Prepared for submission to JHEP

The SM Tests At The 100 TeV Hadron Collider

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Abstract:
In this note, I discuss the SM tests at the 100 TeV hadron collider of the next generation.

ArXiv ePrint: arXiv:MMMM.abcd

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2 The Basics of The SM

In this section, we review the SM with the emphasis on the current LHC experimental results and the perspective on the experimental measurements to be carried out at the future high-energy collider projects.

2.1 The unitarity bound in the vector boson scatterings

In the SM, we have the minimal setup for the EWSB, namely one SM Higgs doublet Φ. With the discovery of a SM-like Higgs boson with mass of 125 GeV at the LHC, it is expected that this Higgs boson would play a role in the vector boson scattering of $VV \to VV$ with $V = (W\,, Z)$. Such a study was first carried out in Ref. [1], where the amplitude can be expanded in terms of the center-of-mass energy squared s:

$$\mathcal{M} = As^2 + Bs + \mathcal{O}(s^0)\,, \tag{2.1}$$

The s^2 term receive contributions purely from the vector boson couplings, which is precisely vanishing due to the YM structure. To have the $\mathcal{O}(s)$ term vanish, authors pointed out the following sum rule for the unitarity condition in the SM:

$$M_V^2 G_{4V} - \frac{3}{4} M_V^2 G_{3V}^2 = \frac{1}{4} G_{hVV}^2\,, \tag{2.2}$$

where $(G_{4V}\,, G_{3V})$ denote the quartic and triple vector boson couplings, and $G_{hVV} = 2m_V^2/v$ denotes the SM Higgs coupling to the vector boson pair.

3 The Basics of The BSM

3.1 The BSM Higgs Boson

In the BSM new physics, it is likely to have extended gauge structure and/or extended Higgs sector. In these cases, the SM sum rule of the (2.2) will be modified to ensure the unitarity condition of the vector boson scattering amplitude of $VV \to VV$. Perhaps the most straightforward extension is due to the 2HDM, where two Higgs doublets $(\Phi_1\,, \Phi_2)$ will trigger the EWSB. Therefore, the sum rule of (2.2) in the SM case will be extended into the form of:

$$M_V^2 G_{4V} - \frac{3}{4} M_V^2 G_{3V}^2 = \frac{1}{4} (G_{hVV}^2 + G_{HVV}^2)\,, \tag{3.1}$$

where both light and heavy Higgs bosons $(h\,, H)$ play the role of canceling the $\mathcal{O}(s)$ term for the unitarity condition.

In more complicated setup where one assumes extended gauge symmetries of $\mathrm{SU}(2)_0 \times \mathrm{SU}(2)_1 \times \mathrm{U}(1)$ for the EW sector, there will be extra vector bosons $V' = (W'\,, Z')$ plus two Higgs doublets. After the EWSB, two Higgs bosons remain in the spectrum. In such a case, both spin-0 states (Higgs bosons) and the spin-1 states (V' vector bosons) play the joint roles for ensuring the unitarity condition. The relevant sum rule as studied in Ref. [2] reads:

$$G_{4V}^2 - \frac{3}{4}(G_{3V}^2 + \frac{M_{V'}^2}{M_V^2}G_{VVV'}^2) = \frac{1}{4M_V^2}(G_{hVV}^2 + G_{HVV}^2)\,. \tag{3.2}$$

The new physics may distort the Higgs-gauge couplings which may be effectively described by:

$$\mathcal{L}_H = \Delta\kappa h(\frac{2m_W^2}{v}W_\mu^+W^{-\mu} + \frac{m_Z^2}{v}Z_\mu Z^\mu) \tag{3.3}$$

which may ruin the sum rules and re-introduce the unitarity violation in the scattering amplitude. In Fig. 1, we demonstrated the sensitivities of the unitarity violation to the magnitude of $\Delta\kappa$.

