
Update of Hh *Final States*

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Coll. with Philipp Basler, Christoph Englert and Sally Dawson, 1812.03542

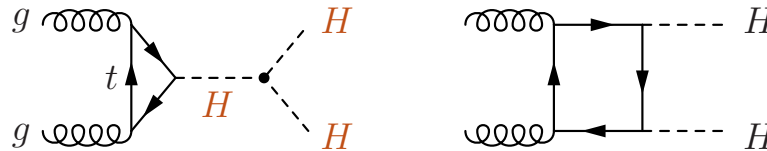
HH Subgroup Meeting
1 March 2019



Higgs Pair Production

- Higgs Pair Production

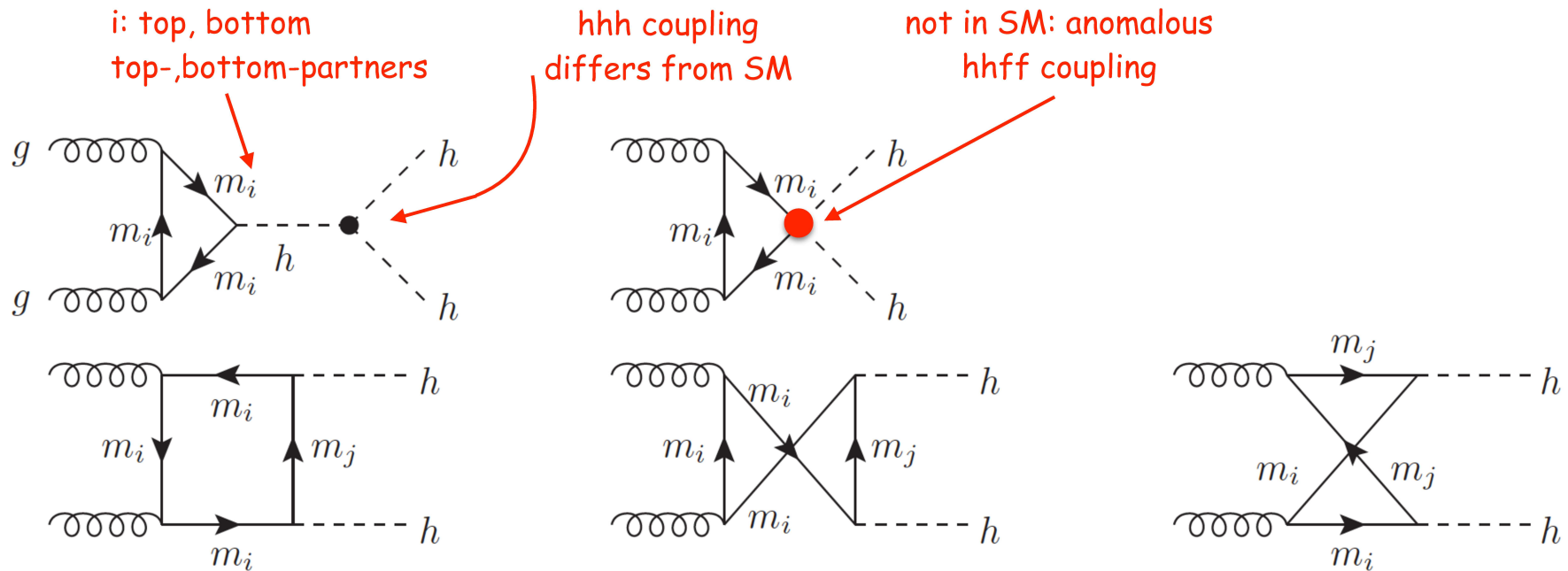
- at LHC dominant through gluon fusion



- measurement of $\lambda_{HHH} \rightsquigarrow$ insights into electroweak symmetry breaking
- SM: $\sigma_{gg \rightarrow HH}^{NLO} = 32.91 \text{ fb @ 14 TeV}$ [Borowka eal '16, Baglio eal '18]
 \rightsquigarrow experimental challenge
- signs of new physics
(even before seen in single Higgs production
 \leftarrow composite Higgs [Gröber,MMM,Spira,Streicher '15])

Di-Higgs Production Beyond the SM

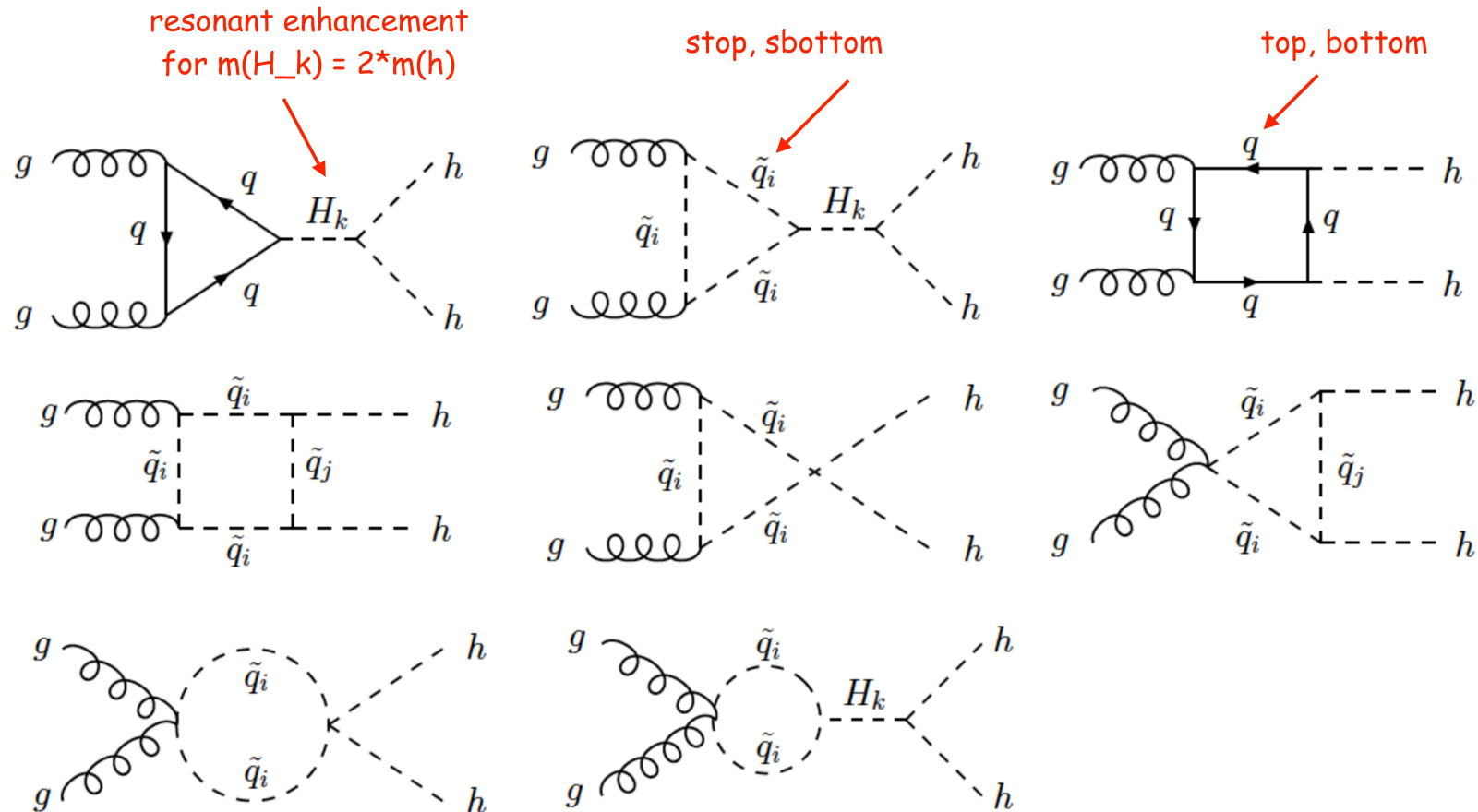
- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: composite Higgs
 - * different λ_{3H} ; * novel couplings; * novel particles in the loop; * resonant enhancement



Di-Higgs Production Beyond the SM

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: NMSSM

* different λ_{3H} ; * novel couplings; * novel particles in the loop; * resonant enhancement



Higgs Pair Production

- **New Physics Features**

- see previous two slides - and:
- di-Higgs production with **different Higgs bosons** in the final state

- **Expect the unexpected:**

- * Higgs-to-Higgs cascade decays in non-minimal Higgs sectors \rightsquigarrow
Exotic multi-fermion and/or multi-photon final states

- * Example NMSSM benchmark point BP7_P2

[King,MM,Nevzorov,Walz]

$$gg \rightarrow A_2 \rightarrow H_s A_1 \rightarrow A_1 A_1 A_1 \rightarrow bb + 4\gamma \quad 13.12\text{fb}$$

$$gg \rightarrow A_2 \rightarrow H_s A_1 \rightarrow A_1 A_1 A_1 \rightarrow 4b + 2\gamma \quad 84.78\text{fb}$$

- **Benchmark Models: CP-violating 2HDM (C2HDM) and NMSSM**

- **common feature:** extended Higgs sector with ≥ 3 neutral Higgs bosons
 \rightsquigarrow **possibility of $gg \rightarrow H_j H_k$ with $H_j \neq H_k$** and Higgs-to-Higgs cascade decays
- **different:** NMSSM Higgs self-couplings in terms of gauge couplings
C2HDM Higgs self-couplings free (modulo exp. & theor. constraints)

The \mathcal{NMSSM} Higgs Sector

- **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; ...

