

Prospects for charged Higgs in Supersymmetric models

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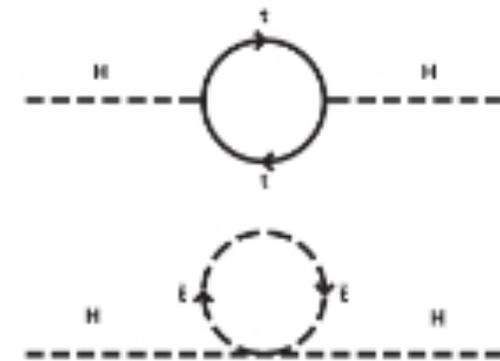
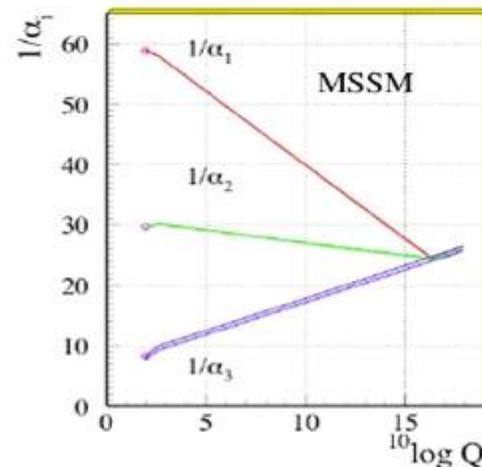
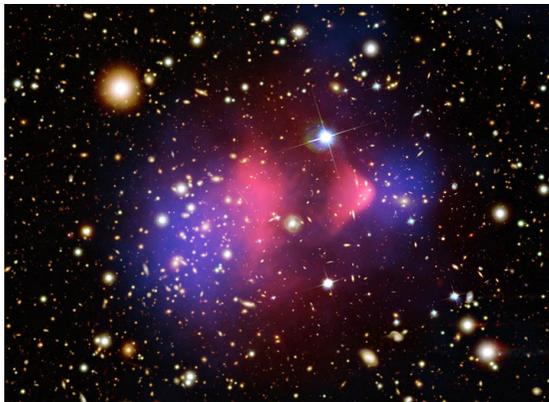
Prospects for Charged Higgs Discovery at Colliders
Uppsala, 2012-10-10



Stockholm
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Supersymmetry?

- Supersymmetry (SUSY) is a hypothetical symmetry relating fermions \leftrightarrow bosons, doubling the degrees of freedom
- No hint for SUSY particles seen at the LHC (but a light Higgs ?!)
- Still considered the most well-motivated candidate theory for physics beyond the SM



- What do LHC Higgs searches tell us about supersymmetry?

MSSM Higgs sector

- Minimal SUSY (MSSM) -> two complex Higgs Doublets: H_u, H_d
8 scalar degrees of freedom, 5 physical Higgs bosons (SM: 4, 1)

- CP conservation: h, H (CP-even), A (CP-odd), and H^\pm
 $m_H > m_h$

- At tree-level, the Higgs sector is determined by two parameters:

$$M_A, \tan \beta \quad \underline{\text{or}} \quad M_{H^\pm}, \tan \beta \qquad \tan \beta = \frac{v_u}{v_d}$$

- Other Higgs masses are *predictions*:

$$M_{h,H}^2 = \frac{1}{2} \left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta} \right]$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2 \qquad M_{h,\text{tree}}^2 \leq M_Z^2 \cos^2 2\beta \leq M_Z^2$$

MSSM Higgs sector beyond leading order

- Beyond leading order, the full SUSY spectrum enters determination of Higgs masses

$$M_h^2 = M_{h,\text{tree}}^2(M_{H^\pm}, \tan \beta) + \Delta M_h^2(M_{\text{SUSY}}, X_t, \dots)$$

- To make predictions must fix the soft-breaking parameters

Top-down

GUT-constrained models evolved down to weak scale

Bottom-up

Benchmark scenarios to study phenomenologically interesting aspects of the Higgs sector without reference to ‘higher’ model

“pMSSM”: $M_{\text{SUSY}}, M_1, M_2, M_3, A_t (A_b, A_\tau), \mu$

Benchmark scenarios

- Public codes with known two-loop corrections implemented:
FeynHiggs (OS) - SoftSusy, Suspect, Spheno, ... (DR)
Typical difference in calculated M_h (theory unc.) of a few GeV

- Leading corrections depend strongly on mixing in stop sector

$$M_h^2 \sim M_Z^2 + \frac{3m_t^4}{2\pi^2 v_u^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2} \right) \right]$$

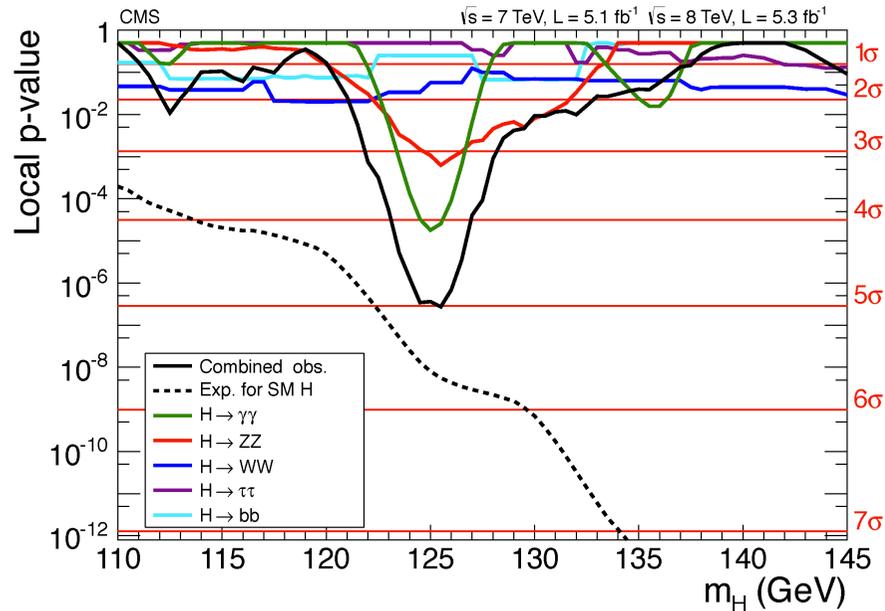
$$\begin{aligned} \text{Decoupling limit: } \quad M_{H^\pm} \gg M_Z & \quad X_t = A_t - \mu \cot \beta \\ \tan \beta \gg 1 & \quad M_S = (m_{\tilde{t}_1} + m_{\tilde{t}_2})/2 \end{aligned}$$

- Basis for M_h -max and 'no mixing' scenarios

$$\begin{aligned} X_t &= 0 & M_h &\lesssim 120 \text{ GeV} \\ X_t^{\overline{\text{DR}}} &= \sqrt{6}M_S \quad X_t^{\text{OS}} = 2M_S & M_h &\lesssim 135 \text{ GeV} \end{aligned}$$

Weak scale supersymmetry predicts a light Higgs boson!

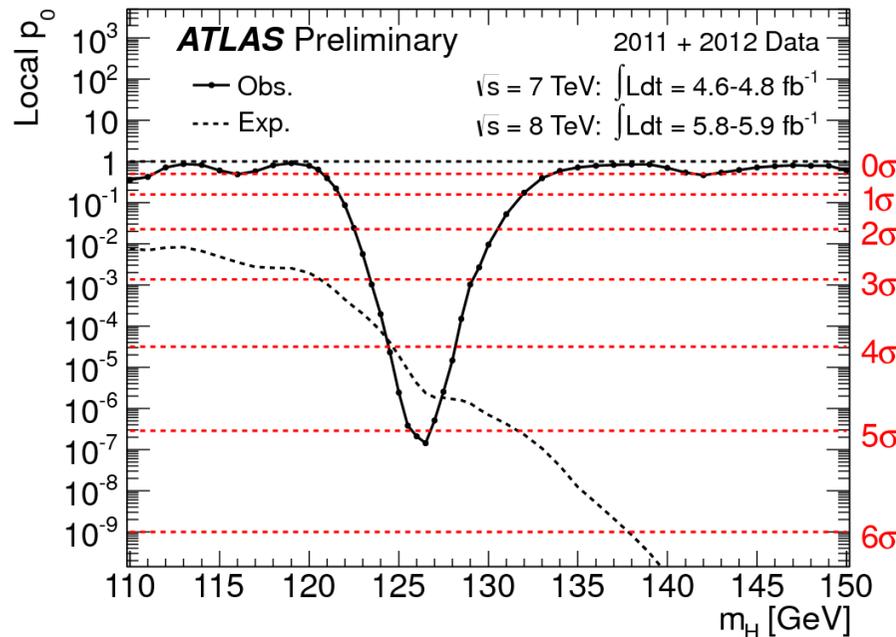
Experimental discovery of a light Higgs*!



