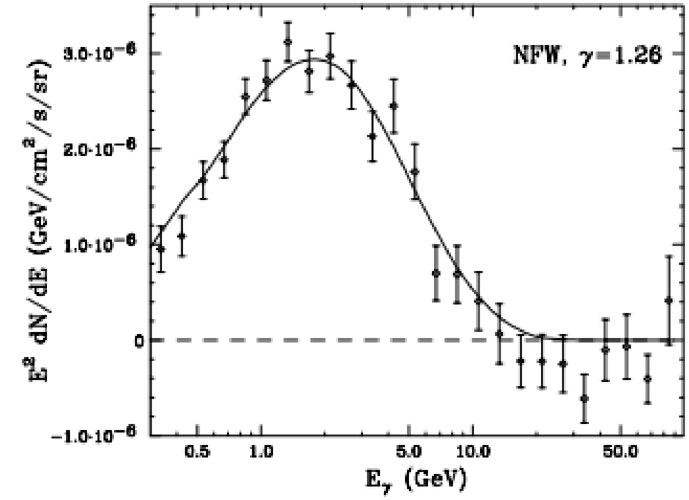
SUSY Scenarios for the Fermi GC Excess



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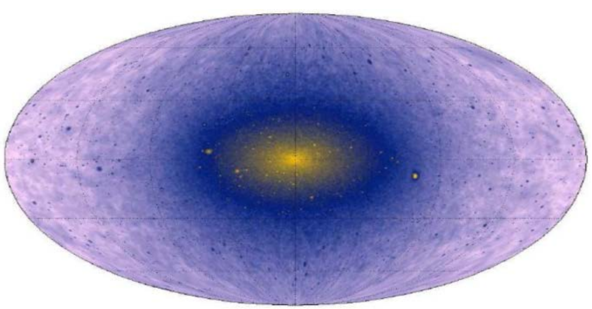

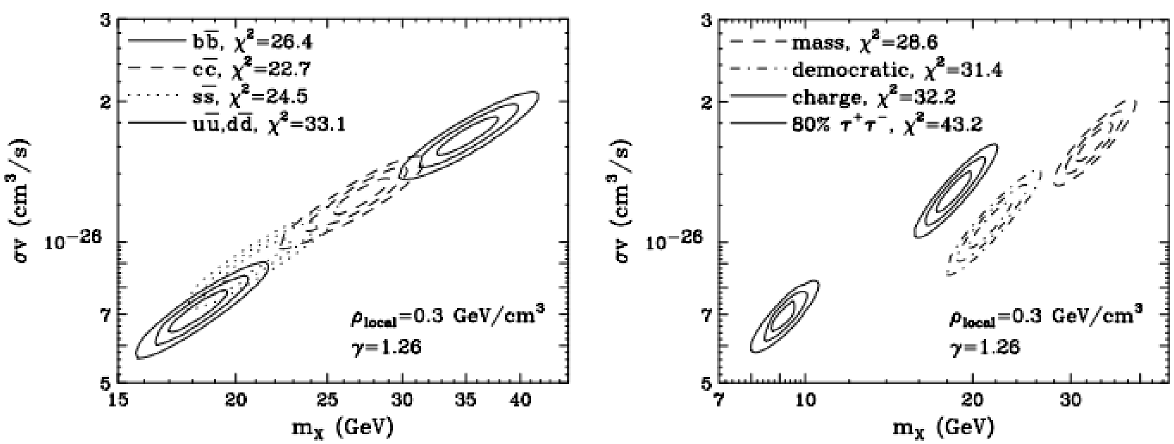

arXiv:1409.1573 v2

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SLAC NATIONAL ACCELERATOR LABORATORY

9/26/14

Model Building Assumptions

→ Assume the Hooper & friends interpretation & fits of the Fermi GC are correct within a SUSY context. What ingredients do we have ?

- The DM LSP has a mass of 30-40 GeV
- The thermal freeze-out $\langle\sigma v\rangle$ gives the observed DM relic density
- The similar (but somewhat smaller) value of $\langle\sigma v\rangle$ today gives the signal
- The b b-bar final state dominates

Add a 'simplifying' assumption: A single, lone mediator is responsible for the DM annihilation process at all times

Exercise: Can we find a not too crazy SUSY model with all these ingredients & satisfying all other experimental constraints ?

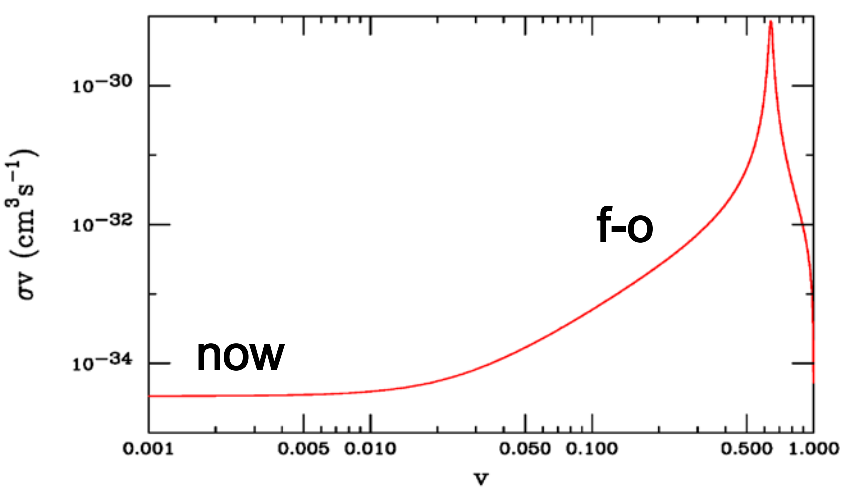
It is useful to examine why some models fail to see that this is non-trivial

Where do we start? At SLAC it's with the pMSSM !

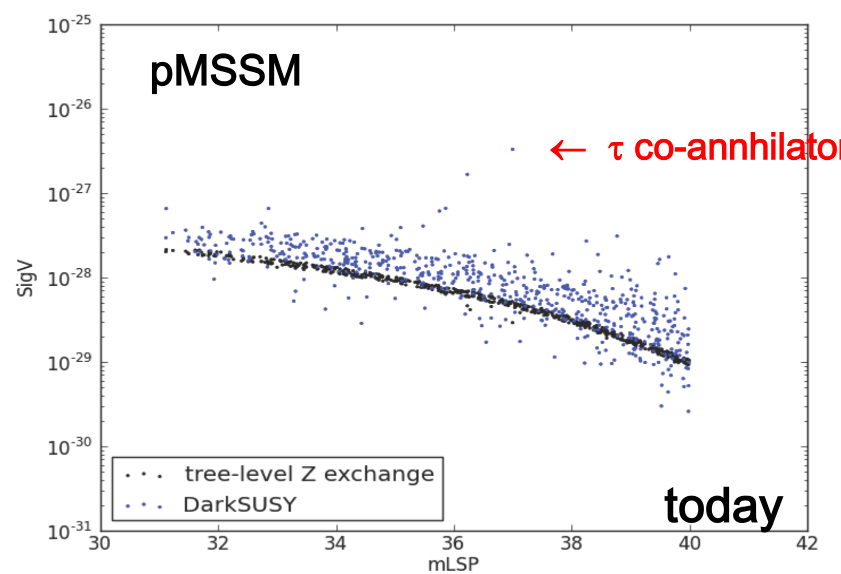
- ~35 GeV DM/LSP in the MSSM must be well-tempered : usually too light for co-annihilation, not wino/Higgsino (LEP) & only funnels are Z or Higgs

- The Higgsino content allows for a coupling to the Z so that at freeze out $\langle \sigma v \rangle$ is large enough to give the measured relic density.. but today it is much too small to produce the observed flux since v is much smaller

- This scenario is toast. Lesson: The Z cannot be the lone mediator due to the strong velocity dependence so we must go beyond the MSSM



Scales up & down with Higgsino content



What Next ? : Dirac Gauginos

- Why? A Dirac LSP will not suffer the same velocity suppression

- However the LSP must be ~pure bino as a Higgsino content produces a Z-coupling that leads to trouble with DD constraints since Dirac gauginos now have a vector coupling to the Z. Thus the LSP relies on t-channel sfermion exchange to achieve the observed relic density:

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

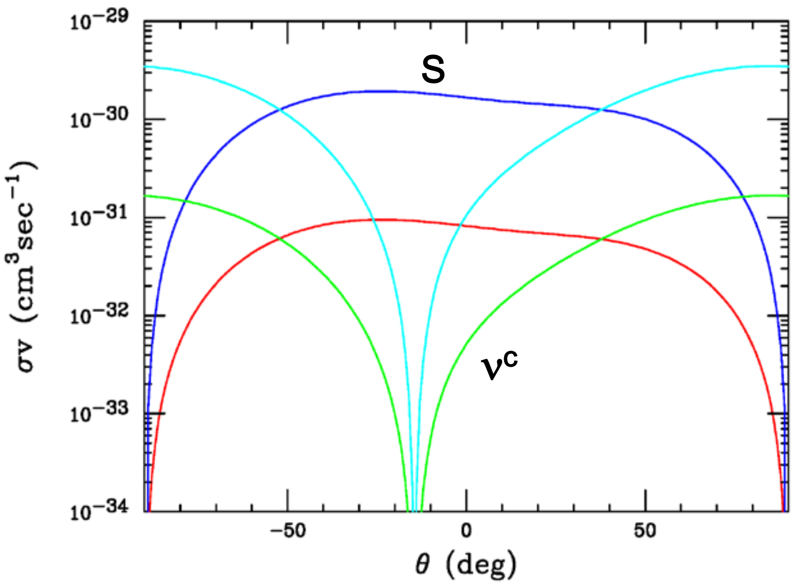
$$\sigma v = \frac{N_c\, g_1^4 m_\chi^2\, \beta_f}{8\pi} \left(\frac{Y_L^4}{(m_\chi^2 - m_f^2 + m_{\tilde{f}_L}^2)^2} + L \to R \right)$$

- But only ~100 GeV staus can produce a large enough $\langle\sigma v\rangle$ to do this. Given (just) the (naïve) LEP constraints sbottoms are much too heavy given their small hypercharge to 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 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 ~35 GeV and 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

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

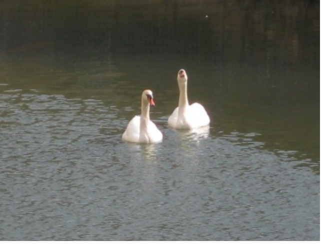
$$-\Delta\mathcal{L}_{\text{soft}} = \lambda A_\lambda\, H_u \cdot H_d\, S + \frac{1}{3}\kappa A_\kappa\, S^3 + \text{h.c.}\,.$$

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

- The ~singlino is the LSP and the ~isosinglet CP-odd a (as noted by other authors) is a good mediator. The coupling to the SM is via mixing & with large tan β to get bb-bars
- The Higgsino content must be small to avoid coupling to the Z & its influence on the relic density. (One mediator only!) . Thus $\lambda v_{u,d}$ must be quite small to avoid this mixing
- However: $\mu_{\text{eff}} = \lambda s$ >100 GeV (LEP) but ALSO $2\kappa s$ ~ 35 GeV is the LSP mass. Furthermore, κ contributes to the overall scale of the $\chi\chi a$ coupling (as we'll see below) so can't be too small

$\rightarrow$ There is not enough parameter freedom here to satisfy all of these requirements simultaneously !

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 parameters, e.g., here μ' , resolve all our problems !

We study the general NMSSM by performing a parameter scan employing a modified version of NMSSMTools4.3.0 *** $\rightarrow$ beware of 'features'…new versions soon

- 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 are fixed

Flat scanned

Value '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.