- **SUSY Higgs Sector:** at least 2 complex Higgs doublets, NMSSM: plus complex singlet field \rightsquigarrow

- **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: $\tilde{\chi}_i^0 (i = 1, \dots, 5)$

- **Significant changes of Higgs boson phenomenology**

The C2HDM

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right].$$

- **CP Violation:** m_{12}^2 , λ_5 can be complex (all others real); $m_{12}^2 \neq \lambda_5 \rightsquigarrow$ CP violation
- **Particle content:**
 - 3 neutral CP-mixing Higgs bosons H_1, H_2, H_3
 - 1 charged Higgs pair H^\pm
- **Flavour-Changing Neutral Currents (FCNC) at tree-level:** forbidden by \mathbb{Z}_2 symmetry

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2.$$

	Type I	Type II	Lepton-Specific	Flipped
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Leptons	Φ_2	Φ_1	Φ_1	Φ_2

The $\mathcal{C}2\text{HDM}$

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right].$$

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C2HDM Parameter Scan

- **Scan over parameter space:**

with ScannerS, checks for: [Coimbra,Sampaio,Santos '13; Ferreira,Guedes,Sampaio,Santos '14]

- **Theoretical constraints:**

boundedness from below, tree-level perturbative unitarity, EW vacuum is global minimum of tree-level potential and also NLO [BSMPT, Basler,MMM '18]

- **Experimental constraints::**

* S, T, U parameters for EW precision observables [Baak eal '14]

* $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$ and $B \rightarrow X_s \gamma$ [Haber,Logan '99;Deschamps eal '09; Mahmoudi,Stal '09; Steinhauser eal '17]

* Higgs exclusion bounds by HiggsBounds [Bechtle eal '08,'11,'13]

* Higgs rates checked via SUSHI and C2HDM_HDECAY [Harlander eal; Fontes eal]

* Electric dipole moment of the electron [The ACME Collaboration]

C2HDM Scan Ranges

	t_β	$\alpha_{1,2,3}$	$\text{Re}(m_{12}^2)$ [TeV ²]	m_{H^\pm} [TeV]	$m_{H_i \neq h}$ [TeV]
min	0.8	$-\frac{\pi}{2}$	0	0.15/0.59	0.01
max	20	$\frac{\pi}{2}$	0.5	1.5	1.5

$$10 \text{ GeV} \leq m_{H_j} < 1.5 \text{ TeV}$$

$$\begin{aligned}
 \alpha(M_Z) &= 1/127.92, & \alpha_s^{\overline{\text{MS}}}(M_Z) &= 0.118, \\
 M_Z &= 91.187 \text{ GeV}, & M_W &= 80.358 \text{ GeV}, \\
 m_t &= 172.5 \text{ GeV}, & m_b^{\overline{\text{MS}}}(m_b^{\overline{\text{MS}}}) &= 4.18 \text{ GeV}, \\
 m_\tau &= 1.777 \text{ GeV}.
 \end{aligned}$$

\mathcal{N} MSSM Scan

- **Conditions on the parameter scan:**

- * At least one CP-even Higgs boson $H_i \equiv h$ with: $124 \text{ GeV} \lesssim M_h \lesssim 126 \text{ GeV}$
- * Compatibility with μ_{XX}^{exp} ($X = b, \tau, \gamma, W, Z$) [SusHi, NMSSMTools, NMSSMCALC]
- * Compatibility with Higgs exclusion bounds [HiggsBounds]
- * Compatibility with SUSY searches
- * Compatibility w/ DM constraints [PLANCK, LUX, XENON1T, micrOmegas]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

NMSSM Scan Ranges

	t_β	λ	κ	M_1	M_2	M_3	A_t	A_b	A_τ	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$	A_λ	A_κ	μ_{eff}
	in TeV													
min	1	0	-0.7	0.1	0.2	1.3	-6	-6	-3	0.6	0.6	-2	-2	-5
max	50	0.7	0.7	1	2	7	6	6	3	4	4	2	2	5

$$m_{\tilde{t}_R} = m_{\tilde{Q}_3}, \quad m_{\tilde{\tau}_R} = m_{\tilde{L}_3} \quad \text{and} \quad m_{\tilde{b}_R} = 3 \text{ TeV}$$

$$m_{\tilde{u}_R, \tilde{c}_R} = m_{\tilde{d}_R, \tilde{s}_R} = m_{\tilde{Q}_{1,2}} = m_{\tilde{L}_{1,2}} = m_{\tilde{e}_R, \tilde{\mu}_R} = 3 \text{ TeV}$$

$$\lambda^2 + \kappa^2 < 0.7^2$$

Update since arXiv version: HiggsBounds5.2.0 \rightarrow 5.3.0;

before rates demanded to be within twice 1σ bound, now HiggsSignals2.2.2 used to demand compatibility within 2σ

Notation

- **Notation C2HDM & NMSSM:**

h - SM-like Higgs boson

H_{\downarrow} - lighter non-SM-like Higgs boson

H_{\uparrow} - heavier non-SM-like Higgs boson

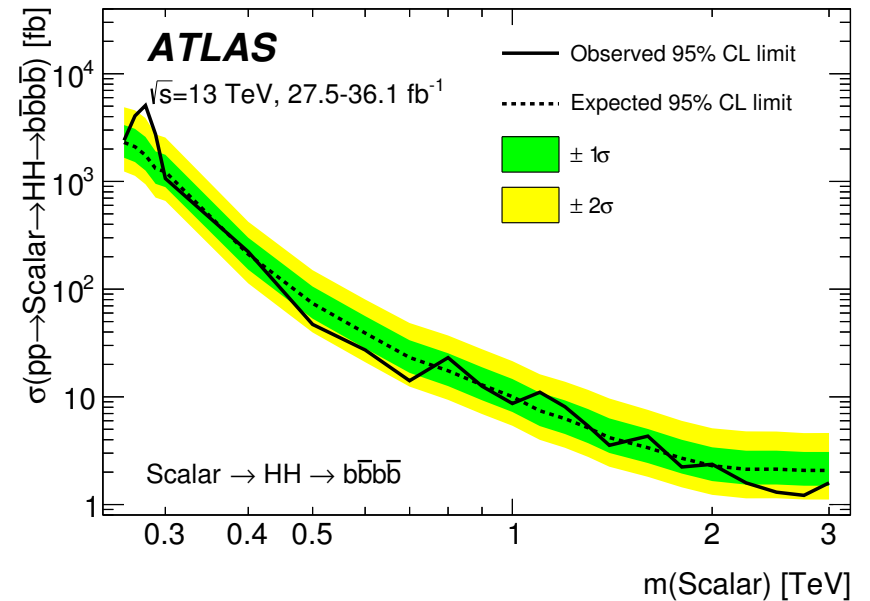
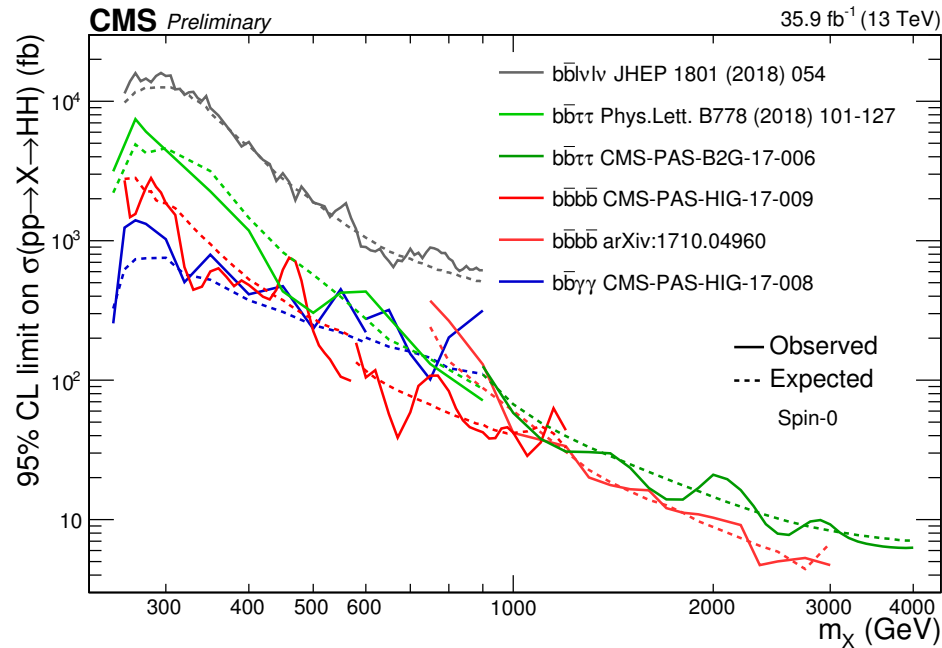
- **Additionally in NMSSM:**

A_{\downarrow} - lighter non-SM-like pseudoscalar Higgs boson

A_{\uparrow} - heavier non-SM-like pseudoscalar Higgs boson

$h, H_{\downarrow}, H_{\uparrow}$ CP-mixing states in C2HDM, pure scalars in CP-conserving NMSSM

Experimental Results - Implications for BSM SM-like Higgs Pair Production



- limits $\mathcal{O}(\text{pb})$ for $m_X \leq 300$ GeV
- limits $\mathcal{O}(\text{fb})$ for $m_X \geq 1$ TeV \rightsquigarrow severely limits enhancement in hh production

Interplay Single Higgs and Di-Higgs Production

- **Heavy Higgs Bosons:**

- * decay into $t\bar{t}$ if kinematically possible
- * **exotic 4-top** final state from production of heavy Higgs boson pair
- * large rates constrained by single Higgs production in $t\bar{t}$ final state
- * **encourage experiments to look into these single Higgs signatures**

- **Light Higgs Bosons:**

- * light Higgs states below 125 GeV possible
- * **huge di-Higgs cross sections**
- * dominant decays into $b\bar{b}$, $\tau\bar{\tau}$, $\gamma\gamma$
- * large rates constrained by single production of light Higgs bosons
- * **encourage experiments to look for light Higgs bosons**

Maximum Cross Section Values

- Maximum cross section values C2HDM:

$H_i H_j / \text{model}$	T1	T2
hh	794	34.2
hH_{\downarrow}	49.17	11.38
hH_{\uparrow}	17.65	10.84
$H_{\downarrow} H_{\downarrow}$	3196	0.18
$H_{\downarrow} H_{\uparrow}$	12.58	0.11
$H_{\uparrow} H_{\uparrow}$	7.10	0.18

