Post Discovery of the Higgs Boson

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Scalars 2013, Sept 13, 2013

References

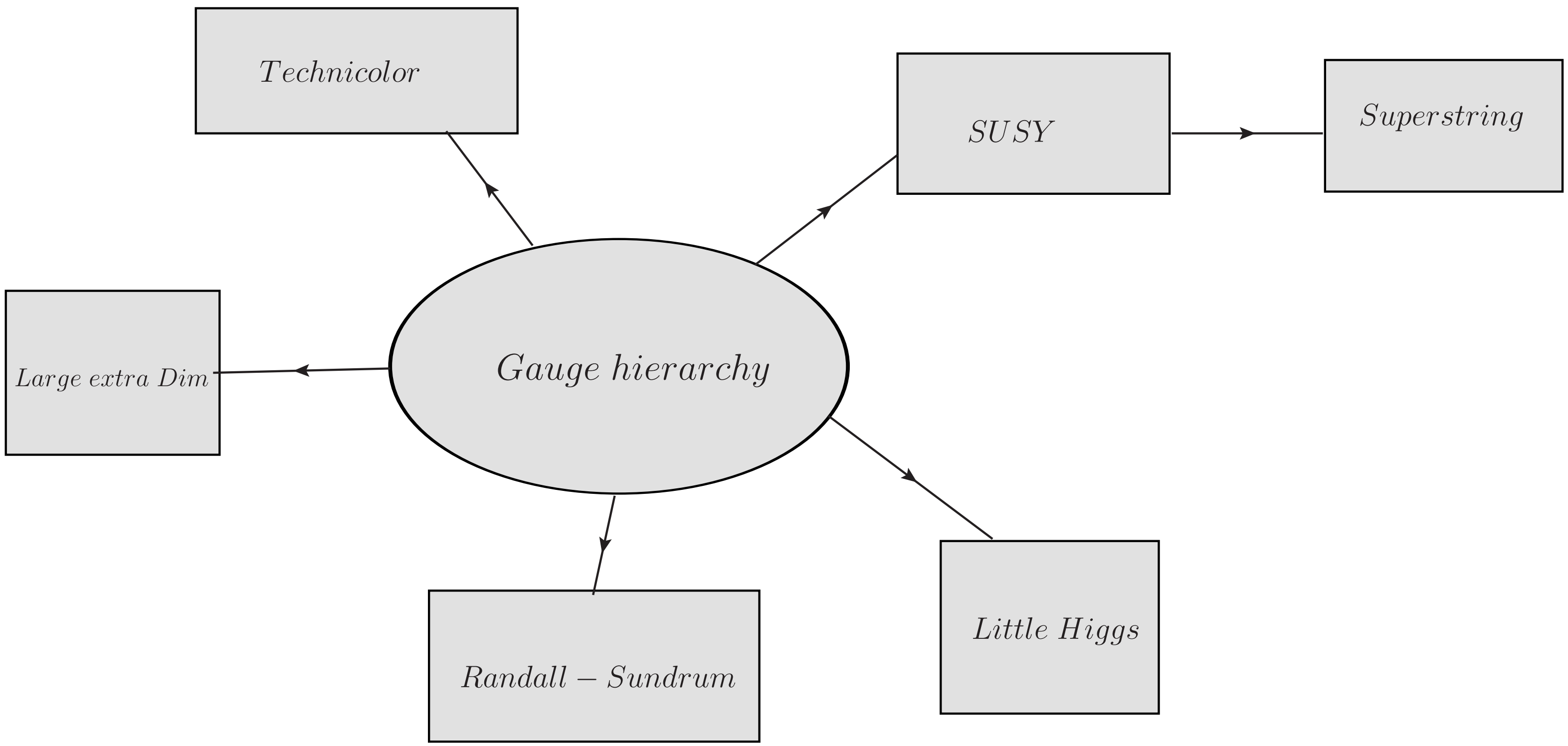
- Jung Chang, KC, Po-Yan Tseng, TC, JHEP 1212 (2012) 058 [1206.5853]
- KC, Chiang, TC, Phys.Rev. D78 (2008) 051701 [0803.2661]
- KC, JS Lee, Po-Yan Tseng 1302.3794 (Higgcision) and update
- Jung Chang, KC, Chih-Ting Lu, TC, Phys. Rev. D87, 093005 [1303.6335].
- KC, Keung, Yuan, 1308.4235

Clearly now: Very similar to the SM Higgs boson

What is next?

Experimenters: Measure all properties of the Higgs, just like the way of the Z boson. Everything will be down to 10^{-3}. Perhaps, want to build a Higgs factory.

Theorists: A real fundamental scalar boson?
If so there must be some other UV physics to stabilize its mass.
If not, composite particle?



Pre-LHC era

After Discovery: SUSY $\gg$ Technicolor $\gg$ Extra Dim $\gg$ Little Higgs

Signal Strengths (ATLAS)

Channel	μ (m_H = 125 GeV) (Before Moriond)	μ (m_H = 125.5 GeV) (After Moriond)	μ (m_H = 125.5 GeV) (Summer 2013)
$VH \to Vb\bar{b}$	-0.4 ± 1.0	-	$0.2 \pm 0.5 \pm 0.4$
$H \to \tau^+\tau^-$	0.8 ± 0.7	-	-
$H \to WW^*$	1.5 ± 0.6	1.0 ± 0.3	$0.99\,^{+0.31}_{-0.28}$
$H \to \gamma\gamma$	1.8 ± 0.4	1.6 ± 0.3	$1.55\,^{+0.33}_{-0.28}$
$H \to ZZ^*$	1.0 ± 0.4	1.5 ± 0.4	$1.43\,^{+0.40}_{-0.35}$
Combined	1.35 ± 0.24	1.30 ± 0.20	$1.33\,^{+0.21}_{-0.18}$

Signal Strengths (CMS)

Channel	μ (Before Moriond)	μ (After Moriond)	μ (Summer 2013)
$VH \to Vb\bar{b}$	$1.31^{+0.65}_{-0.60}$	-	1.15 ± 0.62
$H \to \tau^+\tau^-$ (0/1 j)	$0.85^{+0.68}_{-0.66}$	$0.76^{+0.50}_{-0.52}$	1.10 ± 0.41
$H \to WW^*$ (0/1 j)	$0.77^{+0.27}_{-0.25}$	0.76 ± 0.21	0.68 ± 0.20
$H \to \gamma\gamma$ (untagged)	$1.42^{+0.55}_{-0.49}$	$0.78^{+0.28}_{-0.26}$	0.77 ± 0.27
$H \to ZZ^*$	$0.80^{+0.35}_{-0.28}$	$0.91^{+0.30}_{-0.24}$	0.92 ± 0.28
Combined	0.88 ± 0.21		

Interpretations

- A new particle around 125 – 126 GeV is found, consistent with the SM Higgs boson. The fermionic modes ($\tau\tau$, $b\bar{b}$) need more data. The WW, ZZ modes are consistent. The $\gamma\gamma$ mode is outstanding with 1.6 times of the SM (ATLAS), but CMS only 0.8 of the SM.
- The excesses are all at around 125 – 126 GeV.
- Spin consistent with spin 0^+.

Theoretical Interpretations

- The most obvious – SM
- MSSM – SUSY predicts a light Higgs boson. But to give a 125 GeV Higgs puts a tight constraint on the stop mass sector, and not easy to enhance the $\gamma\gamma$ rate.
- NMSSM: easier to obtain a 125 GeV Higgs boson, and not difficult to achieve enhanced $\gamma\gamma$ rate.
- Other extended MSSM.
- 2HDM.
- RS Radion/dilaton: the anomaly couplings to gg and $\gamma\gamma$ easily enhance the diphoton rate (unlikely)
- Inert Higgs doublet model.
- Fermiophobic Higgs boson (ruled out)

Outlines

1. Higgcision.
2. Use of WW scattering to test the EWSB.
3. An unusual decay of the Higgs boson – Goldstone boson

Higgs Precision – Higgcision

KC, JS Lee, PY Tseng 1302.3794 and update

Formalism: couplings

- Fermionic couplings

$$\mathcal{L}_{H\bar{f}f} = -\sum_{f=u,d,l} \frac{g m_f}{2M_W} \sum_{i=1}^{3} H\,\bar{f}\left(g^S_{H\bar{f}f} + i g^P_{H\bar{f}f}\gamma_5\right) f\ .$$

For the SM $g^S_{H\bar{f}f} = 1$ and $g^P_{H\bar{f}f} = 0$.

- to vector gauge bosons:

$$\mathcal{L}_{HVV} = g\,M_W\left(g_{HWW}\,W^+_\mu W^{-\mu} + g_{HZZ}\frac{1}{2c_W^2}\,Z_\mu Z^\mu\right) H\ .$$

- to two photons:

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi\,v}\left\{S^\gamma(M_H)\,\left(\epsilon^*_{1\perp}\cdot\epsilon^*_{2\perp}\right) - P^\gamma(M_H)\frac{2}{M_H^2}\langle\epsilon^*_1\epsilon^*_2 k_1 k_2\rangle\right\},$$

where

$$S^\gamma(M_H) = 2\sum_{f=b,t,\tau} N_C\,Q_f^2\,g^S_{H\bar{f}f}\,F_{sf}(\tau_f) - g_{HWW}\,F_1(\tau_W) + \Delta S^\gamma\ ,$$

$$P^\gamma(M_H) = 2\sum_{f=b,t,\tau} N_C\,Q_f^2\,g^P_{H\bar{f}f}\,F_{pf}(\tau_f) + \Delta P^\gamma\ ,$$

Numerically, Taking $M_H = 125.5$ GeV, we find that

$$
\begin{aligned}
S^\gamma &\simeq -8.35\, g_{HWW} + 1.76\, g^S_{H\bar{t}t} + (-0.015 + 0.017\, i)\, g^S_{H\bar{b}b} \\
&\quad +(-0.024 + 0.021\, i)\, g^S_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^S_{H\bar{c}c} + \Delta S^\gamma \\
P^\gamma &\simeq 2.78\, g^P_{H\bar{t}t} + (-0.018 + 0.018\, i)\, g^P_{H\bar{b}b} \\
&\quad +(-0.025 + 0.022\, i)\, g^P_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^P_{H\bar{c}c} + \Delta P^\gamma
\end{aligned}
$$

giving $S^\gamma_{\rm SM} = -6.64 + 0.043\, i$ and $P^\gamma_{\rm SM} = 0$.

- to two gluons

$$
\mathcal{M}_{ggH} = -\frac{\alpha_s\, M_H^2\, \delta^{ab}}{4\pi\, v} \left\{ S^g(M_H) \left(\epsilon^*_{1\perp} \cdot \epsilon^*_{2\perp}\right) - P^g(M_H) \frac{2}{M_H^2} \langle \epsilon^*_1 \epsilon^*_2 k_1 k_2 \rangle \right\},
$$

$$
S^g(M_H) = \sum_{f=b,t} g^S_{H\bar{f}f}\, F_{sf}(\tau_f) + \Delta S^g\,, \quad P^g(M_H) = \sum_{f=b,t} g^P_{H\bar{f}f}\, F_{pf}(\tau_f) + \Delta P^g
$$

$$
\begin{aligned}
S^g &\simeq 0.688\, g^S_{H\bar{t}t} + (-0.037 + 0.050\, i)\, g^S_{H\bar{b}b} + \Delta S^g \\
P^g &\simeq 1.047\, g^P_{H\bar{t}t} + (-0.042 + 0.050\, i)\, g^P_{H\bar{b}b} + \Delta P^g
\end{aligned}
$$

Formalism: Signal Strengths

- The signal strength can be written as the product of

$$\widehat{\mu}(\mathcal{P},\mathcal{D}) \simeq \widehat{\mu}(\mathcal{P})\ \widehat{\mu}(\mathcal{D})$$

  where $\mathcal{P} = \mathrm{ggF}, \mathrm{VBF}, \mathrm{VH}, \mathrm{ttH}$ denote the production mechanisms and $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$ the decay channels.

