Low μ NMSSM at the LHC
& Discerning a Hidden `Higgs' Boson

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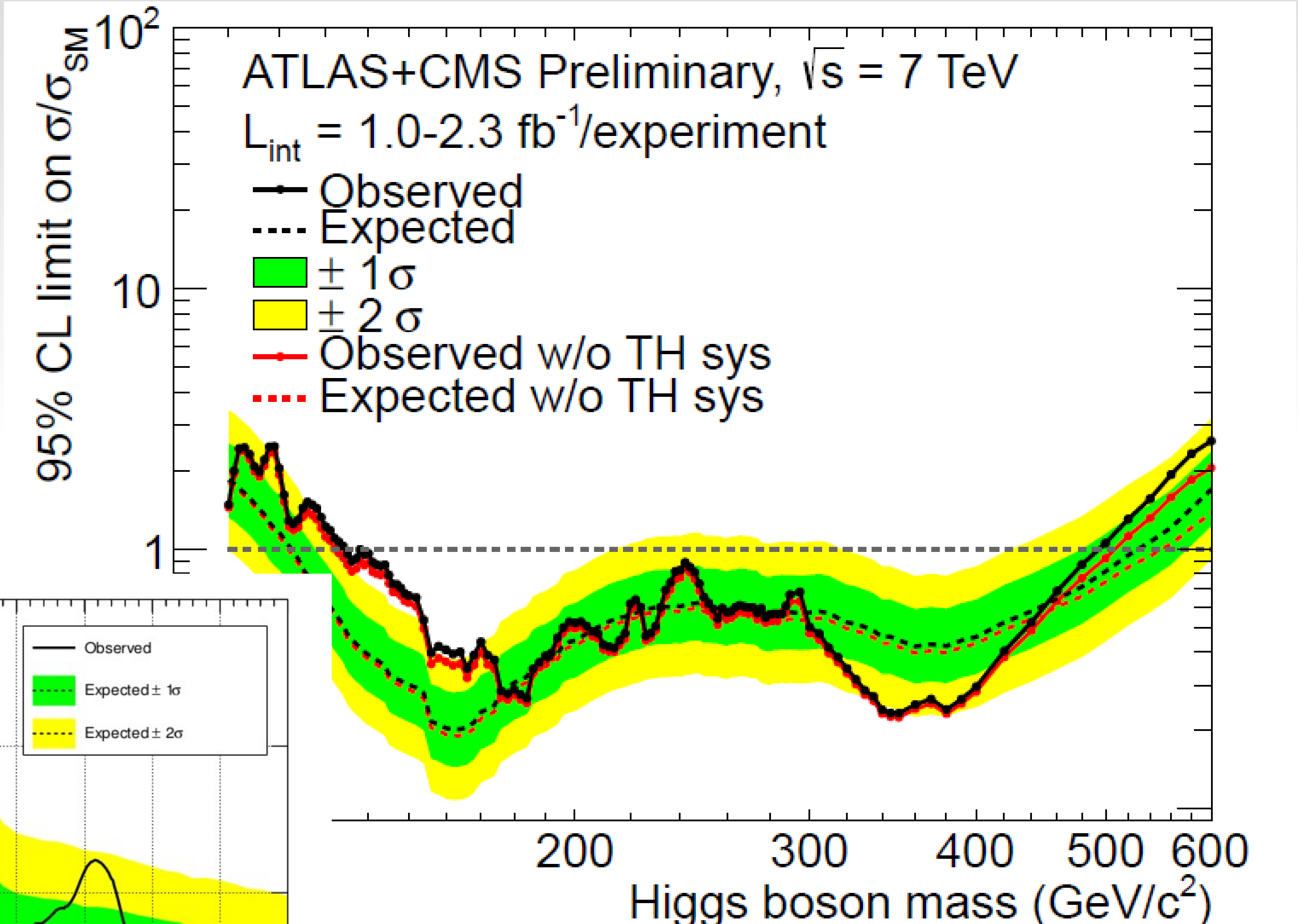
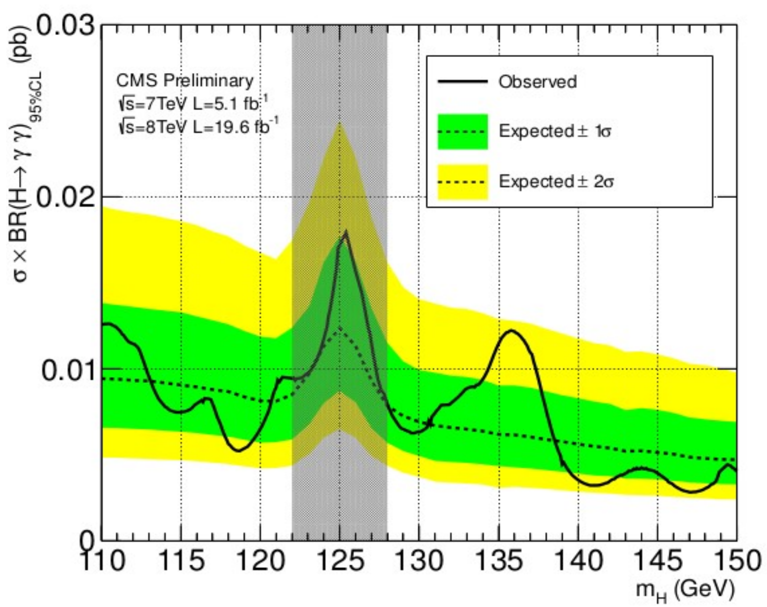
B. Dutta, YG, B. Shakya PRD D91 (2015) 3, 035016
B. Dutta, YG, D. Sanford, J. Walker, working in progress

A natural, yet collider inconvenient Higgs scenario in the NMSSM, & How different it is from MSSM.