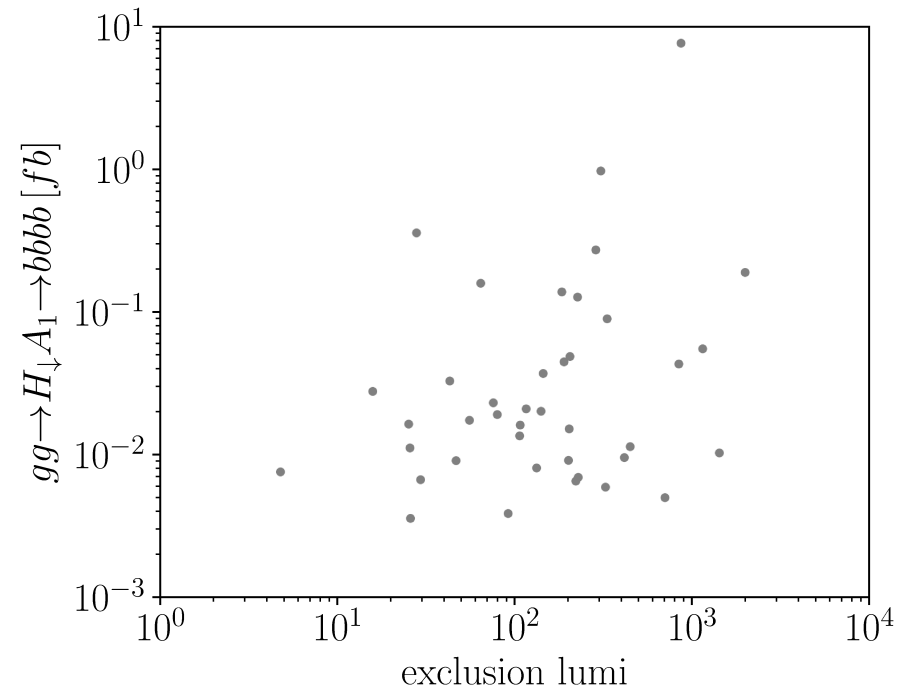
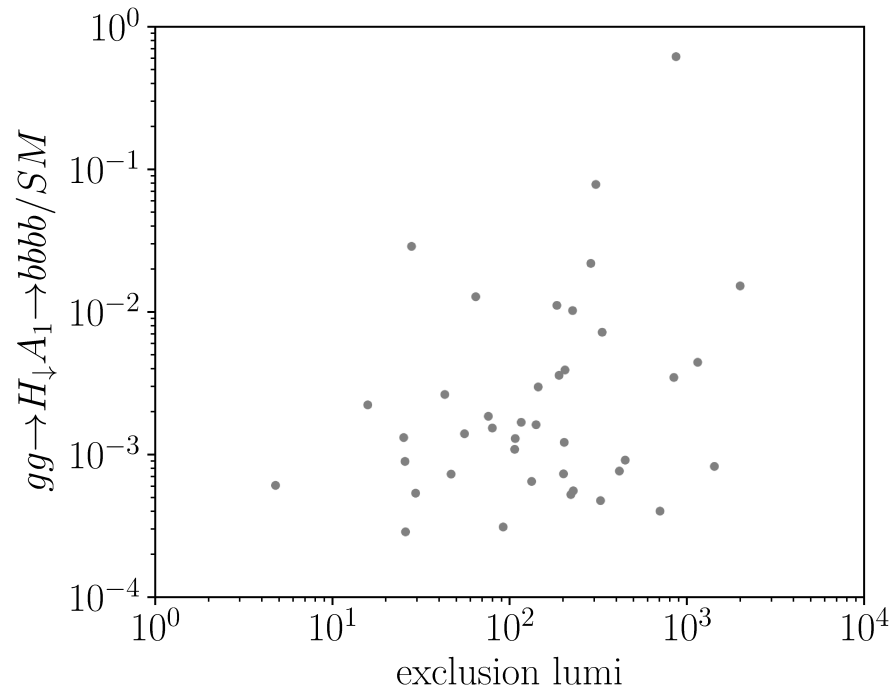
T1 - Type 1, T2 - Type 2

- Maximum cross section values NMSSM:

$H_i H_j$	NMSSM
hh	34
hH_{\downarrow}	125
hA_{\downarrow}	70
hH_{\uparrow}	0.11
$H_{\downarrow} H_{\downarrow}$	3.7
$H_{\downarrow} H_{\uparrow}$	0.2
$H_{\uparrow} H_{\uparrow}$	0.004
$A_{\downarrow} A_{\downarrow}$	70

Scatter Plots $\mathcal{N}MSSM - H_{\downarrow}A_{\downarrow}$ Production in $4b$

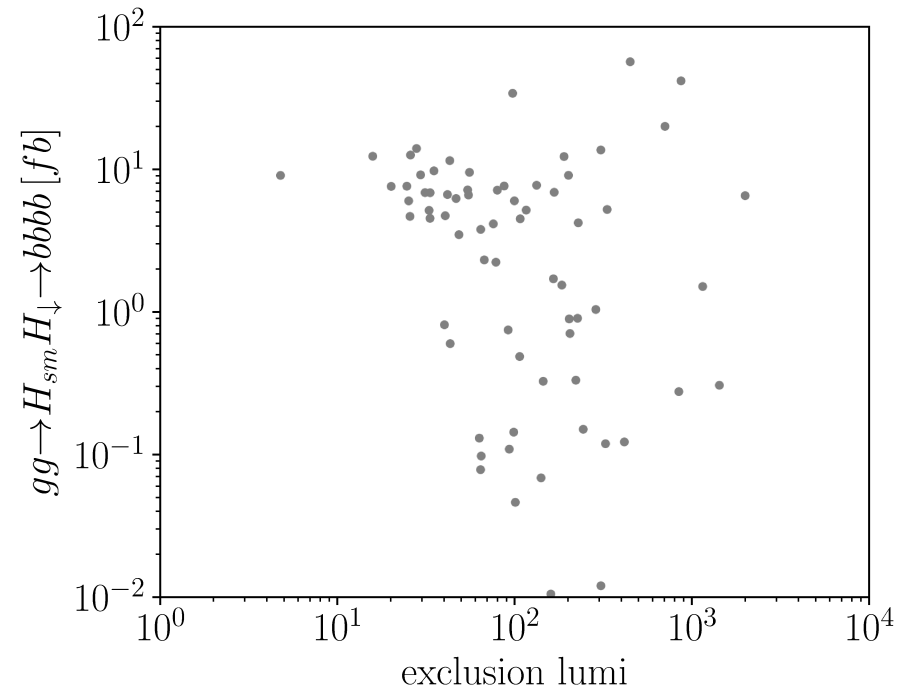
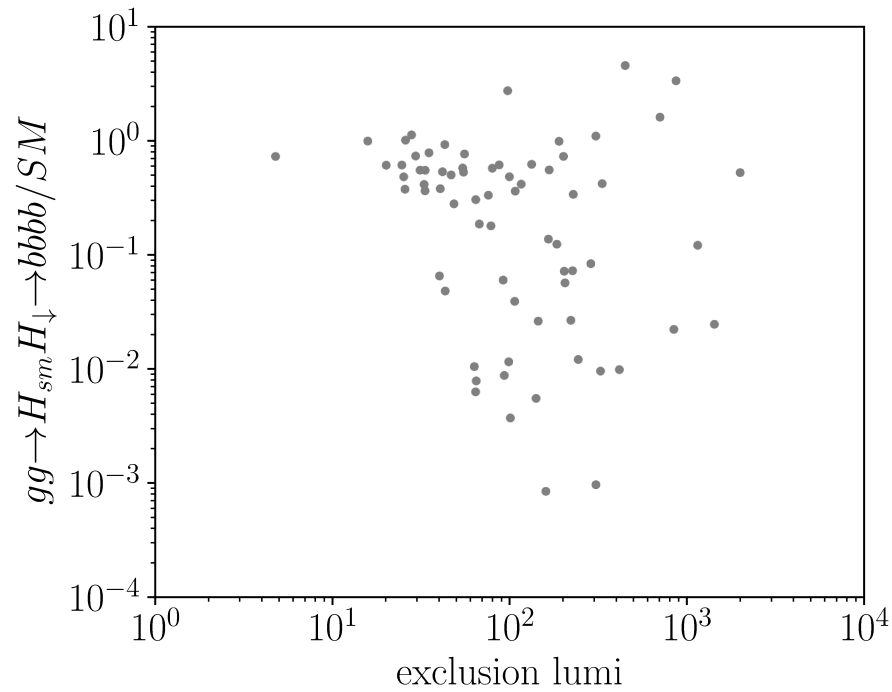
[Basler, Dawson, Englert, MM '19]



- $H_{\downarrow}A_{\downarrow} \rightarrow 4b$ left: normalised to SM

Scatter Plots $\mathcal{N}MSSM$ - hH_{\downarrow} Production in $4b$

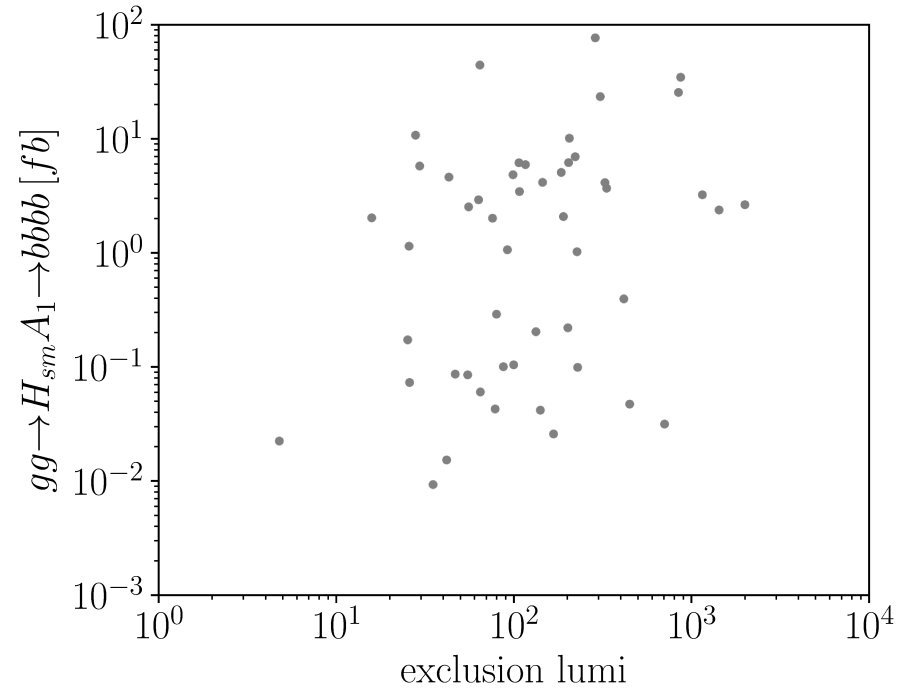
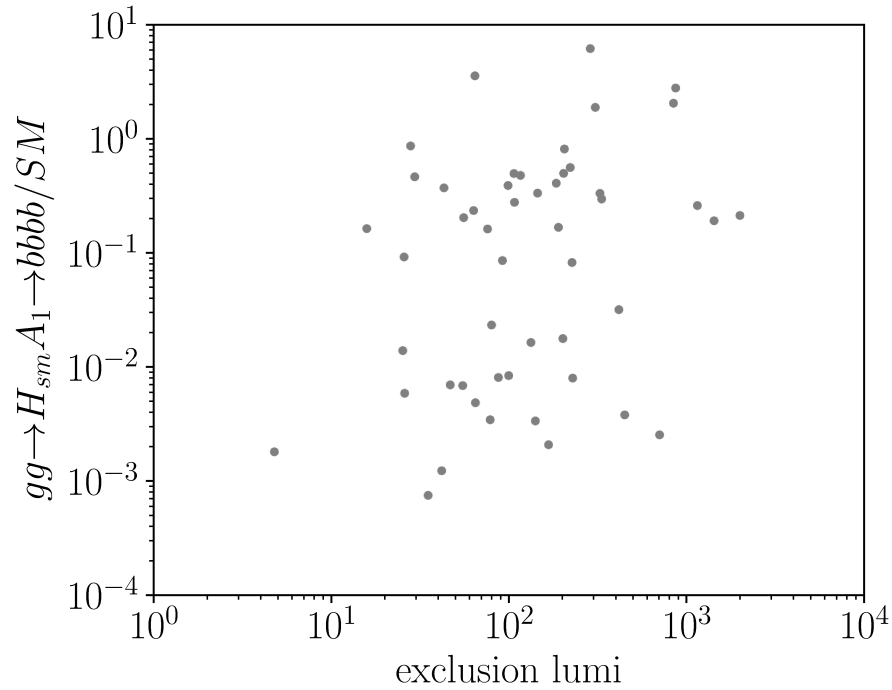
[Basler, Dawson, Englert, MM '19]



