Correlating the W Mass with Higgs Couplings

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(Based on works in progress with
Carlos Wagner and Liantao Wang)

Physics beyond the Standard Model
in light of the CDF W boson mass anomaly

M_W and M_Z Measurements by CDF-II

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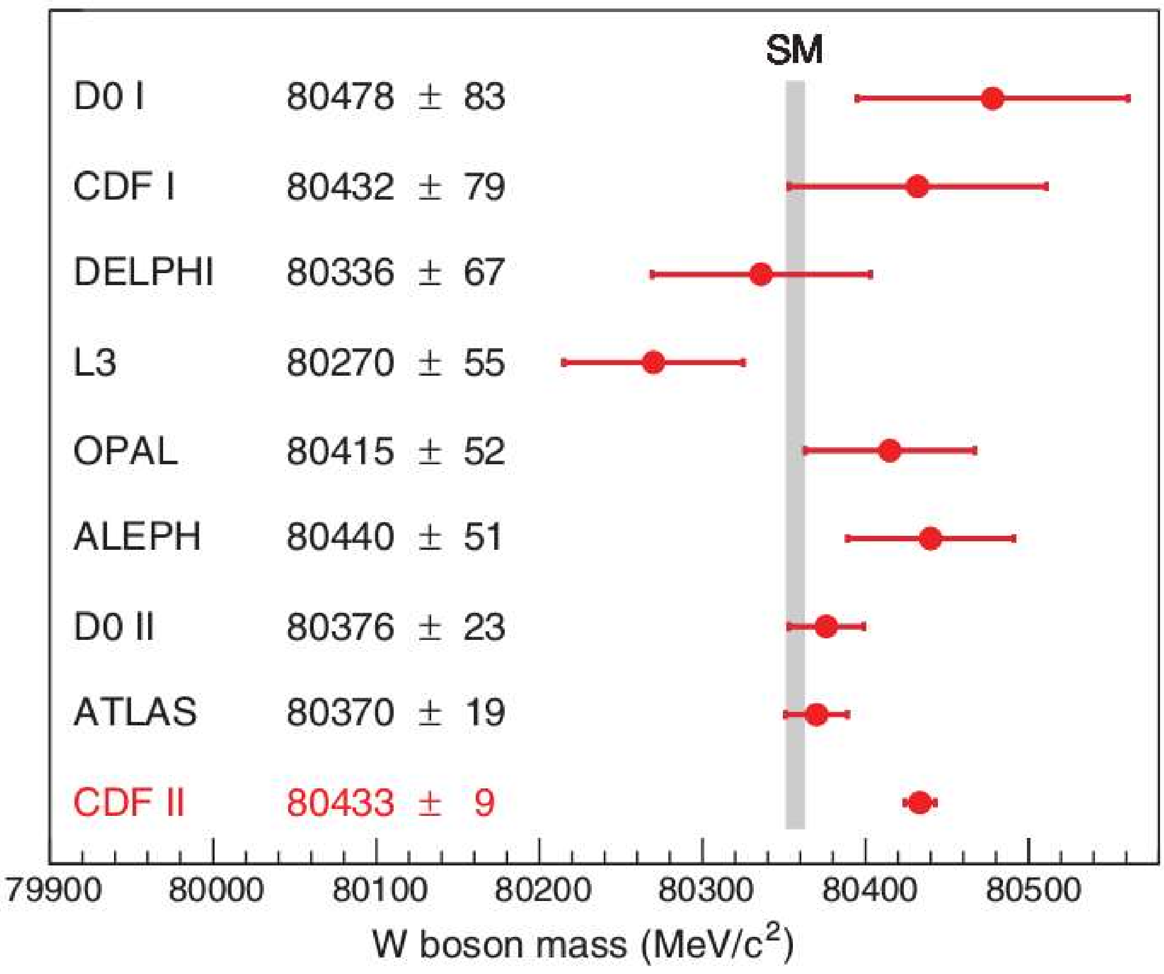

M_W and M_Z Measurements by CDF-II

2. $M_Z = 91{,}192.0 \pm 6.4_{stat} \pm 4.0_{syst}$ MeV

   - Consistent with world-average:
     $M_Z = 91{,}187.6 \pm 2.1$ MeV

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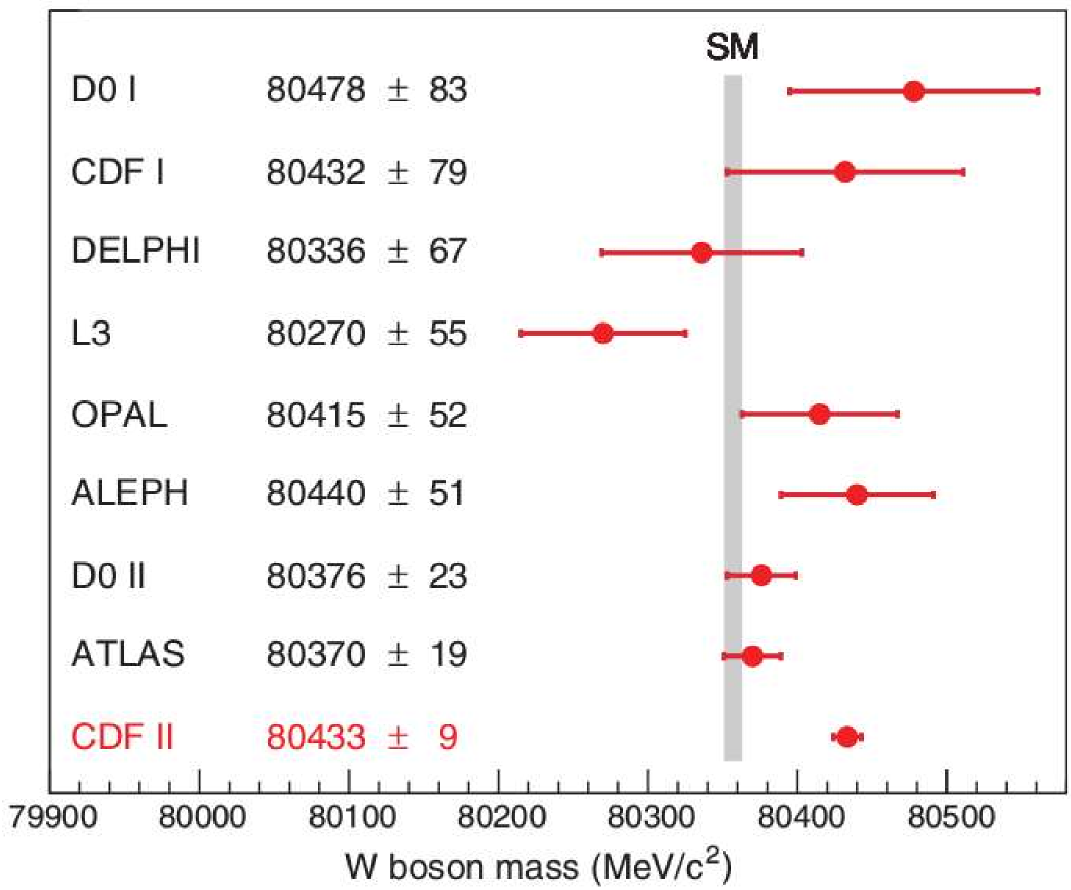
- Consistent with world-average:
  $M_Z = 91{,}187.6 \pm 2.1$ MeV
- Track momentum in COT (central outer tracking drift chamber) calibrated by masses of J/Ψ and Υ (dimuon decay channel)
- Combined momentum calibration then used to measure M_Z (in $Z \to \mu\mu$ channel)

M_W and M_Z Measurements by CDF-II

✸ M_Z is consistent with SM but M_W deviates from SM by 7σ

[CDF Collaboration '22]



M_W and M_Z Measurements by CDF-II

- M_Z is consistent with SM but
  M_W deviates from SM by 7σ

- This suggests that really the tension is in

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_w} (= 1 \text{ in SM})$$

- Deviation from $\rho = 1$ requires extra new physics source of $SU(2)_{cust}$-violation

Cf) Other types of "solutions" to ΔM_W may exist.

New physics? What kind?

General comments

- $\Delta\rho = \alpha T$
- More generally,

$$\Delta M_W = \frac{\alpha M_W}{2(c_w^2 - s_w^2)}\left(-\frac{1}{2}S + c_w^2 T + \frac{c_w^2 - s_w^2}{4s_w^2}U\right)$$

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- In EFT operator language,

$$\mathcal{L} \supset \frac{\alpha S}{4 s_w c_w v^2}(H^+\tau^a H)W^a_{\mu\nu}B^{\mu\nu} - \frac{2\alpha T}{v^2}\left|H^+ D_\mu H\right|^2$$

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$U \leftrightarrow \frac{\left(H^+ W_{\mu\nu} H\right)^2}{\mathrm{M}^4}$ (in this talk, we ignore this effect)

New physics? What kind?

(Q) For what M, can we explain M_W?

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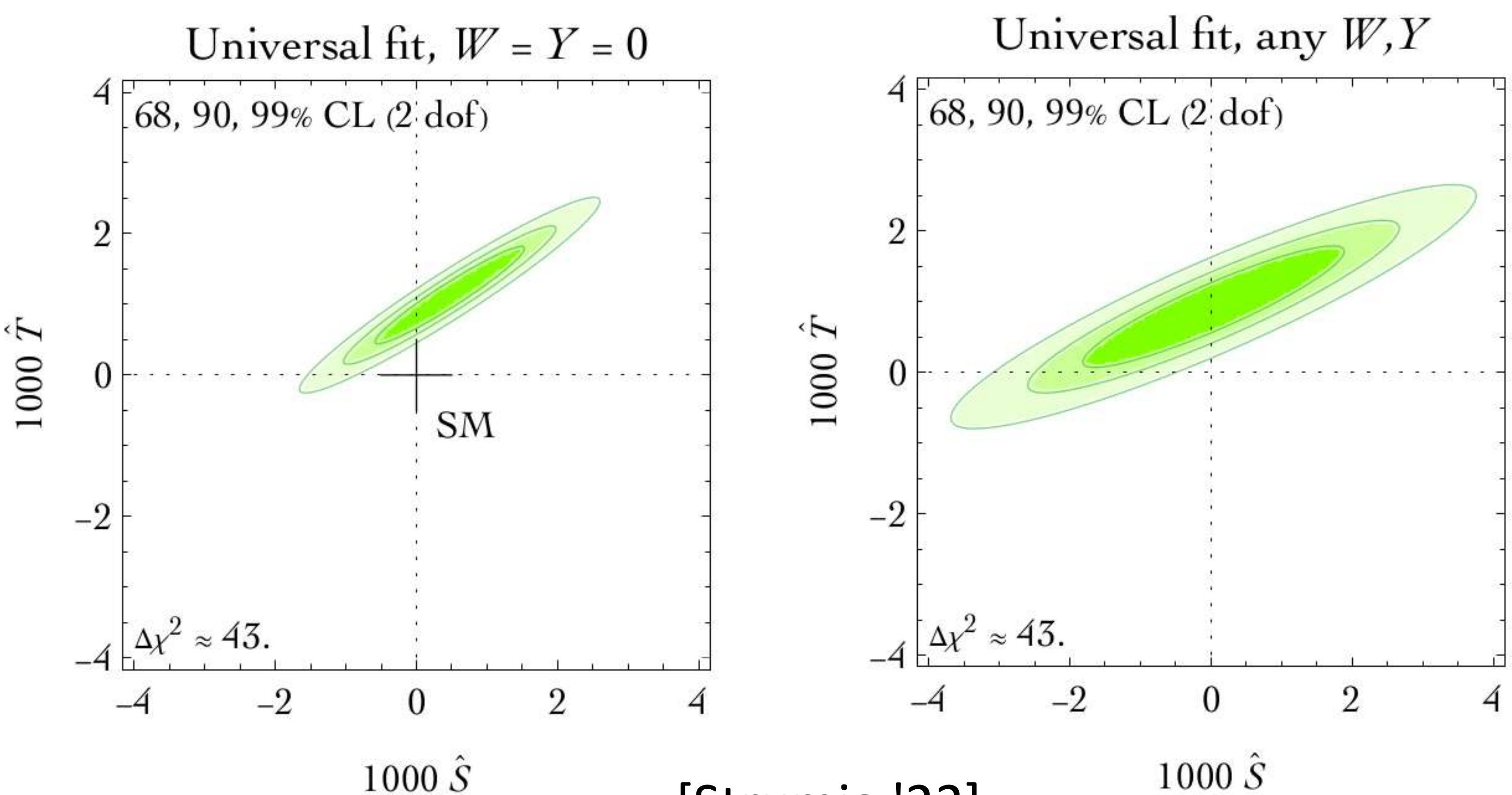

