NMSSM Interpretations of the Observed Higgs Signal

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DESY – LHC Higgs Forum

March, 23rd 2015

Next-to-Minimal Supersymmetric Standard Model - Model and Motivations

Softly-broken SUSY extensions of the SM

- **Hierarchy Problem**: SUSY protects the Higgs mass from sensitivity to high-scale new-physics;
- **Higgs Physics**: $m_H \sim 125$ GeV lies in the SUSY-expected range;
- **One-step Unification**: SUSY matter-content ensures convergence of gauge couplings;
- **Dark matter**: WIMP candidate in the presence of R-parity;
- **Top-down approach**: Supergravity, Superstrings, etc.

But SUSY obviously absent at low-energies: soft-breaking at the ~TeV scale!

The μ-problem

$$W_{MSSM} \ni \mu\, \hat{H}_u \cdot \hat{H}_d \quad \rightarrow \quad W_{NMSSM} \ni \lambda\, \hat{S}\, \hat{H}_u \cdot \hat{H}_d + \kappa \hat{S}^3$$

- μ : SUSY parameter $\rightarrow$ Natural Scale: $O(M_{\text{Planck,GUT,etc.}})\ldots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$
- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*

  v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- $\mathbb{Z}_3$-symmetry: scale-invariant superpotential $\Rightarrow$ *No naturalness problem!*

NMSSM Higgs scenarii since the hints of the 'Higgs' signal at ~ 125 GeV

The NMSSM Higgs sector

- 2 Doublets + 1 Singlet $\Rightarrow$ 3 CP-even + 2 CP-odd + 1 pair of Charged Higgs states;
- 6 parameters at tree level: λ, κ, $\tan\beta$, M_A, $\mu_{\rm eff}$, A_κ.

In the literature...

- Large tree-level effect: 1112.2703, 1112.4835, 1201.2671,1201.5305, 1207.3698, 1209.2115, 1304.3670;
- Light singlet, consequences on the rates of the doublet state: 1112.3548, 1202.5821, 1207.1096, 1210.3751, 1211.0875, 1211.5074;
- Light singlet, rates of the singlet state: 1210.1976, 1304.5437, 1310.4518, 1408.1120;
- Light doublet sector: 1303.2113;
- Searches in pair production: 1301.0453, 1301.6437, 1306.3926, 1306.5541;
- 2 quasi-degenerate Higgs states: 1207.1545, 1211.5074;
- Scenarii with a light CP-odd (even) state: 1205.1683, 1206.1470, 1301.1325, 1309.4939, 1409.8393;
- NMSSM with univ. soft terms: 1201.0982, 1203.5048, 1211.1693, 1308.1333, 1402.4650, 1405.6647;
- NMSSM in a gauge-mediated setup: 1206.6540,1207.3126,1212.5243;
- Variants of the NMSSM: 1205.2486, 1208.2555, 1209.5984;
- In view of relic-density / direct SUSY searches: 1203.3446, 1304.3182, 1305.3214

King, Mühlleitner, Nevzorov, Walz; Bomark, Moretti, Munir, Roszkovski; Ellwanger, Hugonie; Gunion, Jiang, Kraml; Badziak, Olechowski, Pokorski; Cao,et al.; Christensen,et al.; etc.

Exploring the NMSSM parameter space...

NMSSMTools 4.4.0: Higgs masses up to leading two-loop double-log order

- Theory requirements: stability of the EWSB-vacuum, absence of Landau-Poles below GUT, naturalness of soft-terms; [hep-ph/0406215, hep-ph/0508022]
- Limits on supersymmetric particles from LEP; *(Gunion,Ellwanger,Hugonie)*
- Limits from B-physics: $BR(B \to X_s\gamma)$, $BR(B^+ \to \tau\nu_\tau)$, $BR(\bar{B}_s \to \mu^+\mu^-)$, $BR(B \to X_s\mu^+\mu^-)$, $\Delta M_{d,s}$ [arXiv:0710.3714] *(Ellwanger,F.D.)* $\Rightarrow$ χ^2_B;
- $(g-2)_\mu$ [arXiv:0806.0733] *(Ellwanger,F.D.)* $\Rightarrow$ $\chi^2_{(g-2)_\mu}$;
- Dark matter limits discarded (to keep the SUSY spectrum simple);

HiggsBounds 4.2.0

Limits on Higgs sector at 95% CL combining data from LEP, TeVatron, LHC.
[arXiv:0811.4169,arXiv:1102.1898,arXiv:1301.2345] *(Bechtle,Brein,Heinemeyer,Stål,Stefaniak,Weiglein,Williams)*

HiggsSignals 1.3.1

Confrontation of the Higgs sector to the rates measured at TeVatron, ATLAS and CMS ($\sim$ 125 GeV): statistical test (out of 81 observables). [arXiv:1305.1933] $\Rightarrow$ χ^2_H
Uncertainty on NMSSMTools Higgs mass: ± 3 GeV (conservative but limited impact).

$\to \chi^2$ *test of the 'observed' signals studied on the 95% CL allowed parameter space:*

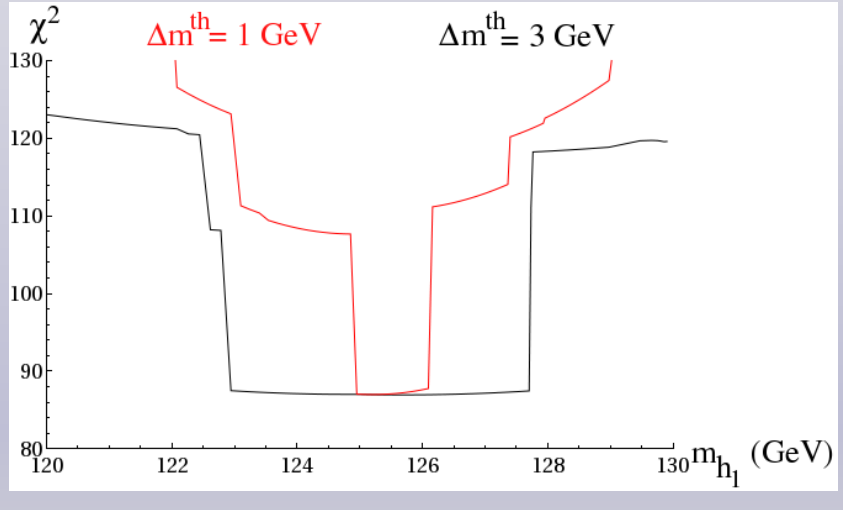
$$\chi^2_{tot}[89obs.] \equiv \chi^2_H[81obs.] + \chi^2_B[7obs.] + \chi^2_{(g-2)_\mu}[1obs.]$$