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

~ 52.8 k models = sets of parameters remain

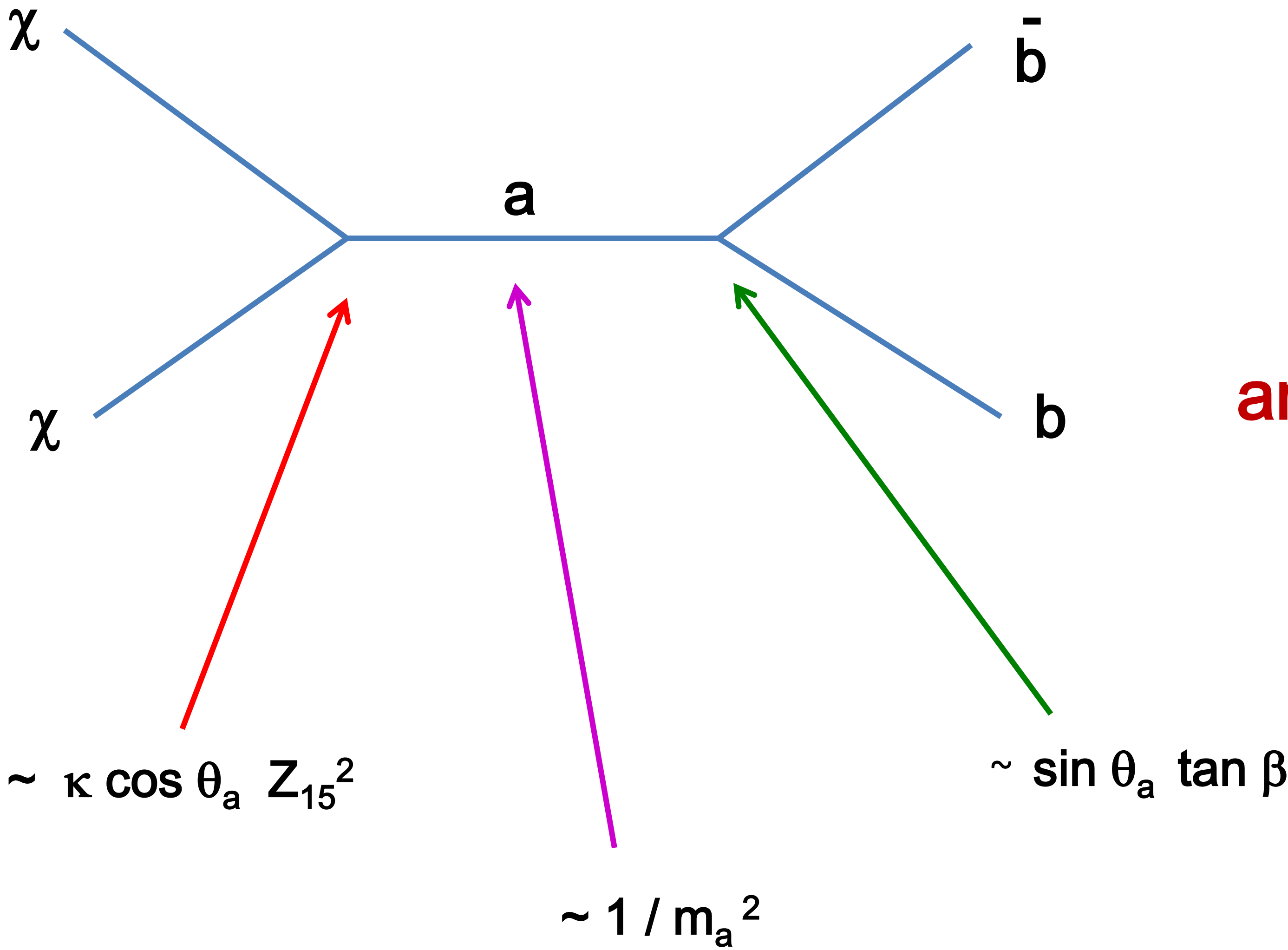
Some useful definitions:

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

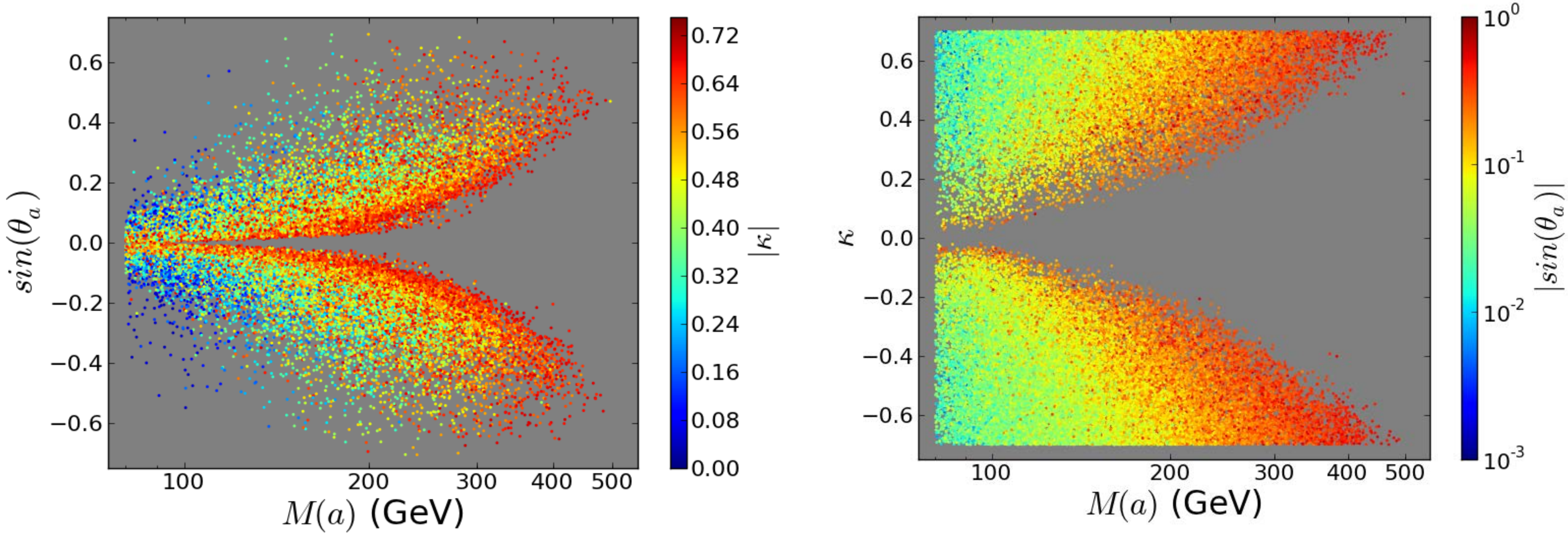
→ We can now make a lot of plots that examine various model properties

*** see paper for an extensive discussion

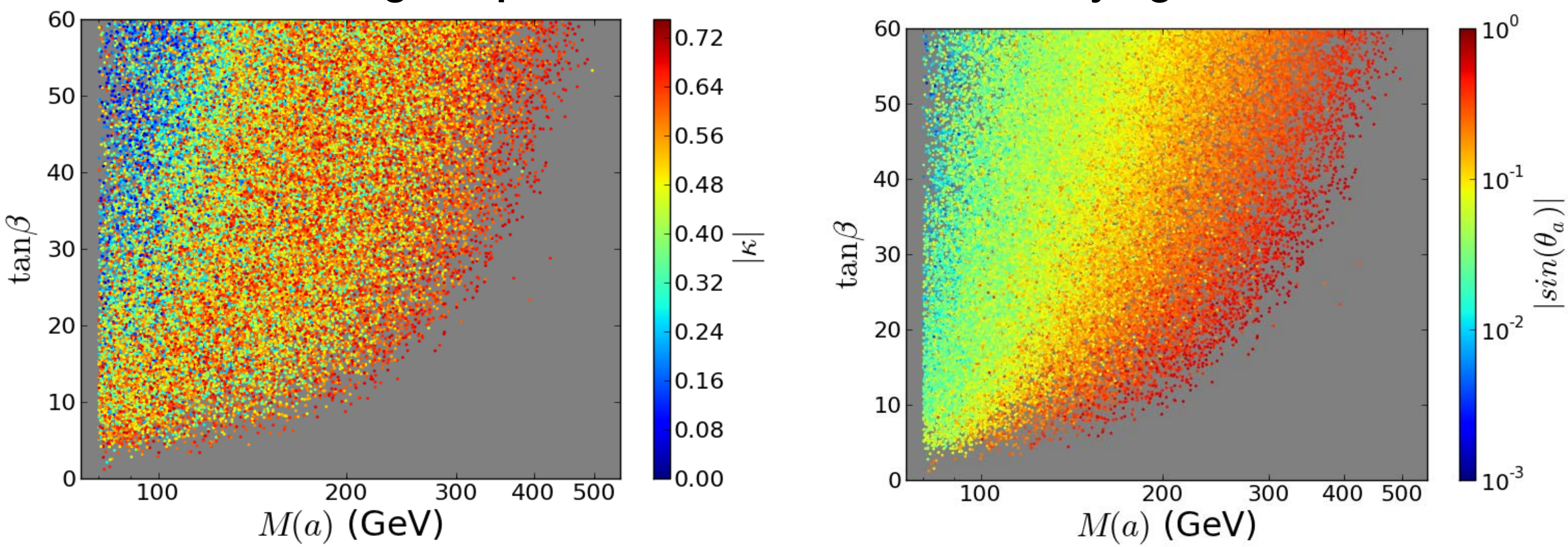


DM annihilation

$\rightarrow$ The values of the various parameters must compensate each other to obtain the correct relic density



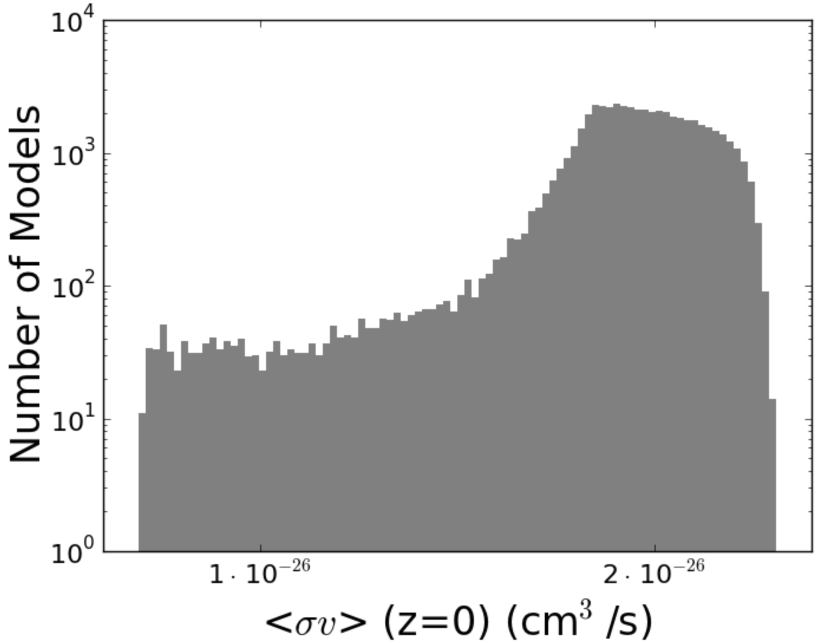
A sizeable range of parameters are allowed satisfying all constraints