- On the production side:

$$\begin{aligned}
\widehat{\mu}(\mathrm{ggF}) &= \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S^g_{\mathrm{SM}}(M_H)|^2} \\
\widehat{\mu}(\mathrm{VBF}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{VH}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{ttH}) &= \left(g^S_{H\bar{t}t}\right)^2 + \left(g^P_{H\bar{t}t}\right)^2
\end{aligned}$$

- On the decay side

$$\widehat{\mu}(\mathcal{D}) = \frac{B(H \to \mathcal{D})}{B(H_{\rm SM} \to \mathcal{D})}$$

$$B(H \to \mathcal{D}) = \frac{\Gamma(H \to \mathcal{D})}{\Gamma_{\rm tot}(H) + \Delta\Gamma_{\rm tot}}$$

- Experimentally observed signal strength is a sum over all production mechanisms:

$$\mu(\mathcal{Q}, \mathcal{D}) = \sum_{\mathcal{P}={\rm ggF,VBF,VH,ttH}} C_{\mathcal{Q}\mathcal{P}}\ \widehat{\mu}(\mathcal{P}, \mathcal{D})$$

  the decomposition coefficients $C_{\mathcal{Q}\mathcal{P}}$ may depend on the relative Higgs production cross sections for a given Higgs-boson mass, experimental cuts, etc.

Formalism: Fitting analysis

- Ratios of Yukawa and gauge couplings

$$C_u^S = g_{H\bar{u}u}^S\,, \quad C_d^S = g_{H\bar{d}d}^S\,, \quad C_\ell^S = g_{H\bar{l}l}^S\,; \quad C_v = g_{HVV}\,;$$
$$C_u^P = g_{H\bar{u}u}^P\,, \quad C_d^P = g_{H\bar{d}d}^P\,, \quad C_\ell^P = g_{H\bar{l}l}^P\,.$$

- Extra loop contributions:

$$\Delta S^g\,, \quad \Delta S^\gamma\,; \quad \Delta P^g\,, \quad \Delta P^\gamma$$

- $\Delta\Gamma_{\rm tot}$
- Effective couplings:

$$C_g \equiv \sqrt{\frac{|S^g|^2 + |P^g|^2}{|S^g_{\rm SM}|^2}}\,; \quad C_\gamma \equiv \sqrt{\frac{|S^\gamma|^2 + |P^\gamma|^2}{|S^\gamma_{\rm SM}|^2}}\,; \quad C_{Z\gamma} \equiv \sqrt{\frac{|S^{Z\gamma}|^2 + |P^{Z\gamma}|^2}{\left|S^{Z\gamma}_{\rm SM}\right|^2}}\,.$$

In most of the fits with the newest data, we have

$$C_\gamma = 1.1, \quad C_g = 0.9$$

Putting back into the previous equations

$$C_\gamma \approx 1.1 \quad = \quad \sqrt{\frac{(-8.4 + 1.76 C_u^S + \Delta S^\gamma)^2 + (2.78 C_u^P + \Delta P^\gamma)^2}{(-6.64)^2}}\,,$$

$$C_g \approx 0.9 \quad = \quad \sqrt{\frac{(0.69 C_u^S + \Delta S^g)^2 + (1.0 C_u^P + \Delta P^g)^2}{(0.65)^2}}\,.$$

and so

$$(7.3)^2 = (-8.4 + 1.76 C_u^S + \Delta S^\gamma)^2 + (2.78 C_u^P + \Delta P^\gamma)^2\,,$$
$$(0.59)^2 = (0.69 C_u^S + \Delta S^g)^2 + (1.0 C_u^P + \Delta P^g)^2\,.$$

SM Fit

Channel	$\chi^2_{\rm sm}$ (before Moriond)	$\rightarrow$ $\chi^2_{\rm sm}$ (After Moriond)
$\gamma\gamma$	8.1	7.9
$ZZ^* \rightarrow 4\ell$	0.33	1.65
$WW^* \rightarrow \ell^-\bar{\nu}\ell^+\nu$	3.8	3.7
$b\bar{b}$	3.6	3.6
$\tau\tau$	1.7	2.15
χ^2/dof	$17.5/22 = 0.8$	$18.94/22 = 0.86$
p-value	0.74	0.65

Case 1: Vary only $\Delta\Gamma_{\rm tot}$

- The $\chi^2/dof = 17.5/21$ (before Moriond) and $18.89/21$ (after Moriond) No improvement at all compared to the SM.
- The 95% allowed range of

$$\Delta\Gamma_{\rm tot} = -0.022\,^{+1.44}_{-0.85}\ {\rm MeV} \quad \longrightarrow 0.10\,^{+1.11}_{-0.74}\ {\rm MeV}$$

The central value consistent with zero, so the 95% C.L. upper limit is

$$\Delta\Gamma_{\rm tot} < 1.4\ {\rm MeV}$$

- For a $M_H = 125$ GeV the standard width is about $4.1 - 4.2$ MeV. So nonstandard decay branching ratio has to be less than

$$B(H \to {\rm nonstandard}) < 25\% \quad \longrightarrow 22\%$$

Case 2: Vary only ΔS^γ and ΔS^g

- All Yukawa couplings are SM. ΔS^γ and ΔS^g can be due to some new particles running in the loop.
- Before Moriond: The best fit

$$\Delta S^\gamma = -2.73^{+1.11}_{-1.15}, \quad \Delta S^g = -0.050^{+0.064}_{-0.065}, \quad \chi^2/dof = 11.27/20 = 0.56$$

This is the most efficient choice of parameters, because the χ^2 is dominated by $\gamma\gamma$. The quantity C_γ and C_g are

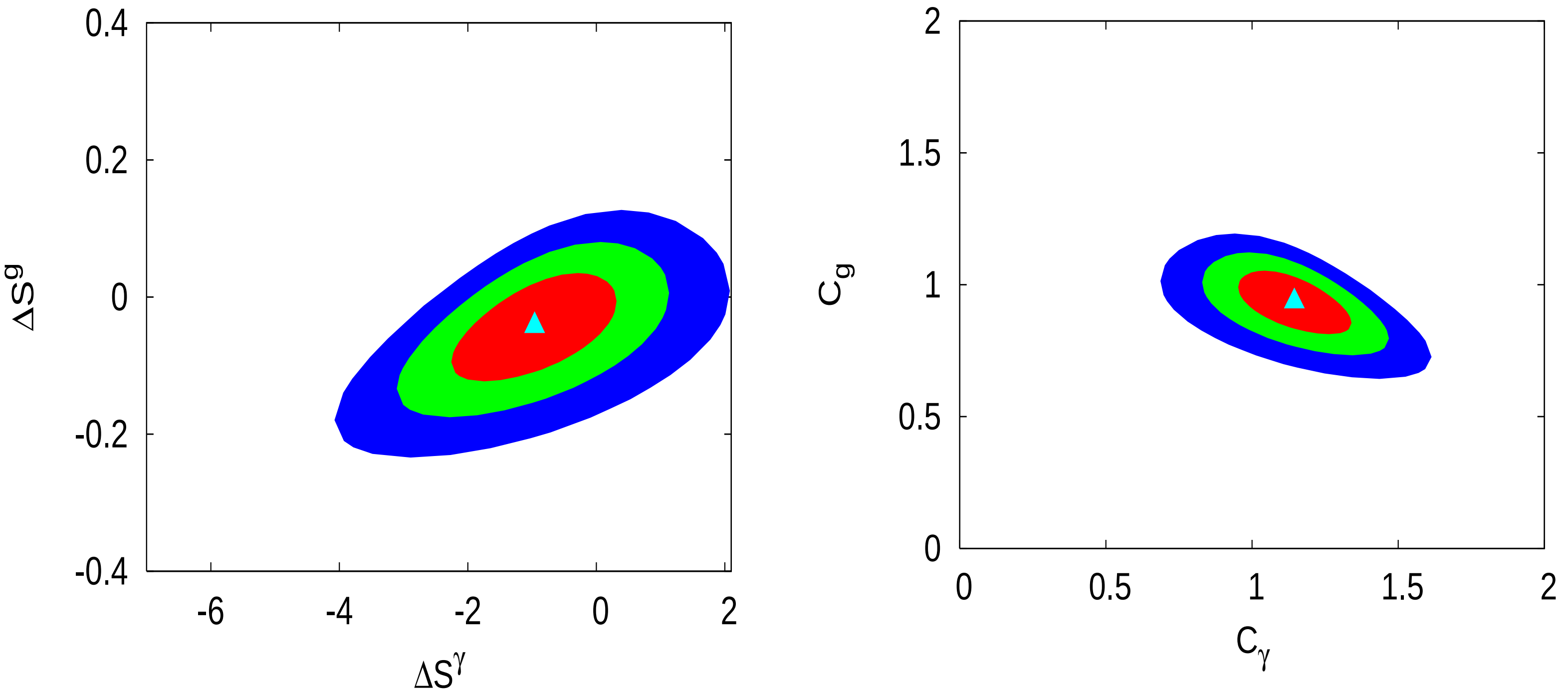
$$C_\gamma \simeq 1.41, \quad C_g \simeq 0.92 \ .$$

- After Moriond:

$$\Delta S^\gamma = -0.96^{+0.84}_{-0.85}, \quad \Delta S^g = -0.043 \pm +0.052, \quad \chi^2/dof = 17.55/20 = 0.88$$

The CMS and ATLAS data are on opposite side of the SM value. The quantity C_γ and C_g are

$$C_\gamma \simeq 1.14, \quad C_g \simeq 0.93 \ .$$


0.4
0.2
0
-0.2
-0.4
-6
-4
-2
0
2
ΔS^g
ΔS^γ
2
1.5
1
0.5
0
0
0.5
1
1.5
2
C_g
C_γ

Case 3: Vary C_u^S, C_d^S, C_ℓ^S, C_v

- Only modified Yukawa and gauge couplings.
- Overall symmetry:

$$C_u^S \leftrightarrow -C_u^S,\ C_d^S \leftrightarrow -C_d^S,\ C_\ell^S \leftrightarrow -C_\ell^S,\ C_v \leftrightarrow -C_v$$

  Fix C_v positive.