A useful variable to probe the Goldstone equivalence in EWSB

Higgs @ the LHC





MSSM's μ problem and A `natural' NMSSM

- In the MSSM, the $\mu H_u H_d$ term for the Higgs mass and μ carries a scale
- In the NMSSM, with a scalar-invariant choice of the superpotential

$$W_{\mathrm{NMSSM}} = W_{\mathrm{Yuk}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

The singlet S can get a vev and dynamically generate an effective μ term

$$\mu_{\mathrm{eff}} = \lambda \langle \hat{S} \rangle$$

(NMSSM→ MSSM + a decoupled singlet at a small λ and large S vev)

Under NMSSM

- One more (weak singlet) CP-even scalar, CP-odd scalar and an extra neutralino.
- The new (pseudo)scalar is inefficiently produced at hard to probe
- Singlino only talks to the scalars (including the 125 GeV h)
- Like the bino, the singlino is conveniently a DM candidate, and almost just as hard to probe.

Higgs more natural

- Makes λ makes tree level contribution to 125 GeV scalar mass. A large λ makes the stop loop contribution less necessary.
- Large λ>0.7 has a UV running problem before GUT scale

$$M_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 + \\ + \frac{3m_t^4}{4\pi^2 v^2} \left(\ln \left(\frac{m_T^2}{m_t^2} \right) + \frac{(A_t - \mu \cot \beta)^2}{m_T^2} \left(1 - \frac{(A_t - \mu \cot \beta)^2}{12 m_T^2} \right) \right)$$

Ellwanger, et.al. 2010

How to access the singlet scalar?

- Via the effective μ term and the cubic singlet term.
- Production requires singlino-higgsino mixing and/or singlet scalar/MSSM Higgs mixing.

$$\begin{array}{c} \tilde{H}_d \\ \tilde{H}_u \\ \tilde{S} \end{array} \begin{pmatrix} 0 & -\mu & -v\lambda\sin\beta \\ -\mu & 0 & -v\lambda\cos\beta \\ -v\lambda\sin\beta & -v\lambda\cos\beta & \frac{2\kappa}{\lambda}\mu \end{pmatrix}$$

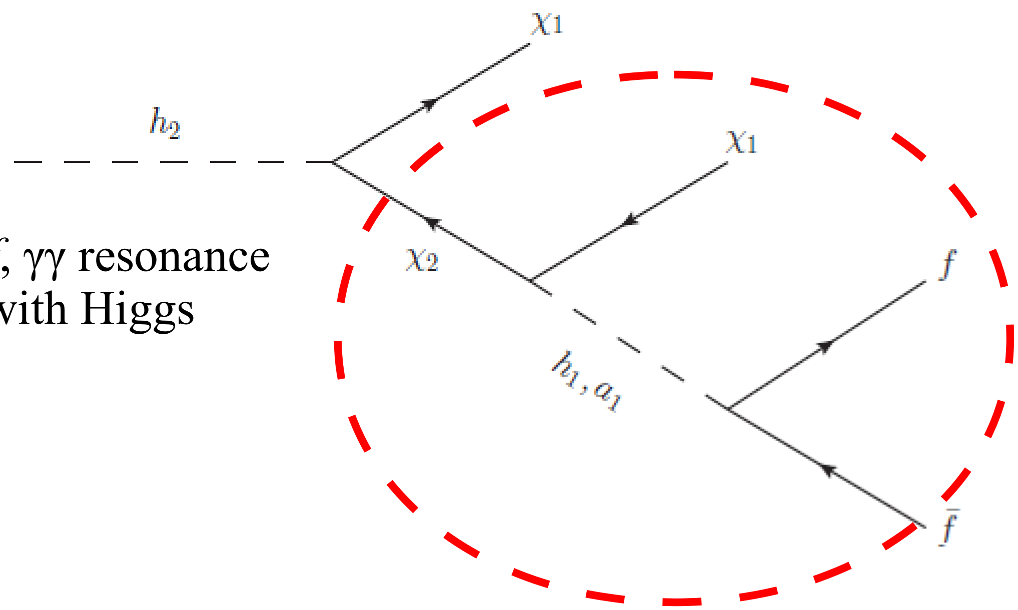
Searches for `Next-to' MSSM

- Smoking gun: a light scalar

U. Ellwanger, J.F. Gunion, C. Hugonie, S. Moretti, 04'

*a very light (pseudo)scalar can emerge from decays
*mostly singlet, unconstrained from Higgs search
*does not mediate interaction between SM fermions

