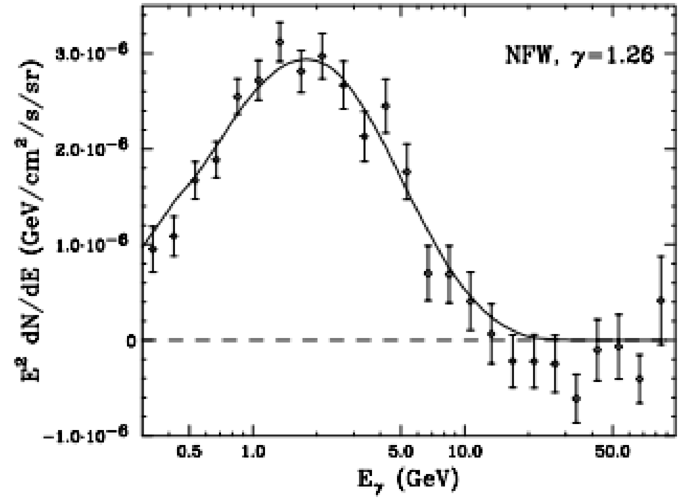
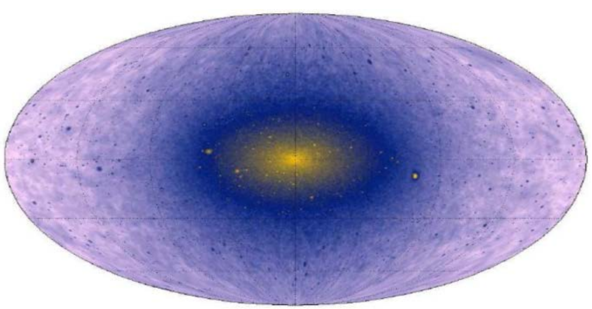
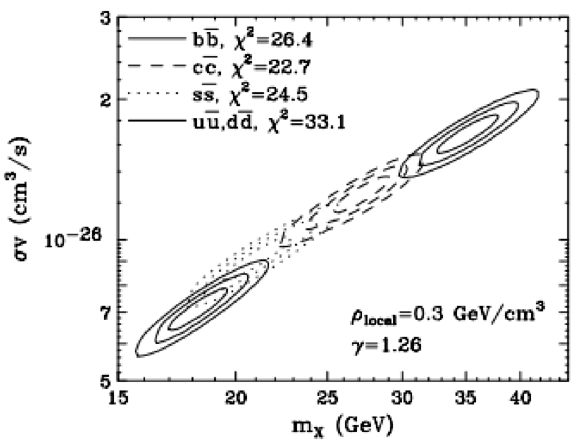
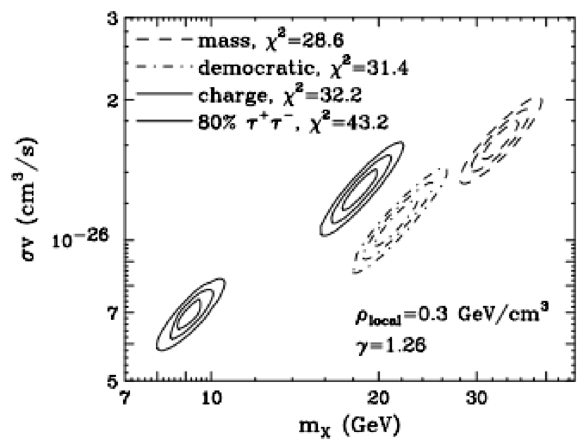
SUSY Scenarios for the Fermi GC Excess



Daylan etal 1402.6703







arXiv:1409.1573 v3 + in progress

M. Cahill-Rowley , J. Gainer, J. Hewett , T.D. Reuter & TGR

UNIVERSITY of FLORIDA

SLAC NATIONAL ACCELERATOR LABORATORY

3/26/15

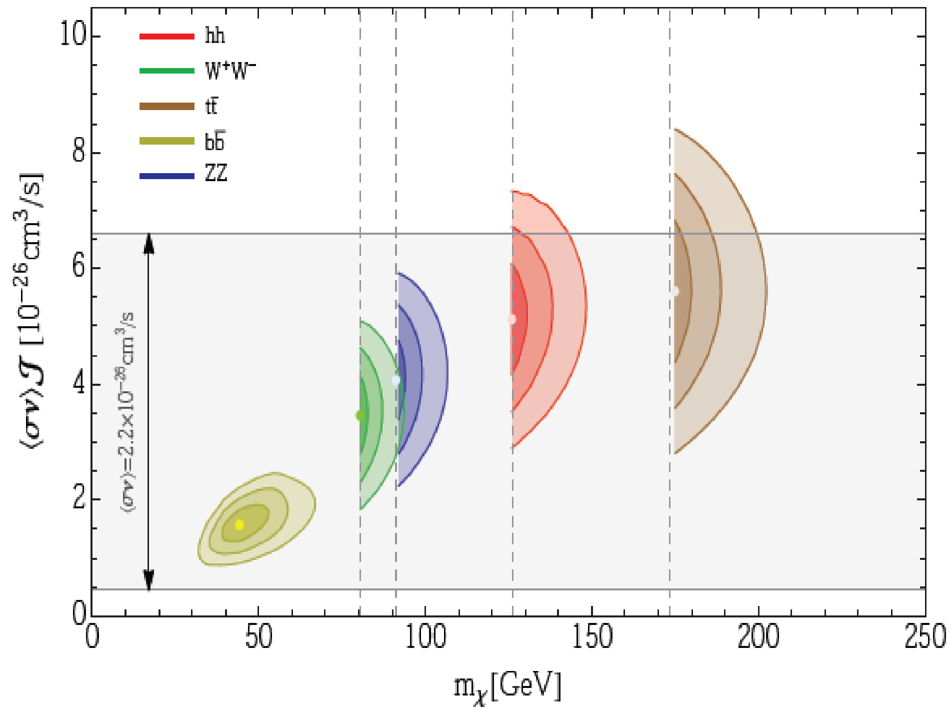
Model Building Assumptions

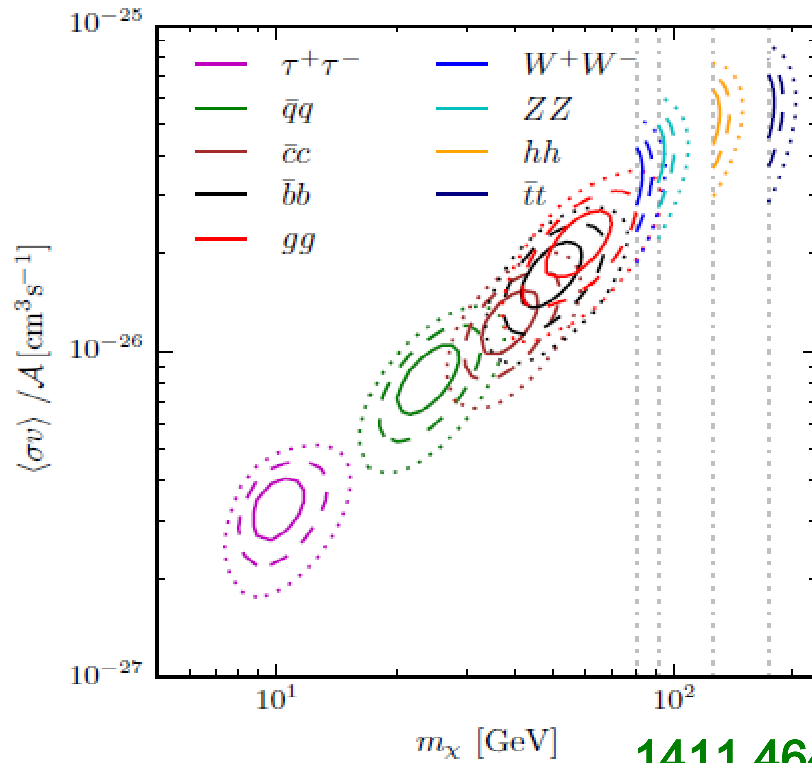
→ Assume the Dylan etal interpretation/fits of the Fermi GC are ~correct within a SUSY context. What ingredients do we have ?

- The DM LSP mass is ~ 30-40 GeV but could be as large as ~70 GeV
- Thermal freeze-out $\langle \sigma v \rangle$ gives the observed DM relic density
- A similar (but likely a bit smaller) value of $\langle \sigma v \rangle$ today → GC signal
- The bb-bar final state is dominant
- Assumption: only a *single* annihilation mediator is active at all times

→→ If the LSP is above the W mass then the MSSM is OK *provided* the WW etc. produce good fits. The low LSP mass + the bb-bar final state makes the model building interesting & challenging.

- It certainly does appear that bb-bar gives the best fit..





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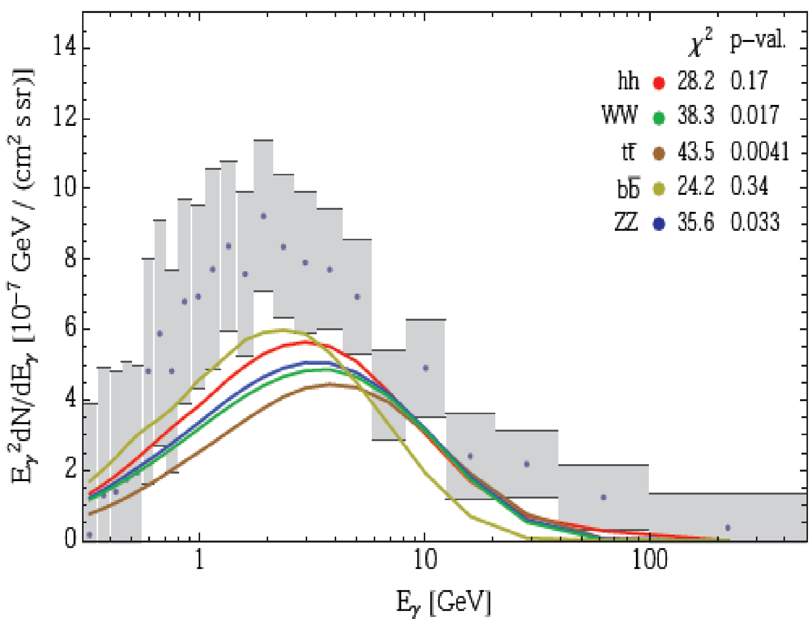

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Channel	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})$	m_χ (GeV)	χ^2_{min}	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.036]_{ICS}$

- Non-bb-bar final states other than hh result in poor fits & require LSPs to produce near-threshold final states with little boost. hh near threshold makes mostly b's similar to LSPs with masses ~60 GeV directly annihilating to bb-bar

- The WW, ZZ & tt-bar final states are easily obtained in the MSSM so are somewhat less 'interesting' in the present context .

- The true hh final state is helicity/p-wave suppressed for Majorana LSPs & so is not relevant in typical SUSY scenarios

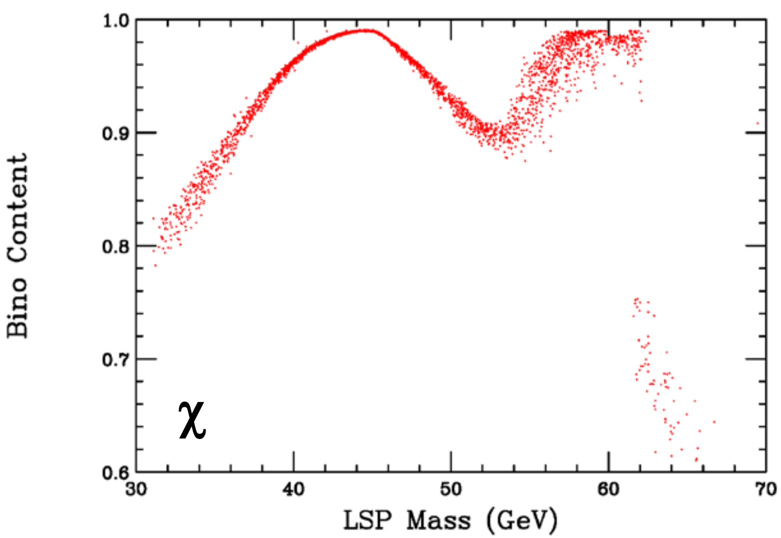
Our Goal: Can we find a 'not too crazy SUSY model' with the ingredients above & satisfying all of the other experimental constraints ? What are the pheno properties of such models?

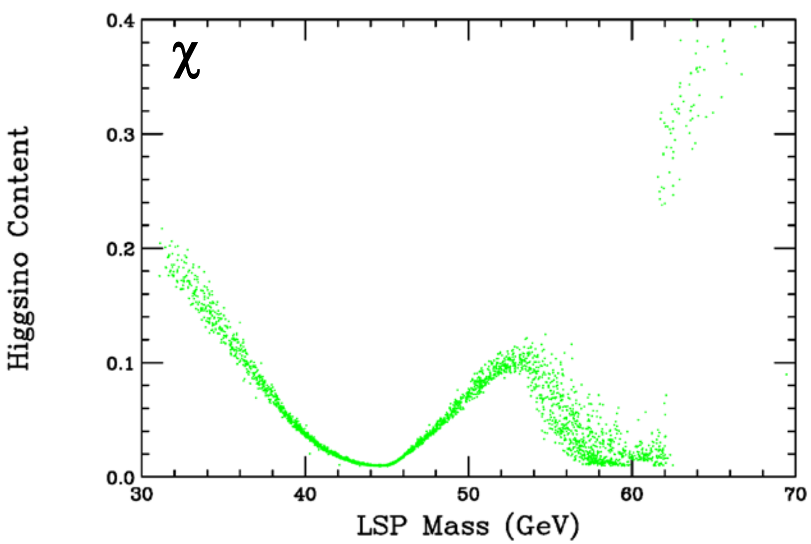
It is useful to examine why some models fail to see that this is non-trivial

Where do we start? The (p)MSSM !

- 30-70 GeV DM/LSP in the pMSSM must be well-tempered : mostly too light for co-annihilation (which is helicity/ p-waved suppressed), can't be ~wino/Higgsino (due to the LEP + relic density constraints) & so only ~ Z/Higgs funnel regions are relevant

- The relative bino-Higgsino content varies with LSP mass so that the Z/h at freeze out can make $\langle\sigma v\rangle$ large enough to give the measured relic density.

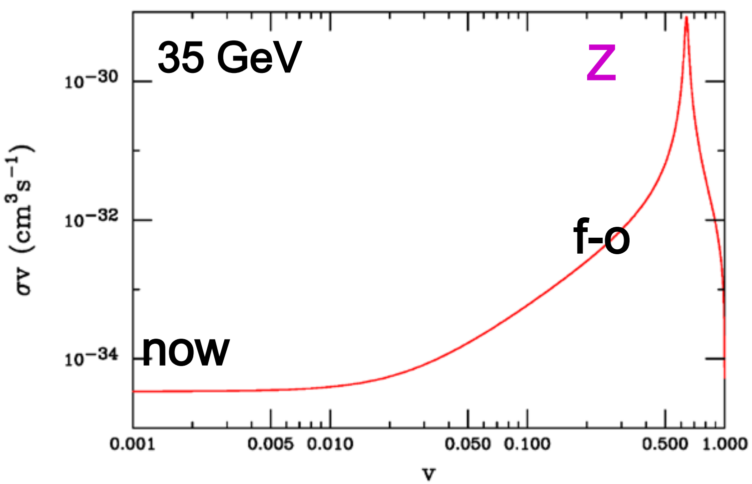


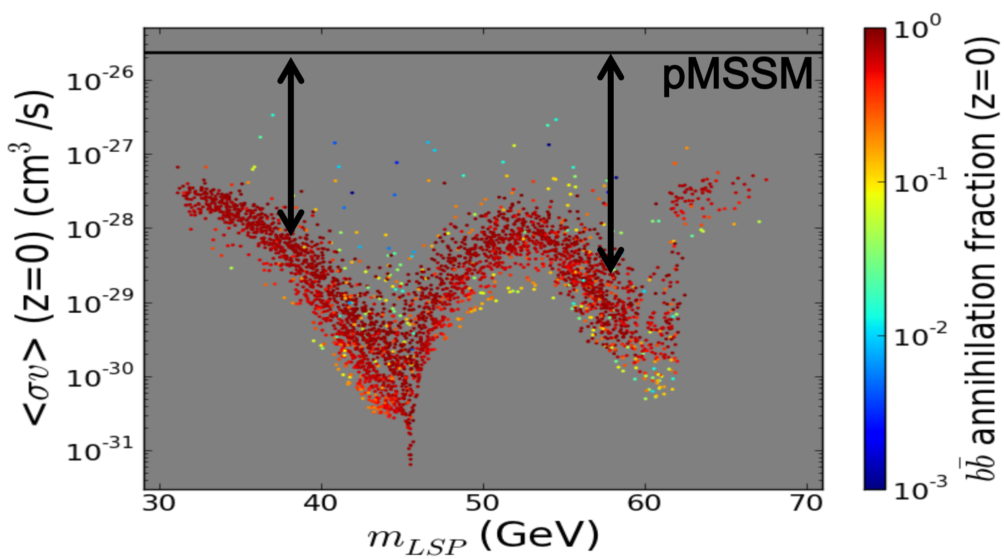


pMSSM (cont.)

- However, the value of ⟨σv⟩ today is too small by ~100 or more to produce the GC flux due its strong velocity-dependence as v is now much smaller (Also recall: bb-bar is not dominant in Z-exchange scenarios)

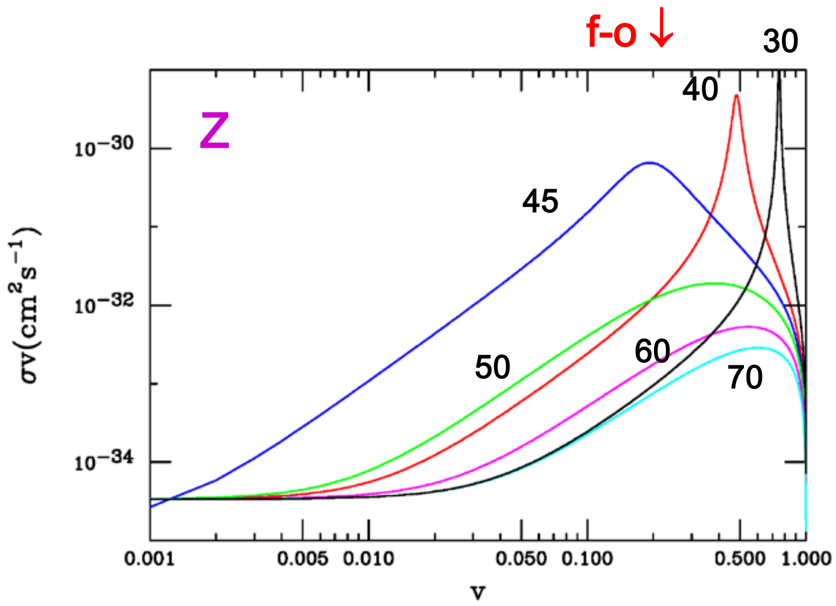
- Hence the Z/h cannot be the lone mediators due to the strong velocity dependence



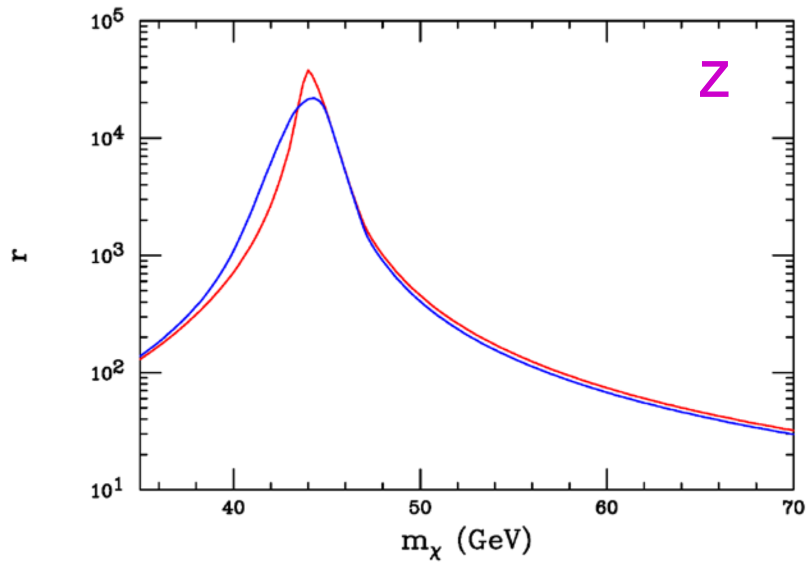


Scales up & down with Higgsino content

pMSSM (aside)



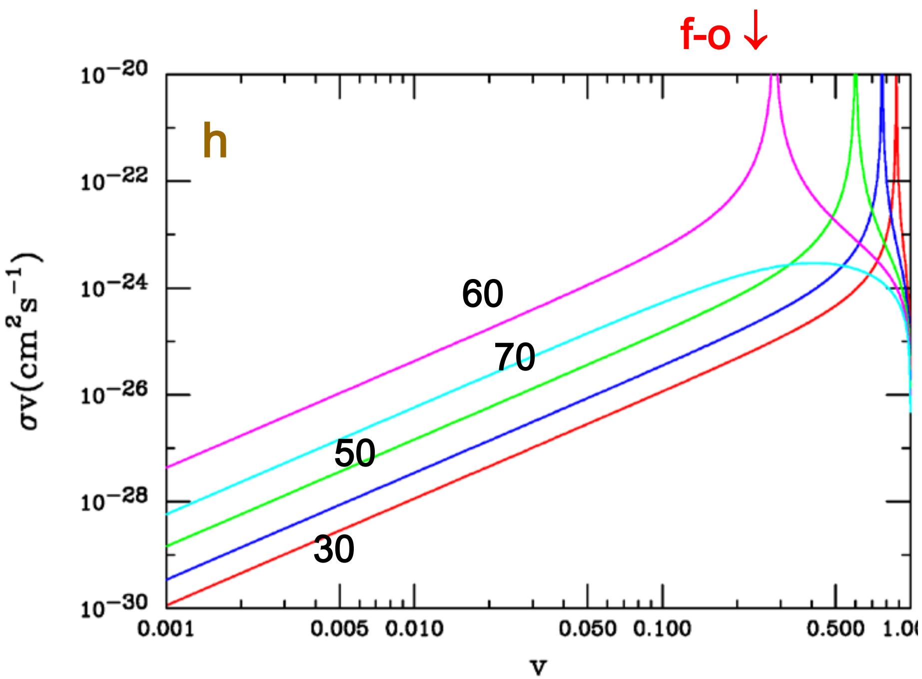
Typical Z-induced annihilation cross sections for various LSP masses via their Higgsino components show a strong velocity dependence unlike, e.g., in the case of pseudoscalar (a) exchange as will be shown later.

