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SUSY after the Higgs

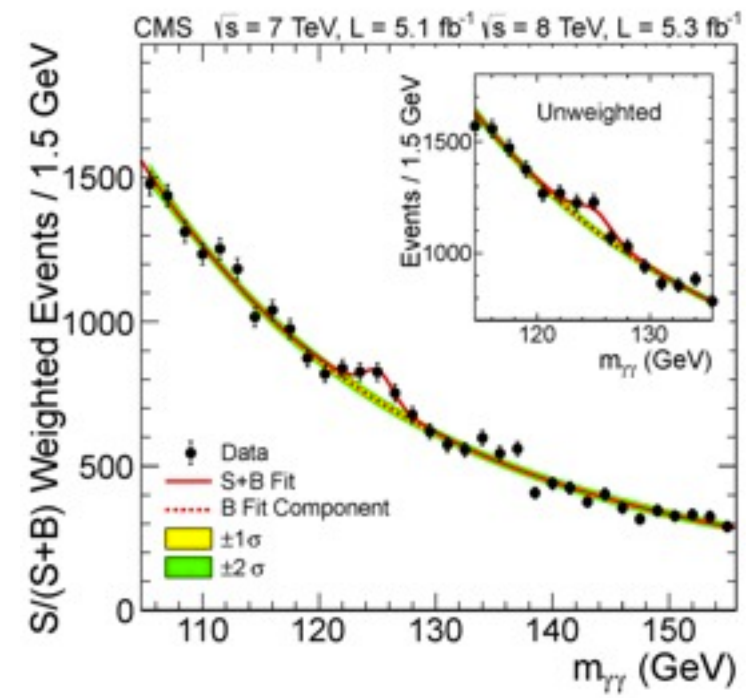
Implications of LHC Higgs results for supersymmetry

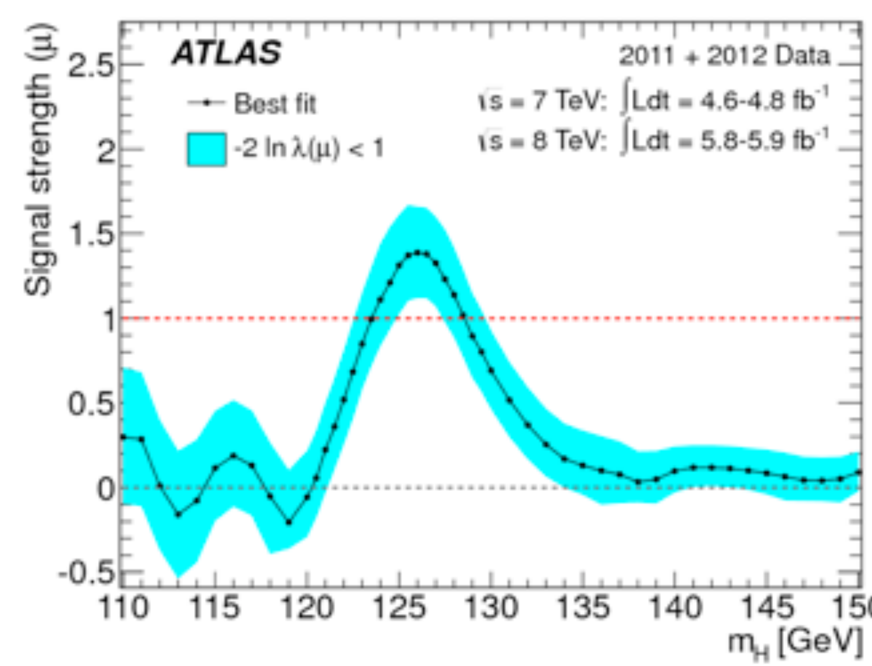
HEFTI Higgs Signal Workshop, UC Davis, 22-26 April 2013

Introduction

- The 2012 Higgs discovery at ~125 GeV is a tremendous first success of the LHC program.
- Completes the Standard Model (SM) of electroweak and strong interactions.
- However, this should not be regarded as the closing of a chapter but the opening of a new one.
- Most pressing issue: to explain the value of the electroweak (EW) scale itself. Why is the Higgs boson so light when it is predicted to be driven to the GUT or Planck scale by radiative corrections?

➩ new physics at the TeV scale
(or extreme fine-tuning)



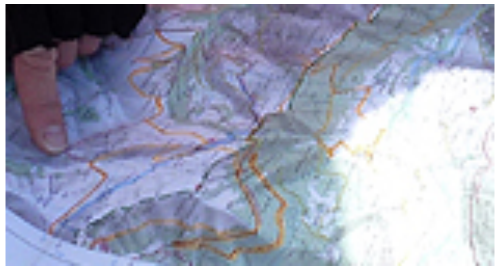


Beyond the SM ?

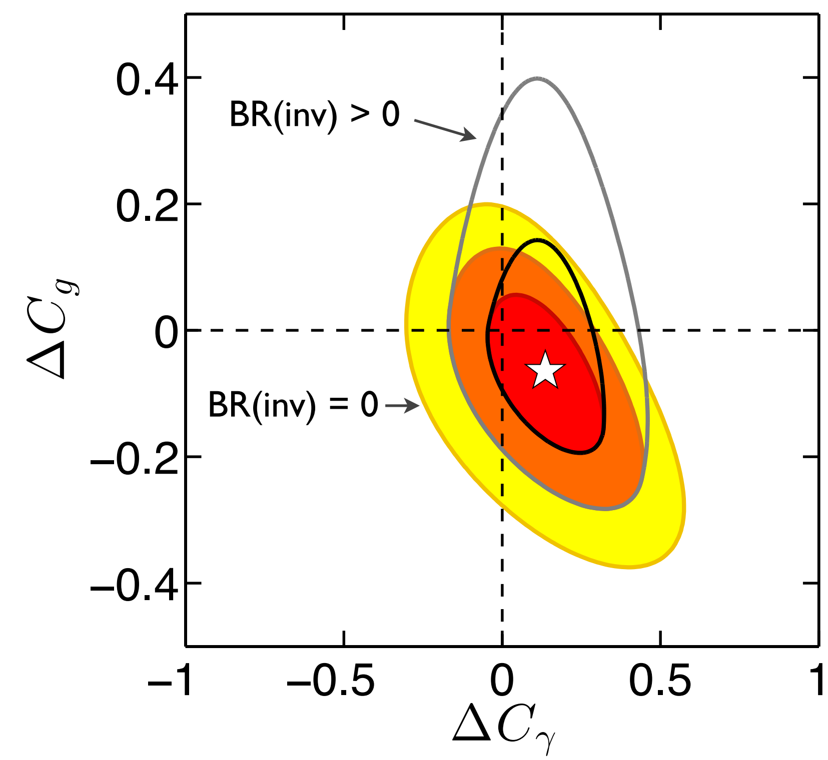
- While the SM provides a good fit to the data, the situation not yet conclusive. E.g. some new physics contributions to the effective couplings to gluons and photons are quite possible.

- Supersymmetry is a very attractive framework to explain the 'smallness' of the Higgs mass.

- With the absence of any sign of new physics, the Higgs results may become our main guide for where to look for SUSY (or other BSM).



- This talk is about what the Higgs can tell us (and cannot tell us) about supersymmetry.



Fit to ATLAS, CMS and Tevatron data for SM-like Higgs couplings to fermions and gauge bosons.

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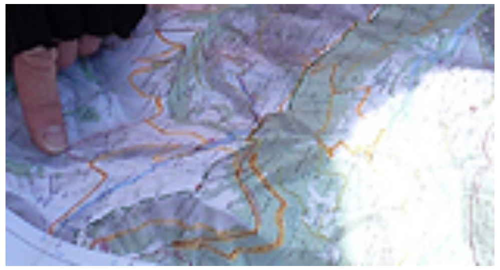
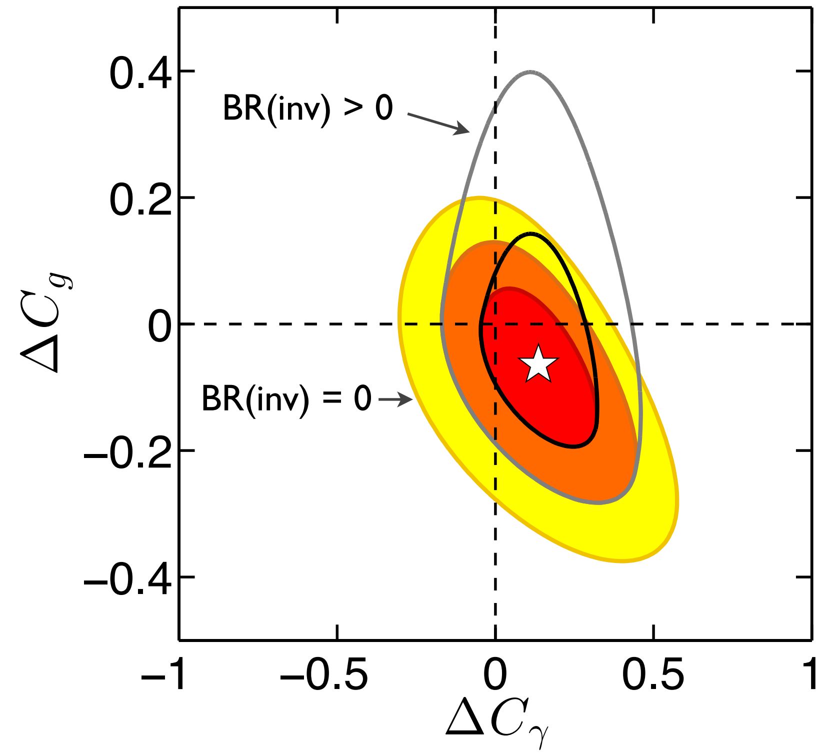




Fit to ATLAS, CMS and Tevatron data for SM-like Higgs couplings to fermions and gauge bosons.

- This talk is about what the Higgs can tell us (and cannot tell us) about supersymmetry.

Two parts:
1. GUT-scale boundary conditions
2. phenomenological MSSM

Disclaimer

This talk has been done on very short notice.

Plots got ready yesterday,
thanks to Suchita Kulkarni and Sezen Sekmen.

Preliminary results,
be kind to me ;-)

MSSM Higgs mass

- Three level prediction for the light Higgs mass in the MSSM: $m_h \leq m_Z$!
- Need ~100% radiative corrections to achieve m_h around 125-126 GeV

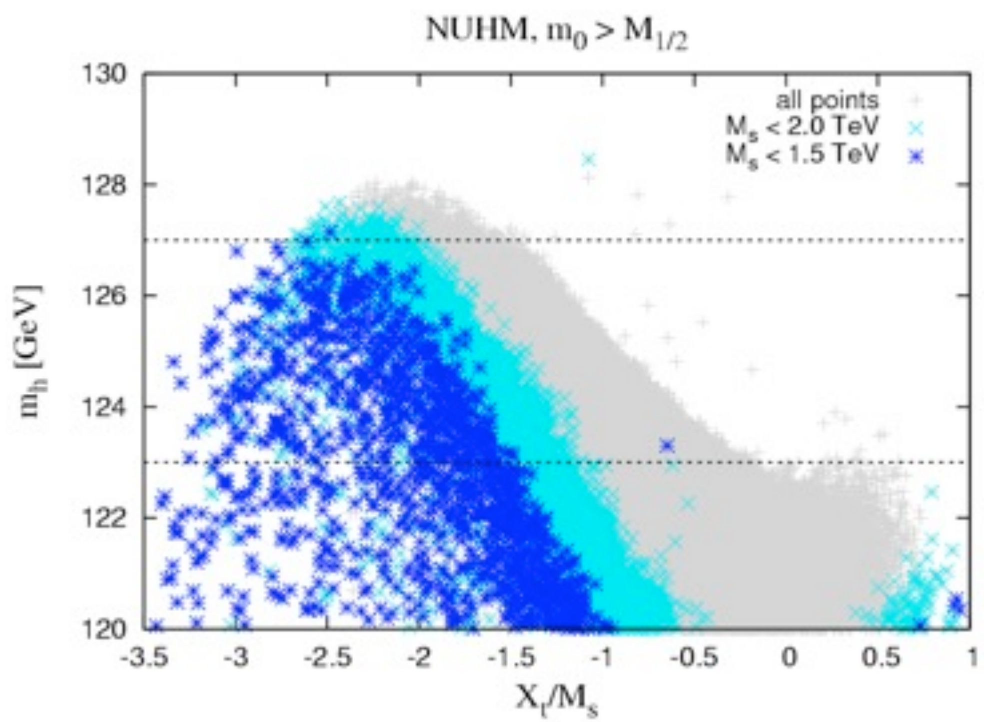
$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$$(126\,\mathrm{GeV})^2 = (91\,\mathrm{GeV})^2 + (87\,\mathrm{GeV})^2$$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\,M_S^2}\right)\right)$$

heavy stops

maximal mixing (large A_t)



Brummer, Kulkarni, SK, arXiv:1204.5977

$$X_t = A_t - \mu\cot\beta,\;\; M_S^2 = m_{\tilde{t}_1}\, m_{\tilde{t}_2}$$

- Δm_h^2 is maximized for $|X_t/M_S| \simeq \sqrt{6}$ .... "maximal mixing"

[Carena et al.]

GUT-scale boundary conditions: Non-universal Higgs mass (NUHM) model

parameters to scan over:

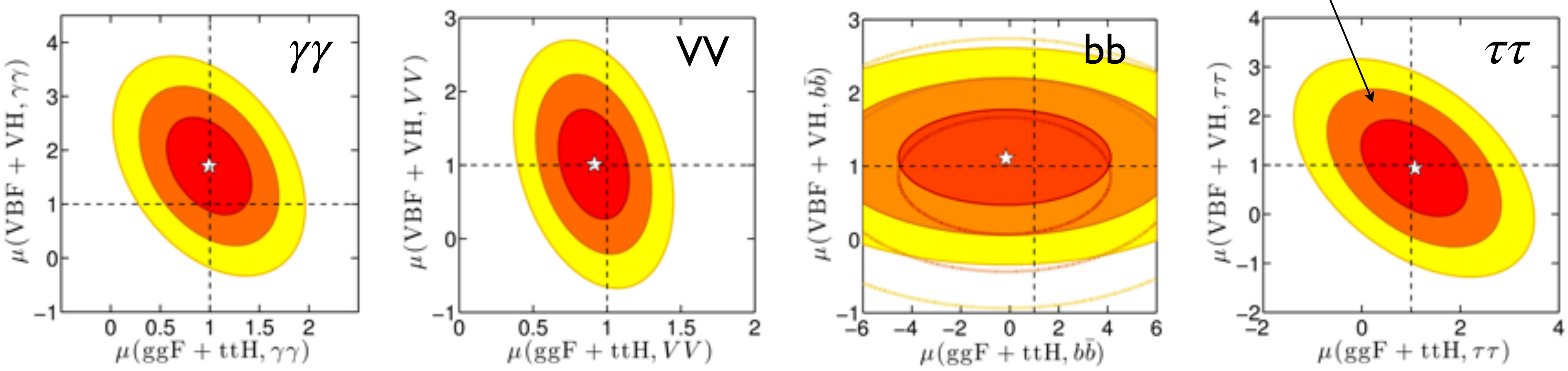
$$m_0,\ M_{1/2},\ A_0\,\Big|_{M_{\rm GUT}} \quad \mu,\ m_A,\ \tan\beta\,\Big|_{M_{\rm EW}}$$

based on
"Anatomy of maximal mixing"
F. Brümmer, SK, S. Kulkarni, arXiv:1204.5977

Constraints

- B-physics: $$2.87 < \mathrm{BR}(b \to s\gamma) \times 10^4 < 4.23$$ $$0.015 < \mathrm{BR}(B_s \to \mu\mu) \times 10^9 < 6.35$$
- SUSY mass limits from LEP; LHC: m(gluino) > 1TeV

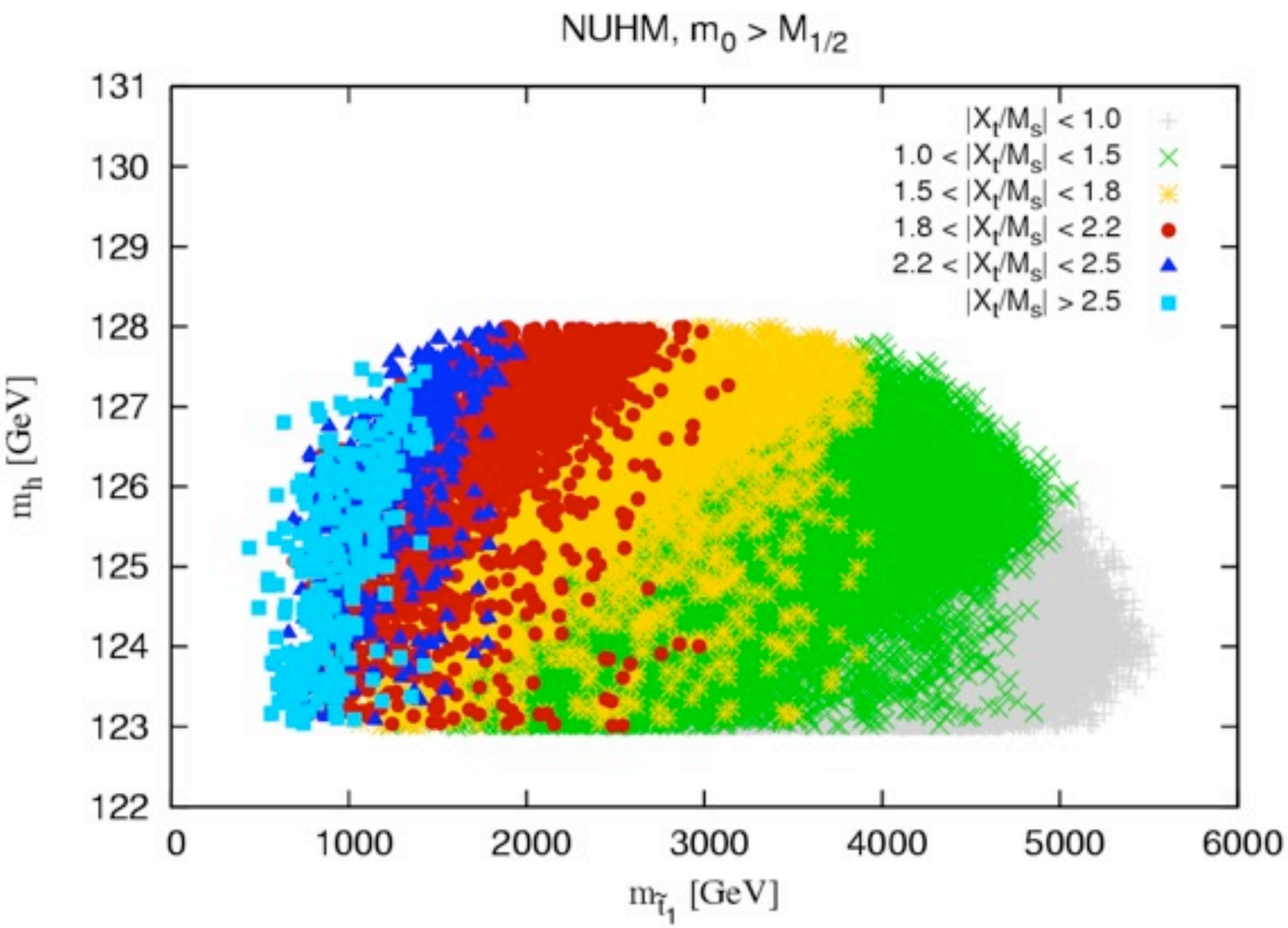
- Higgs mass: m_h^{MSSM} = [123, 128] GeV assuming ~2 GeV theory uncertainty
- For Higgs signal strengths R, require consistency with 95% CL ellipses (orange):



