Pair Production of Higgs Boson in G2HDM at the LHC

CLHCP 2018 - CCNU Wuhan

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2. Pair Higgs Boson Production in G2HDM.
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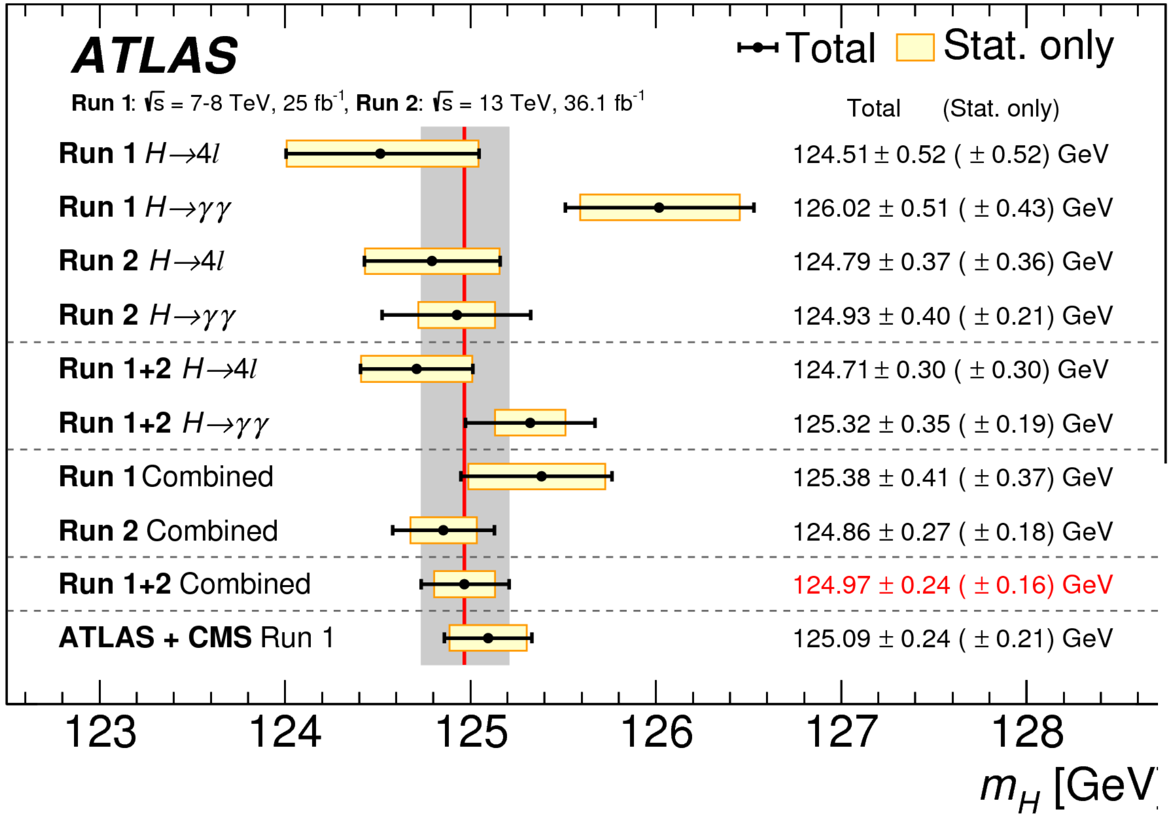
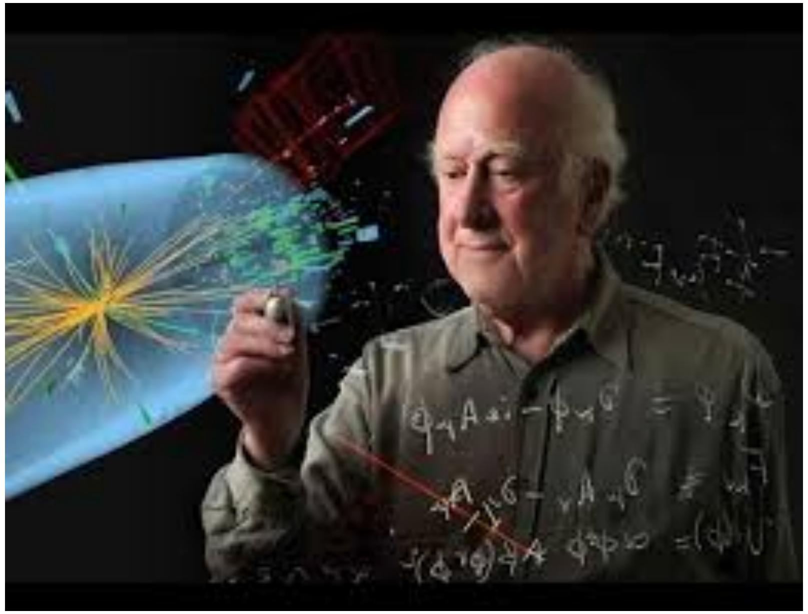
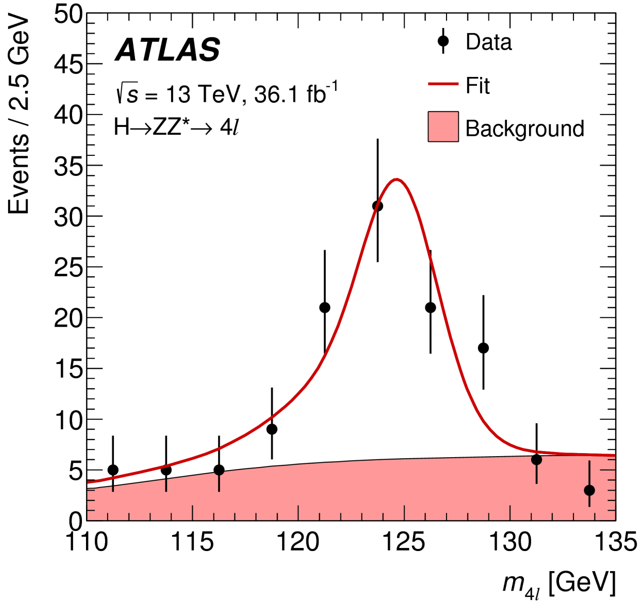
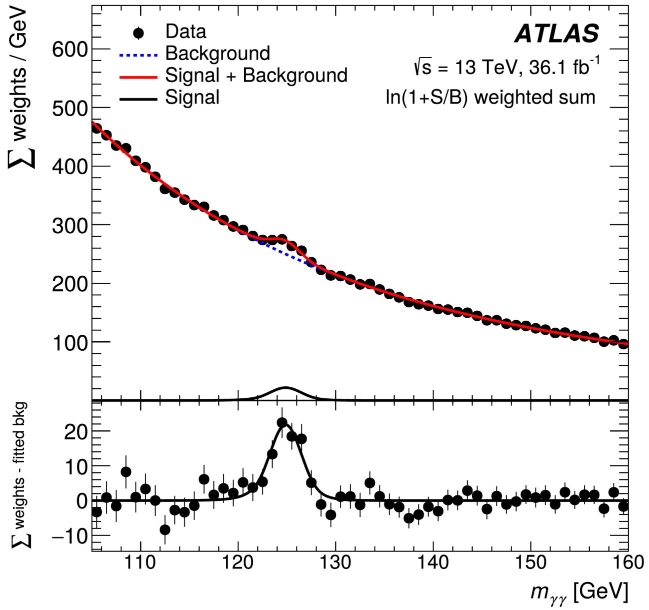
Higgs boson was discovered at LHC!





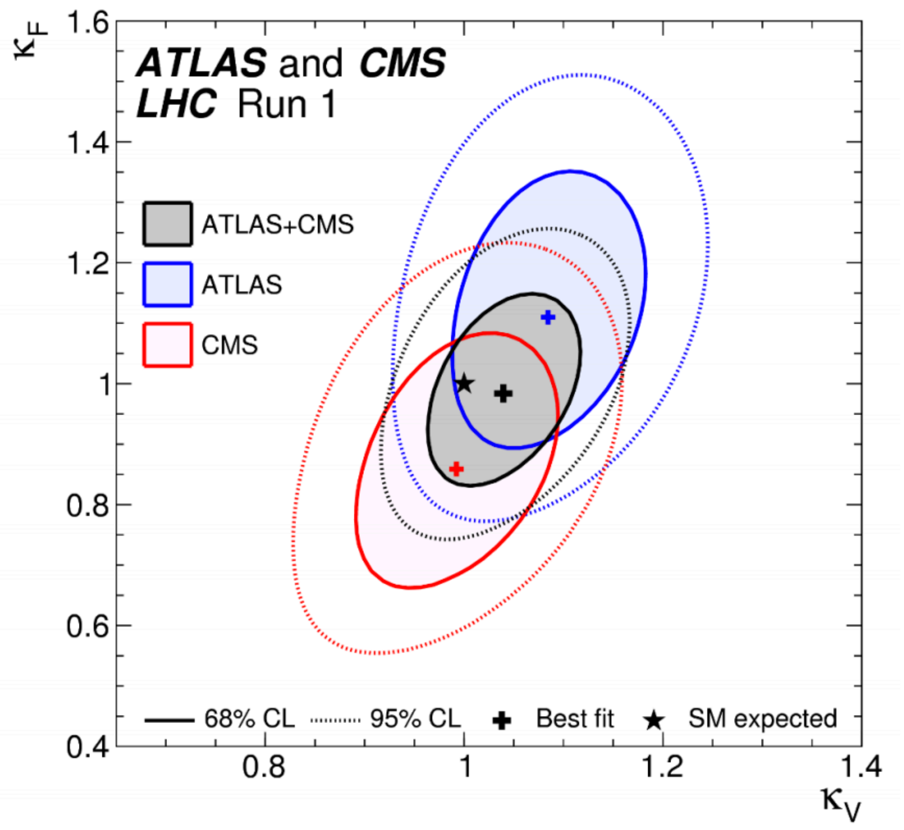
Phys. Lett. B 784 (2018) 345

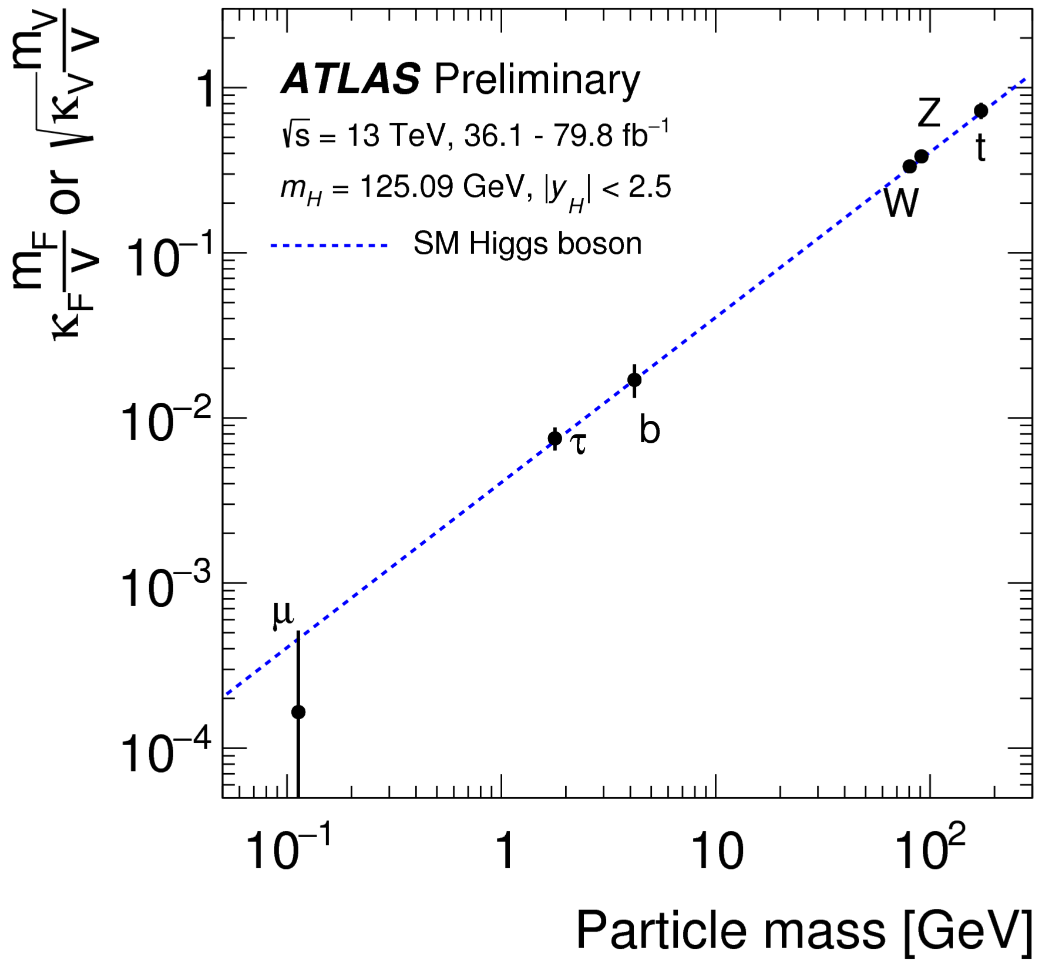




- The current LHC measurements of Higgs boson couplings reach the precision of 10-20%

