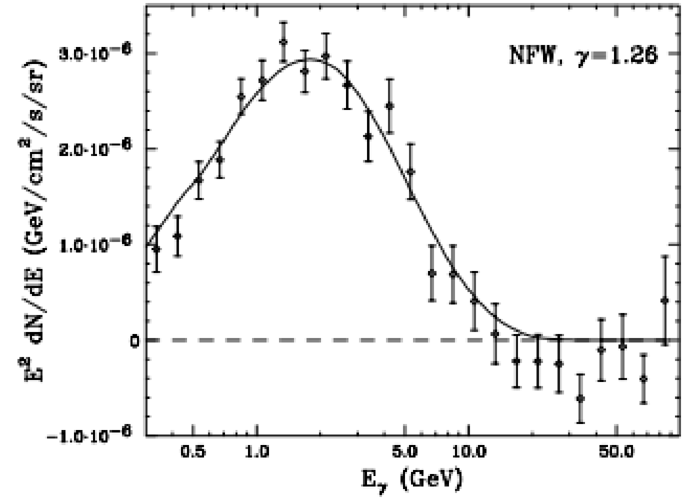
SUSY Scenarios for the Fermi GC Excess



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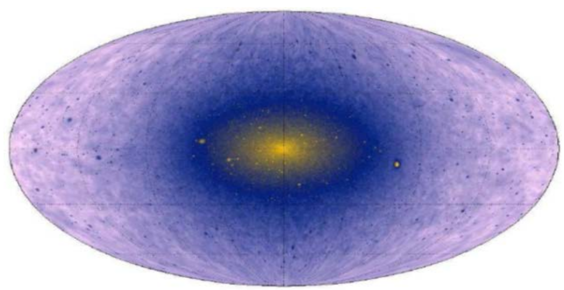

arXiv:1409.1573 v3 + in progress

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8/25/15

Model Building Assumptions

→ Assume the initial interpretations of the Fermi GC as DM are ~correct within a SUSY context. What conditions must we meet?

- The DM mass is ~ 30-40 GeV but can be as heavy as ~70 GeV
- Thermal freeze-out $\langle \sigma v \rangle$ gives the observed DM relic density
- A similar (but likely smaller) $\langle \sigma v \rangle$ today → GC signal
- The bb-bar final state dominates - others require tuned masses

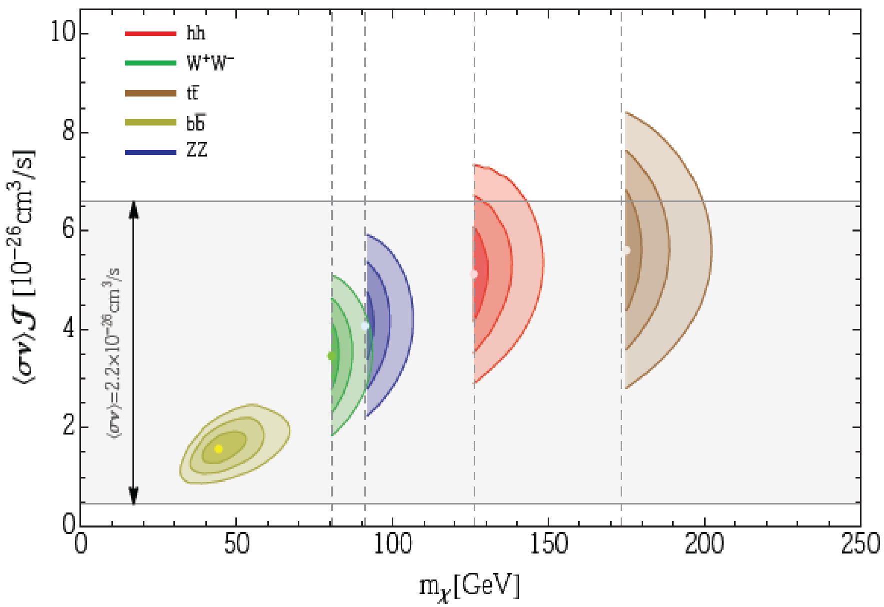
+

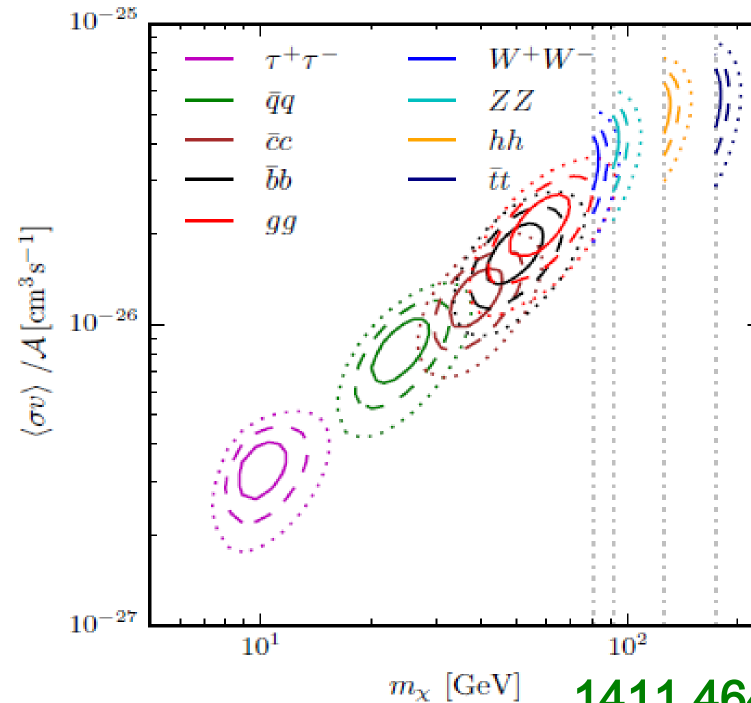
→ Only a *single mediator* for DM annihilation is active at all times

What SUSY scenarios can we construct consistent with conditions?

"simple" → "more complex"

Other scenarios require mass F-T w/ low p-values
→ Masses always very close to threshold





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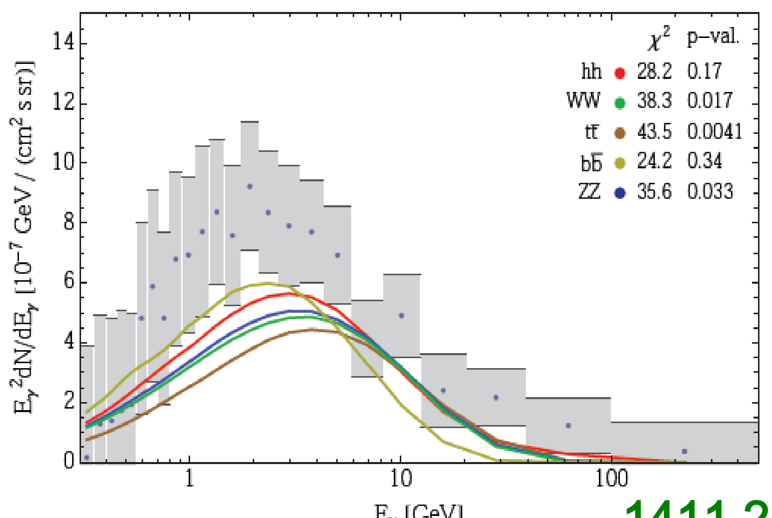

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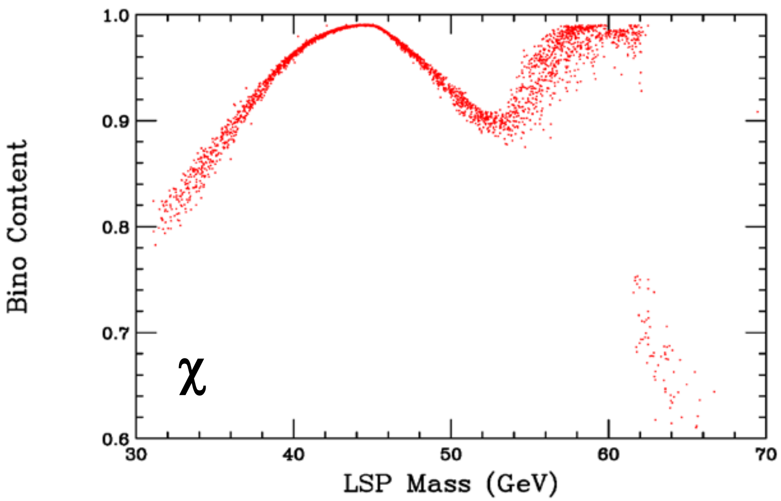
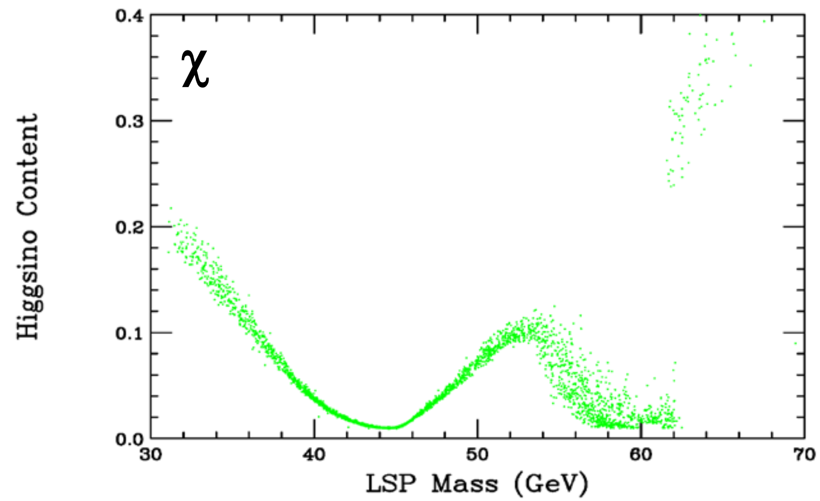
Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	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	0.0036]$_{\rm ICS}$

Where do we start? The (p)MSSM !

- 30-70 GeV DM/LSP in the pMSSM must be well-tempered : too light for co-annihilation (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 makes $\langle\sigma v\rangle$ large enough to give the measured relic density. Note the Z-inv. width constraint below ~30 GeV & LEP above ~70 GeV

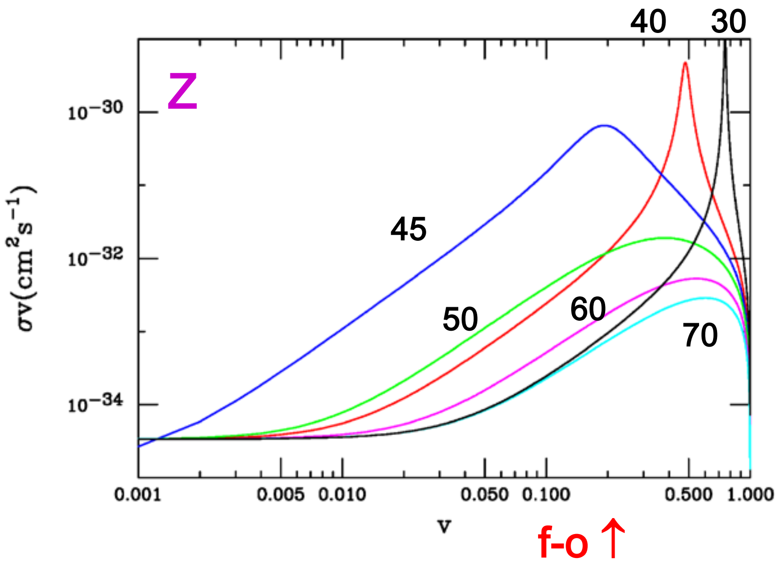


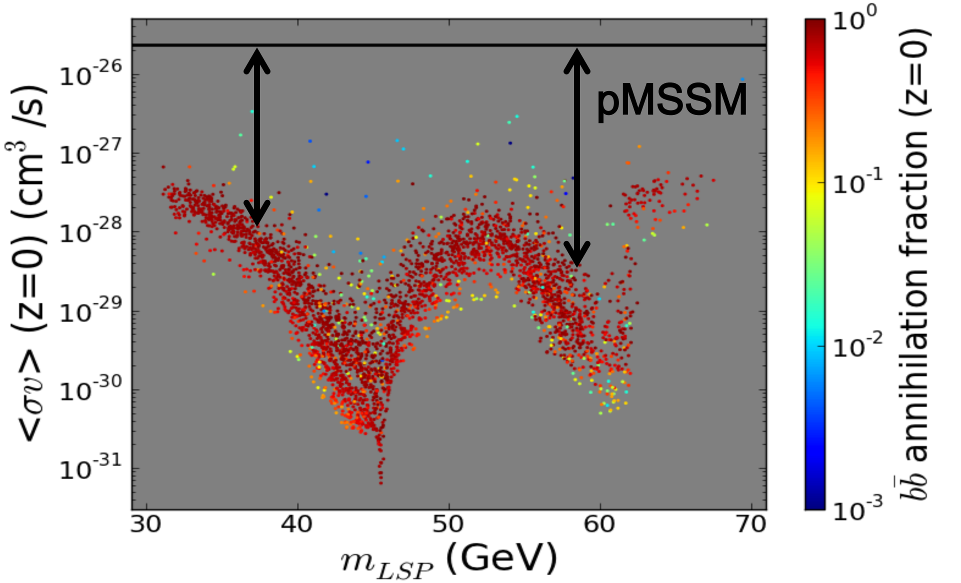


pMSSM (cont.)

- BUT, then ⟨σv⟩ today is too small by ~100 or more to produce the GC flux due its strong velocity-dependence - v is now much smaller. Similar arguments for h-exchange

→ Neither of Z/h can be the lone mediator due to the v dependence





Scales up & down with Higgsino content

What Next ? : Dirac Gauginos

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

- The Dirac LSP must be ~a very pure bino -- any Higgsino content leads to a coherent vector Z-coupling conflicting with SI DD . The LSP annihilates via t-channel sfermion exchange to achieve the correct relic density:

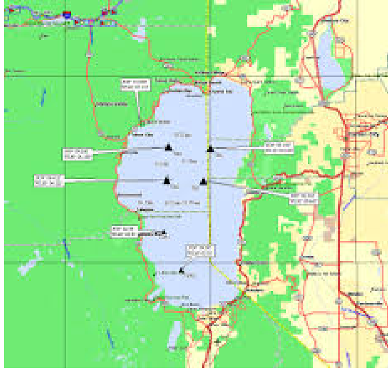
$\chi\bar{\chi} \to f\bar{f}$:

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

- However only ~100 GeV staus can produce a large enough $\langle\sigma v\rangle$. LEP, LHC & DD constraints $\to$ sbottoms are too heavy to give significant rate (due to small hypercharge) to obtain observed relic density

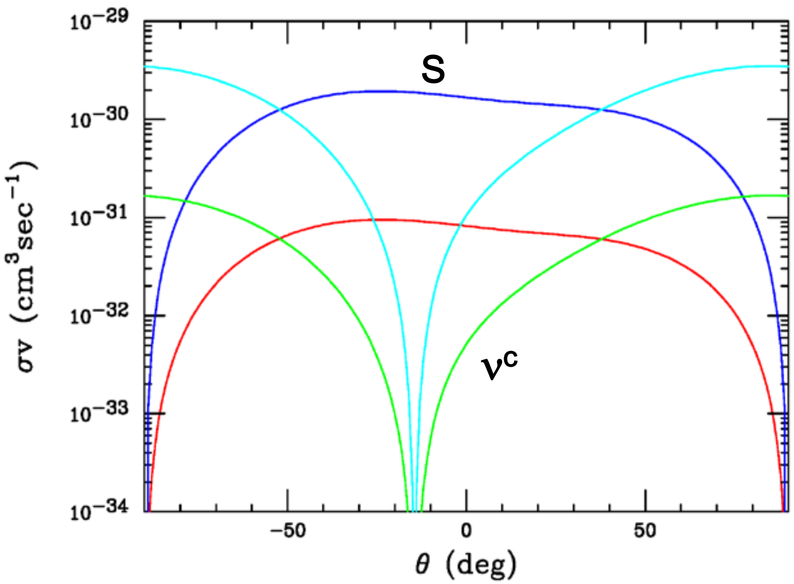
- More TOAST...

E_6SSM : Z' Plus SM Singlets



- SUSY E_6 =TeV-scale Z' + two new SM singlet fields (S, ν^c) which might be either Dirac or Majorana LSPs.

Everything fixed except for the Z' mass and θ-mixing anlge



$M_{Z'}$ = 2 TeV

- The Z' mass is far above that of the LSP so no pole issues & fewer DD problems
- For an LSP mass ~30-70 GeV & a Z' satisfying LHC , ⟨σv⟩ during freeze out is too small for 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 limited + large number of experimental constraints + our assumption of only a single mediator.
- LSP ~singlino & a ~isosinglet CP-odd (as noted by others) is a good mediator. Coupling to the SM is via mixing & needs large tan β for bb
- Higgsino content of the LSP must be kept small to avoid coupling to the Z influence on the relic density. (Single mediator only!) . → $\lambda v_{u,d}$ must be small.

The NMSSM with Z_3 (cont.)

- However: $\mu_{eff} = \lambda s$ >100 GeV (LEP) but $2\kappa s$ ~ 30-70 GeV is the LSP mass & κ contributes to the overall scale of the $\chi\chi a$ coupling (see below) so can't be too small

- Arrange a smallish a mass, a somewhat larger A mass but keep h ~125 GeV from loops while avoiding all the LHC searches

- Algebraic study plus a scan of the parameter space (generating > 10^{10} points) finds no solutions

→ Not enough parameter freedom to satisfy all 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

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

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

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

- The extra **5** parameters, e.g., μ’ , resolve past problems !

Examine the general NMSSM by a parameter scan employing modified version of NMSSMTools4.3.0 *** → ‘features’ (version 4.7.0 out now)

- Simplify: slepton masses = 1 TeV &squark masses to a common value m_Q with $A_{b,t} = \sqrt{6}\, m_Q$ to get a Higgs mass 125±3 GeV (stop mixing) taken as the lightest CP-even state

- 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…

→ Generated 6×10^8 points in this space & applied all the requirements.***

→ Goal : find viable solutions & not to do a detail parameter study !

