Summer Program Report

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Combination of BSM Higgs A→Zh Searches in ATLAS

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Abstract

The method and result are presented for the combination of the neutural CP odd 2HDM Higgs-boson A decay to Z and h boson channels using 20.3 fb^{-1} of proton-proton collisions at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the CERN Large Hadron Collider. The combination is based on the maximum likelihood principle. The upper limits on the cross section times branching ratio of the production of the combined measurement at given mass, parameter-space are summarized. Exclusion regions of the 2HDM parameters α and β are also given.

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Contents

1 Introduction

A theory was first proposed fifty years ago [1]-[6] that by introducing an scalar Standard Model (SM) Higgs boson (which we denote here as h) the generation of the mass of the W and Z boson can be explained. However, the direct measurement and clear evidence of the production of such a neutral boson with identified mass were not announced until nearly fifty years later, in 2012, by the ATLAS [7] and CMS [8] experiment in the Large Hadron Collider (LHC) [9].

After the discovery of the SM Higgs, the main goal of the ATLAS and CMS experiment is to measure the properties of this newly discovered particle. For example, the Higgs mass is measured to be approximately 125.5 GeV by both collaborations [10, 11]. These along with some other measurements, for example its spin and parity [12, 13, 14], its production and decay rate [10, 11] have strongly support the proposal that this particle is responsible for the EW symmetry breaking and thus for the mass of the W and Z boson. However, there are many beyond Standard Model (BSM) theories which says that there exist some other SM-extension Higgs sectors which have similar properties as the discovered SM Higgs. The two-Higgs-doublet-models (2HDM) theory is a famous one among them, in which there are five Higgs particles (h, H, A, H^+, H^-), and the details about this theory will be presented in section 2. Many works have been done or are being done to search the BSM Higgs particles since the discovery of the SM Higgs. For example, the CMS Collaboration have published their searching results of the $H \to hh$ and $A \to Zh$ channels [15], which leads to the exclusion of some portions of the 2HDM theory parameter space. Different channels of the $A \to Zh$ decay in ATLAS Collaboration are also being processed now, and this report will present the process and some preliminary results of the combination of these sub-channels.

This report is organized as follows. The 2HDM theory will be introduced in section 2. Section 3 contains some basic statistical concepts about the combination, including the maximum likelihood combination method and its statistical check concepts such as the asymptotic limits and nuisance parameters pulls check. The combination procedures and results will be summarized in section 4, while section 5 provides the result analysis and conclusions.

2 BSM Higgs: theory and search

2.1 two-Higgs-doublet models

The simplest possible extensions of the SM is the two-Higgs-doublet-model (2HDM) [16, 17]. In 2HDM theory, the Higgs sector is extended by an additional doublet, with expectation values v_1 and v_2. The ratio of v_1 and v_2 is the single most important parameter in studies of 2HDMs, which we denoted by $\tan\beta = \dfrac{v_2}{v_1}$. With these two scalar doublets, there are eight fields, but only five of them are physical scalar ('Higgs') fields, which correspond to five Higgs bosons: two CP even bosons h (lighter)/H (heavier), one neutral CP-odd boson A, and two charged bosons H^+/H^-. The mixing angle α of the two neutral CP-even bosons h and H is another parameter of the 2HDM model. In total, the 2HDM model can be described by the parameters α, β and the masses of the five Higgs particles.

There are four possibilities to satisfy the Paschos-GlashowWeinberg theorem [18] in the 2HDM model, which means that there are four types of 2HDMs as summarized below [17, 19]:

- **Type I:** One Higgs doublet couples to vector bosons, the other couples to fermions.
- **Type II:** One Higgs doublet couples to up-type quarks and the other to down-type quarks and leptons.
- **Type III:** 'Lepton-specific' model, where the quark couplings like Type I, and lepton couplings like Type II.
- **Type IV:** 'Flipped' model, where the Higgs bosons couplings like Type II, and lepton couplings like Type I.