CMS

Observed significance: 5.0σ

$$M_H = 125.3 \pm 0.4 \pm 0.5 \text{ GeV}$$



ATLAS

Observed significance: 5.9σ

$$M_H = 126.0 \pm 0.4 \pm 0.4 \text{ GeV}$$

*TBC

Charged Higgs bosons

- Two kinematic regions for charged Higgs production

- Light charged Higgs

$$M_{H^\pm} < m_t - m_b$$

$$pp \rightarrow t\bar{t} \quad t \rightarrow bH^+$$

- Heavy charged Higgs

$$M_{H^\pm} > m_t - m_b$$

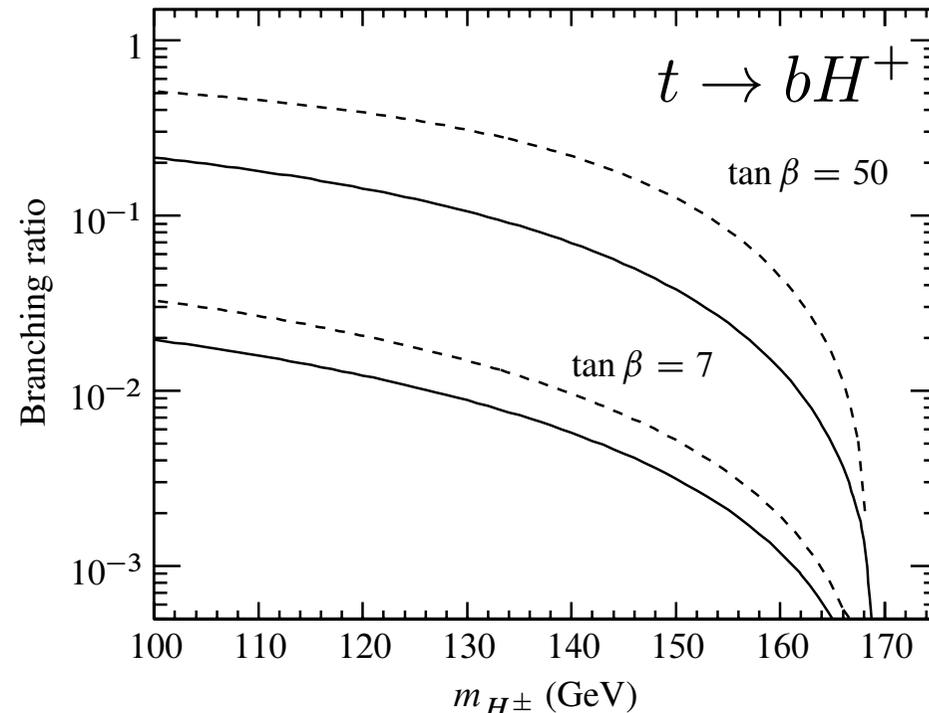
$$gg/gb \rightarrow \bar{t}bH^+$$

-> Talk by S. Heinemeyer

- Complementary production modes

$$pp \rightarrow H^\pm H^\mp \quad pp \rightarrow H^\pm W^\mp$$

-> Talk by R. Pasechnik



Charged Higgs bosons: Decay modes

- MSSM Decay mode also 'fixed' by kinematics

$$\tan \beta > 1$$

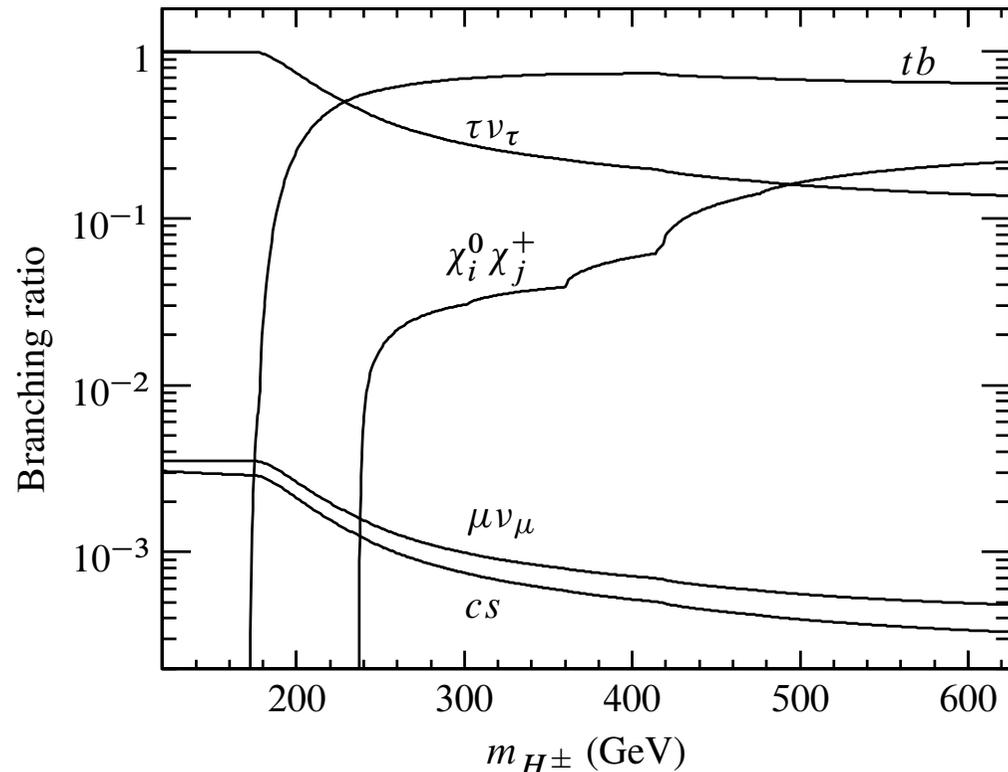
- Light charged Higgs

$$\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) \simeq 1$$

- Heavy charged Higgs

$$\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) \simeq 0.1$$

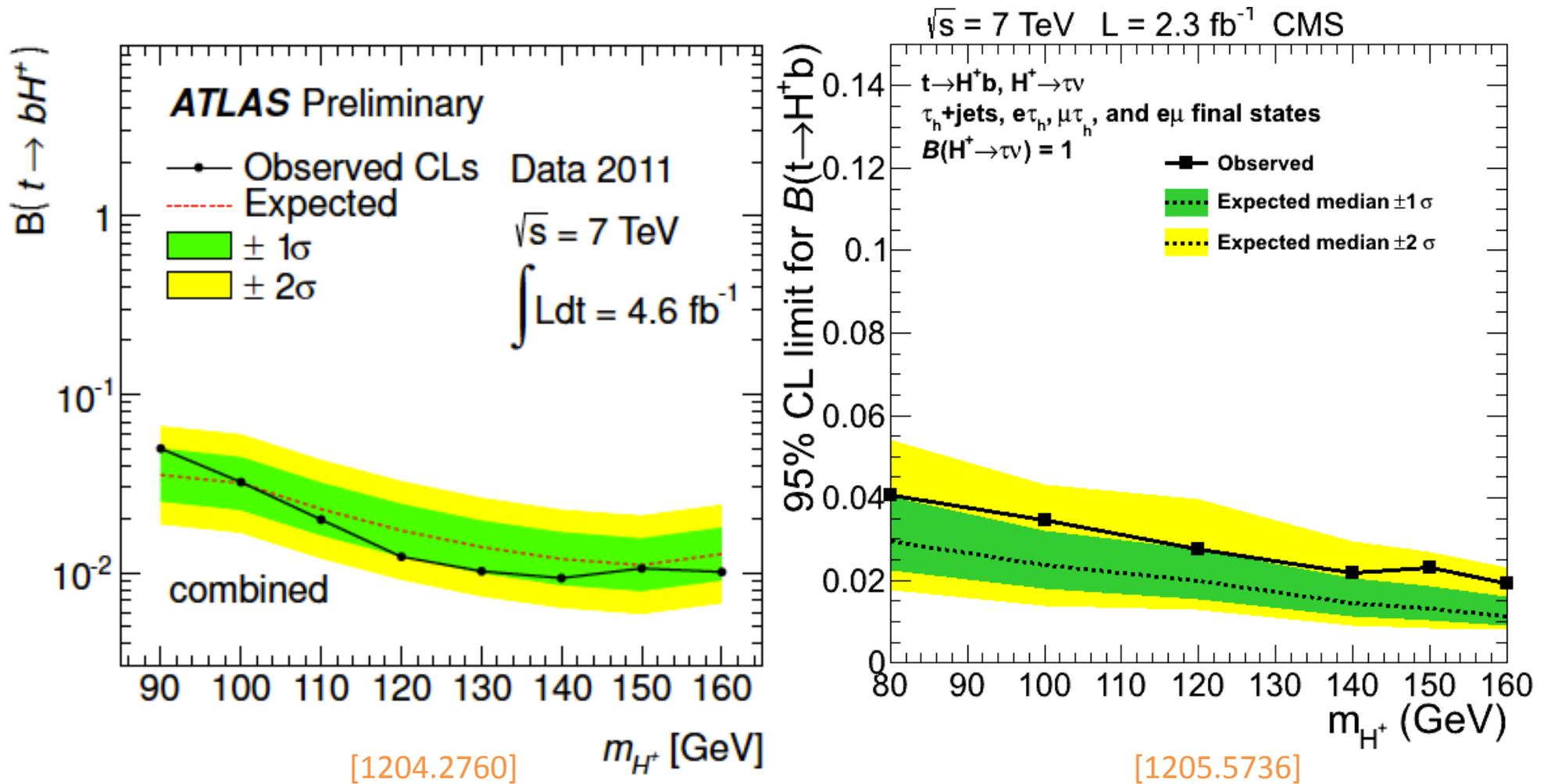
$$\text{BR}(H^+ \rightarrow t\bar{b}) \simeq 0.9$$



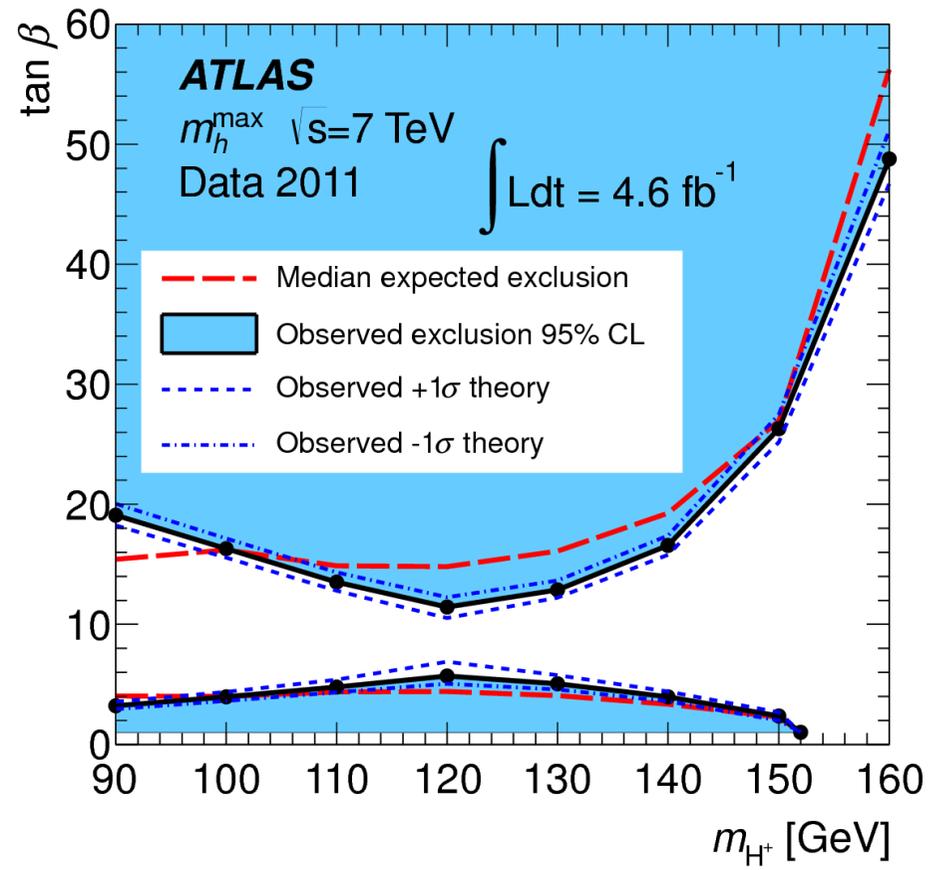
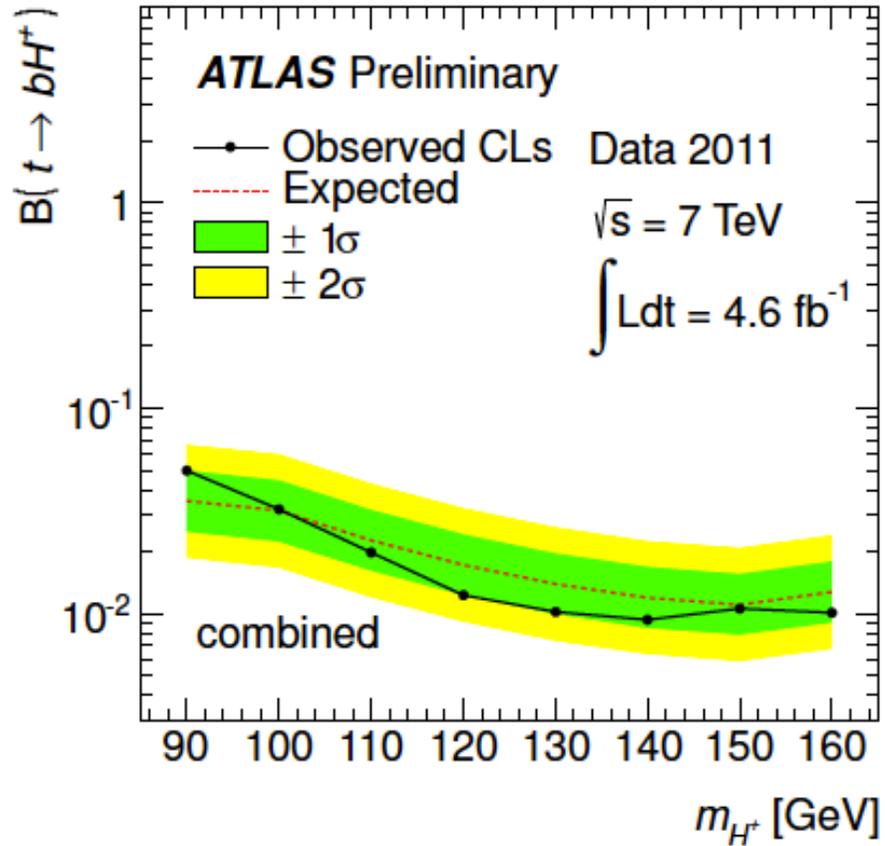
- In the NMSSM should be complemented with searches for

$$H^\pm \rightarrow A_1 W^\pm \quad H^\pm \rightarrow H_1 W^\pm \quad \text{-> Talk by T. Rössler}$$

Experimental H+ limits



From branching ratios to MSSM parameter limits



$$g_{H^+\bar{t}b} = \sqrt{2}iV_{tb} \left[P_L m_b \frac{\tan \beta}{1 + \Delta_b} + P_R m_t \cot \beta \right]$$

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{y_t^2}{16\pi^2} A_t \mu \tan \beta I(M_{\tilde{t}_1}, M_{\tilde{t}_2}, \mu)$$

Charged Higgs implications of a 126 GeV Higgs

S. Heinemeyer, OS, G. Weiglein, [1112.3026]

F. Mahmoudi, OS [work in progress]

- Assume a signal for a (CP-even) MSSM Higgs boson signal is present in LHC data

Experimental result: $M_h = 125.7 \pm 0.6 \text{ GeV}$

- Higgs spectrum up to 2-loop order calculated with **FeynHiggs**.
2 GeV theory uncertainty on M_h added linearly:

$$123 \text{ GeV} \lesssim M_h \lesssim 128 \text{ GeV}$$

- Top mass (1 σ interval) taken as parametric uncertainty

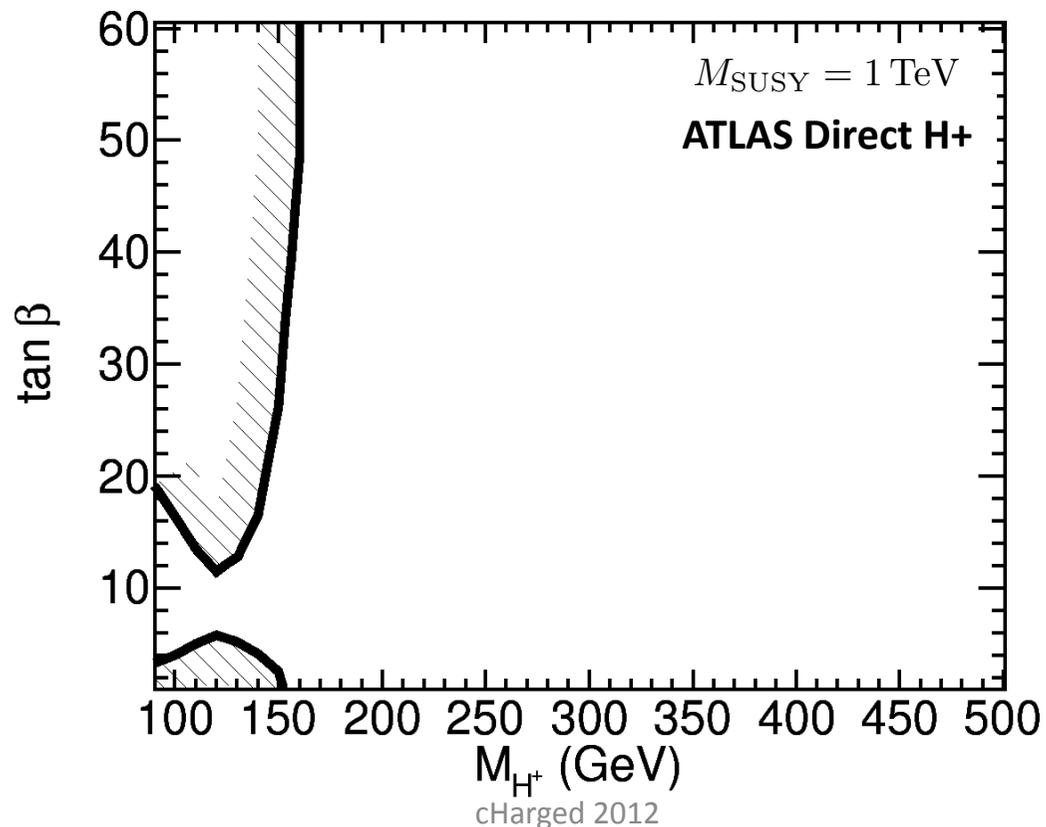
$$m_t = 173.2 \pm 0.9 \text{ GeV}$$

The Higgs mass constrains the MSSM parameters

- M_h is an increasing function of the tree-level parameters M_{H^\pm} , $\tan \beta$

$$M_h^2 = M_{h,\text{tree}}^2 (M_{H^\pm}, \tan \beta) + \Delta M_h^2 (M_{\text{SUSY}}, X_t, \dots)$$

- For a given SUSY mass scale M_{SUSY} , maximize the contributions to ΔM_h from radiative corrections $\rightarrow M_h$ -max scenario

