# Physics (and experiment) at the Crossroads



Jack Gunion
U.C. Davis


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Of course, the situation could be such that we could not even read the possible directions. Or, maybe a select few could, leaving the rest of us in the dark.

# This is a good situation (for experimentalists)!

- We need experimental input to really understand where we are and to pursue the different directions.
- The greater the number of directions and uncertainties, the more the opportunities.
- ATLAS and CMS will play a major role for sure in many of these pursuits.
- New directions may emerge with new data.
- There are many interconnections between the directions:
  - Higgs as a portal to dark matter;
  - Collider limits on SUSY and naturalness vs. anthropics/string landscape;
  - Missing energy and dark matter;
  - Precision Higgs data and compositeness.
  - ....
  - ....

# 125 GeV Higgs and related

- $m_{h_{SM}} \sim 125.5~\mathrm{GeV}$ is both maximally interesting (many competing final states) and maximally confusing [SM (Stable or Metastable Vacuum) or BSM (Multi-Higgs, MSSM Higgs, Composite Higgs, ...)].
- SM?

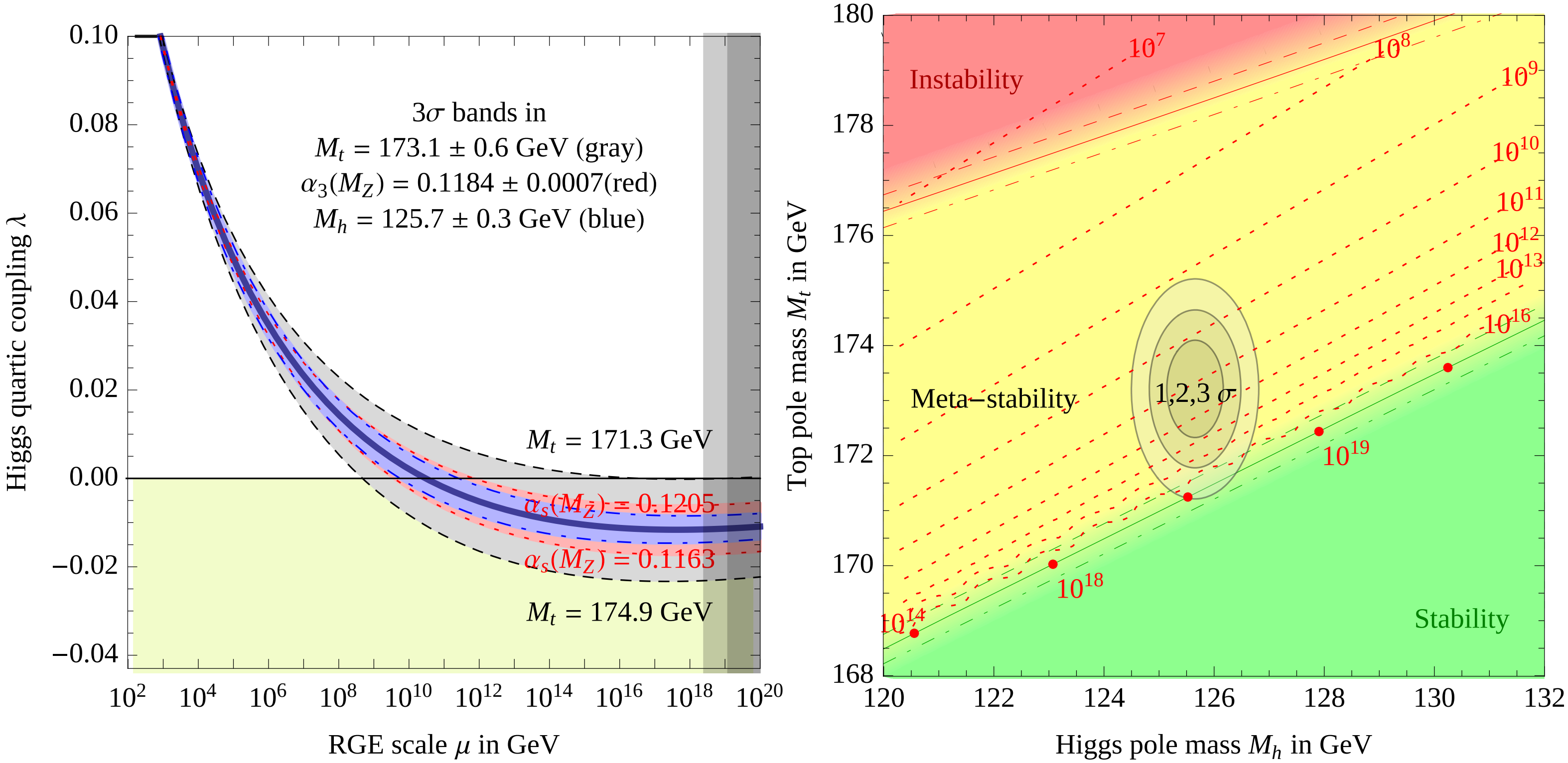



Figure 1: Pure SM implies $\lambda(m_{Pl}) < 0$ for $\mu > 10^{10} - 10^{12}~\mathrm{GeV}$ and metastable (but very long lifetime) early universe vacuum unless $m_t$ is smaller than currently preferred. From arXiv:1307.3536, Buttazzo, *et al.*

– The coefficient $m^2$ of the Higgs bilinear in the scalar potential is the order parameter that describes the transition between the symmetric phase ($m^2 > 0$) and the broken phase ($m^2 < 0$).
  In principle, $m^2$ could take any value between $-m_{Pl}^2$ and $+m_{Pl}^2$, but quantum corrections push $m^2$ away from zero towards one of the two end points of the allowed range.
– The hierarchy problem is that $m^2 \sim 0$, $i.e.$ it sits near the boundary between the symmetric and broken phases.

Therefore, both the parameters of the Higgs potential are near critical lines that separate the EW phase from a different (and inhospitable) phase of the SM.

Is criticality just a capricious numerical coincidence or is it telling us something deep?

The occurrence of criticality could be the consequence of symmetry.

- $125~\mathrm{GeV}$ Higgs in SUSY?

  What does a Higgs mass of 125-126 GeV tell us about natural theories?

  – A Higgs mass smaller than 120 GeV would have been perfect for natural supersymmetry, while a mass larger than 130 GeV would have excluded the simplest scenarios.

– If the Higgs mass is really 125 GeV, right in the middle, theorists are perplexed/unsure of what to think.
  It is often said that in the MSSM, a Higgs mass of 125 GeV can be reached, but only for extreme values of the parameters, especially those of the stop.
  Fig. 2 shows significant probability for $m_{\widetilde{t}_1}, m_{\widetilde{g}} < 1~\mathrm{TeV}$ even after precision Higgs data. CMS is working to exclude these scenarios, but has a ways to go.
– What can be said is that certain natural setups, where parameters are correlated, are in bad shape (for instance gauge mediation, constrained MSSM), but the idea of low-energy supersymmetry of a pMSSM variety (which generically means no high-scale extrapolation, let alone unification) is not (yet) dead.

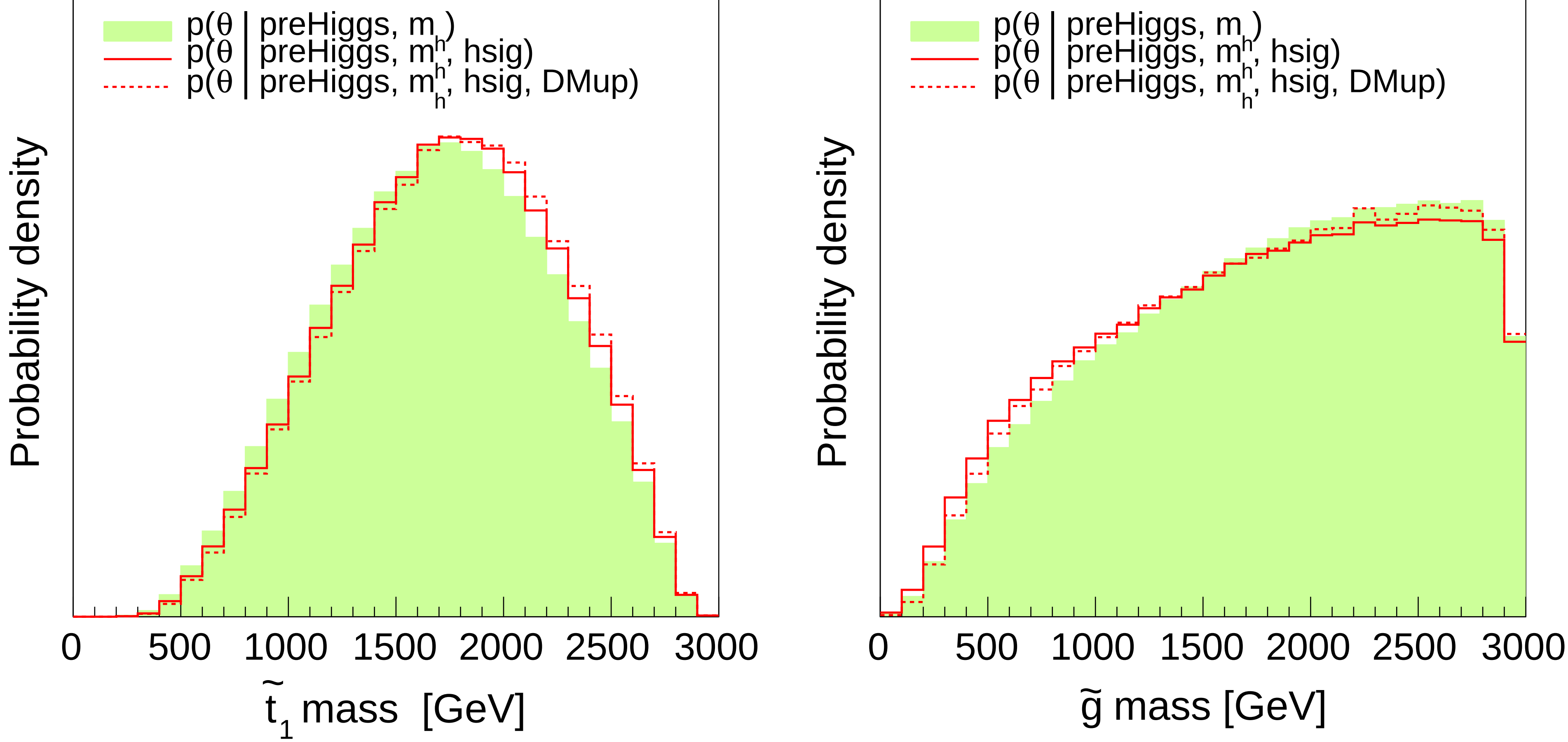



Figure 2: pMSSM bayesian probabillity distributions (arXiv:1312.7027, Dumont *et al.*). Left: $m_{\tilde{t}_1}$; Right: $m_{\tilde{g}}$.