- $hH_{\downarrow} \rightarrow 4b$ left: normalised to SM; factor 10 compared to $H_{\downarrow} A_{\downarrow} \rightarrow 4b$

Scatter Plots $\mathcal{N}MSSM$ - hA_\downarrow Production in $4b$

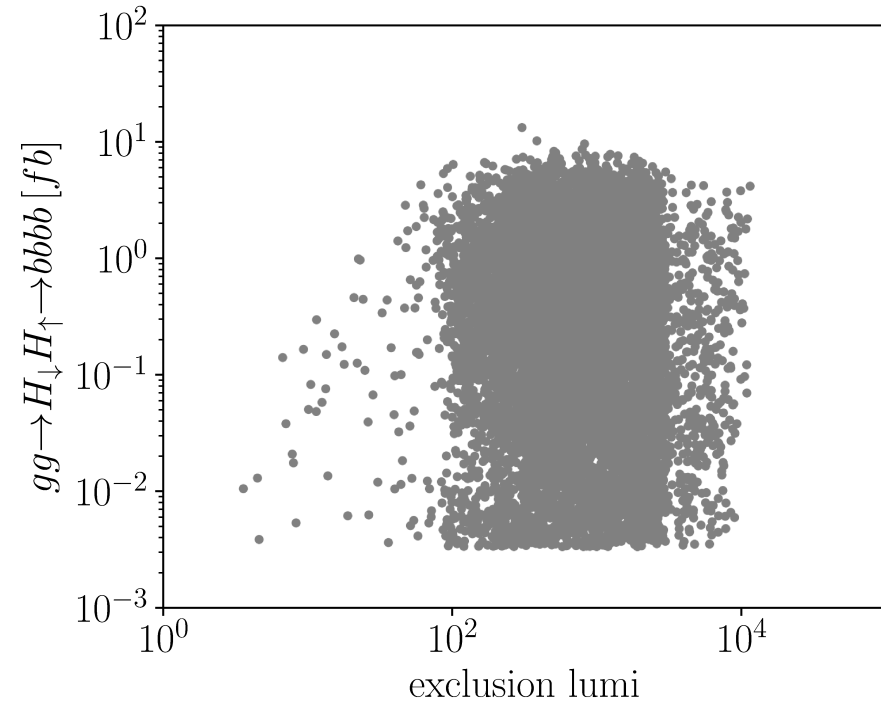
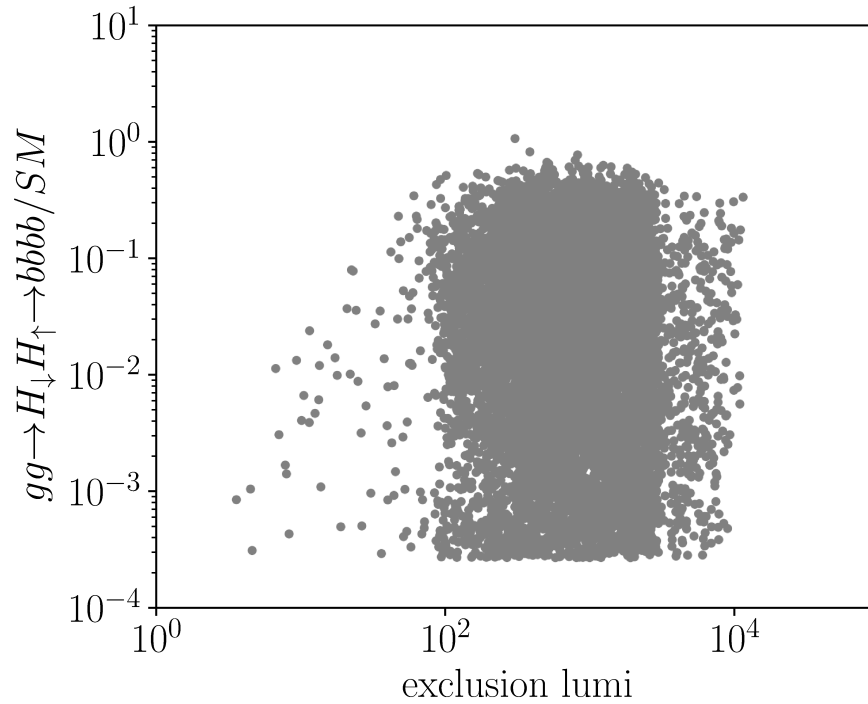
[Basler, Dawson, Englert, MM '19]



- $hA_\downarrow \rightarrow 4b$ left: normalised to SM; comparable to $hH_\downarrow \rightarrow 4b$

Scatter Plots C2HDM T1 - $H_{\downarrow}H_{\uparrow}$ Production in $4b$

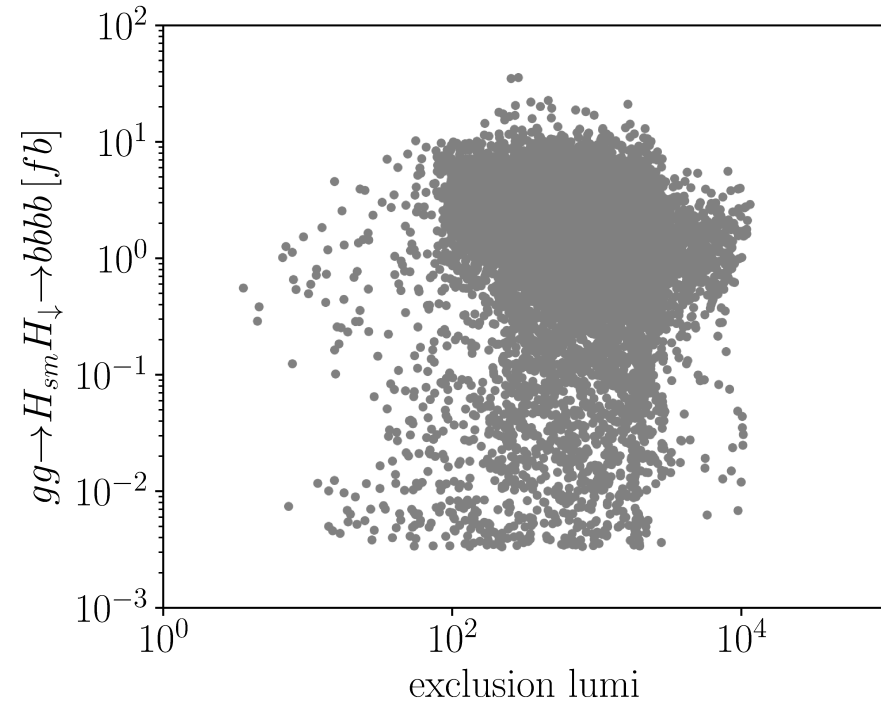
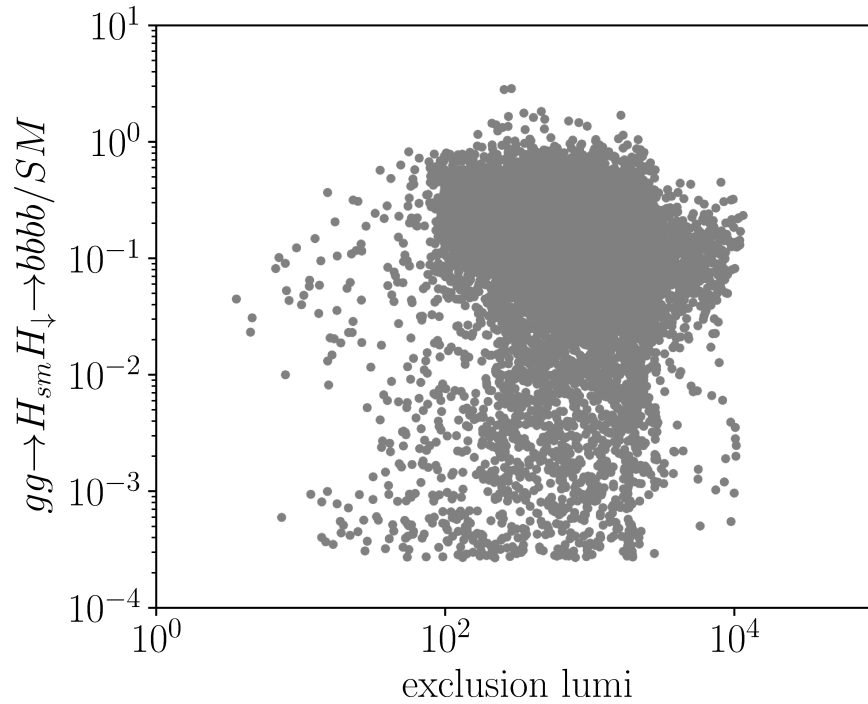
[Basler, Dawson, Englert, MM '18]



- T1 C2HDM: $H_{\downarrow}H_{\uparrow} \rightarrow 4b$; left: normalised to SM; comparable to $A_{\downarrow}H_{\downarrow}$ in NMSSM

Scatter Plots C2HDM T1 - hH_{\downarrow} Production in $4b$

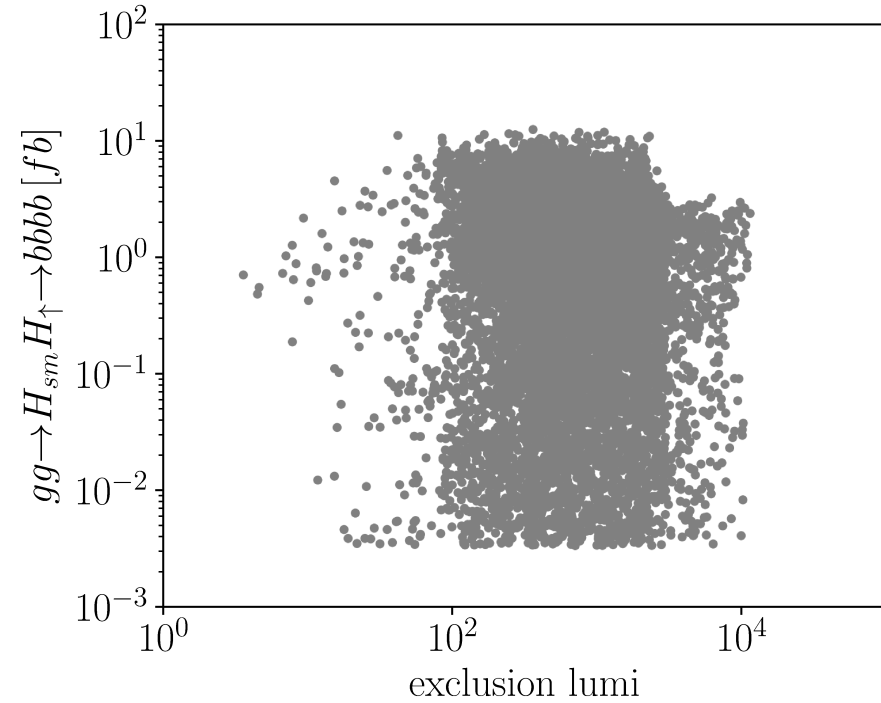
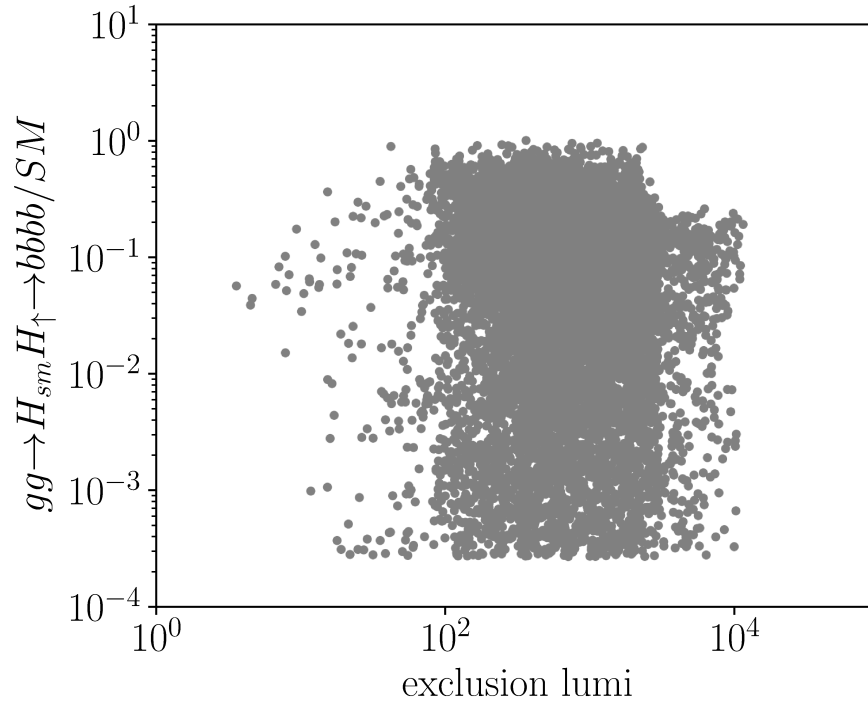
[Basler, Dawson, Englert, MM '18]