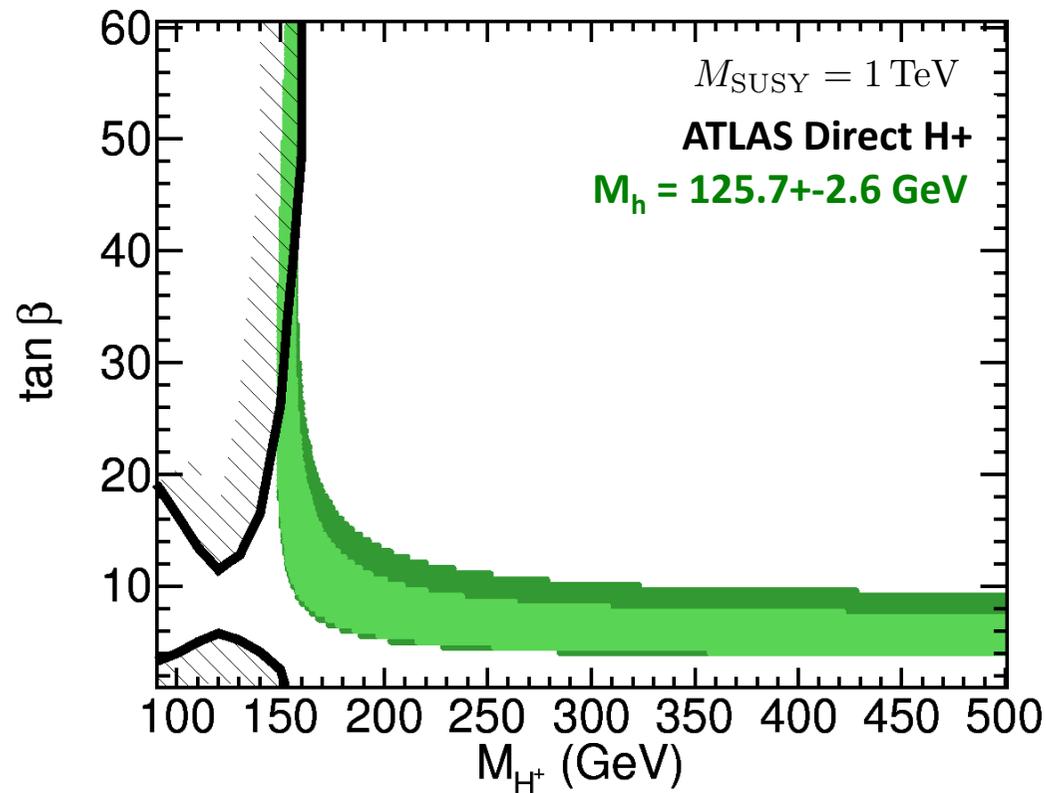


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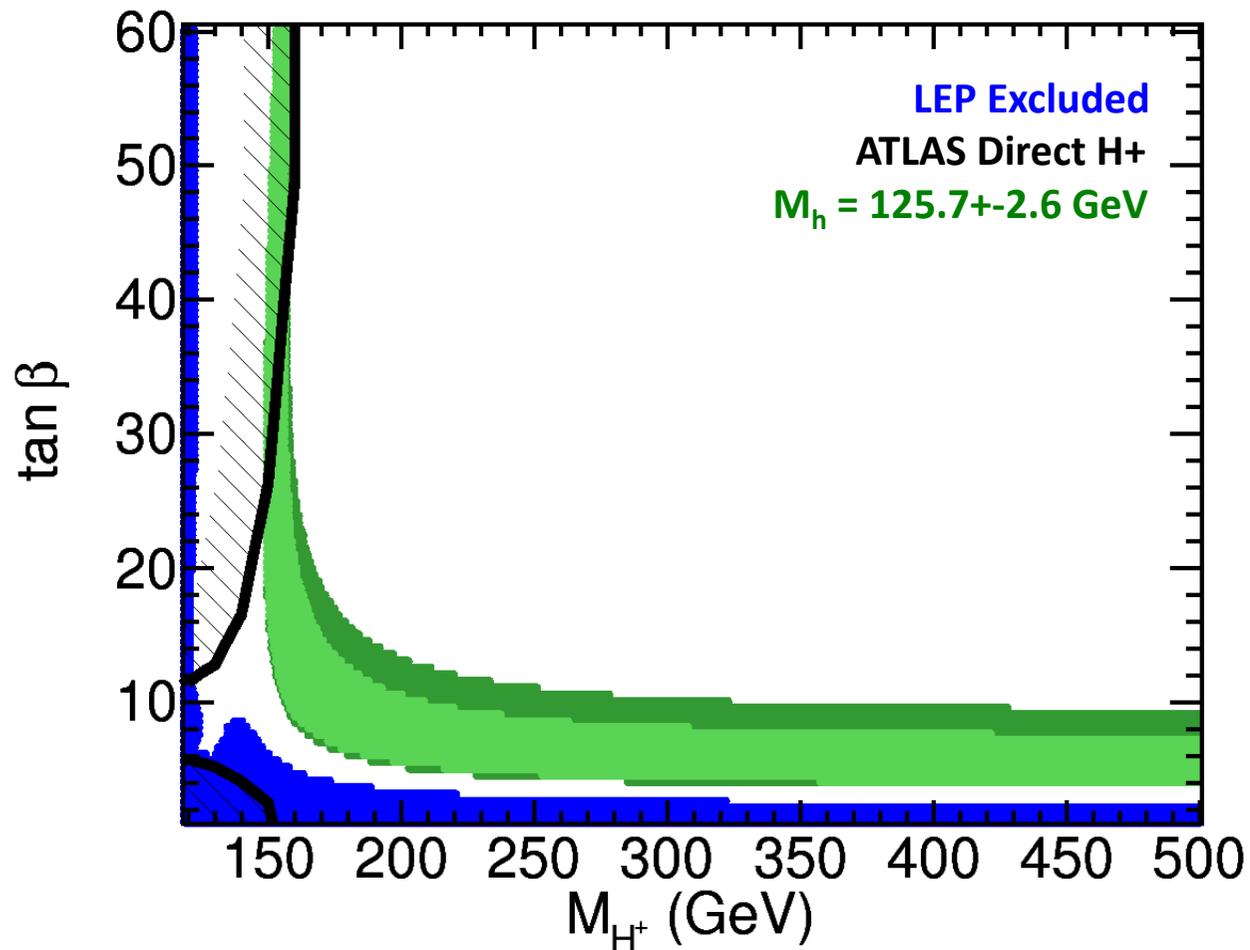
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Including exclusion limits

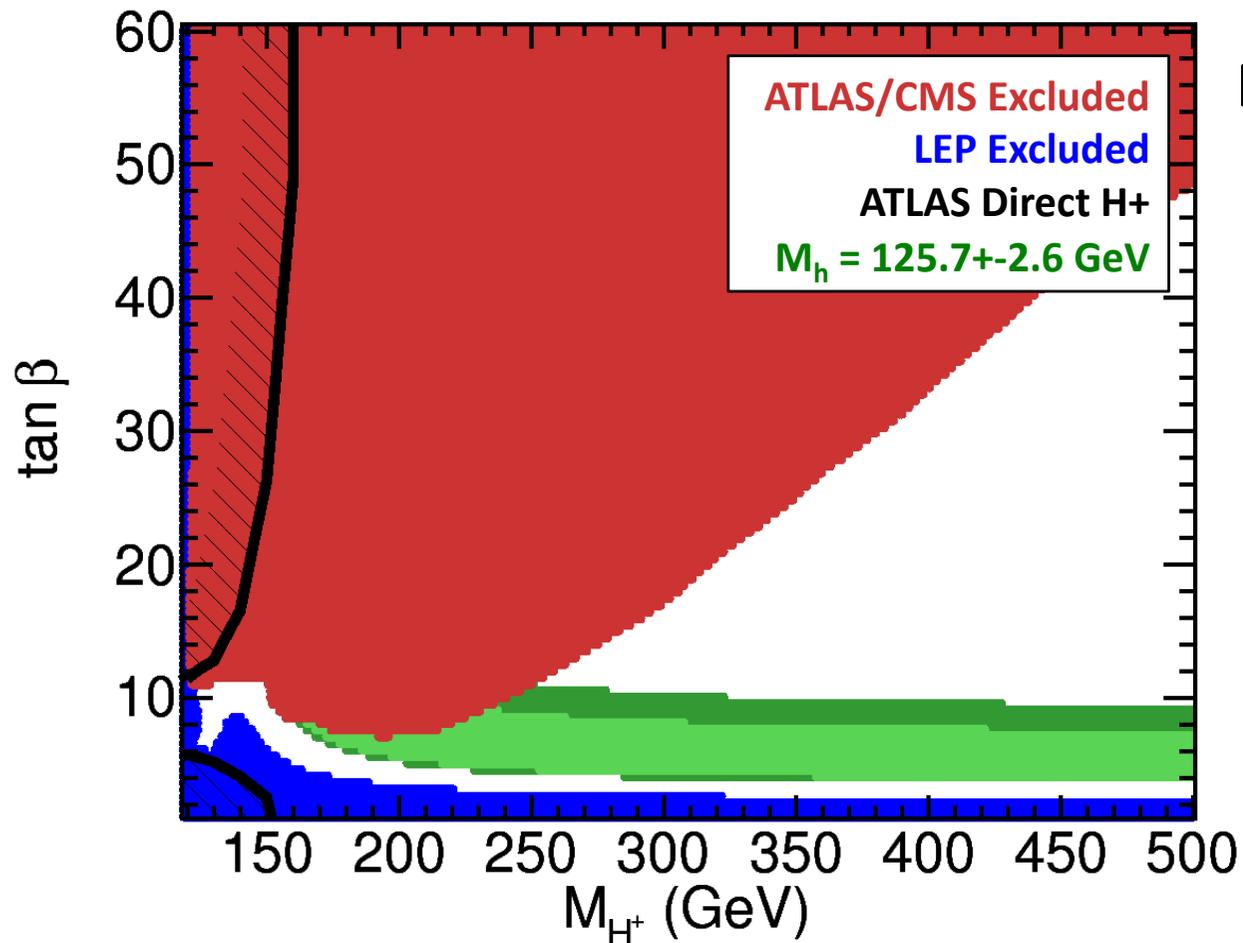
- MSSM Higgs exclusion (at 95% CL) taken into account using **HiggsBounds [3.8.0]** <http://higgsbounds.hepforge.org>

-> Talk by T. Stefaniak



Including exclusion limits

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Most sensitive LHC limit

$$H/A \rightarrow \tau\tau$$

MSSM mass relation

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

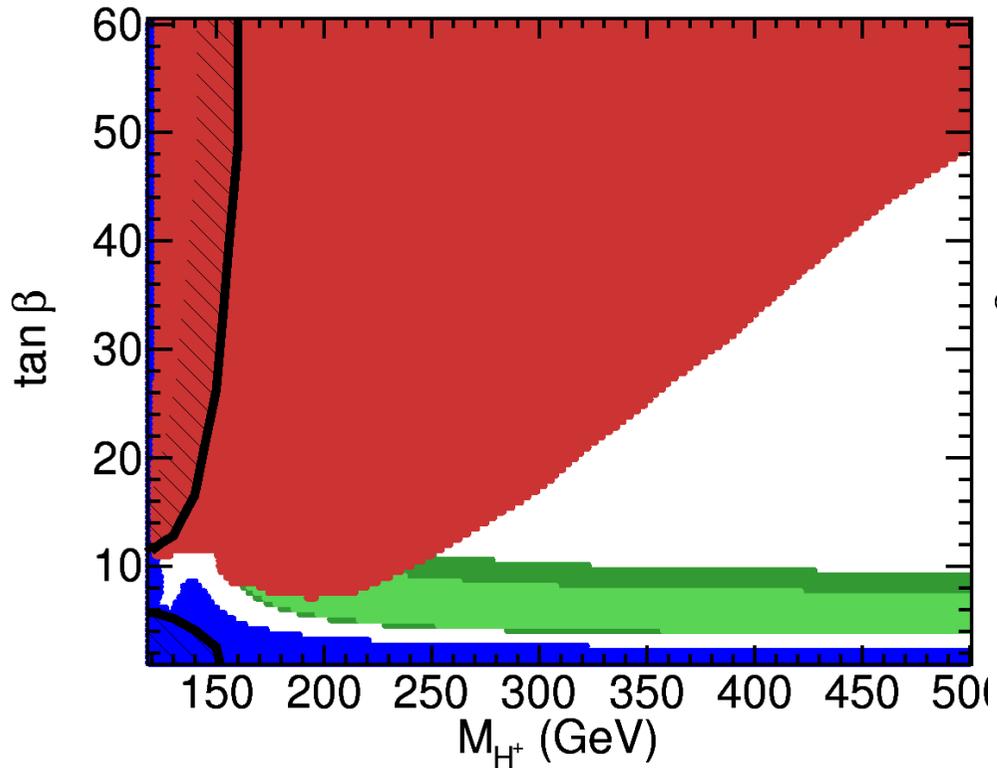
Lower MSSM limit:

$$M_{H^\pm} > 161 \text{ GeV}$$

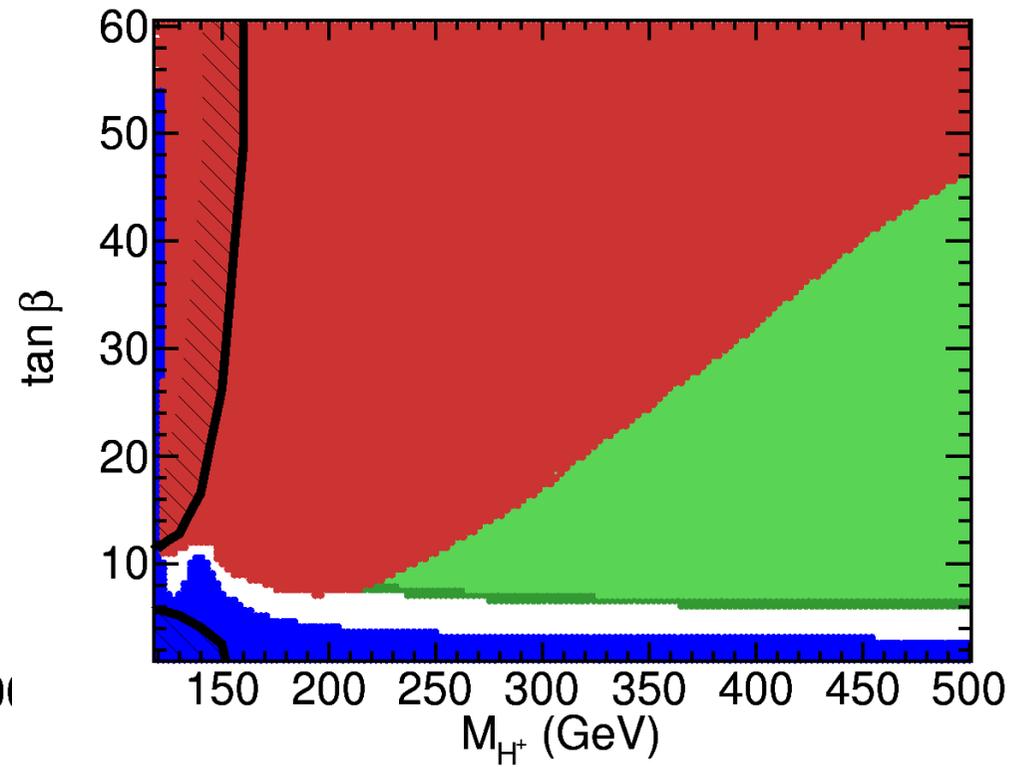
$$\tan \beta > 4$$

Upper limit on $\tan \beta$?