2HDM are fully compatible with the SM-like Higgs. The coupling scale factor of the Higgs boson h to vector bosons, up and d quark, and lepton of each type can be expressed as ratios relative to the SM-Higgs couplings, which are summarized in table 1:

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	sin(β - α)	sin(β - α)	sin(β - α)	sin(β - α)
κ_u	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)
κ_d	cos(α)/sin(β)	-sin(α)/cos(β)	cos(α)/sin(β)	-sin(α)/cos(β)
κ_l	cos(α)/sin(β)	-sin(α)/cos(β)	-sin(α)/cos(β)	cos(α)/sin(β)

Table 1: The coupling scale factor of the Higgs boson h to vector bosons, up and d quark, and lepton of each type expressed as ratios relative to the SM-Higgs couplings.

With the LHC experiments, it is able to probe some exclusion regions for the parameters of α and β in the 2HDMs. In section 4.4 of this report, the exclusion regions derived from the $A \to Zh$ search result is presented for type I and type II 2HDM.

2.2 BSM Higgs search channels

For the particle A in 2HDM, the decay $A \to Zh$ is the primary channel if $2m_h < m_A < 2m_{top}$, where m_h is the mass of SM Higgs and m_{top} is the top quark mass. For the decay channels of A and h boson, we mainly concern the $Z \to ll, Z \to \nu\nu, h \to bb, h \to \tau\tau$ channels, and the τ lepton can decay to leptons or hadrons. So principally there are $2 \times (1 + 3) = 8$ separate kinds of measurements for a $A \to Zh$ event. But as you can see from figure 1 of the SM Higgs decay branch ratios [20], $Br(h \to bb)$ is much larger than $Br(h \to \tau\tau)$, we are unable to analyze the $\nu\nu\tau\tau$ channel now. As a summary, the $A \to Zh$ channels we are going to combine are: $\nu\nu bb, llbb, ll\tau_l\tau_l, ll\tau_l\tau_h, ll\tau_h\tau_h$.

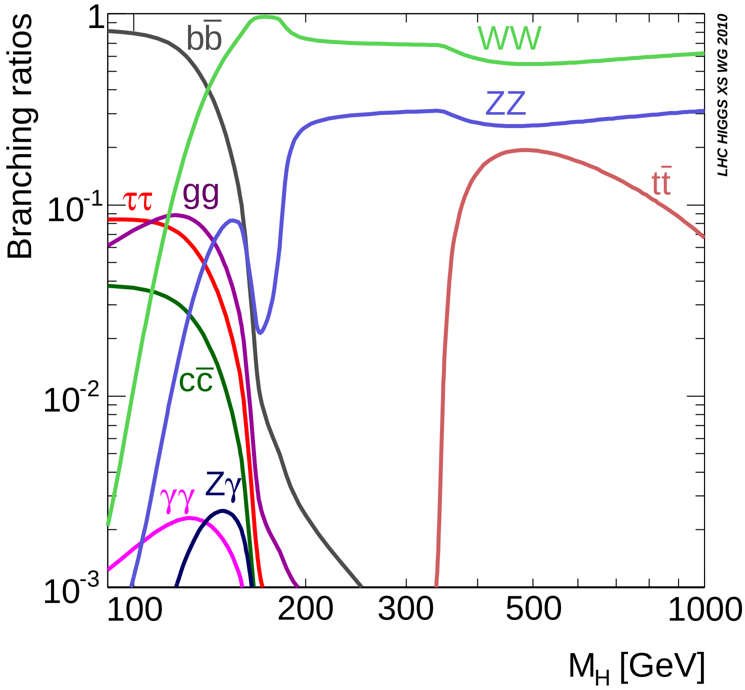

Figure 1: SM Higgs branching ratios as a function of the Higgs-boson mass.

3 Combination method

To see the signal significance of a measurement, we define the signal strength factor μ (which we call parameter of interest POI) - a scale factor of the contribution of the Higgs boson signal to the total observed event. $\mu = 0$ means the background only hypothesis, and $\mu = 1$ corresponds to the normal signal and background hypothesis [21]. To test the hypothesis of one μ value, we introduce the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} \; . \tag{1}$$

Where $\boldsymbol{\theta}$ is the nuisance parameters set. And here $\hat{\hat{\boldsymbol{\theta}}}$ denotes the value of $\boldsymbol{\theta}$ that maximizes L for the specified μ. $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ in the denominator are the maximized (unconditional) likelihood estimations of μ and $\boldsymbol{\theta}$. We can see that $\lambda \to 1$ means good agreement between data and the hypothesized value of μ. To test a μ value in statistical confidence level, we introduce the exclusion limits based on signal confidence level CL_s [22]. For a μ value, when CL_s is less than 5% we say that this μ value is 95% excluded. In this report, we will show the limits of the $\mu = 0$ hypothesis; one basic idea is that the smaller the limits, the stronger the signal.