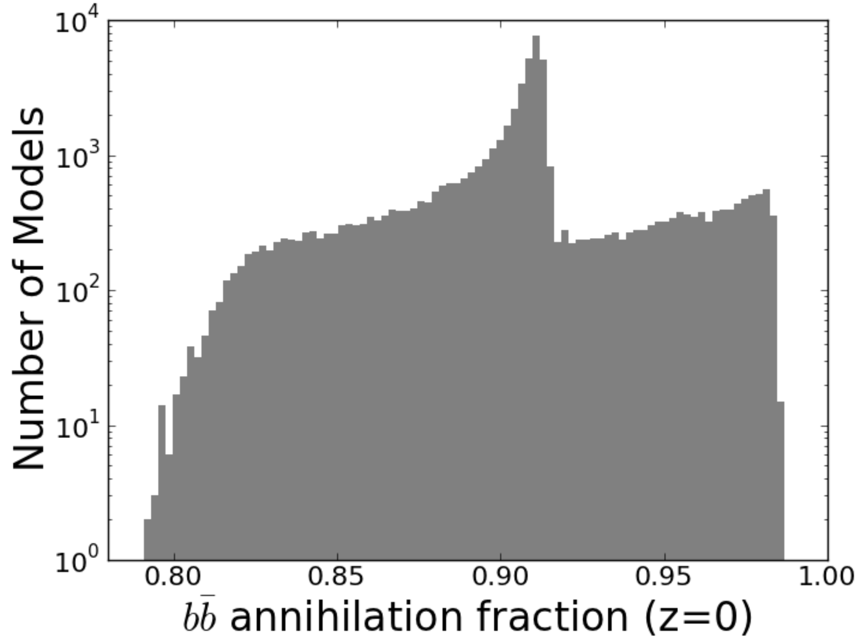


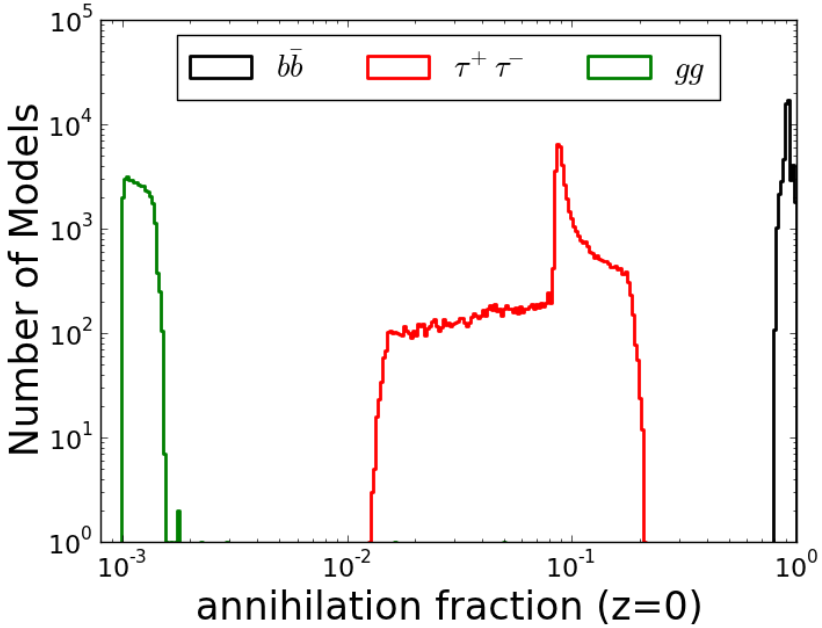
Some questions to answer

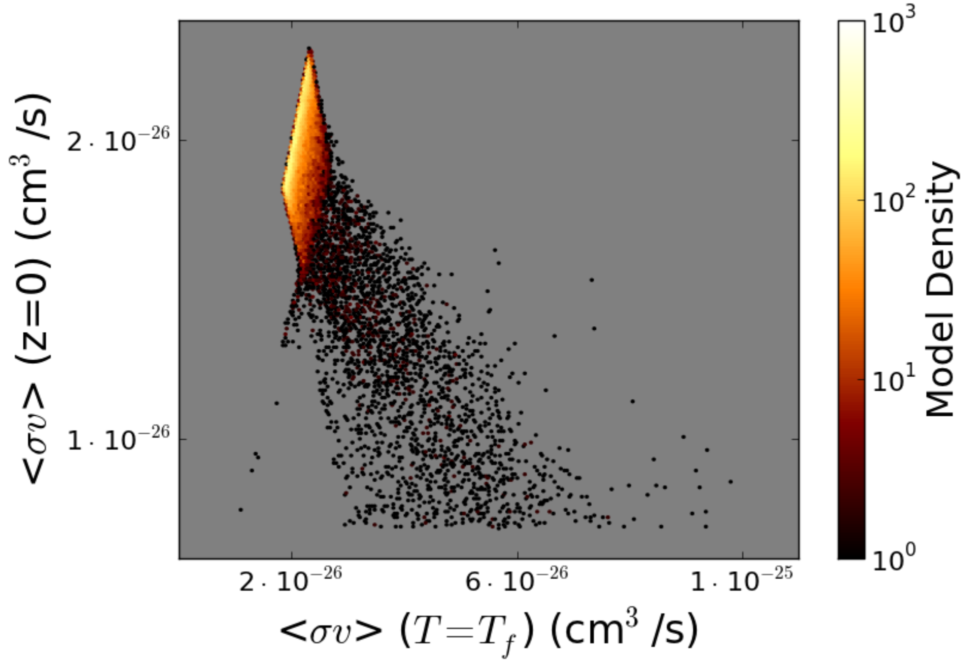
- What are the properties of the LSP/DM ?
- Can it be observed in DD experiments?
- Are the properties of the Higgs modified?
- Other LHC etc. signals?