As a light $f\bar{f}$, γγ resonance associated with Higgs final states

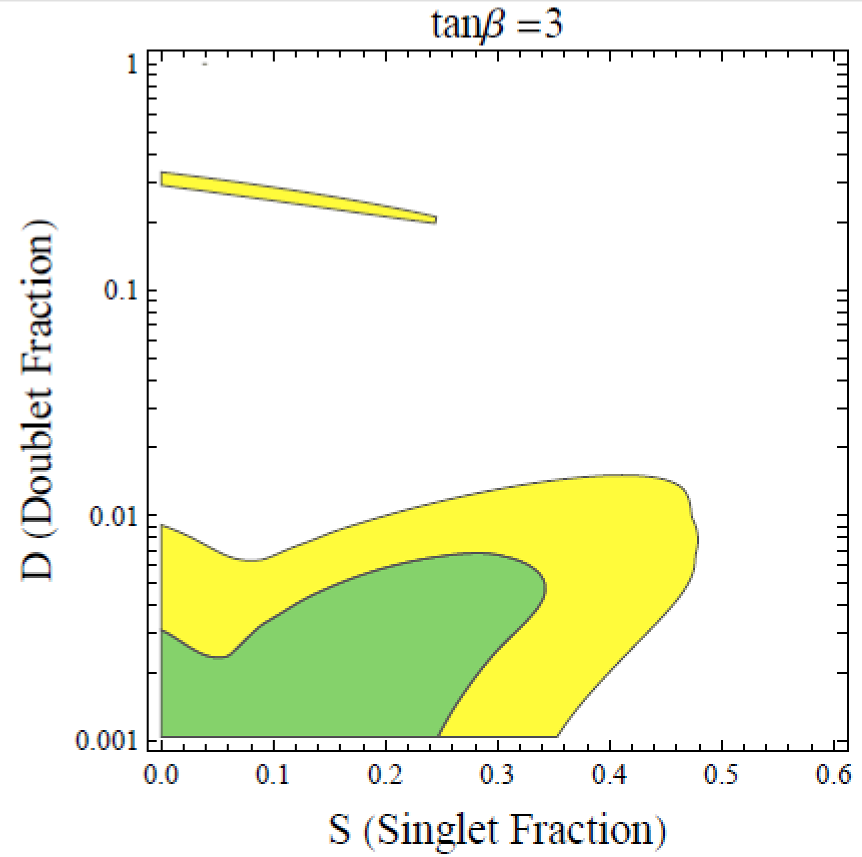


J. Huang, T. Liu, L. Wang, F. Yu, 14'

Motivation: mass can be degenerate

- The singlet scalar mass can be zero (U'(1) Peccei-Quinn) or the same as the SM Higgs, or heavier.
  ---- all three cases still allowed

- Substantial mixings btw the singlet & $H_{u,}$ H_d when close to the SM Higgs mass. Yet the current constraint on non-SM component in the Higgs is far from perfect.