[Strumia '22]

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$$\Delta M_W = \frac{\alpha M_W}{2(c_w^2 - s_w^2)}\left(-\frac{1}{2}S + c_w^2 T\right)$$

1) T-alone : $T \approx 0.11$

2) T and S : $T \approx 0.142, \quad S \approx 0.06$

$$\mathcal{L} \sim \frac{1}{(6\ \mathrm{TeV})^2}(H^+\tau^a H)W^a_{\mu\nu}B^{\mu\nu}, \frac{1}{(6\ \mathrm{TeV})^2}\left|H^+ D_\mu H\right|^2$$

New physics? What kind?

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(A1) New physics at tree-level:

$$\frac{g^2 N_c N_f}{\mathrm{M}^2} \sim \frac{1}{(6\ \mathrm{TeV})^2} \quad \Rightarrow \mathrm{M} \sim 6g\sqrt{N_c N_f}\ \mathrm{TeV}$$

(A2) New physics at loop-level:

$$\frac{g^2 N_c N_f}{16\pi^2 \mathrm{M}^2} \sim \frac{1}{(6\ \mathrm{TeV})^2} \quad \Rightarrow \ \mathrm{M} \sim g\sqrt{N_c N_f}\, 477\ \mathrm{GeV}$$

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Correlating M_W with Higgs Couplings

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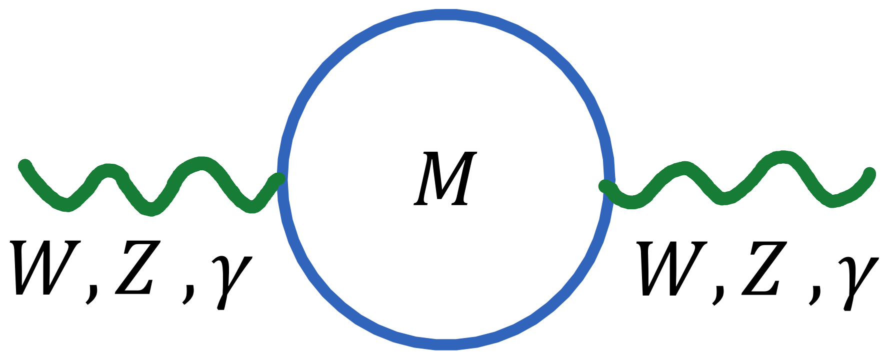
(ii) "Universal" new physics effects:



$\Rightarrow S, T$

(iii) For loop-induced S and T: $M \sim \mathcal{O}(500)$ GeV

Correlating M_W with Higgs Couplings

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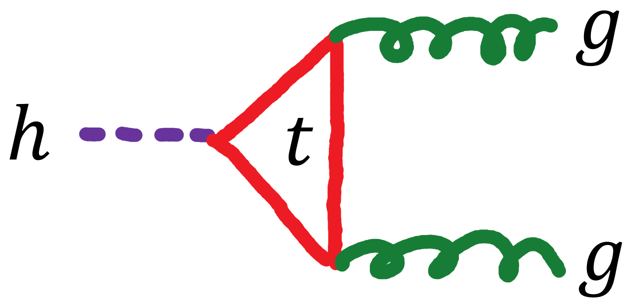

$$\mathcal{L}_{SM} \supset \frac{\alpha_s}{12\pi}\frac{h}{v}\, G^a_{\mu\nu} G^{a\,\mu\nu}$$

Correlating M_W with Higgs Couplings

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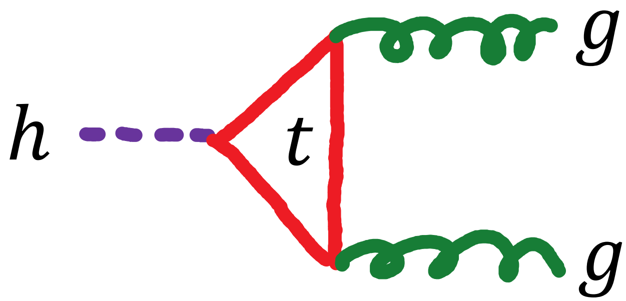

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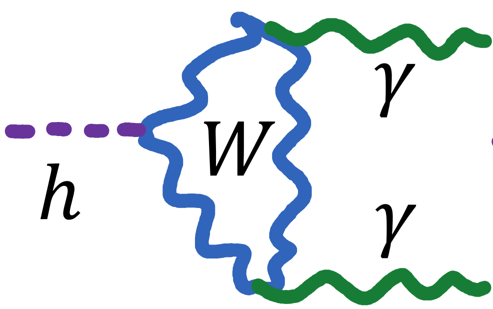

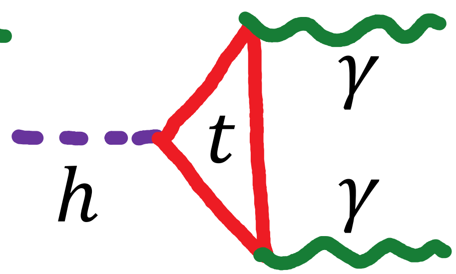

$$\mathcal{L}_{SM} \supset \frac{\alpha(-8.32_W + 1.84_t)}{12\pi}\frac{h}{v}\, F_{\mu\nu}F^{\mu\nu}$$

Correlating M_W with Higgs Couplings

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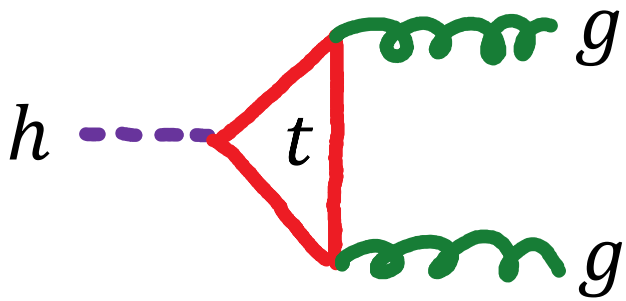

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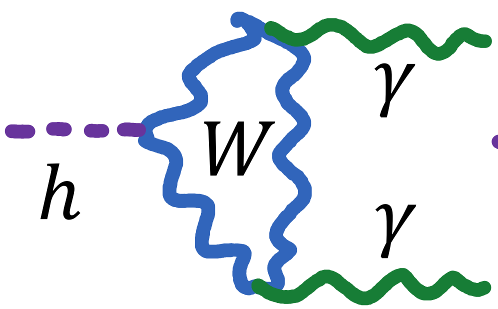

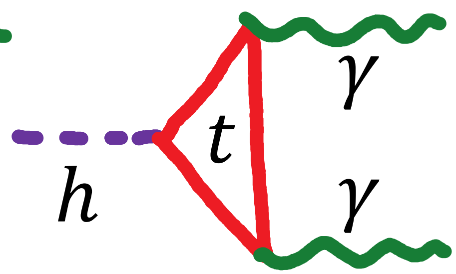

$$\mathcal{L}_{SM} \supset \frac{\alpha(-8.32_W + 1.84_t)}{12\pi}\frac{h}{v}\, F_{\mu\nu} F^{\mu\nu}$$

(v) New physics at $M \sim \mathcal{O}(500)$ GeV can contribute to these couplings. Note: $m_{SM} \sim 100 - 200$ GeV

Correlating M_W with Higgs Couplings

We consider (somewhat) general new physics models and investigate correlations among [Hong, Wagner, Wang '22]

$$\Delta M_W, \delta g_{hgg}, \delta g_{h\gamma\gamma}, \sin^2\theta_{\text{eff}}^{\ell}, M_{\text{light}}$$

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(1) Fermion Model: $\Psi_i = SU(2)_L$ doublets, $\chi_i =$ singlets

$$\mathcal{L} = -y_1\bar{\chi}_1\Psi_2 H - y_2\bar{\chi}_2\Psi_1\widetilde{H} - m_\Psi\bar{\Psi}_1\Psi_2 - m_\chi\bar{\chi}_1\chi_2$$

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$$\Delta M_W, \delta g_{hgg}, \delta g_{h\gamma\gamma}, \sin^2\theta^{\ell}_{\mathrm{eff}}, M_{\mathrm{light}}$$

(2) Scalar Model: $\Phi = SU(2)_L$ doublets, $S_{t,b}$ = singlets

$$\begin{aligned}\mathcal{L} = &-m_\Phi^2|\Phi|^2 - m_{S_t}^2|S_t|^2 - m_{S_b}^2|S_b|^2 - y_1|H\cdot\Phi|^2 \\ &-y_2\left|\widetilde{H}\cdot\Phi\right|^2 - A_t H\cdot\Phi S_t - A_b\widetilde{H}\cdot\Phi S_b \\ &-y_3|H|^2|S_t|^2 - y_4|H|^2|S_b|^2\end{aligned}$$

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- Mass spectrum

$$\Psi_i = (T_i, B_i)^T, \chi_i \;\Rightarrow\; T_h, T_l, B$$

$$M^2_{T(l,h)} = \frac{1}{2}\left[m_\Psi^2 + m_\chi^2 + \frac{v^2}{2}\left(y_1^2 + y_2^2\right)\right] \pm \frac{1}{2}\sqrt{\left((m_\Psi^2 - m_\chi^2 + \frac{v^2}{2}\left(y_1^2 - y_2^2\right)\right)^2 + 2v^2\left(m_\Psi y_2 + m_\chi y_2\right)^2}$$

$$M_B^2 = m_\Psi^2$$

Correlating M_W with Higgs Couplings

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- Analytic results for S and T available.

$$16\pi s_W^2 c_W^2 T = \left(c_L^2 + s_L^2\right)\theta_+(x, y_l) + 2 c_L c_R \theta_-(x, y_l) + \cdots$$

$$x = \frac{M_B^2}{m_Z^2}, \quad y_{l,h} = \frac{M_{T(l,h)}^2}{m_Z^2}$$

Correlating M_W with Higgs Couplings

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- $SU(2)_{cust}$-breaking
  - Recall: $H \;\rightarrow\; \Phi = \left(\widetilde{H}, H\right) \;\Rightarrow\; L\,\Phi\,R^{+}$
  - $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{cust}$ by $\langle\Phi\rangle$