- C2HDM T1: $hH_{\downarrow} \rightarrow 4b$; left: normalised to SM; \sim factor 3 compared to $H_{\downarrow}H_{\uparrow} \rightarrow 4b$;
slightly below hH_{\downarrow} in NMSSM

Scatter Plots C2HDM T1 - hH_{\uparrow} Production in $4b$

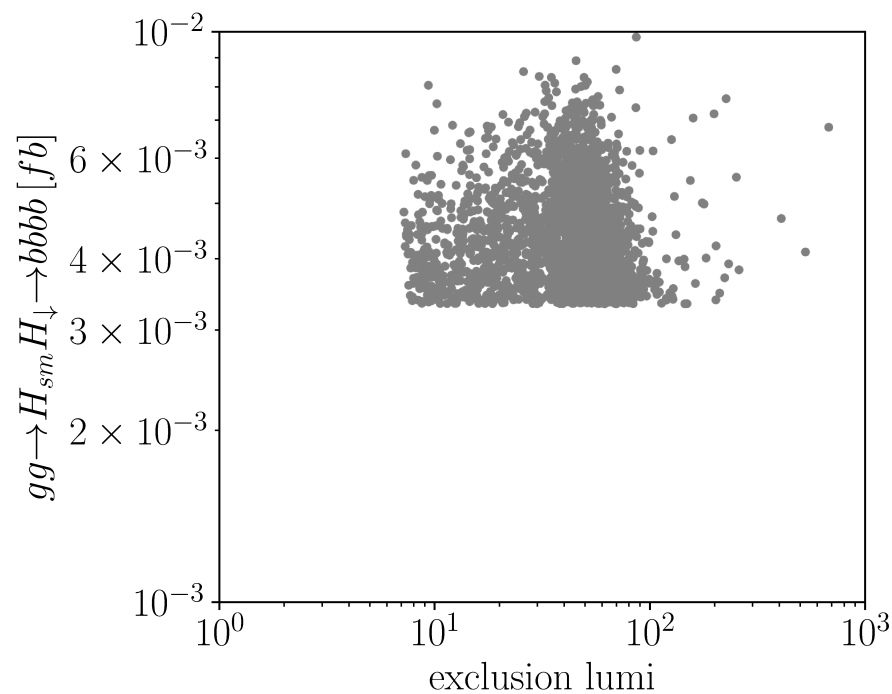
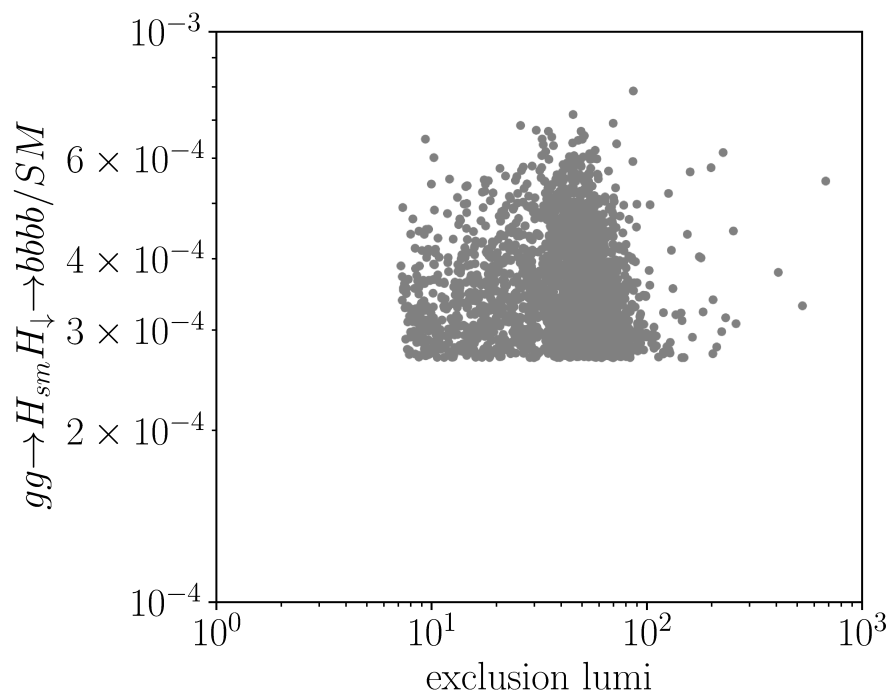
[Basler, Dawson, Englert, MM '18]



- C2HDM T1: $hH_{\uparrow} \rightarrow 4b$ left: normalised to SM; about factor 3 below hH_{\downarrow} ;
factor 10 below hH_{\downarrow} , hA_{\downarrow} production in NMSSM

Scatter Plots C2HDM T2 - hH_{\downarrow} Production in $4b$

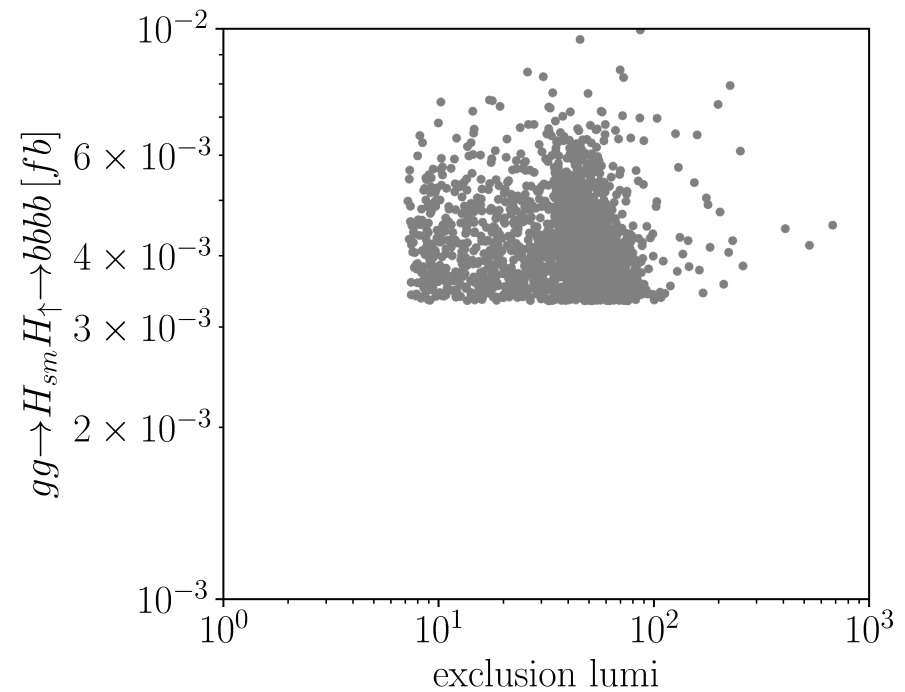
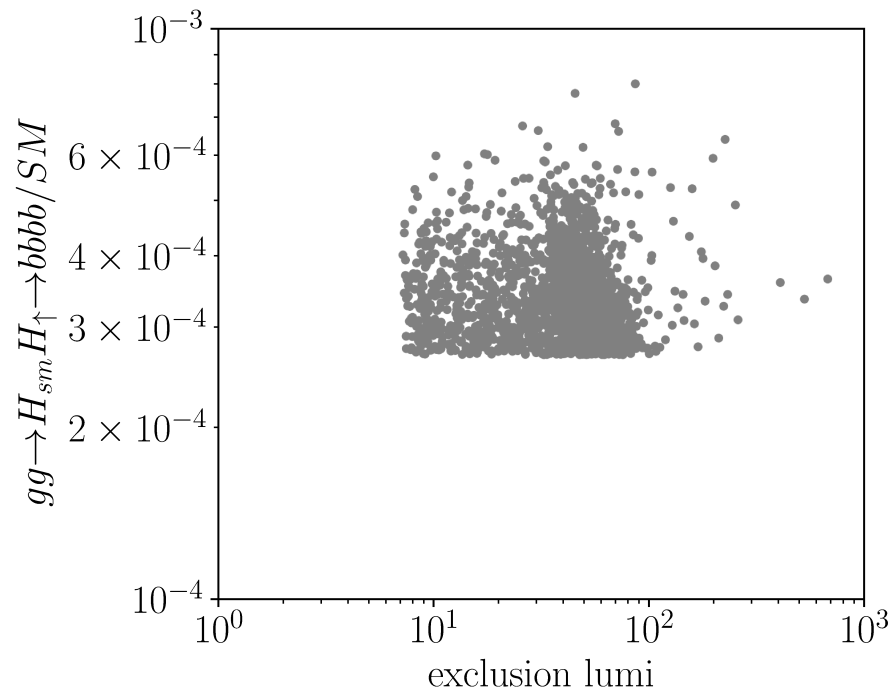
[Basler, Dawson, Englert, MM '18]



- C2HDM T2: $hH_{\downarrow} \rightarrow 4b$; left: normalised to SM; much smaller than in NMSSM and C2HDM T1

Scatter Plots C2HDM T2 - $hH_{\uparrow} \rightarrow 4b$ Production in 4b

[Basler, Dawson, Englert, MM '18]