$$X_t = 2 \text{ TeV } (M_h\text{-max})$$



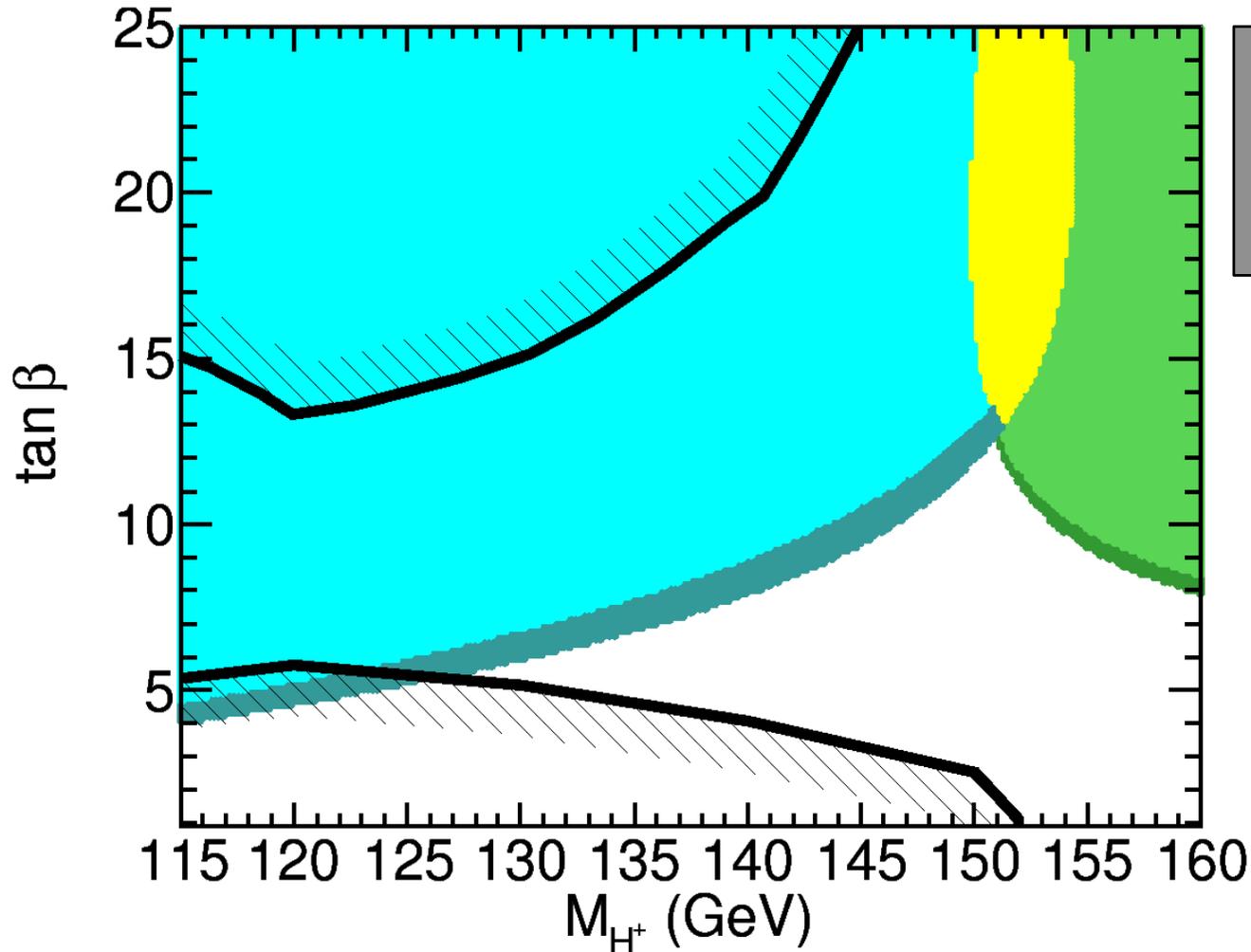
$$X_t = -2 \text{ TeV}$$



- Upper limit from M_h is scenario-dependent.
Can consider full region up to 95% exclusion as still open.

Alternative MSSM interpretation: $M_H = 126$ GeV

- Viable to have the heavier CP-even Higgs boson at 126 GeV?
-> Yes, in a limited region of parameter space!



$M_H = 125.7 \pm 2.6$ GeV
 $M_h = 125.7 \pm 2.6$ GeV
Both
ATLAS Direct H+

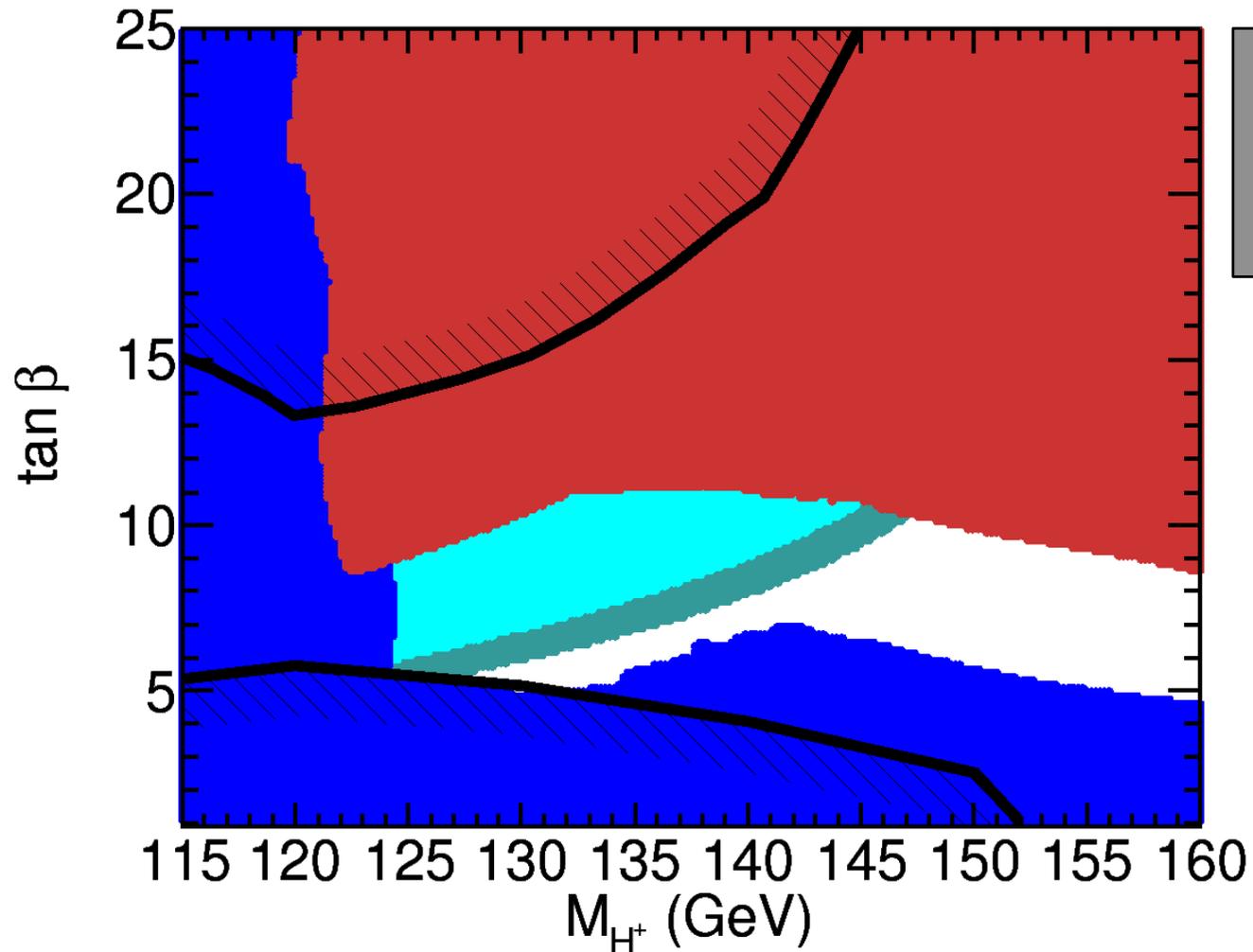
$$\mu = 1 \text{ TeV}$$

$$M_{\text{SUSY}} = 1 \text{ TeV}$$

$$X_t = 2.3 M_{\text{SUSY}}$$

Alternative MSSM interpretation: $M_H = 126$ GeV

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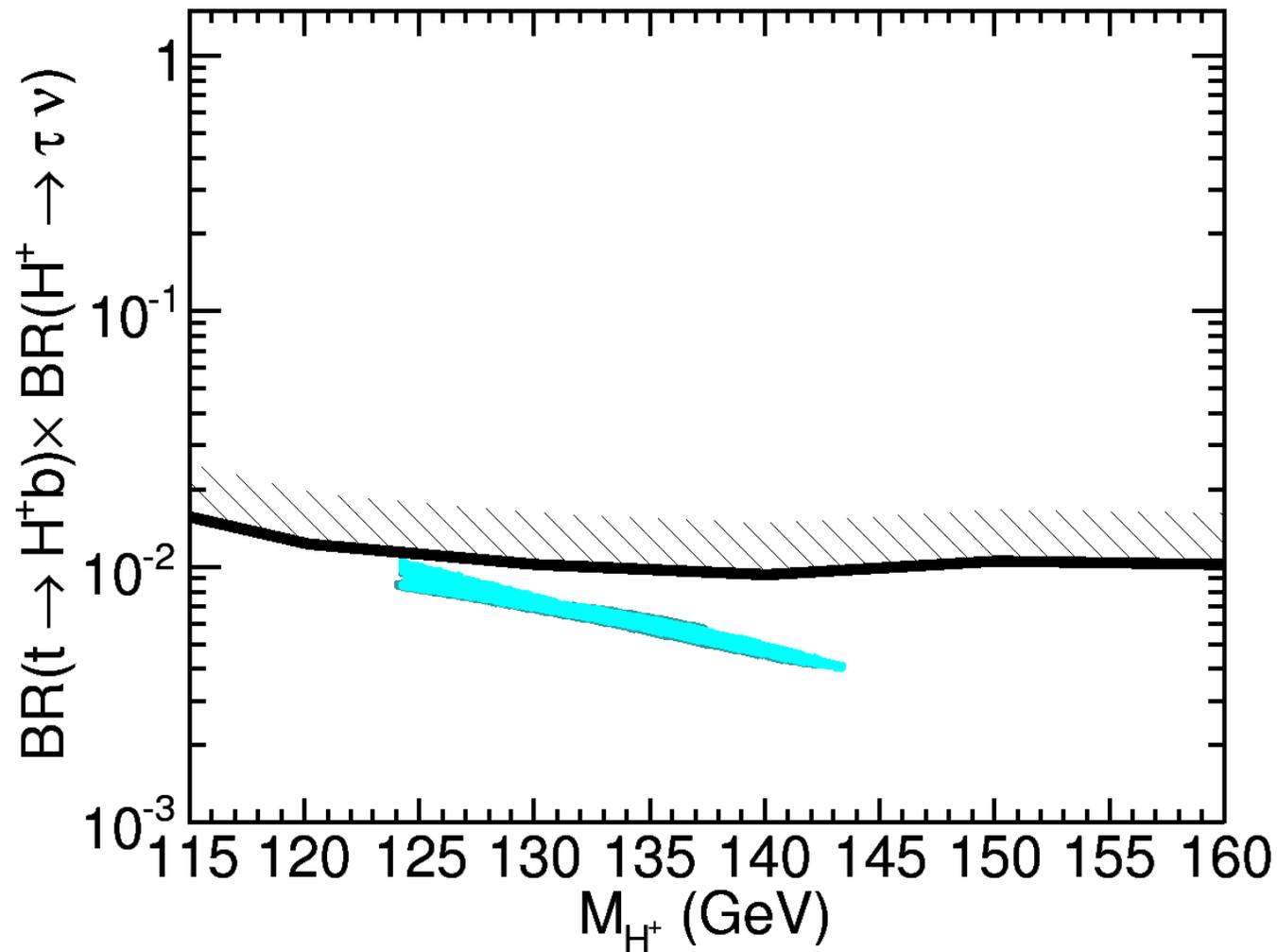
$M_H = 125.7 \pm 2.6$ GeV
ATLAS/CMS exclusion
LEP exclusion
ATLAS Direct H+

$$\mu = 1 \text{ TeV}$$

$$M_{\text{SUSY}} = 1 \text{ TeV}$$

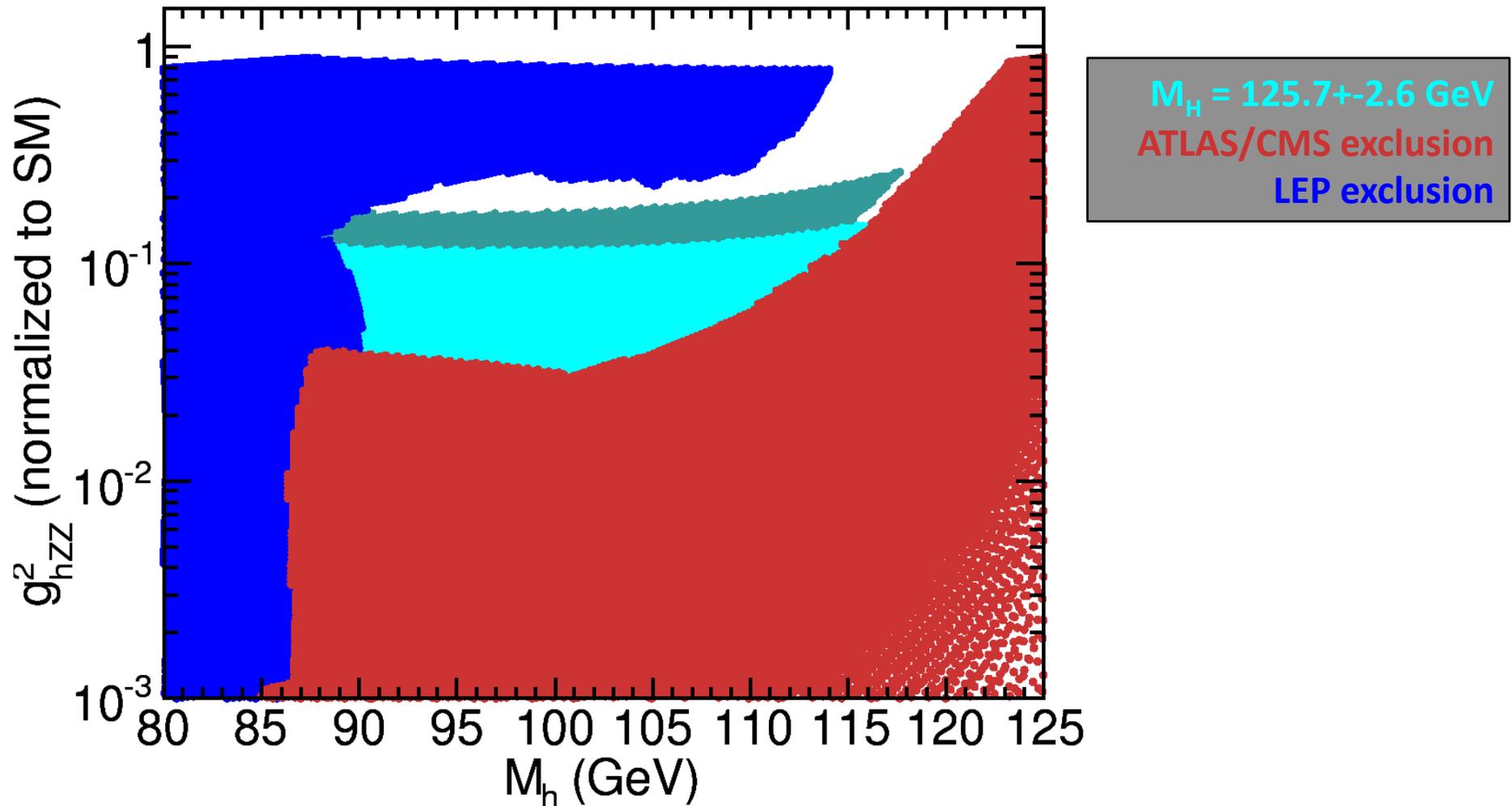
$$X_t = 2.3 M_{\text{SUSY}}$$

Charged Higgs in top decays



- Should be probed very soon in both charged Higgs and neutral $H/A \rightarrow \tau\tau$ searches. Complementary approaches!

