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SUSY after the Higgs

Implications of LHC Higgs results for supersymmetry

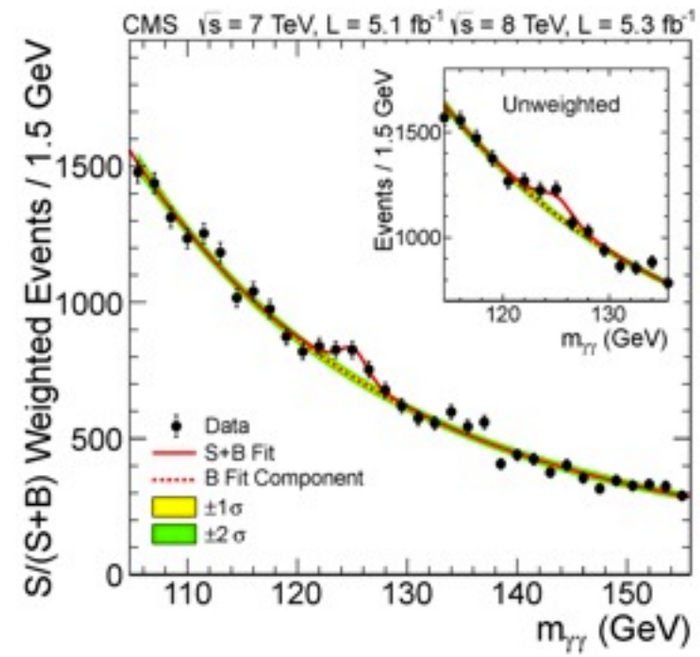
PLANCK 2013: From the Planck Scale to the Electroweak Scale
Bethe Center for Theoretical Physics, Bonn, 20-24 May 2013

Introduction

- The 2012 Higgs discovery at ~125 GeV is a tremendous first success of the LHC program.

- However, why is the Higgs so light when it is predicted to be driven to the GUT or Planck scale by radiative corrections?

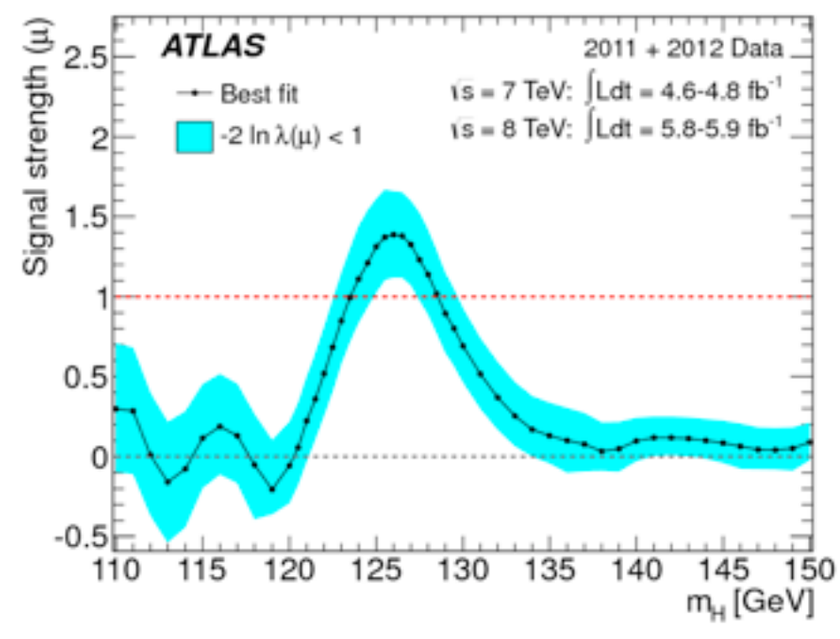
  ➪ new physics at the TeV scale
  (or extreme fine-tuning)



- With the absence, so far, of any sign of new physics the Higgs results become our main guide for where to look for new physics beyond the SM.

- In this talk: implications for the MSSM.

  (i'll try to be complementary to Abdelhak's talk)



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

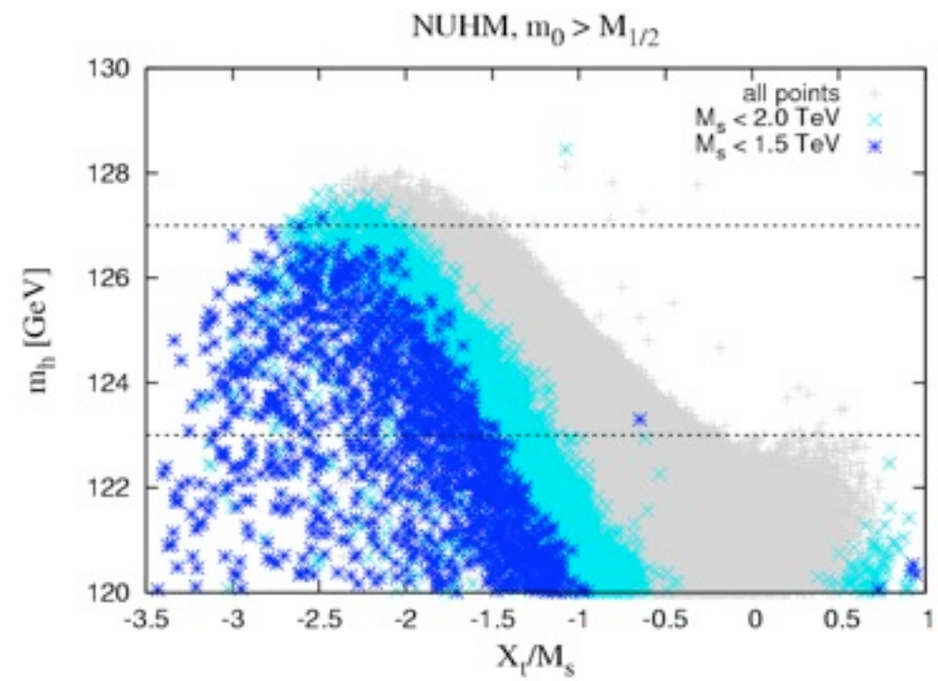
$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2$$

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

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

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.]

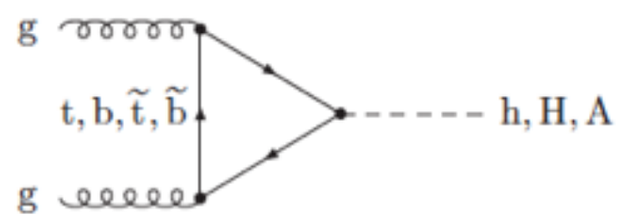
MSSM Higgs signal

A. Djouadi, hep-ph/9806315
M. Carena et al,, 1303.4414
J. Casas et al., 1305.3274
and many others
see talk by A. Djouadi

- h couplings to t, b scale with tanβ; couplings to W, Z with sin(β-α) C(hVV)≤1

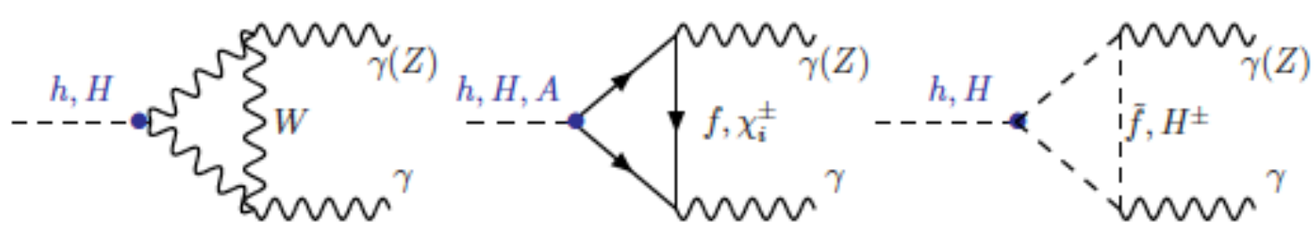
$$y_t = m_t/(\sqrt{2} m_W \sin\beta), \quad y_b = m_b/(\sqrt{2} m_W \cos\beta)$$

- gg → h: top + stop loop (at large tanβ, also (s)bottom loop contribution)



Large stop mixing suppresses σ(gg→h); opposite effect on h→$\gamma\gamma$

- h → $\gamma\gamma$: dominated by W loop, top loop ~20% with opposite sign; SUSY contributions from charginos, staus, stops, charged Higgs

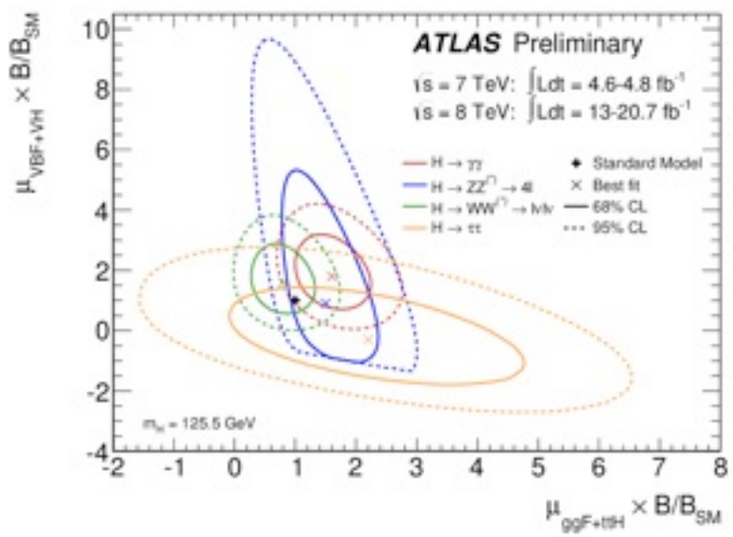


Enhancement of $\gamma\gamma$:
- light staus or charginos.
- $\chi\pm$ contr. max 10%, needs higgsino-wino mixing

- Interference with SM amplitudes depends on sparticle mixings !

Combining ATLAS, CMS and Tevatron results

- Experimental results in several different channels provide a comprehensive picture



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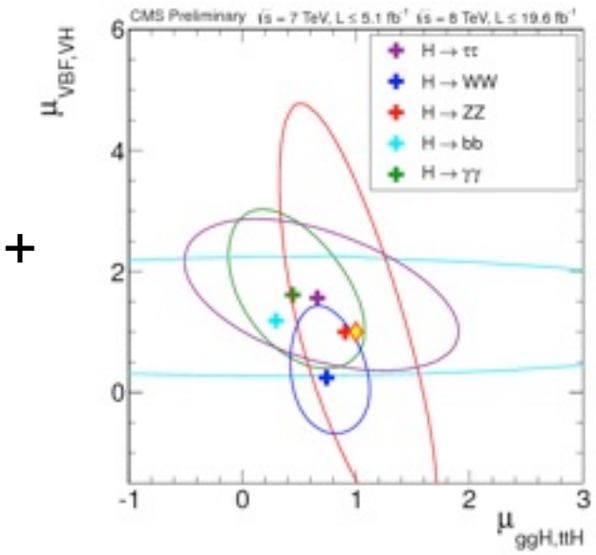
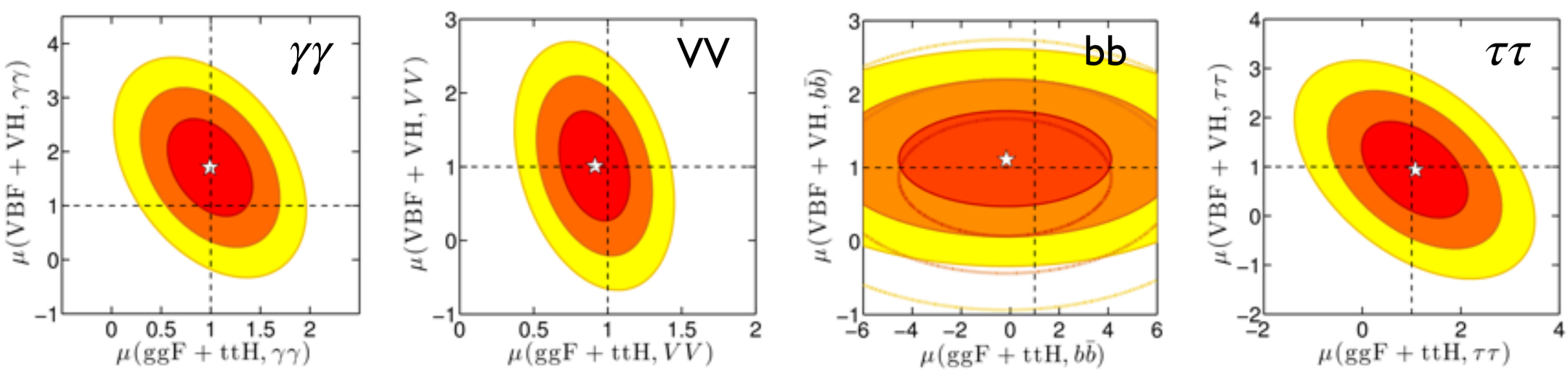