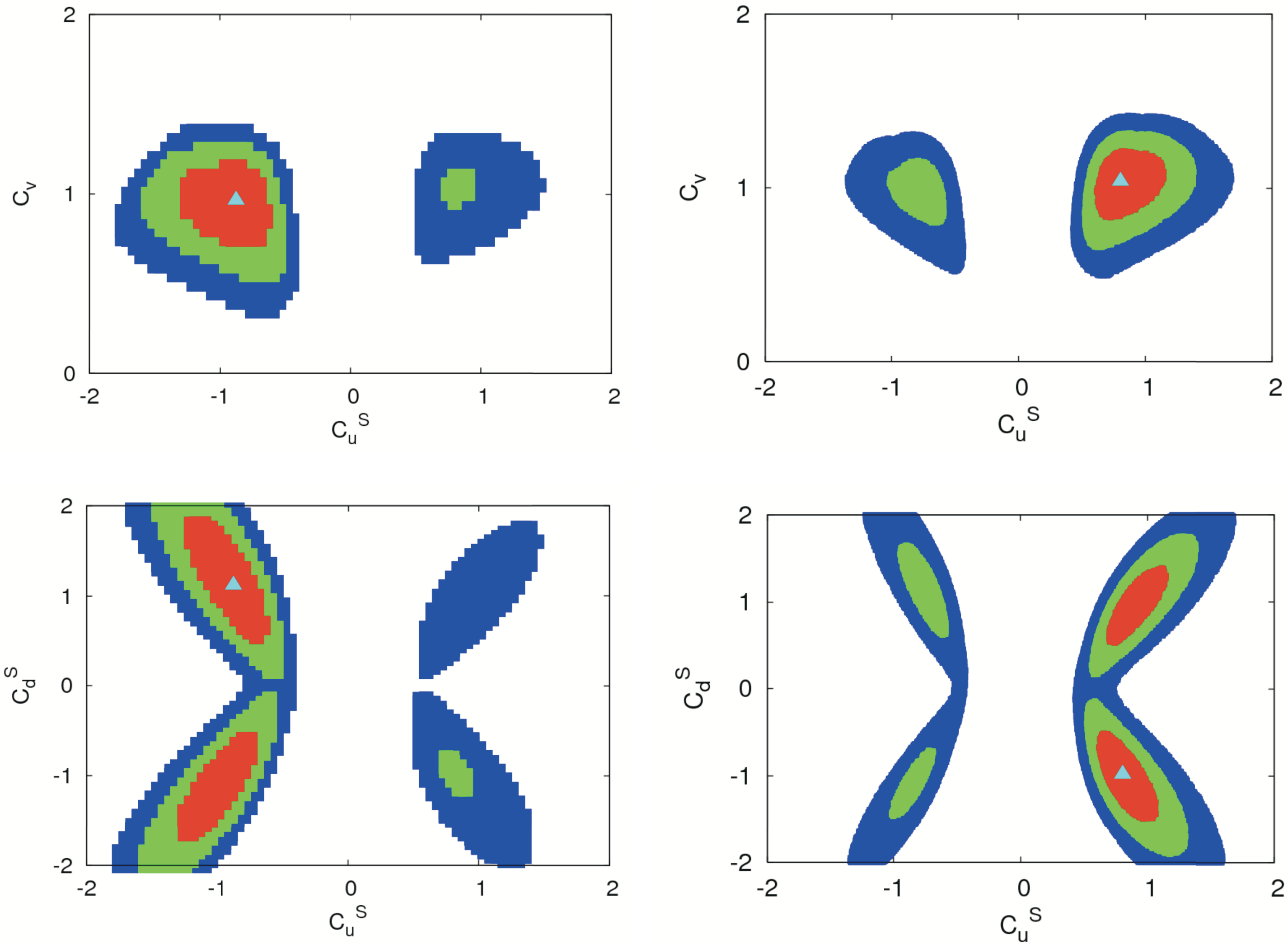
- Approximate symmetry in the results:

$$C_d^S \leftrightarrow -C_d^S,\ \ C_\ell^S \leftrightarrow -C_\ell^S$$

- Sign of C_u^S is important. The W and the top contributions are in opposite sign.

- Before Moriond: The best fit prefers C_u^S negative. The resulting $C_\gamma \approx 1.4$ and $C_g \approx 1$. The diphoton rate is pushed up to fit well with the data. The $\chi^2/dof = 10.46/18$.
- After Moriond: Since the CMS data is on the opposite side of the ATLAS data. The χ^2 cannot be reduced. $C_u^S = 0.8$ and $\chi^2/dof = 17.82/18$ worse than the SM.

Before Moriond $\longrightarrow$ After Moriond



Case 3: Vary C_u^S, C_d^S, C_ℓ^S, C_v, ΔS^γ, ΔS^g

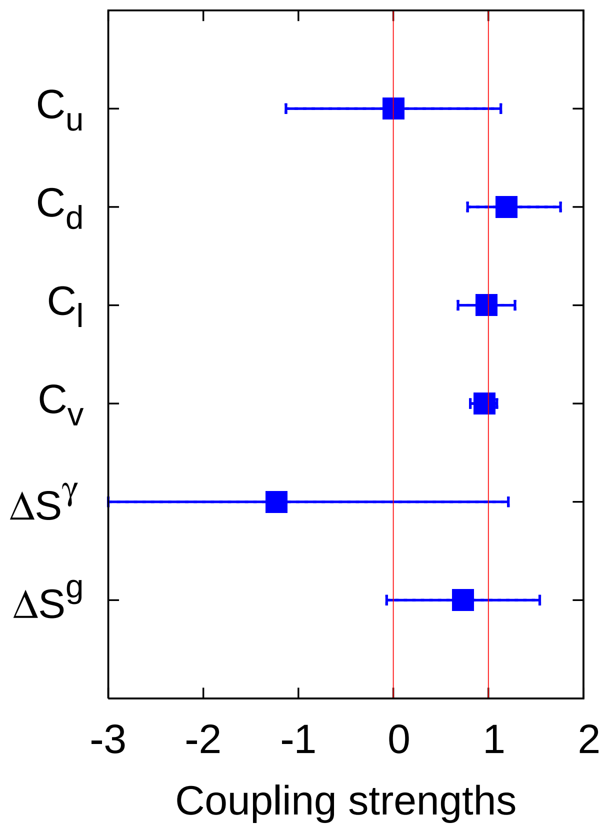
Before Moriond:

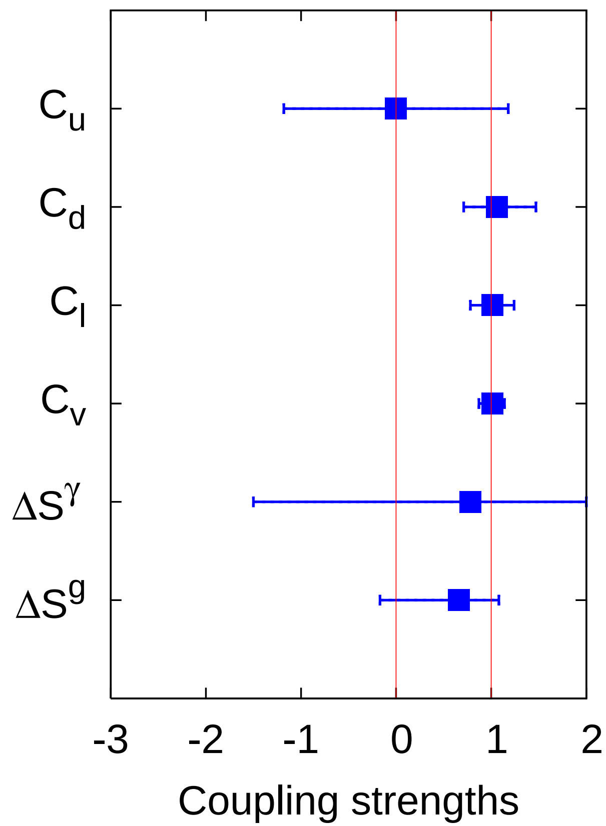
- $C_u^S \to 0$.
- The ΔS^γ and ΔS^g shifted to enhance diphoton.
- $\chi^2/dof = 9.86/16$ good.

After Moriond:

- C_d^S, C_ℓ^S, and C_v all about 1. $C_u^S \to 0$.
- $\chi^2/dof = 16.89/16$ the worst.

Before Moriond $\longrightarrow$ After Moriond





Summary of CP conserving fits (After Moriond)

Para.	Vary $\Delta\Gamma_{\rm tot}$	Vary ΔS^γ, ΔS^g	Vary ΔS^γ, ΔS^g, $\Delta\Gamma_{\rm tot}$	Vary C_u^S, C_d^S, C_ℓ^S, C_v	Vary C_u^S, C_d^S, C_ℓ^S C_v,ΔS^γ, ΔS^g
C_u^S	1	1	1	$0.80^{+0.16}_{-0.13}$	0.00 ± 1.18
C_d^S	1	1	1	$-0.98^{+0.31}_{-0.34}$	$1.06^{+0.41}_{-0.35}$
C_ℓ^S	1	1	1	$0.98^{+0.21}_{-0.21}$	1.01 ± 0.23
C_v	1	1	1	$1.04^{+0.12}_{-0.14}$	$1.01^{+0.13}_{-0.14}$
ΔS^γ	0	$-0.96^{+0.84}_{-0.85}$	$-0.96^{+0.84}_{-0.87}$	0	$0.78^{+2.34}_{-2.28}$
ΔS^g	0	-0.043 ± 0.052	$-0.040^{+0.12}_{-0.086}$	0	$0.66^{+0.42}_{-0.83}$
$\Delta\Gamma_{\rm tot}$	$0.10^{+0.51}_{-0.41}$	0	$0.027^{+1.33}_{-0.80}$	0	0
χ^2/dof	18.89/21	17.55/20	17.55/19	17.82/18	16.89/16
p-value	0.59	0.62	0.55	0.48	0.39

CP Violating fits

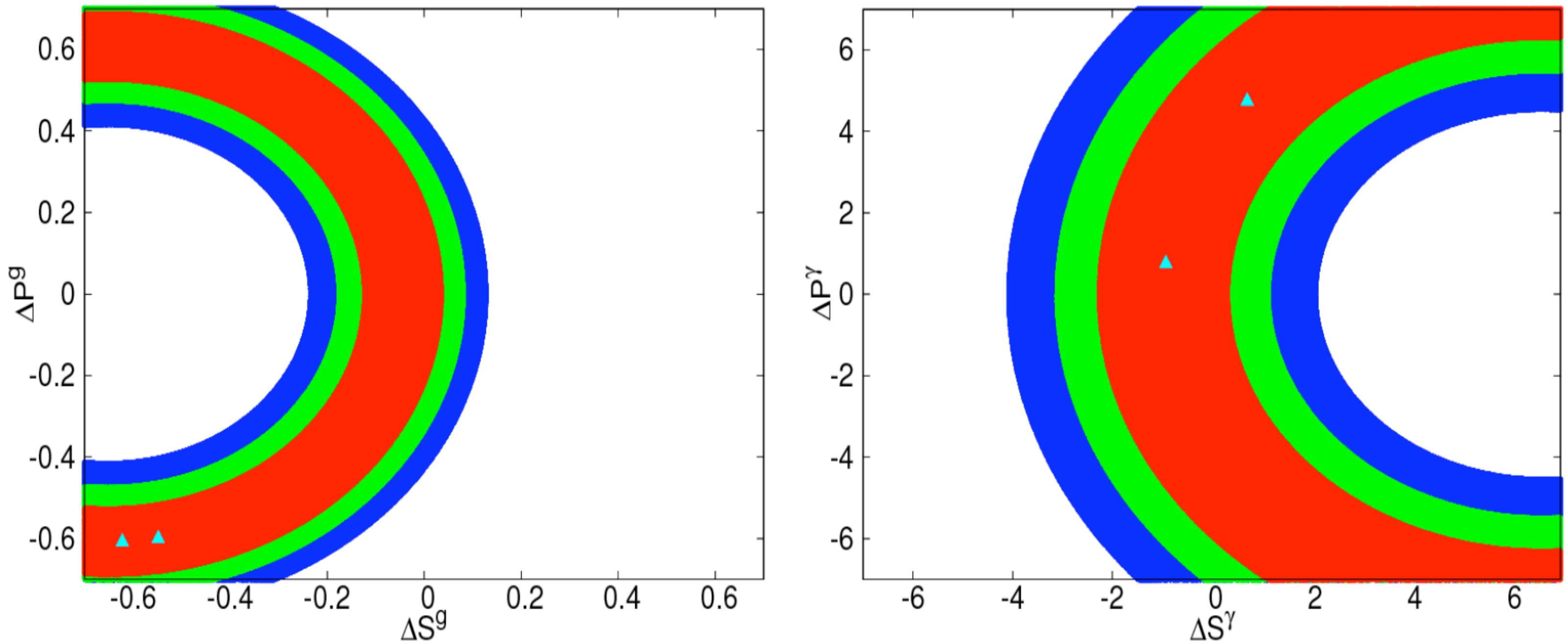
- ΔS^γ, ΔS^g, ΔP^γ and ΔP^g

$$\begin{aligned}(7.3)^2 &= (-6.64 + \Delta S^\gamma)^2 + (\Delta P^\gamma)^2 \\ (0.59)^2 &= (0.65 + \Delta S^g)^2 + (\Delta P^g)^2\end{aligned}$$