JHEP 08 (2016) 045





ATLAS-CONF-2018-031

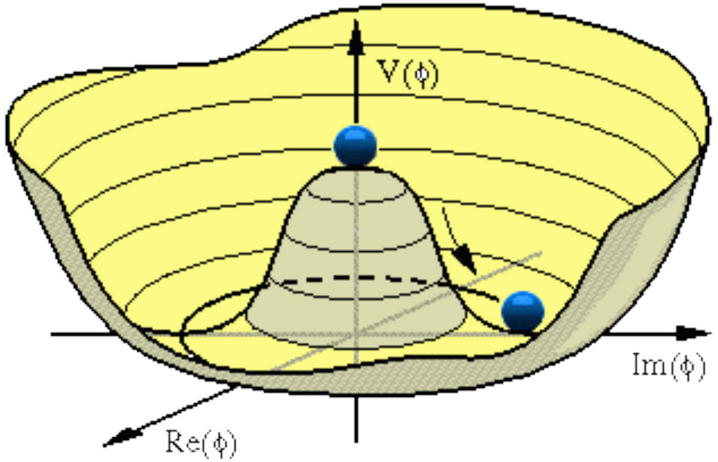
What about the Higgs self-coupling???

Higgs discovery at LHC, $m_h \simeq 125$ GeV

$$V_{SM} = \frac{m_h^2}{2} h^2 + \lambda_{SM} v h^3 + \frac{\kappa_{SM}}{4} h^4, \quad \lambda_{SM} = \kappa_{SM} = \frac{m_h^2}{2v^2} \simeq 0.13$$

double-Higgs production

triple-Higgs production



The Higgs self coupling is a key parameter that can help us reconstructing the shape of the Higgs potential.

- ✓ How EWSB really happens
- ✓ Whether there is an extended Higgs sector

However, it is a challenging measurement for the SM due to its small production cross section

$$\sigma(pp \to h)_{\rm SM} = \mathcal{O}(45\,{\rm pb})$$

easy

$$\Big\downarrow \ \frac{1}{1300}$$

$$\sigma(pp \to hh)_{\rm SM} = \mathcal{O}(35\,{\rm fb})$$

hard

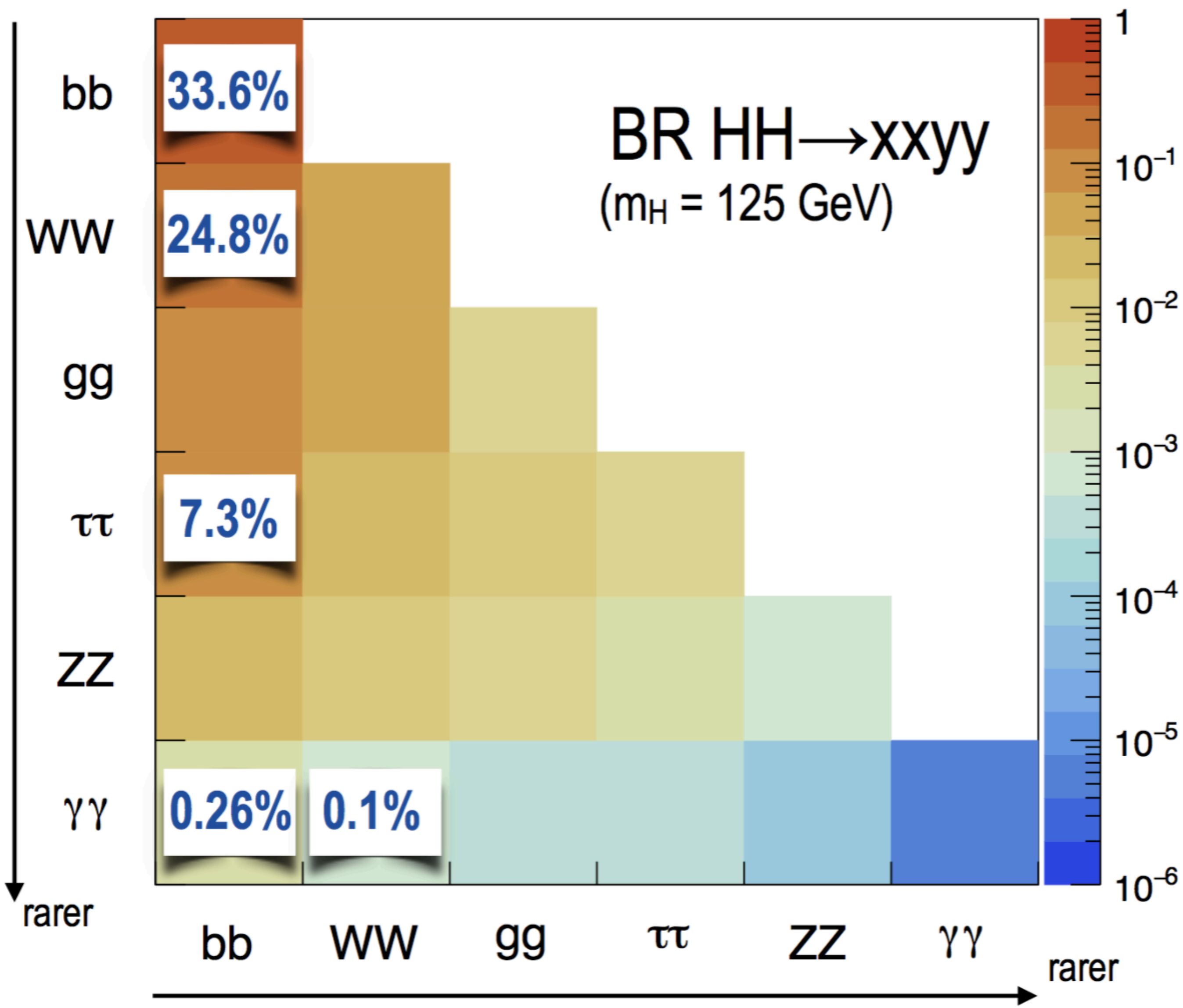
$$\Big\downarrow \ \frac{1}{350}$$

$$\sigma(pp \to 3h)_{\rm SM} = \mathcal{O}(0.1\,{\rm fb})$$

no way

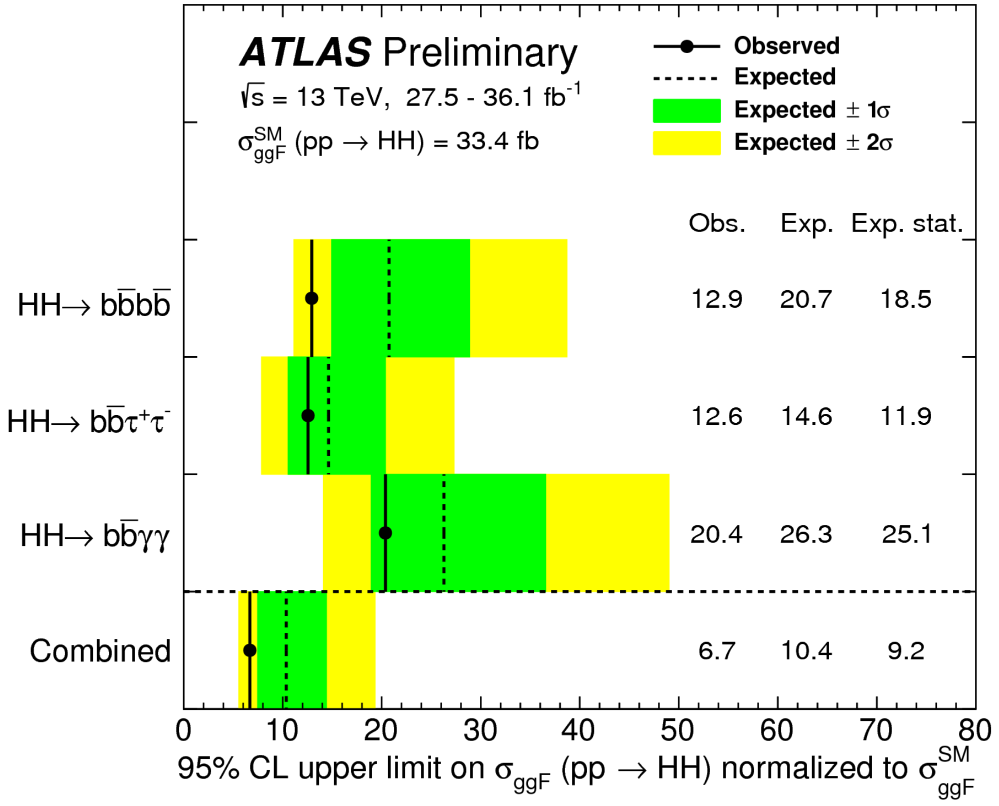
Where to look for the di-Higgs production?

- 4b final state channel has highest BR. But suffer with huge QCD backgrounds.
- γγbb -> clean signal but small BR.

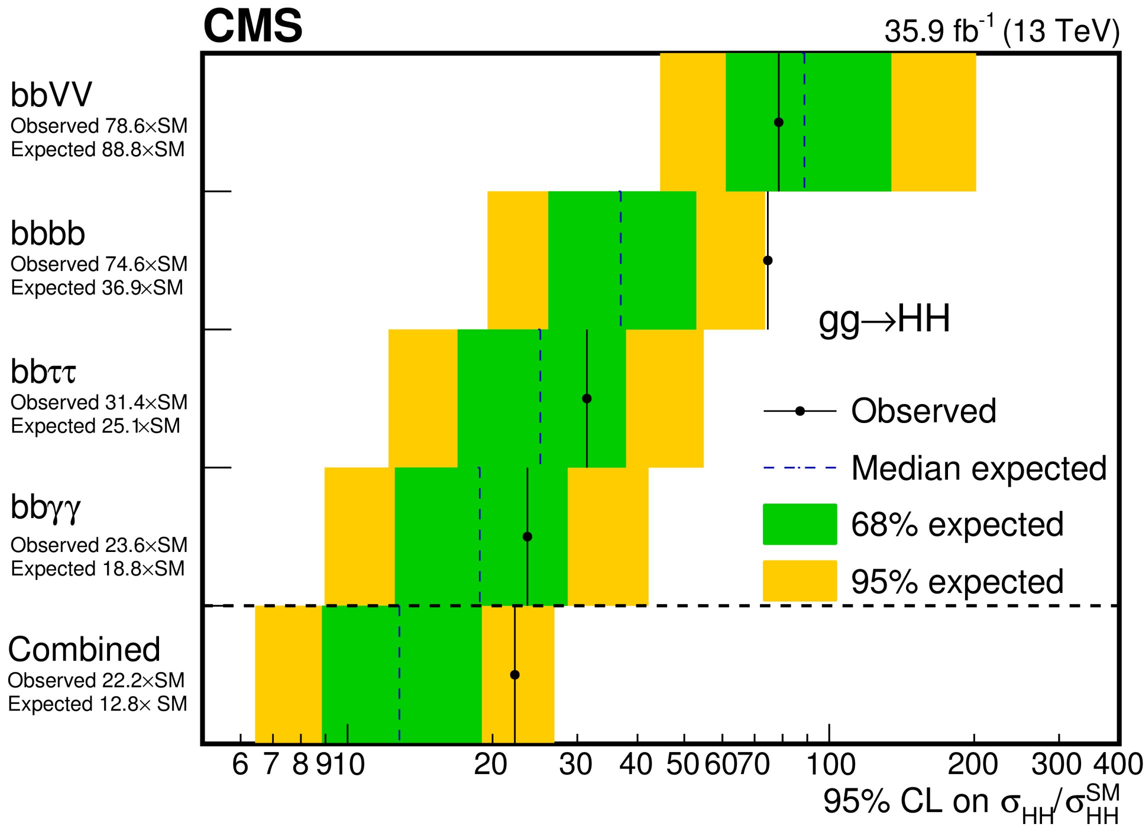


Taken from **Luca Cadamuro**'s talk

Currently, ATLAS and CMS have imposed upper limits on σ/ σSM with various categories of signal final states in Higgs pair searches at the 13 TeV



