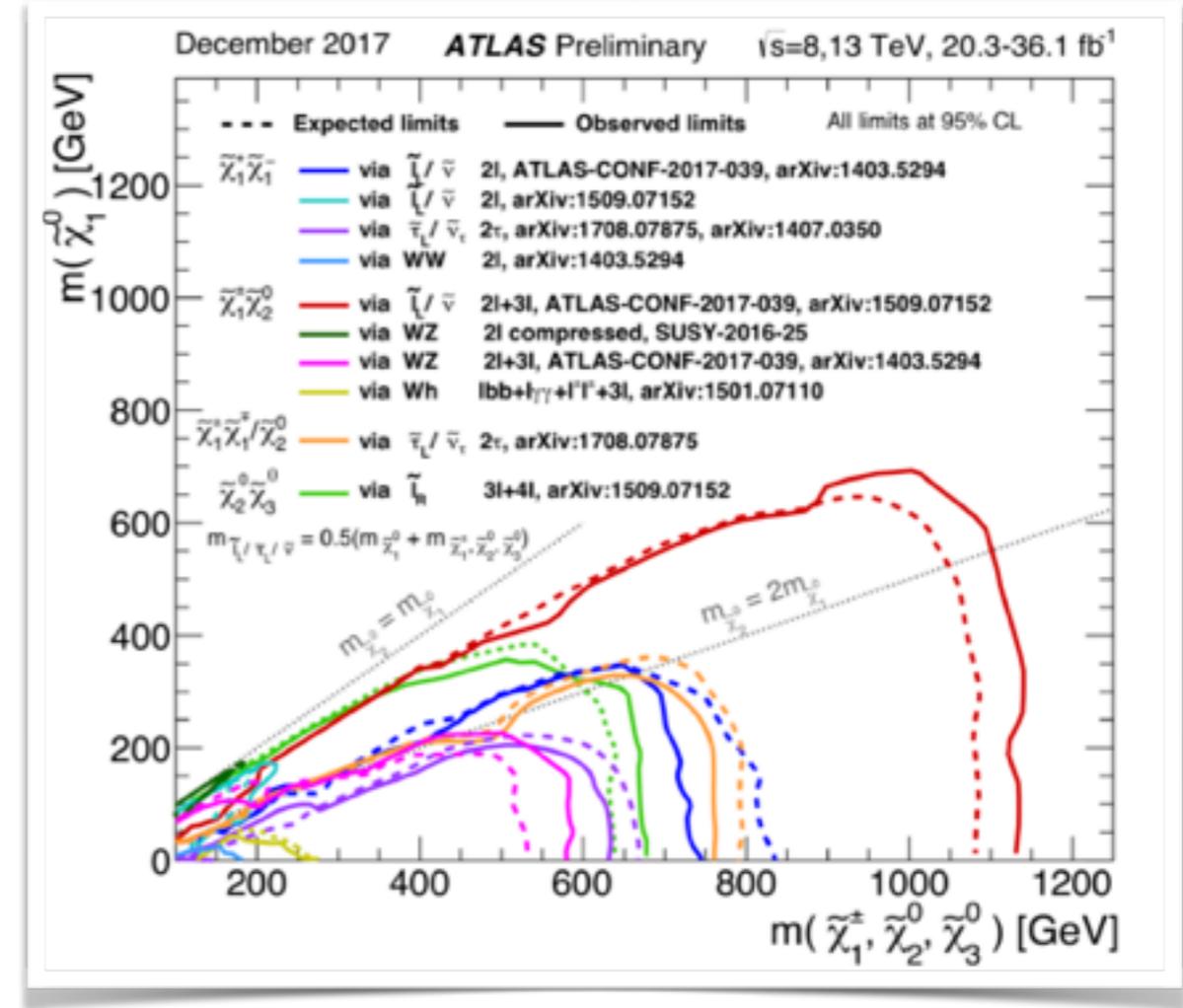
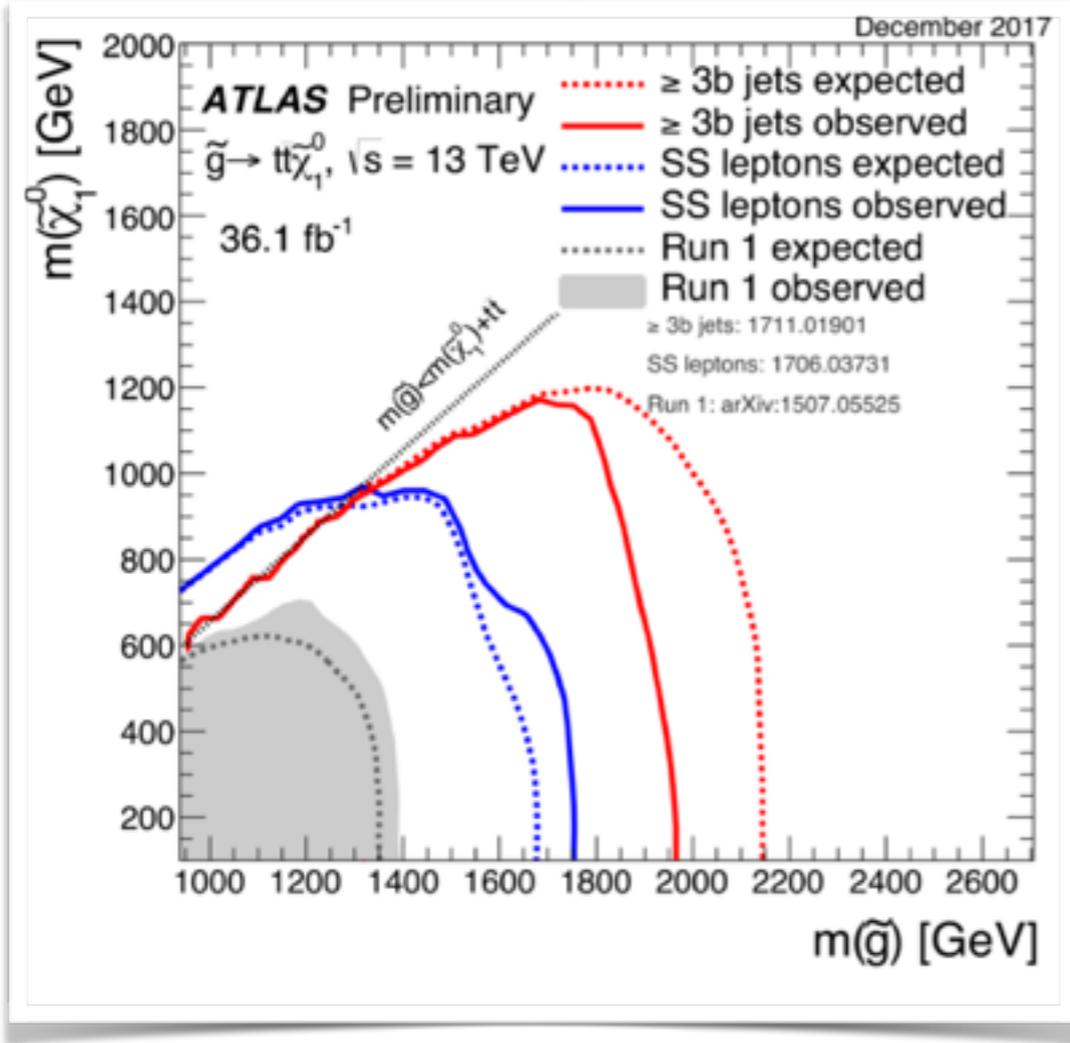


$$m_{\text{NP}} > 1-2 \text{ TeV}$$

NP hidden or weakly coupled

Supersymmetry at the LHC

The MSSM is under strong pressure arising from direct searches



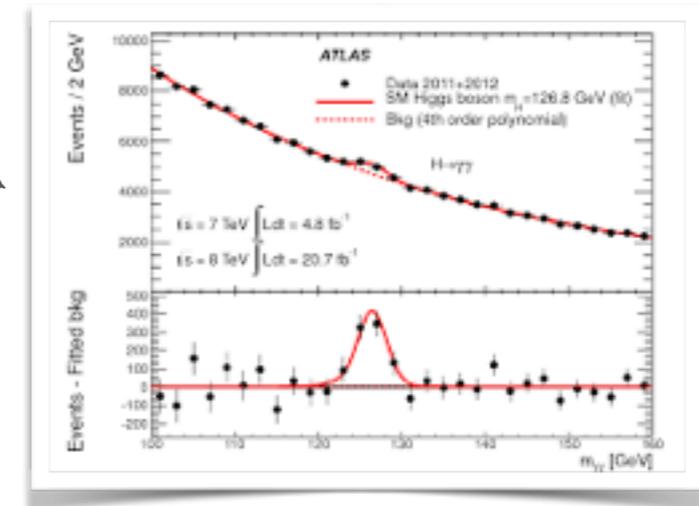
Light SUSY particles are still allowed in compressed spectra scenario

Supersymmetry at the LHC

The measured value of the Higgs mass poses a problem for the MSSM

A light Higgs boson is a strong prediction of the MSSM

$$m_{h^0} \leq m_Z \cos 2\beta + \delta m_{h^0}^{\text{rad}}$$



The measured Higgs mass is at the boundary of the MSSM mass window

- Large fine tuning in the MSSM to accommodate the 125 GeV Higgs

Moreover the MSSM suffers from the mu problem

- What's the origin of the Higgs mass parameter $\mu \hat{H}_u \hat{H}_d$?

Non minimal SUSY extensions

The NMSSM extends the MSSM adding a gauge singlet superfield S

$$W_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3 + h_u \hat{Q} \hat{U}^c \hat{H}_u + h_d \hat{Q} \hat{D}^c \hat{H}_d + h_e \hat{L} \hat{E}^c \hat{H}_d$$

$\mu = \lambda \langle S \rangle$ MSSM part

Global \mathbb{Z}_3 symmetry broken with EWSB: domain walls are generated
Explicit \mathbb{Z}_3 breaking terms have to be introduced: $W \supset \xi_F \hat{S}$, $V \supset \xi_S S$

With $\xi_F \sim M_{\text{SUSY}}^2$ and $\xi_S \sim M_{\text{SUSY}}^3$ one has $\langle S \rangle = M_{\text{SUSY}}$ with $\kappa = 0$

Cubic self interaction of the singlet can be neglected

The singlet appears only in $\hat{S} \hat{H}_u \hat{H}_d$ and in the tadpole terms

This model is called nMSSM

Scalar sector of the nMSSM

On the VEV of the Higgs fields the scalar potential reads

$$V_0 = (-\lambda v_u v_d + \xi_F)^2 + \frac{g^2}{4} (v_u^2 - v_d^2)^2 + m_S^2 s^2 \\ + (m_{H_u}^2 + \mu^2) v_u^2 + (m_{H_d}^2 + \mu^2) v_d^2 - 2\lambda A_\lambda v_u v_d s + 2\xi_S s$$

which is minimized by

$$\begin{cases} v_u \left(m_{H_u}^2 + \mu^2 + \lambda^2 v_d^2 + \frac{g^2}{2} (v_u^2 - v_d^2) \right) - v_d (\mu A_\lambda + \lambda \xi_F) = 0, \\ v_d \left(m_{H_d}^2 + \mu^2 + \lambda^2 v_u^2 + \frac{g^2}{2} (v_d^2 - v_u^2) \right) - v_u (\mu A_\lambda + \lambda \xi_F) = 0, \\ s (m_S^2 + \lambda^2 (v_u^2 + v_d^2)) + \xi_S - \lambda A_\lambda v_u v_d = 0. \end{cases}$$