+ Tevatron results

status post-Moriond 2013

- We combine all publicly available results to test the SM and constrain BSM models



➪ Talk by Beranger Dumont in Thursday p.m. session

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

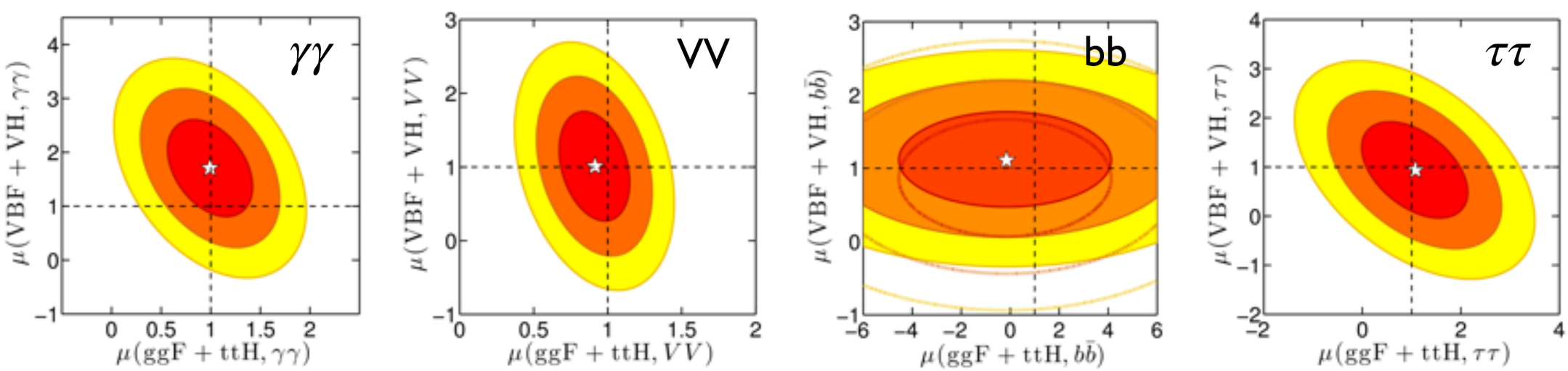
Constraints

- 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

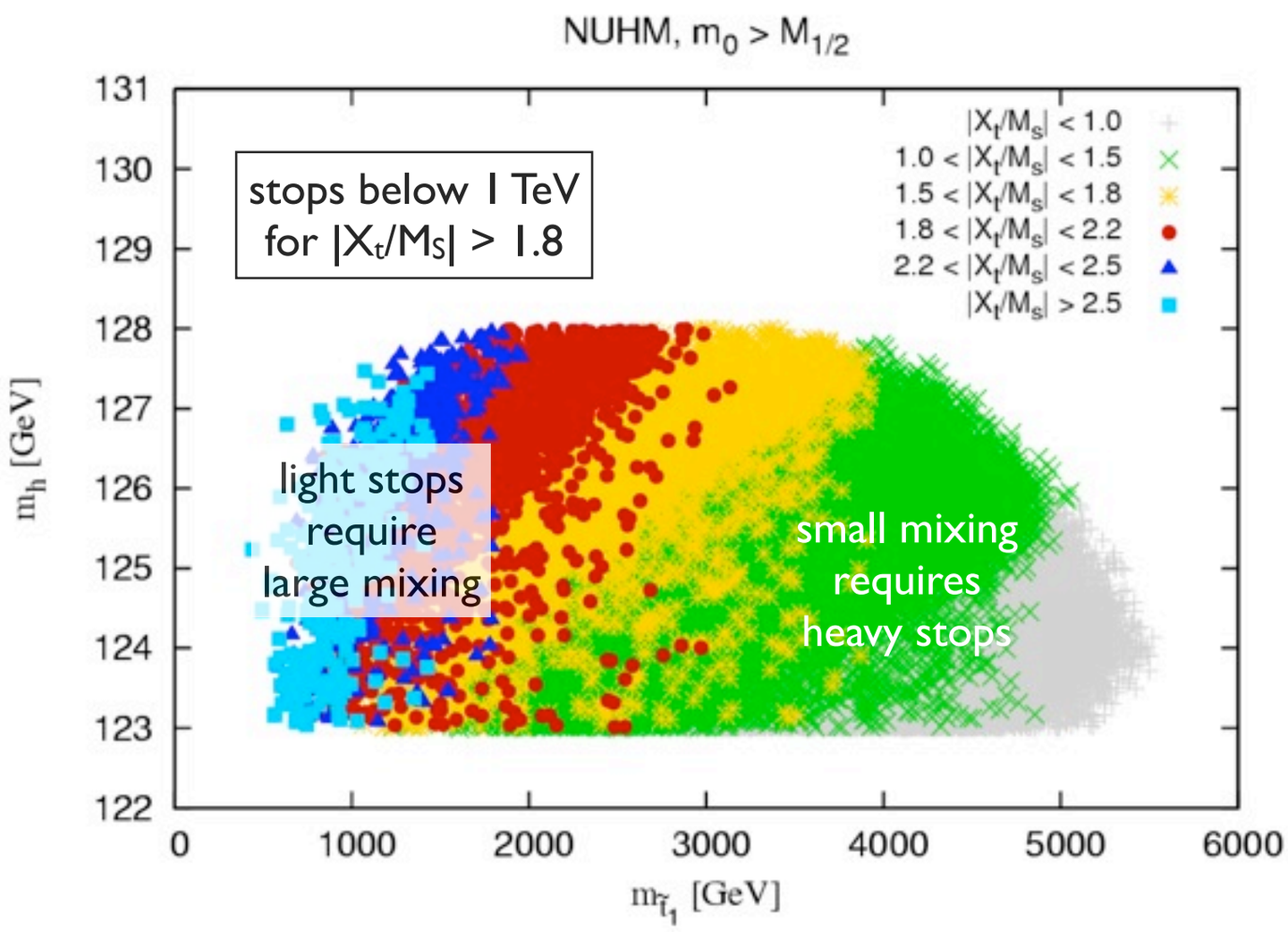
- Require Higgs signal strengths within 95% CL (orange) ellipses ∀ final states:



Combined ATLAS+CMS+Tevatron signal strength ellipses

Higgs versus stop mass

color code shows amount of stop mixing

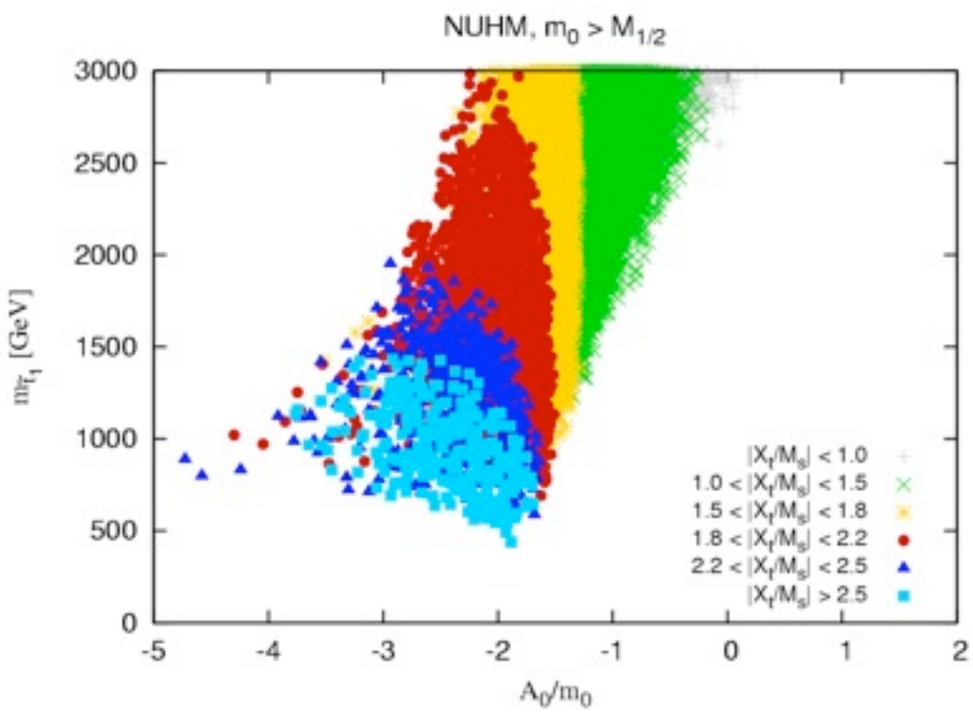


maximal mixing:
$|X_t/M_S| = 2.4$

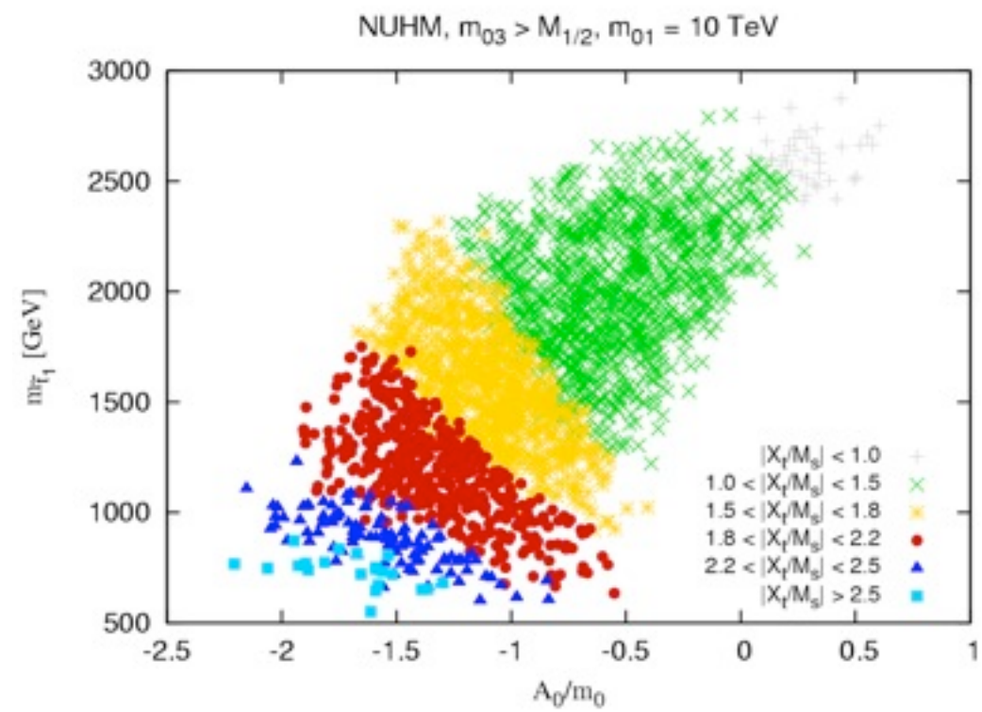
95% CL Higgs signal strength requirement
has marginal effect, excludes less than 1% of points