– Of course, the NMSSM still provides a good escape from being particularly unnatural even when GUT b.c. are employed. For example, in the NUH-NMSSM (NUH=non-universal Higgs soft masses squared), one has

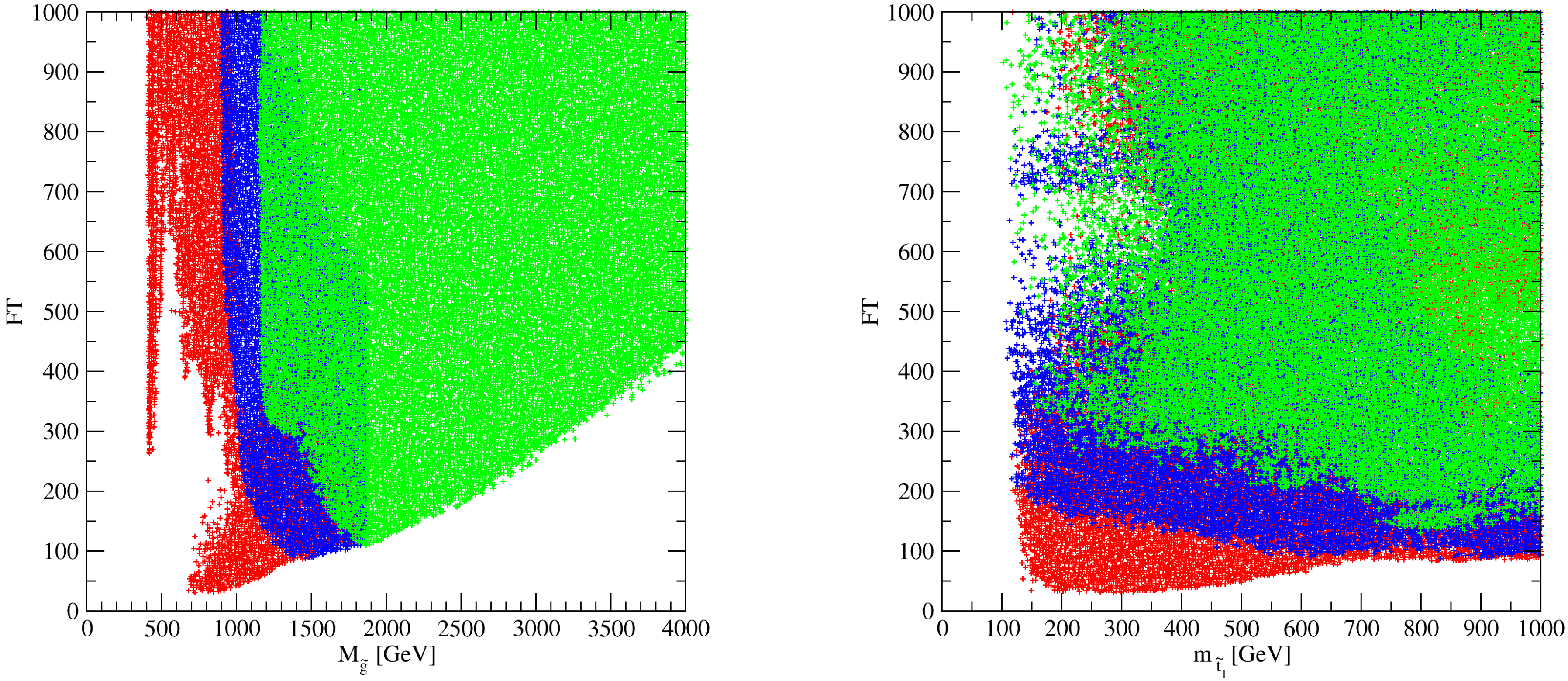



Figure 3: Fine Tuning in the NMSSM vs. $m_{\widetilde{g}}$ and $m_{\widetilde{t}_1}$, arXiv:1405.6647, Ellwanger and Hugonie. Red: absolutely excluded by LHC searches; Blue: still allowed if LSP=highly singlino; Green: still allowed even if LSP not singlino.

We see:

$*$ The LHC forbidden red region increases the lower bound on $FT$ from $\sim 20$ to $FT \gtrsim 80$; the NMSSM-specific alleviation (blue region) has a minor impact on $FT$.

* $*$ The dominant contribution to $FT$ originates from $M_{1/2}$ (i.e. the gluino mass at the GUT scale), or from the soft Higgs mass term $m^2_{H_u}$.
* $*$ If one requires unification of $m_{H_u}$ and $m_{H_d}$ with $m_0$, $FT$ increases to $\gtrsim 400$.
* $*$ In the MSSM – after imposing LHC constraints on squark and gluino masses, defining $FT$ with respect to parameters at the GUT scale and allowing for non-universal Higgs mass terms at the GUT scale – one finds $FT \gtrsim 1000$.
* $*$ The impact of $M_{1/2}$ on $FT$ is actually indirect: heavy gluinos lead to large radiative corrections to the stop masses which, in turn, lead to large radiative corrections to the soft Higgs mass terms.

  Therefore, if one defines $FT$ with respect to parameters at a lower scale, low $FT$ is typically related to light stops (r.h. plot).

– If the LHC eventually definitively forces all SUSY partners to be heavy and we simply give up on naturalness in a quantitative sense (but not in the sense that we give up on the symmetry), then $m_h \sim 126\ \mathrm{GeV}$ becomes quite accidental and forces another kind of fine tuning of the cutoff scale.

  For example, Fig. 4 (l.h. plot) shows that a Higgs mass of 125 GeV rules out the idea of Split Supersymmetry with a high scale, say larger than $10^8$ GeV. However, it fits very well with Split Supersymmetry with a low scale.

  The r.h. plot shows that the correct $m_h$ requires a conspiracy between the SUSY breaking scale, $M_{SS}$, and $\tan\beta$.

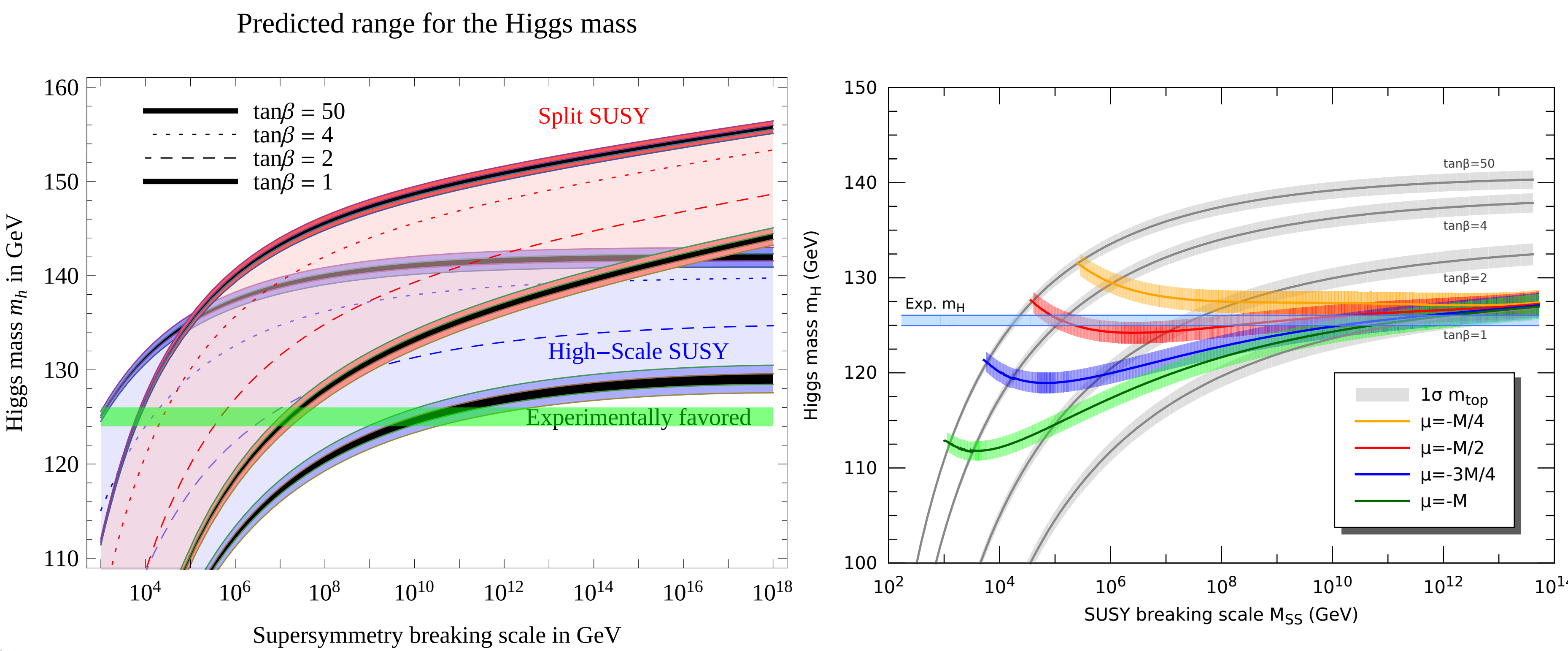



Figure 4: Left: NNLO prediction for the Higgs mass $M_h$ in High-Scale Supersymmetry (blue, lower) and Split Supersymmetry (red, upper) for $\tan\beta = \{1, 2, 4, 50\}$ from arXiv:1108.6077, Giudice *et al.*. Right: Higgs mass versus SUSY breaking scale $M_{SS}$. The grey bands correspond to the Higgs mass for different values of tan$\beta$, for $X_t = 0$, without imposing unification of Higgs soft parameters. The other colored bands correspond to imposing tan$\beta$ values consistent with unification of soft terms, $m_{H_u} = m_{H_d}$. From arXiv:1301.5167, Ibanez, *et al.*

# Other Higgs Bosons

- Even if the $126\ \mathrm{GeV}$ Higgs boson turns out to be extremely SM-like, that does not mean that there are no other Higgs bosons nor does it mean that in models with extra Higgs bosons those Higgs bosons must be very heavy (the decoupling limit).

- For example, in the 2HDM there is the so-called "Alignment Limit" in which parameters are chosen so that $\sin(\beta-\alpha)=1$, $i.e.$ $\alpha=\beta-\pi/2$, in which case all $h$ couplings are exactly equivalent to those of the SM.

| | Type I and II | Type I | | Type II | |
|---|---|---|---|---|---|
| Higgs | $C_V$ | $C_U$ | $C_D$ | $C_U$ | $C_D$ |
| $h$ | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $H$ | $\cos(\beta-\alpha)$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $A$ | 0 | $\cot\beta$ | $-\cot\beta$ | $\cot\beta$ | $\tan\beta$ |

Table 1: Tree-level vector boson couplings $C_V$ ($V=W,Z$) and fermionic couplings $C_F$ ($F=U,D$) normalized to their SM values for the Type I and Type II 2HDMs.

Of course, at the moment there is still a fair amount of freedom. (Following discussion based on Dumont $et\ al.$, arXiv:1405.3584.)