~ 52.8 k 'models' = sets of parameters remain

→ Extend scan up to LSPs of 70 GeV w/ another ~10^8 points

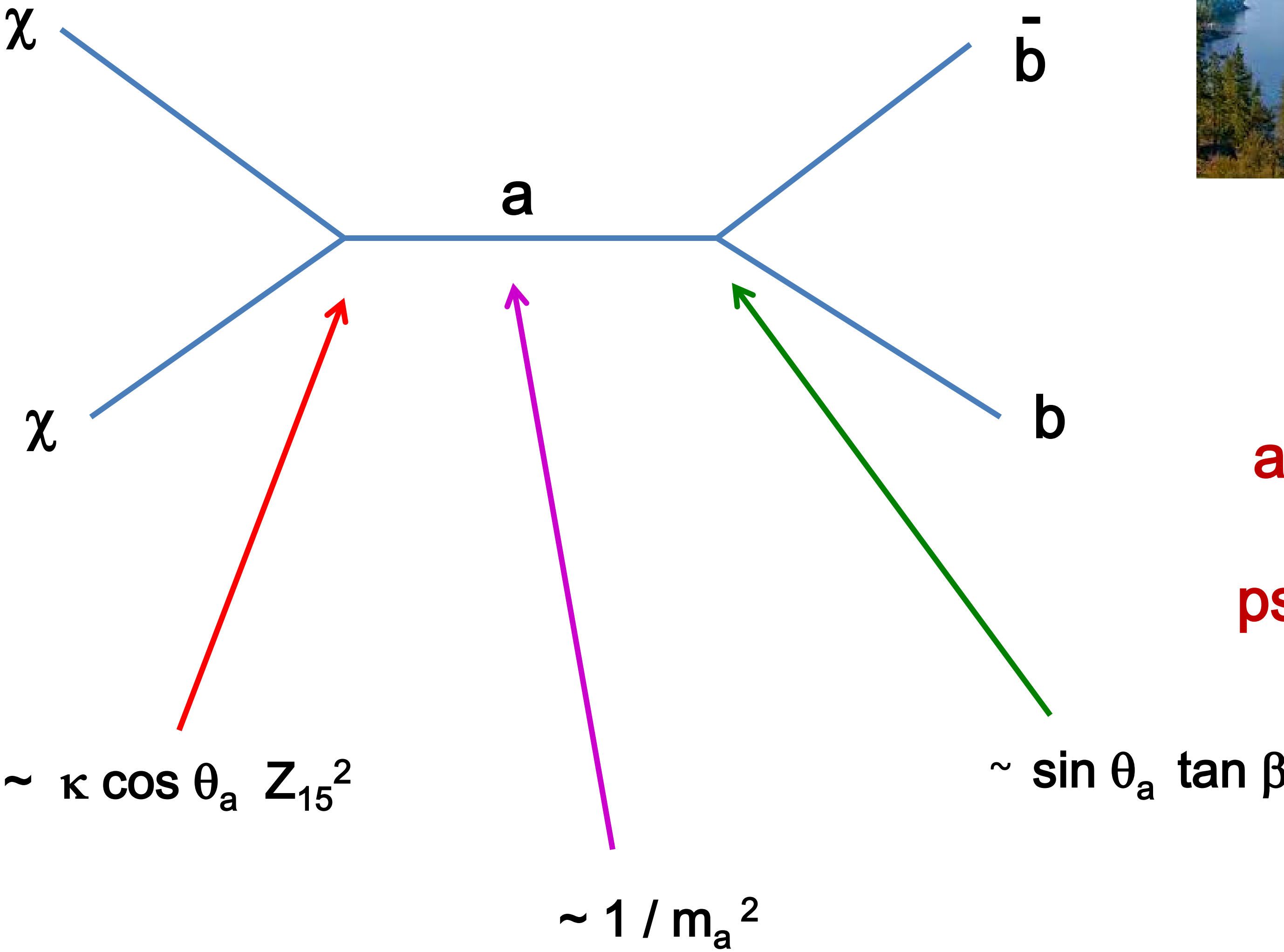
Some useful definitions:

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

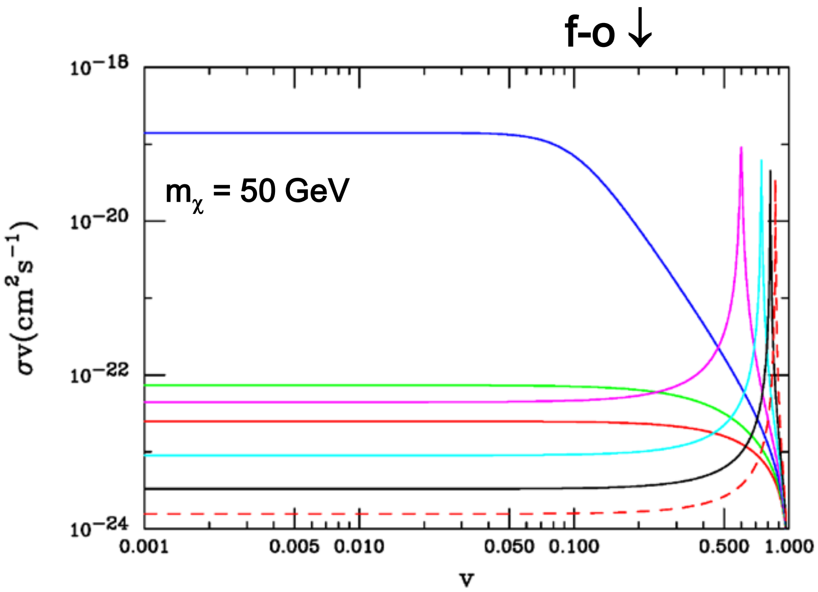
→ Make a lot of plots that examine model properties

*** see paper for an extensive discussion



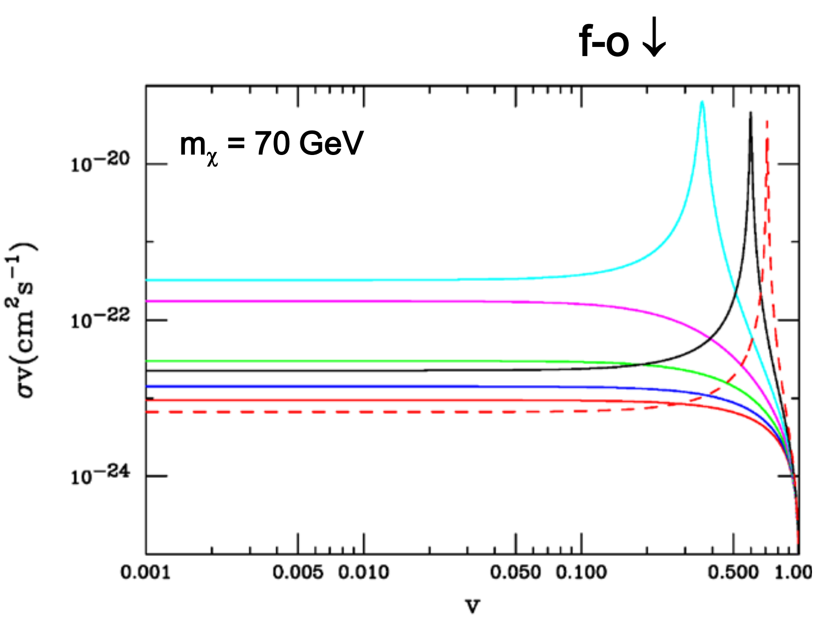
DM annihilation via the pseudoscalar

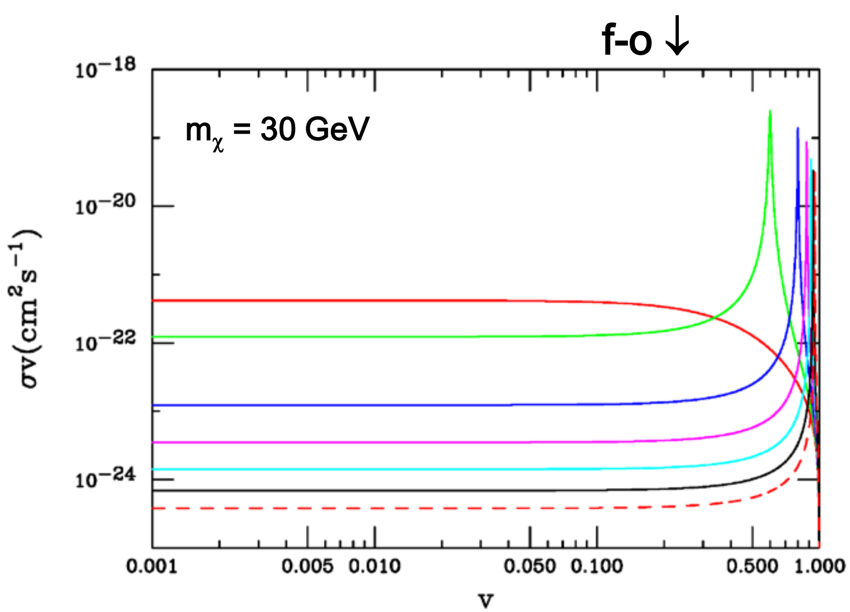
→ The values of the various parameters must compensate each other to obtain the correct relic density



For a wide range of masses a-exchange yields a ~velocity-independent value of σv except 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



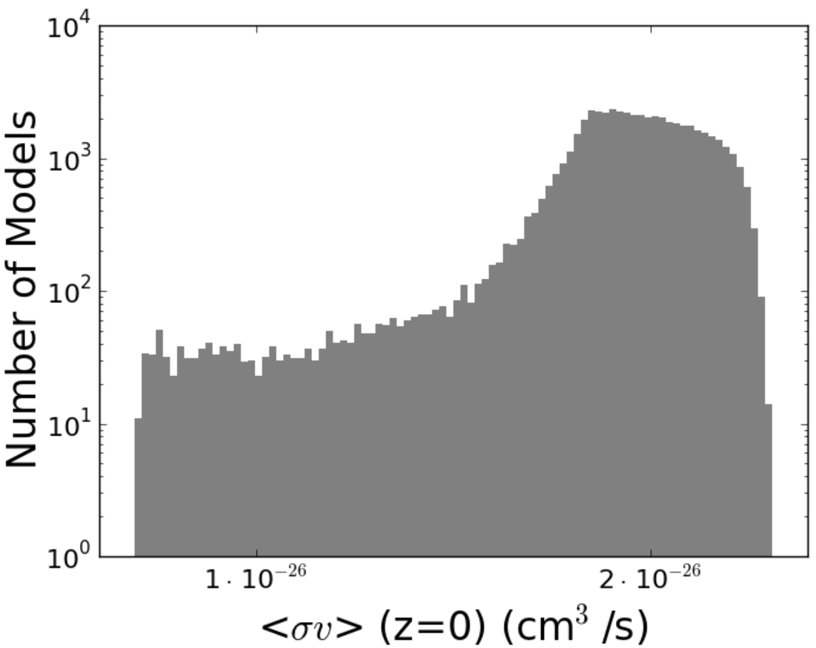


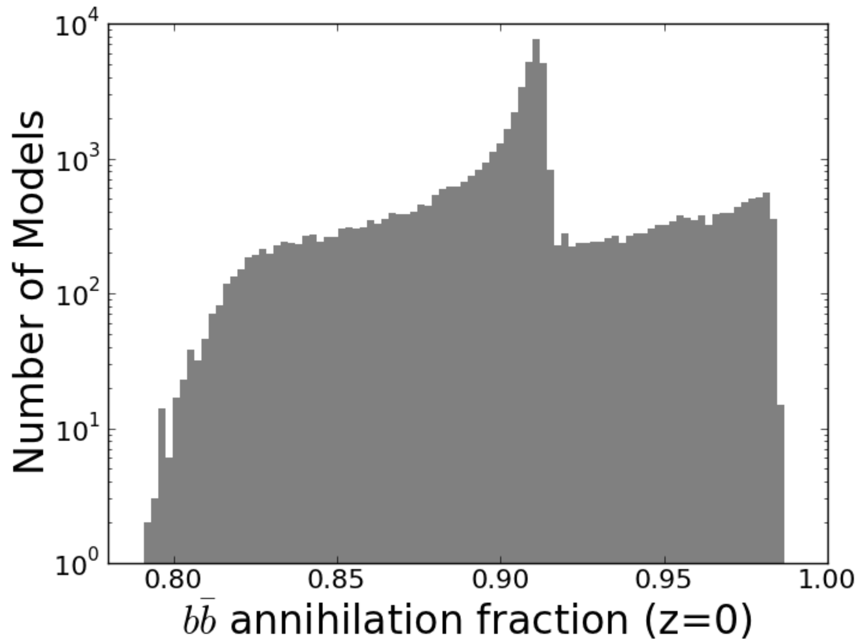
M_a = 50 (r), 75 (g), 100 (b), 125 (m), 150 (cy), 175 (bl), 200 (d)

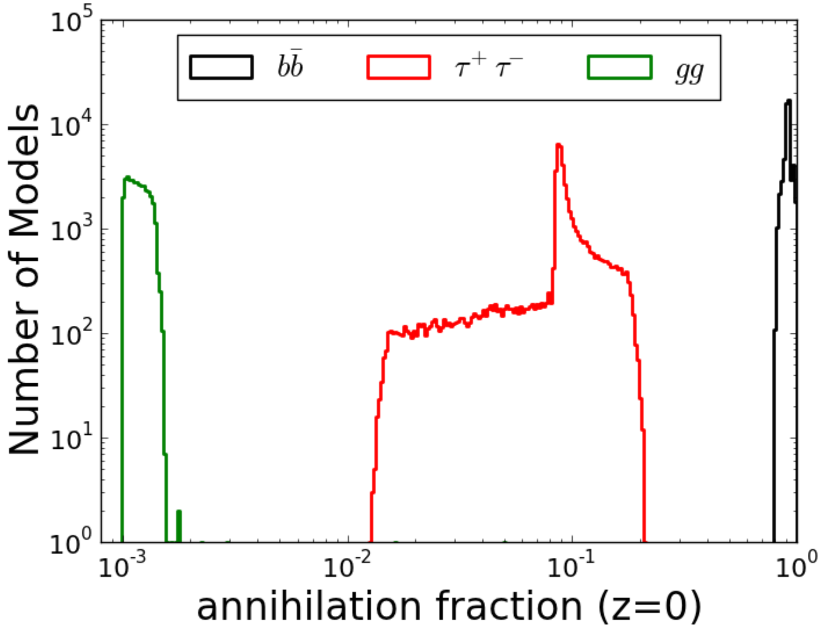
Some possible questions to answer

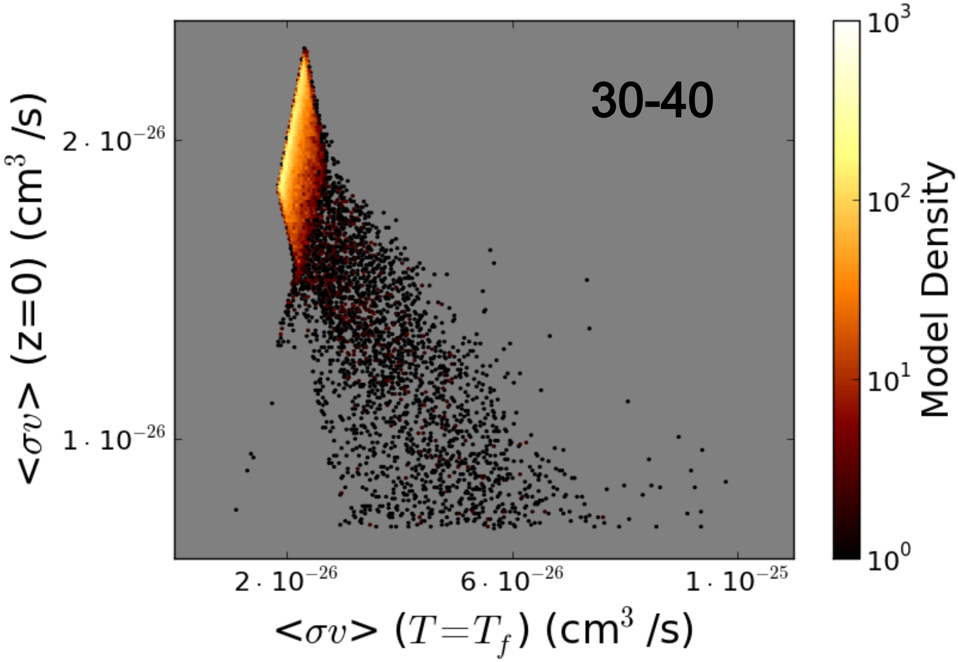
- What are the properties of the LSP/DM ?
- Can it be observed in DD experiments?
- Are the properties of the Higgs modified?
- Are there other LHC, etc. signals?