- C2HDM T2: $hH_{\uparrow} \rightarrow 4b$ left: normalised to SM; much smaller than in NMSSM and C2HDM T1

NMSSM Benchmark Points

- **Criteria for selection:** NMBP3 chosen to maximize $hH_{\downarrow} \rightarrow 4b$;
NMBP6 chosen to maximize $hA_{\downarrow} \rightarrow 4b$; both $\mathcal{L}_{\text{excl}} > 100 \text{ fb}^{-1}$
- **NMSSM rates normalized to SM rate for di-Higgs final state $[H_i H_j]$:**

$$(xx)(yy): [pp \rightarrow H_i H_j \rightarrow (xx)(yy)] / [pp \rightarrow H^{\text{SM}} H^{\text{SM}} \rightarrow (xx)(yy)]$$

	NMBP3	NMBP6
$(b\bar{b})(b\bar{b})_{H_i H_j}$ [fb]	$[hH_{\downarrow}]$: 4.57	$[hA_{\downarrow}]$: 6.17
$(b\bar{b})(\tau\bar{\tau})_{H_i H_j}$ [fb]	$[hH_{\downarrow}]$: 4.43	$[hA_{\downarrow}]$: 5.76
$(b\bar{b})(\gamma\gamma)_{H_i H_j}$ [fb]	$[hH_{\downarrow}]$: 2.42	$[hA_{\downarrow}]$: 3.96

- NMBP3(100), NMBP6: **non-SM-like signature** \leftarrow 2 different Higgs bosons
SM-like Higgs boson can be used to calibrate/tag this exotic configuration

NMSSM Benchmark Points

	NMBP3	NMBP6
$\tan \beta$	2.83	2.92
λ	0.61	0.61
κ	0.33	0.33
A_λ [GeV]	441	-348
A_κ [GeV]	-306	-51
μ_{eff} [GeV]	193	-159
m_{H_1} [GeV]	99.02	125.03
m_{H_2} [GeV]	125.26	170.66
m_{H_3} [GeV]	562.99	454.90
m_{A_1} [GeV]	333.75	69.03
m_{A_2} [GeV]	557.80	446.26
m_{H^\pm} [GeV]	551.94	440.31
$\mathcal{L}_{\text{excl}}$ [fb ⁻¹]	449	287
σ_{hh}^{LO} [fb]	26.04	34.18

\mathcal{N} MSSM Benchmark Points - Phenomenology

- Phenomenological features: NMBP3

$$BR(H_{\uparrow} \rightarrow H_{\downarrow} h) = 0.262$$

$$BR(A_{\uparrow} \rightarrow ZH_{\downarrow}) = 0.189$$

$$BR(H^{\pm} \rightarrow W^{\pm} H_{\downarrow}) = 0.218$$

- Phenomenological features: NMBP6

$$BR(H_{\downarrow} \rightarrow A_{\downarrow} A_{\downarrow}) = 0.966 \text{ !}$$

$$BR(H_{\uparrow} \rightarrow H_{\downarrow} h) = 0.223$$

$$BR(A_{\uparrow} \rightarrow ZH_{\downarrow}) = 0.168$$

$$BR(H^{\pm} \rightarrow W^{\pm} H_{\downarrow}) = 0.192$$

C2HDM Benchmark Points 1 - Continued

- **Criteria for selection:** T1BP2 chosen to maximize $gg \rightarrow hH_\downarrow$ and $\mathcal{L}_{\text{excl}} > 1000 \text{ fb}^{-1}$

- **C2HDM rates normalized to SM rate for di-Higgs final state $[H_i H_j]$:**

$$(xx)(yy): [pp \rightarrow H_i H_j \rightarrow (xx)(yy)] / [pp \rightarrow H^{\text{SM}} H^{\text{SM}} \rightarrow (xx)(yy)]$$

	T1BP2
$(b\bar{b})(b\bar{b})_{H_i H_j}$ [fb]	$[hH_\downarrow]: 1.69$
$(b\bar{b})(\tau\bar{\tau})_{H_i H_j}$ [fb]	$[hH_\downarrow]: 1.70$
$(b\bar{b})(\gamma\gamma)_{H_i H_j}$ [fb]	$[hH_\downarrow]: 0.97$

- T1BP2: **non-SM-like signature** \leftarrow 2 different Higgs bosons

SM-like Higgs boson can be used to calibrate/tag this exotic configuration

- **Phenomenology:** $BR(H_\uparrow \rightarrow H_\downarrow H_\downarrow) = 0.614$!; $BR(H_\uparrow \rightarrow ZH_\downarrow) = 0.384$;
 $BR(H^\pm \rightarrow W^\pm H_\downarrow) = 0.736$

C2HDM Benchmark Points 1

	T1BP2
m_{H_1} [GeV]	125.09
m_{H_2} [GeV]	131.52
m_{H^\pm} [GeV]	282.75
$\text{Re}(m_{12}^2)$ [GeV ²]	12376
α_1	1.249
α_2	-0.032
α_3	-1.570
$\tan \beta$	3.23
m_{H_3} [GeV]	290.17
R_{13}^2	$1.027 \cdot 10^{-3}$
R_{23}^2	0.999
R_{33}^2	$1.217 \cdot 10^{-6}$
$\mathcal{L}_{\text{excl}}$ [fb ⁻¹]	1641
σ_{hh}^{NLO} [fb]	36.59
K -factor	1.95

R_{i3}^2 quantifies
singlet admixture

Summary

- **Multi-Higgs Production**

- * key process to understand mechanism of EWSB
- * phenomenologically highly correlated with single Higgs production
- * might be discovery tool for BSM interactions

- **Representative features of benchmark points:**

- * expected sensitivity of the $t\bar{t}$ resonance crucial for relevance of di-Higgs searches
- * lower exotic Higgs masses: di-Higgs final states typically follow SM decay rates w/ compressed masses \rightsquigarrow achieve high mass resolution in standard search channels, $(2b)(2b)$, $(2b)(2\tau)$, $(2b)(2\gamma)$
- * Higgs exotics can create multiple resonant features \rightsquigarrow large enhancement of SM Higgs pair production \rightsquigarrow discovery tool for BSM physics
- * Possibility of H_1H_2 production with $H_1 \neq H_2$

- **Ongoing activities in NMSSM subgroup:**

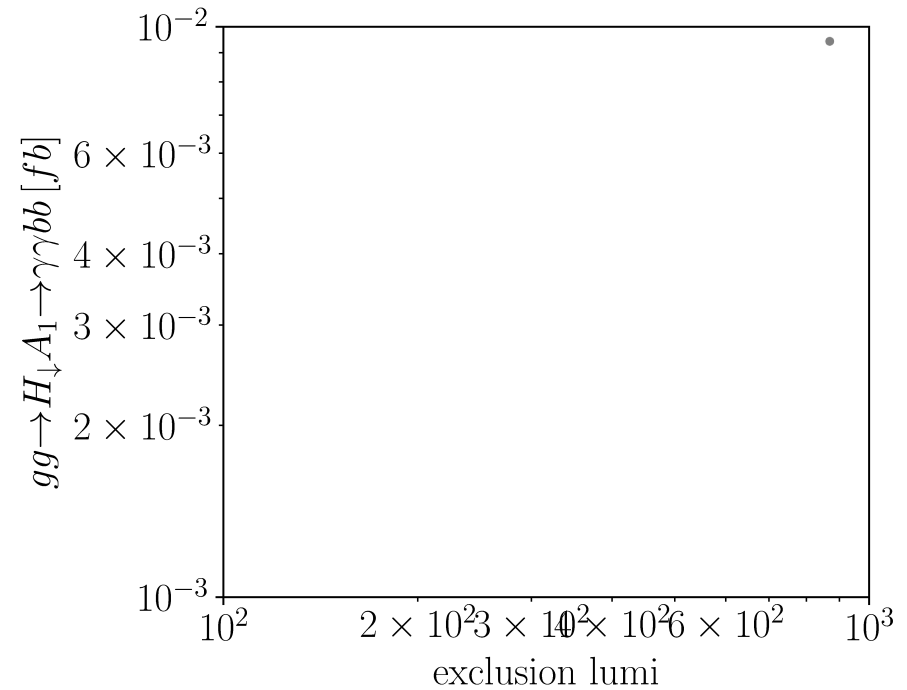
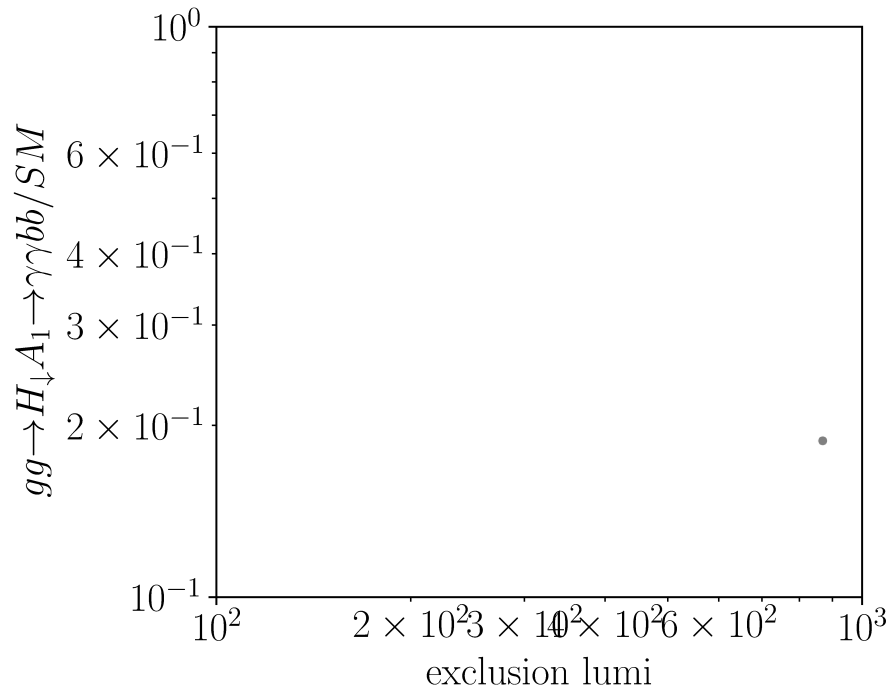
- * Generation of data samples w/ maximized hH_i production in various final states - compatible w/ constraints; benchmark planes

Thank You For Your Attention!