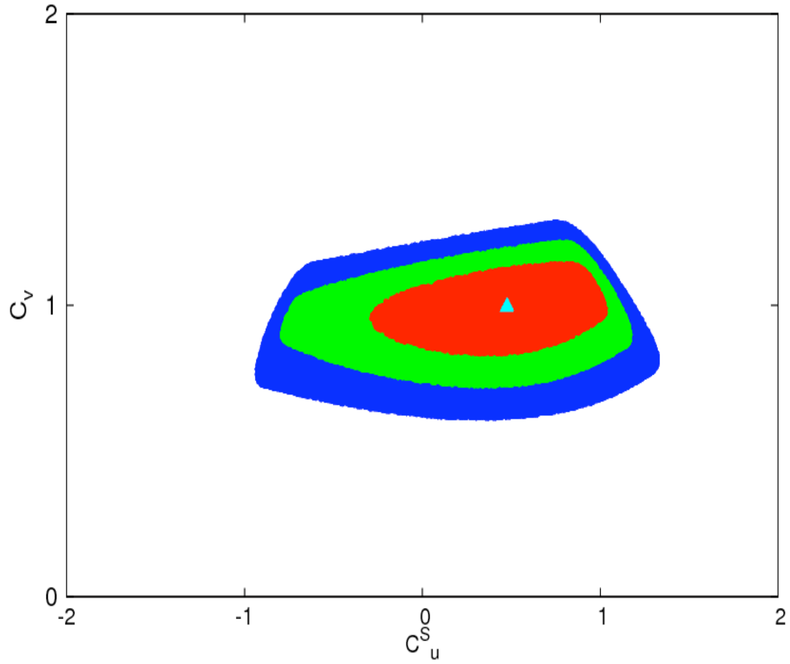
- C_u^S, C_u^P and C_v

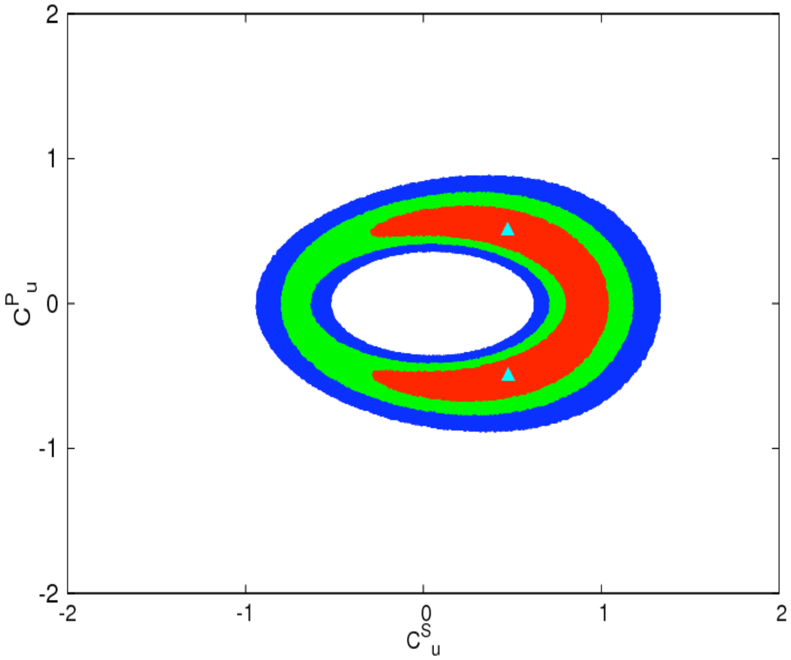
$$\begin{aligned}(7.3)^2 &= (-8.4 + 1.76\, C_u^S)^2 + (2.78\, C_u^P)^2 \\ (0.59)^2 &= (0.688\, C_u^S)^2 + (1.047\, C_u^P)^2\end{aligned}$$

ΔP^γ and ΔP^g



$$C_u^S,\ C_u^P,\ C_v$$





Remarks

- Before the Moriond both ATLAS and CMS diphoton data are above the SM, the dynamics of the fit drives the parameters to the direction that can fit well the data. Thus, improving the fit a lot from the SM.
- However, after Moriond update the dynamics of the fit cannot find an optimal set of parameters to reduce the χ^2 effectively. All the fits are worse than the SM. The SM Higgs boson provides the best fit.
- The nonstandard Higgs decay is limited to be below 22%.
- The HVV coupling is constrained to

$$C_v = 1.01\,^{+0.13}_{-0.14}$$

  leaving very little room for additional Higgs boson that also responsible for EWSB.
- Thus, the current Higgs data do not rule out or favor pseudoscalar couplings.

WW Scattering to test the degree of EWSB of the Discovered Higgs

Jung Chang, KC, TC, 1303.6335
KC, Cheng-Wei Chiang, TC, 0803.2661

WW Scattering to test the degree of EWSB of the Discovered Higgs

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Motivations

If the discovered Higgs boson contributes fully to EWSB, conventional wisdom tells us that the scattering of longitudinal weak gauge bosons would not grow strong at high energies.

But what if the 125 GeV Higgs boson is only partially responsible for EWSB, and the rest is very heavy, then the WW scattering could get strong for a range of energy, until the high energy UV physics for unitarization of the WW scattering.

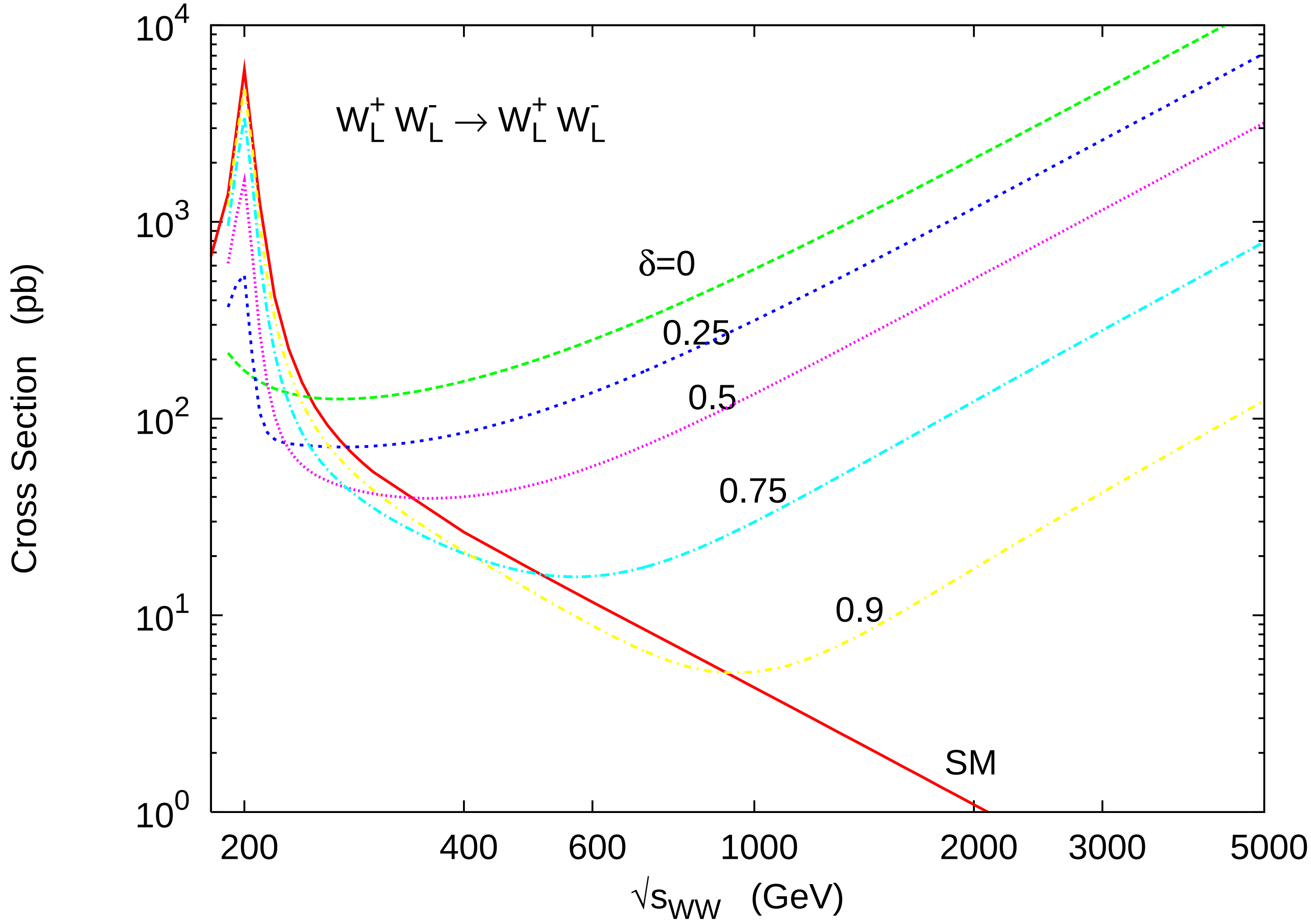
We analyze how the LHC experiments can reveal this interesting possibility of partially strong WW scattering.

Partially Strong $W_L W_L$ Scattering

If the cancellation from the Higgs diagrams is not complete, due to, e.g., the g_{hww} coupling is smaller than the SM value. The $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering amplitude will grow with s.

Suppose the Higgs-W-W coupling is $\sqrt{\delta}$ of the SM value, then amplitudes become

$$
\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4m_W^2}\, u + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{higgs}} &= i\frac{g^2}{4m_W^2}\, u\,\delta + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{all}} &= -i\frac{g^2}{4m_W^2} u(1-\delta) + \mathcal{O}((E/m_W)^0)
\end{aligned}
$$