DM properties

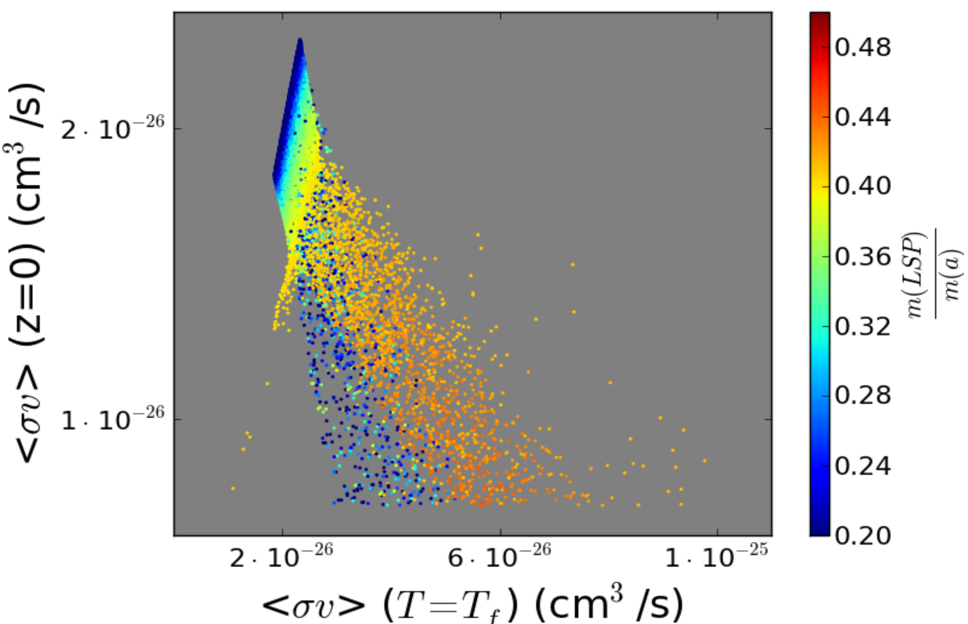


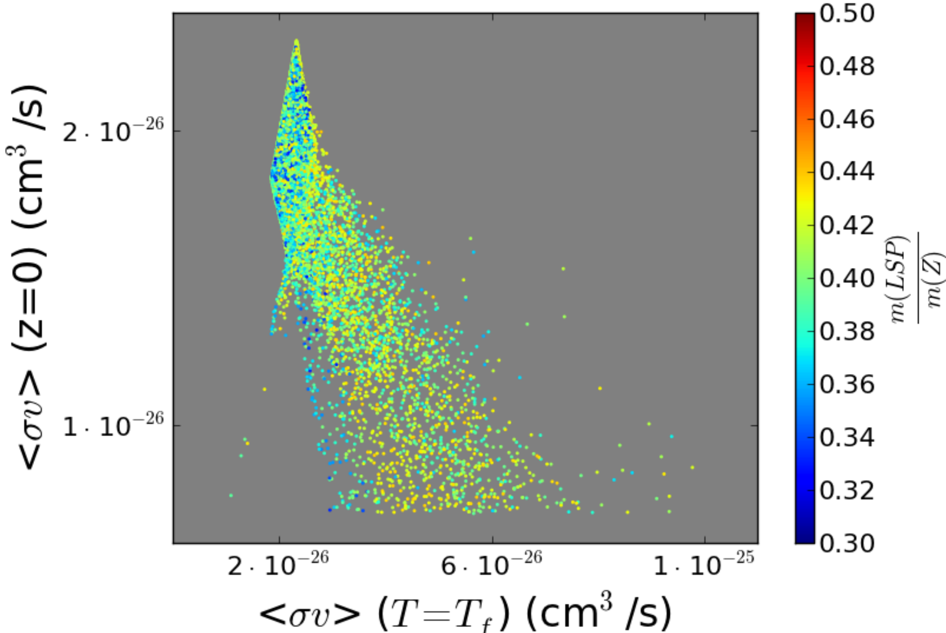


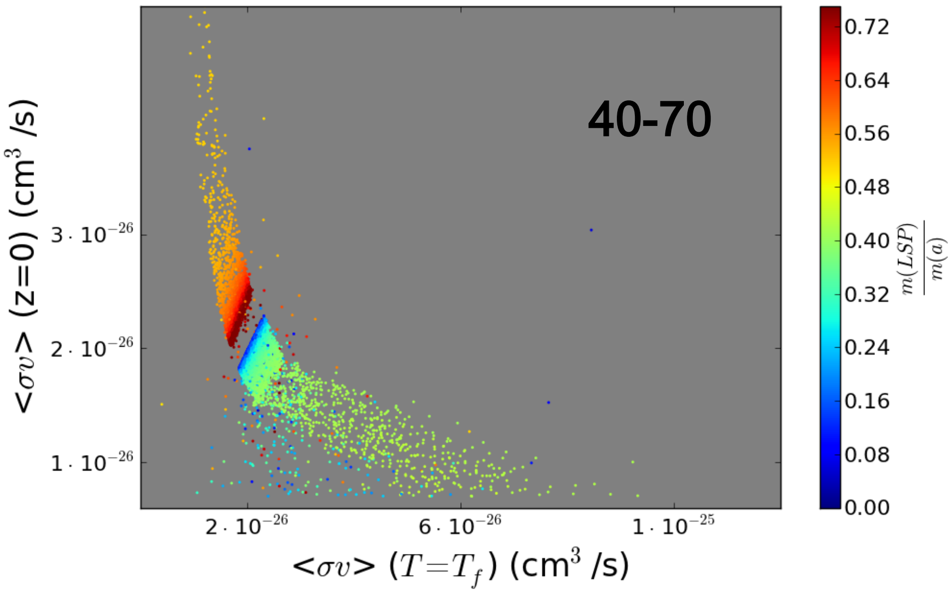


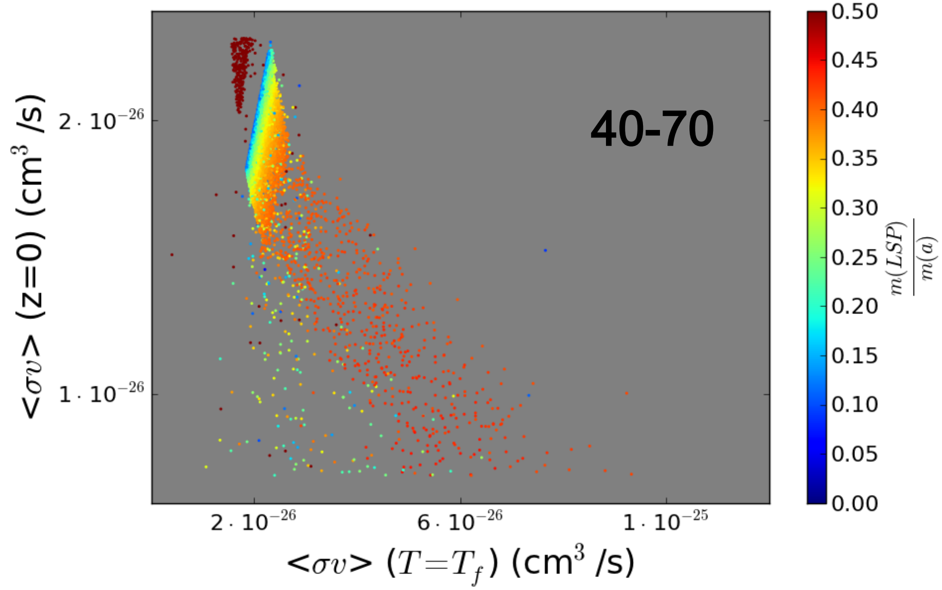


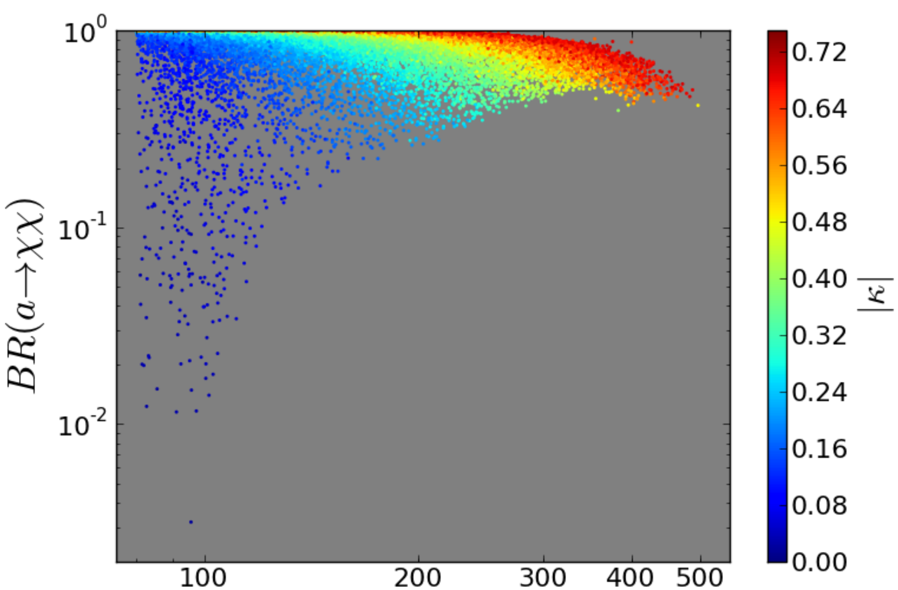
Interesting correlation between the freeze-out and present day values of ⟨σv⟩

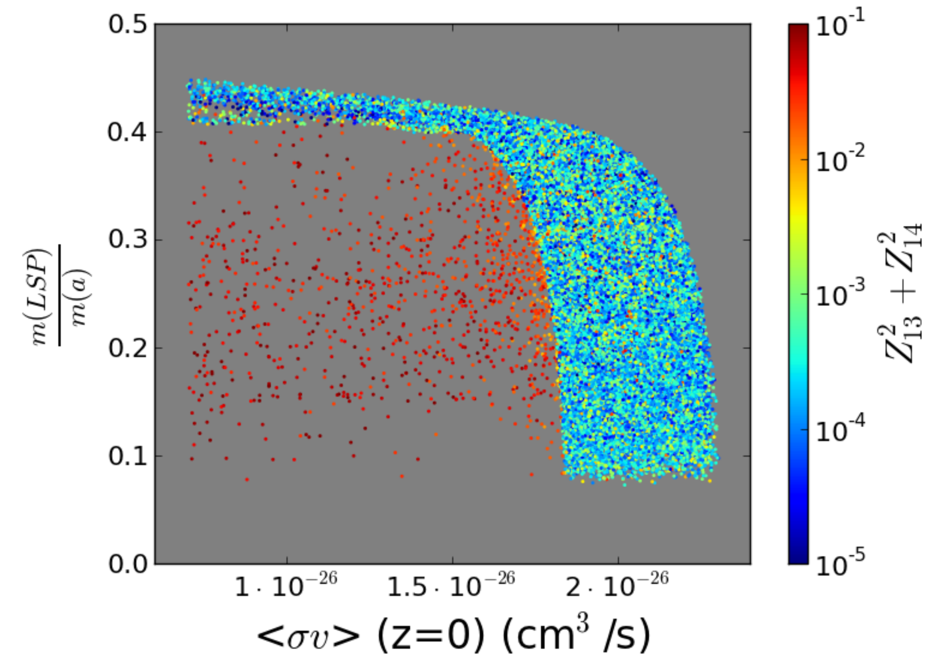


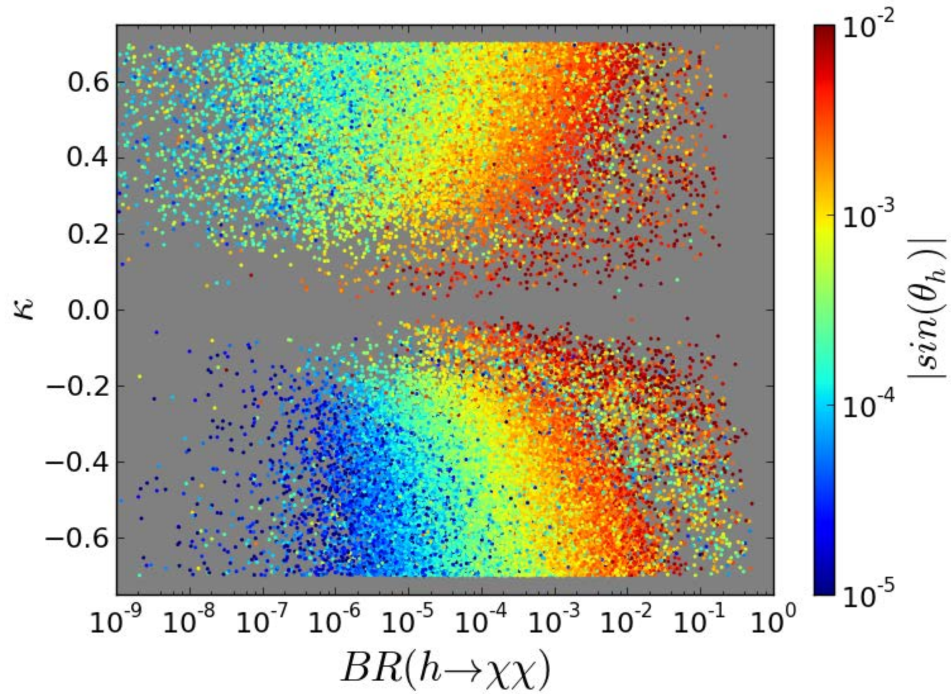



40-70
<σv> (z=0) (cm³ /s)
<σv> (T=T_f) (cm³ /s)
m(LSP)/m(a)
3 · 10^-26
2 · 10^-26
1 · 10^-26
2 · 10^-26
6 · 10^-26
1 · 10^-25
0.72
0.64
0.56
0.48
0.40
0.32
0.24
0.16
0.08
0.00


40-70
<σv> (z=0) (cm³ /s)
<σv> (T=T_f) (cm³ /s)
m(LSP)/m(a)
2 · 10^-26
1 · 10^-26
2 · 10^-26
6 · 10^-26
1 · 10^-25
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

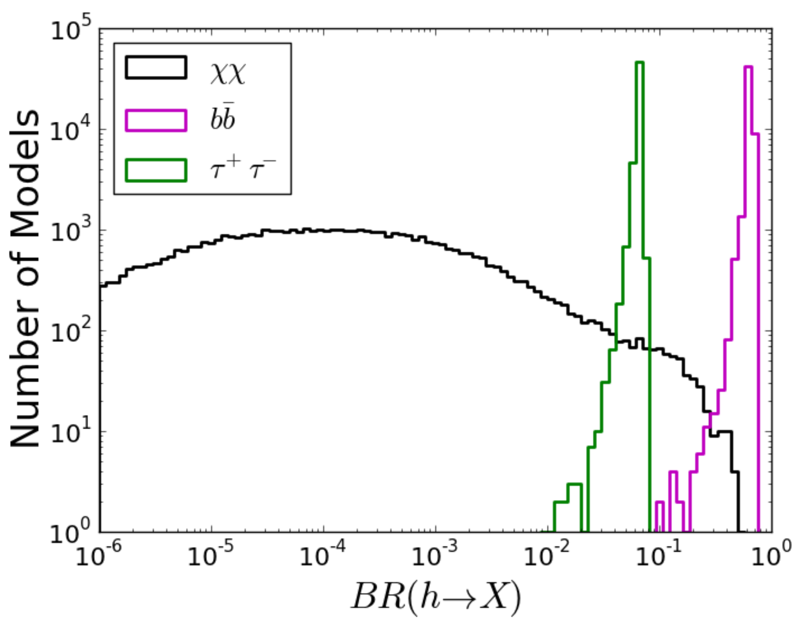

BR(a→χχ)
M(a) (GeV)
|κ|
10^0
10^-1
10^-2
100
200
300
400
500
0.72
0.64
0.56
0.48
0.40
0.32
0.24
0.16
0.08
0.00

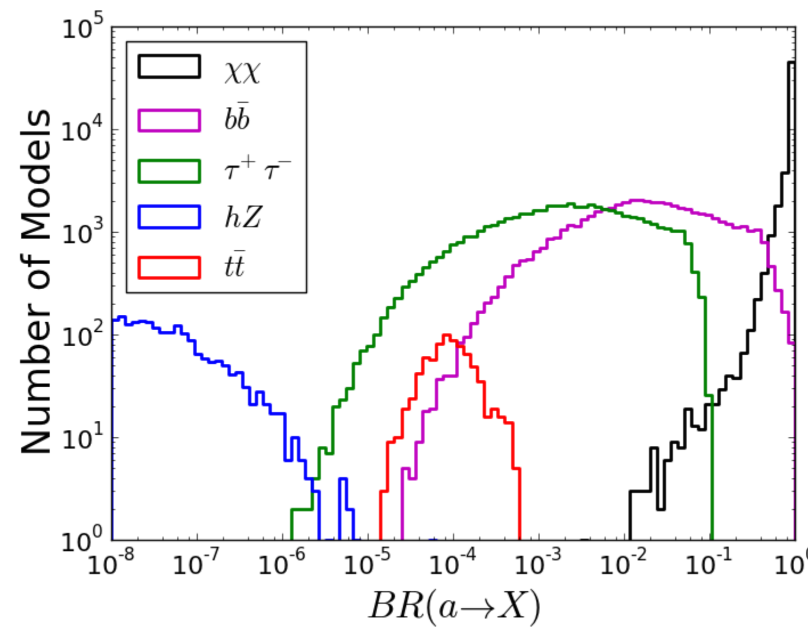

m(LSP)/m(a)
<σv> (z=0) (cm³ /s)
Z²_13 + Z²_14
0.5
0.4
0.3
0.2
0.1
0.0
1 · 10^-26
1.5 · 10^-26
2 · 10^-26
10^-1
10^-2
10^-3
10^-4
10^-5

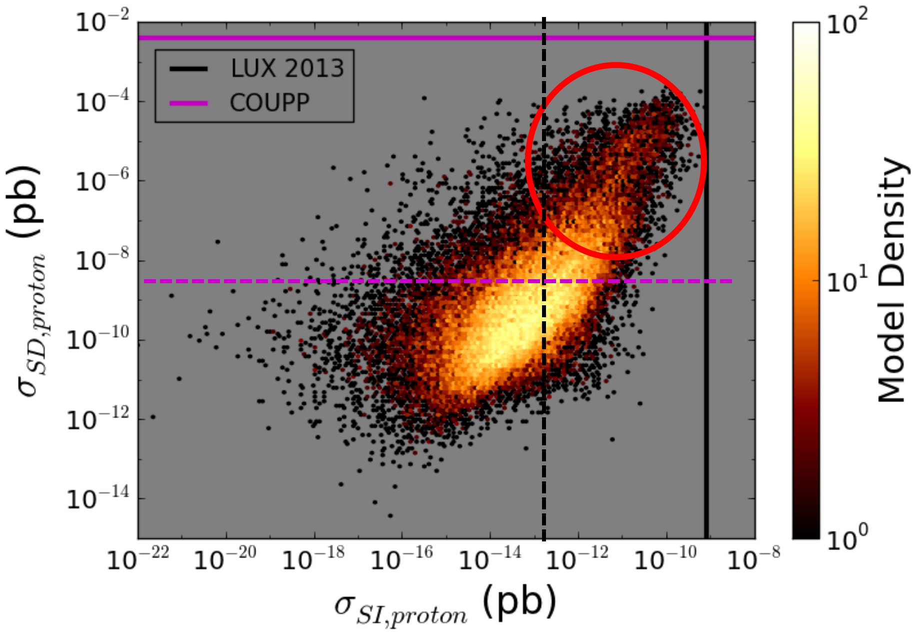


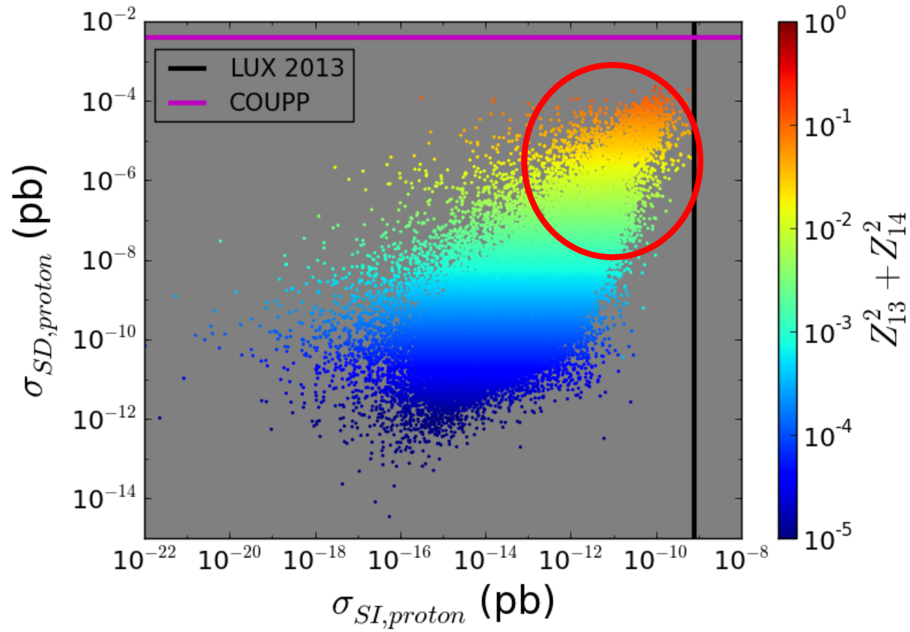
- The Higgs remains SM-like but picks up a generally very small BF (~ <1%) for the decays to the LSP. LC??