ATLAS-CONF-2018-043

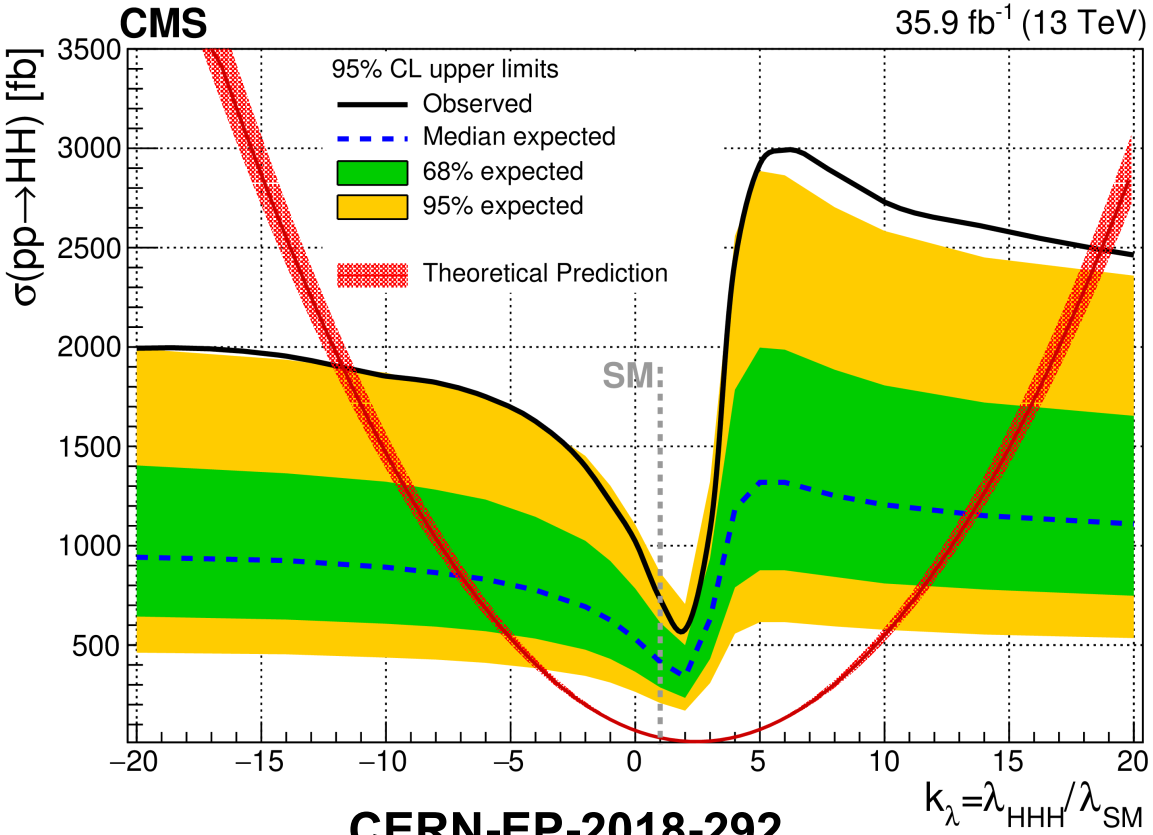


CERN-EP-2018-292

ATLAS: $\sigma_{HH\ comb} < 6.7\times$SM (10.4 exp.)

CMS: $\sigma_{HH\ comb} < 22.2\times$SM (12.8 exp.)

Limits on Higgs self-coupling



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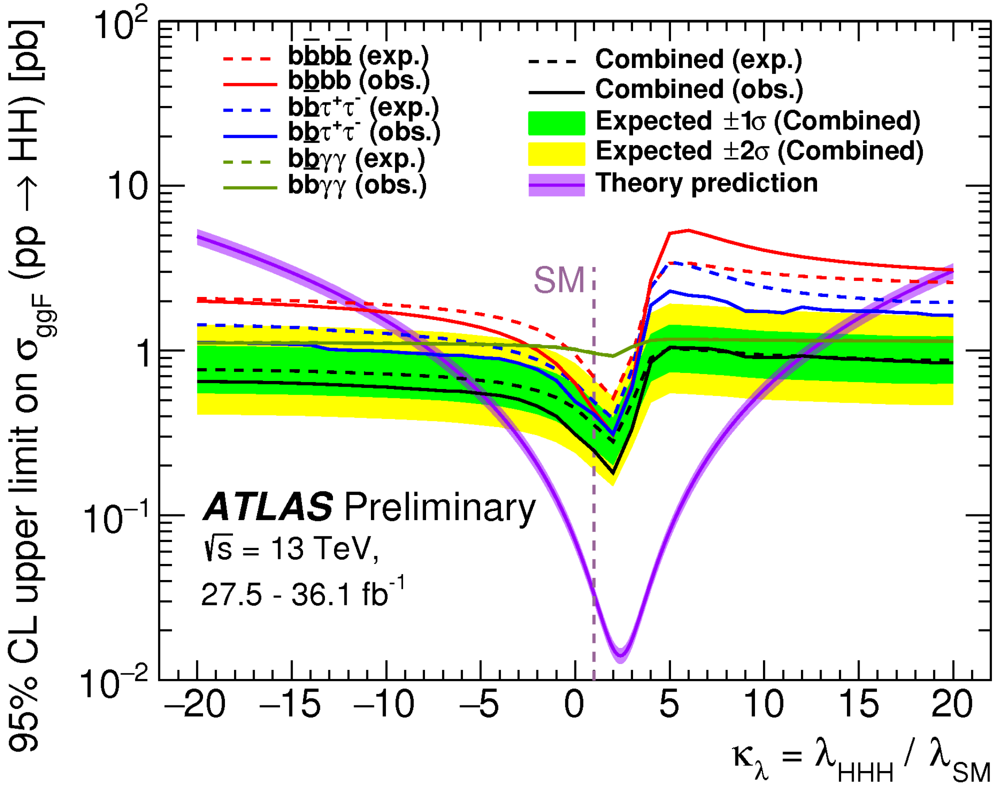


ATLAS-CONF-2018-043

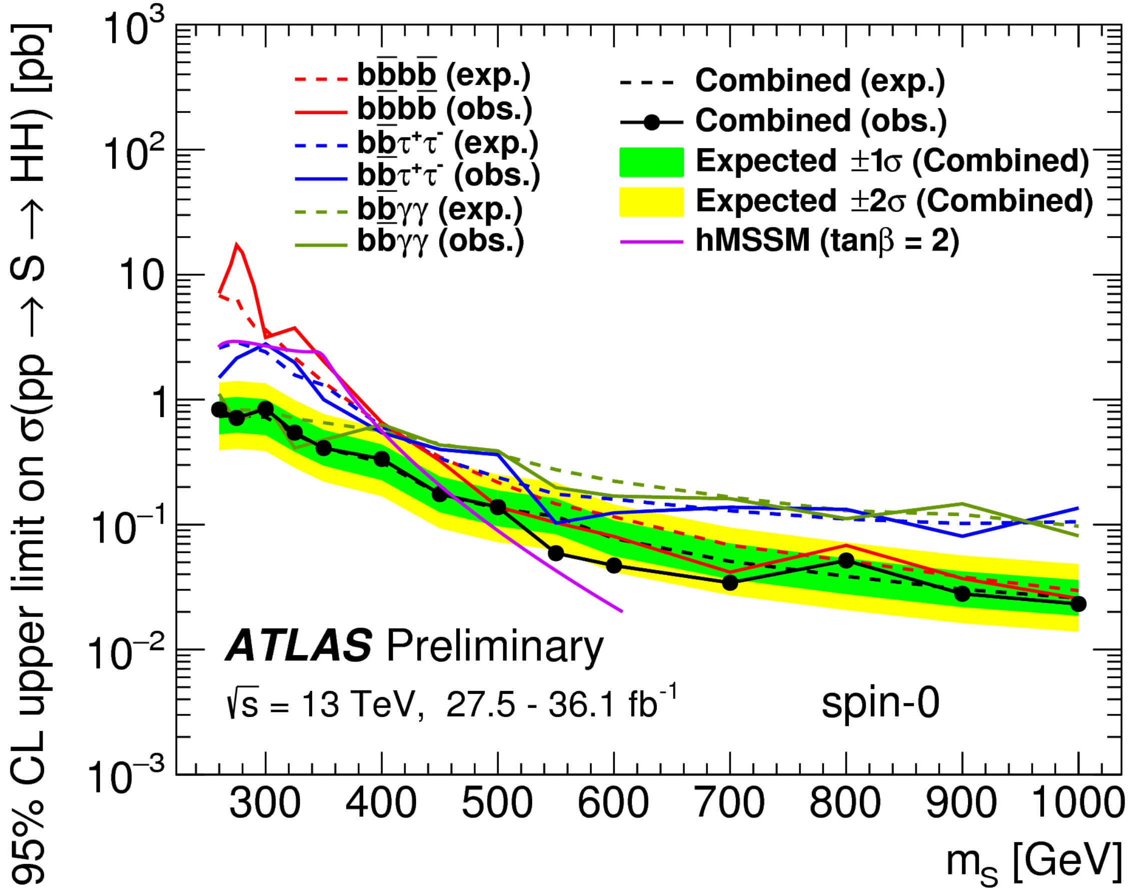
CMS:

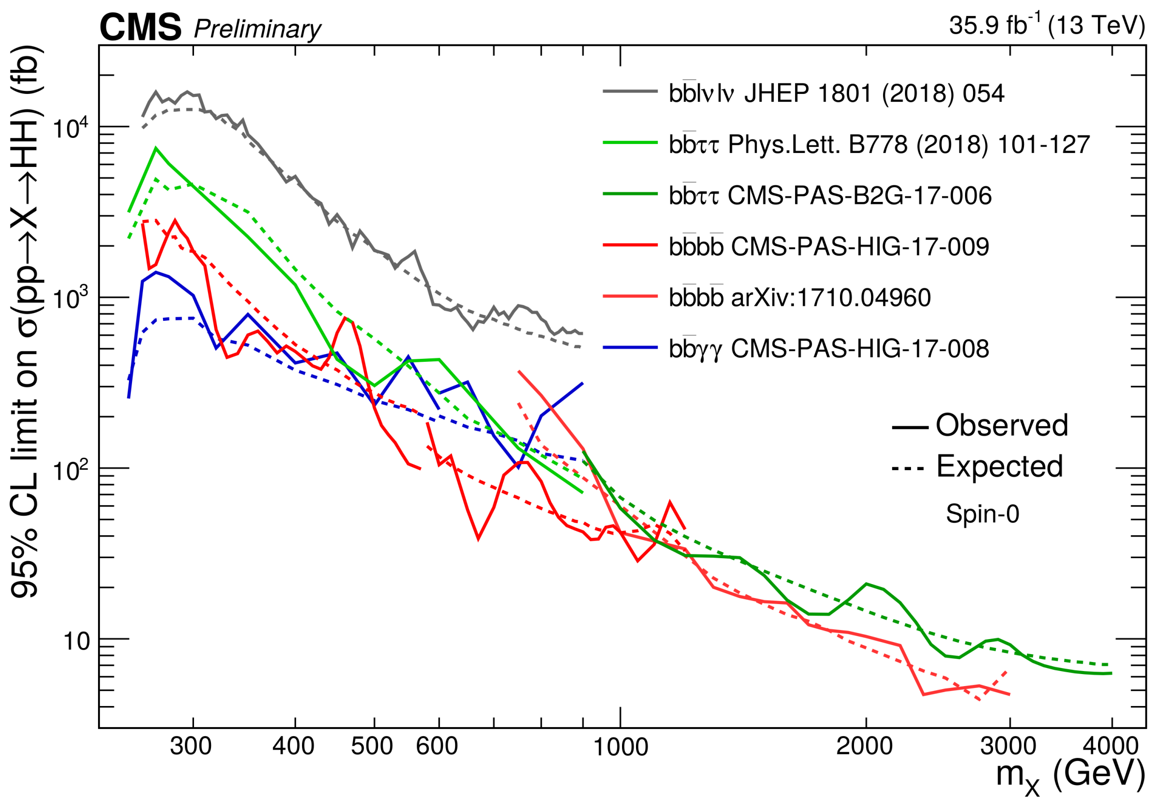
$$-11.8 < \kappa_\lambda < 18.8$$
$$-7.1 < \kappa_\lambda < 13.6\,(exp.)$$