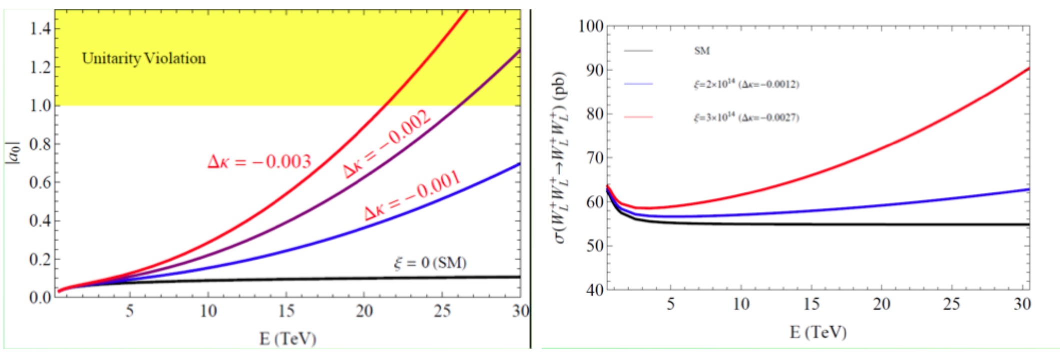

Figure 1. Left: Sensitivity of unitarity violation to $\Delta\kappa$. Right: the $W_L^+W_L^- \to W_L^+W_L^-$ cross section for different ξ or $\Delta\kappa$ values.

3.2 The Exotic State Searches

3.2.1 The heavy neutral Higgs boson searches

Now we would also mention the searches for the BSM Higgs bosons via the exotic channels. Our discussions will be based on the generic two Higgs doublet model (2HDM), and it is possible to extend into other models with multiple Higgs fields. In the 2HDM, there are five physical states in the scalar spectrum after the EWSB: $(h\,, H\,, A\,, H^\pm)$.

The conventional search modes for $H\,, A$

Perhaps the most conventional search modes for the $H\,, A$ states were studied in the context of MSSM, where one essentially has a type-II 2HDM setup the Higgs sector. The global fit to the light CP-even Higgs boson h 2HDM would point to the alignment limit of the parameter choices: $\cos(\beta-\alpha)\to 0$. Under such a limit, the heavy CP-even Higgs boson H couplings to vector bosons $(W\,, Z)$ become highly suppressed, and the corresponding experimental searches via the $H\to(WW\,, ZZ)$ are thus quite challenging. Together with the large $\tan\beta$ inputs, one has H and A couplings to the bottom quarks and τ being $\propto \tan\beta$. In this case, the current direct searches for the $(H\,, A)$ focus on the $(b\bar{b}\,, \tau^+\tau^-)$ final states.

In Fig. 2, we demonstrated the exclusion of the heavy CP-even Higgs H via the $\tau^+\tau^-$ final states.

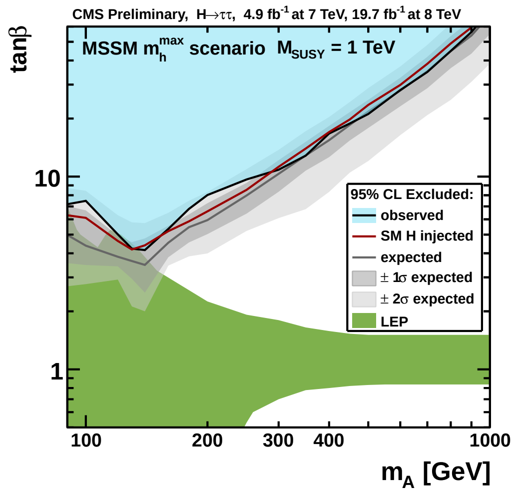

Figure 2. Exclusion at 95 % CL in the $\tan\beta - M_A$ parameter space via the $H \to \tau\tau$ searches at the CMS, with the LHC running at the $7 \oplus 8$ TeV.

The exotic search modes for $H\,, A$

Besides of the final states mentioned above, recent studies show certain possibilities of searching for heavy Higgs boson via exotic final states. Two typical examples are $A \to hZ$ and $H \to hh$ decay modes pointed out in Ref. [4] within the context of general 2HDM, where one has one or two SM-like Higgs boson h as the decay final state. These two decay modes are particularly involved when the H or A masses are below the $\bar{t}t$ threshold: $M_{H\,,A} \lesssim 2m_t$. With the current measurement of the signal strengths of the 125 GeV Higgs boson, it is reasonable to check the SM Higgs boson decay branching ratio in order to obtain the possible search modes:

$$\begin{aligned} &\mathrm{Br}(h \to \bar{b}b) \approx 57.7\,\%\,, \qquad \mathrm{Br}(h \to \tau^+\tau^-) \approx 6.37\,\%\,, \qquad \mathrm{Br}(h \to WW) \approx 21.6\,\%\,, \\ &\mathrm{Br}(h \to gg) \approx 8.55\,\%\,, \qquad \mathrm{Br}(h \to ZZ) \approx 2.66\,\%\,, \qquad \mathrm{Br}(h \to \gamma\gamma) \approx 0.2\,\%\,. \end{aligned} \tag{3.4}$$

Recent experimental studies from the CMS collaboration have performed analysis to various decay modes of $H \to hh$ and $A \to hZ$. The combinations of these decay modes are listed in Table. 1 and Table. 2 respectively.