The combination of all the sub-channels is basically based on the maximum likelihood thoughts: to get the combined measurement, what we do is to maximize the probability of the events of simultaneous multi-channels with nuisance parameter constraints. The realization of such ML combination process is RooFit/RooStats based [23, 24].

4 Combination procedures and results

4.1 Strategy and scheme

We already know from figure 1 that $A \to Zh(bb)$ channels have the biggest branch ratios. But in fact there are also lots of backgrounds in the bb channel. The branch ratio for $A \to Zh(\tau\tau)$ is small but the backgrounds are clean. And snowmass prospect studies ($14\ TeV, PU = 140$) have shown that $Zh(\tau\tau)$ are more or less the same sensitive as $Zh(bb)$ in the low mass regions ($\sim 300GeV$), and in the high mass regions $Zh(bb)$ are better. So for our combination, we simultaneously fit among all channels and by looking at the limits under different configurations (single channel $vs.$ combined channel) we can see the influence of the single channel to the combined measurement.

To do the combination, we first define the global $POI = \sigma(gg \to A) \times Br(A \to Zh)$. And then we define the correlation scheme, which means that we correlate some common nuisance parameters of the sub-channels and let them change the same among the sub-channels, currently to test the combination methods we just correlate the Luminosity and the Jet-Energy-Resolution because there is still no agreement among the analyzers of the different channels until now, and after the agreement is set, we will have a full correlation scheme in the future and present a mature combination result. And in the combination we assume that $Br(h \to \tau\tau)$ and $Br(h \to bb)$ are fixed at the SM values, although as you can see from table 1 that they are no longer constant but may change with the parameter α and β at a fixed mass point in the 2HDM model. But in section 4.4 you will see that this problem can be solved by some simple tricks for type I and type II 2HDM.

4.2 Asymptotic Limits results

The limits for the null hypothesis ($\mu = 0$) for different mass points of the combined workspace is summarized in table 2. To see the influence of the sub-channels to the combined measurement, we also list the limits under different configuration in table 3. We can see from table 3 that the bb channel is more significant than the $\tau\tau$ channel.

Mass/GeV	$+2\sigma$	$+1\sigma$	-1σ	-2σ	Median
220	1.43171	1.05678	0.545955	0.40667	0.757687
240	1.82685	1.35959	0.708558	0.527789	0.98335
260	1.23602	0.913161	0.471574	0.351265	0.65446
300	1.04089	0.766472	0.39518	0.294361	0.548438
340	0.531632	0.387499	0.198298	0.147708	0.275201
350	0.52209	0.38105	0.195216	0.145412	0.270924
400	0.324671	0.23399	0.118796	0.0884887	0.164868
500	0.172401	0.122969	0.0620266	0.0462022	0.0860816
800	0.0573804	0.0380171	0.0183574	0.013674	0.0254767
1000	0.0407681	0.0258109	0.0122104	0.00909525	0.0169458

Table 2: Limits for the null hypothesis ($\mu = 0$) for different mass points of the $A \to Zh$ channel.

Mass/GeV	$bb(ll+\nu\nu)$	$\tau\tau(lh+hh)$	$bb+\tau\tau$
300	0.637968	1.12461	0.548438
500	0.087507	0.548827	0.086082
1000	0.016953	0.522132	0.016946

Table 3: Limits of different channels.

4.3 Pull distributions

To test whether the nuisance parameters are properly treated in the combination, we check the pull distributions [25] of all the nuisance parameters. The pull of nuisance parameter should be close to standard Gaussian distribution. If the mean μ is largely different from 0, then there might be some systematic errors, and if the variance σ is not equal to 1, then the errors are underestimated ($\sigma > 1$) or overestimated ($\sigma < 1$). Figure 2 contains the pull distribution of all the nuisance parameters. We can see that most of the pulls are near to $N(0,1)$ distribution.