ATLAS:

$$-5.0 < \kappa_\lambda < 12.1$$
$$-5.8 < \kappa_\lambda < 12.0\,(exp.)$$

Constraints on new heavy scalars

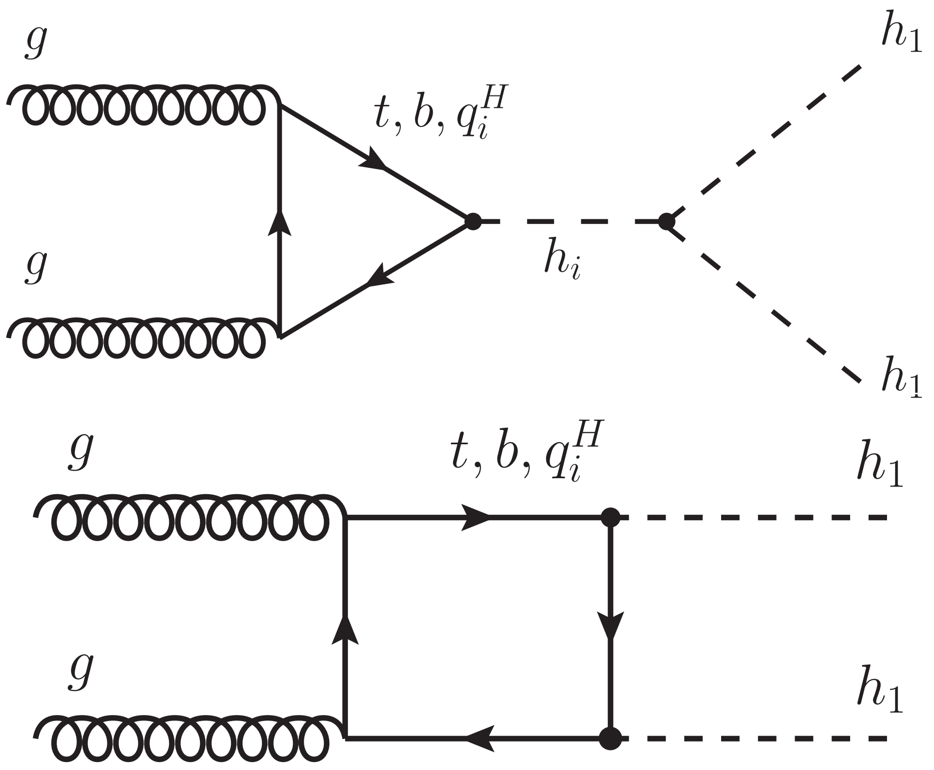




BSM physics can easily affect the Higgs pair production cross section through:

1. Modification in the quark Yukawa couplings
2. Modification in the trilinear Higgs self-coupling
3. New colored particles running in triangle and box loops
4. Existence of new heavy scalars decaying into Higgs pairs

➤ (1)—(3) belong to the non-resonance effect, while (4) belongs to the resonance effect.



G2HDM has all these ingredients!

G2HDM: Gauged 2 Higgs Doublet Model

JHEP 1604 (2016) 019

- G2HDM = Using gauge symmetry, instead of the Z_2 discrete symmetry, to protect DM candidate in the inert 2 Higgs Doublet Model (iDHM).

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$H = (H_1\ ,\ H_2)^T$	1	2	2	1/2	1

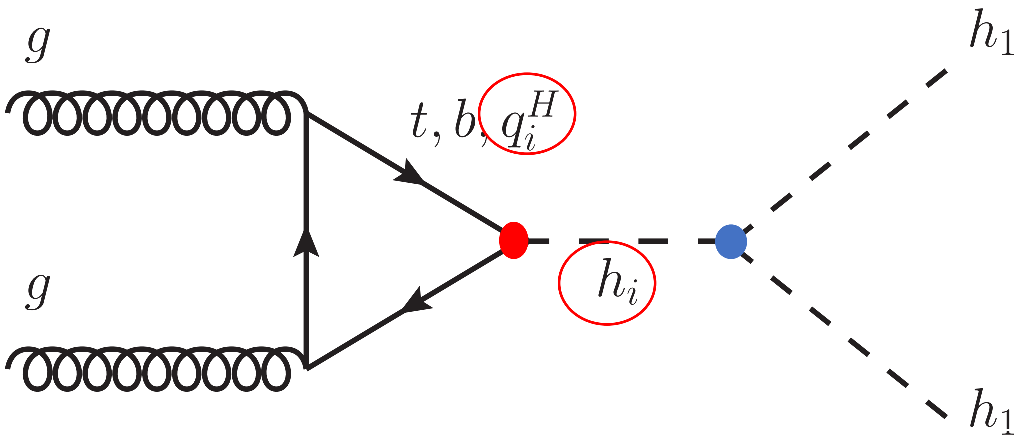
$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}$$

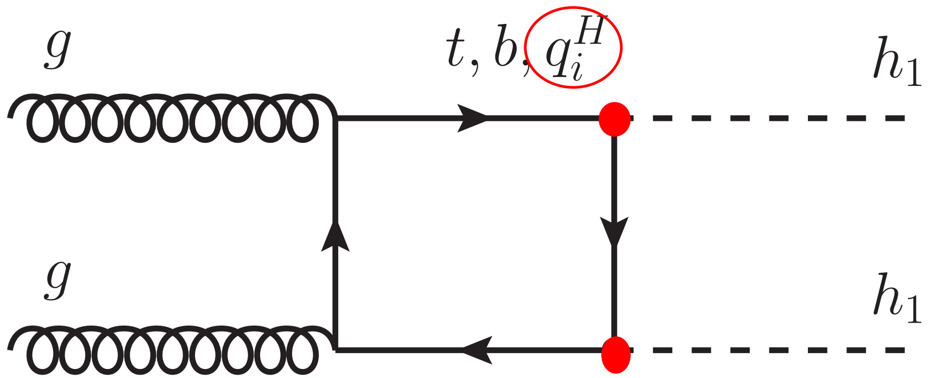
H_2^0 is stable (DM candidate) under protection of $SU(2)_H$

New fermions and new scalars are introduced in this model!

Relevant couplings in G2HDM

$h_1 \equiv h_{SM}$





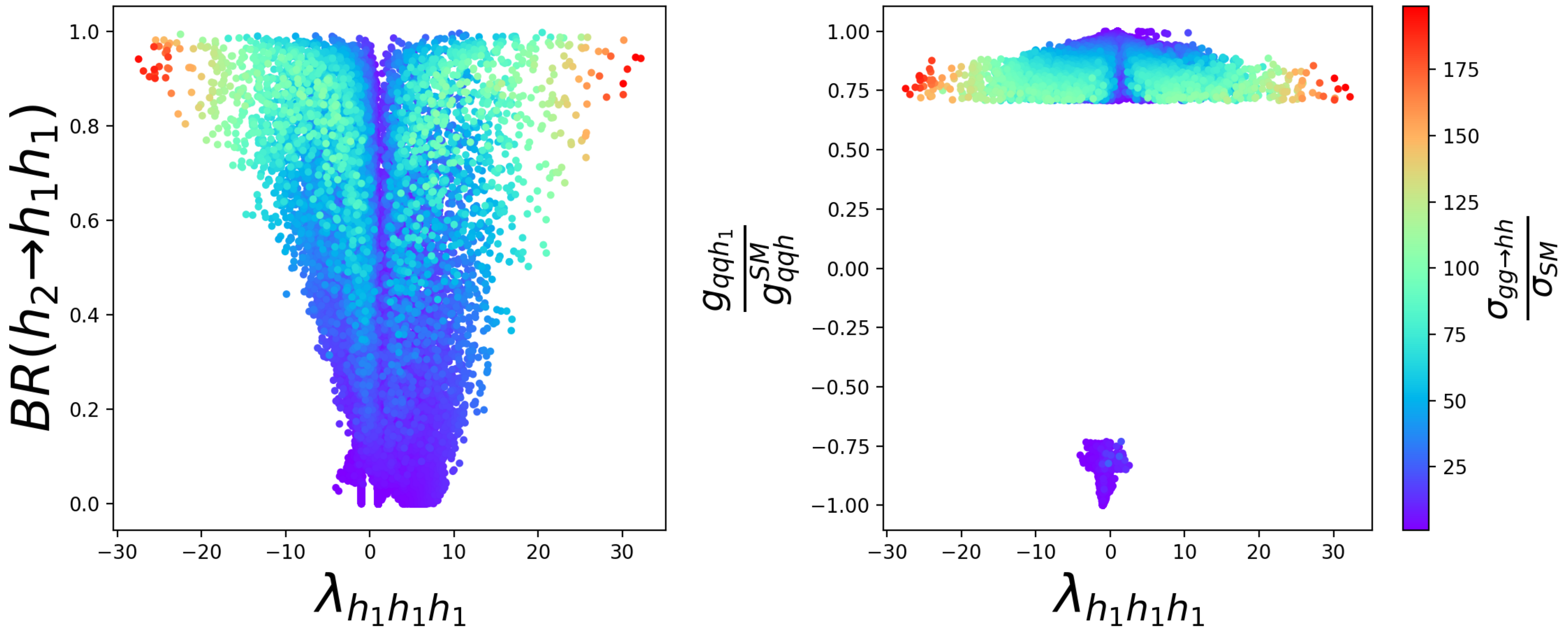
g^{SM}_{qqh} g^{SM}_{hhh}

$$g_{qqh_i} = O^H_{1i}\frac{m_q}{v},$$
$$g_{q^Hq^Hh_i} = O^H_{2i}\frac{m_{q^H}}{v_\Phi},$$

$$\begin{aligned} g_{h_1h_1h_1} = {} & 6\left(\lambda_H v (O^H_{11})^3 + \lambda_\Phi v_\Phi (O^H_{21})^3 - \lambda_\Delta v_\Delta (O^H_{31})^3\right) \\ & + \frac{3}{2}\left((M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta)(O^H_{11})^2 O^H_{31} + (M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta)(O^H_{21})^2 O^H_{31}\right) \\ & + 3(\lambda_{H\Phi})\left(v O^H_{11}(O^H_{21})^2 + v_\Phi (O^H_{11})^2 O^H_{21}\right) \\ & + 3\left(\lambda_{H\Delta} v O^H_{11}(O^H_{31})^2 + \lambda_{\Phi\Delta} v_\Phi O^H_{21}(O^H_{31})^2\right), \end{aligned}$$