Higgs mass parameter

$$\mu \simeq -\frac{\lambda \xi_S}{m_S^2}$$

Singlet masses

$$\mathcal{M}_{P,22}^2 = \frac{\lambda^2 A_\lambda v_u v_d - \lambda \xi_S}{\mu} = \mathcal{M}_{S,33}^2$$

Depend on the free parameter ξ_S

Neutralino sector of the nMSSM

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix} \quad \psi^0 = (-i\lambda_1, -i\lambda_2^3, \psi_d^0, \psi_u^0, \psi_S)$$

$$m_{\tilde{S}} \simeq \frac{\mu \lambda^2 v^2}{\mu^2 + \lambda^2 v^2} \sin 2\beta$$

Small λ mixing implied almost massless singlino

No light chargino: lower bound on μ

Perturbativity up to GUT scale: upper bound on λ

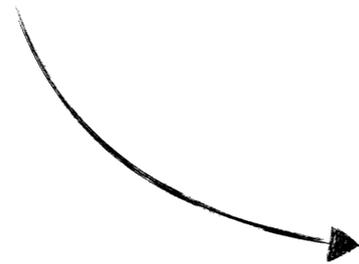
$$m_{\tilde{S}} < 75 \text{ GeV}$$

A light LSP is the main characteristic of the nMSSM

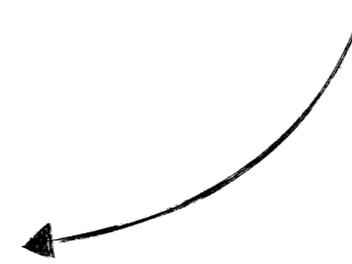
The nMSSM: parameter scan

We Scan the nMSSM parameter space for

$m_0, M_{1/2}, A_0,$ $\mu, \tan \beta, \lambda,$ $\xi_F, \xi_S, A_\lambda,$



GUT scale



using NMSSMTools via MCMC routines

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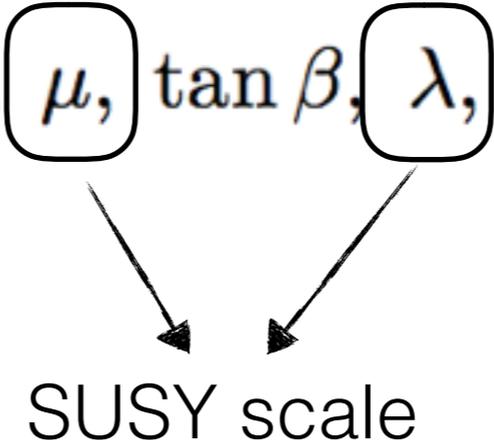
M_Z

using NMSSMTools via MCMC routines

The nMSSM: parameter scan

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SUSY scale

The diagram shows the parameters μ and λ from the list above enclosed in rounded rectangular boxes. Two arrows originate from the bottom of these boxes and point downwards towards the text 'SUSY scale'.

using NMSSMTools via MCMC routines

The nMSSM: parameter scan

We Scan the nMSSM parameter space for

$m_0, M_{1/2}, A_0, \mu, \tan \beta, \lambda, \xi_F, \xi_S, A_\lambda,$

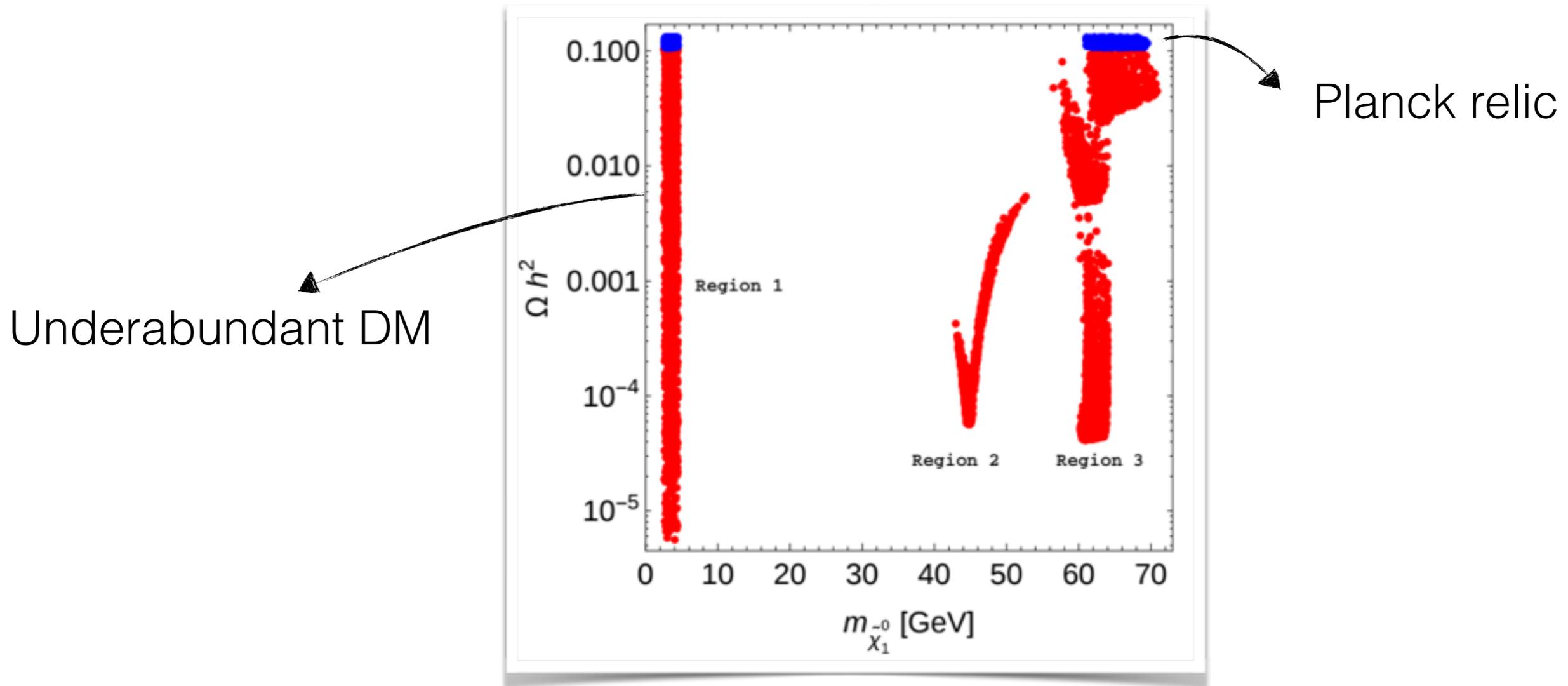
using NMSSMTools via MCMC routines

Constraints

- no unphysical minimum of the Higgs potential
- no Landau pole below the GUT scale
- basic LEP and Tevatron searches
- basic LHC searches and Higgs fit
- Upper bound on the relic density
- Compatibility with LUX bound on σ_{SI}

The nMSSM: parameter scan

We identify three regions in the $m_{\tilde{\chi}_1^0} - \Omega h^2$ parameter space



Annihilation processes

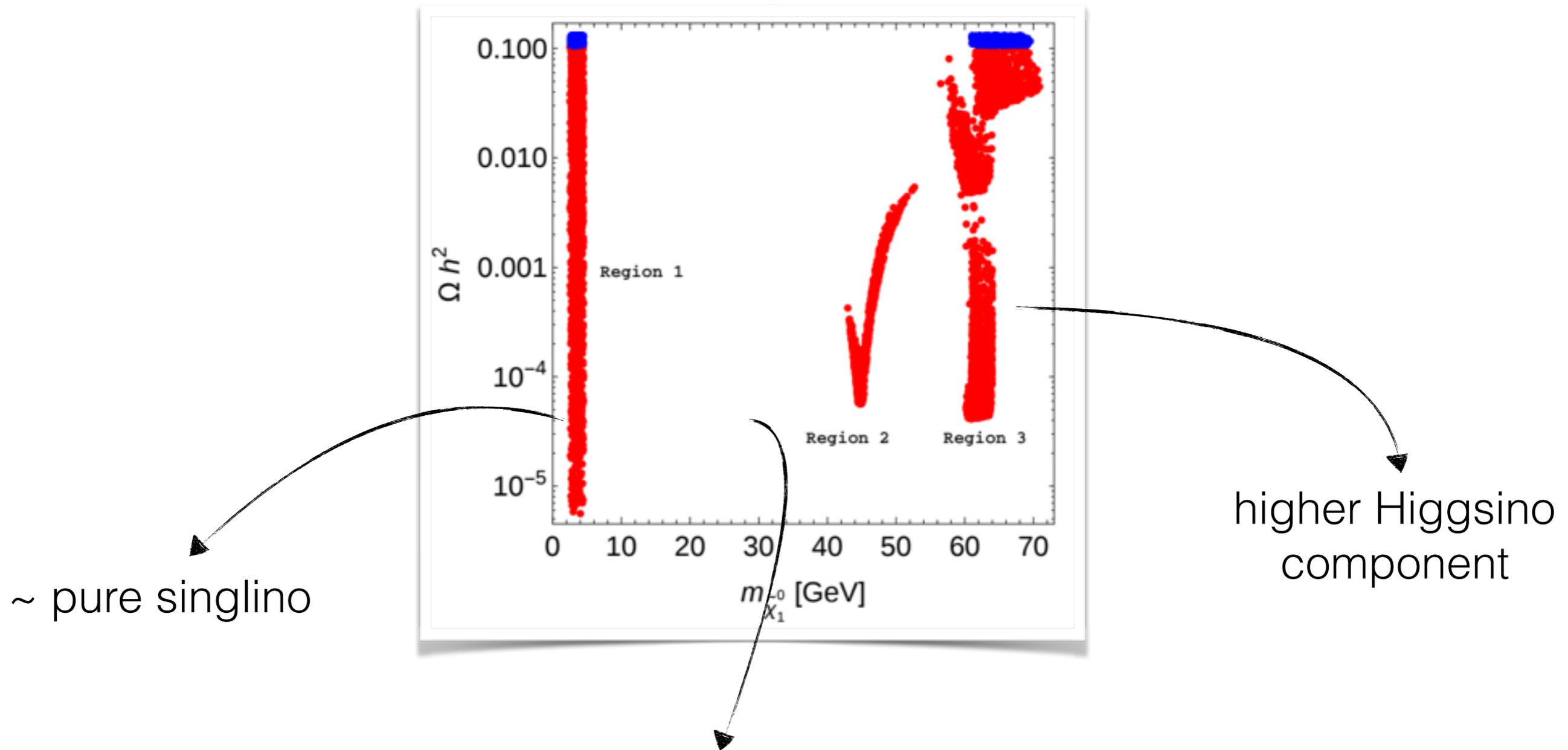
Region 1: light pseudoscalar $m_A \sim 2 m_{\tilde{\chi}_1^0}$

Region 2: Z boson

Region 3: Higgs and Z boson

The nMSSM: parameter scan

We identify three regions in the $m_{\tilde{\chi}_1^0} - \Omega h^2$ parameter space