Lightest Higgs below the LEP limit



- Could have $M_H = 126$ GeV and $M_h = 98$ GeV (small LEP excess)

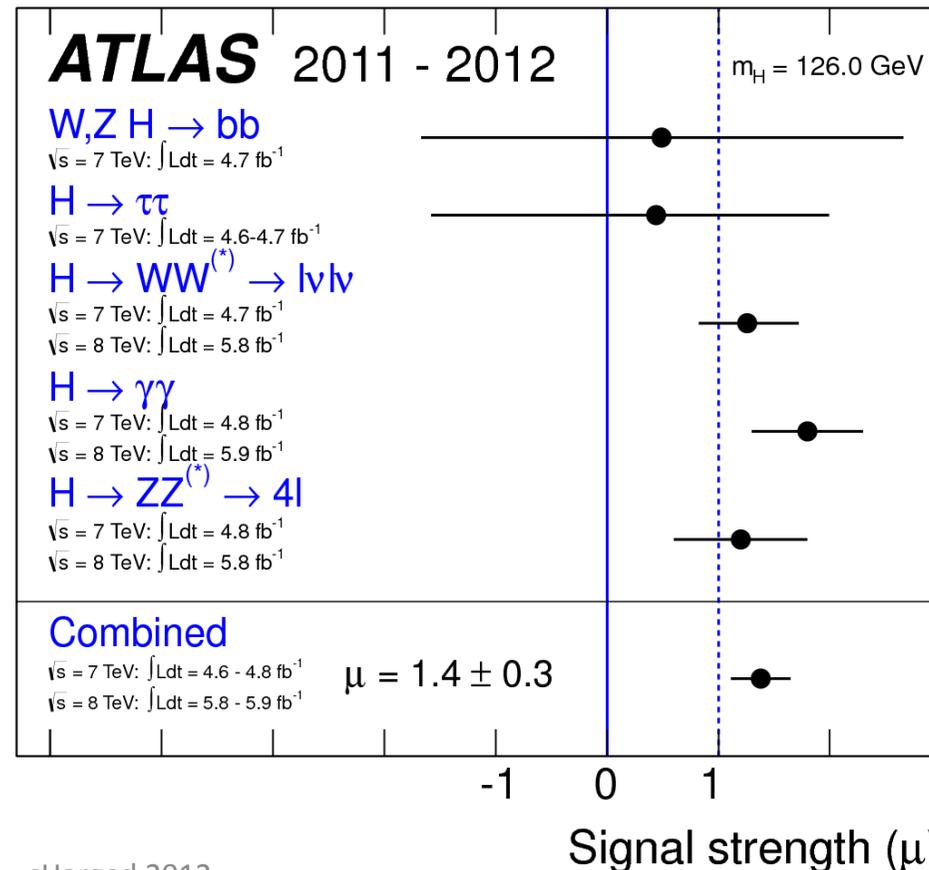
Global MSSM Implications of 126 GeV Higgs: Rates

P. Bechtle, S. Heinemyer, OS, T. Stefaniak, G. Weiglein, L. Zeune, [12XX.XXXX]

- Combined measurements compatible with the SM...
 - + Higgs mass in the range favored by EW fit
 - + Overall rate close to expected for SM Higgs
 - + gg/VBF production modes present
 - + H \rightarrow VV decays look SM

... still one can ask:

- Is H \rightarrow $\gamma\gamma$ enhanced?
- Does H \rightarrow $\tau\tau$ exist?
- Does H \rightarrow bb exist?
What about the Tevatron?



Statistical procedure

- Standard χ^2 measure

$$\chi^2 = \sum_{i=1}^{N_{\text{obs}}} \frac{(R_i - \hat{R}_i)^2}{\sigma_i^2} + \frac{(M_h - M_h^{\text{ref}})^2}{(\Delta M_h)^2}$$

$$M_h^{\text{ref}} = 125.7 \text{ GeV}$$

$$\Delta M_h = 1 \text{ GeV}$$

$$N_{\text{obs}} = N_{\text{ATLAS}} + N_{\text{CMS}} + N_{\text{other}} \quad (\text{SM } \forall i : R_i = 1)$$

Correlations neglected (since they are not available)

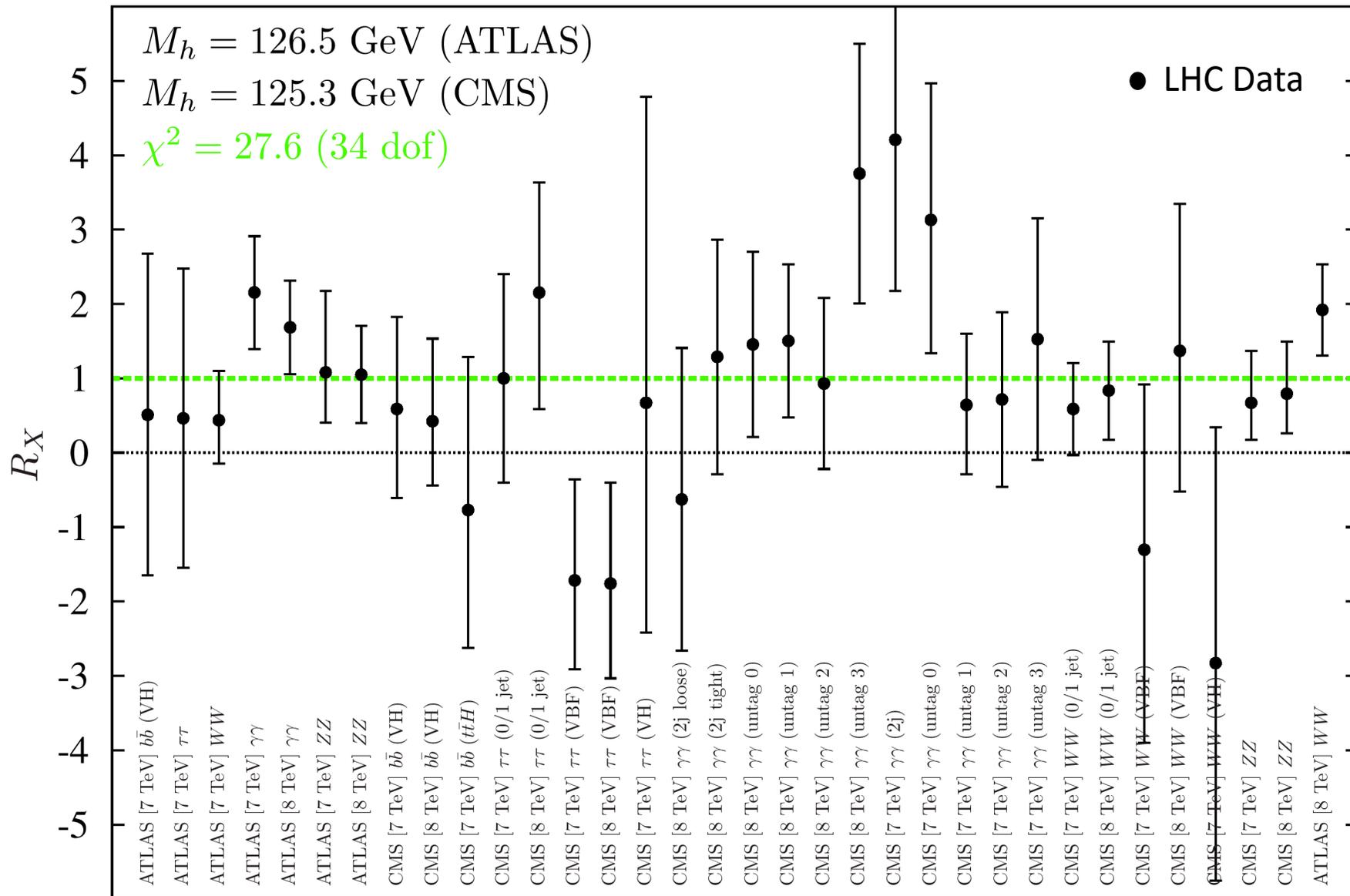
- Predictions take into account channel efficiencies as weights (w_k)...

$$R_{\gamma\gamma} = \frac{\sum_k w_k \sigma_k \text{BR}(h \rightarrow \gamma\gamma)}{\sum_k w_k \sigma_k^{\text{SM}} \text{BR}(h \rightarrow \gamma\gamma)^{\text{SM}}}$$

... where available ($\gamma\gamma$). Other final states: “naïve” prediction.