Correlating M_W with Higgs Couplings

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  - $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{cust}$ by $\langle \Phi \rangle$
  - R acts horizontatlly

$$\xrightarrow{\quad R \quad}$$

$$\Phi = \begin{pmatrix} \phi_0^* & \phi^+ \\ -\phi^- & \phi_0 \end{pmatrix} \Big\downarrow L$$

Correlating M_W with Higgs Couplings

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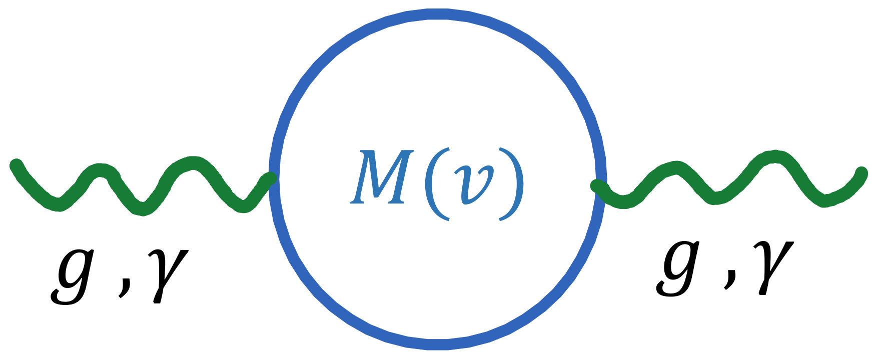
- $SU(2)_{cust}$-breaking
  - Any parameter treating H and $\widetilde{H}$ differently

"$y_1 - y_2$"

Correlating M_W with Higgs Couplings

- Δg_{hgg} and $\Delta g_{h\gamma\gamma}$

For new physics scale M modestly larger than v we can use **"Higgs low energy theorem"**



$$\mathcal{L} \supset -\frac{1}{4}\left(\sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{M(v)^2}\right) F_{\mu\nu}F^{\mu\nu}$$

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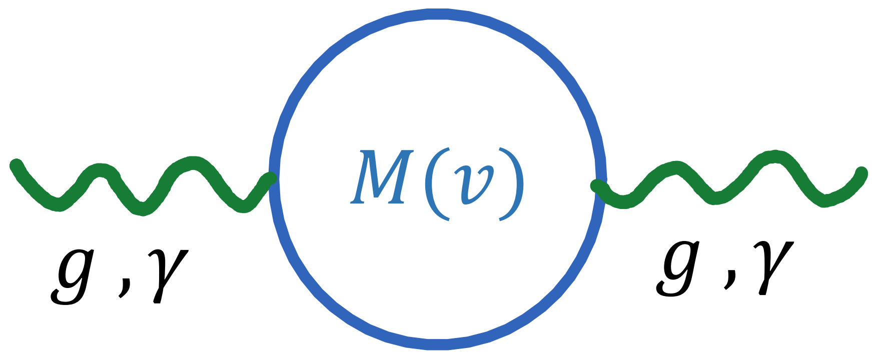

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$$\rightarrow \mathcal{L} \supset \frac{\alpha}{16\pi}\frac{h}{v}\left(\sum_i \frac{\partial}{\partial \log v}\log\left(\det M^2(v)\right)\right)F_{\mu\nu}F^{\mu\nu} \qquad (v \rightarrow v + h)$$

Correlating M_W with Higgs Couplings

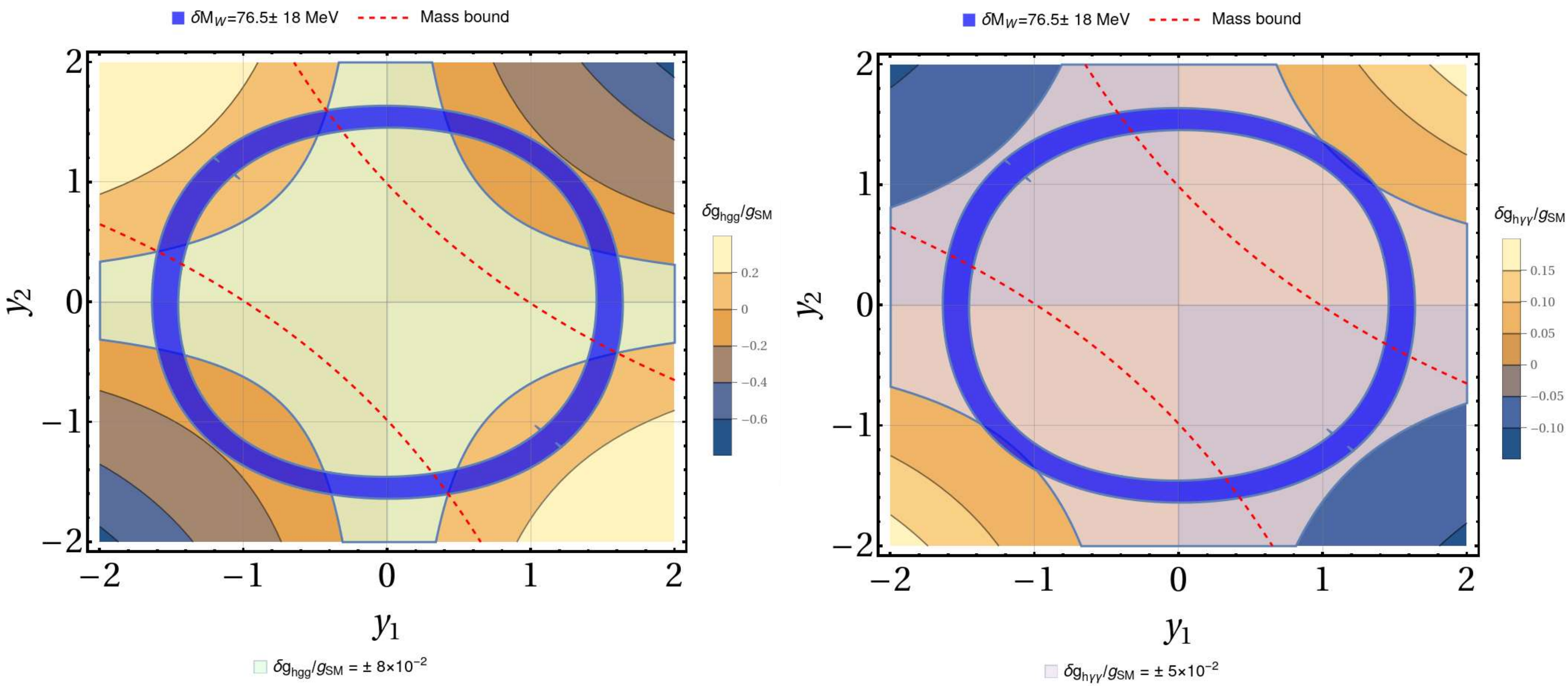
- Δg_{hgg} and $\Delta g_{h\gamma\gamma}$

  In our fermion model

$$\frac{\Delta g_{h\gamma\gamma}}{\alpha/16\pi} = \frac{\Delta g_{hgg}}{\alpha_s/16\pi} = \frac{b_{1/2}v}{M_{Tl}^2 M_{Th}^2}\left(y_1^2 y_2^2 v^2 - 2m_\Psi m_\chi y_1 y_2\right)$$

Correlating M_W with Higgs Couplings

- Interplay M_W--Higgs Couplings--Mass bound



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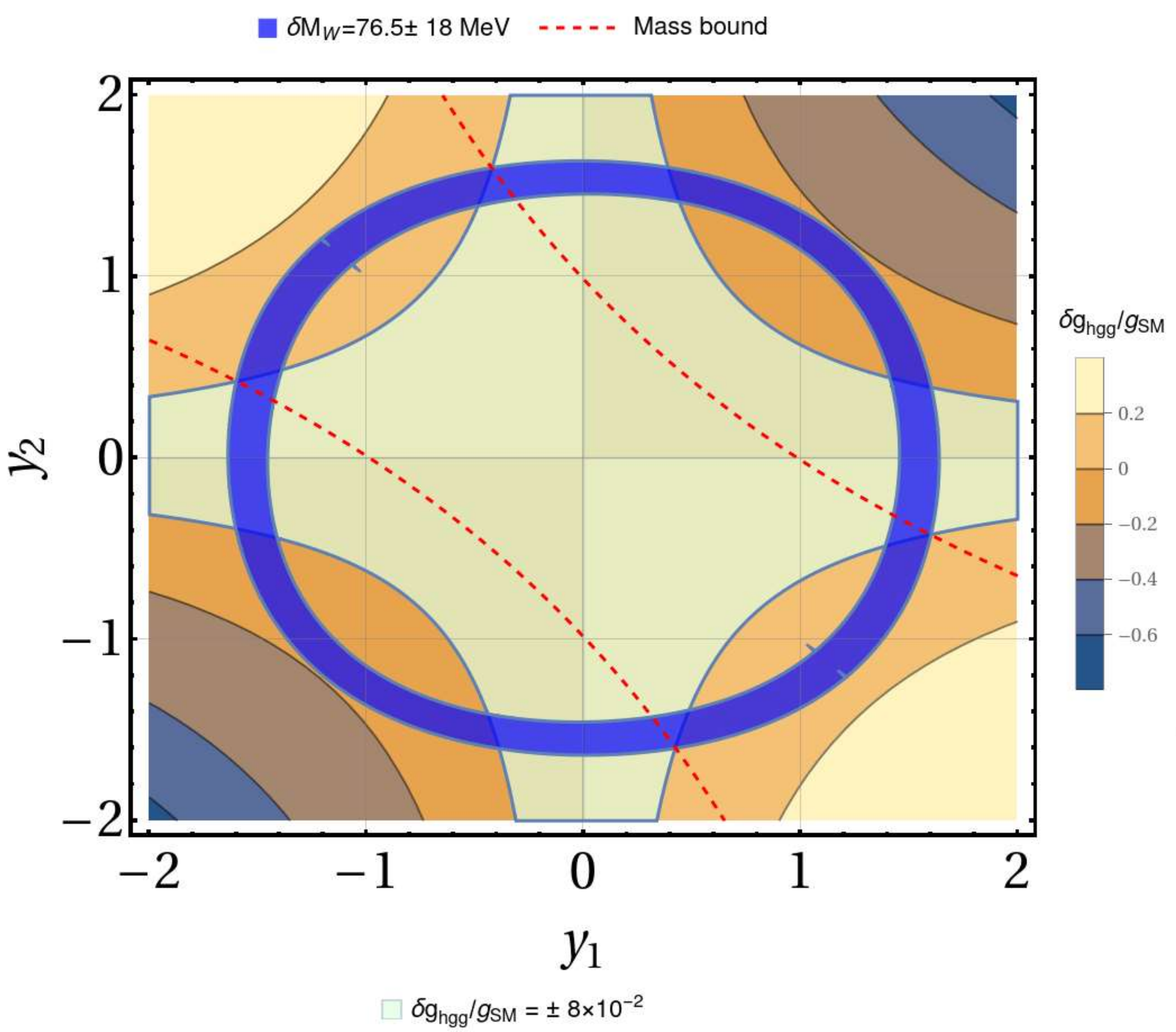