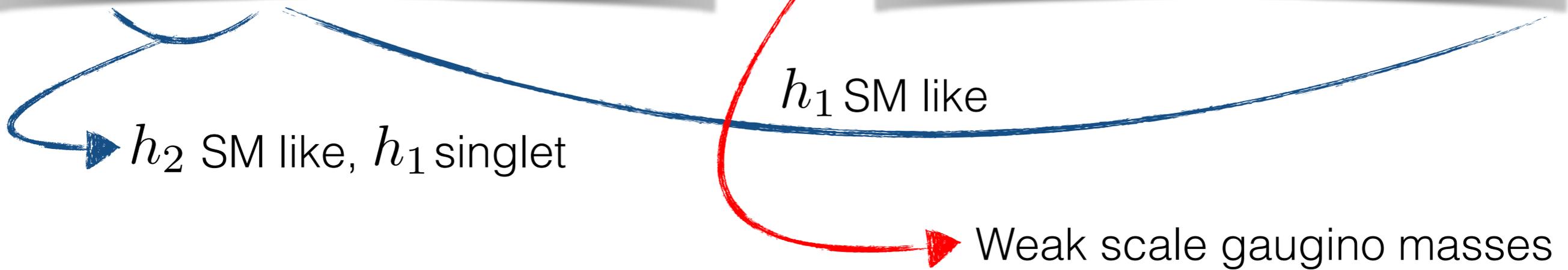
Higher higgsino component: invisible Higgs width constraints

The nMSSM: parameter scan

Overview of the regions

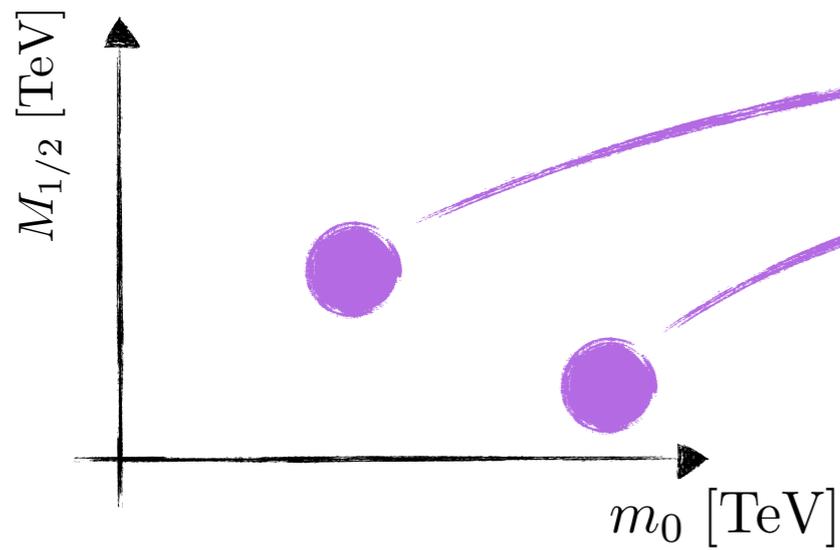
Region	1A		1B		2	
$\tan \beta$	6.6	10	6	8	1.5	2.1
λ	0.33	0.53	0.49	0.52	0.68	0.80
μ	240	400	350	430	115	180
m_0	0	1080	4040	4800	$2 \cdot 10^4$	$6 \cdot 10^5$
$M_{1/2}$	630	1200	280	440	180	470
A_0	-1700	50	6700	7900	$-3.7 \cdot 10^4$	$-2.5 \cdot 10^3$
A_λ	1400	6000	7000	7900	$-1.3 \cdot 10^4$	$3.3 \cdot 10^4$
ξ_F	10	100	$-1.5 \cdot 10^4$	$-1.4 \cdot 10^4$	$3.7 \cdot 10^4$	$5.1 \cdot 10^6$
ξ_S	$-6 \cdot 10^4$	$2 \cdot 10^4$	$-1.9 \cdot 10^7$	$-1.6 \cdot 10^7$	$-5.2 \cdot 10^{10}$	$9.7 \cdot 10^8$
M_1	270	520	110	190	95	225
M_2	500	950	200	340	160	400
$m_{\tilde{q}}$	1300	2400	> 3000		> 20000	
$m_{\tilde{t}_1}$	350	1300	1050	1900	> 3000	
$m_{\tilde{l}}$	180	1100	> 3000		> 20000	
$m_{\tilde{g}}$	1450	2600	780	1250	800	1500

Region	3A		3B		3C	
$\tan \beta$	1.8	2.5	1.8	2.8	1.3	1.8
λ	0.64	0.77	0.66	0.74	0.65	0.74
μ	-140	-90	-110	-90	110	150
m_0	$3.9 \cdot 10^3$	$6.6 \cdot 10^4$	170	2500	0	3150
$M_{1/2}$	130	210	200	560	$5.6 \cdot 10^3$	$2.3 \cdot 10^4$
A_0	11	$3.3 \cdot 10^4$	440	3600	$-1.9 \cdot 10^4$	$4.7 \cdot 10^3$
A_λ	$6.2 \cdot 10^3$	$2.7 \cdot 10^4$	450	3500	4	8200
ξ_F	$4.8 \cdot 10^5$	$3.4 \cdot 10^7$	$4.3 \cdot 10^5$	$7.5 \cdot 10^6$	$4.6 \cdot 10^5$	$1.8 \cdot 10^7$
ξ_S	$2.0 \cdot 10^9$	$1.3 \cdot 10^{11}$	$1.0 \cdot 10^8$	$4.9 \cdot 10^9$	$-1.9 \cdot 10^9$	$3.0 \cdot 10^9$
M_1	52	65	85	230	$2.6 \cdot 10^3$	$1.1 \cdot 10^4$
M_2	83	108	160	430	$4.6 \cdot 10^3$	$2.0 \cdot 10^4$
$m_{\tilde{q}}$	> 3000		780	2500	> 10000	
$m_{\tilde{t}_1}$	500	> 20000	150	550	> 5000	
$m_{\tilde{l}}$	> 3000		100	2500	100	3000
$m_{\tilde{g}}$	450	650	590	1300	> 10000	



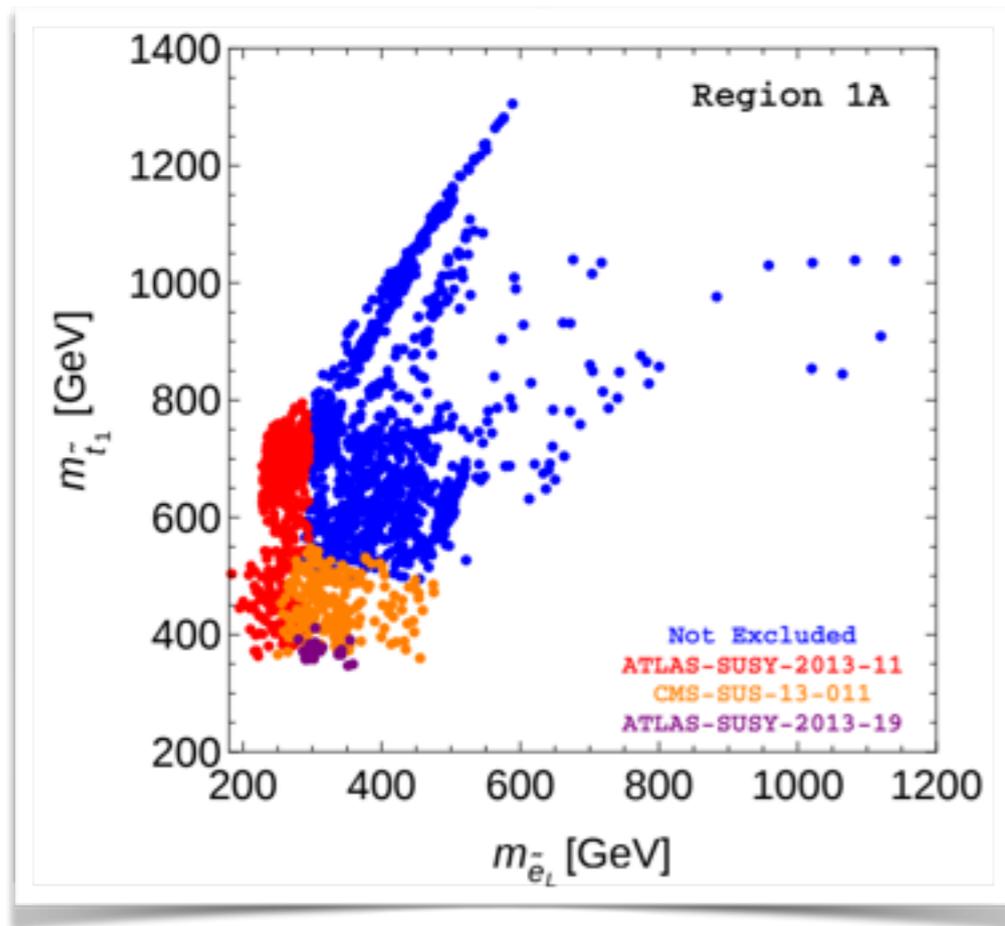
Light gaugini in all regions
 Light stops and sleptons also present
 Low $M_{1/2}$: TeV scale gluino

$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region



- 1A: light stop and sleptons, light h_1 and a_1
- ~~1B: light gluinos excluded~~

Sfermions



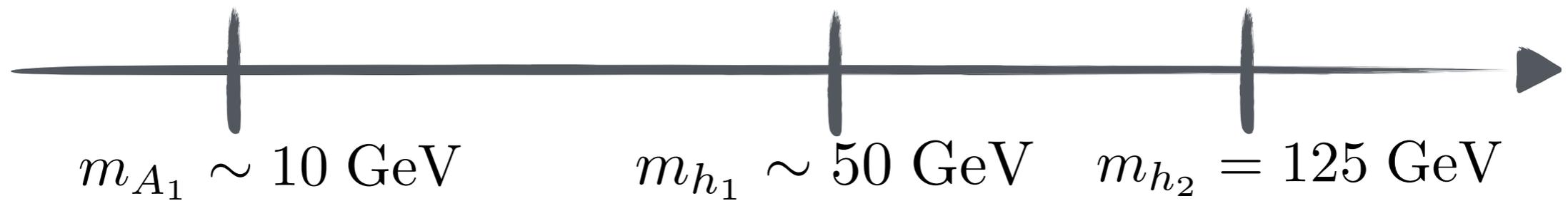
Singlino LSP: long decay chains

$$\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow t\tilde{\chi}_1^0 Z, \text{ instead than } \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$$