NUHM with 10 TeV squarks

universal m_0



heavy 1st/2nd generation



m_h~125 GeV with light stops requires very large negative A_0

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

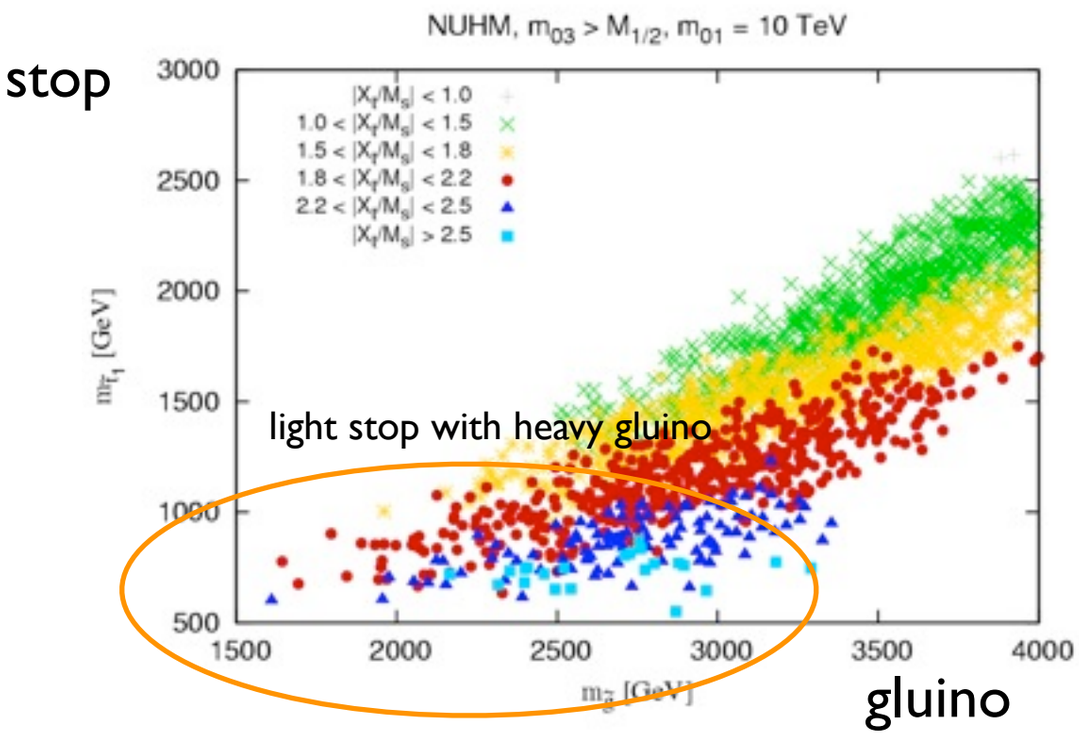
→ talk by F. Brümmer on Thu

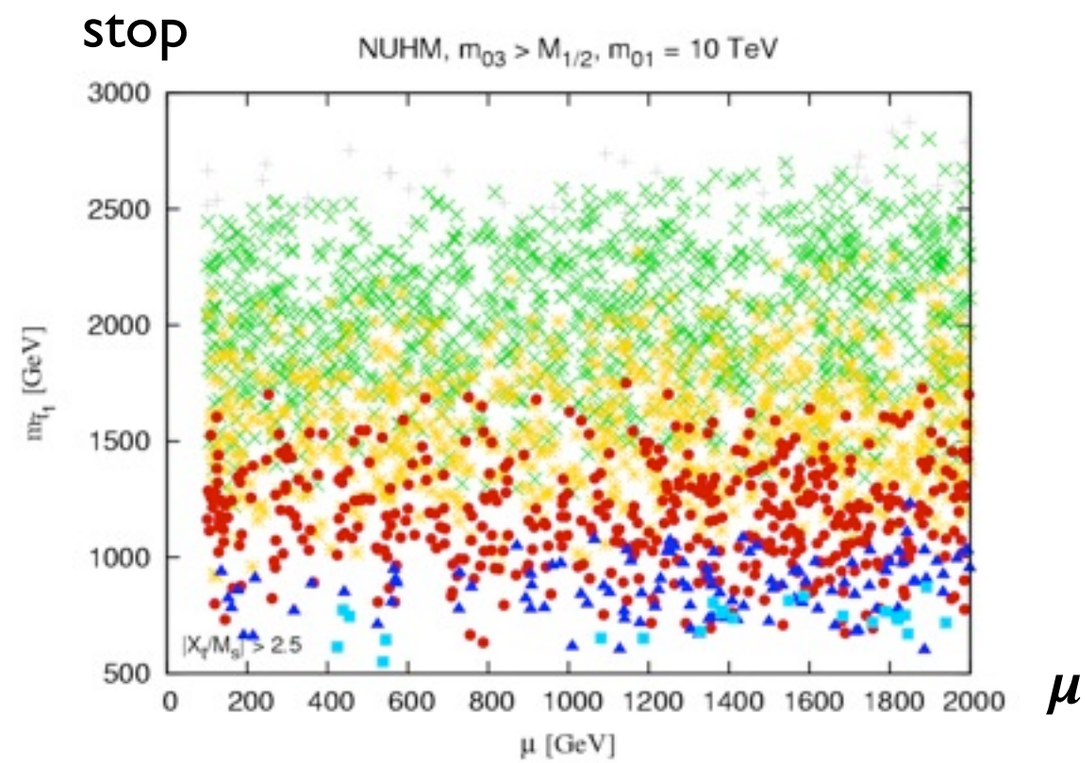
2-loop effects in the RGE running drive M_S down.

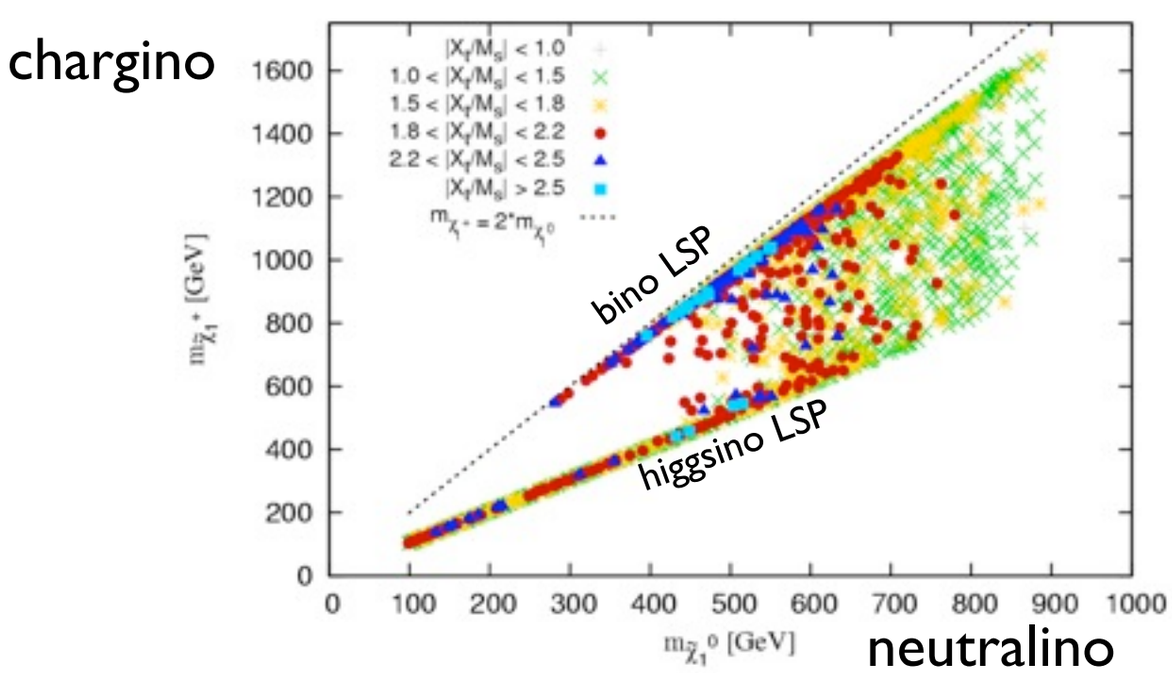
Light stops, near-maximal mixing and m_h~125 GeV even for moderate A_0

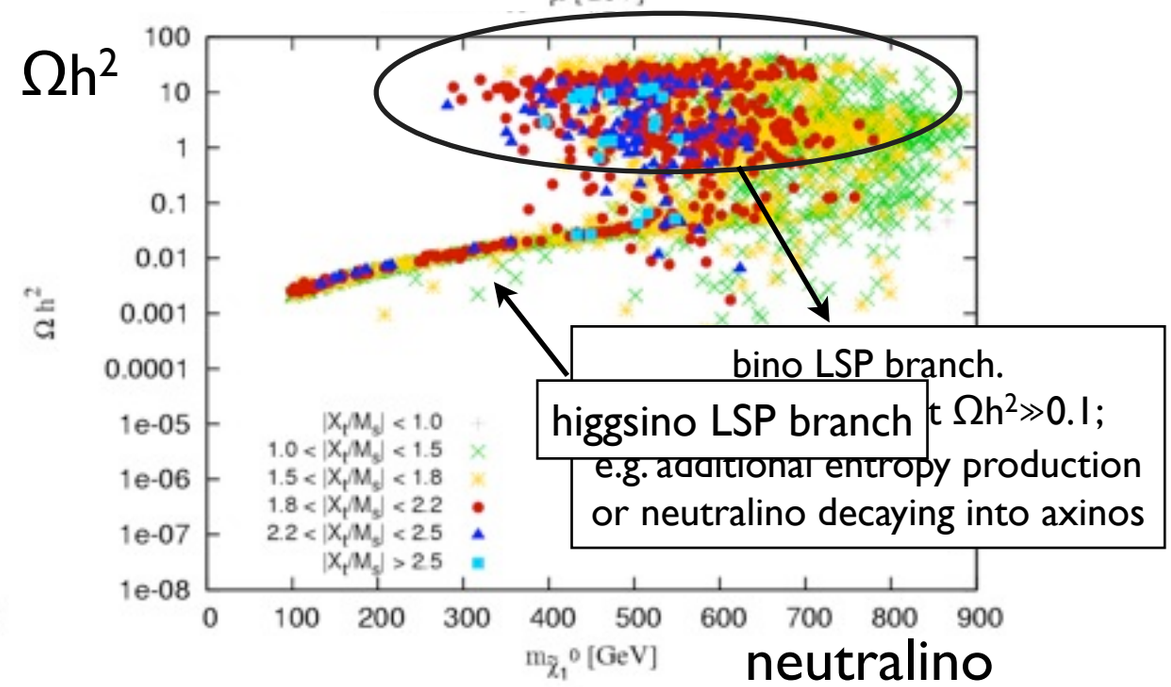
see also H. Baer et al.,1203.5539
M. Badziak et al., 1205.1675

SUSY particles









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
S. Sekmen et al.