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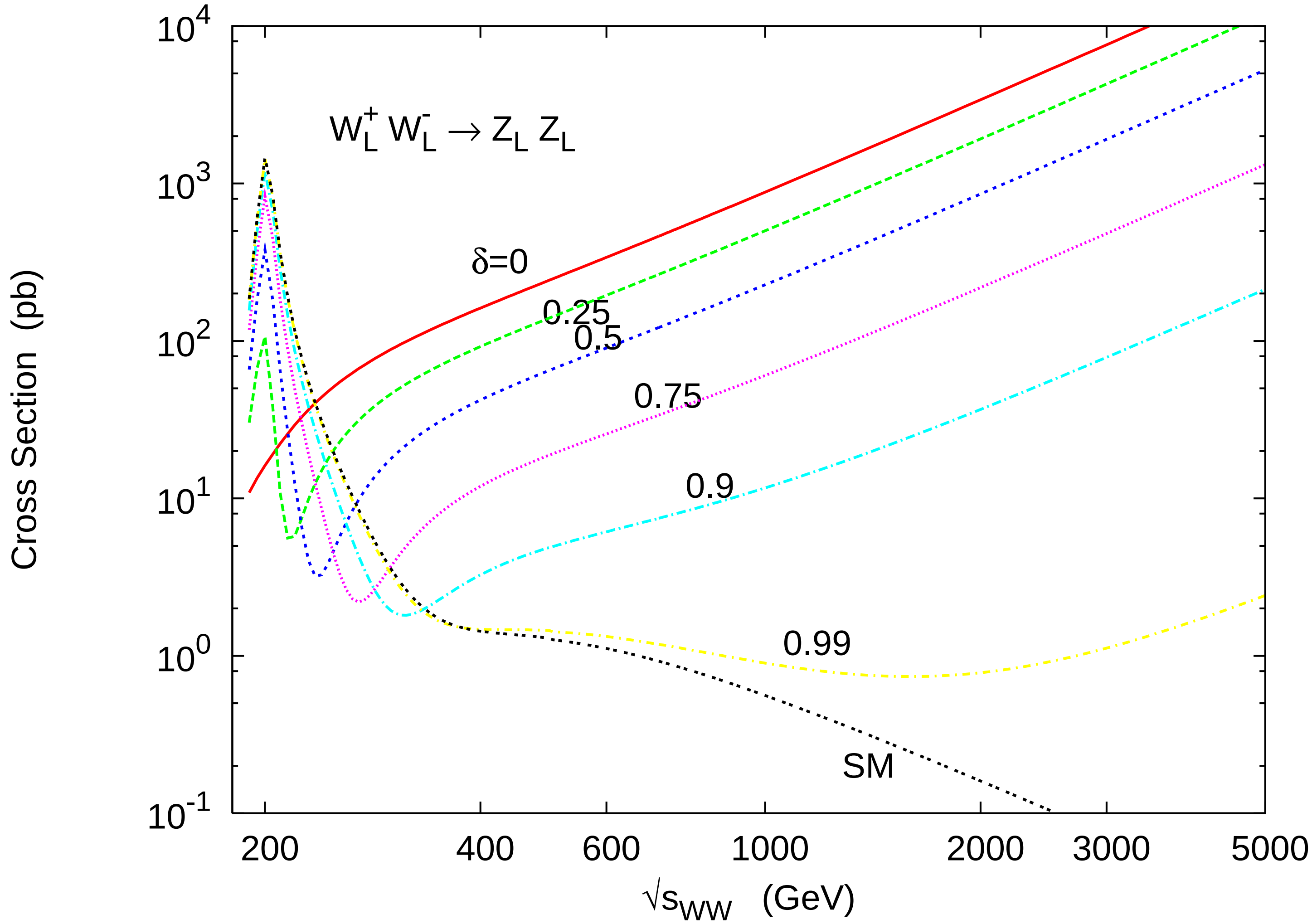

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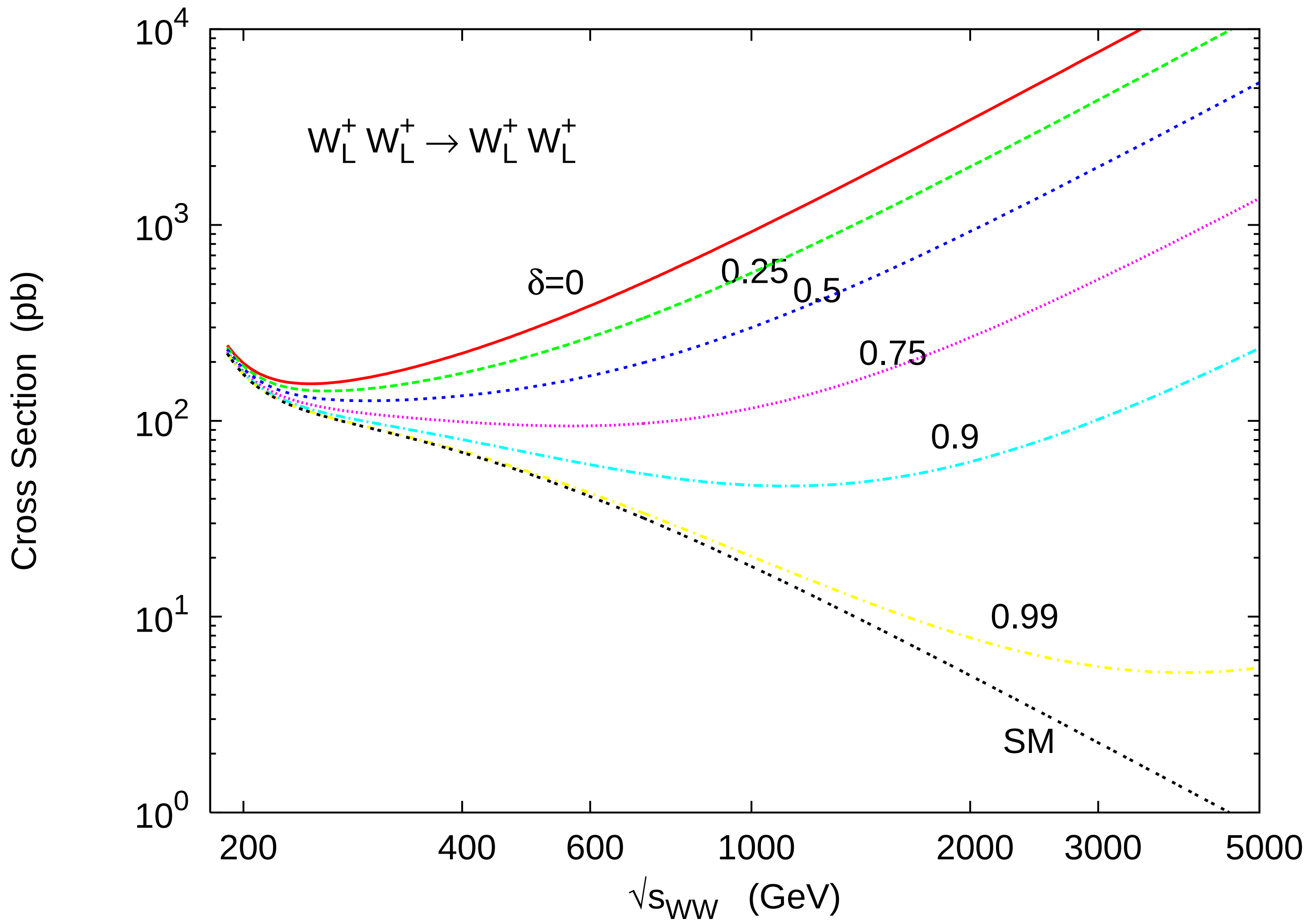

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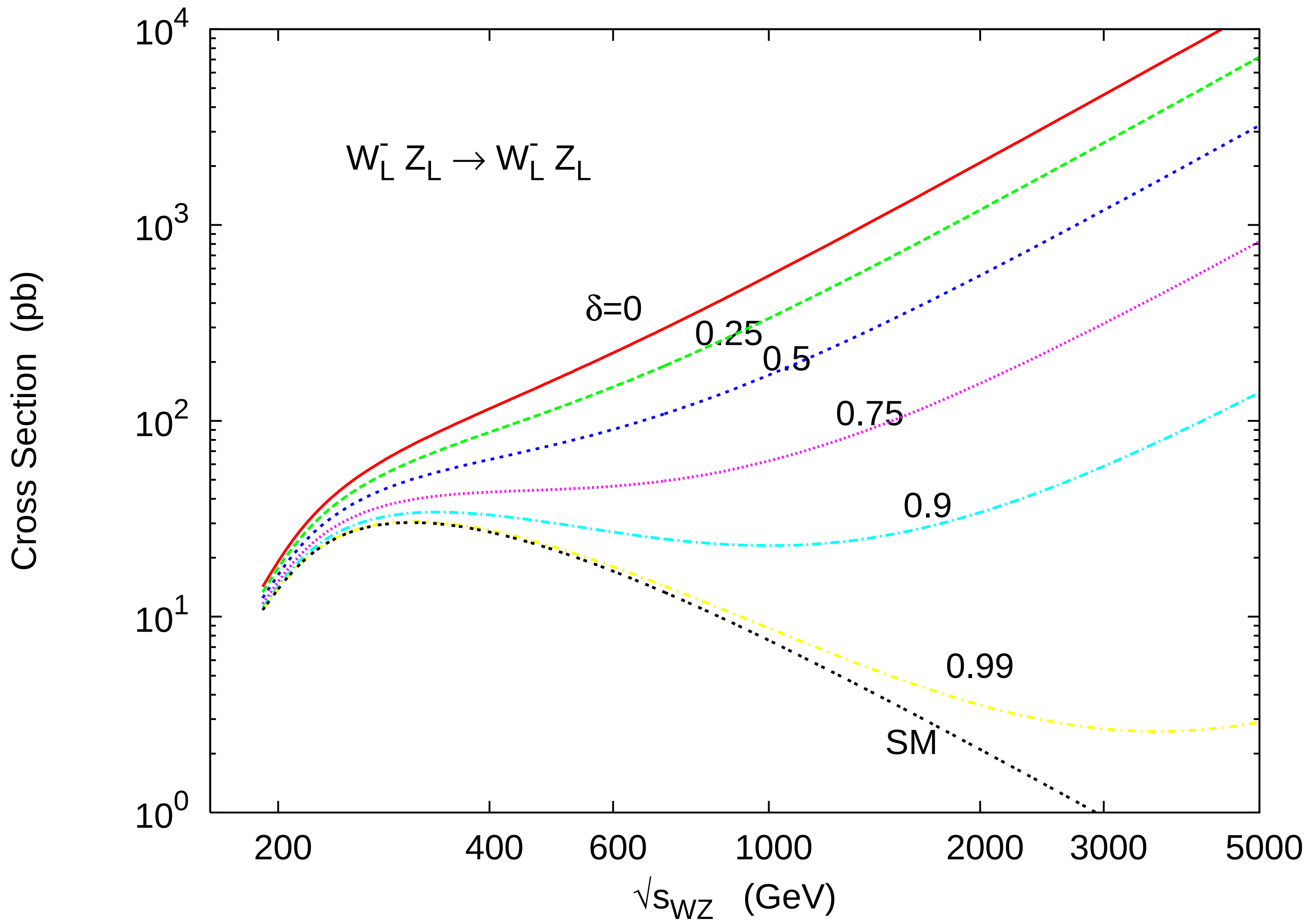