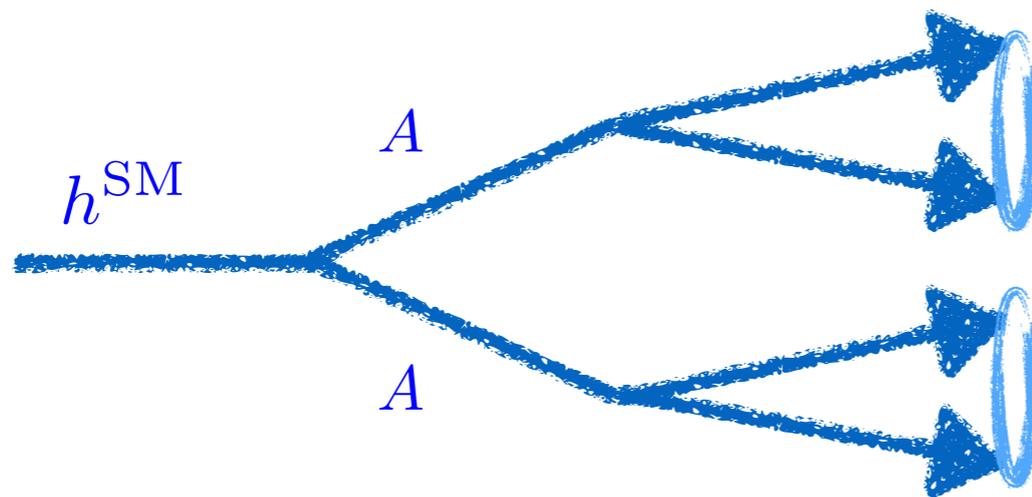
$$tZ + E_T^{\text{miss}} \text{ or } th_2 + E_T^{\text{miss}}$$

from one or both the stop decays can provide characteristic signatures

$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region



Opens the possibility for Higgs-to-Higgs decay: $h^{\text{SM}} \rightarrow h^1 h^1 \rightarrow 4X$



$$\Delta R \sim 2 \frac{m_A}{p_T^A} \sim 4 \frac{m_A}{m_{h^{\text{SM}}}}$$

$$m_A < 10 \text{ GeV}$$

$$m_A \sim 8 \text{ GeV}$$

$$\Delta R \sim 0.25$$

Boosted techniques

$$m_A \sim 15 - 20 \text{ GeV}$$

Neither collimated
nor separated

Challenging region

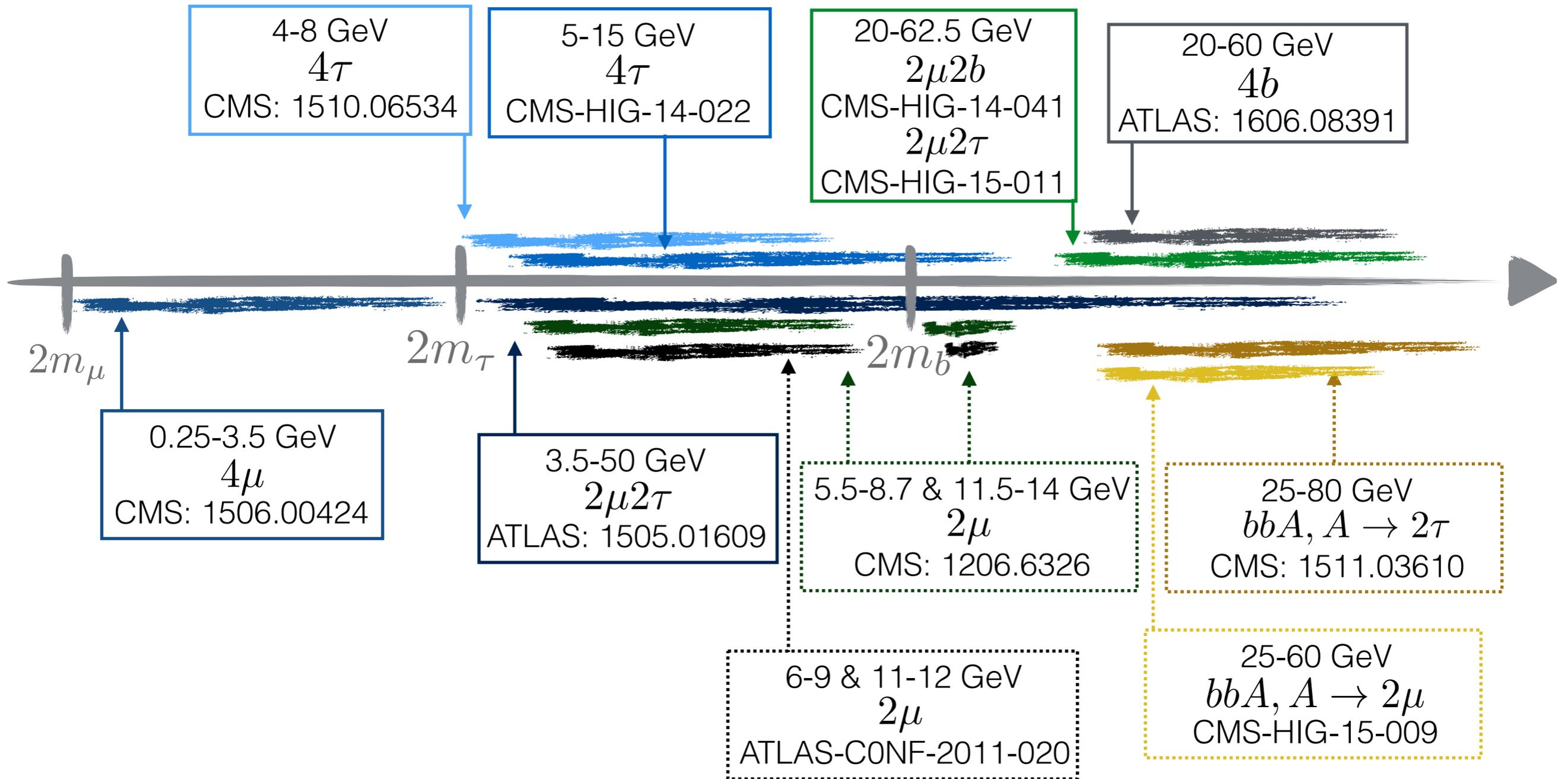
$$m_A > 20 \text{ GeV}$$

$$\Delta R > 0.6$$

Standard techniques

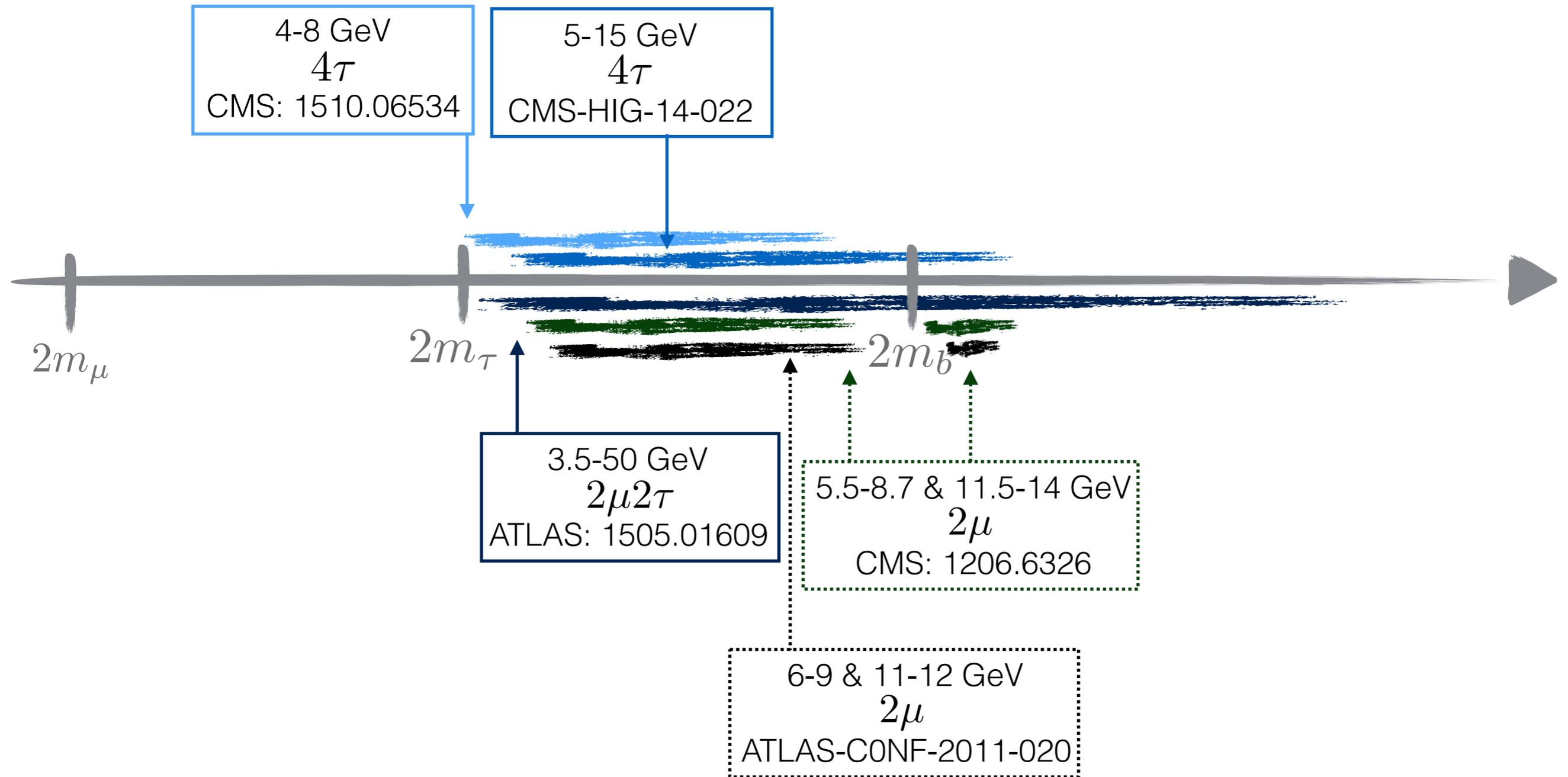
$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region

Numerous searches at the LHC targeting low mass scalars from h^{SM} decay



$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region

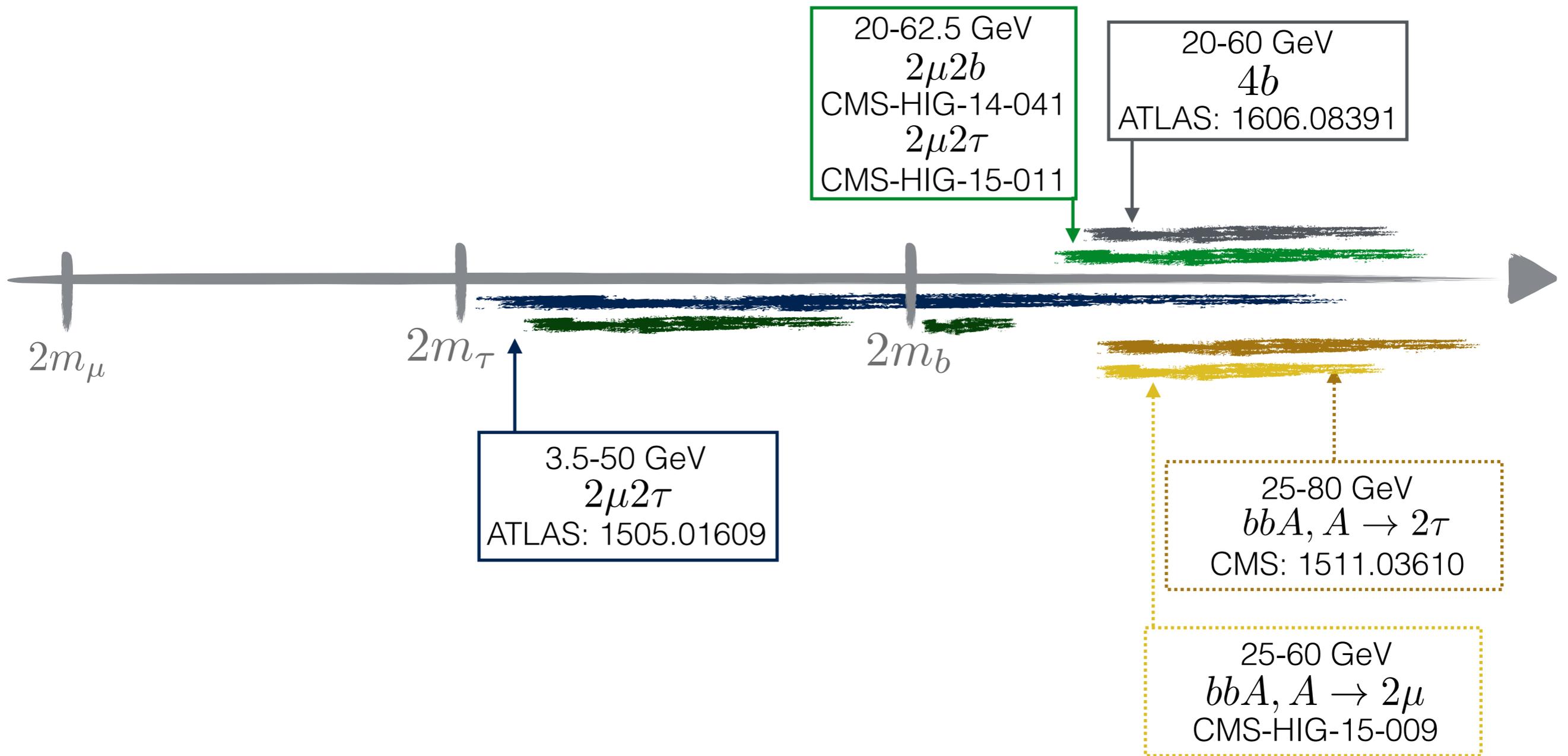
Numerous searches at the LHC targeting low mass scalars from h^{SM} decay