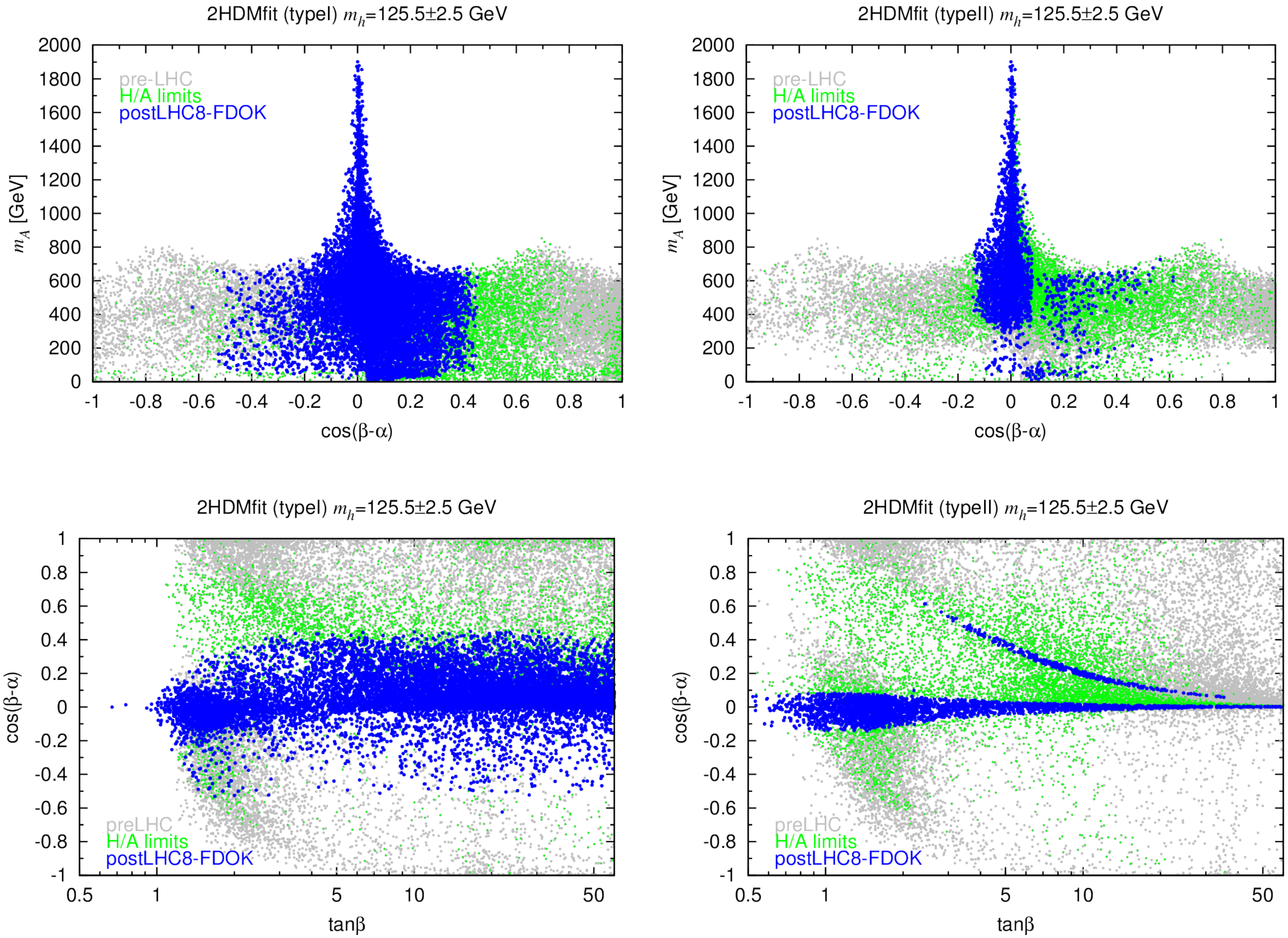



Figure 5: Grey points satisfy preLHC constraints, while green points satisfy in addition the LHC limits on $H$ and $A$ production. Blue points satisfy precision Higgs fitting in addition. Extra type II branch = wrong-sign-$C_D^h$. From arXiv:1405.3584.

- Prospects for LHC observation of the $H$, $A$, $H^{\pm}$ are significant. $e.g.$ $\tau\tau$ final state.

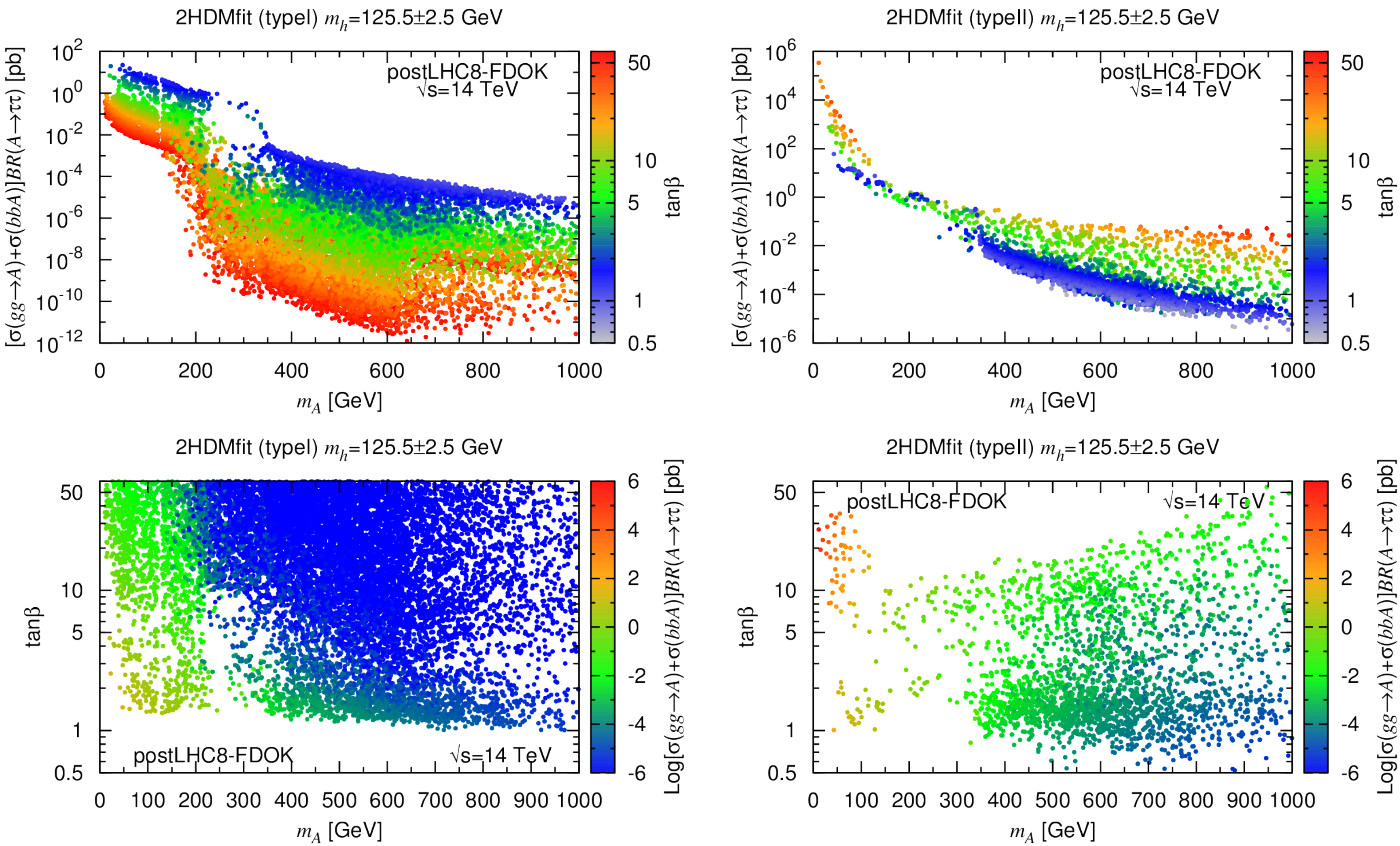



Figure 6: 2HDM points agreeing at 95% C.L. with precision Higgs data as well as $B$ physics, ..... From arXiv:1405.3584.

Note especially the very large possible cross sections (esp. Type II) of points at low $m_A$ (with $\mathcal{B}(h \to AA) \lesssim 0.1$ to avoid messing with $h$ fits). Remarkably, they are still allowed by LEP and by existing 7+8 TeV analyses, although I feel certain that the existing analyses can be extended to $M_{\tau\tau} < 90~\mathrm{GeV}$, in which case the bulk of these points would be eliminated (or observed).

These low-$m_A$ points are also not exactly SM-like in that $C_\gamma^h \lesssim 0.95$ because of a non-decoupling heavy charged Higgs while $C_g^h \sim 1.13$ because the $hb\bar{b}$ Yukawa coupling is opposite in sign (but same magnitude) from the SM value. (See also Ferreira $et~al.$, arXiv:1403.4736.)

- According to the recent Snowmass studies, the LHC can measure $C_g^h$ to $6$–$8\%$ for $L = 300~\mathrm{fb}^{-1}$ and $3$–$5\%$ for $L = 3000~\mathrm{fb}^{-1}$, based on fitting all the rates rather than directly observing the $gg$ final state.
  At the ILC, $e^+e^- \to Z^* \to Zh$ determines the $ZZh$ coupling very accurately and isolation of the $gg$ final state is easier. The error on $C_g^h$ estimated is $2\%$ for a combination of $L = 250~\mathrm{fb}^{-1}$ at $\sqrt{s} = 250~\mathrm{GeV}$ and $L = 500~\mathrm{fb}^{-1}$ at $\sqrt{s} = 500~\mathrm{GeV}$.
  Thus, both the LHC and ILC will be able to determine whether or not $C_D^h$ is positive using the indirect fit and direct measurement of $C_g^h$, respectively.
- The $5\%$ suppression of $C_\gamma^h$ for $C_D^h < 0$ should be measurable at the $\sqrt{s} = 14~\mathrm{TeV}$

LHC run for $L = 3000~\mathrm{fb}^{-1}$.

Of course, there is also the $\mu\mu$ final state. There are a number of relevant CMS analyses (probably also ATLAS). Recall the CMS analysis of arXiv:1206.6326, which obtained limits of $\sigma(gg \to A)\mathcal{B}(A \to \mu\mu) \leq 2-3~\mathrm{pb}$ for $m_A \in [11-14]~\mathrm{GeV}$ using $1.3~\mathrm{fb}^{-1}$ of data. This can be compared to the predictions shown in Fig. 7.

From this, it seems that Type-II is ruled out for $m_A < 14~\mathrm{GeV}$, but not Type-I.

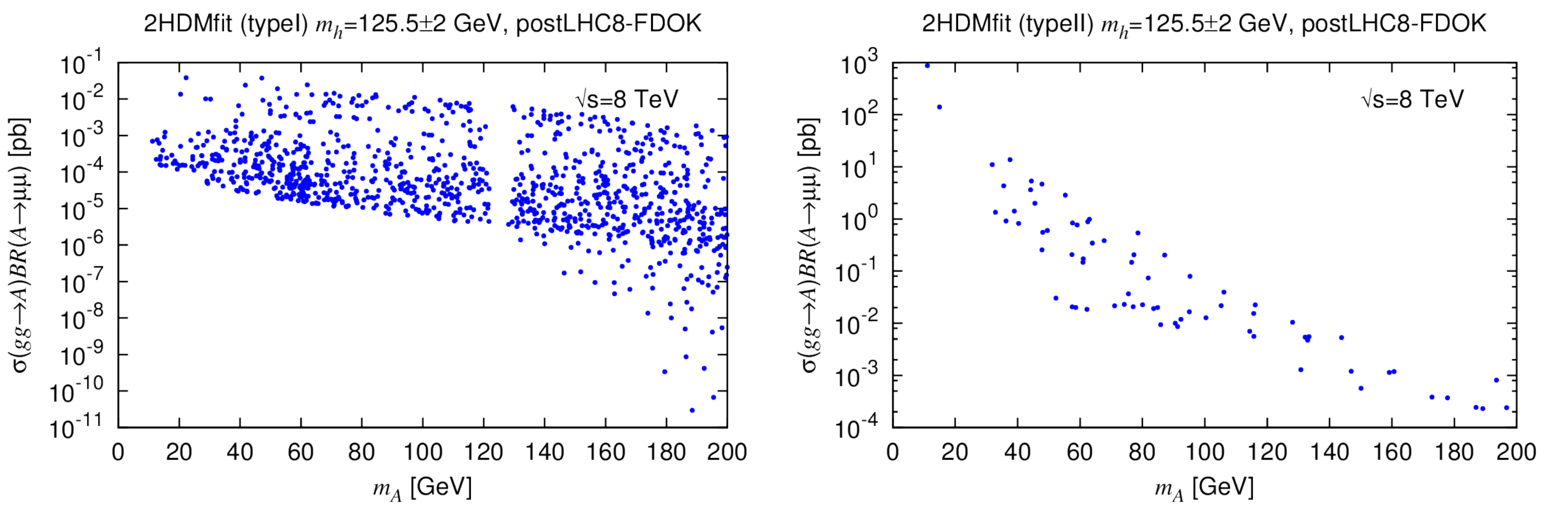



Figure 7: We plot $\sigma(gg \to A)\mathcal{B}(A \to \mu\mu)$ for $m_A < 200~\mathrm{GeV}$ in models of Type-I and Type-II. All points pass all constraints at the postLHC8 level, including $m_h = 125~\mathrm{GeV}$ higgs fitting.