4.4 2HDM contours of the limits

As stated above, with the limits calculated by ML fit, we can get some exclusion regions of the parameters α and β in the 2HDMs. As an example, figure 3 contains the 2HDM contour for 300 GeV in the tanβ - cos$(\beta-\alpha)$ plane.

However, there is one problem while plotting the contour. We know that in the 2HDM model, different parameters of $(cos(\beta-\alpha), tan\beta)$ have different branch ratios of $h \to bb$ and $h \to \tau\tau$. However, when we are calculating the limits, we assume that the branch ratios are fixed at SM values. So, if we want to use the Asymptotic limits to draw the

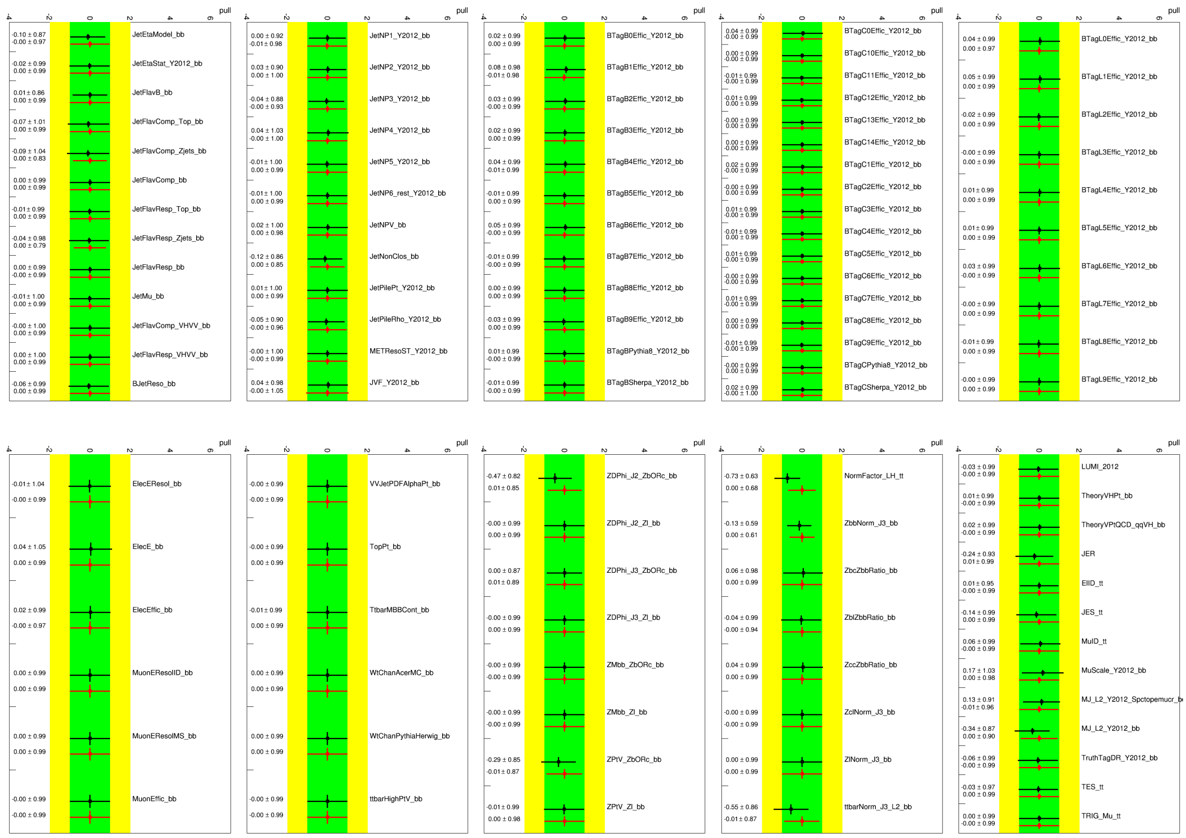

Figure 2: Pull distributions of the nuisance parameters.

2HDM plots to get the exclusion region of the parameters $(cos(\beta - \alpha), tan\beta)$, we need some correction about the un-constant of the branch ratios. For type I and type II 2HDM, we propose one simple trick to solve the problem as following.