Relevant for $h_2 \rightarrow A_1 A_1$ $m_{A_1} \sim 10 \text{ GeV}$

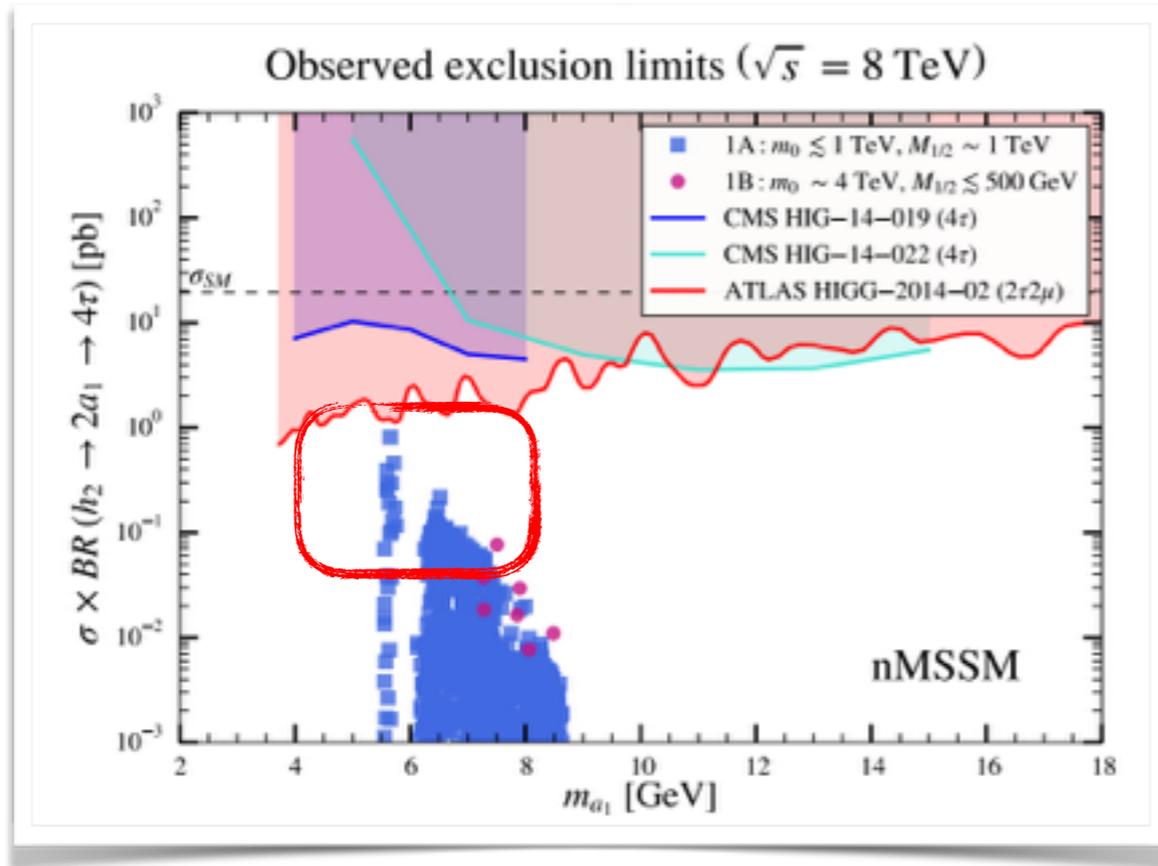
$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region

Numerous searches at the LHC targeting low mass scalars from h^{SM} decay



Relevant for $h_2 \rightarrow h_1 h_1$ $m_{h_1} \sim 30 - 60 \text{ GeV}$

$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region



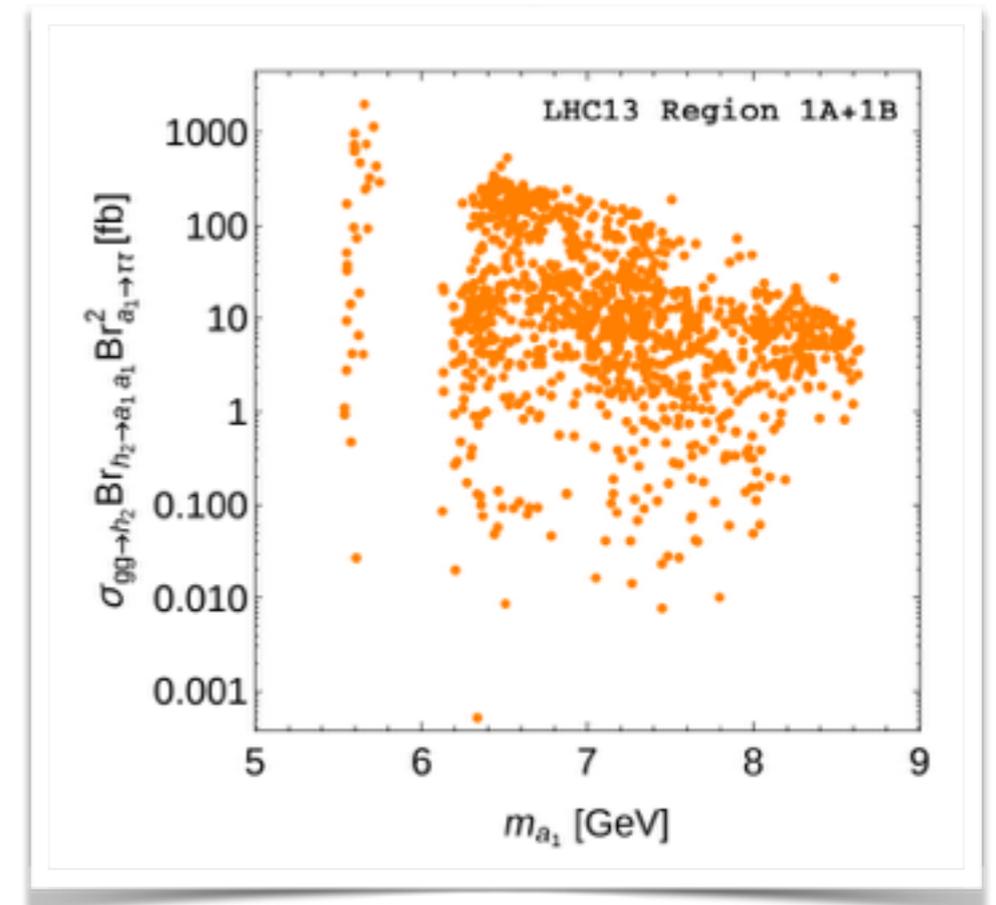
Best Sensitivity from ATLAS $2\mu 2\tau$ search

$$\sigma^{\text{LHC8}}(gg \rightarrow h_2) \sim 20 \text{ pb}$$

$$\text{BR}(h_2 \rightarrow A_1 A_1, h_1 h_1) \sim 10\%$$

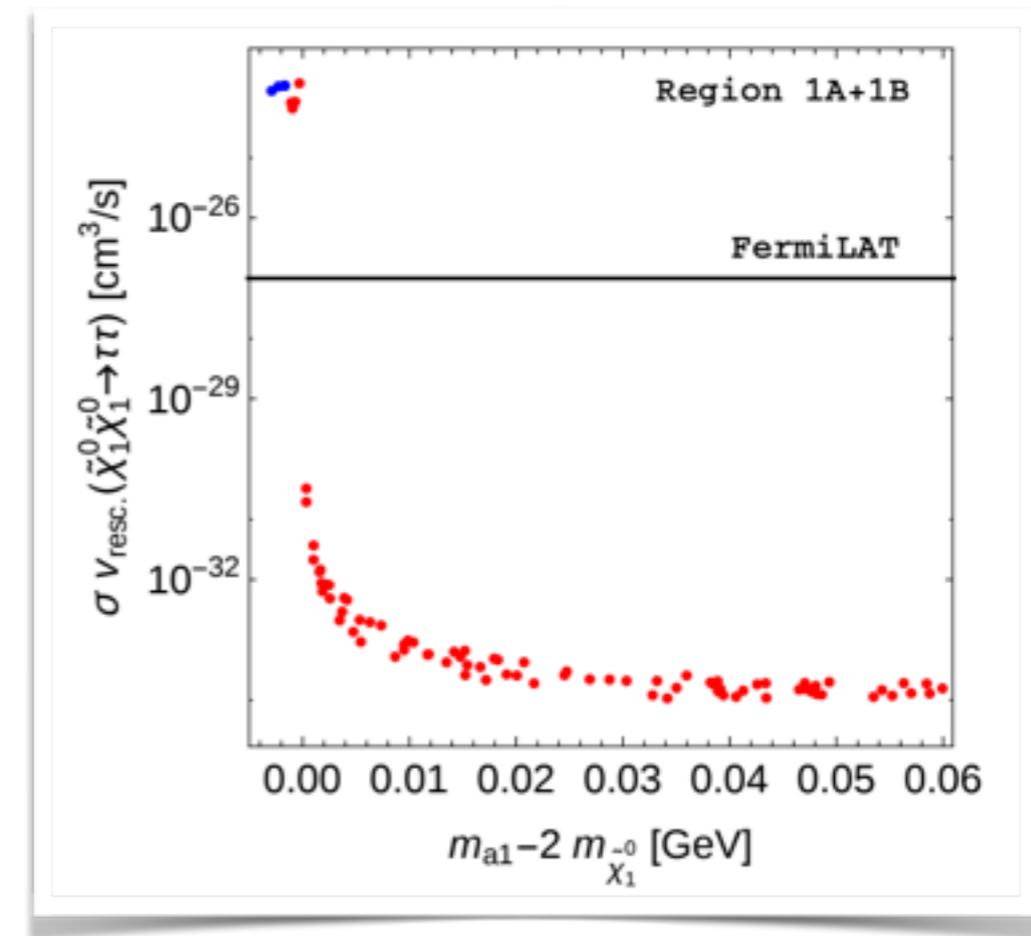
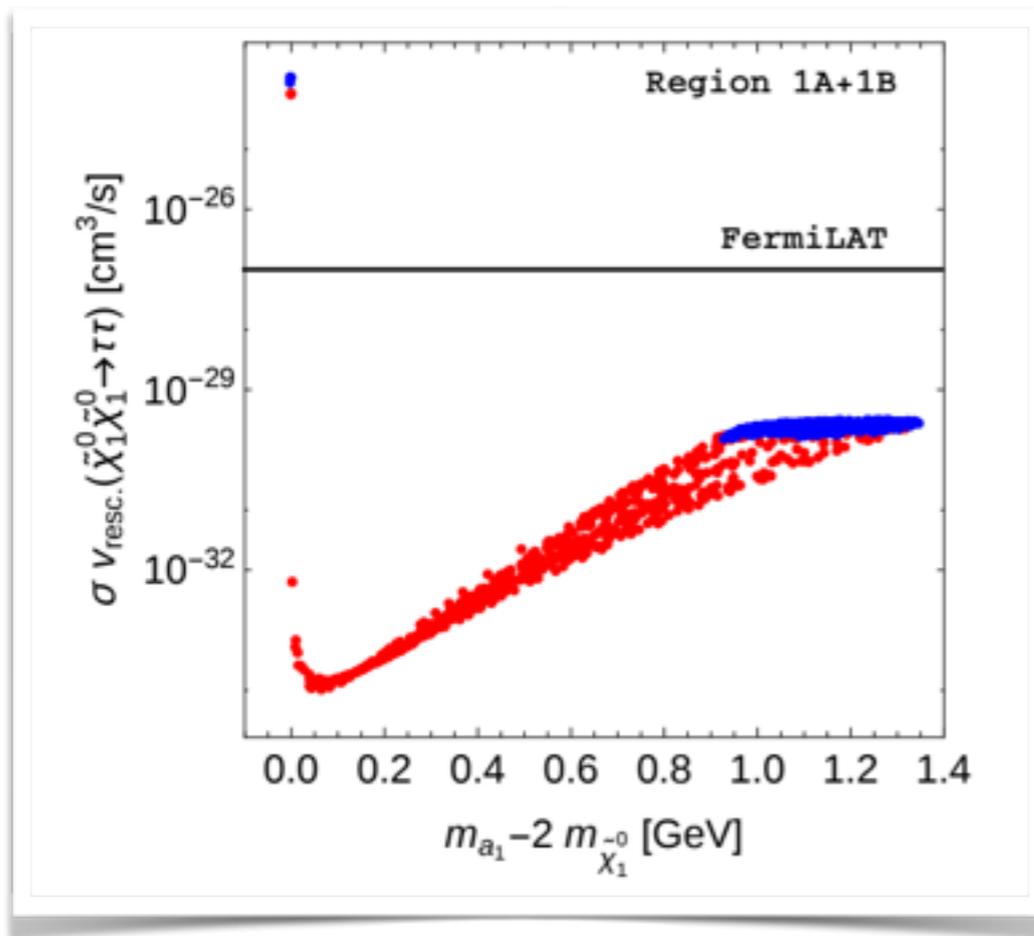
Factor two increase in cross section at LHC13