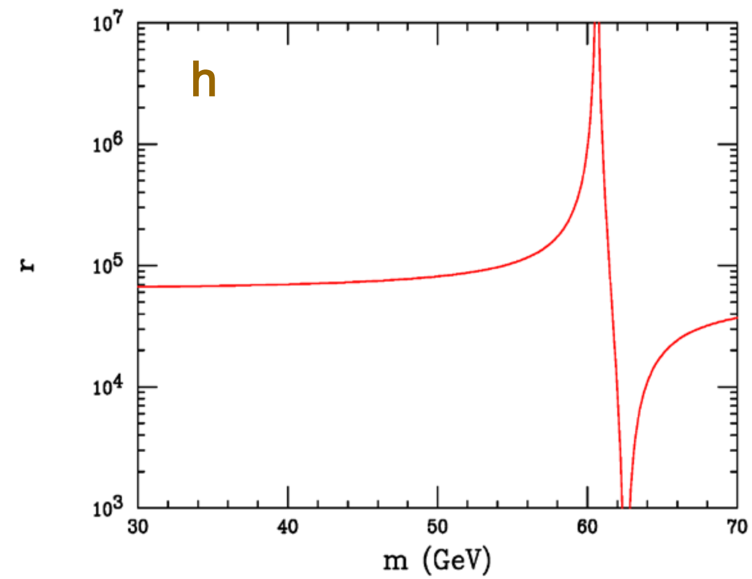


Ratio (r) of freeze-out to present day annihilation cross sections for pure Z exchange . This gives us an upper bound on the LSP Higgsino component since the apparent observed value of r is <~ 1

pMSSM (aside II)

For Higgs-dominated annihilation the velocity dependence becomes even stronger leading to typical values of r ~10^5 Once $2m_\chi$ is much past the Higgs pole the coupling strength is too weak to yield the observed relic density. Z/h exchange are inadequate → we need to go beyond the MSSM..





Toast !

What Next ? : Dirac Gauginos

- Why? Dirac LSP co-annihilation is not p-wave /helicity suppressed.

- The Dirac LSP of this mass must be ~a very pure bino -- any Higgsino content leads to a coherent vector Z-coupling conflicting with SI DD constraints . (Squarks must also be >1 TeV to satisfy SI DD in this case). The LSP can only rely on t-channel sfermion exchange to achieve the correct relic density:

$\chi\bar{\chi} \to f\bar{f}$:

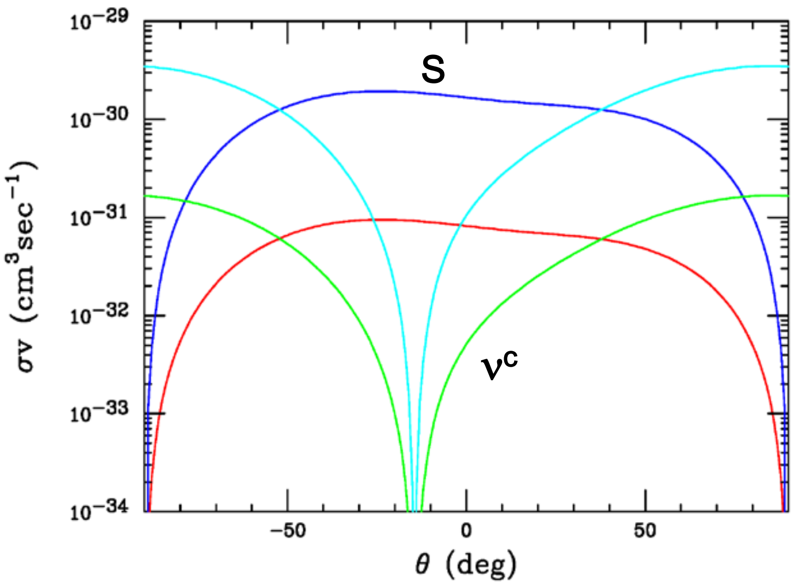
$$\sigma v = \frac{N_c\, g_1^4 m_\chi^2\, \beta_f}{8\pi}\left(\frac{Y_L^4}{(m_\chi^2 - m_f^2 + m_{\tilde{f}_L}^2)^2} + L \to R\right)$$

- However only ~100 GeV staus can produce a large enough ⟨σv⟩ . LEP, LHC & DD constraints → sbottoms are much too heavy to give a significant rate due to their small hypercharge & cannot produce the observed relic density

- More TOAST...

E_6SSM : Z' Plus SM Singlets

- SUSY E_6 has a TeV-scale Z', with couplings determined by a mixing angle, θ, as well as two new SM singlet fields (S, ν^c) which might be either a Dirac or Majorana LSP. Note that everything is completely fixed by group theory except for the Z' mass and θ



$M_{Z'}$ = 2 TeV

- The Z' mass is far above that of the LSP so no DM 'running up the pole' issues & no DD problems

- However, for an LSP mass of ~30-70 GeV & a Z' satisfying the LHC constraints we find that $\langle\sigma v\rangle$ during freeze out is too small to obtain the observed relic density

Toast !

The NMSSM with Z_3

$$W_{\rm Higgs} = \lambda \widehat{S}\, \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \,,$$

$$-\Delta \mathcal{L}_{\rm soft} = \lambda A_\lambda \, H_u \cdot H_d \, S + \frac{1}{3} \kappa A_\kappa \, S^3 + {\rm h.c.}\,.$$

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s + \cancel{\mu'} \end{pmatrix}$$

- The parameter space is actually rather limited & there are a large number of experimental constraints given our assumption of only a single mediator.

- The ~singlino is the LSP and the ~isosinglet CP-odd a (as noted by many authors) is a good mediator. The coupling to the SM is via mixing & requires large tan β to get bb-bars

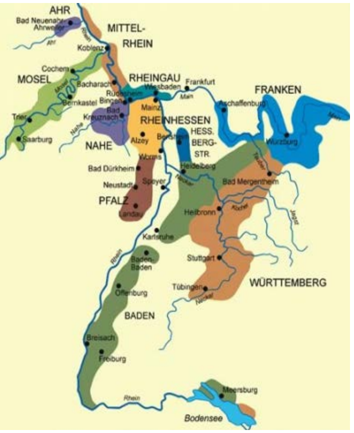
- We know that the Higgsino content of the LSP must be kept small to avoid coupling to the Z & its influence on the relic density. (Single mediator only!) . $\lambda v_{u,d}$ must be small to avoid this mixing .

The NMSSM with Z_3 (cont.)

- However: $\mu_{eff} = \lambda s > 100$ GeV (LEP) & ALSO $2\kappa s \sim 30$-70 GeV is the LSP mass. Furthermore, κ contributes to the overall scale of the $\chi\chi a$ coupling (see below) so can't be too small
- Then we need to arrange a smallish a mass, a somewhat larger A mass and also keep h ~125 GeV from loops while avoiding the LHC search constraints
- We performed both an algebraic study of these requirements as well as a scan of the parameter space (generating > 10^{10} points) finding no solutions

→ There is not enough parameter freedom to satisfy all of these requirements (& those on the rest of the spectrum) simultaneously with only a single mediator. (But Z + a will work in a small region.)

Toast !



The General NMSSM Without Z_3

$$W_{\rm Higgs} = \lambda \widehat{S}\, \widehat{H}_u \cdot \widehat{H}_d + \xi_F \widehat{S} + \frac{1}{2}\mu' \widehat{S}^2 + \frac{\kappa}{3}\widehat{S}^3 \,,$$

$$-\Delta\mathcal{L}_{\rm soft} = \lambda A_\lambda\, H_u \cdot H_d\, S + \frac{1}{3}\kappa A_\kappa\, S^3 + m_3^2\, H_u \cdot H_d + \frac{1}{2} m_S'^2\, S^2 + \xi_S\, S + {\rm h.c.}$$

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s + \mu' \end{pmatrix}$$

- The extra **5** parameters, e.g., μ' , resolve these problems !

We studied the general NMSSM by performing a parameter scan employing a modified version of NMSSMTools4.3.0 *** → 'features' (new version 4.5.1 out now)

- To simplify we set slepton masses to 1 TeV and all squark masses to a common value m_Q with $A_{b,t} = \sqrt{6}\, m_Q$ to get an observed Higgs mass of 125±3 GeV (stop mixing) which we assume is the lightest CP-even state

- Furthermore we also set $2M_1 = M_2 = M_3/3 = 1$ TeV & $A_\tau = 1.5$ TeV

Parameter	Value	Lower Bound	Upper Bound
M_1	500 GeV	—	—
M_2	1 TeV	—	—
M_3	3 TeV	—	—
$m_{\tilde{L}(\tilde{e})_{1,2,3}}$	1 TeV	—	—
m_3^2	0	—	—
$m_{S'}^2$	0	—	—
A_τ	1.5 TeV	—	—
$\tan\beta$	Scanned	1	60
λ	Scanned	0	0.7
κ	Scanned	-0.7	0.7
A_λ	Scanned	-30 TeV	30 TeV
A_κ	Scanned	-30 TeV	30 TeV
$\mu_{\rm eff}$	Scanned	-5 TeV	5 TeV
$m_{\tilde{Q}}$	Replaced	—	—
$A_{t,b}$	Replaced	—	—
ξ_F	Replaced	—	—
ξ_S	Replaced	—	—
μ'	Replaced	—	—

These parameters are fixed

These are flat scanned

These 'solved for' numerically to obtained desired value of the physical quantities in the ranges given here

Parameter	Value	Lower Bound	Upper Bound
m_h	Scanned	122 GeV	128 GeV
m_a	Scanned	80 GeV	800 GeV
m_A	Scanned	500 GeV	5 TeV
$\lvert m_{\chi_1^0}\rvert$	Scanned	30 GeV	40 GeV

$m_a > 2m_\chi$ so that $\langle\sigma v\rangle$ is smaller now than during freeze out

Large M_A helps with flavor & LHC direct search constraints

And So…

→ We generated 6×10^8 sets of points in this parameter space & applied all the requirements above + stability, no tachyons, etc. Our goal was to find viable solutions & not to do a detail parameter study !

Of course all the DM, flavor & LHC search constraints are also applied***

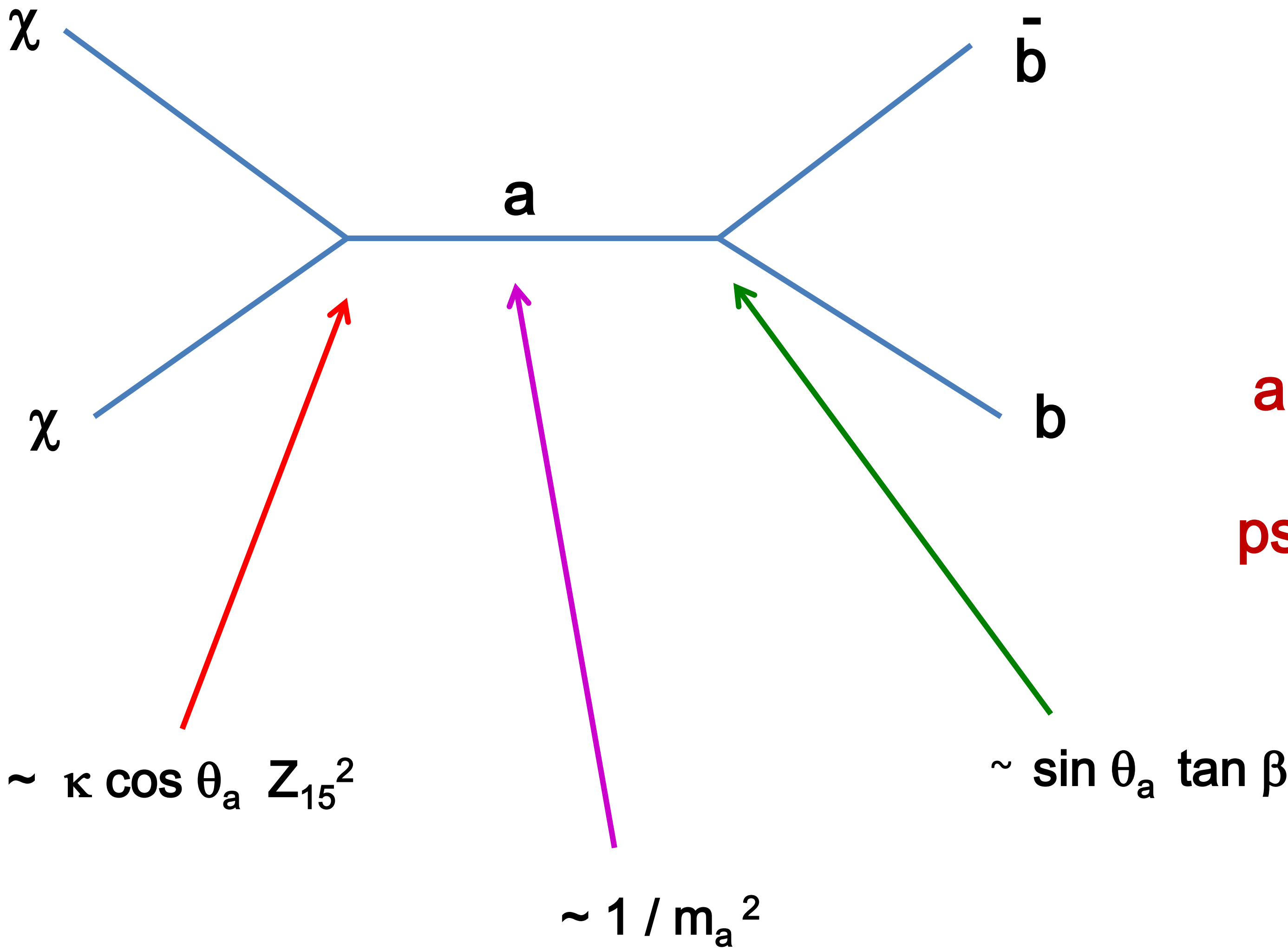
~ 52.8 k 'models' = sets of parameters remain

Some useful definitions:

- The mixing angle θ_a measures the isodoublet content of the lighter CP-odd state
- The mixing angle θ_h measures the isosinglet content of the ~125 GeV Higgs

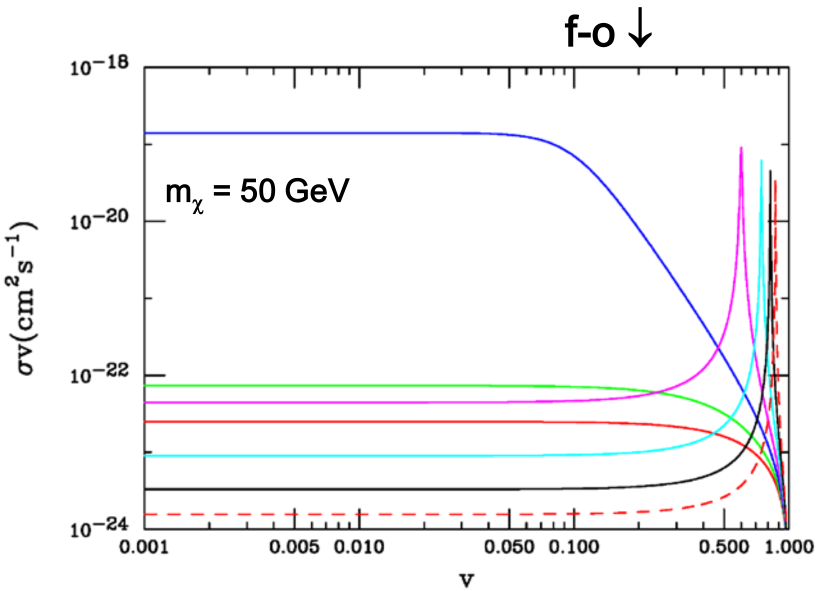
→ We can now make a lot of plots that examine various model properties

*** see paper for an extensive discussion



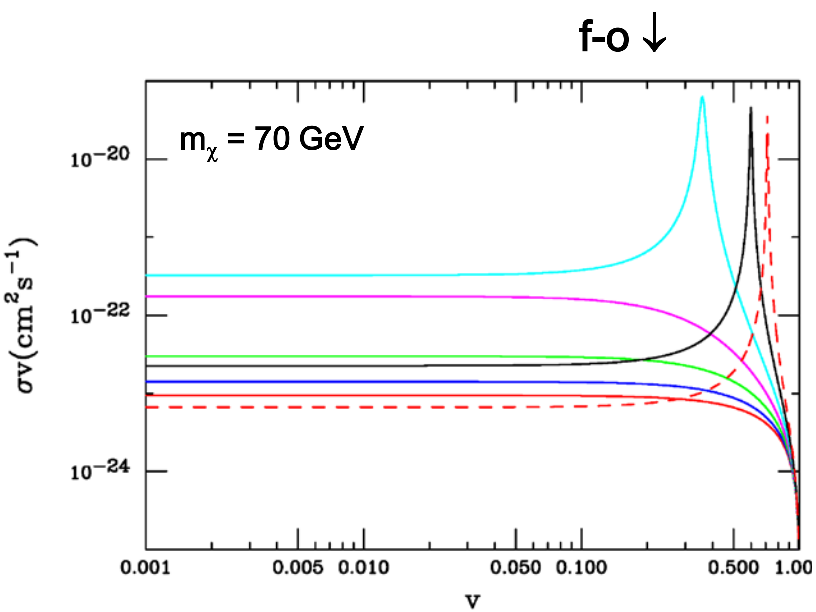
DM annihilation via the pseudoscalar

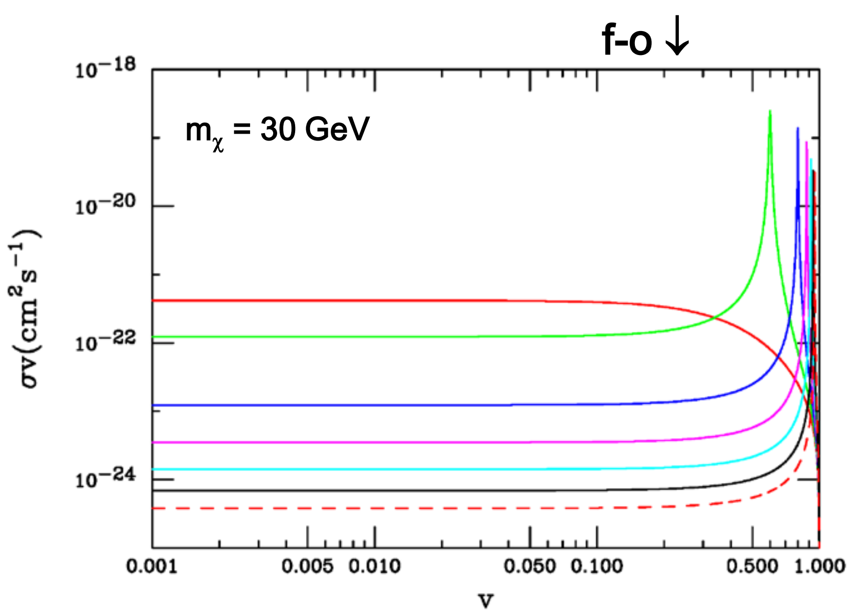
→ The values of the various parameters must compensate each other to obtain the correct relic density



For a wide range of masses a-exchange yields a ~velocity-independent value of σv except when we get quite near the resonance.