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

*) prompt chargino requirement to be able to compare with CMS analysis, see later

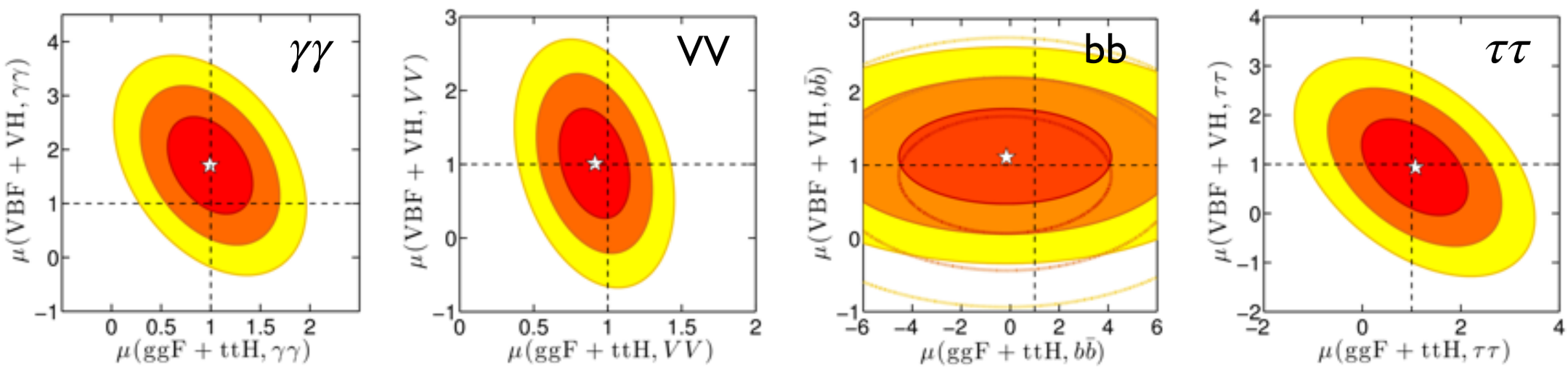
We sample 20 x 10^6 points in 20 chains, convergence tests OK

Constraints: observed Higgs

- Higgs mass: in MCMC sampling: m_h >112 GeV, afterwards hard cut requiring m_h = [123, 128] GeV

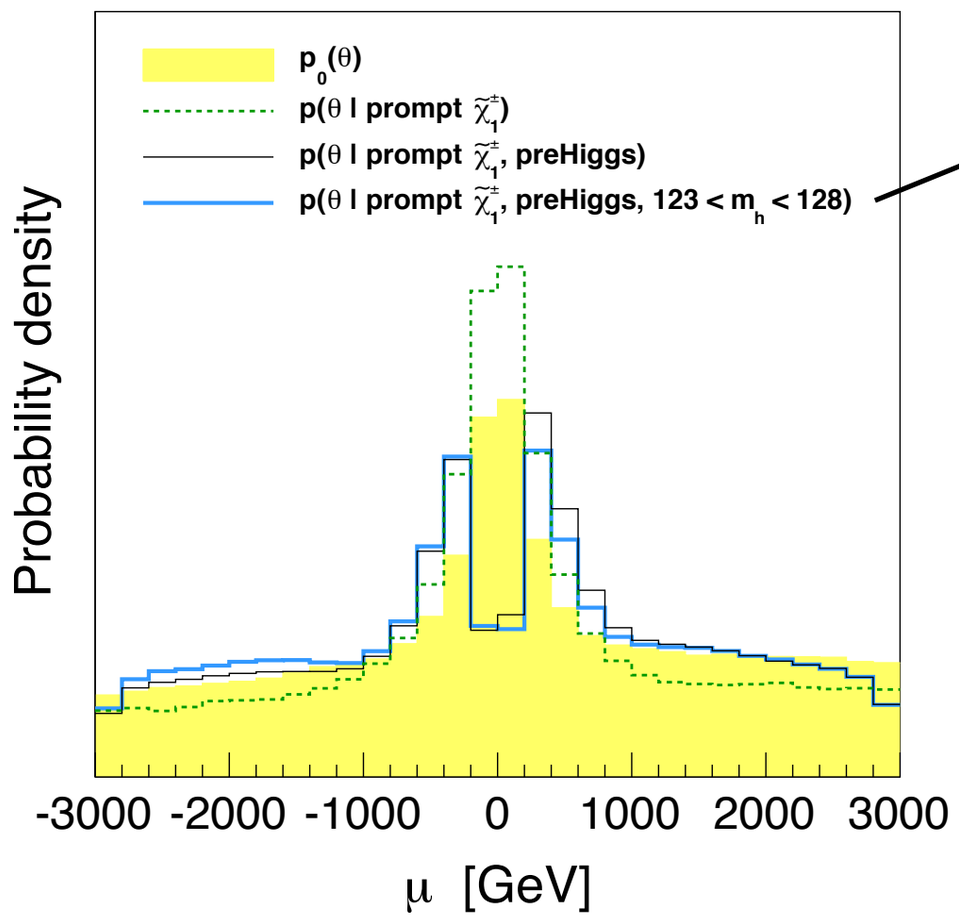
- Higgs signal strengths: likelihood computed as L=exp($-\chi^2/2$) from fit to experimental Higgs results

cf. Beranger Dumont's talk on Thursday

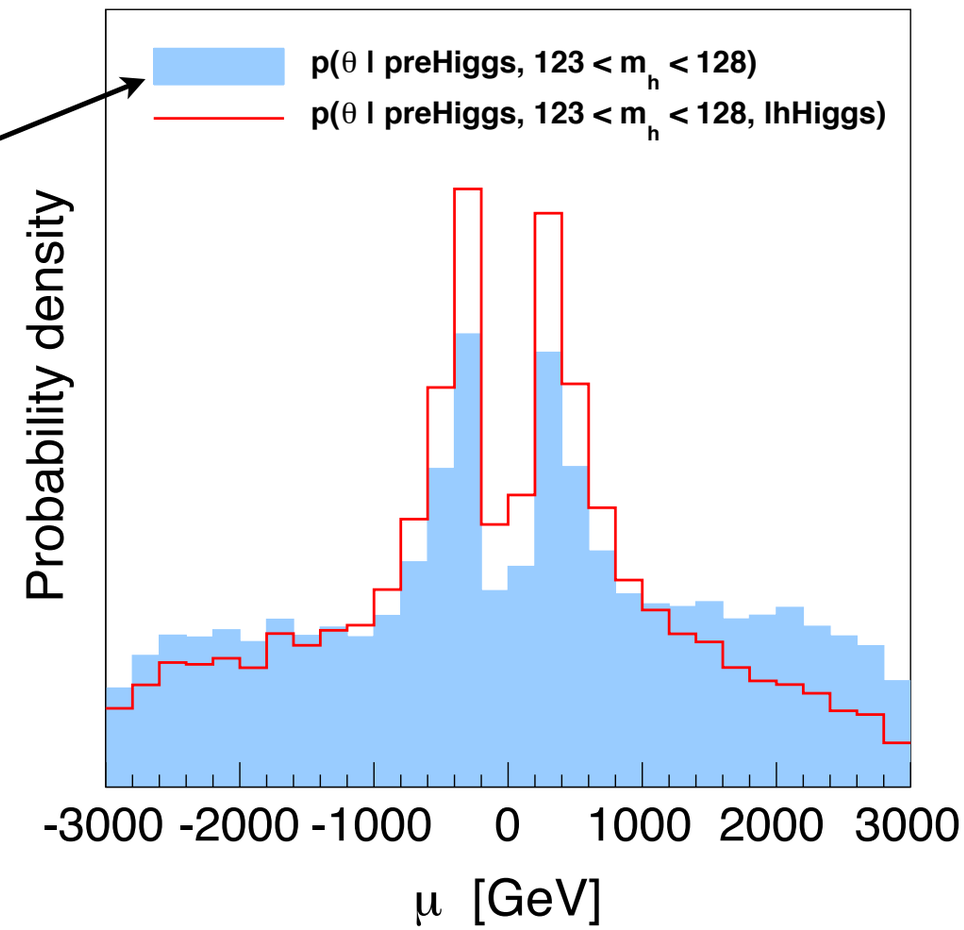


- L(Higgs) multiplied a posteriori on top of L(preHiggs)
  → see how this affects the probability distributions