Most promising channel to be explored



$m_{\tilde{\chi}_1^0} \sim 5 \text{ GeV}$: nMSSM like region

DM relic through annihilation via A_1 with $2m_{\tilde{\chi}_1^0} \sim m_{A_1}$



- FermiLAT excludes only region where $m_{A_1} < 2m_{\tilde{\chi}_1^0}$

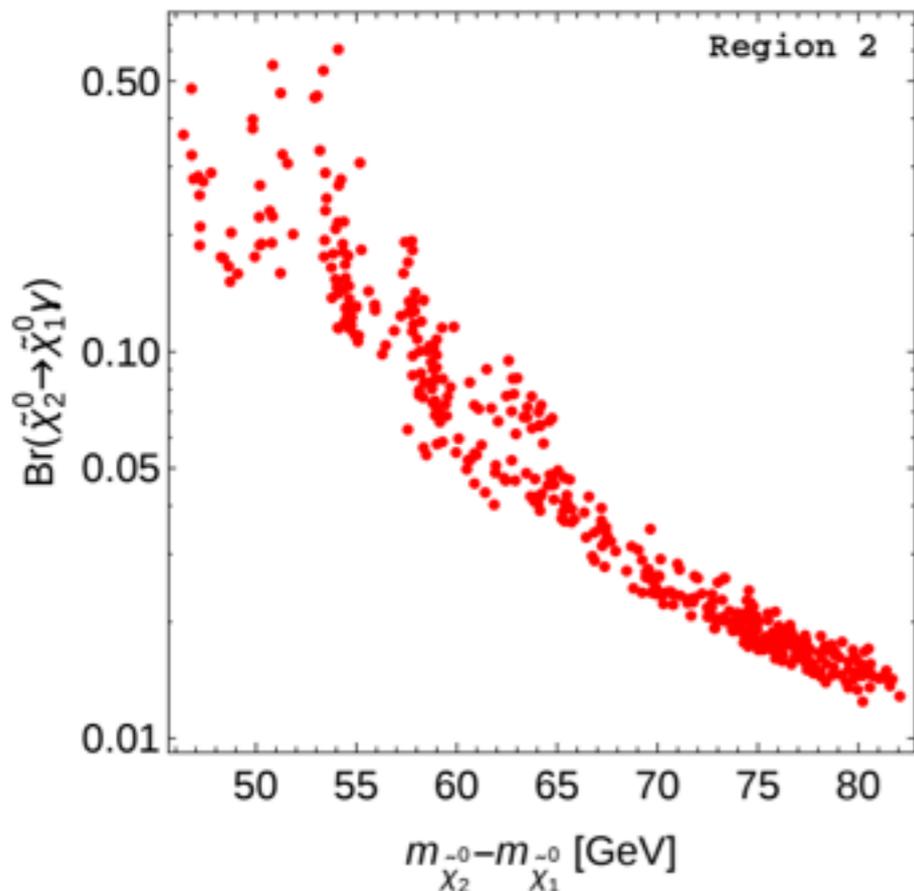
- DD rates $\mathcal{O}(10^{-10} \text{ pb})$ below the neutrino floor $\sim 10^{-9} \text{ pb}$

$$m_{\tilde{\chi}_1^0} \sim 45 \text{ GeV} \quad \mathbf{LSP}$$

Mixed LSP $\left\{ \begin{array}{l} 40\% \quad \tilde{H} \\ 40\% \quad \tilde{S} \\ 20\% \quad \tilde{B} \end{array} \right.$ Relic density always below Planck value

High m_0 , sfermions decoupled. Low $M_{1/2}$ sub-TeV gluinos

EWinos decay occurs through off-shell W and Z due to $\tilde{\chi}$ masses
Competitive decay channels such as $\tilde{\chi}_0^2 \rightarrow \tilde{\chi}_0^1 \gamma$ arise



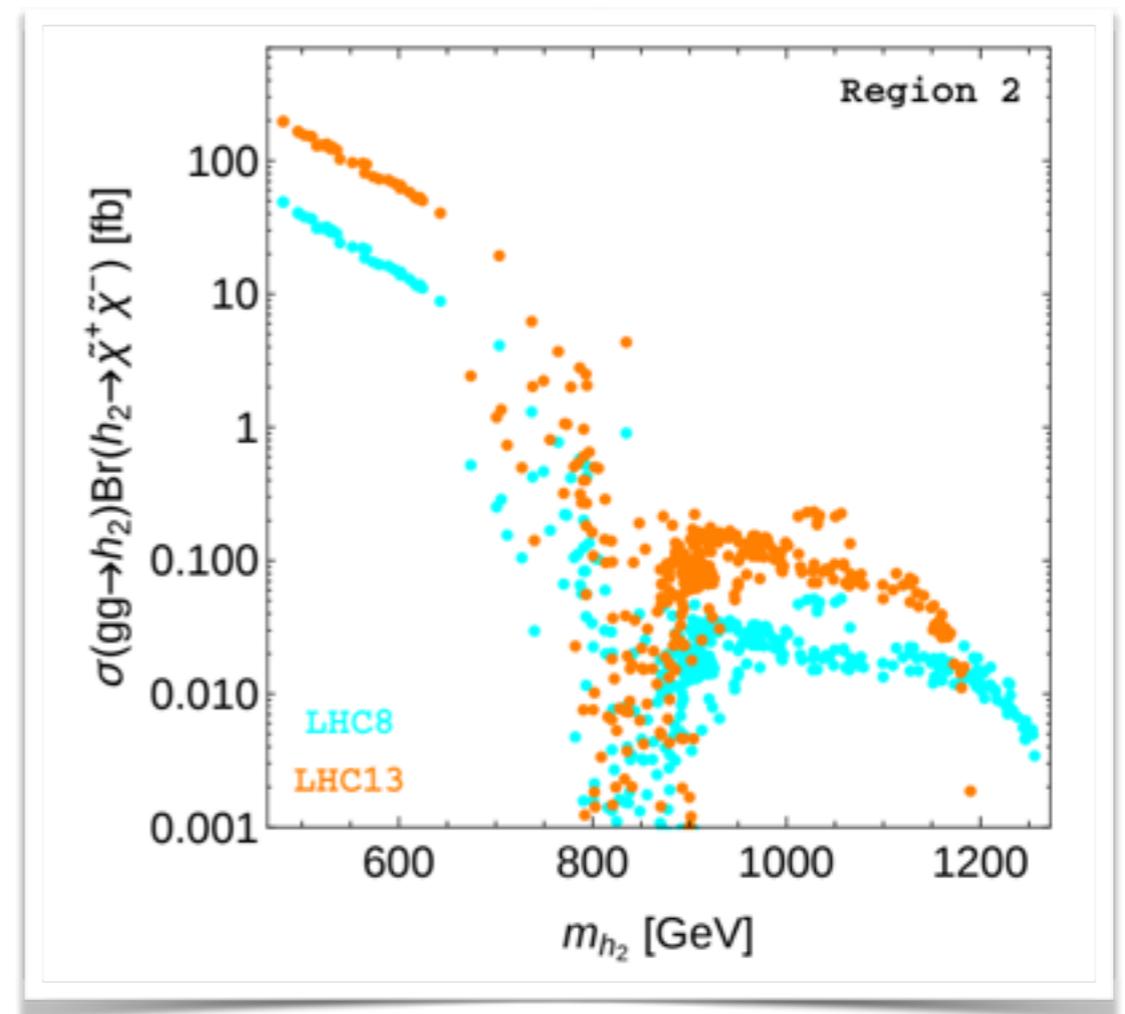
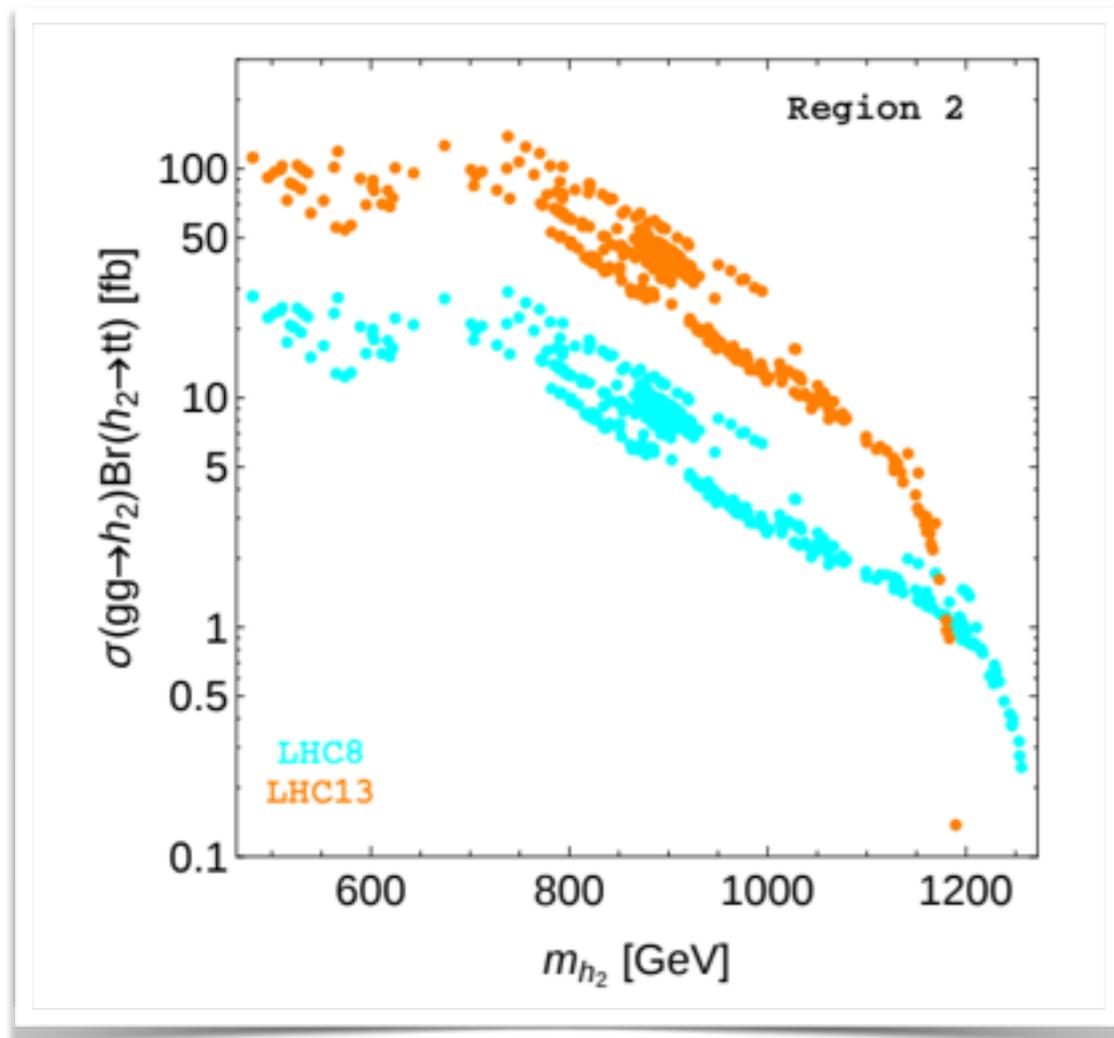
$\mathcal{O}(\text{pb})$ cross-sections $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^0$