Note that if $2m_\chi < M_a$ then the cross today is ~ equal or below that during freeze-out as seems to be the case with the GC signal + dSph constraints



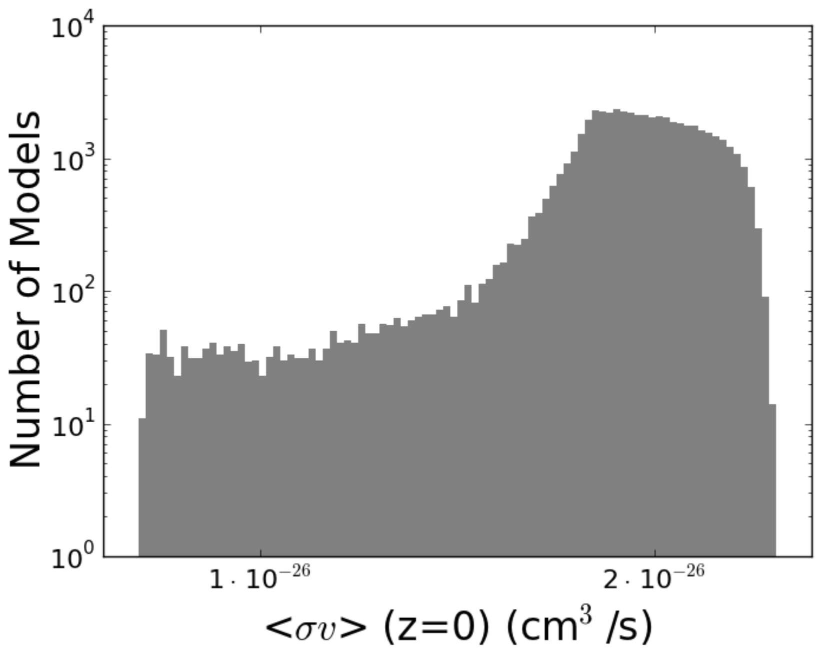


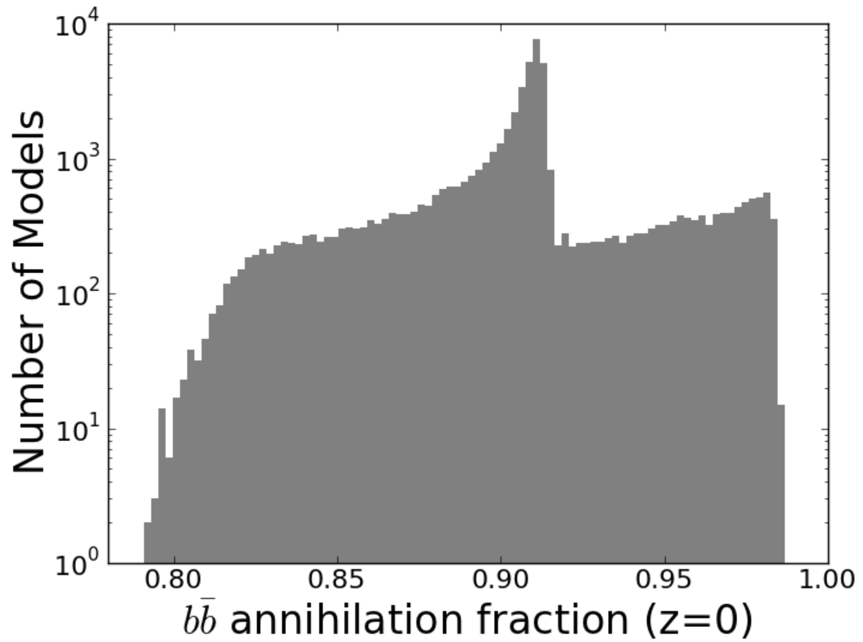
M_a = 50 (r), 75 (g), 100 (b), 125 (m), 150 (cy), 175 (bl), 200 (d)

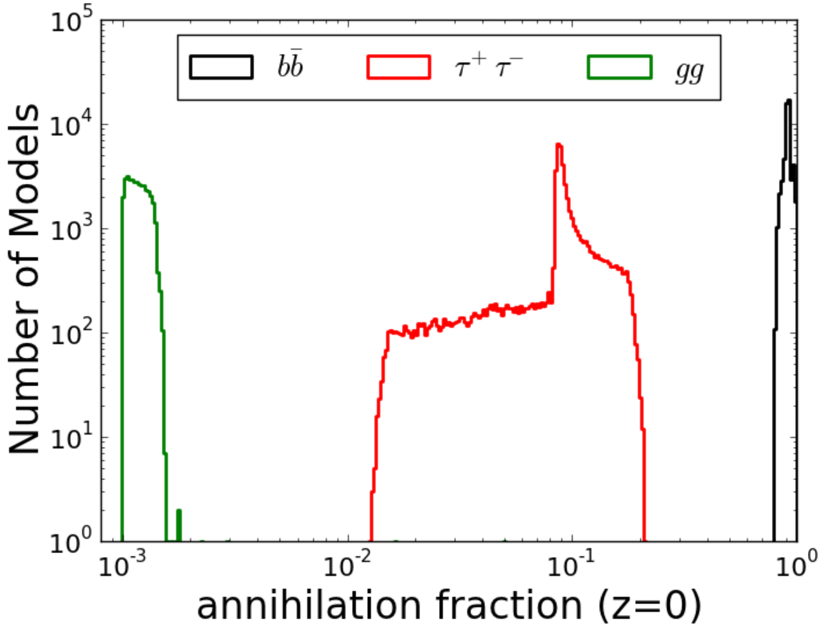
Some questions to answer

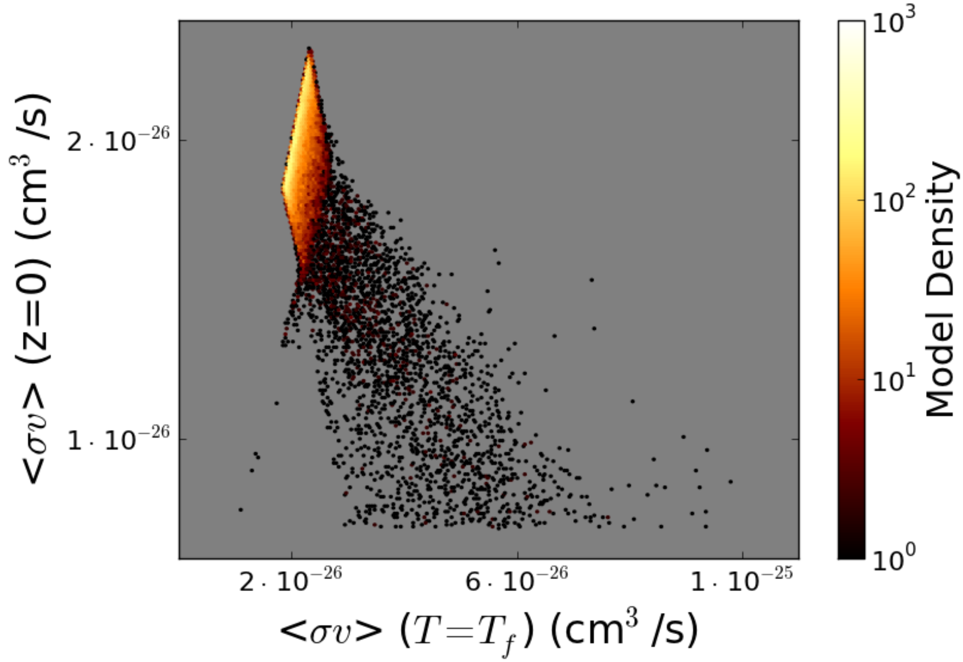
- What are the properties of the LSP/DM ?
- Can it be observed in DD experiments?
- Are the properties of the Higgs modified?
- Are there other LHC, etc. signals?

DM properties

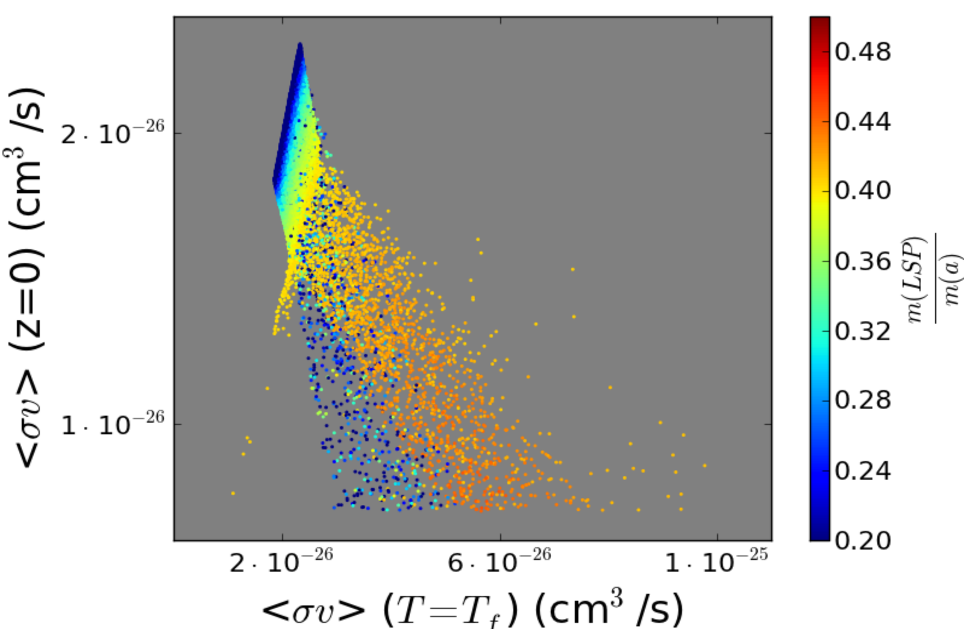


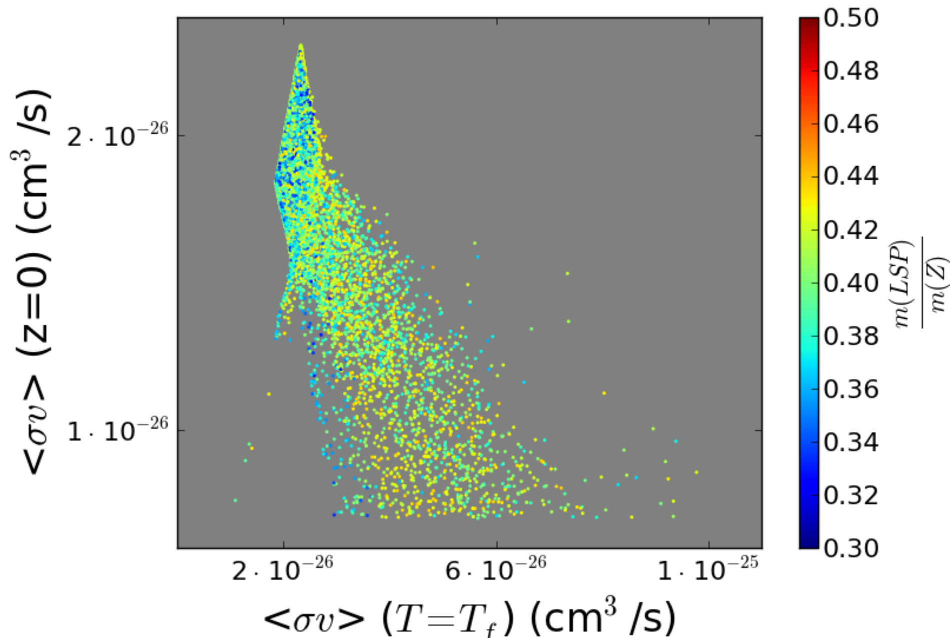


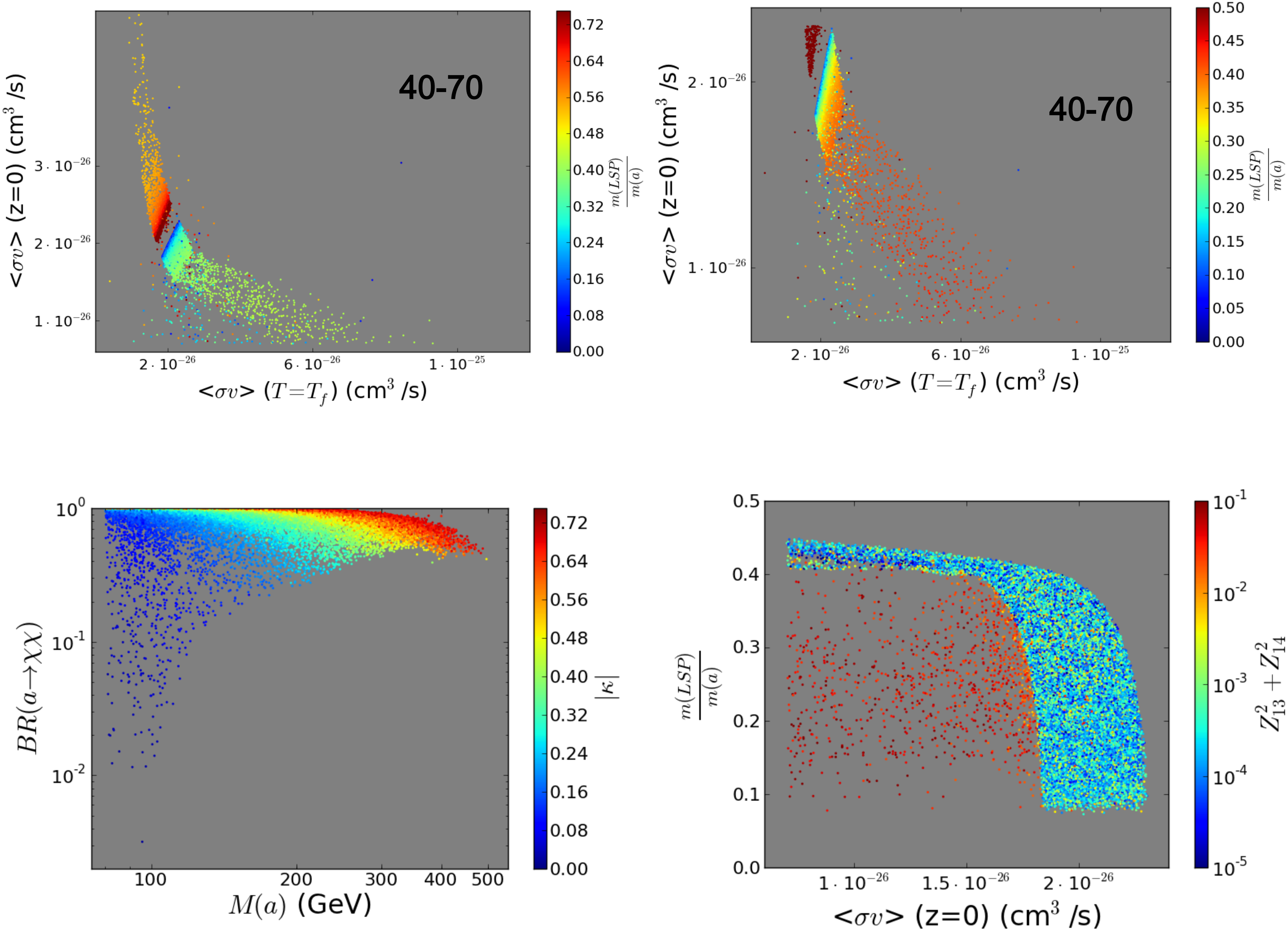




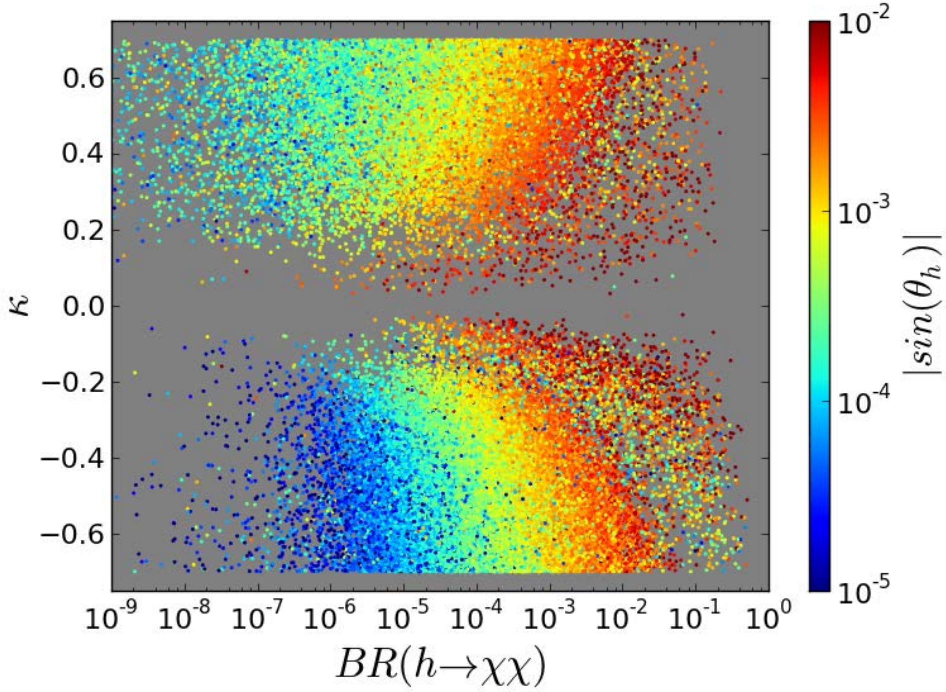
Interesting correlation between the freeze-out and present day values of ⟨σv⟩