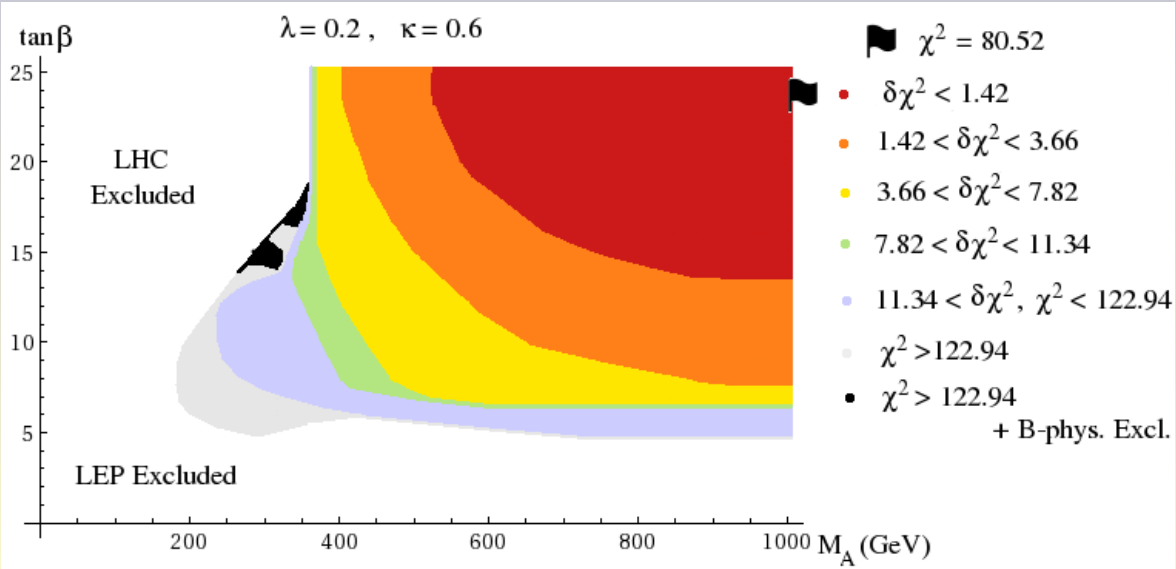
The SM and the Decoupling limits

SM-limit

- Singlet decoupling: $\lambda \sim \kappa \to 0$ (MSSM limit);
- Heavy SUSY sector;
- Decoupling of the heavy-doublet states: $M_A \gg M_Z$;
- $\tan\beta \gtrsim 10$ to fit the observed mass.

$\Rightarrow$ *light doublet state with SM-like couplings.*
But: χ^2 pull from $(g-2)_\mu \simeq 8-9$





Decoupling limit

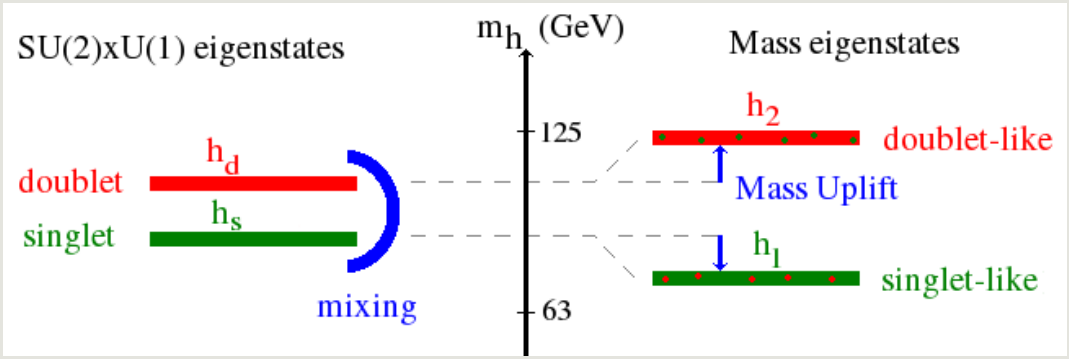
Decoupling of the heavy-doublet states:
$M_A \gg M_Z$;
Correct kinematical range for the light doublet ensured through:

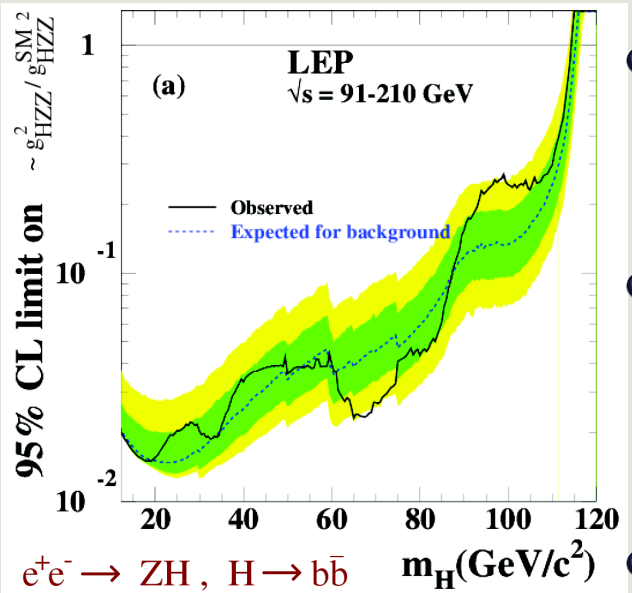
* **Loop corrections**
(MSSM-like, large $\tan\beta$);
* **λ contribution at Tree-level**
(NMSSM specific, low $\tan\beta$).