Combined ATLAS+CMS+Tevatron signal strength ellipses, cf. Beranger Dumont's talk on Monday

Higgs versus stop mass

color code shows amount of stop mixing



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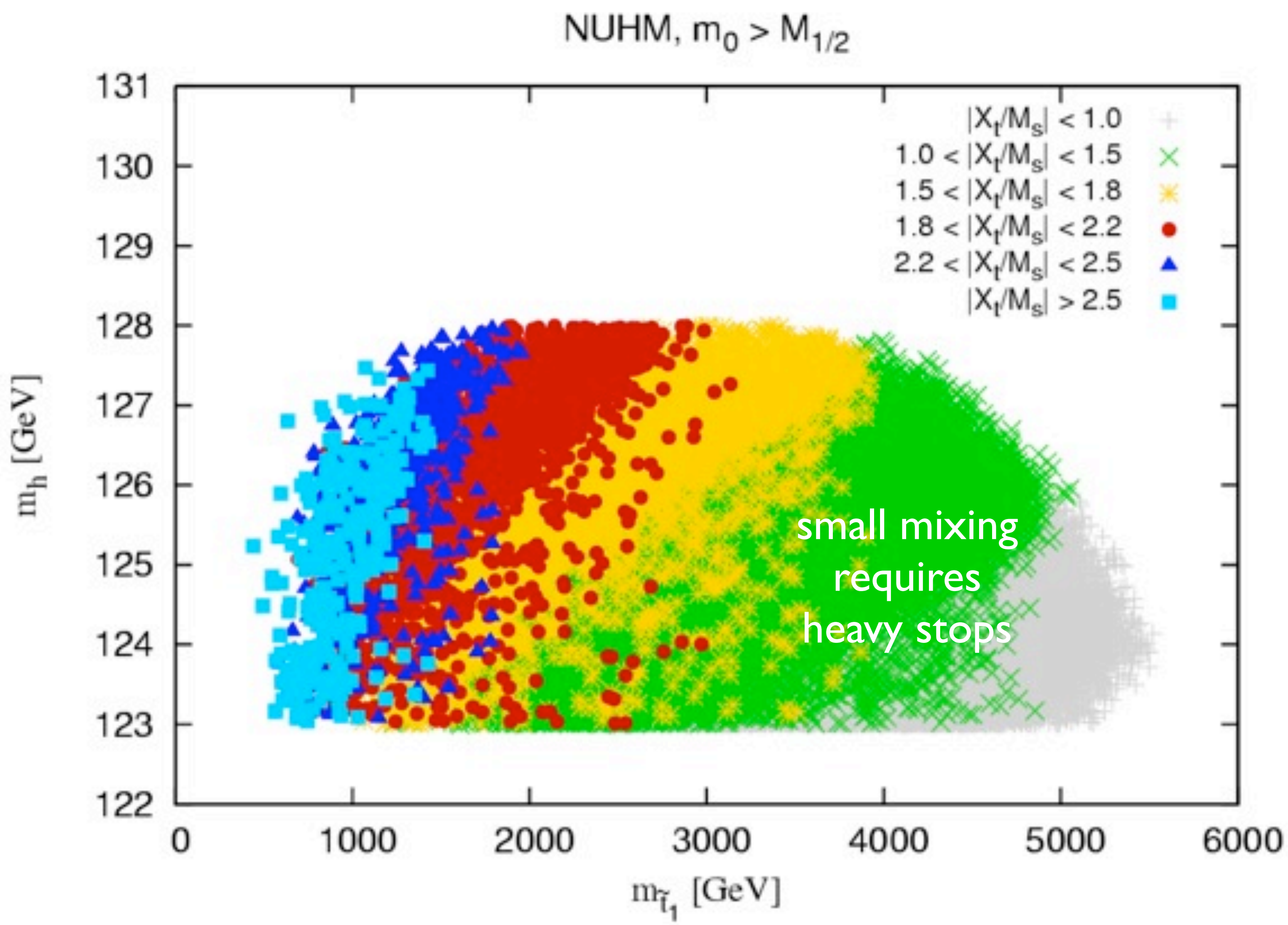

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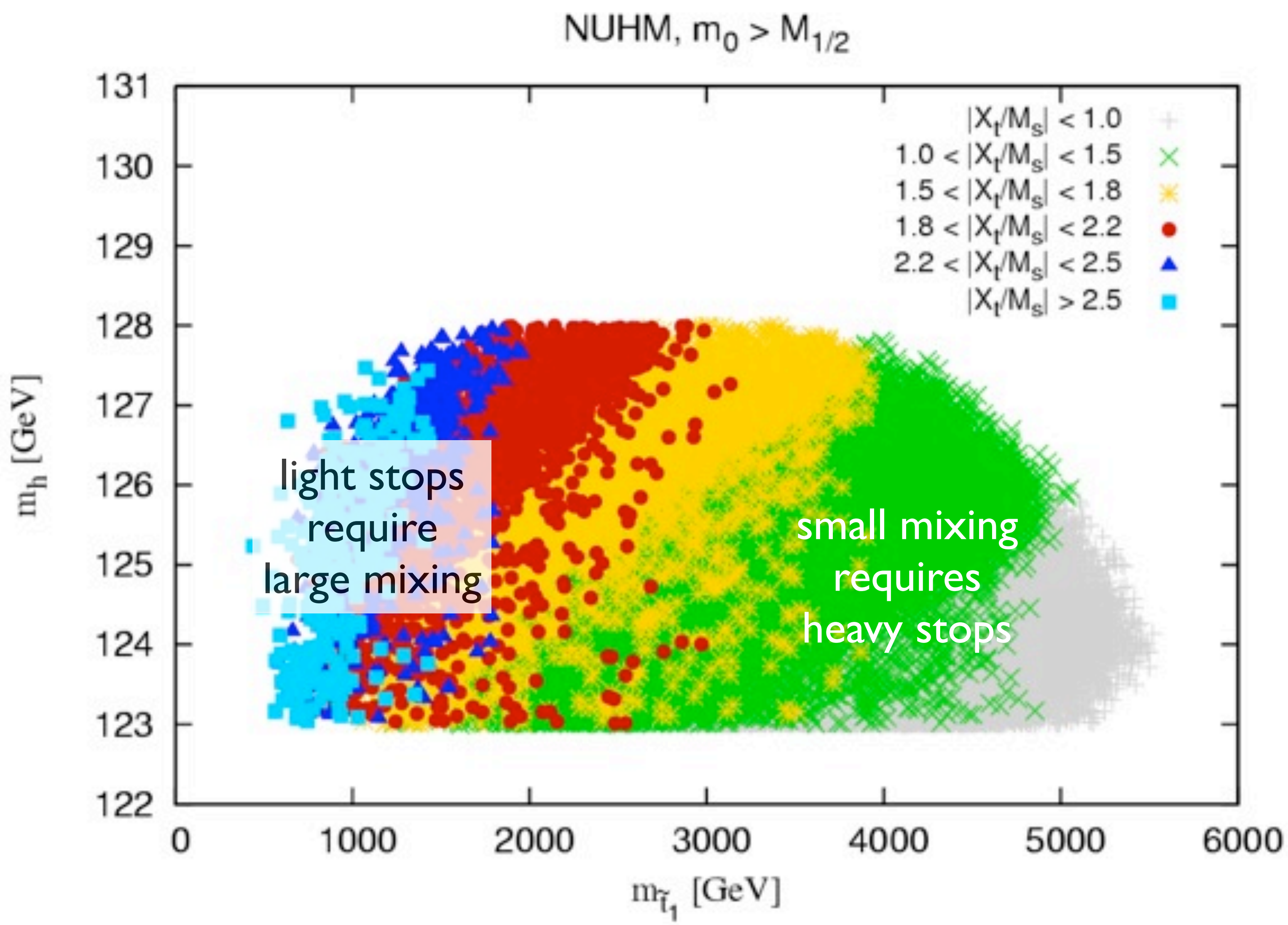

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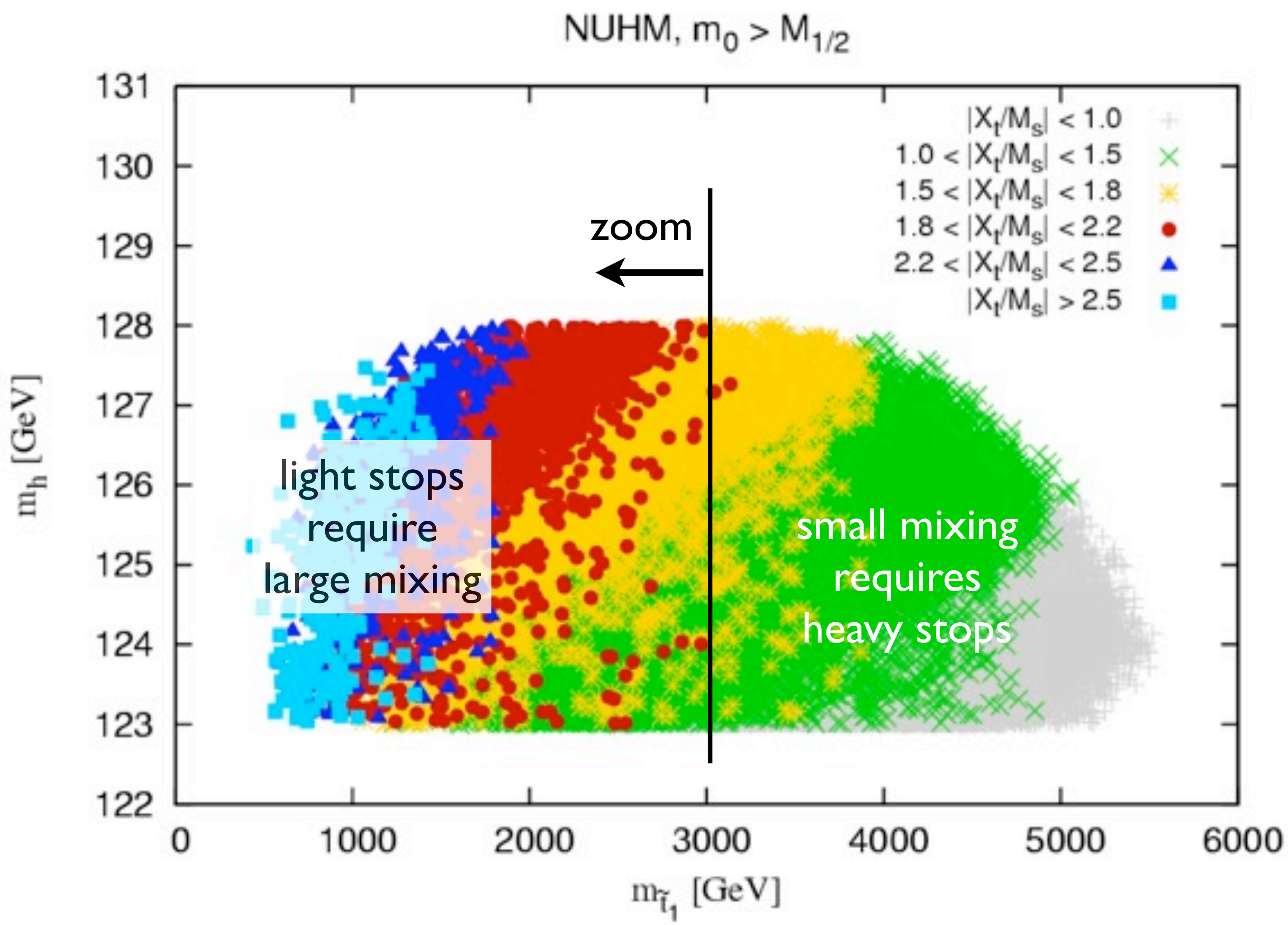

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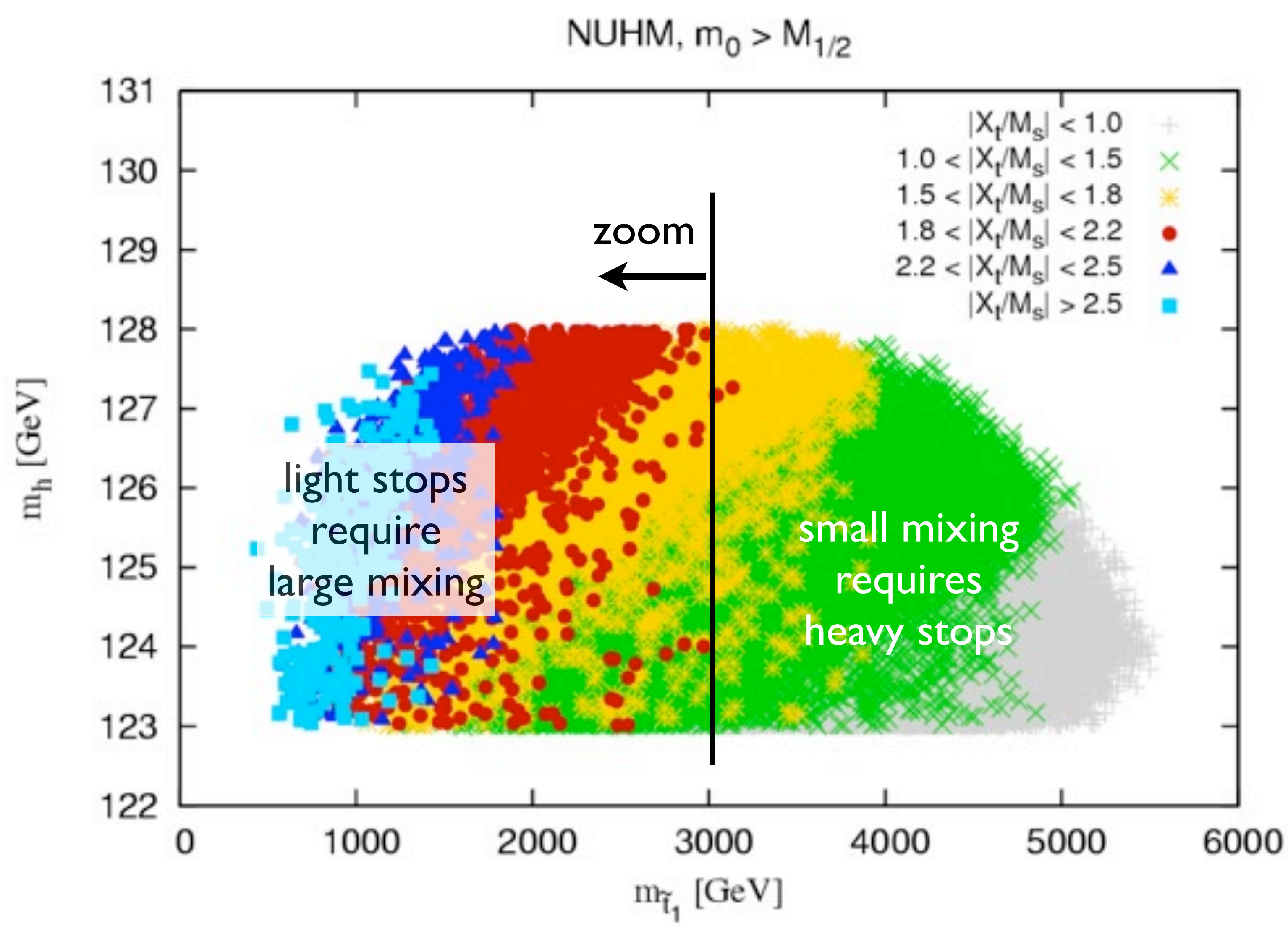
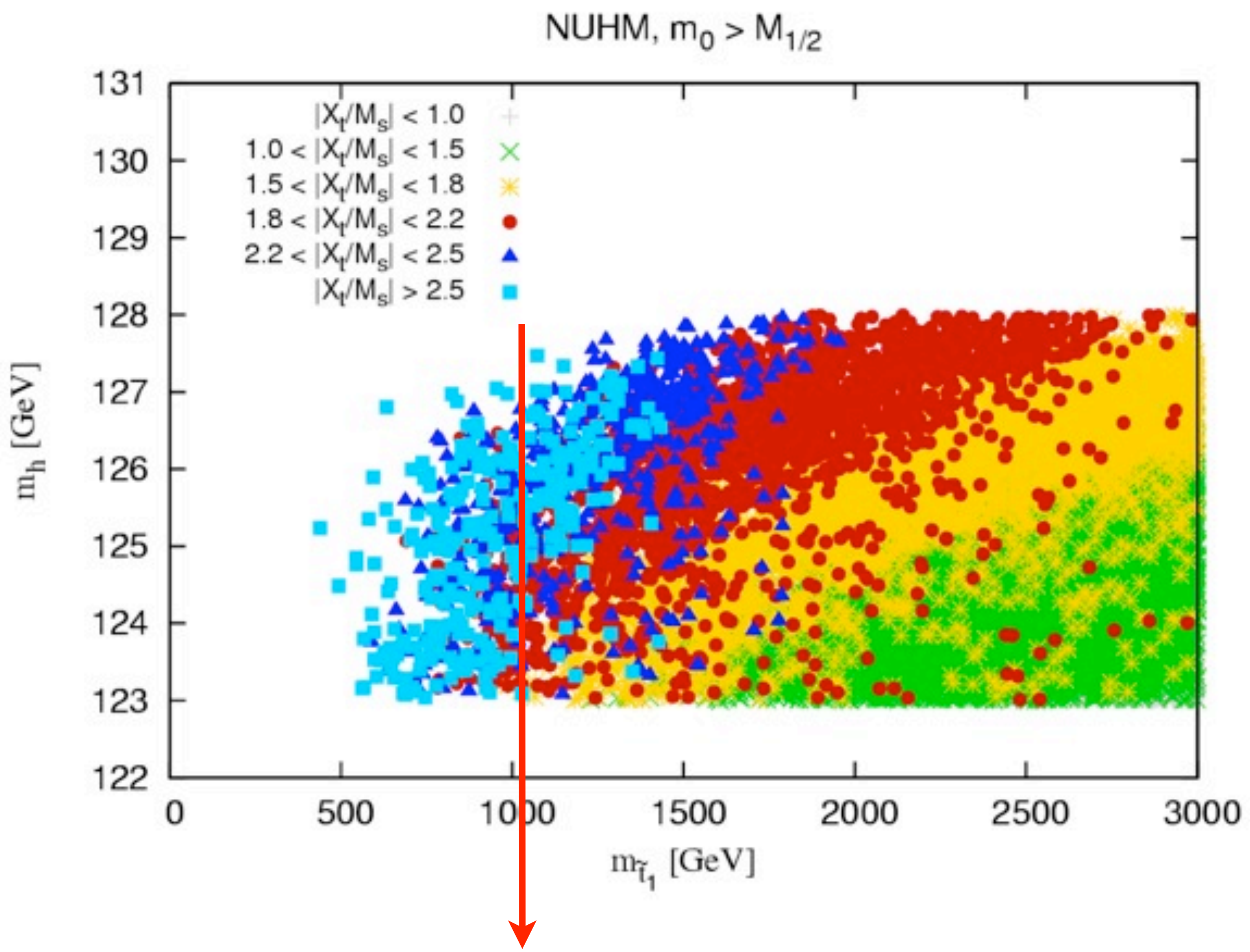


95% CL Higgs signal strength requirement
has marginal effect, excludes only <1% of points

