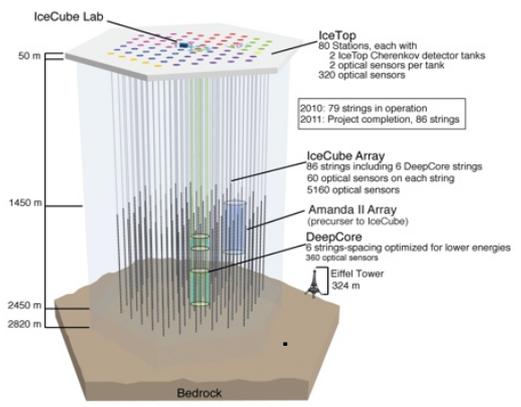
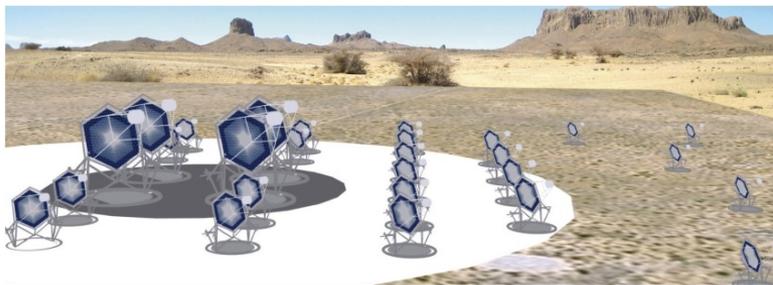
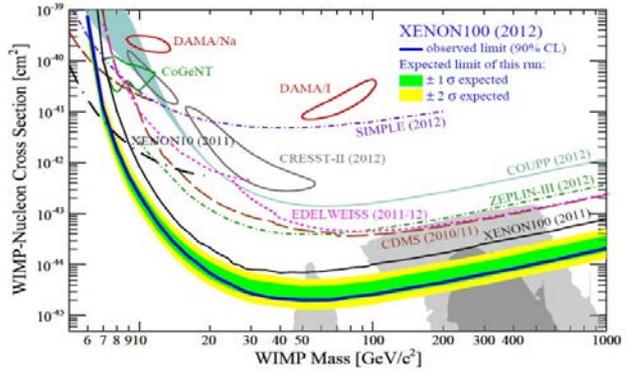
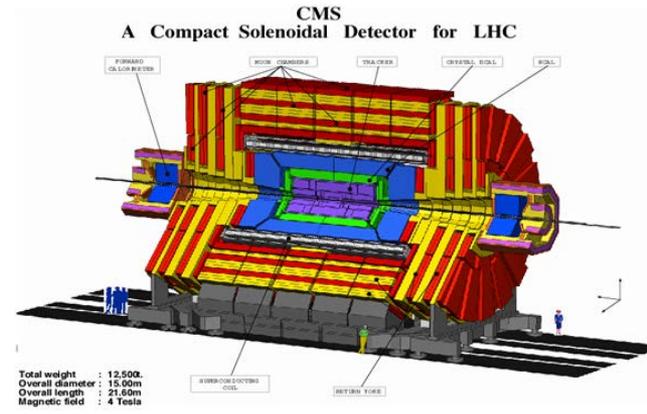
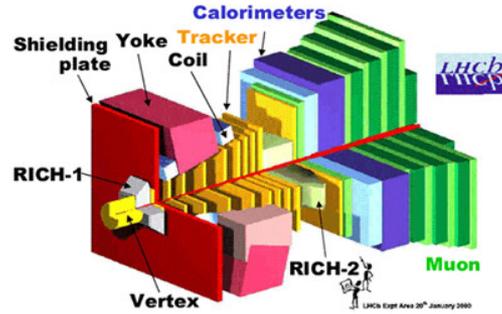
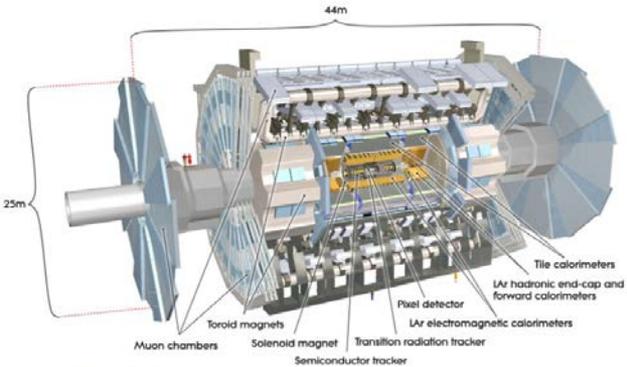


Complementarity & Searches for DM in pMSSM

SUSY: A Status Report



3/8/13

M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner,
 S. Funk, J. Hewett, A. Ismail, M. Wood, T.G.R.

The p(henomenological)MSSM

→ The MSSM has > 100 parameters -- so we make assumptions to reduce these to a reasonable level

- CP-conservation & R-parity
- Minimal Flavor Violation at the TeV scale (the CKM controls flavor)
- The lightest neutralino (or gravitino) 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 relic density is not necessarily saturated by the LSP (we allow for >1 component)

→ the pMSSM with **19** TeV-scale parameters...

Goal: find $\sim 200k$ points ('models') satisfying existing data & study them...going for 'breadth not depth'. **NO FITS!**

Complementarity Study : Some Pieces

- 7 & 8 TeV LHC MET & non-MET → 14 TeV
- DD w/ XENON & COUPP
- ID w/ FERMI & CTA
- ICE³
- Complementarity

For full details, see the excellent talks by :

Matthew C-R. (Th)

Randy C. (Th & Fri) ,

Alex D-W. (Wed)

Ahmed I. (Th)

Matthew W. (Th)

ATLAS SUSY Analyses @ 7 & 8 TeV (so far..)

Search	Energy	Reference
2-6 jets	7 TeV	ATLAS-CONF-2012-033
multijets	7 TeV	ATLAS-CONF-2012-037
1 lepton	7 TeV	ATLAS-CONF-2012-041
2-6 jets	8 TeV	ATLAS-CONF-2012-109
multijets	8 TeV	ATLAS-CONF-2012-103
1 lepton	8 TeV	ATLAS-CONF-2012-104
SS dileptons	8 TeV	ATLAS-CONF-2012-105
Gluino \rightarrow stop/sbottom	7 TeV	1207.4686
Very light stop	7 TeV	ATLAS-CONF-2012-059
Medium stop	7 TeV	ATLAS-CONF-2012-071
Heavy stop (0l)	7 TeV	1208.1447
Heavy stop (1l)	7 TeV	1208.2590
GMSB direct stop	7 TeV	1204.6736
Direct sbottom	7 TeV	ATLAS-CONF-2012-106
3 leptons	7 TeV	ATLAS-CONF-2012-108
1-2 leptons	7 TeV	1208.4688
Direct slepton/gaugino (2l)	7 TeV	1208.2884
Direct gaugino (3l)	7 TeV	1208.3144
HSCP	7 TeV	1205.0272
Disappearing tracks	7 TeV	ATLAS-CONF-2012-111
$\gamma\gamma + MET$ (\tilde{G} LSP)	7 TeV	1209.0753

- We (almost) exclusively follow the **ATLAS analysis suite** with **fast MC** (modified PGS/Pythia), validated using **ATLAS cMSSM benchmark points** & employing **ATLAS SM backgrounds**

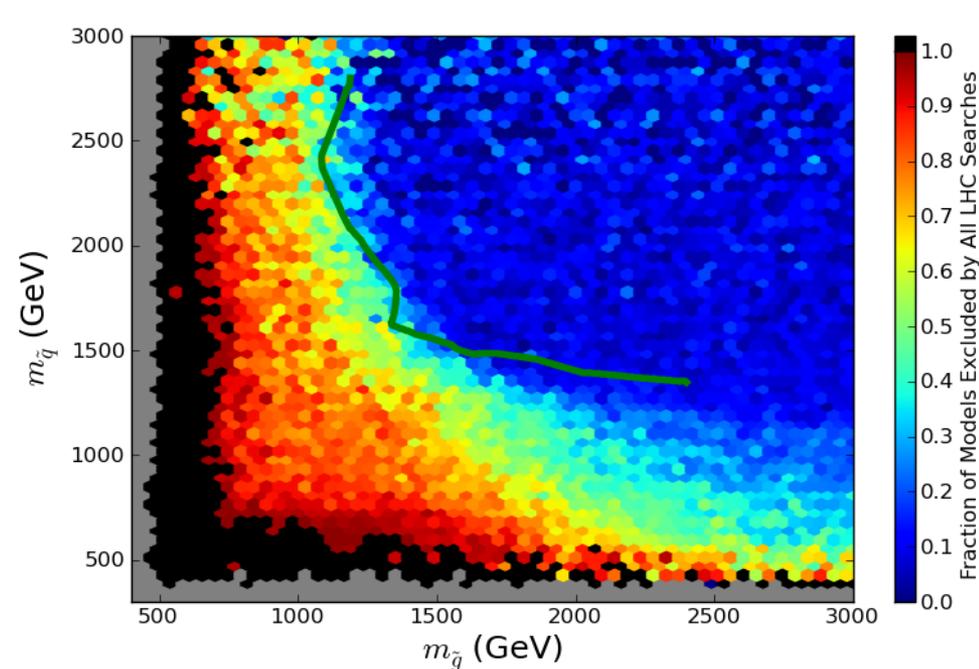
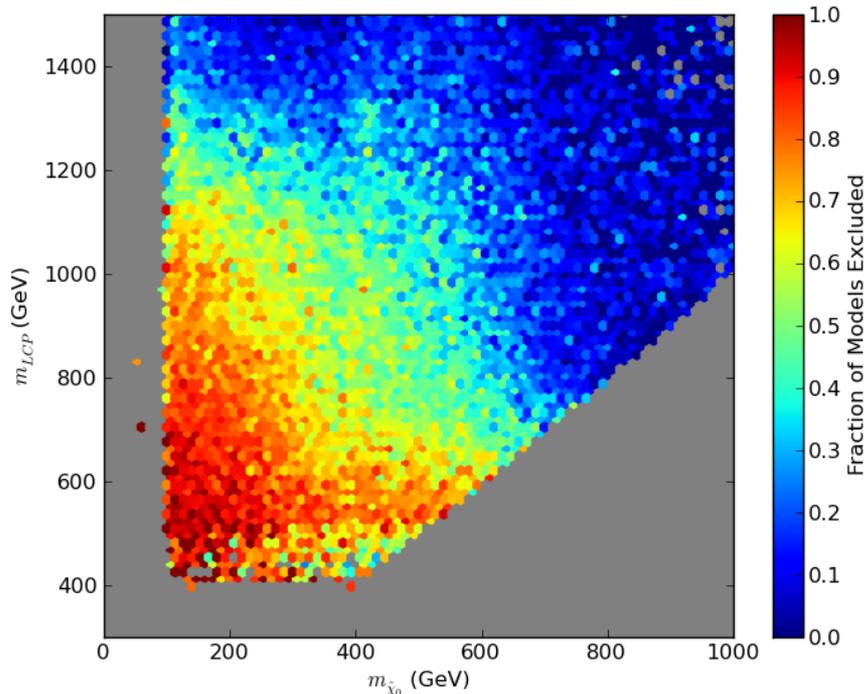
- We determine which models are excluded by each analysis **(for each signal region)** & then **combine them to determine the total exclusion**

- We are now in the process of **extending the list of 7 & 8 TeV analyses** & will also be looking at **14 TeV for Snowmass**

+ LHCb $B_s \rightarrow \mu\mu$ + CMS $A/H \rightarrow \tau\tau$

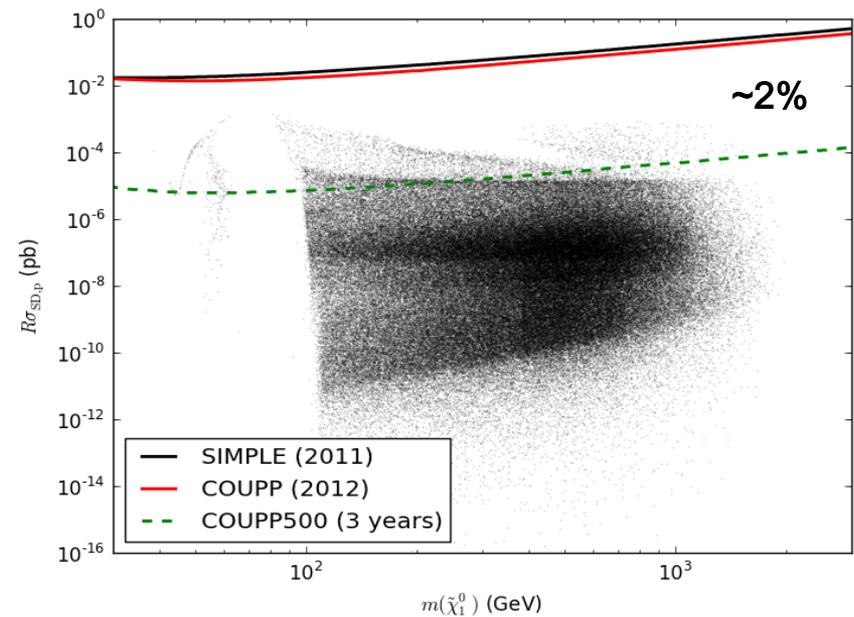
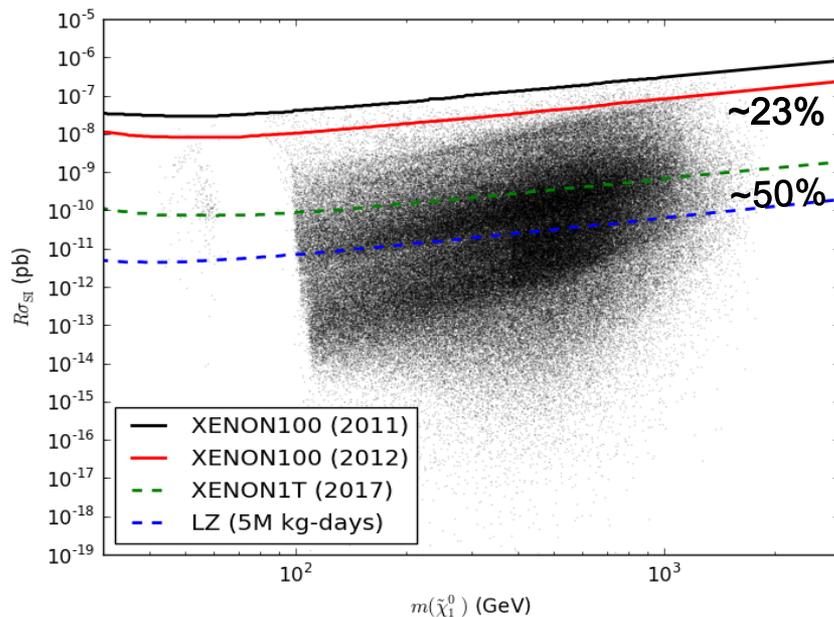
Some Results

- ~33% of our model points are currently excluded by ATLAS SUSY searches & this will grow as more searches are added
- This fraction is independent of the $m_h = 126 \pm 3$ GeV constraint
- Multiple searches play important roles in obtaining this result

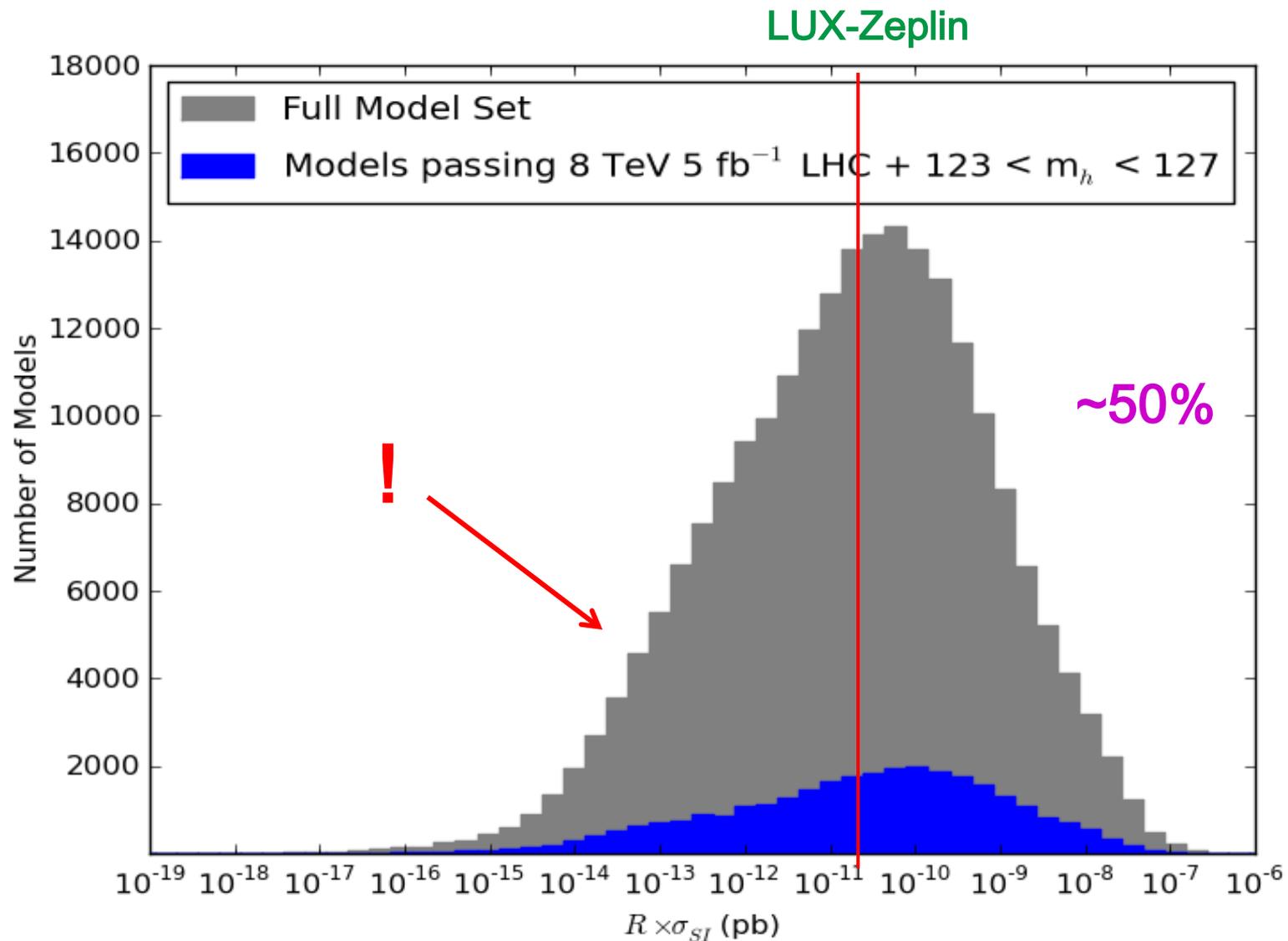


DM : Direct Detection

- SD & SI DD searches **both** probe regions of the pMSSM parameter space
- The potential coverage is quite significant for SI searches

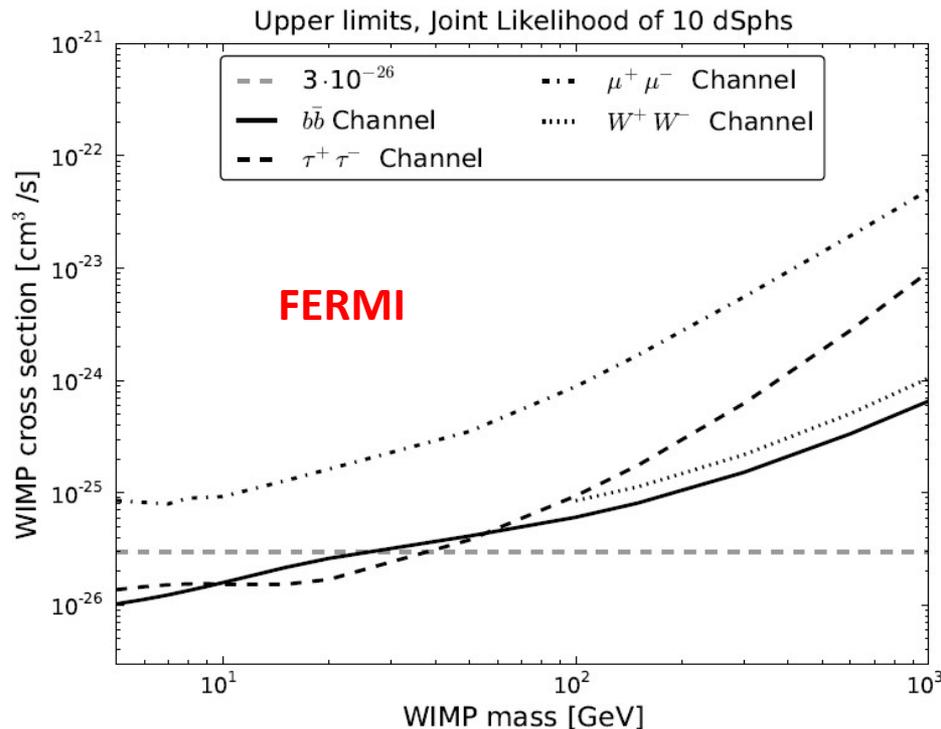


pMSSM models go quite deep in terms of SI cross sections

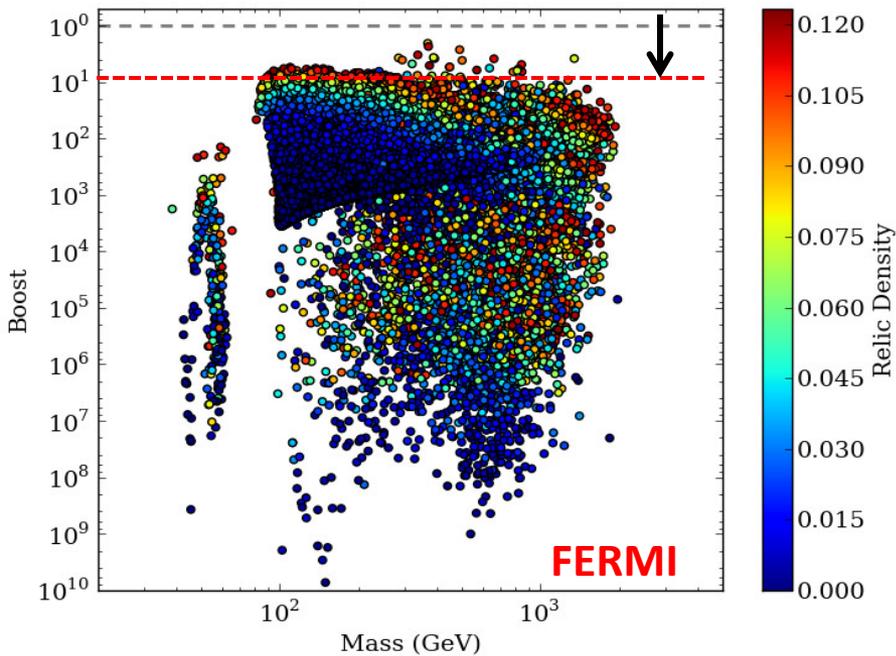


Indirect Detection: FERMI & CTA

- Conventionally, IDM searches assume that WIMPs annihilate into only one final state & quote a cross section limit based on the corresponding flux limit