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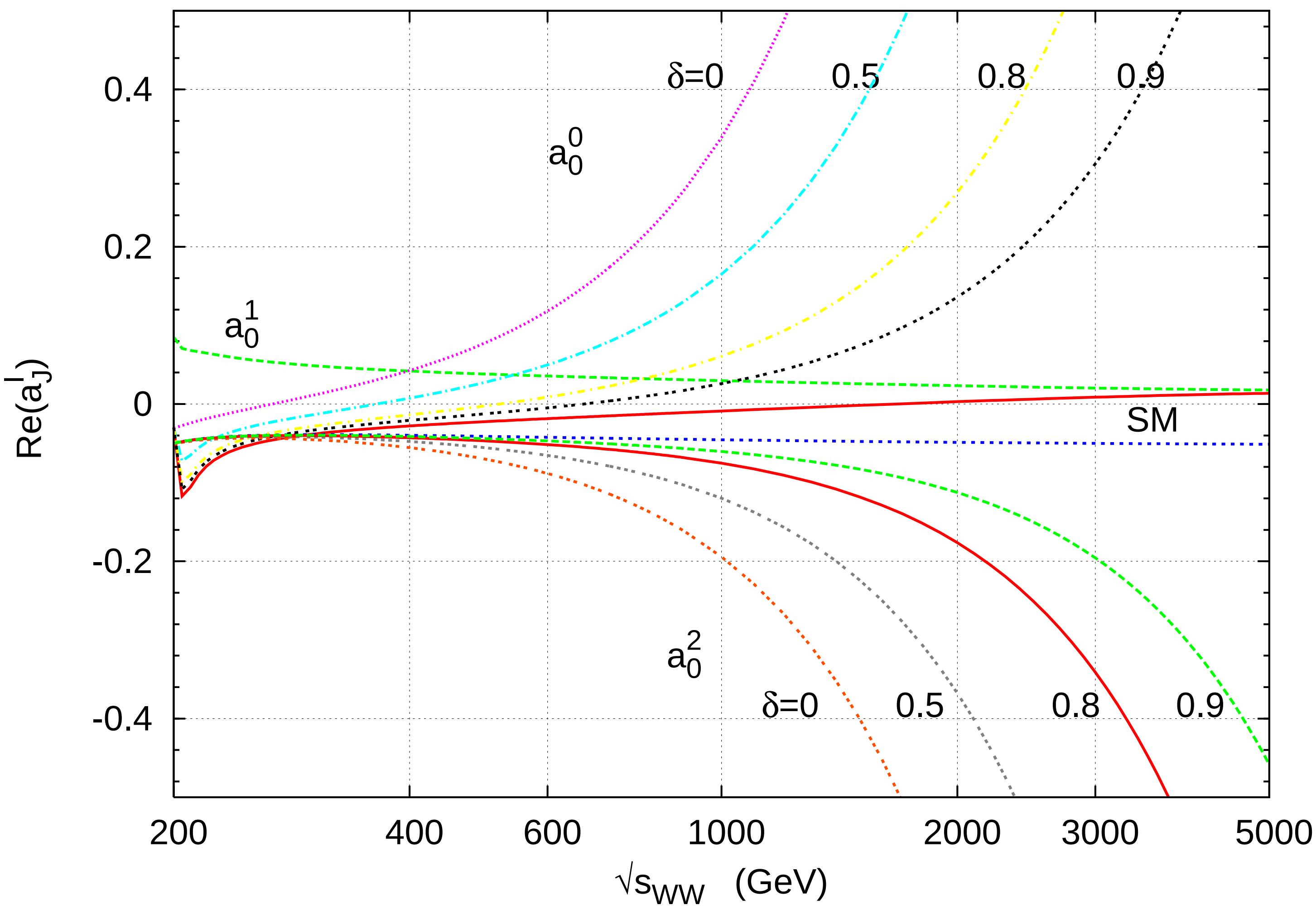


δ=0
0.5
0.8
0.9
a_0^0
a_0^1
SM
a_0^2
δ=0
0.5
0.8
0.9
0.4
0.2
0
-0.2
-0.4
$Re(a_J^I)$
200
400
600
1000
2000
3000
5000
$\sqrt{s_{WW}}$ (GeV)

Partially-Strong $W_L W_L$ Scattering models

- Two-Higgs-doublet model – in a general setting there are parameters in the model such that the mass of the Higgs bosons, $\tan\beta$, and α can be chosen freely. If the light Higgs boson couples to gauge boson with a strength

$$g_{hww} = \sin(\beta - \alpha)\, g_{hww}^{\rm sm}$$

and the mass of the heavy CP-even Higgs boson very heavy $\sim$ TeV. Note that $g_{Hww} = \cos(\beta - \alpha) g_{hww}^{\rm sm}$. One would find that when $s_{ww} > m_H^2$ the energy-growing behavior of the $W_L W_L$ amplitudes is tamed. But still when the energy in between m_h and m_H is large, growing behavior is expected.

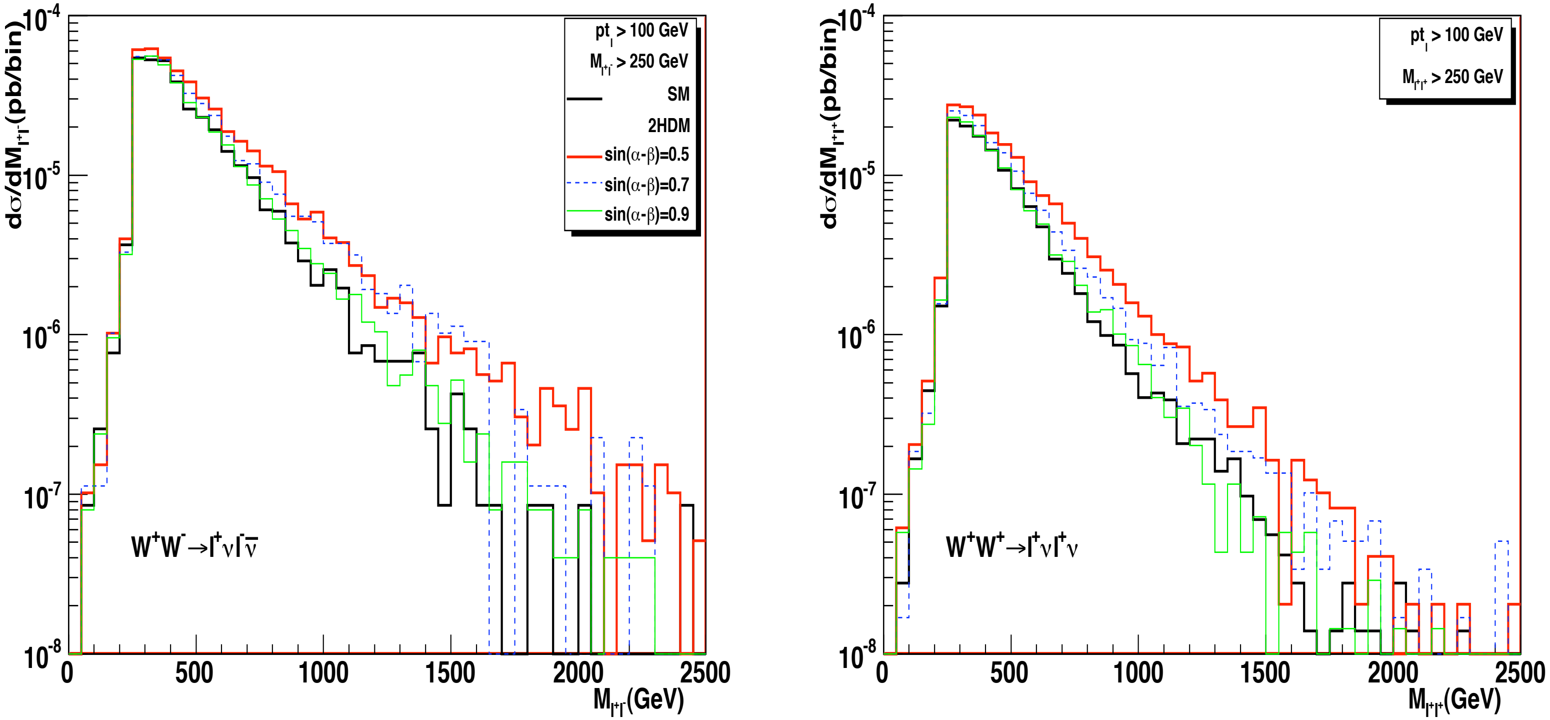
Experimental signals at the LHC

- Energetic forward jets:

$$E_{T_j} > 30 \text{ GeV}, \quad |\eta_j| < 4.7, \quad |\eta_{j1} - \eta_{j2}| > 3.5, \quad \eta_{j1}\eta_{j2} < 0, \quad M_{jj} > 500 \text{ GeV}$$

- Enhancement in the large invariant mass region.
- Leptonic cuts:

W^+W^-	$W^\pm W^\pm$	WZ	ZZ
$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 50$ GeV
$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$
$M_{\ell^+\ell^-} > 250$ GeV	$M_{\ell^\pm\ell^\pm} > 250$ GeV	$M_{3\ell} > 375$ GeV	$M_{4\ell} > 500$ GeV



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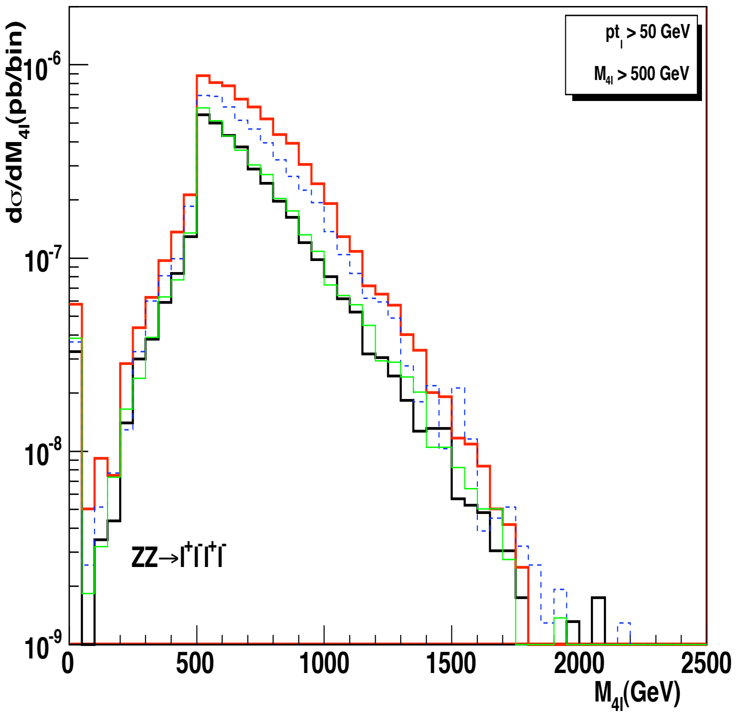

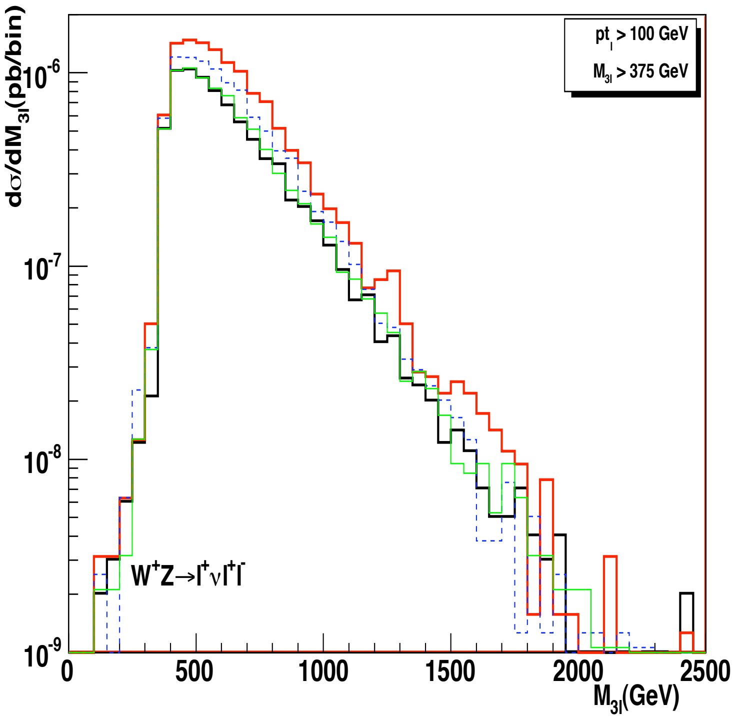

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Cross Sections (fb) for the LHC at 13 TeV

Channels	$\sin(\beta-\alpha)=0.5$	0.7	0.9	SM ($C_v=1$)
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	0.51	0.46	0.40	0.39
$W^+W^+ \to \ell^+\nu\ell^+\nu$	0.20	0.17	0.14	0.14
$W^-W^- \to \ell^-\bar{\nu}\ell^-\bar{\nu}$	0.083	0.075	0.070	0.069
$W^+Z \to \ell^+\nu\ell^+\ell^-$	0.016	0.013	0.011	0.010
$W^-Z \to \ell^-\bar{\nu}\ell^+\ell^-$	1.0×10^{-2}	8.5×10^{-3}	7.6×10^{-3}	7.4×10^{-3}
$ZZ \to \ell^+\ell^-\ell^+\ell^-$	8.4×10^{-3}	6.4×10^{-3}	4.6×10^{-3}	4.4×10^{-3}