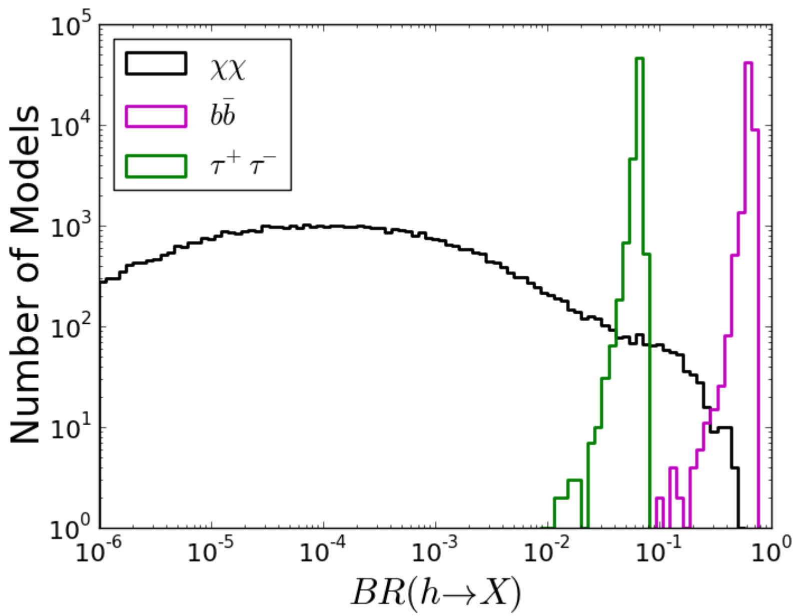


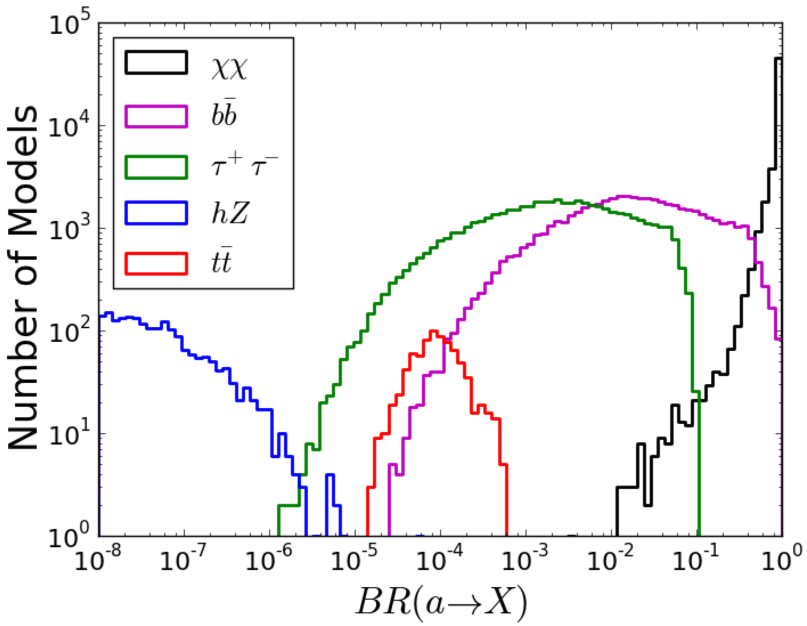


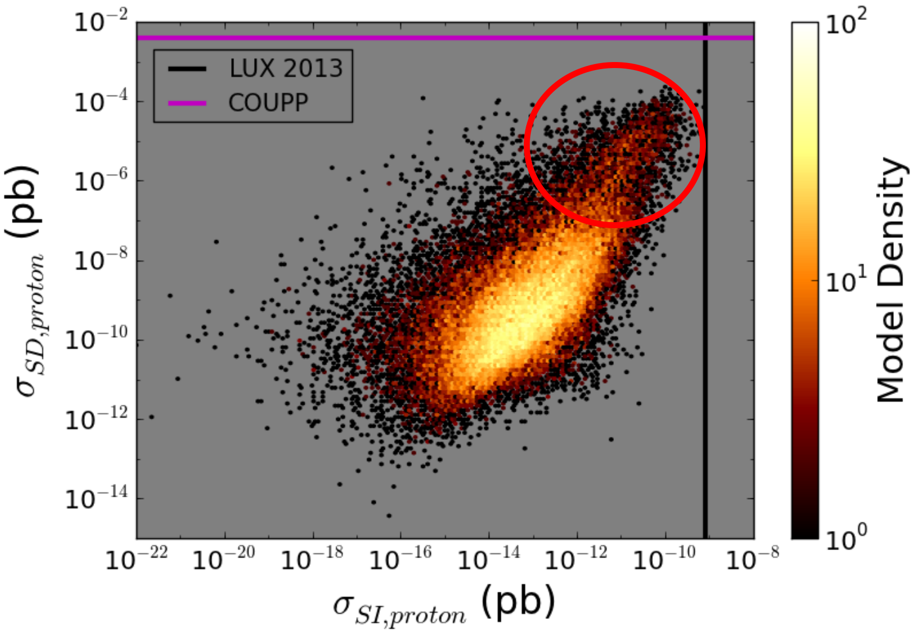
40-70
<σv> (z=0) (cm³ /s)
<σv> (T=T_f) (cm³ /s)
m(LSP)/m(a)
40-70
<σv> (z=0) (cm³ /s)
<σv> (T=T_f) (cm³ /s)
m(LSP)/m(a)
BR(a→χχ)
M(a) (GeV)
|κ|
m(LSP)/m(a)
<σv> (z=0) (cm³ /s)
Z²₁₃ + Z²₁₄

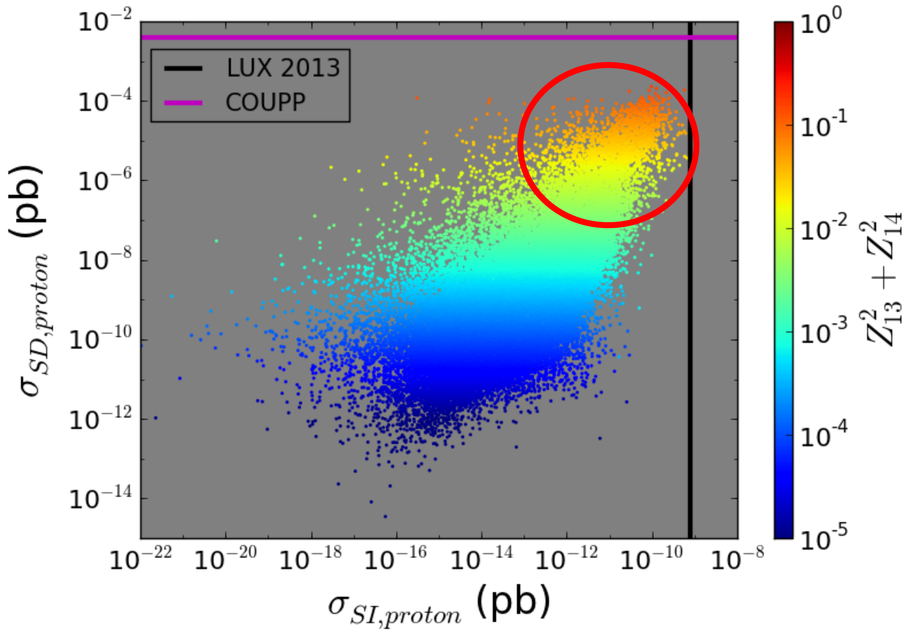


- The Higgs remains SM-like but picks up a generally very small BF (~ < 1%) for the decays to the LSP. LC??
- The light CP-odd field, a, decays almost entirely to LSP pairs but with a small bb-bar BF

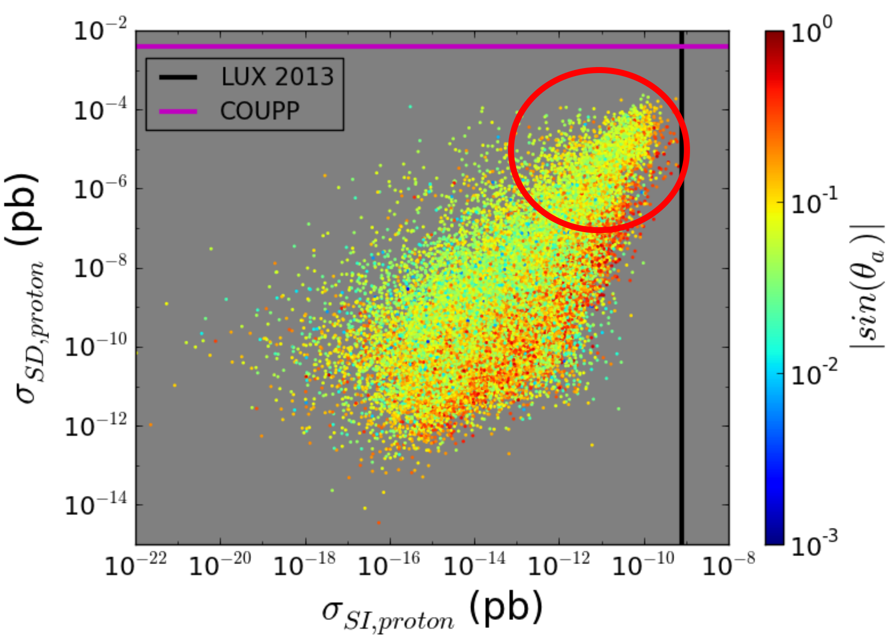


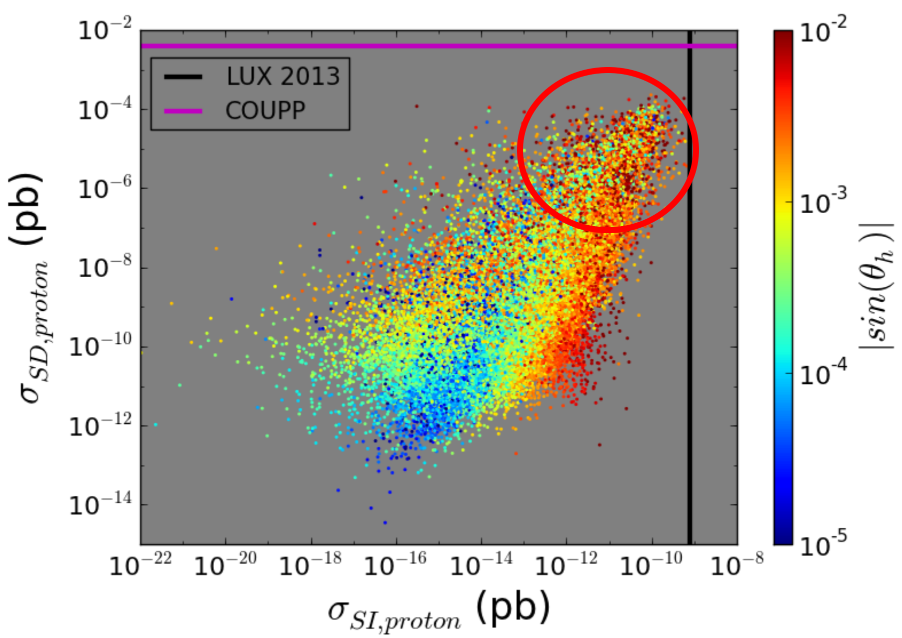


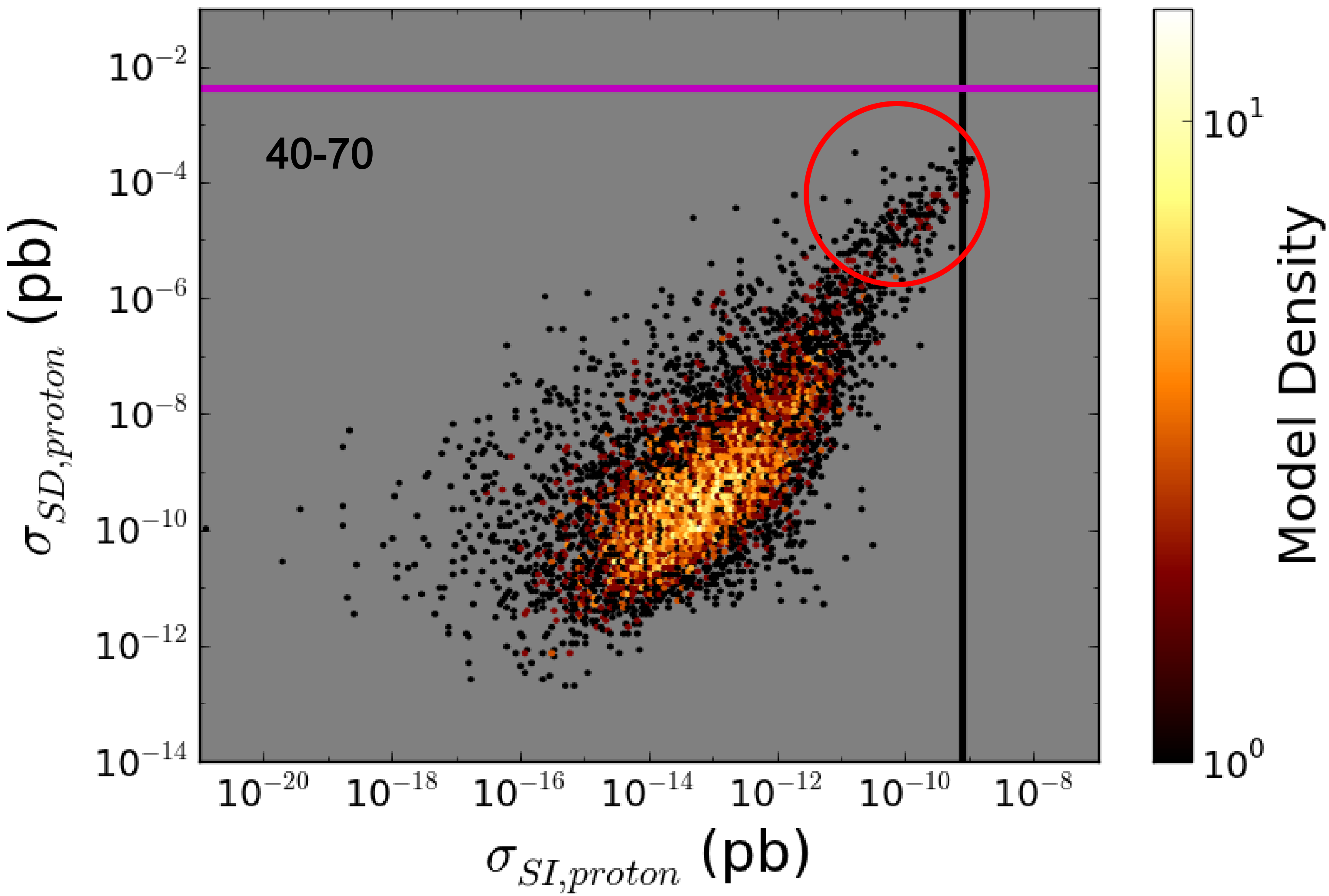




Expectations for DD are generally not very good…

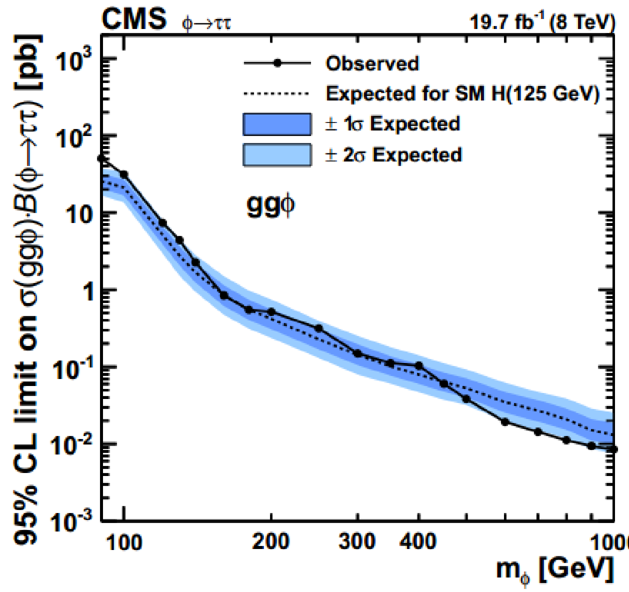


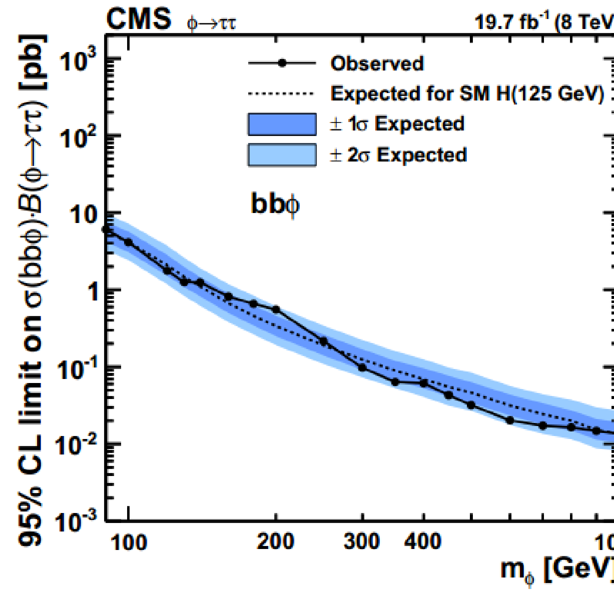


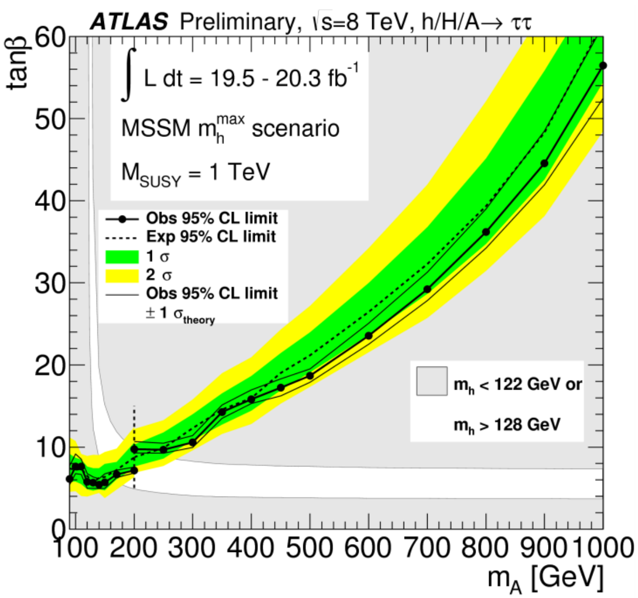


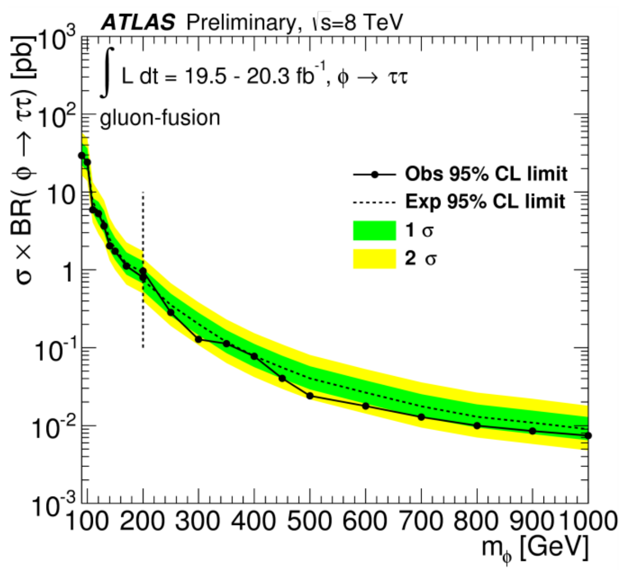
40-70
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$\sigma_{SD,proton}$ (pb)
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
$\sigma_{SI,proton}$ (pb)
10^{1}
10^{0}
Model Density

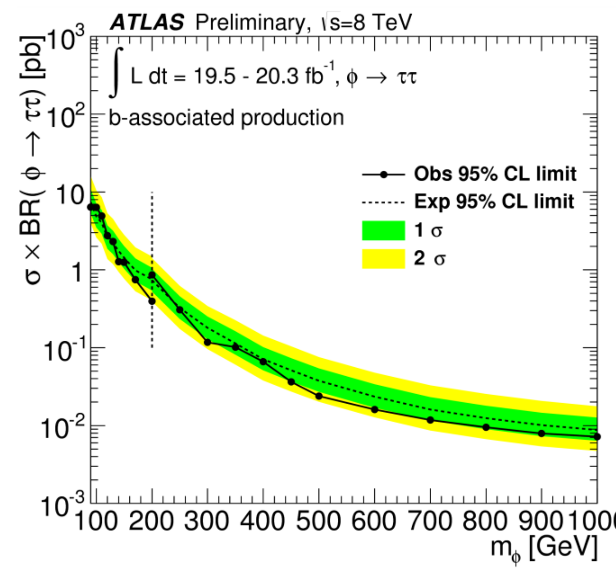
Heavy Higgs Searches @ LHC

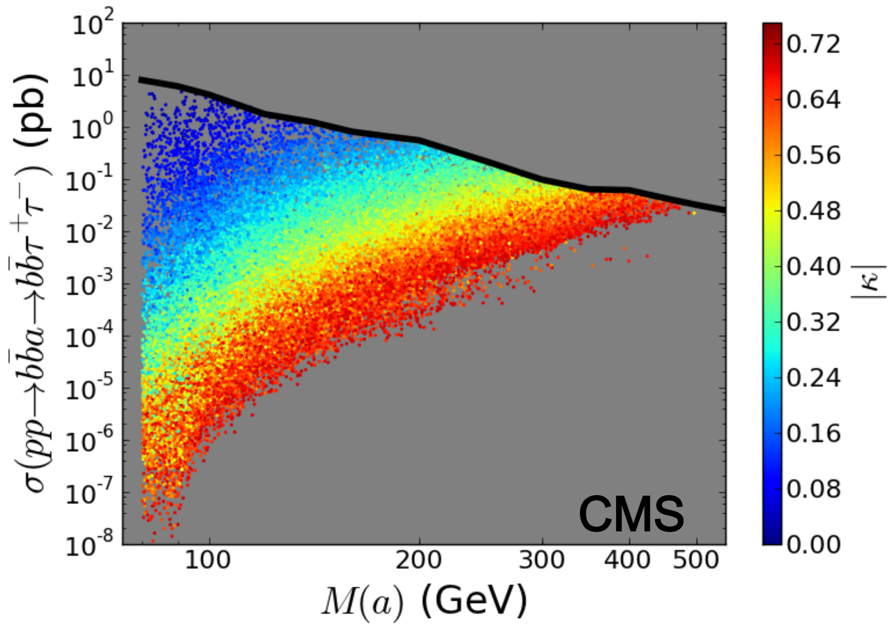


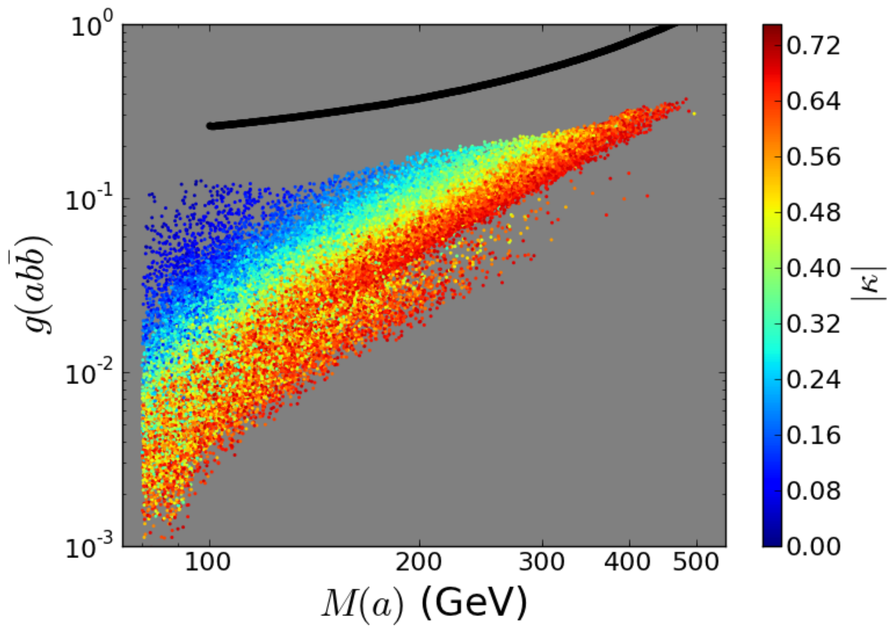












Heavy Higgs Search Impact

- The usual LHC 'A/H $\to\tau\tau$' searches @ 7/8 TeV are quite easily satisfied but do provide some constraints & cut off the a mass distribution from above @ ~500 GeV . Clearly 13-4 TeV data will have some significant impact here..