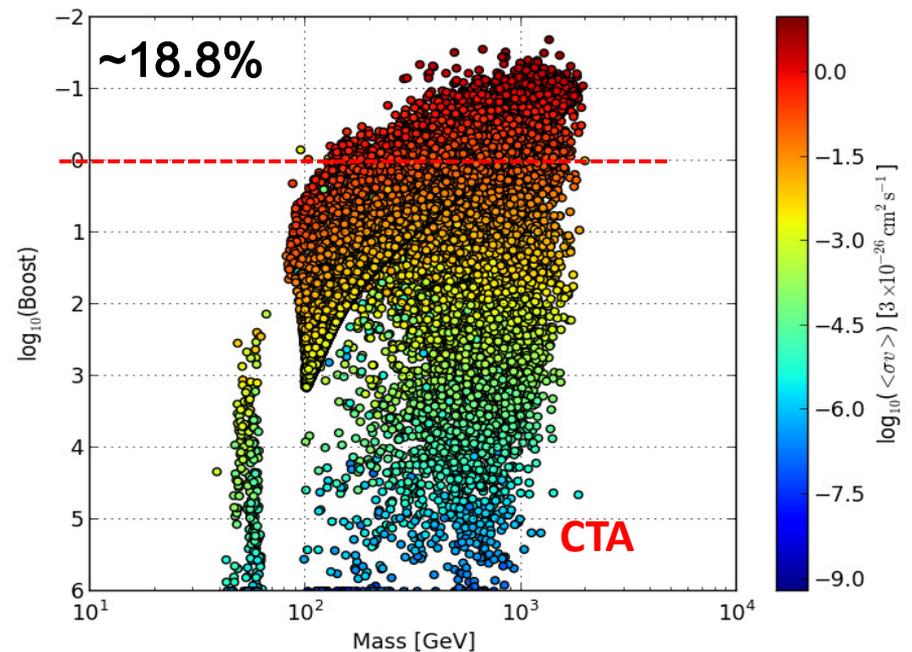
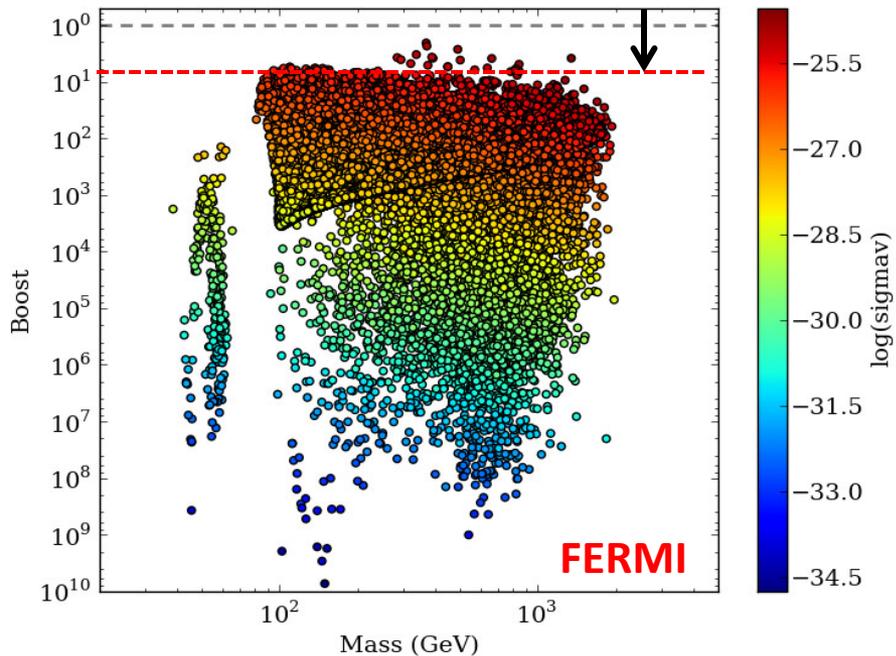


- **However** in the pMSSM the LSP properties & SUSY mass spectra are more complicated so that multiple final states will contribute to the γ flux
- Thus the flux limit **itself** is the quantity of interest & must be calculated for each model



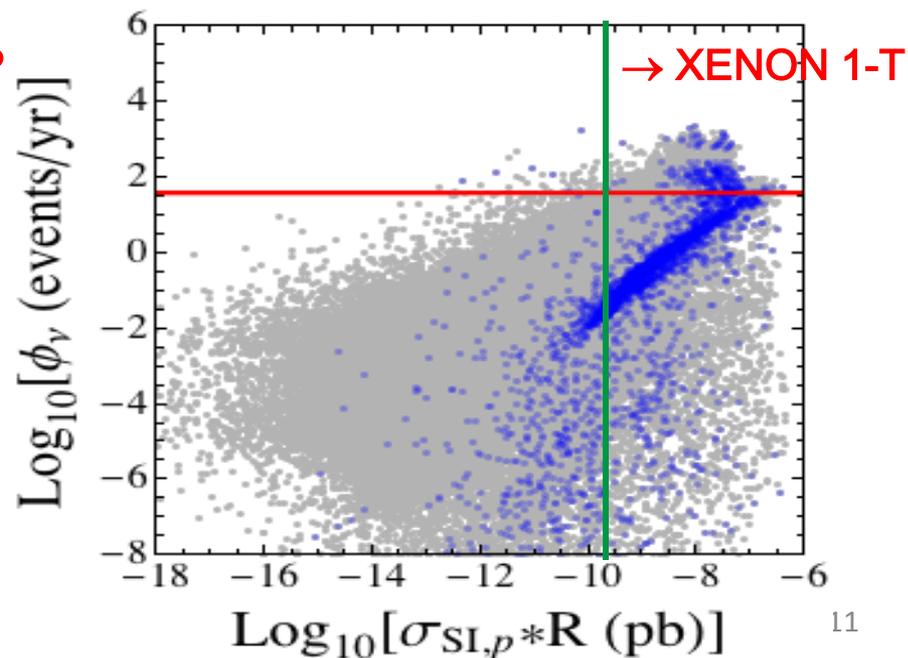
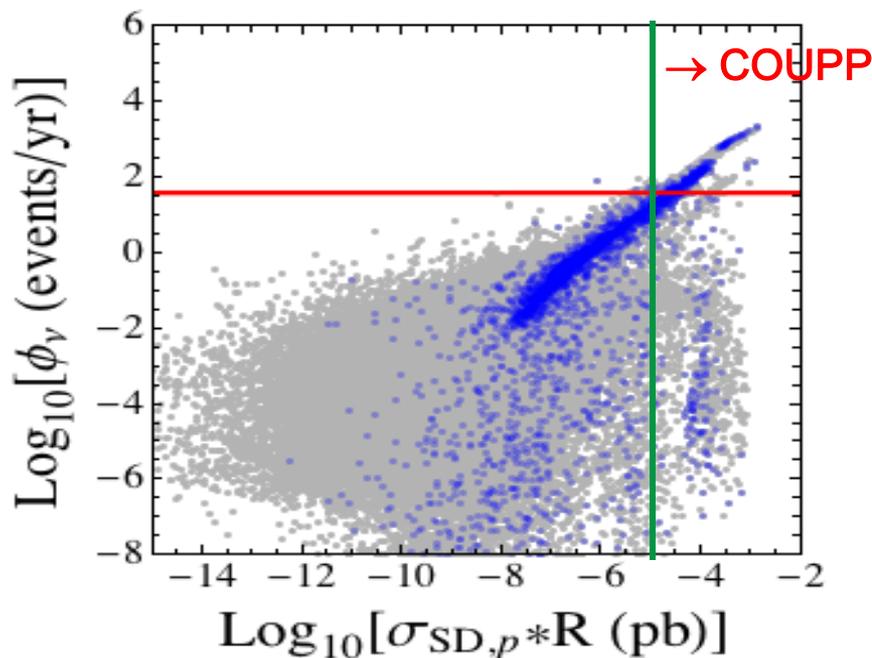
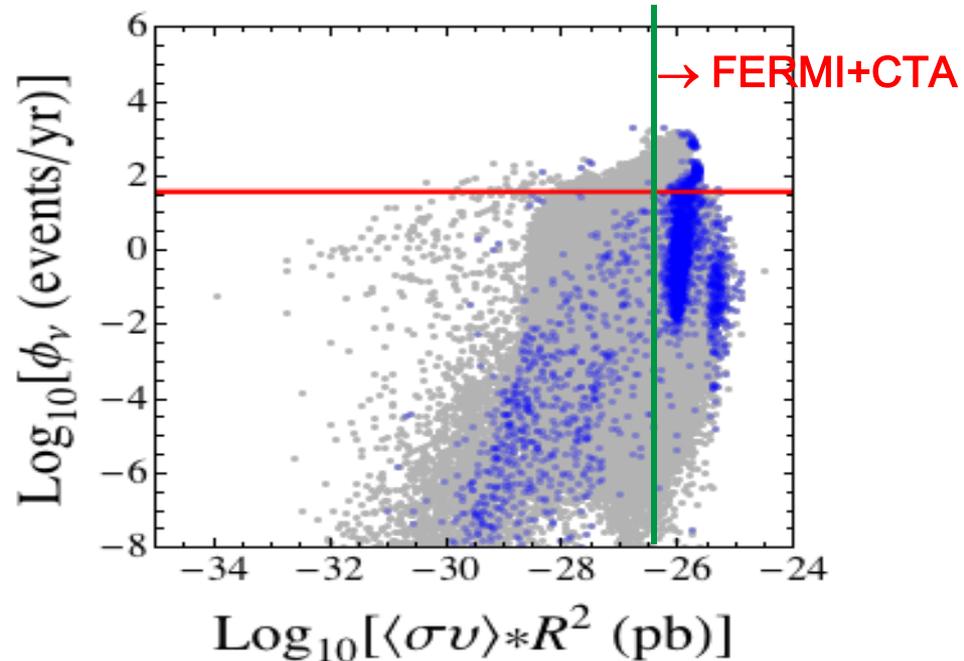
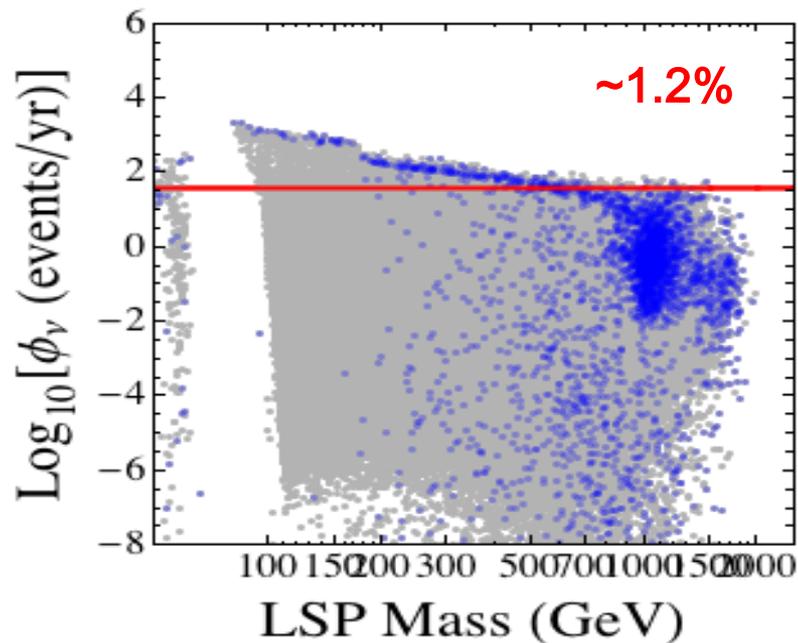
- FERMI 2-yr Dwarfs are still a factor of a few away from this model set but they will soon get there

- CTA @ 5 yrs will have access to a reasonable fraction of these models



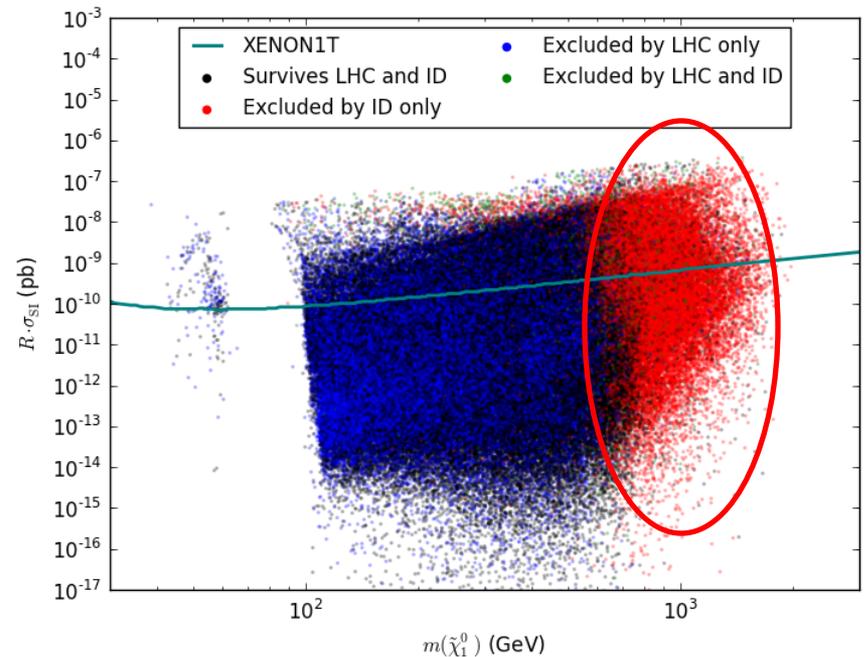
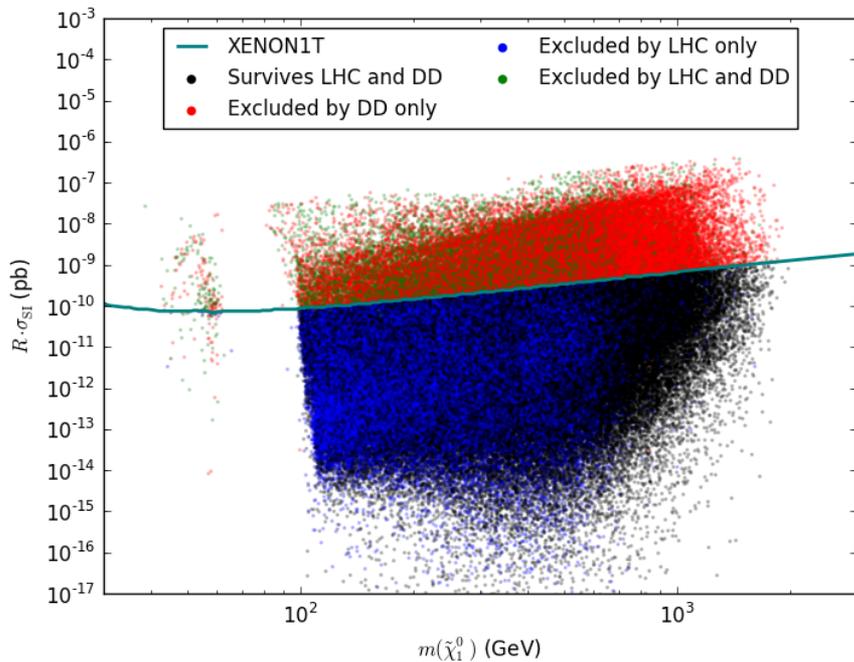
ICE³ @ 5yrs

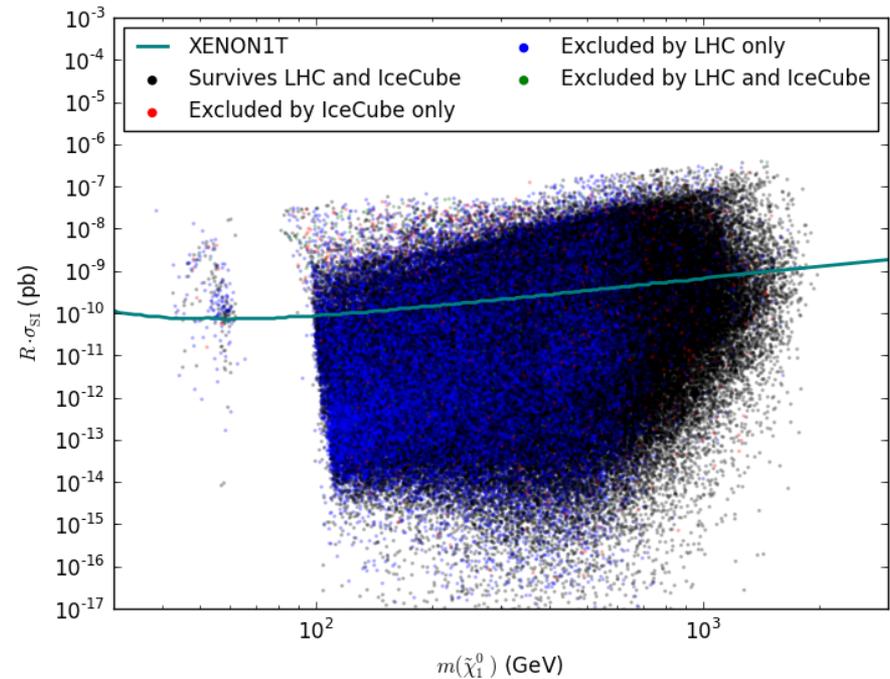
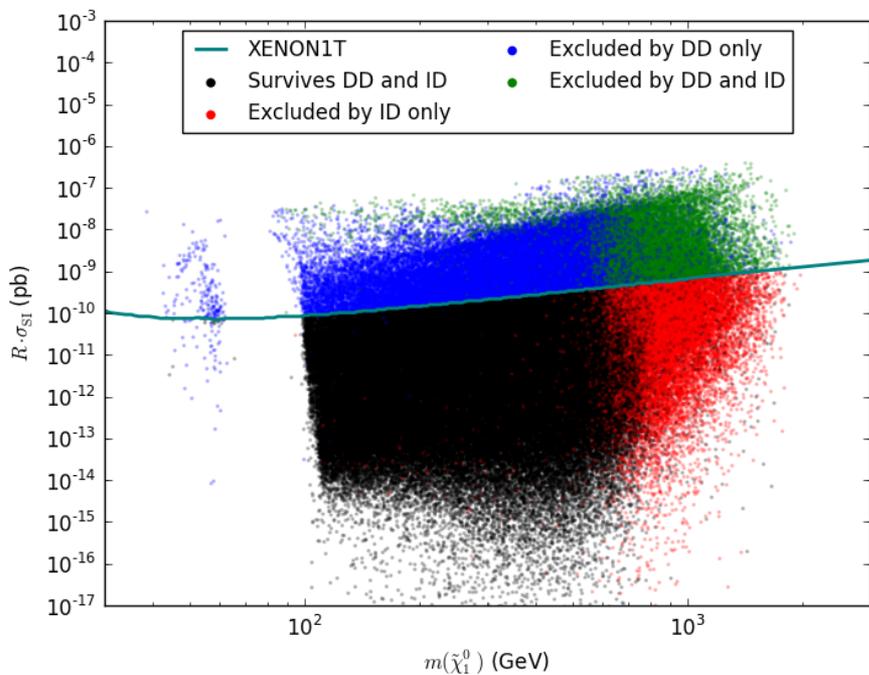
- DM swept up by the sun can collect & then pair-annihilate in the solar core thus producing high-E neutrinos from the decay of the corresponding annihilation products
- Again, since the LSP properties & SUSY spectra vary widely in the pMSSM the potential flux must be calculated for each model separately & then compared with the expected limit
- Models not leading to an equilibrium in capture/annihilation rate for DM in the sun (~ 48% !) are not well-probed by ICE³ . It is mostly mixed bino-Higgsino LSP combinations that are visible & these have large relic densities.



Putting it ALL Together : Only Some Samples...

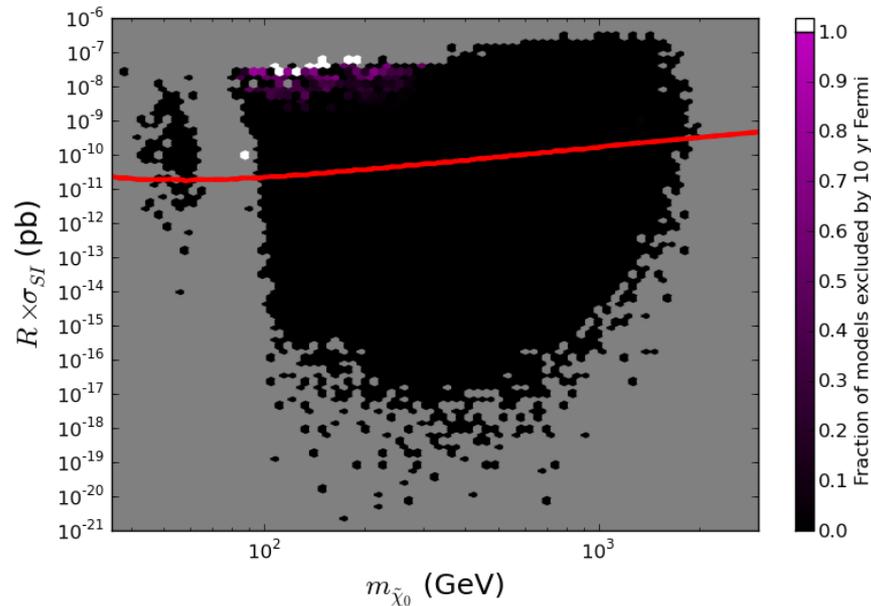
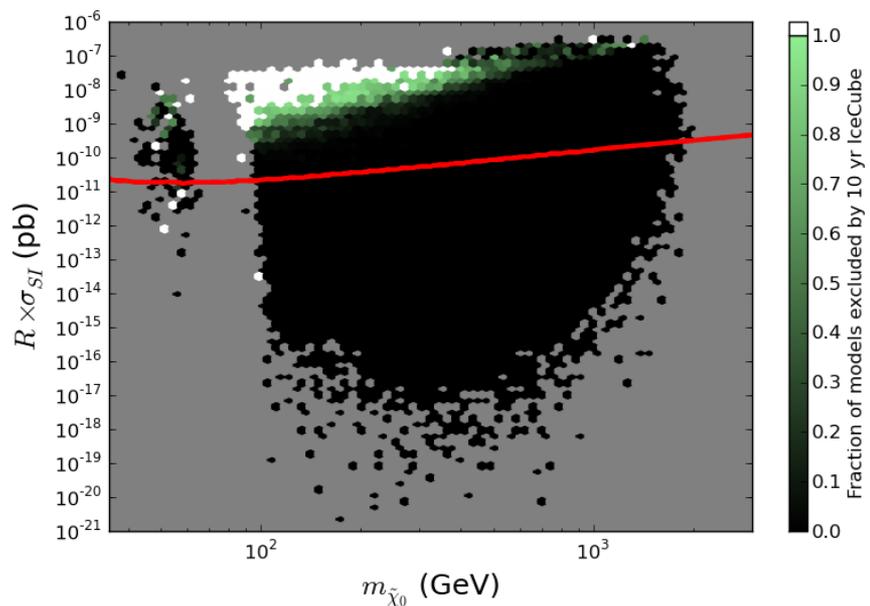
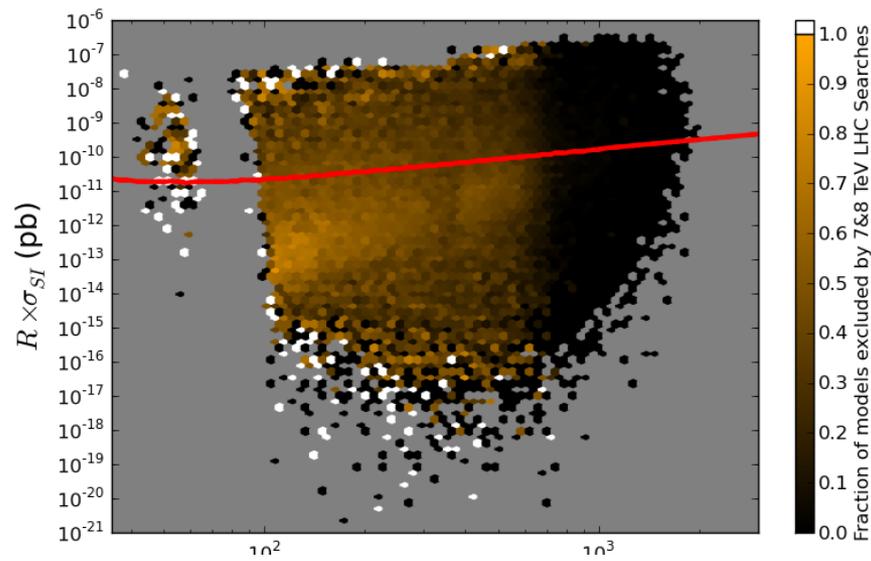
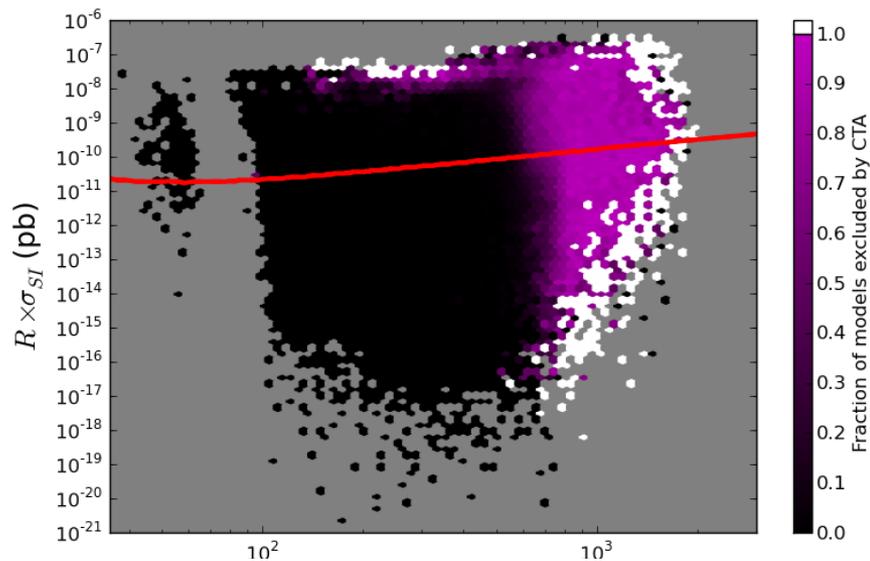
- The number of possible comparisons is quite LARGE !
(see the large set of backup slides)
- We first can compare present LHC coverage w/ DD and ID