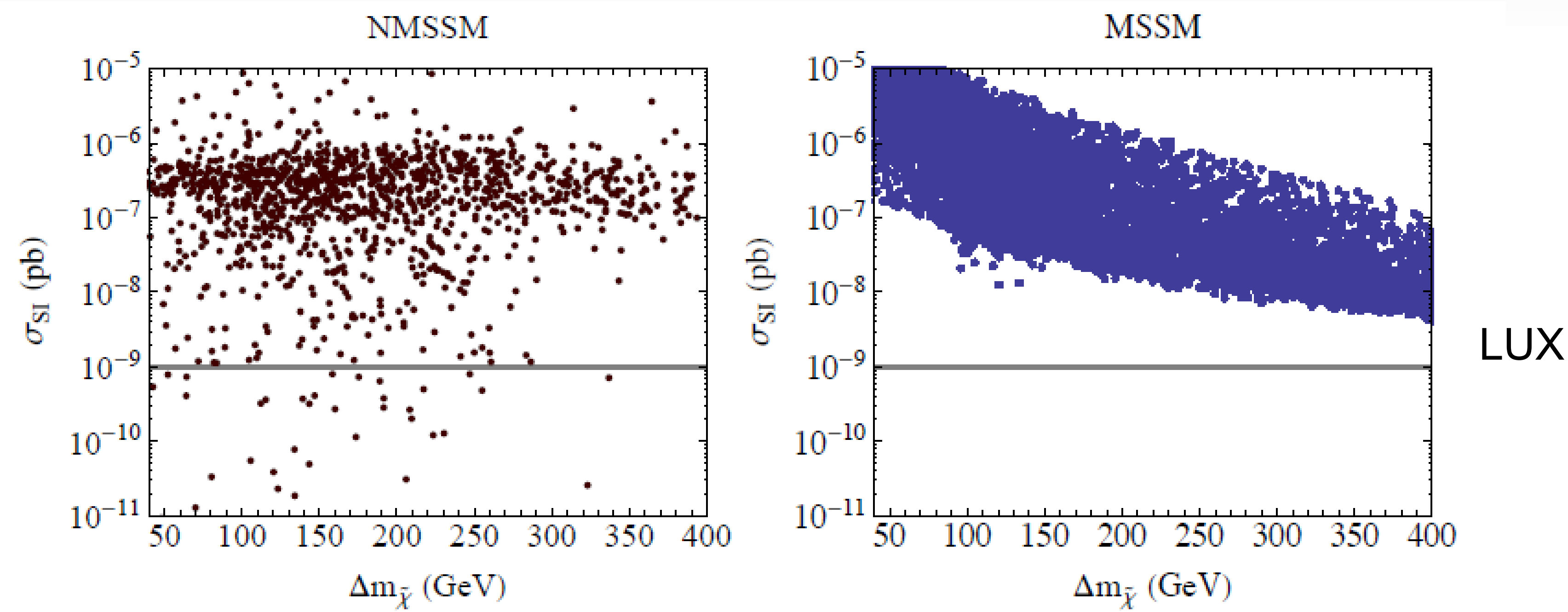


$$h^0_{126} = \alpha_h h^0_v + \alpha_H H^0_v + \alpha_s h^0_s$$

M. Farina, M. Perelstein, B. Shakya, 2014

Direction detection, in the NMSSM

- Can avoid DD constraints with negative μ, like the MSSM
- For positive μ, more neutralino/scalar mixing options to restrict the χχh coupling. (aka `sweet spot' in the MSSM)
- The singlet part of the 125 GeV scalar does not contribute.



$\mu > 0$

Minimal NMSSM parameter search

- Like mass between the lighter of the two scalars, with the lightest ~ 125 GeV.
- <50% singlet in the 125 GeV state.
- For the neutralinos, $m_{\chi 2} > m_{\chi 1} + m_h$
- Singlet LSP; Higgsino NLSP(s)
- Not too much wino in the NLSP
- Other susy particles heavy (for simplicity)

How low Higgsinos can go --- versus visibility @ LHC

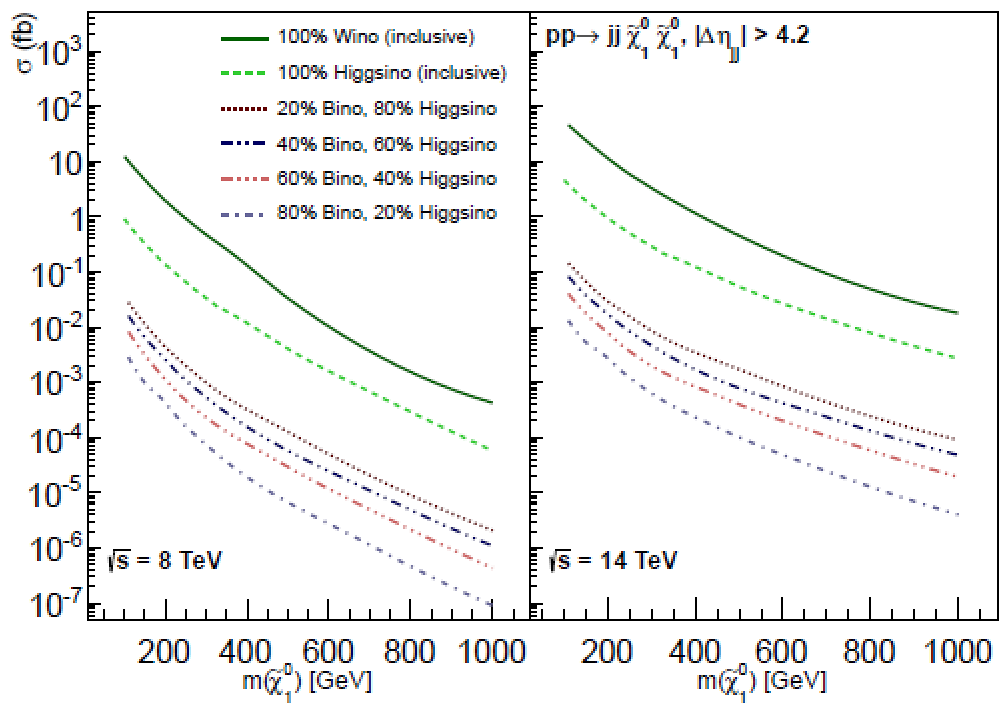


FIG. 1: Production cross section as a function of $m_{\tilde{\chi}_1^0}$ after requiring $|\Delta\eta(j_1, j_2)| > 4.2$, at LHC8 and LHC14. For the pure Wino and Higgsino cases, inclusive $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, and $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ production cross sections are displayed.

VBF cross-sections,
A. G. Delannoy, et. al. 2014

Benchmark points & their mixings

- Point A: a typical low μ NMSSM point
- Point B & C: the new pseudoscalar also show up in the decays, and it is also mass-degenerate with *h*.
- A large singlet mixing in *h* isn't mandatory.