- Searches for bb-bar +MET can be reinterpreted to look for a+bb-bar associated production where then $a\to\chi\chi$. Again, safely within current constraints…but @ 13-4 TeV…

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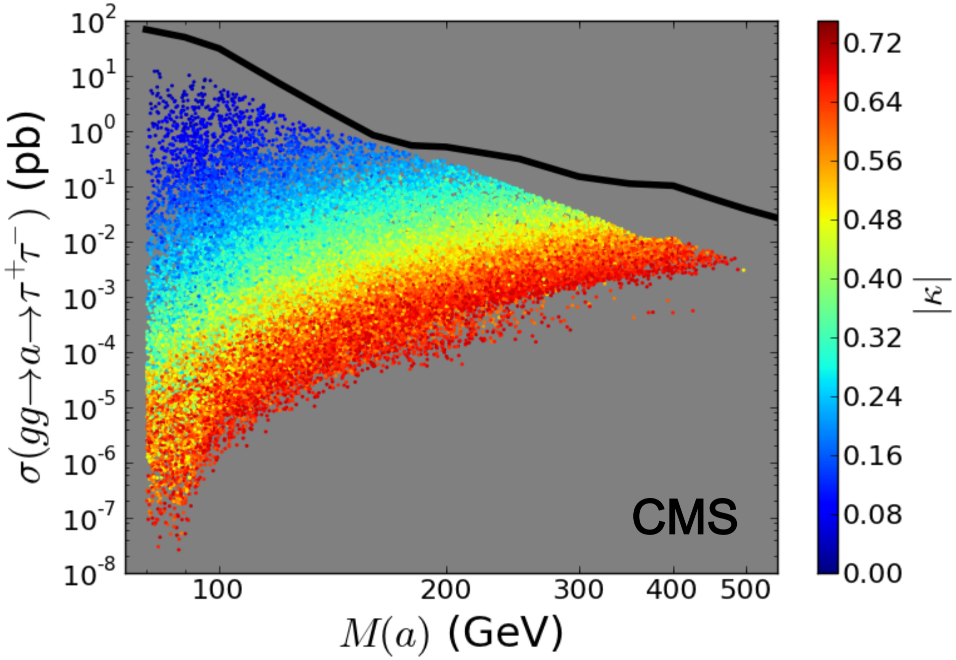
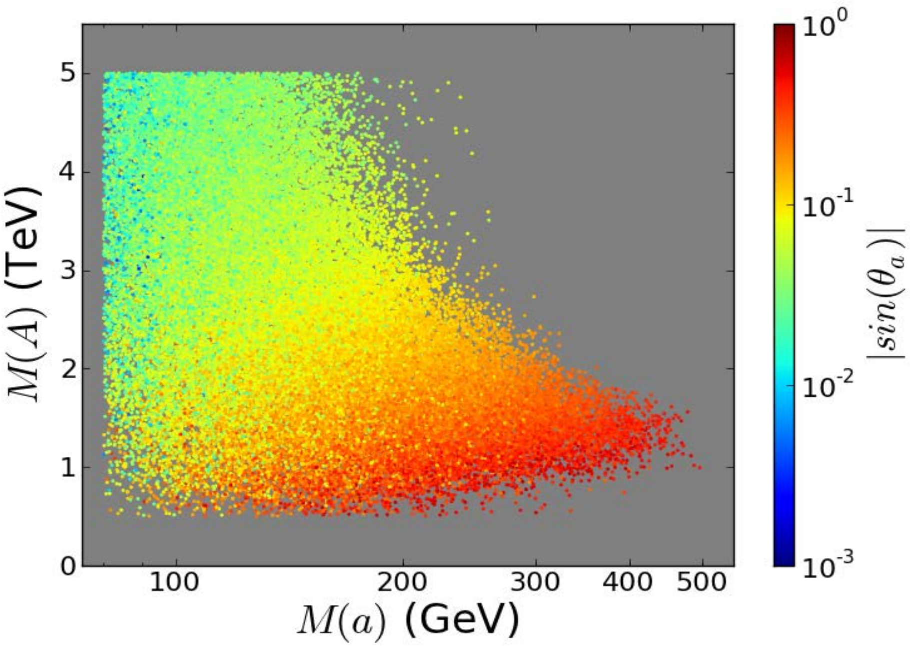
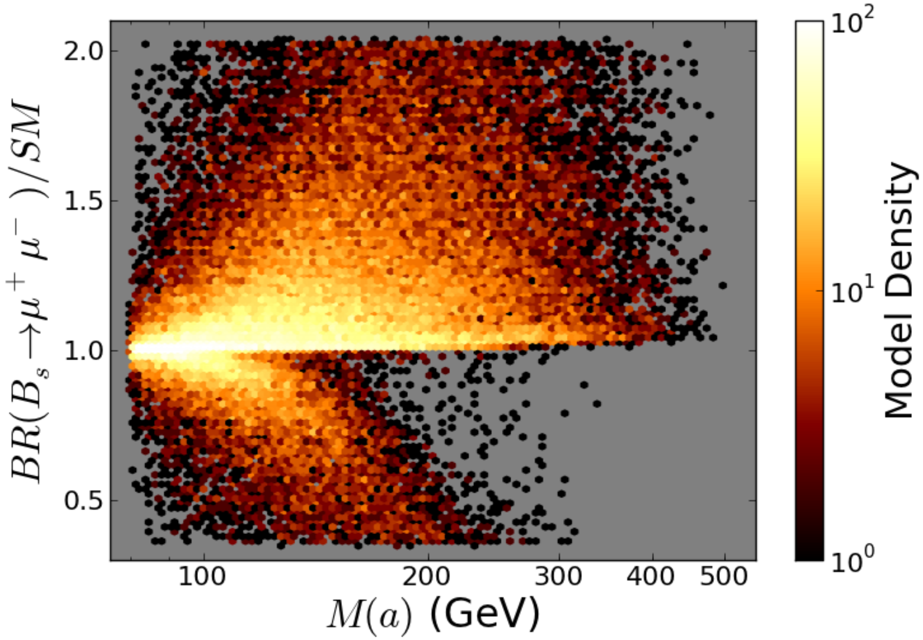
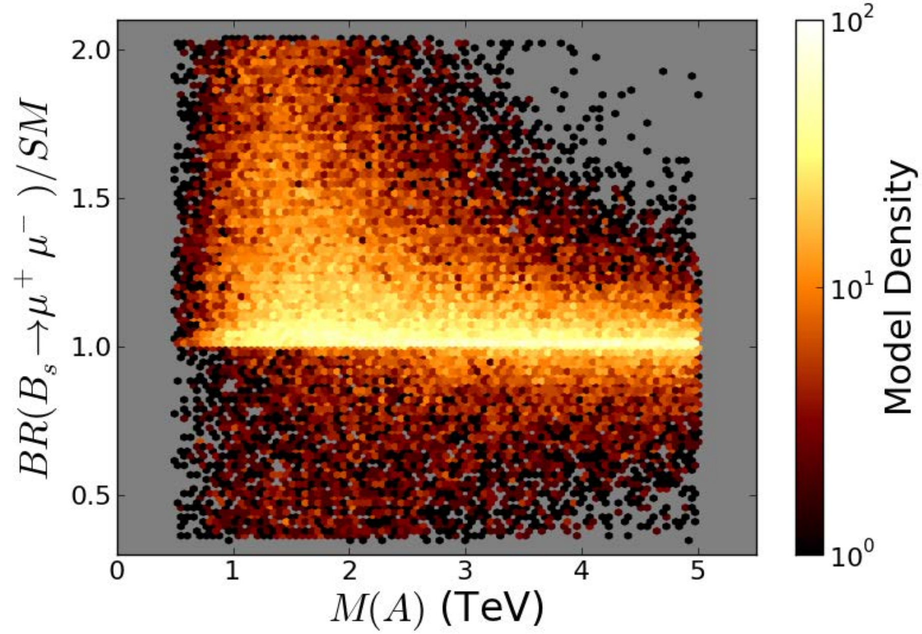


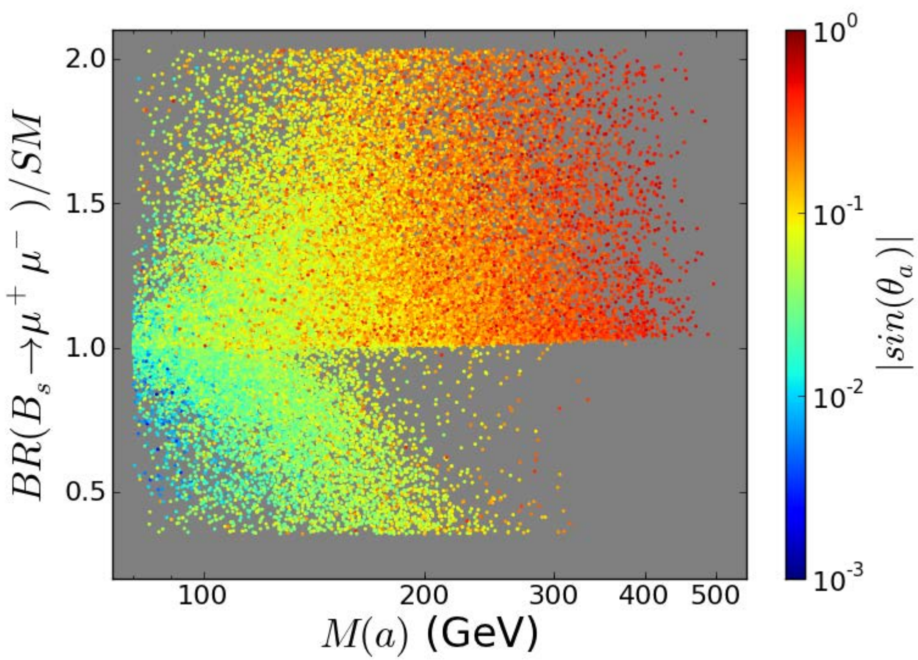
- Similar constraints are obtainable for the direct gg-induced channel but are easily satisfied for these points



- Interestingly the constraints allow both pseudoscalars to be quite close in mass near the top end of the range & with significant mixing





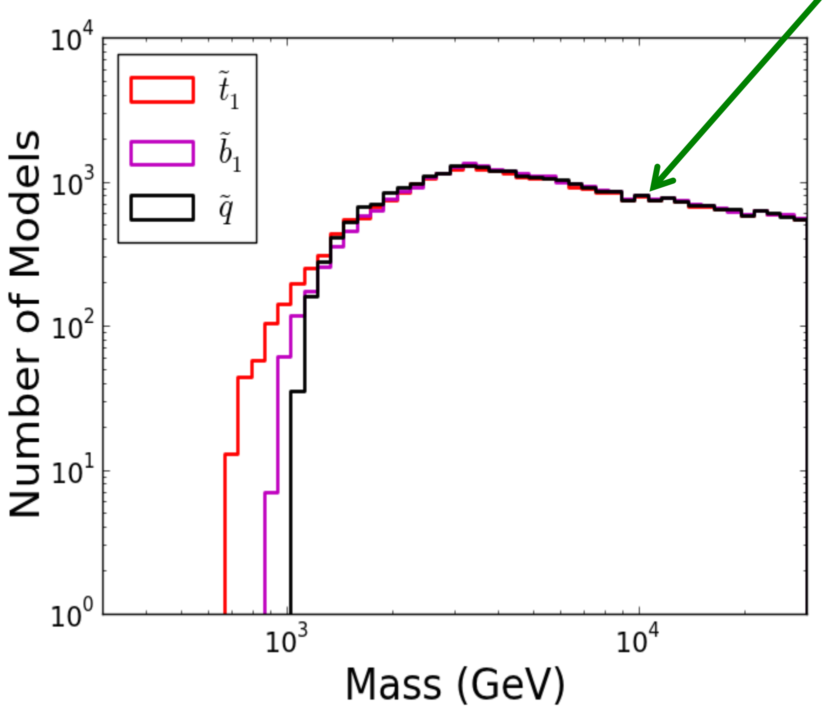


- Reduction in the uncertainties in the NMSSM theory calculation would be useful
- Most model predictions lie quite close to the SM value but there are some tails
- RC via sign of μ splits models into two subsets

LHC (cont.)

- The role of the 'traditional' part of the SUSY spectrum (& the associated searches) has been relegated to a subsidiary position in our analysis by picking 'obviously OK' points

- Here to simplify our study as much as possible, we set gaugino masses to fixed values & we chose squarks heavy to avoid the LHC constraints & give the observed Higgs mass. We wanted an existence proof!



- Of course we don't need to make these assumptions in a MORE detailed study

- E.g., here we see that although we placed a cut on the lightest stop mass >0.7 TeV very few models would have much smaller values

Summary & Conclusions

- It is a non-trivial model building challenge to find a SUSY scenario that can incorporate the Fermi GC γ-ray excess with a single DM mediator while also satisfying all other phenomenological & theoretical constraints assuming 30-70 GeV LSPs . Models can easily fail for many reasons.

- The general NMSSM provides a successful proof of principle framework

- This idea can be tested to a limited degree by DD, searches for heavy Higgs partners (including bb-bar+MET), a possible small Higgs BF for decay to LSPs, some changes in some flavor measurements and, of course, direct SUSY searches. ID of DM signals from Dwarfs by Fermi would verify this interpretation. Tension!

- This scenario can be generalized to more complex SUSY spectra by relaxing several of our simplifying scanning constraints

- Hopefully we'll soon find out more about this signal from FERMI

Backups

The p(henomenological)MSSM

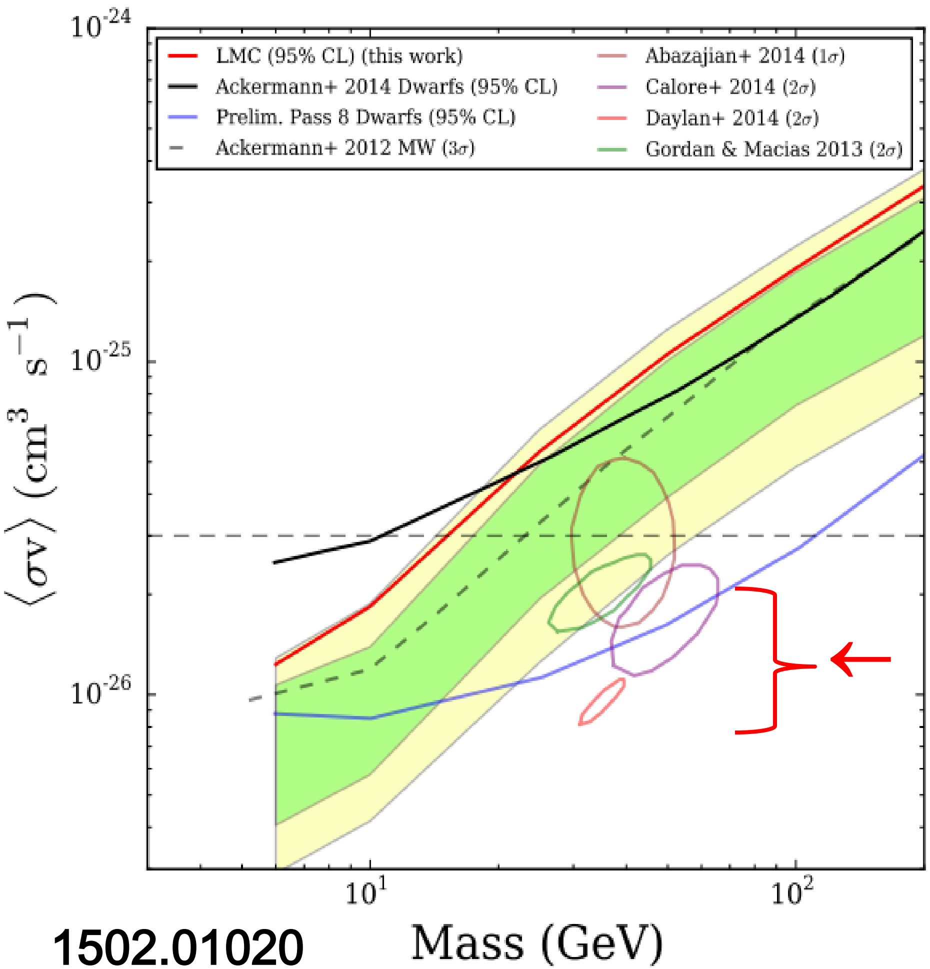
→ The MSSM has > 100 parameters -- we make experimentally motivated assumptions to reduce these to some 'reasonable' level :

- The general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale (the CKM controls flavor)
- The lightest neutralino is the LSP
- The first two sfermion generations are degenerate (type by type).
- The first two generations have negligible Yukawa's & A-terms.
- The WMAP/Planck relic density is not necessarily saturated by the LSP

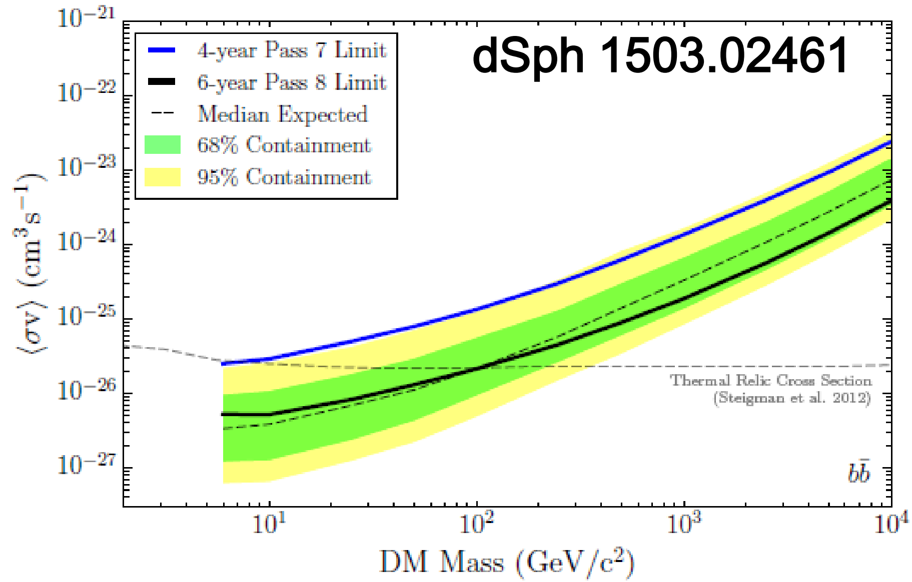
→ the pMSSM with 19 TeV-scale parameters…

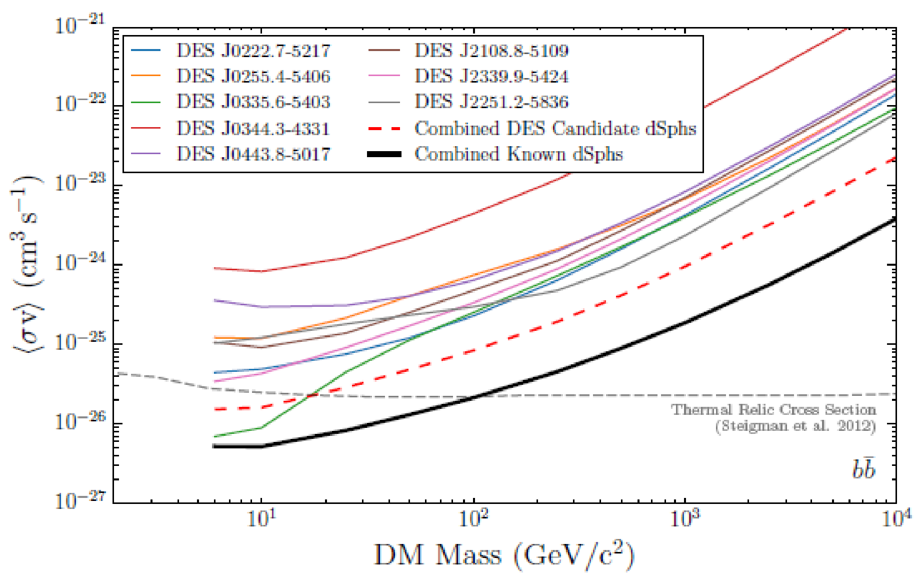
Goal: obtain many points ('models') satisfying existing data & study them…going for 'breadth not depth'. NO FITS!