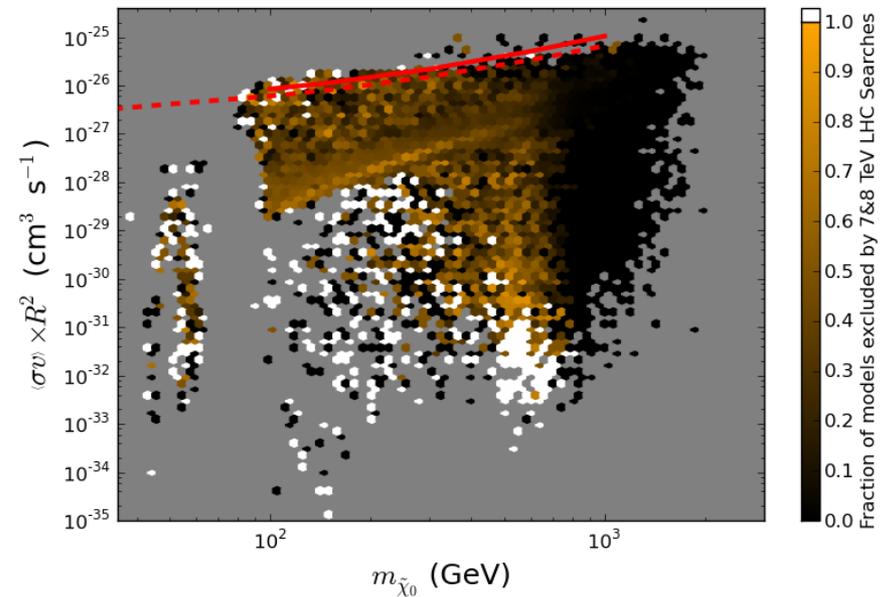
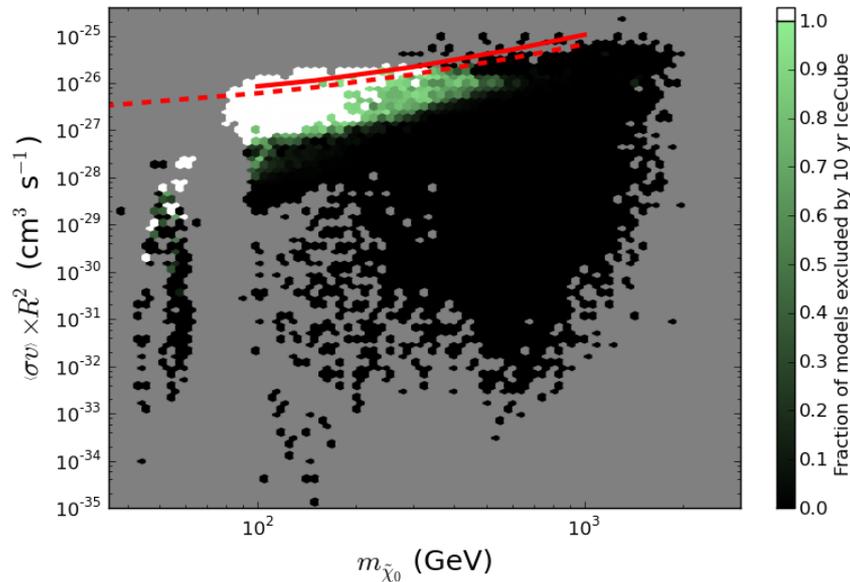
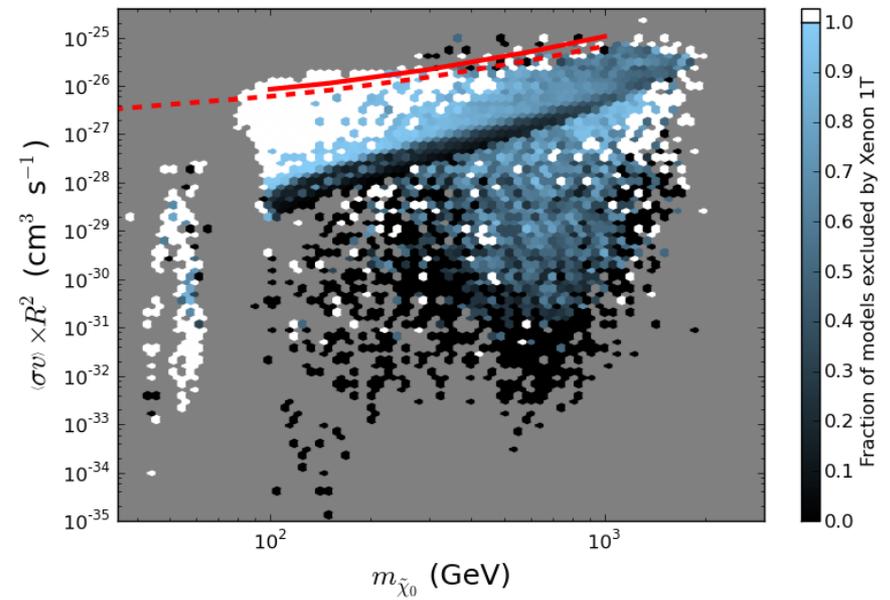
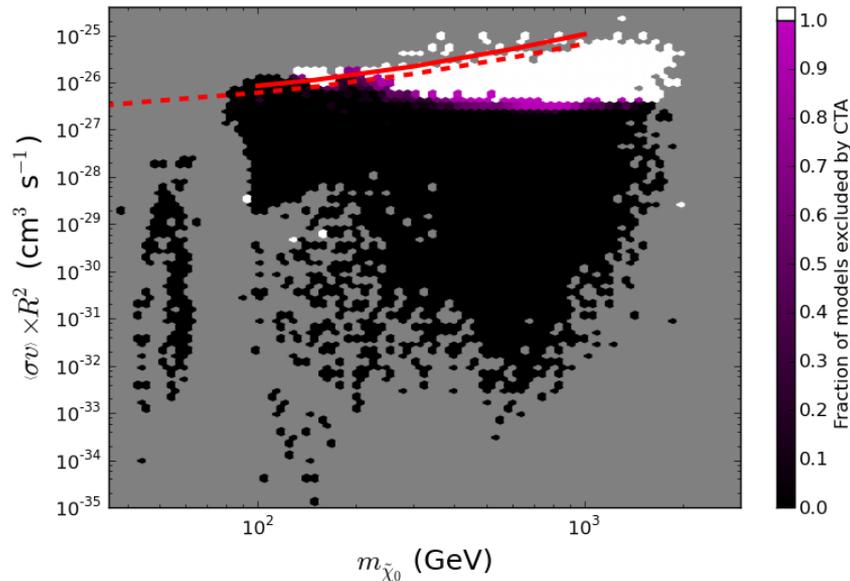


- Of course it would be nice to examine how a given search is doing using the variables employed by the other searches...but there are many combinations

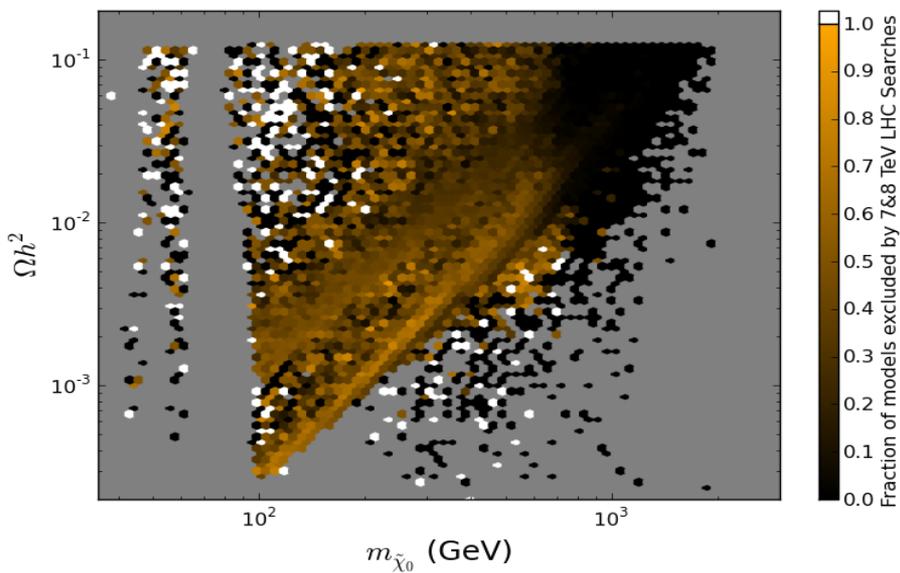
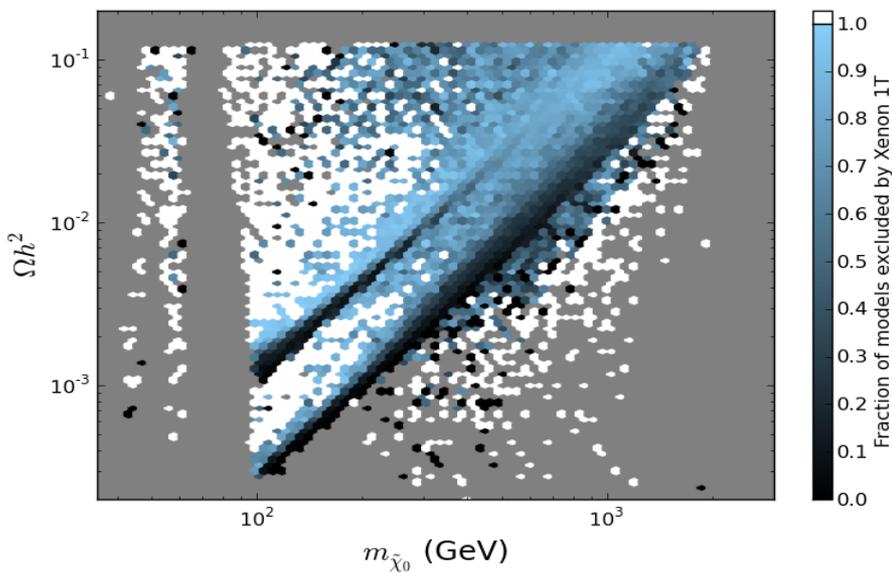
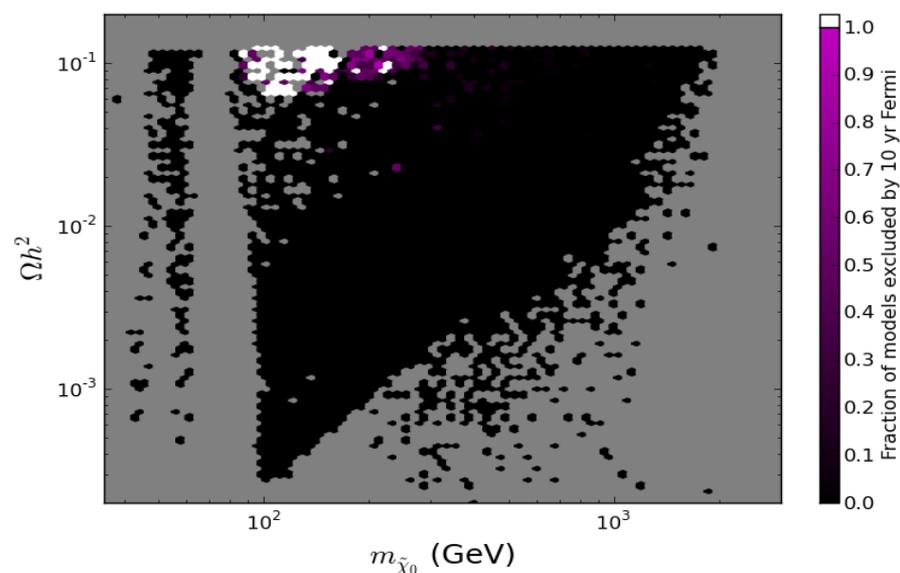
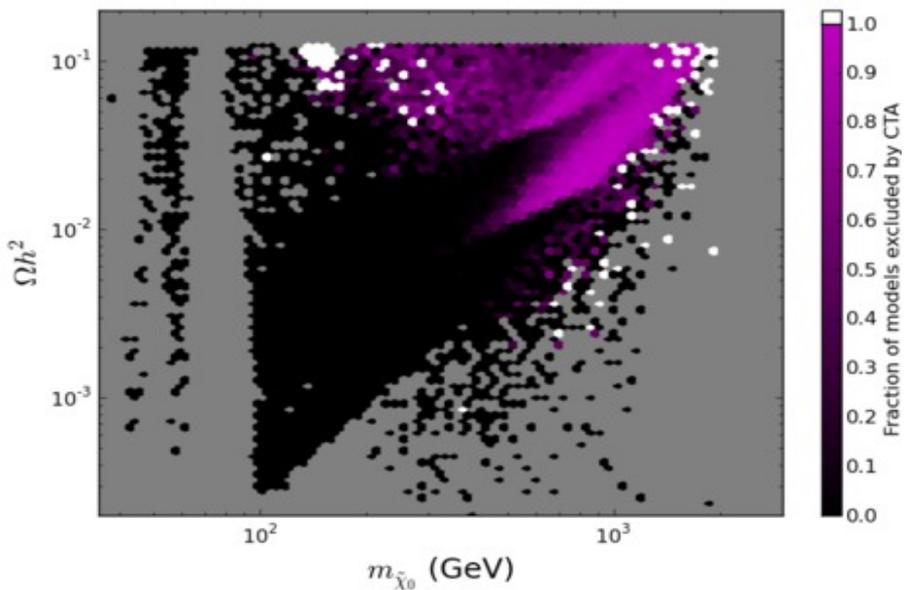
Search Exclusion Efficiencies: Xenon-axis



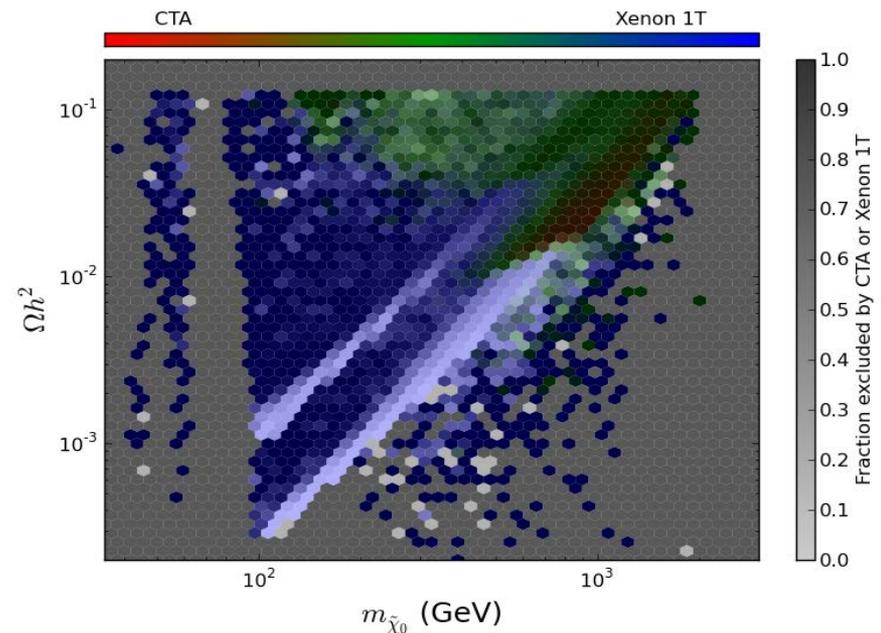
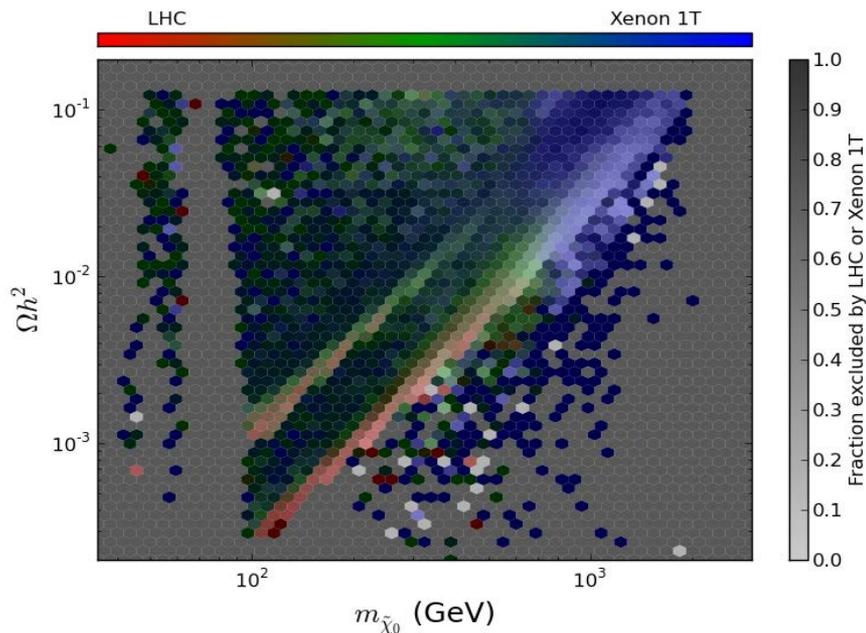
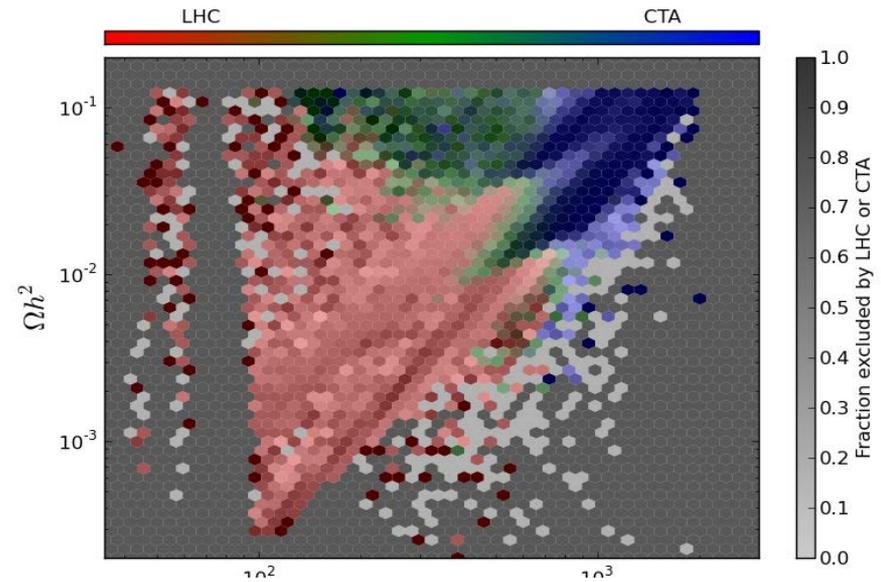
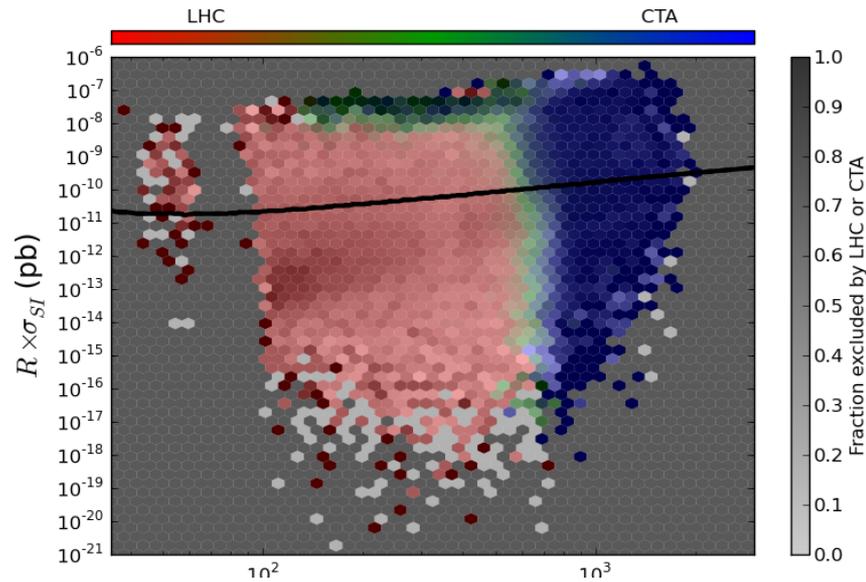
Search Exclusion Efficiencies: CTA-axis