For the $H \to hh$ searches, the sensitivity mostly comes from $h \to WW^*$ and $h \to \tau^+\tau^-$ decays, hence the multi-lepton channels are expected to contribute. The final states from the $H \to hh$ decays and the search channels are listed in Table. 3.

For the $A \to hZ$ searches, there is a Z in the signal final state, hence channels with an OSSF pair on Z-pole would reduce the Drell-Yan background significantly. The various decay modes of h and Z are given in Table. 4.

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau^+\tau^-$	$h \to \bar{b}b$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	×	✓
$h \to ZZ^*$	–	✓	✓	✓	✓
$h \to \tau^+\tau^-$	–	–	✓	×	✓
$h \to \bar{b}b$	–	–	–	×	×
$h \to \gamma\gamma$	–	–	–	–	×

Table 1. The decay mode combinations of two h final states in CMS analysis [5].

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau^+\tau^-$	$h \to \bar{b}b$	$h \to \gamma\gamma$
$Z \to \ell\ell$	✓	✓	✓	–	✓
$Z \to qq$	×	✓	×	×	×
$Z \to \nu\nu$	×	✓	×	–	×

Table 2. The decay mode combinations of two h final states in CMS analysis [5].

Final states from hh decays	Search channels h decays populate
WW^*WW^* $WW^*\tau\tau$ $\tau\tau\tau\tau$ $ZZ^*\tau\tau$ $ZZbb$	Three or four leptons (up to one τ_h) OSSF pair off-Z or no OSSF pair in bins of MET and b-tag
$\gamma\gamma WW^*$ $\gamma\gamma ZZ^*$ $\gamma\gamma\tau\tau$	diphoton within Higgs bin +1 or more leptons (up to 2 τ_h), in bins of MET

Table 3. The various combinations to h decay modes and the search channels they populate.

Final states from hZ decays	Search channels hZ decays populate
$Z(\to \ell\ell)WW^*$ $Z(\to \ell\ell)ZZ^*$ $Z(\to \ell\ell)\tau\tau$ $qqZ(\to \ell\ell)Z^*$ $\nu\nu Z(\to \ell\ell)Z^*$	1 on-shell $Z(\to \ell\ell)$ + 1 or more leptons (up to 1 τ_h) in bins of MET and b-tag
$\gamma\gamma\ell\ell$	diphoton within higgs bin + 1 or more leptons, in bins of MET

Table 4. The various combinations to h decay modes and the search channels they populate.

In the above experimental analysis to the heavy neutral Higgs boson searches at the LHC8, the $h \to \bar{b}b$ final states are generally neglected. Particularly for the $H \to hh \to 4b$ and $A \to hZ \to 2b + 2q$ final states, one would encounter huge QCD background. Yet some other combinations such as $H \to hh \to (bbWW\,, bb\gamma\gamma)$ and $A \to hZ \to bb + \ell\ell$ are still interesting in that the corresponding SM backgrounds are relatively manageable. Here we presented several relevant studies to these modes. In Fig. 3, we presented the signal reaches for the $H \to hh \to \bar{b}b\gamma\gamma$ searches on the $(M_H\,, \tan\beta)$ plane.