Benchmark	λ	κ	μ	$\tan\beta$	A_λ	A_κ	N_{15}^2	S_{h3}^2	m_{a_1}	σ_{SI} (pb)	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$\tilde{\xi}^{Zh}$
A	0.8	0.25	220	2.9	710	45	62%	50%	161	9×10^{-11}	143	270	270	2.1
B	0.8	0.24	210	2.9	682	100	62%	42%	115	1.6×10^{-10}	133	259	261	0.7
C	0.8	0.25	230	2.9	710	100	64%	25%	119	3.4×10^{-10}	150	279	279	0.7
A' (MSSM), $M_1 = 140$GeV	-	-	260	20	-	-	93%($\tilde{B}$)	-	10^3	2.3×10^{-9}	134	270	275	1.6

- Lightest Higgsino NLSP ~ 260 GeV for less than 50% singlet in *h*.

Around Point A ...

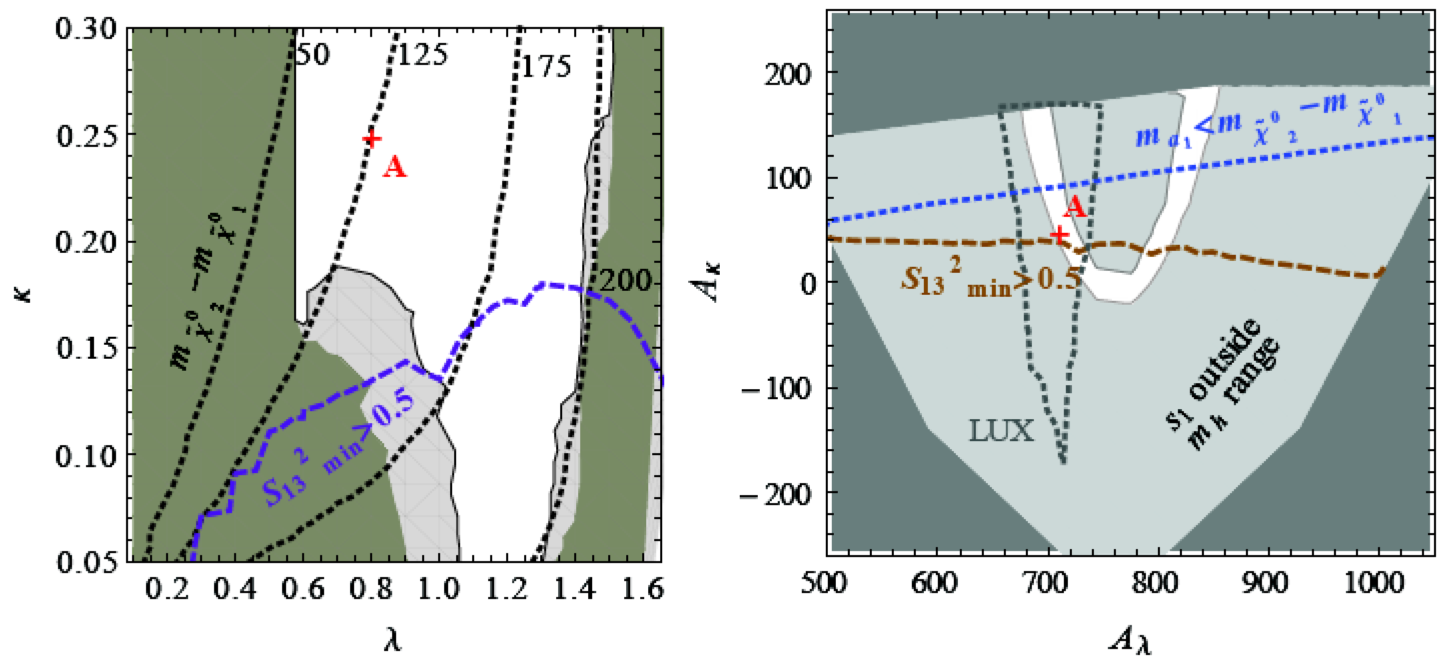


FIG. 2: (λ, κ) and (A_λ, A_κ) planes near the Benchmark Point A.

LHC search channel

- MET becomes a problem when the LSP has no momentum.
- Additional jets kick the missing mass into MET B. Dutta, et.al. 2013
- $\chi\chi$+jet(s) can be better than Drell-Yan w/o jets.
- Wino in the NLSP helps with cross-section but suppresses the NLSP's decay branching ratio into Z and h.
- $4l$, $(2l+2b)$ and/or $4b$+MET+j(s) final states, bb,ll reconstruct to two Z or h masses.