The light-singlet scenario - setup

CP-even singlet state with mass in the range ~ [63, 120] GeV

- **Uplift** of the doublet Higgs (h_2) mass via its mixing with the singlet;

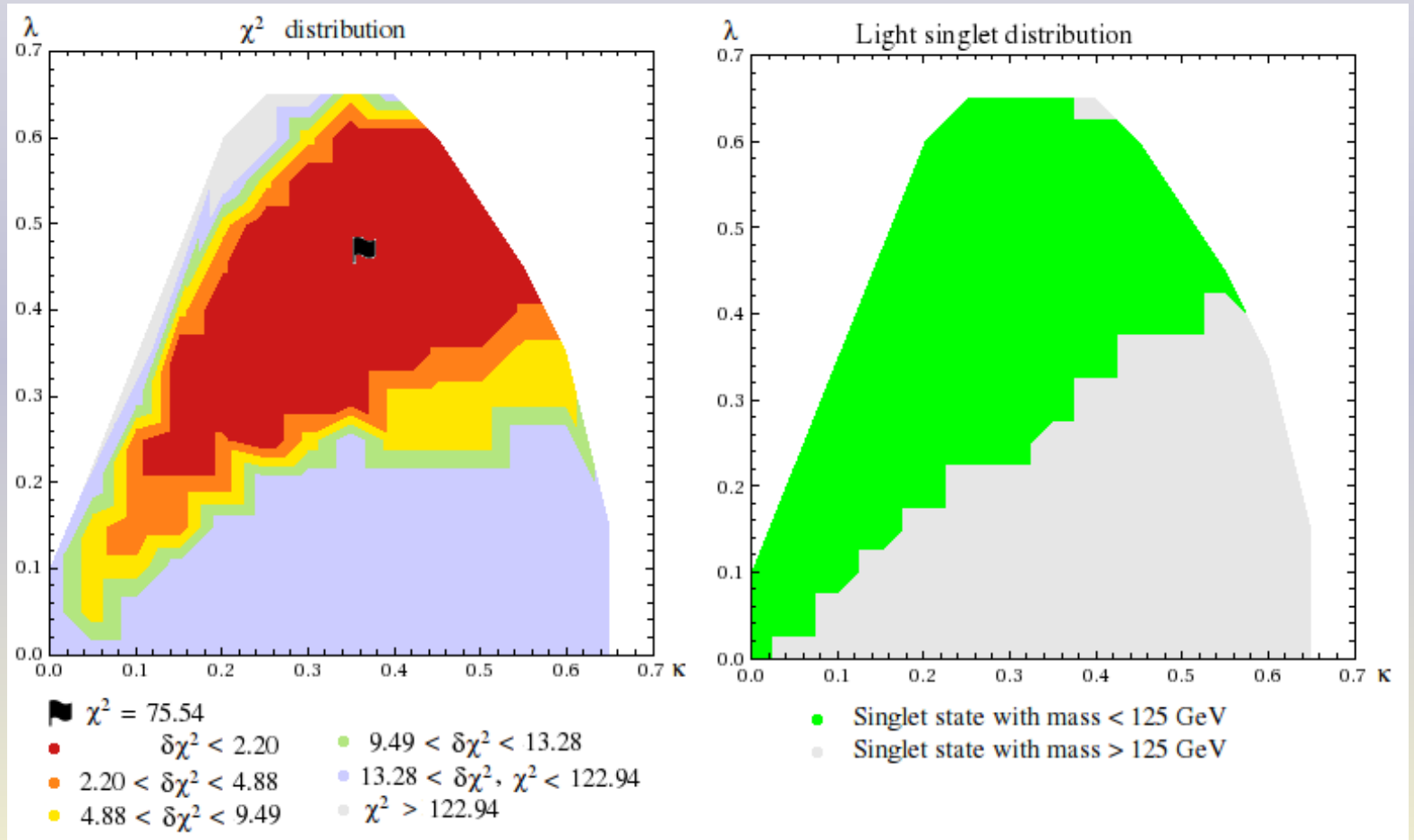




- A singlet-like state has **suppressed couplings** to SM particles ⇒ *suppressed production cross-section*.
  ⇒ safe with LEP!
  + 2.3σ excess at ~ 100 GeV!
- **Three-state mixing** ⇒ 3 mixing angles
  ⇒ Additional freedom in the composition of the doublet state / its couplings to SM particles
  ⇒ Possibility to interpret deviations from SM couplings at ~ 125 GeV.
- Best fit: $\chi^2 \sim 75$

