WHAT CAN A GLOBAL COMBINATION TELL US ABOUT THE HIGGS?

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Based on:

"Updated Global Analysis of Higgs Couplings"
John Ellis and T.Y.
arXiv:1303.3879 [hep-ph].

"Associated Production Evidence against Higgs Impostors and Anomalous Couplings"
John Ellis, Veronica Sanz and T.Y.
arXiv:1303.0208 [hep-ph].

OUTLINE

- Introduction
- Phenomenological Framework
- Global Constraints – Couplings
- Global Constraints – Decay
- Global Constraints – Spin
- Global Constraints – Dim-6
- Conclusion

- INTRODUCTION
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INTRODUCTION

- Main aim: What can we infer from the limited data?
- Fundamental question: What is responsible for EWSB?

$$SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$$?

- Technicolor
- 2HDM
- Composite Higgs
- NMSSM
- Composite 2HDM

- Fundamental Scalar (SM Higgs)
- Higgs + SUSY
- Little Higgs
- Walking Technicolor
- Extra Dimensions

Introduction

- Naturalness is "real"

$$\delta m_h^2 = \left[\frac{1}{4}(9g^2 + 2g'^2) - 6y_t^2 + 6\lambda\right]\frac{\Lambda^2}{32\pi^2}$$

or

$$\delta m_\phi^2 \propto m_{\text{heavy}}^2, \qquad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\text{heavy}}}{\mu}\right)$$

- Hierarchy problem: $(m_h)^2_{\text{tree}} + (m_h)^2_{\text{radiative}} = (m_h)^2_v$

- Earliest example: $m_{\text{inertial}} = m_{\text{gravity}}$
- Classical EM:

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{coulomb}}, \qquad \Delta E_{\text{coulomb}} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

- Pions, etc.

- Introduction
- **PHENOMENOLOGICAL FRAMEWORK**
- Global Constraints – Couplings
- Global Constraints – Decay
- Global Constraints – Spin
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PHENOMENOLOGICAL FRAMEWORK

- **Global** symmetry-breaking pattern gives low-energy effective theory regardless of the UV mechanism responsible for it

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W / M_Z \cos\theta_w \sim 1)$$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma - m_i \bar{\psi}_L^i \Sigma \psi_R^i + \text{h.c.}$$

$$\Sigma = \exp\left(i \frac{\sigma^a \pi^a}{v} \right)$$

Phenomenological Framework

- Add a singlet scalar with general couplings
- Coefficients scaled with respect to SM Higgs

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1+c\frac{h}{v}+\ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+\frac{1}{2}(\partial_\mu h)^2+\frac{1}{2}m_h^2h^2+d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3+d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4+\ldots\quad,$$

$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right)$$

See e.g. Azatov, Contino, Galloway [arXiv:1202.3415]