Selection cuts & event rates

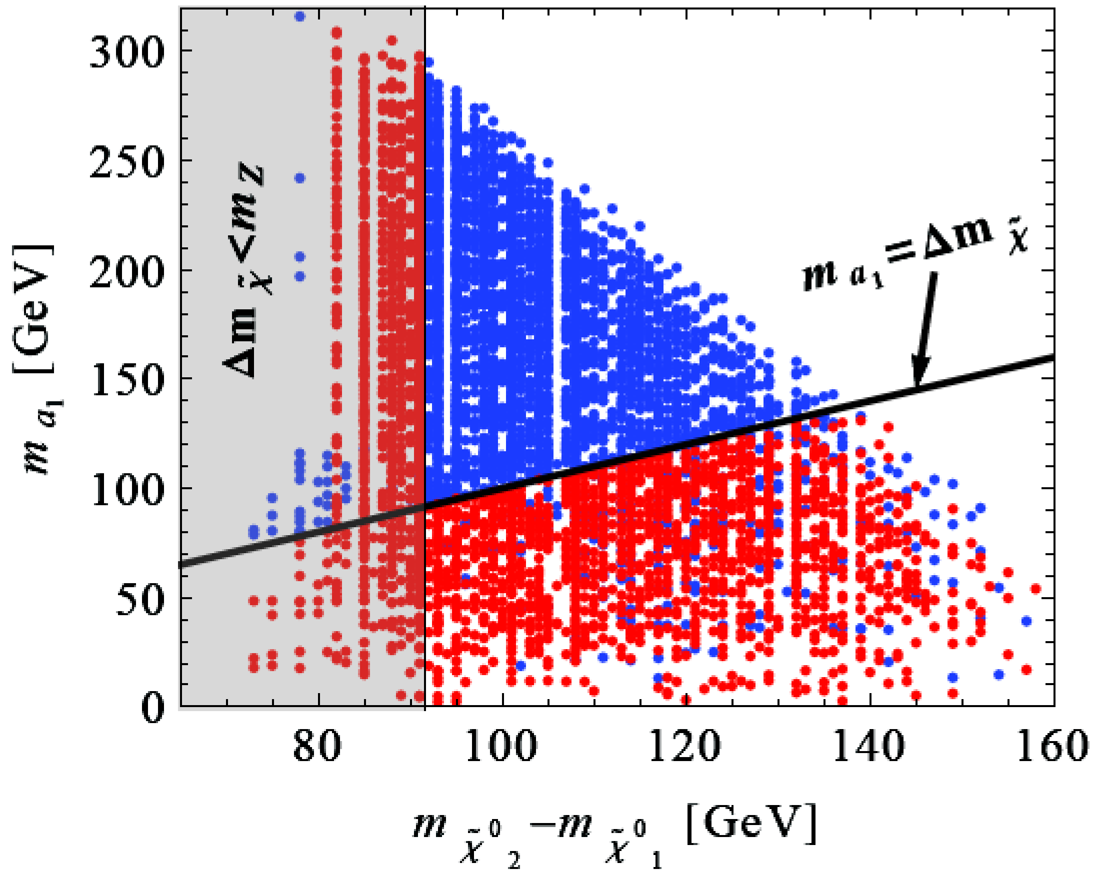
1. number of jets $N_j > 4$ and missing energy $\not{E}_T > 150$ GeV,
2. lepton and hadronic τ veto in the central region $|\eta| < 2.5$,
3. the leading central jet $P_T > 100$ GeV,
4. four tagged b jets with $|\eta| < 2.5$.

Cut/probability	Point A	Point B	Point C
dijet+$\not{E}_T$ cuts	3.5 fb	3.0 fb	2.6 fb
4 b branching with tagging efficiency	0.59%	1.2%	1.4%
bb rates	0.04 fb	0.07 fb	0.07fb

TABLE II: Kinematic efficiencies and $b\bar{b}$ rates at the NMSSM benchmark points.