- The light CP-odd field, a, decays almost entirely to LSP pairs but also has a small BF to bb-bar

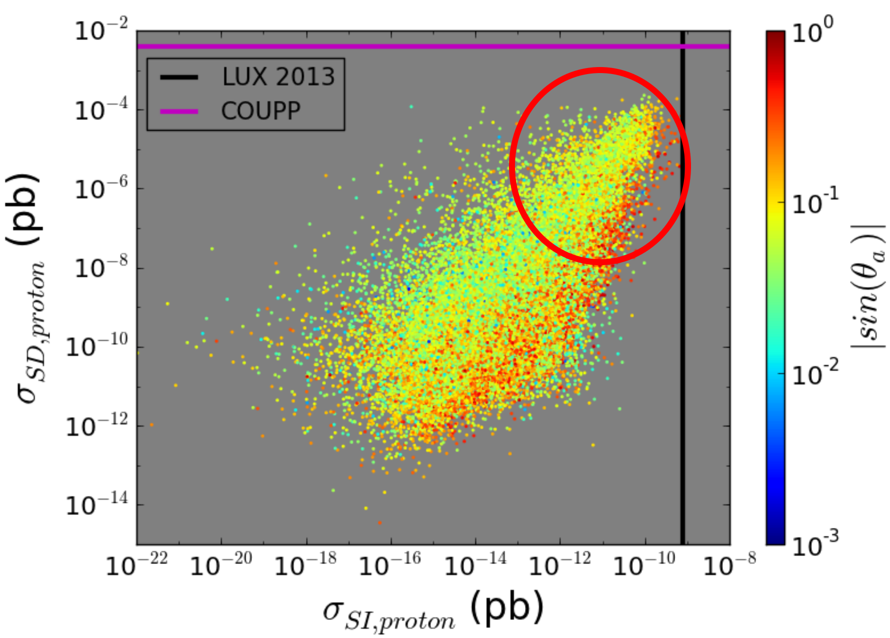


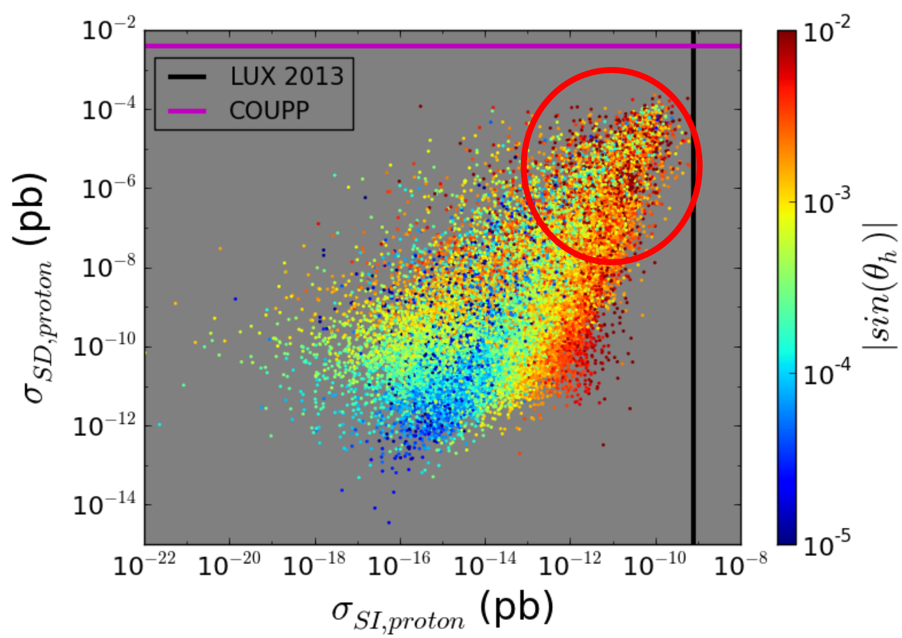


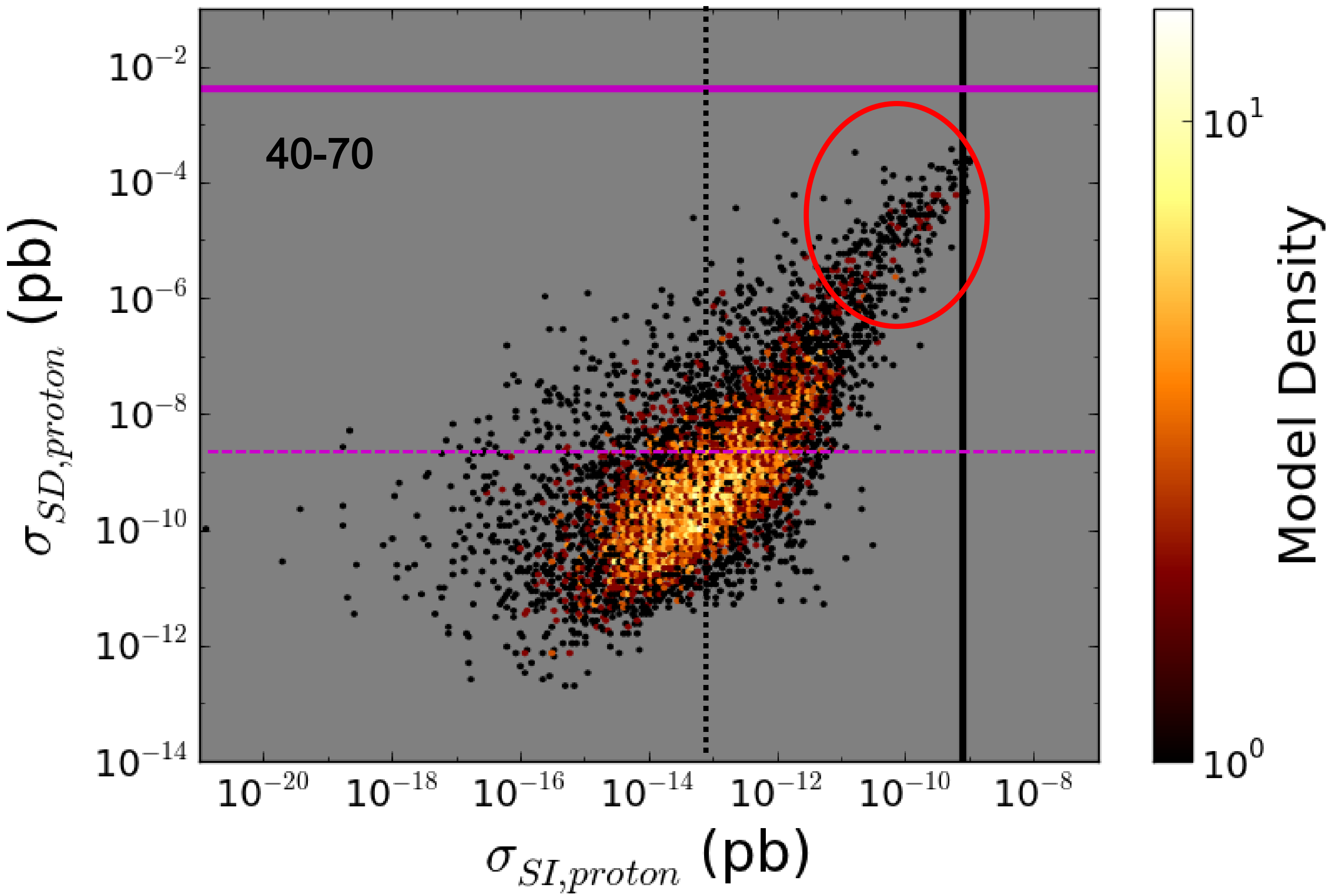




Expectations for DD are generally not very good…

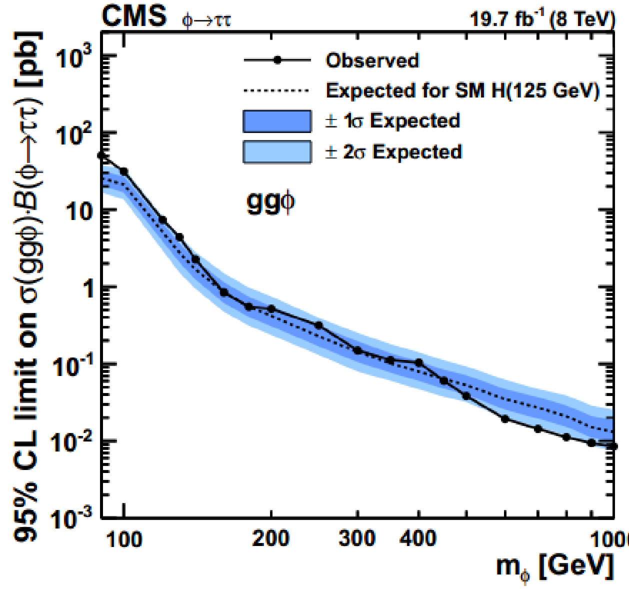


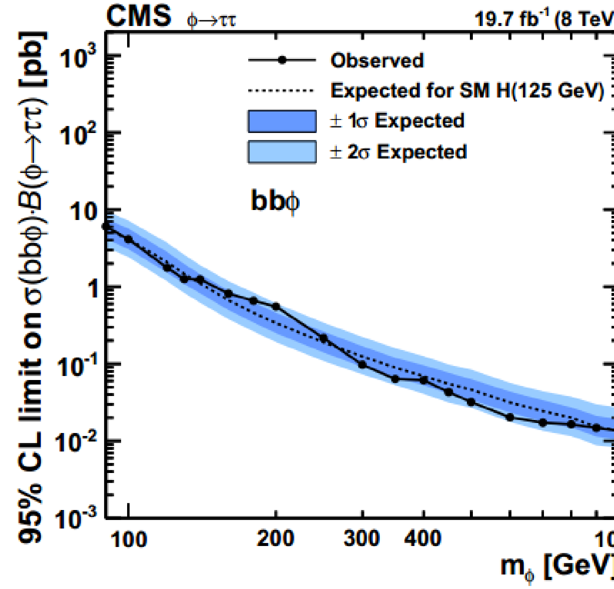


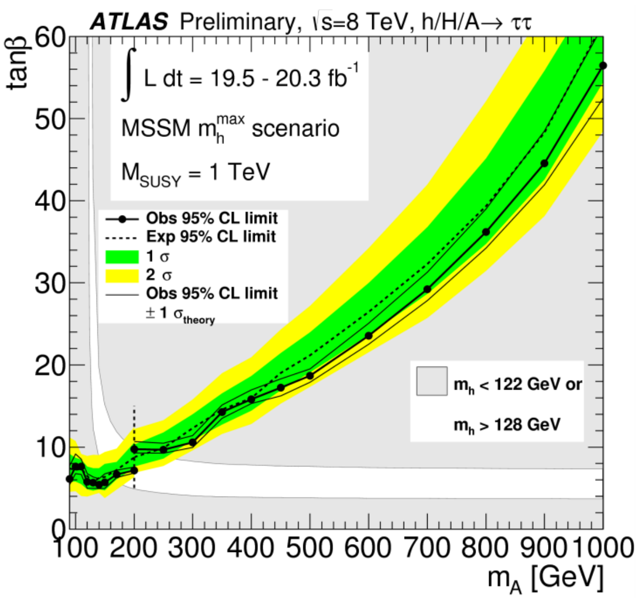


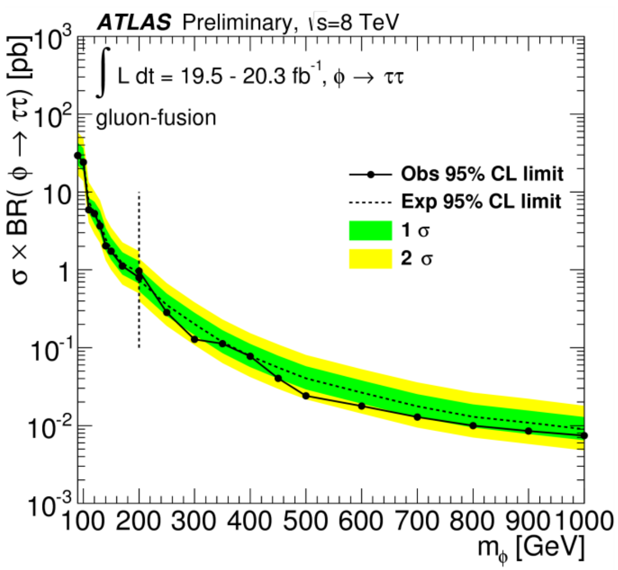
40-70
$\sigma_{SD,proton}$ (pb)
$\sigma_{SI,proton}$ (pb)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
Model Density
10^{1}
10^{0}

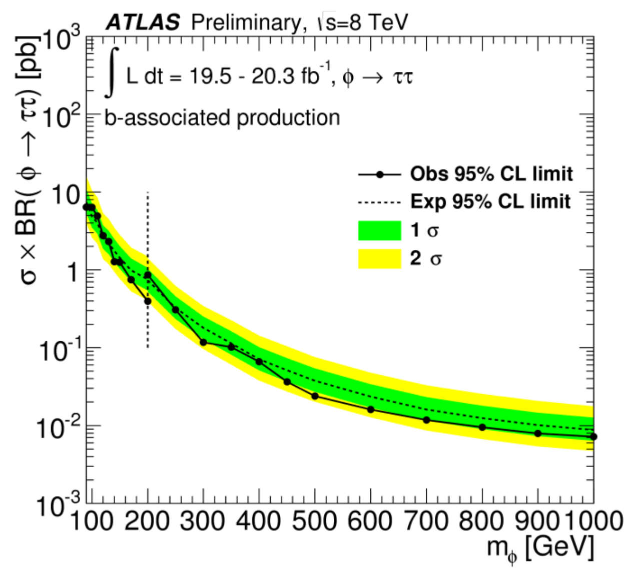
Heavy Higgs Searches @ LHC

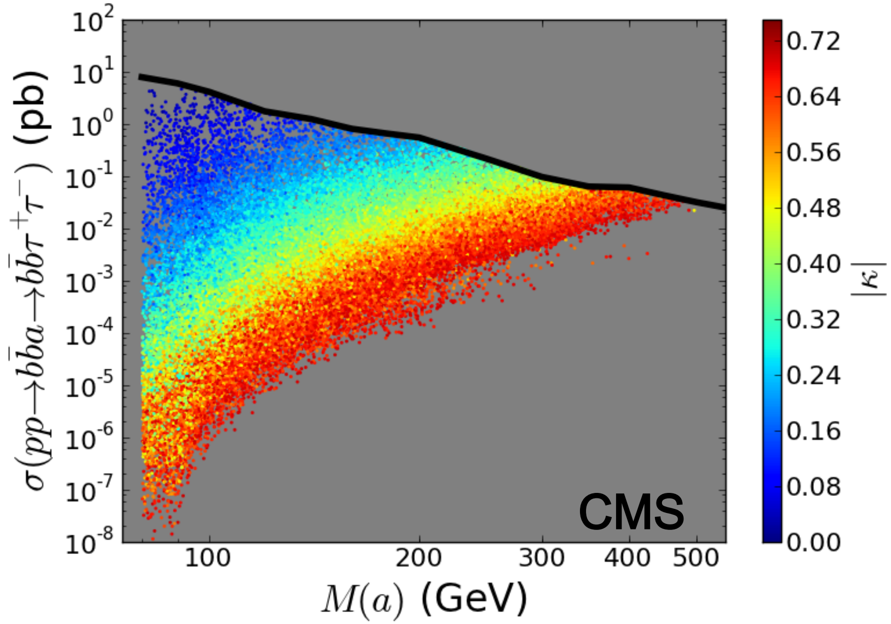






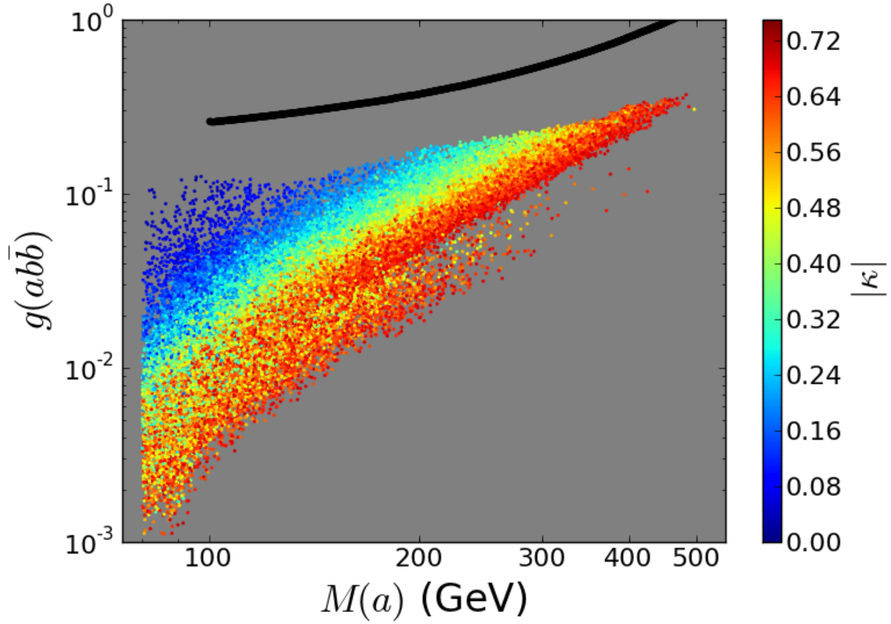






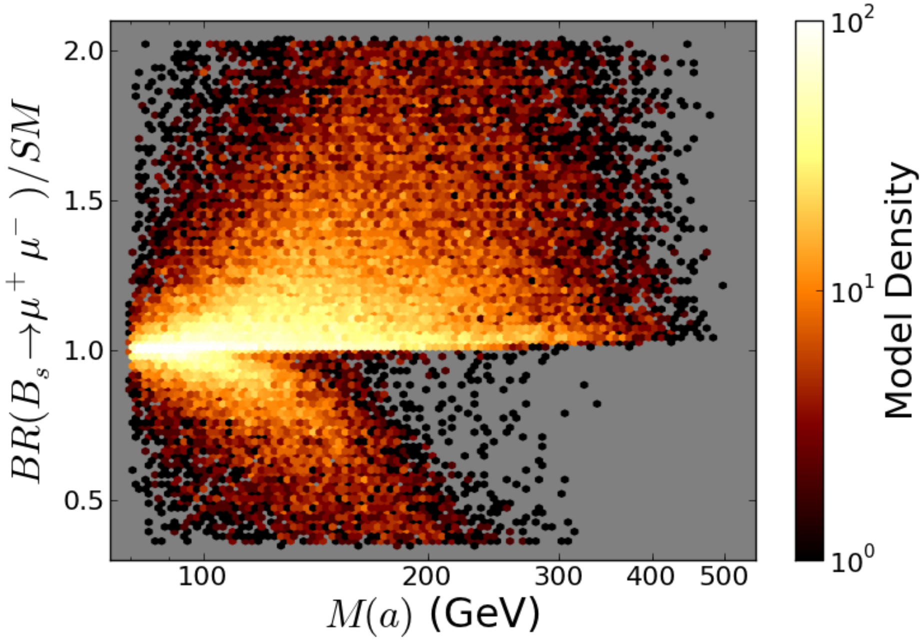
Heavy Higgs Search Impact

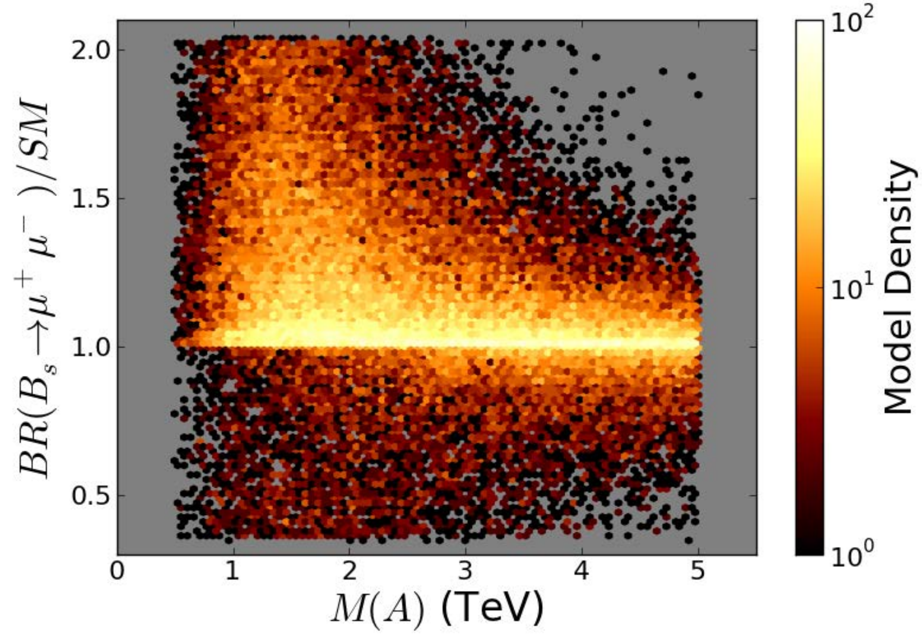
- LHC 'A/H →ττ' searches easily satisfied but provide constraints & cut off the a from above @ ~500 GeV . Run-II will have significant impact here..