Search for Goldstone Boson in Higgs Decay

KC, Wai-Yee Keung, Tzu-Chiang Yuan 1308.4235

Motivations

- Planck, WMAP9 polarization data, and ground-based observations give $N_{eff} = 3.36 \pm 0.34$.
- Weinberg suggested to bring a Goldstone boson into weak interaction with the SM particles in the early Universe, then let the GB decouple around the neutrino-decoupling temperature. Then the GB contributes a fraction of 0.39 to N_{eff}.
- The scalar boson associated with the GB is rather light (500 MeV) and can be produced in the Higgs boson decay.

$$gg \to H \to \sigma\sigma \to (\alpha\alpha)(\pi\pi)$$

The Model

- $$\mathcal{L} = (\partial_\mu S^\dagger)(\partial^\mu S) + \mu^2 S^\dagger S - \lambda (S^\dagger S)^2 - g(S^\dagger S)(\Phi^\dagger \Phi) + \mathcal{L}_{\rm sm}$$

  where
  $$S(x) = \frac{1}{\sqrt{2}} \left(\langle r \rangle + r(x) \right) e^{i2\alpha(x)}$$
  and
  $$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \langle \phi \rangle + \phi(x) \end{pmatrix}$$

- Expanding around the VEVs, redefining $\alpha(x)$ to be canonical,

$$\begin{aligned} \mathcal{L} \quad \supset \quad & \frac{1}{2}(\partial_\mu r)(\partial^\mu r) + \frac{1}{2}\frac{(\langle r \rangle + r)^2}{\langle r \rangle^2}(\partial_\mu \alpha)(\partial^\mu \alpha) + \frac{\mu^2}{2}(\langle r \rangle + r)^2 - \frac{\lambda}{4}(\langle r \rangle + r)^4 \\ & + \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \frac{\mu^2_{\rm sm}}{2}(\langle \phi \rangle + \phi)^2 - \frac{\lambda_{\rm sm}}{4}(\langle \phi \rangle + \phi)^4 \\ & - \frac{g}{4}(\langle r \rangle + r)^2(\langle \phi \rangle + \phi)^2 \end{aligned}$$

- The $\phi(x)$ and $r(x)$ will mix

$$\mathcal{L}_{\rm m} = -\frac{1}{2}\,(\phi(x) \quad r(x)) \begin{pmatrix} 2\lambda_{\rm sm}\langle\phi\rangle^2 & g\langle r\rangle\langle\phi\rangle \\ g\langle r\rangle\langle\phi\rangle & 2\lambda\langle r\rangle^2 \end{pmatrix} \begin{pmatrix} \phi(x) \\ r(x) \end{pmatrix} .$$

Rotate $(\phi(x) \;\; r(x))^T$ by an angle θ into physical fields $H(x)$ and $\sigma(x)$.

- The physical masses of the $H(x)$ and $\sigma(x)$, and the mixing angle are given by, in the small θ limit

$$\begin{aligned} m_H^2 &\approx 2\lambda_{\rm sm}\langle\phi\rangle^2 \,, \\ m_\sigma^2 &\approx 2\lambda\langle r\rangle^2 \,, \\ \theta &\approx \frac{g\langle r\rangle\langle\phi\rangle}{m_H^2 - m_\sigma^2} \,. \end{aligned} \tag{1}$$

- Relevant interactions for $\theta \ll 1$ and $m_\sigma \ll m_H$:

$$\begin{aligned} \mathcal{L}_{H\alpha\alpha} &= \frac{\theta}{\langle r\rangle}\, H\,(\partial_\mu\alpha)(\partial^\mu\alpha) \,, \\ \mathcal{L}_{\sigma\alpha\alpha} &= \frac{1}{\langle r\rangle}\, \sigma\,(\partial_\mu\alpha)(\partial^\mu\alpha) \,, \\ \mathcal{L}_{H\sigma\sigma} &= -\frac{g}{2}\langle\phi\rangle\, H\,\sigma^2 \,. \end{aligned} \tag{2}$$

Constraints

- *Search for invisibly decaying Higgs boson.* The σ can be produced in the place of H but with a mixing angle θ (m_H close to 1 GeV):

$$\sigma(Z\sigma) \approx \sigma(ZH_{\rm sm}) \times \theta^2$$

Using

$$\frac{\sigma(Zh)B(h \to \chi^0\chi^0)}{\sigma(ZH_{\rm sm})} \lesssim 10^{-4} \qquad \text{(OPAL)}$$

we can constrain $\theta \lesssim 0.01$.

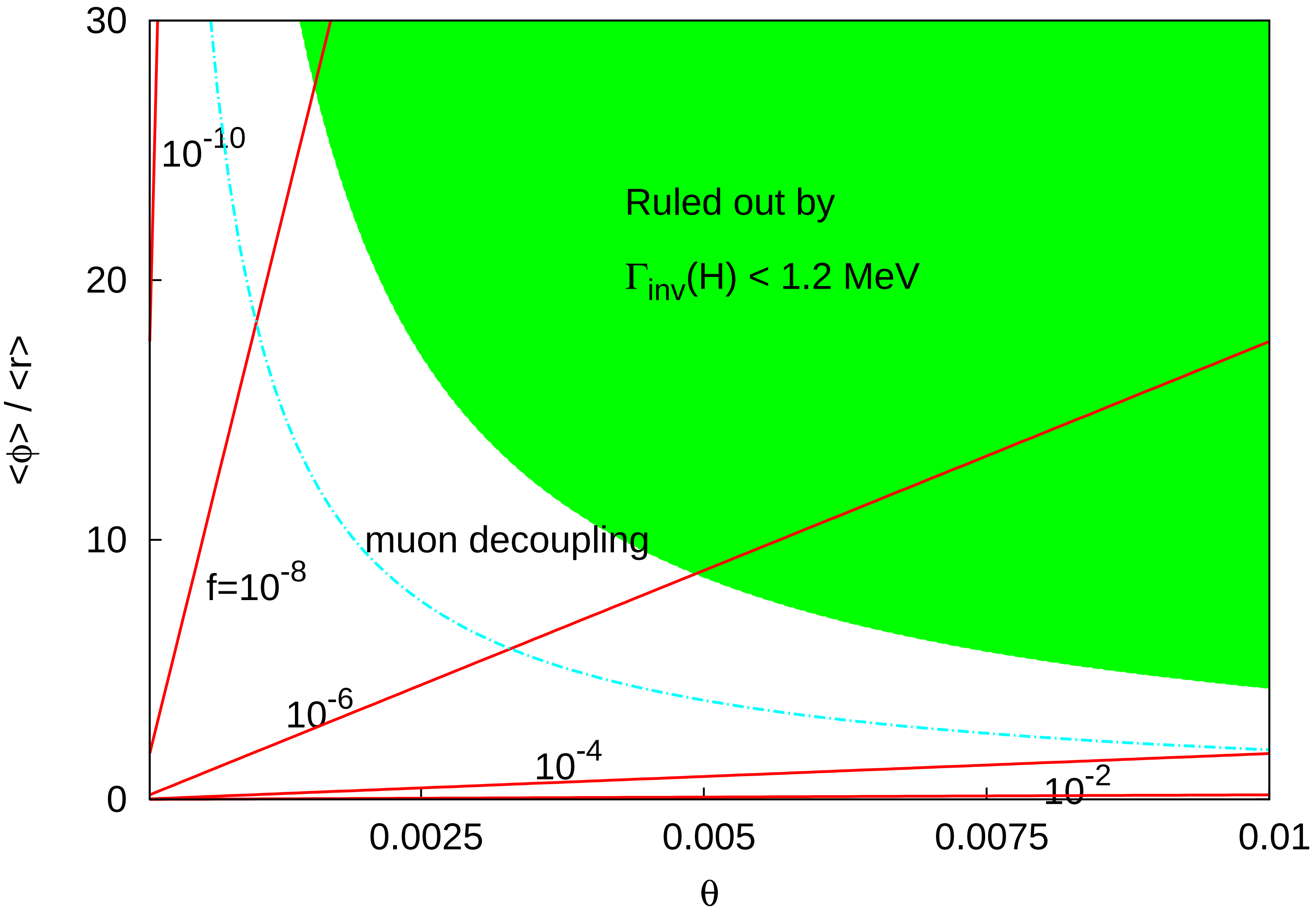
- *Invisible width of the Higgs boson.* The Higgs can decay via

$$H \to \alpha\alpha, \qquad H \to \sigma\sigma \to 4\alpha$$

$$\Gamma(H \to \alpha\alpha) = \frac{1}{32\pi}\frac{m_H^3}{\langle\phi\rangle^2}\frac{\langle\phi\rangle^2}{\langle r\rangle^2}\theta^2, \qquad \Gamma(H \to \sigma\sigma) \approx \frac{1}{32\pi}\frac{m_H^3}{\langle\phi\rangle^2}\frac{\langle\phi\rangle^2}{\langle r\rangle^2}\theta^2$$

The global fit to the observed Higgs boson restricts the nonstandard decay to be less than about 22% ($\sim$ 1.2 MeV). So we have

$$\theta\,\frac{\langle\phi\rangle}{\langle r\rangle} \leq 0.043\;.$$


30
20
10
0
<φ> / <r>
0.0025
0.005
0.0075
0.01
θ
Ruled out by
Γinv(H) < 1.2 MeV
muon decoupling
10-10
f=10-8
10-6
10-4
10-2

Decays of the σ field

- Decays into e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$.
- Decay into pion pairs. The only hadron that σ can decay is pions:

$$\Gamma(\sigma \to \pi\pi) = \theta^2 \frac{3}{32\pi} \frac{m_\sigma^3}{\langle \phi \rangle^2} \left(1 - \frac{4m_\pi^2}{m_\sigma^2}\right)^{1/2} \left(1 + \frac{2m_\pi^2}{m_\sigma^2}\right)^2 .$$