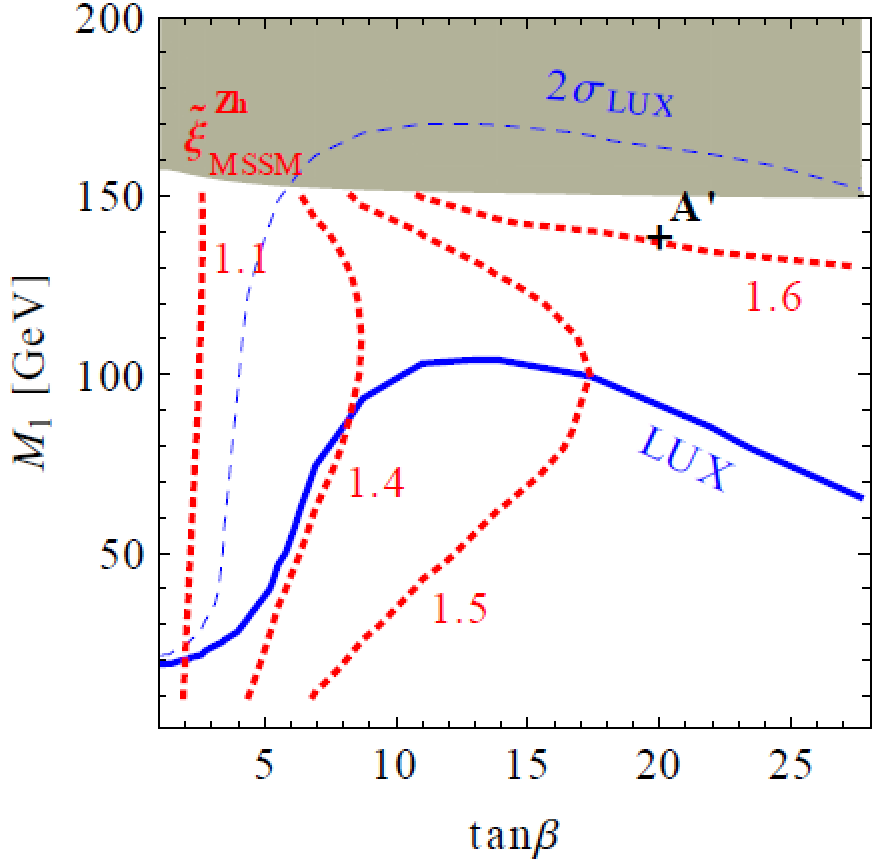
MSSM versus NMSSM @ LHC

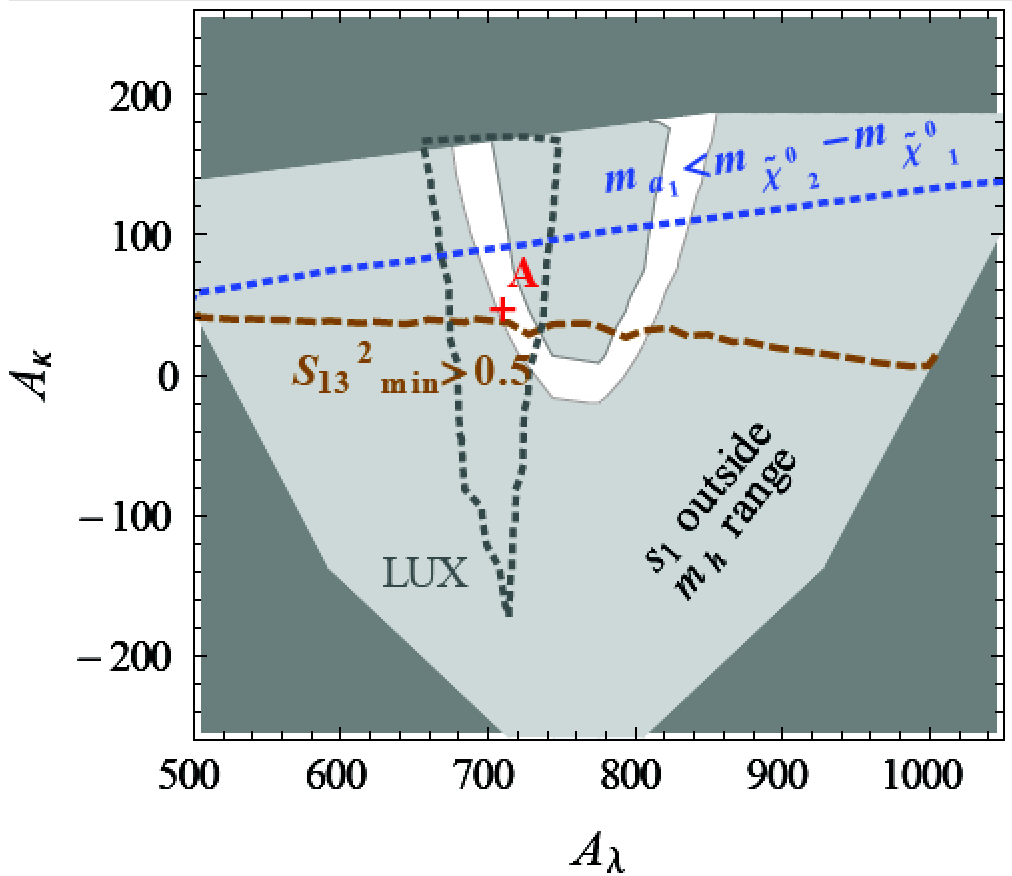
- The two Higgsino dominated NLSPs are produced at almost equal rates.



$$\tilde{\xi}^{Zh} \equiv \frac{BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z) + BR(\tilde{\chi}^0_3 \to \tilde{\chi}^0_1 Z)}{BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h^*) + BR(\tilde{\chi}^0_3 \to \tilde{\chi}^0_1 h^*)}$$

MSSM versus NMSSM @ XENON





So yes we have a chance to distinguish even when the singlet hides itself.

- $\xi^{Zh}<1$ means a singlet pseudoscalar from the decays. Such a deviation can hint for an extra (non-Higgs) scalar.
- If *Z/h* ratio is within the MSSM range (1~2), check direct detection constraints: Like parameter points of a 260 GeV Higgsino in the MSSM is on the brink of being ruled out by XENON.
- Needs high luminosity.

Upcoming: DM-minded models, with SU(2) doublets.

