Probing New Physics with di-Higgs signal

Hao-Lin Li (李浩林)
ITP,CAS

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Hao-Lin Li, Michael Ramsey Musolf, Stephane Willocq
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Motivation

- Matter anti-Matter asymmetry[1]:

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

- Electroweak Baryogenesis:

Andrey Dmitriyevich Sakharov

Sakharov Conditions:

1. Departure from thermal equilibrium
   Strong First Order Electroweak Phase Transition (SFOEWPT)

2. C and CP violation

3. Baryon Number violation

1. Ade, P. A. R., et al. Planck 2015 results.

Motivation

- Reason for singlet model:

  Simpliest model that can generate SFOEWPT.

  Observed correlation between SFOEWPT and enhanced $h_2h_1h_1$ couplings

S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, JHEP 0708, 010 (2007)
J. R. Espinosa, T. Konstandin and F. Riva, Nucl. Phys. B 854, 592 (2012)
J. M. No and M. Ramsey-Musolf, Phys. Rev. D 89, 095031 (2014)

Outline

- Introduction to the xSM
- EW phase transition in the xSM
- Review of resonant di-Higgs search
- Analysis of di-Higgs 4b final state
- Result
- Bouns: non-resonant di-Higgs search with SMEFT
- Summary

Introduction to the xSM

Introduction to the xSM

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$$H \to h + v_0 \quad S \to s + x_0$$

SM-like

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix},$$

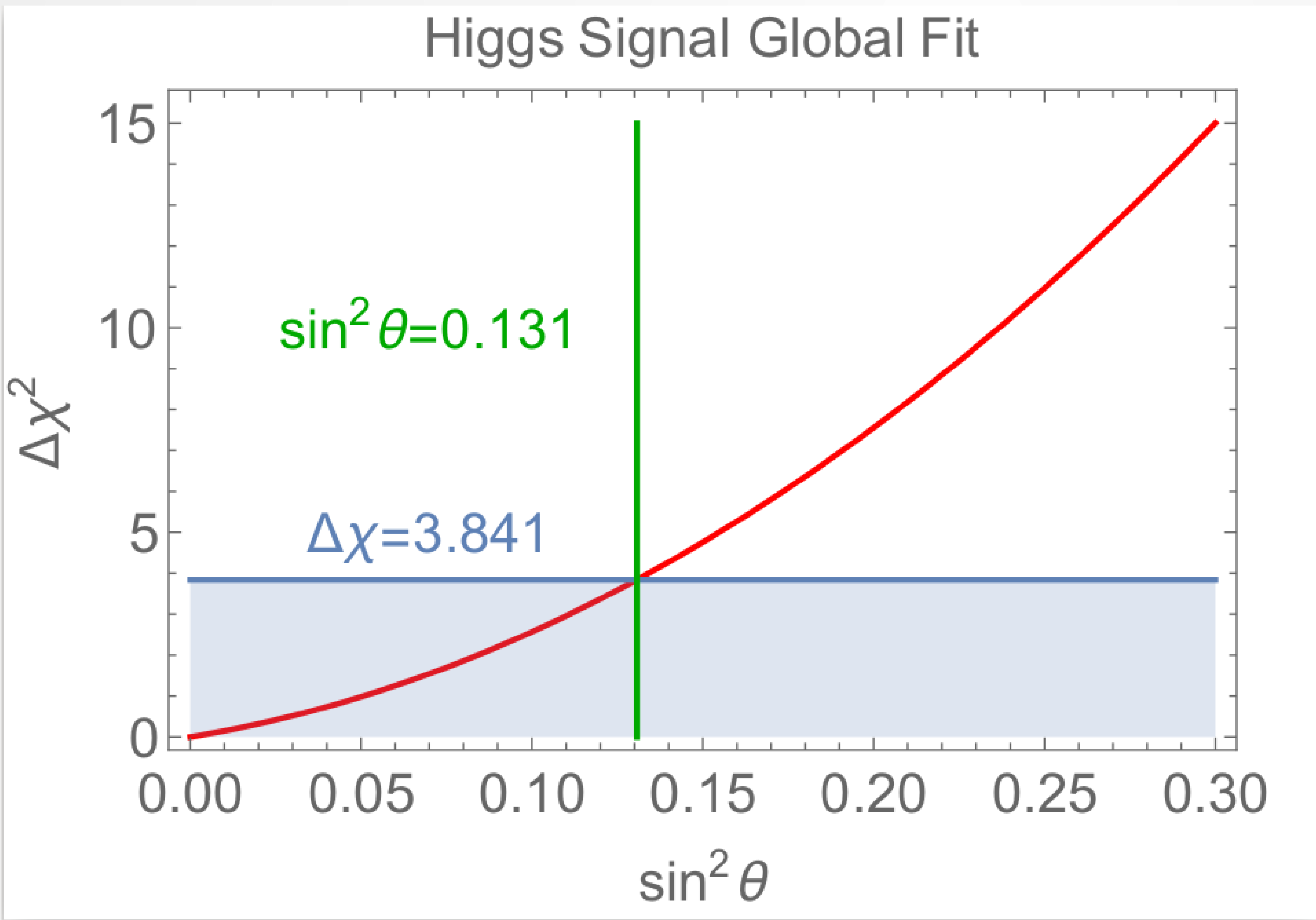
singlet-like

$$-\pi/4 < \theta < \pi/4$$

Introduction to the xSM

$$g_{h_1 XX} = \cos\theta \, g^{\rm SM}_{hXX}, \quad g_{h_2 XX} = \sin\theta \, g^{\rm SM}_{hXX}$$

$$\mu_{h_1 \to XX} = \frac{\sigma_{h_1} \cdot {\rm BR}}{\sigma^{\rm SM}_{h_1} \cdot {\rm BR}^{\rm SM}} = \cos^2\theta \qquad \mu_{h_2 \to XX} = \sin^2\theta \left(\frac{\sin^2\theta \, \Gamma^{\rm SM}(m_2)}{\Gamma_{h_2}} \right)$$



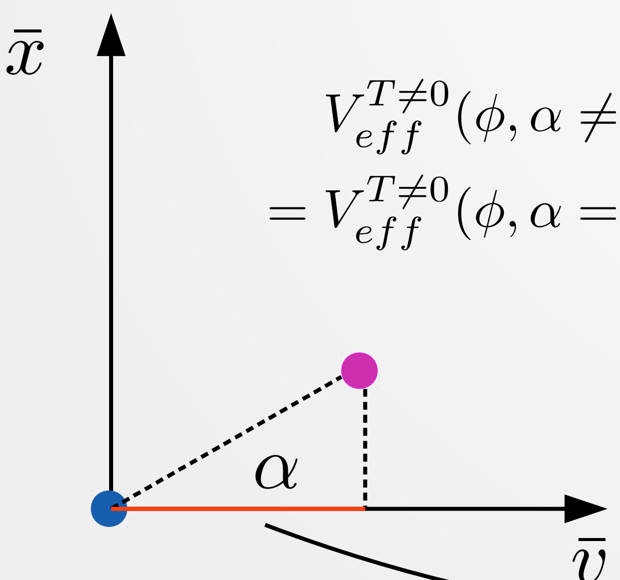
LHC Run2 data with Lilith package

EWPT in the xSM

EWPT in the xSM

$$V_{\rm eff}^{\rm high-T}(h,s,T) \approx V_{\rm tree}(h,s) + \frac{T^2}{24}\left[{\rm Tr} M_{ij}^2(h,s) + 3m_A^2(h) + m_t^2(h)/2\right]^1$$

$$\bar{v}(T)/\sqrt{2} = \bar{\phi}(T)\cos\alpha(T), \quad \bar{x}(T) = \bar{\phi}(T)\sin\alpha(T)$$



$$V_{eff}^{T\neq 0}(\phi, \alpha \neq \pi/2, T_c)$$
$$= V_{eff}^{T\neq 0}(\phi, \alpha = \pi/2, T_c)$$