Tension With FERMI ?



1502.01020

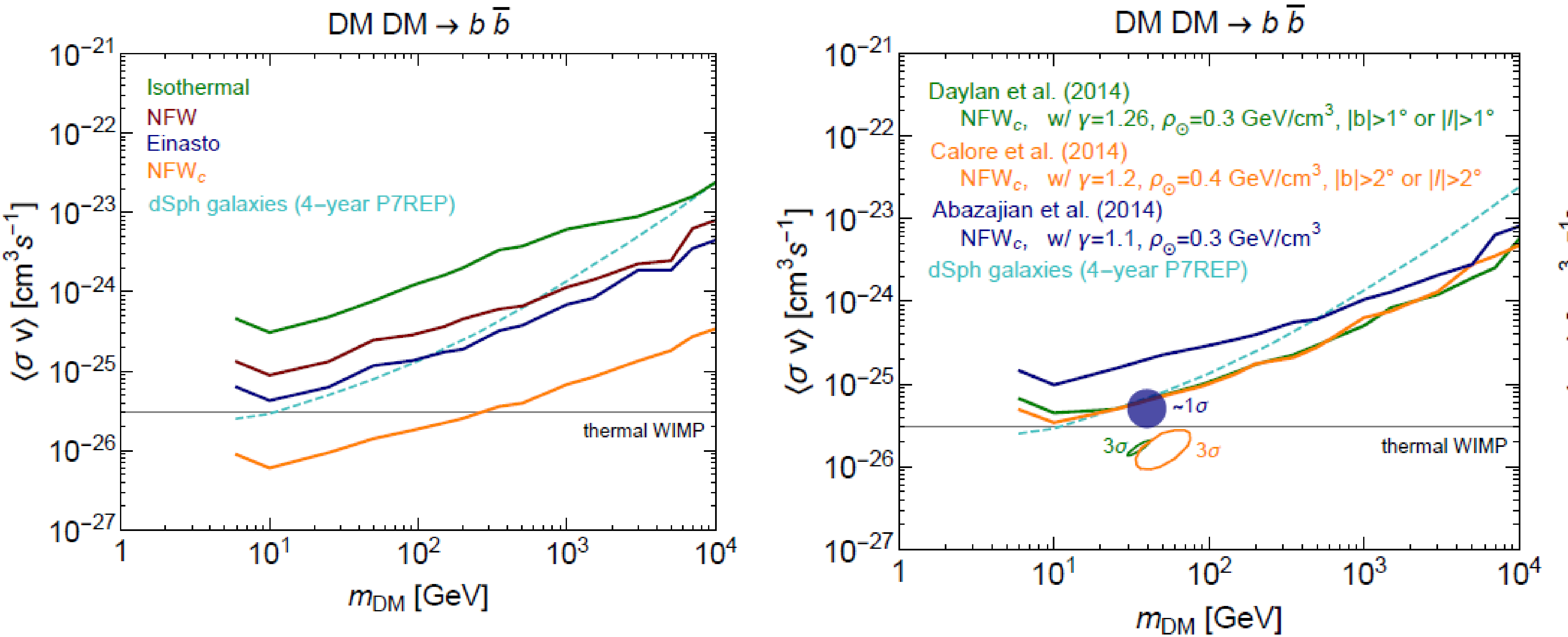




Fermi Dwarf DM searches constrain the present day annihilation cross section for DM but in a model-dependent way

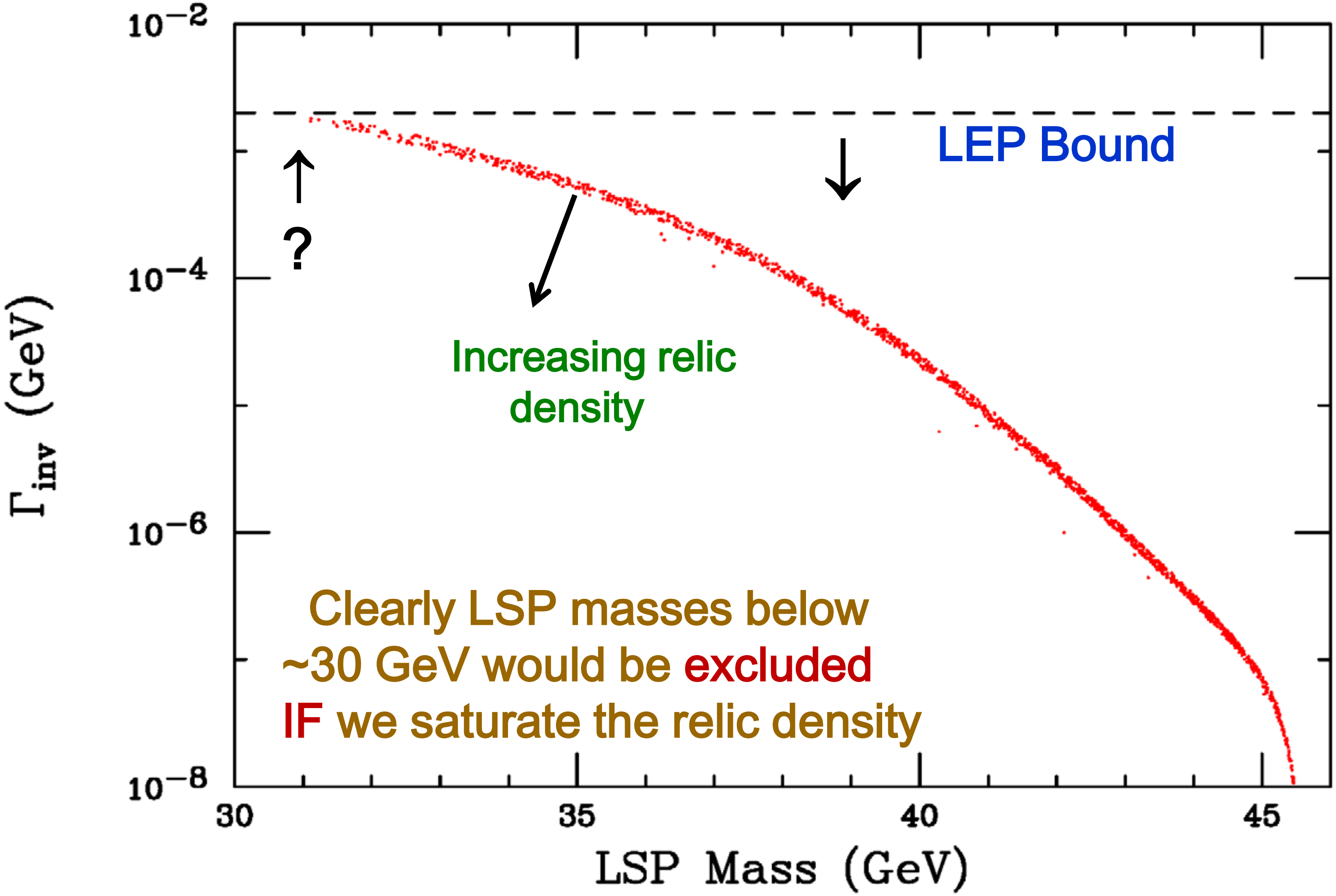
DES Candidates 1503.02632

Tension With FERMI ? (II)



1503.07169

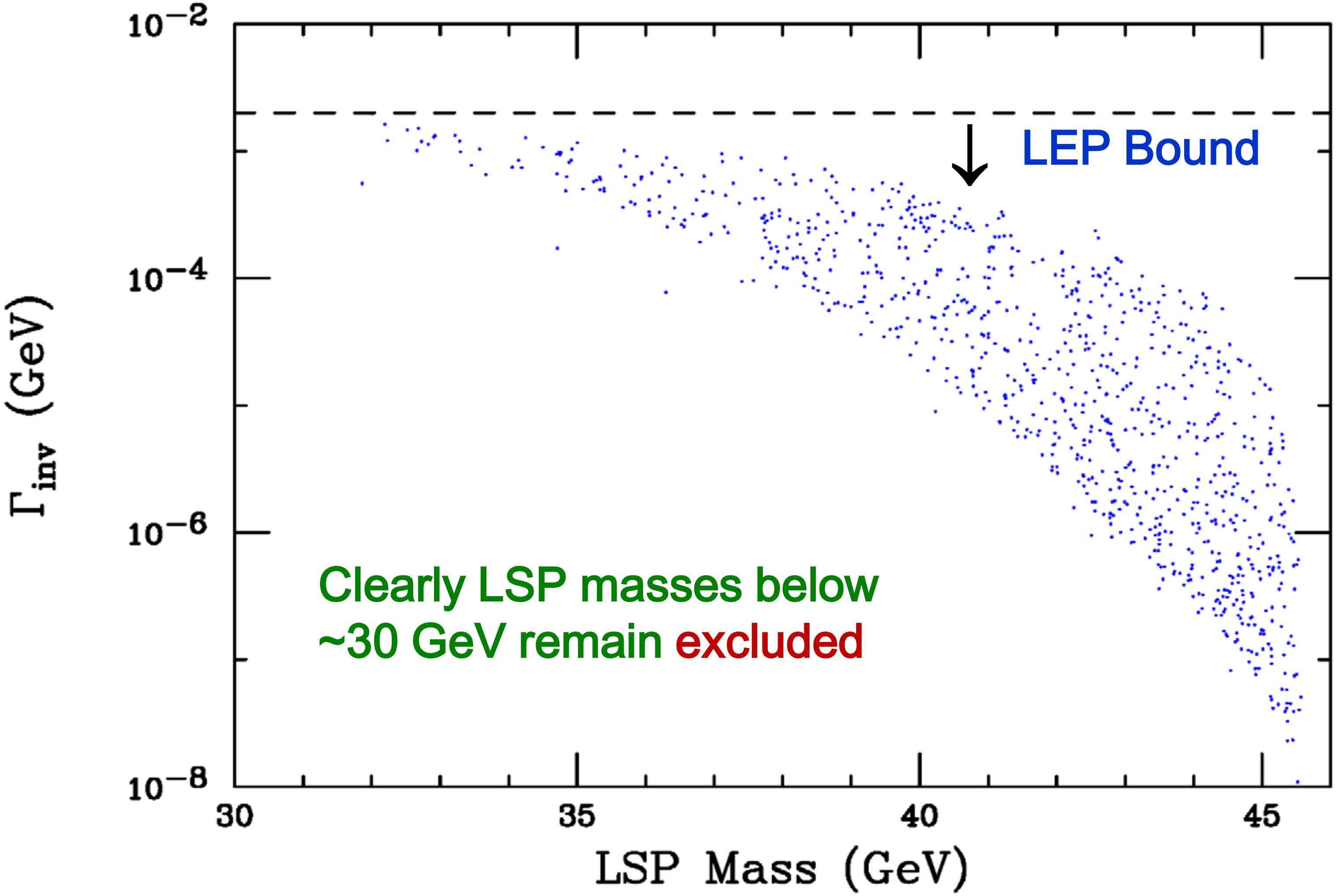
$\Gamma(Z \to \chi\chi) < 2$ MeV



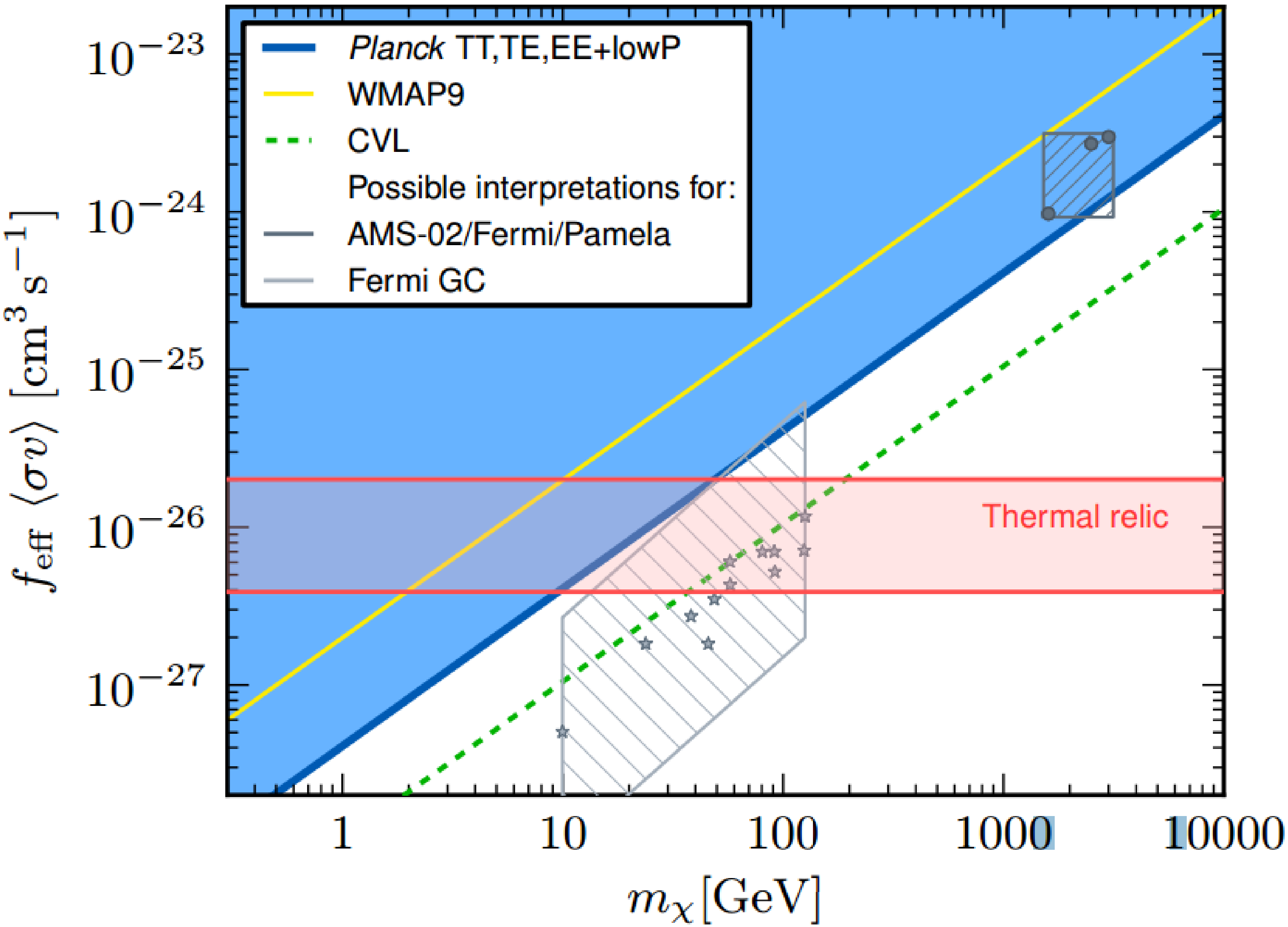
pMSSM models w/ relic density saturated

General χ Models

$\Gamma(Z \to \chi\chi) < 2$ MeV



Γ_{inv} will increase if we also increase the Higgsino content & go below the Planck/WMAP relic density



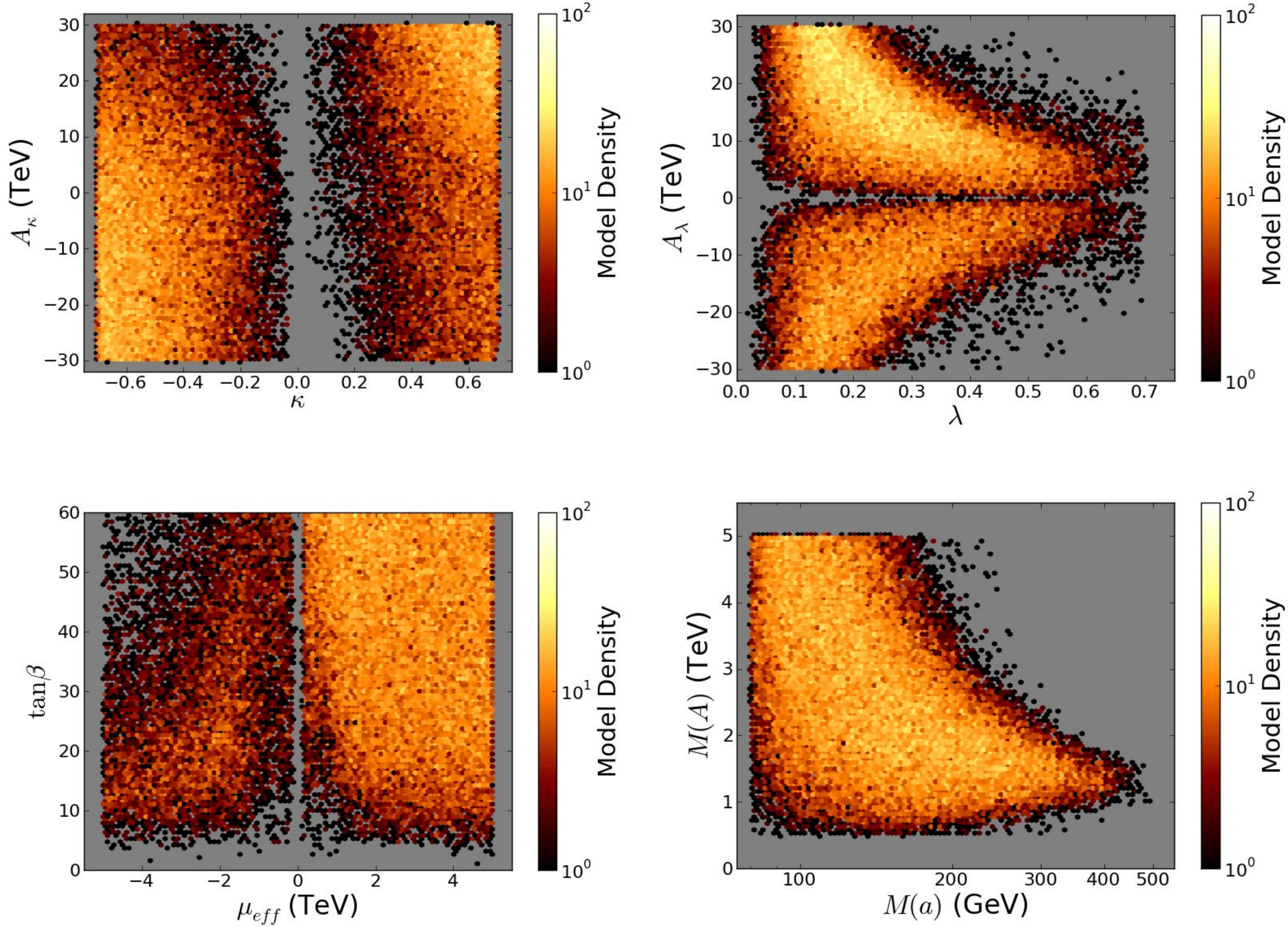
Planck TT,TE,EE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC
Thermal relic
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$f_{\rm eff}\ \langle\sigma v\rangle\ [\rm cm^3\, s^{-1}]$
1
10
100
1000
10000
$m_\chi\,[\rm GeV]$