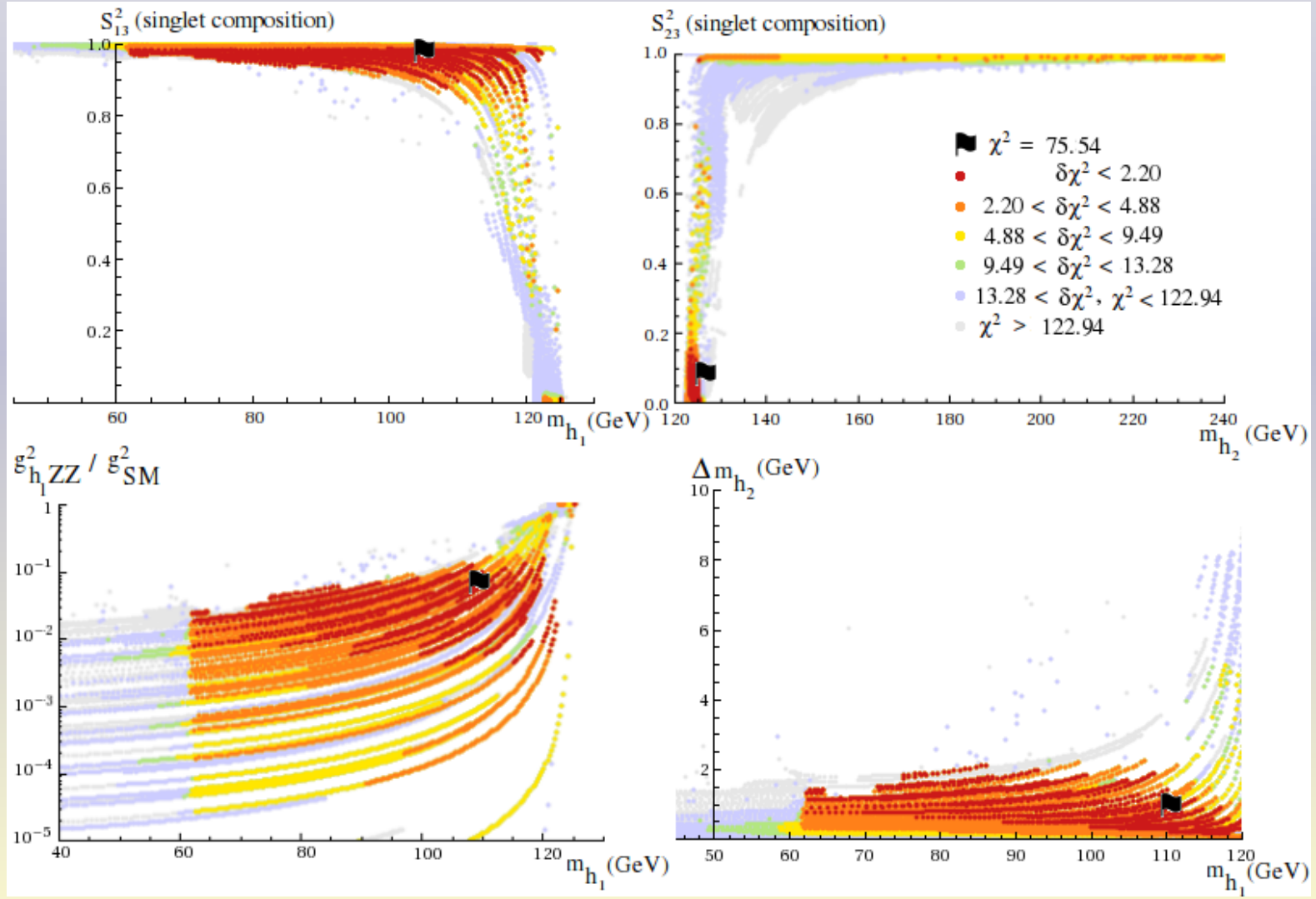
- **Observe the singlet**? → Look at low-mass in $\gamma\gamma$, $\tau\bar{\tau}$, $b\bar{b}$ + higgs pair production
  + hypothetical SUSY cascades?

The light-singlet scenario - results 1



$\tan\beta = 8$, $M_A \simeq 1$ TeV, $m_{\tilde{T}} \simeq 1$ TeV, $A_t \simeq -2$ TeV

The light-singlet scenario - results 2



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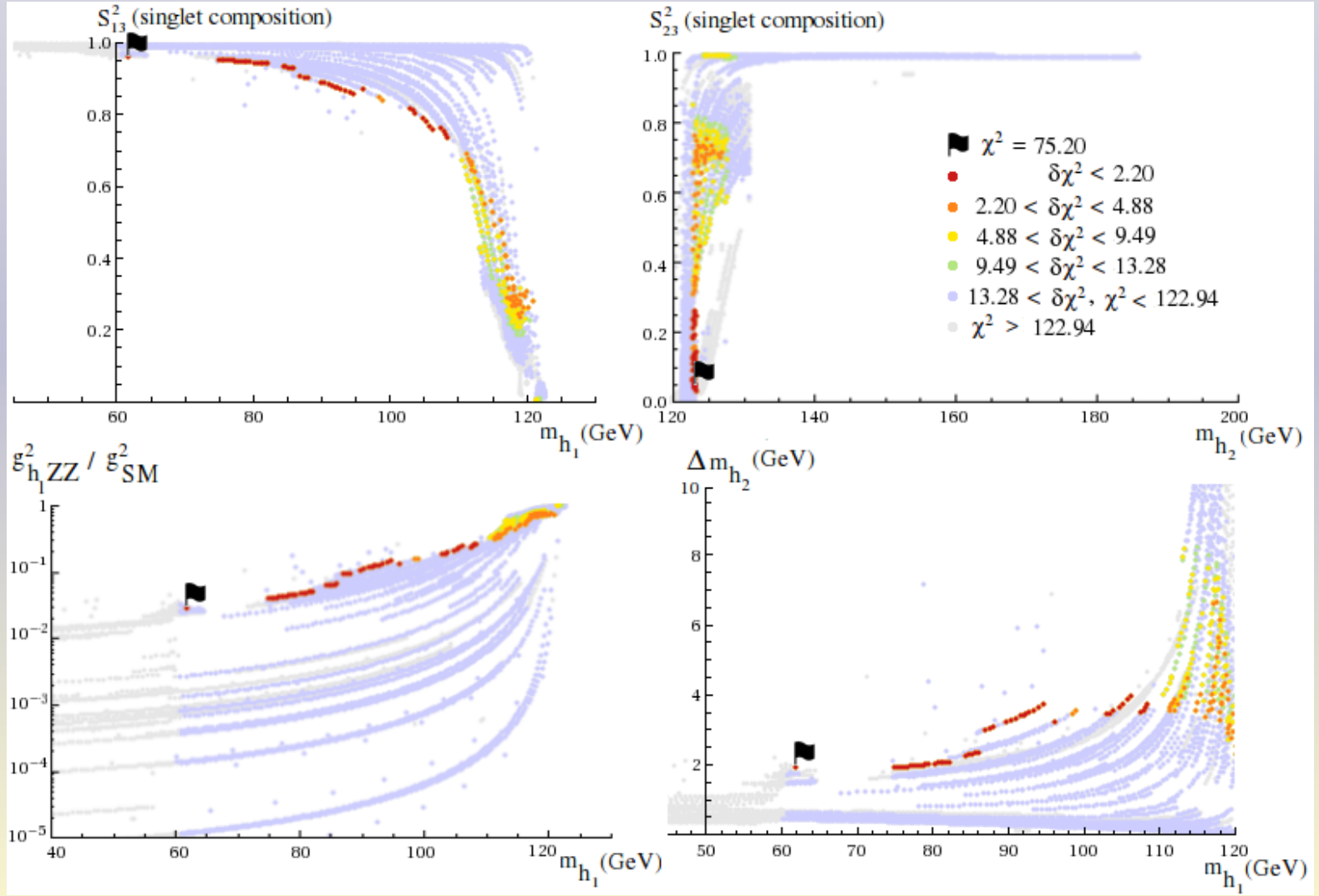
The light-singlet scenario - results 2