An aside: there are limits from CMS PAS HIG-13-007 of order $0.02-0.03~\mathrm{pb}$ for $m_A \in [100, 150]~\mathrm{GeV}$ assuming that the $A$ and $H$ behave similarly in the $\mu\mu$ channels as regards efficiencies and acceptance. = getting close.

$A$ production with exotic decays such as $A \to Zh$ can have large cross section. In fact, current data are already relevant in limiting these scenarios.

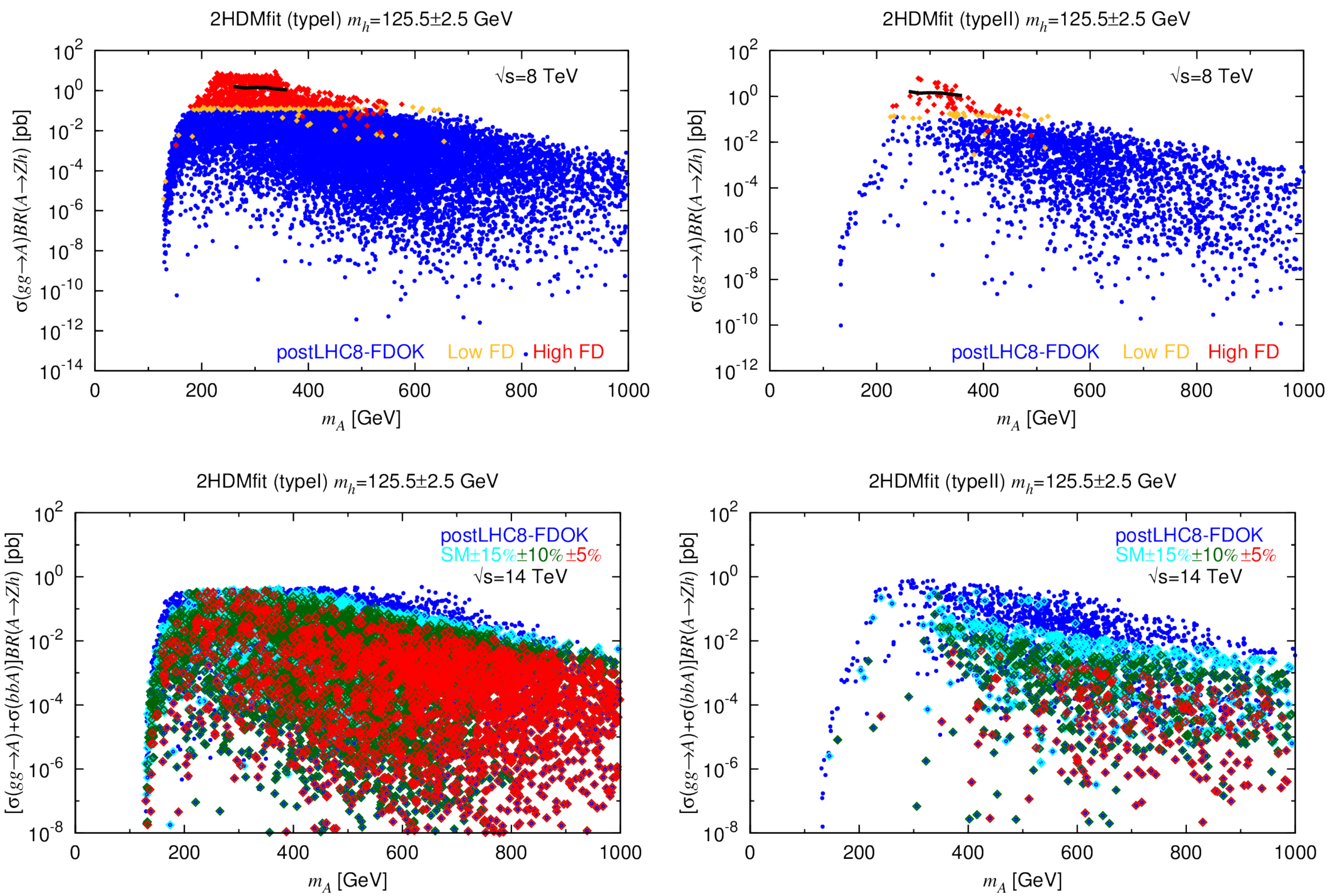



Figure 8: $gg$ and $bb$ production of $A$ with $A \to Zh$. Top: $\sqrt{s} = 8\,\mathrm{TeV}$. Bottom: $\sqrt{s} = 14\,\mathrm{TeV}$. Effect of increasingly SM-like $h$ is shown. Black line: early CMS limits; would have screwed up $h$ fits.

- In the MSSM, $m_A$ is tied to $m_h$ and cannot be small. Expectations are generically that the $A$, $H$ and $H^\pm$ will be heavy. In the pMSSM, we have the following.

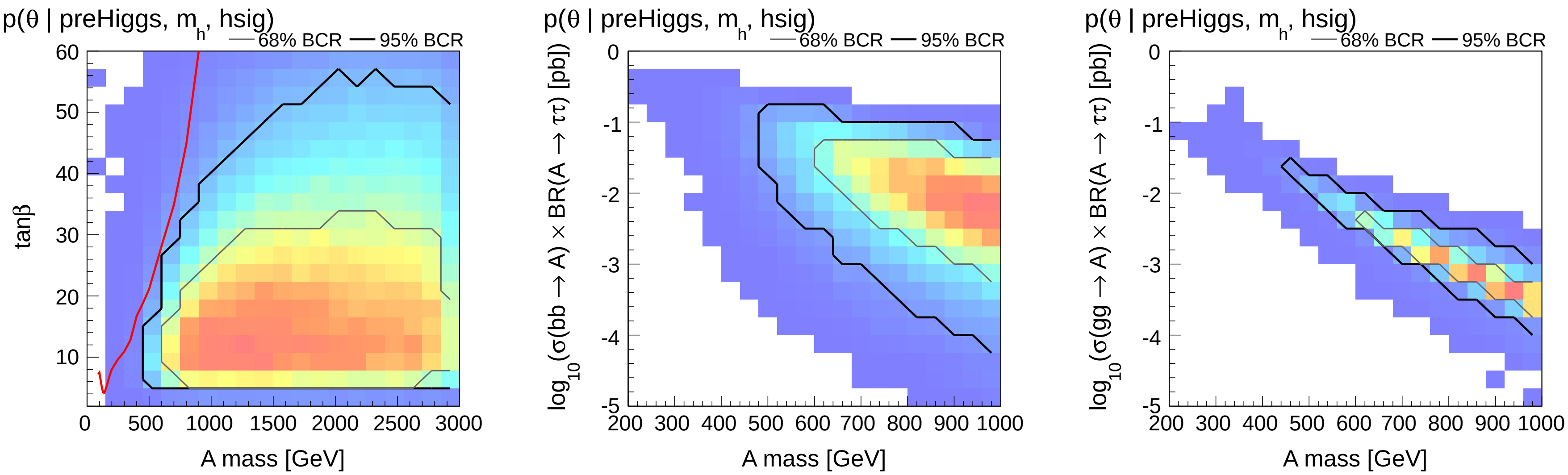
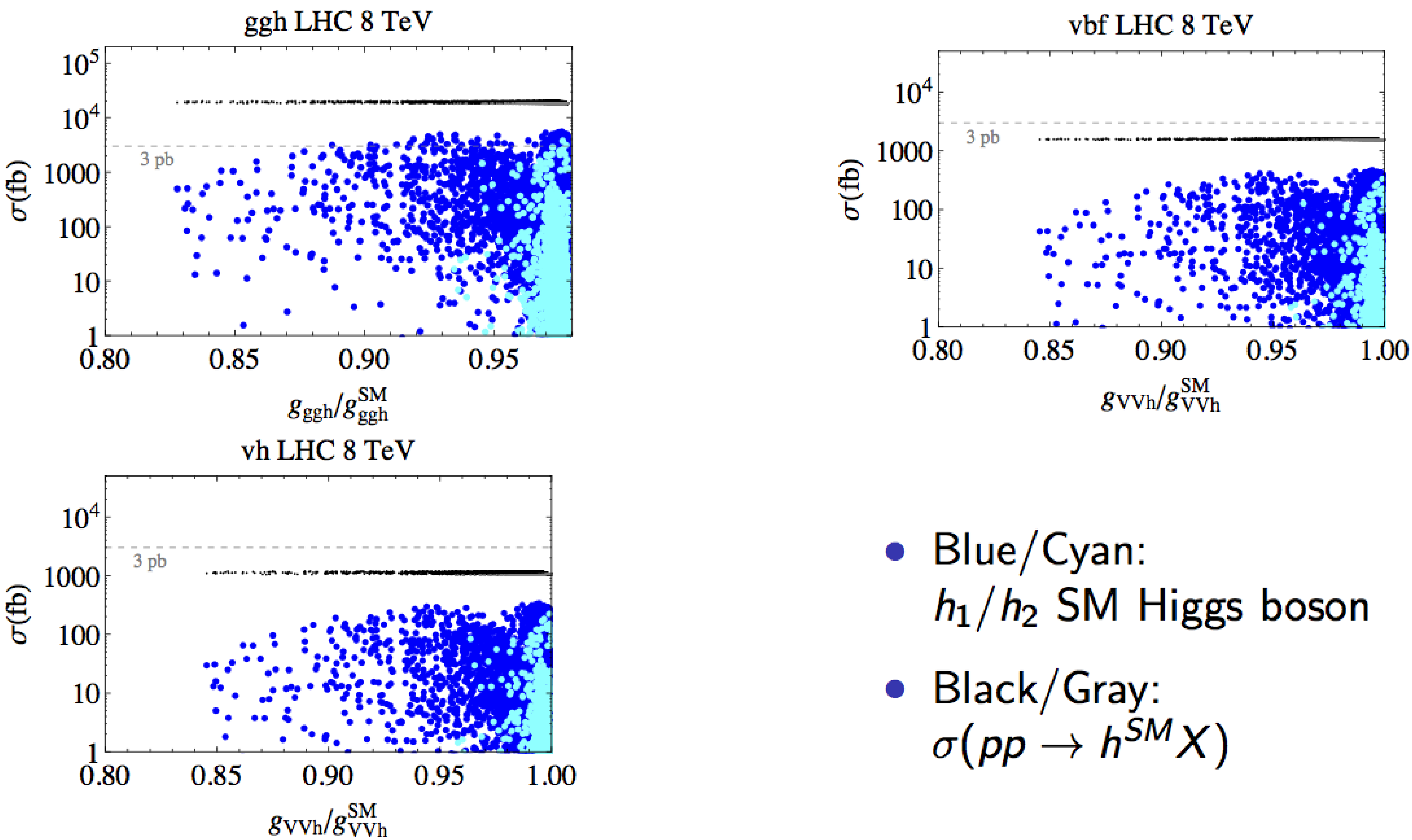



Figure 9: pMSSM results for the $A$ after Higgs fitting. SUSY limits as per SUS-13-020 have no impact. Cross sections are for $\sqrt{s} = 14~\mathrm{TeV}$. Much of the predicted range can be probed at the next LHC run!. Plot taken from pMSSM Higgs paper, Dumont *et al.*, arXiv:1312.7027.

- In the NMSSM, we have $h_1, h_2, h_3$ and $a_1, a_2$ and $H^\pm$. Many possibilities!