Can it be used as a distinctive signature?

Large mass splitting leads to high $p_T \gamma$ s

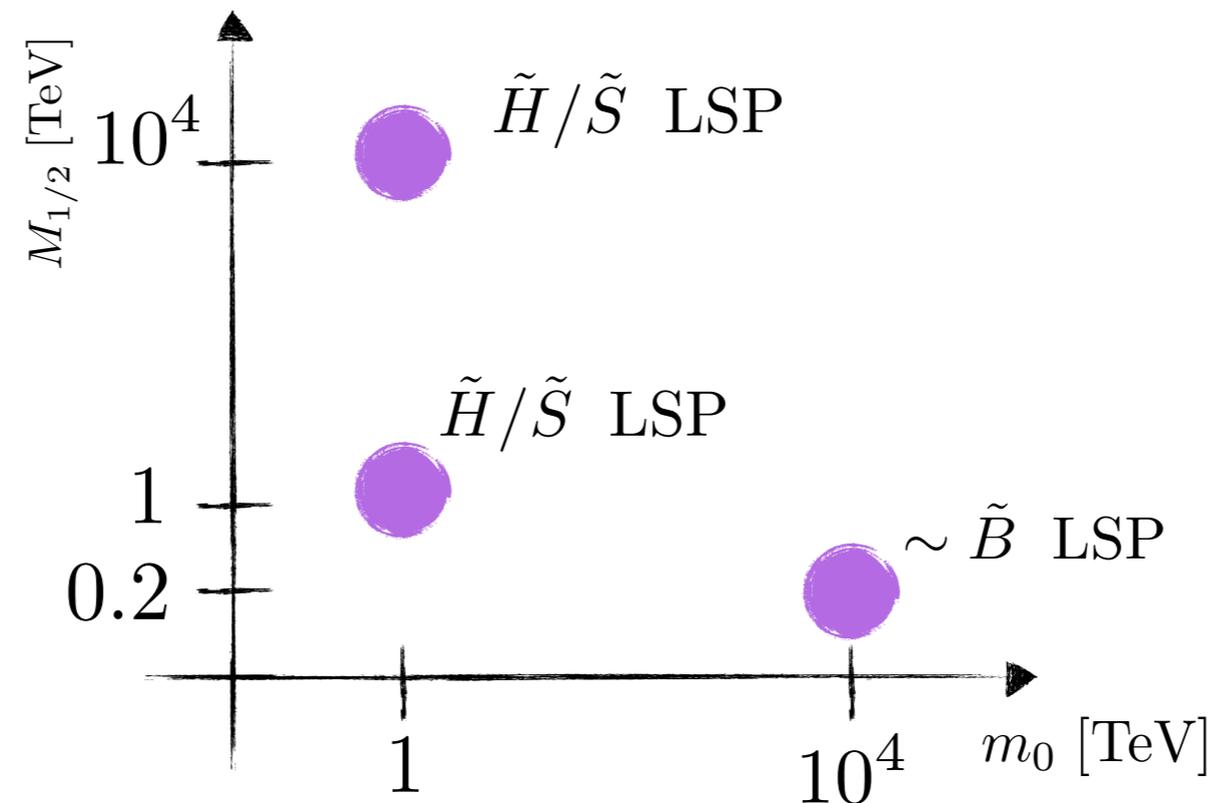
$$m_{\tilde{\chi}_1^0} \sim 45 \text{ GeV} \quad \mathbf{LSP}$$

The SM-like Higgs state is h_1 . Sub-TeV h_2 with $h_2 > 2m_{\text{top}}, 2m_{\tilde{\chi}}$

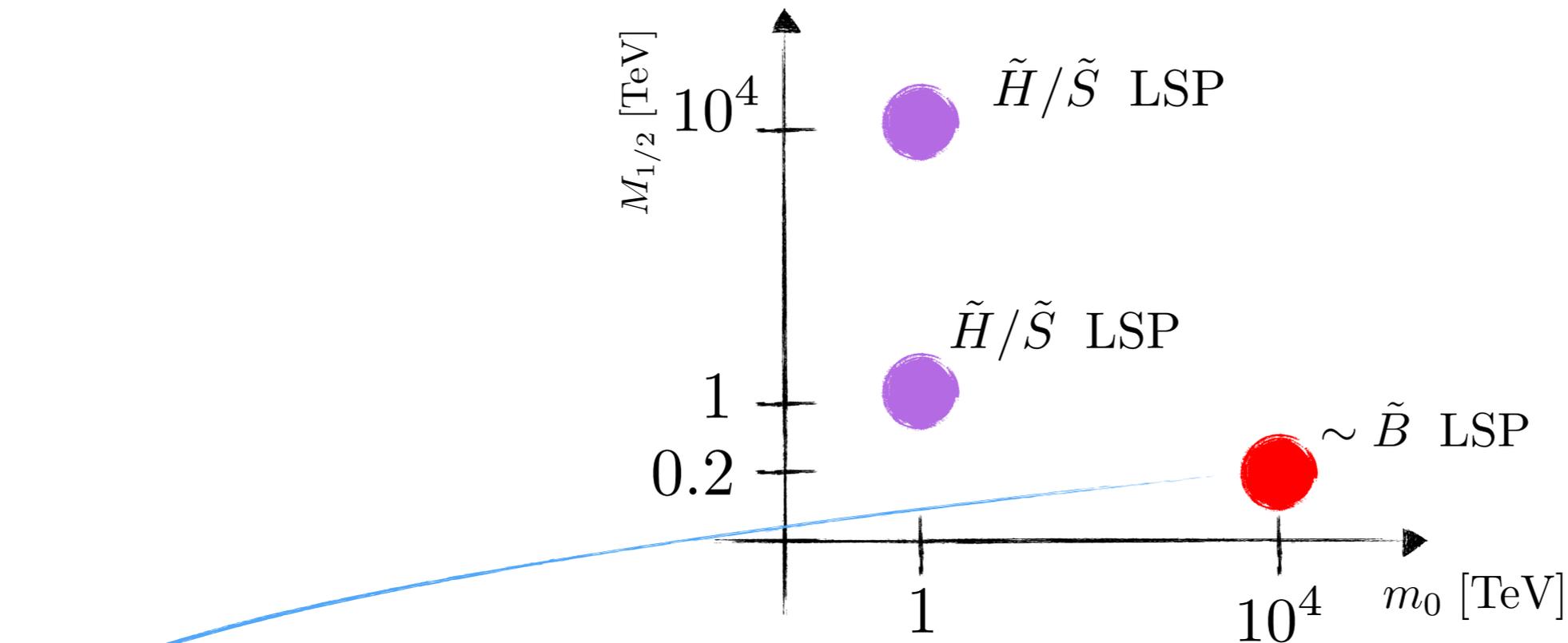


$\mathcal{O}(100 \text{ fb})$ cross sections at LHC 13 for top-pair and chargino pair production

$m_{\tilde{\chi}_1^0} \sim 65 \text{ GeV}$ high mass LSP



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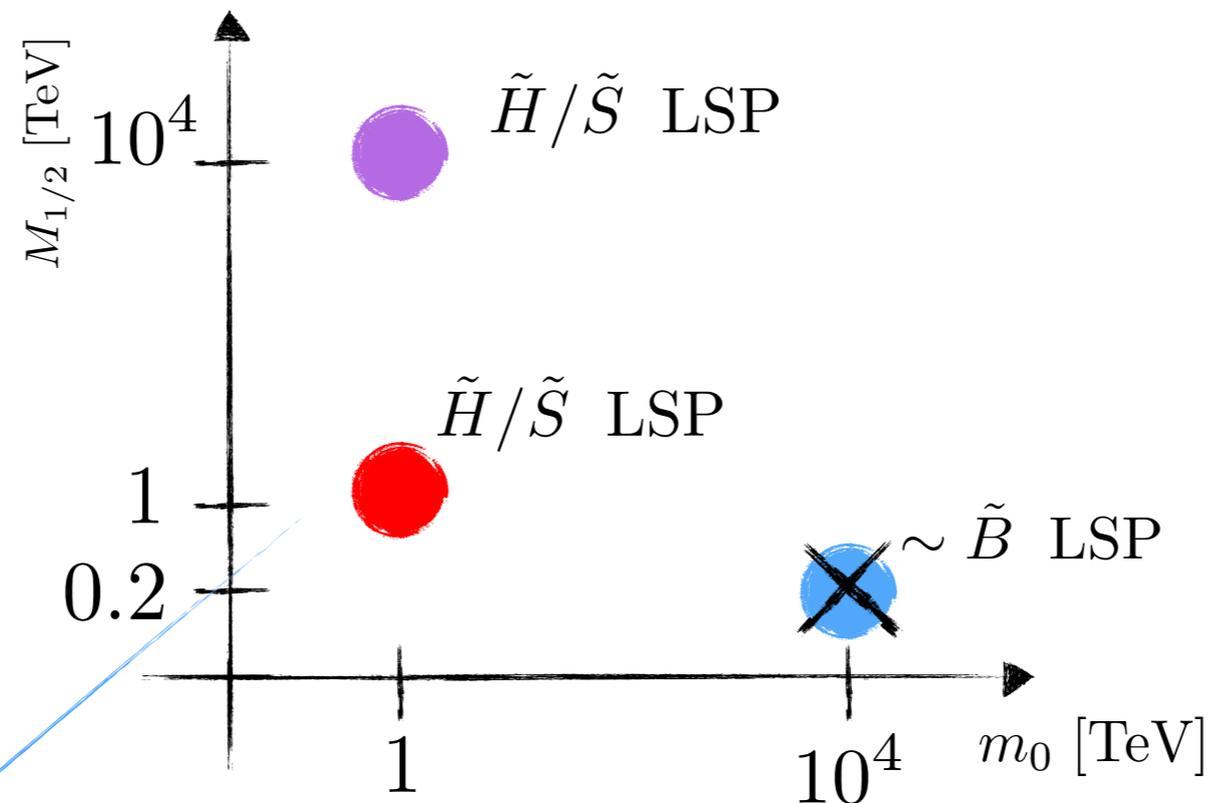
$$m_{\tilde{g}} \sim 3 M_{1/2} \quad m_{\tilde{B}} \sim 1/6 M_{1/2} \quad m_{\tilde{B}} < m_{\tilde{S}} < \frac{\mu \lambda^2 v^2}{\mu^2 + \lambda^2 v^2} \sin 2\beta$$