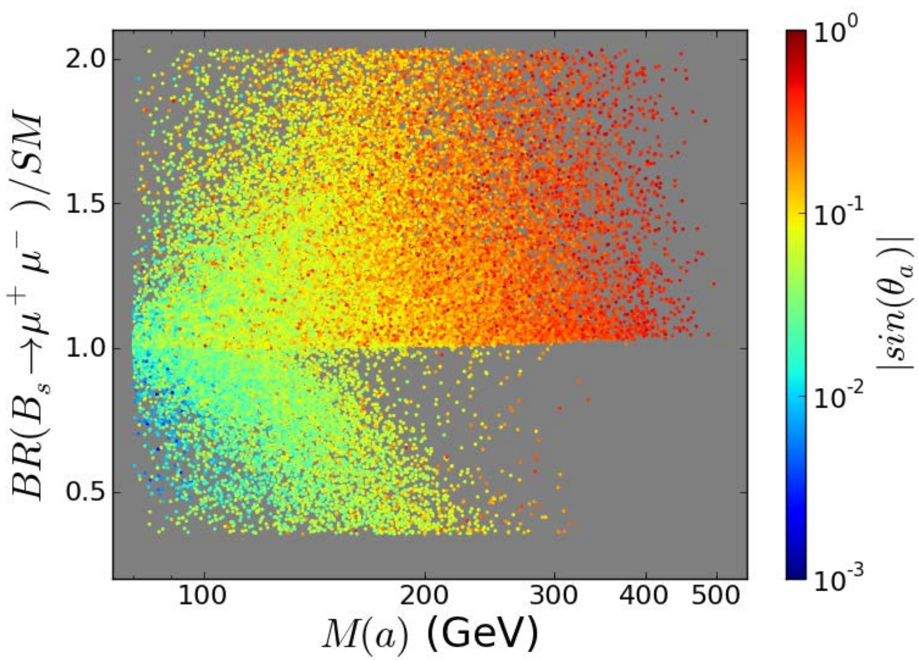


- Searches for bb-bar +MET can be reinterpreted to look for a+bb-bar associated production where then a→χχ. Safely within the current constraints…but @ 13-4 TeV…

1404.2018







- 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 tails
- RC via sign of μ splits models into two subsets

Summary & Conclusions

- Non-trivial model building challenge to find a SUSY scenario that incorporates the Fermi GC excess with a single DM mediator & satisfying all other constraints with 30-70 GeV LSPs . Models easily fail for many reasons.

- The general NMSSM provides a successful proof of principle framework

- Can be tested to a limited degree by DD, searches for heavy Higgs (including bb-bar+MET), a small Higgs BF to LSPs, some rare decay measurements and direct SUSY searches. Fermi Dwarf DM limits produce some tension!

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

- Point sources? DM ? Hopefully we'll soon learn more about this signal.

Backups

The p(henomenological)MSSM

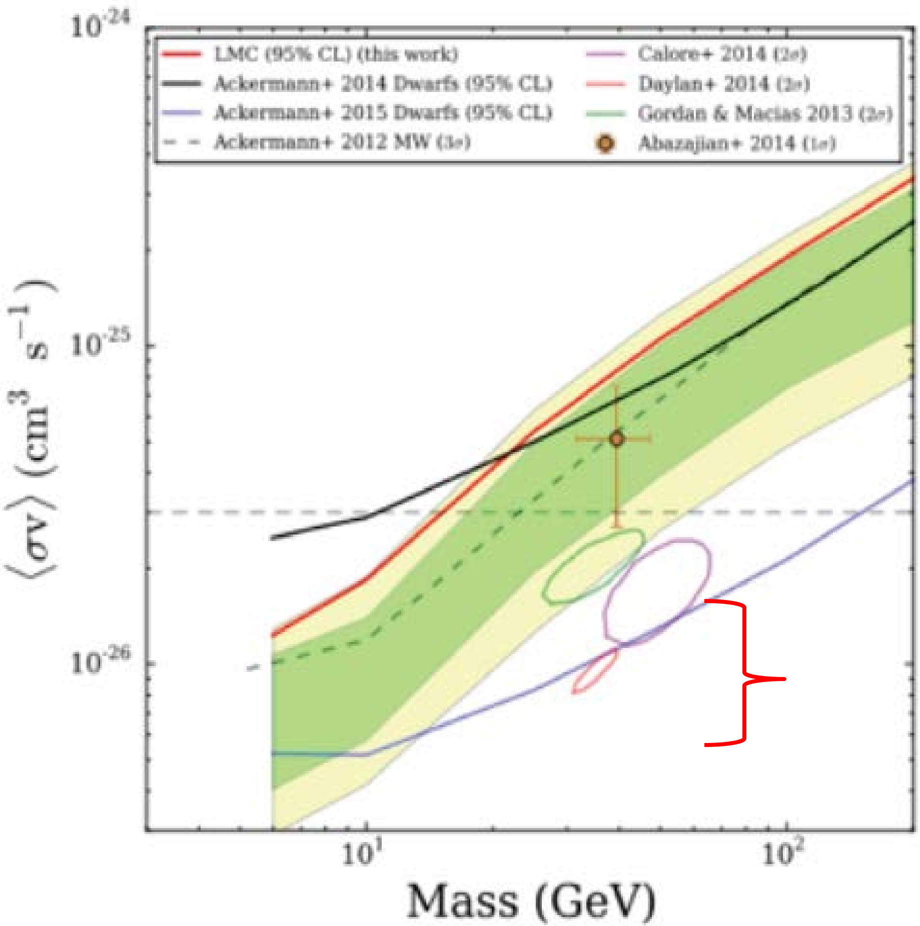
→ The MSSM has > 100 parameters -- we make experimentally motivated assumptions to reduce these to some 'reasonable' level :

- 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 ?



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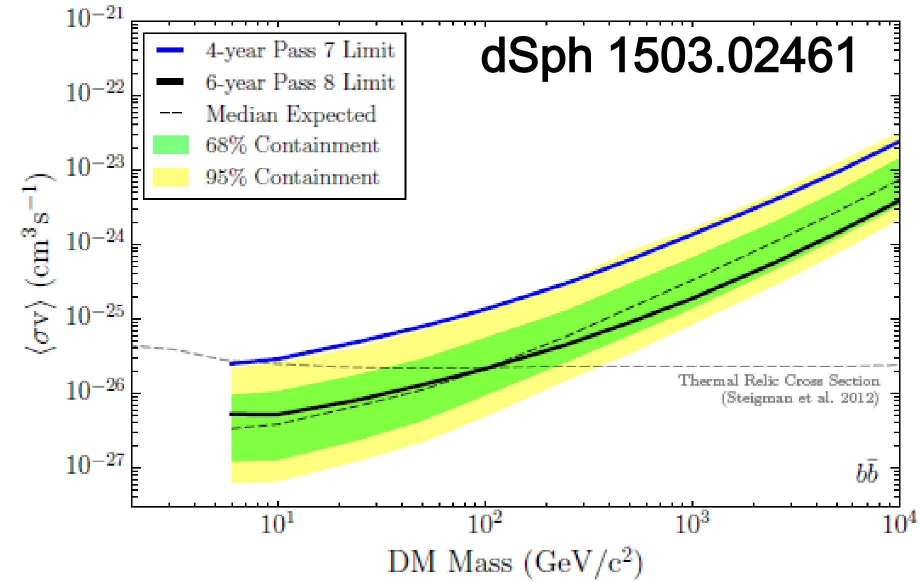
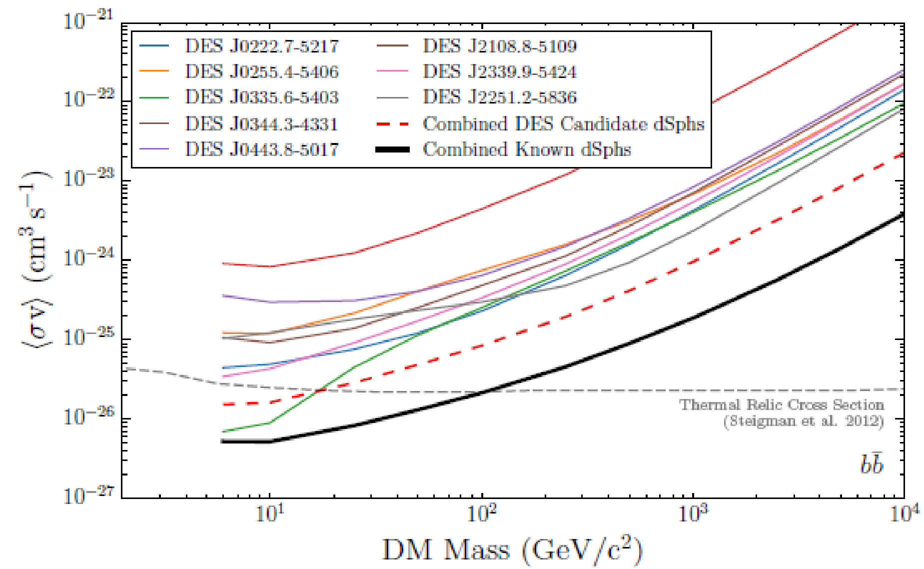
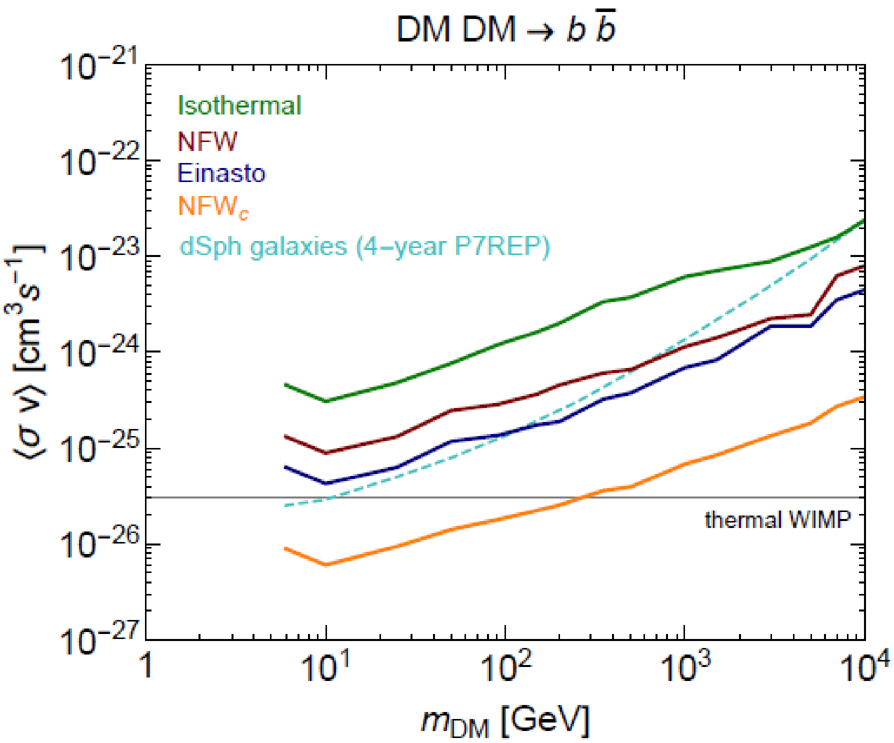


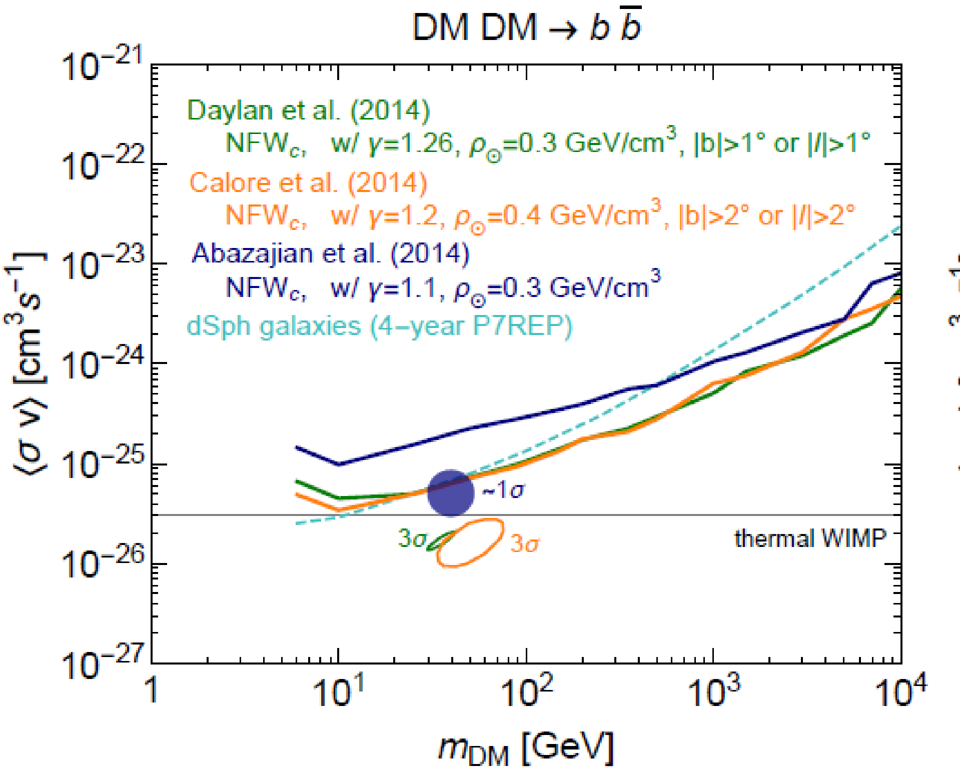


Fermi Dwarf DM searches constrain the present day annihilation cross section for DM but in a model-dependent way

DES Candidates 1503.02632

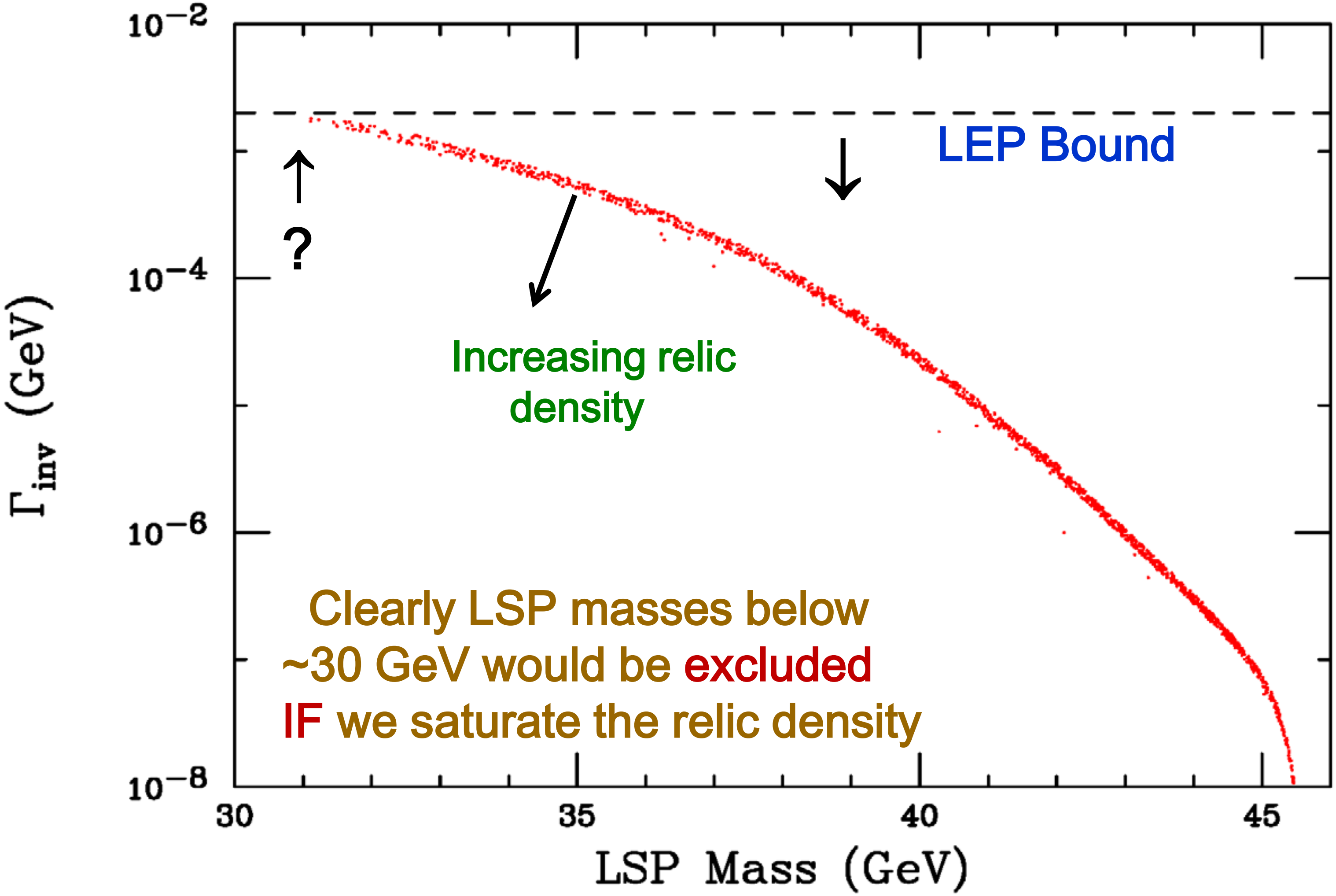
Tension With FERMI ? (II)