We know that for a single channel, the limits is proportional to the inverse of the branch ratio of this channel - large branch ratio means stronger signal and thus smaller limtis. So, for the single channel, the correction is simple, we define a new quantity as the product of the limit and the branch ratio ($br(h \rightarrow bb)$ or $br(h \rightarrow \tau\tau)$), and then draw this quantity in the $(cos(\beta - \alpha), tan\beta)$ plane instead of just the limits, then the region we got on this plan is the exclusion region we want. This is because that the quantity limit times branch ratio is an unique constant for each mass point even though the Br might change with α and β. But for the combined workspace, things become complicated - there are two branch ratios we need to consider (($br(h \rightarrow bb)$ and $br(h \rightarrow \tau\tau)$)), and the relationship between the limits and the branch ratios is not known by us. Fortunately, for type I and type II, the bb and $\tau\tau$ branch ratios change the same as the parametersα and β change. We can see from table 1 that the coupling scale factor for bb and $\tau\tau$ of type I and II are the same, so ratio of the bb and $\tau\tau$ branch ratio is a constant and equal to the ratio of the Standard Model for different parameters of α and β. Under

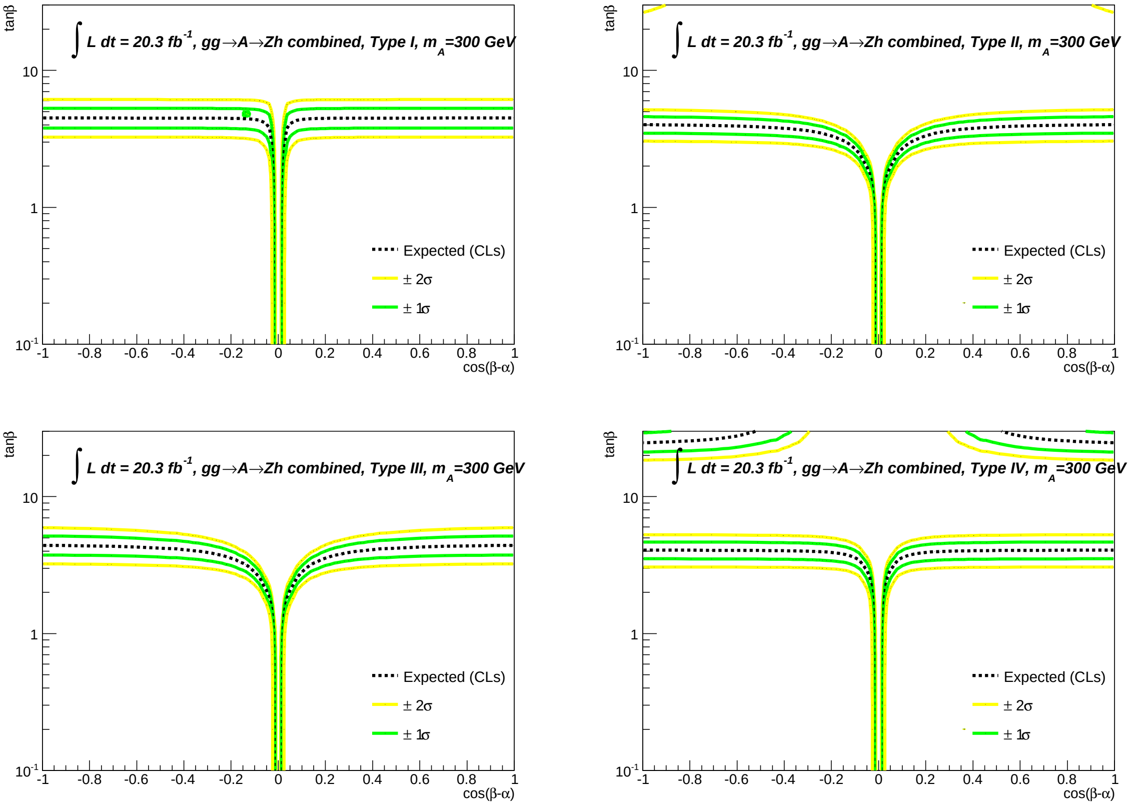

Figure 3: 2HDM contours for different types of 2HDM model of $mass = 300GeV$.

this situation, the two branch ratios reduces to one independent quantity and thus the limit is still proportional to the inverse of the bb branch ratio or the $\tau\tau$ branch ratio. So, for type I and type II combined limits contour, the correction is the same as a single channel - we just need to plot the product of the limit and the branch ratio ($br(h \to bb)$ or $br(h \to \tau\tau)$) instead of just the limits in the ($cos(\beta - \alpha), tan\beta$) plane.