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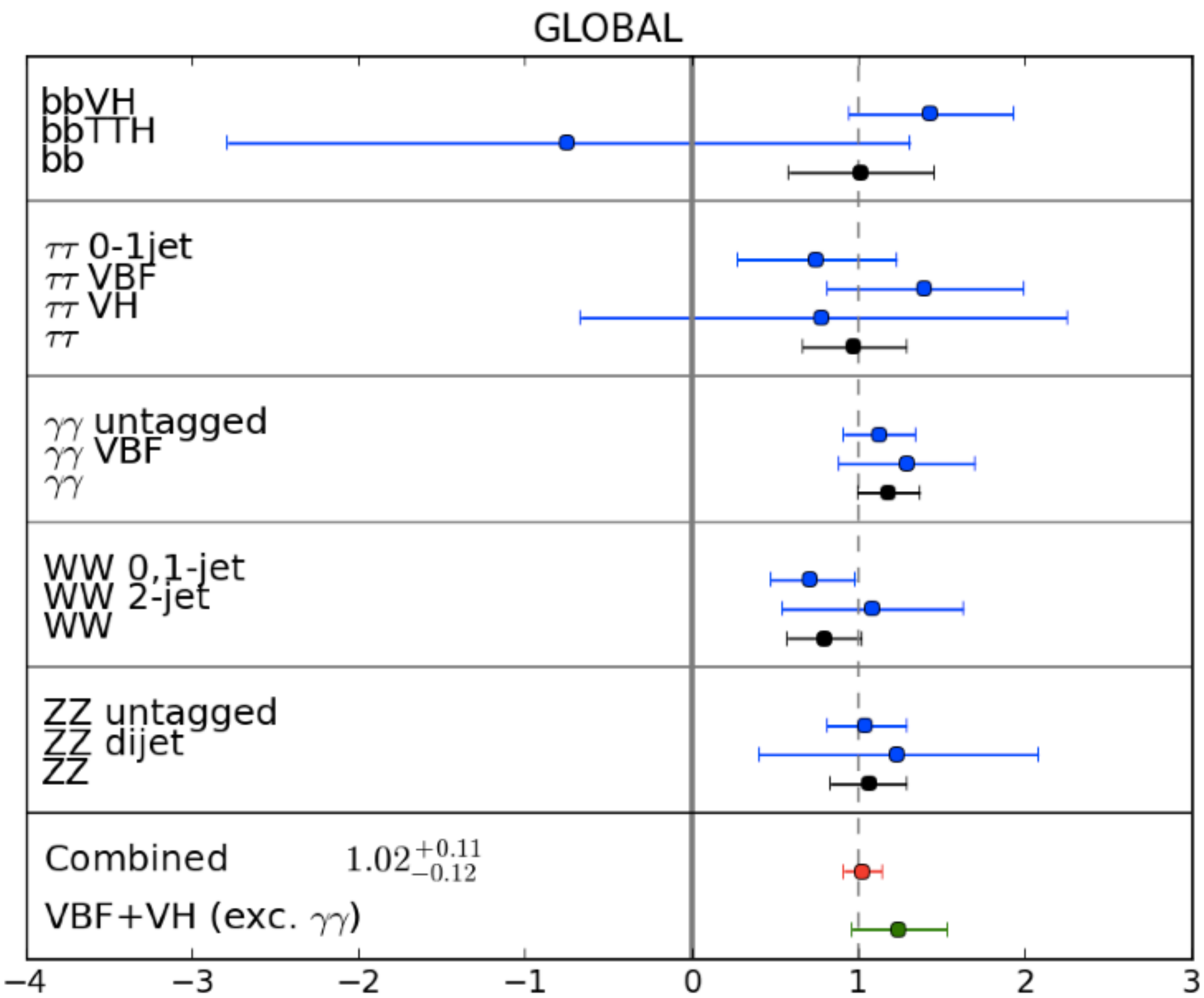
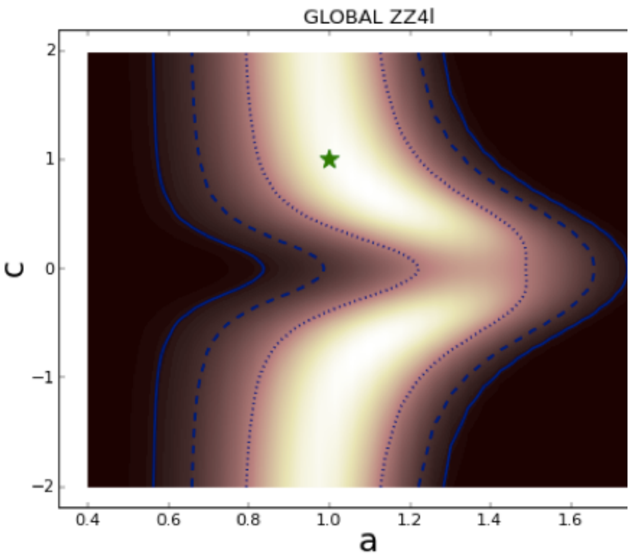
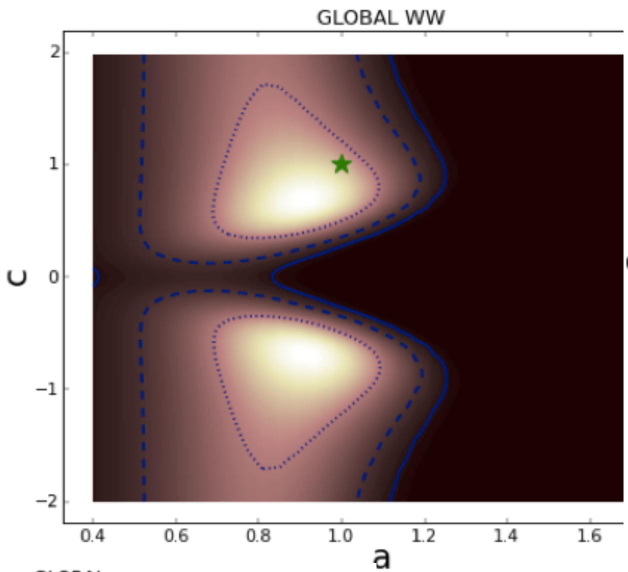
GLOBAL CONSTRAINTS - COUPLINGS