DM properties

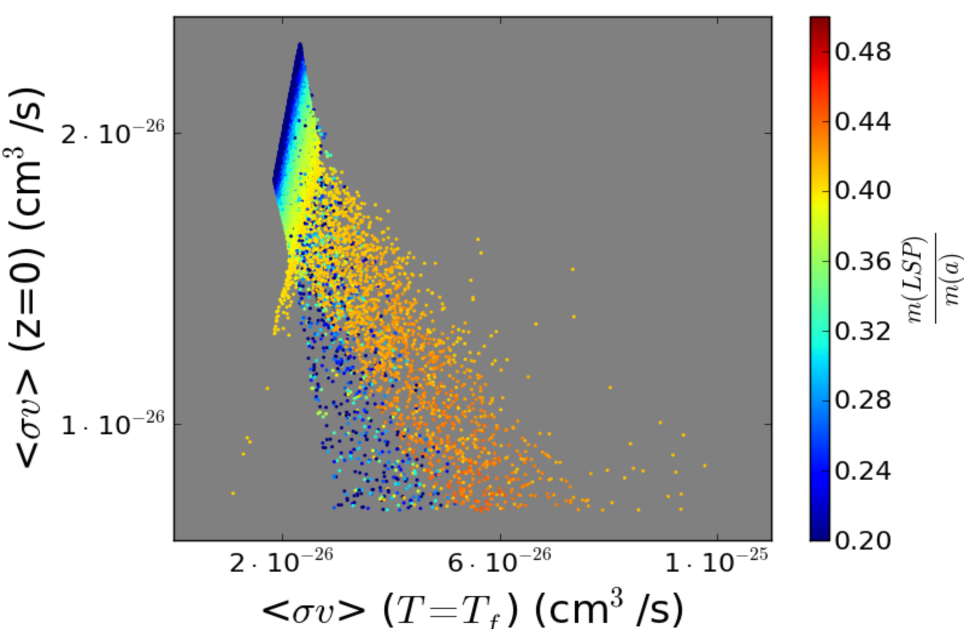


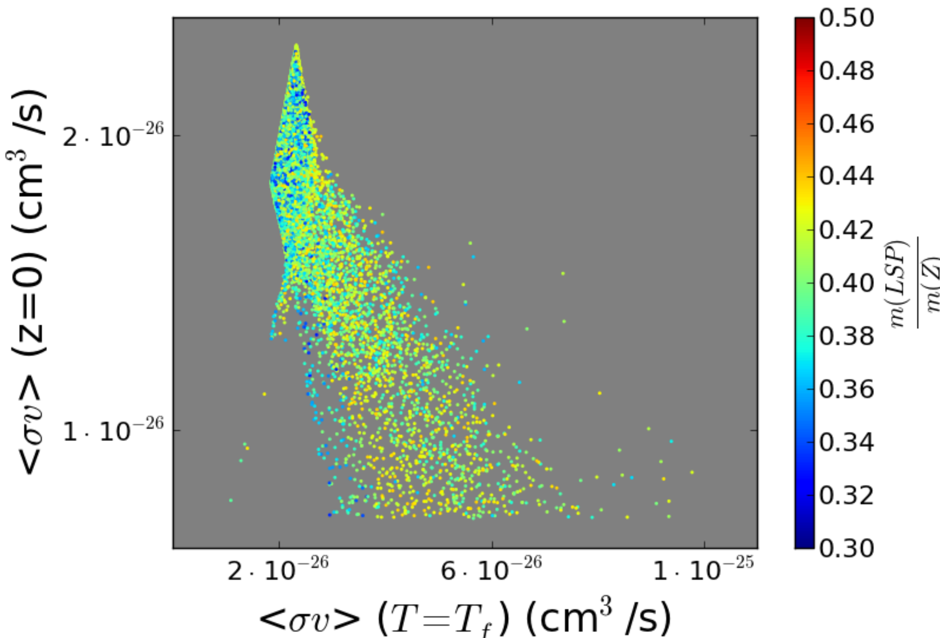


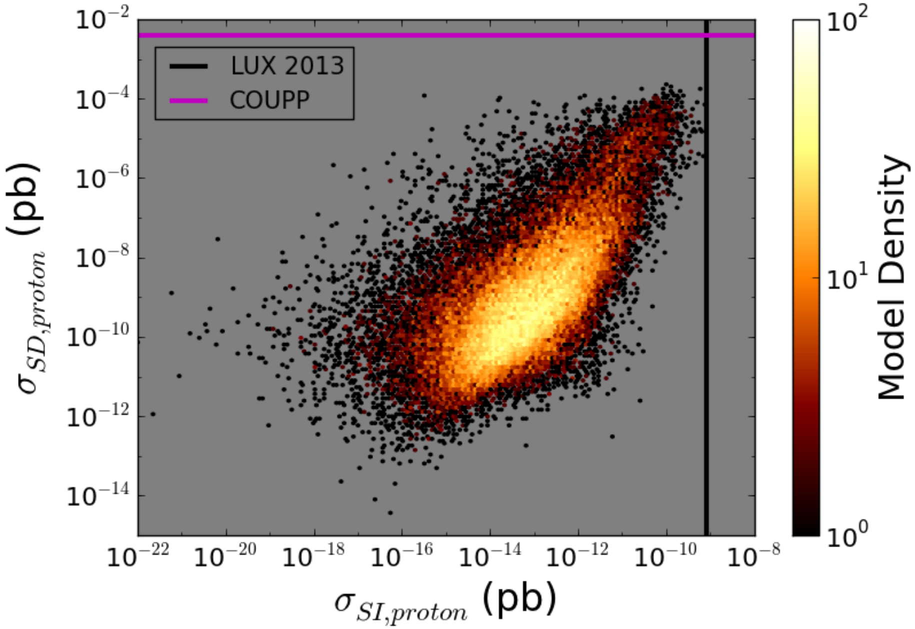


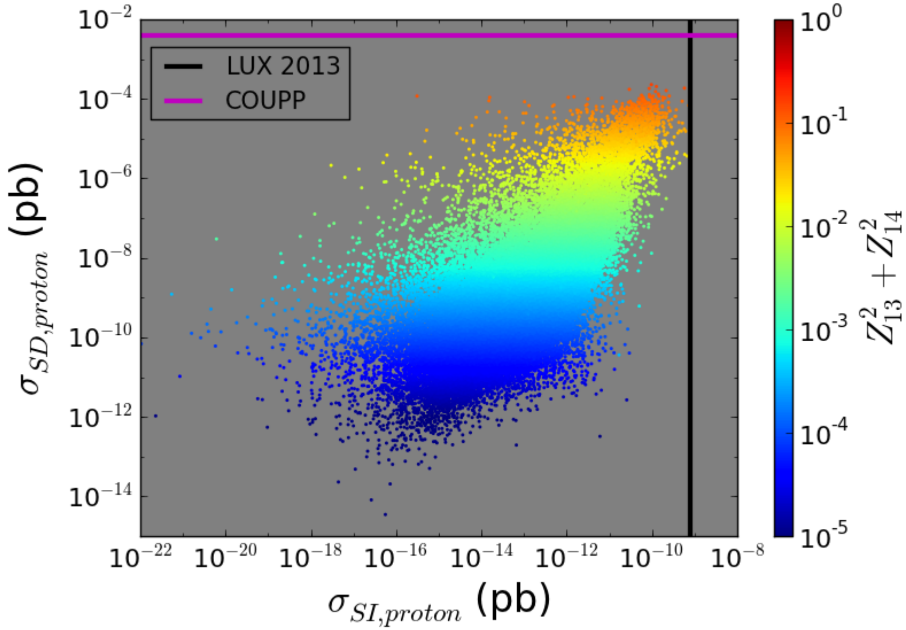


Interesting correlation between the freeze-out and present day values of ⟨σv⟩

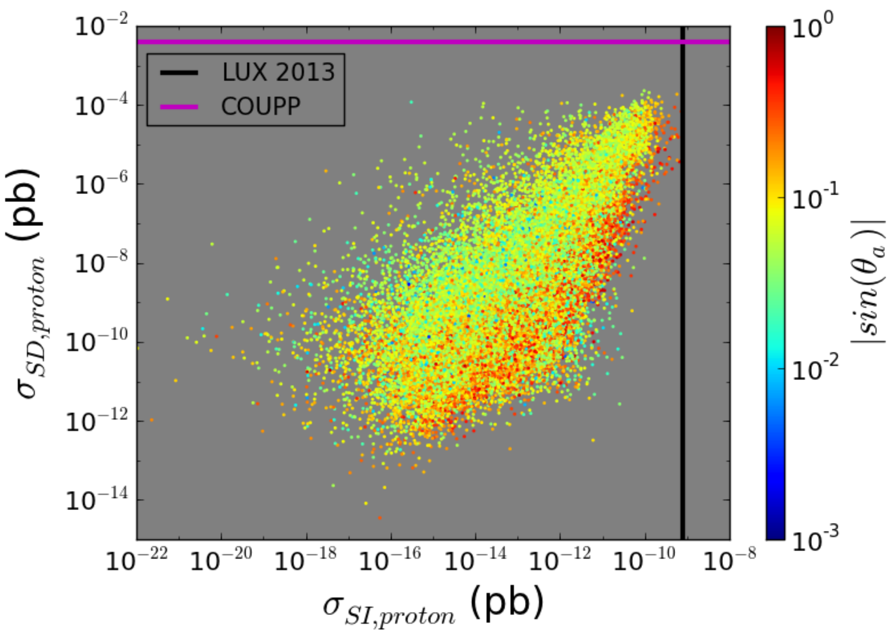


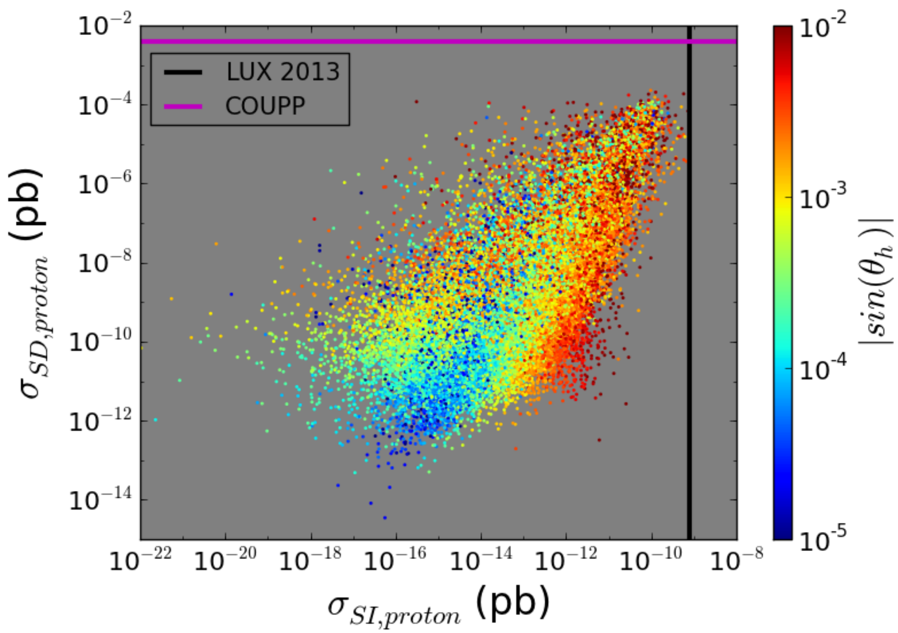


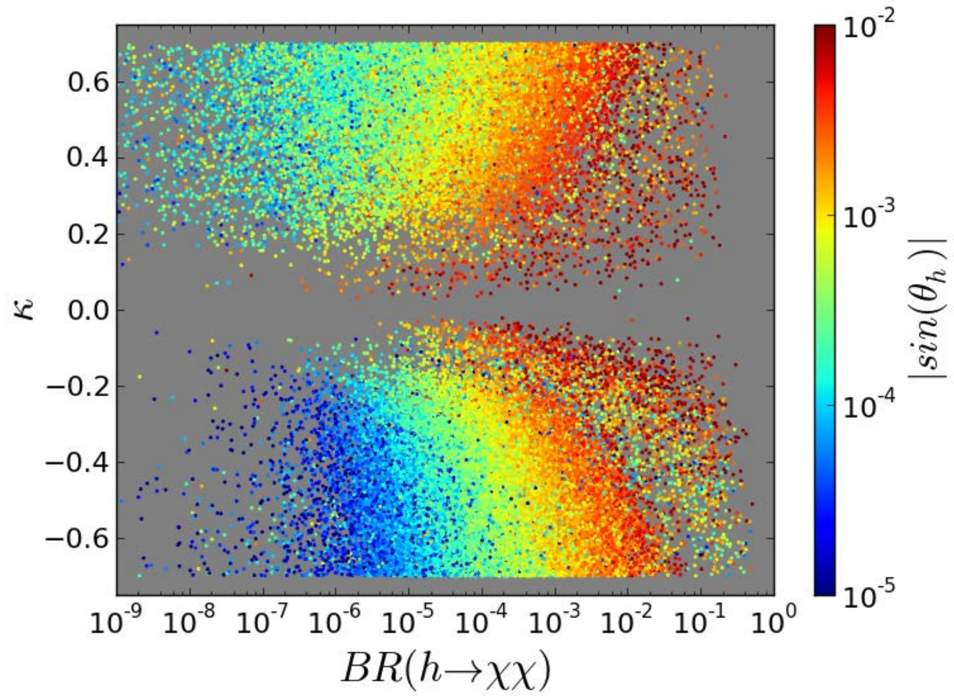




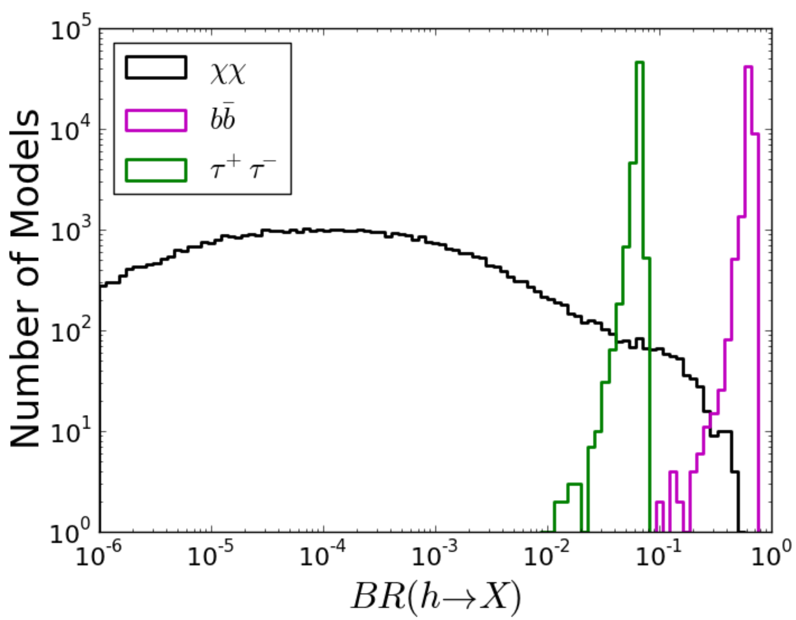
Expectations for DD are generally not very good…

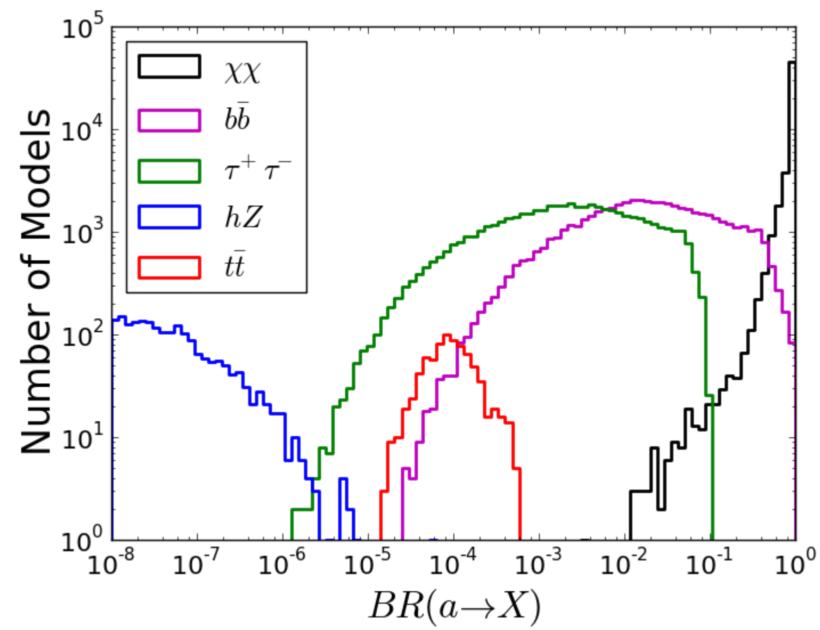


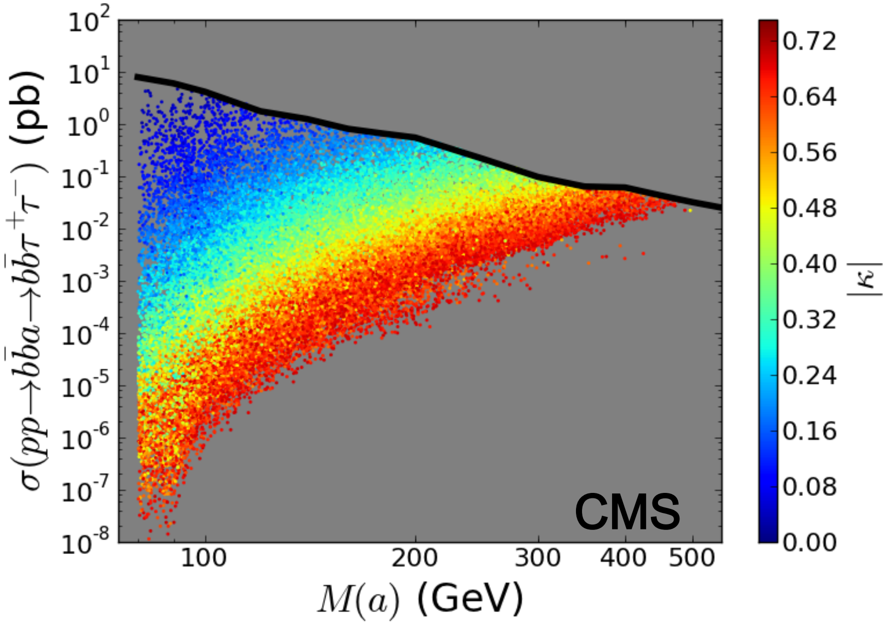


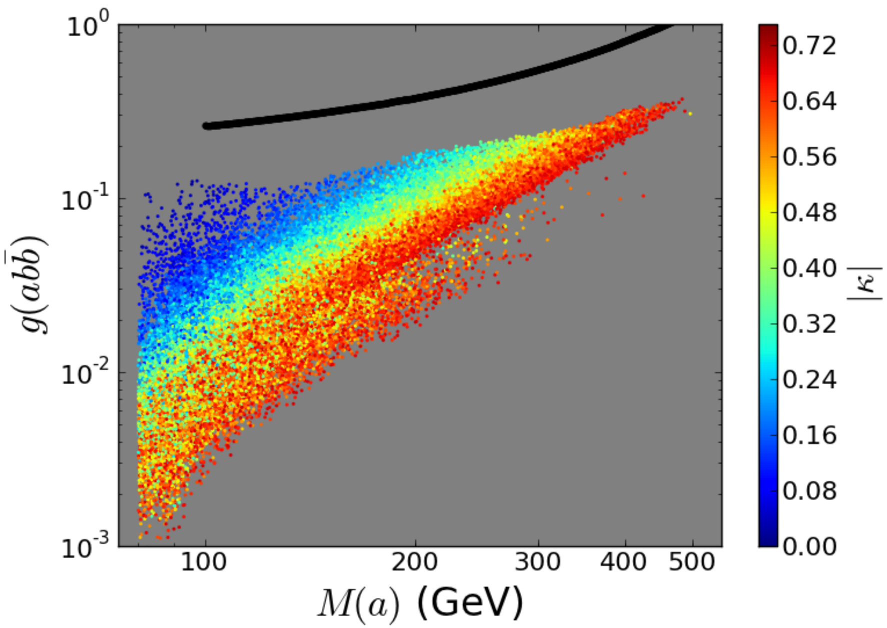


- The Higgs remains SM-like but picks up a generally very small BF (~ < 0.1-1%) for the decays to the LSP. LC??
- The light CP-odd field, a, decays almost entirely to LSP pairs with a small bb-bar BF









Heavy Higgs Searches ?