1502.01589

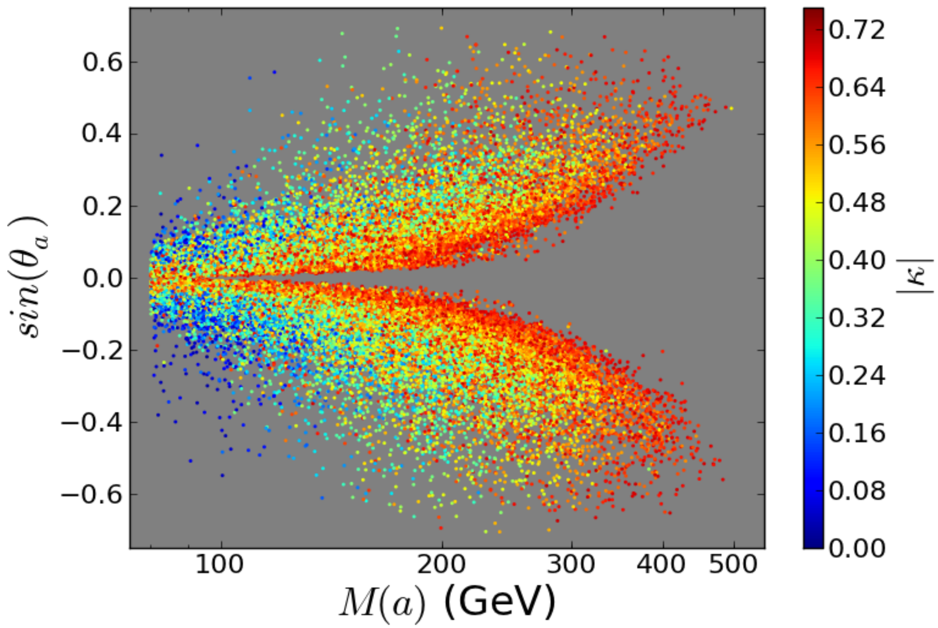
$$
\begin{aligned}
\mathcal{M}^2_{P,11} &= \frac{2(\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)}{\sin 2\beta} \,, \\
\mathcal{M}^2_{P,22} &= \lambda(B_{\rm eff} + 3\kappa s + \mu')\frac{v_u v_d}{s} - 3\kappa A_\kappa s - 2m_S'^2 - \kappa\mu' s - \xi_F\left(4\kappa + \frac{\mu'}{s}\right) - \frac{\xi_S}{s} \,, \\
\mathcal{M}^2_{P,12} &= \lambda(A_\lambda - 2\kappa s - \mu')\, v \,,
\end{aligned}
$$

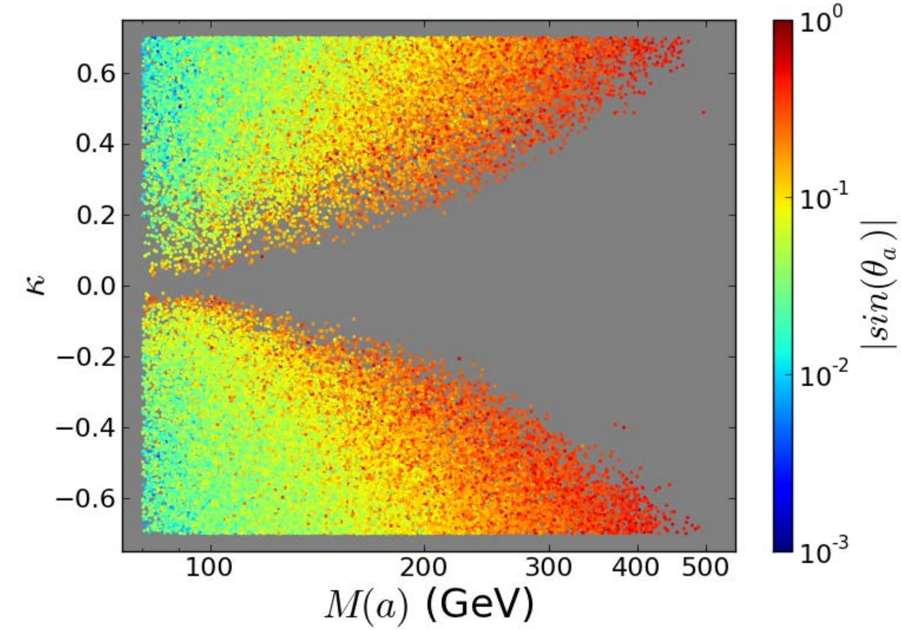
$$
B_{\rm eff} = A_\lambda + \kappa s \,, \quad \widehat{m}_3^2 = m_3^2 + \lambda(\mu' s + \xi_F) \,.
$$

$$
\begin{aligned}
\mathcal{M}^2_{S,11} &= g^2 v_d^2 + (\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2) \tan\beta \,, \\
\mathcal{M}^2_{S,22} &= g^2 v_u^2 + (\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)/\tan\beta \,, \\
\mathcal{M}^2_{S,33} &= \lambda(A_\lambda + \mu')\frac{v_u v_d}{s} + \kappa s(A_\kappa + 4\kappa s + 3\mu') - (\xi_S + \xi_F \mu')/s \,, \\
\mathcal{M}^2_{S,12} &= (2\lambda^2 - g^2) v_u v_d - \mu_{\rm eff}\, B_{\rm eff} - \widehat{m}_3^2 \,, \\
\mathcal{M}^2_{S,13} &= \lambda(2\mu_{\rm eff}\, v_d - (B_{\rm eff} + \kappa s + \mu') v_u) \,, \\
\mathcal{M}^2_{S,23} &= \lambda(2\mu_{\rm eff}\, v_u - (B_{\rm eff} + \kappa s + \mu') v_d) \,.
\end{aligned}
$$

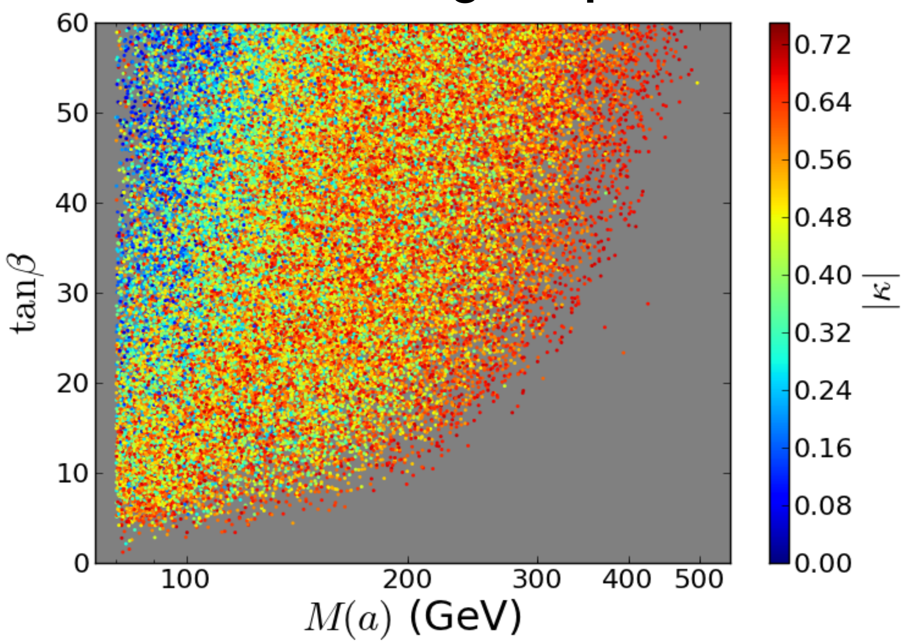


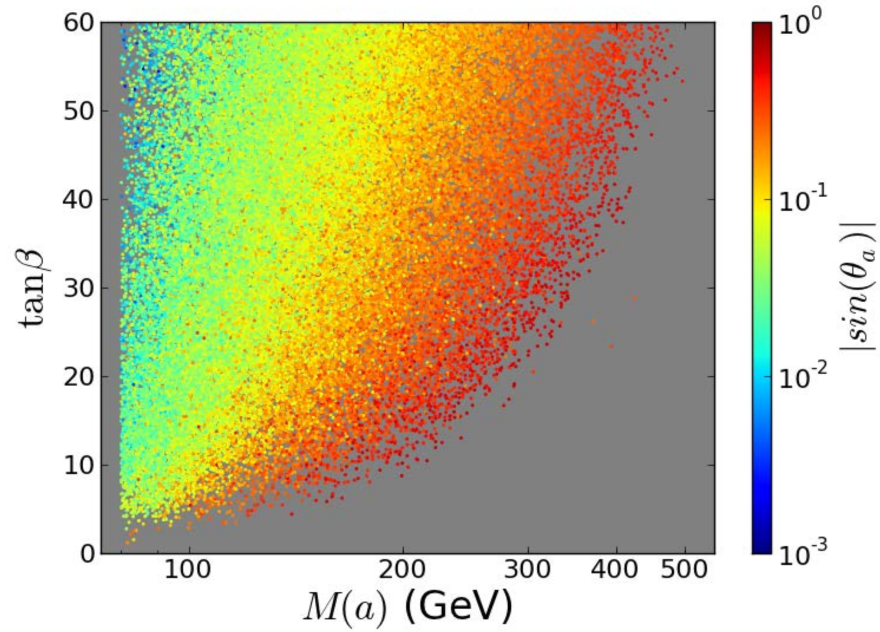
A_κ (TeV)
κ
Model Density
A_λ (TeV)
λ
Model Density
$\tan\beta$
μ_{eff} (TeV)
Model Density
$M(A)$ (TeV)
$M(a)$ (GeV)
Model Density

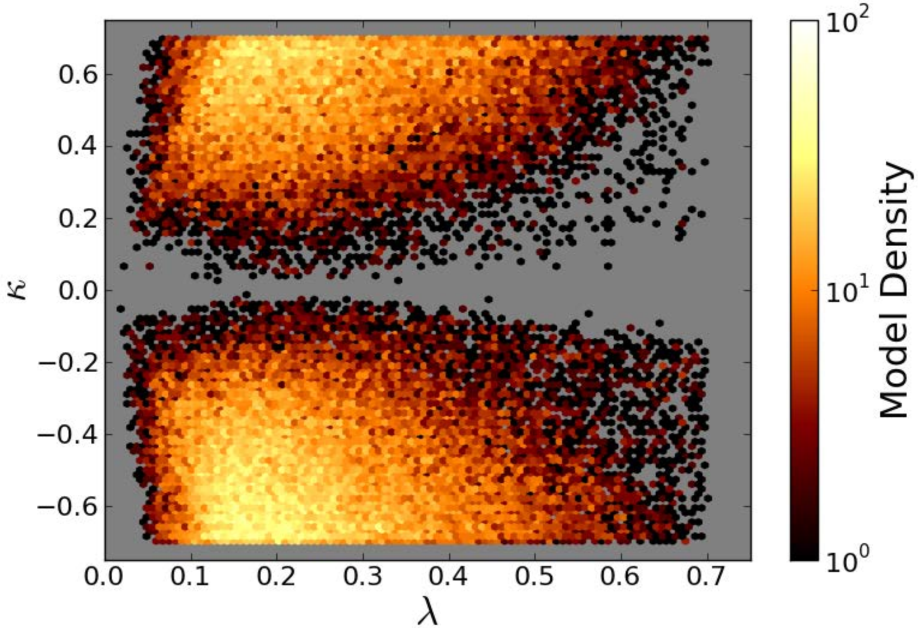




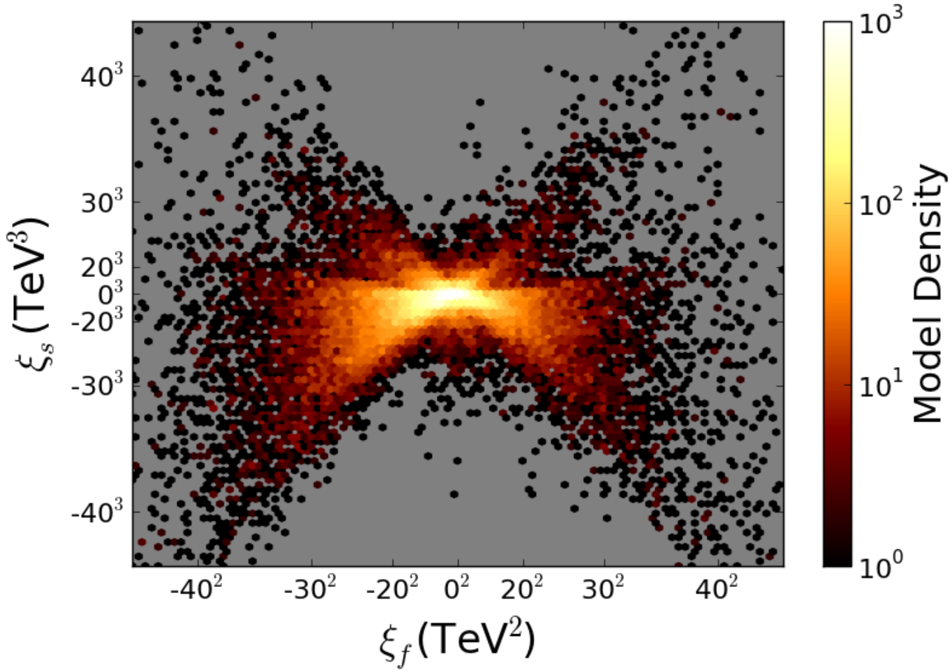
A sizeable range of parameters are allowed satisfying all constraints



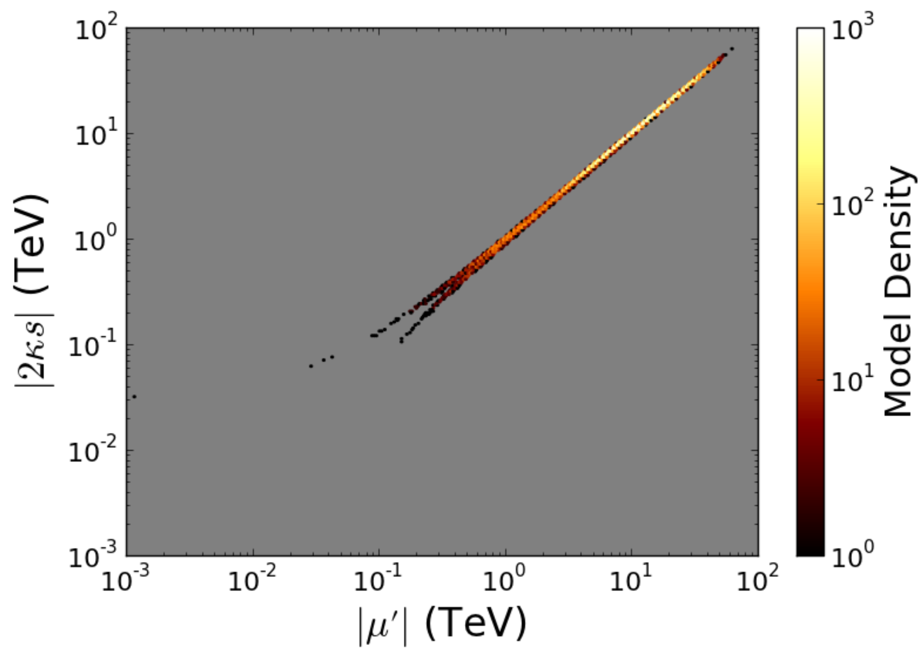




κ
λ
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
10^2
10^1
10^0
Model Density

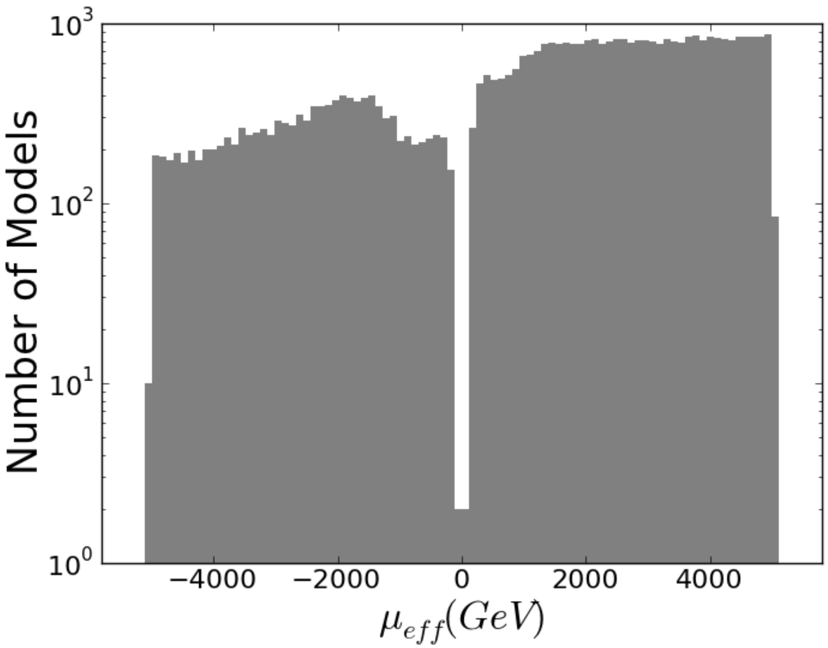


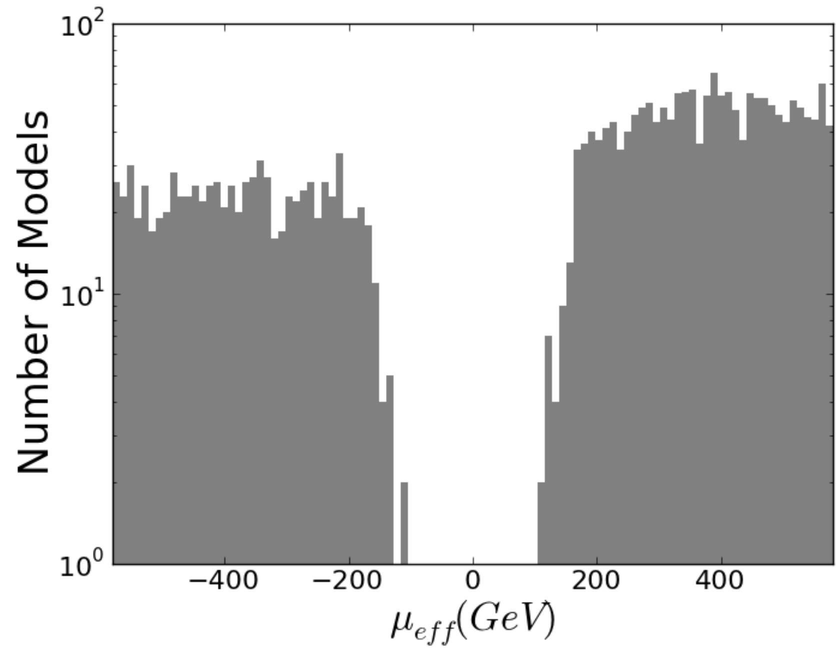
ξ_s (TeV^3)
ξ_f (TeV^2)
40^3
30^3
20^3
0^3
-20^3
-30^3
-40^3
-40^2 -30^2 -20^2 0^2 20^2 30^2 40^2
10^3
10^2
10^1
10^0
Model Density