1503.07169

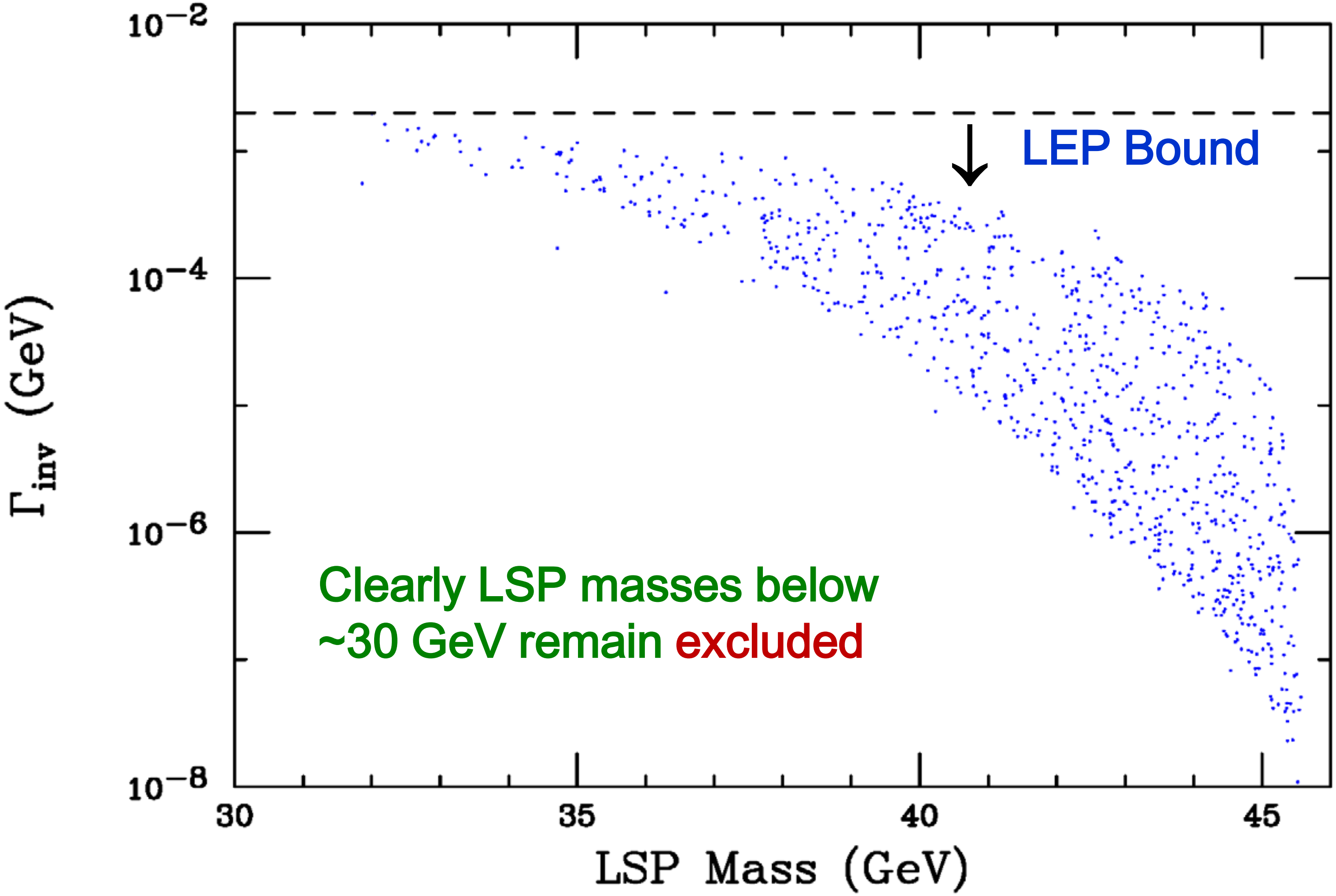
$\Gamma(Z \to \chi\chi) < 2$ MeV



pMSSM models w/ relic density saturated

General χ Models

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

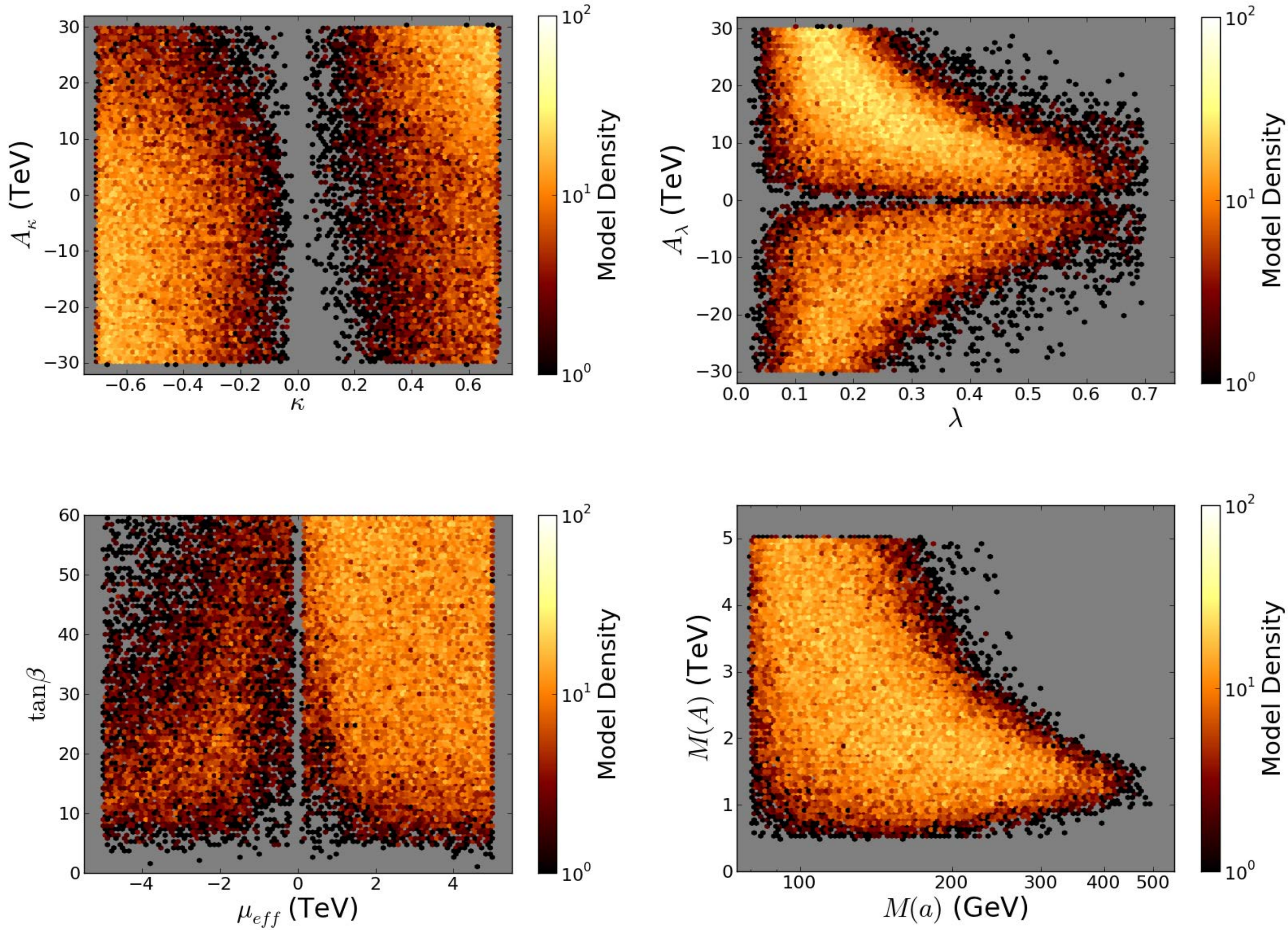


Γ_{inv} will increase if we also increase the Higgsino content & go below the Planck/WMAP relic density

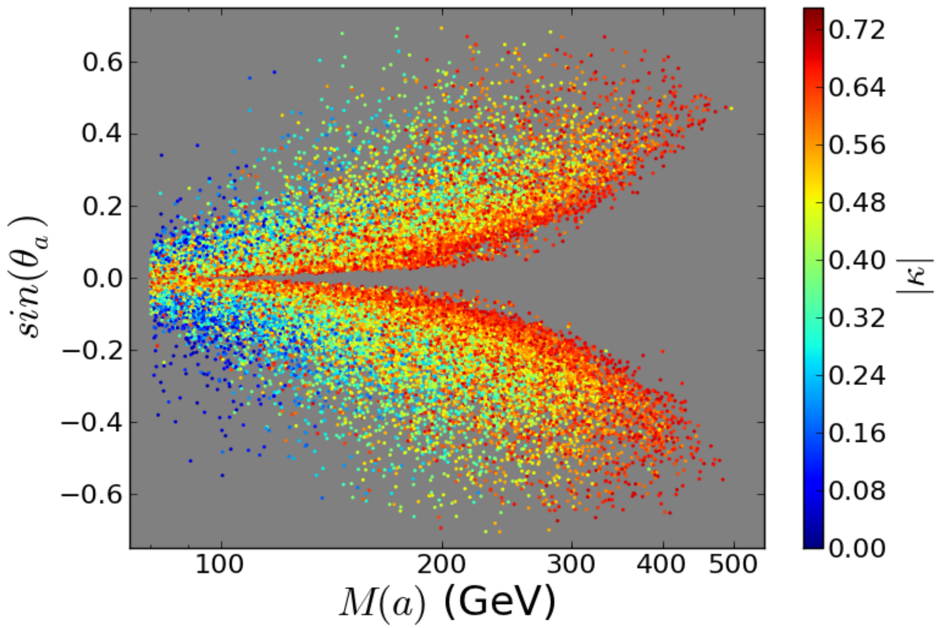
$$
\begin{aligned}
\mathcal{M}^2_{P,11} &= \frac{2(\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)}{\sin 2\beta} \,, \\
\mathcal{M}^2_{P,22} &= \lambda(B_{\rm eff} + 3\kappa s + \mu')\frac{v_u v_d}{s} - 3\kappa A_\kappa s - 2m_S'^2 - \kappa\mu' s - \xi_F\left(4\kappa + \frac{\mu'}{s}\right) - \frac{\xi_S}{s}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

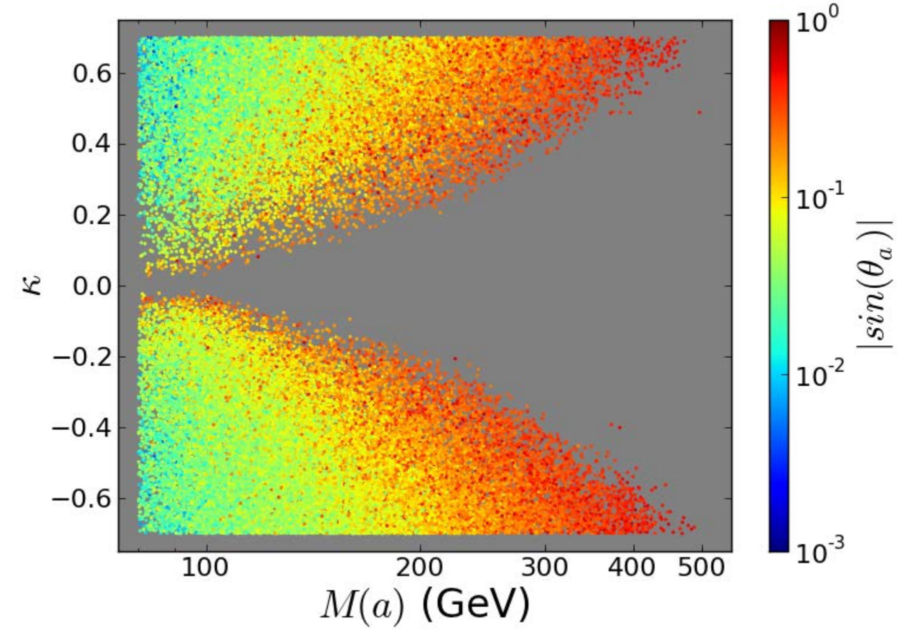
$$
B_{\rm eff} = A_\lambda + \kappa s \,, \quad \widehat{m}_3^2 = m_3^2 + \lambda(\mu' s + \xi_F) \,.
$$

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

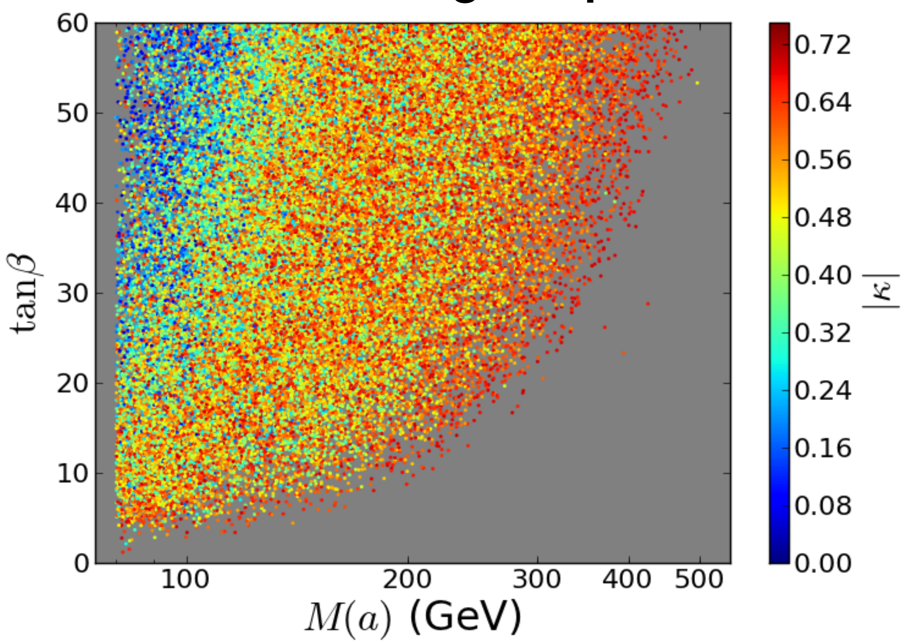


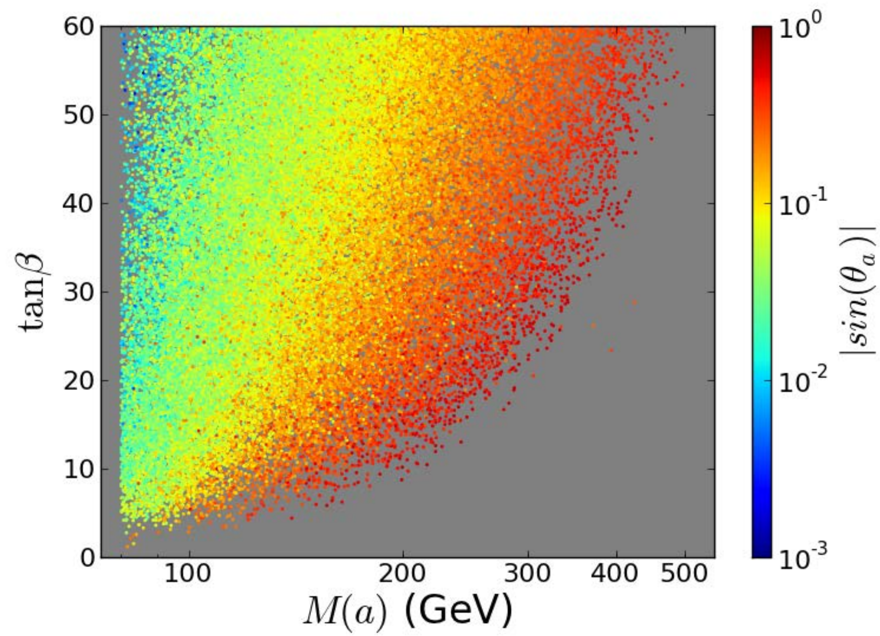
A_κ (TeV)
κ
Model Density
A_λ (TeV)
λ
Model Density
$\tan\beta$
μ_{eff} (TeV)
Model Density
$M(A)$ (TeV)
$M(a)$ (GeV)
Model Density

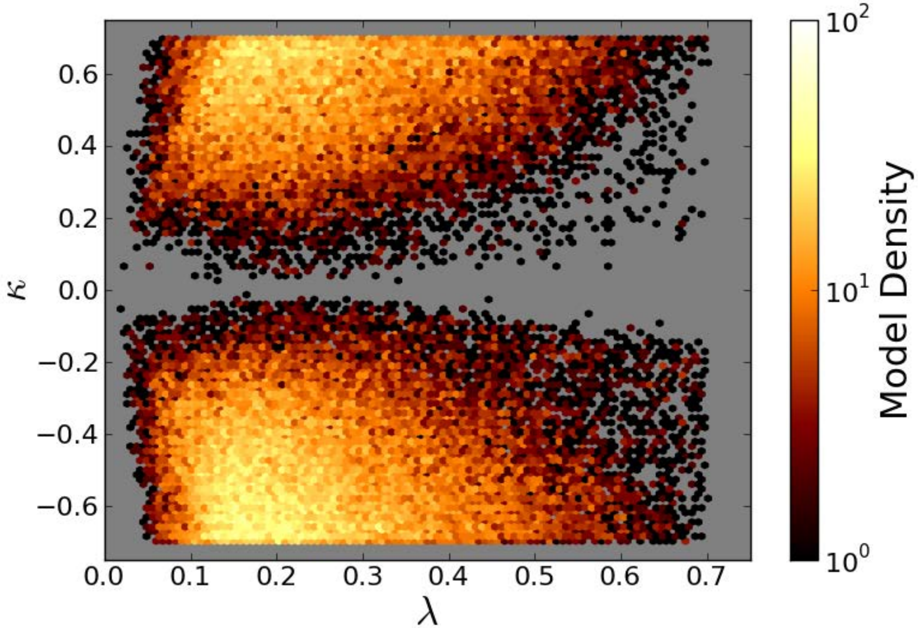




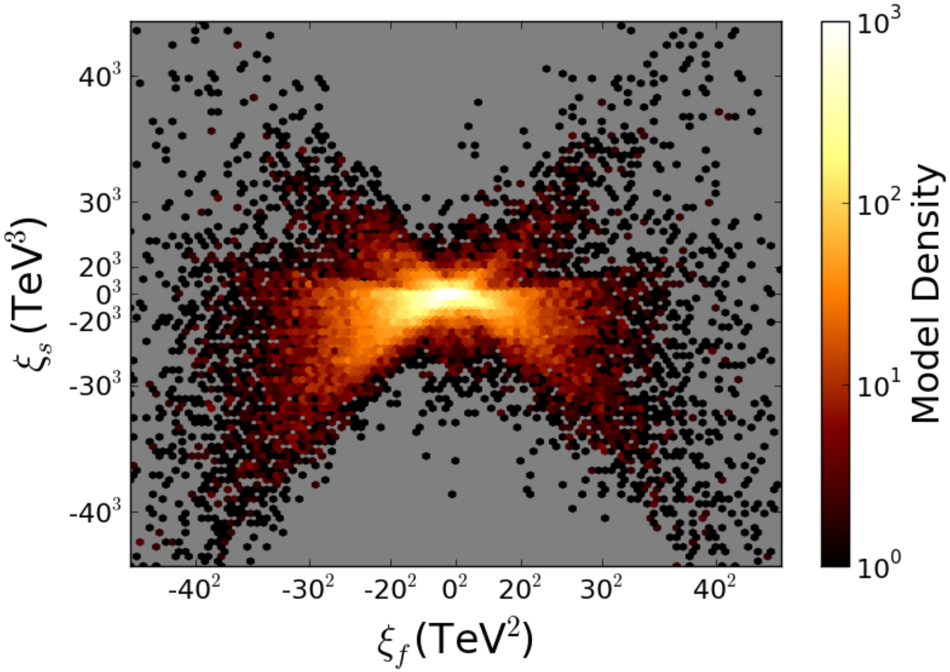
A sizeable range of parameters are allowed satisfying all constraints