- 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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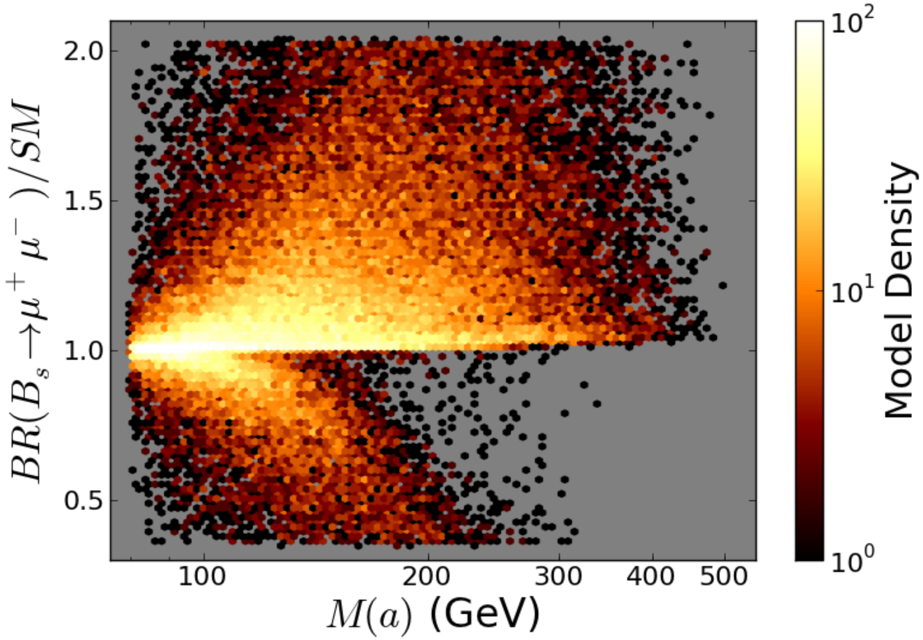
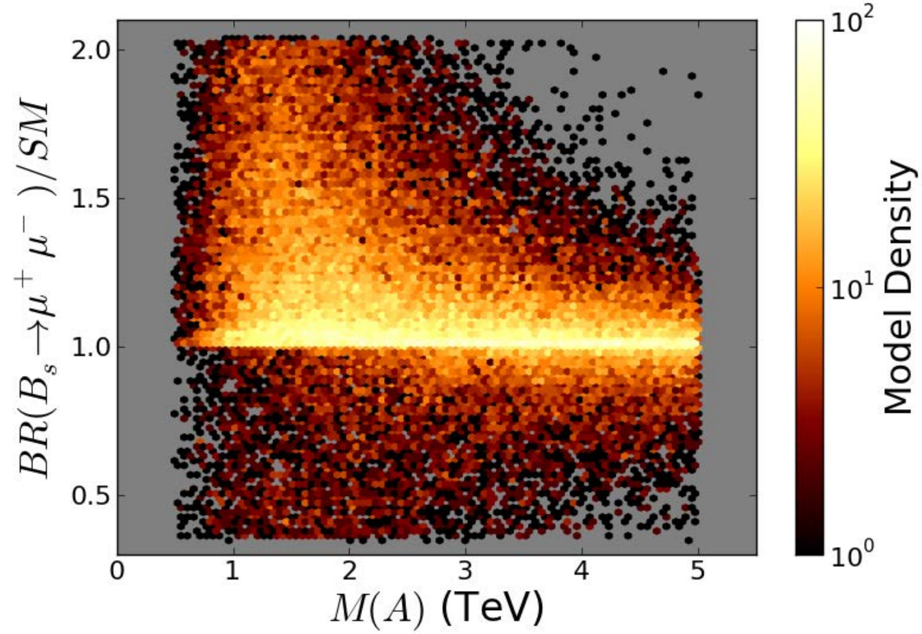
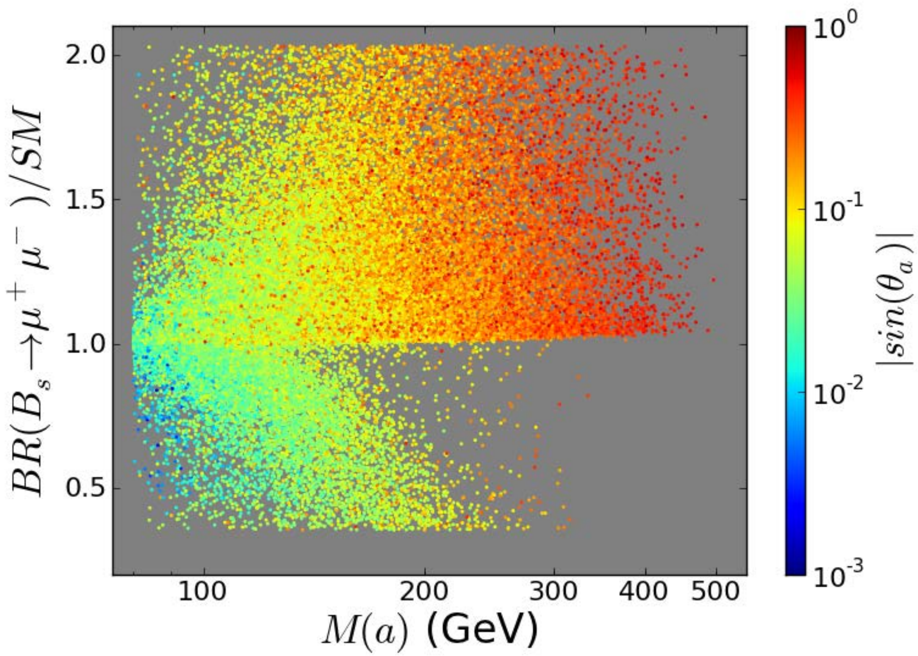




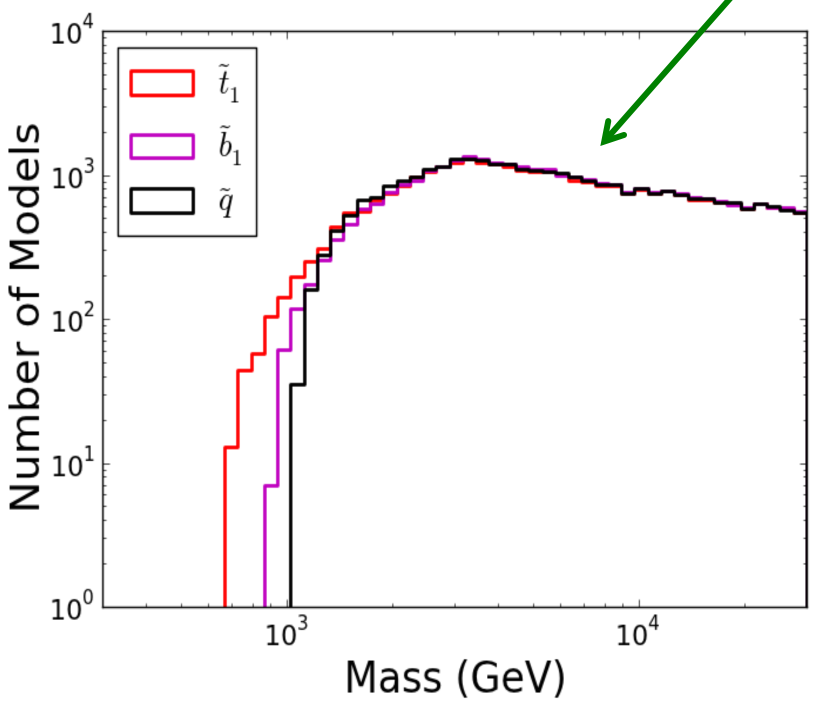


- Reduction in the uncertainties in the NMSSM theory calculation would be useful
- Most model predictions lie quite close to the SM value but there are some tails
- Note sign of μ splits models into two subsets

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.

- 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 an even MORE detailed study

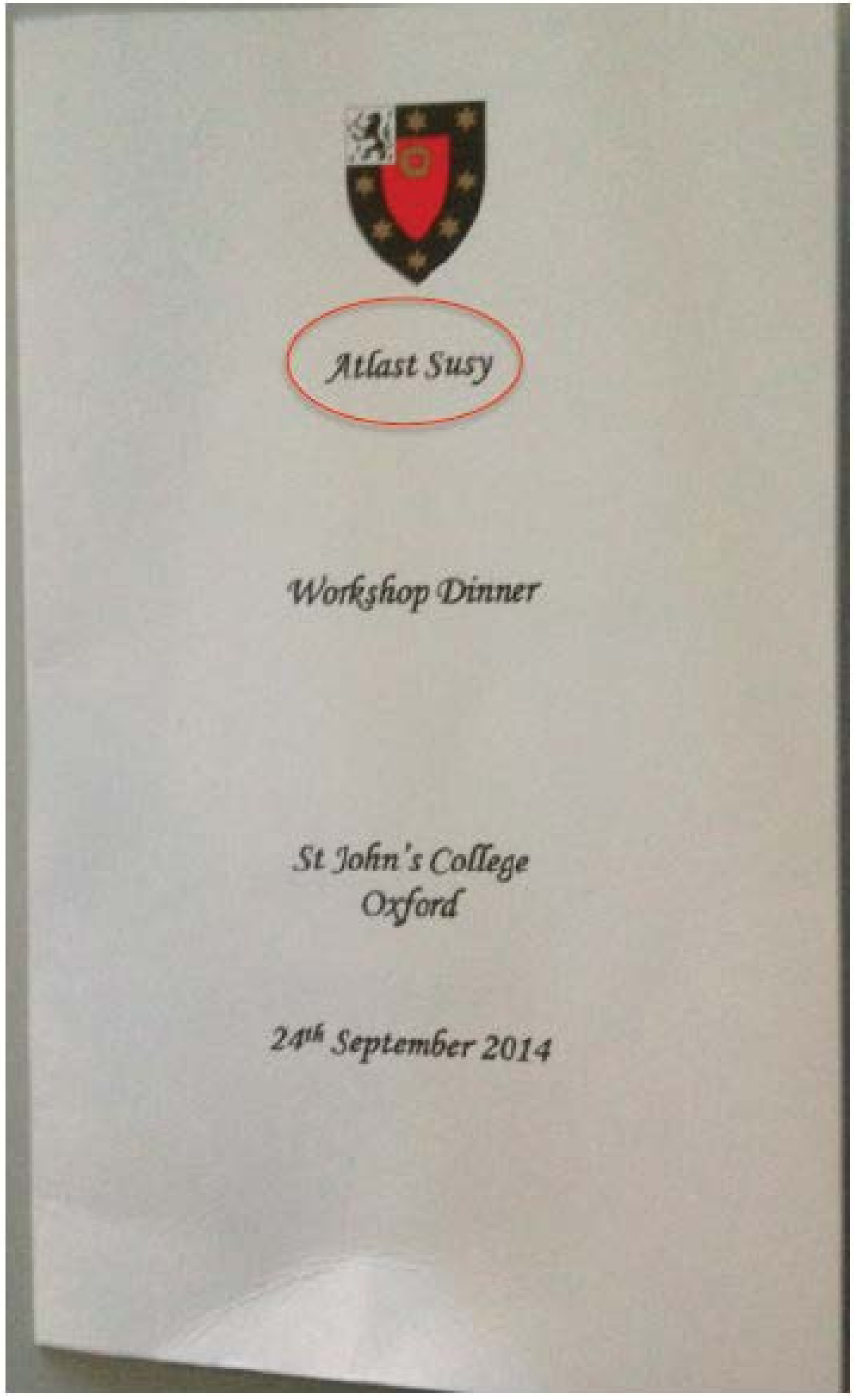
- E.g., here we see that although we placed a cut on the lightest stop mass >0.7 TeV very few models would have smaller values

- With this **specific** spectrum type, lots of leptons at ends of cascades

?

?

?


Atlast Susy
Workshop Dinner
St John's College
Oxford
24th September 2014

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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. Models can easily fail for many reasons.