Results

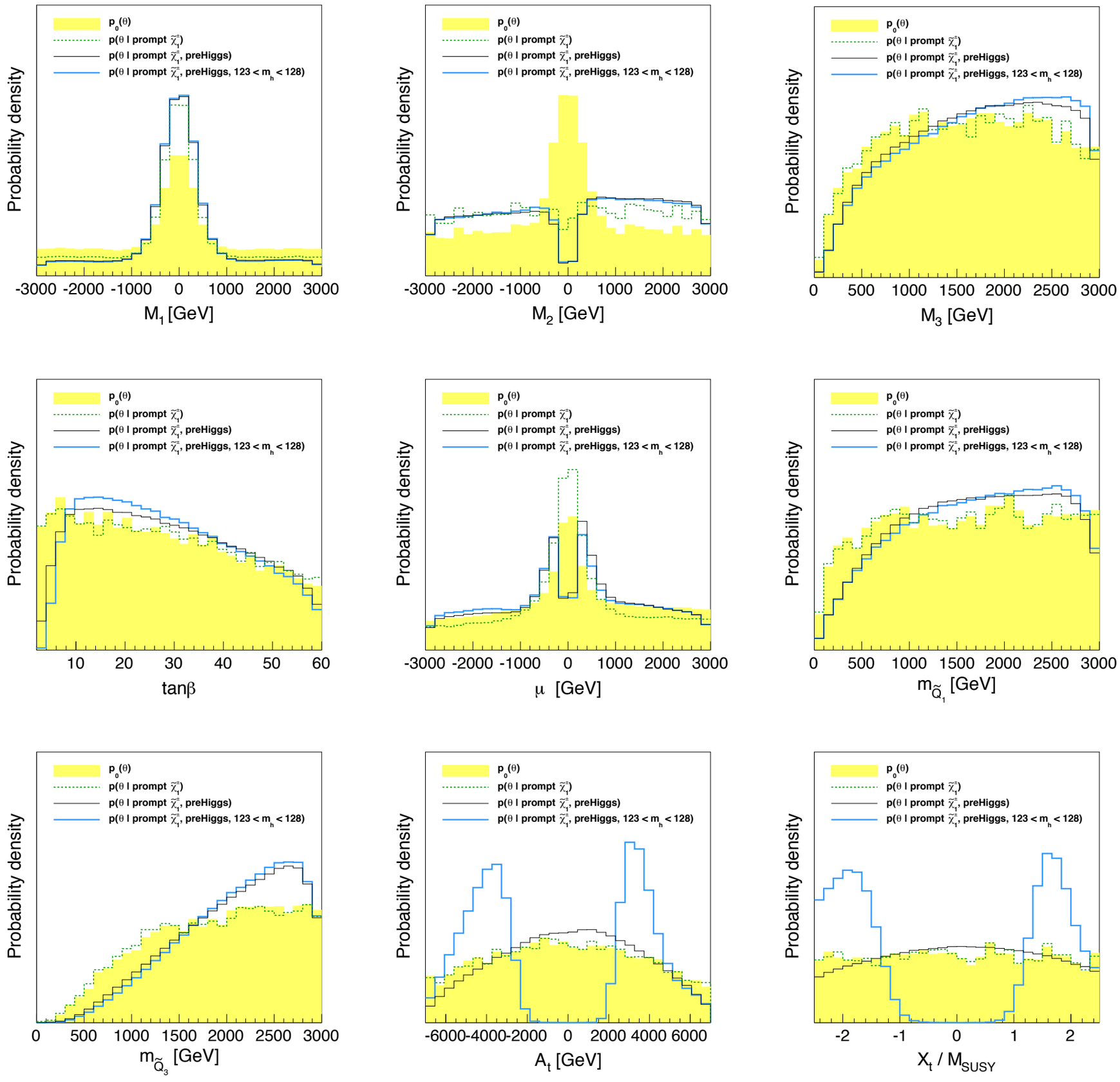


effects of "preHiggs" and Higgs mass constraints

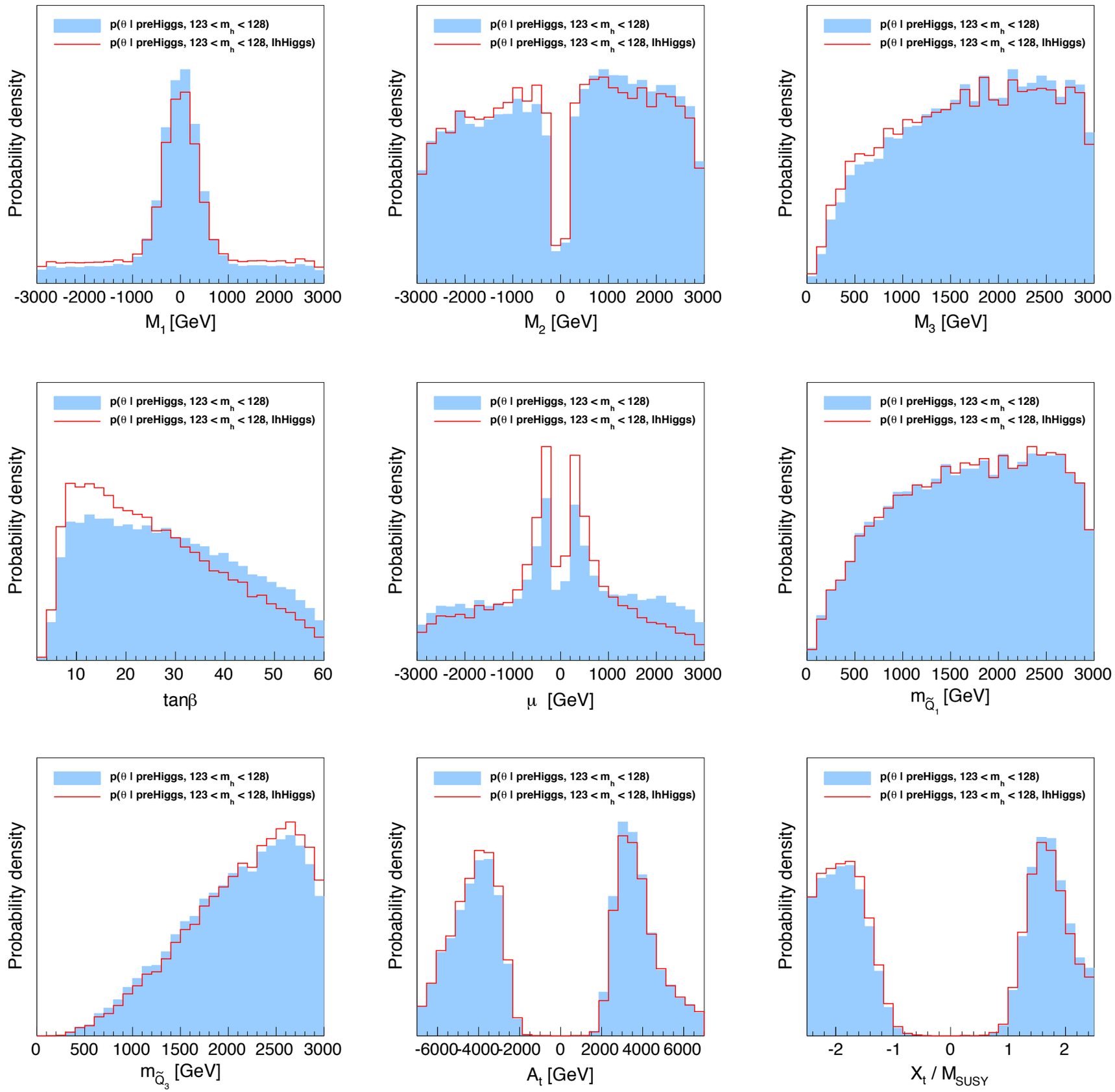


effect of Higgs signal strengths

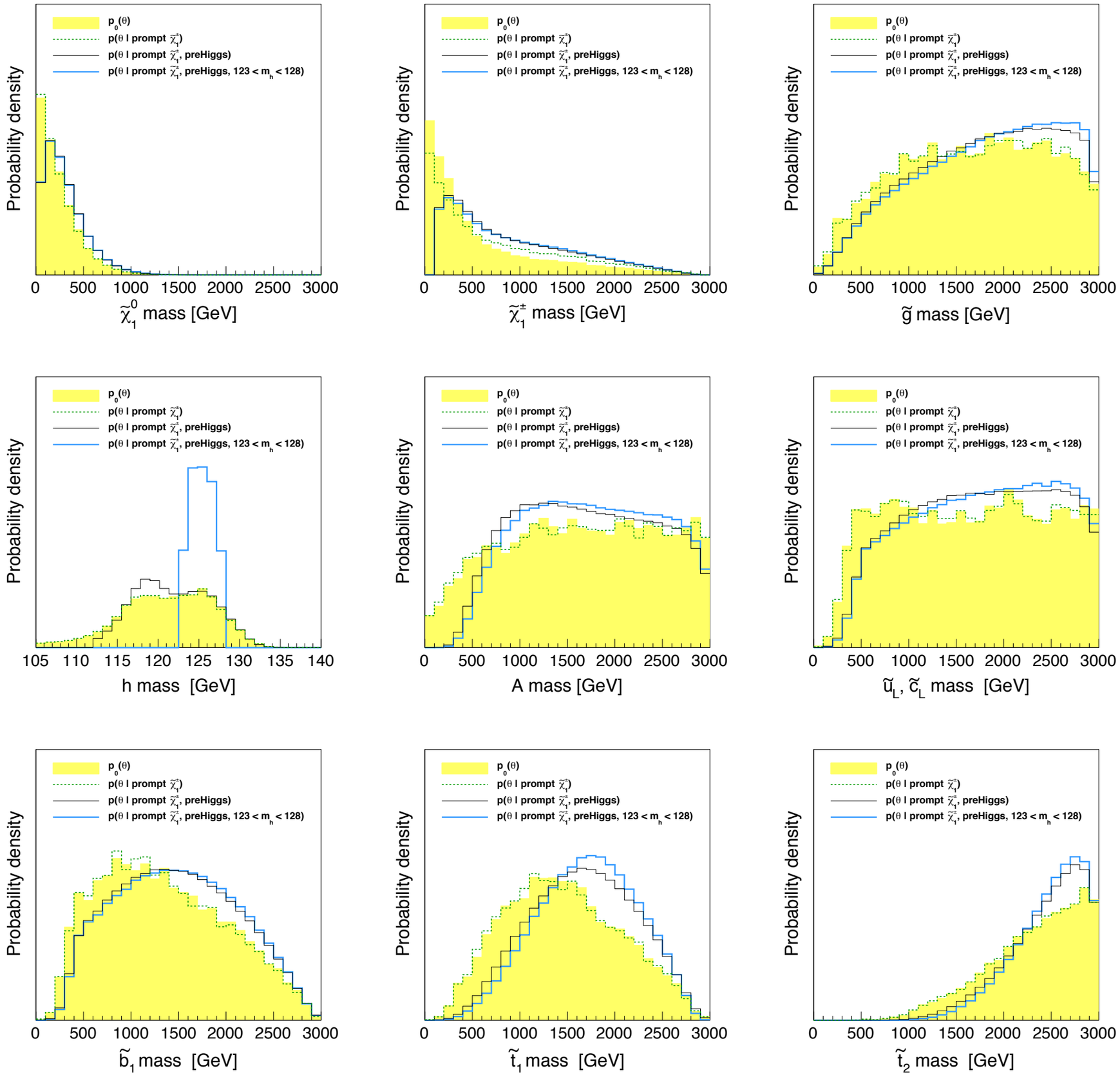
Parameters


$p_0(\theta)$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm)$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm, \text{preHiggs})$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm, \text{preHiggs}, 123 < m_h < 128)$
Probability density
M_1 [GeV]
M_2 [GeV]
M_3 [GeV]
tanβ
μ [GeV]
$m_{\tilde{Q}_1}$ [GeV]
$m_{\tilde{Q}_3}$ [GeV]
A_t [GeV]
X_t / M_{SUSY}

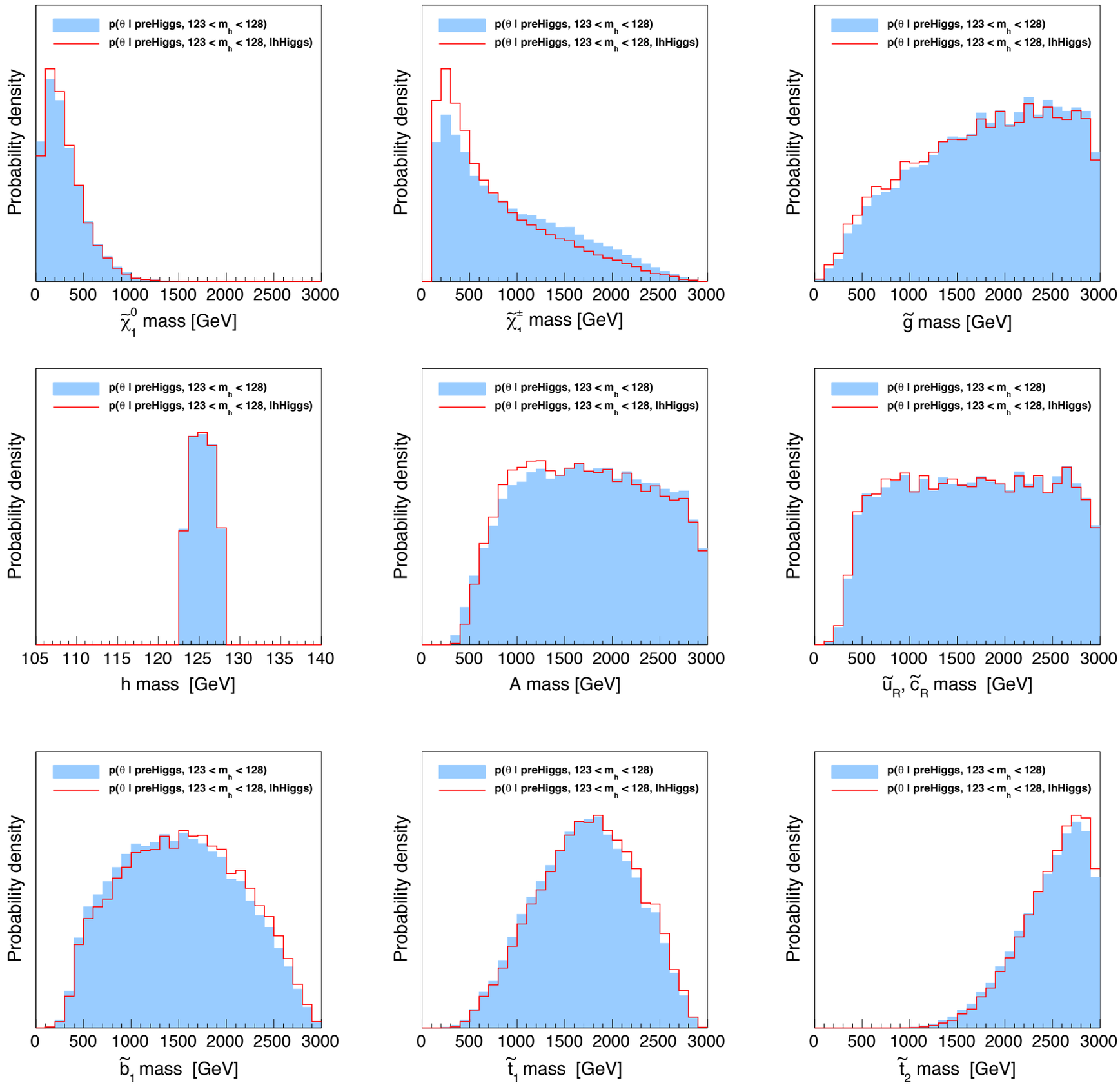
Parameters


p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
M_1 [GeV]
M_2 [GeV]
M_3 [GeV]
tanβ
μ [GeV]
m_Q̃1 [GeV]
m_Q̃3 [GeV]
A_t [GeV]
X_t / M_SUSY