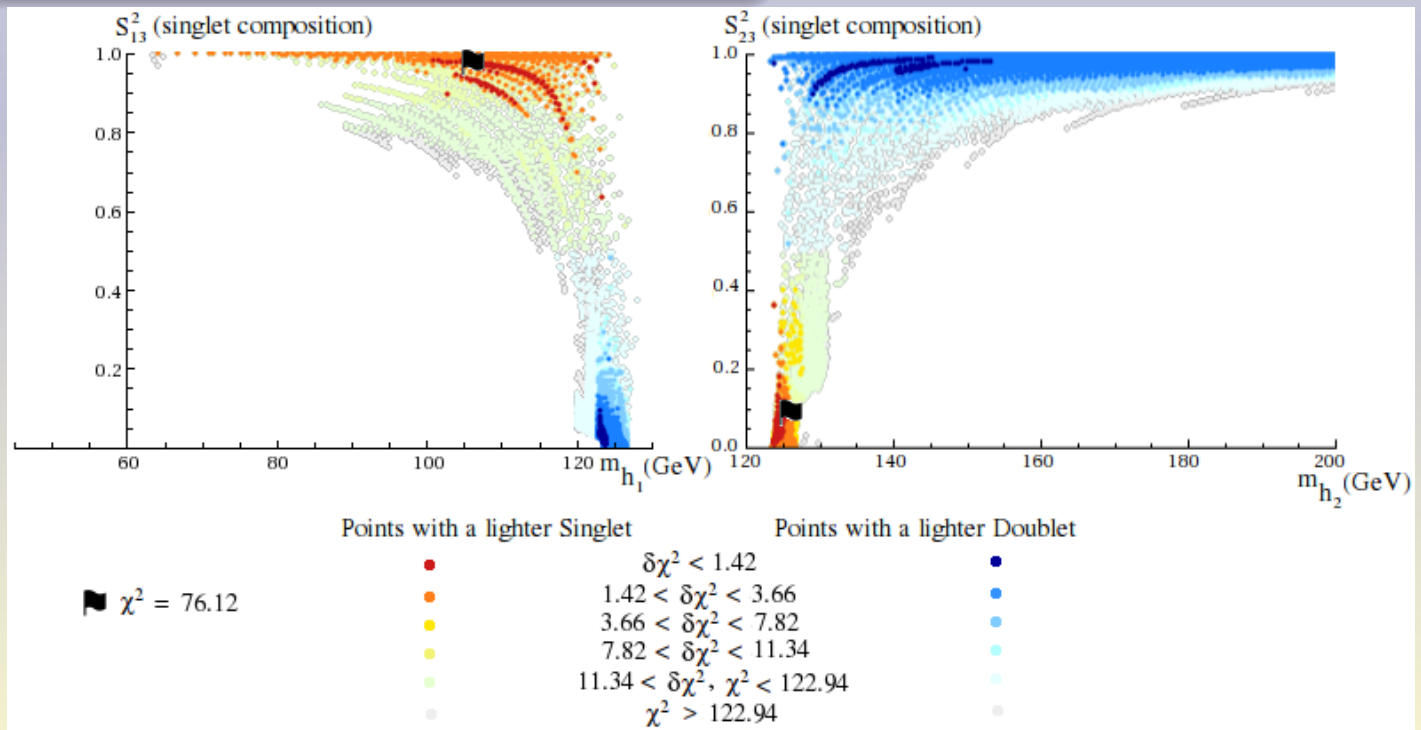
$\tan\beta = 8$, $M_A \simeq 1$ TeV, $m_{\tilde{T}} \simeq 1$ TeV, $A_t \simeq -1.5$ TeV

The low tan $\beta_{(\sim 2)}$ / large $\lambda_{(\sim 0.7)}$ region

- Additional tree-level contribution: $m^2_{h_{\sim \mathrm{SM}}} \simeq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$;
- Singlet scale $\sim O(\frac{\kappa}{\lambda}\mu)$: naturally light;
- **No need for large stop effects** ($m_{\tilde{T}} \sim 500$ GeV, $A_t \sim -100$ GeV below);