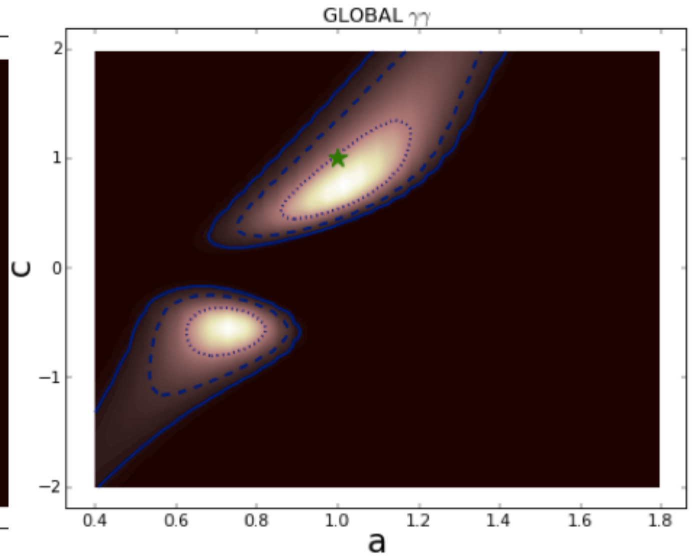
- ATLAS+CMS+Tevatron signal strengths

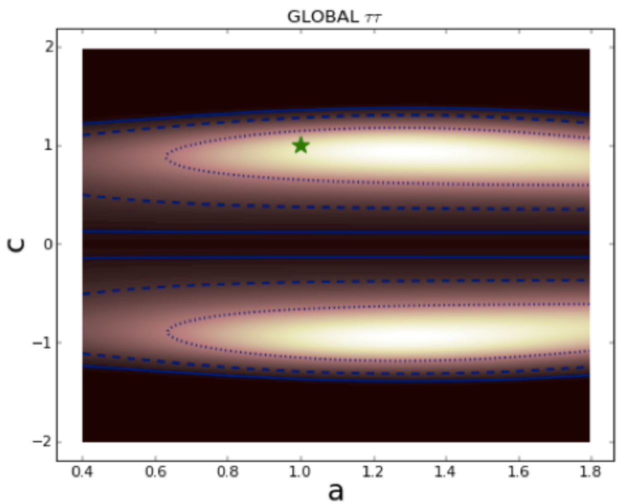


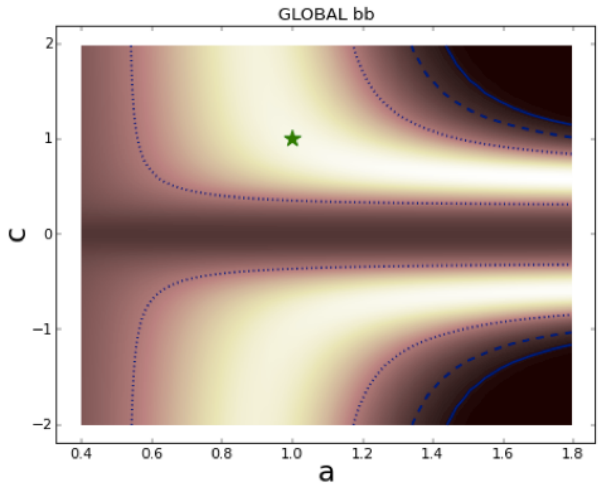