Higgs versus stop mass

color code shows amount of stop mixing



stop below 1 TeV requires $|X_t/M_S| \gtrsim 1.8$

Higgs versus stop mass

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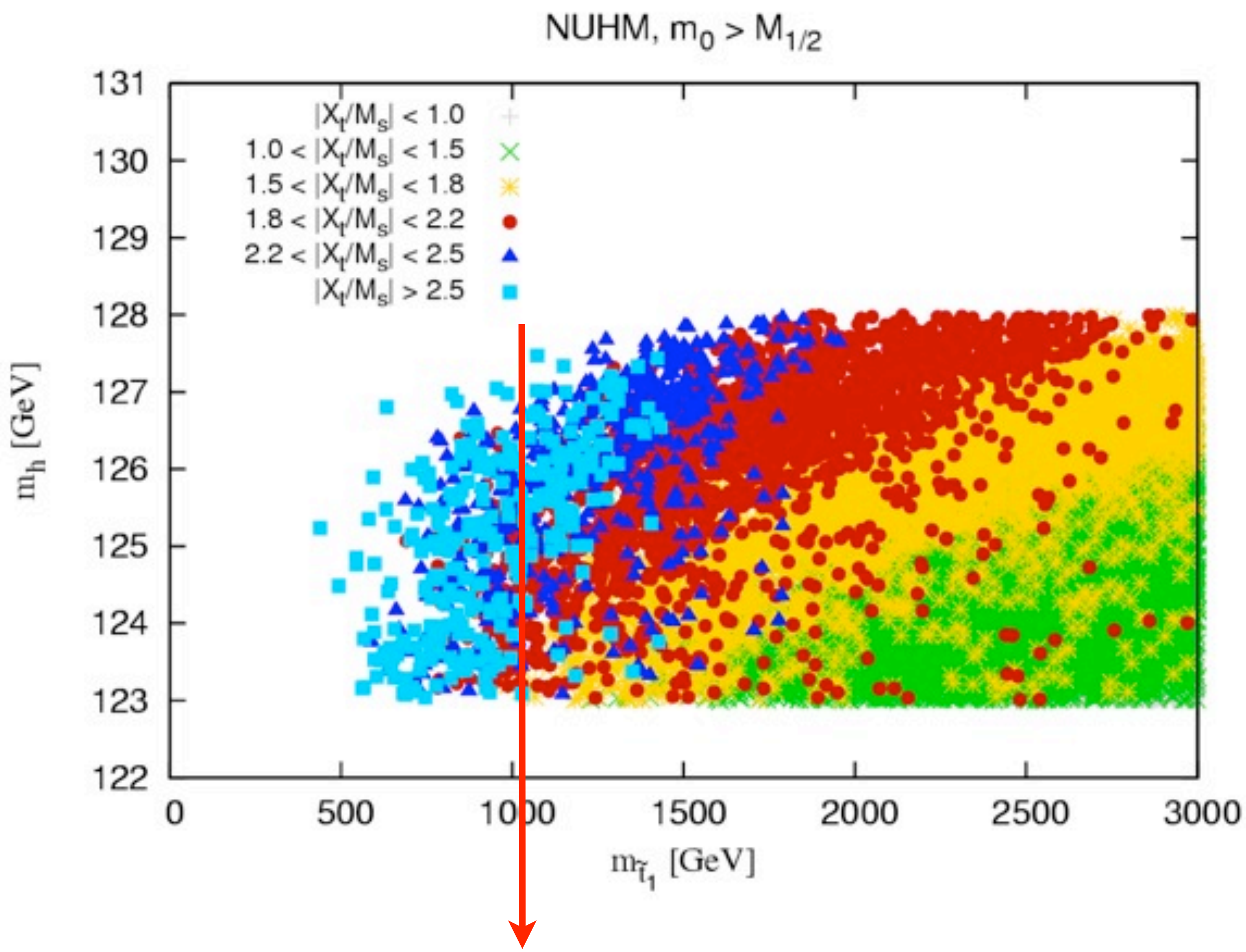

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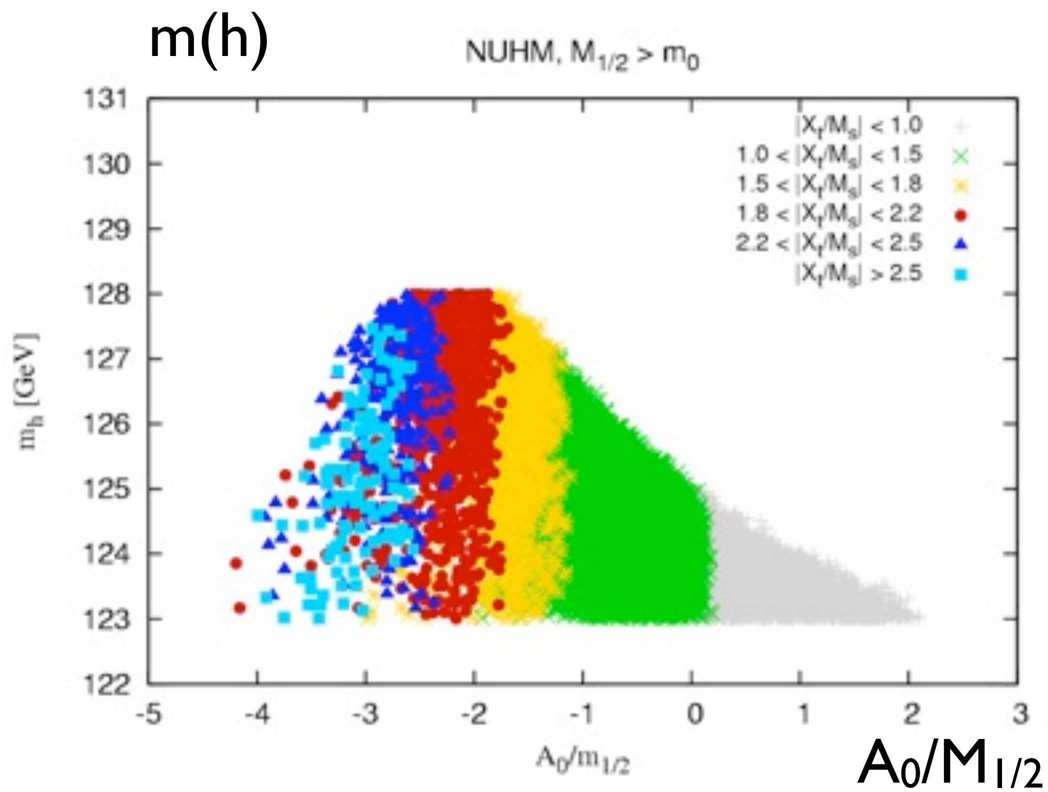
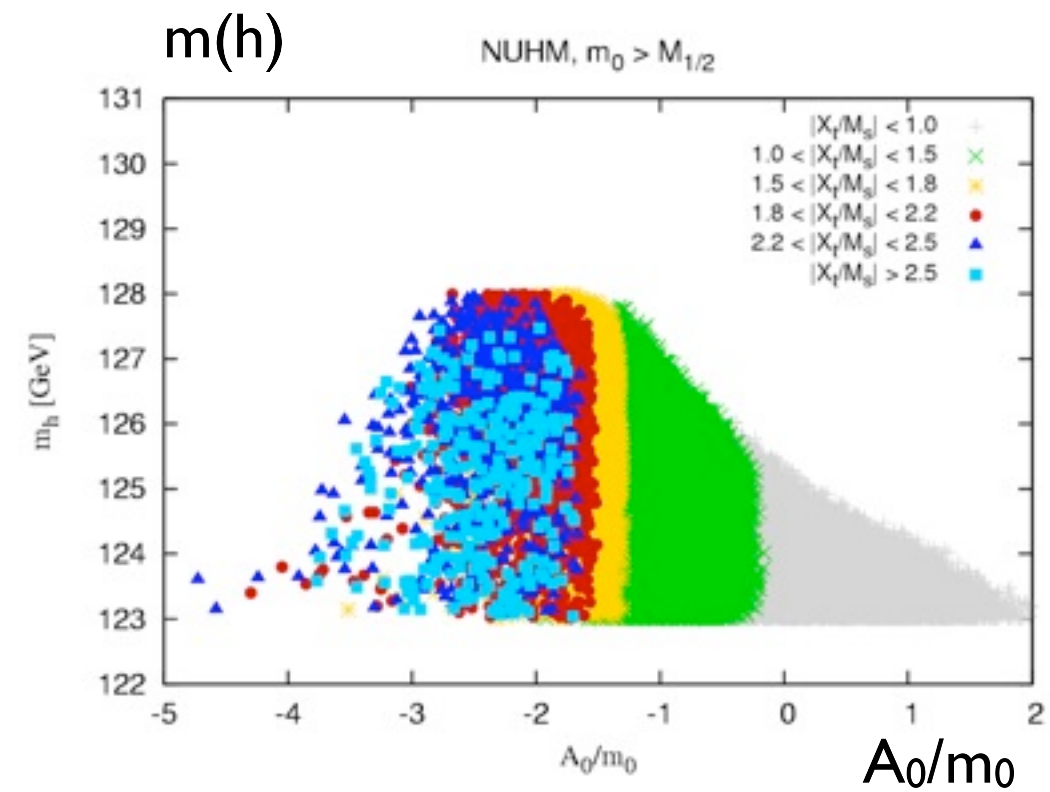
A terms





with universal m_0:
m_h~125 GeV from maximal mixing (light stops)
requires very large negative A_0

$A_0 \approx$ (-2 to -3) × max(m_0, $M_{1/2}$)

$$X_t^4 \approx 9.4\, M_{1/2}^4 - 7.5\, A_0\, M_{1/2}^3 + 2.2\, A_0^2\, M_{1/2}^2 - 0.3\, A_0^3\, M_{1/2} + 1.1\, M_{1/2}^3\, \widehat{\mu} - 0.7\, A_0\, M_{1/2}^2\, \widehat{\mu}\,.$$

$$M_S^4 = m_{\tilde{U}_3}^2 m_{\tilde{Q}_3}^2\big|_{M_S} \approx 8.7\, M_{1/2}^4 + 2.5\, M_{1/2}^2\, \widehat{m}_{U_3}^2 + 1.7\, M_{1/2}^2\, \widehat{m}_{Q_3}^2 + 1.2\, A_0\, M_{1/2}^3 - 0.4\, A_0^2\, M_{1/2}^2 - 0.9\, M_{1/2}^2\, \widehat{m}_{H_u}^2 + 0.8\, \widehat{m}_{U_3}^2\, \widehat{m}_{Q_3}^2\,.$$

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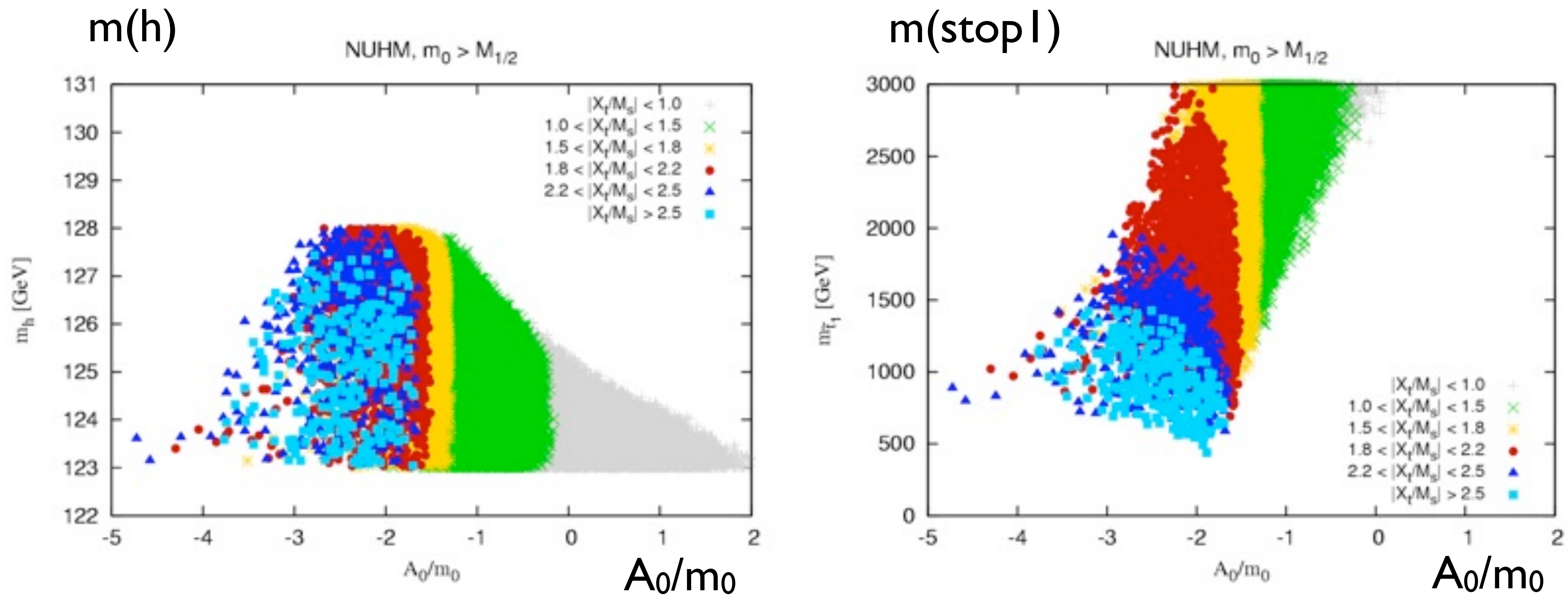

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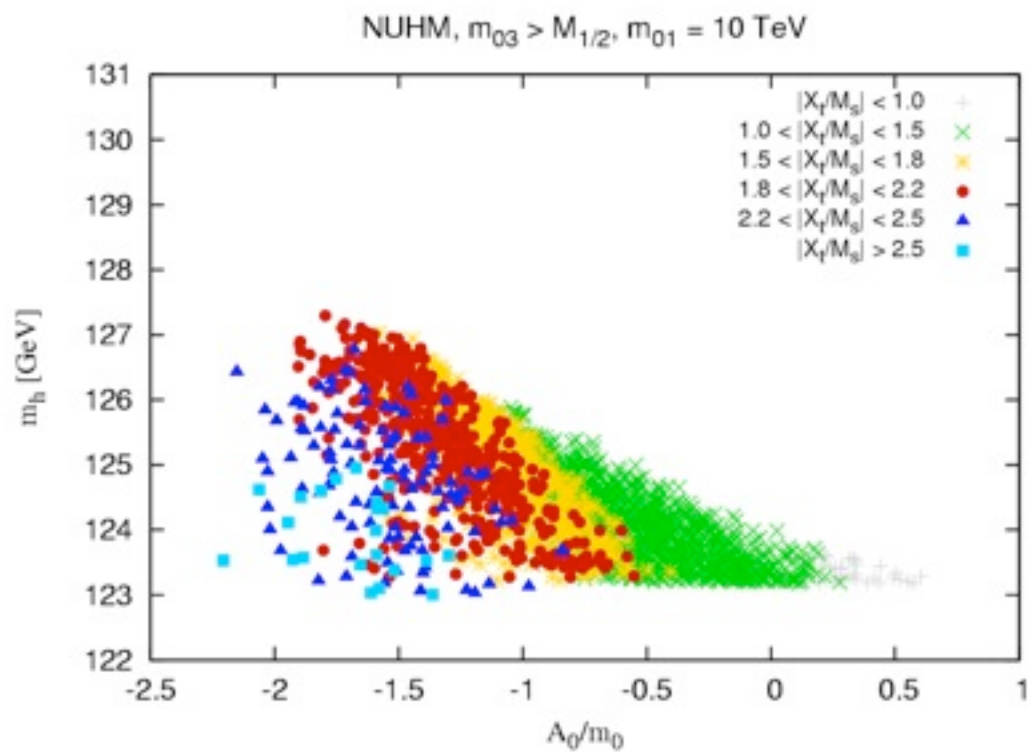
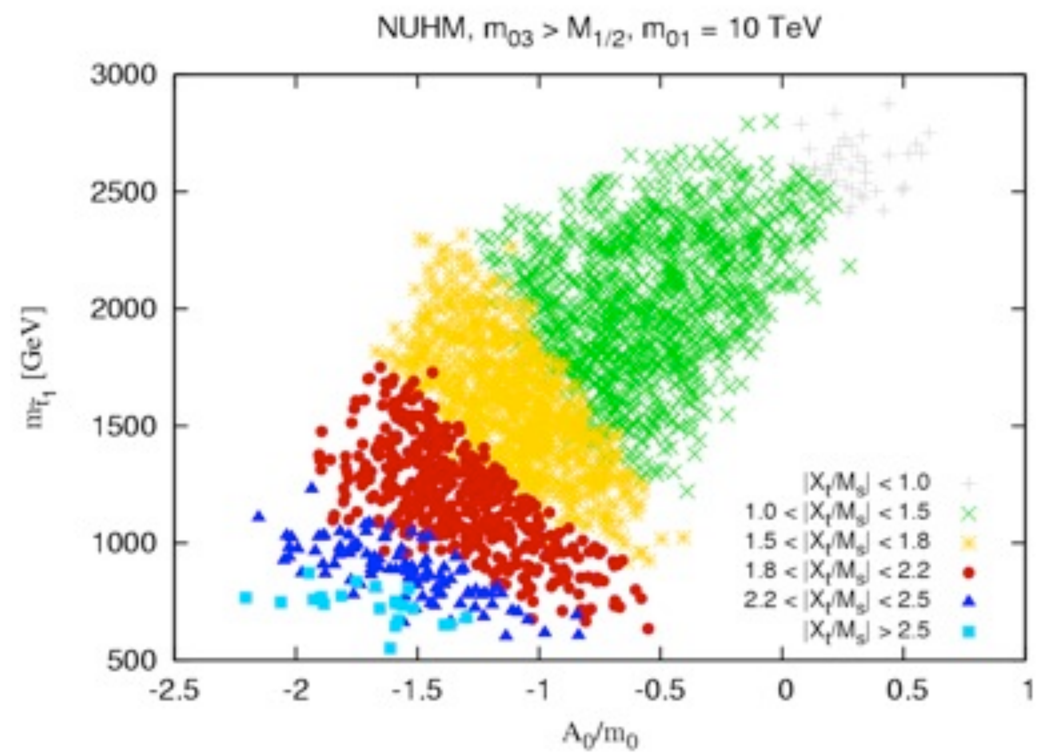
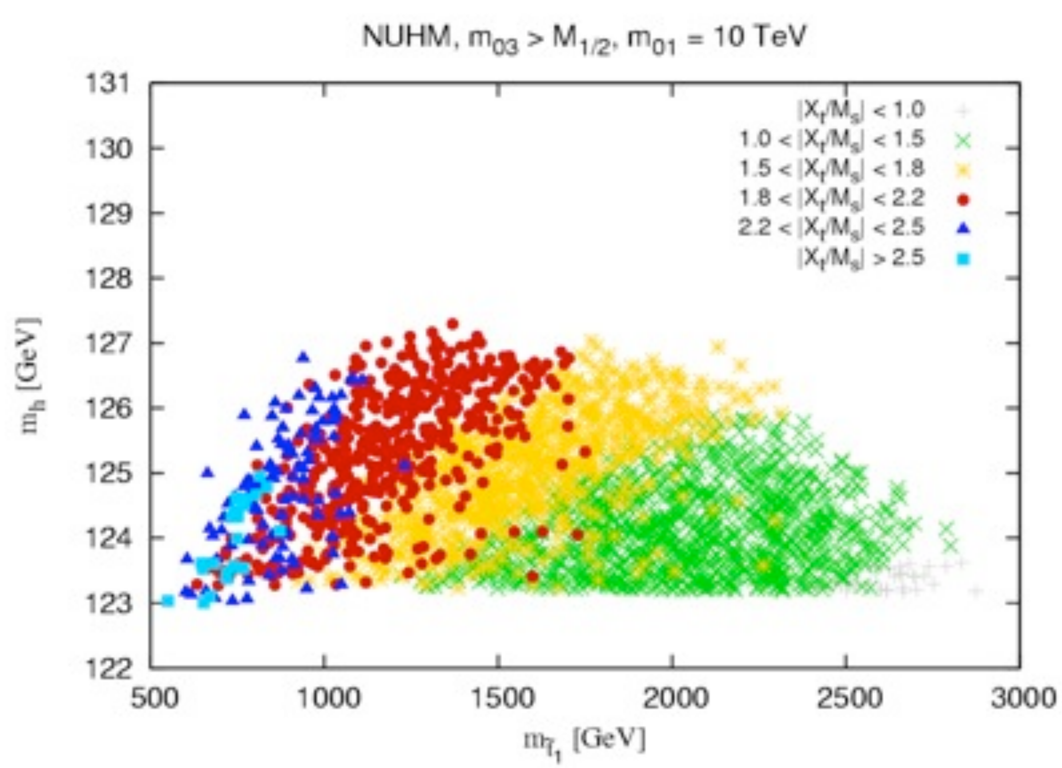
NUHM with 10 TeV squarks