Figure 4 is the comparison of the corrected contour $vs.$ the contour without correction. We can see that there are some strange regions in the corrected contours. The only difference between them is that an additional ($br(h \to bb)$ or $br(h \to \tau\tau)$) is introduced in the contour. To find the reason, we can have a look at the distribution of the ($br(h \to bb)$ in figure 4 - the plots of the ($br(h \to bb)$ matches very well with the limits times branch ratio contours!

5 Conclusions

As a summary, we have successfully construct the procedure of the combination of the BSM $A \to Zh$ searches. Limits of the combined measurement are presented, and pull

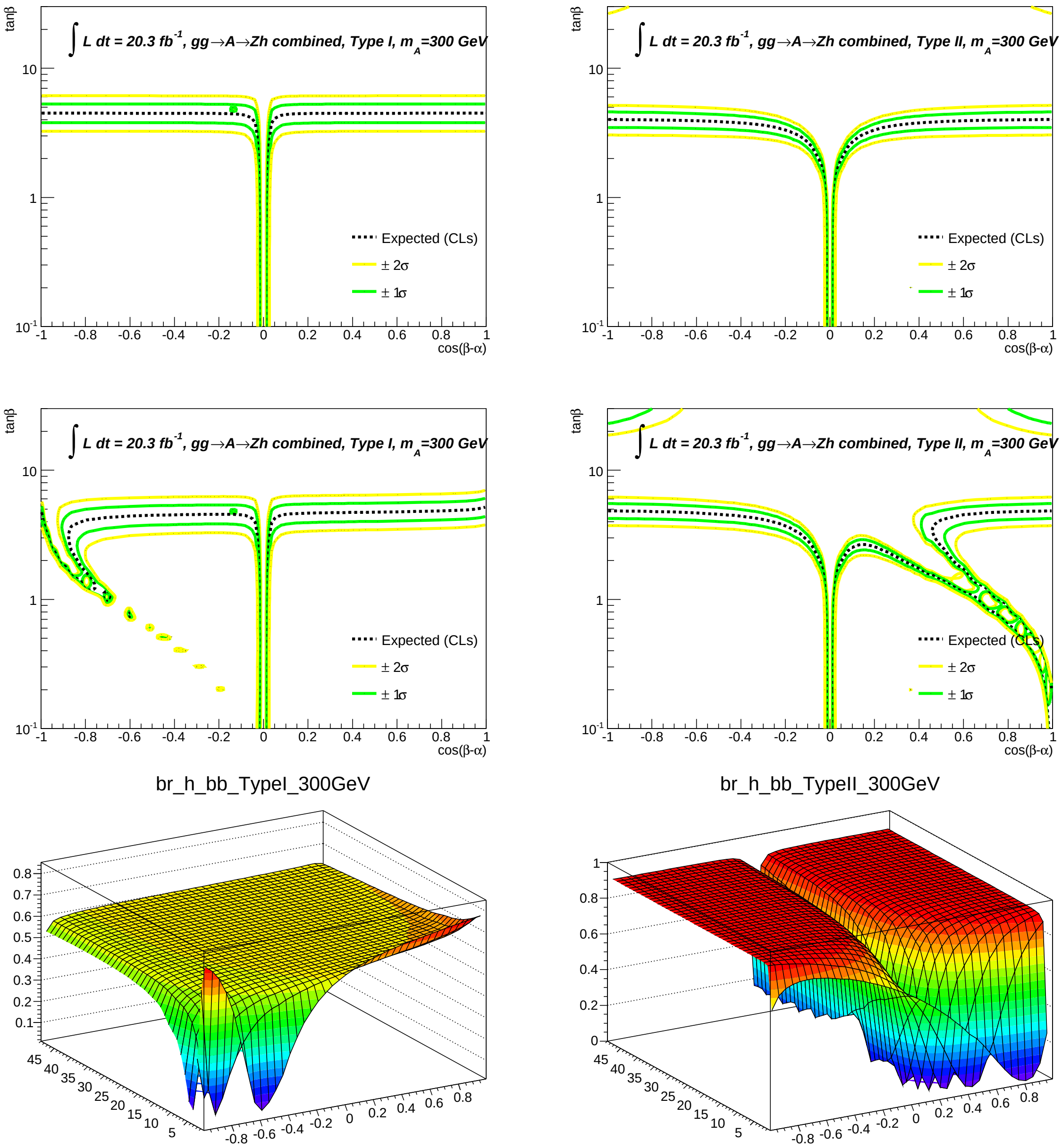

Figure 4: Type I and II 2HDM branch ratio correction of $mass = 300\ GeV$. Up: without correction; middle: with correction; bottom: $br(h \to bb)$. Left: type I; right: type II.

distributions of the nuisance parameters are provided. We also get some exclusion regions of the 2HDM models parameters. The result is preliminary, and a mature result will be provided after further cooperation with the sub-channel teams. Hopefully this work can provide results for the $A \to Zh$ final result and the Grand BSM combination result(s).

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References

[1] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*. Phys. Rev. Lett. 13.321 (1964).

[2] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*. Phys. Lett. 12.132 (1964).

[3] P. W. Higgs, *Broken symmetries and the masses of gauge bosons*. Phys. Rev. Lett. 13.508 (1964).

[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global conservation laws and massless particles*. Phys. Rev. Lett. 13.585 (1964).

[5] P. W. Higgs, *Spontaneous symmetry breakdown without massless bosons*. Phys. Rev. 145.1156 (1966).

[6] T. W. B. Kibble, *Symmetry breaking in non-Abelian gauge theories*. Phys. Rev.155.1554 (1967).

[7] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*. Physics Letters B 716.1 (2012): 1-29, `arXiv:1207.7214 [hep-ex]`.