GLOBAL CONSTRAINTS - COUPLINGS







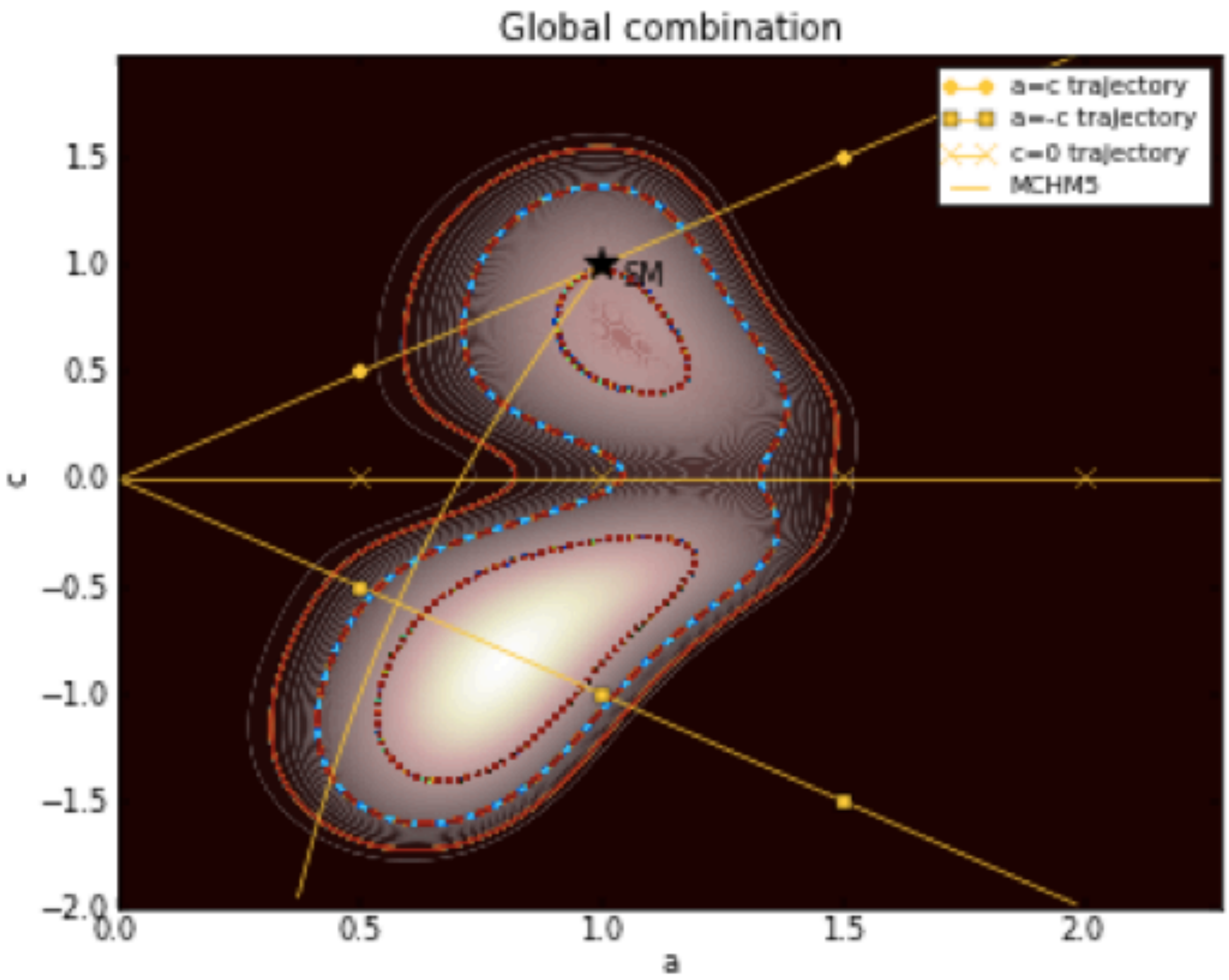




- Maximise information from combination.. Lucky to get the Higgs at ~125 GeV!