Scatter Plots $\mathcal{N}MSSM$ - $H_{\downarrow}A_{\downarrow}$ Production in $(2b)(2\gamma)$

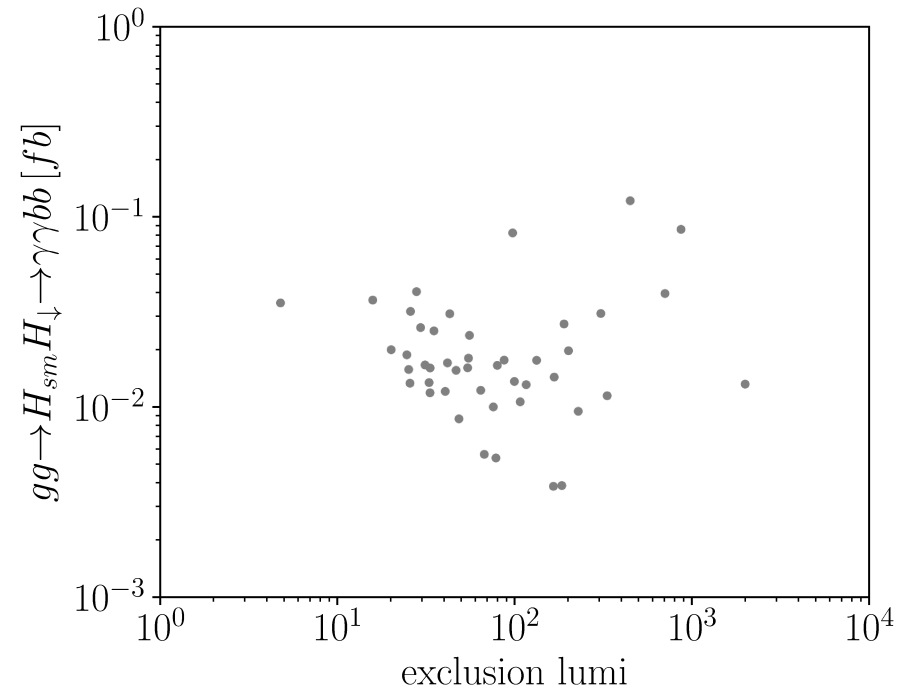
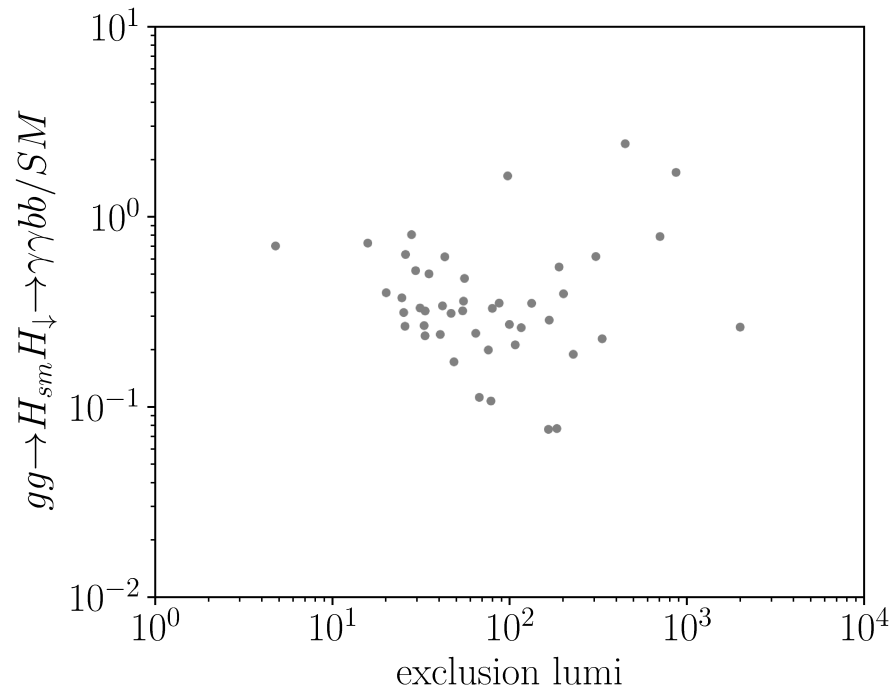
[Basler, Dawson, Englert, MM '19]



- $H_{\downarrow}A_{\downarrow} \rightarrow (2b)(2\gamma)$ left: normalised to SM

Scatter Plots \mathcal{N} MSSM - hH_{\downarrow} Production in $(2b)(2\gamma)$

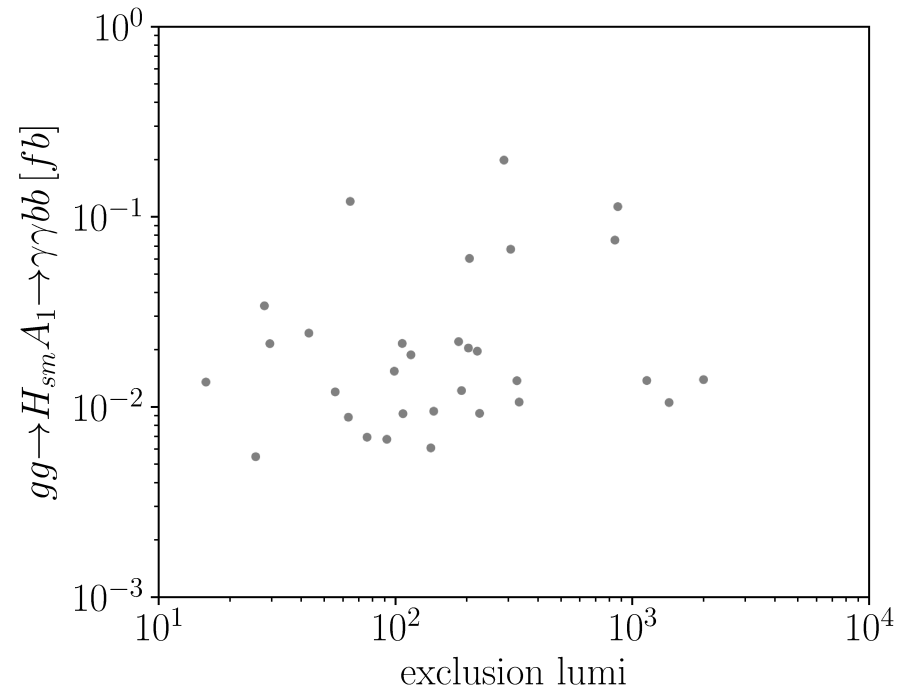
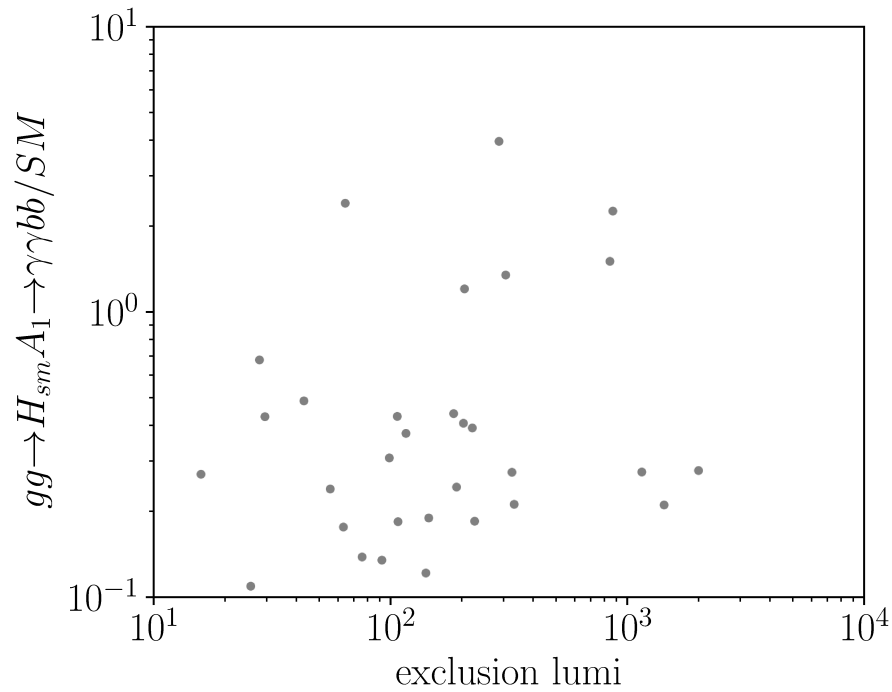
[Basler, Dawson, Englert, MM '19]



- $hH_{\downarrow} \rightarrow (2b)(2\gamma)$ left: normalised to SM; factor 10 compared to $H_{\downarrow}A_{\downarrow} \rightarrow (2b)(2\gamma)$

Scatter Plots \mathcal{N} MSSM - hA_\downarrow Production in $(2b)(2\gamma)$

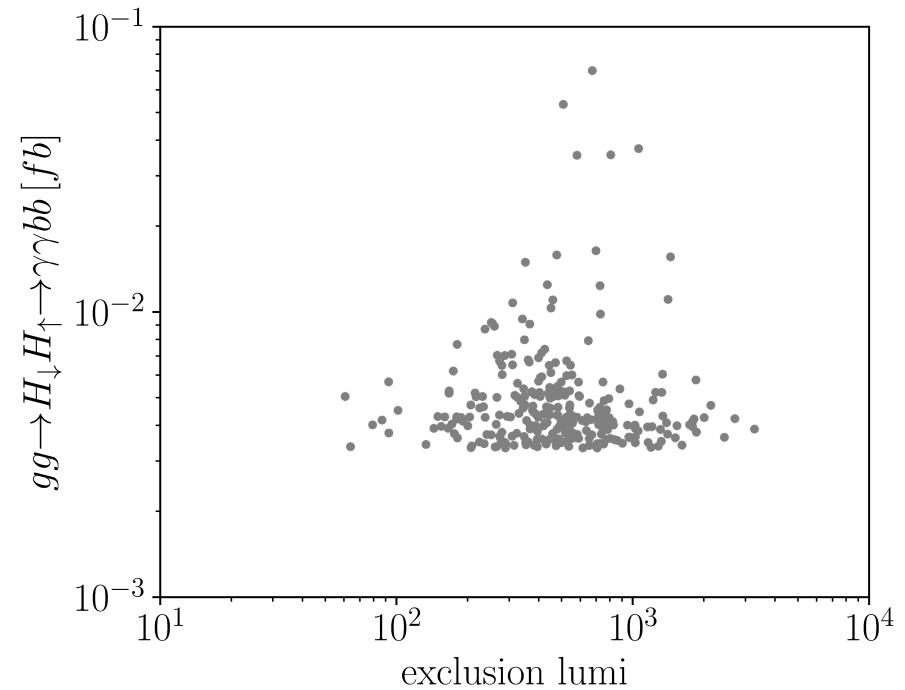
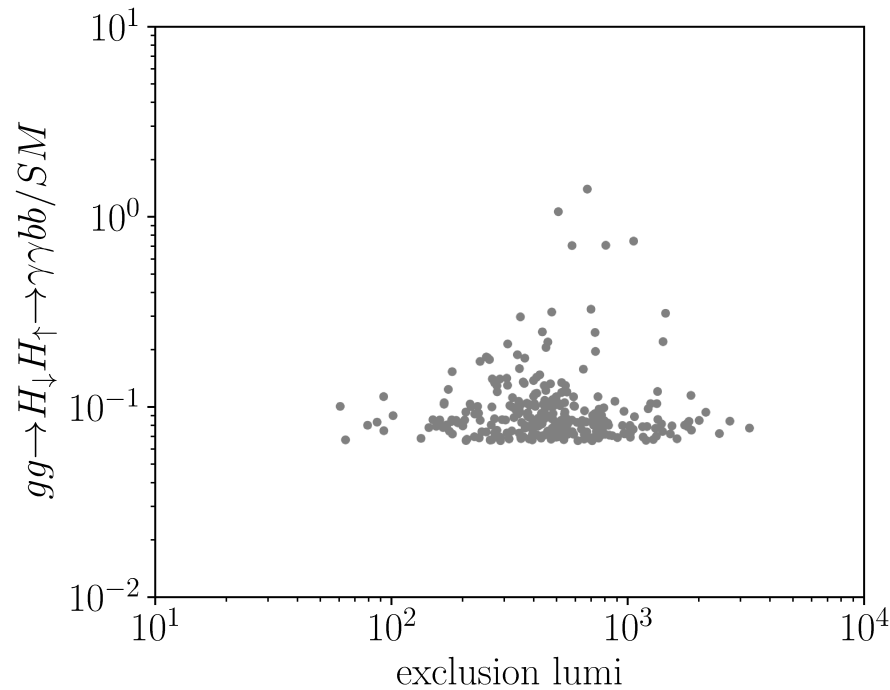
[Basler, Dawson, Englert, MM '19]