Numerical Results

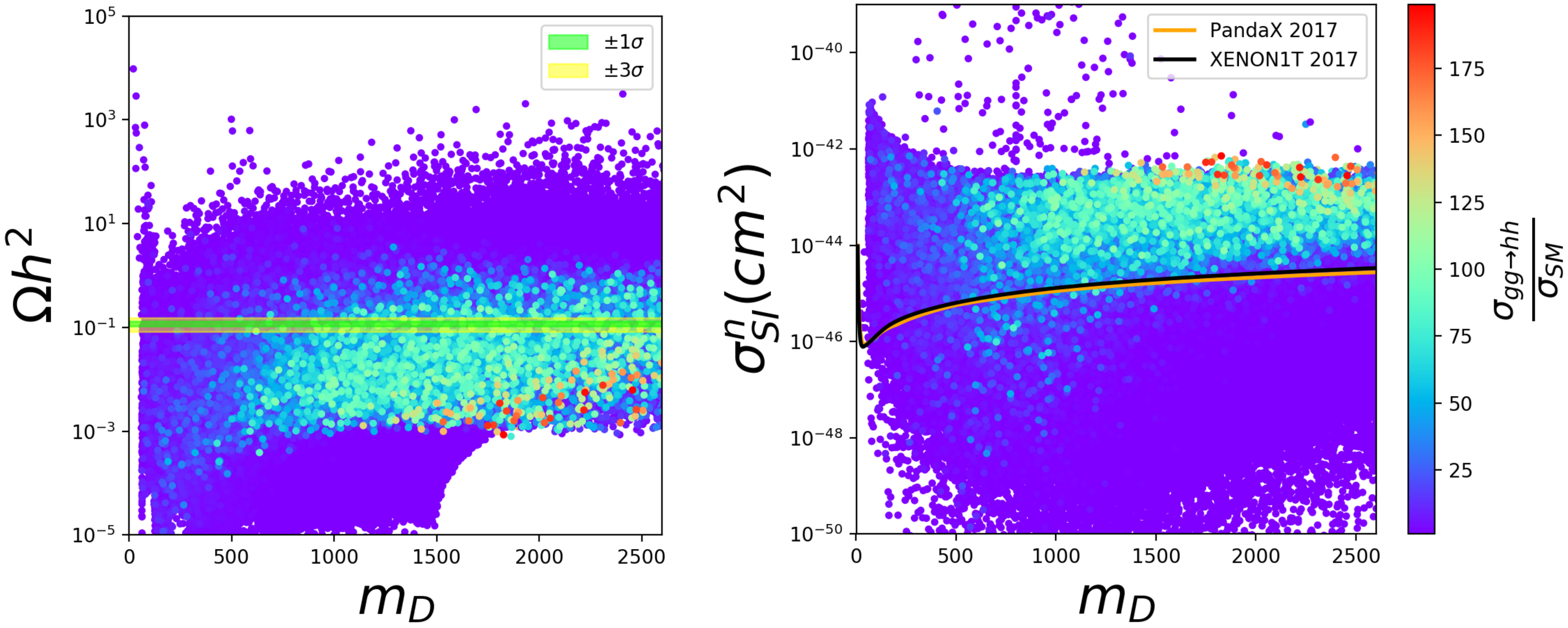
$$\lambda_{h_1h_1h_1} = {g_{h_1h_1h_1}}\Big/{g^{SM}_{hhh}}$$



✓ The cross section of Double Higgs Boson production is up to $\sim O(10^2)$ times SM value in the G2HDM

arXiv:1810.04837 [hep-ph]

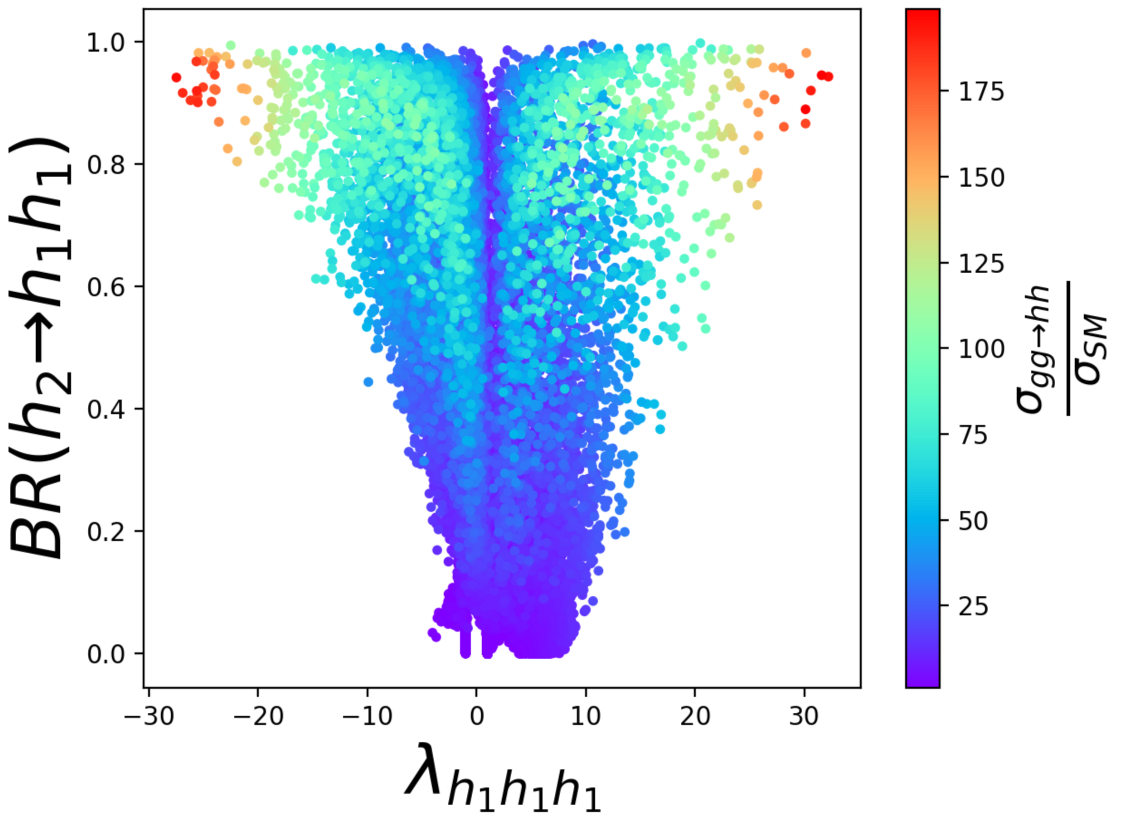
DM constraints



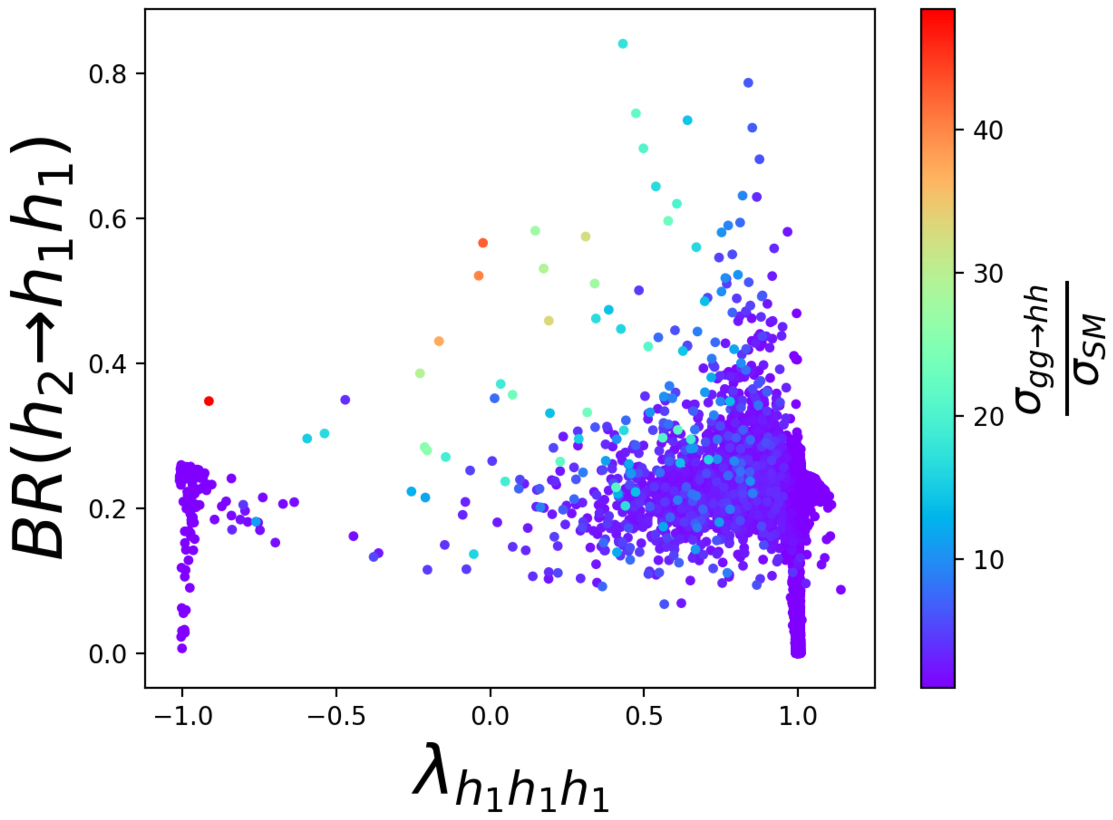
✓ DM constraints cut off almost all the parameter space which significantly enhances the cross section of double Higgs boson production.

Numerical Results

Without DM constraints



With DM constraints



- ✓ Higgs boson trilinear coupling is stringently constrained by DM searches
- ✓ The production cross section is about one order of magnitude lower as compared with the one before imposing the DM constraints

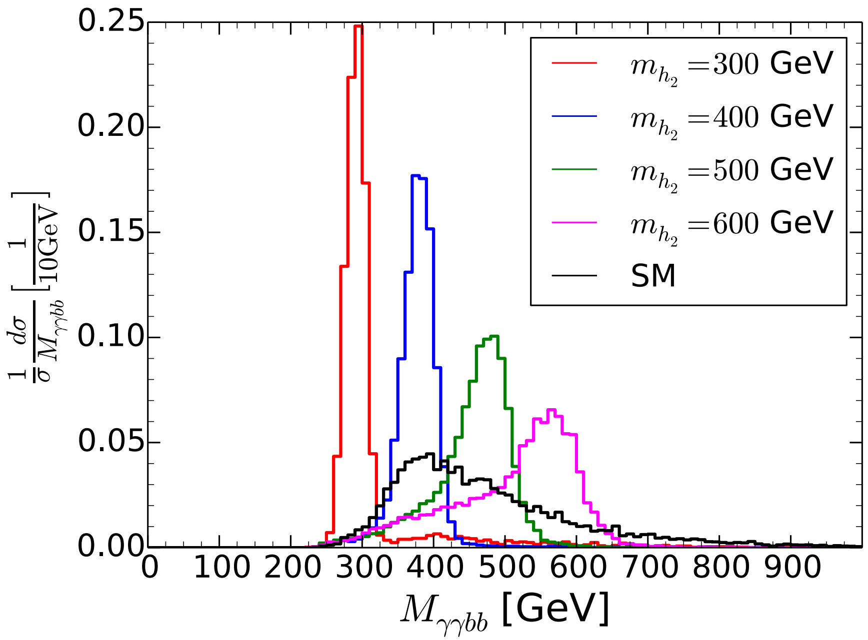
Benchmark point	A	B	C	D	E	F	G
$\lambda_{h_1h_1h_1}$	0.85	0.15	-0.53	-0.20	0.84	0.35	0.41
$\lambda_{h_2h_1h_1}$	0.76	3.03	3.88	3.25	-3.32	5.42	-7.16
κ_{qqh_1}	0.95	0.91	0.81	-0.77	0.93	0.75	0.86
κ_{qqh_2}	0.29	0.41	0.58	0.64	-0.37	0.65	-0.52
$\kappa_{q^Hq^Hh_1}$	-5×10^{-5}	-10^{-4}	3.7×10^{-4}	-10^{-5}	4×10^{-5}	-8×10^{-5}	7×10^{-5}
$\kappa_{q^Hq^Hh_2}$	2×10^{-4}	1.7×10^{-4}	5.1×10^{-4}	4×10^{-5}	9×10^{-5}	9×10^{-5}	8×10^{-5}
m_{h_2}(GeV)	300	400	500	600	700	800	900
m_{h_3}(TeV)	85	69.49	70.77	68.22	88.35	158.2	87.39
m_D(GeV)	398	1278	1210	467	883	619	553
$m_{\tilde{\Delta}}$(TeV)	62.94	67.61	81.03	59.29	44.38	38.87	58.45
$m_{H^\pm}$(TeV)	62.94	67.60	81.03	59.29	44.39	38.87	58.44
$\mathrm{BR}(h_2\to h_1h_1)$	0.33	0.58	0.30	0.12	0.18	0.10	0.16
$\frac{\sigma(gg\to h_1h_1)}{\sigma_{SM}}$	8.2	27.3	16.7	4.6	2.1	2.1	2.1

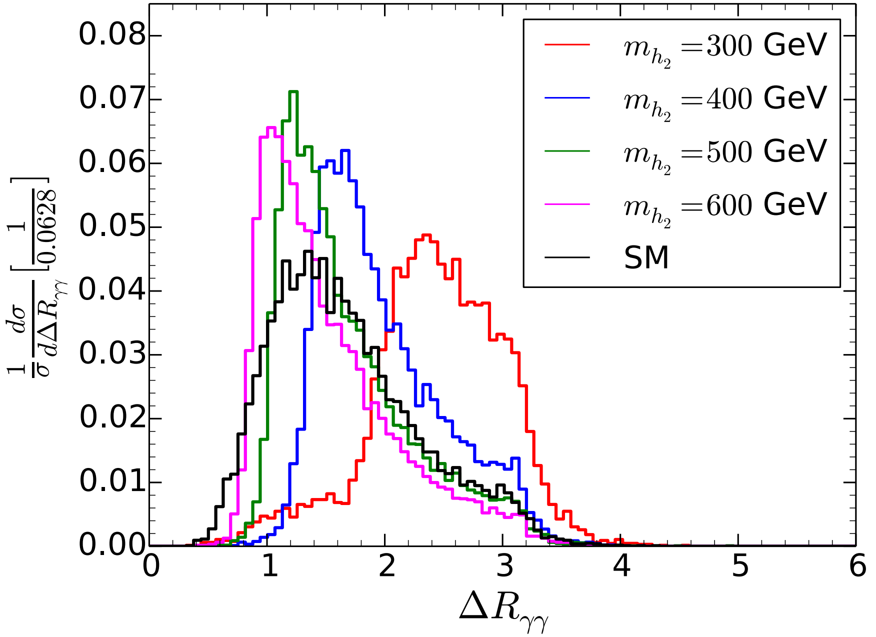
Pick up 7 benchmark points which allowed by the combined (VS+PU+HP+DM) constraints

- Higgs self coupling is negative in the points , C, D
- 125 GeV Higgs boson Yukawa coupling is almost the same as SM value.
- A, B, C, D points are used for studying $b\bar{b}\gamma\gamma$ final state channel. E, F, G for $b\bar{b}b\bar{b}$ final state channel.