Criteria for SFOEWPT:

$$\cos\alpha(T_c)\,\frac{\bar{\phi}(T_c)}{T_c} \gtrsim 1$$

1. M. Gonderinger, Y. Li, H. Patel and M. J. Ramsey-Musolf, JHEP 1001, 053 (2010)

EWPT in the xSM

Parameter Scan:

$$a_1/\mathrm{TeV}, \quad b_3/\mathrm{TeV} \in [-1,1], \quad x_0/\mathrm{TeV} \in [0,1], \quad b_4, \lambda \in [0,1]$$

$$\sin^2\theta < 0.131$$

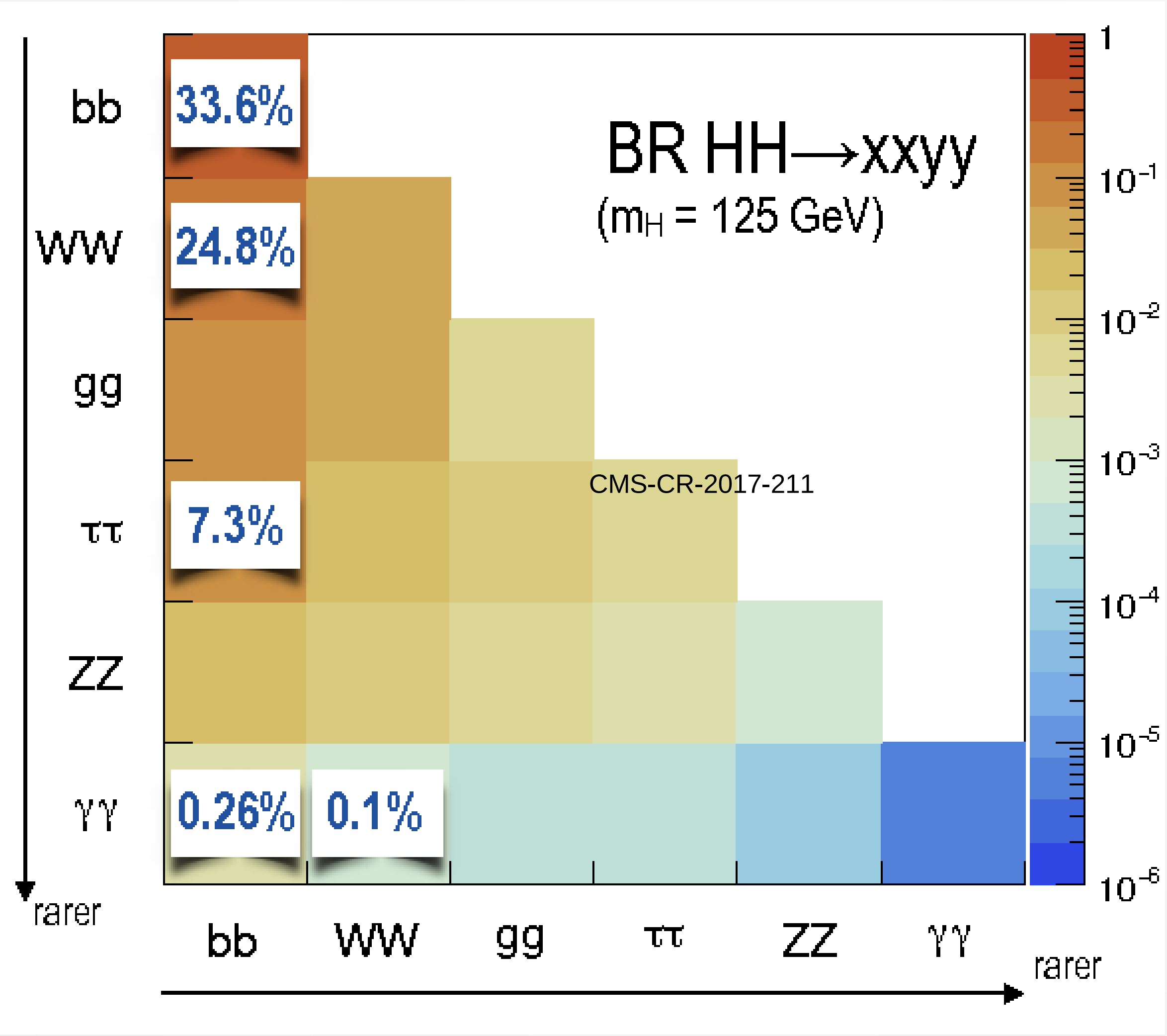
$$\Delta\mathcal{O} = (c_\theta^2 - 1)\mathcal{O}^{\mathrm{SM}}(m_1) + s_\theta^2\,\mathcal{O}^{\mathrm{SM}}(m_2) = s_\theta^2\left[\mathcal{O}^{\mathrm{SM}}(m_2) - \mathcal{O}^{\mathrm{SM}}(m_1)\right] \quad \mathcal{O} = S,\ T$$

$$\Delta\chi^2(m_2, c_\theta) = \sum_{i,j}\left[\Delta\mathcal{O}_i(m_2,c_\theta) - \Delta\mathcal{O}_i^0\right](\sigma^2)_{ij}^{-1}\left(\Delta\mathcal{O}_j(m_2,c_\theta) - \Delta\mathcal{O}_j^0\right) < 5.99$$

we identify benchmark points with maximum and $\sigma(pp \to h_2) \times \mathrm{BR}(h_2 \to h_1 h_1)$ minimum signal rate from 11 consecutive h_2 mass windows of width 50 GeV ranging from 300 to 850 GeV.

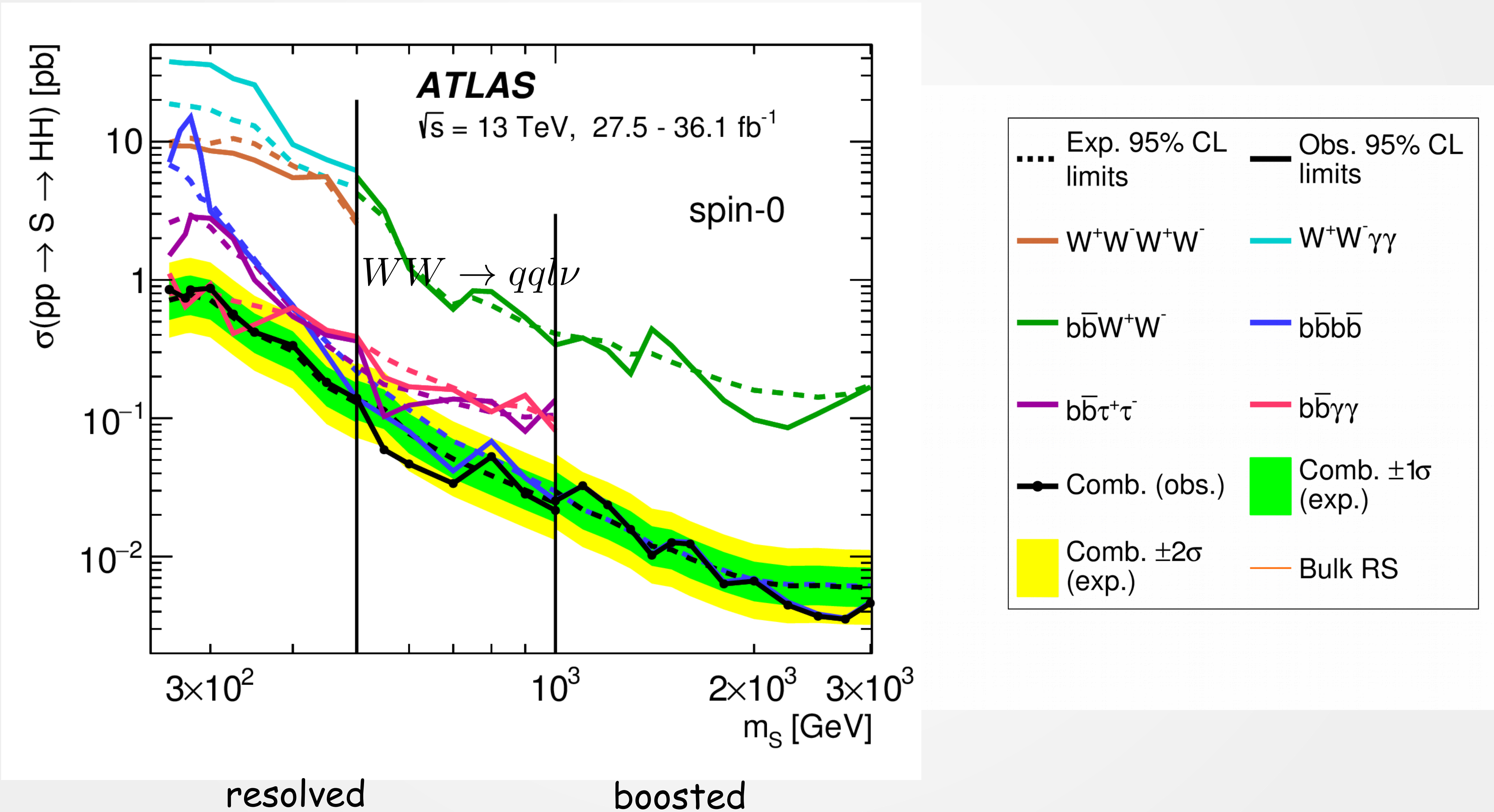
Review of resonant di-Higgs search

Review of resonant di-Higgs search



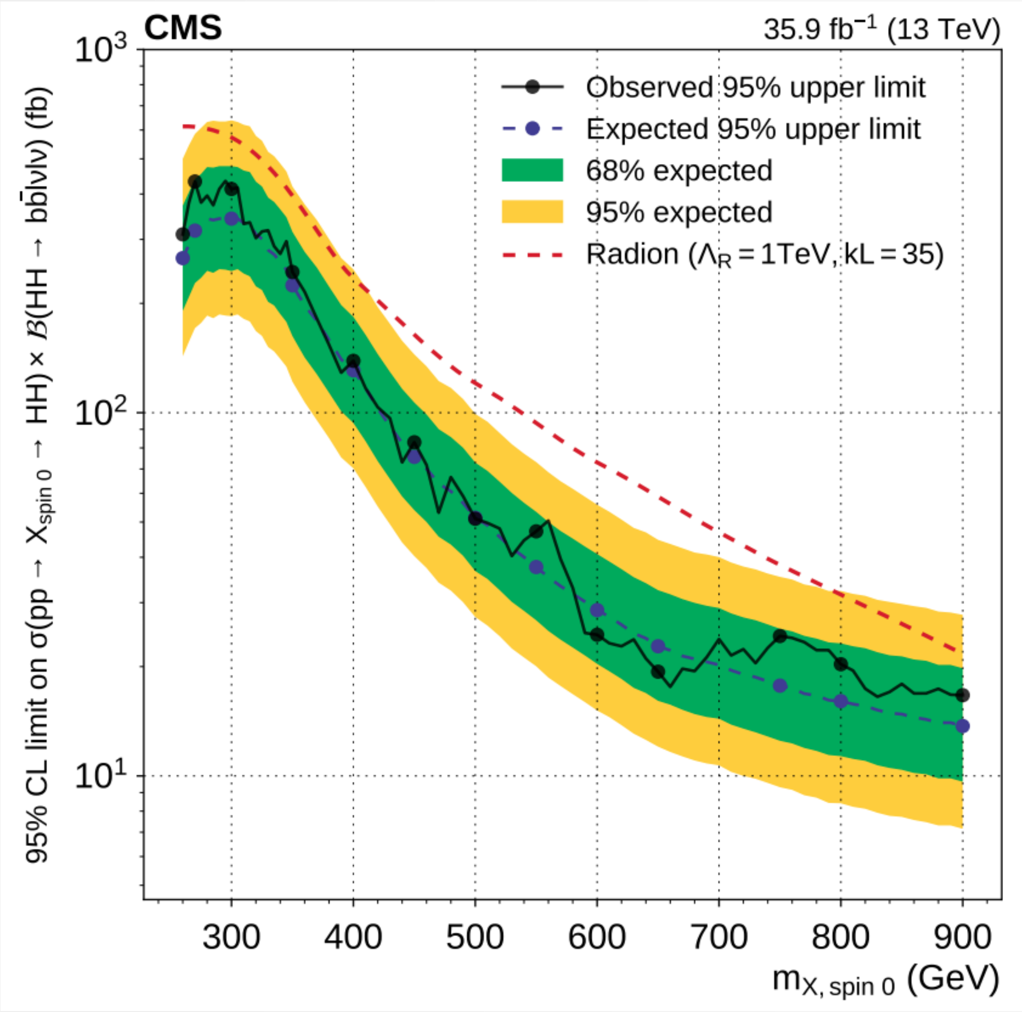
CMS-CR-2017-211

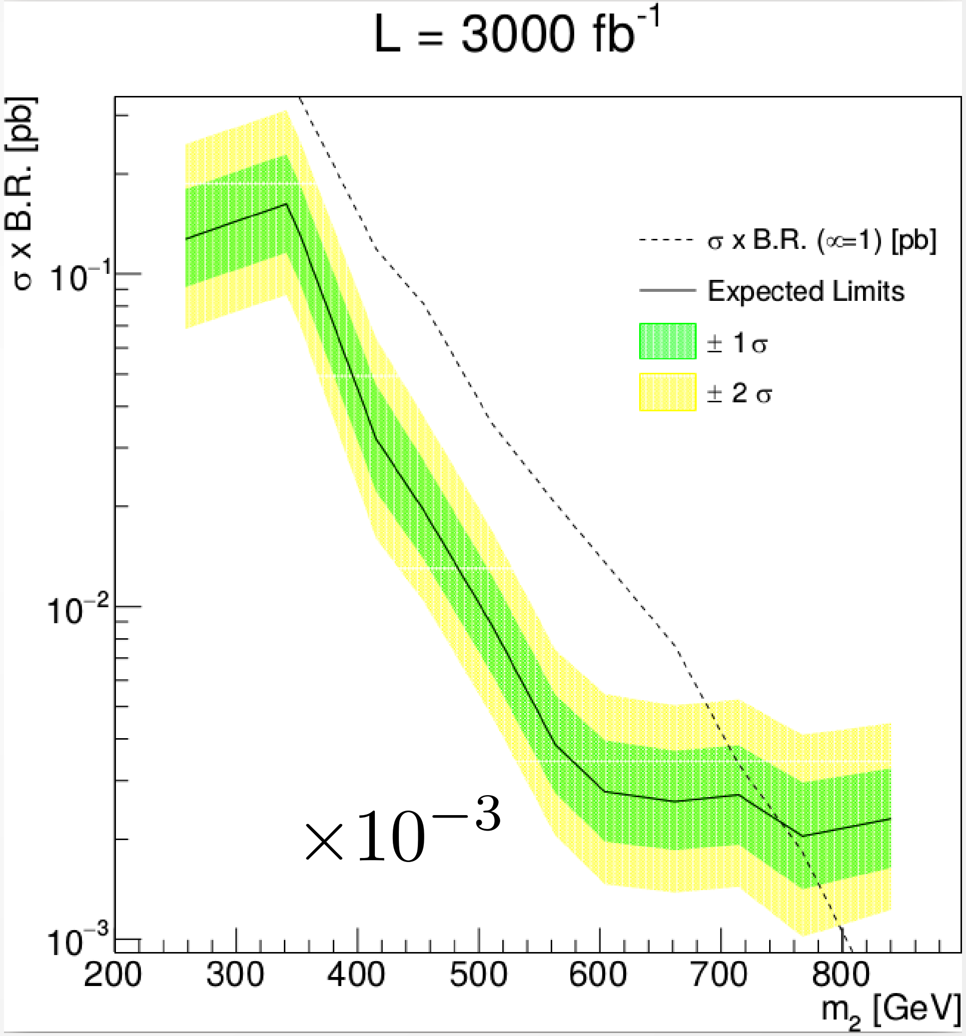
Review of resonant di-Higgs search



Phys.Lett. B800 (2020) 135103

Review of resonant di-Higgs search





Naive rescale with hh→bblvlv and luminosity, it is 1000 times better than current result!

A. M. Sirunyan et al. [CMS Collaboration], JHEP 1801, 054 (2018)
T. Huang, J. M. No, L. Perni, M. Ramsey-Musolf, A. Safonov, M. Spannowsky and P. Winslow, Phys. Rev. D 96, 035007 (2017)

Review of resonant di-Higgs search

Possible reason:

1. underestimation of the systematic uncertianties
2. The use of Heavy Mass Estimator (HME)

Review of resonant di-Higgs search

Heavy Mass Estimator (HME):

$$\not{E}_{Tx} = p_x(\nu_{\ell_1}) + p_x(\nu_{\ell_2}), \quad (23)$$

$$\not{E}_{Ty} = p_y(\nu_{\ell_1}) + p_y(\nu_{\ell_2}), \quad (24)$$

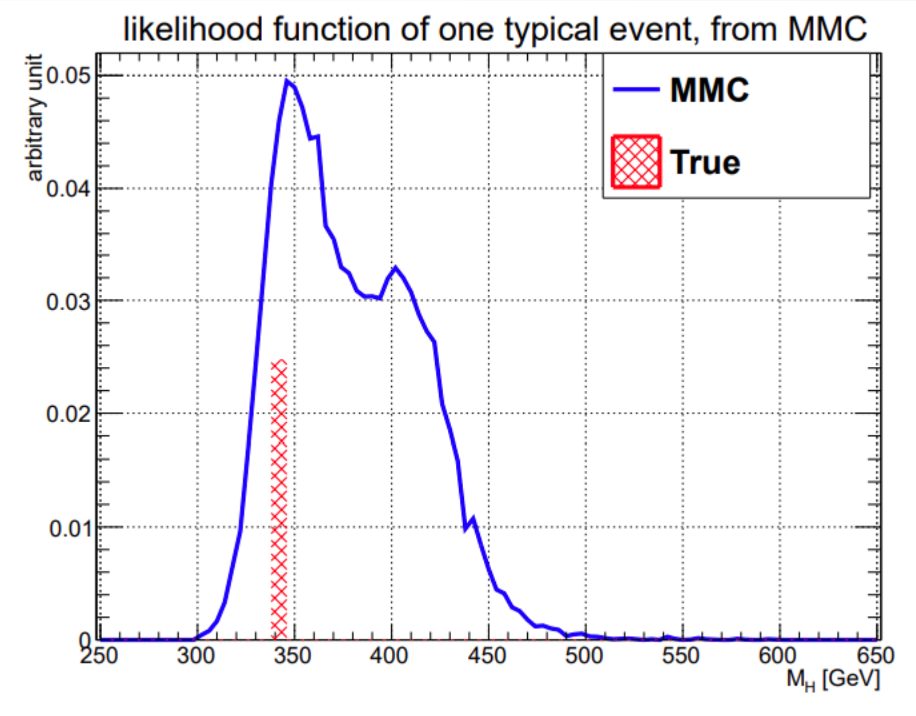
$$\sqrt{p^2(\ell_1, \nu_{\ell_1})} = M_W, \quad (25)$$

$$20 \text{ GeV} < \sqrt{p^2(\ell_2, \nu_{\ell_2})} < 45 \text{ GeV}, \quad (26)$$

$$(p(\ell_1) + p(\ell_2) + p(\nu_{\ell_1}) + p(\nu_{\ell_2}))^2 = m^2_{h_1}, \quad (27)$$

$$(p(b_1) + p(b_2))^2 = m^2_{h_1}, \quad (28)$$

For each events, scan the two variables with prior distribution of $\eta_{\nu1}$ $\varphi_{\nu1}$, and verify that wether they satisfis the off-shell constraint, if they do, then calculate m_{h2} and record the value. Record the peak of the m_{h2} distribution as mh2 for this events.



3+3=6 unkown variables,
5 eq.s + 1 constraint,
4 are neutrino related,

$$\eta_{\nu_1}, \ \phi_{\nu_1}$$

Analysis of di-Higgs 4b final state

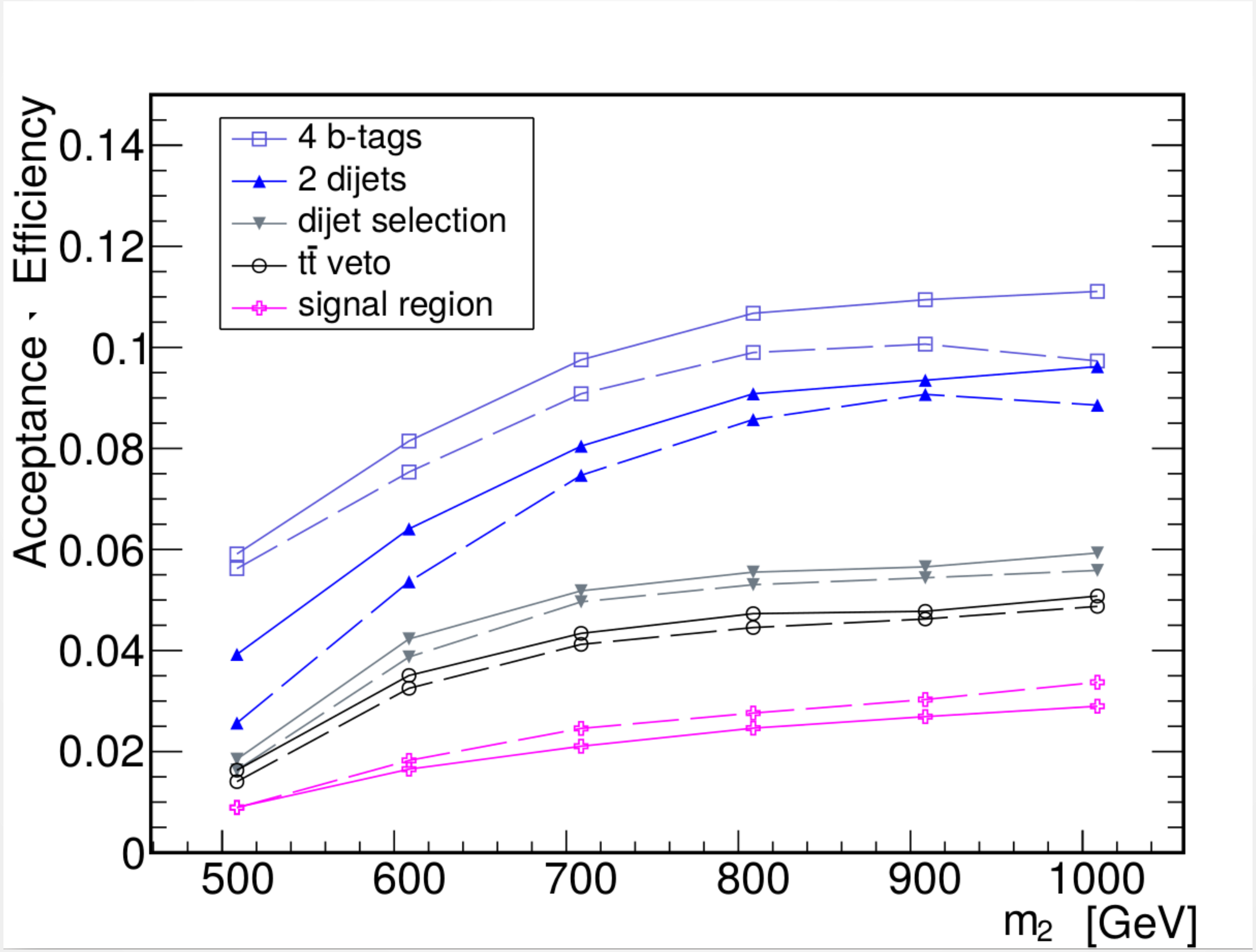
We follow the resolve analysis of ATLAS to calibrate our simulation:

1. Select events with #b tagged jets >=4 with pt>40 GeV and |η| <2.5 and select 4 b-tagged jets as candidates with highest pt
2. Selecting two di-jets systems: ΔR_{bb}<1.5, pt>200(150) GeV
3. $$p_T^{\rm lead} > \begin{cases} 400\,\mathrm{GeV} & \text{if } m_{4\mathrm{j}} > 910\,\mathrm{GeV}, \\ 200\,\mathrm{GeV} & \text{if } m_{4\mathrm{j}} < 600\,\mathrm{GeV}, \\ 0.65\, m_{4\mathrm{j}} - 190\,\mathrm{GeV} & \text{otherwise,} \end{cases} \quad p_T^{\rm subl} > \begin{cases} 260\,\mathrm{GeV} & \text{if } m_{4\mathrm{j}} > 990\,\mathrm{GeV}, \\ 150\,\mathrm{GeV} & \text{if } m_{4\mathrm{j}} < 520\,\mathrm{GeV}, \\ 0.23\, m_{4\mathrm{j}} + 30\,\mathrm{GeV} & \text{otherwise,} \end{cases}$$
$$|\Delta\eta_{\rm dijets}| < \begin{cases} 1.0 & \text{if } m_{4\mathrm{j}} < 820\,\mathrm{GeV} \\ 1.6 \times 10^{-3}\, m_{4\mathrm{j}} - 0.28 & \text{otherwise.} \end{cases}$$
4. extra jets pt>30 GeV and |η| <1.5 within ΔR_{bb}<1.5 with di-jet system, need to pass the cuts:
$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4\,\mathrm{GeV}}{0.1\, m_W}\right)^2 + \left(\frac{m_t - 172.5\,\mathrm{GeV}}{0.1\, m_t}\right)^2} < 3.2$$
5. Finaly the signal region cuts:
$$X_{h_1h_1} = \sqrt{\left(\frac{m_{2\mathrm{j}}^{\rm lead} - 120\,\mathrm{GeV}}{0.1\, m_{2\mathrm{j}}^{\rm lead}}\right)^2 + \left(\frac{m_{2\mathrm{j}}^{\rm subl} - 113\,\mathrm{GeV}}{0.1\, m_{2\mathrm{j}}^{\rm subl}}\right)^2} < 1.6$$

M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. D 94, 052002 (2016)

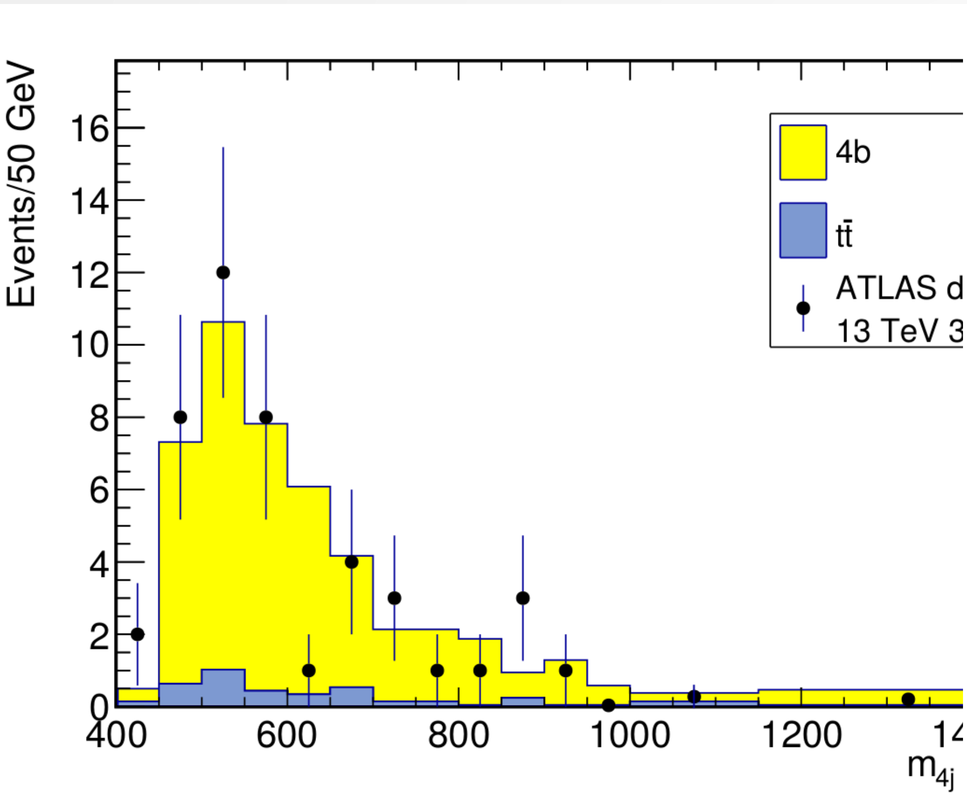
Analysis of di-Higgs 4b final state

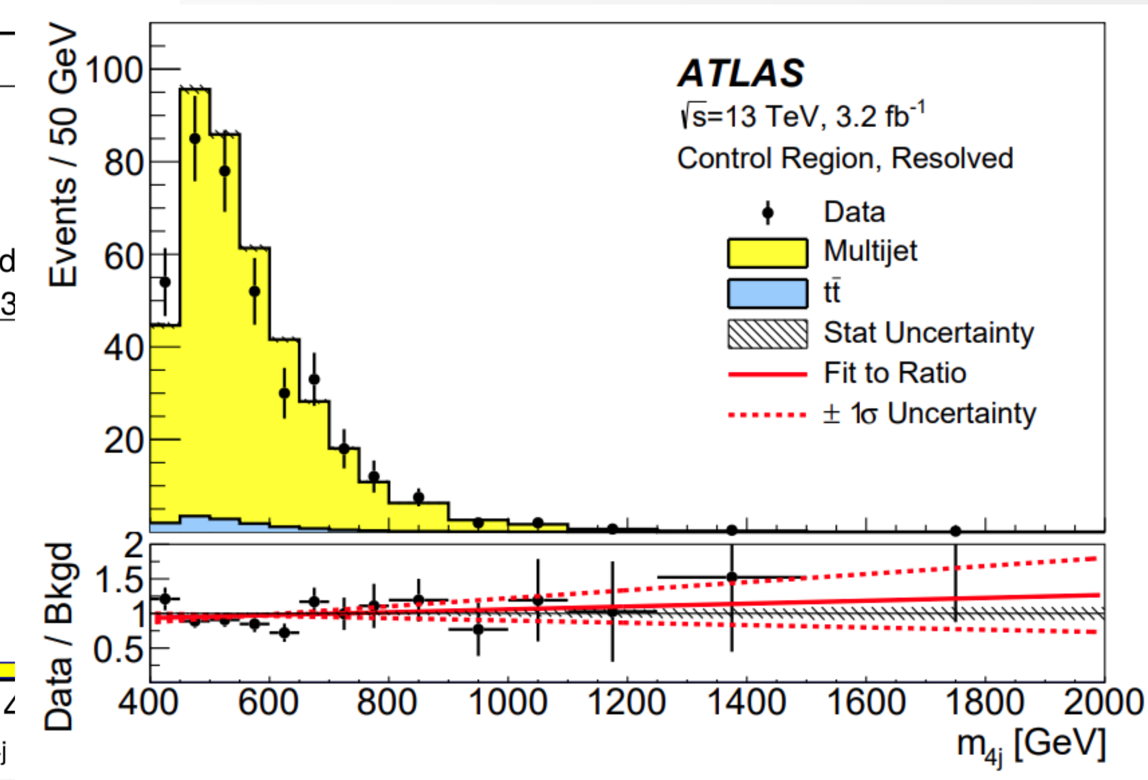
Analysis of di-Higgs 4b final state



M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. D 94, 052002 (2016)

Analysis of di-Higgs 4b final state





$$N_{bbcc} = N_{4b} \times \frac{\sigma_{bbcc}}{\sigma_{4b}} \times \left(\frac{\epsilon_c^{\mathrm{tag}}}{\epsilon_b^{\mathrm{tag}}} \right)^2$$

M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. D 94, 052002 (2016)

Analysis of di-Higgs 4b final state

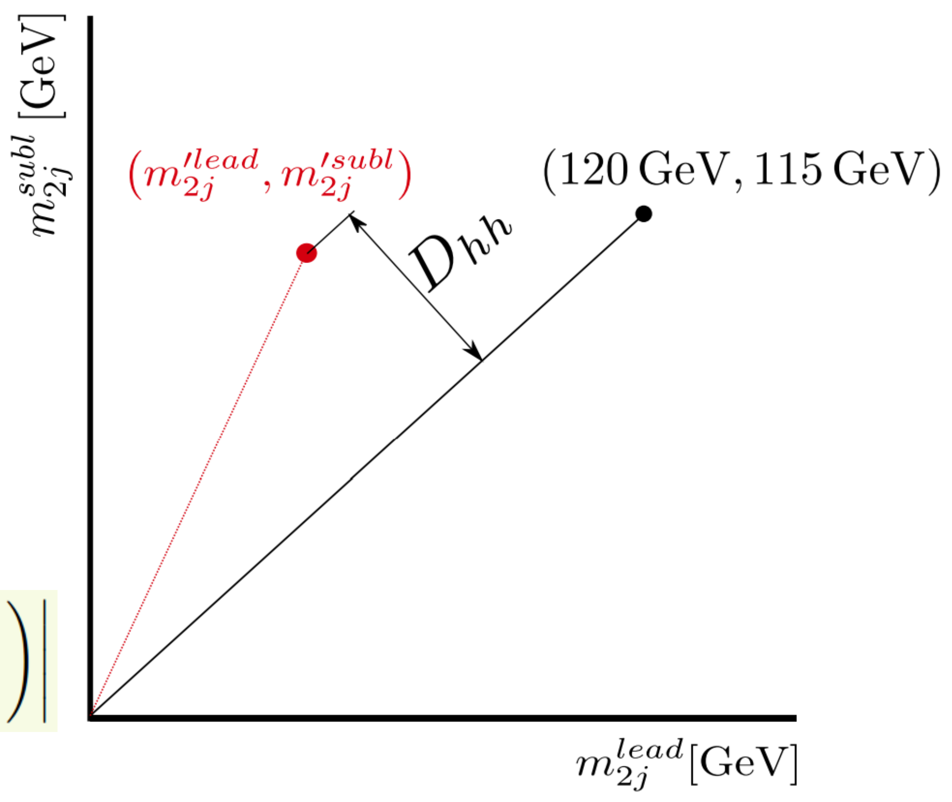
We then use the BDT to optimize the cut to forcast 14TeV sensitivity:

1. selecting di-jet system:
   4 b jets with pt>30 GeV and |η| <2.5

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

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

$$D_{h_1 h_1} = \sqrt{(m_{2j}^{lead})^2 + (m_{2j}^{subl})^2} \left| \sin\left(\tan^{-1}\left(\frac{m_{2j}^{subl}}{m_{2j}^{lead}} \right) - \tan^{-1}\left(\frac{115}{120} \right) \right) \right|$$

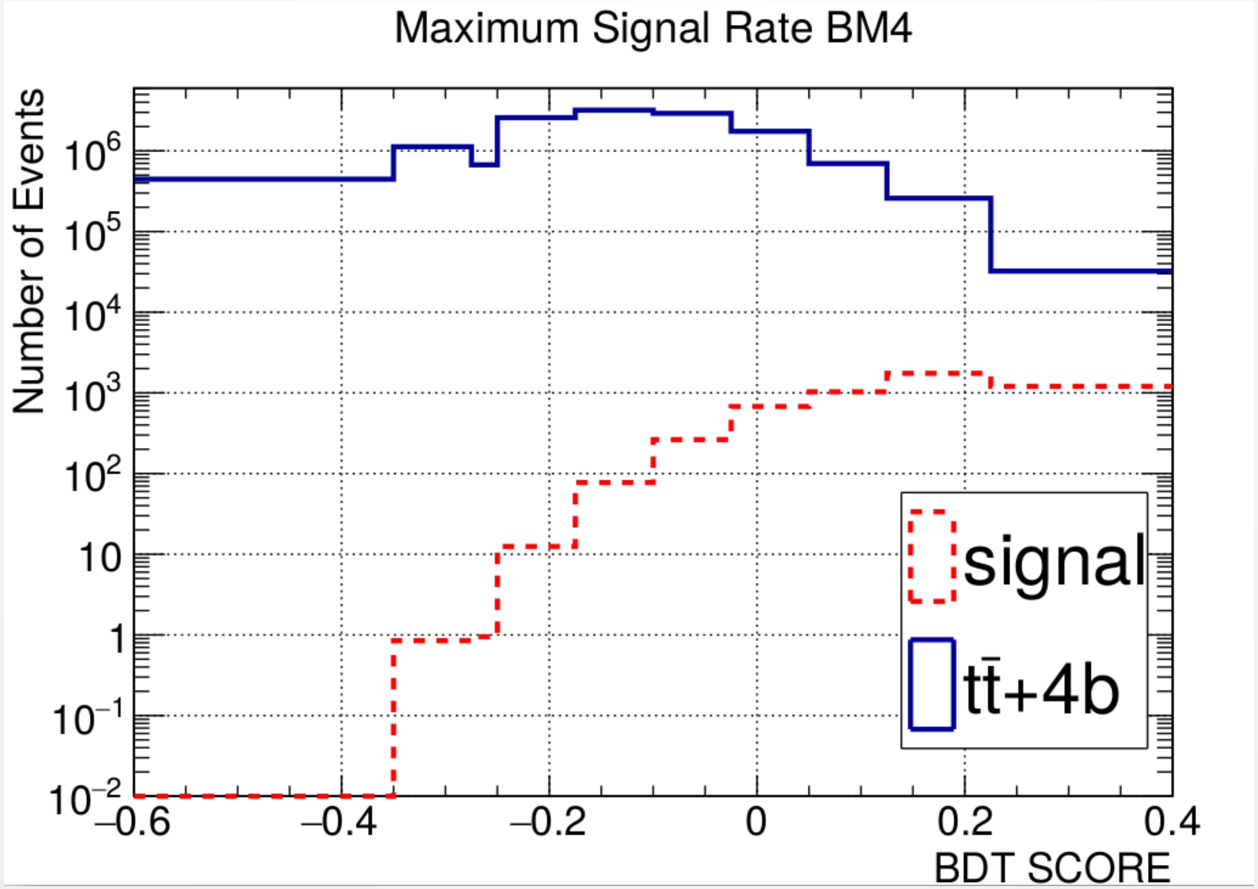


ATLAS-CONF-2016-049, 2016

Analysis of di-Higgs 4b final state

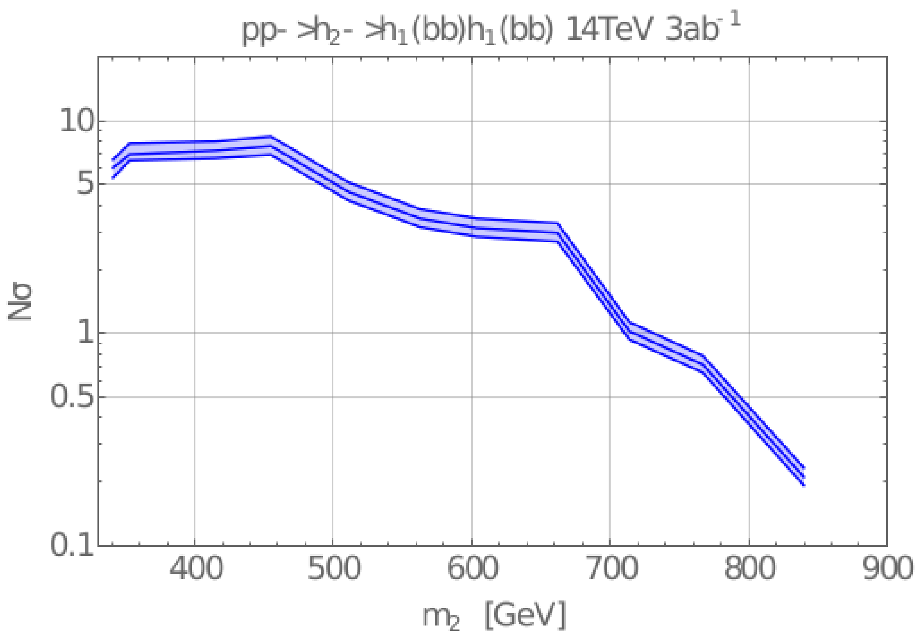
Put the following variables into the BDT

$$p_T^{\rm lead},\ p_T^{\rm subl}, \Delta R_{\rm jj}^{\rm lead}, \Delta R_{\rm jj}^{\rm subl}, \Delta R_{h_1 h_1}, \Delta\phi_{h_1 h_1}, \Delta\eta_{h_1 h_1}, m_{\rm 2j}^{\rm lead}, m_{\rm 2j}^{\rm subl}, X_{h_1 h_1}, m_{\rm 4j},$$

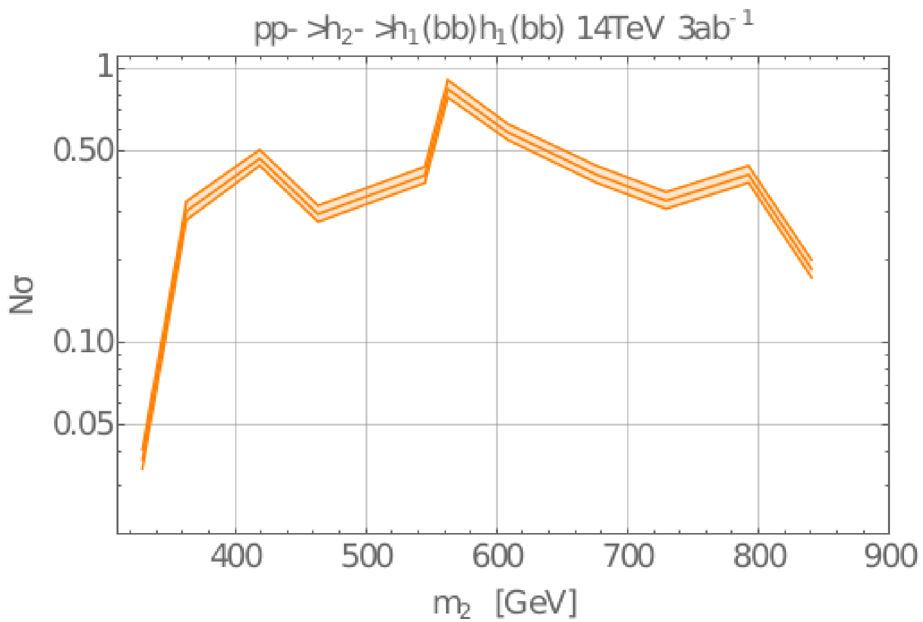


$$m_{h_2} = 445 GeV$$

Result



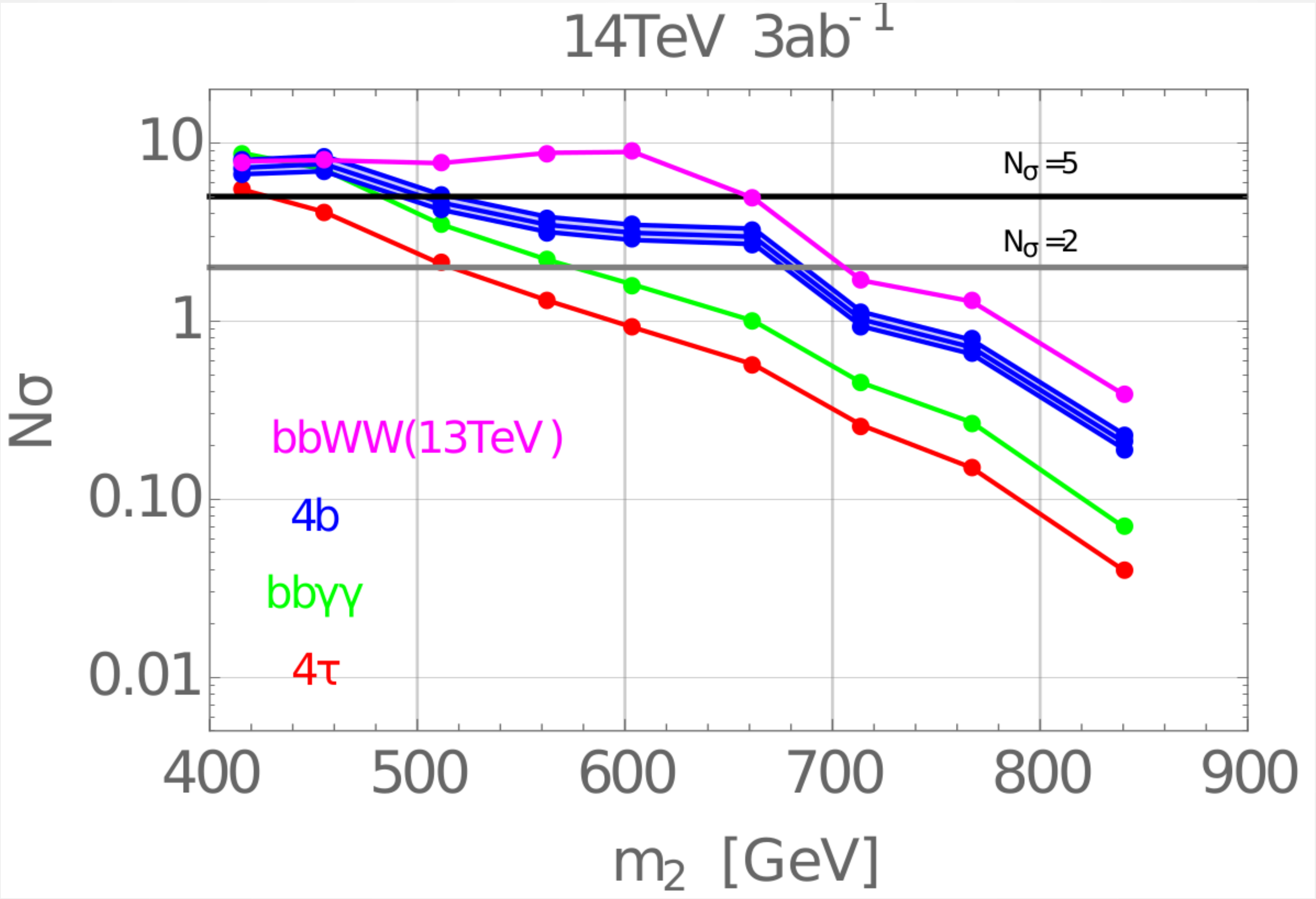
(a) $\mathrm{BM}_{\mathrm{max}}$ benchmark



(b) $\mathrm{BM}_{\mathrm{min}}$ benchmark

convert $1 - \mathrm{CL_b}$ to N_σ

Result



convert $1 - \mathrm{CL_b}$ to N_σ

Summary

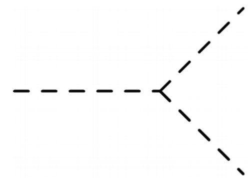
1. Di-Higgs resonant search is a good way to test EWPT.
2. $bb\gamma\gamma$ is the best channel for relatively light h_2.
3. 4b is good for m_{h2}>500 GeV but not as good as bbWW.

Bouns: non-resonant di-Higgs production

DiHiggs in SM EFT

JHEP 1805 (2018) 061 T.Cobett, A. Joglekar, H.-L Li, J.-H Yu

EWSB in SM

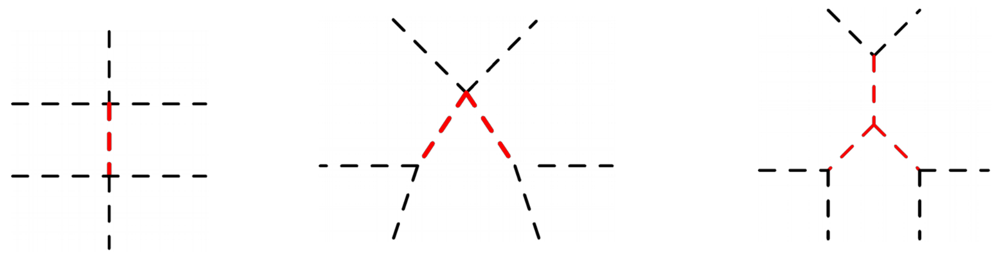


$$\lambda_{SM} = \frac{m_h^2}{2v}$$

Leading Order Correction in SM EFT:

$$c_H (H^\dagger H)^3$$

Tree Level Produce:



Need Interaction:

HHΦ

$$2 \otimes 2 = 3 \oplus 1$$

Triplet and Singlet

HHHΦ

$$2 \otimes 2 \otimes 2 = 4 \oplus 2$$

Quadruplet and Doublet

$$c_{HD} |H^\dagger D_\mu H|^2$$

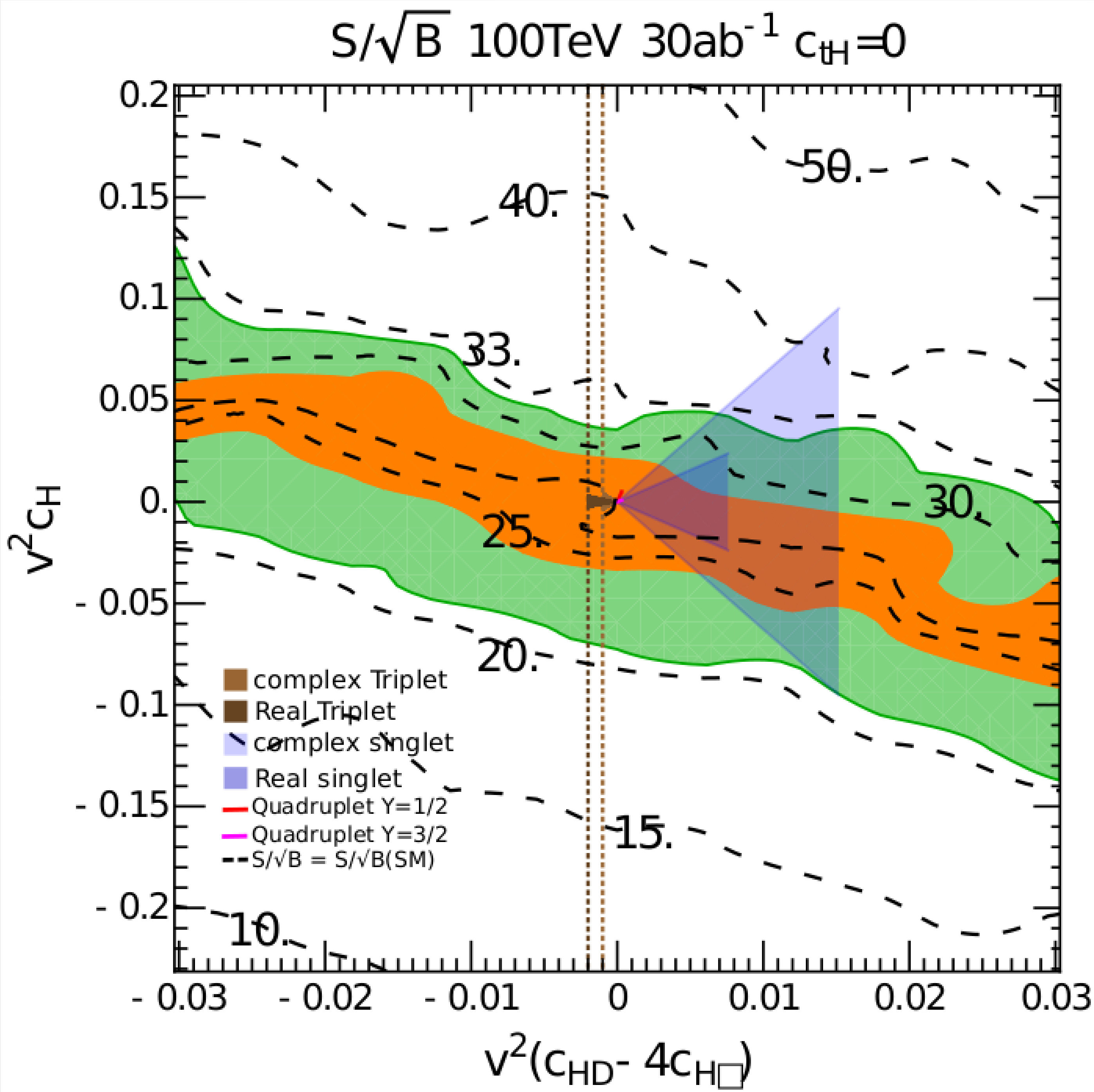
Strong T parameter constraint

$$c_{HD} \sim c_H$$

Correction to λ_{SM} can not be observed even in 100TeV pp collider for M=1~2TeV.

No T parameter constraint, Possible to generate correction to λ_{SM} which can be observed in 100TeV pp collider for M=1~2TeV.

Theory:	$\mathbf{c_H}$	$\mathbf{c_{H\Box}}$	$\mathbf{c_{HD}}$	$\mathbf{c_{eH}}$	$\mathbf{c_{uH}}$	$\mathbf{c_{dH}}$
$\mathbb{R}$ Singlet	$-\frac{\lambda_{HS}}{2}\frac{g_{HS}^2}{M^4}$	$-\frac{g_{HS}^2}{2M^4}$	-	-	-	-
$\mathbb{C}$ Singlet	$-\left(\frac{\lvert g_{HS}\rvert^2\lambda'_{H\Phi}}{2M^4}+\frac{\mathrm{Re}[g_{HS}^2\lambda_{H\Phi}]}{M^4}\right)$	$-\frac{\lvert g_{HS}\rvert^2}{M^4}$	-	-	-	-
2HDM, Type I	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Type II:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
Lepton-Specific:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Flipped:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
$\mathbb{R}$ Triplet $(Y=0)$	$-\frac{g^2}{M^4}\left(\frac{\lambda_{H\Phi}}{8}-\lambda\right)$	$\frac{g^2}{8M^4}$	$-\frac{g^2}{2M^4}$	$\frac{g^2}{4M^4}Y_l$	$\frac{g^2}{4M^4}Y_u$	$\frac{g^2}{4M^4}Y_d$
$\mathbb{C}$ Triplet $(Y=-1)$	$-\frac{\lvert g\rvert^2}{M^4}\left(\frac{\lambda_{H\Phi}}{4}+\frac{\lambda'}{8}-2\lambda\right)$	$\frac{\lvert g\rvert^2}{2M^4}$	$\frac{\lvert g\rvert^2}{M^4}$	$\frac{\lvert g\rvert^2}{2M^4}Y_l$	$\frac{\lvert g\rvert^2}{2M^4}Y_u$	$\frac{\lvert g\rvert^2}{2M^4}Y_d$
$\mathbb{C}$ Quadruplet $(Y=1/2)$	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{2\lvert\lambda_{H3\Phi}\rvert^2v^2}{2M^4}$	-	-	-
$\mathbb{C}$ Quadruplet $(Y=3/2)$	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{6\lvert\lambda_{H3\Phi}\rvert^2v^2}{2M^4}$	-	-	-



$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,,$$
$$Q_{HD} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)$$

$$Q_H = (H^\dagger H)^3\,,$$