- The general NMSSM provides a successful proof of principle framework

- This model 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, small changes in some flavor measurements and, of course, direct SUSY searches. ID of DM signals from Dwarfs by Fermi would verify this interpretation

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

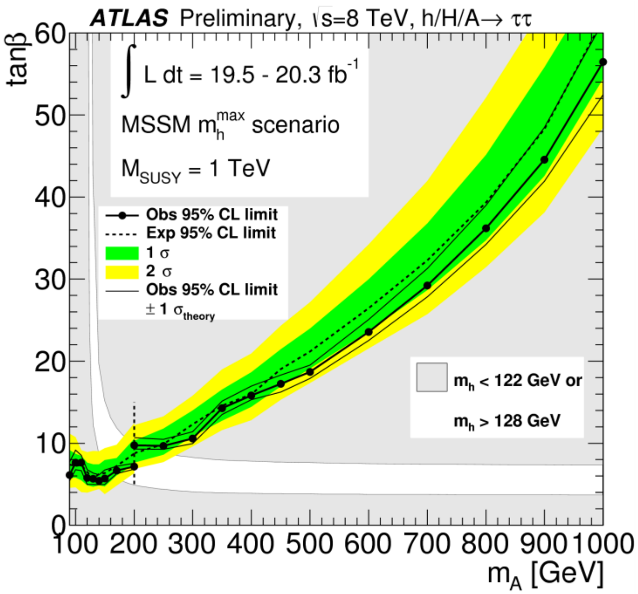
- Hopefully we'll soon find out about this signal

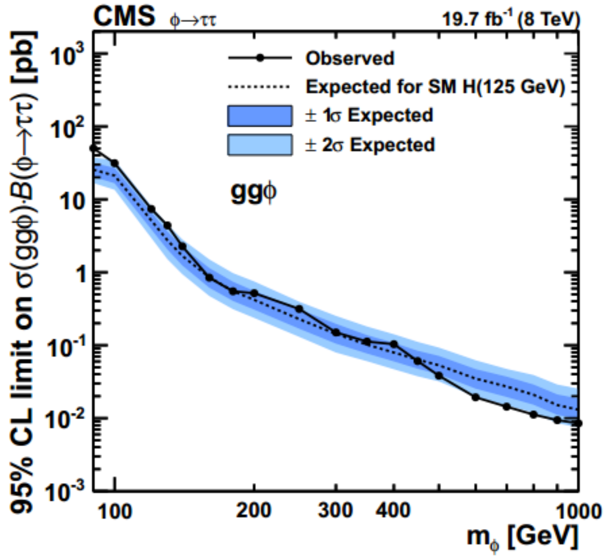
Backups

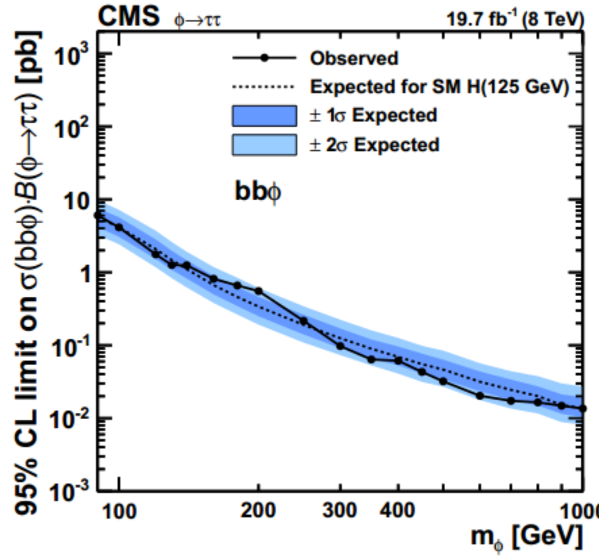
$$
\begin{aligned}
\mathcal{M}^2_{P,11} &= \frac{2(\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)}{\sin 2\beta}\,, \\
\mathcal{M}^2_{P,22} &= \lambda(B_{\rm eff} + 3\kappa s + \mu')\frac{v_u v_d}{s} - 3\kappa A_\kappa s - 2m_S'^2 - \kappa\mu' s - \xi_F\left(4\kappa + \frac{\mu'}{s}\right) - \frac{\xi_S}{s}\,,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

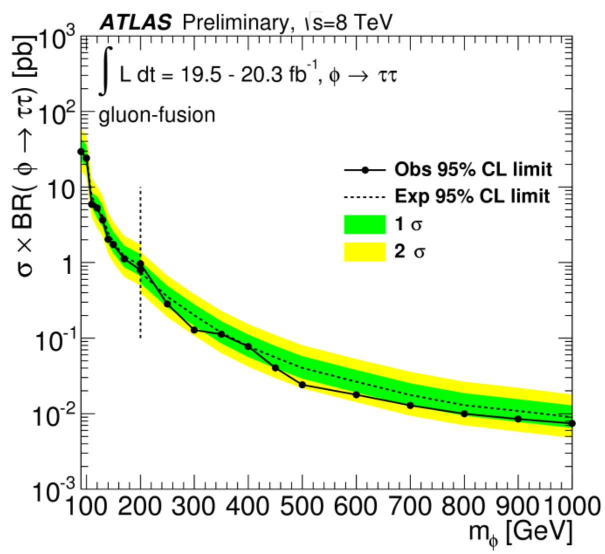
$$
B_{\rm eff} = A_\lambda + \kappa s\,, \quad \widehat{m}_3^2 = m_3^2 + \lambda(\mu' s + \xi_F)\,.
$$

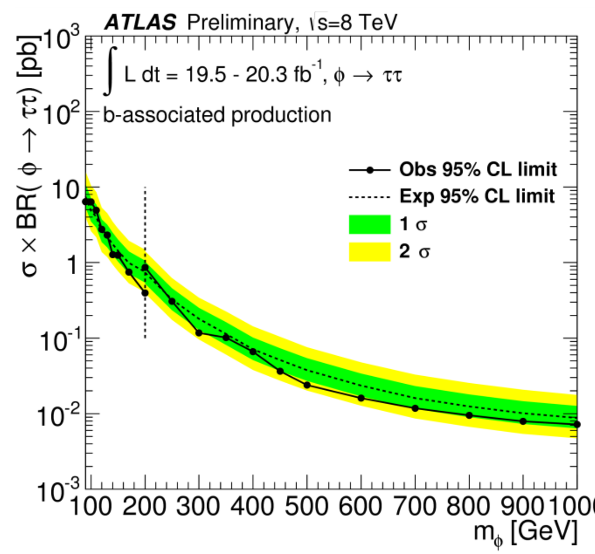
$$
\begin{aligned}
\mathcal{M}^2_{S,11} &= g^2 v_d^2 + (\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)\tan\beta\,, \\
\mathcal{M}^2_{S,22} &= g^2 v_u^2 + (\mu_{\rm eff}\, B_{\rm eff} + \widehat{m}_3^2)/\tan\beta\,, \\
\mathcal{M}^2_{S,33} &= \lambda(A_\lambda + \mu')\frac{v_u v_d}{s} + \kappa s(A_\kappa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

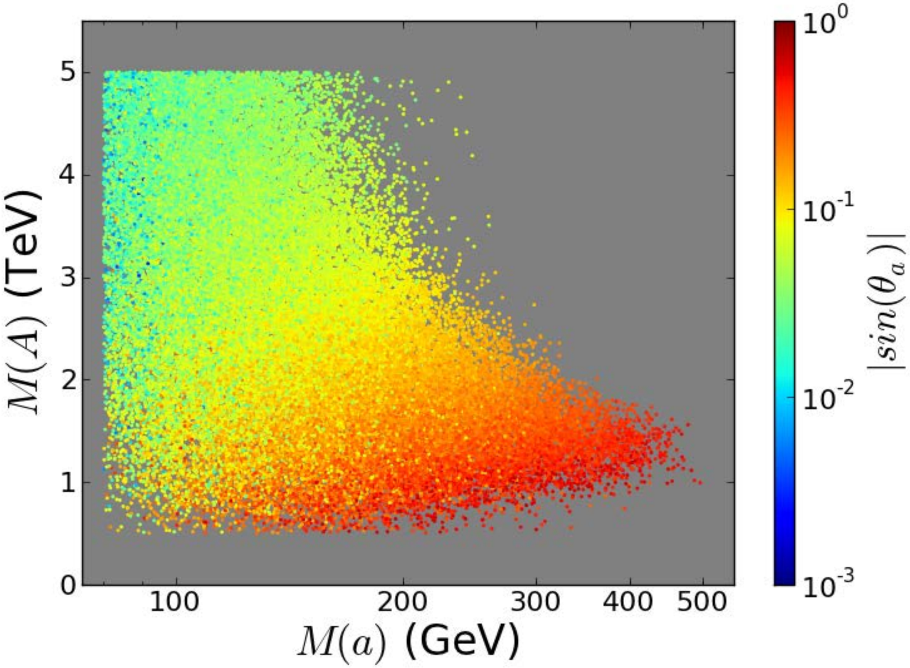

ATLAS Preliminary, √s=8 TeV, h/H/A→ ττ
tanβ
∫ L dt = 19.5 - 20.3 fb^-1
MSSM m_h^max scenario
M_SUSY = 1 TeV
Obs 95% CL limit
Exp 95% CL limit
1 σ
2 σ
Obs 95% CL limit
± 1 σ_theory
m_h < 122 GeV or
m_h > 128 GeV
m_A [GeV]

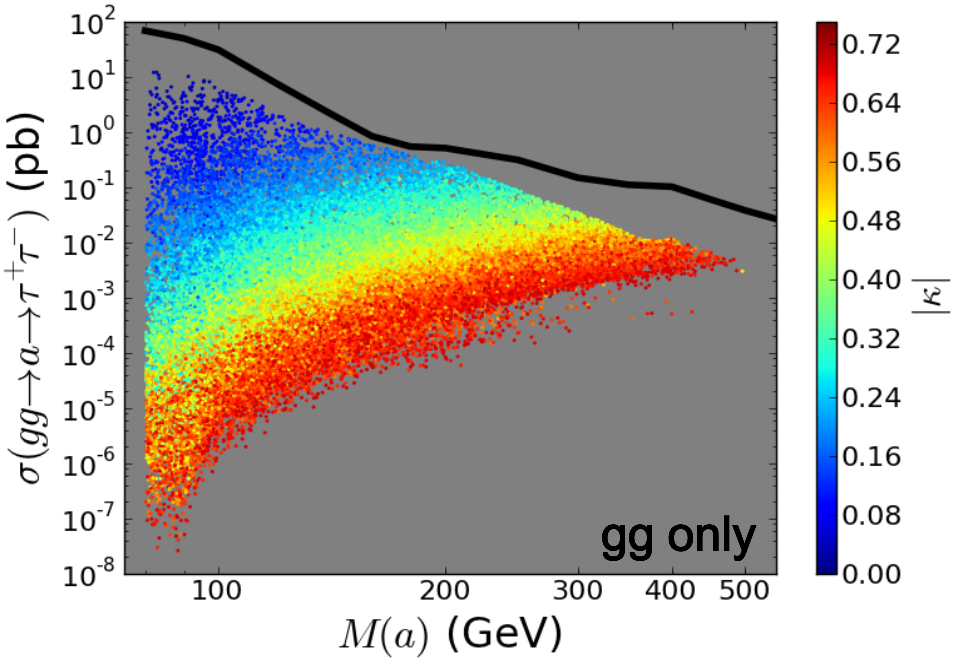

CMS φ→ττ
19.7 fb^-1 (8 TeV)
Observed
Expected for SM H(125 GeV)
± 1σ Expected
± 2σ Expected
ggφ
95% CL limit on σ(ggφ)·B(φ→ττ) [pb]
m_φ [GeV]

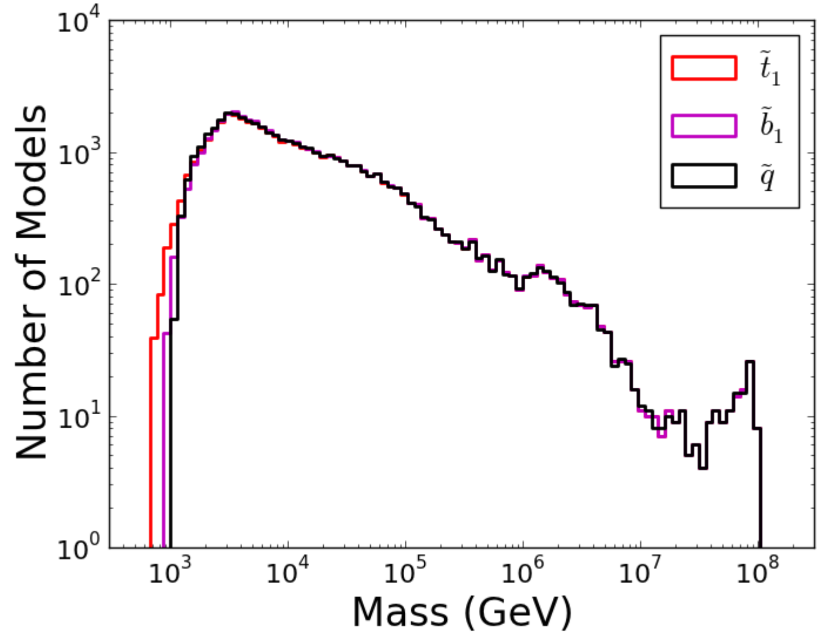

CMS φ→ττ
19.7 fb^-1 (8 TeV)
Observed
Expected for SM H(125 GeV)
± 1σ Expected
± 2σ Expected
bbφ
95% CL limit on σ(bbφ)·B(φ→ττ) [pb]
m_φ [GeV]