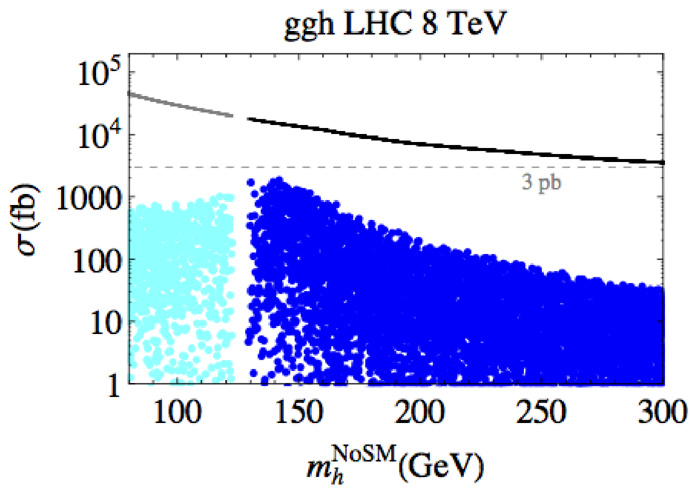
  It is still very relevant to consider CP-even Higgs production with decay to $a_1 a_1$. Some recent scans from Barducci are of interest. He considers $A_\kappa \to 0$, $m_{a_1} < 10~\mathrm{GeV}$, and demands that $h_1$ or $h_2$ fit the Higgs data at 95% C.L. He also computes the contribution of the non-SM-like $h_2$ or $h_1$ to the $4\tau$ final state. NB. $4\tau$ mass resolution is poor.

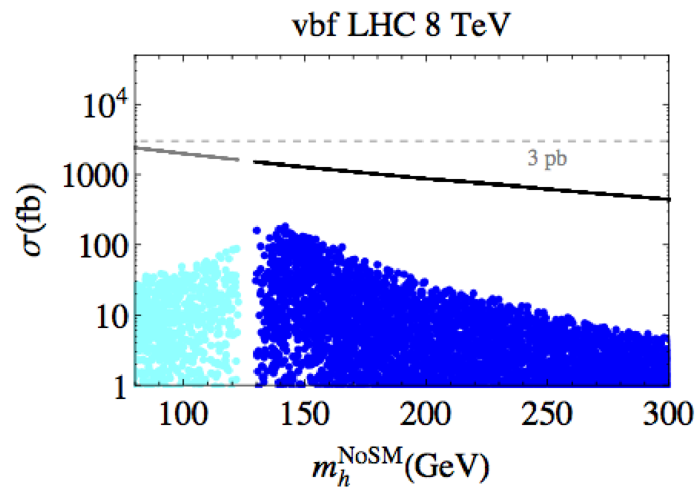
# $h_{1,2}^{SM} \to a_1 a_1 \to 4\tau$ topology ($m_{a_1} < 10$ GeV) LHC8

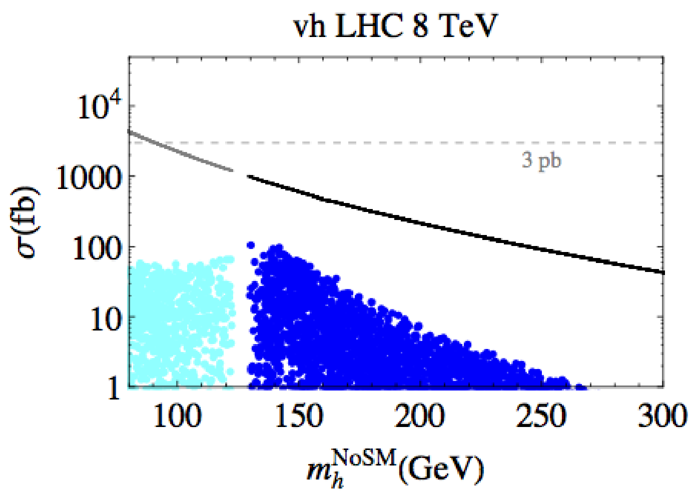



- Blue/Cyan:
  $h_1/h_2$ SM Higgs boson
- Black/Gray:
  $\sigma(pp \to h^{SM} X)$

# $h_{1,2}^{SM} \to a_1 a_1 \to 4\tau$ topology ($m_{a_1} < 10$ GeV) LHC8




- Blue/Cyan:
  $h_1/h_2$ SM Higgs boson
- Black/Gray:
  $\sigma(pp \to h^{noSM} X)$

Contribution of both the lightest CP even Higgs to the signal

# SUSY

- We should never give up on SUSY or some other high scale theory to regulate Higgs mass. Symmetry/... has always worked in the past and most theorists believe it applies now, even if it is at an unnaturally high scale.

- But, we have not reached that point yet! Aside from the NMSSM scans mentioned earlier which had modest FT, but did not include $\delta a_\mu$, there were also the earlier NUH-NMSSM scans of arXiv:1201.0982, JFG, Jiang, Kraml.

  We found 'perfect' points that satisfied everything, including $\delta a_\mu$, and that were at the time uncomfortably SM-like for the $125~\mathrm{GeV}$ state. Model II had $A_\lambda = A_\kappa = 0$ at $M_U$ while Model III allowed any values. Sample points are below — Starred points are the perfect points satisfying all constraints, including $\delta a_\mu > 5.77 \times 10^{-10}$ and $0.094 < \Omega h^2 < 0.136$. Unstarred points are the almost perfect points that have $4.27 \times 10^{-10} < \delta a_\mu < 5.77 \times 10^{-10}$ and $0.094 < \Omega h^2 < 0.136$.

  The only thing wrong with these points is that at $\sigma_{SI} \sim few \times 10^{-8}~\mathrm{pb}$, they are a bit above the new LUX limit.

| | Model II | | | Model III | | | |
|---|---|---|---|---|---|---|---|
| Pt. # | 1* | 2* | 3 | 4* | 5 | 6 | 7 |
| $\tan\beta(m_Z)$ | 17.9 | 17.8 | 21.4 | 15.1 | 26.2 | 17.9 | 24.2 |
| $\lambda$ | 0.078 | 0.0096 | 0.023 | 0.084 | 0.028 | 0.027 | 0.064 |
| $\kappa$ | 0.079 | 0.011 | 0.037 | 0.158 | –0.045 | 0.020 | 0.343 |
| $m_{1/2}$ | 923 | 1026 | 1087 | 842 | 738 | 1104 | 1143 |
| $m_0$ | 447 | 297 | 809 | 244 | 1038 | 252 | 582 |
| $A_0$ | $-1948$ | $-2236$ | $-2399$ | $-1755$ | $-2447$ | $-2403$ | $-2306$ |
| $A_\lambda$ | 0 | 0 | 0 | $-251$ | $-385$ | $-86.8$ | $-2910$ |
| $A_\kappa$ | 0 | 0 | 0 | $-920$ | 883 | $-199$ | $-5292$ |
| $m_{h_1}$ | 124.0 | 125.1 | 125.4 | 123.8 | 124.5 | 125.2 | 125.1 |
| $m_{h_2}$ | 797 | 1011 | 1514 | 1089 | 430 | 663 | 302 |
| $m_{a_1}$ | 66.5 | 9.83 | 3.07 | 1317 | 430 | 352 | 302 |
| $C_u$ | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| $C_d$ | 1.002 | 1.002 | 1.001 | 1.003 | 1.139 | 1.002 | 1.002 |
| $C_V$ | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| $C_{\gamma\gamma}$ | 1.003 | 1.004 | 1.004 | 1.004 | 1.012 | 1.003 | 1.001 |
| $C_{gg}$ | 0.987 | 0.982 | 0.988 | 0.984 | 0.950 | 0.986 | 0.994 |
| $\mu_{\rm eff}$ | 400 | 447 | 472 | 368 | 421 | 472 | 477 |
| $m_{\tilde g}$ | 2048 | 2253 | 2397 | 1876 | 1699 | 2410 | 2497 |
| $m_{\tilde q}$ | 1867 | 2020 | 2252 | 1685 | 1797 | 2151 | 2280 |
| $m_{\tilde b_1}$ | 1462 | 1563 | 1715 | 1335 | 1217 | 1664 | 1754 |
| $m_{\tilde t_1}$ | 727 | 691 | 775 | 658 | 498 | 784 | 1018 |
| $m_{\tilde e_L}$ | 648 | 581 | 878 | 520 | 1716 | 653 | 856 |
| $m_{\tilde e_R}$ | 771 | 785 | 1244 | 581 | 997 | 727 | 905 |
| $m_{\tilde\tau_1}$ | 535 | 416 | 642 | 433 | 784 | 443 | 458 |
| $m_{\tilde\chi_1^+}$ | 398 | 446 | 472 | 364 | 408 | 471 | 478 |
| $m_{\tilde\chi_1^0}$ | 363 | 410 | 438 | 328 | 307 | 440 | 452 |

Since $m_{\tilde t_1}$ and $\mu_{\rm eff}$ are both modest in size, these scenarios have modest FT.

- Of course, it is very possible that demanding substantial unification at $M_U$ is simply not nature's choice given the plethora of string landscapes that would have 'random' $\sim\ \mathrm{TeV}$ SUSY parameters along with other new physics at intermediate scales.

- Thus, we should consider the pMSSM where all inputs are at the $\sim\ \mathrm{TeV}$ scale and extrapolation to higher scales of order $M_U$ or $m_{Pl}$ typically fails without additional new physics entering.

- The same plots given earlier suggest in the pMSSM context that quite large masses for superparticles have the highest probability given the Higgs data.

- Current LHC analyses within the pMSSM context (CMS) do not dramatically alter the $m_{\widetilde{t}_1}$ distribution (which was already pushed to large values by $b \to s\gamma$ limits), but do push $m_{\widetilde{g}}$ and $m_{\widetilde{\chi}_1^0}$ values higher.

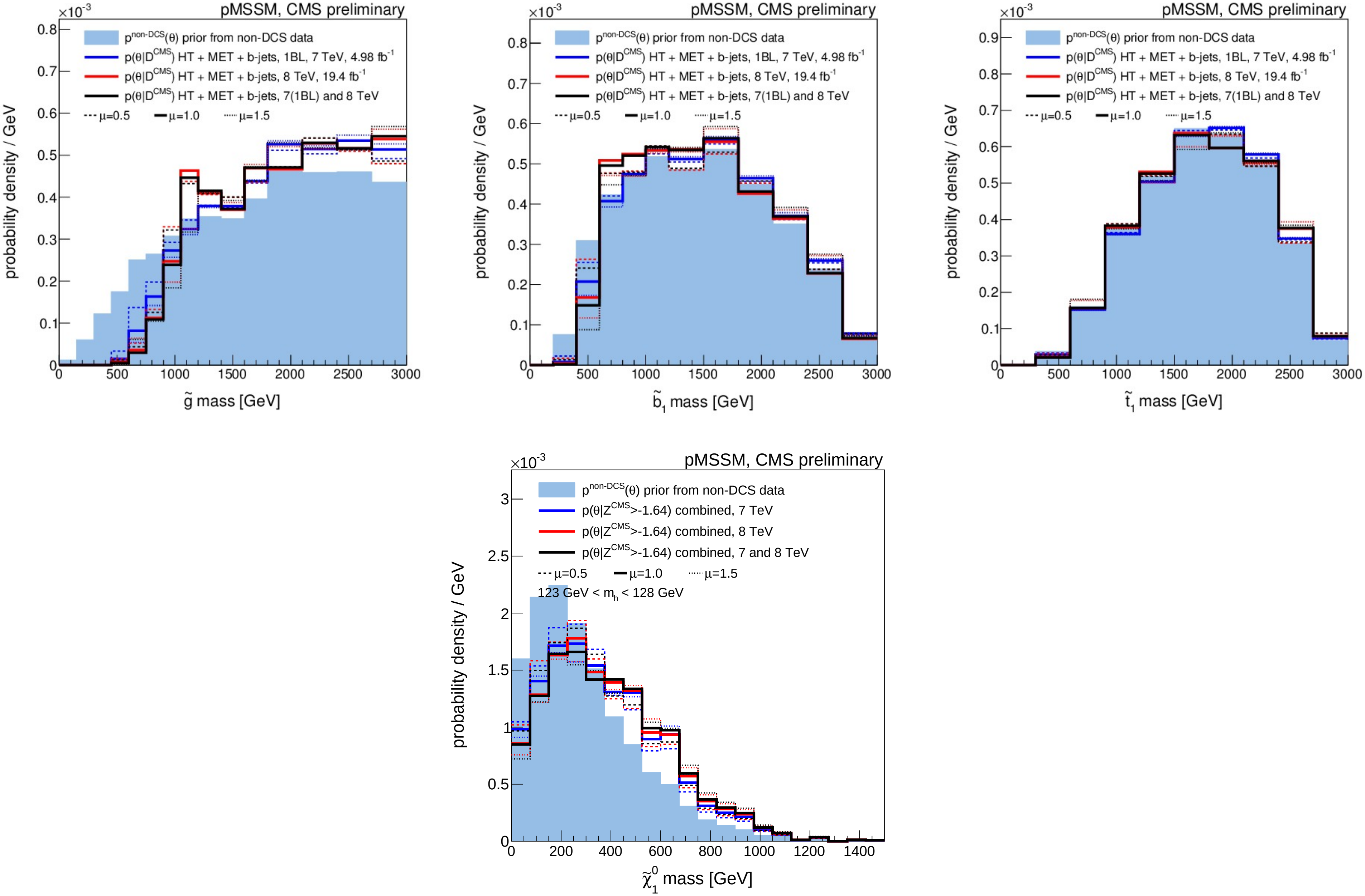



Figure 10: Marginalized pMSSM distributions from PAS-13-020, Vanelderen, Sekmen *et al.*

- But, these analyses are only valid for $c\tau < 10\ \mathrm{mm}$. One should ask how probable this chargino lifetime is.