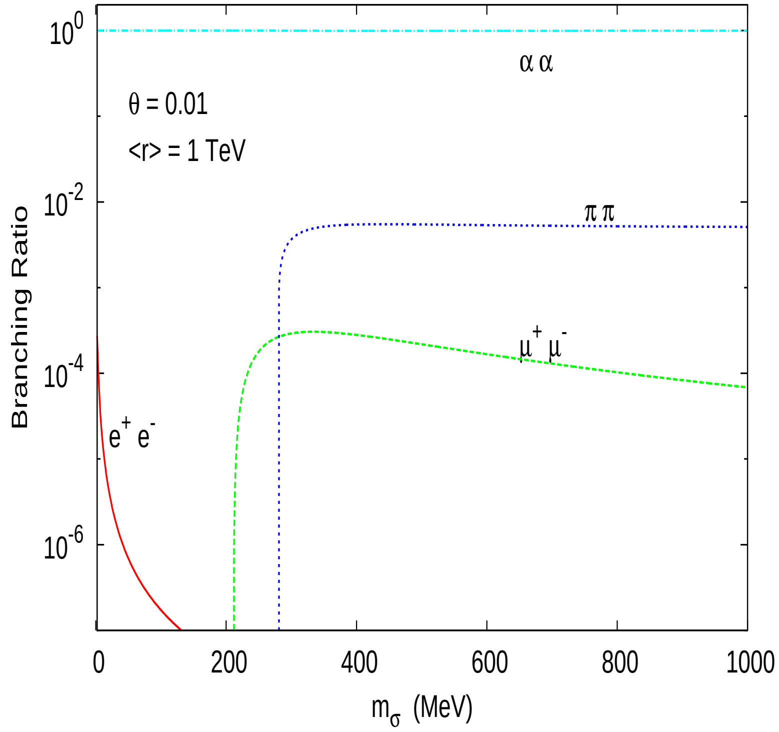
- Decay into $\alpha\alpha$

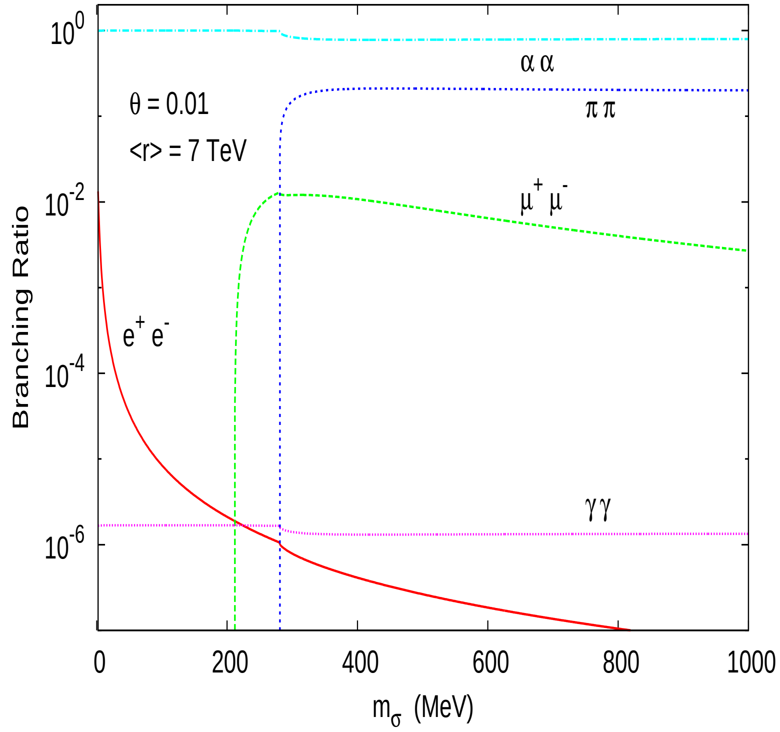
$$\Gamma(\sigma \to \alpha\alpha) = \frac{m_\sigma^3}{32\pi \langle r \rangle^2} .$$

- Define the ratio for visibility of the σ:

$$f \equiv \frac{\Gamma(\sigma \to \pi\pi)}{\Gamma(\sigma \to \alpha\alpha)} = 3\,\theta^2 \frac{\langle r \rangle^2}{\langle \phi \rangle^2} \left(1 - \frac{4m_\pi^2}{m_\sigma^2}\right)^{1/2} \left(1 + \frac{2m_\pi^2}{m_\sigma^2}\right)^2$$

Branching ratios of the σ





Collider Signatures

- Nonstandard decay of the Higgs is less than about 20%. Take $B(H \to \sigma\sigma) \approx 10\%$ and $B(\sigma \to \pi\pi) \approx 20\%$ we can have

$$gg \to H \to \sigma\sigma \to (\pi\pi)\,(\alpha\alpha)$$

- The cross section at the LHC-8 would be

$$\begin{aligned} \sigma(gg \to H) \times B(H \to \sigma\sigma) \times B(\sigma \to \pi\pi) \times B(\sigma \to \alpha\alpha) &\approx 19 \text{ pb} \times 0.1 \times 0.2 \times 0.8 \\ &\approx 300 \text{ fb} \end{aligned}$$

At the LHC-14, it would be 2.8 times as much.

- Difficulties: the angular separation between the two pions is very small: $1/60 \sim 2m_\sigma/p_{T_\sigma} \approx 0.015$. It appears to be a microjet having two pions, and experimentally like a τ jet.

Conclusions

- It is just the beginning of an exciting era.
- Global fitting of Higgs parameters – Higgcision.
- If the WW scattering becomes strong, it means the light Higgs boson is only partially responsible for EWSB.
- Non-standard decay of the Higgs boson is still exciting.

Backup Slides

$H \to \gamma\gamma$ data

Channel	Signal strength μ		M_H	Production mode				$\chi^2_{\rm SM}$(each)	
	Before	*After*		ggF	VBF	VH	ttH	*Before*	*After*
ATLAS ($4.8{\rm fb}^{-1}$ at 7TeV + 13.0 (20.7) ${\rm fb}^{-1}$ at 8TeV)									
$\mu_{ggH+ttH}$	1.8 ± 0.49	1.6 ± 0.4	126.8	100%	-	-	-	2.67	2.25
μ_{VBF}	2.0 ± 1.4	1.7 ± 0.9	126.8	-	100%	-	-	0.53	0.60
μ_{VH}	1.9 ± 2.6	$1.8^{+1.5}_{-1.3}$	126.8	-	-	100%	-	0.12	0.38
CMS ($5.1{\rm fb}^{-1}$ at 7TeV + 5.3 (19.6)${\rm fb}^{-1}$ at 8TeV)									
untagged	$1.42^{+0.55}_{-0.49}$	$0.78^{+0.28}_{-0.26}$	125	87.5%	7.1%	4.9%	0.5%	0.73	0.62
VBF tagged	$2.25^{+1.34}_{-1.04}$	$2.25^{+1.34}_{-1.04}$	125.8	17%	83%	-	-	1.44	1.44
Tevatron ($10.0{\rm fb}^{-1}$ at 1.96TeV):									
Combined	$6.14^{+3.25}_{-3.19}$	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60	2.60
						subtot:		8.09	7.89

$H \to ZZ^{(*)}$ Data

Channel	Signal strength μ *Before*	*After*	M_H	Production mode ggF	VBF	VH	ttH	$\chi^2_{\rm SM}$(each) *Before*	*After*
ATLAS (4.8fb^{-1} at 7TeV + 13 (20.7)fb^{-1} at 8TeV)									
Inclusive	1.0 ± 0.4	1.5 ± 0.4	125.5	87.5%	7.1%	4.9%	0.5%	0.0	1.56
CMS (5.1fb^{-1} at 7TeV + 12.2 (19.6) fb^{-1} at 8TeV)									
Inclusive	$0.80^{+0.35}_{-0.28}$	$0.91^{+0.30}_{-0.24}$	125.8	87.5%	7.1%	4.9%	0.5%	0.33	0.09
						subtot:		0.33	1.65

$H \to WW^*$ Data

Channel	Signal strength μ		M_H	Production mode				$\chi^2_{\rm SM}$(each)	
	Before	*After*		ggF	VBF	VH	ttH	*Before*	*After*
ATLAS (4.8fb^{-1} at 7TeV + 13 (20.7) fb^{-1} at 8TeV)									
Inclusive	1.5 ± 0.6	1.0 ± 0.3	125.5	87.5%	7.1%	4.9%	0.5%	0.69	0.00
CMS (up to 4.9 fb^{-1} at 7TeV + 12.1 (19.5) fb^{-1} at 8TeV)									
0/1 jet	$0.77^{+0.27}_{-0.25}$	0.76 ± 0.21	125	97%	3%	-	-	0.73	1.31
VBF tag	$-0.05^{+0.74}_{-0.55}$	$-0.05^{+0.74}_{-0.55}$	125.8	17%	83%	-	-	2.01	2.01
VH tag	$-0.31^{+2.22}_{-1.94}$	$-0.31^{+2.22}_{-1.94}$	125.8	-	-	100%	-	0.35	0.35
Tevatron (10.0fb^{-1} at 1.96TeV):									
Combined	$0.85^{+0.88}_{-0.81}$	$0.85^{+0.88}_{-0.81}$	125	78%	5%	17%	-	0.03	0.03
						subtot:		3.81	3.70

$H \to b\bar{b}$ Data

Channel	Signal strength μ c.v $\pm$ error	M_H(GeV)	Production mode ggF	VBF	VH	ttH	$\chi^2_{\rm sm}$(each)
ATLAS ($4.8fb^{-1}$ at 7TeV + $13.0fb^{-1}$ at 8TeV): (Dec. 2012)							
VH tag	-0.4 ± 1.0	125	-	-	100%	-	1.96
CMS (up to $5.0fb^{-1}$ at 7TeV + $12.1fb^{-1}$ at 8TeV): (Nov. 2012)							
VH tag	$1.31^{+0.65}_{-0.60}$	125.8	-	-	100%	-	0.27
ttH tag	$-0.80^{+2.10}_{-1.84}$	125.8	-	-	-	100%	0.73
Tevatron ($10.0fb^{-1}$ at 1.96TeV): (Nov. 2012)							
VH tag	$1.56^{+0.72}_{-0.73}$	125	-	-	100%	-	0.59
							subtot: 3.55

$H \to \tau\tau$. The correlation for the $\tau\tau$ data of ATLAS is $\rho = -0.49$.

Channel	Signal strength μ		M_H	Production mode				$\chi^2_{\rm SM}$(each)	
	Before	*After*		ggF	VBF	VH	ttH	*Bef*	*Aft*
ATLAS (4.6fb^{-1} at 7TeV + 13.0fb^{-1} at 8TeV)									
μ_{ggF}	2.38 ± 1.57	2.30 ± 1.60	125.5	100%	-	-	-	1.60	1.41
μ_{VBF+VH}	$-.25 \pm 1.02$	$-.22 \pm 1.06$	125.5	-	59.4%	40.6%	-		
CMS (up to 4.9fb^{-1} at 7TeV + 12.1 (19.4) fb^{-1} at 8TeV)									
0/1 jet	$0.85^{+0.68}_{-0.66}$	$0.76^{+0.50}_{-0.52}$	125	77.8%	13.8%	7.6%	.8%	.05	.23
VBF tag	$0.82^{+0.82}_{-0.75}$	$1.40^{+0.59}_{-0.57}$	125	20.9%	79.1%	-	-	.05	.49
VH tag	$0.86^{+1.92}_{-1.68}$	$0.77^{+1.49}_{-1.42}$	125	-	-	100%	-	.005	.02
					subtot:			1.70	2.15

Summary of CP conserving fits (before Moriond)

Para.	Vary $\Delta\Gamma_{\rm tot}$	Vary ΔS^γ, ΔS^g	Vary ΔS^γ, ΔS^g, $\Delta\Gamma_{\rm tot}$	Vary C_u^S, C_d^S, C_ℓ^S, C_v	Vary C_u^S, C_d^S, C_ℓ^S C_v,ΔS^γ, ΔS^g
C_u^S	1	1	1	$-0.88^{+0.16}_{-0.21}$	0.00 ± 1.13
C_d^S	1	1	1	$1.12^{+0.45}_{-0.38}$	$1.19^{+0.57}_{-0.41}$
C_ℓ^S	1	1	1	$-0.97^{+0.30}_{-0.29}$	0.98 ± 0.30
C_v	1	1	1	$0.97^{+0.13}_{-0.15}$	$0.96^{+0.13}_{-0.15}$
ΔS^γ	0	$-2.73^{+1.11}_{-1.15}$	$-2.93^{+1.19}_{-1.31}$	0	$-1.23^{+2.44}_{-2.49}$
ΔS^g	0	$-0.050^{+0.064}_{-0.065}$	$0.0063^{+0.15}_{-0.11}$	0	$0.73^{+0.81}_{-0.80}$
$\Delta\Gamma_{\rm tot}$	$-0.022^{+0.63}_{-0.48}$	0	$0.79^{+2.01}_{-1.11}$	0	0
χ^2/dof	17.48/21	11.27/20	10.83/19	10.46/18	9.89/16

The most crucial parameters are C_u^S and ΔS^γ. The best values are

$$C_u^S = 0.92^{+0.094}_{-0.095}, \quad \Delta S^\gamma = -2.62^{+1.02}_{-1.04}, \quad \chi^2/dof = 11.17/20 \ .$$