$b\bar{b}\gamma\gamma$ final state channel

- Invariant mass distribution peaked at the mass of h_2
- SM peaked at 400 GeV

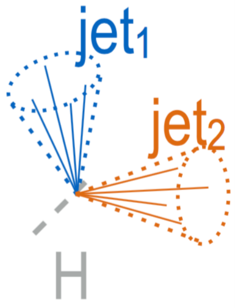




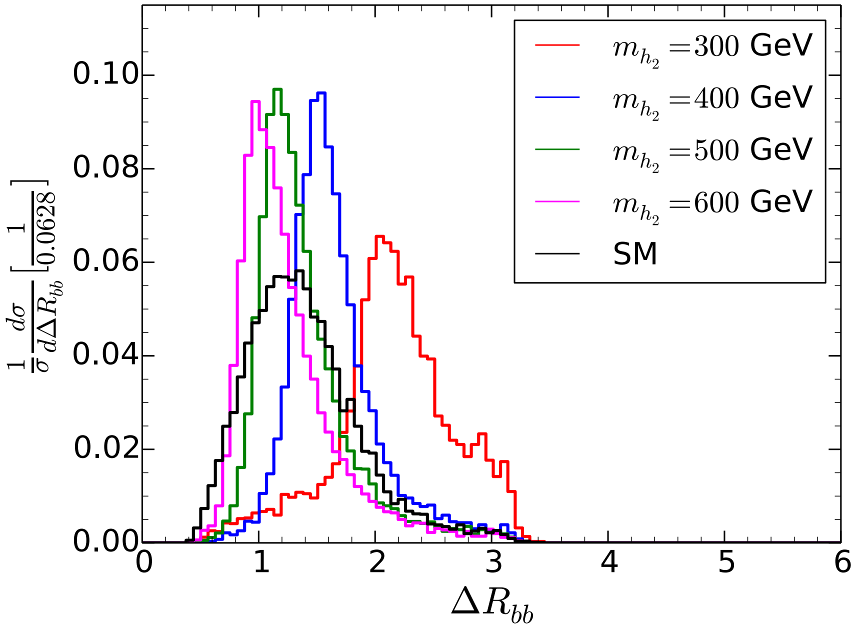
- Roughly $\Delta R \approx 2m_h/\text{PT(h)}$,

where PT(h) = transverse momentum of h.

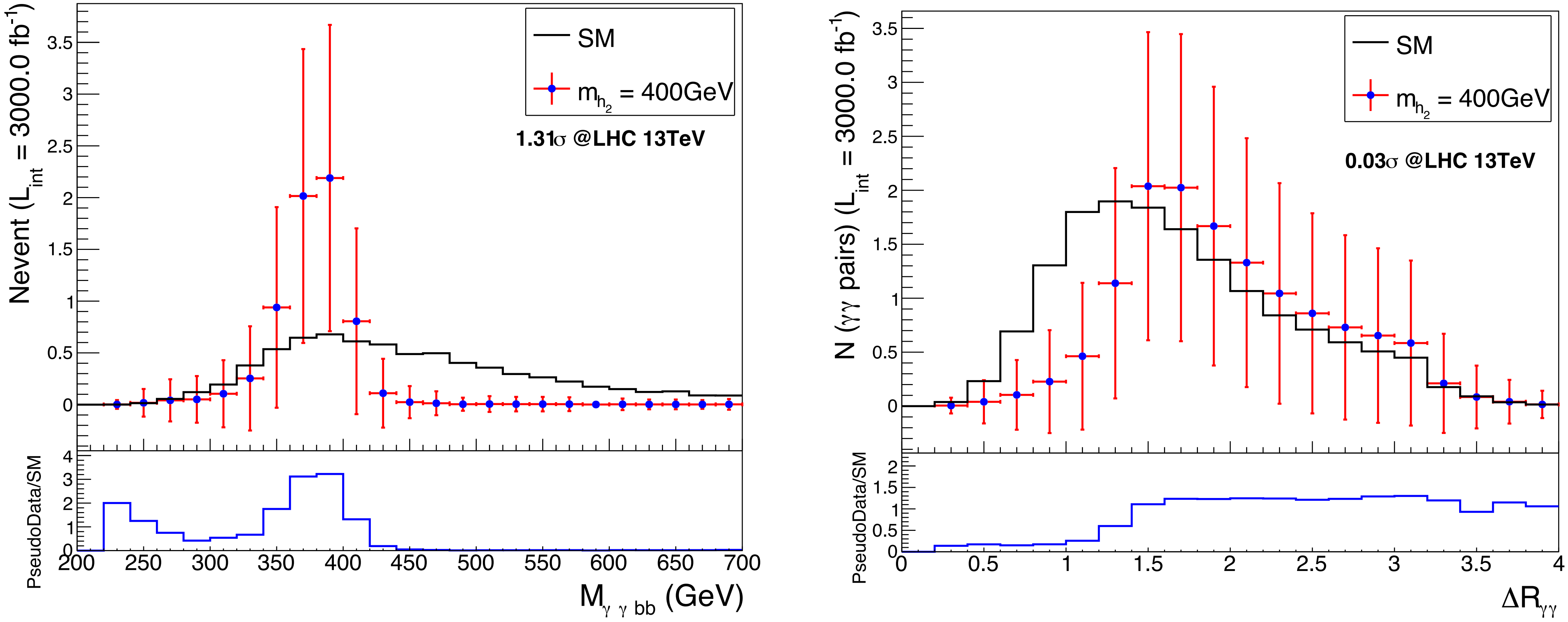
h_2 becomes lighter



h_2 becomes heavier

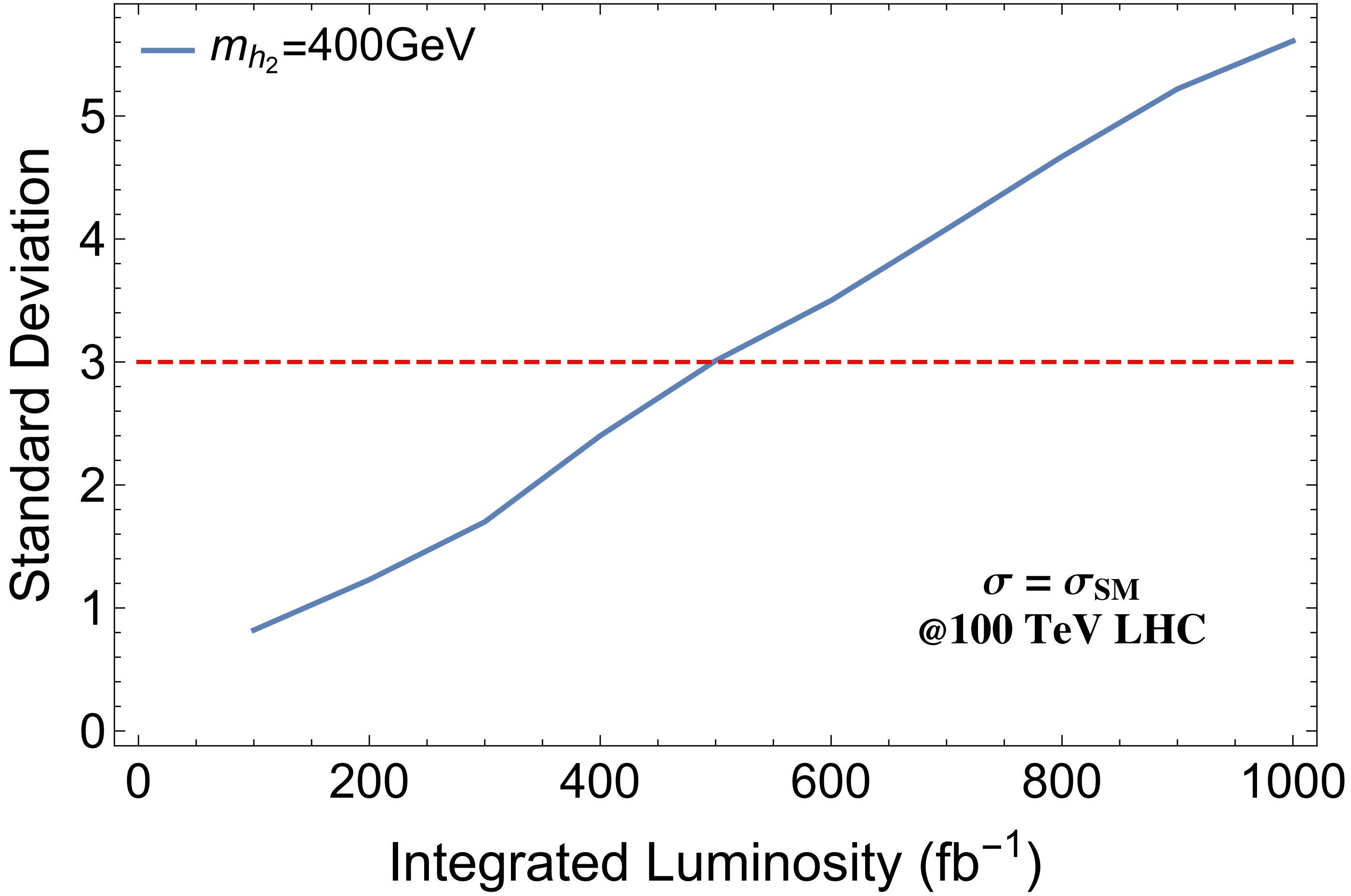


χ^2 test for distribution of a benchmark points B' ($m_{h_2} = 400GeV$ and $\sigma = \sigma_{SM}$) and SM in the $\gamma\gamma\bar{b}b$ final state



✓ We can not distinguish the signals between the heavy scalar resonance with a mass of 400 GeV and the SM at 13TeV HL-LHC

However, one can distinguish the resonant at 400GeV with integrated luminosity = 500 fb^{-1} at 100 TeV LHC



Conclusion

- ✓ Studying Higgs boson pair production is an important way to probe for the details of Higgs boson properties, especially for the self-coupling of the Higgs boson
- ✓ The G2HDM not only addresses the DM issue but also Higgs pair production. It has all ingredients to explore the impacts of new Physics beyond SM on the Higgs boson pair production.
- ✓ We find out that the Higgs boson trilinear coupling is stringently constrained by the DM relic density and direct searches.

Thank You

Backup Slides

The G2HDM

- H_1, H_2 are embedded into $SU(2)_H$.
- ϕ_H is introduced to gives a Dirac mass to heavy fermions.
- Triplet Higgs Δ_H VEV will contribute to the mass of charge Higgs mass.
- $SU(2)_L$ doublet fermions are singlets under $SU(2)_H$, while $SU(2)_L$ singlet fermions pair up with heavy fermions as $SU(2)_H$ doublets.

Anomaly free!