After a simple Higgs mass cut and requiring $\Omega h^2$ below the WMAP/Planck upper bound (denoted ULO), large $c\tau$ is emphasized.

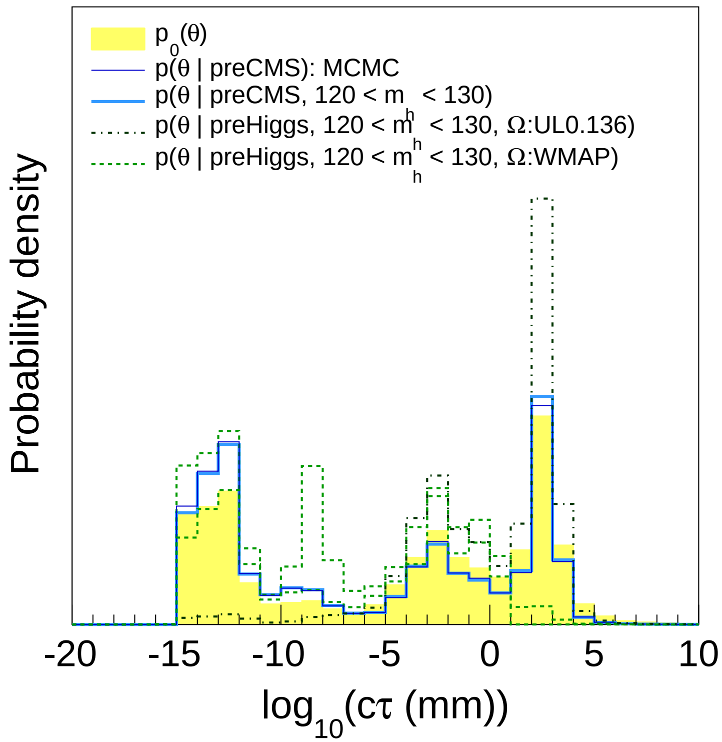



Figure 11: Marginalized pMSSM $c\tau(\widetilde{\chi}_1^\pm)$ distribution (arXiv:1312.7027, Dumont *et al.*).

This is to say that the upper bound favors rapid annihilation that occurs when $\widetilde{\chi}_1^0$ is mainly a wino with highly degenerate $\widetilde{\chi}_1^0, \widetilde{\chi}_1^\pm$.

But, this means that $\Omega h^2$ within the WMAP/Planck window is highly improbable. The figure shows that requiring correct $\Omega h^2$ shifts the emphasis to small $c\tau$.

The $\Omega h^2$ probability distribution with just ULO (called DMup here) imposed is shown below.

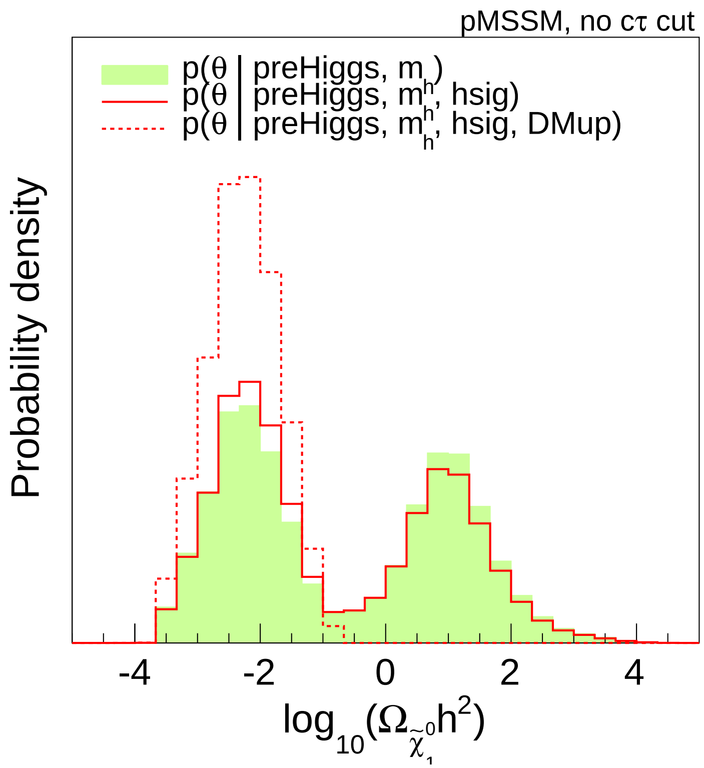



Figure 12: Marginalized pMSSM $\Omega h^2$ distribution (arXiv:1312.7027, Dumont *et al.*).

Correct $\Omega h^2$ requires a rather finely tuned $\widetilde{\chi}_1^0$ composition! Almost purely a higgsino-bino state with almost no wino.

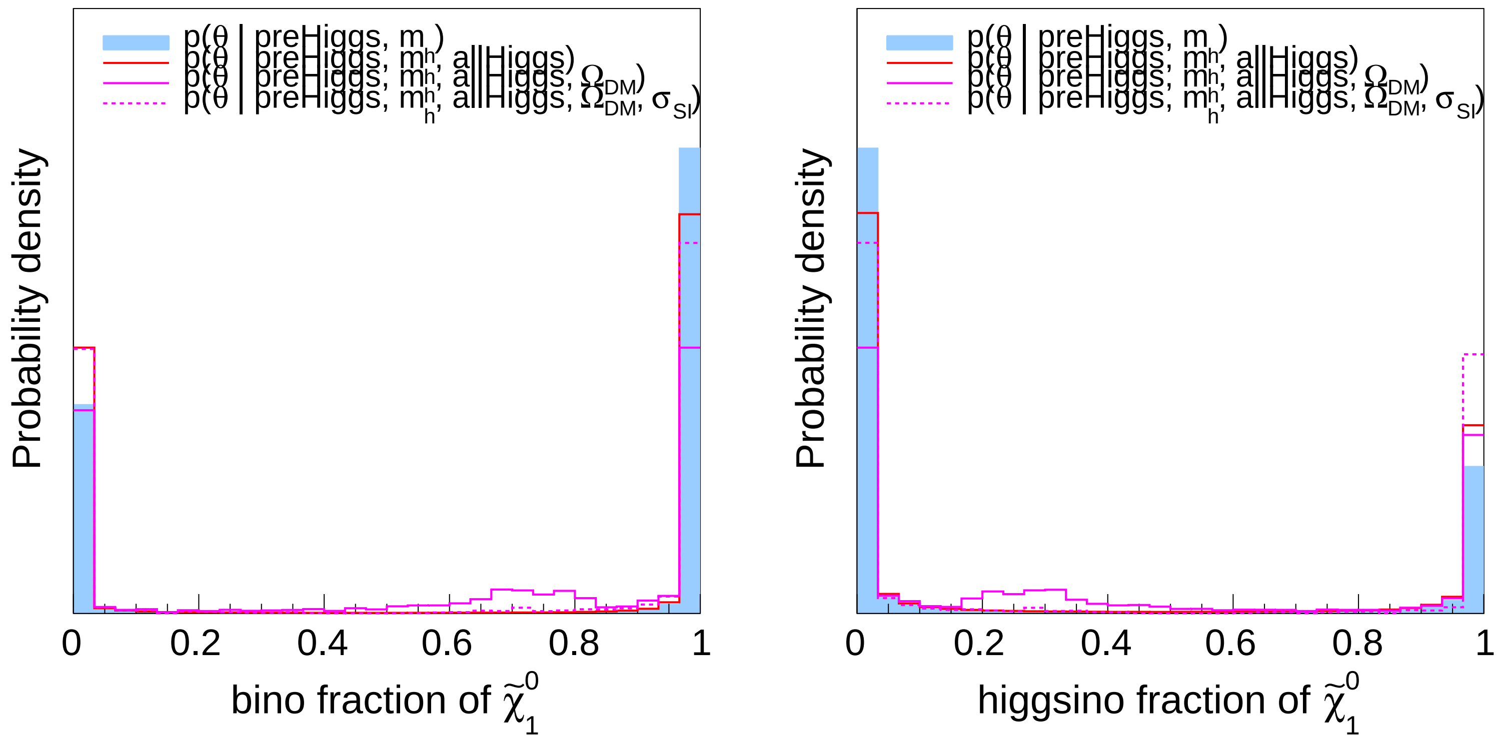



Figure 13: Marginalized pMSSM $\widetilde{\chi}_1^0$ composition distributions (arXiv:1312.7027, Dumont *et al.*).

Let us entertain for the moment the idea that we should abandon explaining correct $\Omega h^2$ using SUSY. Then we should pay greater attention to the ULO/DMup probabilities.

$\Rightarrow$ greater attention to large or fairly large $c\tau$, a region not probed in the standard SUSY searches (PAS-EXO-13-006 or PAS-SUS-12-030 in the case of CMS) focusing on $c\tau < 10~\mathrm{mm}$.

Of course, large $c\tau$ is the region originally discussed by JFG, Chen and Drees (hep-ph/9607421) in a superstring approach and later rediscovered as AMSB.

- A CMS-EXO analysis has targeted large $c\tau$ as below.