Correlating M_W with Higgs Couplings

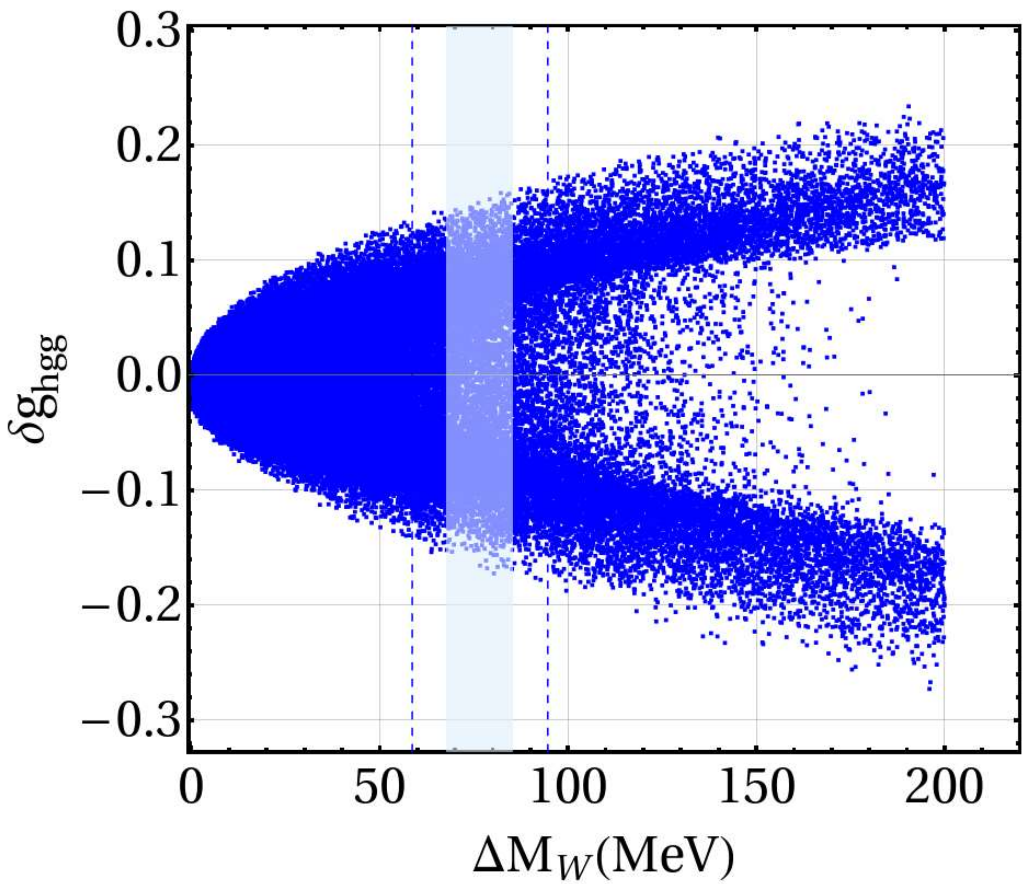
- Parameter Scan

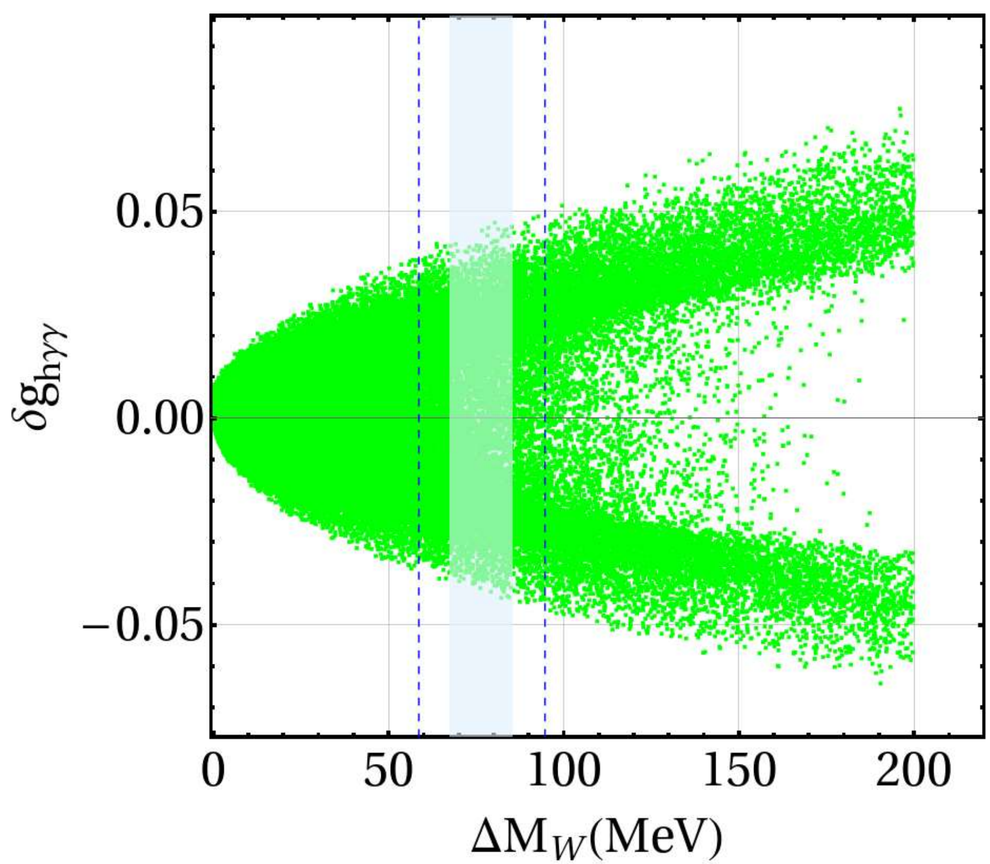
  We ask: given choices of m_Ψ, m_χ, y_1, y_2 $(-2 \leq y_{1,2} \leq 2)$
  and discrete choices: (un)colored, (un)charged

  Is there non-trivial correlations among observables?

Correlating M_W with Higgs Couplings

○ Parameter Scan





$$700 \leq m_\Psi, m_\chi \leq 1500 \text{ GeV}, \ \ -2 \leq y_1, y_2 \leq 2$$

Correlating M_W with Higgs Couplings

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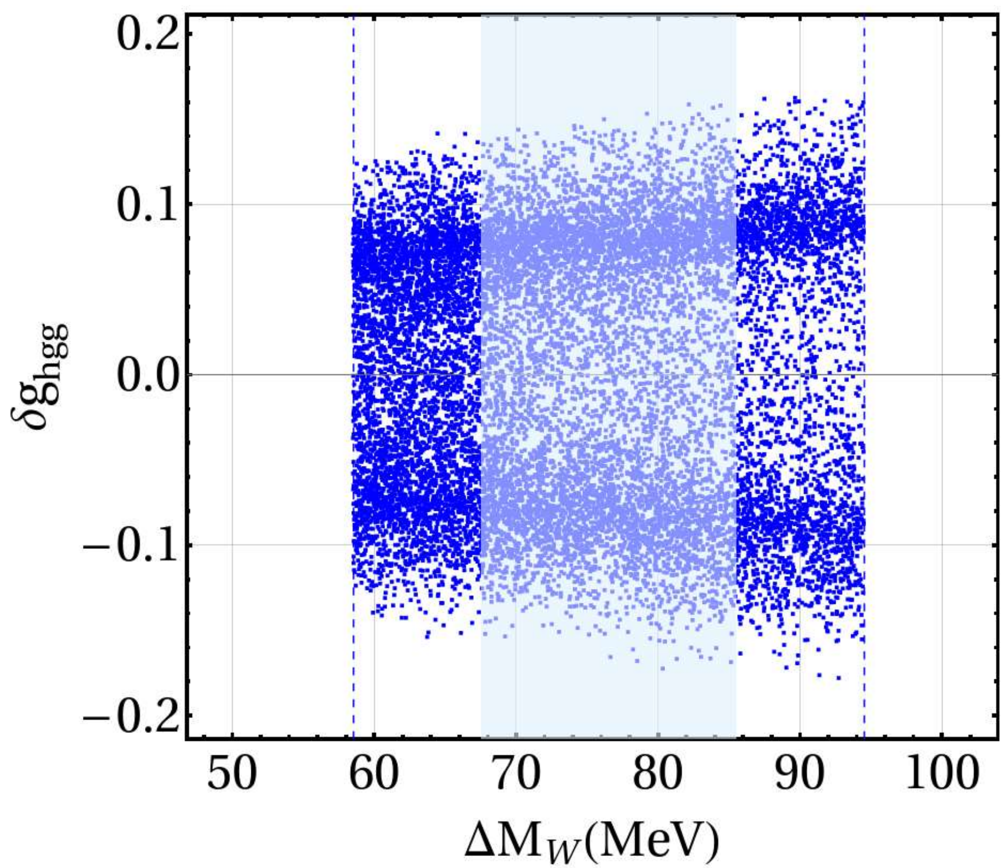