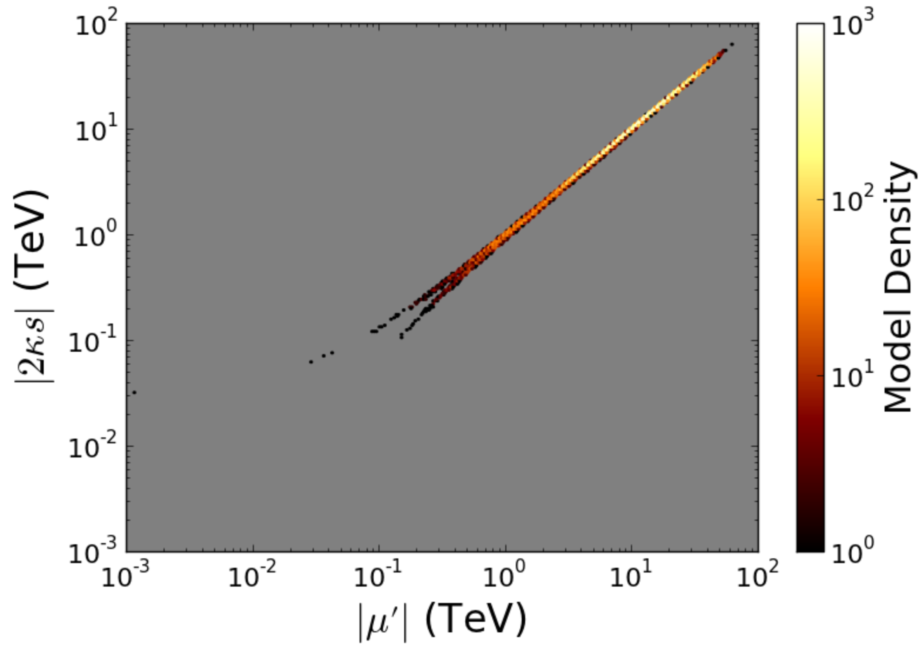




κ
λ
Model Density

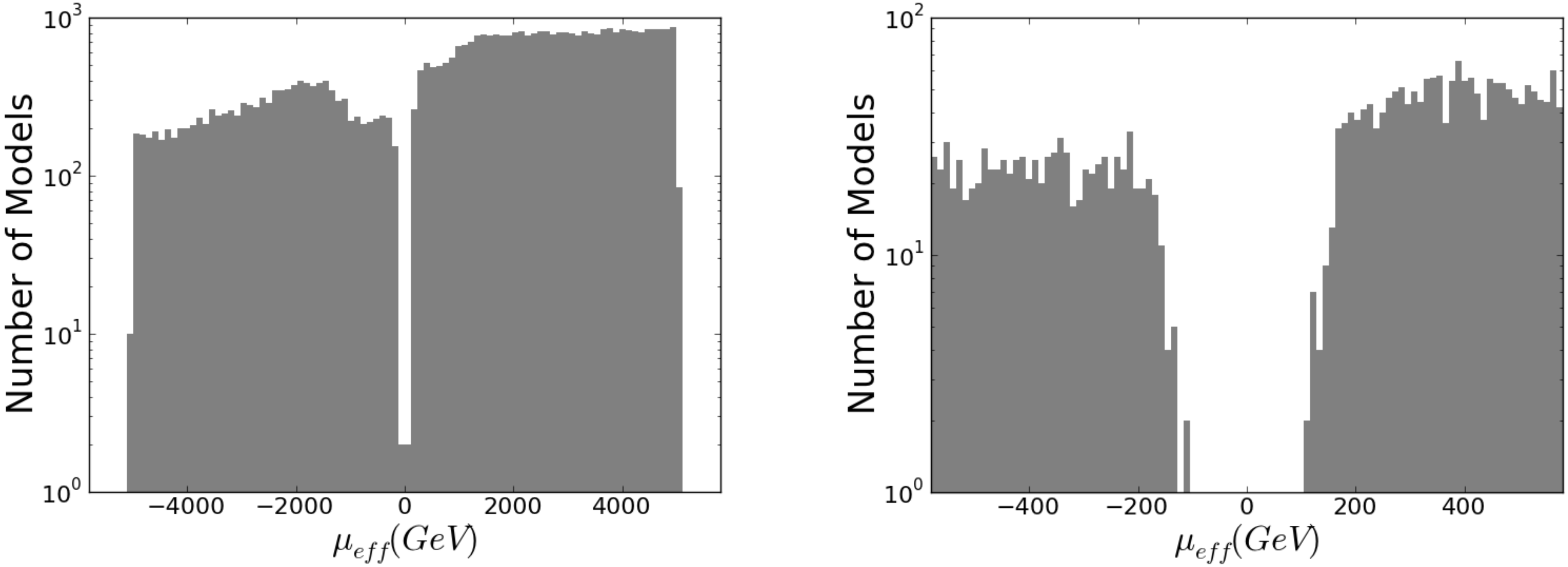


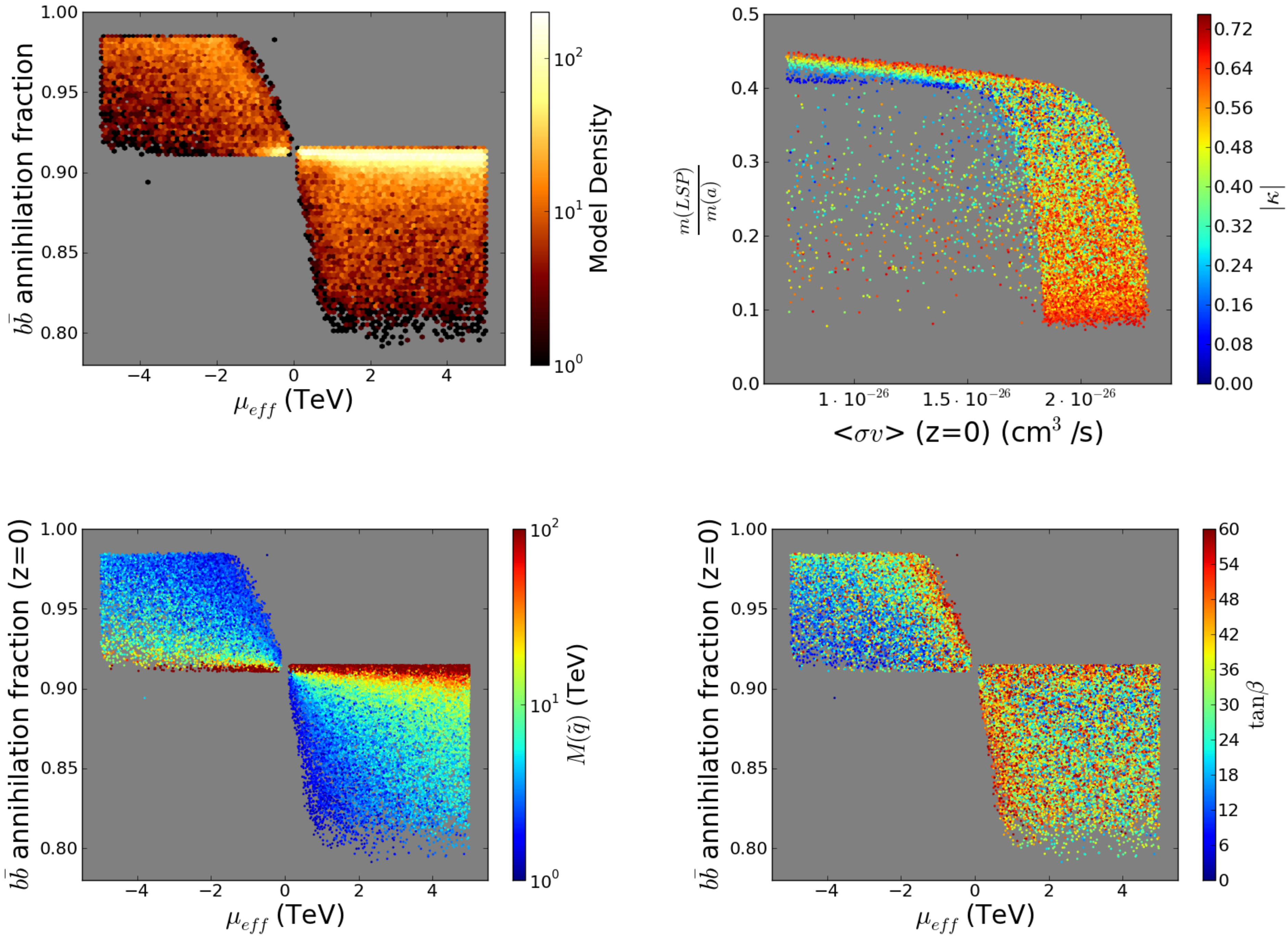
ξ_s (TeV^3)
ξ_f (TeV^2)
Model Density



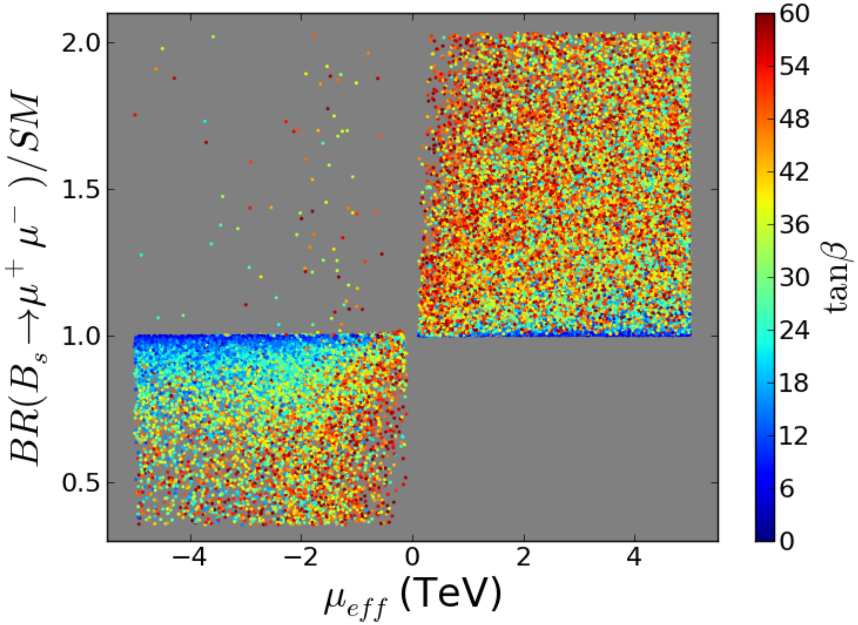
$|2\kappa s|$ (TeV)
$|\mu'|$ (TeV)
Model Density

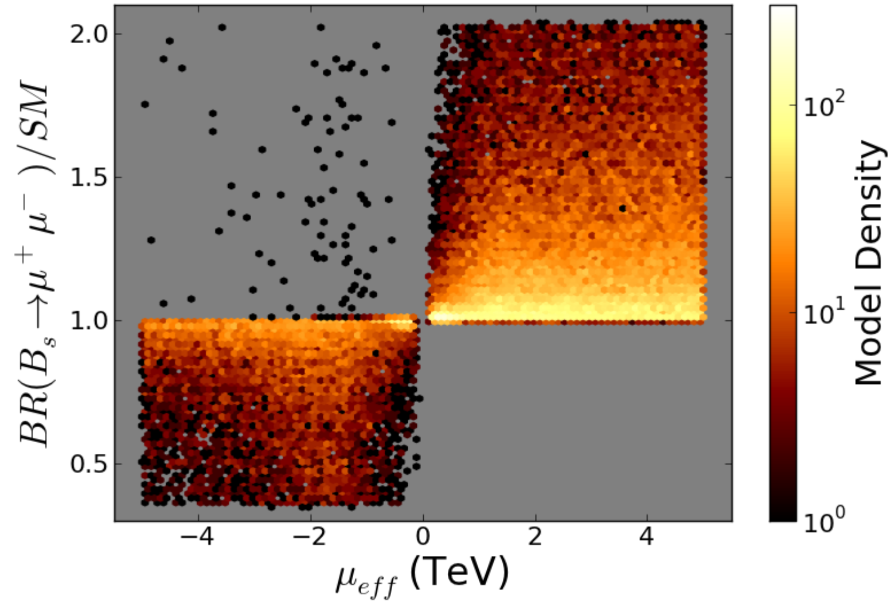
There are really two unequal populations of models here each with its specific sign of μ_{eff} . This sign contributes in multiple places…in particular in the radiative corrections to the Higgs couplings and in $B_s \to \mu\mu$

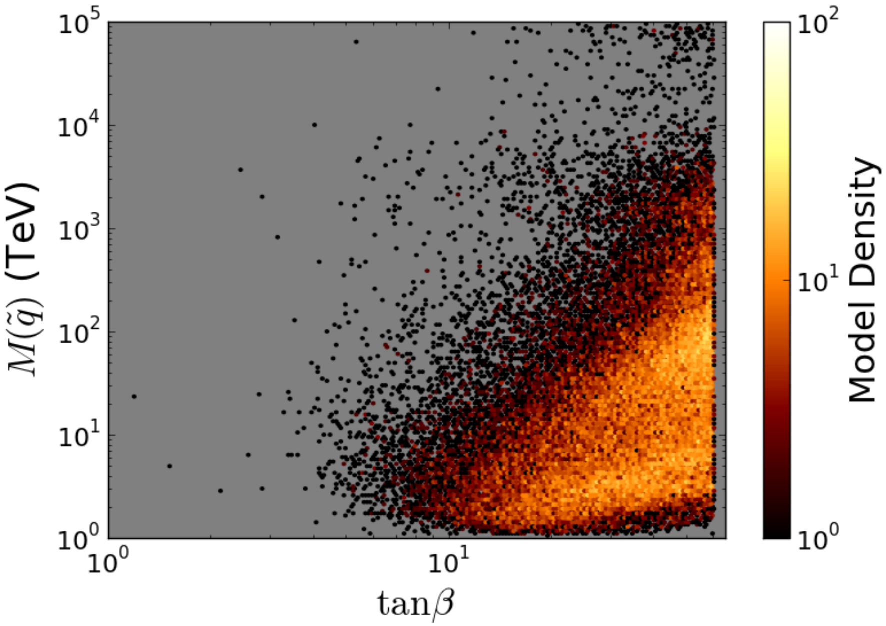


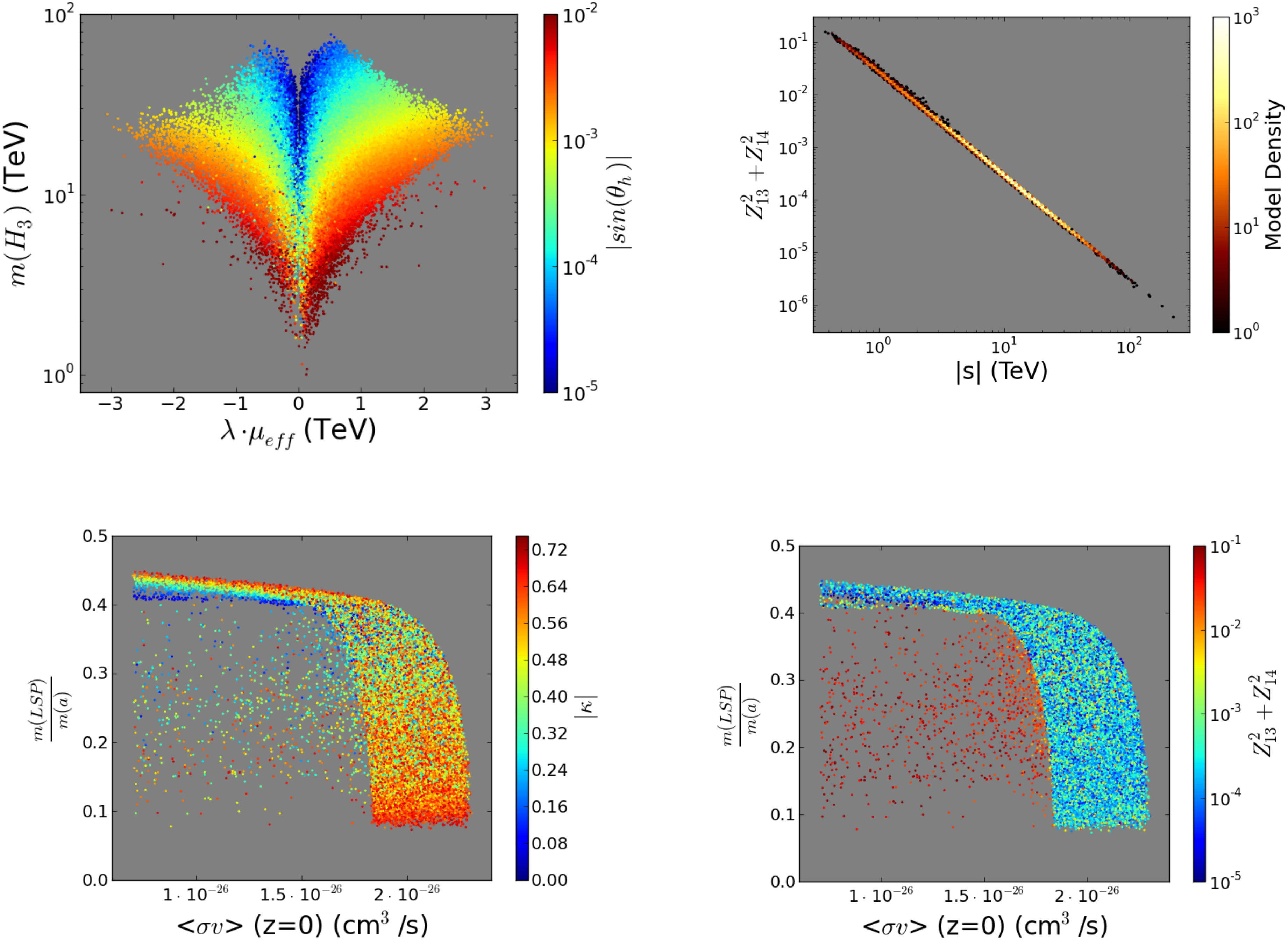


$b\bar{b}$ annihilation fraction
1.00
0.95
0.90
0.85
0.80
−4
−2
0
2
4
μ_{eff} (TeV)
Model Density
10^0
10^1
10^2
$\frac{m(LSP)}{m(a)}$
0.5
0.4
0.3
0.2
0.1
0.0
$1 \cdot 10^{-26}$
$1.5 \cdot 10^{-26}$
$2 \cdot 10^{-26}$
<σv> (z=0) (cm^3 /s)
$|\kappa|$
0.72
0.64
0.56
0.48
0.40
0.32
0.24
0.16
0.08
0.00
$b\bar{b}$ annihilation fraction (z=0)
$M(\tilde{q})$ (TeV)
$\tan\beta$
60
54
48
42
36
30
24
18
12
6
0