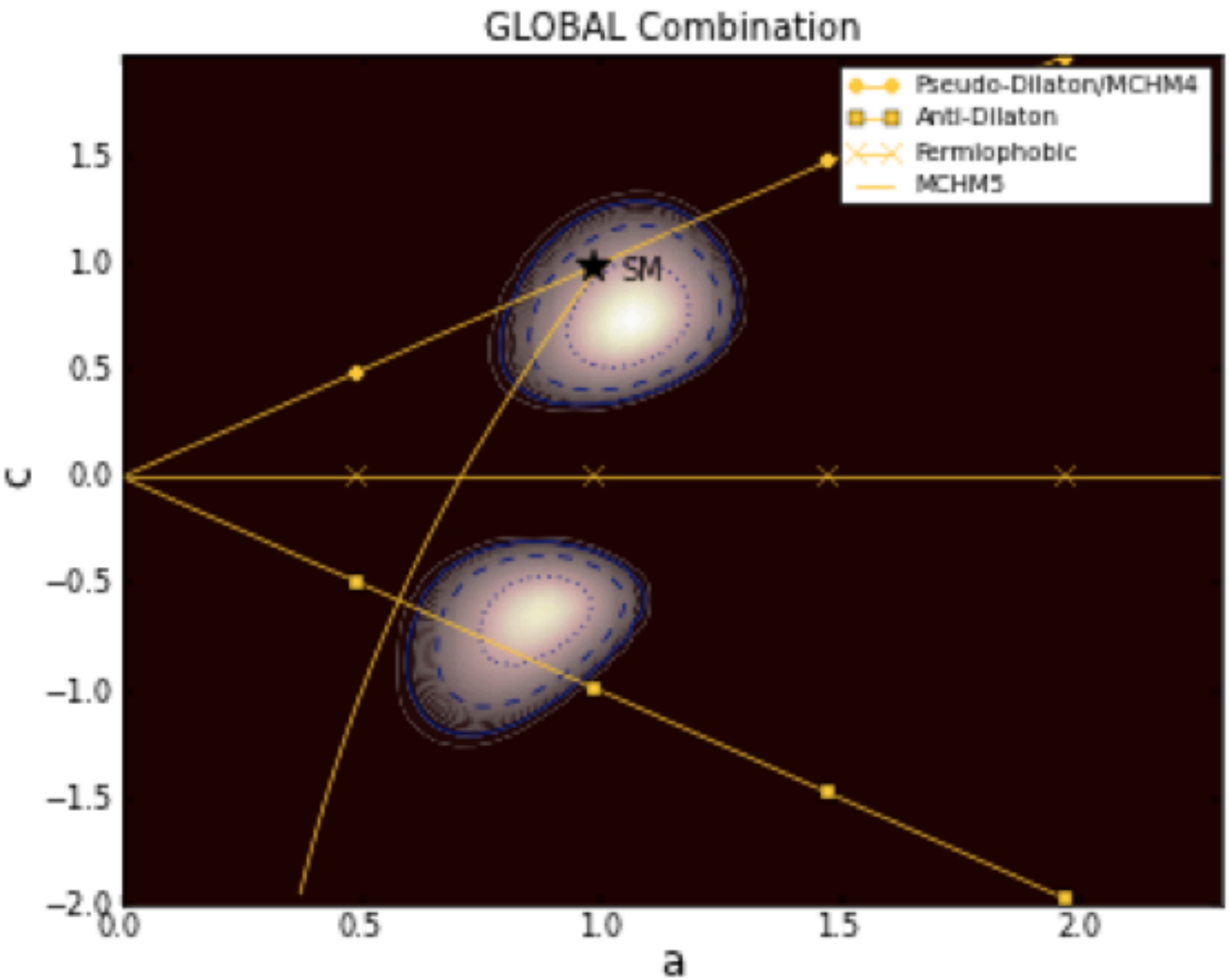
Global Constraints – Couplings

- March 2012 – pre-discovery [arXiv:1204.0464]