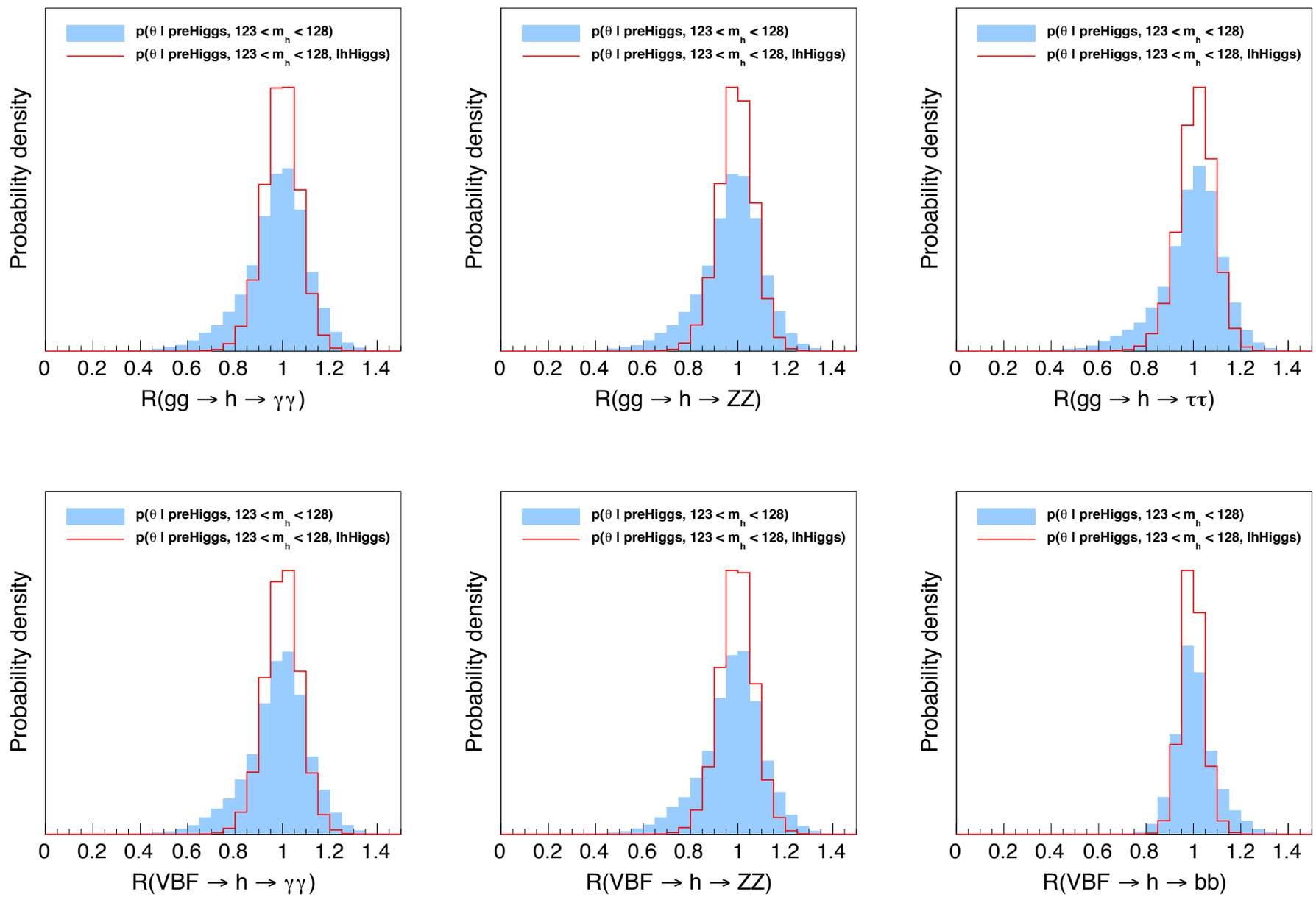
Masses


$p_0(\theta)$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm)$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm, \text{preHiggs})$
$p(\theta \mid \text{prompt } \tilde{\chi}_1^\pm, \text{preHiggs}, 123 < m_h < 128)$
Probability density
$\tilde{\chi}_1^0$ mass [GeV]
$\tilde{\chi}_1^\pm$ mass [GeV]
$\tilde{g}$ mass [GeV]
h mass [GeV]
A mass [GeV]
$\tilde{u}_L, \tilde{c}_L$ mass [GeV]
$\tilde{b}_1$ mass [GeV]
$\tilde{t}_1$ mass [GeV]
$\tilde{t}_2$ mass [GeV]

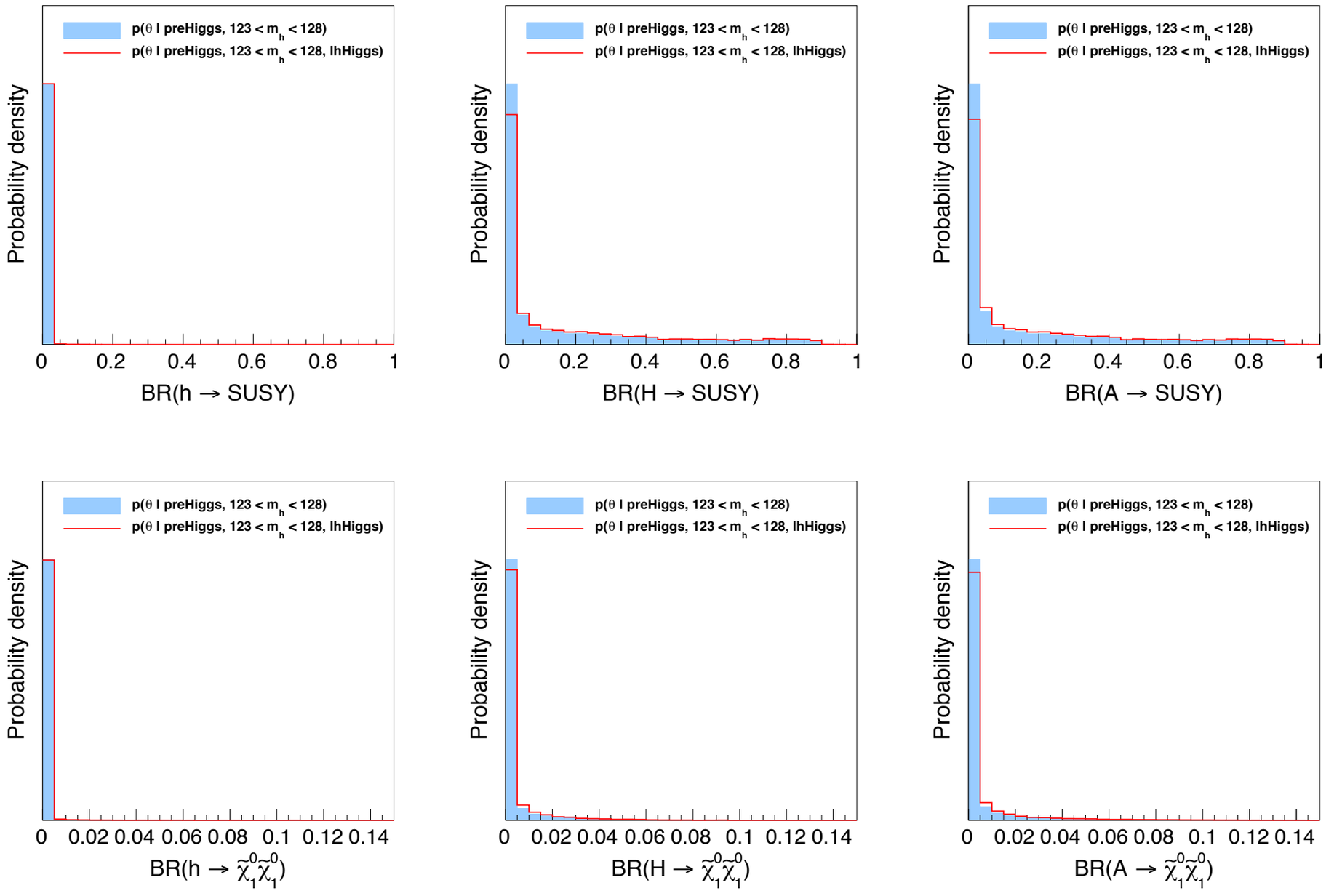
Masses


p(θ | preHiggs, 123 < m_h < 128)
p(θ | preHiggs, 123 < m_h < 128, lhHiggs)
Probability density
$\tilde{\chi}_1^0$ mass [GeV]
$\tilde{\chi}_1^\pm$ mass [GeV]
$\tilde{g}$ mass [GeV]
h mass [GeV]
A mass [GeV]
$\tilde{u}_R$, $\tilde{c}_R$ mass [GeV]
$\tilde{b}_1$ mass [GeV]
$\tilde{t}_1$ mass [GeV]
$\tilde{t}_2$ mass [GeV]