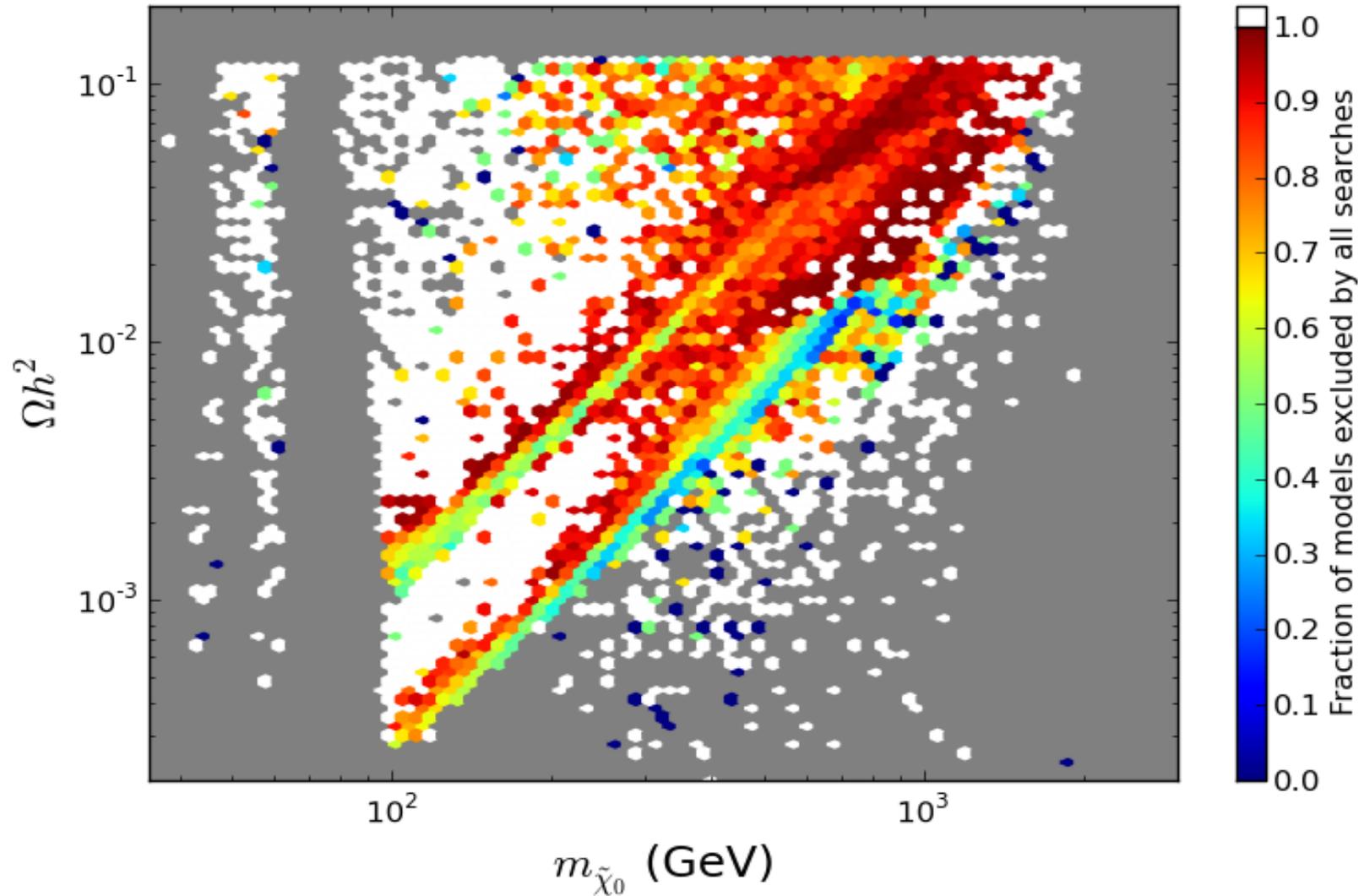
Search Exclusion Efficiencies: Ω -axis



Pair-Wise Search Comparison

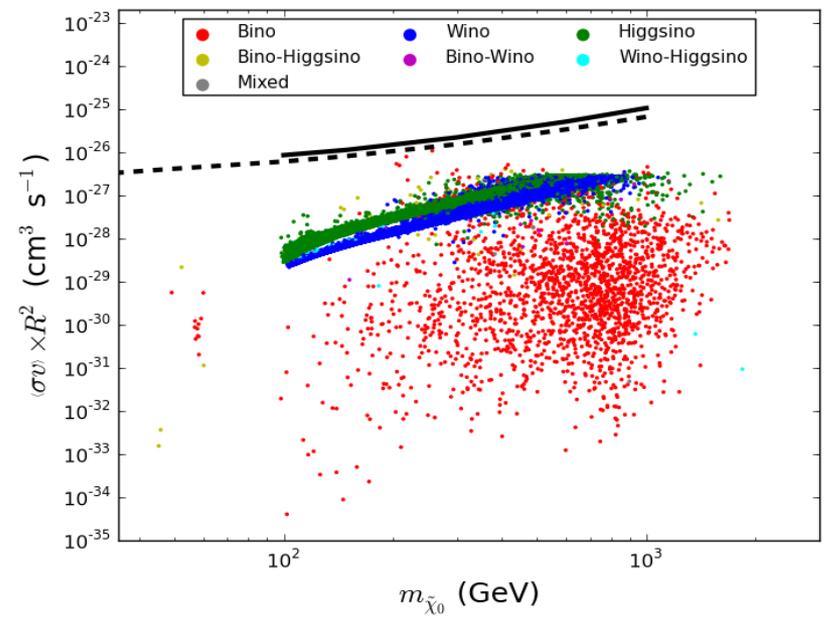
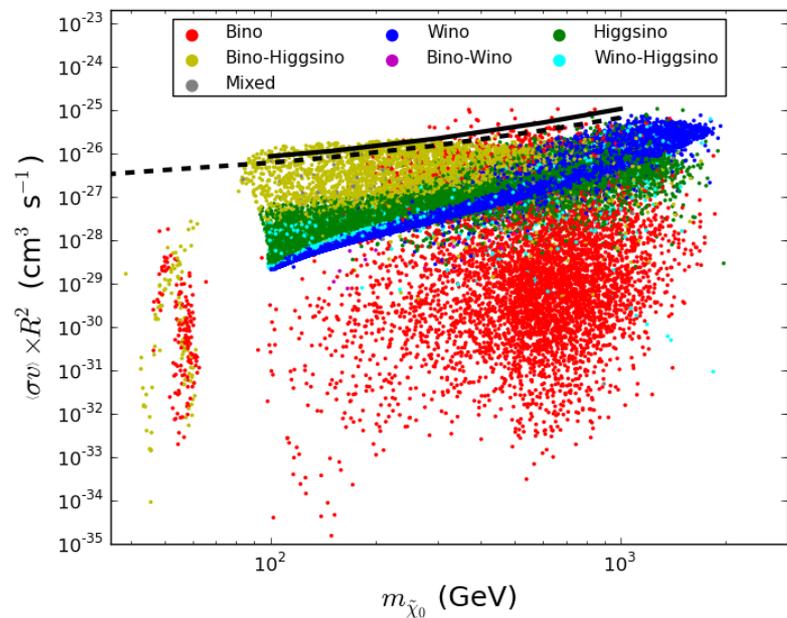
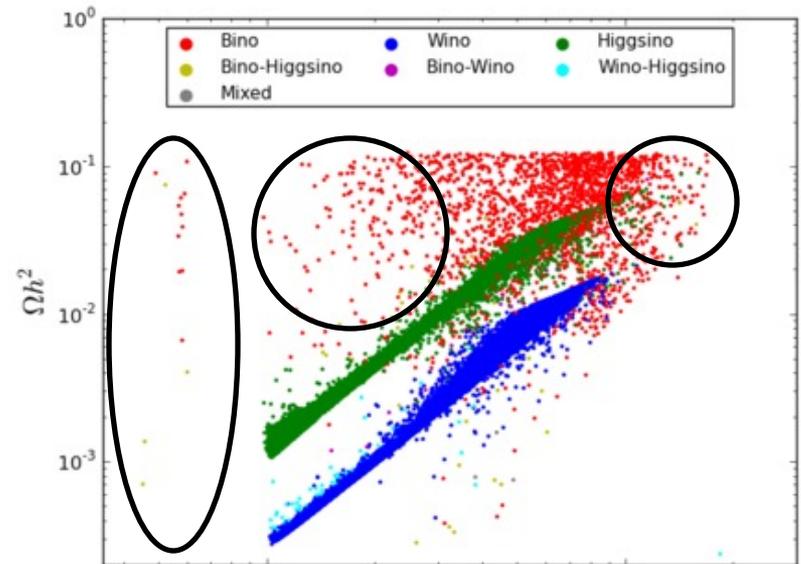
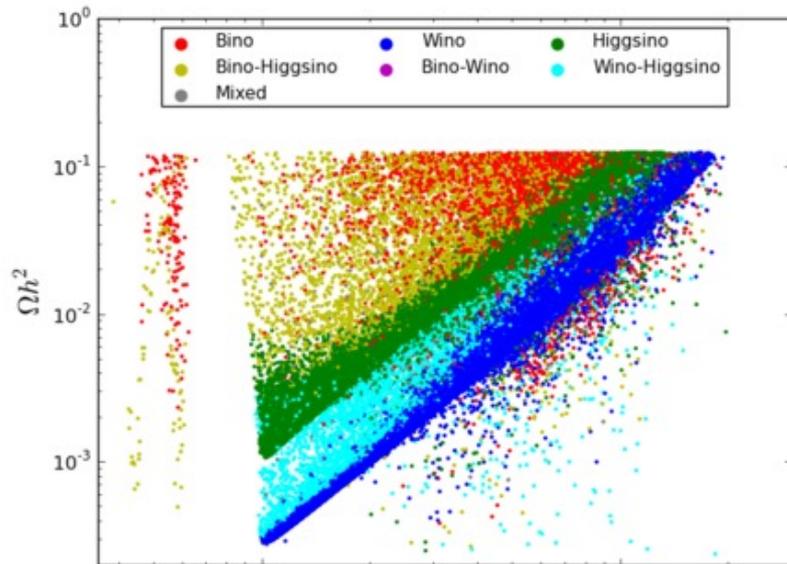


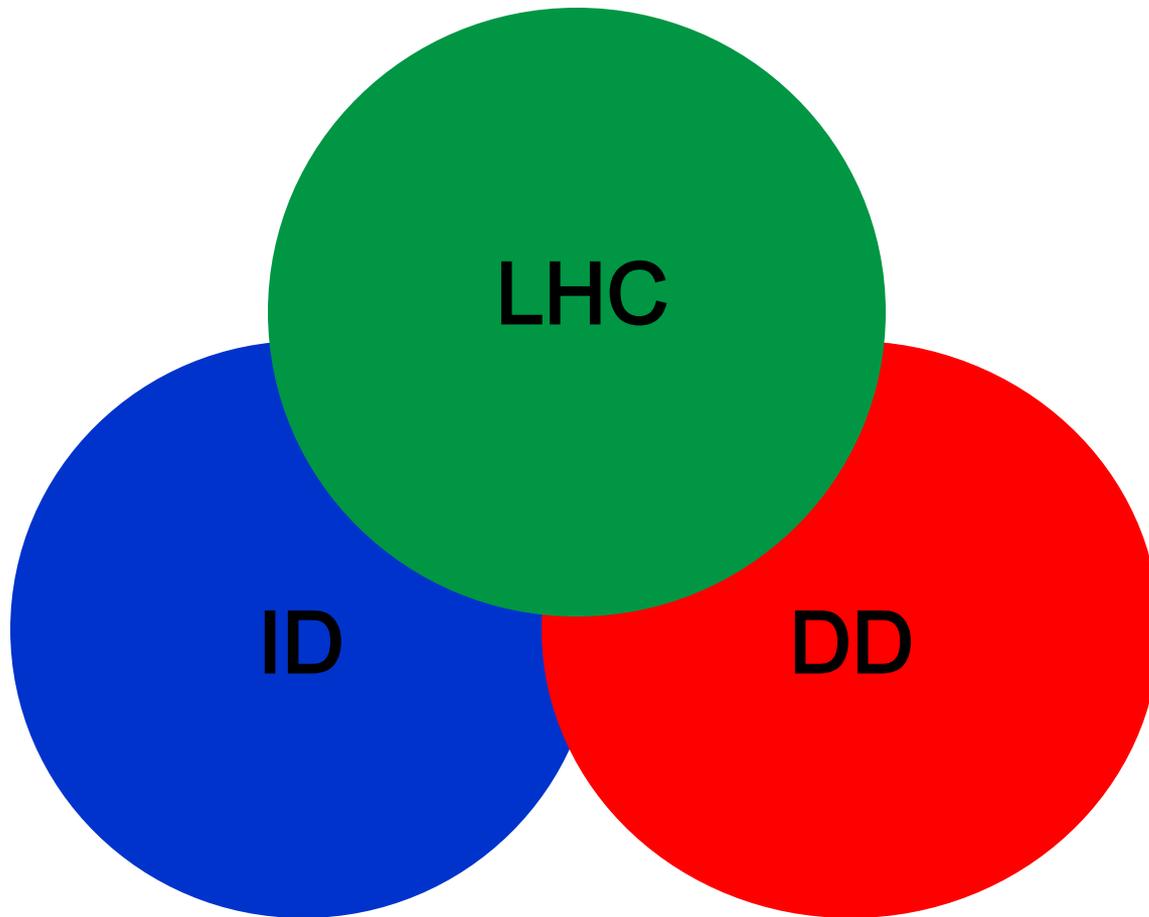
OVERALL Combined Search Efficiency



~61% of models excluded

Before & After LSP Property Distributions





Complementarity Indeed !

Summary & Outlook

- Our study is still preliminary but interesting results are seen
- The pMSSM nicely shows the complementarity of the various searches for SUSY DM : SI + CTA + LHC14 will likely cover most of the pMSSM space (right now ~61%)
- Multiple/overlapping searches will allow for extensive parameter space coverage.. even for very 'sub-thermal' densities. This will be important if a signal is seen!
- Null searches will point to a co-annihilating bino if the relic density is saturated
- Still lots more work to do especially on LHC-14!

BACKUPS

pMSSM Scan Ranges: Neutralino LSPs

(via [SOFTSUSY](#))

$$100 \text{ GeV} \leq m_{\text{Le}1,3} \leq 4 \text{ TeV}$$

$$400 \text{ GeV} \leq m_{\text{Qud}12} \leq 4 \text{ TeV} \quad 200 \text{ GeV} \leq m_{\text{Qud}3} \leq 4 \text{ TeV}$$

$$50 \text{ GeV} \leq |M_1| \leq 4 \text{ TeV} \quad 100 \text{ GeV} \leq |M_2, \mu| \leq 4 \text{ TeV}$$

$$400 \text{ GeV} \leq M_3 \leq 4 \text{ TeV} \quad |A_{t,b,\tau}| \leq 4 \text{ TeV}$$

(flat scan)

$$100 \text{ GeV} \leq M_A \leq 4 \text{ TeV}$$

$$1 \leq \tan\beta \leq 60$$

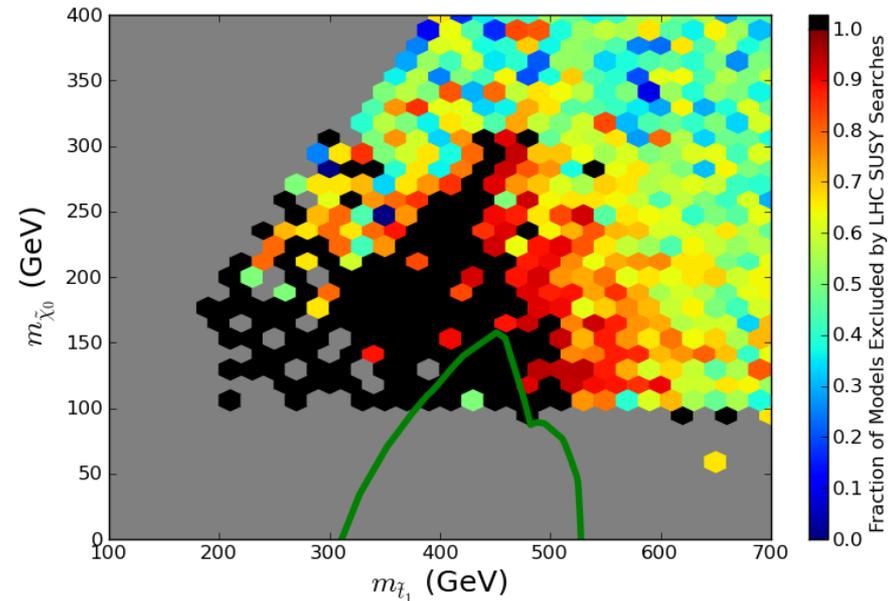
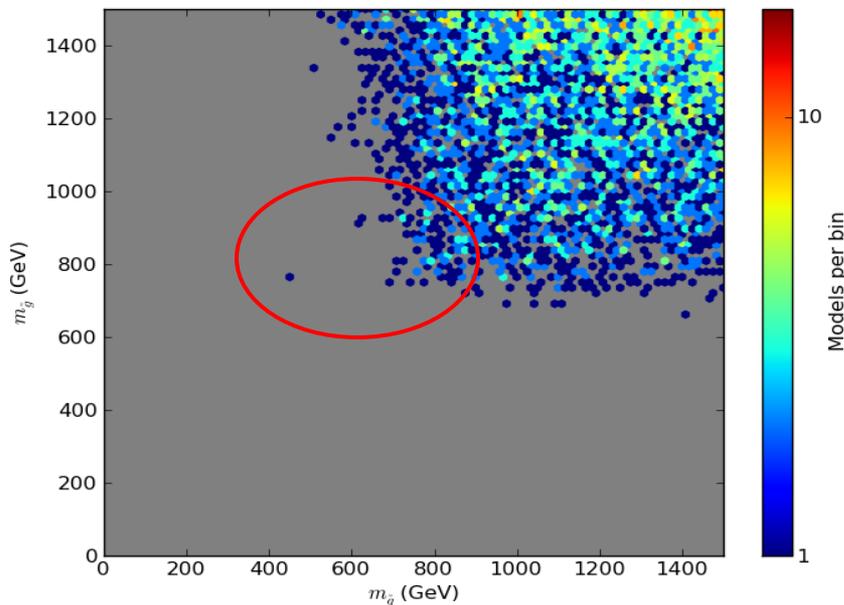
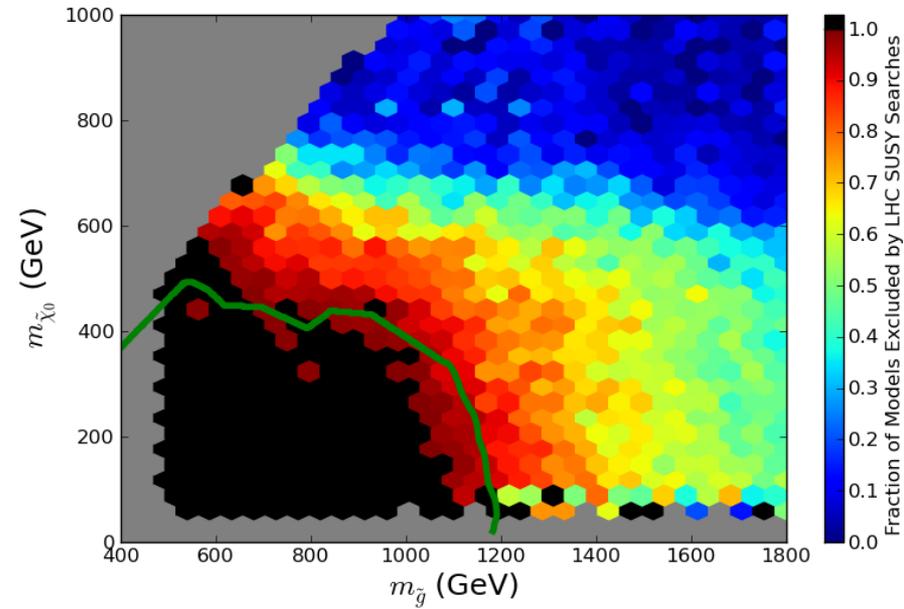
- Generate points & then **apply all the usual non-LHC + all LHC non-MET constraints (as of 12/2011)** to make a preliminary selection.

Some Constraints

- $\Delta\rho$ / W-mass
- $b \rightarrow s \gamma$
- $\Delta(g-2)_\mu$
- $\Gamma(Z \rightarrow \text{invisible})$
- Meson-Antimeson Mixing
- $B \rightarrow \tau \nu$
- $B_s \rightarrow \mu\mu$
- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches
- BBN energy deposition for gravitinos
- Relic ν 's & diffuse photon bounds
- No tachyons or color/charge breaking minima
- Stable vacua only

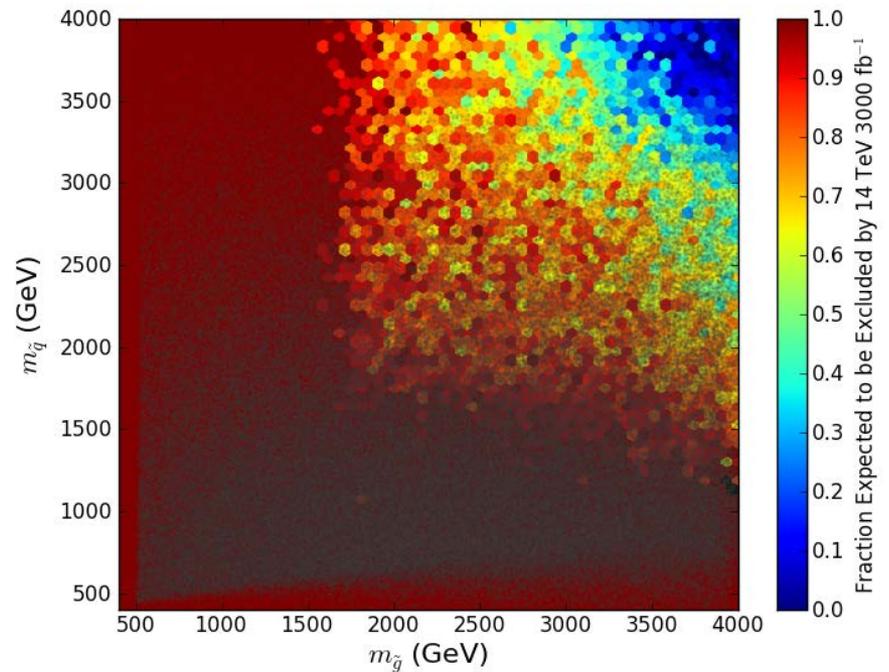
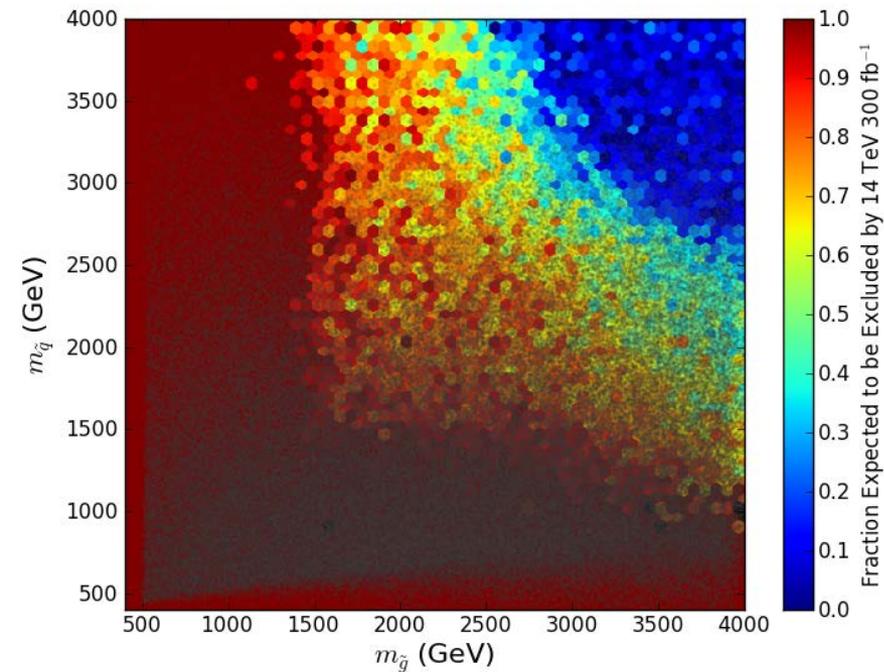
Some Results II