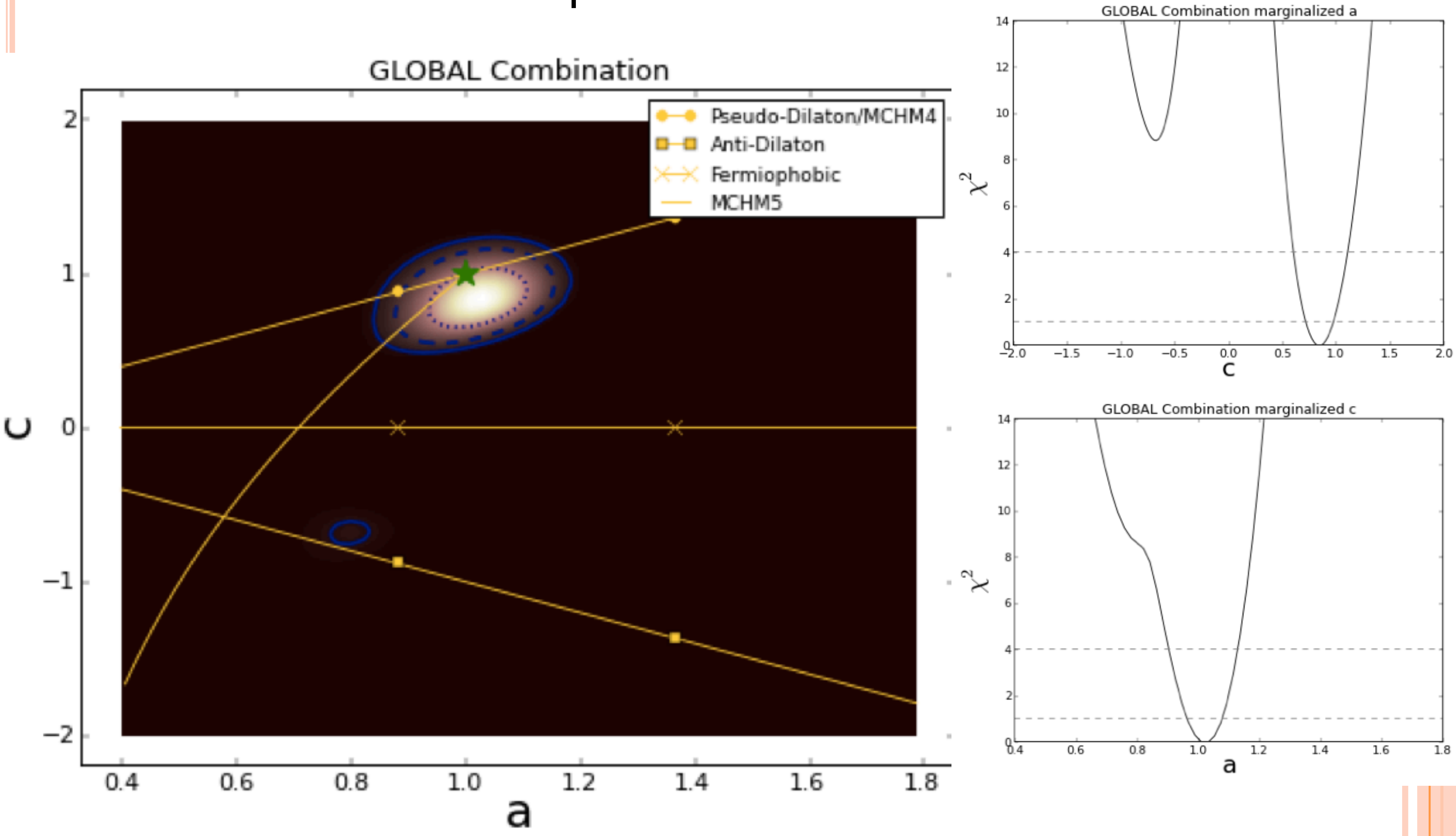
GLOBAL CONSTRAINTS – COUPLINGS

- July 2012 – post-discovery [arXiv:1207.1693]