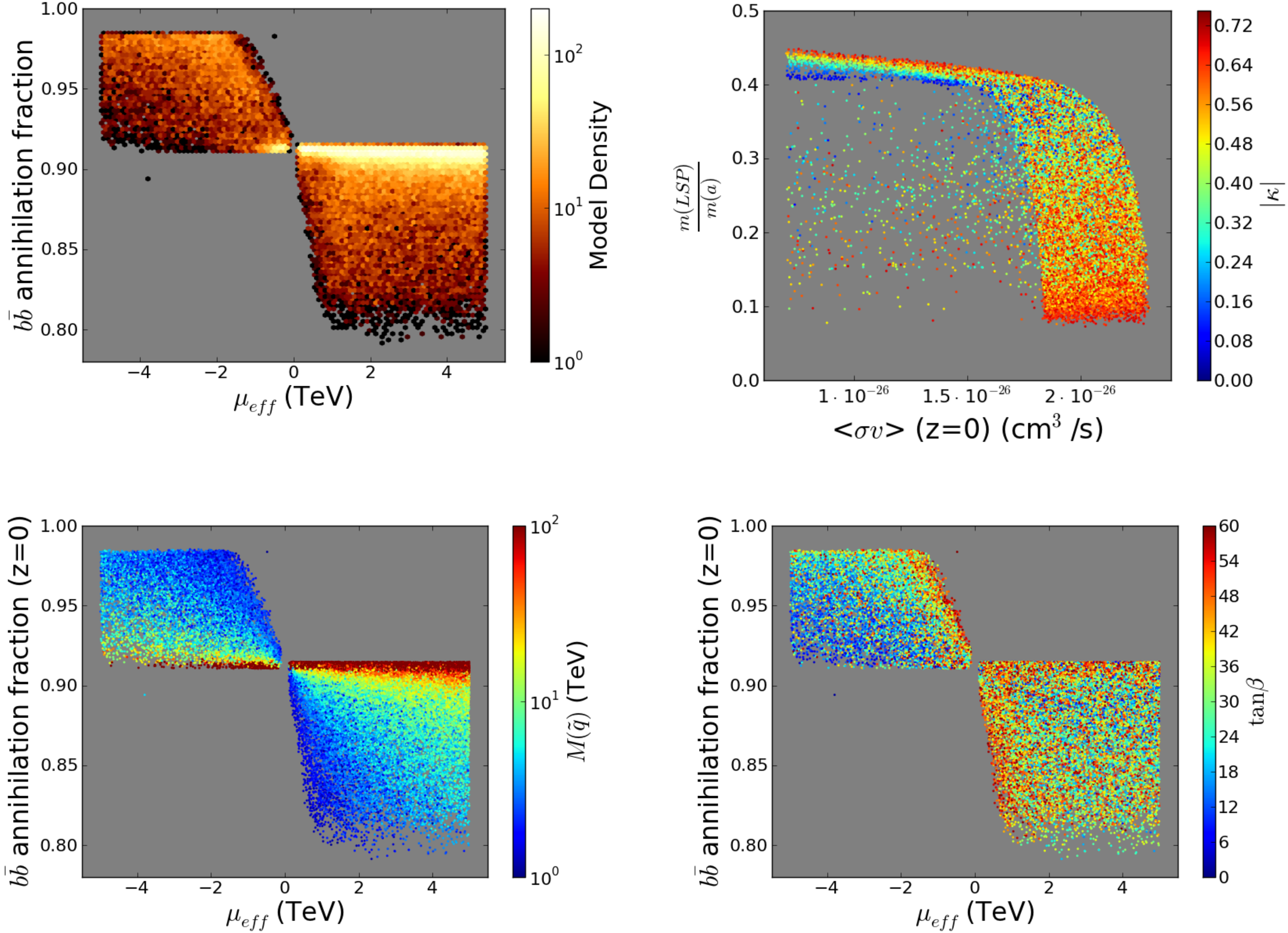


$|2\kappa s|$ (TeV)
$|\mu'|$ (TeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
10^3
10^2
10^1
10^0
Model Density

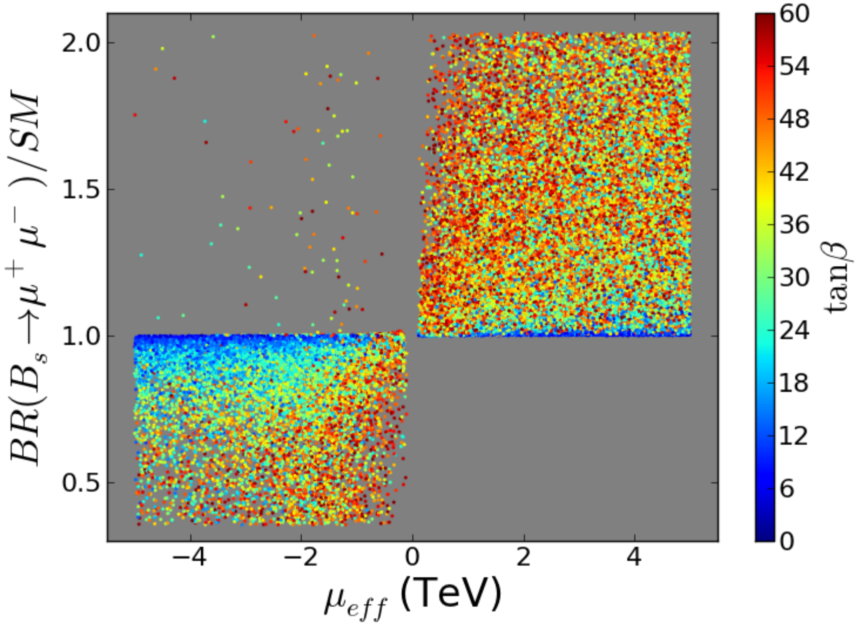
There are really two unequal populations of models here each with its specific sign of μ_{eff} . This sign contributes in multiple places…in particular in the radiative corrections to the Higgs couplings and in $B_s \to \mu\mu$

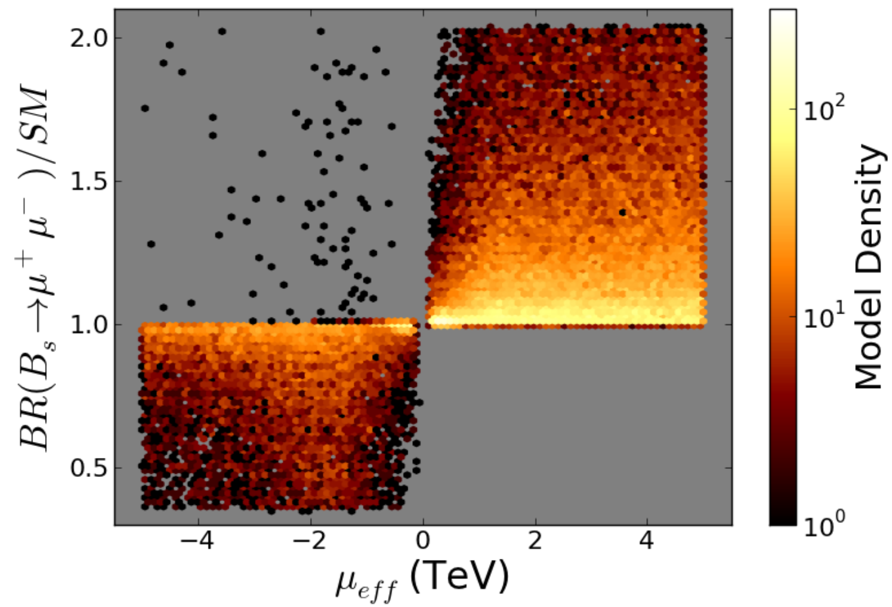


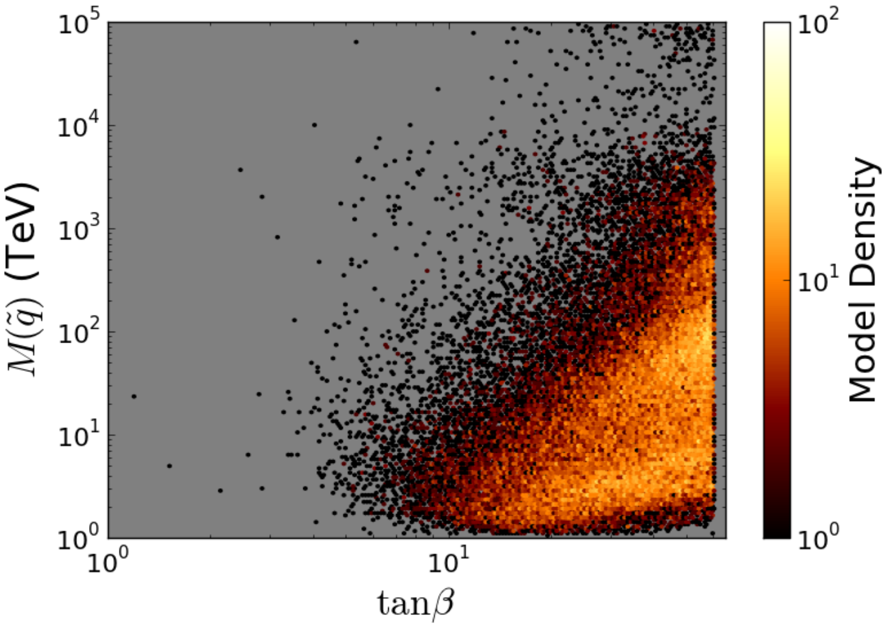


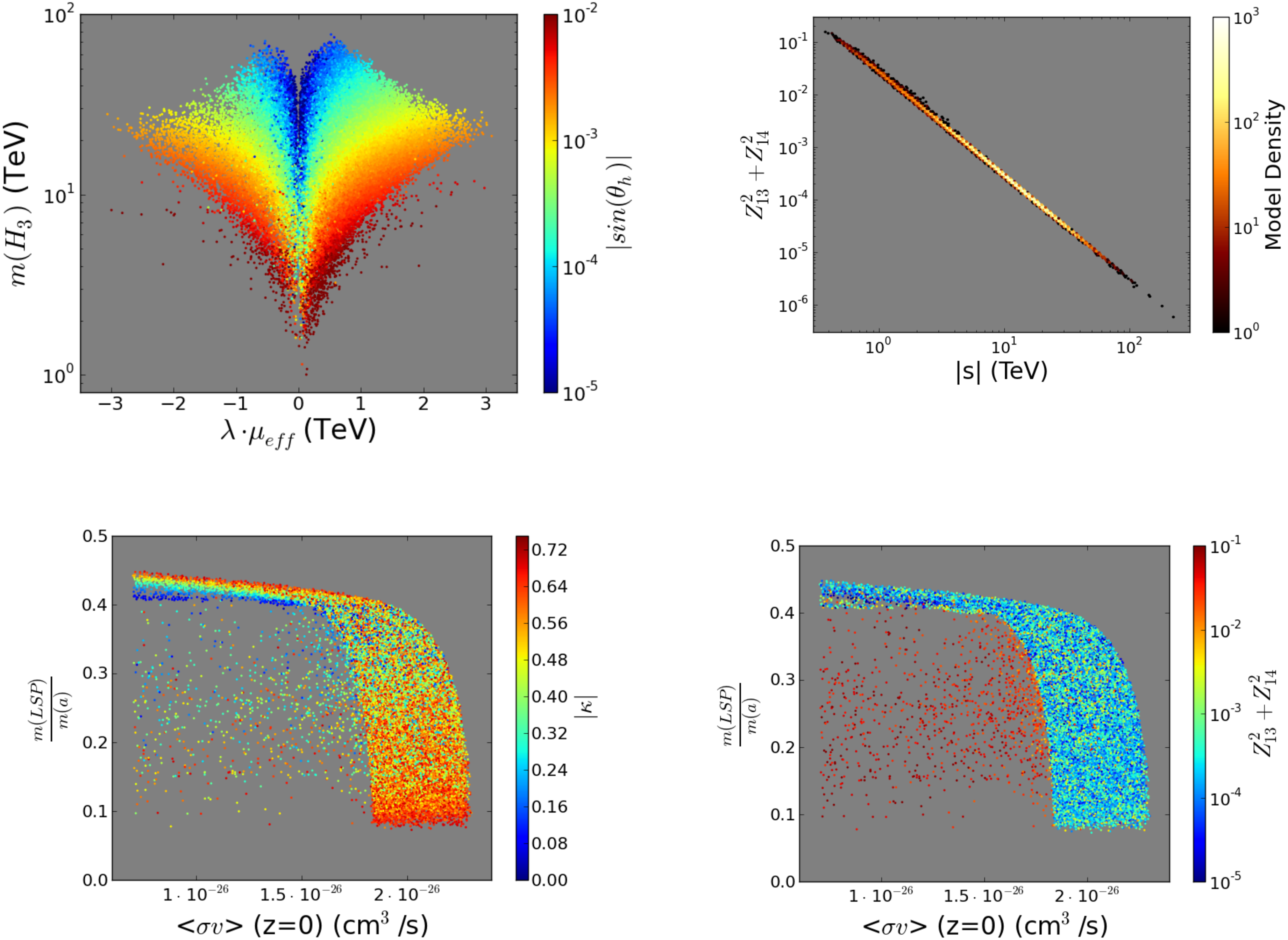


$b\bar{b}$ annihilation fraction
Model Density
μ_{eff} (TeV)
$\frac{m(LSP)}{m(a)}$
$|\kappa|$
$<\sigma v>$ (z=0) (cm^3 /s)
$b\bar{b}$ annihilation fraction (z=0)
$M(\tilde{q})$ (TeV)
μ_{eff} (TeV)
$b\bar{b}$ annihilation fraction (z=0)
$\tan\beta$
μ_{eff} (TeV)

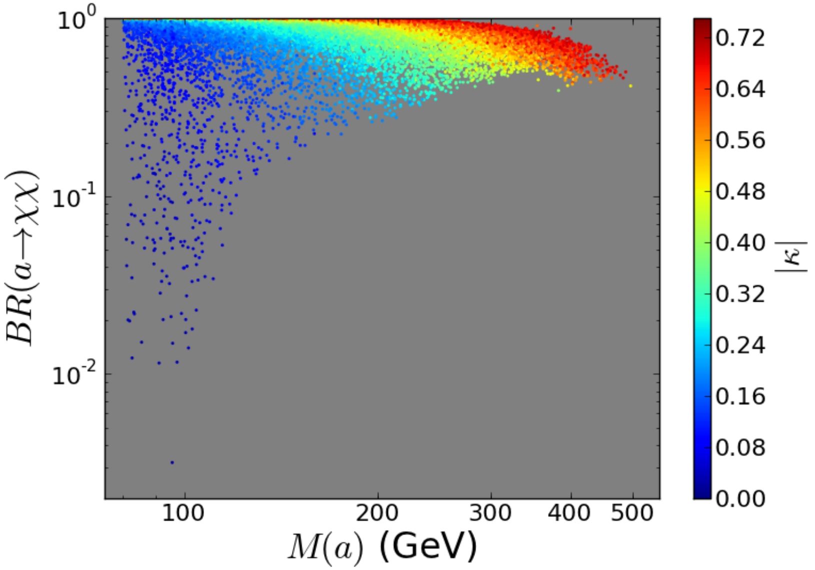

$BR(B_s \to \mu^+ \mu^-)/SM$
2.0
1.5
1.0
0.5
−4
−2
0
2
4
μ_{eff} (TeV)
60
54
48
42
36
30
24
18
12
6
0
$\tan\beta$

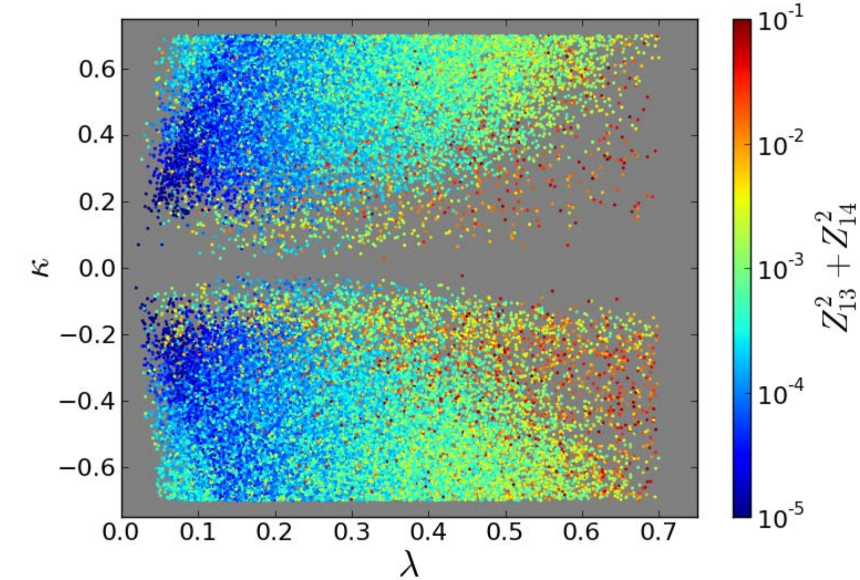

$BR(B_s \to \mu^+ \mu^-)/SM$
2.0
1.5
1.0
0.5
−4
−2
0
2
4
μ_{eff} (TeV)
10^2
10^1
10^0
Model Density

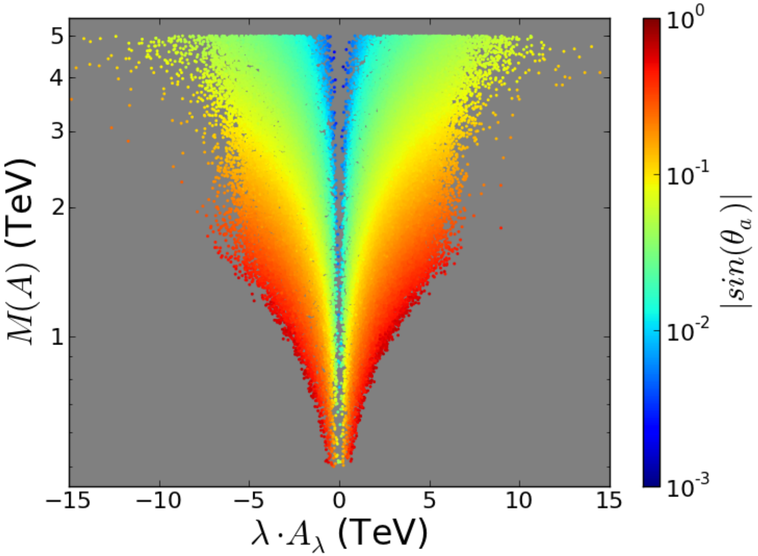

$M(\tilde{q})$ (TeV)
10^5
10^4
10^3
10^2
10^1
10^0
10^0
10^1
$\tan\beta$
10^2
10^1
10^0
Model Density

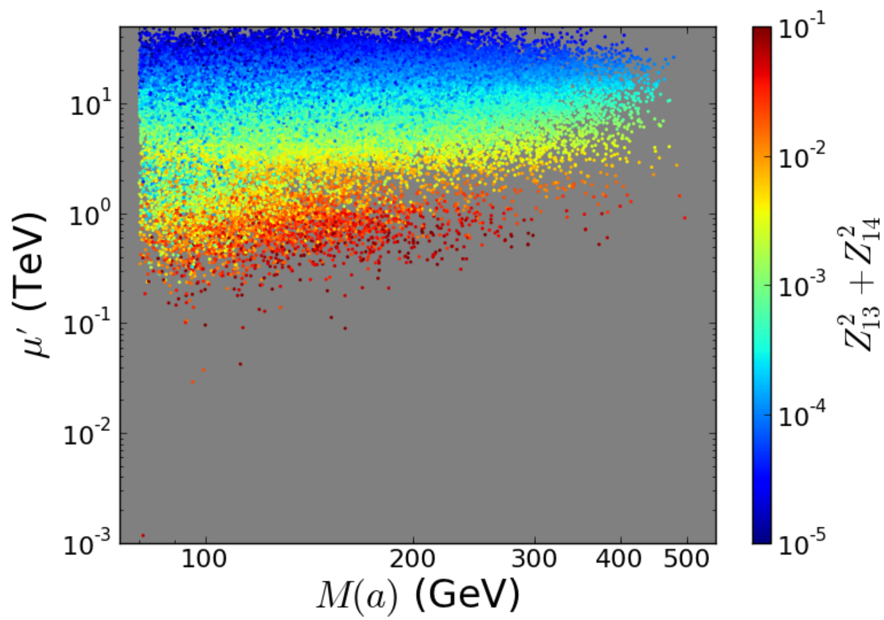


$m(H_3)$ (TeV)
$\lambda \cdot \mu_{eff}$ (TeV)
$|sin(\theta_h)|$
$Z_{13}^2 + Z_{14}^2$
|s| (TeV)
Model Density
$\frac{m(LSP)}{m(a)}$
<σv> (z=0) (cm^3 /s)
$|\kappa|$
$\frac{m(LSP)}{m(a)}$
<σv> (z=0) (cm^3 /s)
$Z_{13}^2 + Z_{14}^2$


$BR(a \to \chi\chi)$
$M(a)$ (GeV)
$|\kappa|$


κ
λ
$Z_{13}^2 + Z_{14}^2$


$M(A)$ (TeV)
$\lambda \cdot A_\lambda$ (TeV)
$|sin(\theta_a)|$


μ' (TeV)
$M(a)$ (GeV)
$Z_{13}^2 + Z_{14}^2$