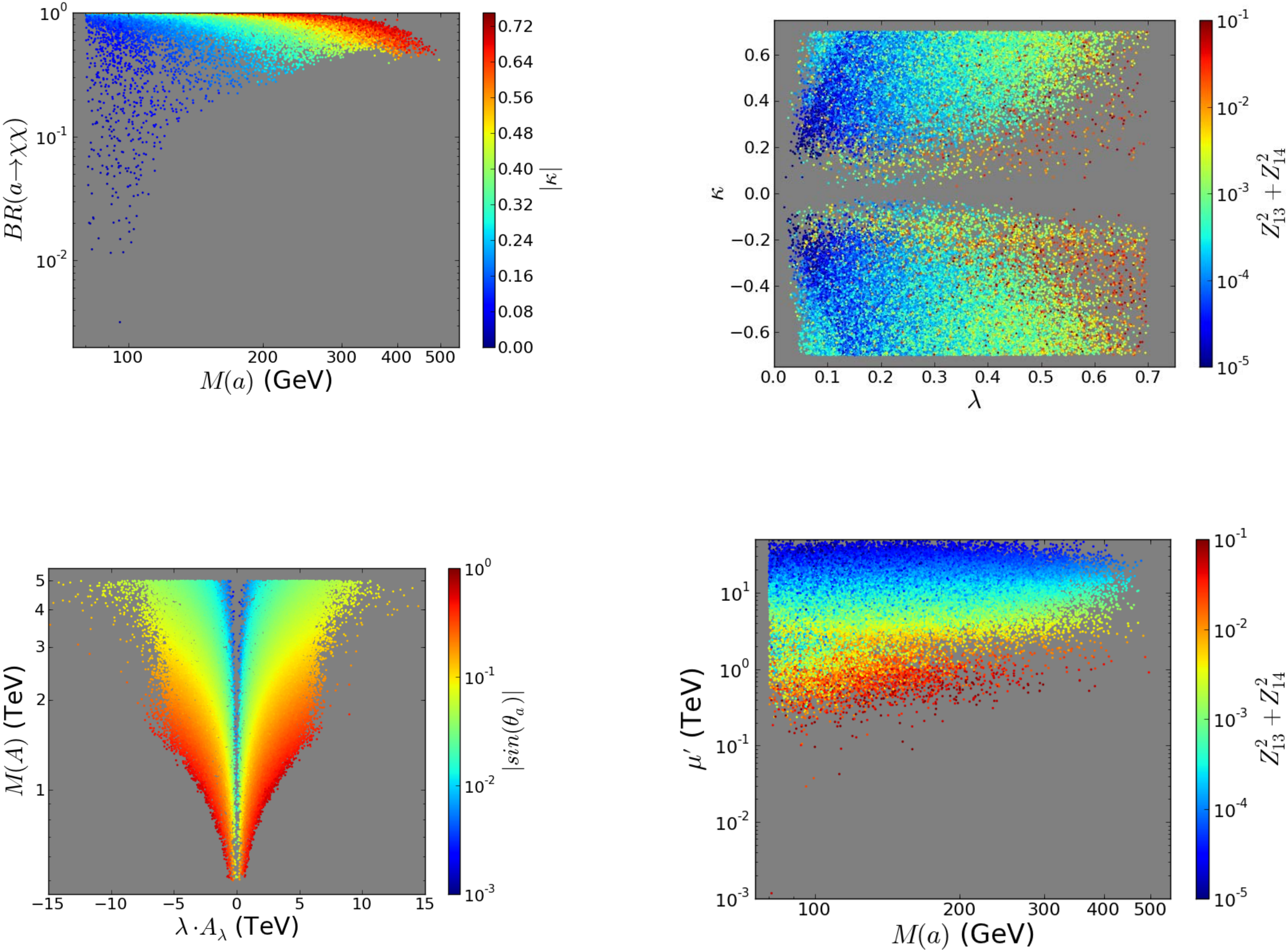

$BR(B_s \to \mu^+ \mu^-)/SM$
μ_{eff} (TeV)
$\tan\beta$


$BR(B_s \to \mu^+ \mu^-)/SM$
μ_{eff} (TeV)
Model Density


$M(\tilde{q})$ (TeV)
$\tan\beta$
Model Density

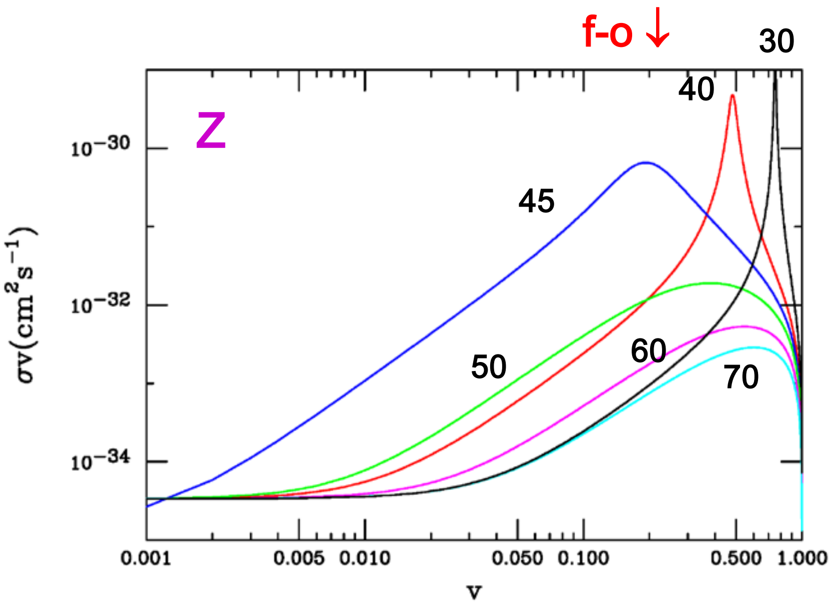


$m(H_3)$ (TeV)
$\lambda \cdot \mu_{eff}$ (TeV)
$|sin(\theta_h)|$
$Z_{13}^2 + Z_{14}^2$
|s| (TeV)
Model Density
$\frac{m(LSP)}{m(a)}$
<σv> (z=0) (cm^3 /s)
$|\kappa|$
$\frac{m(LSP)}{m(a)}$
<σv> (z=0) (cm^3 /s)
$Z_{13}^2 + Z_{14}^2$

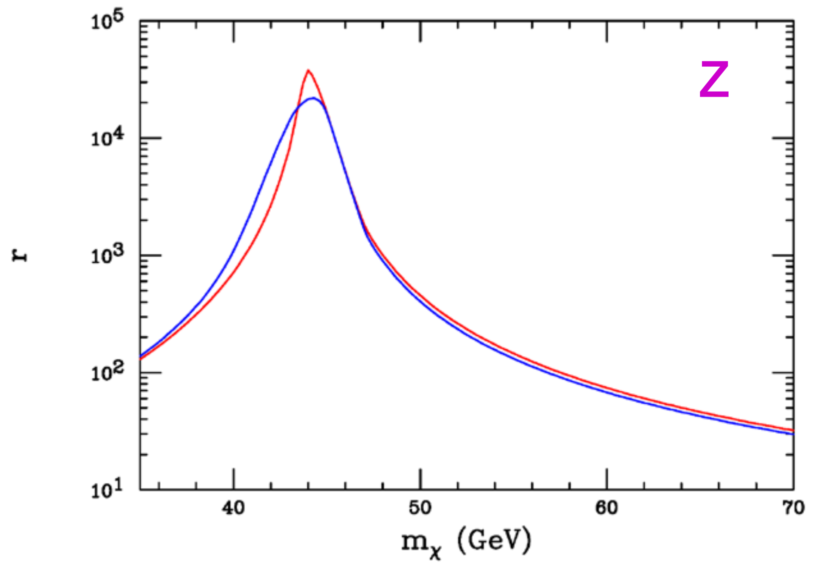


$BR(a\to\chi\chi)$
$M(a)$ (GeV)
$|\kappa|$
κ
λ
$Z_{13}^2 + Z_{14}^2$
$M(A)$ (TeV)
$\lambda \cdot A_\lambda$ (TeV)
$|sin(\theta_a)|$
μ' (TeV)
$M(a)$ (GeV)
$Z_{13}^2 + Z_{14}^2$

pMSSM (aside)



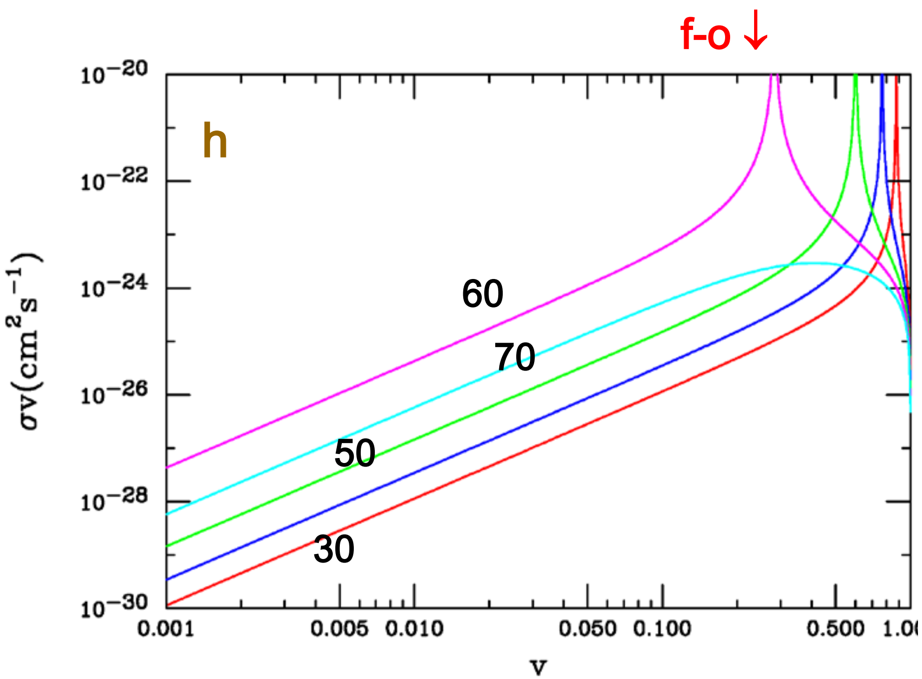
Typical Z-induced annihilation cross sections for various LSP masses via their Higgsino components show a strong velocity dependence unlike, e.g., in the case of pseudoscalar (a) exchange as will be shown later.

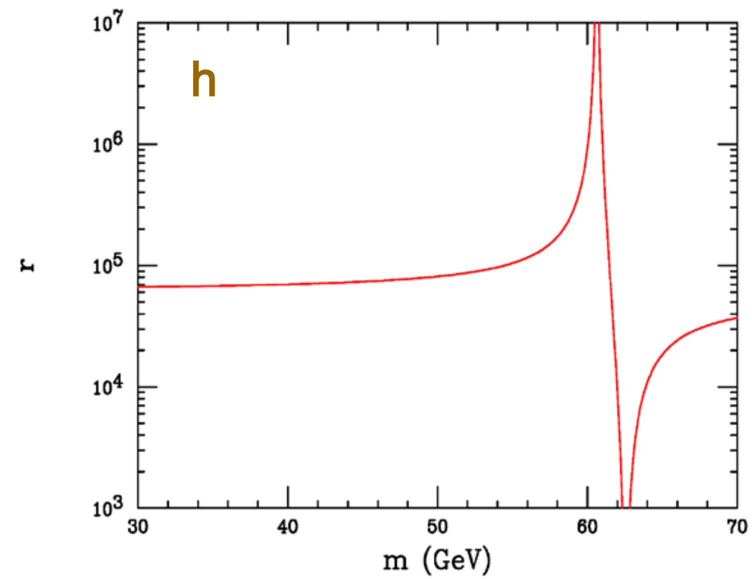


Ratio (r) of freeze-out to present day annihilation cross sections for pure Z exchange . This gives us an upper bound on the LSP Higgsino component since the apparent observed value of r is $\lesssim 1$

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..



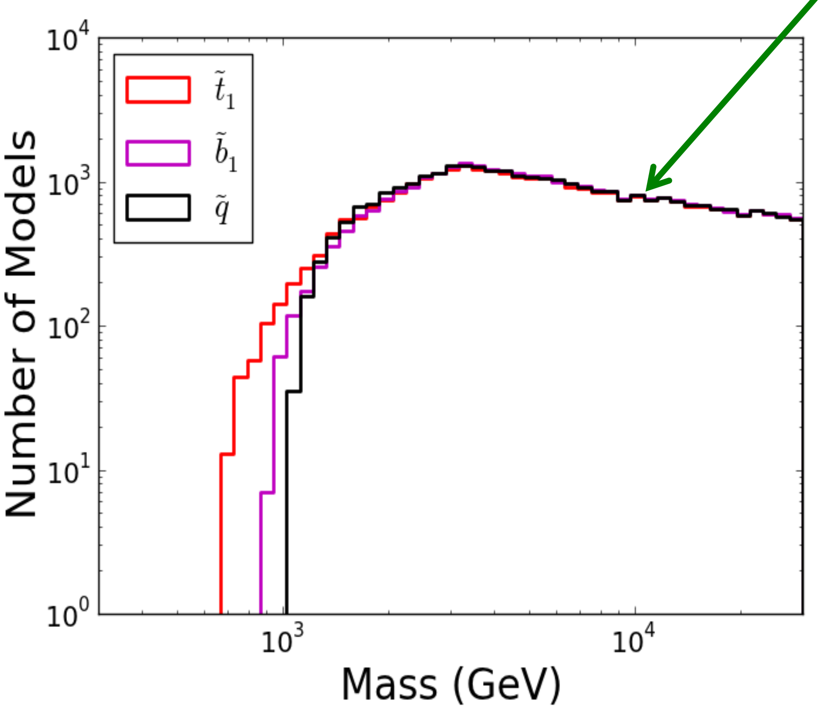


Toast !

LHC (cont.)

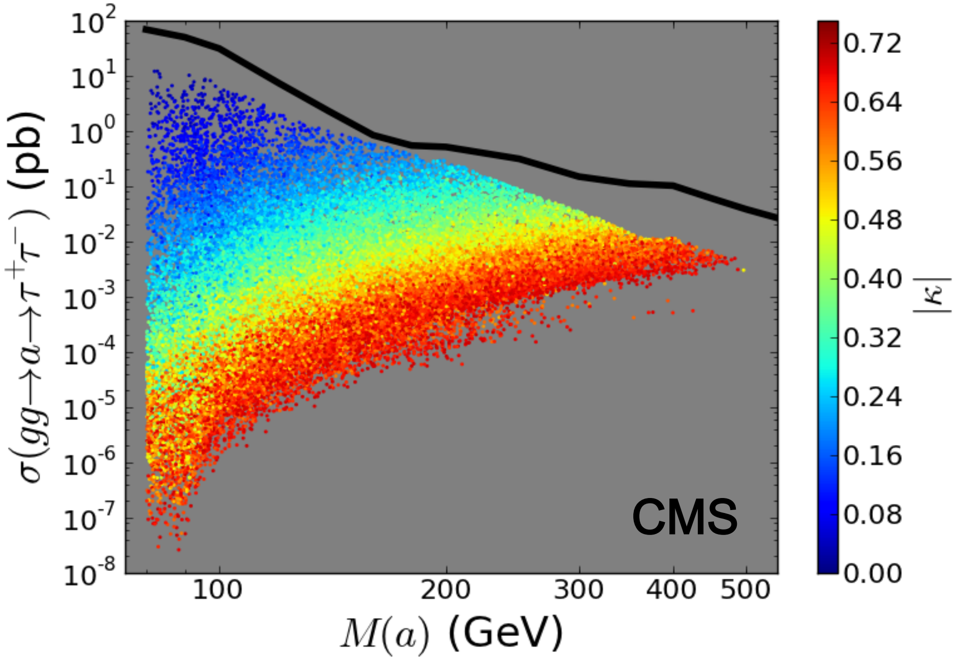
- The role of the 'traditional' part of the SUSY spectrum (& the associated searches) has been relegated to a subsidiary position in our analysis by picking 'obviously OK' points

- 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!

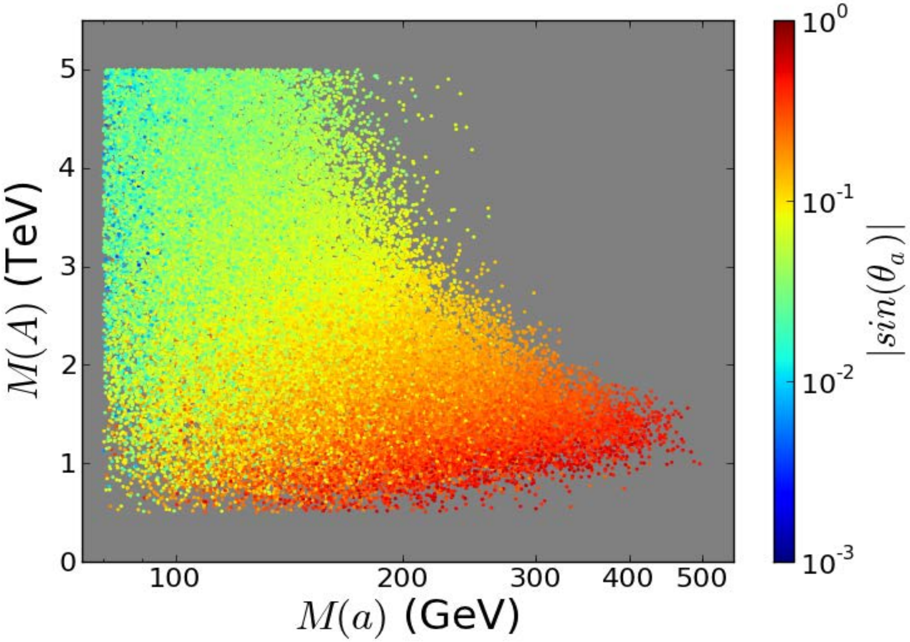


- Of course we don't need to make these assumptions in a MORE detailed study

- 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



- Similar constraints are obtainable for the direct gg-induced channel



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