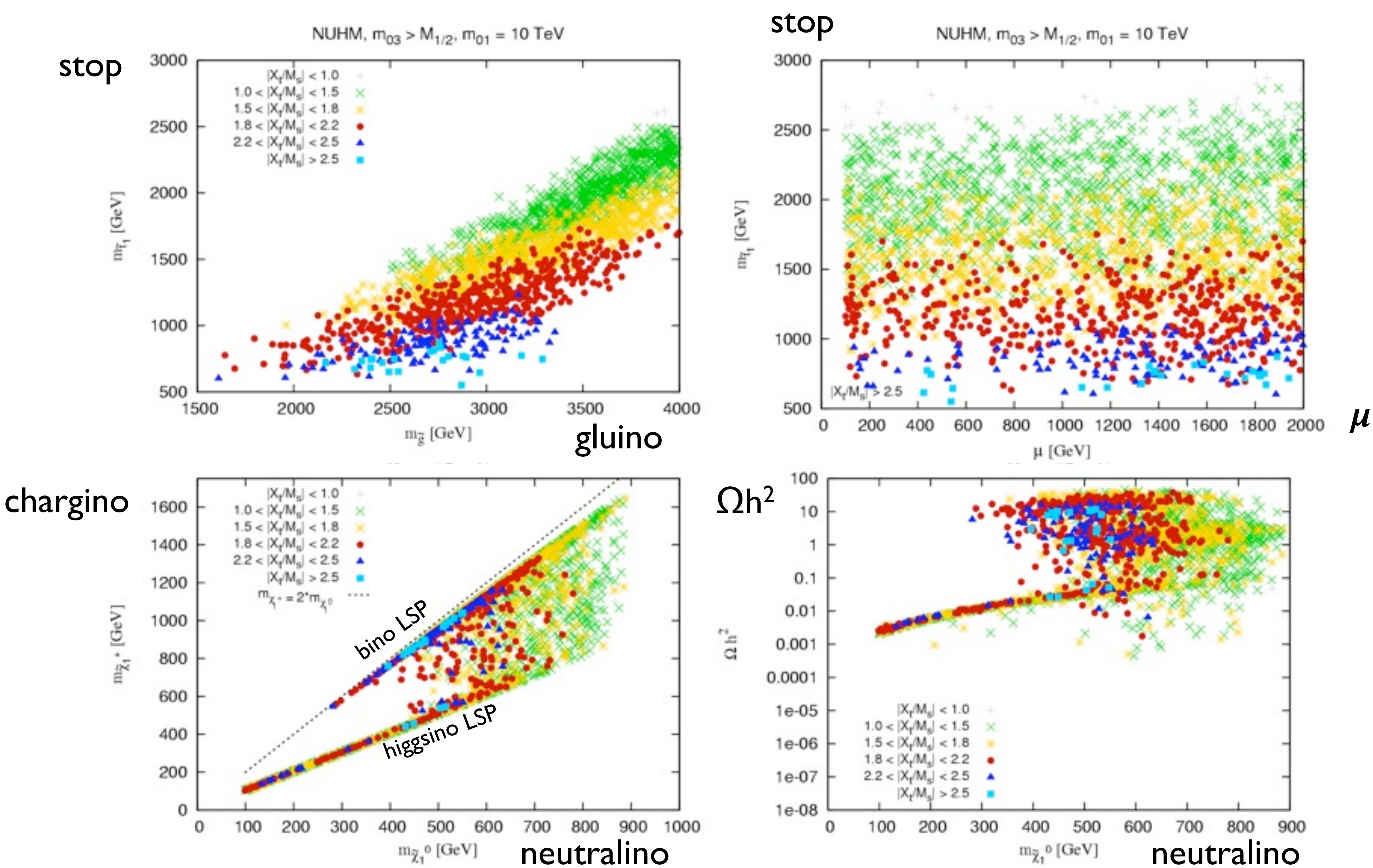


2-loop effects in the RGE running drive M_S down.

Light stops, near-maximal mixing and m_h~125 GeV even for moderate A_0

→ Howie Baer's talk tomorrow

SUSY particles



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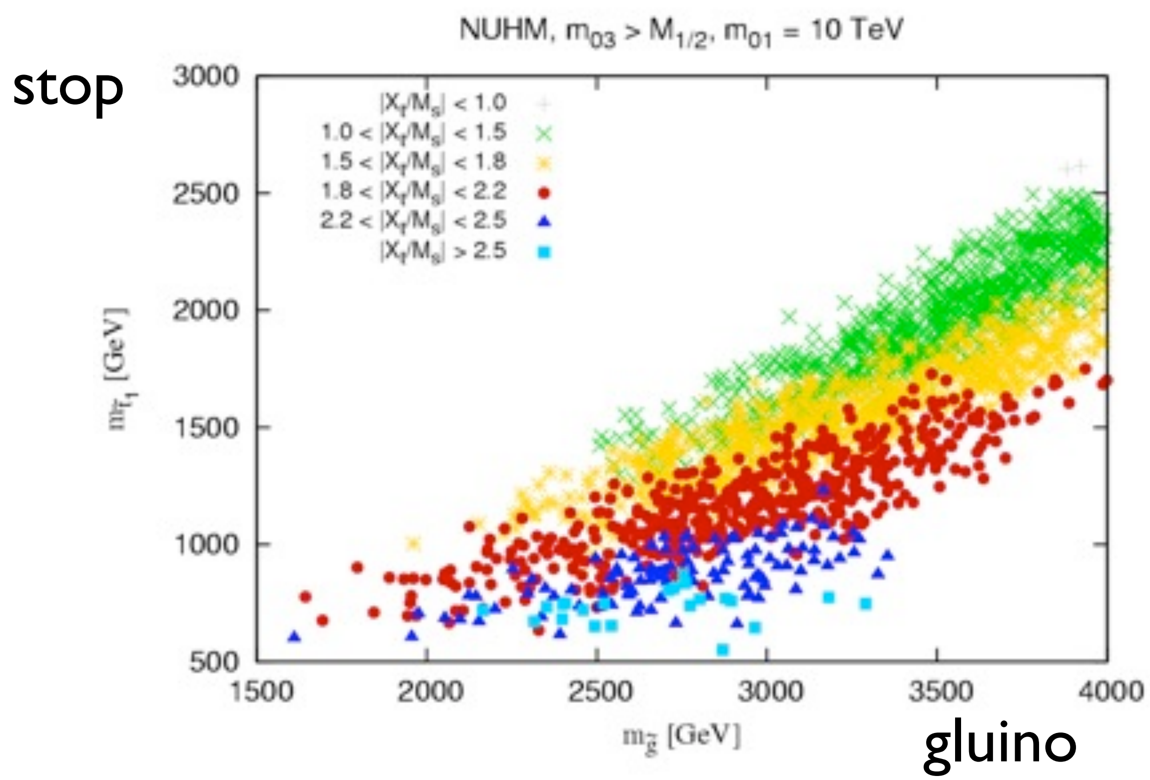