GLOBAL CONSTRAINTS – COUPLINGS

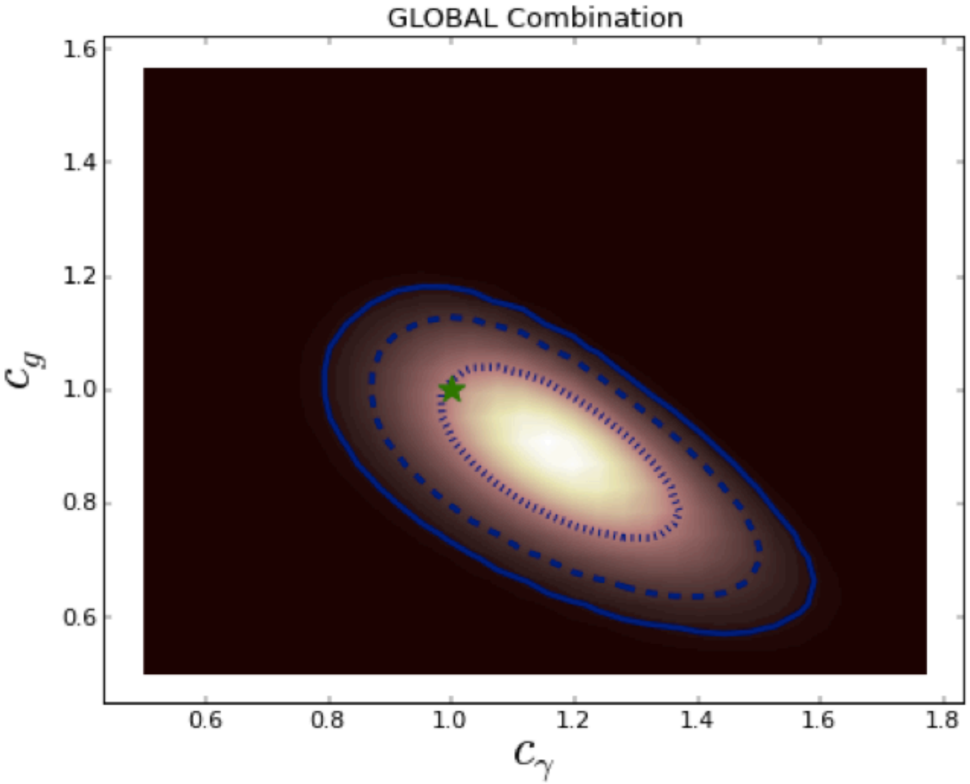
- Now: March 2013 – post-Moriond

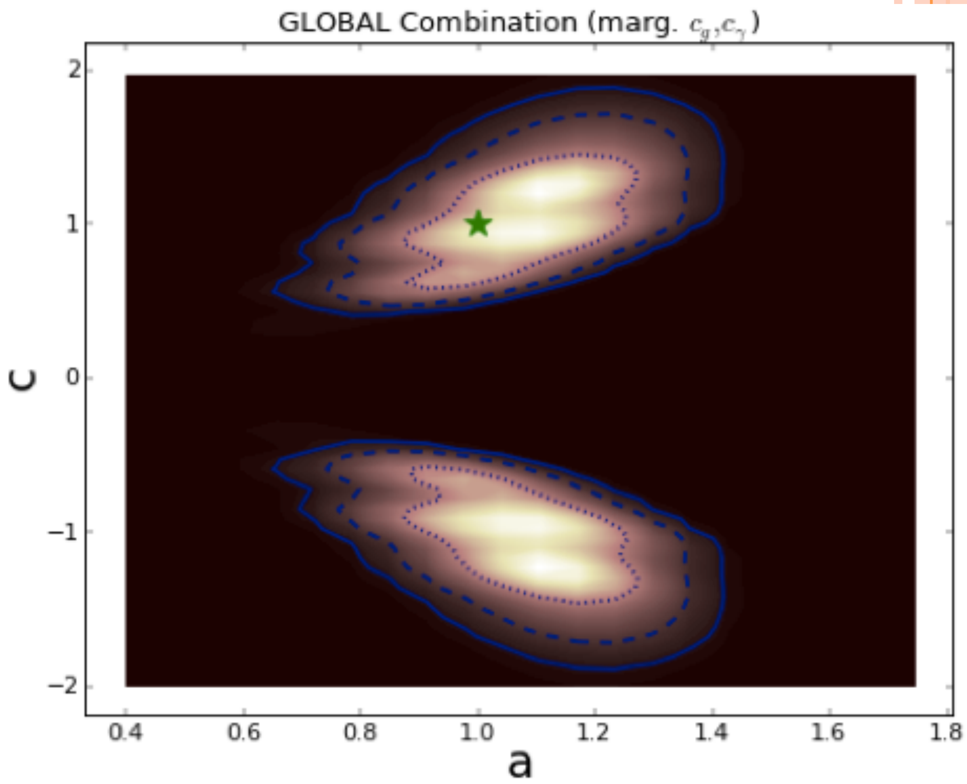


GLOBAL CONSTRAINTS - COUPLINGS

- More freedom by adding general factors for loop-induced couplings

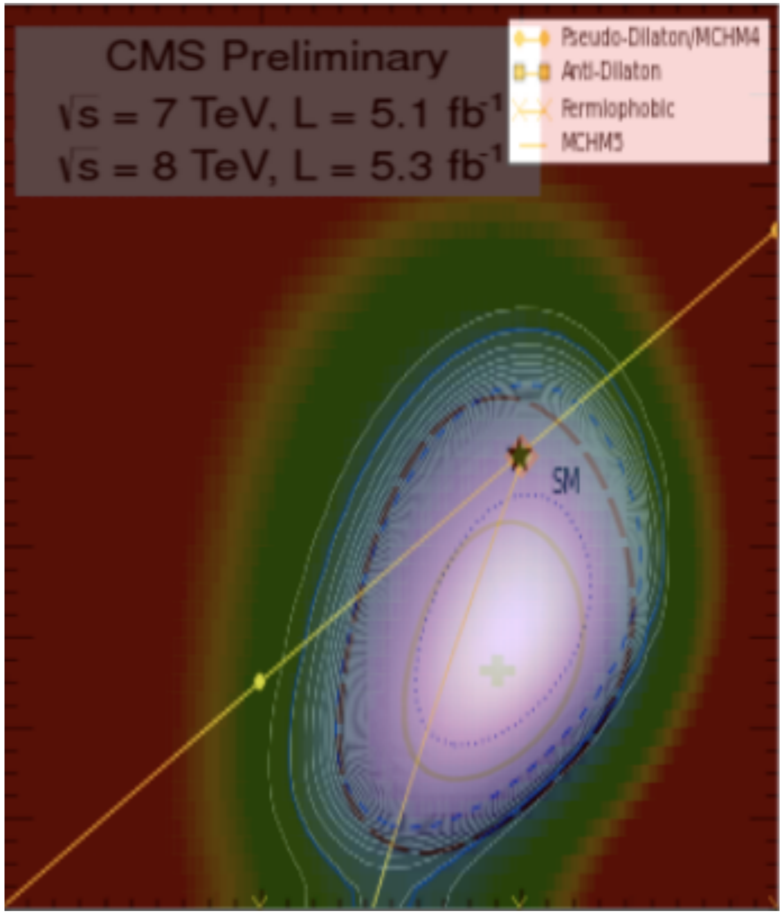
$$\mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi} c_g b_g G_{a\mu\nu} G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \left(\frac{H}{V}\right)$$





GLOBAL CONSTRAINTS – COUPLINGS