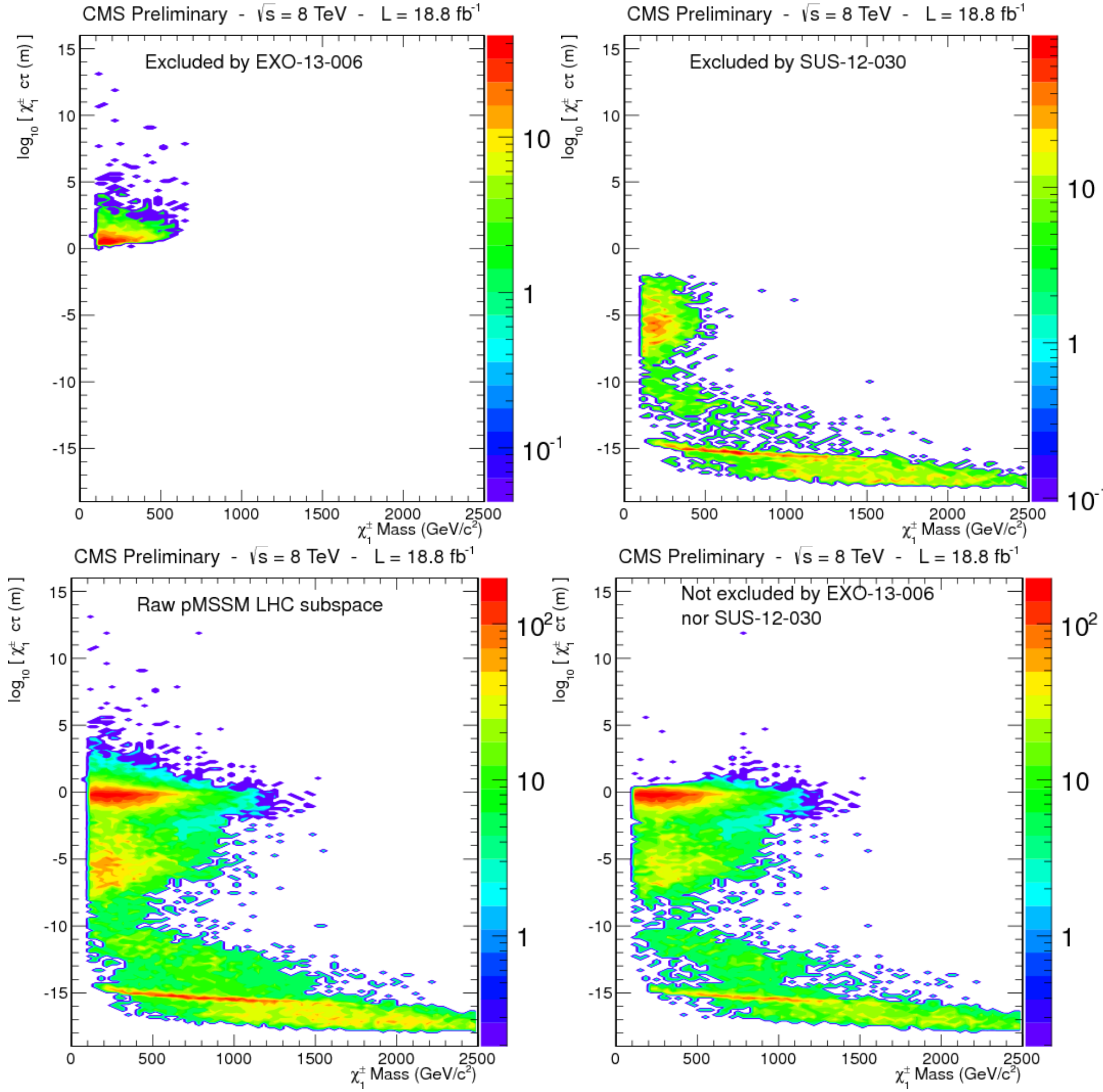



Figure 14: Marginalized pMSSM $c\tau$ exclusion/nonexclusion distributions from PAS-EXO-13-006 and PAS-SUS-12-030.

CMS is actively pursuing the intermediate $c\tau$ range where one has things like disappearing tracks (DITs), KINK tracks and STUBs (using the language of Gunion-Mrenna, hep-ph/9906270).

- RPV Models

  Perhaps we should take these more seriously since they can have smaller Fine Tuning in cases where the mass limits, especially on stops and gluinos are weaker than for RP conserving models.

  Especially difficult are the baryonic RPV scenarios since signals have little missing energy and large hadronic backgrounds.

  Some examples of recent limits include:

  – $\widetilde{g}\widetilde{g}$ pair production with $\widetilde{g} \to tbs$.

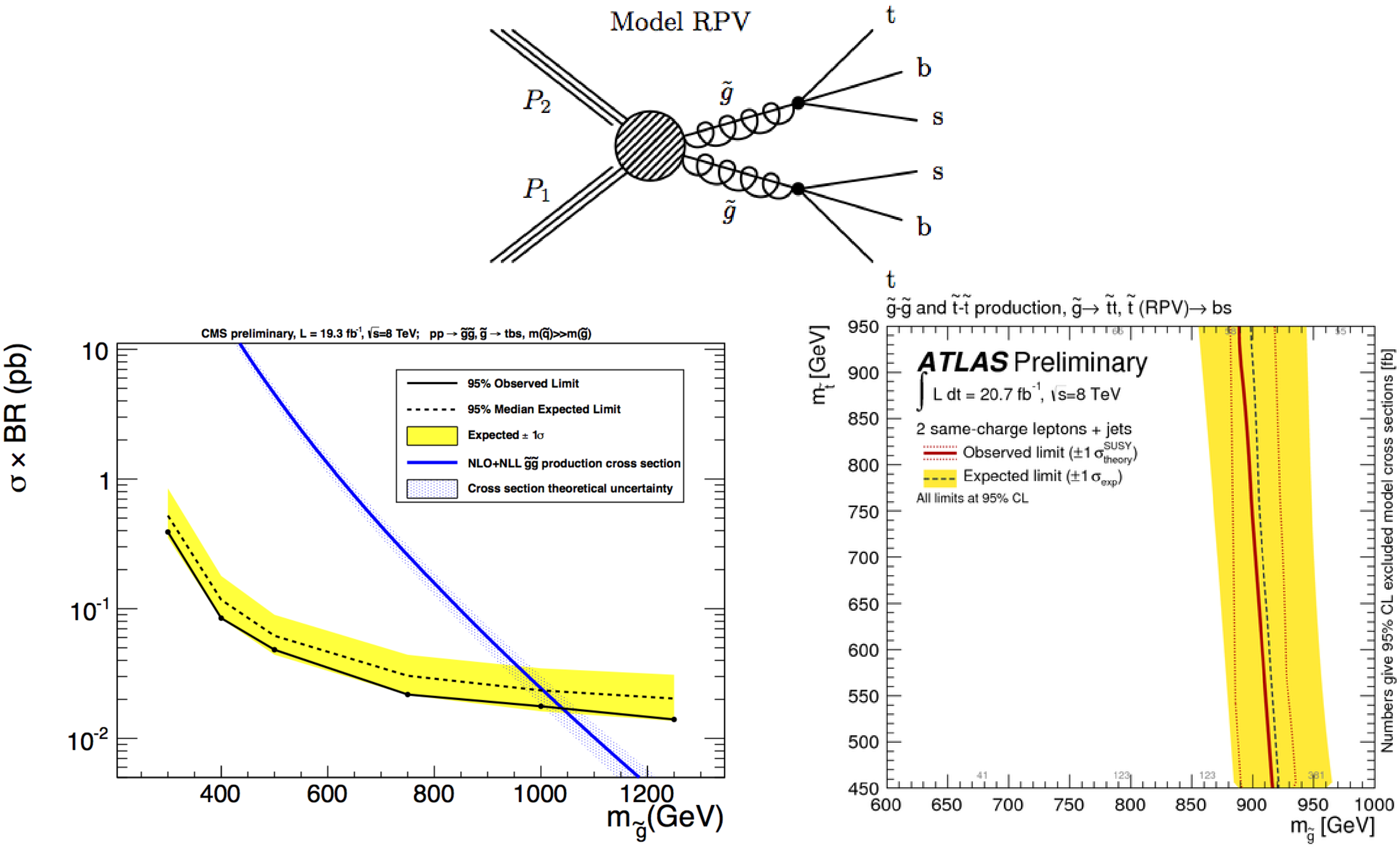
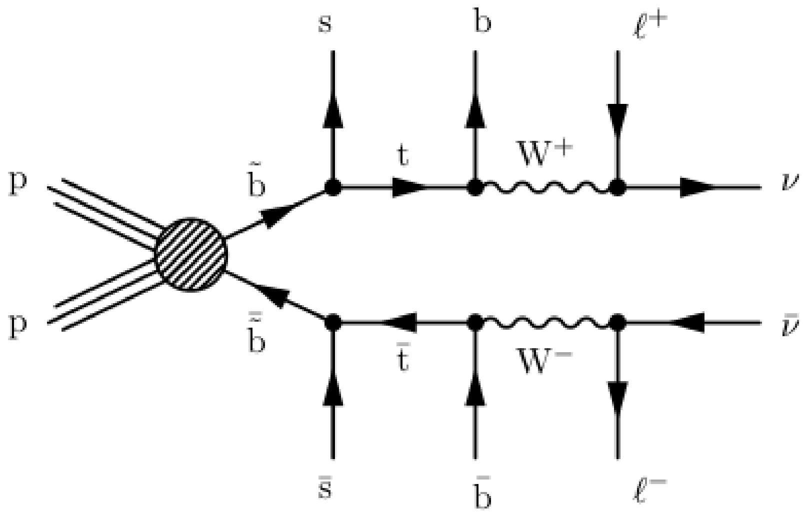



Figure 15: $\tilde{g} \to tbs$ limits from CMS SUS-12-015 and ATLAS-CONF-2013-007.

For $\tilde{g} \to qqq$ (light quarks), the limits are still weaker, e.g. about $700~\mathrm{GeV}$ from EXO-12-049, arXiv:1311.1799.

Gluino mass limits are a lot weaker than for RPC scenarios.

– $\tilde{b}\tilde{b}$ pair production with $\tilde{b}$ decay via BRPV



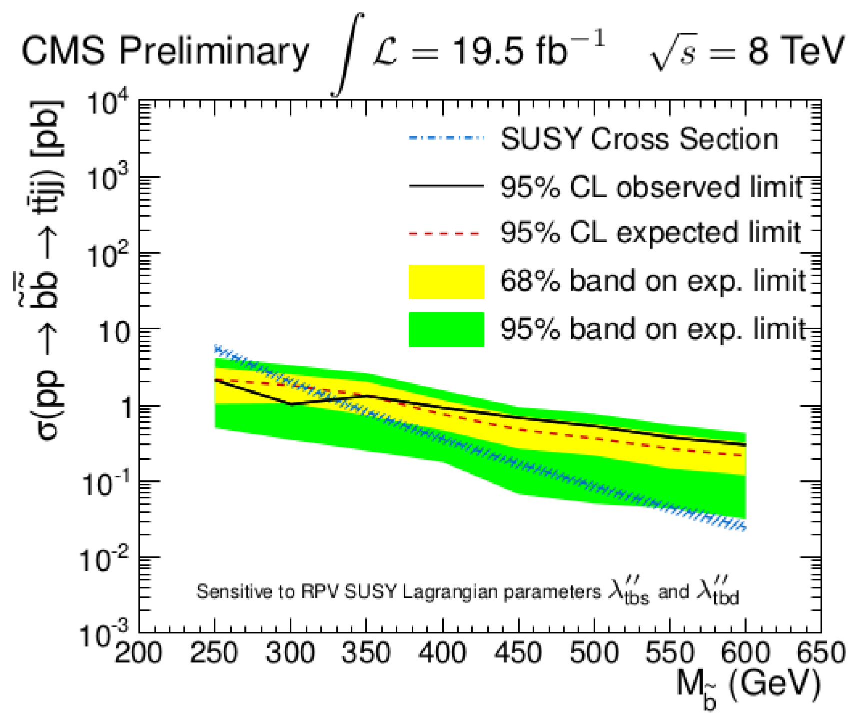




Figure 16: Limits on $\tilde{b}\tilde{b}$ production with BRPV decays. B2G-12-008.

Sbottom mass limits are especially weak.

– $\tilde{t}\tilde{t}$ pair production with $\tilde{t}$ decay via BRPV.