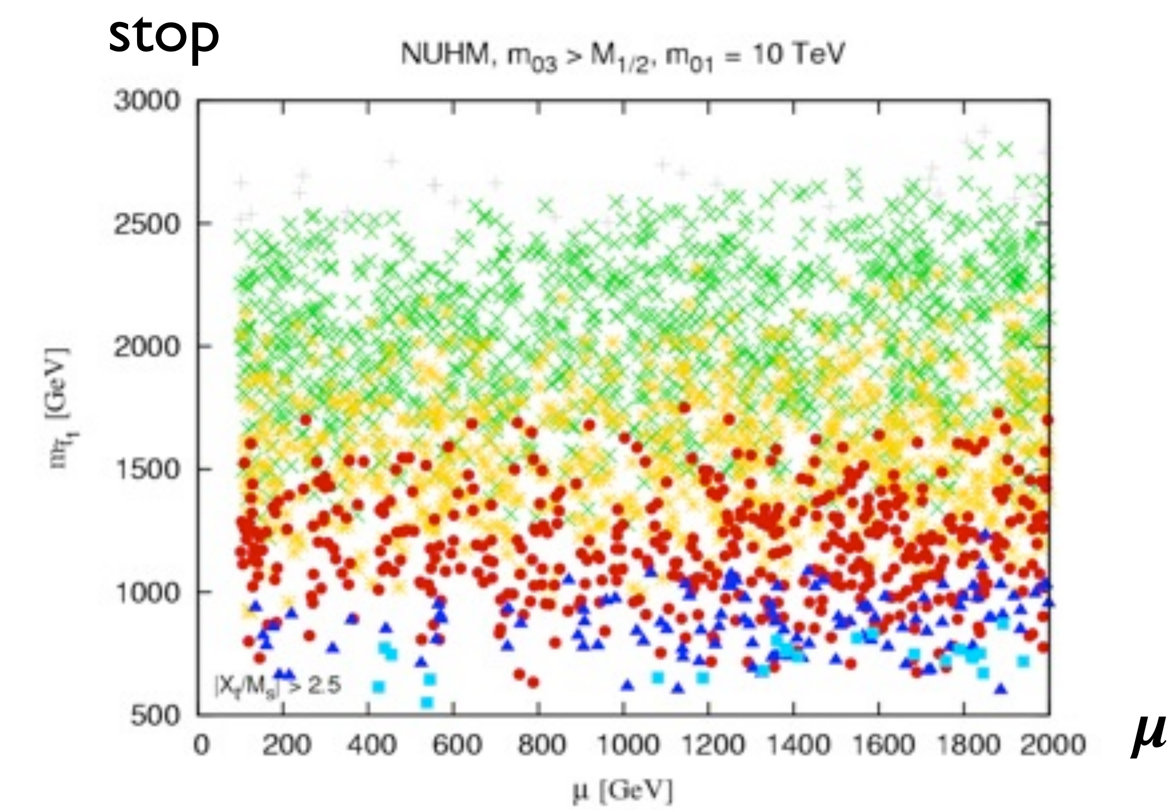

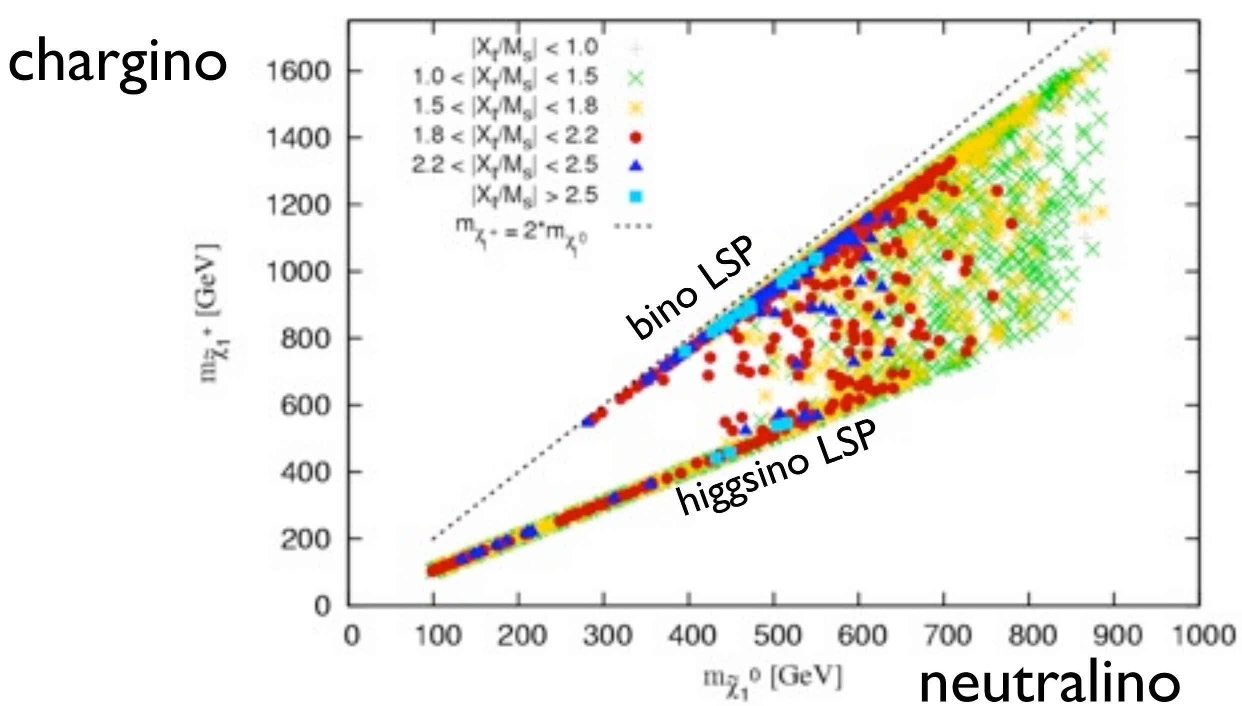

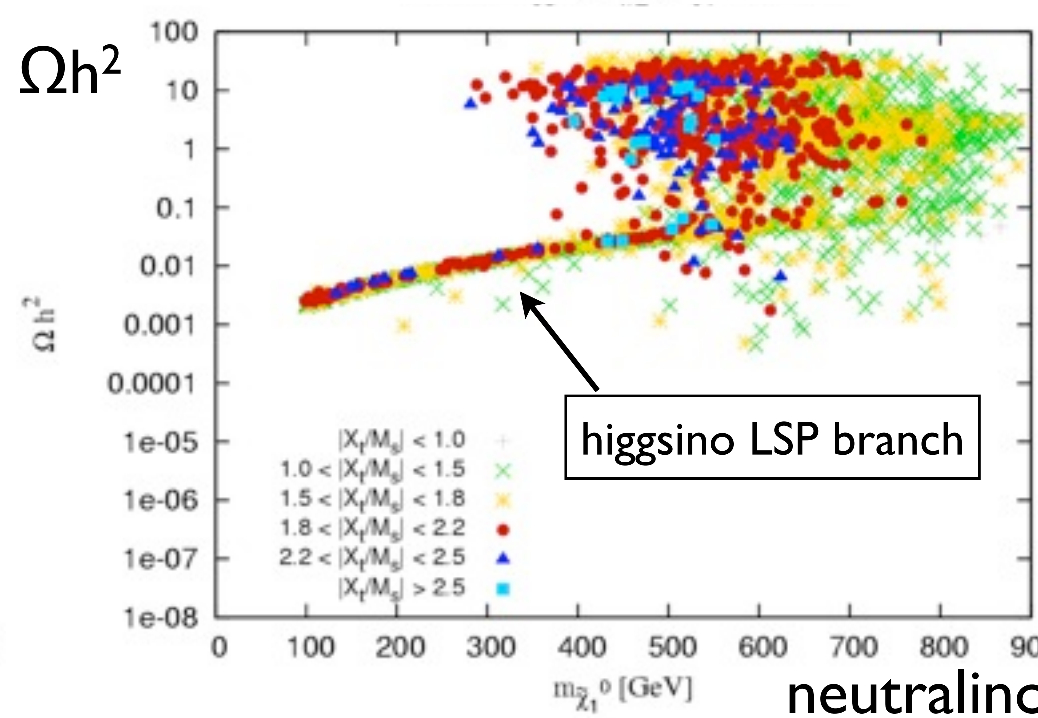

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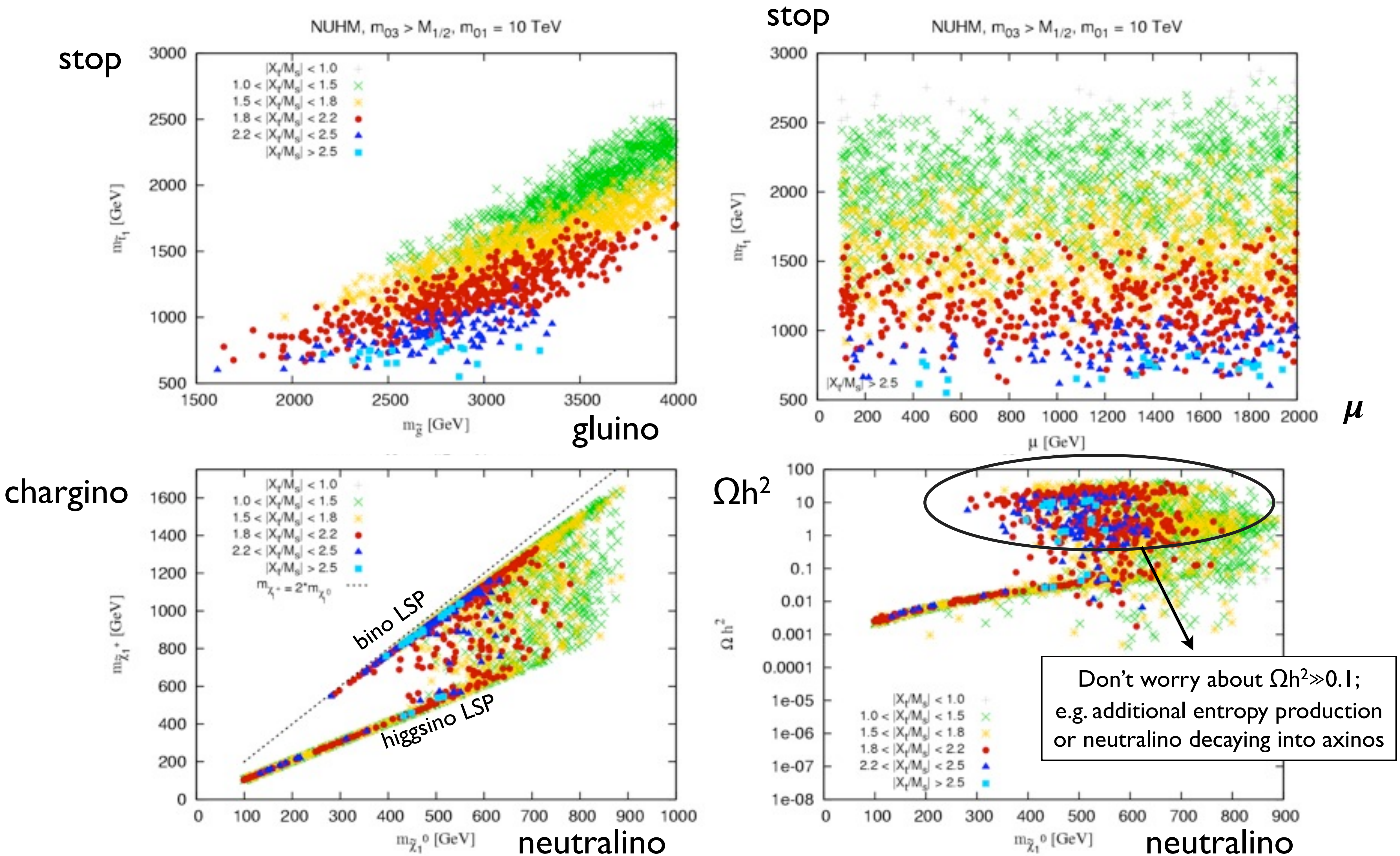
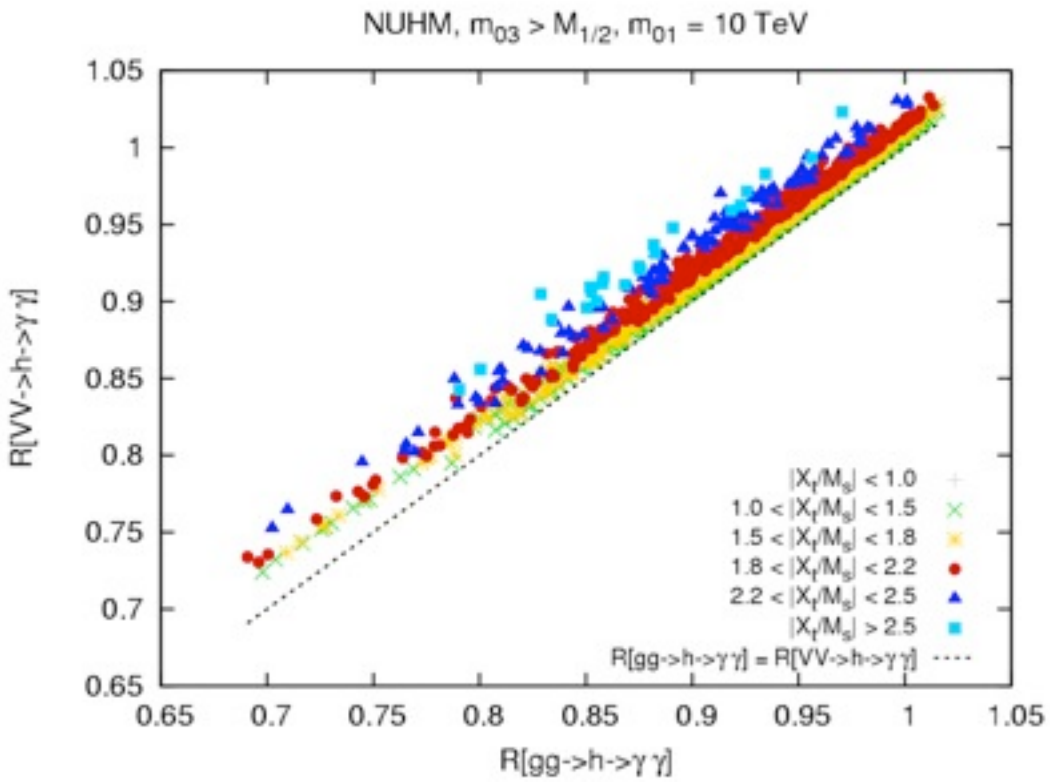
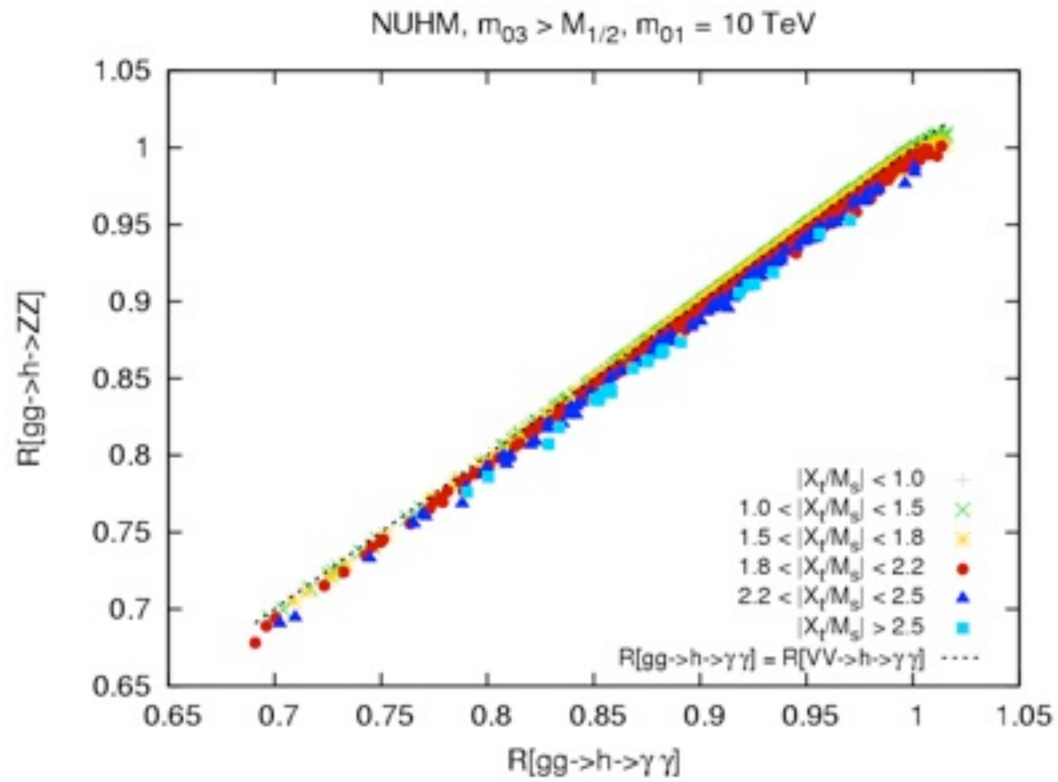


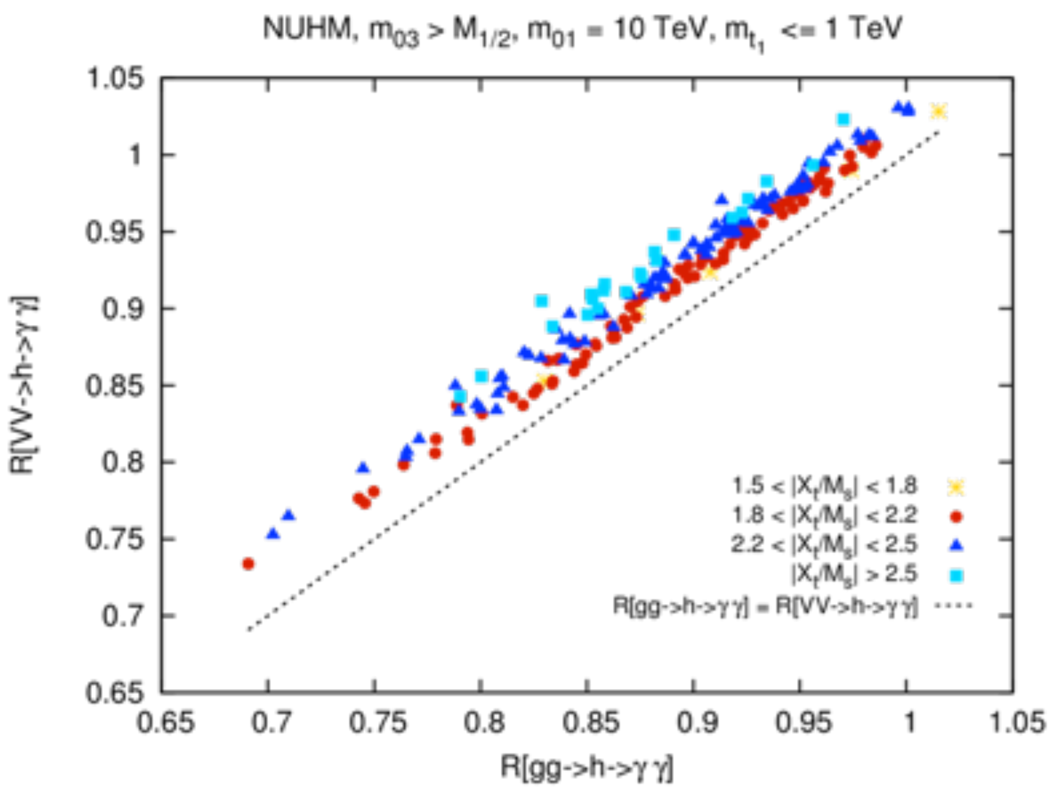
Signal strengths

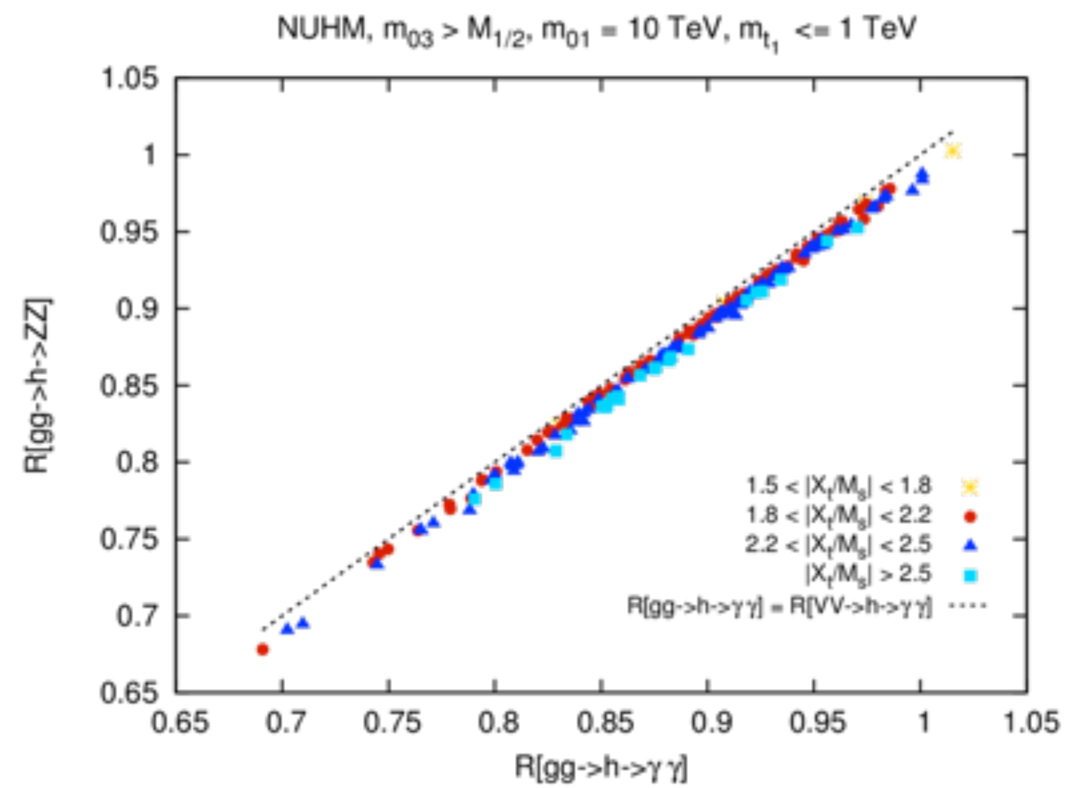




$$R(X \to h \to Y) = \frac{\Gamma(h \to X)\,\mathrm{BR}(h \to Y)}{\Gamma(H_{\mathrm{SM}} \to X)\,\mathrm{BR}(H_{\mathrm{SM}} \to Y)}$$

Signal strengths, m(stop1)<1TeV





$$R(X \to h \to Y) = \frac{\Gamma(h \to X)\,\mathrm{BR}(h \to Y)}{\Gamma(H_{\rm SM} \to X)\,\mathrm{BR}(H_{\rm SM} \to Y)}$$

Phenomenological MSSM

(19-parameter realization of general MSSM)

parameters defined at the weak scale,
no SUSY breaking prejudices, no RGE running

Markov Chain Monte Carlo analysis
based on work with
Sezen Sekmen, JFG, et al.

CMS analysis not approved yet !

MCMC

- Markov Chain Monte Carlo (MCMC): random walk through parameter space guided by the likelihood function
- Sampling of parameter space with flat prior

$$
\begin{gathered}
-3\,\mathrm{TeV} \leq M_1, M_2 \leq 3\,\mathrm{TeV} \\
0 \leq M_3 \leq 3\,\mathrm{TeV} \\
-3\,\mathrm{TeV} \leq \mu \leq 3\,\mathrm{TeV} \\
0 \leq m_A \leq 3\,\mathrm{TeV} \\
2 \leq \tan\beta \leq 60 \\
0 \leq \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \leq 3\,\mathrm{TeV} \\
-7\,\mathrm{TeV} \leq A_t, A_b, A_\tau \leq 7\,\mathrm{TeV}
\end{gathered}
$$

- Minimal assumptions: R-parity, neutralino LSP, flavor-diagonal mass-matrices and A terms, 1st/2nd gen. degenerate, no new CP phases
- Results are probability distributions of parameters, masses, etc; advantage: it gives rigorous Bayesisan statistics interpretation

Constraints: "preHiggs"

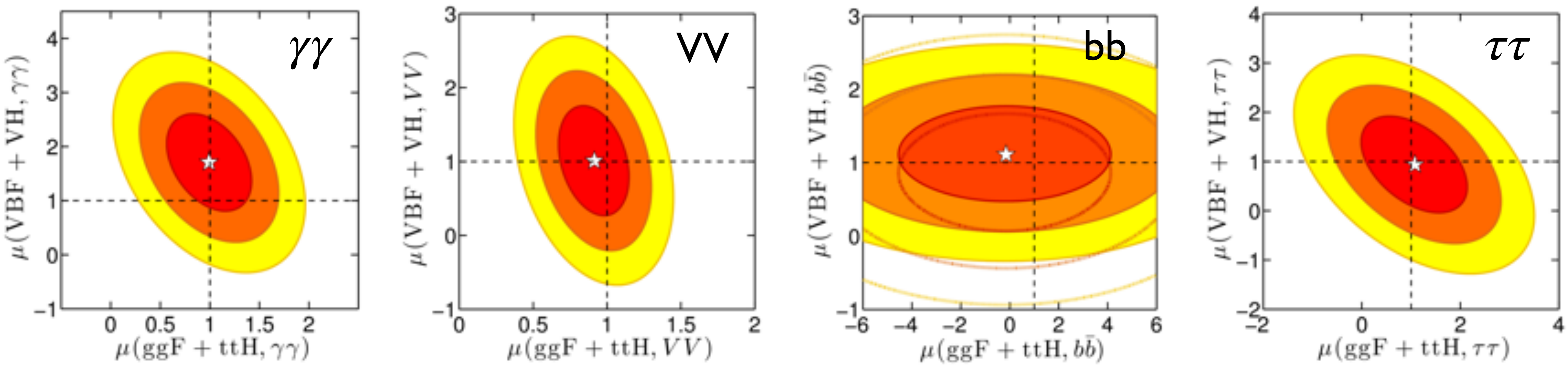
i	Observable $\mu_j(\theta)$	Constraint D_j^{preCMS}	Likelihood function $L(D_j^{\text{preCMS}}\|\mu_j(\theta))$	MCMC / post-MCMC
1	$BR(b \to s\gamma)$ [27, 28]	$(3.55 \pm 0.23^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.09^{\text{sys}}) \times 10^{-4}$	Gaussian	MCMC
2a	$BR(B_s \to \mu\mu)$ [29]	observed CLs curve from [29]	$d(1 - CLs)/dx$	MCMC
2b	$BR(B_s \to \mu\mu)$ [30]	$3.2^{+1.5}_{-1.2} \times 10^{-9}$	2-sided Gaussian	post-MCMC
3	$R(B_u \to \tau\nu)$ [31]	1.63 ± 0.54	Gaussian	MCMC
4	Δa_μ [32]	$(26.1 \pm 8.0^{\text{exp}} \pm 10.0^{\text{th}}) \times 10^{-10}$	Gaussian	MCMC
5	m_t [33]	$173.3 \pm 0.5^{\text{stat}} \pm 1.3^{\text{sys}}($ GeV	Gaussian	MCMC
6	$m_b(m_b)$ [31]	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	MCMC
7	$\alpha_s(M_Z)$ [31]	0.1184 ± 0.0007	Gaussian	MCMC
8a	m_h	pre-LHC: $m_h^{low} = 112$	1 if $m_h \geq m_h^{low}$ 0 if $m_h < m_h^{low}$	MCMC
8b	m_h	LHC: $m_h^{low} = 123$ $m_h^{up} = 128$	1 if $m_h^{low} \leq m_h \leq m_h^{up}$ 0 if $m_h < m_h^{low}$ or $m_h > m_h^{up}$	post-MCMC
9	sparticle masses	LEP [34] (via micrOMEGAs [23])	1 if allowed 0 if excluded	MCMC
10	prompt $\tilde{\chi}_1^{\pm}$	$c\tau(\tilde{\chi}_1^{\pm}) < 10$ mm	1 if allowed 0 if excluded	post-MCMC

1-7, 8a, 9, 10: "pre-Higgs" constraints used in MCMC sampling

Constraints: Higgs

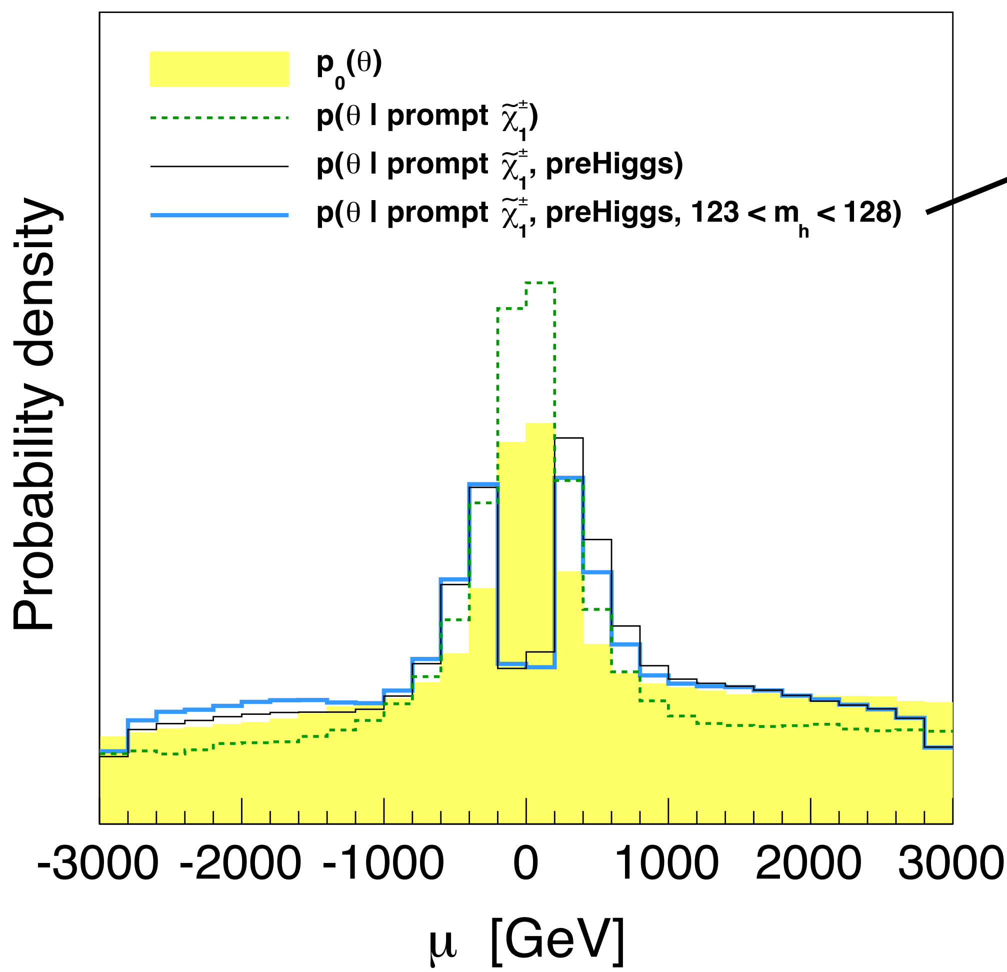
- Higgs mass: in MCMC sampling: m_h >112 GeV, afterwards hard cut requiring m_h = [123, 128] GeV
- Higgs signal strengths: likelihood computed as $L=\exp(-\chi^2/2)$ from fit to experimental Higgs results