- Parameter regions killed in the CMSSM still survive here
- The allowed/excluded regions are not always well-represented by either the CMSSM or the simplified model approaches

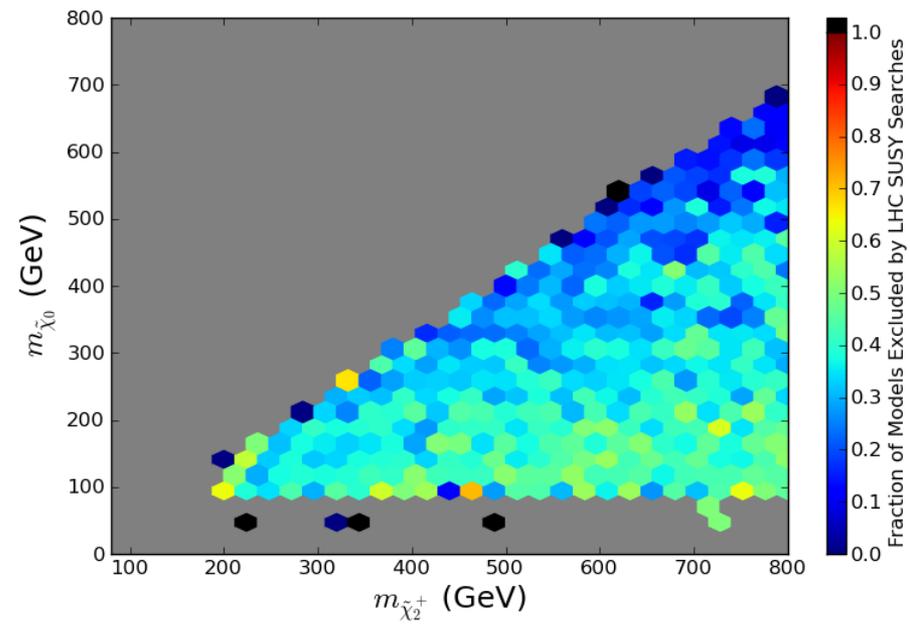
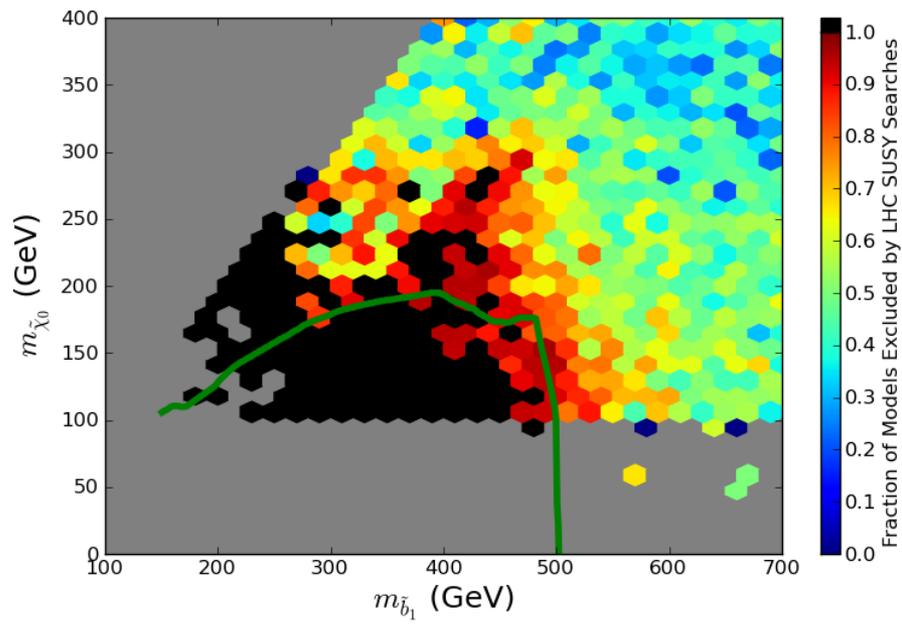


Educated Guess at LHC pMSSM Coverage for Both 0.3 & 3 ab^{-1}

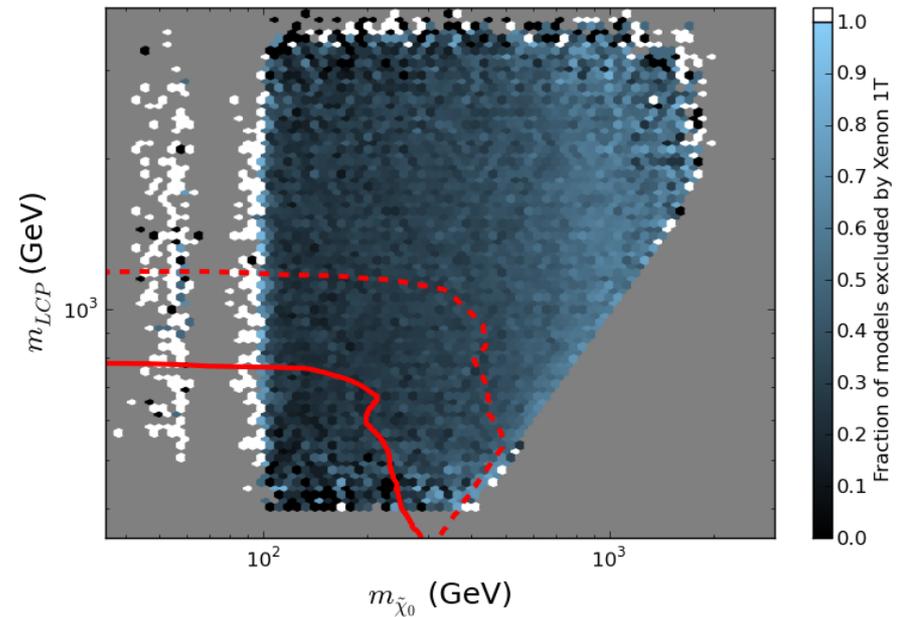
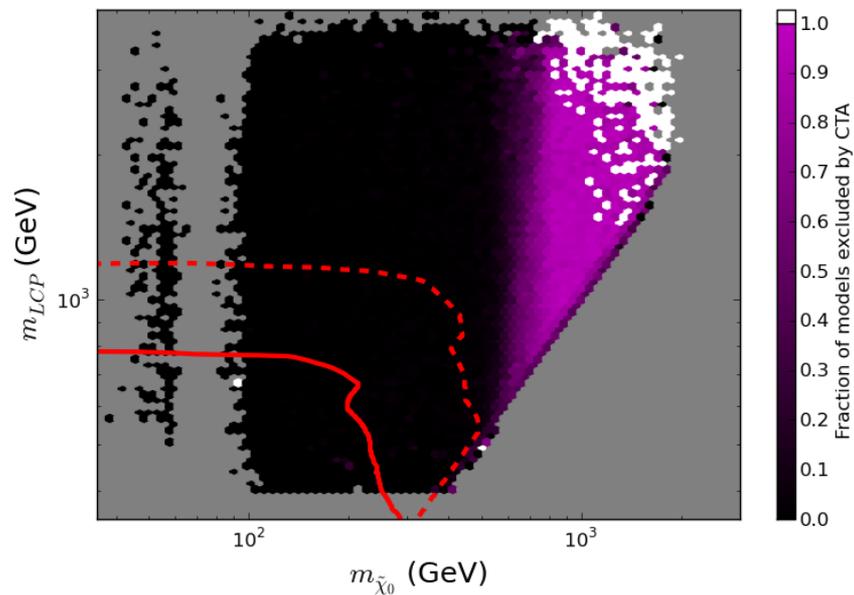
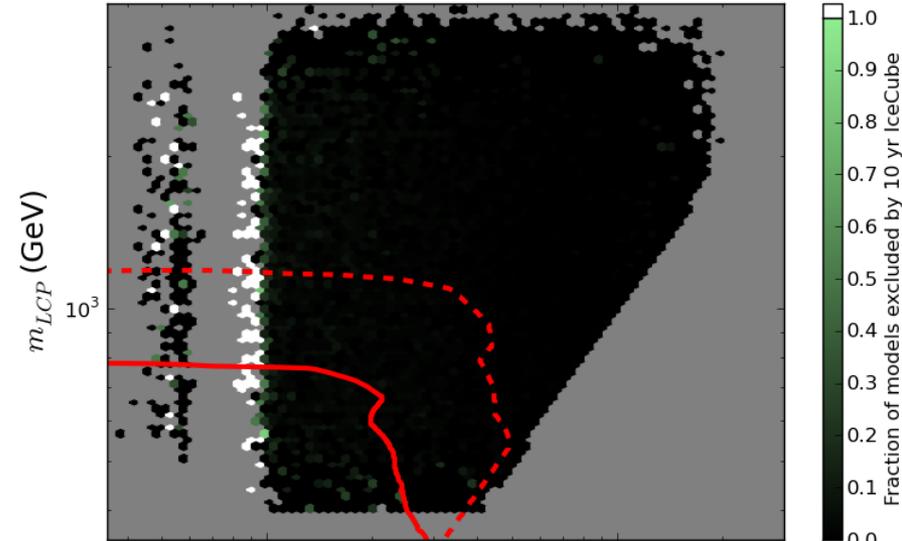
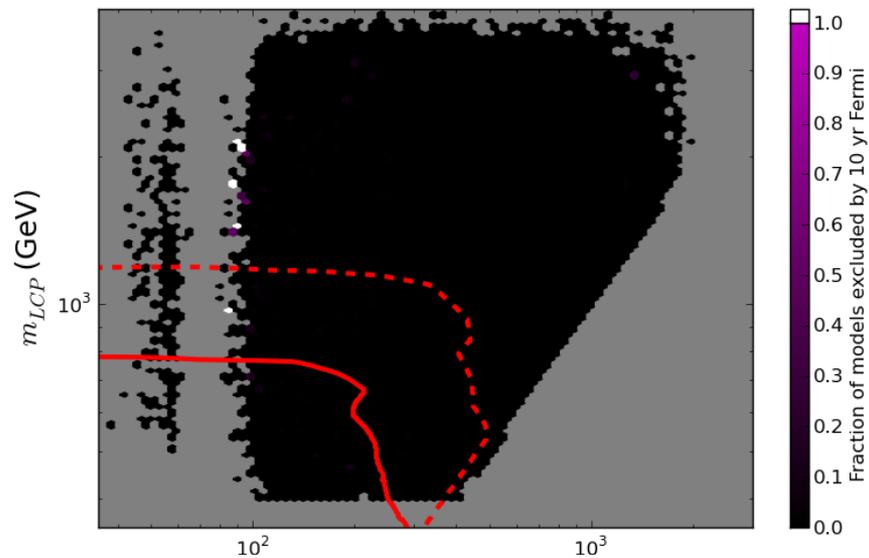
An actual real estimate of coverage will require doing the 14 TeV analyses...



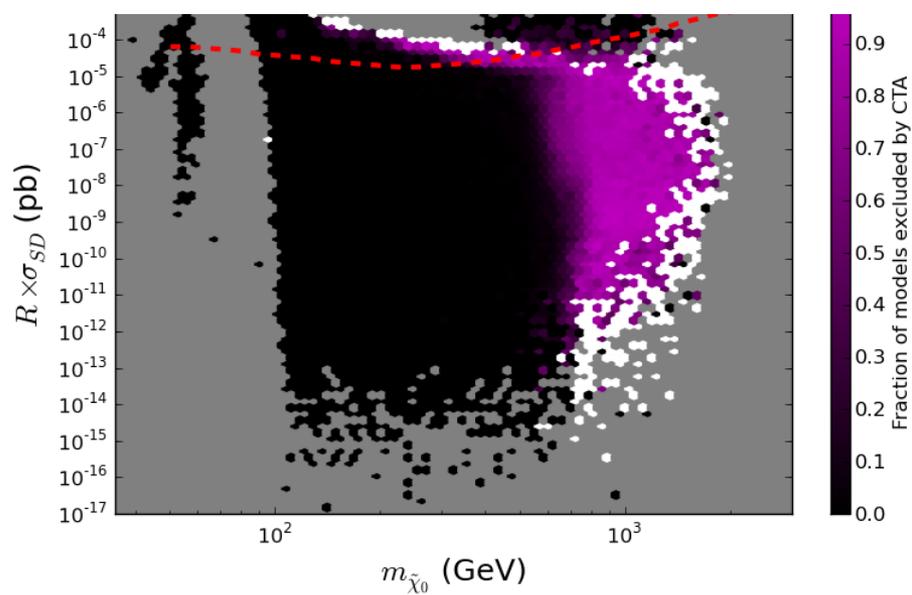
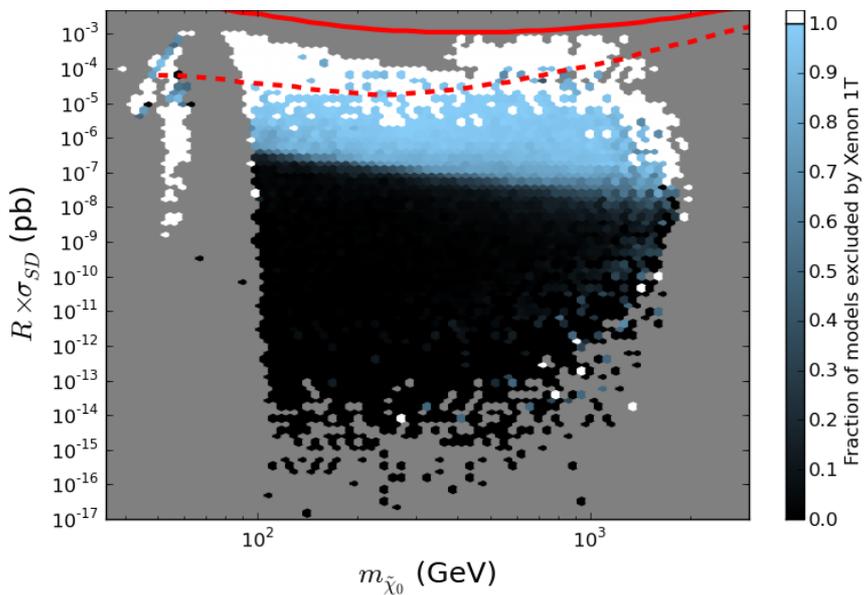
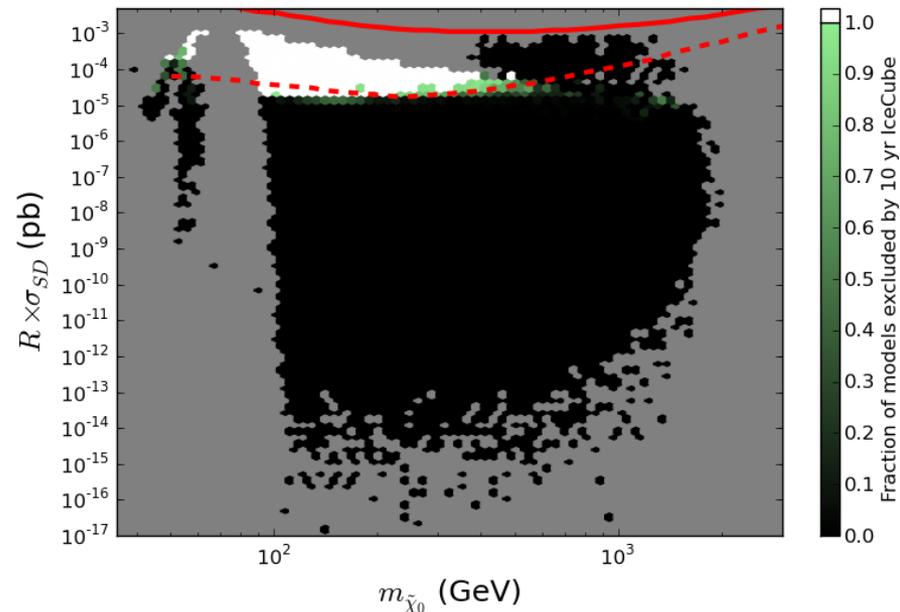
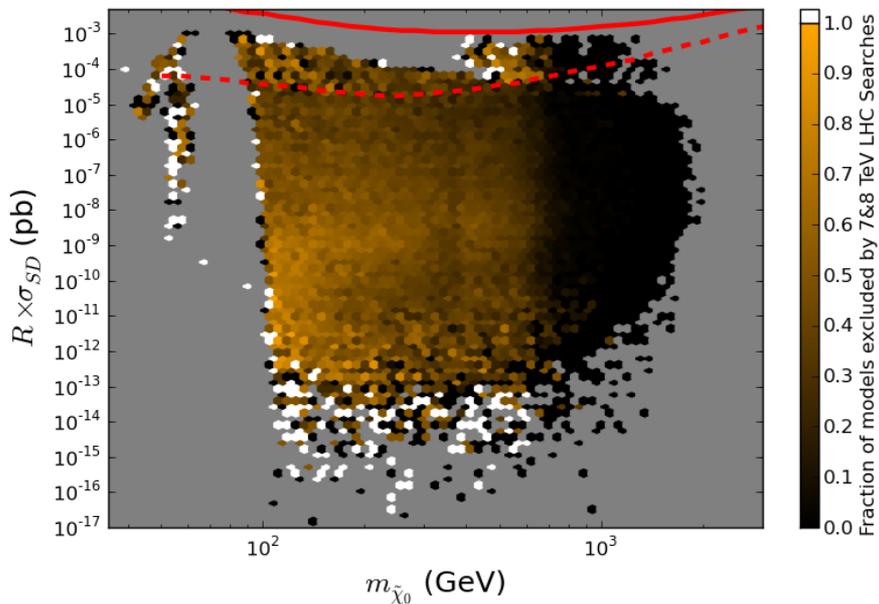
More LHC Results from 7 & 8 TeV Searches



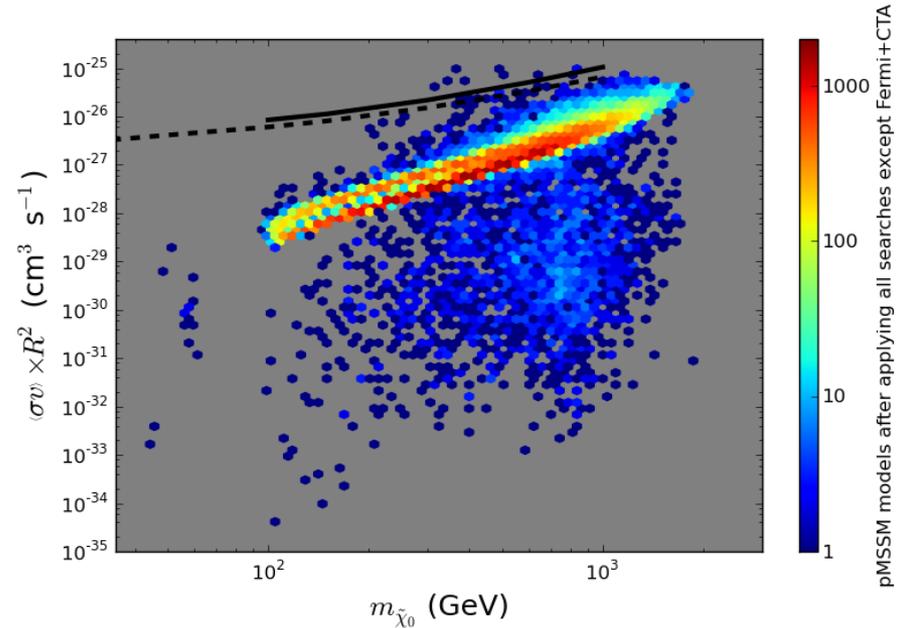
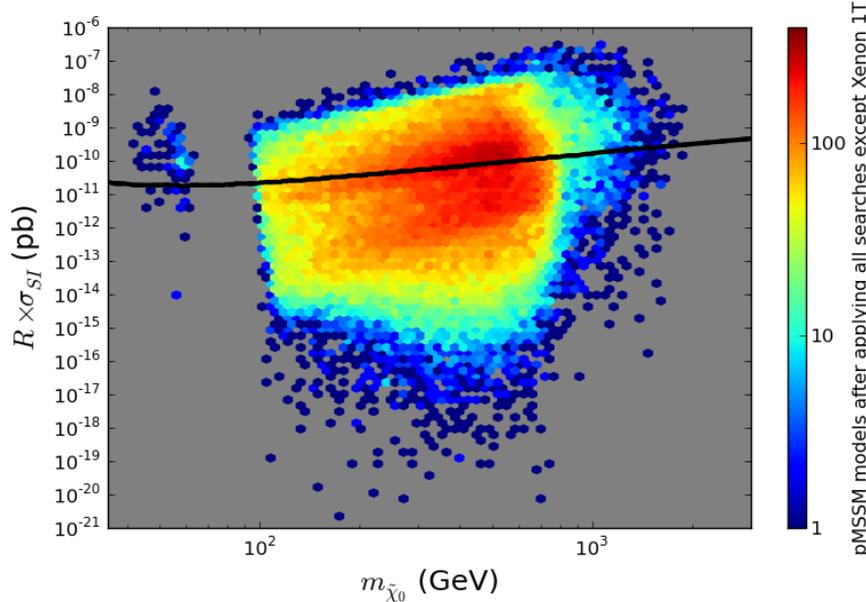
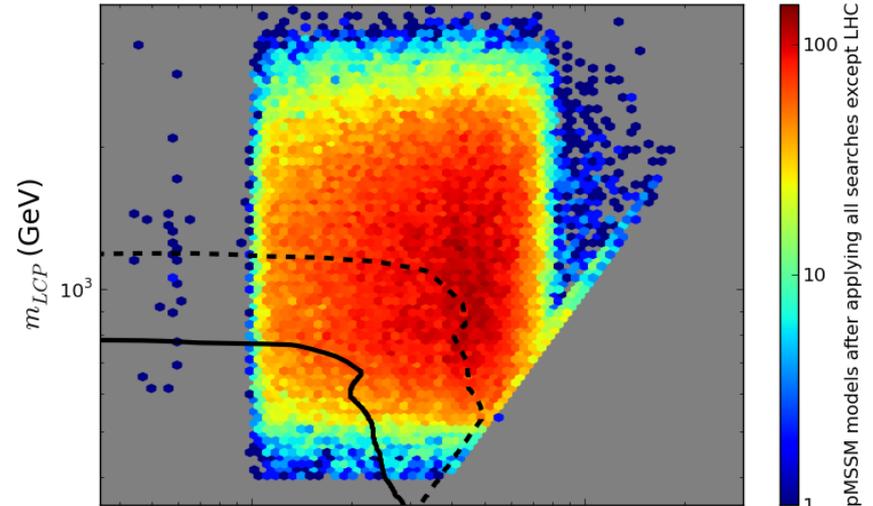
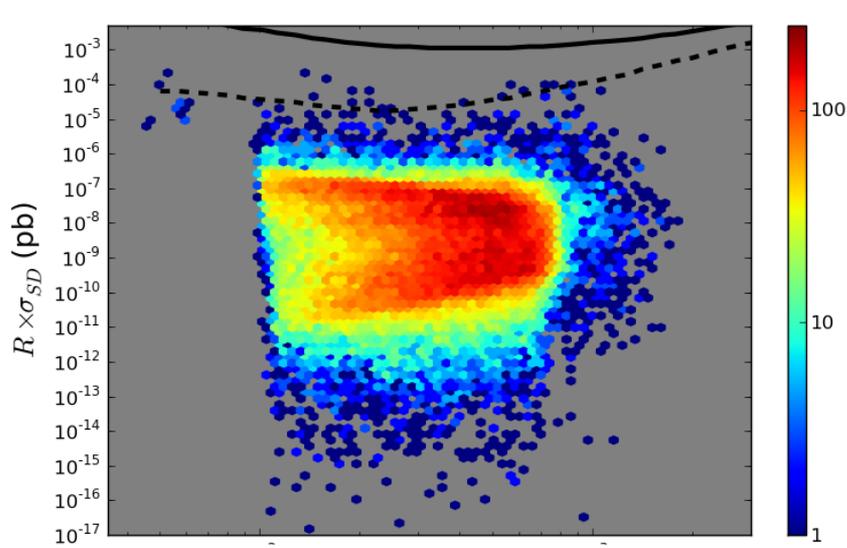
Search Exclusion Efficiencies: LHC-axis



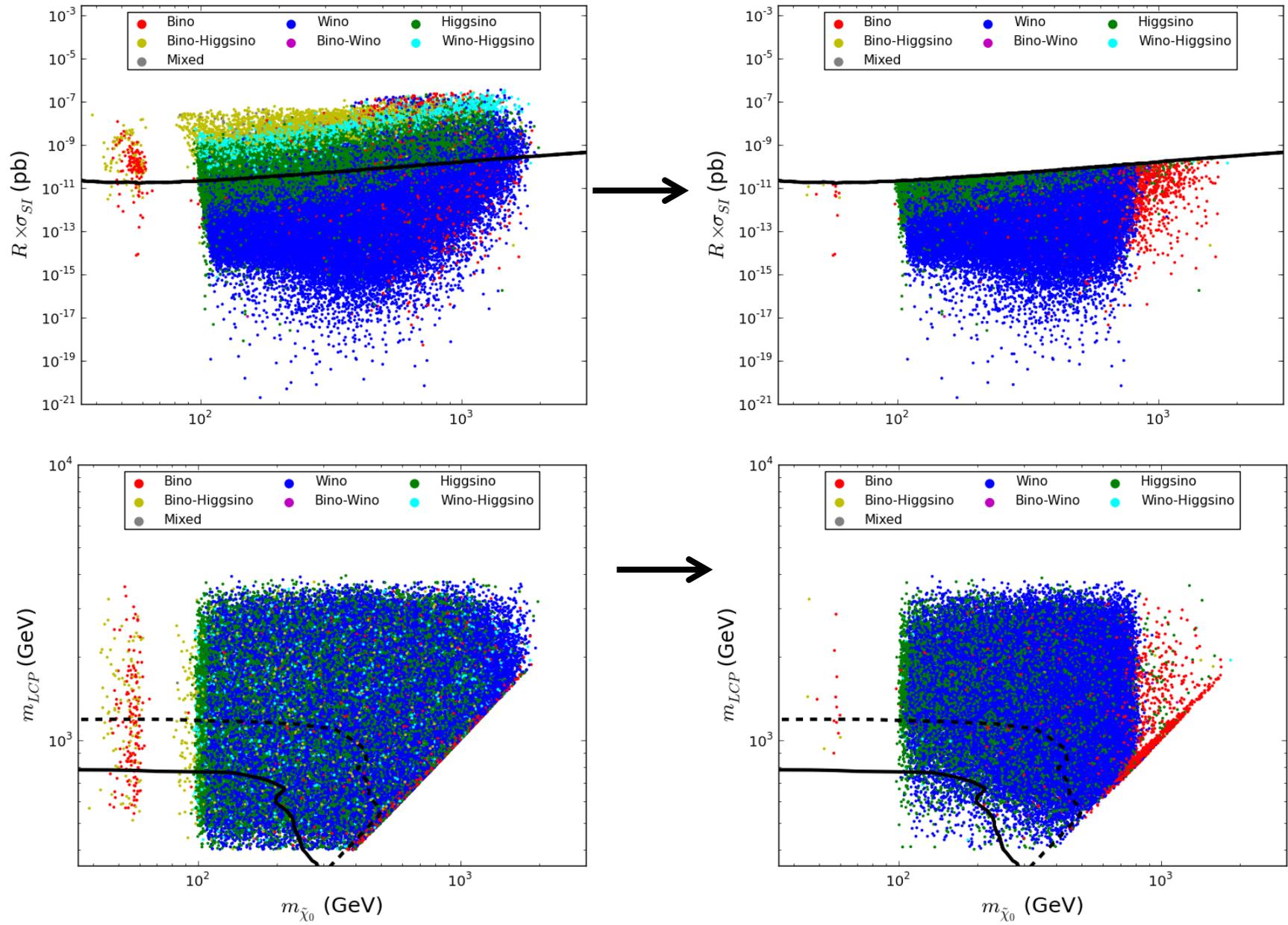
Search Exclusion Efficiencies: ICE³ -axis



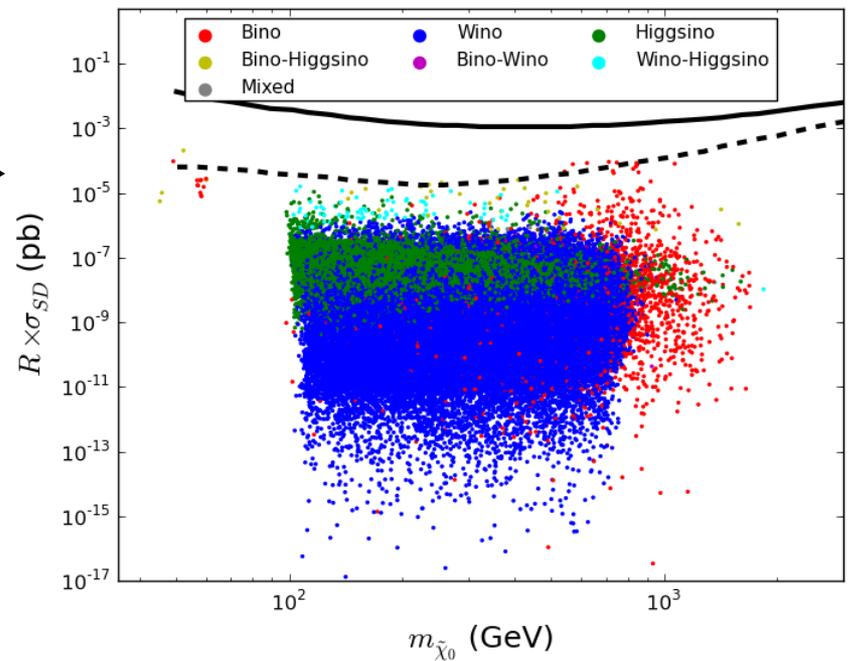
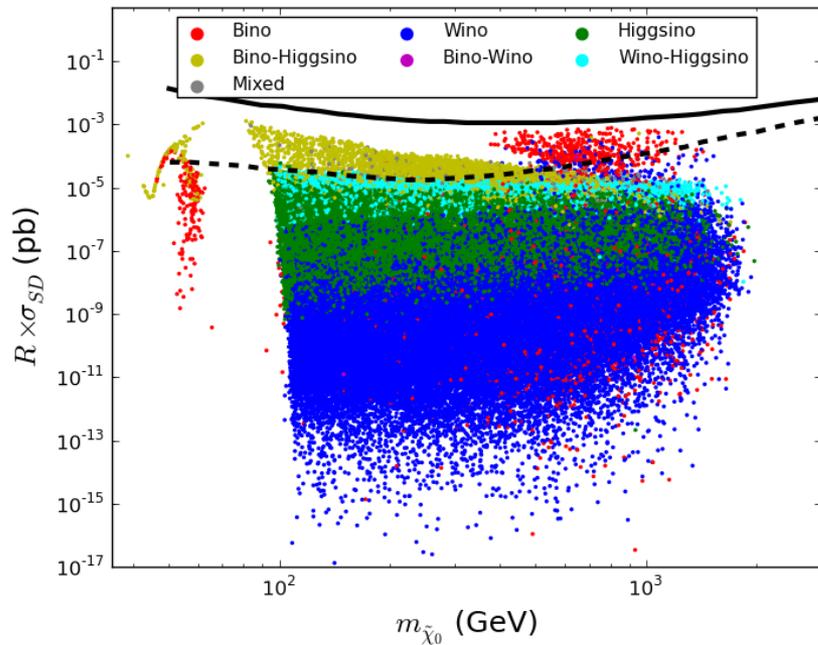
'All-But' Survivor Density Distributions



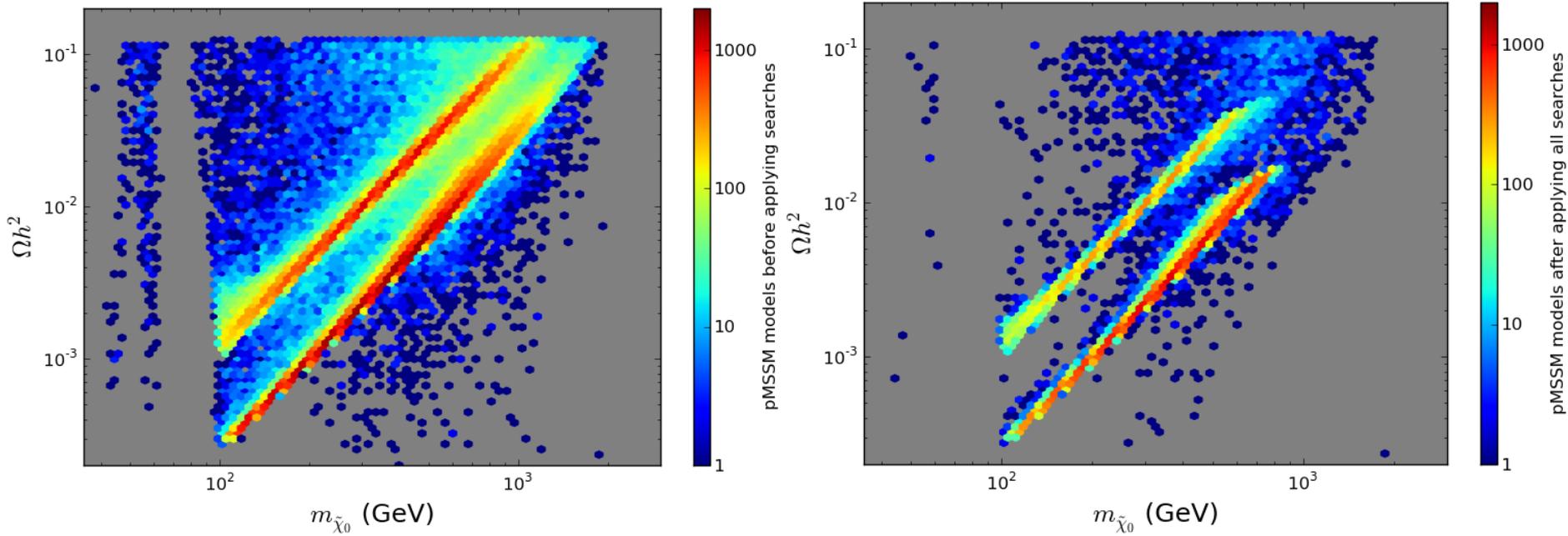
Before & After LSP Property Distributions II

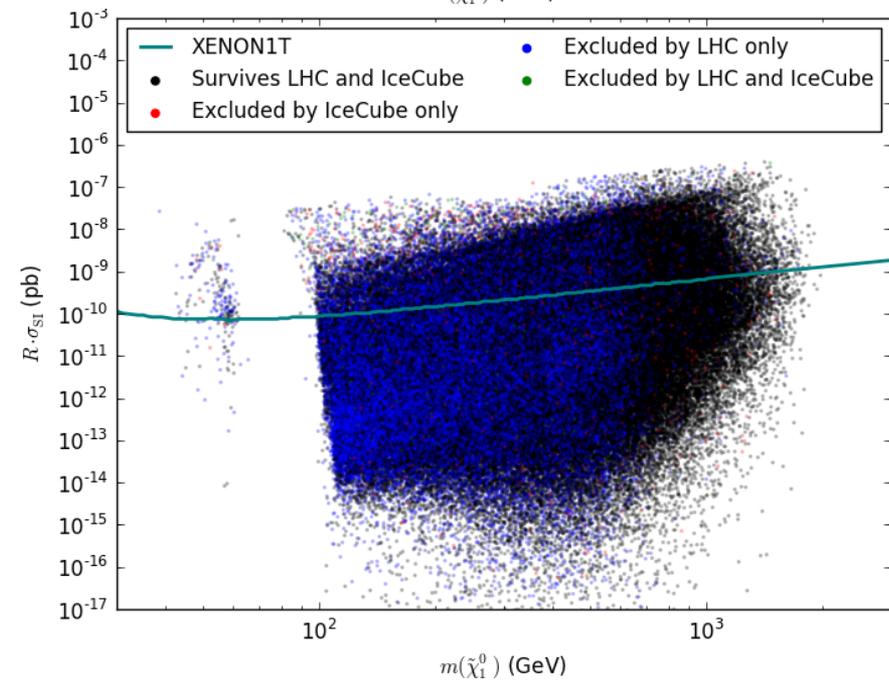
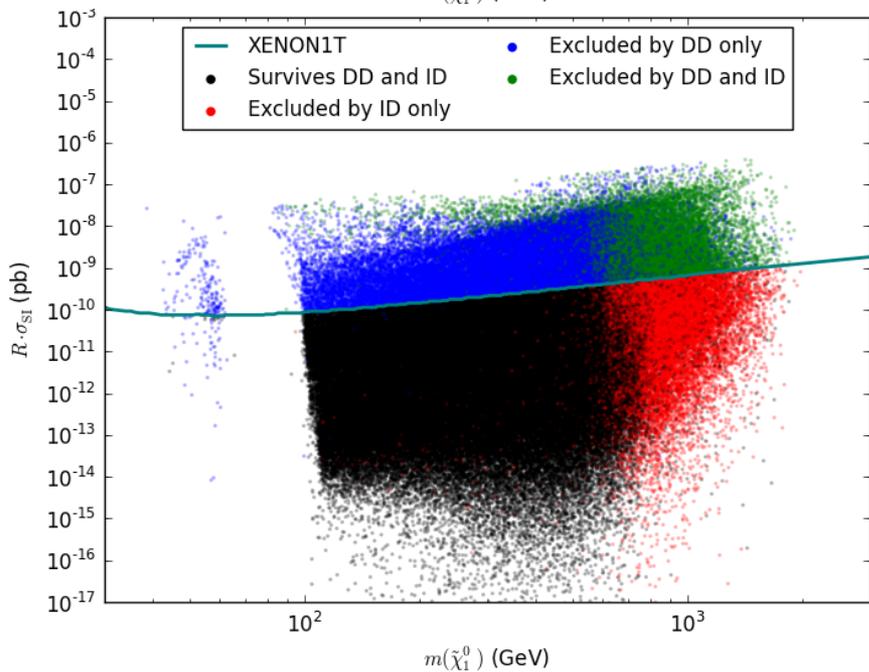
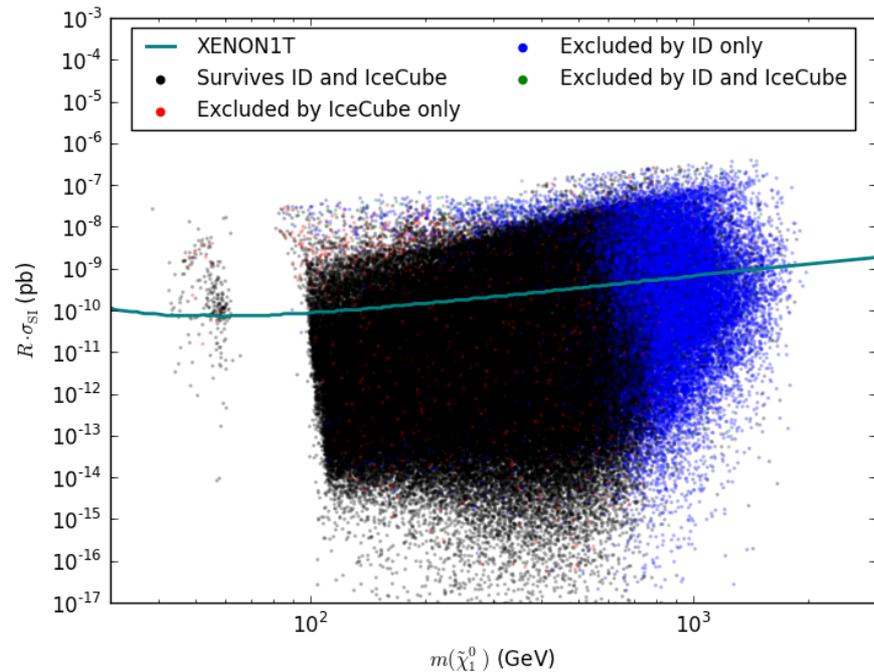
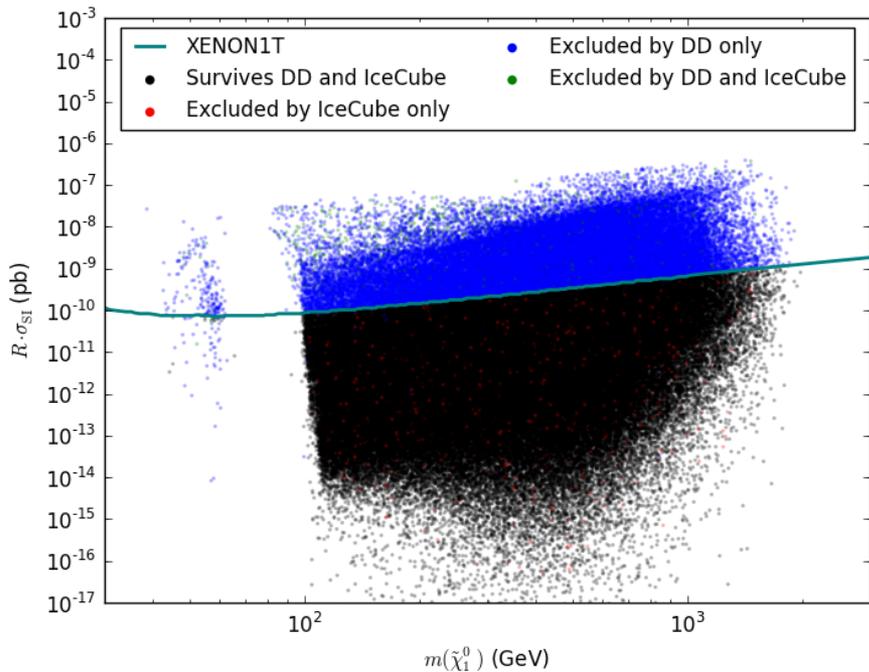


Before & After LSP Property Distributions III

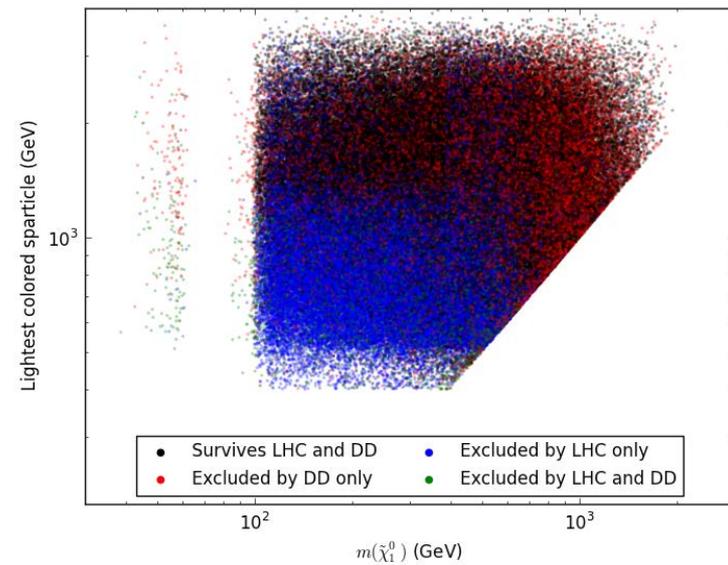
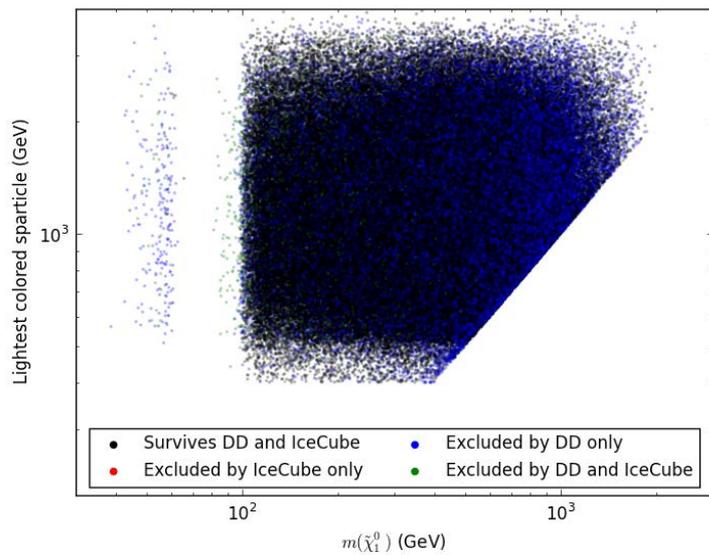
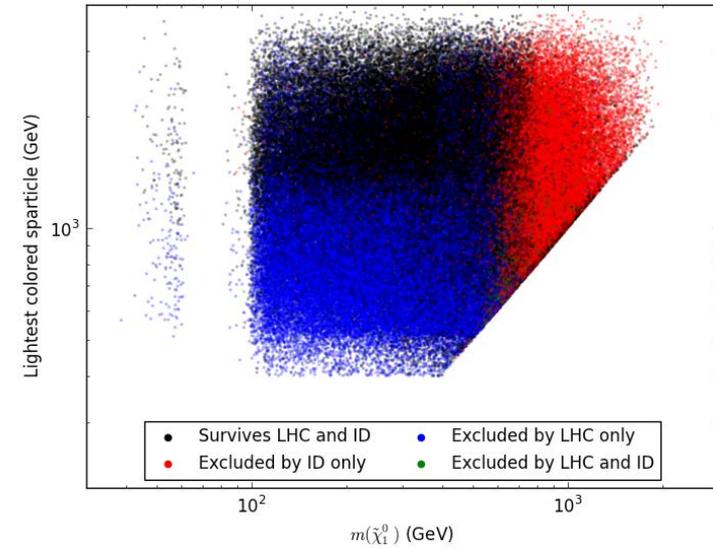
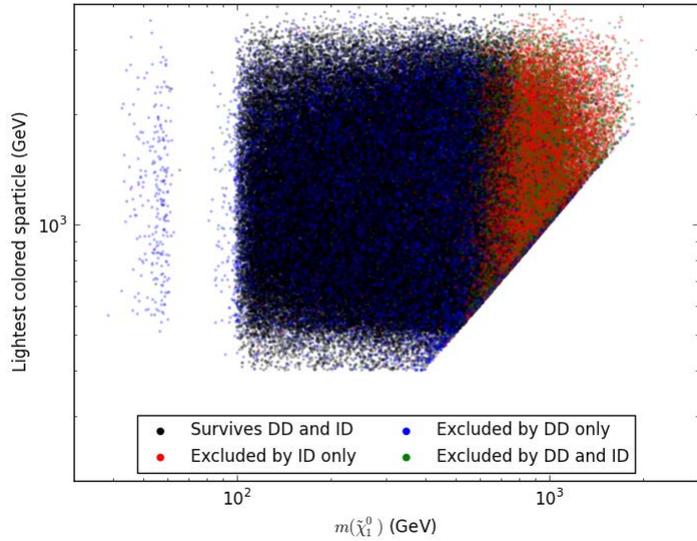


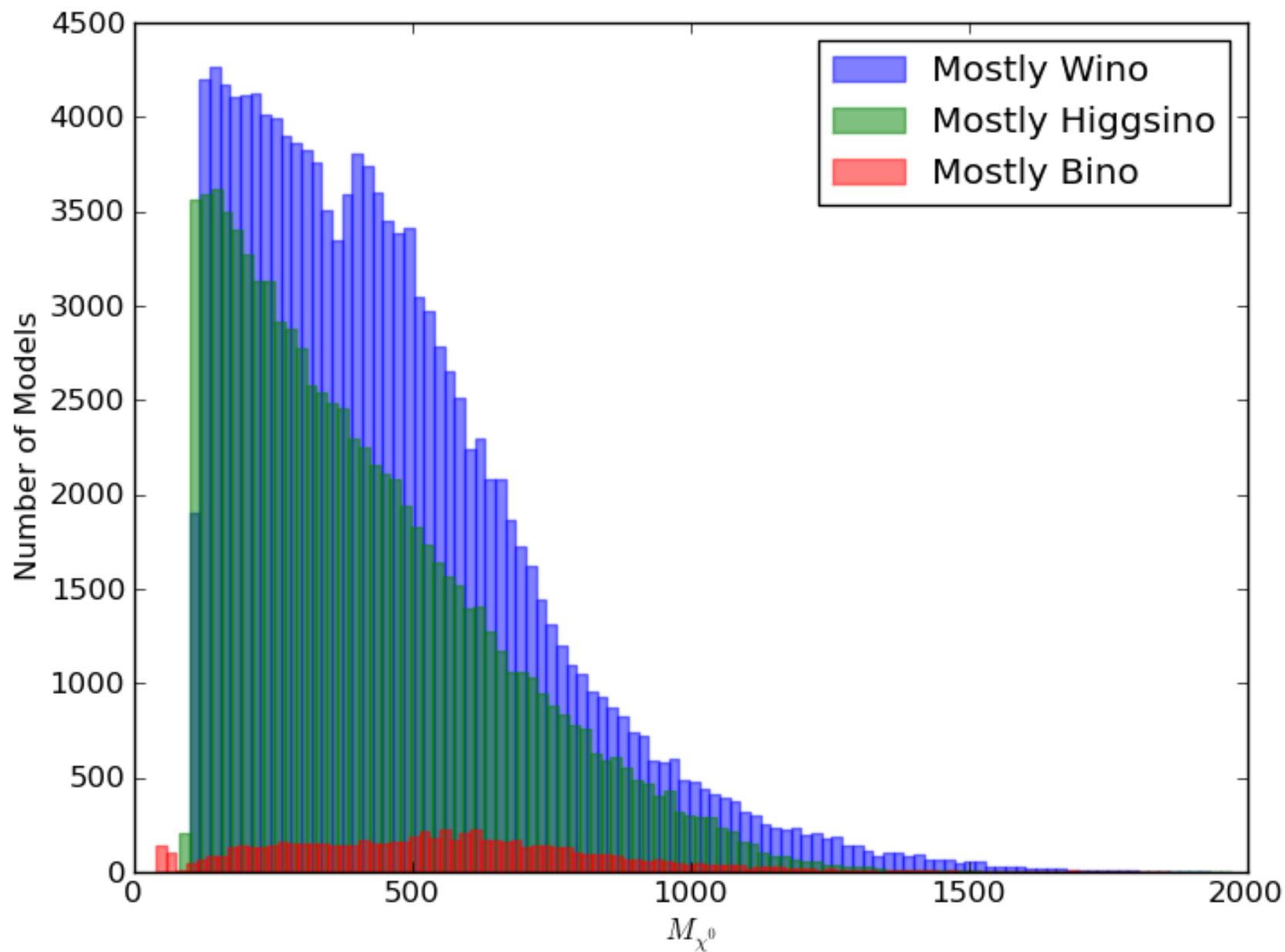
Before & After Relic Density Distributions

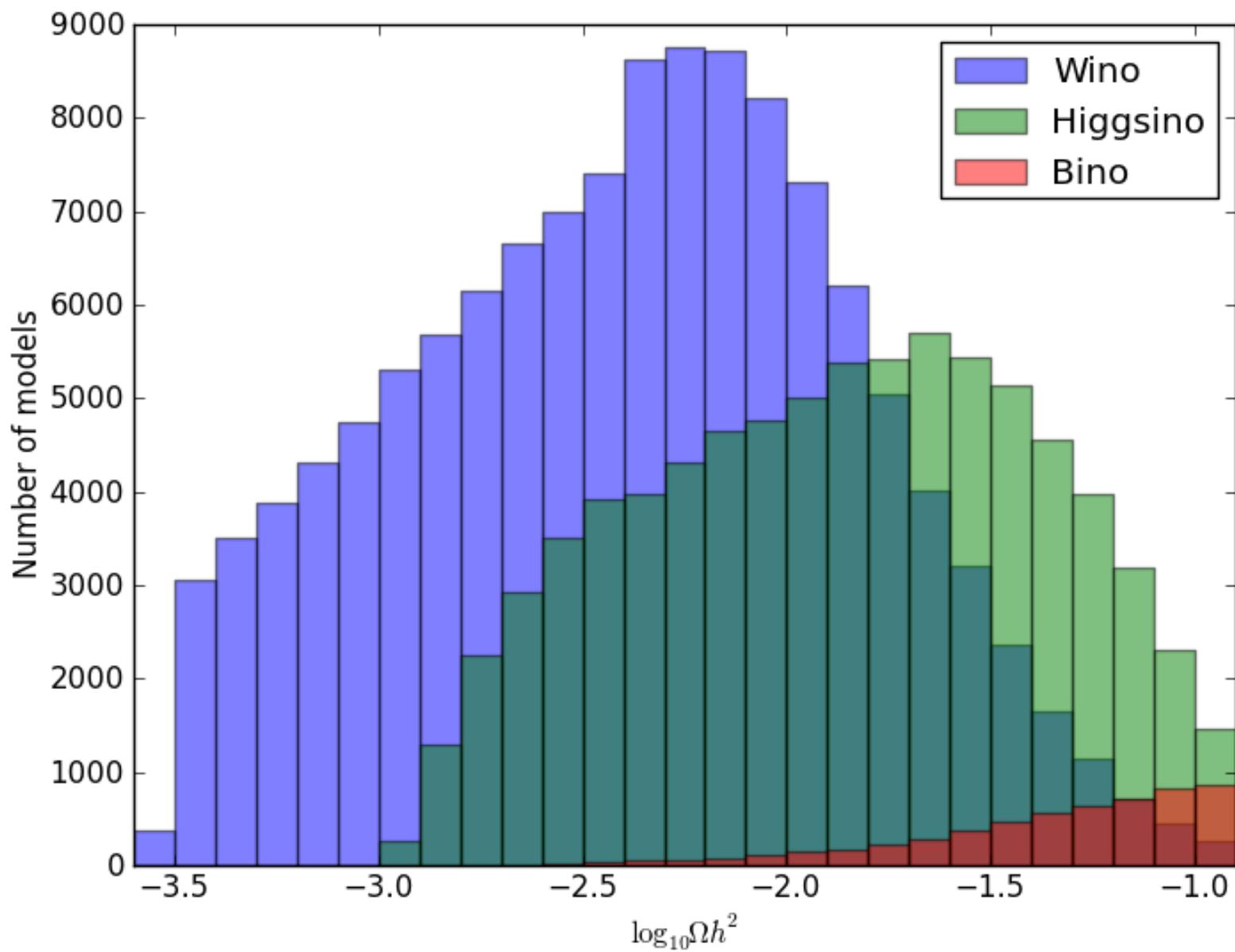




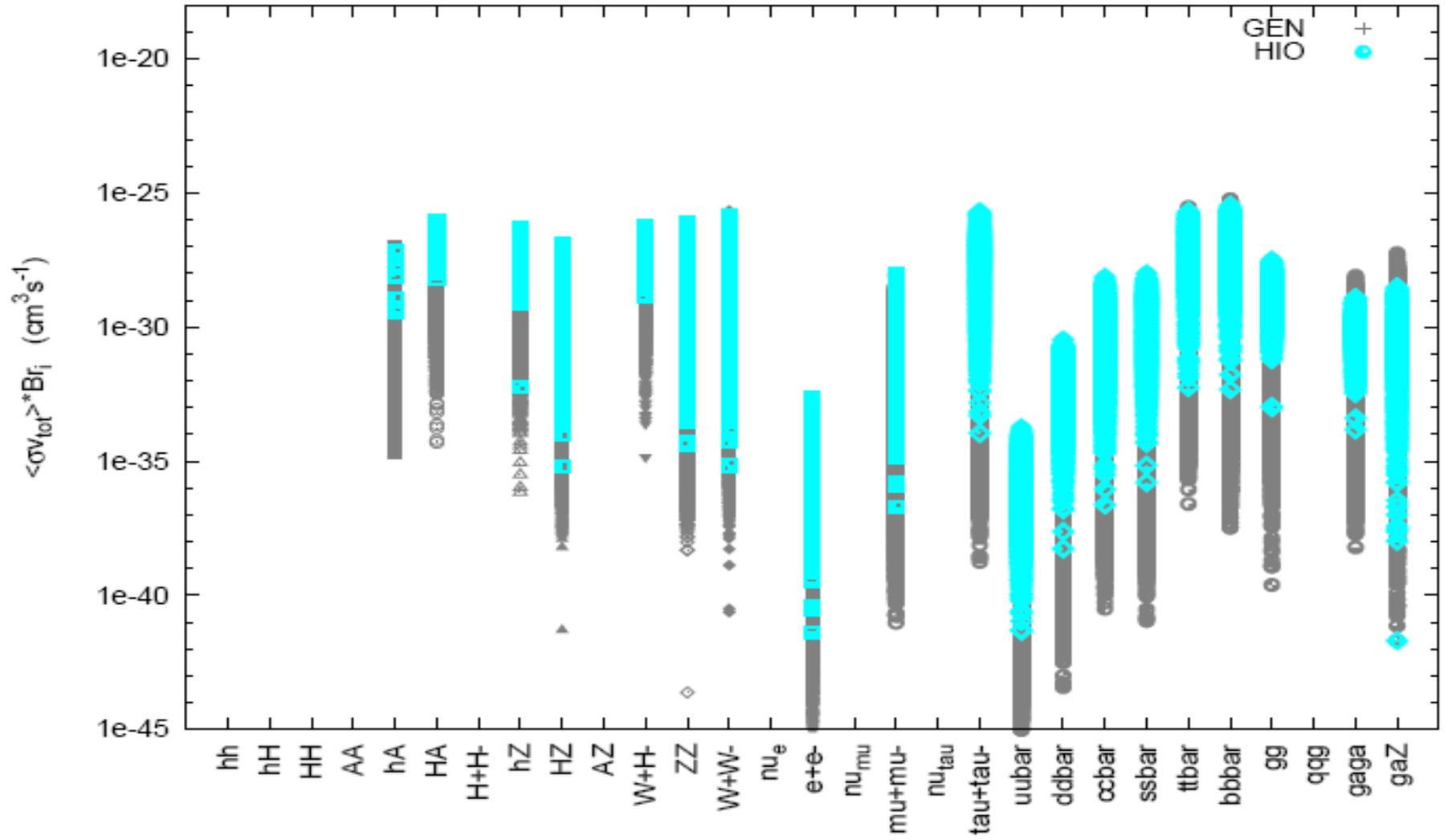
More Survivor Pairs



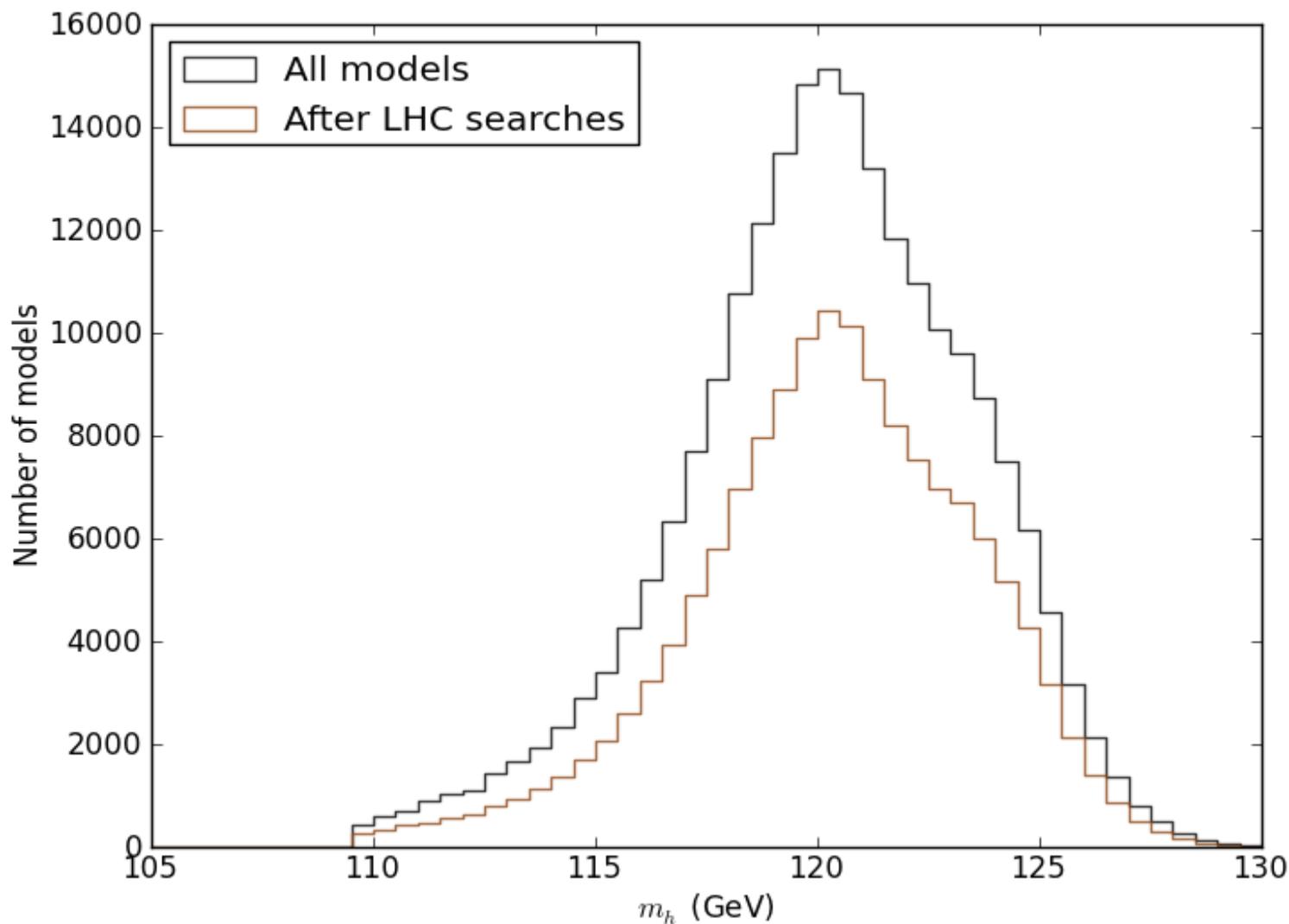




Weighted σ 's cover an enormous range...

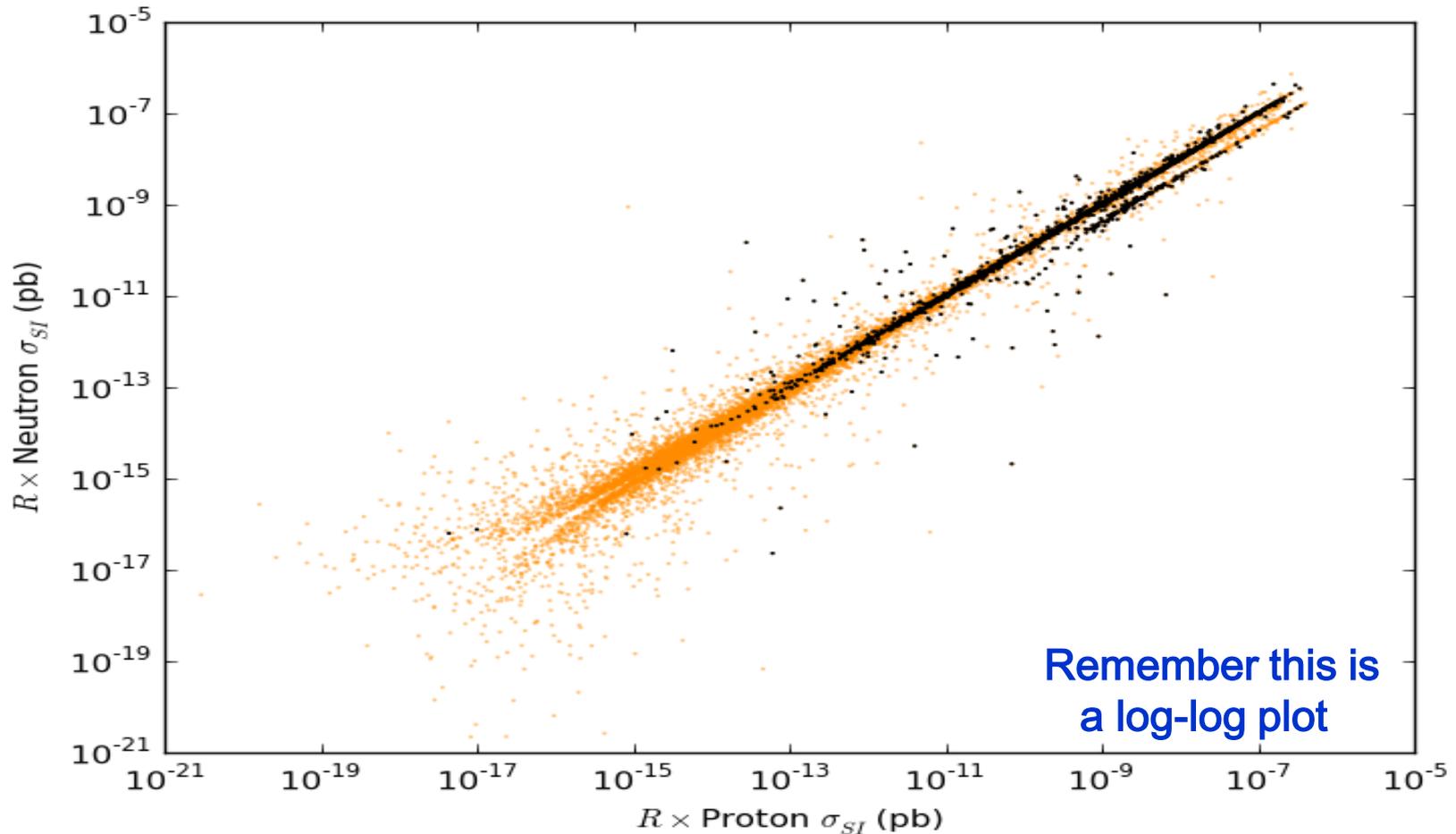


As the SUSY searches are roughly independent of the value of the Higgs mass, the predicted mass of the Higgs is roughly independent of the SUSY searches

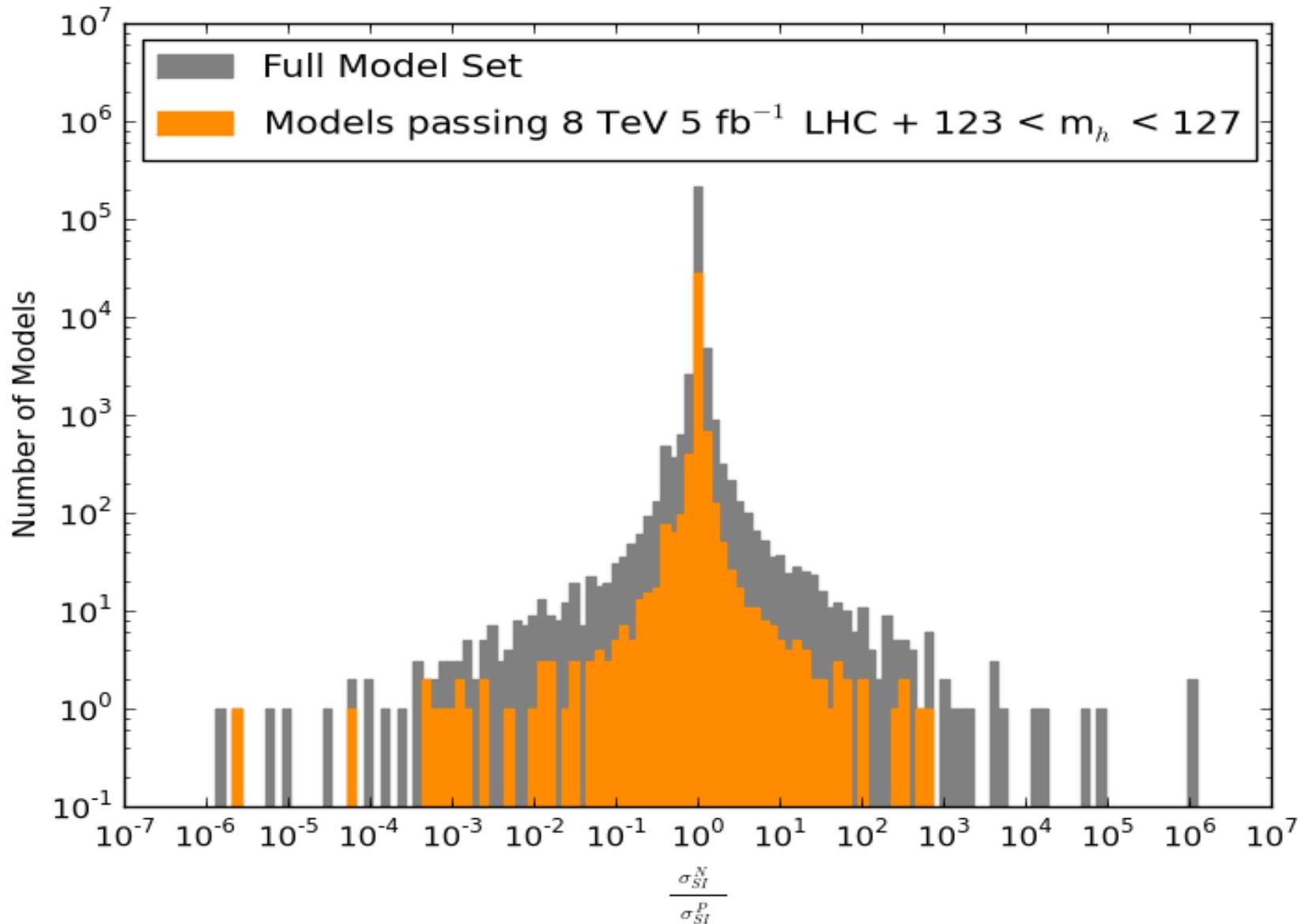


Isospin Violation in SI Cross sections

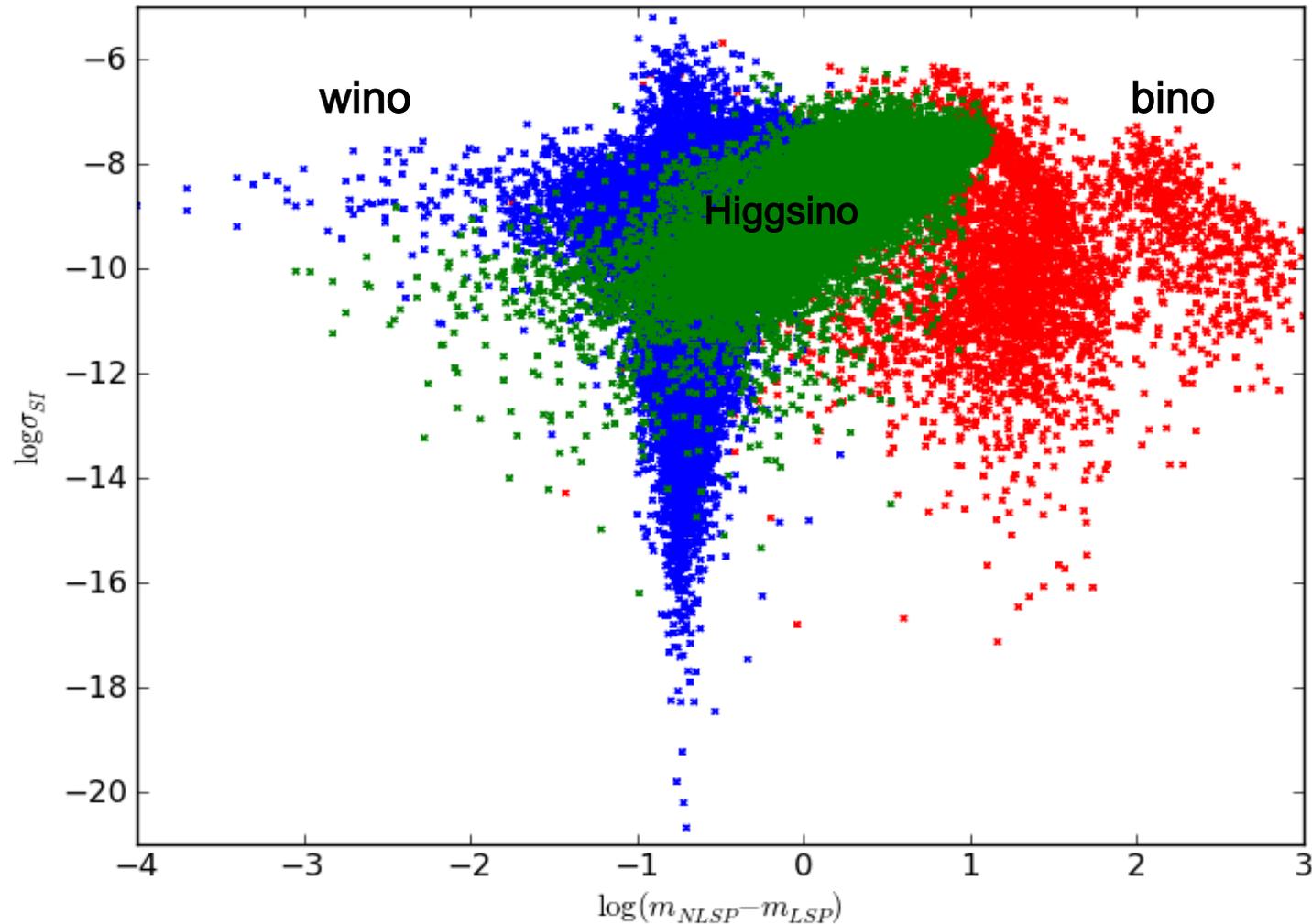
This arises due to, e.g., the LSP's EWK nature, different up & down squark masses which happens very infrequently in the CMSSM as well as from Higgs exchanges..some variation from exact symmetry is observable in the pMSSM.