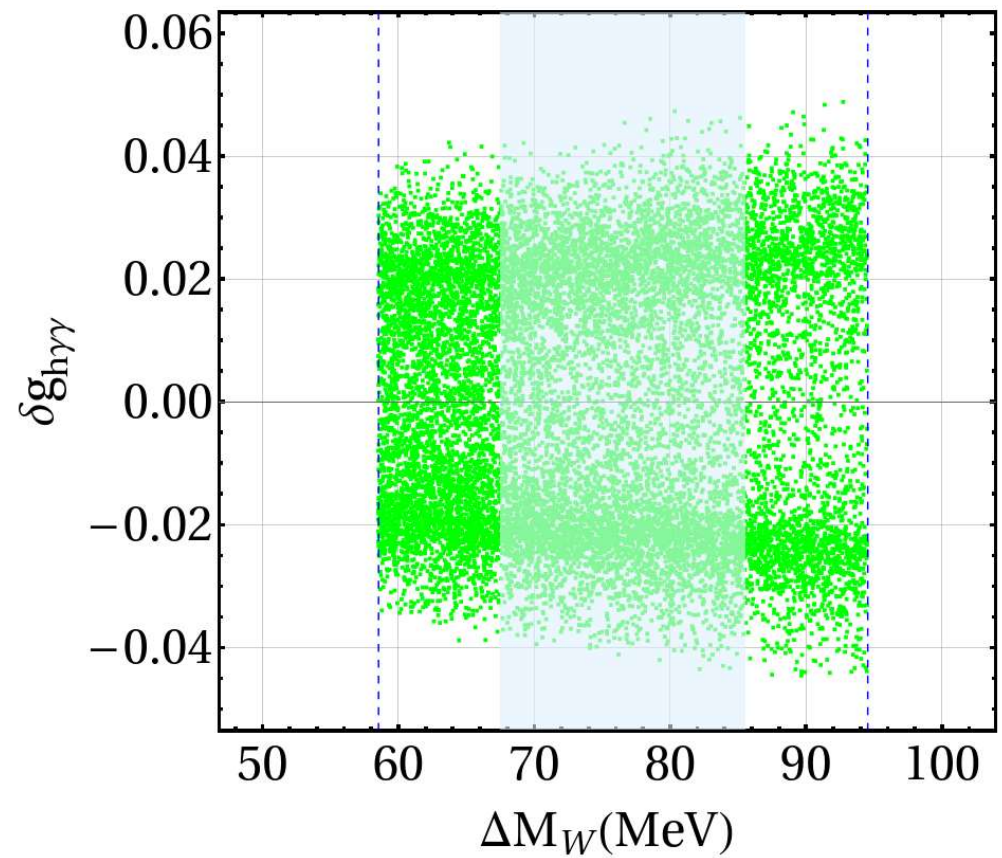

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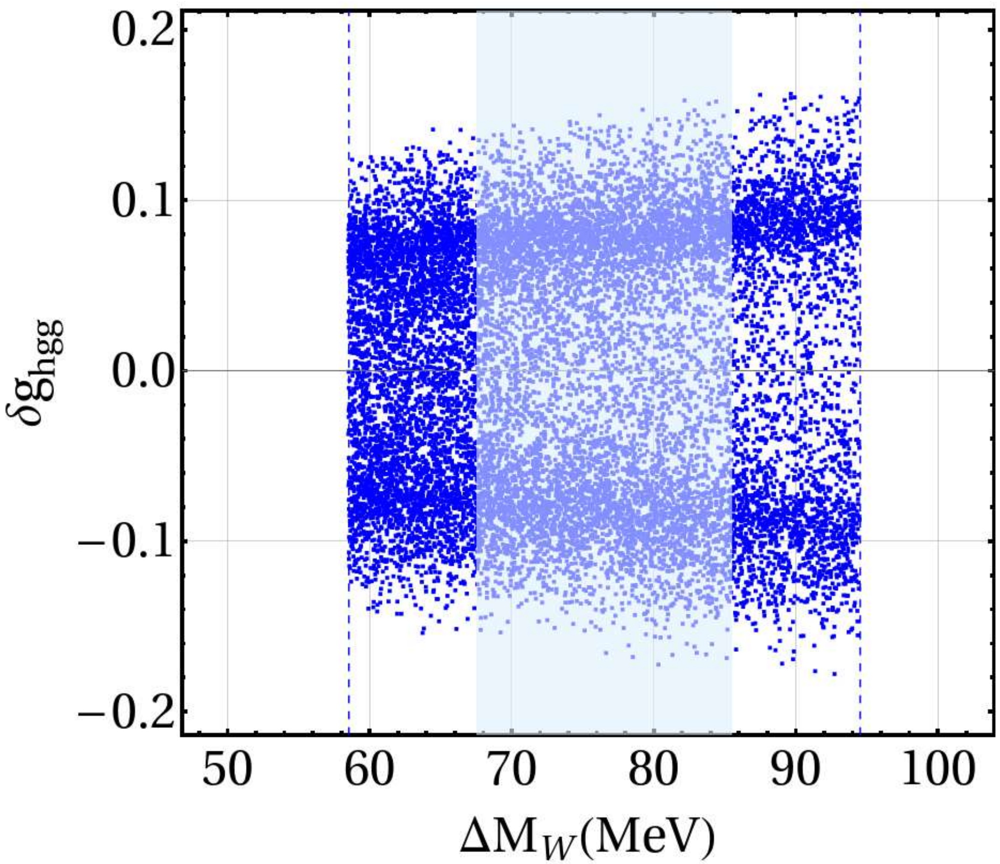

[ATLAS (13 TeV, 139 fb^{-1}) '21]

Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96\ ^{+\ 0.04}_{-\ 0.05}$
κ_W	1.06 ± 0.06	$1.00\ ^{+\ 0.00}_{-\ 0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07\ ^{+\ 0.25}_{-\ 0.30}$	$1.03\ ^{+\ 0.23}_{-\ 0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37\ ^{+\ 0.31}_{-\ 0.37}$	$1.33\ ^{+\ 0.29}_{-\ 0.35}$
κ_g	$0.92\ ^{+\ 0.07}_{-\ 0.06}$	$0.89\ ^{+\ 0.07}_{-\ 0.06}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.16 at 95% CL

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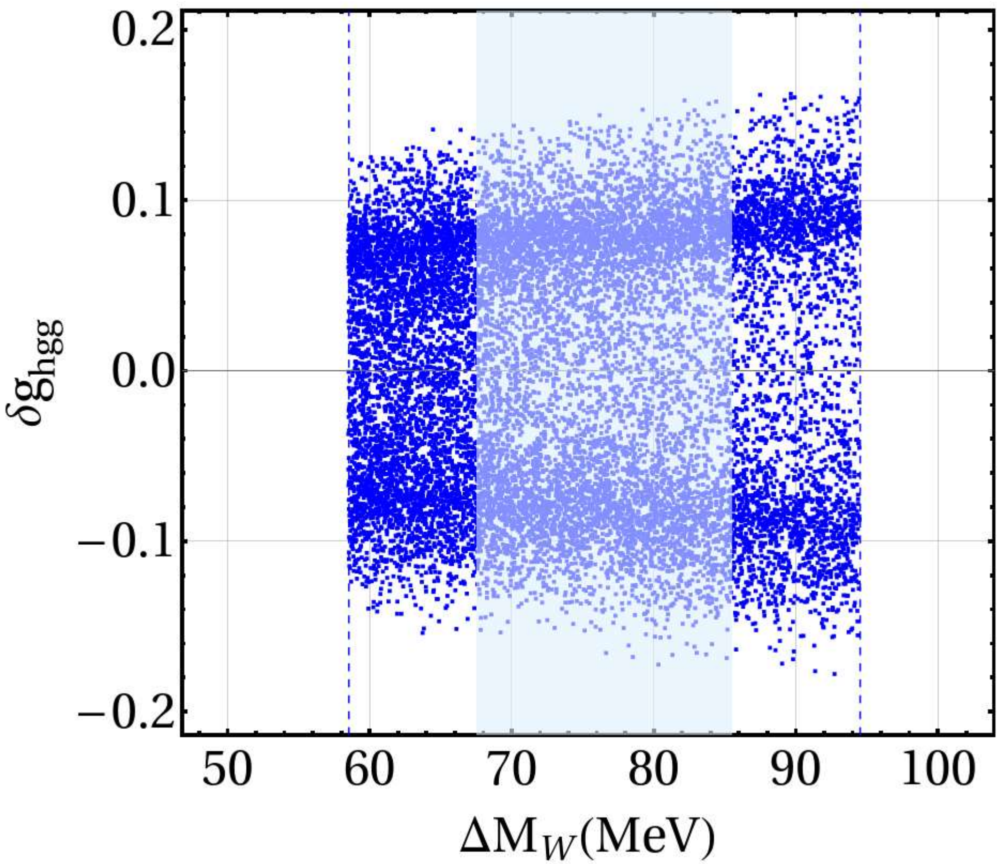

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$B_{u.}$	-	< 0.16 at 95% CL

$\sigma_{hgg} \sim 8\%$

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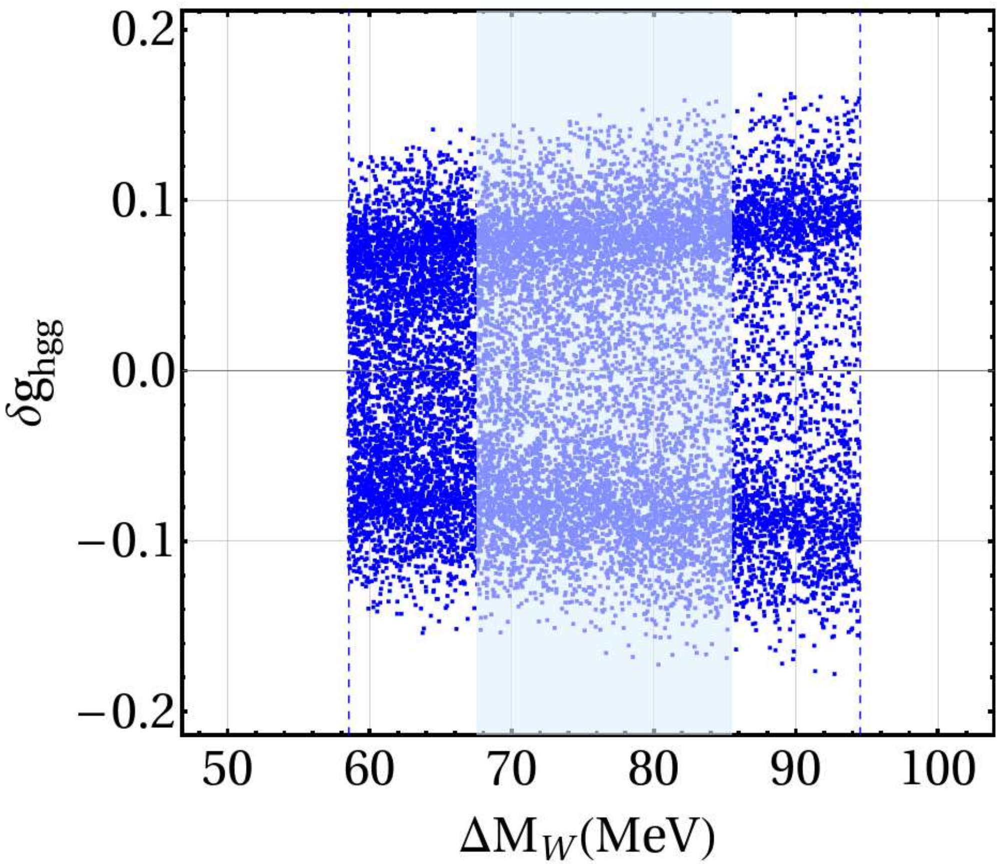

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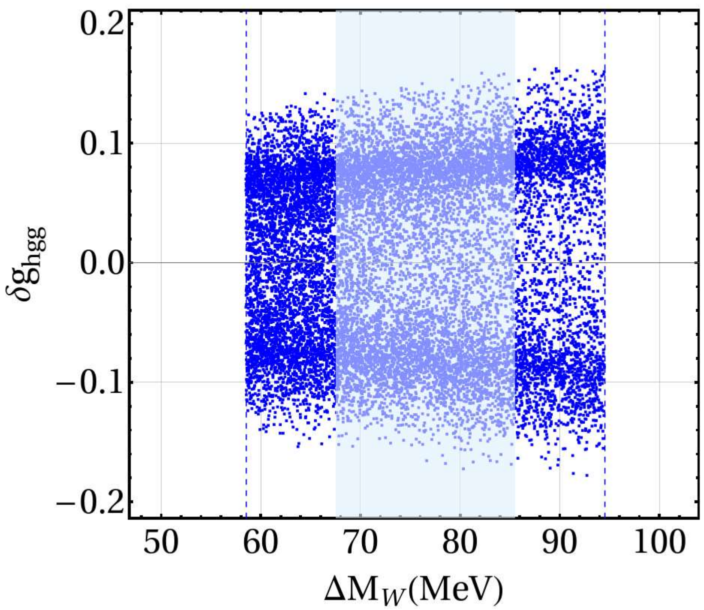
κ_Z	0.99 ± 0.06	$0.96^{+0.04}_{-0.05}$
κ_W	1.06 ± 0.06	$1.00^{+0.00}_{-0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07^{+0.25}_{-0.30}$	$1.03^{+0.23}_{-0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37^{+0.31}_{-0.37}$	$1.33^{+0.29}_{-0.35}$
κ_g	$0.92^{+0.07}_{-0.06}$	$0.89^{+0.07}_{-0.06}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.16 at 95% CL