- $hA_\downarrow \rightarrow (2b)(2\gamma)$ left: normalised to SM; comparable to $hH_\downarrow \rightarrow (2b)(2\gamma)$

Scatter Plots C2HDM T1 - $H_{\downarrow}H_{\uparrow}$ Production in $(2b)(2\gamma)$

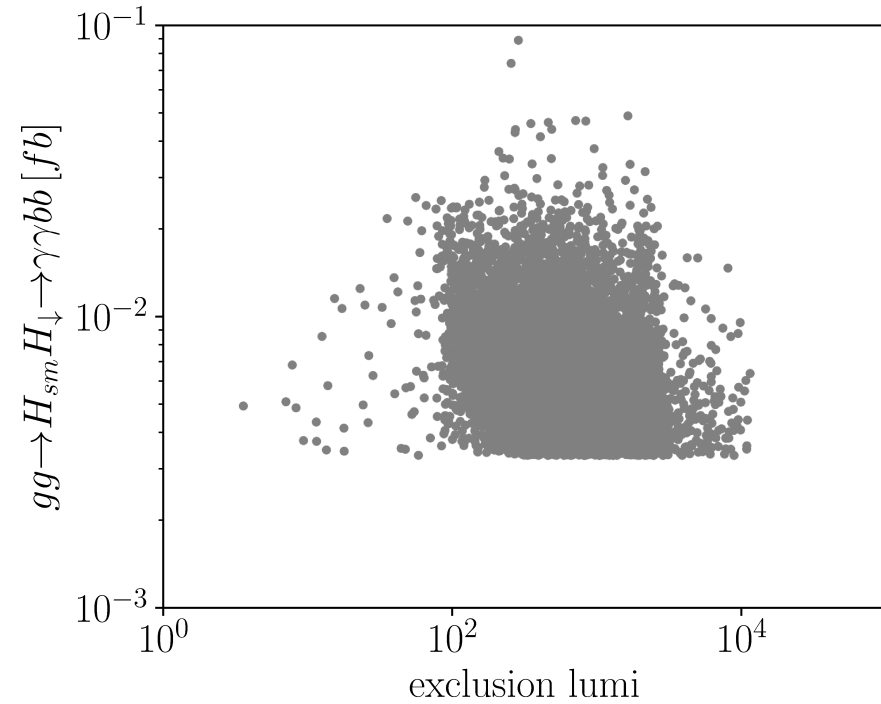
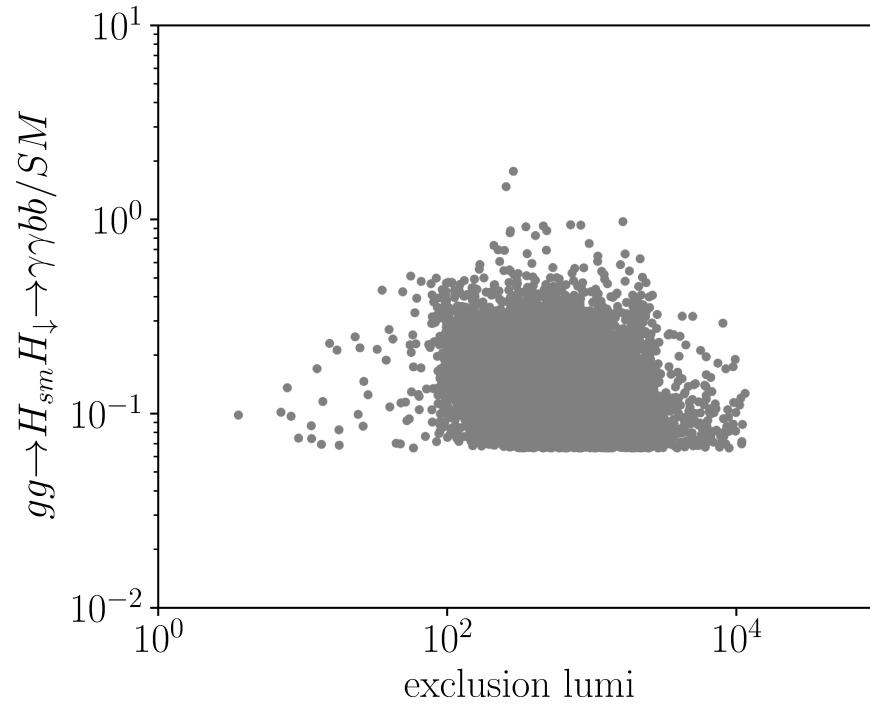
[Basler, Dawson, Englert, MM '18]



- T1 C2HDM: $H_{\downarrow}H_{\uparrow} \rightarrow (2b)(2\gamma)$; left: normalised to SM;
factor 10 larger than $A_{\downarrow}H_{\downarrow}$ in NMSSM

Scatter Plots C2HDM T1 - hH_\downarrow Production in $(2b)(2\gamma)$

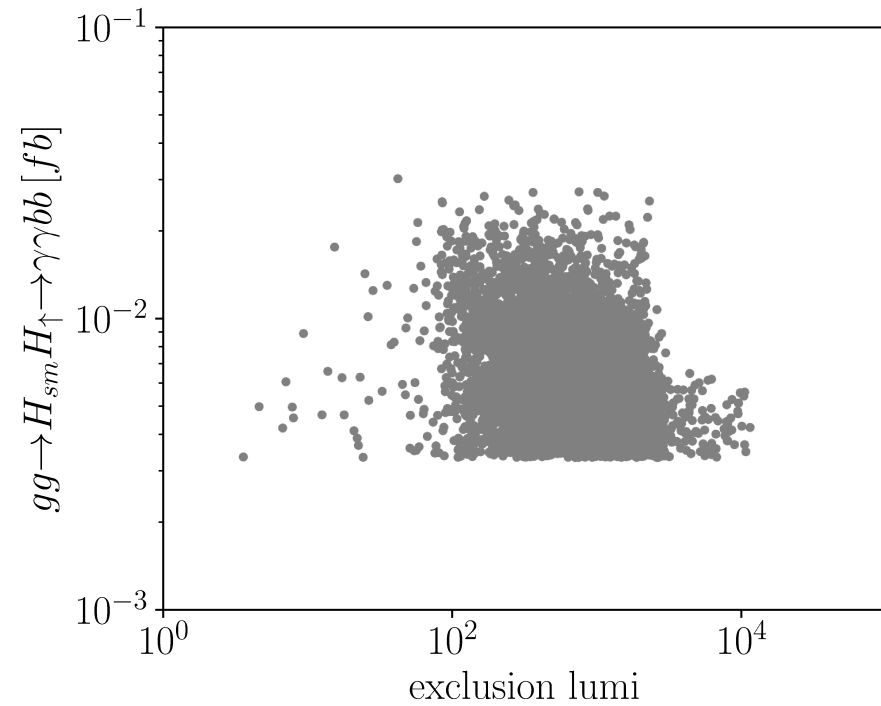
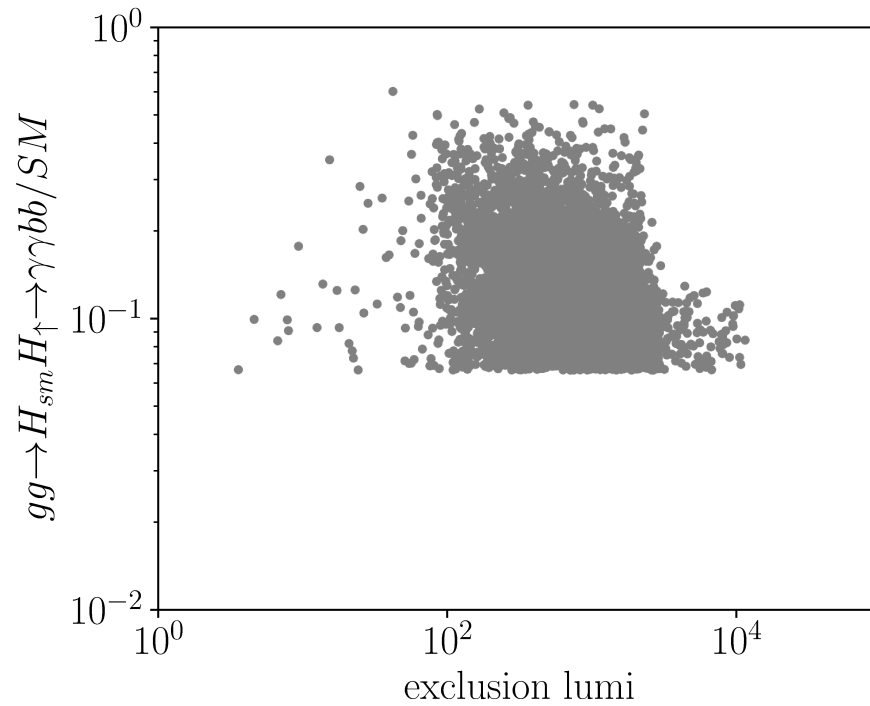
[Basler, Dawson, Englert, MM '18]



- C2HDM T1: $hH_\downarrow \rightarrow (2b)(2\gamma)$; left: normalised to SM; comparable to $H_\downarrow H_\uparrow \rightarrow (2b)(2\gamma)$; comparable to hH_\downarrow in NMSSM

Scatter Plots C2HDM T1 - hH_{\uparrow} Production in $(2b)(2\gamma)$

[Basler, Dawson, Englert, MM '18]



- $hH_{\uparrow} \rightarrow (2b)(2\gamma)$ left: normalised to SM; smaller than $hH_{\downarrow} \rightarrow (2b)(2\gamma)$;
factor 10 smaller than hH_{\downarrow} , hA_{\downarrow} production in NMSSM