- Flavour (BPO) and g-2 taken into account using SuperIso

LHC data set



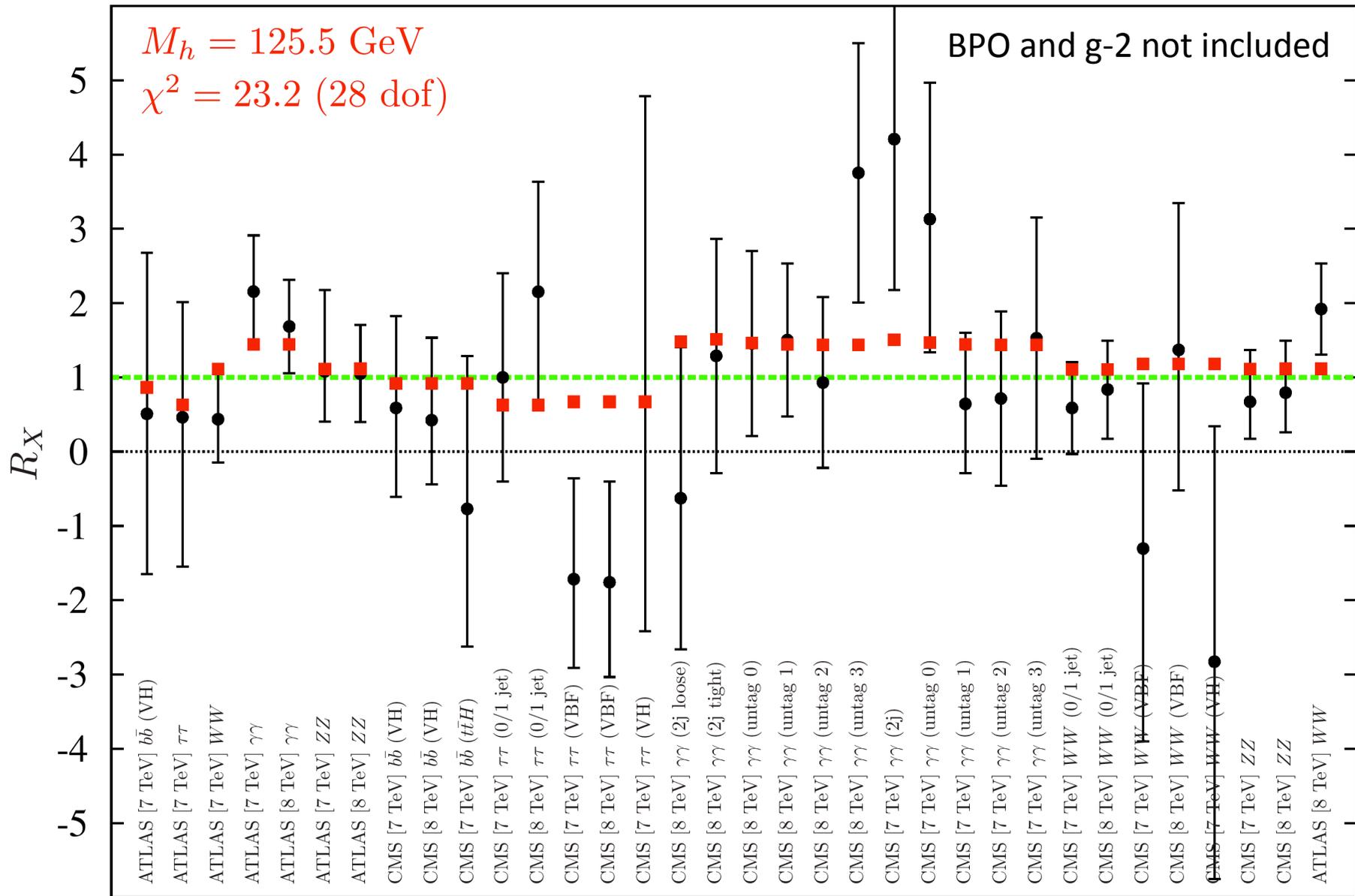
MSSM Results

Light Higgs case

$$M_h \simeq 126 \text{ GeV}$$

Best fit for LHC rates

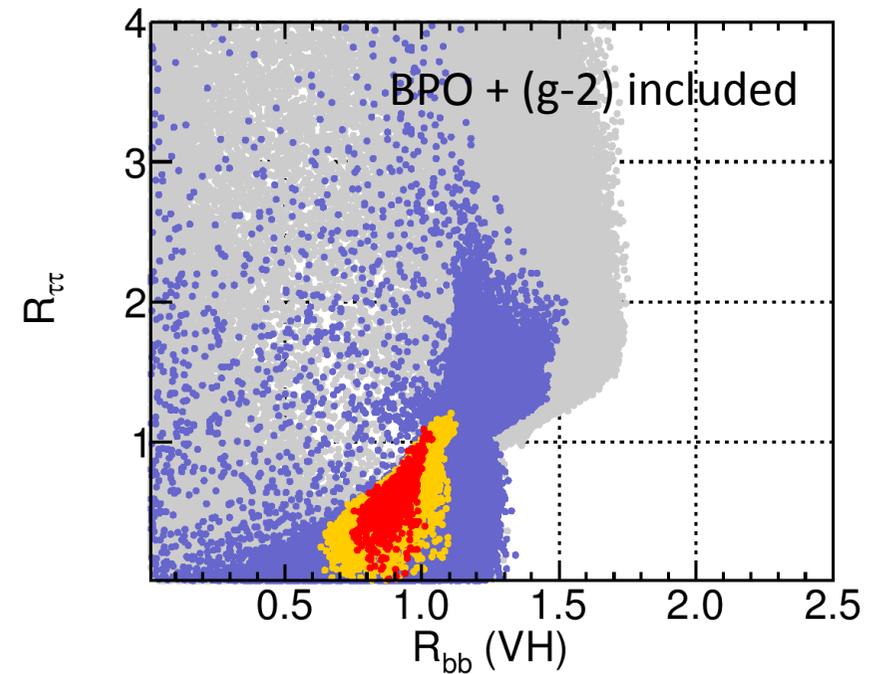
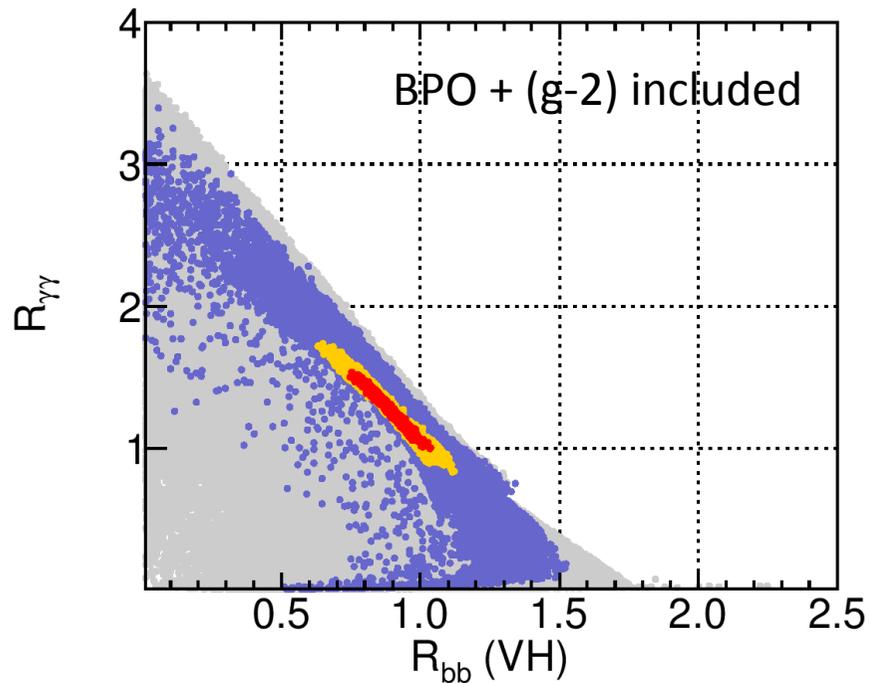
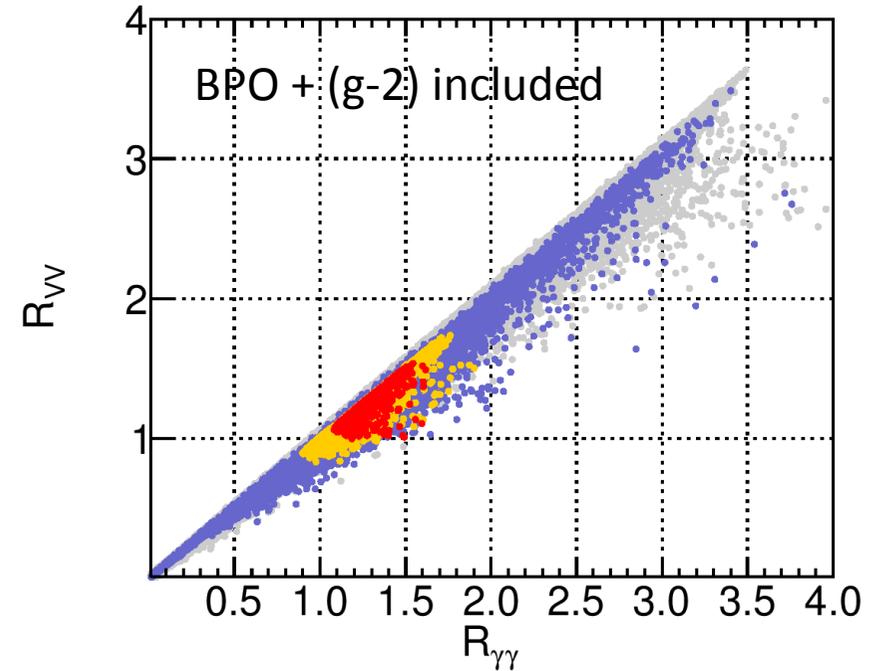
- LHC Data
- MSSM best fit



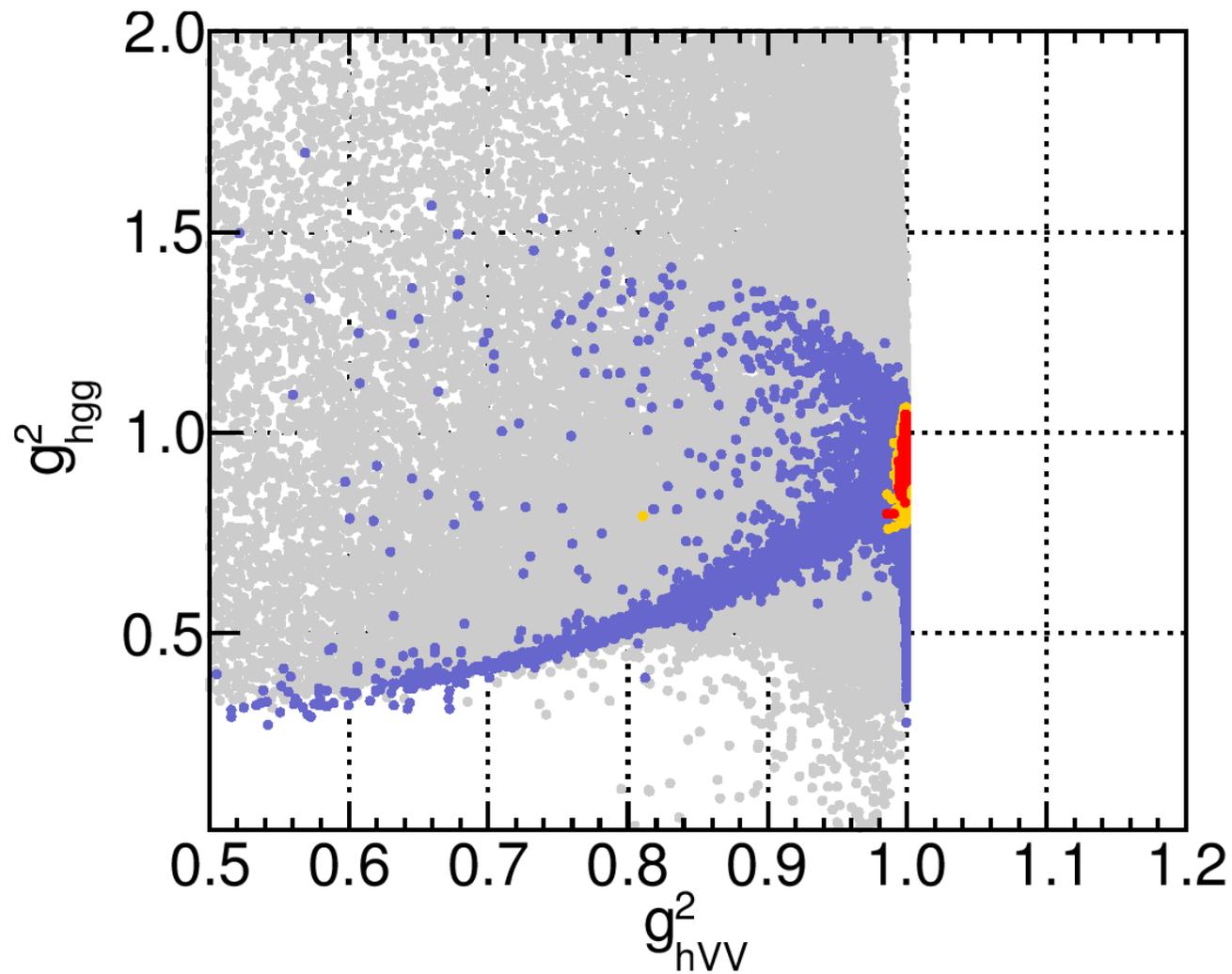
Rate modifiers

- All points: $121 < M_h < 129$ GeV
- Allowed by HiggsBounds
- $\Delta\chi^2 < 2.30$
- $\Delta\chi^2 < 5.99$

$$\Delta\chi^2 = \chi^2 - \chi_{\min}^2$$



Reduced couplings for Higgs production



- Production rates are close to SM -> Mainly decay rates modified

Higgs mixing to suppress bb , $\tau\tau$, enhance $\gamma\gamma$

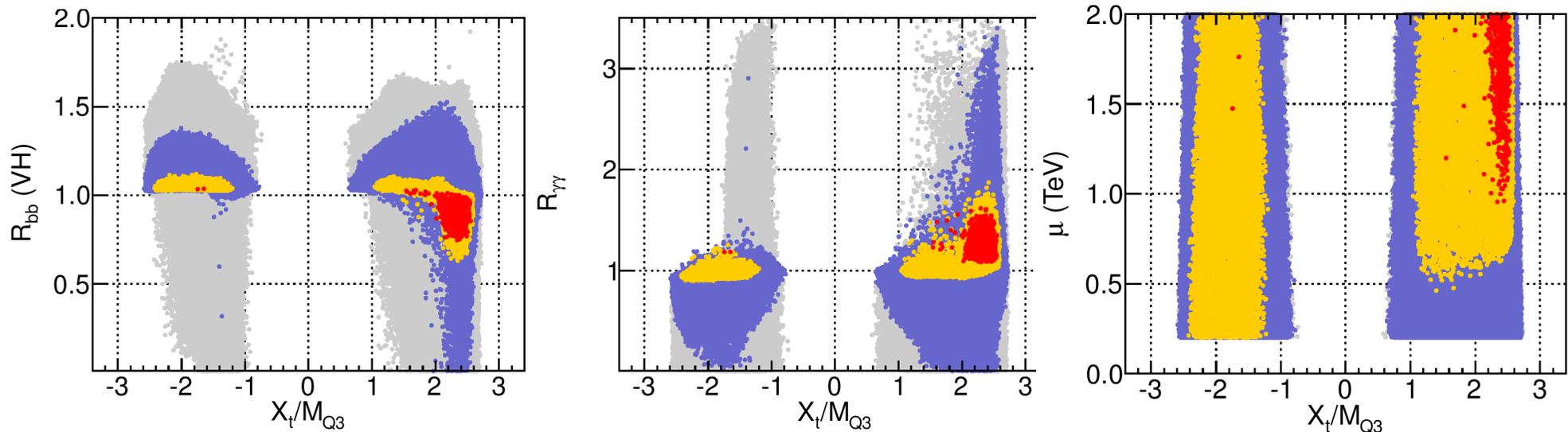
- Reduced coupling to down-type fermions, “small α_{eff} ”

$$\frac{g_{hb\bar{b}}}{g_{H_{\text{SM}}b\bar{b}}} = \frac{g_{h\tau\tau}}{g_{H_{\text{SM}}\tau\tau}} = -\frac{\sin\alpha}{\cos\beta} \rightarrow -\frac{\sin\alpha_{\text{eff}}}{\cos\beta}$$

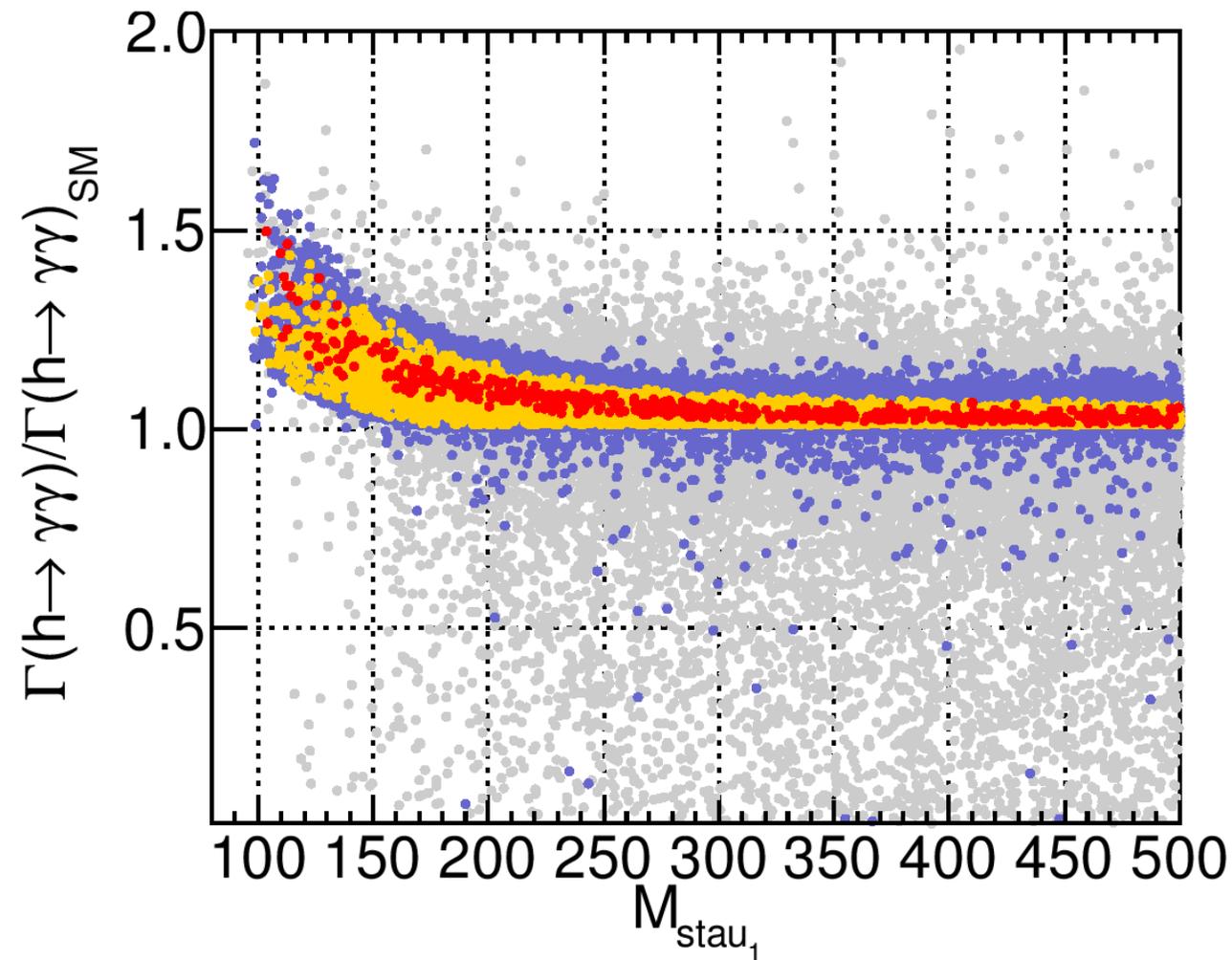
α tree-level mixing angle for CP-even Higgses