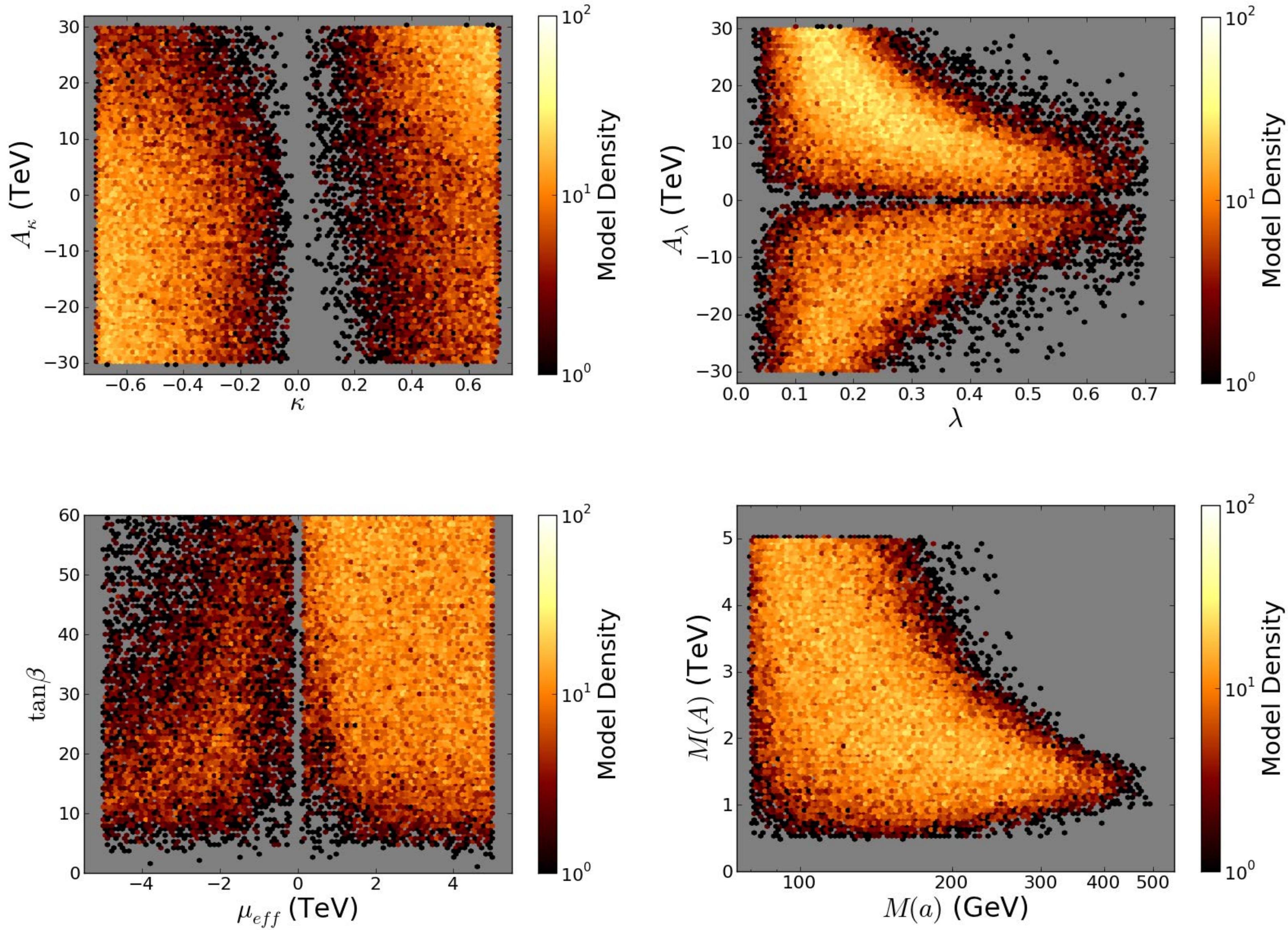

ATLAS Preliminary, √s=8 TeV
∫ L dt = 19.5 - 20.3 fb^-1, φ → ττ
gluon-fusion
Obs 95% CL limit
Exp 95% CL limit
1 σ
2 σ
σ × BR(φ → ττ) [pb]
m_φ [GeV]


ATLAS Preliminary, √s=8 TeV
∫ L dt = 19.5 - 20.3 fb^-1, φ → ττ
b-associated production
Obs 95% CL limit
Exp 95% CL limit
1 σ
2 σ
σ × BR(φ → ττ) [pb]
m_φ [GeV]

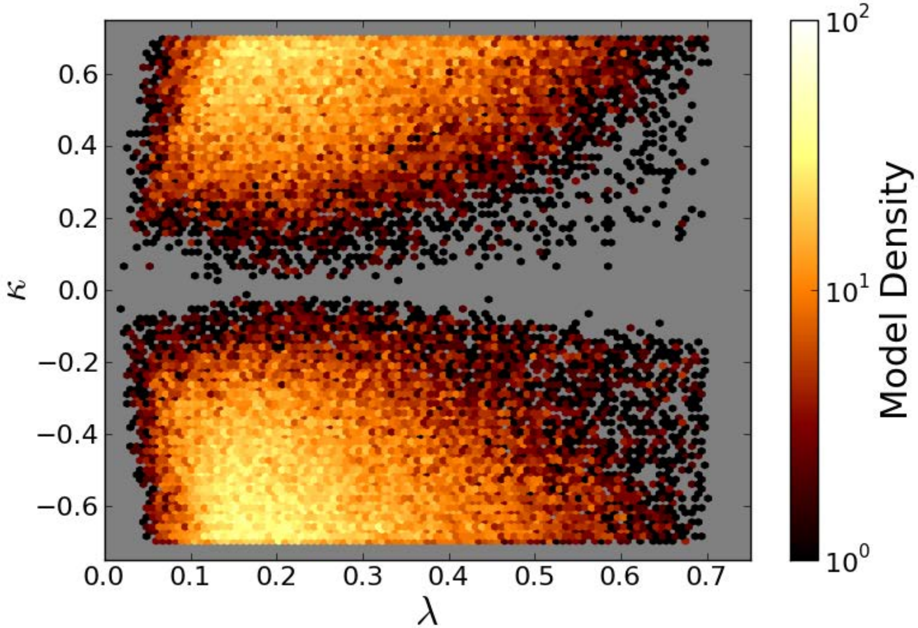

$M(A)$ (TeV)
$M(a)$ (GeV)
$|sin(\theta_a)|$
100
200
300
400
500
10^0
10^{-1}
10^{-2}
10^{-3}

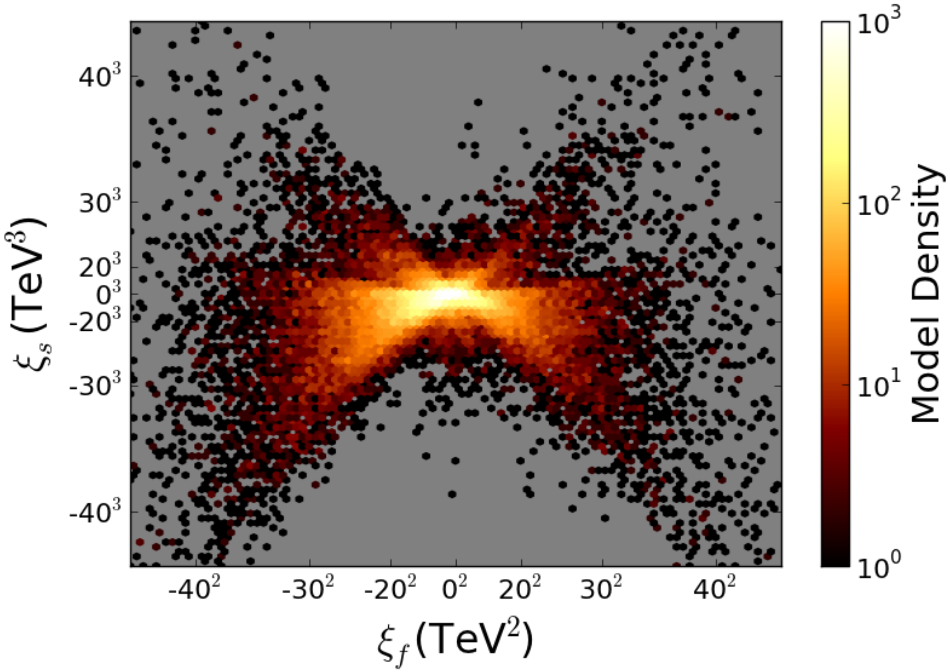

$\sigma(gg \to a \to \tau^+\tau^-)$ (pb)
$M(a)$ (GeV)
$|\kappa|$
gg only
100
200
300
400
500
0.00
0.08
0.16
0.24
0.32
0.40
0.48
0.56
0.64
0.72

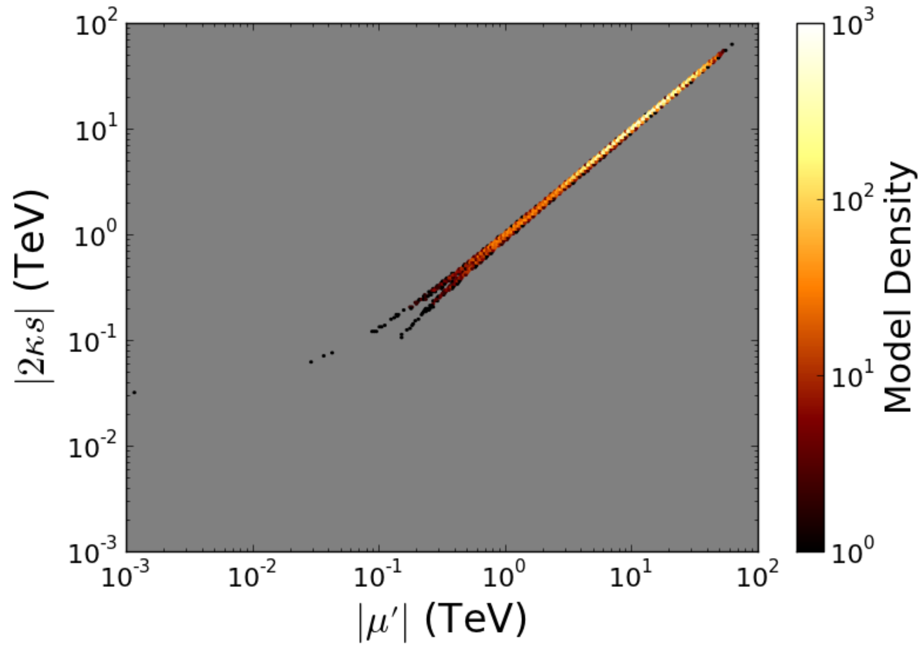

Number of Models
Mass (GeV)
$\tilde{t}_1$
$\tilde{b}_1$
$\tilde{q}$
10^3
10^4
10^5
10^6
10^7
10^8



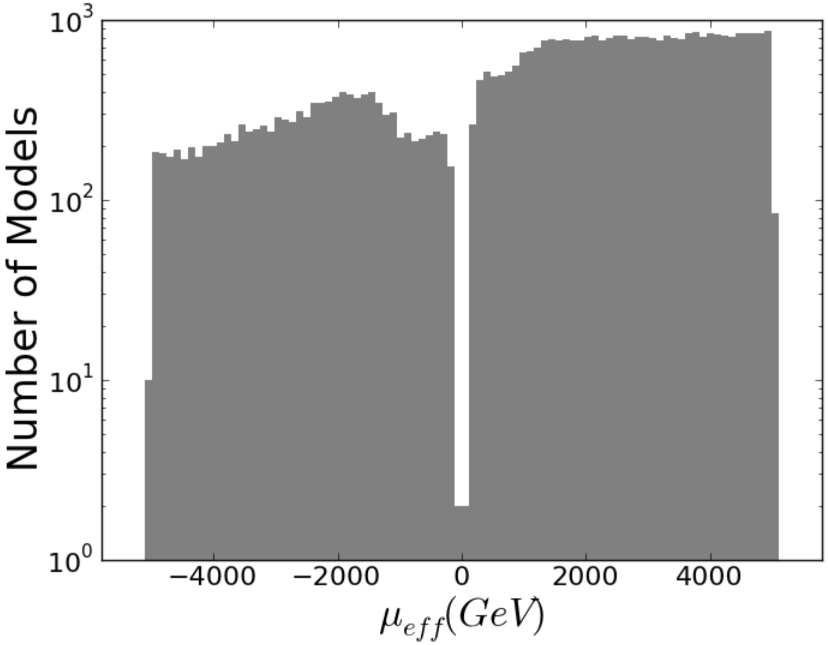
A_κ (TeV)
κ
Model Density
A_λ (TeV)
λ
Model Density
$\tan\beta$
μ_{eff} (TeV)
Model Density
$M(A)$ (TeV)
$M(a)$ (GeV)
Model Density