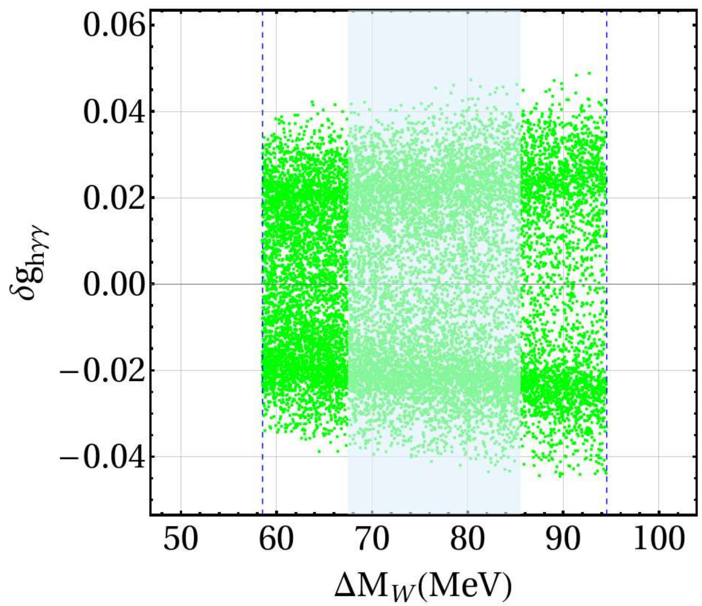
$\sigma_{hgg} \sim 8\%$, $\sigma_{h\gamma\gamma} \sim 5\%$

$$700 \leq m_\Psi, m_\chi \leq 1500 \text{ GeV}, \ \ -2 \leq y_1, y_2 \leq 2$$

Correlating M_W with Higgs Couplings

○ Parameter Scan

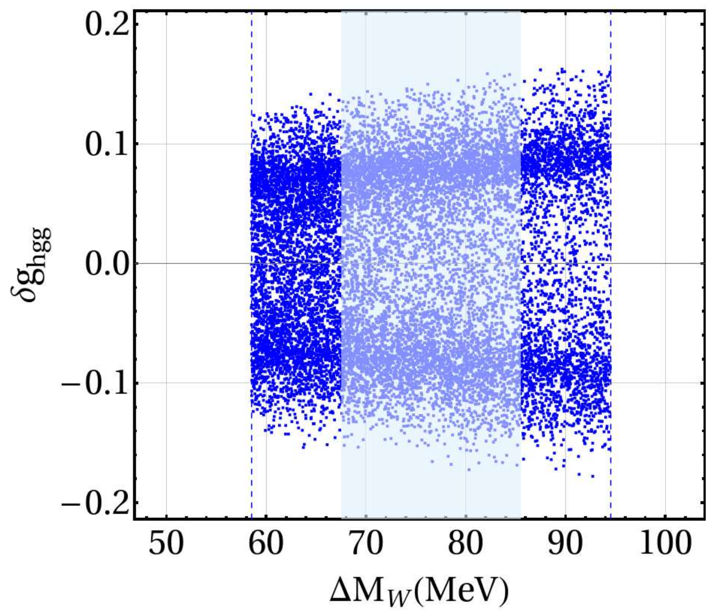


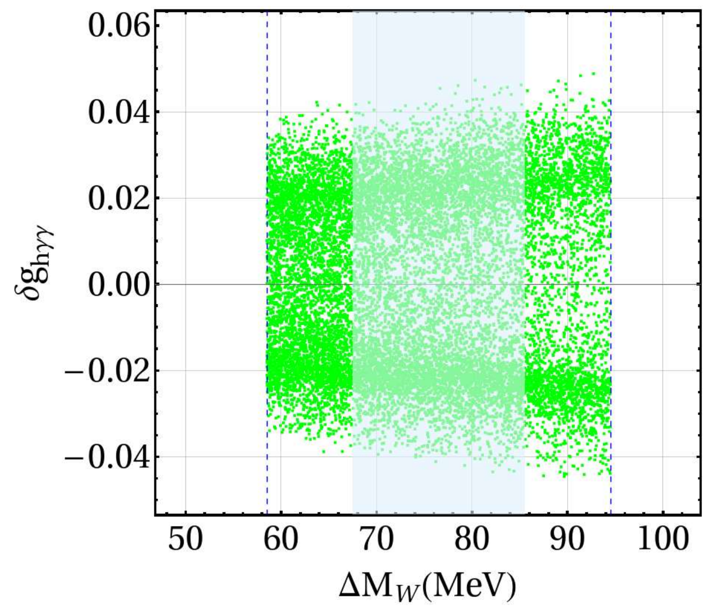


- With $\boldsymbol{\sigma_{hgg} \sim 8\%}$, $\boldsymbol{\sigma_{h\gamma\gamma} \sim 5\%}$ some models already constrained.
- Sensitivity will improve in HL-LHC and future (lepton) colliders
- For Lepton Collider, we expect $\sigma \sim 1\ \%$
- This will provide very strong and invaluable test of M_W anomaly and BSM theory that might be responsible for it.

Correlating M_W with Higgs Couplings

○ Parameter Scan

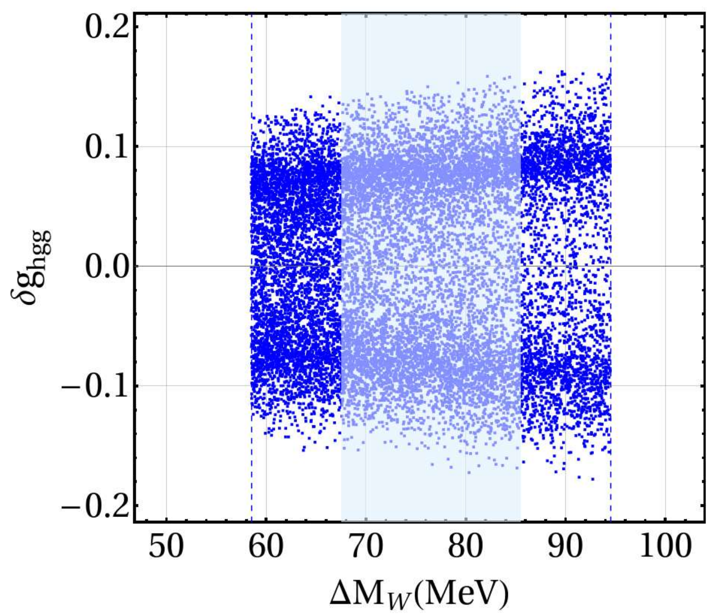


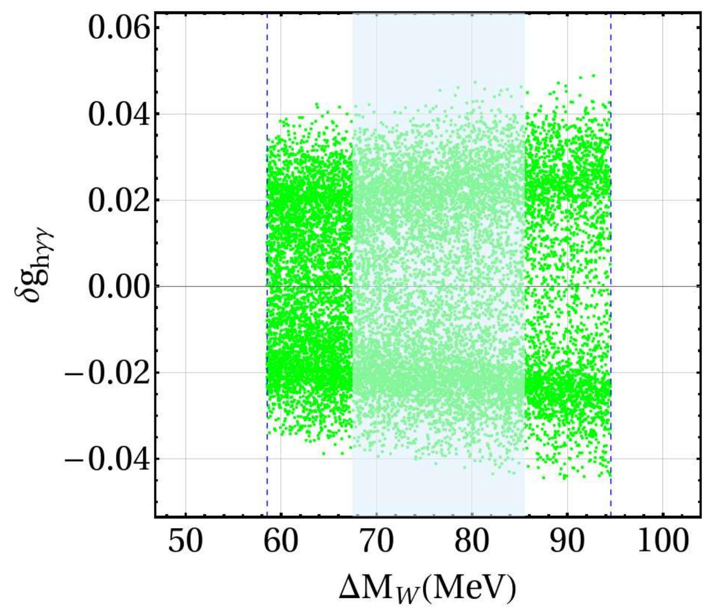


- Note: at least kinematically, new physics might be in the **LHC** reach or they can be comfortably in the range of **future colliders**
- M_W-Higgs coupling correlation provides complementary test to the direct searches.

Correlating M_W with Higgs Couplings

○ Parameter Scan

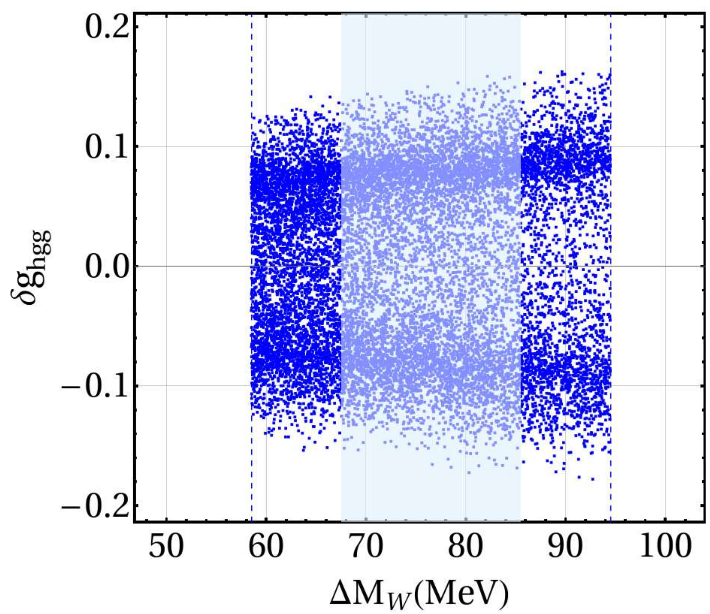


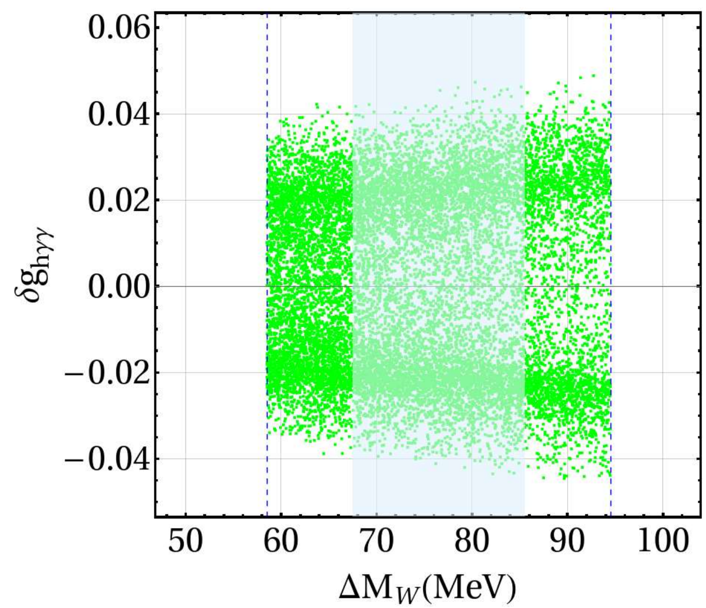


- $\delta g \ll 1$ possible?