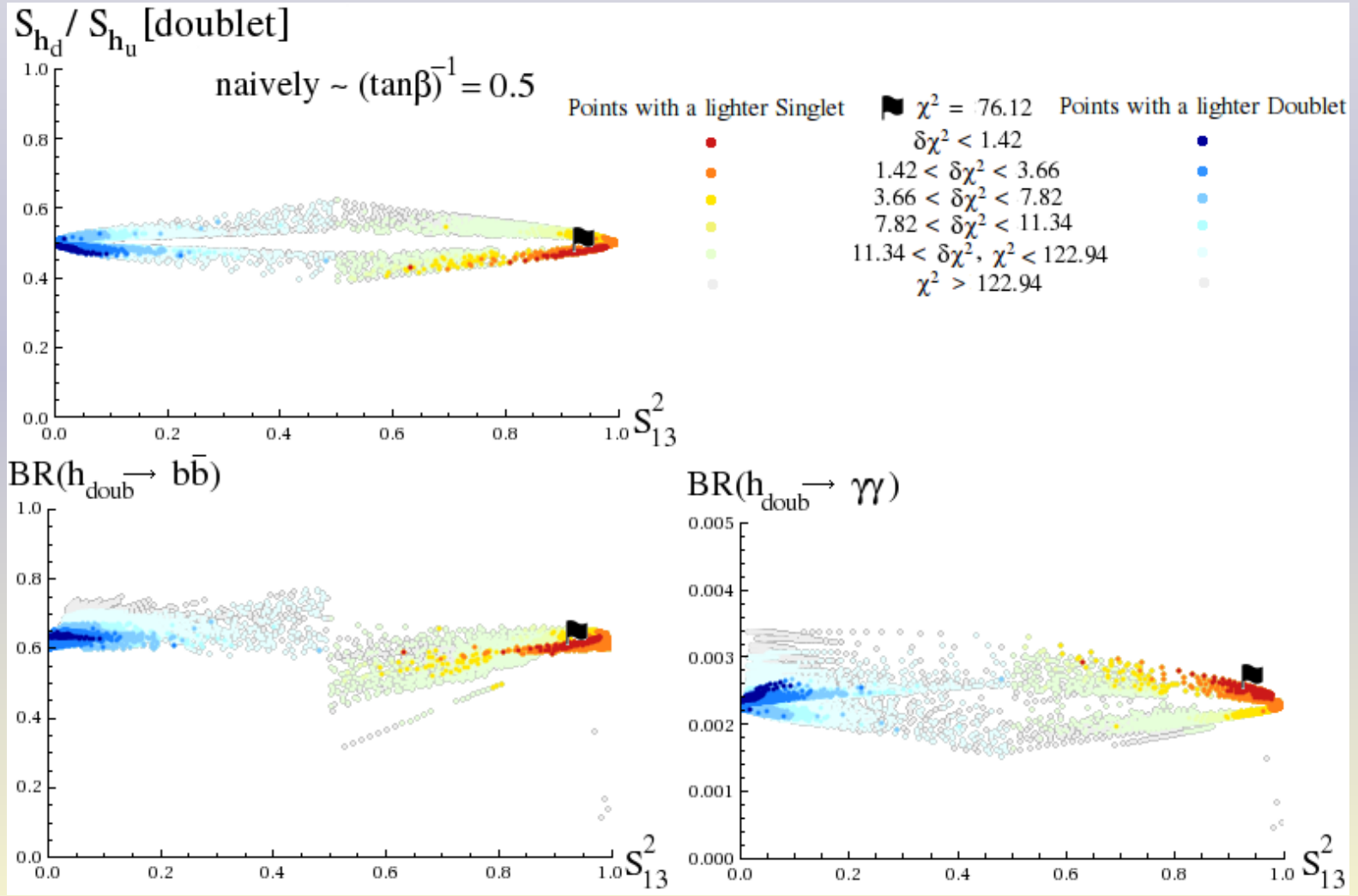
- Lightest Higgs state may be doublet or singlet or a strong admixture

m_{h_1} (GeV)	125.2 D	105.3 S	124.4 S/D
m_{h_2} (GeV)	131.7 S	124.7 D	124.8 D/S
S^2_{13}	4%	94%	63%
χ^2 (/92)	76.6	76.1	77.1



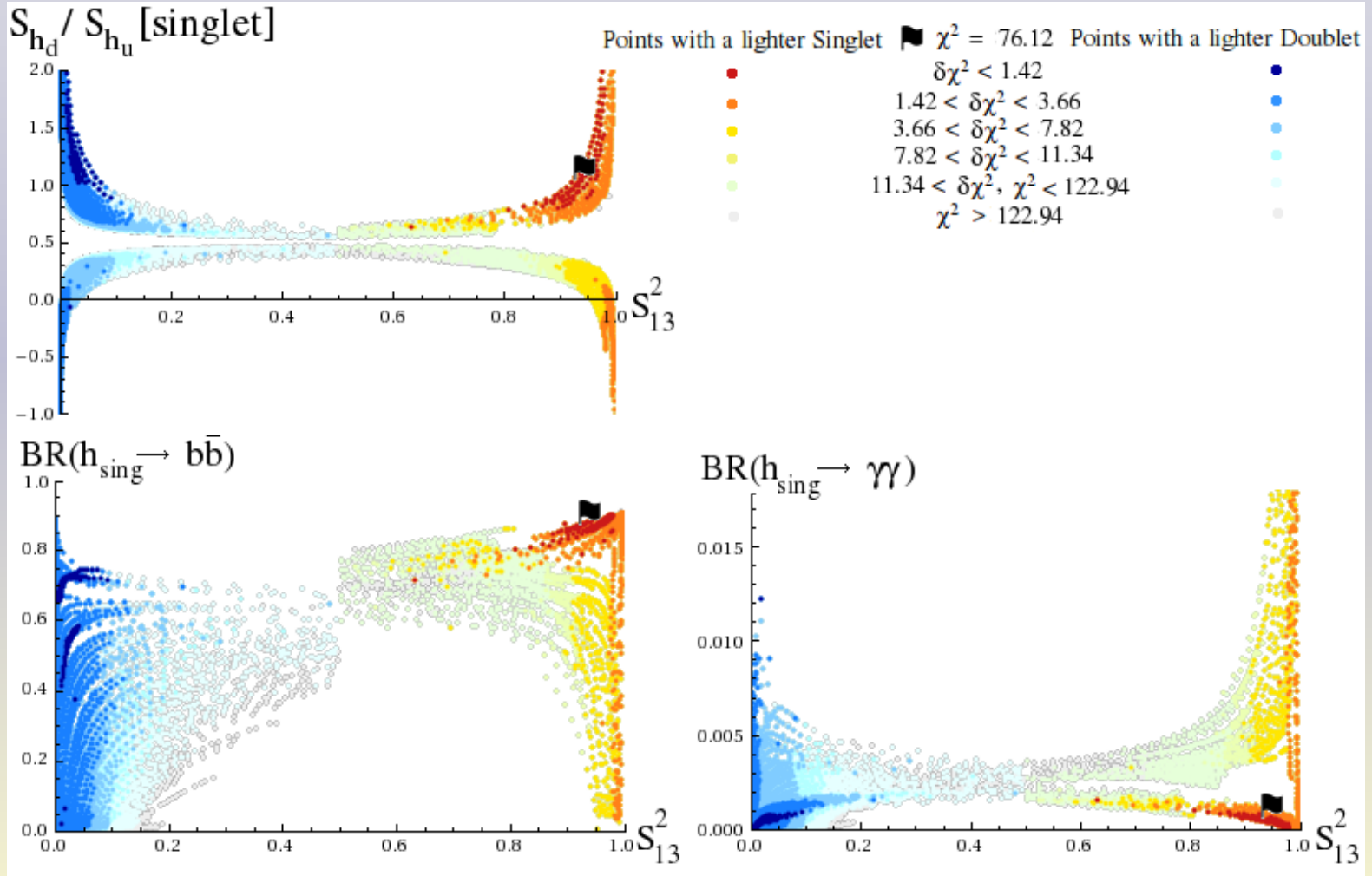
$\tan\beta = 2$, $\lambda = 0.7$, $\kappa = 0.1$, $m_{\tilde{T}} \simeq 0.5$ TeV, $A_t \simeq -0.1$ TeV