α_{eff} approximates coupling behavior beyond LO

- Largest suppression of fermion modes prefers large X_t , μ



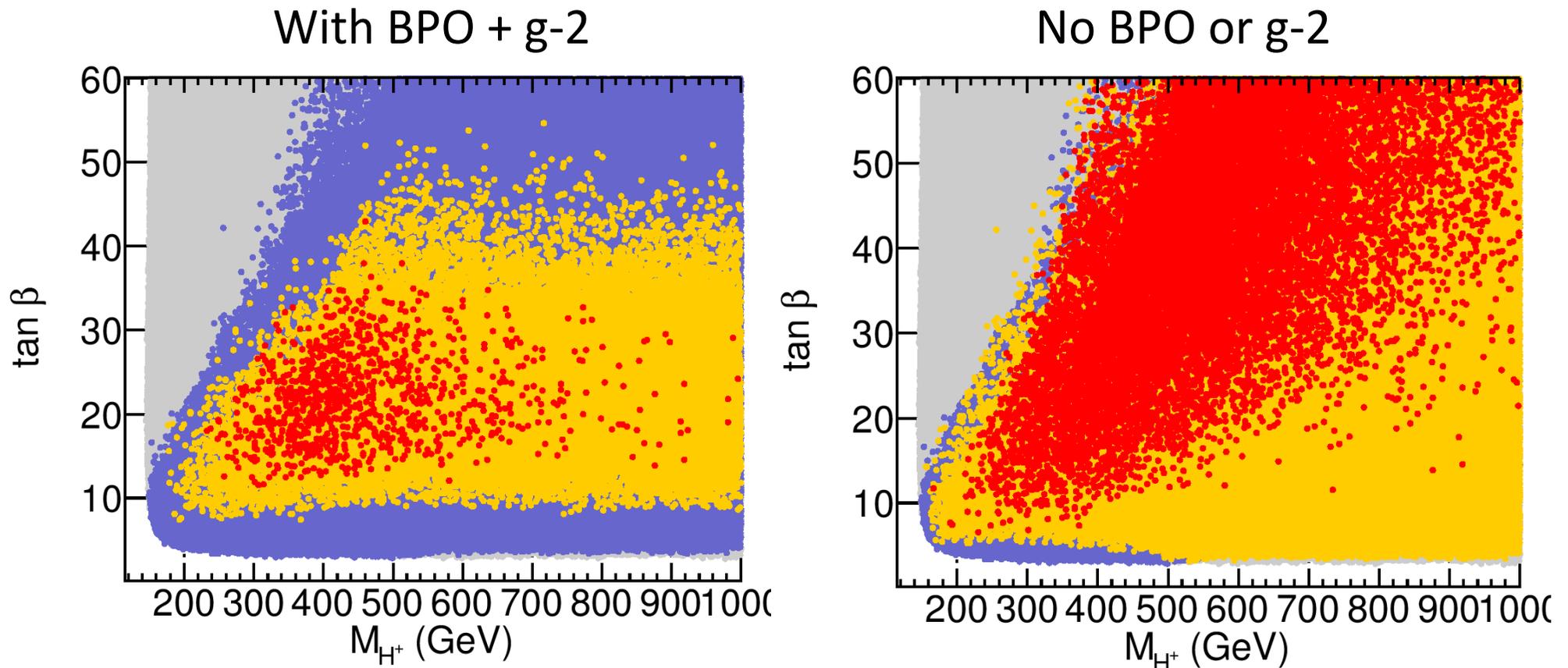
Direct $\gamma\gamma$ enhancement: Light staus



- Up to 50% enhancement directly on $\gamma\gamma$ width

Carena, Gori, Shah, Wagner, Wang [1112.3336], [1205.5842]

Tree-level Higgs parameters



- Largest/smallest values for $\tan \beta$ disfavored in full analysis
- Decoupling limit $M_{H^\pm} \rightarrow \infty$ viable solution in Higgs sector

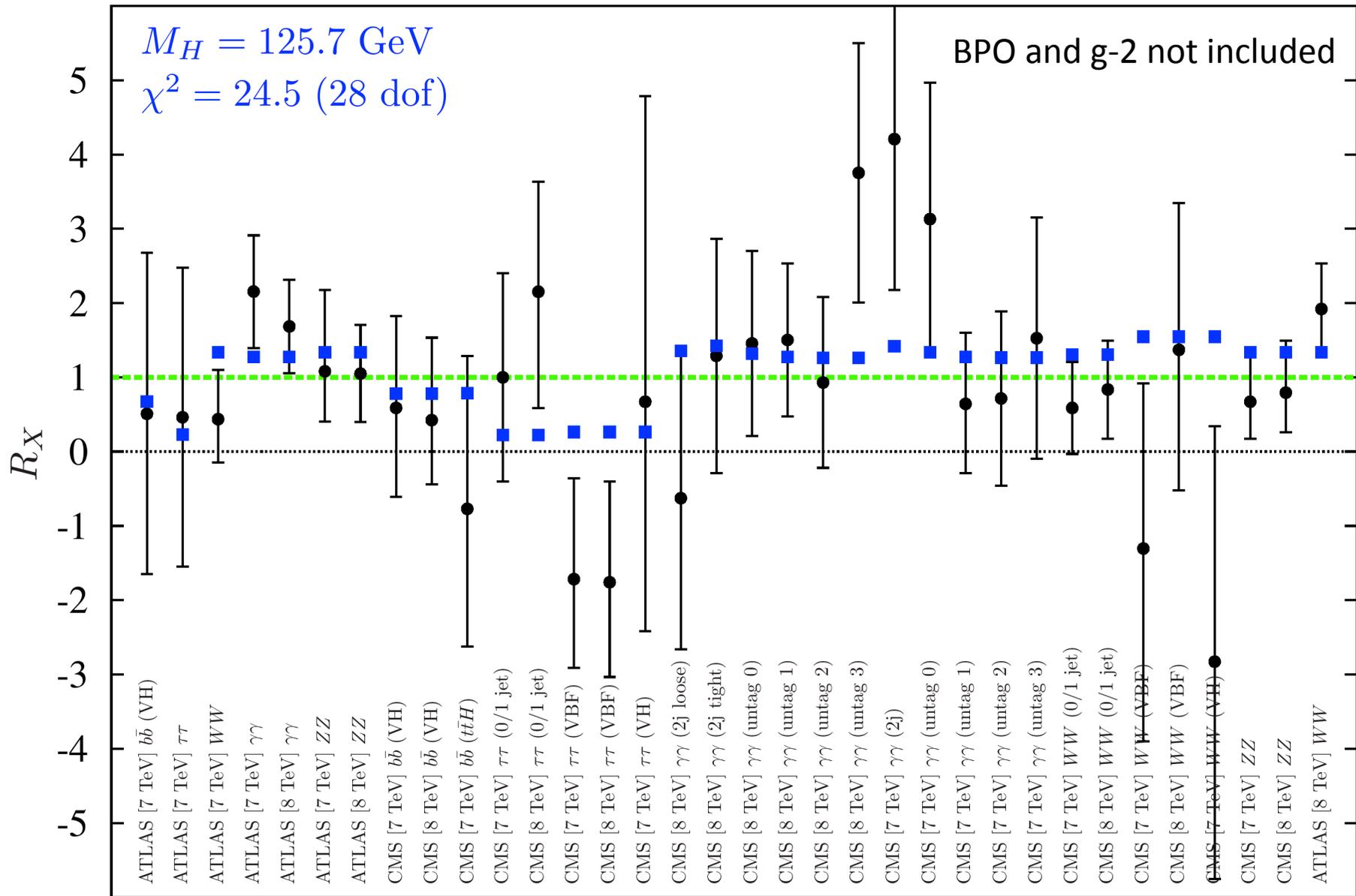
MSSM Results

Heavy Higgs case

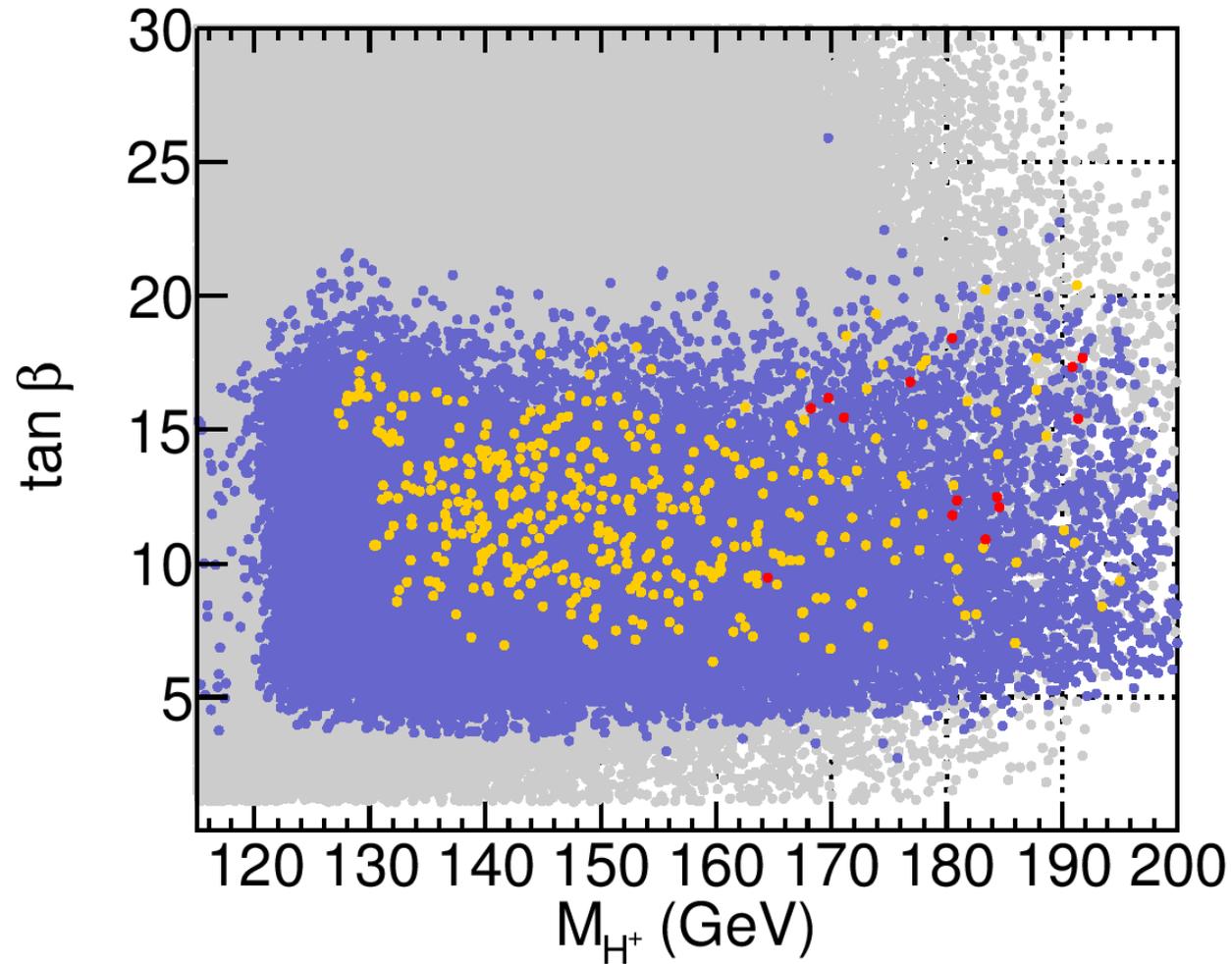
$$M_H \simeq 126 \text{ GeV}$$

Best Fit Rates

- LHC Data
- MSSM best H fit



Tree-level parameters in heavy Higgs case



- Allowed H solutions in the 'LHC wedge', but extrapolating...
... other states (A/H[±]) should be accessible soon!

Conclusions

- No sign of a charged Higgs (yet), its mass is unconstrained by theory. But: the MSSM predicted a light Higgs boson, compatible with what has now been discovered by ATLAS/CMS

MSSM Interpretation I: Lightest Higgs (h)

- > Light charged Higgs bosons ($M_{H^\pm} < m_t$) ruled out
- > Overall rates favor suppressed Higgs couplings to fermions, enhanced $\gamma\gamma$ and (smaller) enhancement of VV channels
- > Higgs decoupling limit viable (but not the only) solution

MSSM Interpretation II: Heavy Higgs (H):

- > Small corner of parameter space with light H^\pm still exists
 - > Best fit rates similar to those for light Higgs case
 - > Should be accessible soon. Lightest Higgs hidden below LEP limit
- H^\pm limits from other Higgs searches (h, A, ...) only apply in the MSSM
Need to independently exclude (or discover) H^\pm over full mass range!

BACKUP

MSSM Lightest Higgs Mass

- Higher-order corrections are particularly important for M_h

$$M_h^2 = M_{h,\text{tree}}^2(M_A, \tan \beta) + \Delta M_h^2(M_{\text{SUSY}}, A_i, M_i, \dots)$$

- Long development to know these corrections very precisely

| | | |
|--|-----------|--|
| Dominant 1-loop corrections | 1991 | Okada, Yamaguchi, Yanagida Ellis, Ridolfi, Zwirner Haber, Hempfling |
| Complete 1-loop | 1992-96 | Brignole Chankowski, Rosiek, Pokorski Dabelstein Pierce, Bagger, Matchev, Chang |
| RGE-improved 1-loop | 1995-96 | Carena, Espinosa, Quiros, Wagner Haber, Hempfling, Hoang |
| Dominant 2-loop $\mathcal{O}(y_t^2 \alpha_s + y_b^2 \alpha_s + y_t^4 + y_b^4)$ | 1998-2002 | Heinemeyer, Hollik, Weiglein Brignole, Degrandi, Slavich, Zwirner |
| Leading 3-loop $\mathcal{O}(y_t^2 \alpha_s^2)$ | 2010 | Harlander, Kant, Mihaila, Steinhauser |

Scanning parameters

- Random scan of 7 “pMSSM” parameters (~ 10 M points)
($+m_t$ varied in 2σ interval)

| | Min | Max |
|--------------|--------------|-------------|
| M_A | 90 | 1000 |
| $\tan \beta$ | 1 | 60 |
| M_{Q_3} | 200 | 1500 |
| A_t | $-3 M_{Q_3}$ | $3 M_{Q_3}$ |
| μ | 200 | 3000 |
| M_{L_3} | 200 | 1500 |
| M_2 | 200 | 500 |

$$M_{Q_{1,2}} = M_{U_{1,2}} = M_{D_{1,2}} = 1 \text{ TeV}$$

$$M_{D_3} = M_{U_3} = M_{Q_3}$$

$$M_{L_{1,2}} = M_{E_{1,2}} = 300 \text{ GeV}$$

$$M_{E_3} = M_{L_3}$$

$$A_b = A_\tau = A_t$$

$$M_3 = 1 \text{ TeV}$$

M_1 fixed by GUT relation

- MSSM predictions calculated using [FeynHiggs \[2.9.4\]](#)
No additional MSSM uncertainties assumed on rates/xsections
- Two cases: either light or heavy CP-even Higgs @ 126 GeV

LHC data: signal strength modifiers

- Signal strength data R_X taken for *different* Higgs masses from ATLAS and CMS, corresponding to two best-fit values
- Normalized rate predictions compared at mass for experimental observation, regardless of calculated MSSM Higgs mass.
-> incorporates MSSM uncertainty on the M_h prediction.
- Data treated separately for 7 and 8 TeV for consistent predictions.
For ATLAS WW, ZZ only results for 7 TeV, 7+8 TeV is public

Espinosa, Grojean, Mühlleitner, Trott, [1207.1717]

8 TeV results “reconstructed” assuming uncorrelated Gaussians

$$\frac{(R_X)_{7+8}}{\sigma_{7+8}^2} = \frac{(R_X)_7}{\sigma_7^2} + \frac{(R_X)_8}{\sigma_8^2} \qquad \frac{1}{\sigma_{7+8}^2} = \frac{1}{\sigma_7^2} + \frac{1}{\sigma_8^2}$$

Additional constraints and observables

- “Hard” limits (not included in χ^2):
 - Higgs constraints at 95% CL (up to LHC-7) : [HiggsBounds \[3.8.0\]](#)
 - Sparticle masses from the PDG
 - Neutral LSP (but no CDM constraint applied)
- χ^2 evaluated with / without B-physics observables and $(g-2)_\mu$:

| Observable | Experiment | SM prediction | Total unc. used |
|---|---|----------------------------------|-----------------------|
| $\text{BR}(B \rightarrow X_s \gamma)_{E_0 > 1.6 \text{ GeV}}$ | $(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ | $(3.08 \pm 0.24) \times 10^{-4}$ | 0.7×10^{-4} |
| $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ | $< 4.5 \times 10^{-9}$ (95% CL) | $3.5 \pm 0.4 \times 10^{-9}$ | 0.5×10^{-9} |
| $\text{BR}(B \rightarrow \tau^+ \nu_\tau)$ | $(1.64 \pm 0.34) \times 10^{-4}$ | $(1.01 \pm 0.29) \times 10^{-4}$ | 0.45×10^{-4} |
| δa_μ | $(30.2 \pm 8.8) \times 10^{-10}$ | 0 | 9×10^{-10} |

F. Mahmoudi [[SuperIso v. 3.2](#)]
<http://superiso.in2p3.fr>

Summary of fits

| Case | Only LHC data | | | | LHC + BPO + $(g-2)_\mu$ | | | |
|-----------|---------------|-----|---------------------|------|---------------------------|-----|----------------------------------|------|
| | min χ^2 | dof | χ^2/dof | p | min χ_{tot}^2 | dof | $\chi_{\text{tot}}^2/\text{dof}$ | p |
| SM | 27.6 | 34 | 0.811 | 0.77 | 42.3 | 38 | 1.11 | 0.29 |
| MSSM- h | 23.2 | 28 | 0.828 | 0.72 | 28.3 | 32 | 0.886 | 0.65 |
| MSSM- H | 24.5 | 28 | 0.874 | 0.65 | 31.0 | 32 | 0.969 | 0.52 |

$$\text{dof} = N_{\text{obs}} - N_{\text{para}}$$

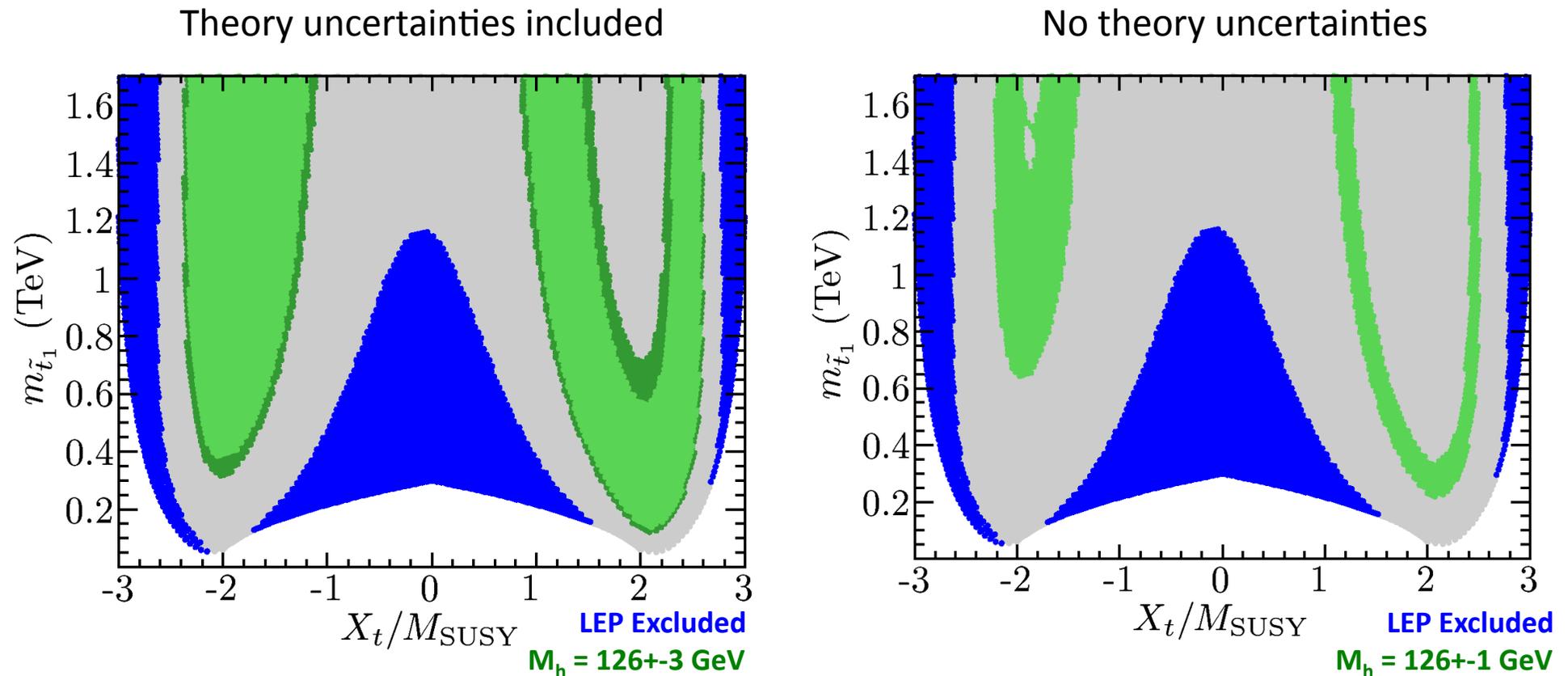
- Fits are in good shape (almost too good) for both the SM, MSSM- h , and MSSM- H interpretations
- Since $(g-2)_\mu$ deviates by more than 3σ , the SM receives a major punishment when this is included

Example points

| Parameter | $M_h \sim 126$ GeV | $M_H \sim 126$ GeV |
|-------------------|--------------------|--------------------|
| M_A (GeV) | 277.0 | 107.3 |
| $\tan \beta$ | 17.49 | 15.88 |
| M_{Q_3} (GeV) | 567.46 | 738.79 |
| A_t (GeV) | 1344. | 1733. |
| μ (GeV) | 2400. | 1411. |
| M_{L_3} (GeV) | 1239. | 953.6 |
| M_2 (GeV) | 459.5 | 245.9 |
| Calculated | | |
| M_h (GeV) | 125.8 | 86.4 |
| M_H (GeV) | 235.7 | 125.4 |
| M_A (GeV) | 277.0 | 107.3 |
| M_{H^\pm} (GeV) | 280.0 | 130.5 |

Constraints on the stop sector

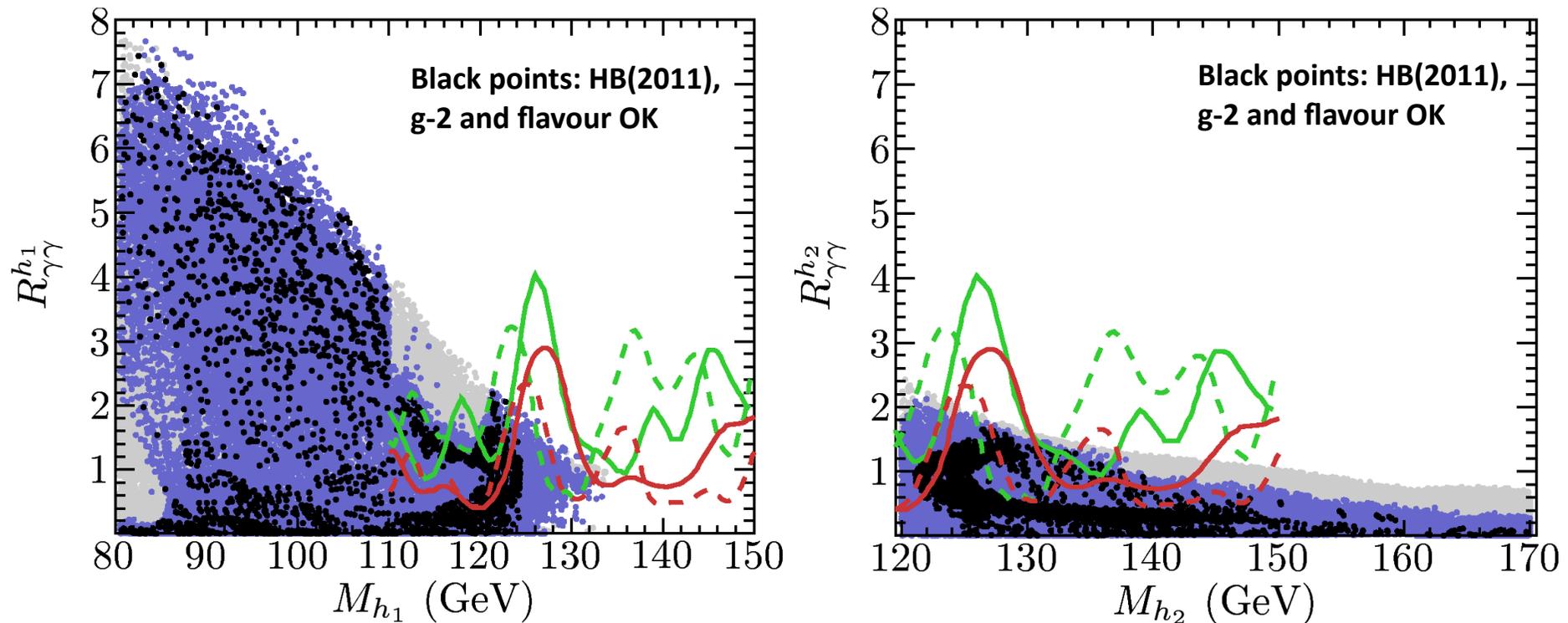
- Can also determine lower limit on dominant contribution to radiative corrections (in decoupling limit)



$$m_{\tilde{t}_1} \gtrsim 150 \text{ GeV}$$

NMSSM interpretations of the LHC Higgs signal

- Scan of parameter region “orthogonal” to MSSM scenarios above (i.e. no light staus, no $h \rightarrow b\bar{b}$ suppression by doublet mixing)
- Both h_1 and h_2 interpretations viable for $M_H = 126$ GeV

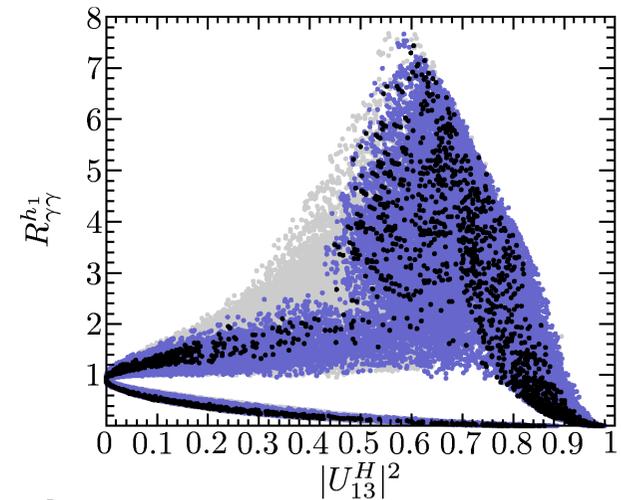
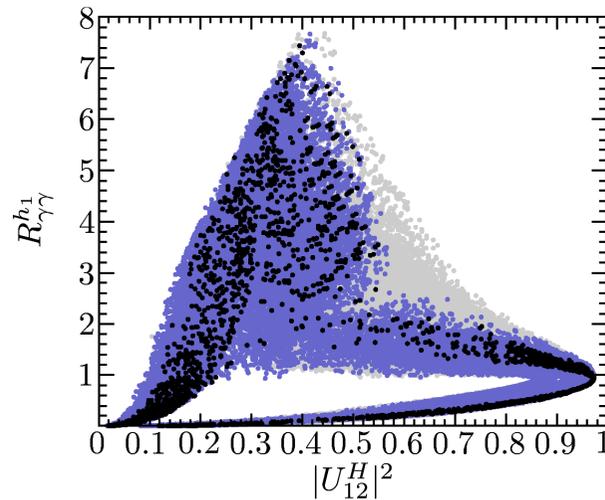
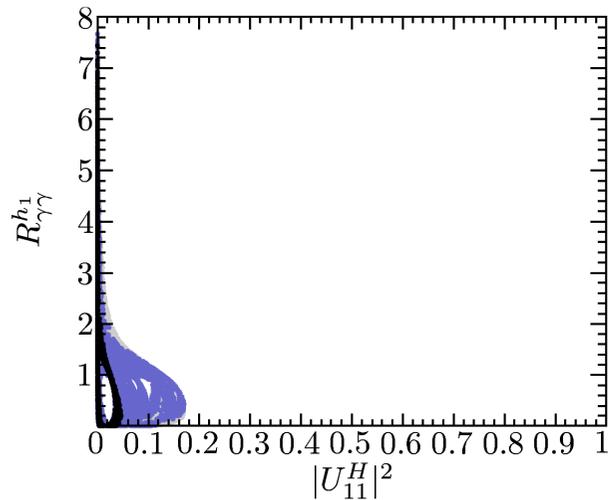


- Sizeable enhancements of the two photon mode possible

NMSSM enhancement of $h \rightarrow \gamma\gamma$

- Higgs with enhanced $\gamma\gamma$ rate has a suppressed $h_i \rightarrow b\bar{b}$ mode due to a non-zero singlet component -> Genuine feature of the NMSSM

Ellwanger, [1012.1201], [1112.3548]



- Similar enhancement of $h_i \rightarrow WW, ZZ$ observed as in the MSSM case

Note: $R_{WW} < R_{\gamma\gamma}$