Correlating M_W with Higgs Couplings

○ Parameter Scan



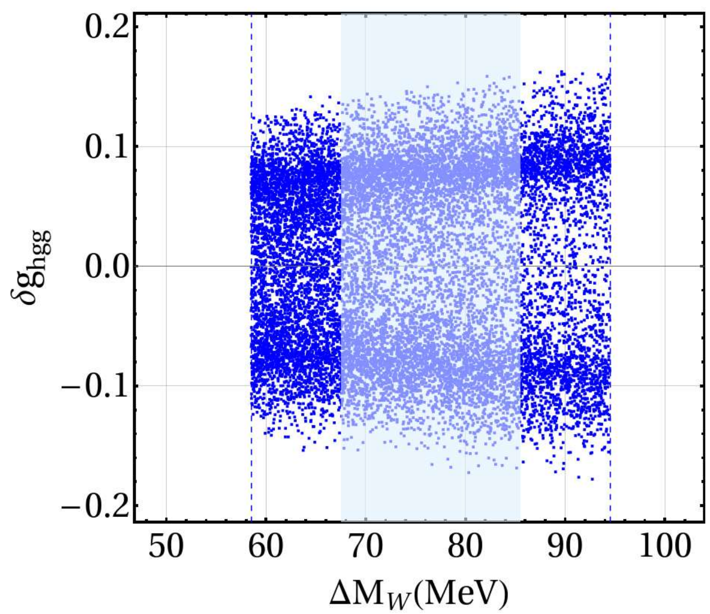


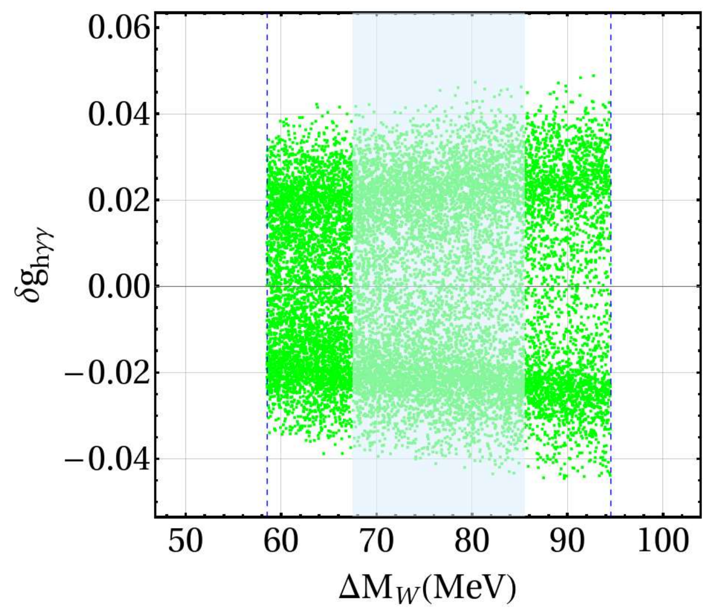
- $\delta g \ll 1$ possible? Yes, but at the price of unnatural fine-tunning!

$$\frac{\Delta g_{h\gamma\gamma}}{\alpha/16\pi} = \frac{\Delta g_{hgg}}{\alpha_s/16\pi} = \frac{b_{1/2}v}{M_{Tl}^2 M_{Th}^2}\left(y_1^2 y_2^2 v^2 - 2m_\Psi m_\chi y_1 y_2\right)$$

Correlating M_W with Higgs Couplings

○ Parameter Scan





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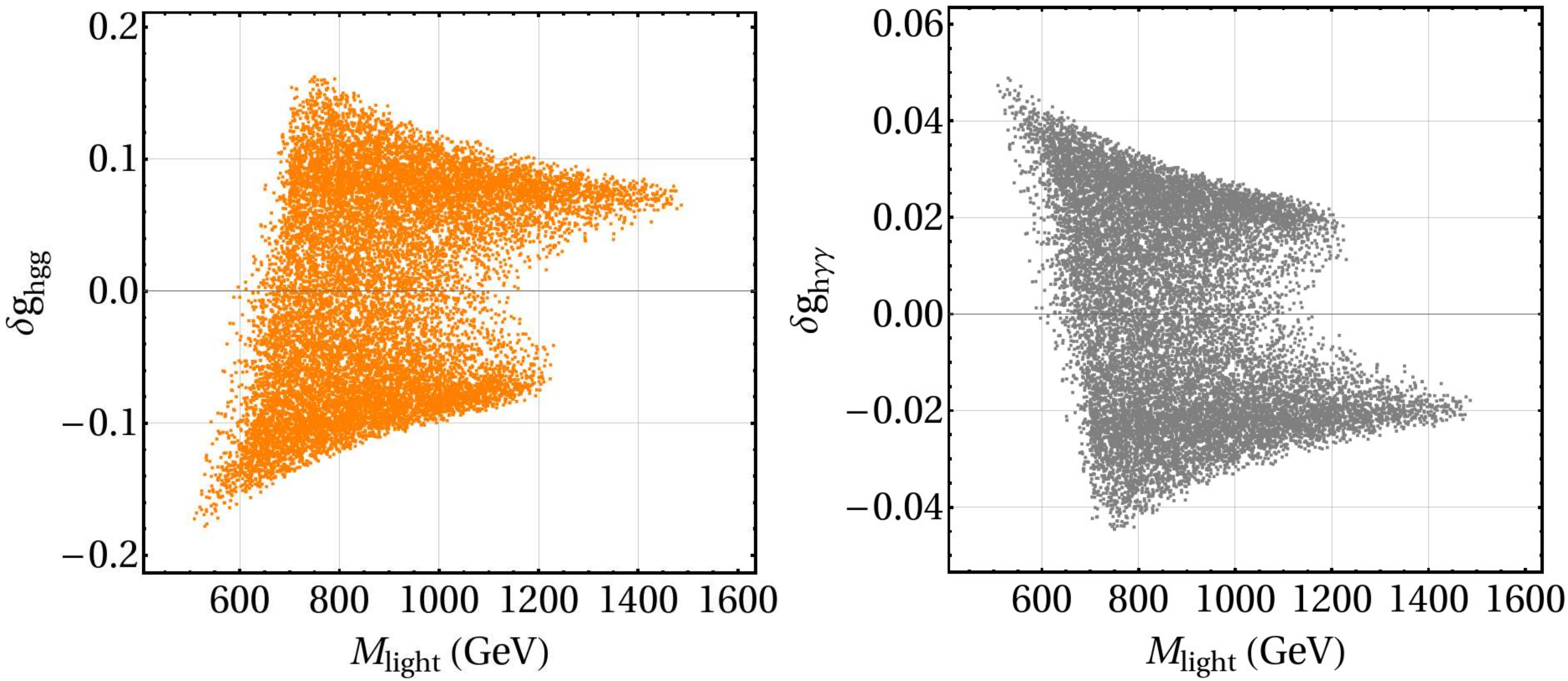
Four different parameters must conspire + why would weak scale be anything to do with heavy scales and their couplings?