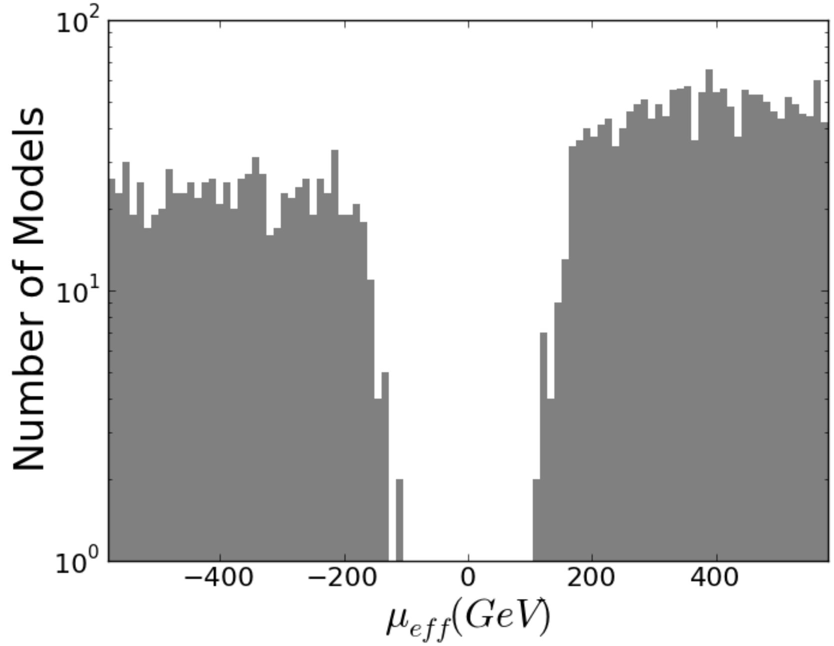

0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
κ
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
λ
10^2
10^1
10^0
Model Density

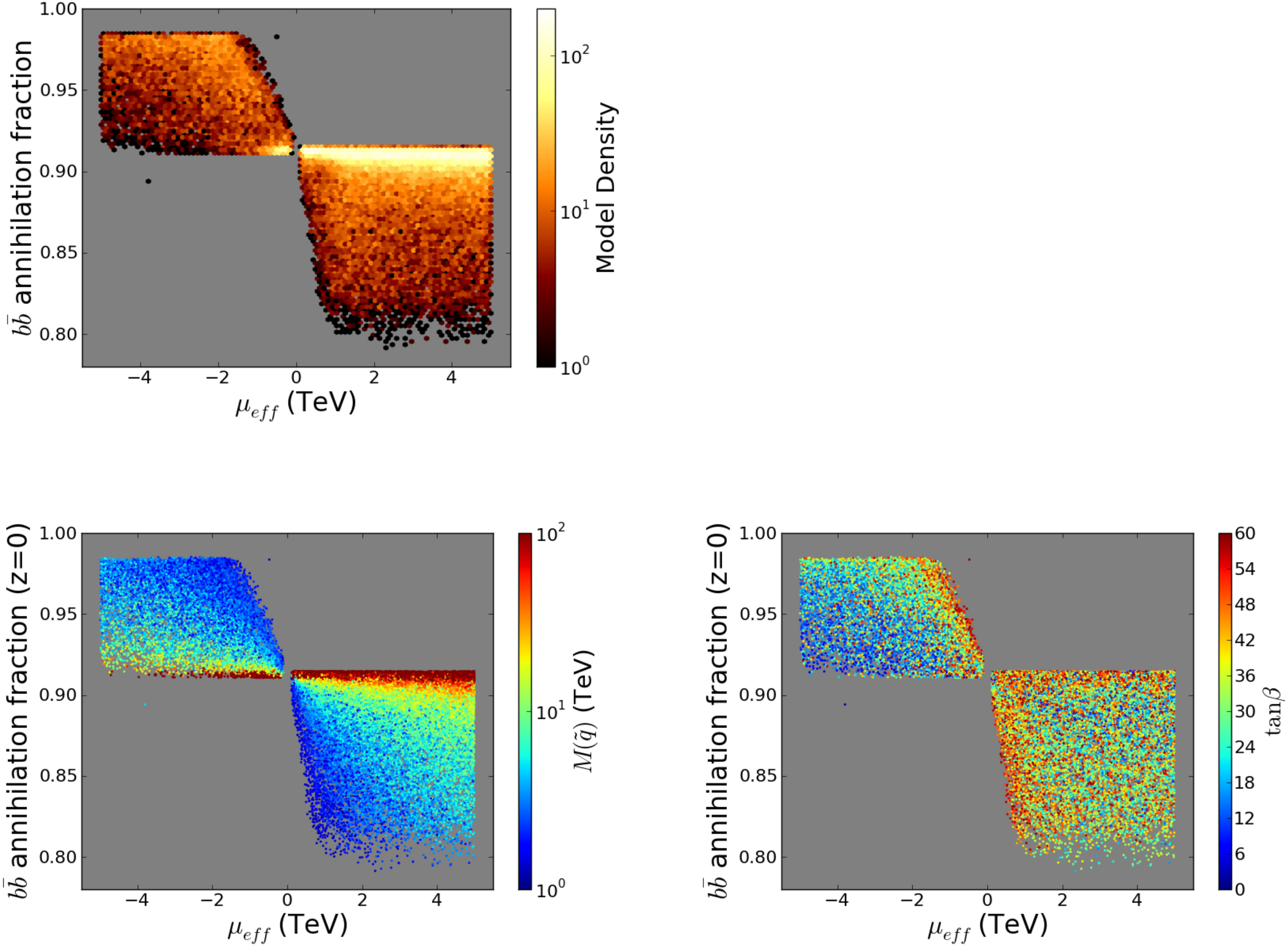

40^3
30^3
20^3
0^3
-20^3
-30^3
-40^3
ξ_s (TeV^3)
-40^2 -30^2 -20^2 0^2 20^2 30^2 40^2
ξ_f (TeV^2)
10^3
10^2
10^1
10^0
Model Density


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

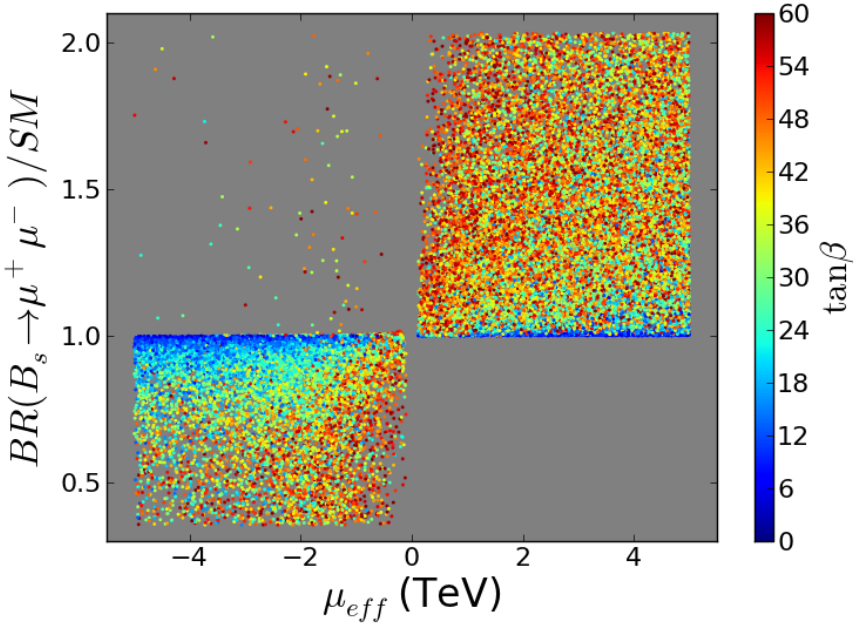
There are really two unequal populations of models here each with its specific sign of μ_{eff} . This sign contributes in multiple places…in particular in the radiative corrections to the Higgs couplings and in $B_s \to \mu\mu$

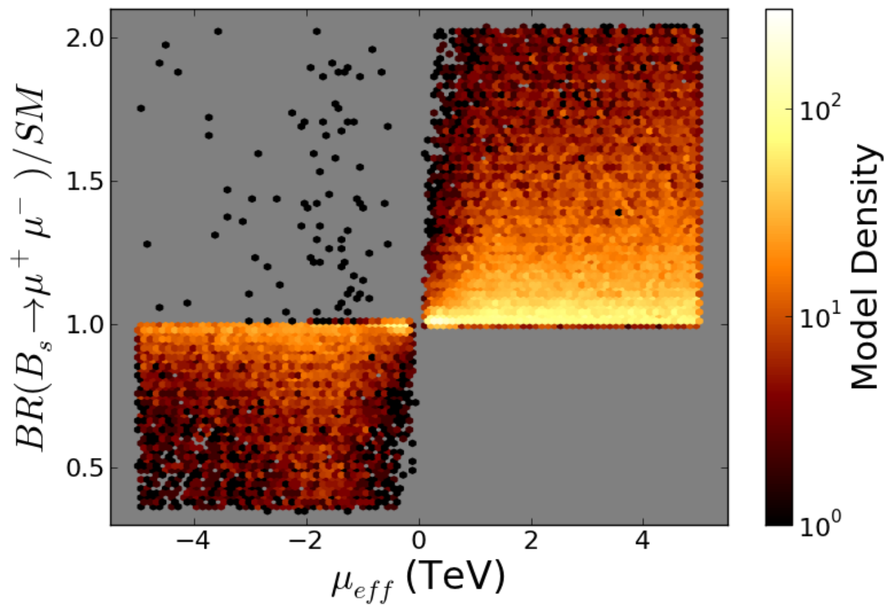


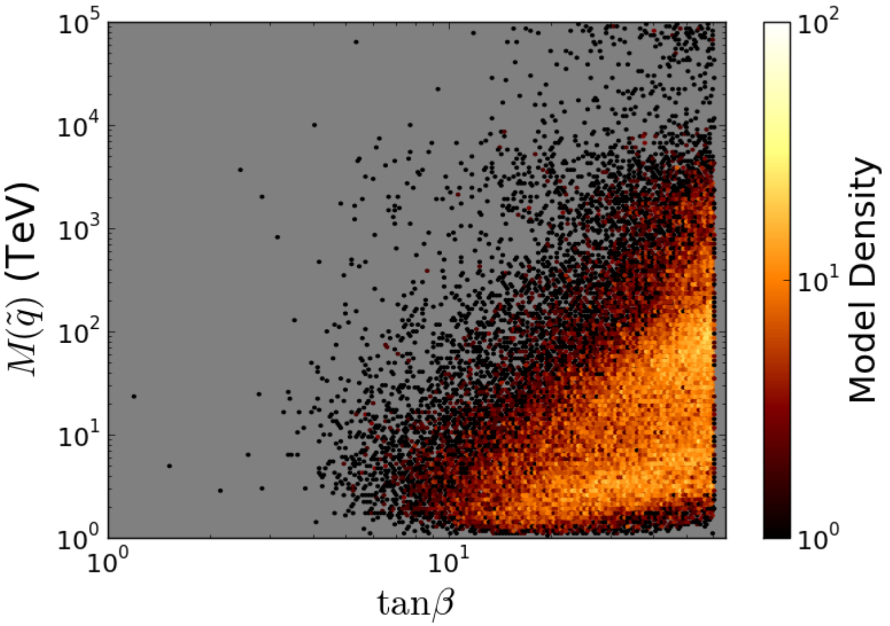




$b\bar{b}$ annihilation fraction
μ_{eff} (TeV)
Model Density
$b\bar{b}$ annihilation fraction (z=0)
$M(\tilde{q})$ (TeV)
$\tan\beta$


$BR(B_s \to \mu^+ \mu^-)/SM$
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

SUSY is complex:
not a single model but
a very large framework