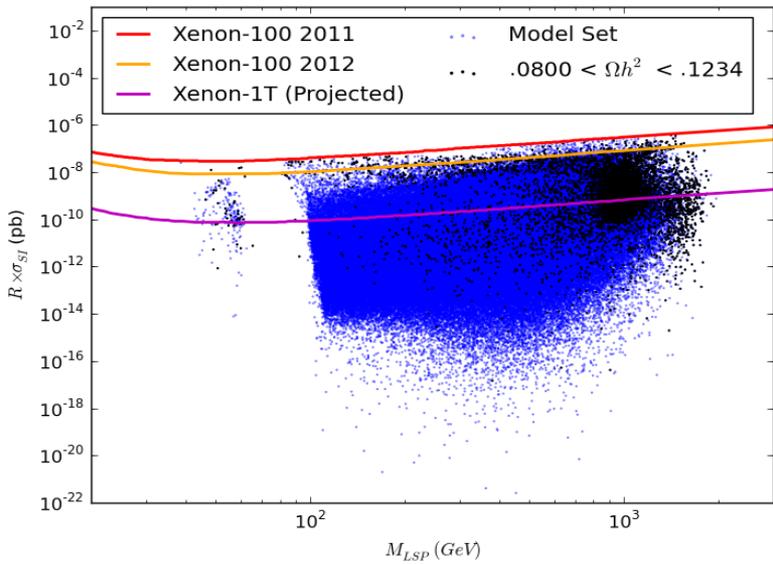


Substantial isospin violation is possible !

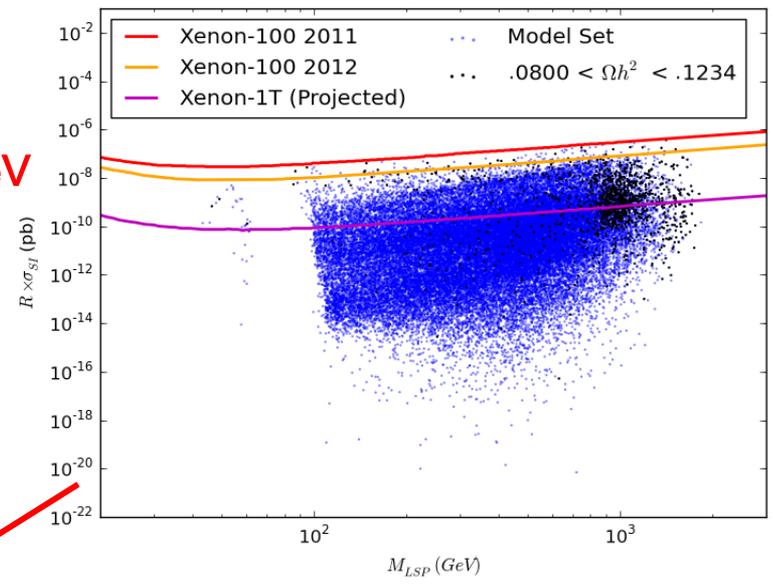


The SI cross section is sensitive to the NLSP-LSP mass splitting which also probes the LSP EWK content

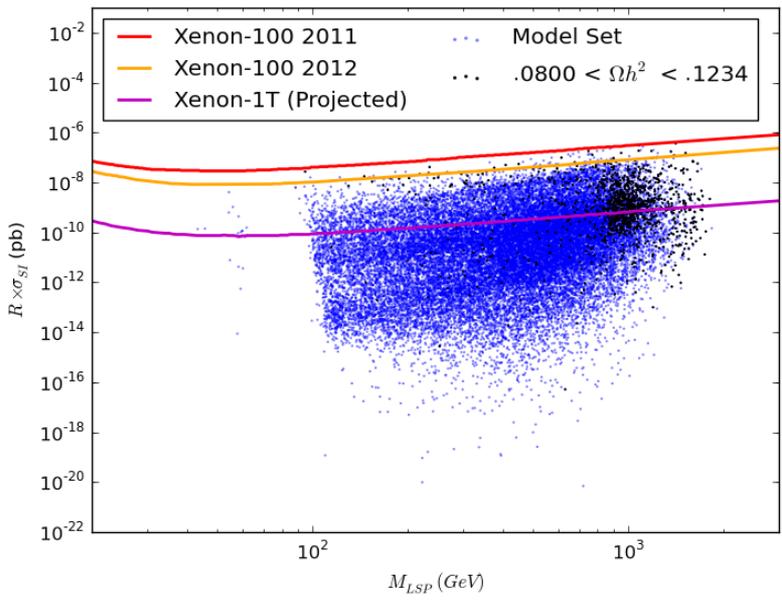




$M_h = 126 \pm 3 \text{ GeV}$

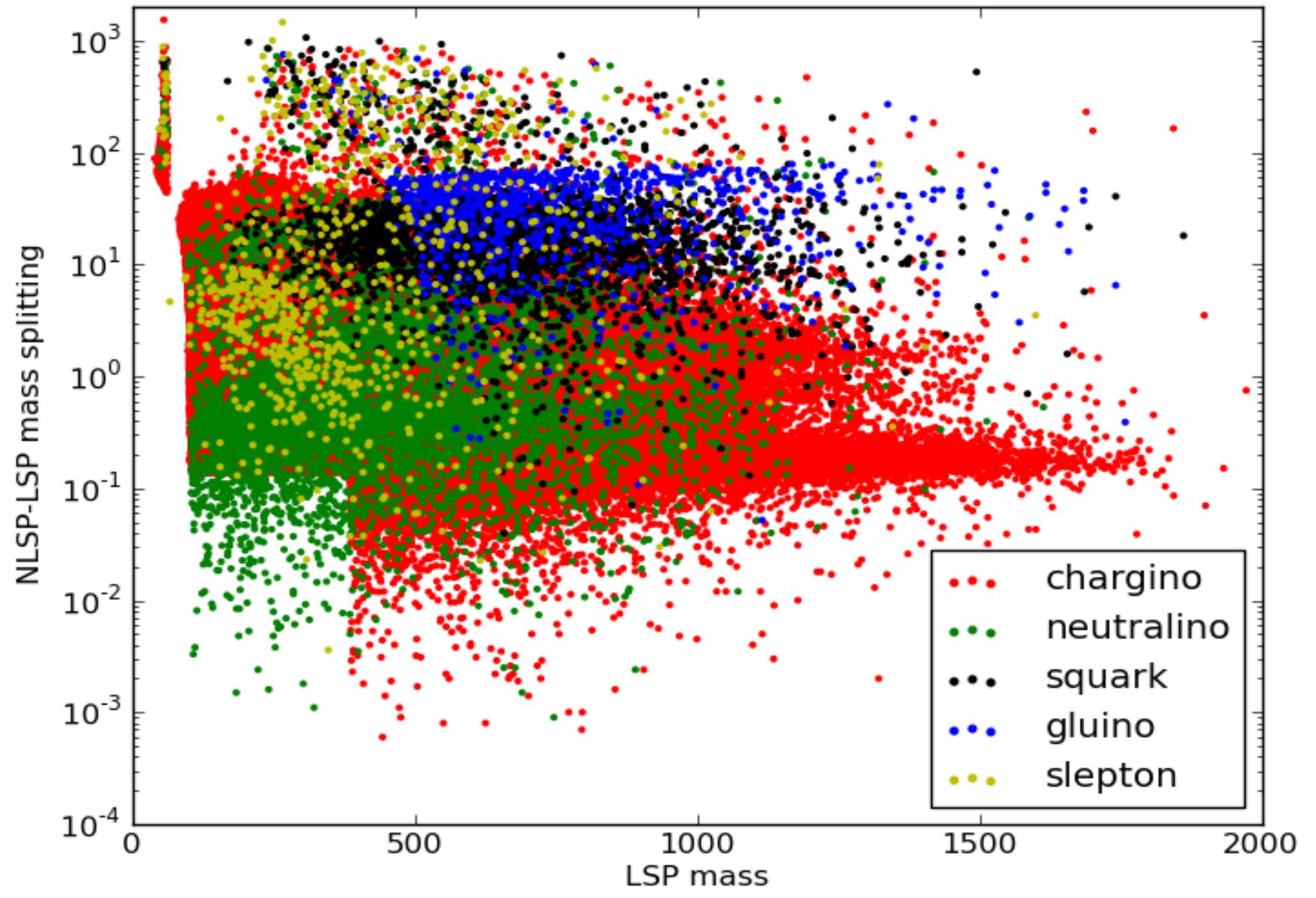


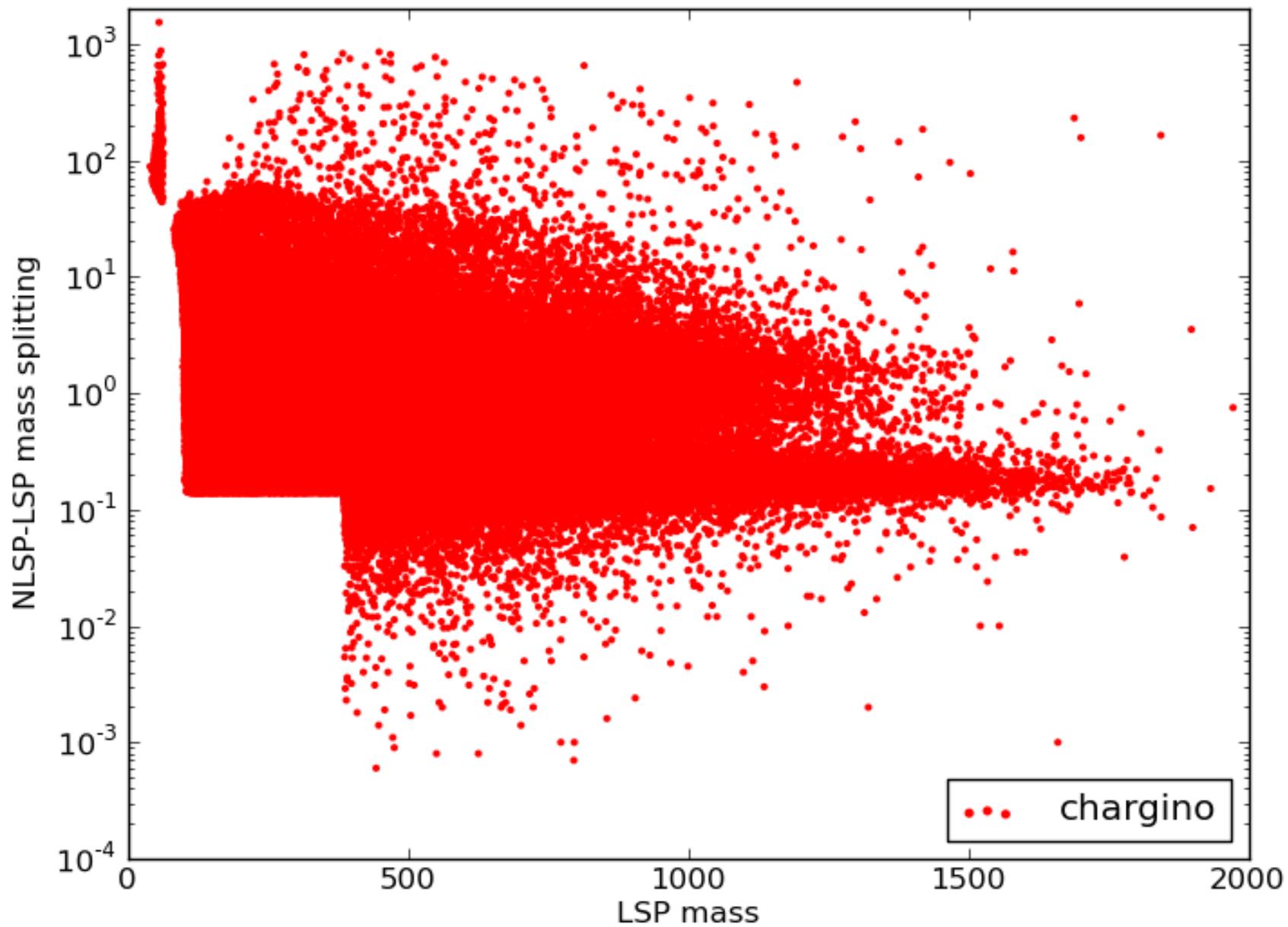
LHC w/ $\sqrt{s}=8 \text{ TeV } 5 \text{ fb}^{-1}$



The range of SI cross section expectations is not much influenced by the Higgs discovery or the lack of any SUSY signals at the LHC..

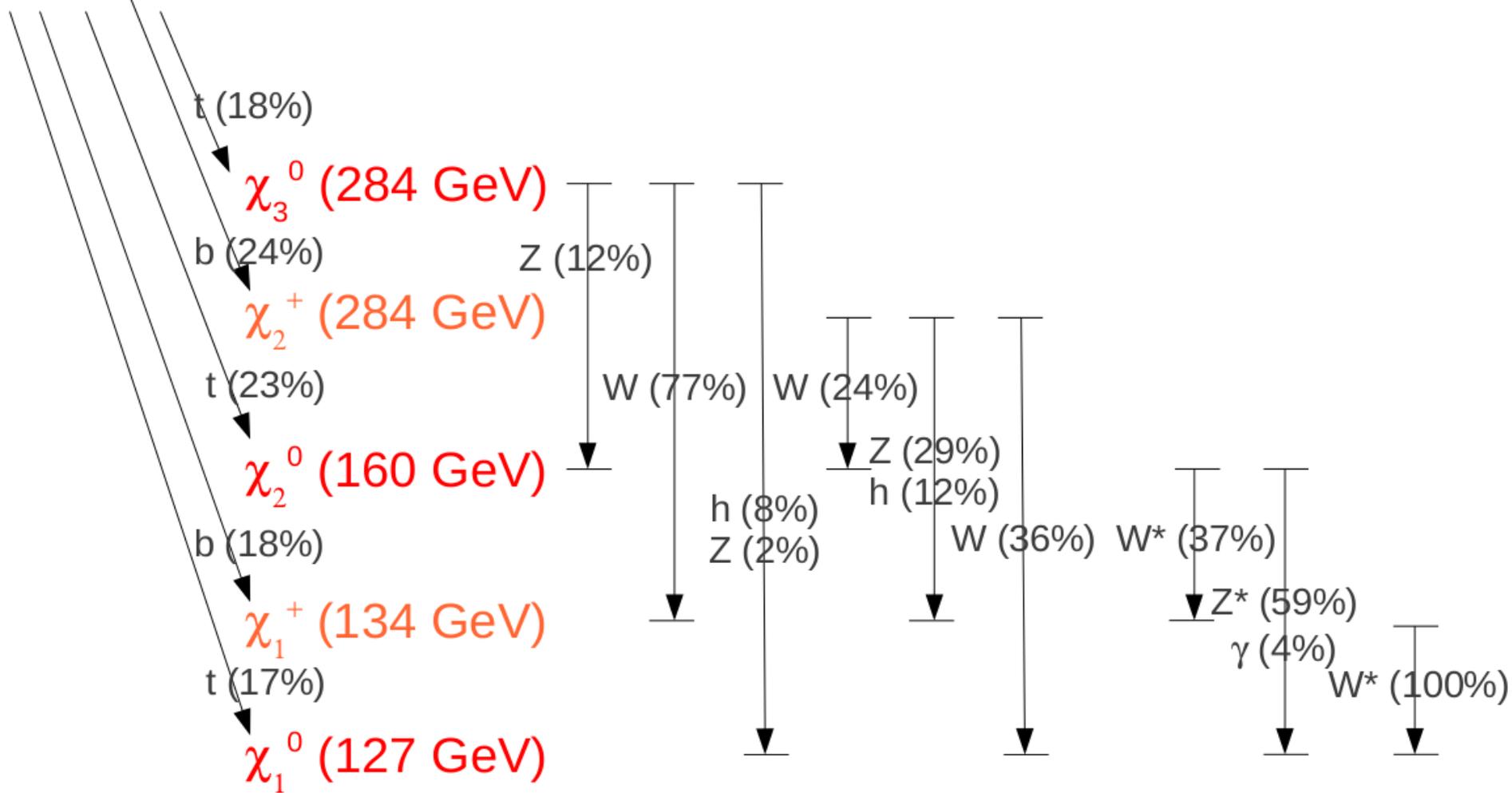
χ_1^0 LSP

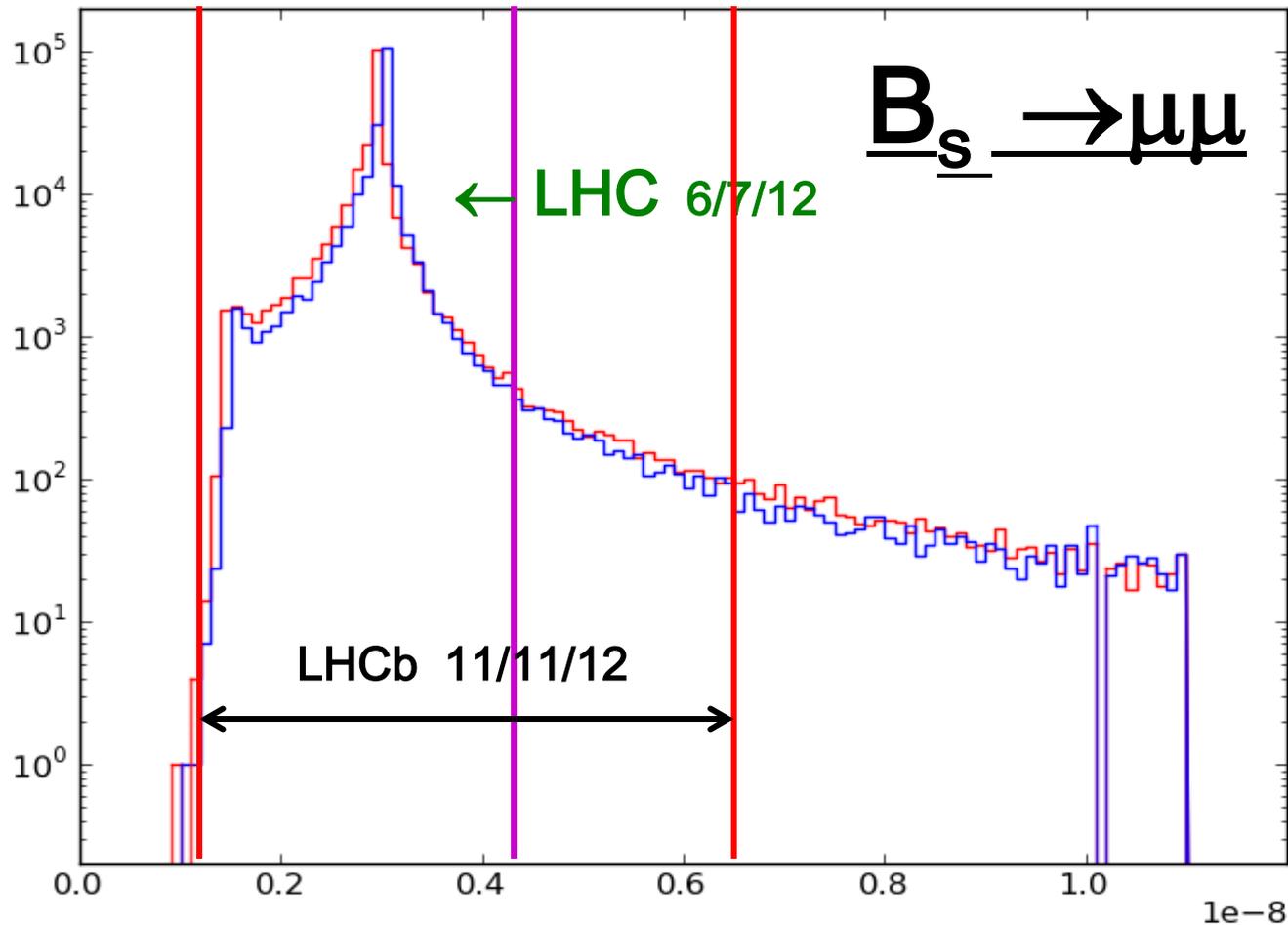




An example low-FT model

t_1 (601 GeV)





- The old **LHC** result had removed a total of **6035** (**7147**) models in the **neutralino** (**G**) LSP model set ... The actual LHCb ‘observation’ removes only **1819** (**2167**) models.
- **non-MET** searches **ARE** important !

The pMSSM provides paths through (& over!) the Frontiers