Correlating M_W with Higgs Couplings

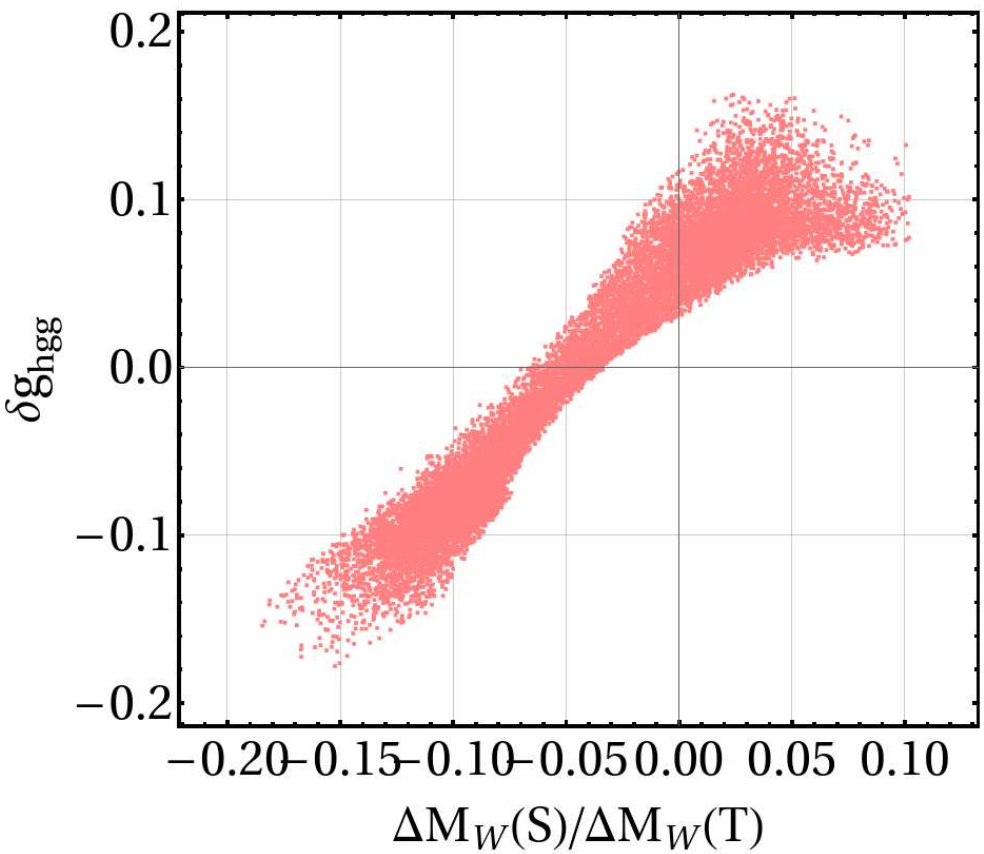
○ Parameter Scan

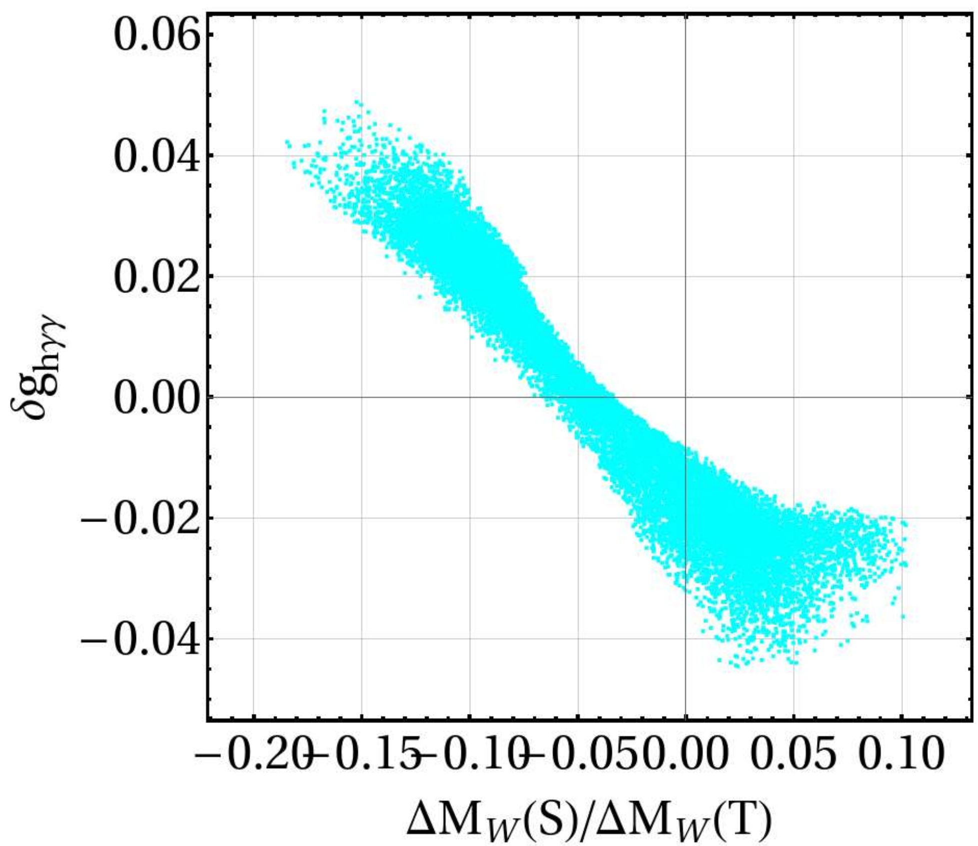


$$700 \leq m_\Psi, m_\chi \leq 1500 \text{ GeV}, \quad -2 \leq y_1, y_2 \leq 2$$

Correlating M_W with Higgs Couplings

- Parameter Scan





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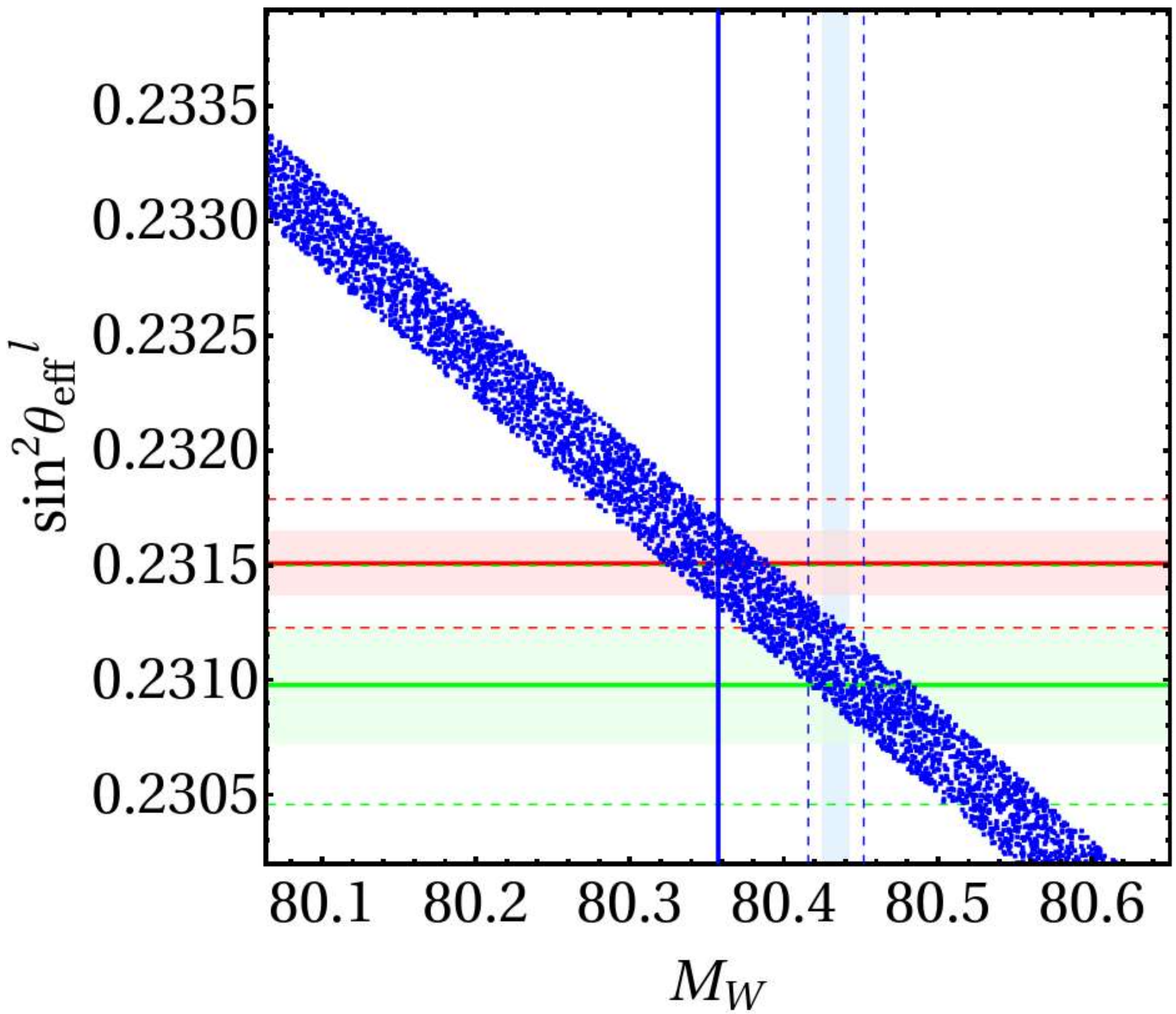
Correlating M_W with Higgs Couplings

○ Parameter Scan

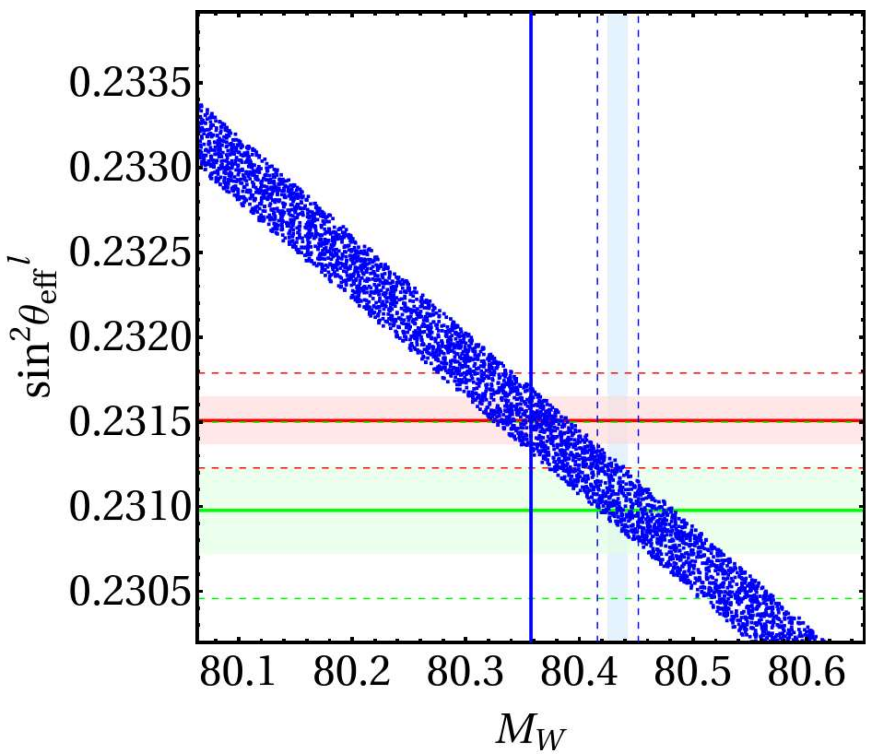


Red: World-average

Green: SLD

Correlating M_W with **Higgs Couplings**

- Parameter Scan



Red: World-average

Green: SLD

- For ***T*-dominant** case,

$$\Delta M_W = \frac{\alpha M_W c_w^2}{2(c_w^2 - s_w^2)} T$$

$$\Delta \sin^2\theta_{\rm eff}^{\ell} = \frac{-\alpha s_w^2 c_w^2}{c_w^2 - s_w^2} T$$

$$\to \ \Delta \sin^2\theta_{\rm eff}^{\ell} = \left(-\frac{2s_w^2}{M_W}\right)\Delta M_W^2$$

Lessons

1. Generically, for needed (large) $\Delta M_W \sim 76$ MeV, one should expect $\mathcal{O}(5-10)\%$ deviation in loop-induced Higgs couplings, $hgg,\ h\gamma\gamma$

2. This is large enough either to be already constrained or to be well-tested in the near future

3. If CDF-II result in correct, there is a good chance we will see another excess in $hgg,\ h\gamma\gamma$ couplings, or even direct production of new physics states (exciting)!

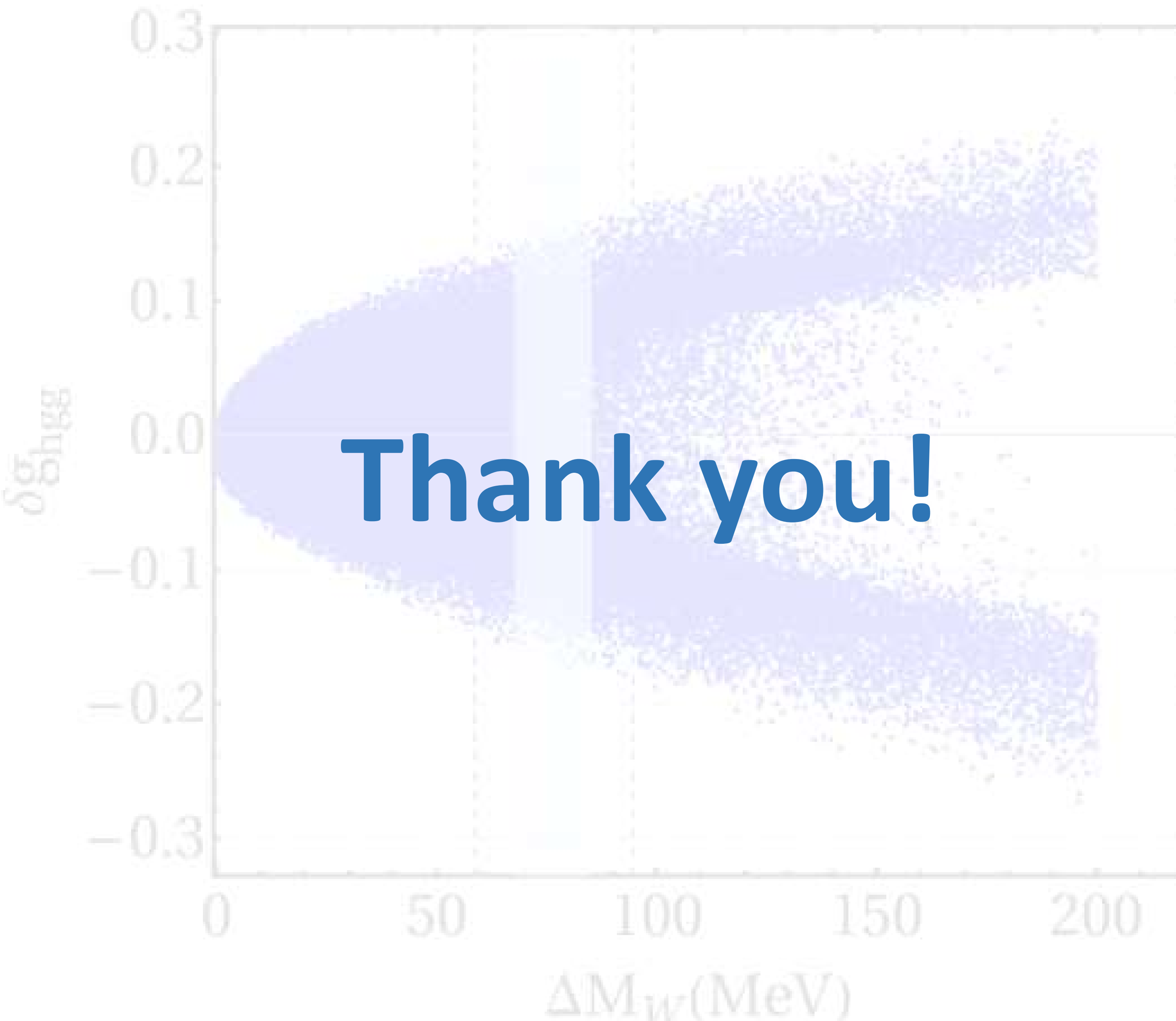
Lessons

4. Generically, $\Delta g_{hgg} \approx 3|\Delta g_{h\gamma\gamma}|$.

5. Uncolored new physics can be better hidden.

6. But, ultimately with lepton collider with $\sigma \sim 1\%$
   we should see something.

7. If CDF-II result is correct, we have to face another issue
   with $\sin^2 \theta^{\ell}_{\rm eff}$ tension.



Thank you!