[8] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*. Physics Letters B 716.1 (2012): 30-61, `arXiv:1207.7235 [hep-ex]`.

[9] L. Evans and P. Bryant (editors), *LHC Machine*. JINST.3.S08001 (2008).

[10] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*. Phys. Lett. B 726.88 (2013).

[11] CMS Collaboration, *Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV*. CMS-PAS-HIG-13-005 (2013).

[12] ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*. Phys.Lett. B 726.120 (2013).

[13] CMS Collaboration, *Study of the Mass and Spin-Parity of the Higgs Boson Candidate Via Its Decays to Z Boson Pairs*. Phys. Rev. Lett. 110.081803 (2013).

[14] CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state.* arXiv:1312.5353 [hep-ex].

[15] CMS Collaboration, *Measurements of the properties of the new boson with a mass near 125 GeV.* CMS-PAS-HIG-13-025 (2013).

[16] J. F. Gunion and H. E. Haber, *The CP conserving two Higgs doublet model: The approach to the decoupling limit.* Phys. Rev. D. 67.075019 (2003).

[17] Branco, Gustavo Castelo, et al. *Theory and phenomenology of two-Higgs-doublet models.* Physics Reports 516.1 (2012), arXiv:1106.0034 [hep-ph].

[18] S. L. Glashow and S. Weinberg, *Natural conservation laws for neutral currents.* Phys. Rev. D 15.1958 (1977).

[19] CMS Collaboration, *Constraints on New Phenomena via Higgs Boson Coupling Measurements with the ATLAS Detector.* ATLAS-CONF-2014-010.

[20] CERN, *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables.* CERN Report 2011-002.

[21] Cowan, Glen, et al., *Asymptotic formulae for likelihood-based tests of new physics.* Eur. Phys. J. C 71.1554 (2011).

[22] Read, Alexander L., *Presentation of search results: the CLs technique.* J. Phys. G 28.2693 (2002).

[23] Verkerke, Wouter, and David Kirkby, *The RooFit toolkit for data modeling.* arXiv:physics/0306116 [physics.data-an].

[24] Moneta, Lorenzo, et al. *The RooStats Project* arXiv:1009.1003 [physics.data-an].

[25] Demortier, Luc, and Louis Lyons, *Everything you always wanted to know about pulls.* CDF note 43 (2002).