cf. Beranger Dumont's talk on Monday

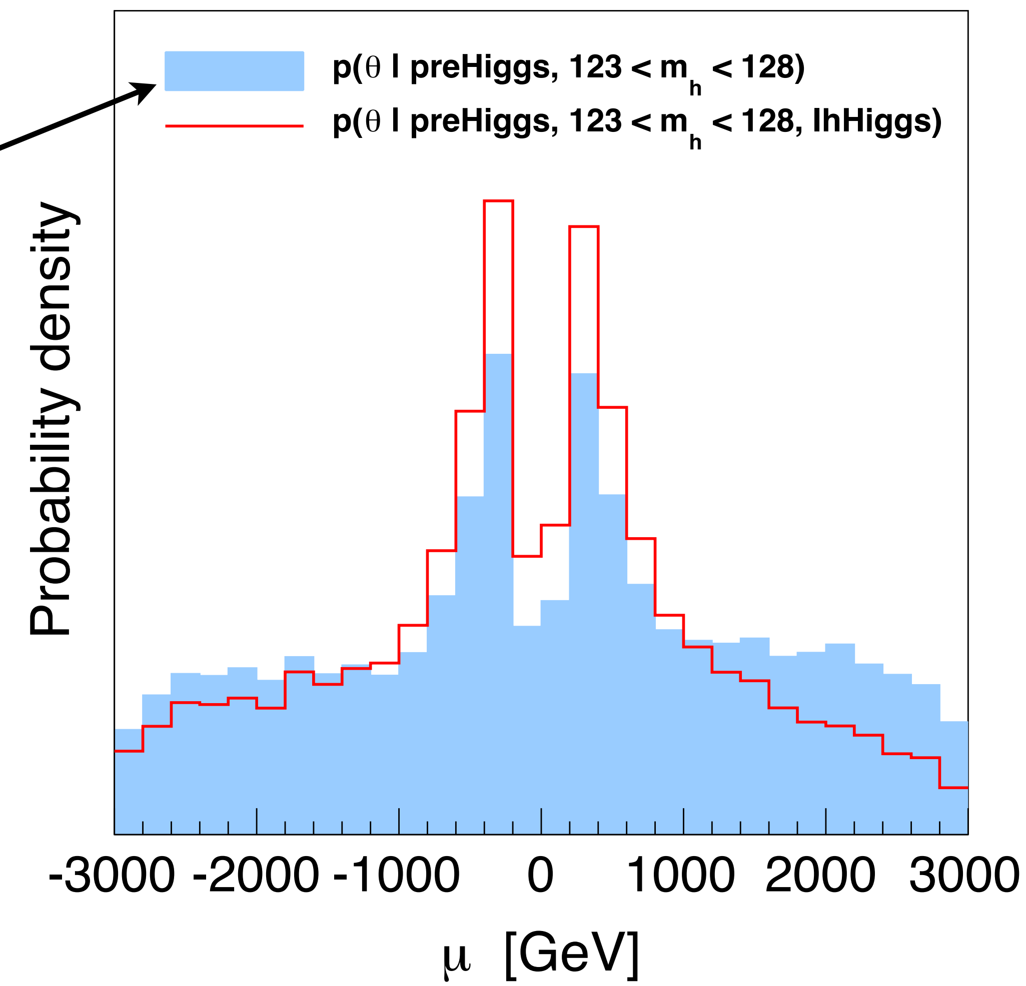


- L(Higgs) multiplied a posteriori on top of L(preHiggs) → see how this affects the probability distributions

Results

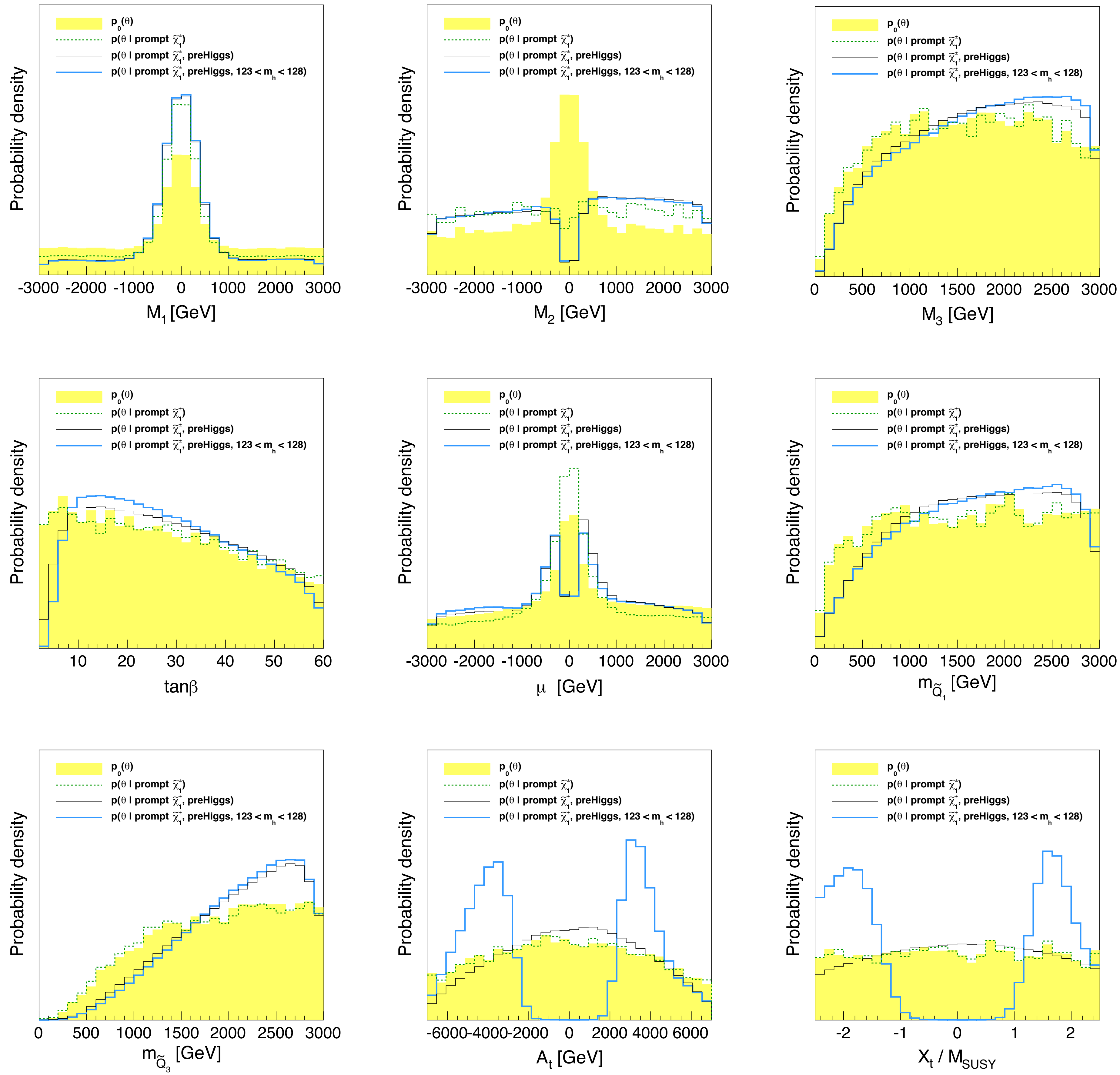


effects of "preHiggs" and Higgs mass constraints



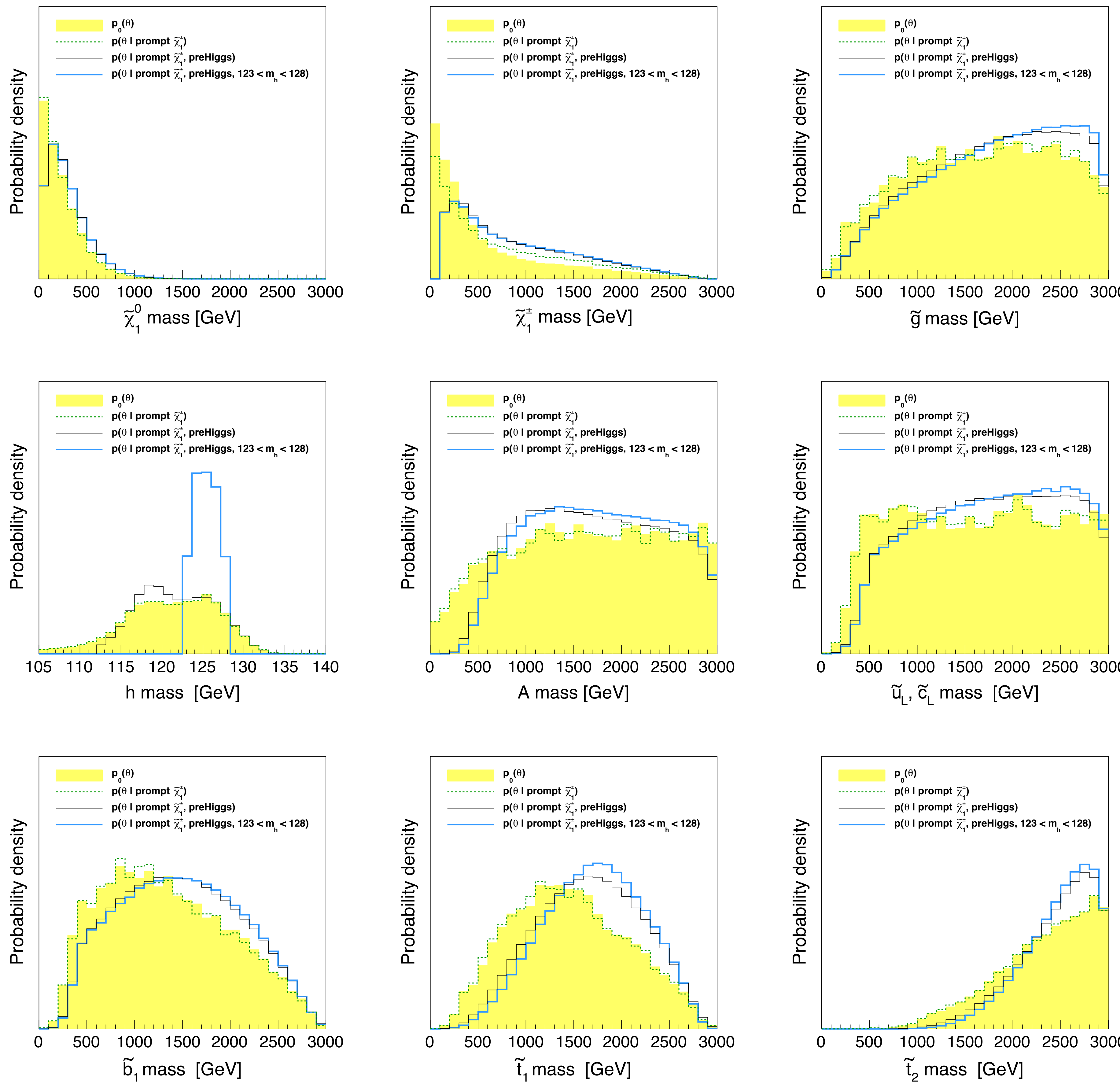
effect of Higgs signal strengths

Parameters



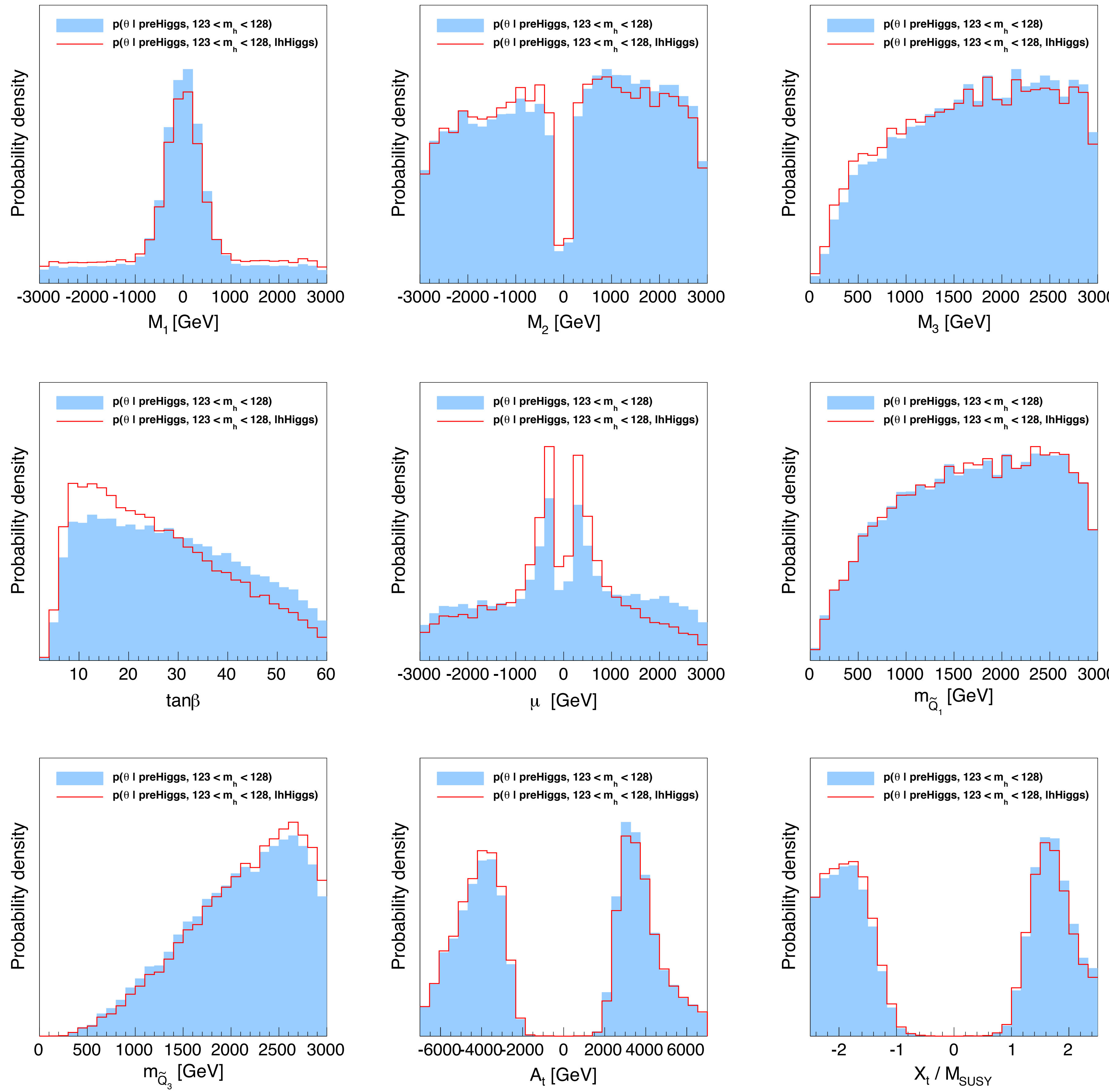
p0(θ)
p(θ | prompt χ̃1)
p(θ | prompt χ̃1, preHiggs)
p(θ | prompt χ̃1, preHiggs, 123 < mh < 128)
Probability density
M1 [GeV]
M2 [GeV]
M3 [GeV]
tanβ
μ [GeV]
mQ̃1 [GeV]
mQ̃3 [GeV]
At [GeV]
Xt / MSUSY

Masses



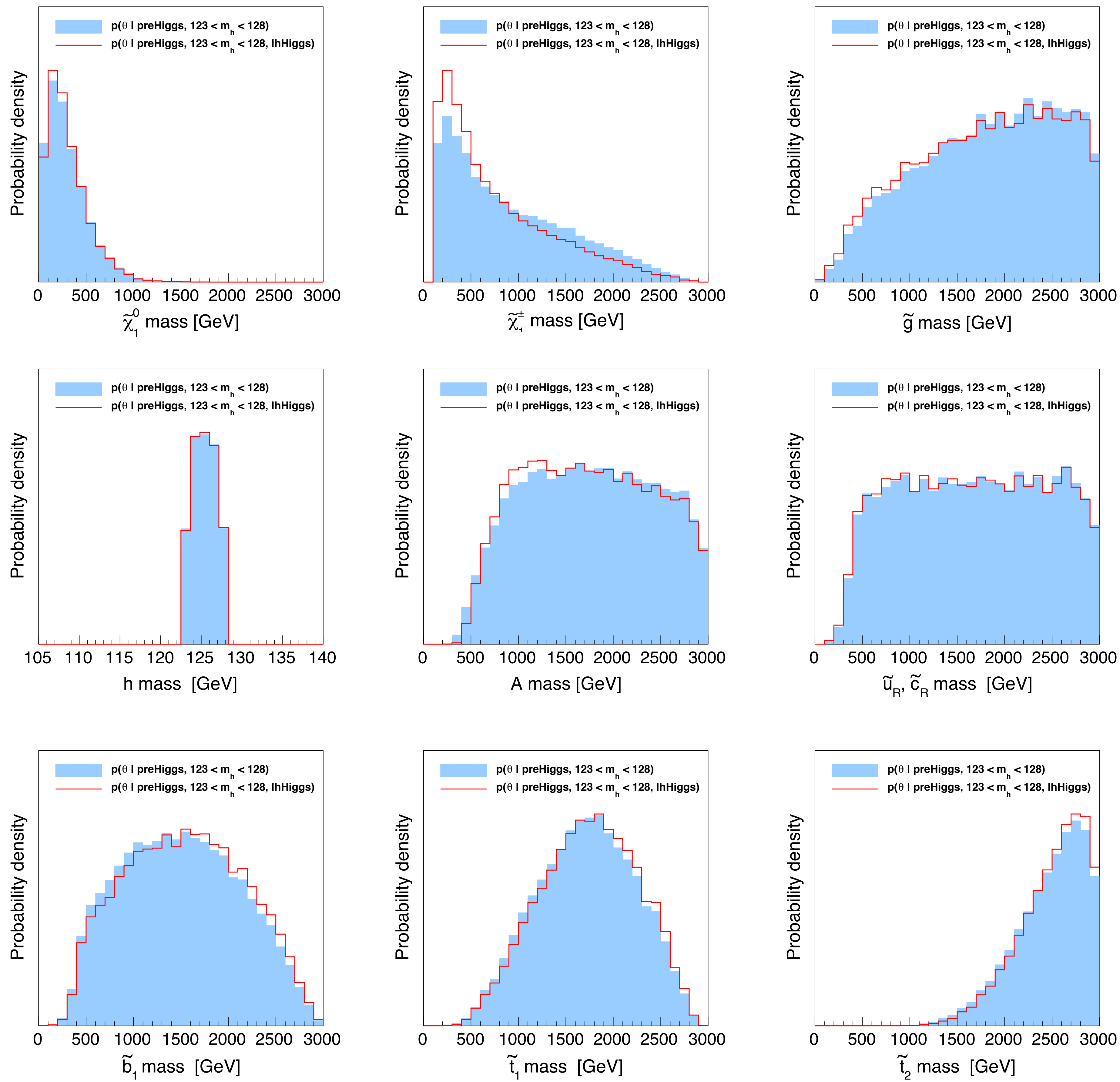
p0(θ)
p(θ | prompt χ̃1±)
p(θ | prompt χ̃1±, preHiggs)
p(θ | prompt χ̃1±, preHiggs, 123 < mh < 128)
Probability density
χ̃1⁰ mass [GeV]
χ̃1± mass [GeV]
g̃ mass [GeV]
h mass [GeV]
A mass [GeV]
ũL, c̃L mass [GeV]
b̃1 mass [GeV]
t̃1 mass [GeV]
t̃2 mass [GeV]

Parameters



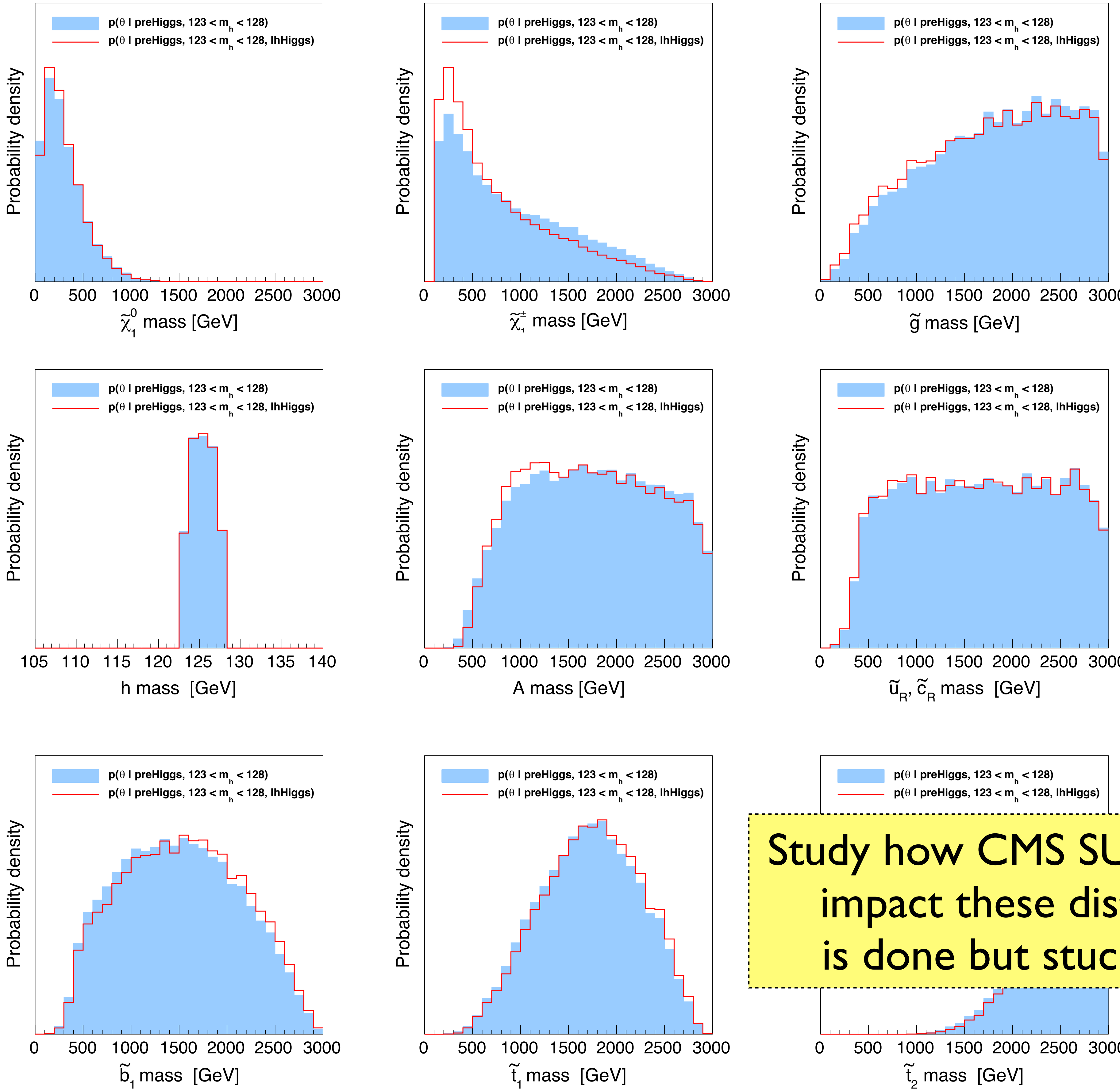
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
-3000 -2000 -1000 0 1000 2000 3000
M_1 [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
-3000 -2000 -1000 0 1000 2000 3000
M_2 [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
0 500 1000 1500 2000 2500 3000
M_3 [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
10 20 30 40 50 60
tanβ
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
-3000 -2000 -1000 0 1000 2000 3000
μ [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
0 500 1000 1500 2000 2500 3000
m_Q̃1 [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
0 500 1000 1500 2000 2500 3000
m_Q̃3 [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
-6000-4000-2000 0 2000 4000 6000
A_t [GeV]
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
-2 -1 0 1 2
X_t / M_SUSY

Masses

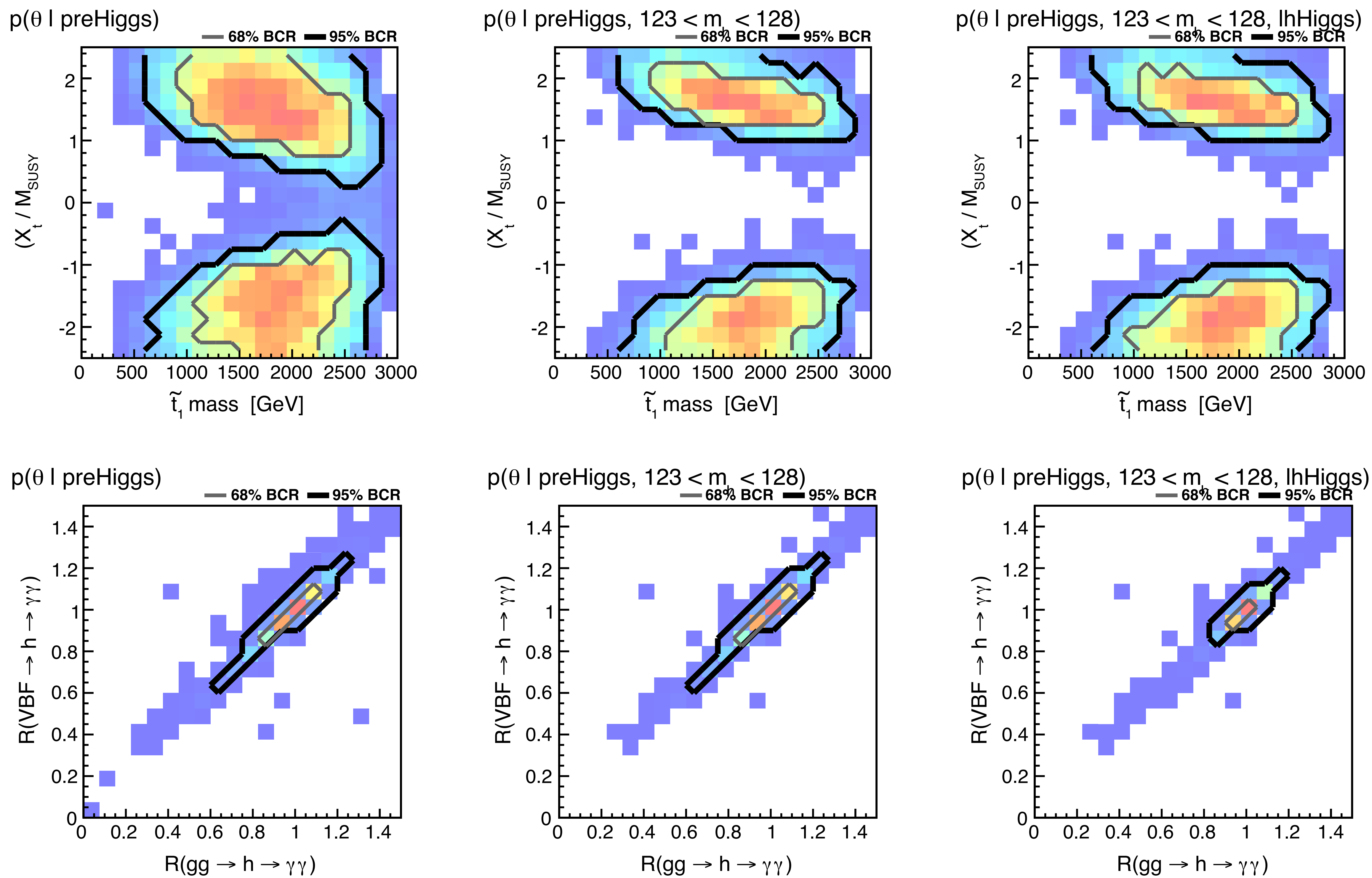


p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
χ̃₁⁰ mass [GeV]
χ̃₁± mass [GeV]
g̃ mass [GeV]
h mass [GeV]
A mass [GeV]
ũ_R, c̃_R mass [GeV]
b̃₁ mass [GeV]
t̃₁ mass [GeV]
t̃₂ mass [GeV]

Masses

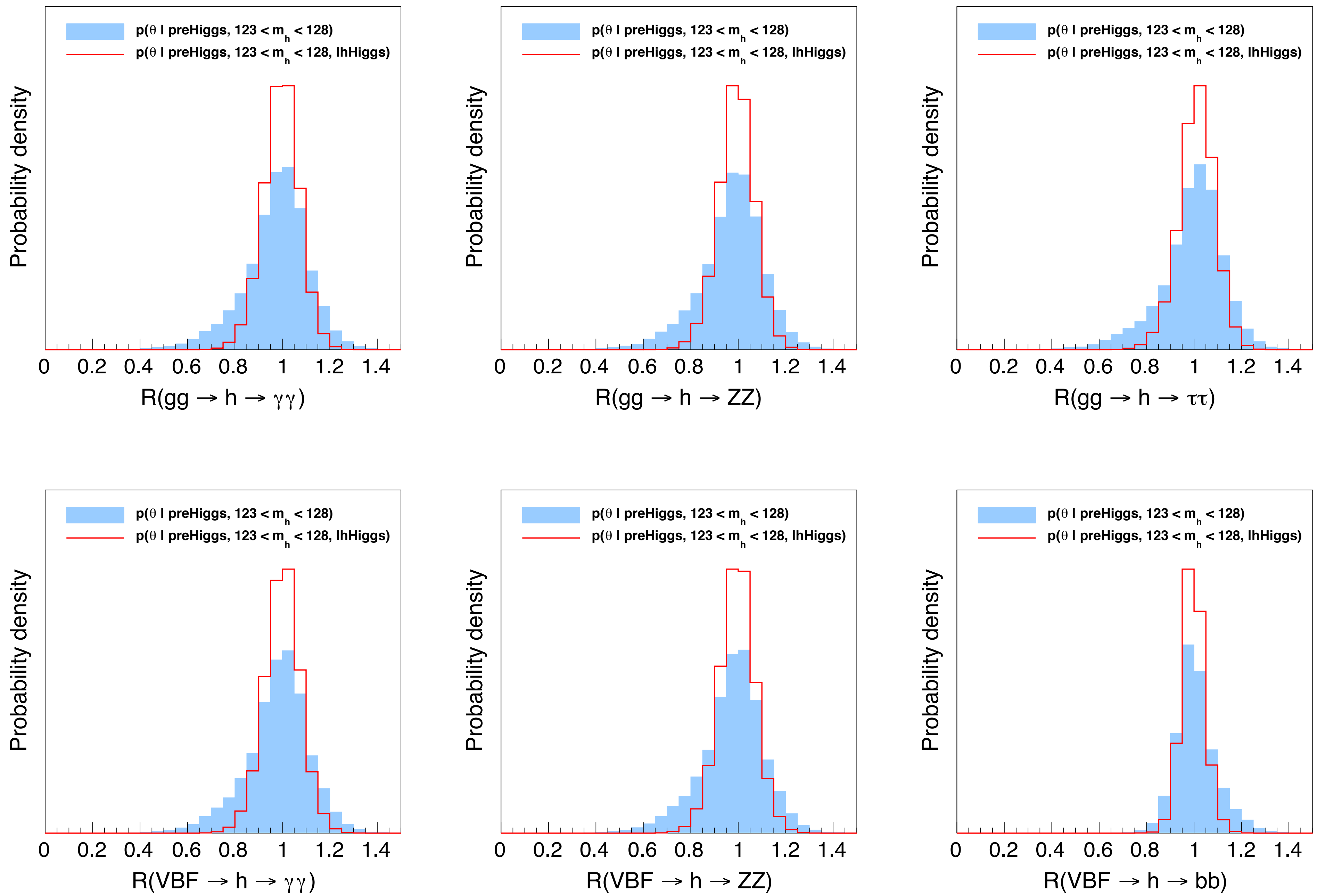


Study how CMS SUSY searches impact these distributions is done but stuck in CMS.

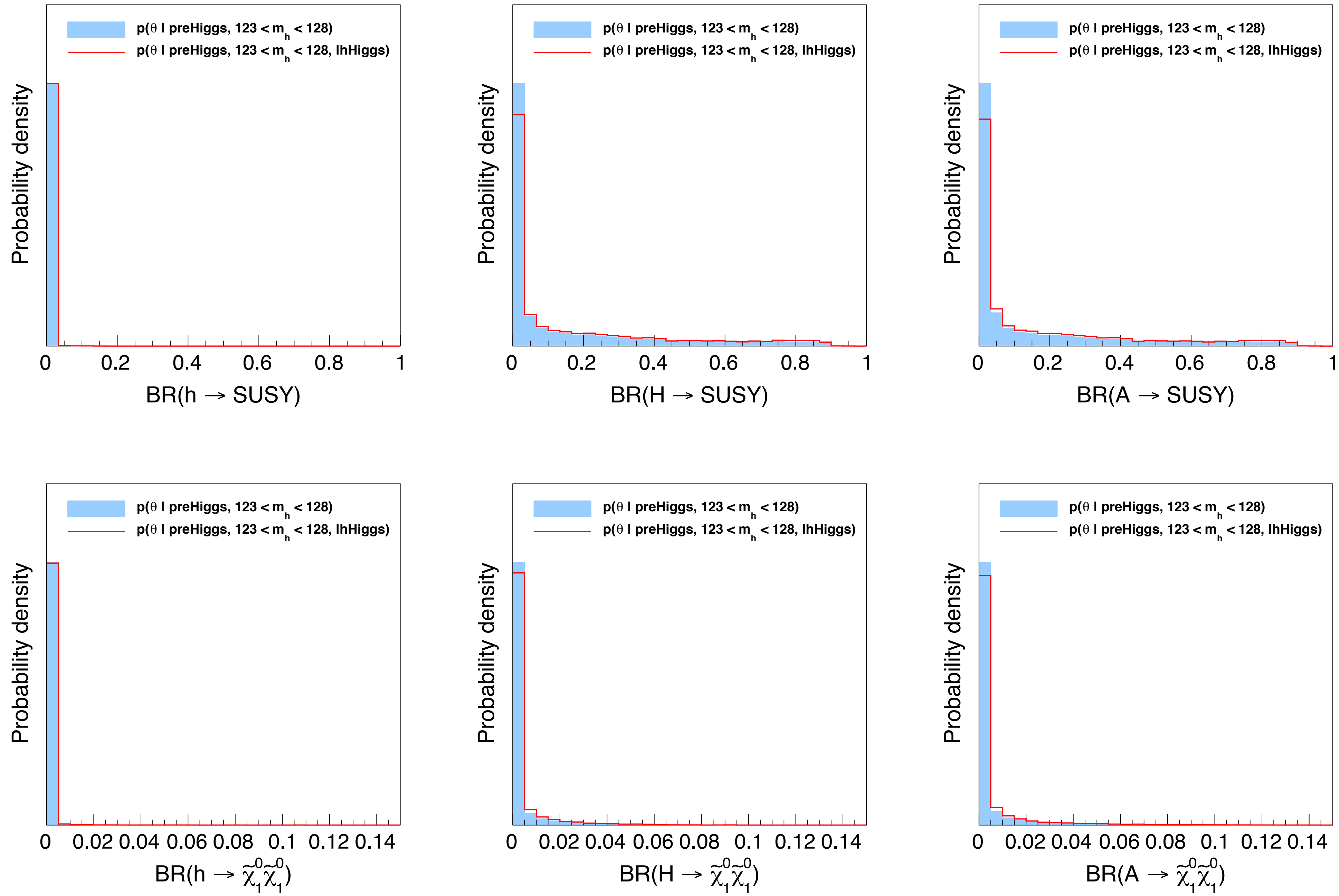


p(θ | preHiggs)
p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
68% BCR
95% BCR
(X_t / M_SUSY)
t̃_1 mass [GeV]
R(VBF → h → γγ)
R(gg → h → γγ)

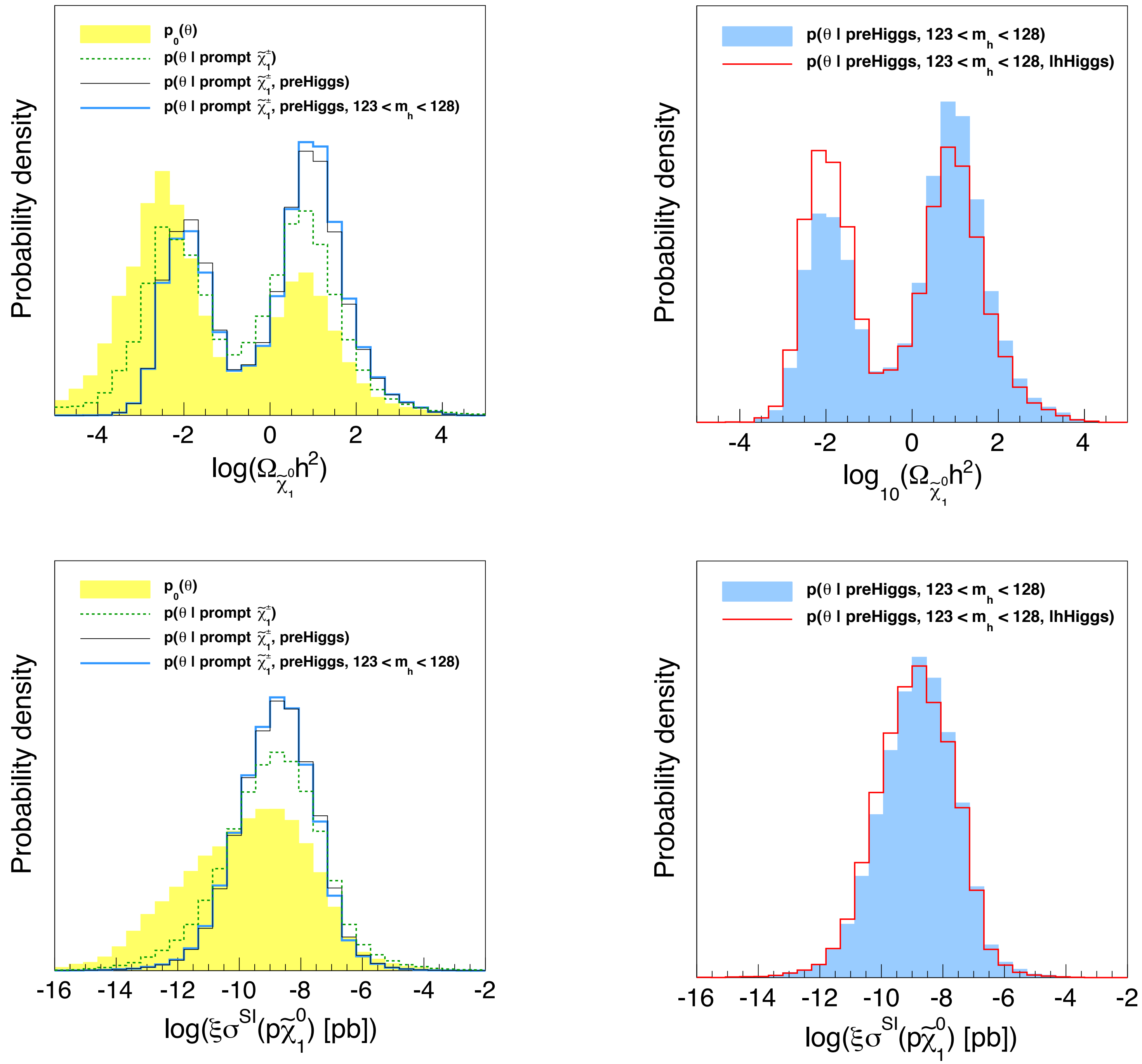
Light Higgs signal



Higgs decays into SUSY



Dark matter

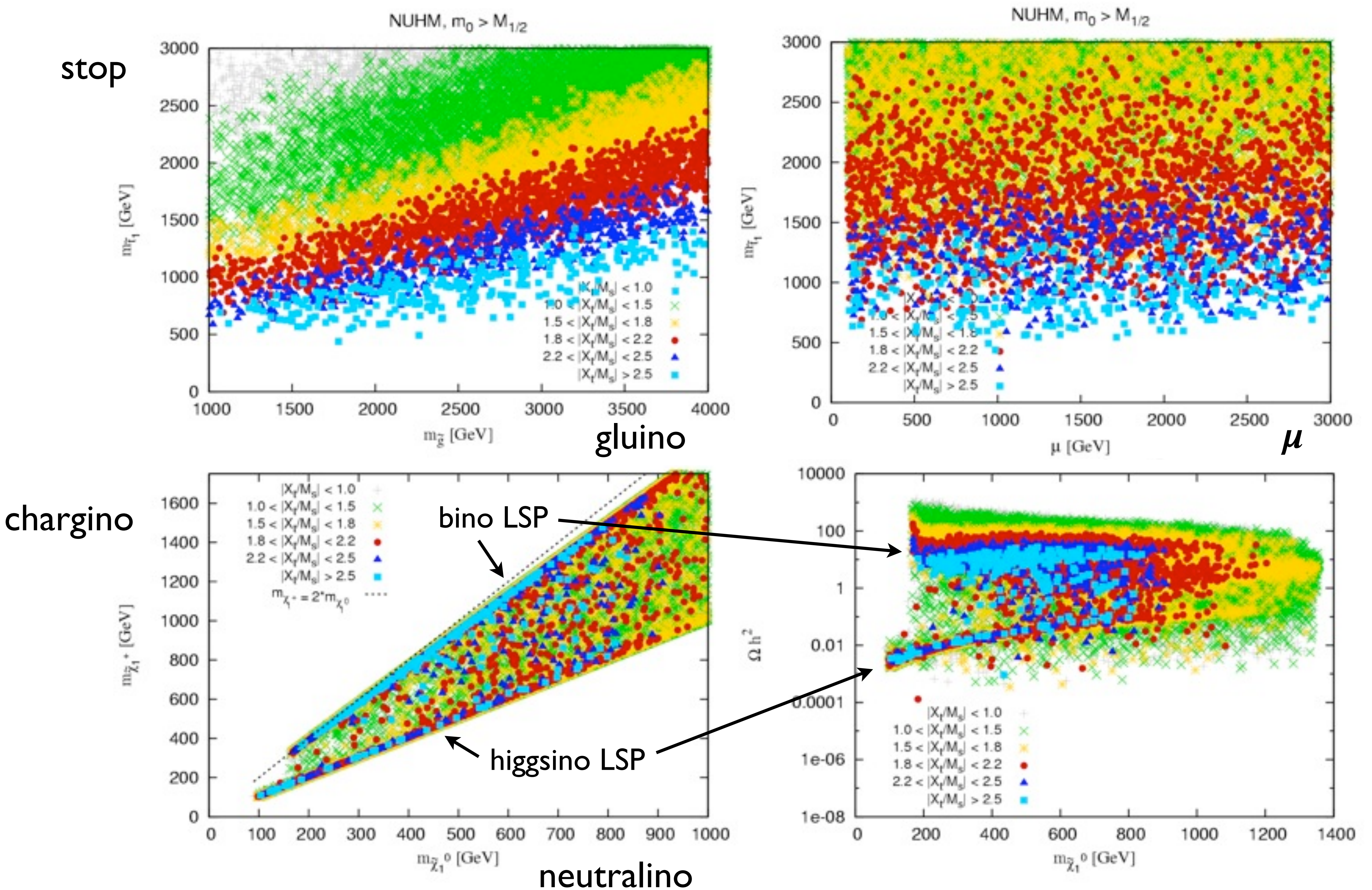

$p_0(\theta)$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm})$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm}$, preHiggs$)$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm}$, preHiggs, $123 < m_h < 128)$
Probability density
$\log(\Omega_{\tilde{\chi}_1^0} h^2)$
$p(\theta$ | preHiggs, $123 < m_h < 128)$
$p(\theta$ | preHiggs, $123 < m_h < 128$, lhHiggs$)$
Probability density
$\log_{10}(\Omega_{\tilde{\chi}_1^0} h^2)$
$p_0(\theta)$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm})$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm}$, preHiggs$)$
$p(\theta$ | prompt $\tilde{\chi}_1^{\pm}$, preHiggs, $123 < m_h < 128)$
Probability density
$\log(\xi\sigma^{SI}(p\tilde{\chi}_1^0)$ [pb]$)$
$p(\theta$ | preHiggs, $123 < m_h < 128)$
$p(\theta$ | preHiggs, $123 < m_h < 128$, lhHiggs$)$
Probability density
$\log(\xi\sigma^{SI}(p\tilde{\chi}_1^0)$ [pb]$)$

Conclusions

- We have a SM-like Higgs with ~125 GeV mass.
- In the absence, so far, of any sign of new physics, it is interesting to use the Higgs mass and couplings (signal strength measurements) for constraining BSM theories.

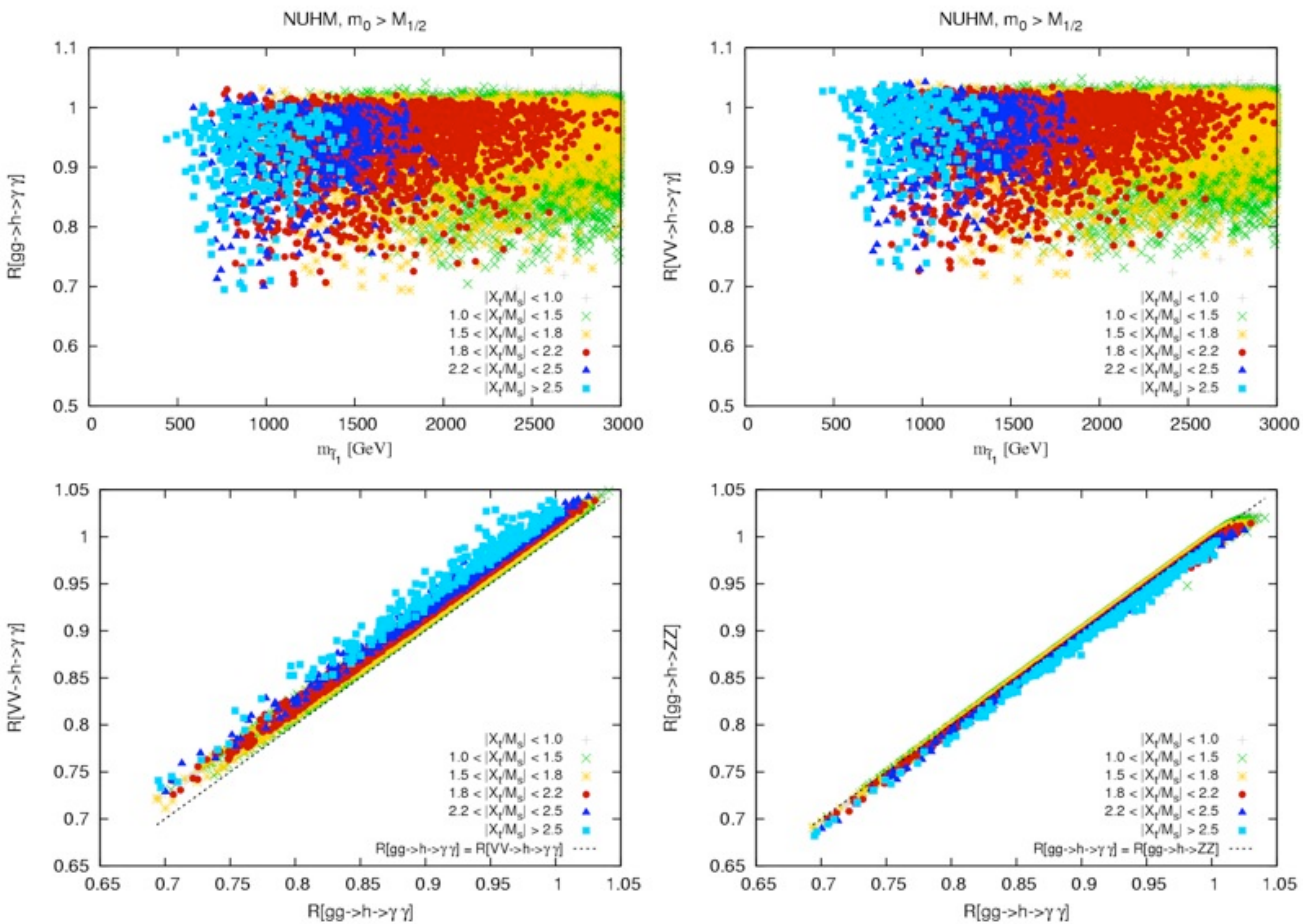
  ➠ Use the Higgs as a guide to where to look for new physics.
- In the MSSM case, it turns out that the strongest effect still comes from the Higgs mass itself; fitting Higgs signal strengths so far has little impact. reason: the Higgs is too SM-like :-(
- Stay tuned for NMSSM results

SUSY particles

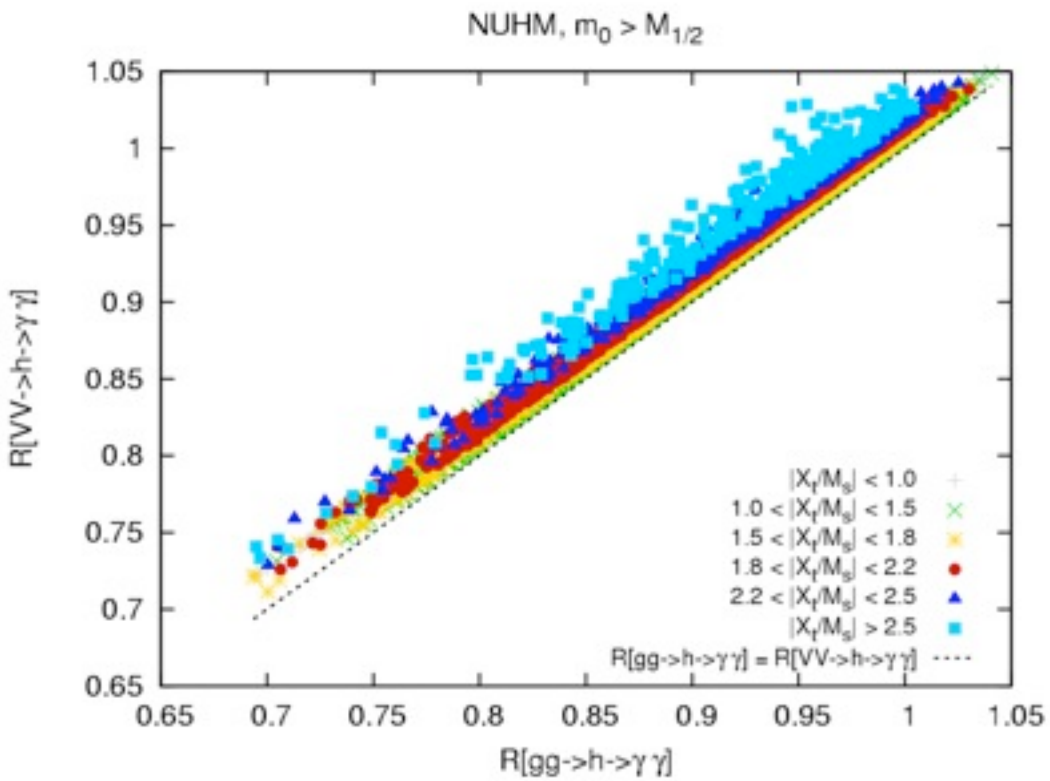


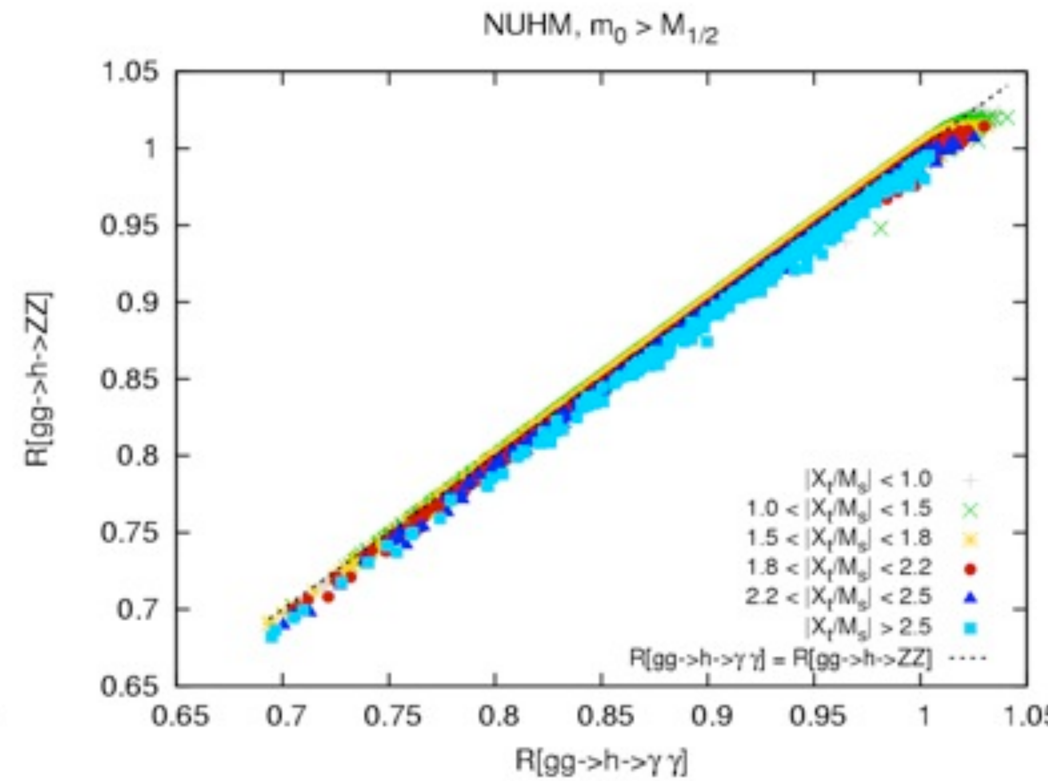
Signal strengths

$$R(X \to h \to Y) = \frac{\Gamma(h \to X)\,\mathrm{BR}(h \to Y)}{\Gamma(H_{\rm SM} \to X)\,\mathrm{BR}(H_{\rm SM} \to Y)}$$

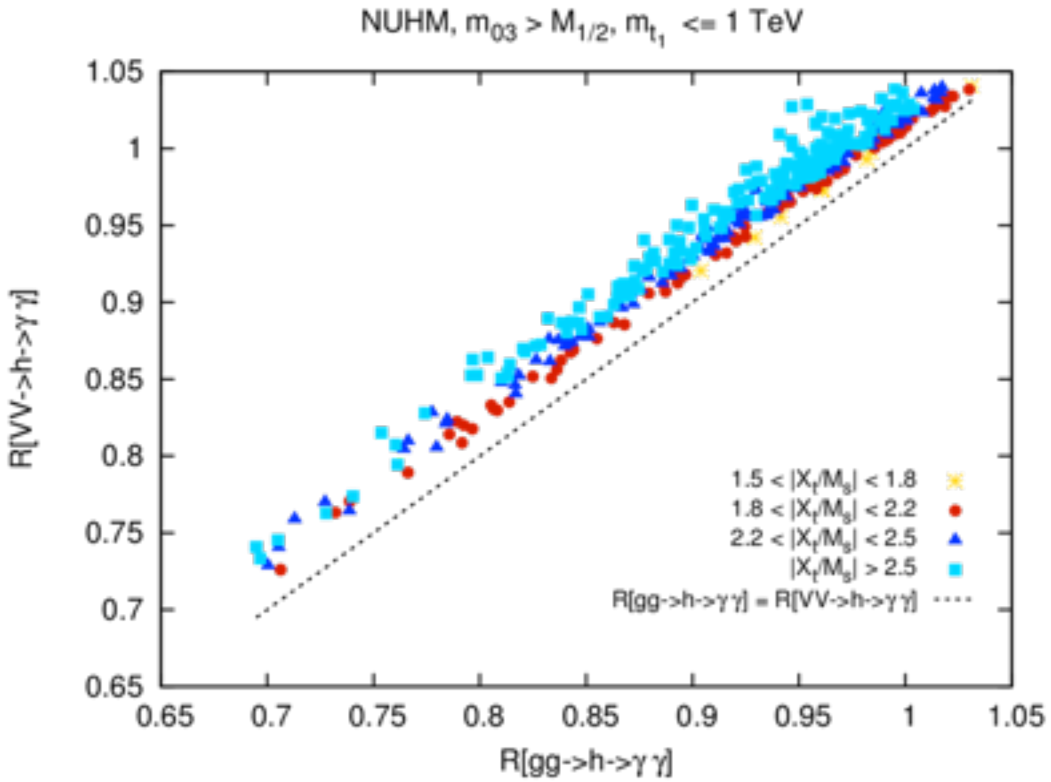


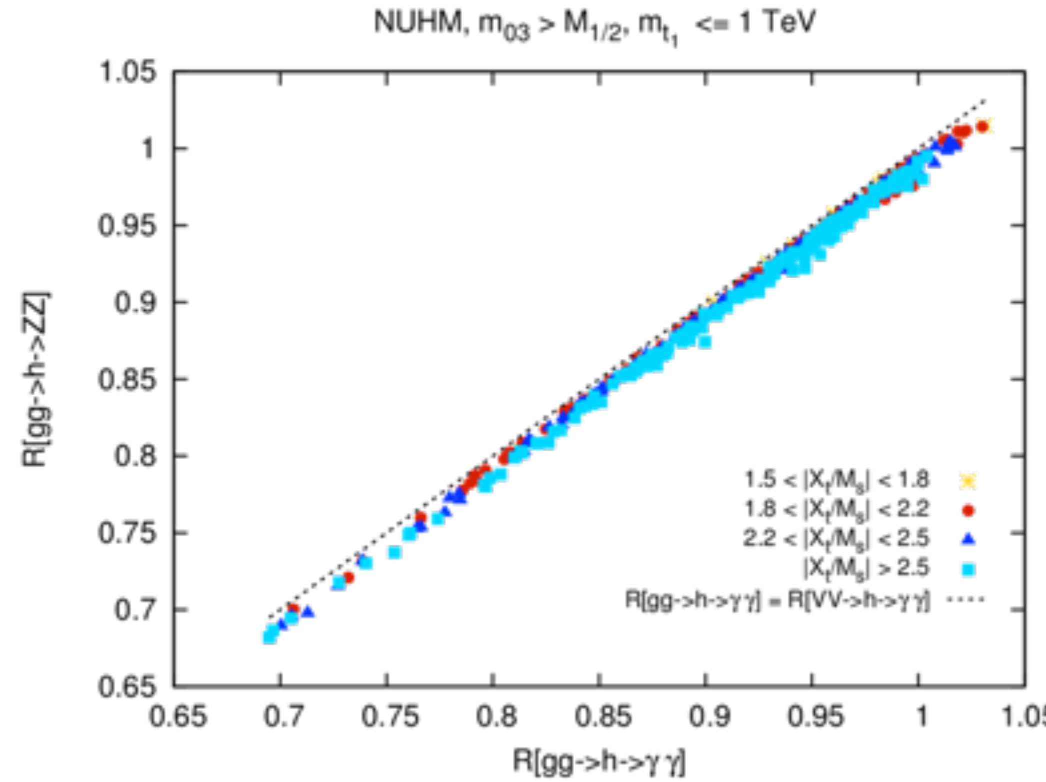
Signal strengths





Signal strengths, m(stop1)<1 TeV





NUHM with inverted mass hierarchy

(splits generations, very heavy 1st/2nd gen. squarks)