Triple-state mixing: Effect on doublet couplings ('125' GeV)



$\tan\beta = 2$, $\lambda = 0.7$, $\kappa = 0.1$, $m_{\tilde{T}} \simeq 0.5$ TeV, $A_t \simeq -0.1$ TeV

Triple-state mixing: Effect on singlet couplings

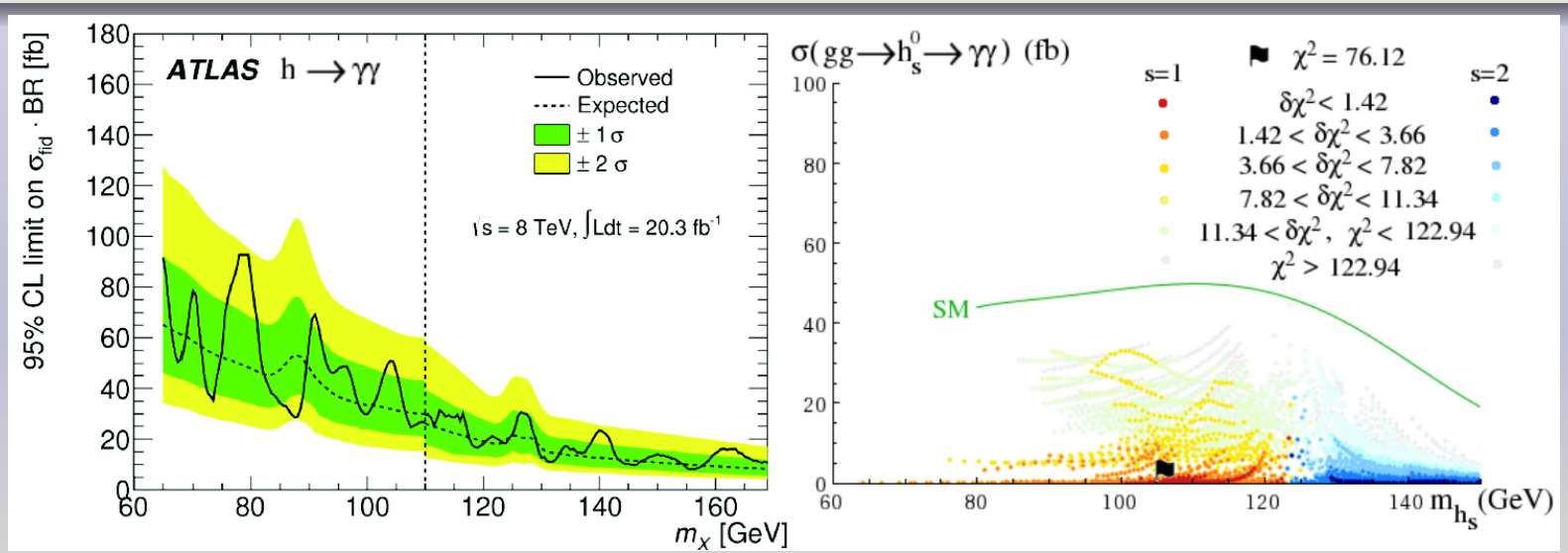


$\tan\beta = 2$, $\lambda = 0.7$, $\kappa = 0.1$, $m_{\tilde{T}} \simeq 0.5$ TeV, $A_t \simeq -0.1$ TeV

Search for a light singlet?

Mostly singlet $\Rightarrow$ reduced production cross-section $\propto 1 - S_{13}^2$

$\rightarrow$ *look for a signal at the percent level w.r.t. SM in low-mass region?*



$\tan\beta = 2$, $\lambda = 0.7$, $\kappa = 0.1$, $m_{\tilde{T}} \simeq 0.5$ TeV, $A_t \simeq -0.1$ TeV

Other search channels

- production with EW gauge bosons ($\propto 1 - S_{13}^2$);
- Higgs-pair production: $h_1^0 - h_2^0$ triple Higgs couplings may reach $O(30\%)$ of the SM Higgs couplings;
- In the decay cascade of some heavy (SUSY) state?

$\rightarrow$ *The singlet could well escape detection...*

Other (more anecdotical) scenarios...

2 CP-even Higgs unresolved at ~ 125 GeV

Singlet+light-doublet at ~ 125 GeV:

→ apparent couplings may differ from SM at the percent level

CP-odd Higgs in the 100 GeV range

Mostly singlet-state with up to ~ 10% doublet component:

→ effects in the fermionic channels / pair production from Higgs state

Unconventional Higgs decays

Light states X (CP-even/CP-odd scalars, neutralino) under threshold for $h[\sim 125\ \text{GeV}] \to 2X$;

BUT couplings $h[\sim 125\ \text{GeV}] - X - X$ have to be suppressed for consistency with the Higgs data.

Light doublet?

Light doublet sector ($m_{h_1^0, A_1^0} \sim 70$ GeV, $m_{H^\pm} \sim 105$ GeV) with vanishing couplings

$h_1^0 - WW/ZZ$: compatible with current results;

HOWEVER: under pressure from $t \to H^\pm b$ searches + B-physics; very fine-tuned.