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$H = (H_1\,,\,H_2)^T$	1	2	2	1/2	1
$\Phi_H = (\Phi_1\,,\,\Phi_2)^T$	1	1	2	0	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
$Q_L = (u_L\,,\,d_L)^T$	3	2	1	1/6	0
$U_R = (u_R\,,\,u_R^H)^T$	3	1	2	2/3	1
$D_R = (d_R^H\,,\,d_R)^T$	3	1	2	$-1/3$	-1
u_L^H	3	1	1	2/3	0
d_L^H	3	1	1	$-1/3$	0
$L_L = (\nu_L\,,\,e_L)^T$	1	2	1	$-1/2$	0
$N_R = (\nu_R\,,\,\nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H\,,\,e_R)^T$	1	1	2	-1	-1
ν_L^H	1	1	1	0	0
e_L^H	1	1	1	-1	0

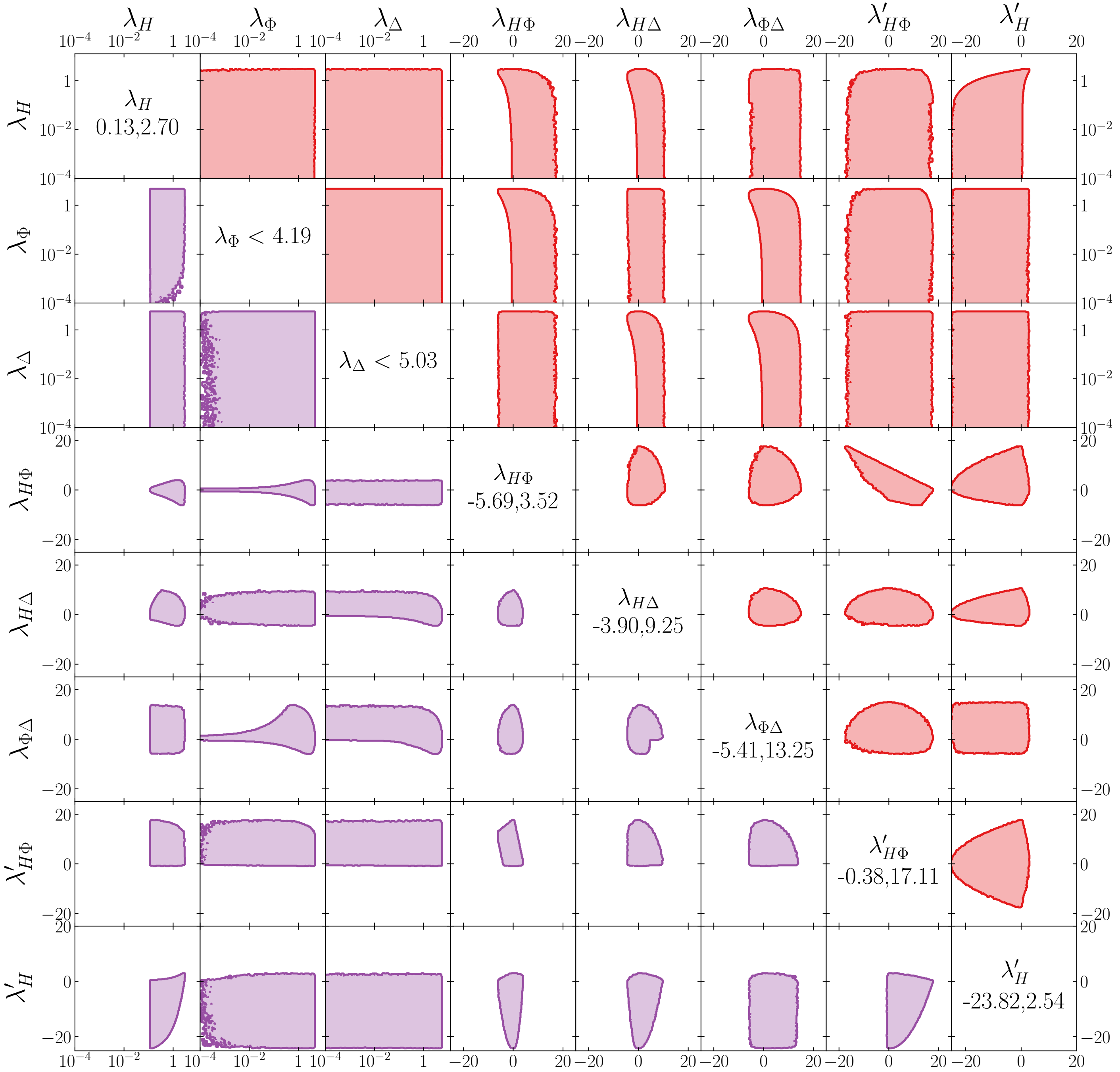
TABLE I. Matter field contents and their quantum number assignments in G2HDM.

Huang, Tsai, Yuan 1708.02355

Theoretical and Higgs Phenomenological Constraints

- Vacuum stability (VS),
- Perturbative unitarity (PU)
- Higgs boson mass
- Signal strengths of Higgs boson decays into diphoton and $\tau^+\tau^-$ from the LHC

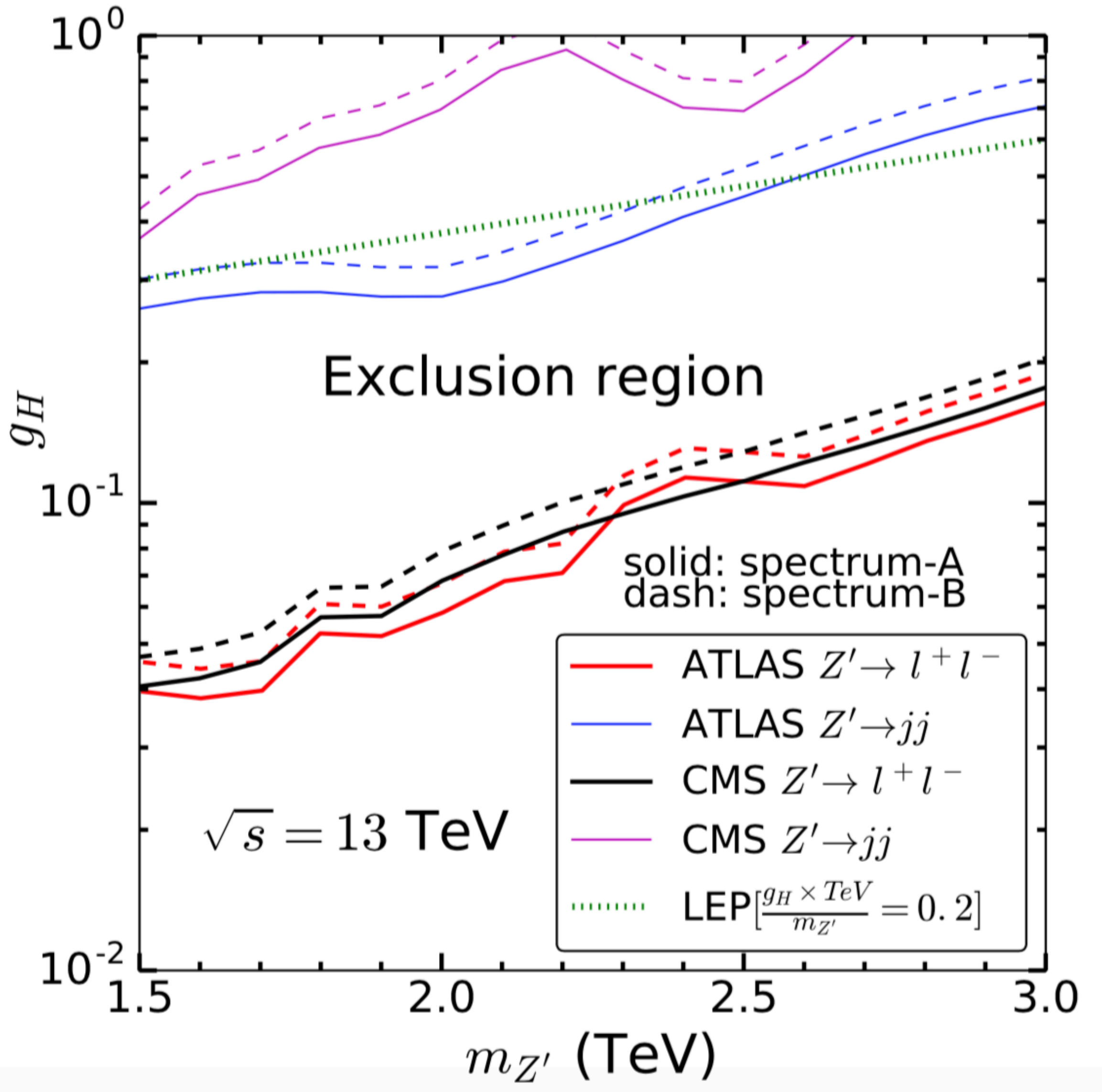
A. Arhrib, W. C. Huang, R. Ramos, Y. L. S. Tsai & T. C. Yuan 1806.05632



Direct Z′ resonance search at the latest ATLAS and CMS 13 TeV.

$$m_{Z'}^2 \approx \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2\right)$$

$$g_H = 0.1 \rightarrow v_\Phi > 50\ TeV$$



W. C. Huang, H. Ishida, C. T. Lu, Y. L. S. Tsai and T. C. Yuan 1708.02355

Branching ratios of the two body decays of h_2 in the benchmark points.

Benchmark point	A	B	C	D	E	F	G
$h_2 \to h_1 h_1$	0.329	0.575	0.298	0.113	0.175	0.100	0.161
$h_2 \to W^+W^-$	0.462	0.255	0.391	0.496	0.471	0.529	0.500
$h_2 \to ZZ$	0.206	0.119	0.186	0.240	0.230	0.260	0.247
$h_2 \to t\bar{t}$	0	0.049	0.123	0.150	0.122	0.114	0.091
$h_2 \to b\bar{b}$	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0

We observe that the heavy scalar h_2 mainly decays into a pair of SM-like Higgs boson h_1, *W* and *Z* bosons, and top quark

$\gamma\gamma\bar{b}b$ final state channel

Cuts:

$$N_\gamma \geq 2,\ N_b = 2\ ,\ P_T(j) > 25\ \text{GeV}\ ,\ P_T(b)^{\text{lead,subl}} > 55,\ 35\ \text{GeV}$$

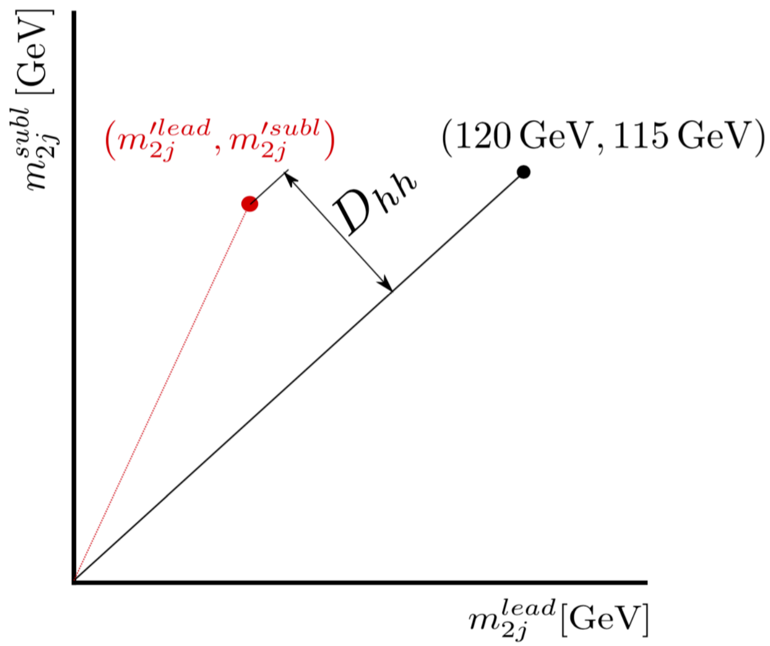
$$105\ \text{GeV} < M_{\gamma\gamma} < 160\ \text{GeV},\ 95\ \text{GeV} < M_{bb} < 135\ \text{GeV}\ .$$

$b\bar{b}b\bar{b}$ final state channel

ATLAS-CONF-2016-049

Cuts: At least four b-jets with PT > 30 GeV and |η| < 2.5.