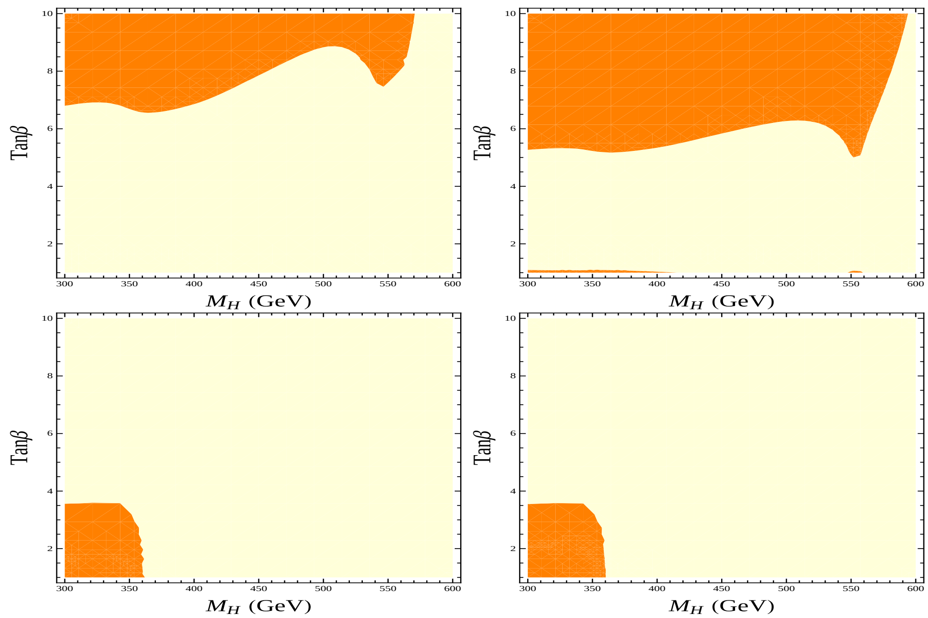

Figure 3. The signal reaches for the $H \to hh \to b\bar{b}\gamma\gamma$ searches on the $(M_H\,, \tan\beta)$ plane. *Upper left*: 2HDM-I for the $\int \mathcal{L}dt = 1000\,\mathrm{fb}^{-1}$, *upper right*: 2HDM-I for the $\int \mathcal{L}dt = 3000\,\mathrm{fb}^{-1}$, *lower left*: 2HDM-II for the $\int \mathcal{L}dt = 1000\,\mathrm{fb}^{-1}$, and *lower right*: 2HDM-II for the $\int \mathcal{L}dt = 3000\,\mathrm{fb}^{-1}$. Parameter regions of $(M_H\,, \tan\beta)$ in orange color are within the reach for each case.

3.2.2 The heavy single-charged Higgs boson searches

3.2.3 The heavy doubly-charged Higgs boson searches

Here in Fig. 4, we present the total cross sections for the pair-production $q\bar{q} \to (\gamma/Z) \to H^{\pm\pm}H^{\mp\mp}$ and $q'\bar{q} \to (W) \to H^{\pm}H^{\mp\mp}$ associated productions at the high energy pp colliders with different mass inputs and center-of-mass energies $\sqrt{s}$.

4 Conclusion and Discussion

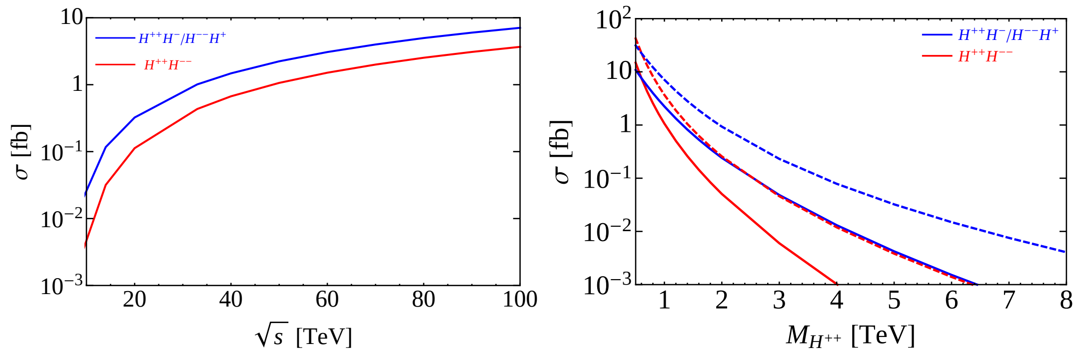

Figure 4. Left: production cross sections for the doubly charged Higgs boson at a proton-proton collider with $M_{H^{\pm\pm}} = 1\,\text{TeV}$ as a function of $\sqrt{s}$. Right: production cross sections for the doubly charged Higgs boson at a proton-proton collider as a function of $M_{H^{\pm\pm}}$. Solid and dashed curves represent $\sqrt{s} = 50$ TeV and 100 TeV, respectively.

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