Conclusions

- The NMSSM Higgs sector offers several unconventional possibilities **as compatible** with TeVatron/ATLAS/CMS results as a SM-like Higgs boson.
- Light-singlet scenario: natural uplift of the SM-like mass;
  offers a possible interpretation for non-SM couplings at $\sim$ 125 GeV;
  look for a low-mass singlet?
  Enhanced $\gamma\gamma$, Higgs-pair production:
  spectacular effects possible but not guaranteed / favoured by the fit;
- Low $\tan\beta$ + large λ: with or without a light singlet + no need for large radiative corrections to the Higgs mass;
- Other possibilities...

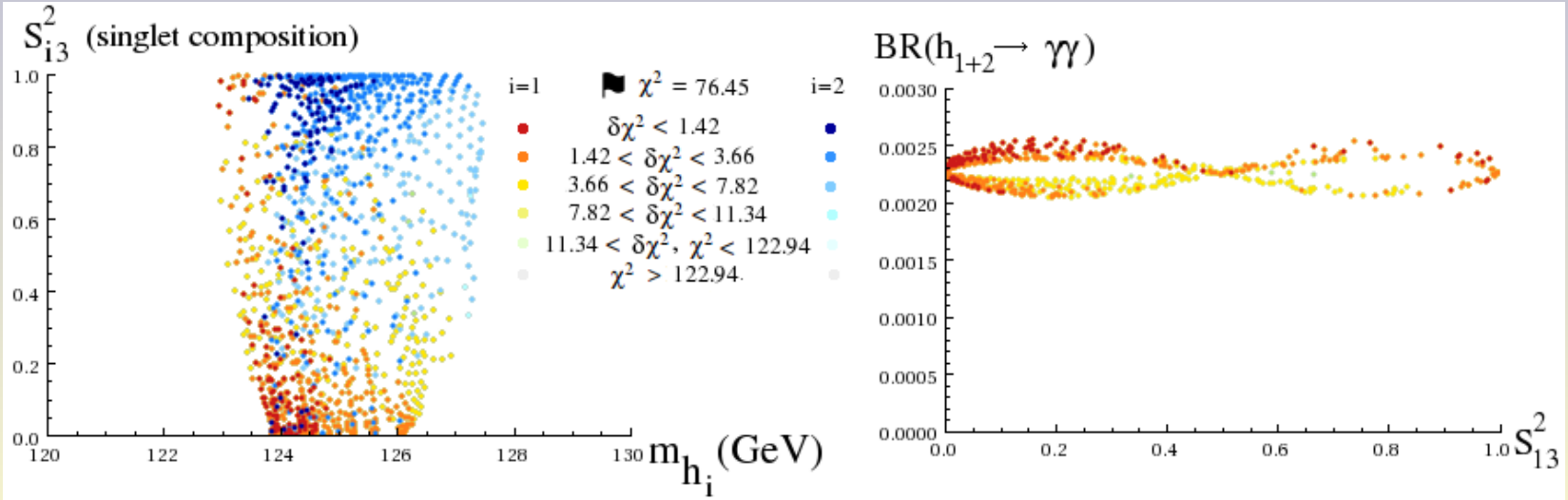
Degenerate states at 125 GeV…

Singlet+light-doublet at ~ 125 GeV

Two "halves" of a SM-like Higgs bosons

⇒ resolve two separate peaks in the data within a few 100 MeV;

+ apparent 'global' couplings may differ from SM at the percent level.



Unconventional Higgs decays...

Light state under 63 GeV

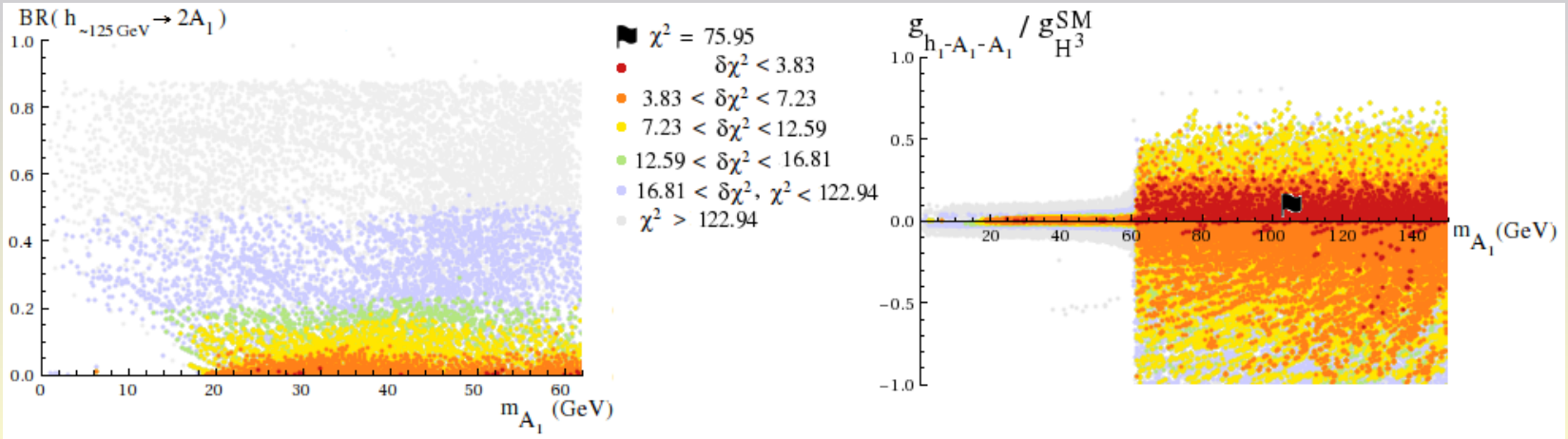
May be CP-even or CP-odd singlet or neutralino (singlino)

$\Rightarrow$ opens the decay channels $h[\sim 125\ \text{GeV}] \to 2X$;

Compatibility with existing data$\Rightarrow$ suppressed $h[\sim 125\ \text{GeV}] - X - X$ coupling

(especially for scalars)

$h[\sim 125\ \text{GeV}] \to 2X$ may yet be the only possible test of X!



Light doublet scenario…

Heavy doublet identified with signal at 125 GeV

⇒ light CP-even + CP-odd doublet states with suppressed couplings to EW gauge bosons;

fine-tuned / tension with B-physics.

Essentially excluded by the current bounds on $t \to H^+ b$.