$$\left.\begin{array}{r}\frac{360}{m_{4j}} - 0.5 < \Delta R_{jj,\mathrm{lead}} < \frac{655}{m_{4j}} + 0.475 \\ \frac{235}{m_{4j}} < \Delta R_{jj,\mathrm{subl}} < \frac{875}{m_{4j}} + 0.35\end{array}\right\} \text{if } \mathrm{m_{4j}} < 1250\,\mathrm{GeV}$$



$$\left.\begin{array}{r}0 < \Delta R_{jj,\mathrm{lead}} < 1 \\ 0 < \Delta R_{jj,\mathrm{subl}} < 1\end{array}\right\} \text{if } \mathrm{m_{4j}} > 1250\,\mathrm{GeV}$$

Select the b-jet pairs that have minimum of D_{hh}

$$D_{hh} = \sqrt{\left(m_{2j}^{\mathrm{lead}}\right)^2 + \left(m_{2j}^{\mathrm{subl}}\right)^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{\mathrm{subl}}}{m_{2j}^{\mathrm{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

Cuts (con't)

$$\begin{aligned} P_T^{\rm lead} &> 0.5\, m_{4j} - 90\,{\rm GeV}\,, \\ P_T^{\rm subl} &> 0.33\, m_{4j} - 70\,{\rm GeV}\,, \\ \Delta R(h,h) &> 1.5\,, \end{aligned}$$

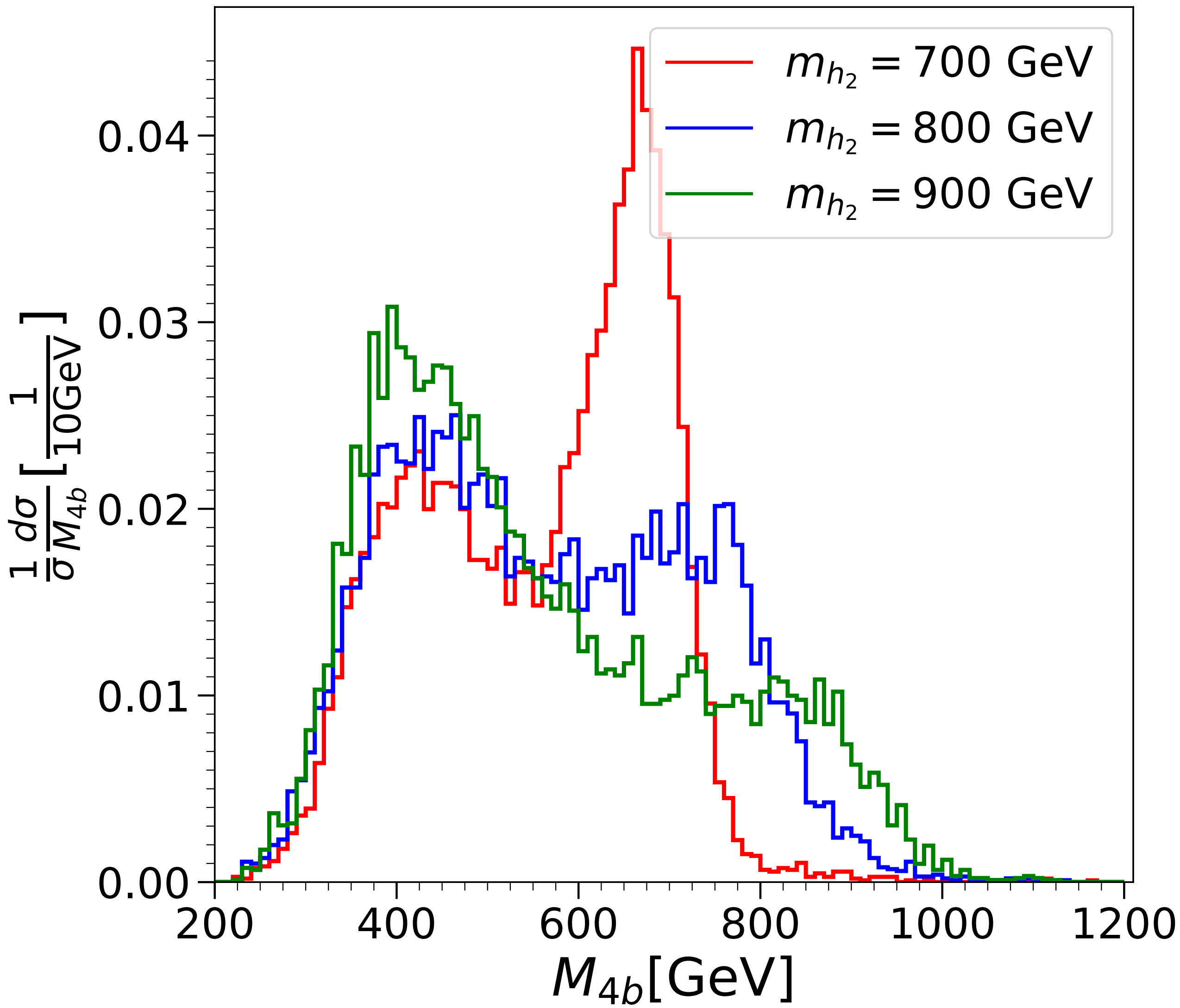
$$|\Delta\eta_{hh}| < \begin{cases} 1.1 & \text{if}\, m_{4j} < 850\,{\rm GeV} \\ 2\times 10^{-3}\,(m_{4j}/{\rm GeV}) - 0.6 & \text{if}\, m_{4j} > 850\,{\rm GeV} \end{cases}$$

Finally, the mass of Higgs boson candidate must lie in the signal region:

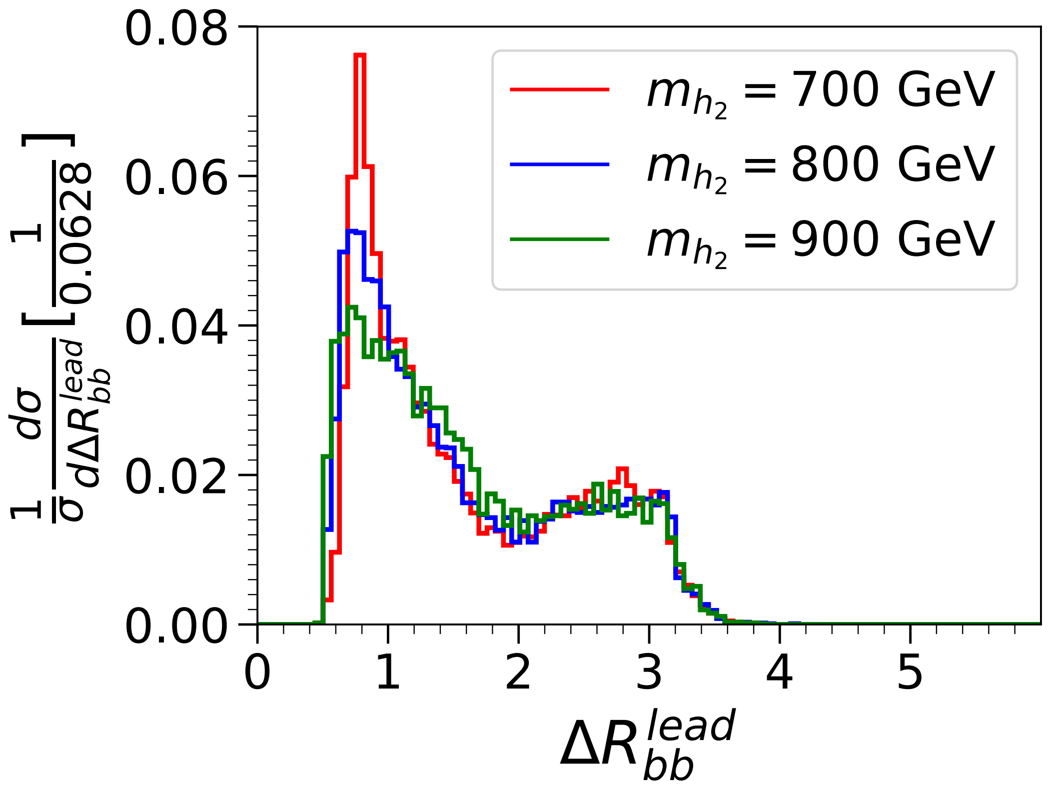
$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{\rm lead} - 120\,{\rm GeV}}{0.1\, m_{2j}^{\rm lead}}\right)^2 + \left(\frac{m_{2j}^{\rm subl} - 115\,{\rm GeV}}{0.1\, m_{2j}^{\rm subl}}\right)^2} < 1.6$$

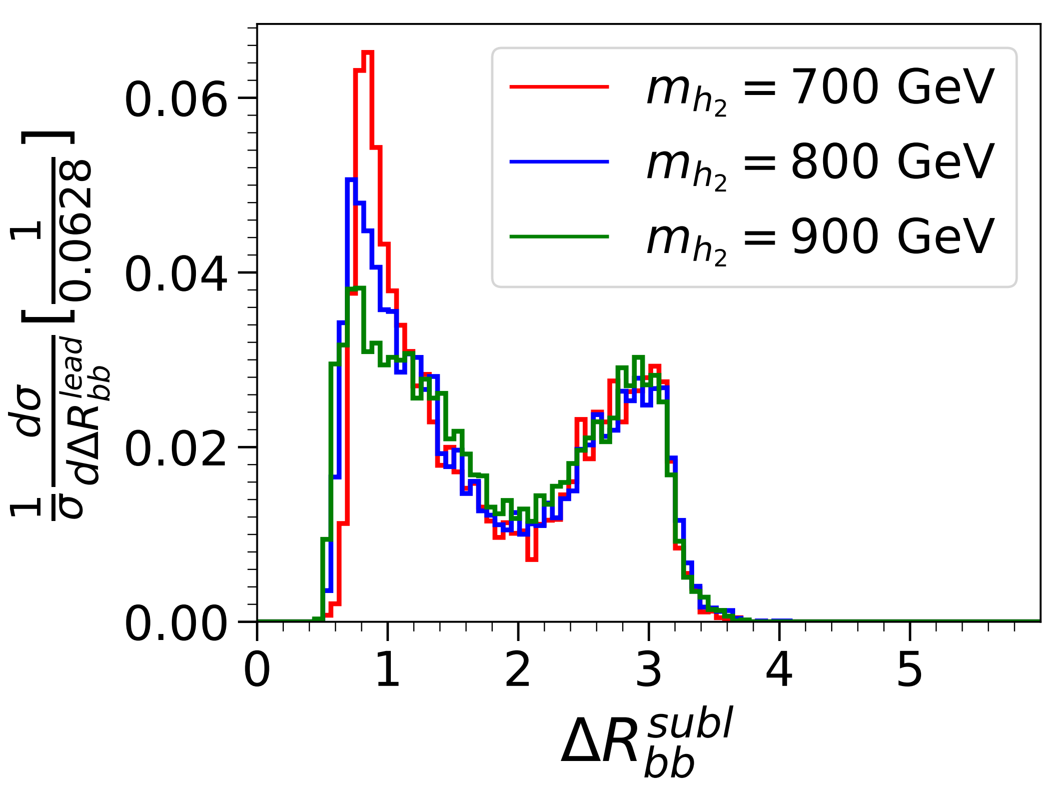
$b\bar{b}b\bar{b}$ final state channel

- BP E has more dominant contribution from the resonant process
- While BP F G are behavior another way around for



$b\bar{b}b\bar{b}$ final state channel





- The ΔR distributions tend to separate into two peaks, one is about $\Delta R \approx 1$, while another is about $\Delta R \approx 3$
- The peak about 1 represents the resonant contribution, while the peak about 3 represents non-resonant contribution

Signal Significances of Higgs pair production

- At HL-LHC (14 TeV, 3000fb^{-1})

✓ATLAS: 1.05σ for $\gamma\gamma b\bar{b}$ final state channel

ATL-PHYS-PUB-2017-001

✓CMS:

  - ✓1.6σ for $\gamma\gamma b\bar{b}$ final state channel
  - ✓0.39σ for $b\bar{b}\tau^+\tau^-$
  - ✓0.45σ for $b\bar{b}$VV*
  - ✓0.39σ for $b\bar{b}b\bar{b}$

CERN-CMS-DP-2016-064

- AT 100 TeV LHC: the pair Higgs will be discovered at L = 256 ifb with bbyy final channel.