Upper limit on Bino LSP implies upper limit on gluino mass

Region completely excluded by gluino searches

Only the 5 GeV LSP region can have a relic compatible with Planck

$m_{\tilde{\chi}_1^0} \sim 65 \text{ GeV}$ high mass LSP



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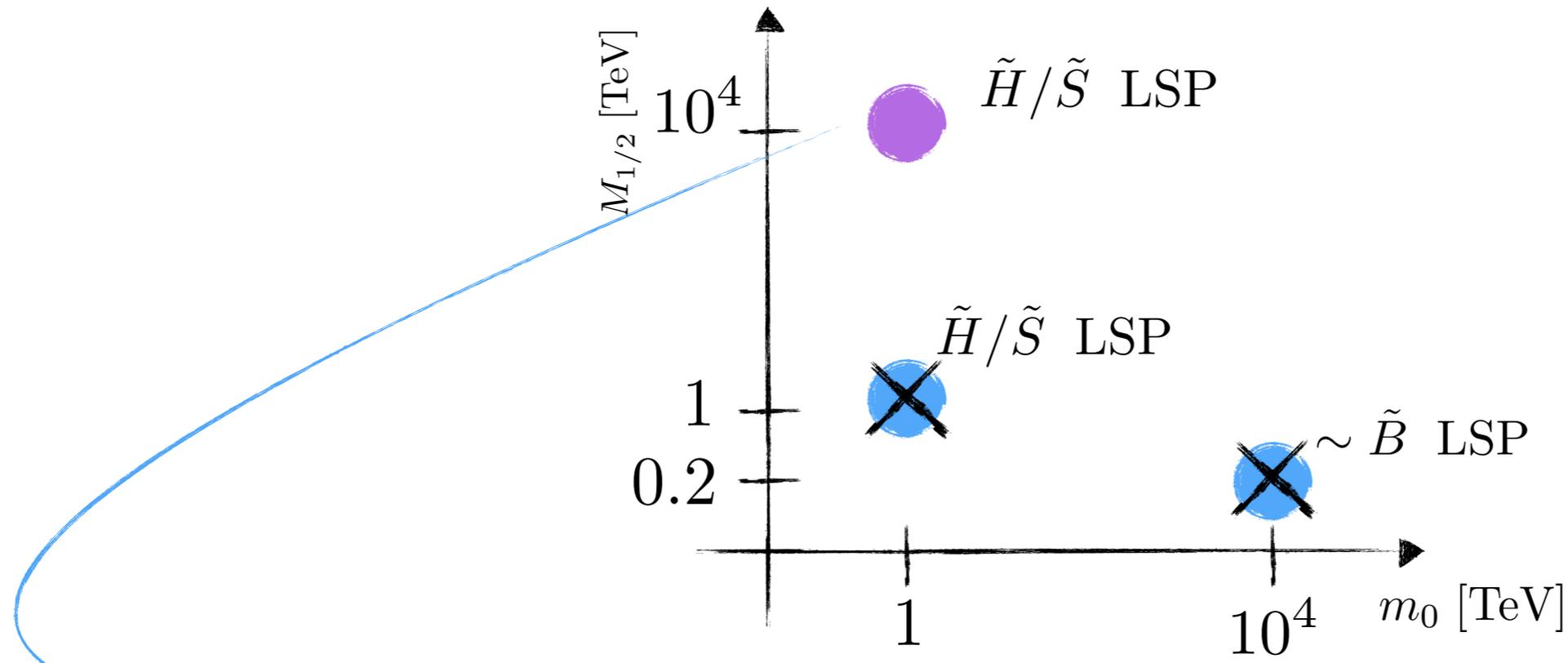
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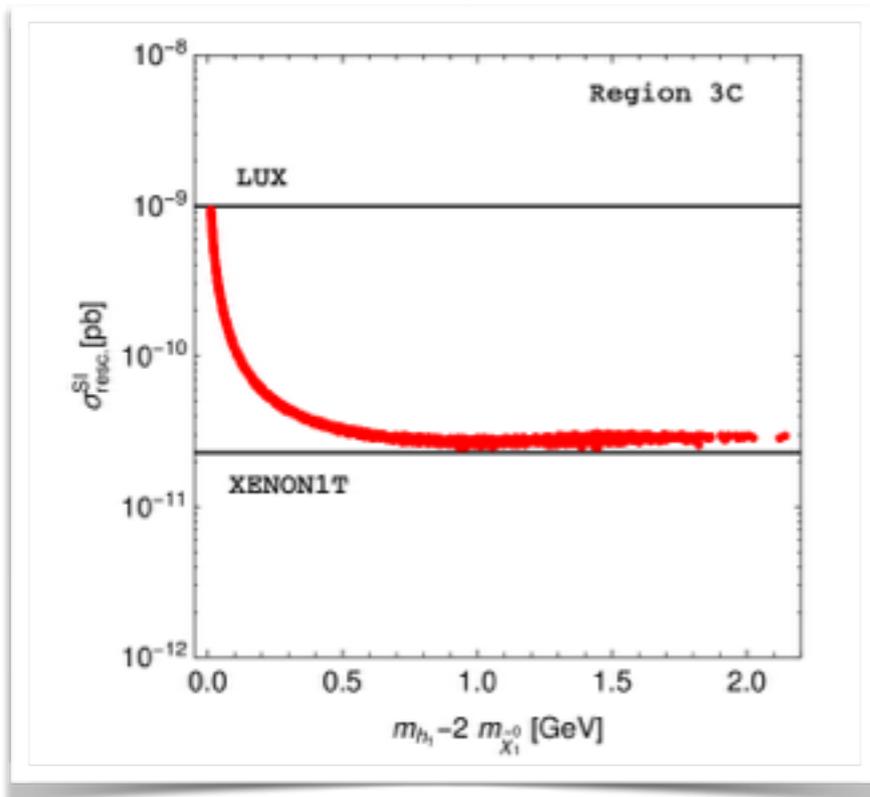
Only the 5 GeV LSP region can have a relic compatible with Planck

Also excluded from gluino searches

$m_{\tilde{\chi}_1^0} \sim 65 \text{ GeV}$ high mass LSP



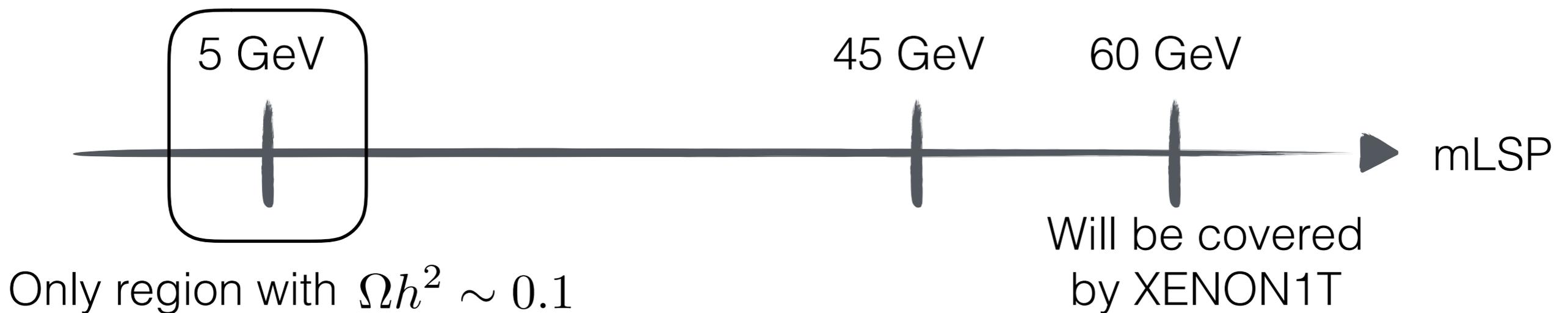
Decoupled gluino and bino / wino, light staus with weak sensitivity



Future DD experiments will test this region of the nMSSM

Conclusions

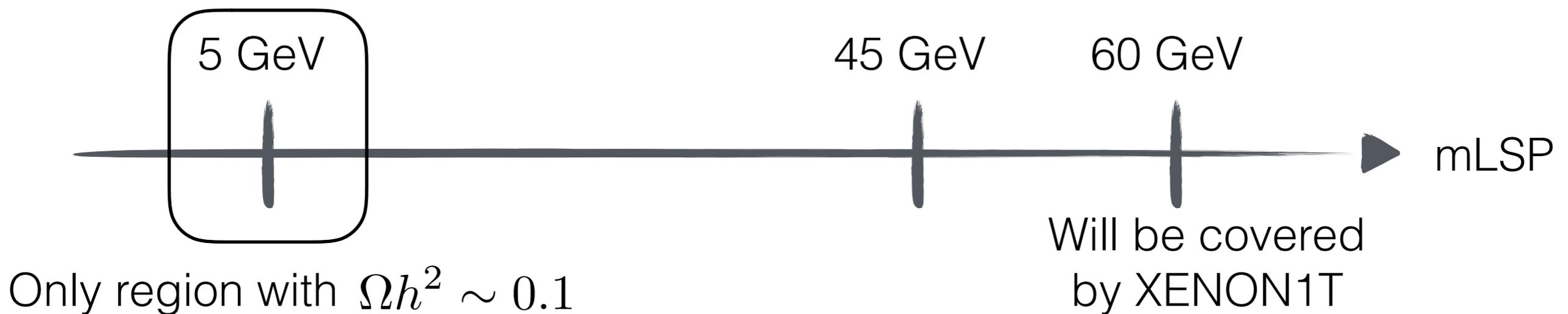
- The nMSSM is a variation of the \mathbb{Z}_3 inv NMSSM featuring a light singlino
- LHC and Dark Matter experiment are testing this hypothesis
- Three region compatible with experimental data survive



- Light new physics still survives LHC searches and will be tested
- Higgs-to-light Higgs decay and non standard sparticles decay peculiar signatures of the nMSSM
- Benchmark scenarios for the nMSSM in CERN YR

Conclusions

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Thank you!