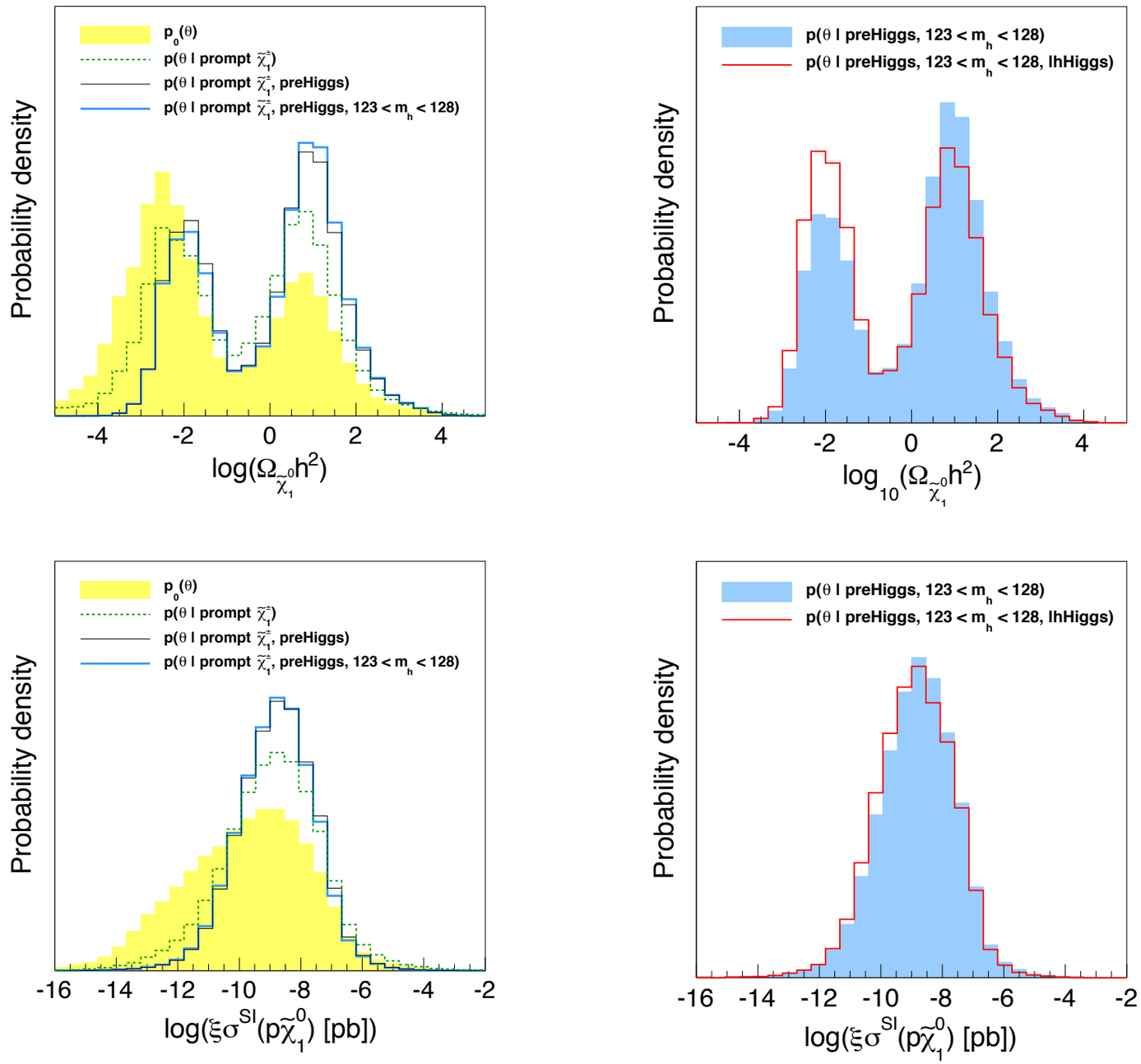
Light Higgs signal



Higgs decays into SUSY



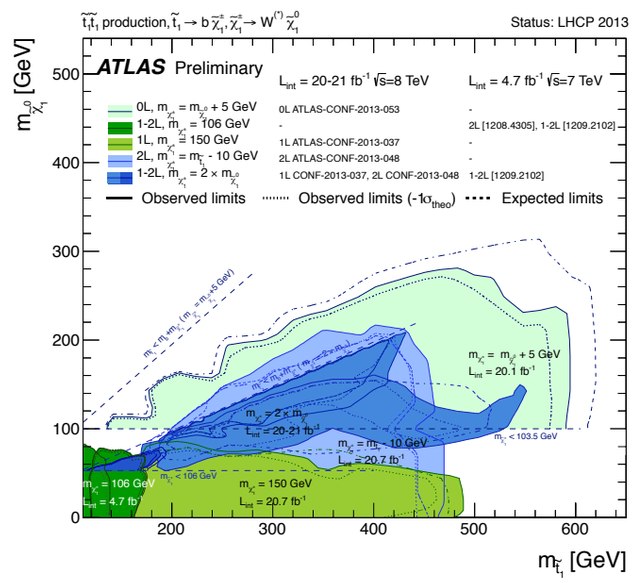
Dark matter

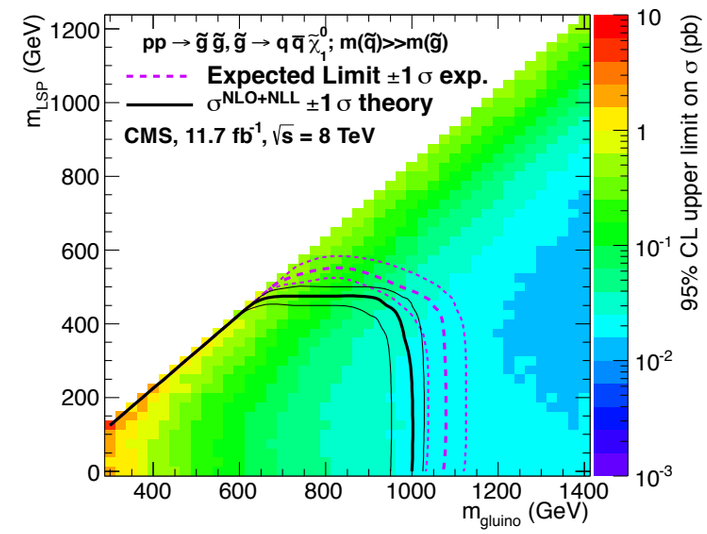

p0(θ)
p(θ I prompt χ̃1±)
p(θ I prompt χ̃1±, preHiggs)
p(θ I prompt χ̃1±, preHiggs, 123 < mh < 128)
Probability density
log(Ωχ̃1 0h2)
p(θ I preHiggs, 123 < mh < 128)
p(θ I preHiggs, 123 < mh < 128, lhHiggs)
log10(Ωχ̃1 0h2)
log(ξσSI(pχ̃1 0) [pb])

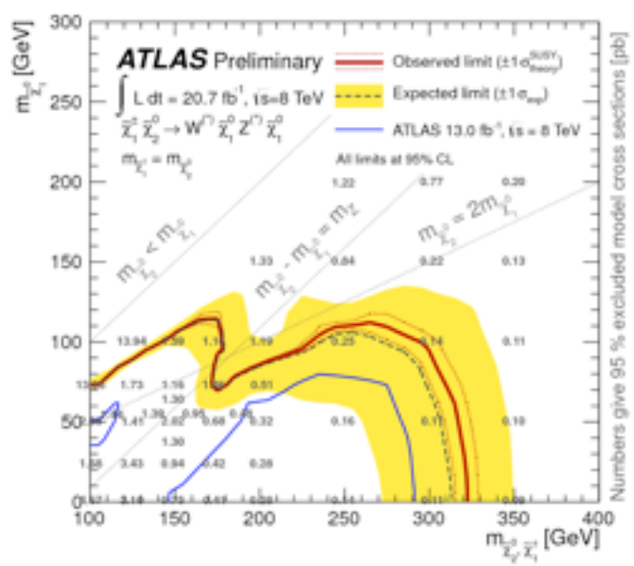
Constraints from direct SUSY searches

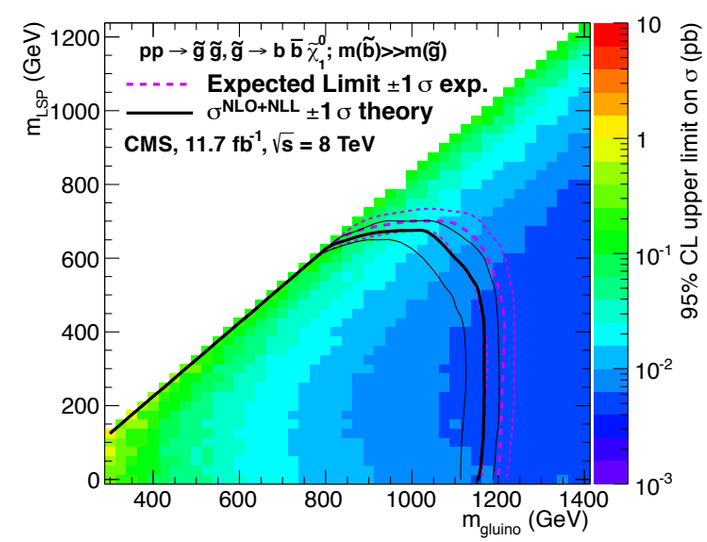
ATLAS and CMS SUSY searches

- Many different searches in many different channels. Limits however assume specific model or 100% BR for a specific topology









Combining searches: pMSSM interpretation

- **Phenomenological MSSM interpretation of the CMS 2011 5/fb results.** The CMS Collaboration, CMS-SUS-12030

We interpret within the phenomenological MSSM (pMSSM) results obtained by CMS using a pp data set collected in 2011 at 7~TeV, corresponding to an integrated luminosity of 5 / fb. [....] **We provide conclusions that are more generic, and therefore more robust, than those derived in more constrained setups**, including simplified models and models that impose particular SUSY breaking schemes, such as the CMSSM. We also study implications for the MSSM Higgs sector, as well as for dark matter searches. Furthermore, we discuss which scenarios currently escape detection despite a high production cross section. Our study thus gives a **coherent global picture of how the current CMS searches constrain supersymmetry in general.**

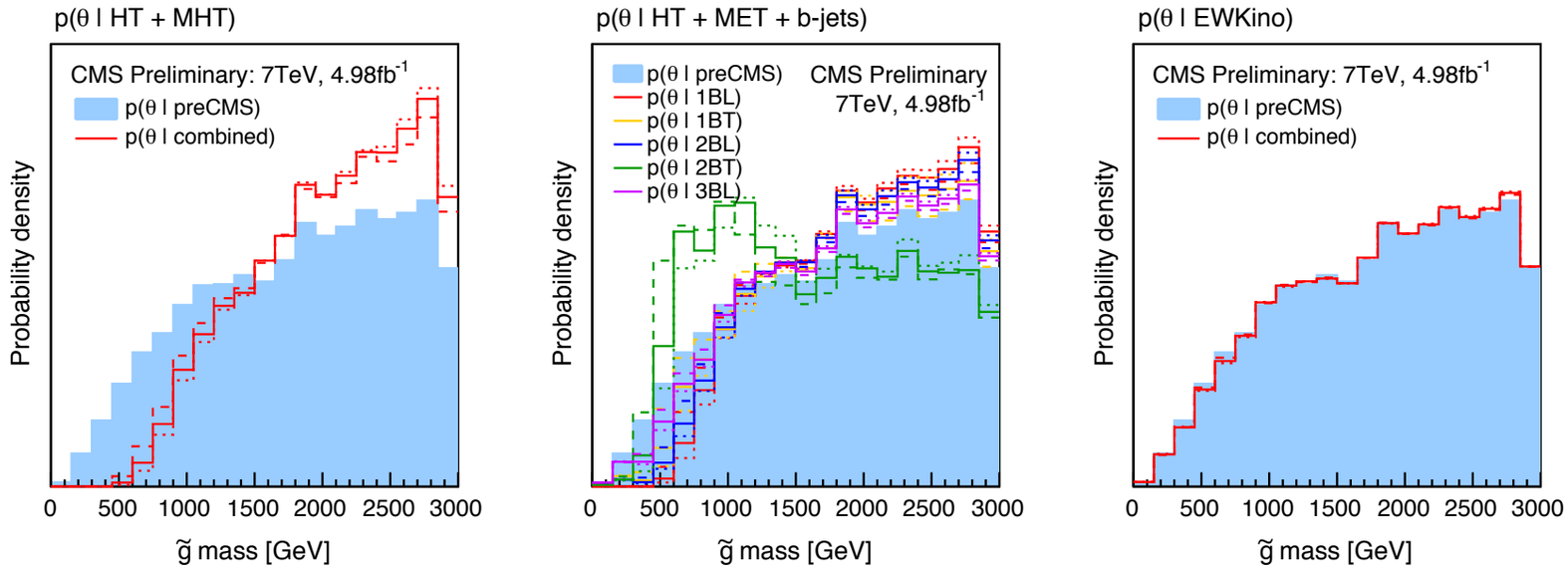
Analysis	CERN doc. no & reference
Hadronic $H_T + H_T^{miss}$ search	CMS-SUS-12-011 [42]
Hadronic $H_T + E_T^{miss} + b$-jets search	CMS-SUS-12-003 [43]
Hadronic $H_T + E_T^{miss} + \tau$s search	CMS-SUS-12-004 [44]
Hadronic monojet $+E_T^{miss}$ search	CMS-EXO-11-059 [45]
Leptonic same sign (SS) 2ℓ search	CMS-SUS-11-010 [46]
Leptonic opposite sign (OS) 2ℓ search	CMS-SUS-11-011 [47]
Leptonic electroweakino (EWKino) search	CMS-SUS-12-006 [48]