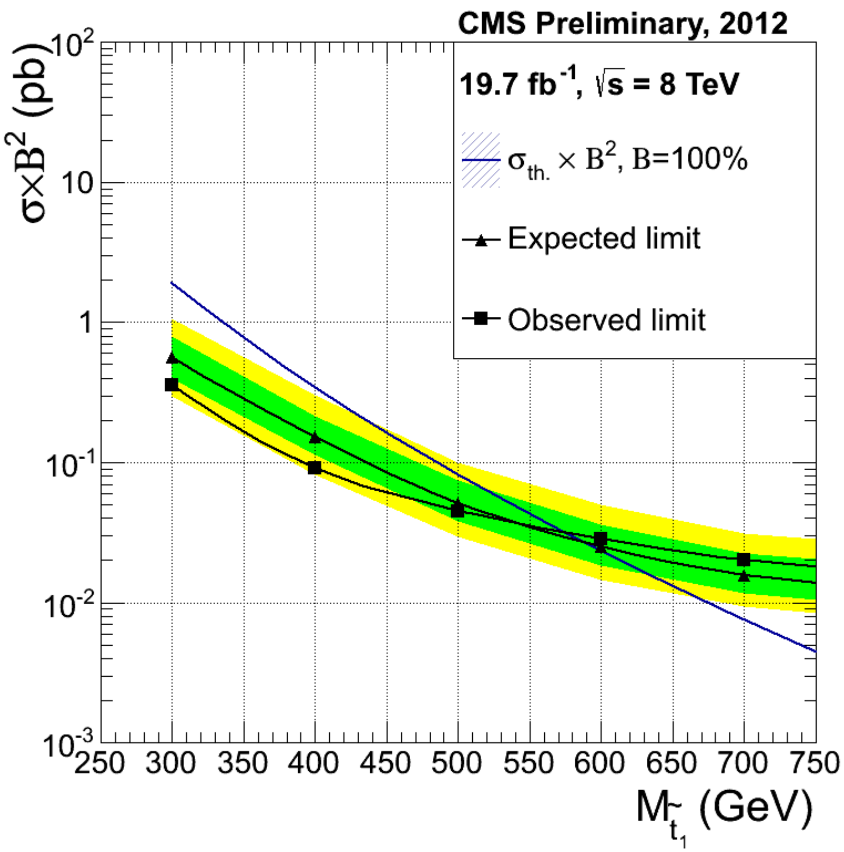



Figure 17: Limits on $\tilde{t}\tilde{t}$ production with BRPV decays. EXO-12-032.

Stop mass limits are not particularly strong even in the experimentally most favorable BRPV decay mode.

# Alternative Dark Matter Models

- Suppose there is no SUSY or similar.

  Where can dark matter come from?

- Expanded Higgs sector

  Add a singlet Higgs field that is stable because of an extra $Z_2$ symmetry that forbids it from having couplings to $f\overline{f}$ and from mixing with the Higgs-doublet field(s) required for standard EWSB.

  An example is starting from the 2HDM and adding a singlet $S$. After imposing symmetries one ends up with a Higgs potential of the form:

$$V(H_1, H_2, S) \quad = \quad V_{\rm 2HDM} + \frac{1}{2}m_0^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \kappa_1 S^2 (H_1^\dagger H_1) + \kappa_2 S^2 (H_2^\dagger H_2) \quad (1)$$

  Symmetry forbids any linear terms in $S$. The Higgs portal couplings are the $\kappa_1$ and $\kappa_2$ terms that induce Higgs-$SS$ couplings when $\langle H_1 \rangle, \langle H_2 \rangle \neq 0$.

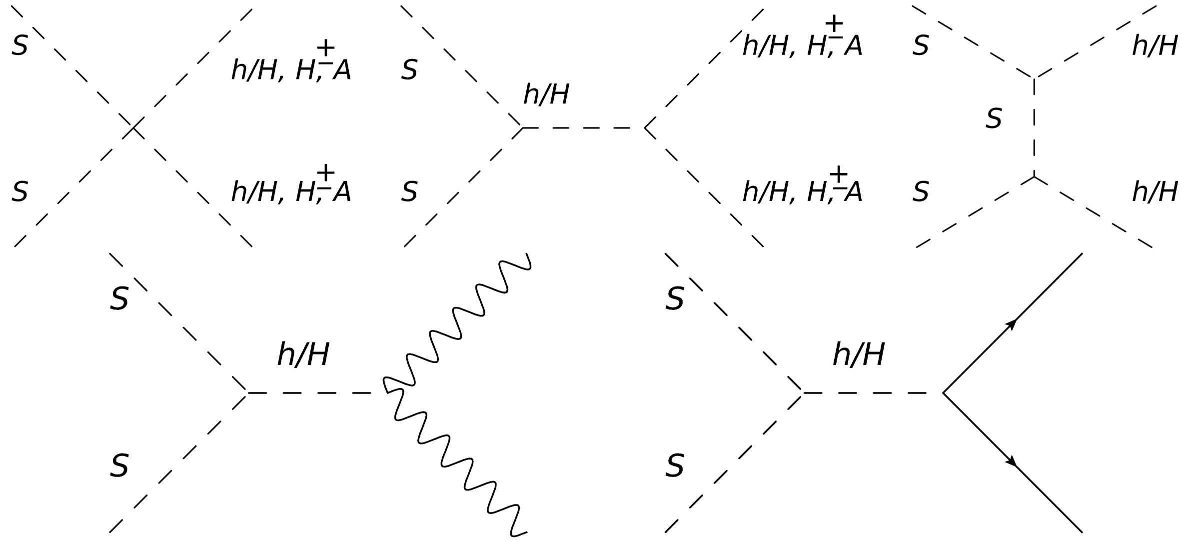



Figure 18: Singlet anihillation diagrams relevant for the relic density calculation.

Singlets are made and annihilate in the early universe by Higgs-related diagrams.

Identifying $h$ of 2HDM sector with the $126~\mathrm{GeV}$ state, one can retain good Higgs fits and get perfectly reasonable dark matter scenarios obeying all limits.

Possibilities in the $m_S < 125~\mathrm{GeV}/2$ region are limited by the need to have very small $hSS$ coupling to keep $\mathcal{B}(h \to SS) < 0.1$ so as to preserve the Higgs fits.

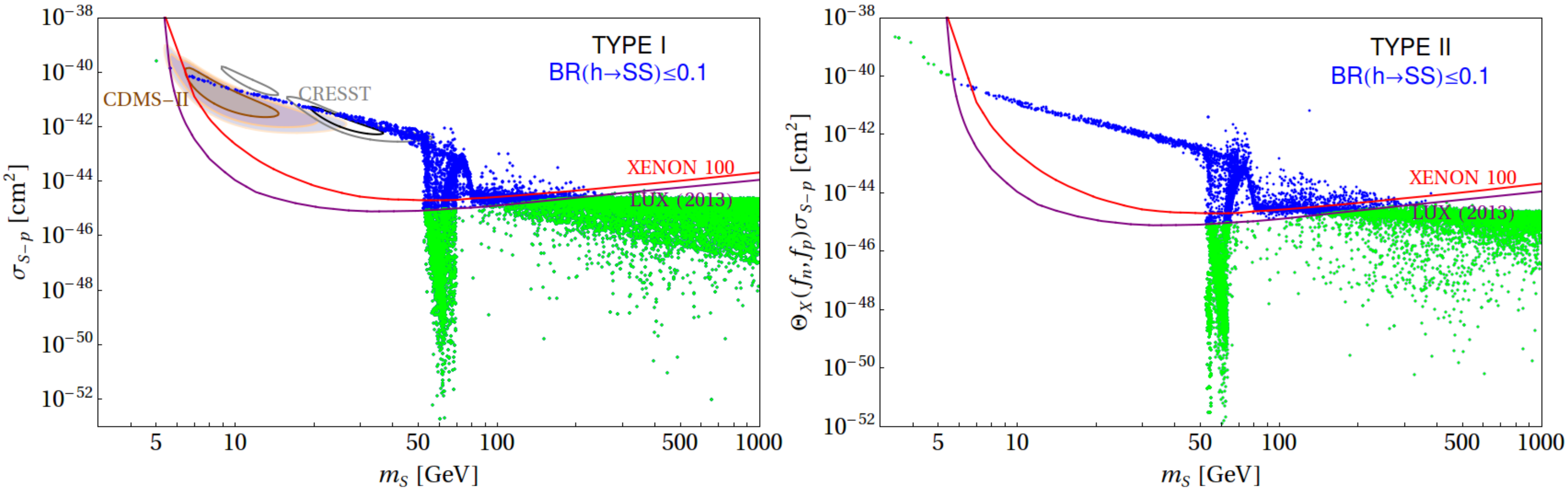



Figure 19: Cross section for DM - proton scattering for the type I and type II] models. All points shown satisfy the full set of preLUX constraints, including $\mathcal{B}(h \to SS) < 0.1$, while the green points satisfy in addition the LUX limits.

- Axion dark matter

  "There are viable theories and there are natural and elegant theories. However, all viable, natural and elegant theories contain dark-matter axions" - Ann Nelson.

  Physics has two perplexing mysteries:

  – What suppresses the expected large amount of CP violation in the strong

interactions (the "Strong CP Problem");
– and the nature of dark matter.

The axion is a hypothetical elementary particle originally postulated to solve the strong CP problem. The axion is also an extremely attractive dark matter candidate — It is very weakly interacting and very long lived.

The axion would allow these two mysteries (strong CP + dark matter) to fit naturally into our understanding of the universe.

In the early universe, cold axion populations arise from vacuum realignment and string and wall decay. Which mechanisms contribute depends on whether the Peccei-Quinn symmetry breaks before or after inflation.

These cold axions were never in thermal equilibrium with the rest of the universe and could provide the missing dark matter.

The axions have very small mass (given many years of experimental limits).

Their interactions with normal matter are so weak that they cannot be produced at a reasonable rate at a collider — and, there is no possibility of a parent particle being produced and then decaying to an axion.

Basically, this is a bad news scenario for CMS —- one needs an experiment like ADMX.

- SUSY $+$ axions.

  If BRPV applies, SUSY could still be relevant for solving naturalness, the neutralino or other LSP would not be stable. Dark matter could be provided by the axions.

  $\Rightarrow$ pay more attention to RPV scenarios.

  Of course, there are the mixed axion-neutralino dark matter scenarios of Baer and collaborators. (See, for example, arXiv:1310.1859). This is a possibility, but kind of artificial in many respects.

  Not really much advantage with regard to the scenario in which we have BRPV $+$ pure axion dark matter.

# Conclusions

- It seems quite certain that the Higgs responsible for EWSB has emerged.

- At the moment, there is no sign of other Higgs-like signals except for the old LEP excess at $98~\mathrm{GeV}$.

- Survival of enhanced signals for the $125~\mathrm{GeV}$ state (as still seen by ATLAS) would be one of the most exciting outcomes of the next LHC run and would guarantee years of theoretical and experimental exploration of BSM models with elementary scalars.

- Close to SM signals at the LHC would imply that a linear collider or LEP3 or muon collider might be needed to look for BSM physics indirectly via deviations of Higgs properties from the SM.

- Although current data is converging to a SM-like Higgs, there is still room for additional Higgs bosons in important model classes.

  Thus, we must push hard to improve limits/sensitivity to additional Higgs bosons.

- SUSY remains the best-motivated technically natural model. But, it is being pushed.

  If there is some kind of high-scale unification, then low FT is best accommodated in the NMSSM.

  The pMSSM sets SUSY scales without regard to the ultimate high-scale theory — this may be quite appropriate in the context of the string landscape.

- Perhaps it is best to separate Dark Matter from SUSY!

  - Correct $\Omega h^2$ is quite improbable, even in the pMSSM approach.
  - R-parity conservation implies SUSY is kind of easy to see if at low mass and so now limits are uncomfortably ($i.e.$ unnaturally) high.
  - The axion is in any case needed for the strong CP problem and is certainly an excellent dark matter candidate.

The two big questions/bottom lines are:

- **Whither Higgs?** — fortunately, **we need not worry about** **Wither Higgs?**.

- However, despite G. Ross's objection to the **Wither SUSY?** option, it is becoming increasingly frustrating to continue the **Whither SUSY?** approach.

In any case, while the waiting for a 1st Higgs signal is over, watching for more Higgs or some sign of BSM is not: