# NMSSM Higgs Boson Phenomenology at the LHC

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# After Higgs Discovery: Which Higgs Boson?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

# The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

- **The $\mu$-problem of the MSSM:**

  Higgsino mass parameter $\mu$ must be of order of EWSB scale — Kim,Nilles

- **Solution in the NMSSM:**

  $\mu$ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

| | |
|---|---|
| 7 Higgs bosons: | $H_1, H_2, H_3, A_1, A_2, H^+, H^-$ |
| 5 neutralinos: | $\tilde{\chi}_i^0$ $(i = 1, ..., 5)$ |

- **Significant changes of Higgs boson phenomenology**

# $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on NMSSM Higgs of $\sim 125$-$126$ GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; Cheng eal; Bélanger eal; Kowalska eal; Badziak eal; Moretti eal: Choi eal; Munir eal; Barbieri eal; Beskidt eal; Berg eal; Gherghetta eal; Cerdeno eal; Das eal; Christensen eal; Bhattacherjee eal; Guo eal; ...

- **Compatibility of NMSSM Higgs mass with LHC Searches:**

  $\star$ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

  MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

  NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 126$ requires:

  MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections are needed $\rightsquigarrow$ conflict with fine-tuning

  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning — Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

# NMSSM Higgs Boson Mass

- **Higgs mass prediction** as precise as possible:

  distinguish between MSSM and NMSSM

  properly define scenarios with Higgs-to-Higgs decays

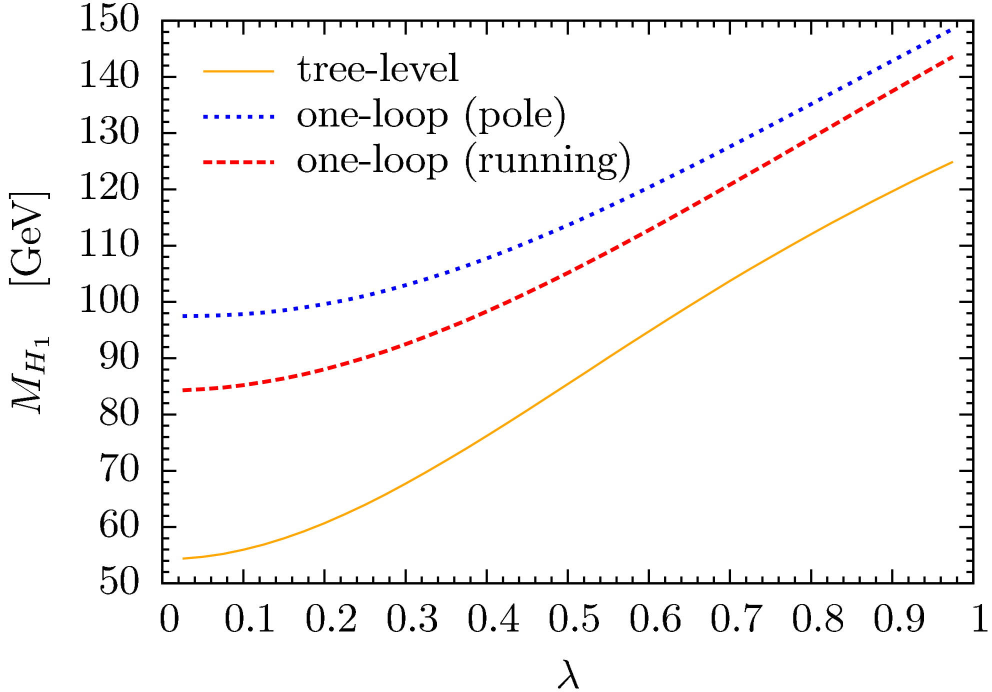
  correctly interpret experimental data

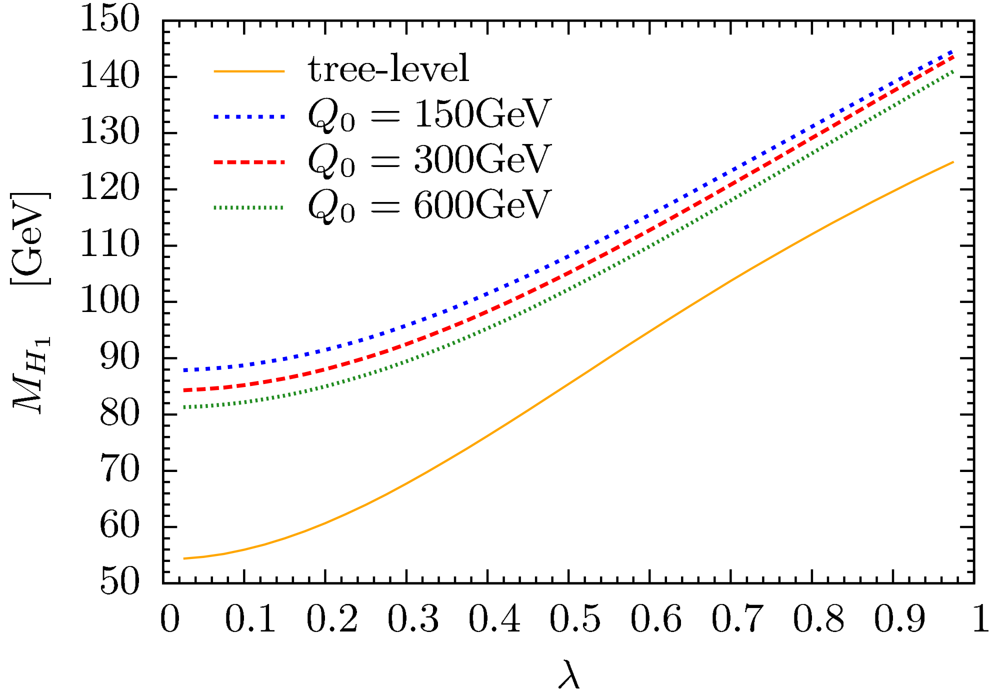
- **Status of Higgs mass calculations:**

  - 1-loop corrections in effective potential approach — Ellwanger eal; Elliott eal; Pandita
  - 1-loop corrections in Feynman-diagramatic approach — Degrassi,Slavich; Ender,Graf,MMM,Rzehak '11
  - 2-loop $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ — Degrassi,Slavich
  - 1-loop w/ CP violation in effective potential approach — Ham eal; Cheung eal
  - 1-loop w/ CP violation in Feynman-diagramatic approach — Graf,Grober,MMM,Rzehak,Walz '12

# $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

Ender,Graf,MMM,Rzehak '11




Top quark mass:

$m_t^{pole} = 173.3$ GeV

$m_t^{\overline{DR}} = 150.6$ GeV at $Q = 300$ GeV

$\Rightarrow$ theoretical uncertainty of the one-loop calculation: $\mathcal{O}(10\%)$

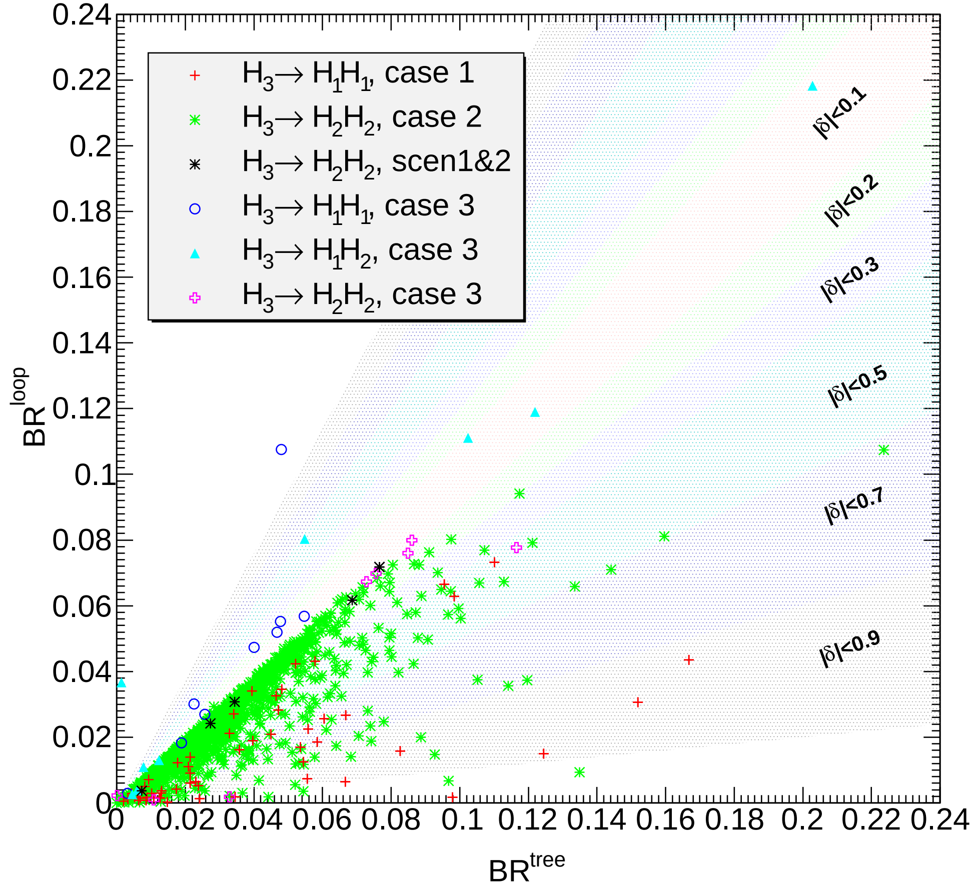
For 1-loop mass corrections in the complex NMSSM, see Graf,Grober,MMM,Rzehak,Walz '12

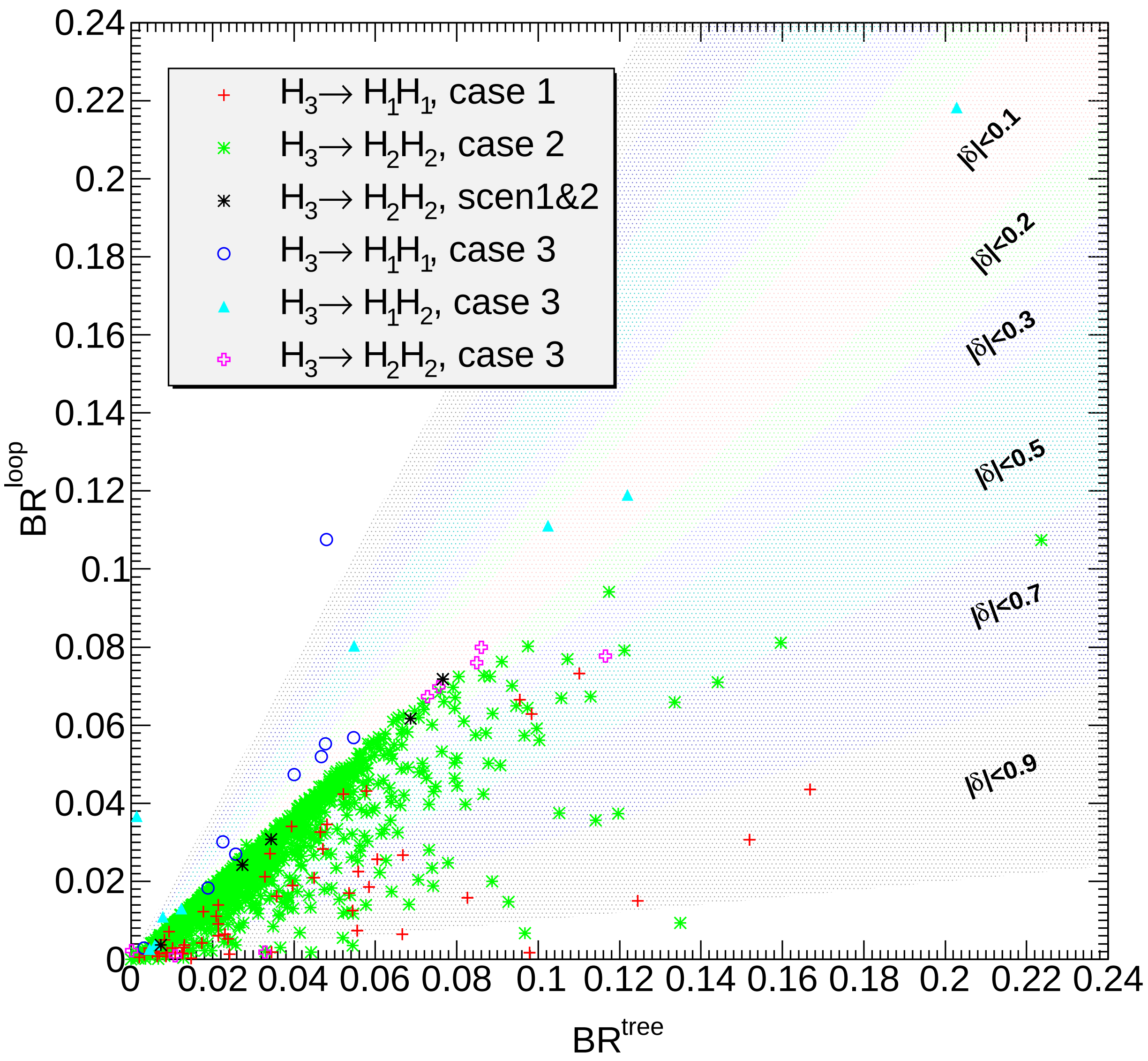
# $\mathcal{L}$oop $\mathcal{C}$orrected $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

- **Higgs mass and self-couplings:** determined from Higgs potential $\rightsquigarrow$ consistent description of Higgs sector at higher order requires loop corrections to masses and self-couplings

$\Rightarrow$ determination of higher order corrections to trilinear Higgs self-couplings

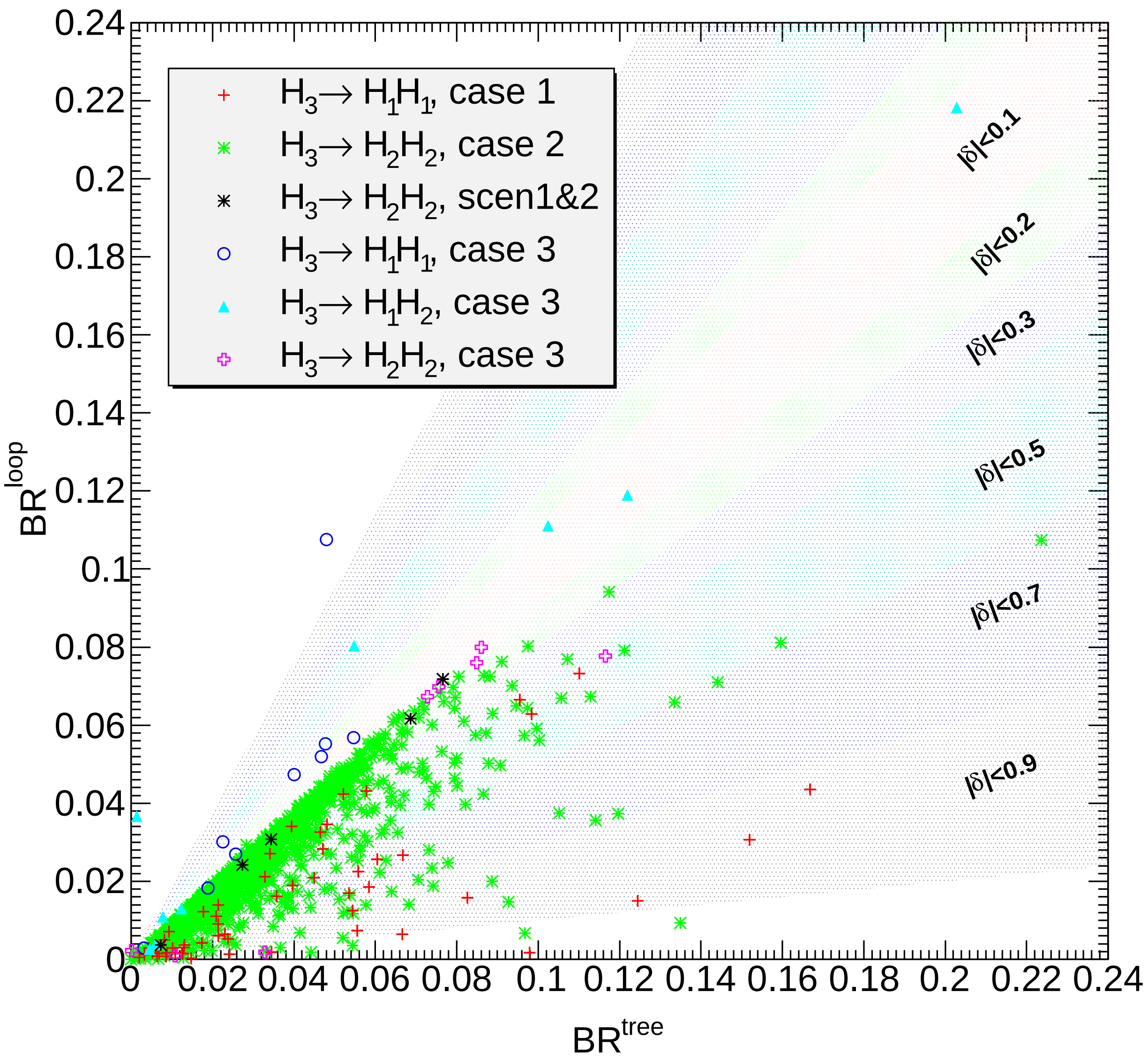
Dao,MMM,Streicher,Walz '13



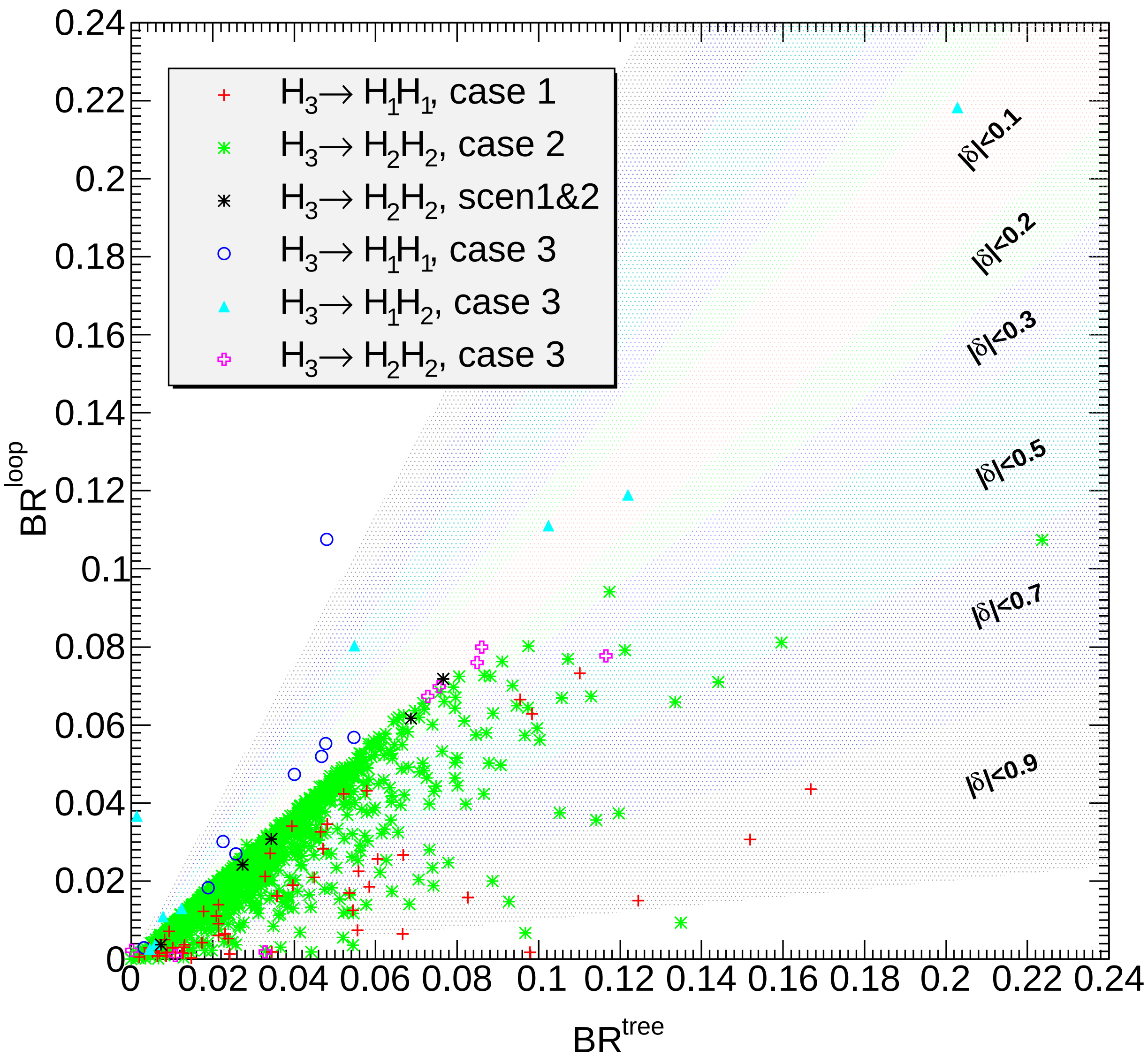



* $H_3$ decays into SM-like Higgs bosons $h$: $h = H_{1,2}$ (case 1,2); $H_1, H_2$ degenerate in mass (case 3)

Dao,MMM,Streicher,Walz '13




$$\delta \equiv \frac{BR^{loop} - BR^{tree}}{BR^{tree}}$$




∗ Effect of higher order corrections on branching ratios can be up to 90% and higher

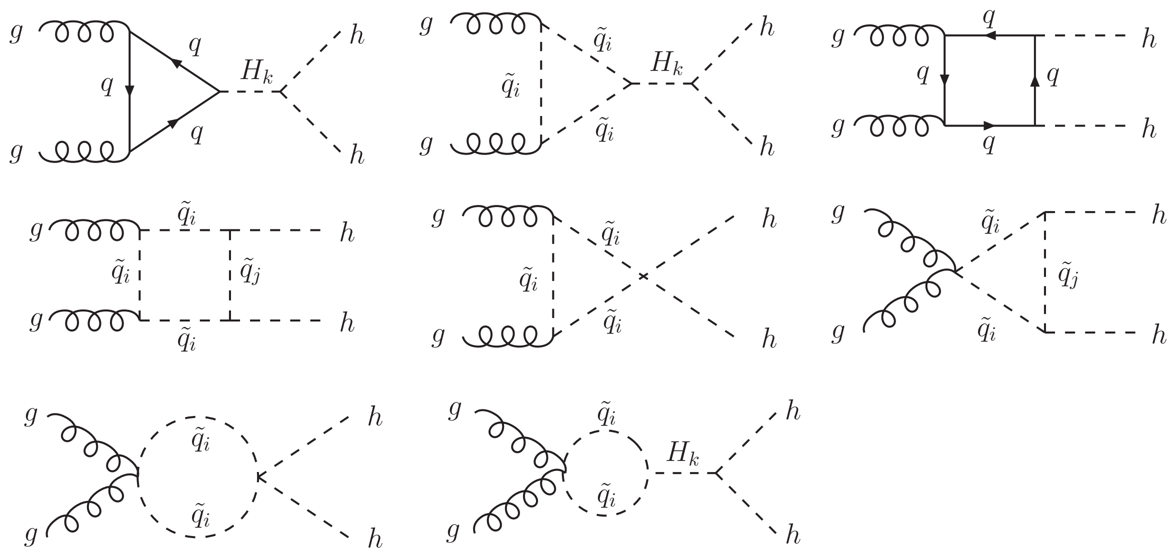
∗ Black points: excluded if only tree-level BR considered: loop corrections decrease $h$ decays into pair of lighter Higgs bosons ⇝ signal rates into SM particles compatible w/ LHC results

# $\mathcal{L}$oop $\mathcal{C}$orrected $\lambda_{\phi_i\phi_j\phi_k}$ and $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction

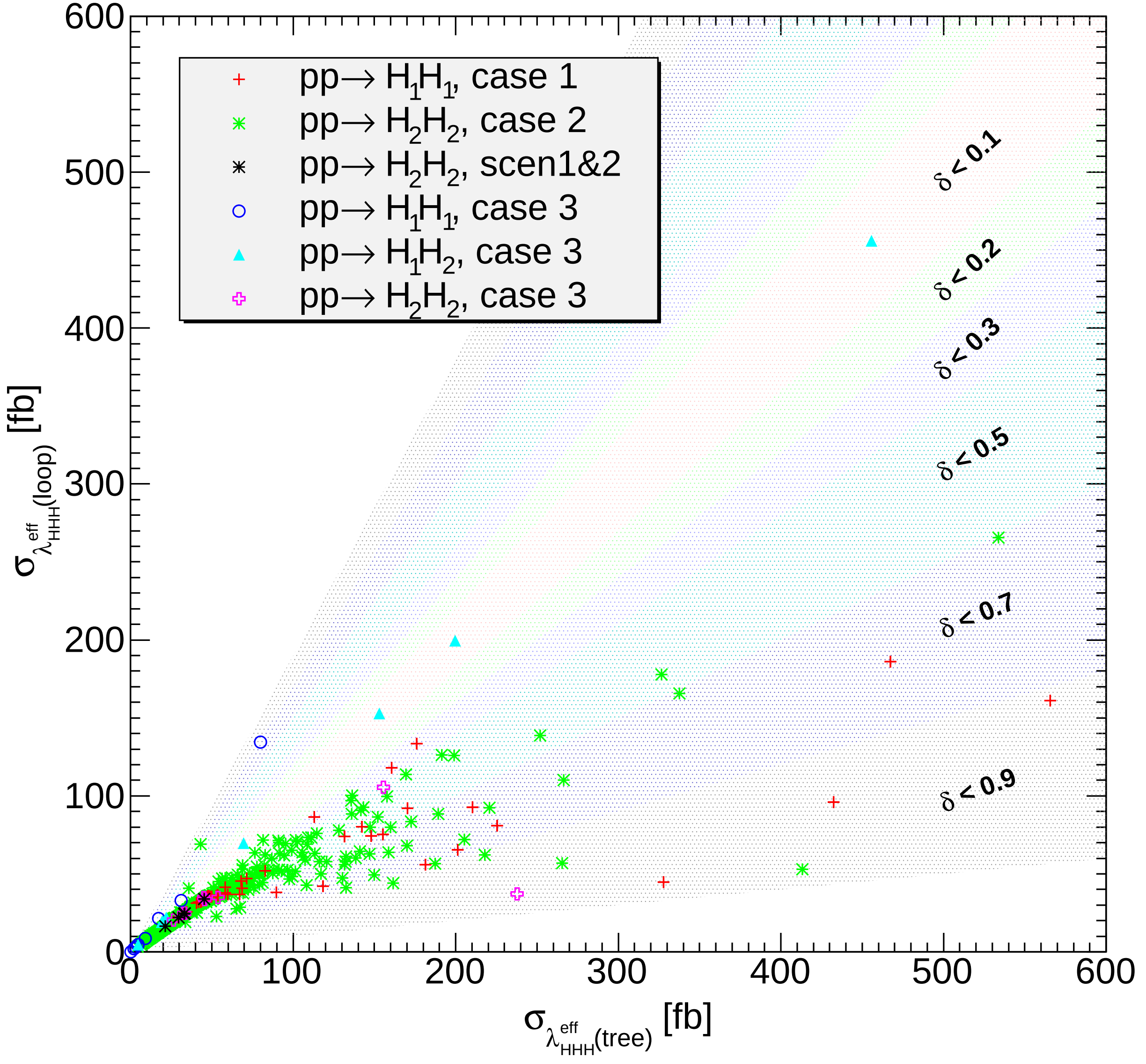
- **Higgs Pair Production:** Access to trilinear Higgs self-coupling

  Djouadi,Kilian,MMM,Zerwas; Boudjema,Chopin; Barger eal; Osland eal; Asakwa eal; Baur eal; Grober, MMM; Dolan eal; Papaefstathiou eal; Goertz eal; Butterworth eal; Baglio,Djouadi,Grober,MMM,Quevillon,Spira; Gupta eal; De Florian eal; Cao eal; Shao eal; Dao,MMM,Walz; ...

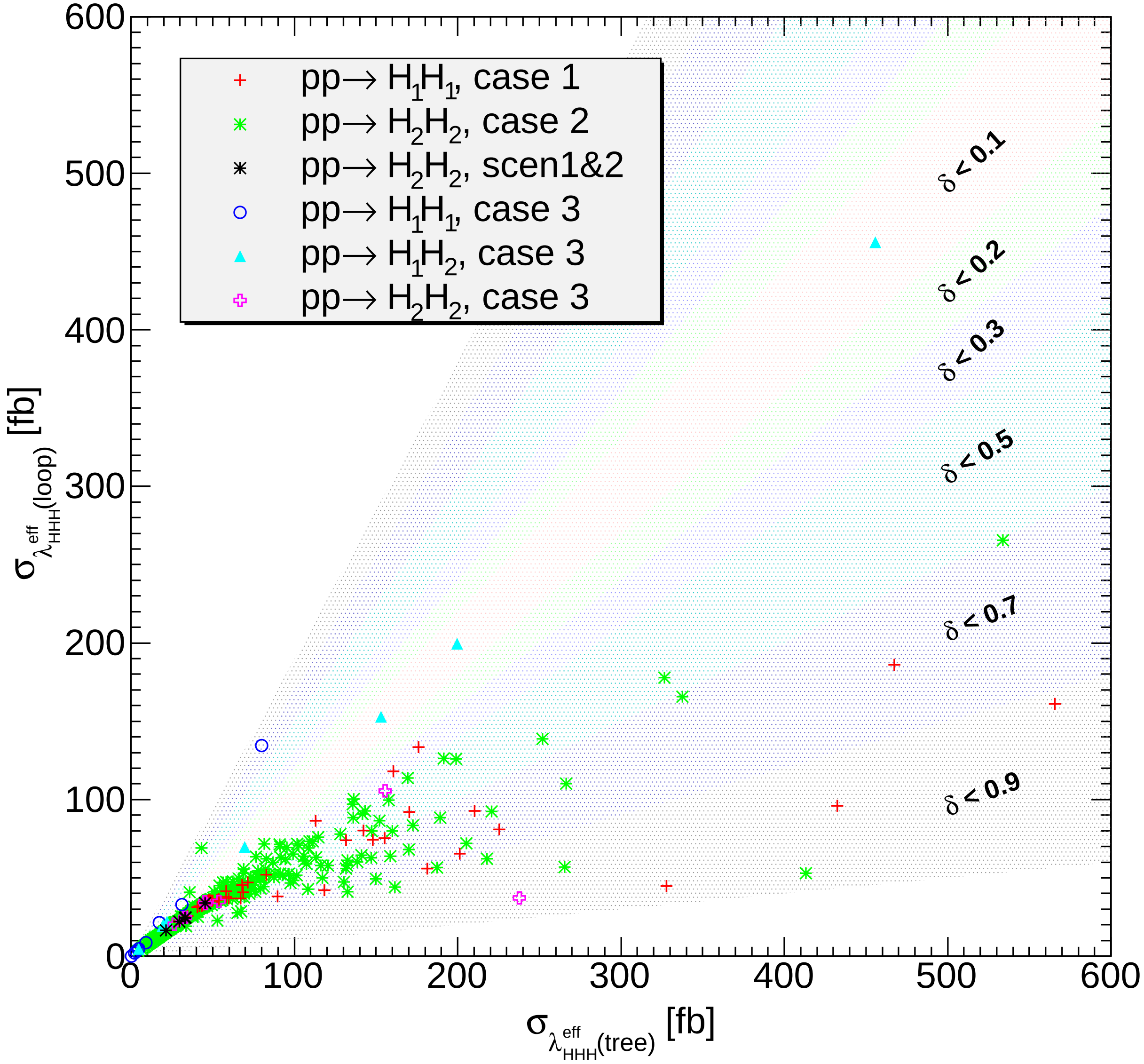
- **Dominant process at LHC:** $gg \to \phi_i\phi_k$ Dao,MMM,Streicher,Walz '13




Measurement of Higgs self-couplings ⇒ reconstruction of Higgs potential.




$$\delta \equiv \frac{\sigma_L - \sigma_T}{\sigma_T}$$




Large deviations (up to 90%) due to large deviations between tree-level and loop-corrected $BR(H_3 \to hh)$.

# $\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

- **SM-like NMSSM scalar boson of $\sim 126$ GeV**

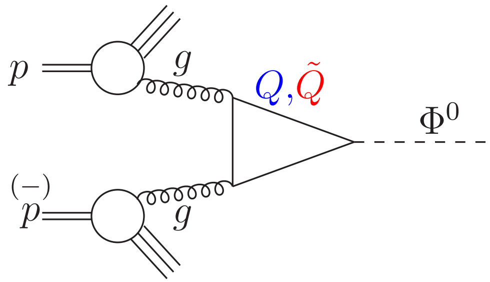
  Can be either $H_1$ or $H_2$ ($H_1$ singlet-like, suppr. SM couplings)

- **Enhanced Diphoton rate (now only ATLAS)**

  * Enhance branching ratio (enhance $\Gamma_{\gamma\gamma}$, suppress $\Gamma_{b\bar{b}}$)

$$BR(h^{126\,\text{GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{126\,\text{GeV}}]}$$

  * Enhance gluon fusion production (enhanced for small stop mixing)



# $\mathcal{NMSSM}$ $\mathcal{S}$can - $\mathcal{L}$ight $\mathcal{S}$top $\mathcal{M}$asses

$\star$ $\tan\beta = 2$, 4 — maximize tree-level mass of lightest Higgs boson

$\star$ $0.55 \le \lambda \le 0.8$ , $10^{-4} \le \kappa \le 0.4$ — validity of perturbativity — 2-loop RGE's

$\star$ $100$ GeV $\le \mu_{\text{eff}} \le 200$ GeV — avoid finetuning

$\star$ $500$ GeV $\le M_{Q_3} = M_{t_R} \le 800$ GeV — avoid finetuning

$A_t = 0$ GeV, $1$ TeV

$*$ $-500$ GeV $\le A_\kappa \le 0$ GeV

$200$ GeV $\le A_\lambda \le 800$ GeV

$*$ $M_{\tilde{u}_R} = M_{\tilde{c}_R} = M_{\tilde{D}_R} = M_{\tilde{Q}_{1,2}} =$ — comply with LHC results

$M_{\tilde{e}_R} = M_{\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 2.5$ TeV

$M_{\tilde{\tau}_R} = M_{\tilde{L}_3} = 300$ GeV , $A_D = A_E = 1$ TeV

$*$ $M_1 = 150$ GeV, $M_2 = 300$ GeV, $M_3 = 1$ TeV

# $\mathcal{NMSSM}$ $\mathcal{S}$can

- **Typical mass values:**

$$m_{\tilde{t}_1} = 400 - 820 \text{ GeV}\,, \quad m_{\tilde{t}_2} = 530 - 890 \text{ GeV}$$

$$M_{H^\pm} = 200 - 500 \text{ GeV}\,, \quad M_{\tilde{\chi}_1^\pm} = 105 - 165 \text{ GeV}\,, \quad M_{\tilde{\chi}_2^\pm} = 345 - 360 \text{ GeV}$$

# $\mathcal{NMSSM}$ $\mathcal{S}$can

- **Conditions on the parameter scan:**
  - $*$ At least one CP-even Higgs boson $h$ with: 124 GeV $\lesssim M_h \lesssim$ 127 GeV
  - $*$ The reduced cross section for $\gamma\gamma$ must fulfill: $\mu_{\gamma\gamma}(h) \gtrsim 0.8$ with 124 GeV $\lesssim M_h = M_{H^{\text{SM}}} \lesssim$ 127 GeV
  - $*$ No restriction on rates into $WW$, $ZZ$, $b\bar{b}$, $\tau^+\tau^-$
  - $*$ Higgs bosons outside $124...127$ GeV: exclusion limits of LEP, Tevatron and LHC searches

- **Signal can be superposition of two Higgs boson rates close in mass: $h$ and $\Phi = H_i, A_j$**

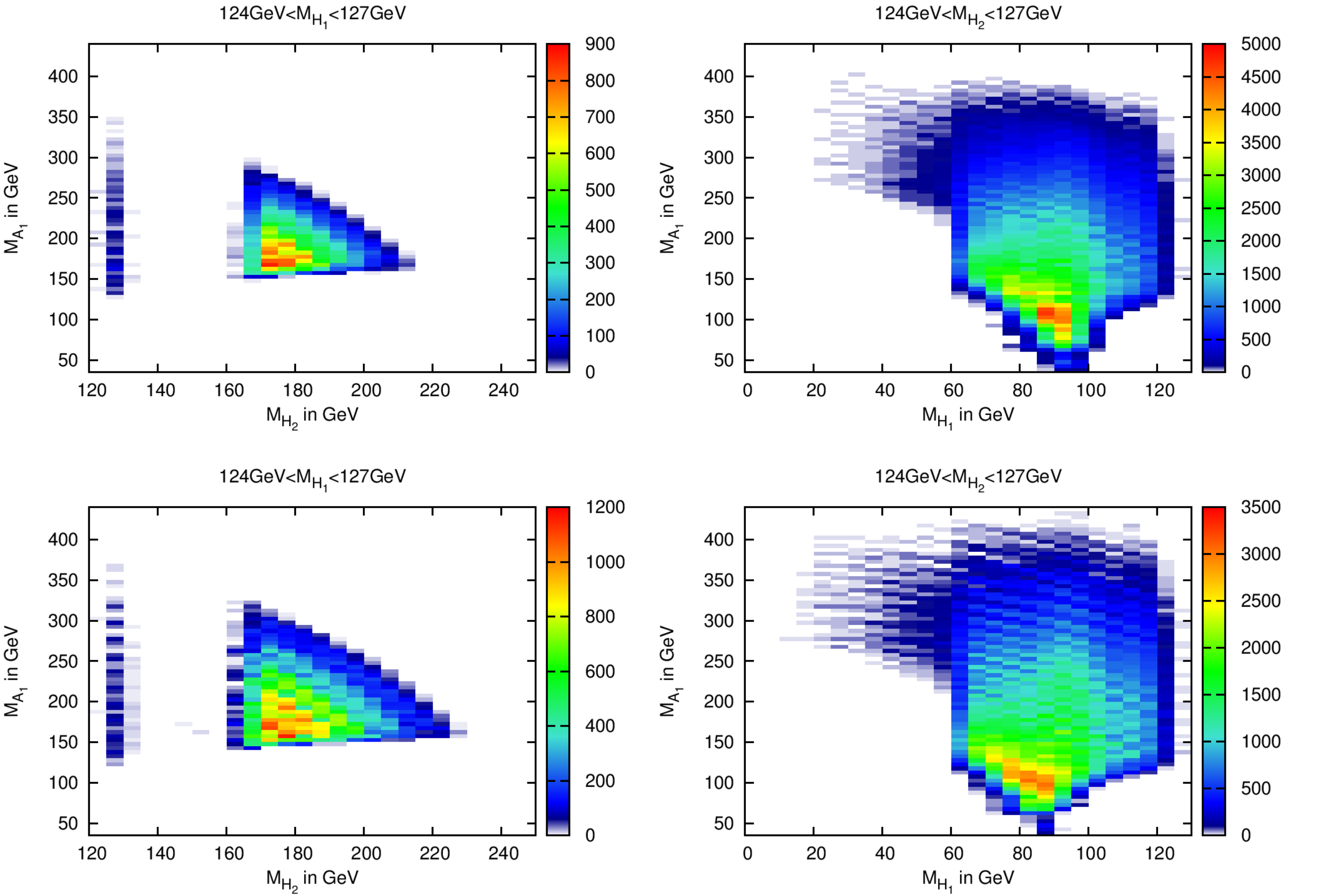
$$\mu_{XX}(h) \equiv R_\sigma(h)\, R^{BR}_{XX}(h) \;+ \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R^{BR}_{XX}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

$\delta$ : mass resolution in the respective $XX$ final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

$d_{XX}$: experimental resolution of final state $XX$

NMSSMTools

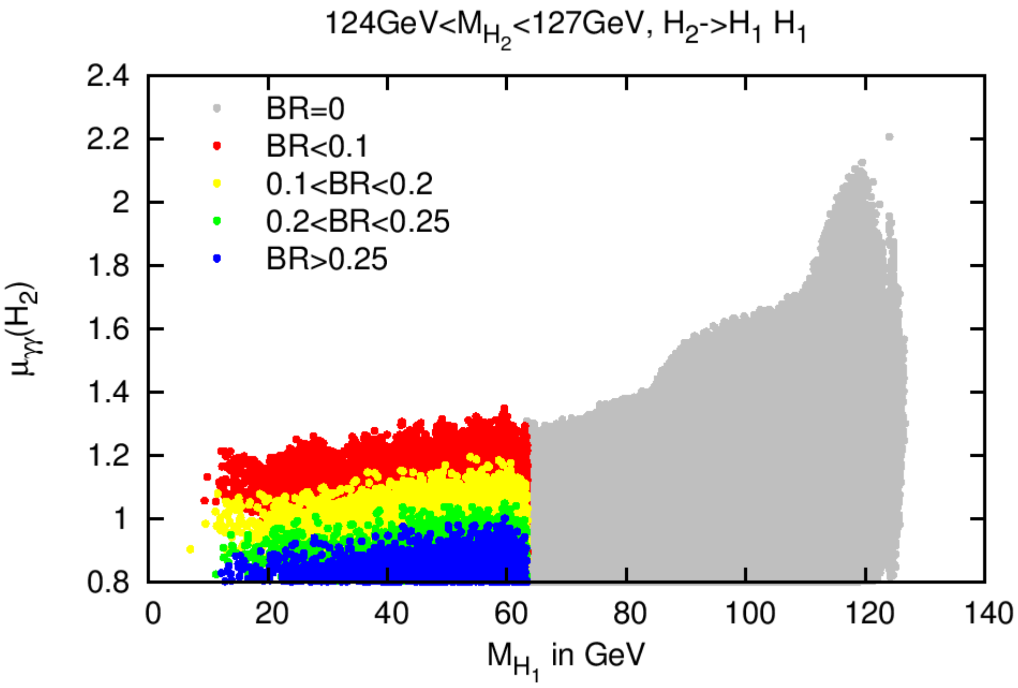


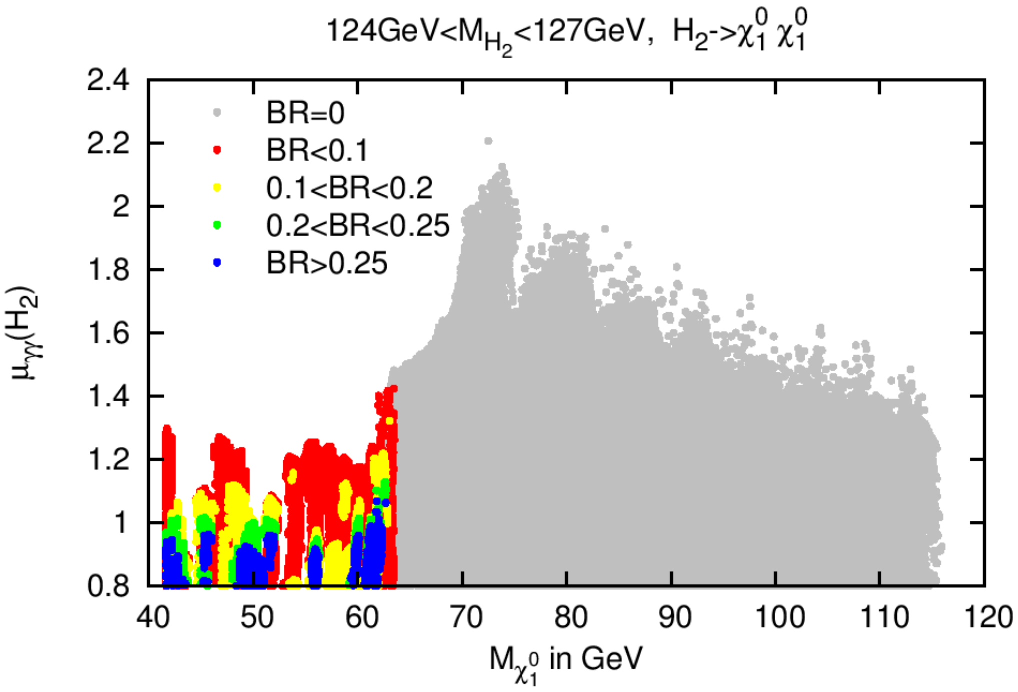

⋆ Upper/Lower: $A_t = 0$, 1 TeV ⋆ $M_{H_3}, M_{A_2}$ between 300 and 500 GeV

⋆ Possible degeneracy of $h - H_{1,2}$ ($H_{1,2} \neq h$), $h - A_1$, possible decays $H_2 \to H_1 H_1, A_1 A_1, \chi_1^0 \chi_1^0$

# $\mathcal{E}$xotic $\mathcal{D}$ecays

King,MMM,Nevzorov,Walz

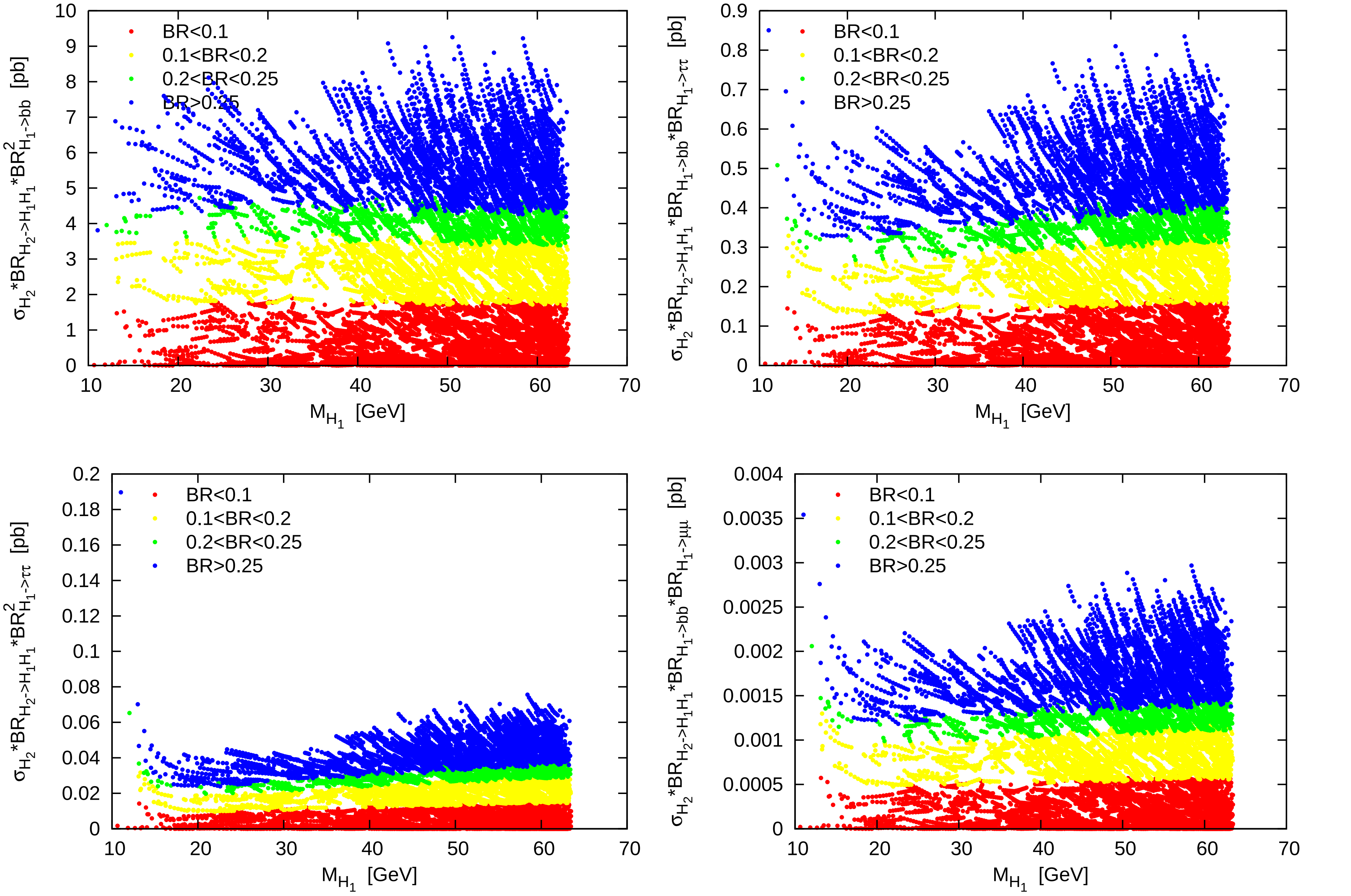



$*$ $\tan\beta = 2,\ A_t = 1$ TeV

$*$ $BR^{\text{max}}_{H_2}(H_1H_1) \approx 0.36,\ BR^{\text{max}}_{H_2}(A_1A_1) \approx 0.35$ and $BR^{\text{max}}_{H_2}(\tilde{\chi}^0_1\tilde{\chi}^0_1) \approx 0.43$

$*$ $\sigma_{\text{prod}}(H_2) \times BR(H_2 \to \chi^0_1\chi^0_1) \approx 4 - 8.5$ pb

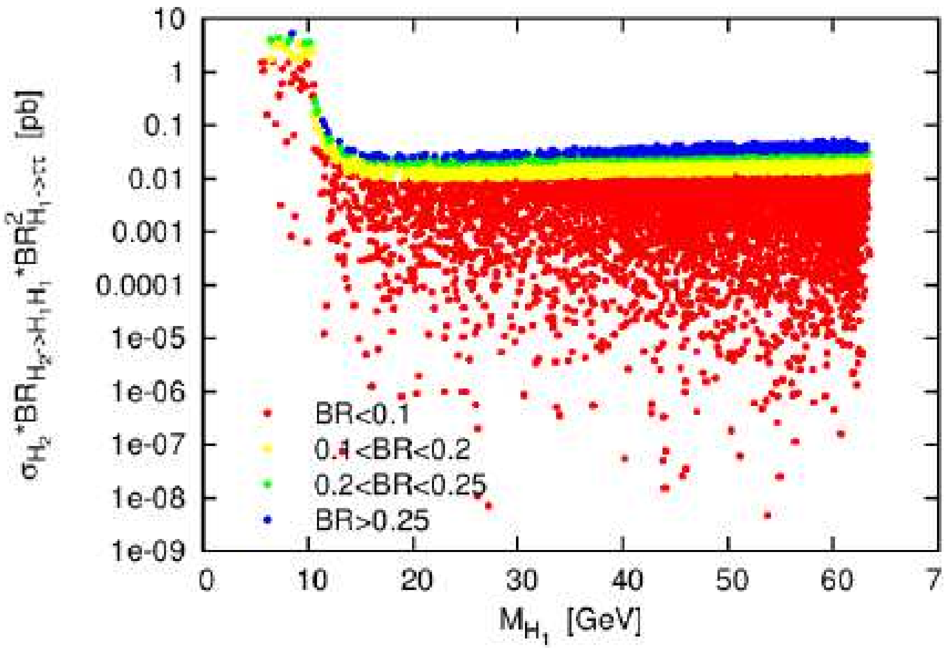



$*$ Decays $H_2 \to H_1 H_1$ $\quad A_t = 0$ TeV

$* \ BR(H_1 \to b\bar{b}) \approx 0.9 \quad BR(H_1 \to \tau^+\tau^-) \approx 0.07 - 0.085 \quad BR(H_1 \to \mu^+\mu^-) \lesssim 0.0006$

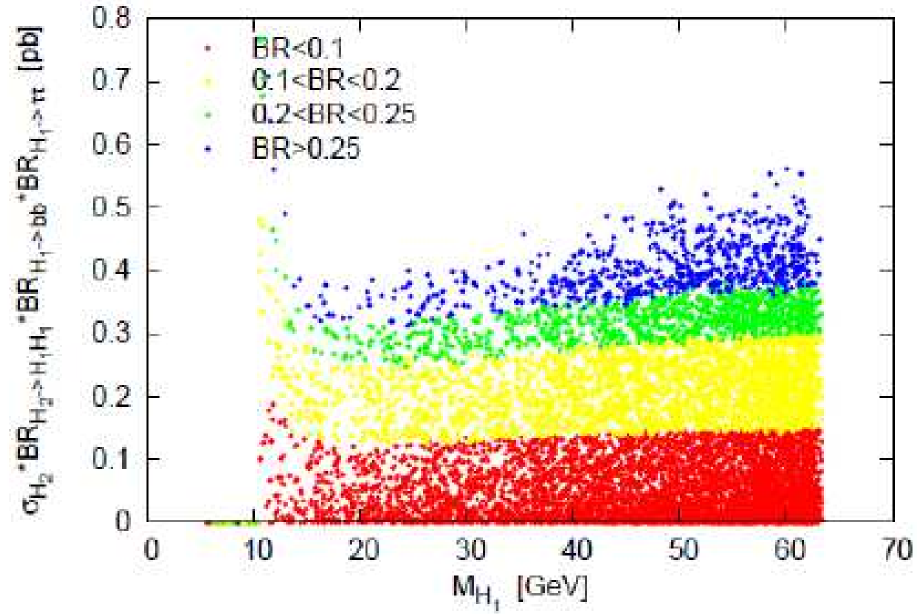
## $\mathcal{E}$xpected $\mathcal{S}$ignal - $\mathcal{R}$esults by $\mathcal{S}$asha $\mathcal{N}$ikitenko

**Consider two mass regions for $m_{H1}$**




**6 GeV < $m_{H1}$ < $2m_b$**

**ττττ dominates**




**2mb < $m_{H1}$ < $2m_{H2}$**

**ττbb and bbbb dominates**

# Expected signal event yield for 20 $fb^{-1}$ at 8 TeV

| σ x Br (ττττ) from theory : 3 pb | 60 000 |
|---|---|
| Two τ->μ, two τ->hadr: $0.17^2 \times 0.65^2 \times 6 = 0.0732$ | 4392 |
| $p_T^{\mu1}>17$ GeV, $\lvert\eta^{\mu1}\rvert<2.1$, $p_T^{\mu2}>10$ GeV, $\lvert\eta^{\mu2}\rvert<2.4$: 0.0713 | 313 |
| $p_T^{\tau h}>10$ GeV, $\lvert\eta^{\tau h}\rvert<2.4$ : 0.277 | 87 |
| ΔR(μ–μ) > 1.0 : 0.579 | 50 |
| Probably ask SS muons against DY, tt~, WW: 0.5 | 25 |
| Probably ask only 1 track around muon against QCD: $0.75^2$= 0.56 | 14 |

- $\tau\tau\tau\tau \to \tau_\mu \tau_\mathrm{h} \tau_\mu \tau_\mathrm{h}$ from inclusive $H_2$ production and $2m_\tau < M_{H_1} < 2m_b$ promising, but estimate of expected bkg needed

## $\mathcal{C}$onclusions

- **Higher order corrections to masses and trilinear self-couplings**
  - ⋆ Crucial to properly interpret experimental data

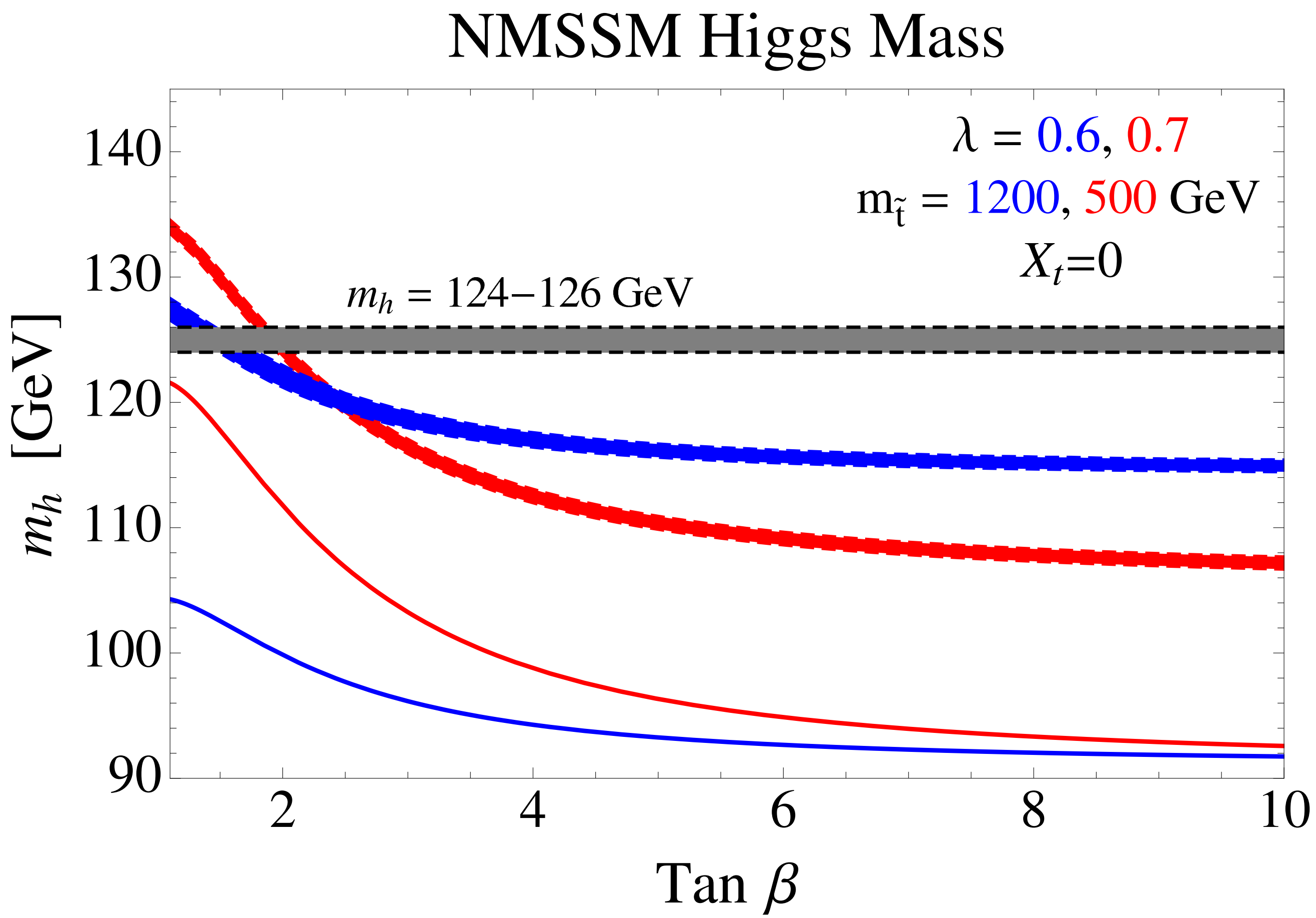
- **SM-like Supersymmetric Higgs boson**
  - ⋆ Possible at $\sim 126$ GeV, can be either $H_1$, $H_2$
  - ⋆ In NMSSM with low fine-tuning
  - ⋆ Can accommodate enhanced diphoton width (and also the non-enhanced one)
  - ⋆ Signal can be built up by two Higgs bosons close in mass

- **Exotic decays**
  - ⋆ Scenarios with $H_2 \to H_1H_1$, $H_2 \to A_1A_1$, $H_2 \to \chi_1^0\chi_1^0$ decays
  - ⋆ Exotic final states: $E_T^{\text{miss}}$, $4b$, $2b2\tau$, ...

Thank you for your attention!

# $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

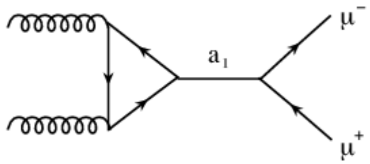
Hall,Pinner,Ruderman 1112.2703




◇ $m_h$ maximized for small values of $\tan\beta$

◇ $m_h \approx 126$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

# $\mathcal{U}$pper $\mathcal{L}$imit on $\mathcal{NMSSM}$ $a_1$ $\mathcal{P}$roduction

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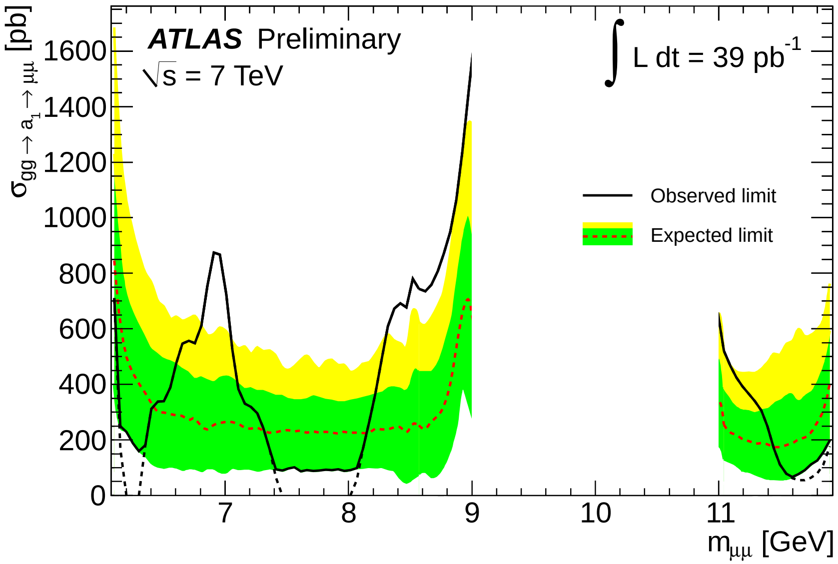
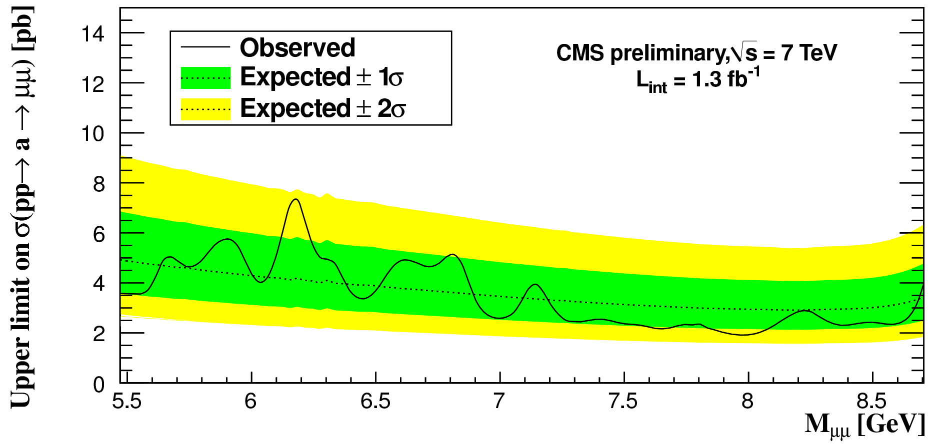



CMS 1206.6356



# $\mathcal{R}$enormalisation $\mathcal{S}$cheme

- **Mixed renormalisation scheme:**

$$\underbrace{M_Z, M_W, M_{H^\pm}, t_{h_u}, t_{h_d}, t_{h_s}, e}_{\text{on-shell scheme}}, \underbrace{\tan\beta, \lambda, v_s, \kappa, A_\kappa}_{\overline{\text{DR}}\text{ scheme}}$$

# $\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

- **SM-like NMSSM scalar boson of $\sim 126$ GeV**

  Can be either $H_1$ or $H_2$ ($H_1$ singlet-like, suppr. SM couplings)

- **Enhanced Diphoton rate (now only ATLAS)**

$$BR(h^{126\,\text{GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{126\,\text{GeV}}]}$$

$*$ Suppression of $\Gamma(h^{126\,\text{GeV}} \to b\bar{b})$ due to Hall,Pinner,Ruderman; Ellwanger; King,MMM,Nevzorov; Cao,Heng,Yang,Zhang,Zhu; Albornoz-Vasquez,Belanger,Boehm,DaSilva,Richardson,Wymant

  - $\diamond$ strong singlet-doublet mixing $\rightsquigarrow$ reduced coupling to $b\bar{b}$
  - $\diamond$ $\Delta_b$ corrections to $h^{126\,\text{GeV}} b\bar{b}$ coupling Carena eal

# $\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

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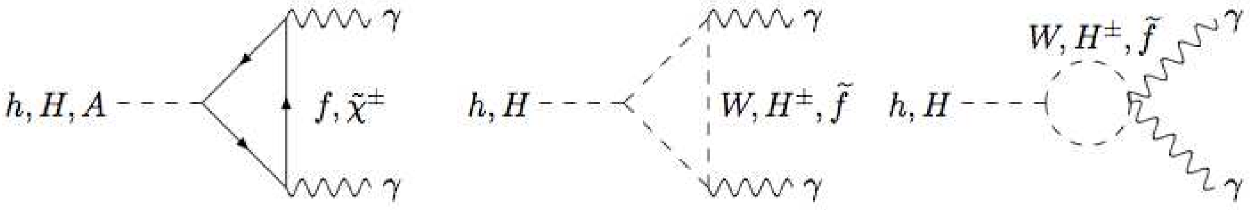
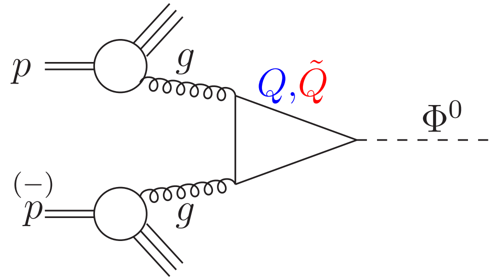
  * Enhanced $\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)$ due to charged boson, chargino, stop loop contributions



# $\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

- **Enhancement on the production side**




- **Enhanced gluon fusion production** See e.g. King,MMM,Nevzorov,Walz

  * Stop, sbottom loop contributions in $gg \to H_i$ can enhance the production cxn for small mixing
  * Associated *slight* suppression in $BR(h^{126\,\text{GeV}} \to \gamma\gamma)$ compensated by charged boson, chargino loop contributions
  * $\Rightarrow$ overall enhanced production in $\gamma\gamma$ final states, $\mu_{\gamma\gamma} > 1$
  * Couplings to $WW, ZZ$ must be suppressed in this case $\rightsquigarrow$ overall production in $VV$ final states $\approx$ SM-like, $\mu_{ZZ,WW} \approx 1$

# $\mathcal{NMSSM}$ $\mathcal{S}$can

- **Typical mass values:**

$$m_{\tilde{t}_1} = 400 - 820 \text{ GeV}, \quad m_{\tilde{t}_2} = 530 - 890 \text{ GeV}$$

$$M_{H^\pm} = 200 - 500 \text{ GeV}, \quad M_{\tilde{\chi}_1^\pm} = 105 - 165 \text{ GeV}, \quad M_{\tilde{\chi}_2^\pm} = 345 - 360 \text{ GeV}$$

- **Constraints from comparison w/ experimental signal rates:**

$$\mu_{XX}(h) \equiv R_\sigma(h)\, R^{BR}_{XX}(h) \quad \text{with} \quad R_\sigma(h) = \frac{\sigma^{\text{NMSSM}}_{\text{prod}}}{\sigma^{\text{SM}}_{\text{prod}}} \quad \text{and} \quad R^{BR}_{XX}(h) = \frac{BR^{\text{NMSSM}}_{XX}}{BR^{\text{SM}}_{XX}}$$

$$\sigma_{\text{prod}} = \sigma^{\text{NNLO QCD}}_{gg} + \sigma^{\text{NNLO QCD}}_{VV} + \sigma^{\text{NNLO QCD}}_{VH} + \sigma^{\text{NLO QCD}}_{ttH} \approx \sigma^{\text{NNLO QCD}}_{gg}$$

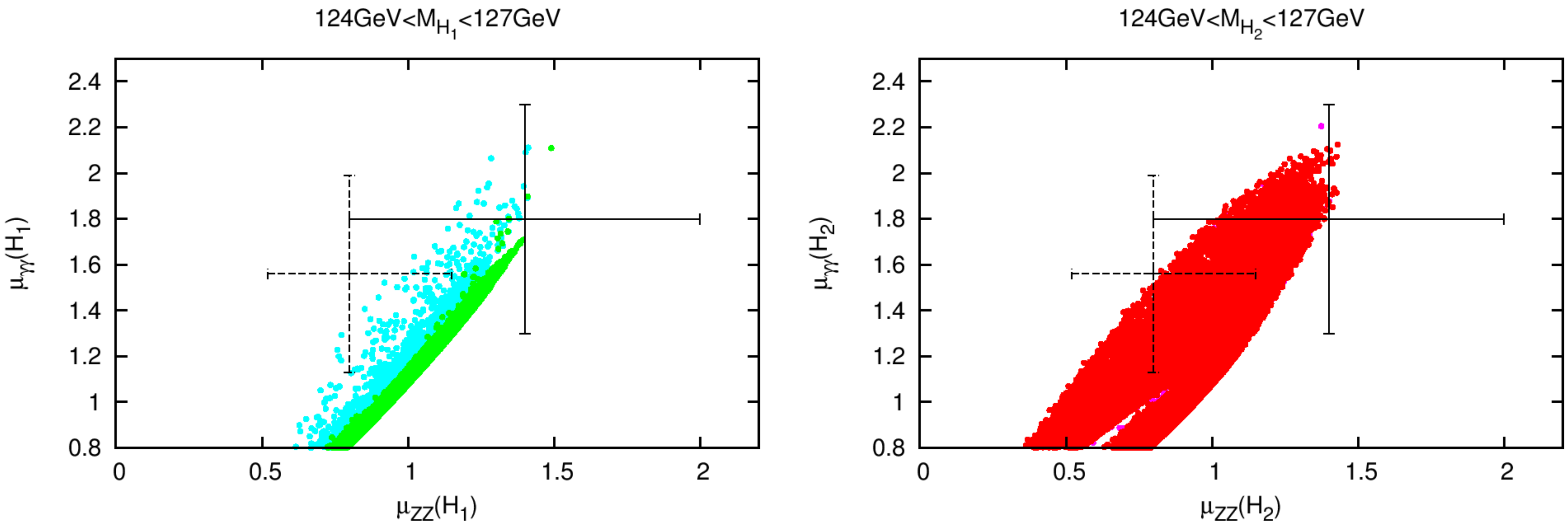
The NMSSM cxn $\sigma^{\text{NMSSM}}_{gg}$ @ NNLO QCD can be obtained from modified version of `HIGLU` Spira

Note #1: EW corrections cannot be taken over from the SM or MSSM.

Note #2: $R_{gg}(h)$ approximation by $R_{\Gamma_{gg}}(h)$ at (N)NLO QCD has to be checked explicitly, can deviate!

# $\mathcal{NMSSM}$ $\mathcal{S}$can - $\mathcal{P}$re-$\mathcal{M}$oriond

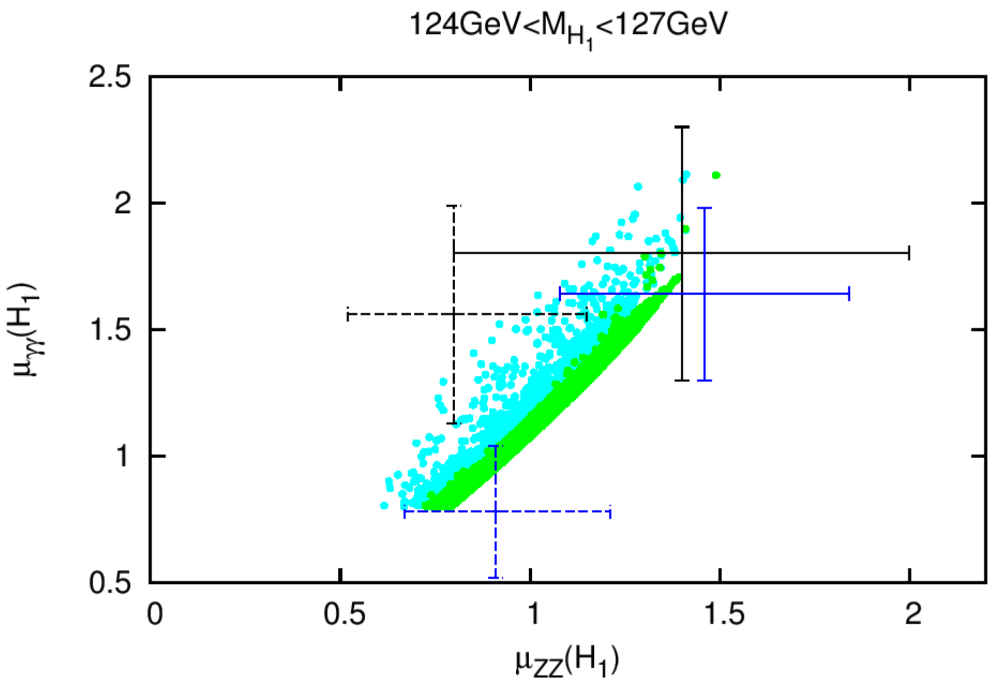
King,MMM,Nevzorov,Walz

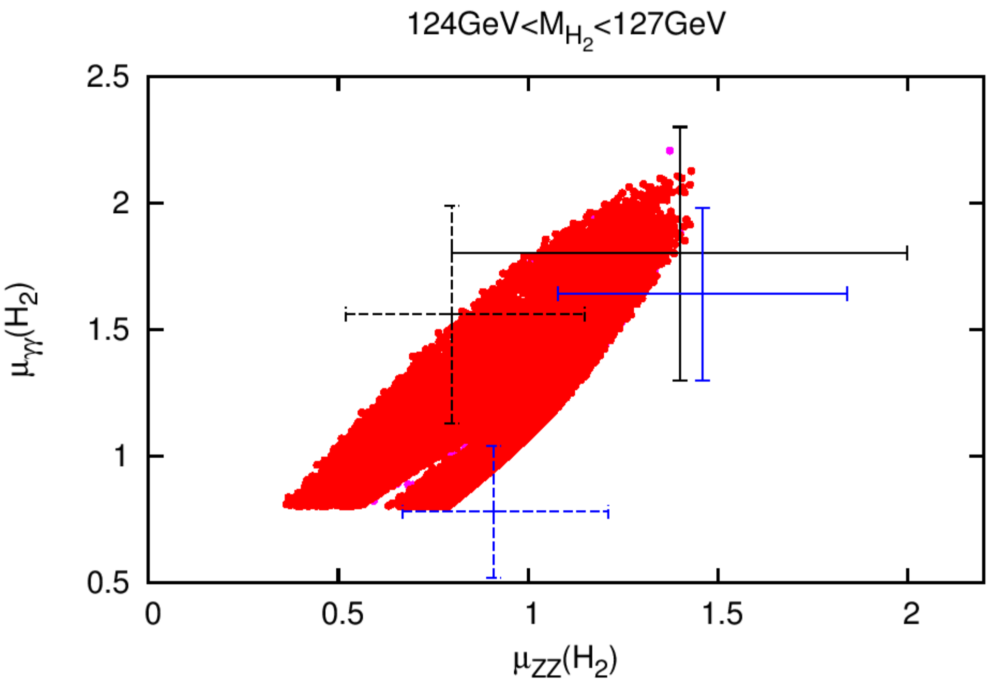



* cyan/pink points: two signals overlap
* crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS

# $\mathcal{NMSSM}$ $\mathcal{S}$can - $\mathcal{A}$fter-$\mathcal{M}$oriond

King,MMM,Nevzorov,Walz

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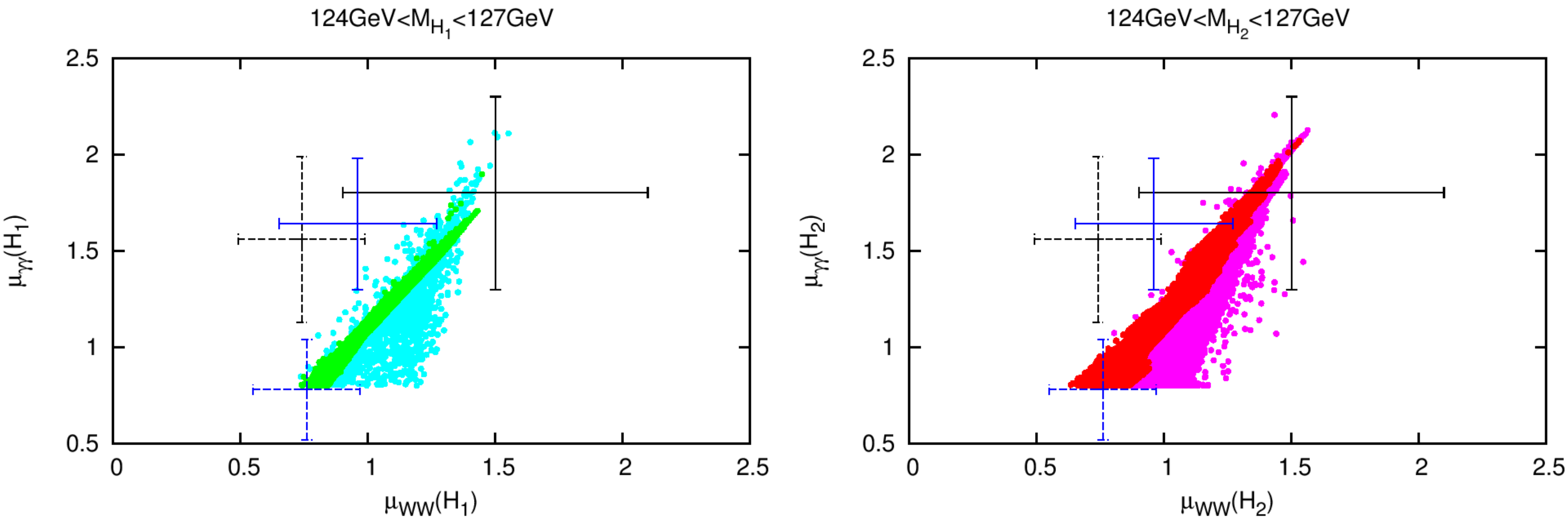


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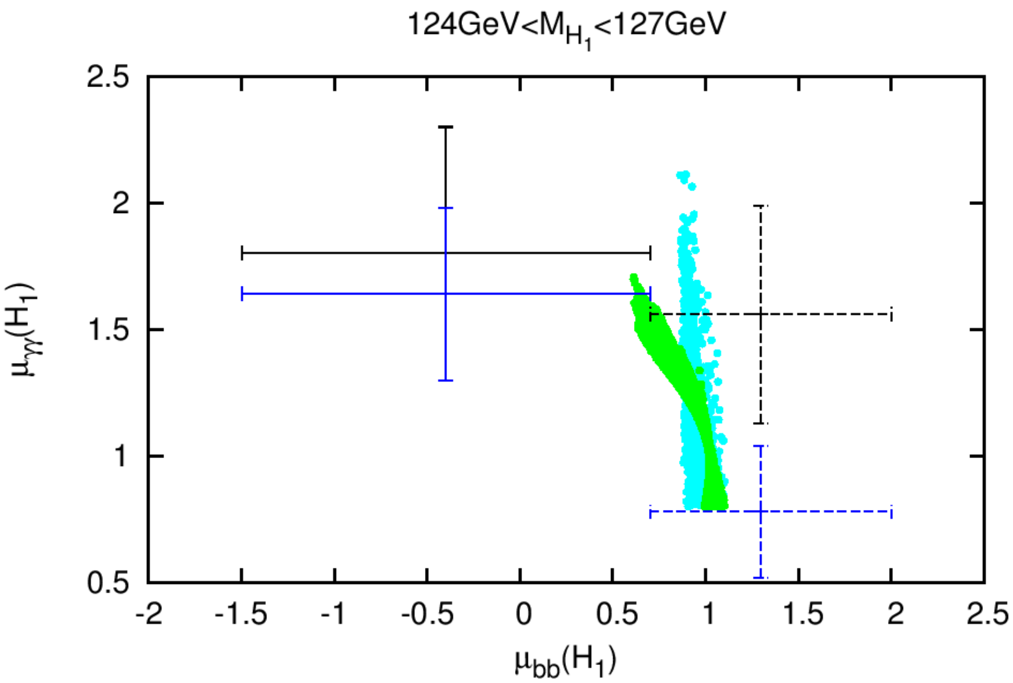
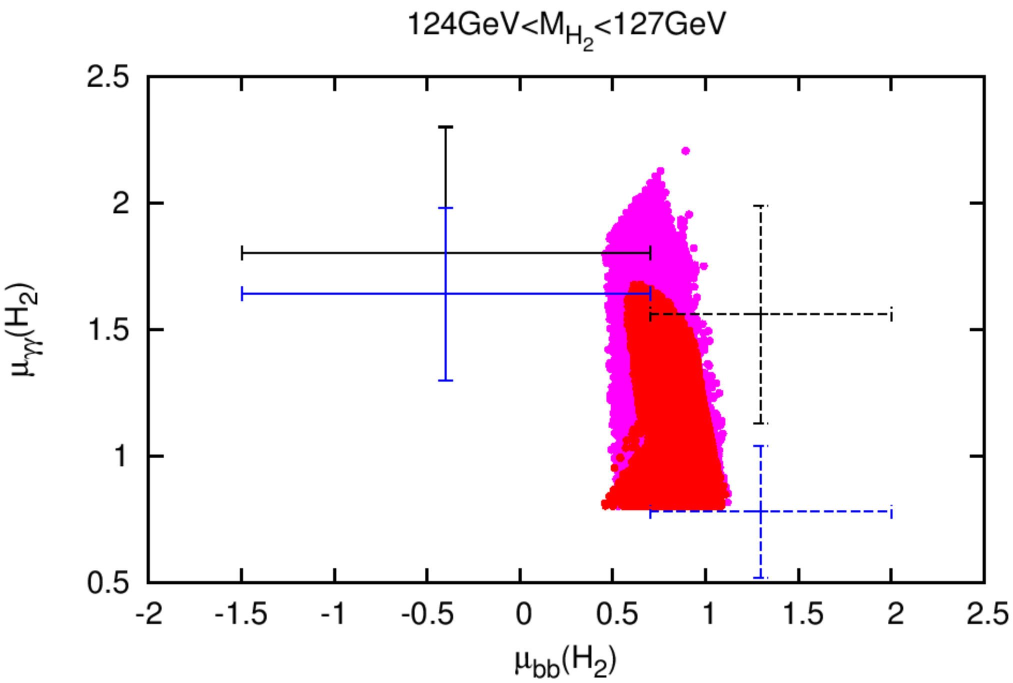
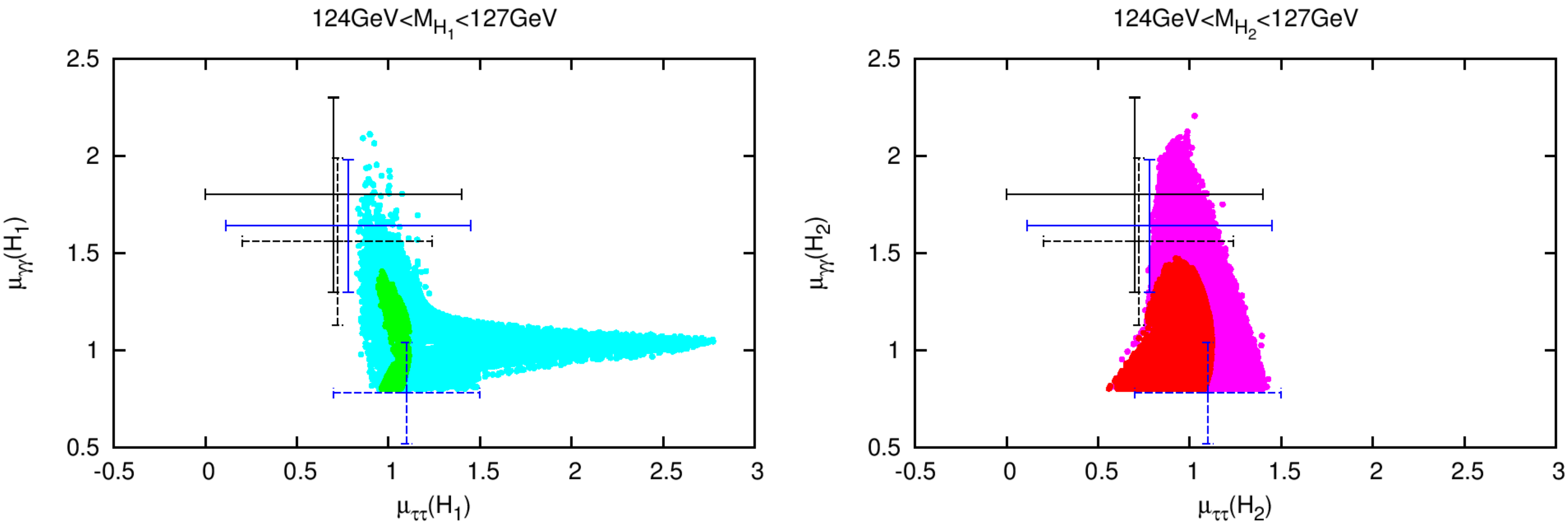



- $*$ cyan/pink points: two signals overlap
- $*$ crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS

# $\mathcal{NMSSM}$ $\mathcal{S}$can - $\mathcal{A}$fter $\mathcal{M}$oriond

King,MMM,Nevzorov,Walz




* cyan/pink points: two signals overlap
* crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS

## $\mathcal{S}$uperposition of $\mathcal{S}$ignal $\mathcal{R}$ates

$$R_{pp,H_i} = \frac{\sigma_{\rm incl}^{\rm NMSSM}}{\sigma_{\rm incl}^{\rm SM}} \cdot \frac{{\rm BR}(H_i \to pp)^{\rm NMSSM}}{{\rm BR}(H_i \to pp)^{\rm SM}} \qquad \text{with} \quad i = 1..5.$$

$$R_{pp,H_i}^{\rm combined} = \sum_{k=1}^{5} R_{pp,H_k} \cdot \underbrace{\exp\left(\frac{-(M_{H_k} - M_{H_i})^2}{2\,(d_p \cdot M_{H_k})^2}\right)}_{F_p(M_{H_k})}$$

This weighting factor depends on the mass difference and on a factor $d_p$ which is decay specific:

| $p$ | $\tau\tau$ | $WW$ | $bb$ | $ZZ$ | $\gamma\gamma$ |
|---|---|---|---|---|---|
| $d_p$ | 0.2 | 0.2 | 0.1 | 0.02 | 0.02 |