Same MCMC as before, with random selection of 7.2K points for CMS simulation

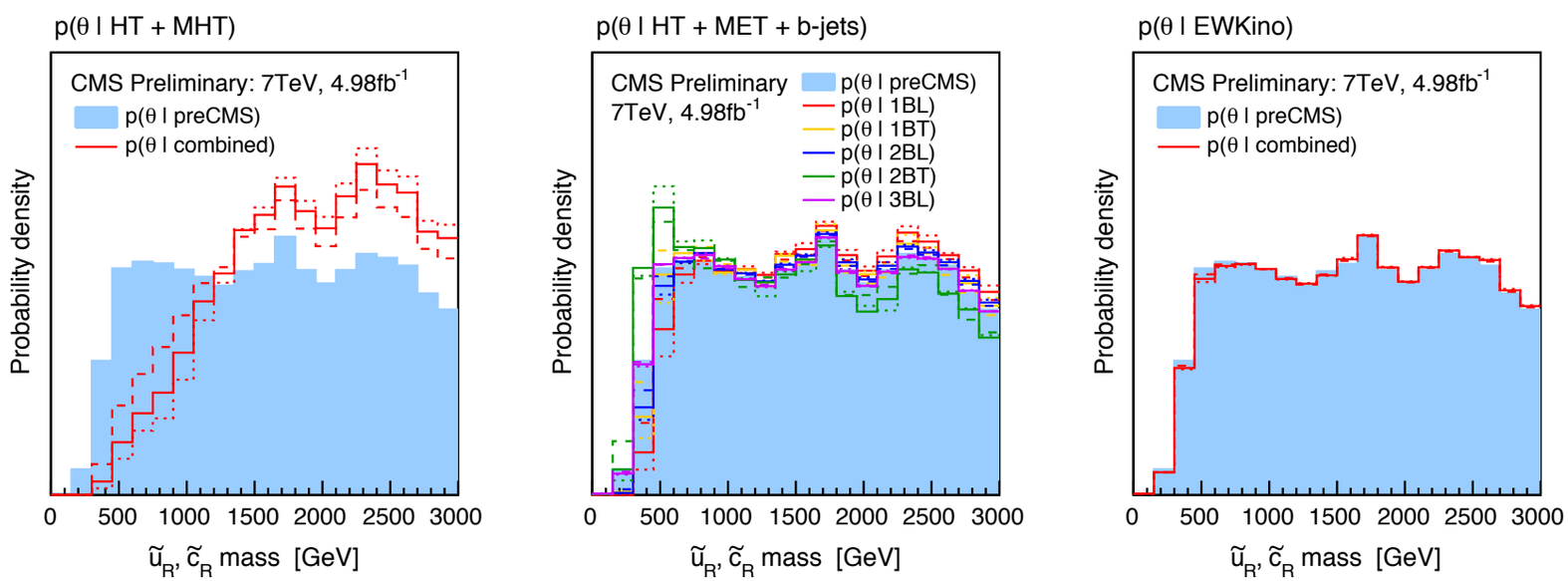
Personally, I wish to thank S. Bein, J.F. Gunion, H. Prosper, S. Sekmen, L. Vanvelderen and W. Waltenberger for a most rewarding collaboration.

Impact of different searches

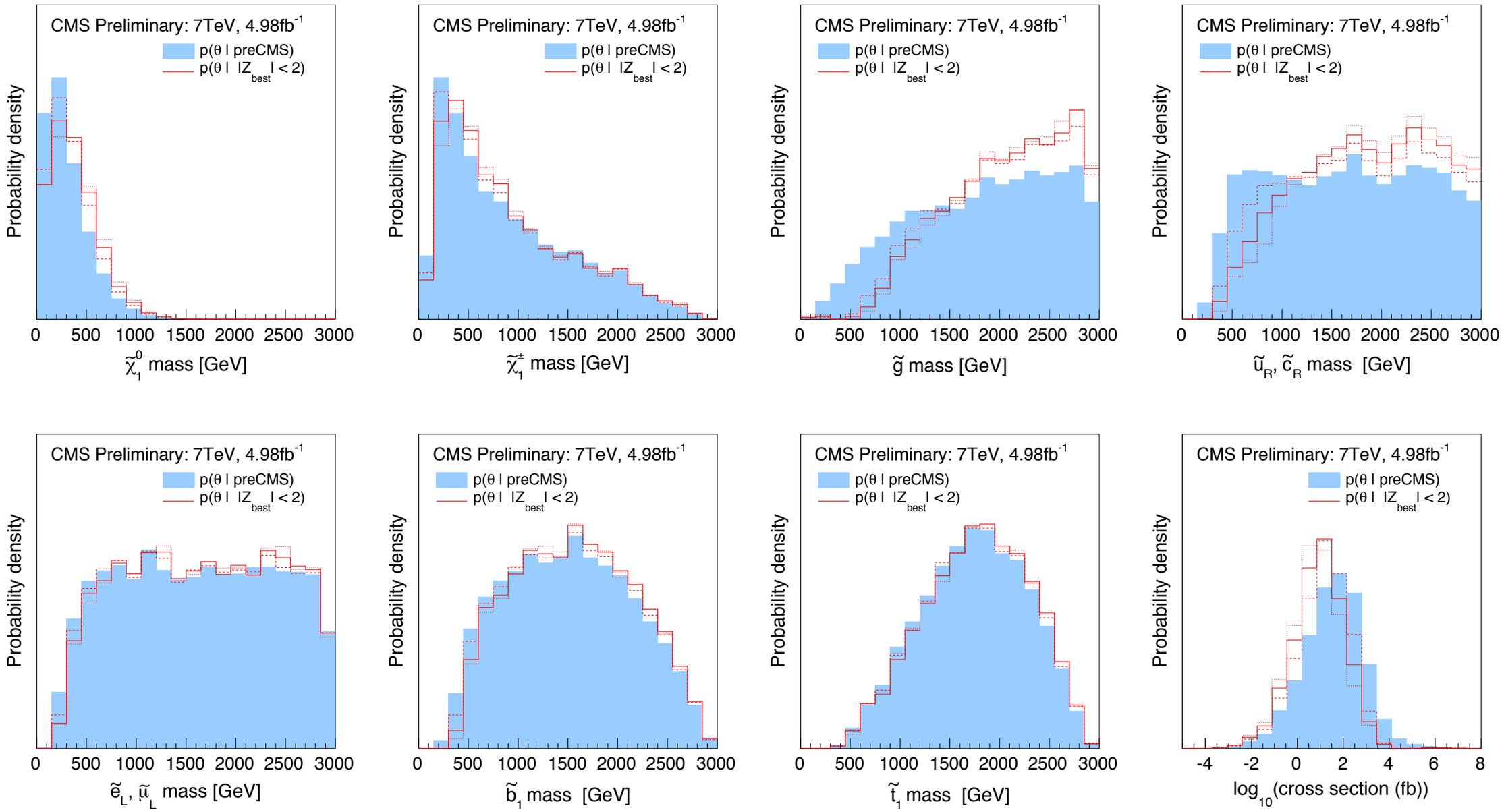
gluino



squarks

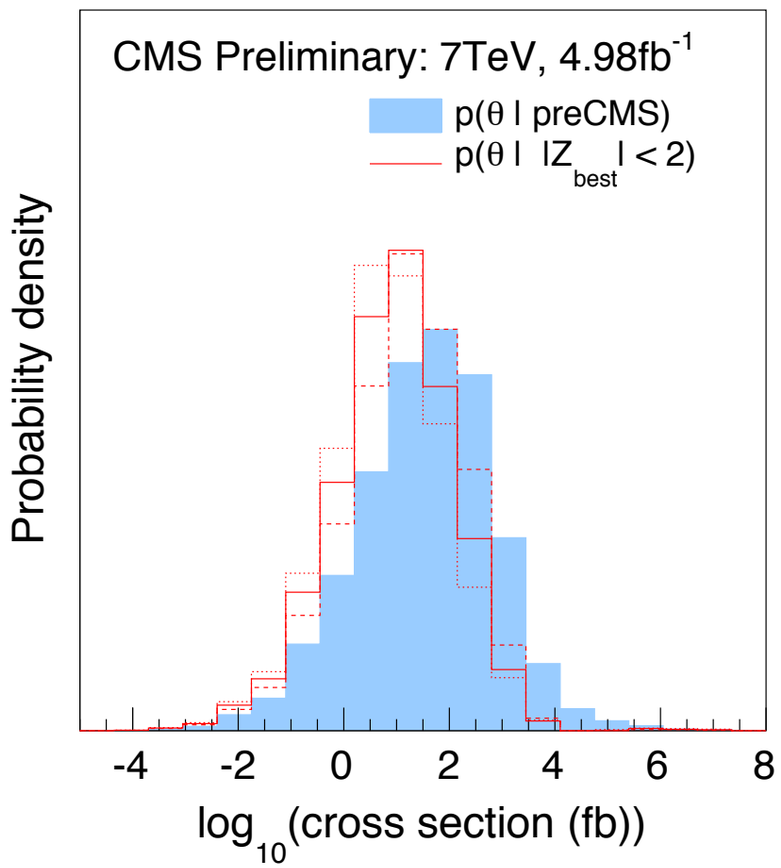


Probability distributions for not-excluded points



Z=significance; $|Z_{best}|<2$ means not excluded by any search; dashed lines: ±50% error on signal rate

Unexplored scenarios



- Of the 7205 model points explored, the seven analyses included in this study excluded 2701, or 37%.
- Of the remaining points, 49% have a total cross section > 10 fb.
- These unexplored high-cross section points are characterized by
  - ★ mainly EW production of almost mass-degenerate neutralinos and charginos (higgsino scenarios, 36% Δm<5 GeV) or
  - ★ production of light squarks and/or gluinos in compressed spectra
- Stay tuned for 8 TeV analysis

On the presentation of experimental results

- To make the most of the LHC physics potential, the LHC results should be presented in a way that their are useable for the whole community.
- Experience: even within the exp. collaboration it was difficult to re-interpret some of the analyses (incomplete documentation, ...)
- Please give a complete description of each analysis, cut-flows, efficiencies, all the signal and background numbers, etc such that results are reproducible. (this concerns also the Higgs results)

➠ Les Houches Recommendations for the Presentation of LHC Results

EPJC72 (2012), arXiv:1203.2489

Abstract

We present a set of recommendations for the presentation of LHC results on searches for new physics, which are aimed at providing a more efficient flow of scientific information between the experimental collaborations and the rest of the high energy physics community, and at facilitating the interpretation of the results in a wide class of models. Implementing these recommendations would aid the full exploitation of the physics potential of the LHC.

Conclusions

Quo vadis SUSY

- 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: observed Higgs is very SM-like
  → (too) easy to achieve in the MSSM

- LHC SUSY searches at 7+8 TeV have pushed squark and gluino masses beyond ~1.5 TeV. However, holes and unexplored regions remain: e.g., natural SUSY with light higgsinos, or compressed SUSY spectra evade limits.
- Need efficient flow of information between experimental collaborations and the "rest" of the HEP community for fully exploiting the LHC physics potential.

From the report to the European Strategy Group

In short, while the simplest SUSY models are becoming less favored by the data, natural SUSY at the weak scale is still viable in seemingly more complex models. A first signal of such models is still possible at the 8 TeV run, but resolving these scenarios likely requires the full 300 /fb at 14 TeV.

The discovery of SUSY would give additional physics opportunities at the LCs, allowing for precision measurements of all SUSY particles that are within kinematic reach.