- Singlet-doublet fermion DM model

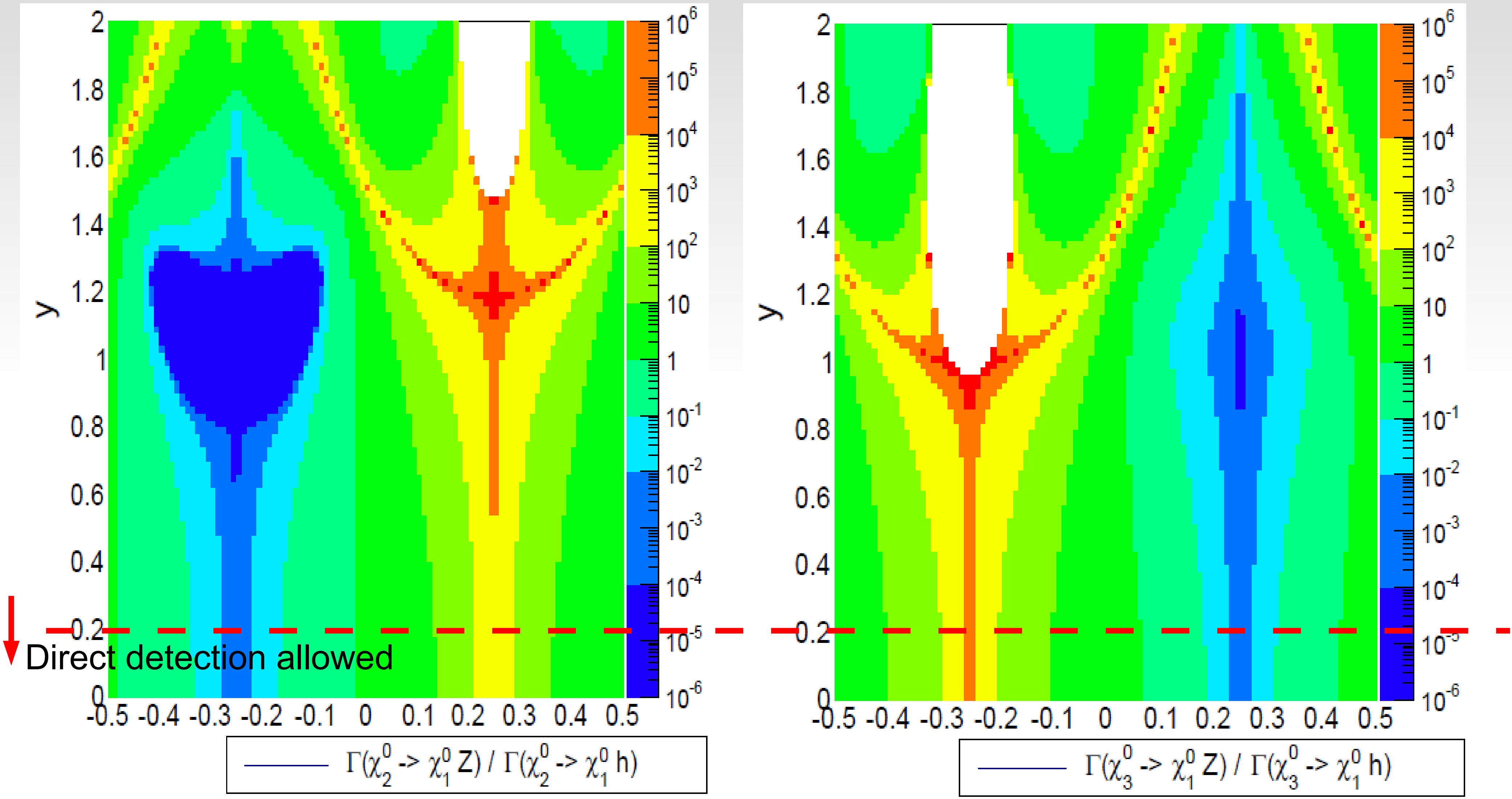
SD Fermion		
Field	Charges	Spin
S	$(\mathbf{1}, 0)$	$1/2$
D_1	$(\mathbf{2}, -1/2)$	$1/2$
D_2	$(\mathbf{2}, 1/2)$	$1/2$

C. Cheung, D. Sanford, 2013

$$-\mathcal{L}_{SD\ Fermion} = \frac{1}{2} M_S S^2 + M_D D_1 D_2 + y_{D_1} S H D_1 + y_{D_2} S H^\dagger D_2$$

A minimal DM model with two heavy weak doublets,
analogous to the two Higgsinos in MSSM,
but w/o modification to the Higgs sector

(almost) symmetric Z/h branching between the two doublets..



*A general test for the **BSM** weak sector*

- Visibility at the LHC means (relatively) light doublets, and even lower DM masses
- For the neutral particles in the doublets, (s-channel) *Z* mediation can be importation for pair production
- ***Goldstone equivalence theorem*** give $\xi^{Zh}\sim 1$, if no other singlet (pseudo)scalars are present
- $4l$, ($2l$+$2b$) and $4b$ + MET+ jet(s) to measure the decay branching fractions into *Z, h*.

SM backgrounds

- $t\bar{t}$: pre-cut cross-section at ~500pb and cut efficiency is $10^{-6\sim-7}$. This includes a *b*-pair invariant mass window cut and assume 1% *b*-faking probability from central jets.
- $t\bar{t}h$: starts from a pre-cut 0.5 pb and becomes less than signal.
- VV+jets: the combination of 4*b* and MET cut suppress this background (to similar to or less than the signal)

Upcoming study: (semi) leptonic final states

- Reconstruct the weak doublet's decay branching into Z and \`h'.
- 4l and (2l+2b) + MET+ jets offer a better $t\bar{t}$ bkg reduction
- 4b final states needs relatively light doublet mass to boost their significance at the LHC.
- Effective when Z/h isn't small.

See in Joel Walker's talk on Friday