- Note: Currently within ~10% of official combinations, but as statistical errors get smaller, efficiencies and correlations become more important…



Global Constraints – Couplings

- Couplings proportional to mass?
- We assumed deformations of SM Higgs couplings

$$\lambda_f = \sqrt{2}\frac{m_f}{v}, \quad g_V = 2\frac{m_v^2}{v}$$

- Generalize scale and power

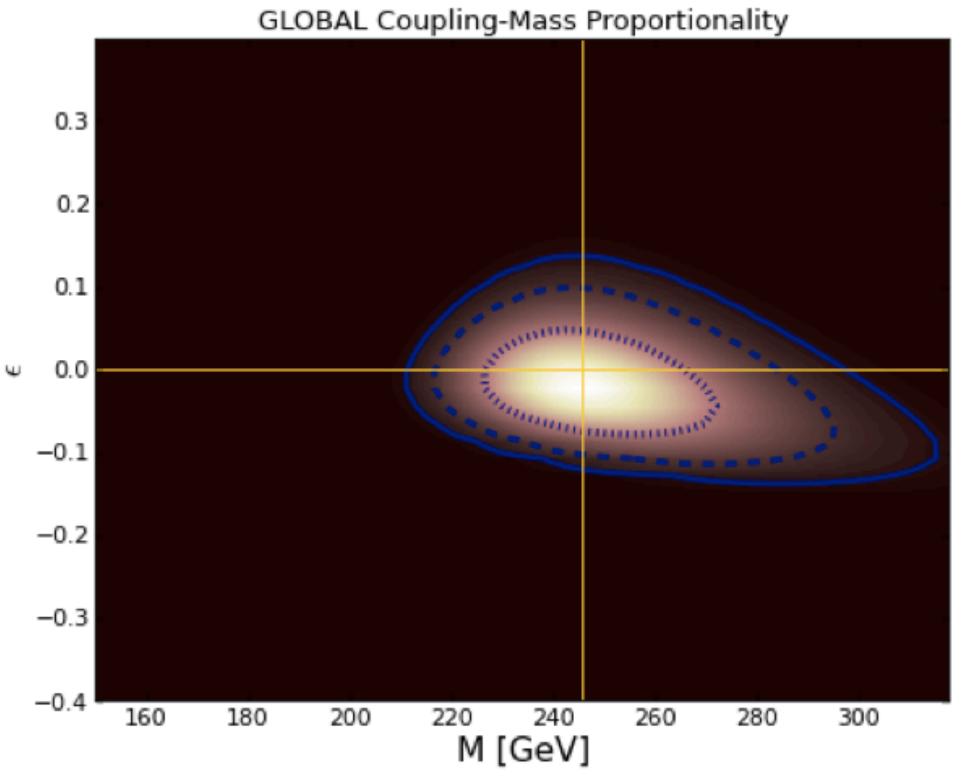
$$\lambda_f' = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V' = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

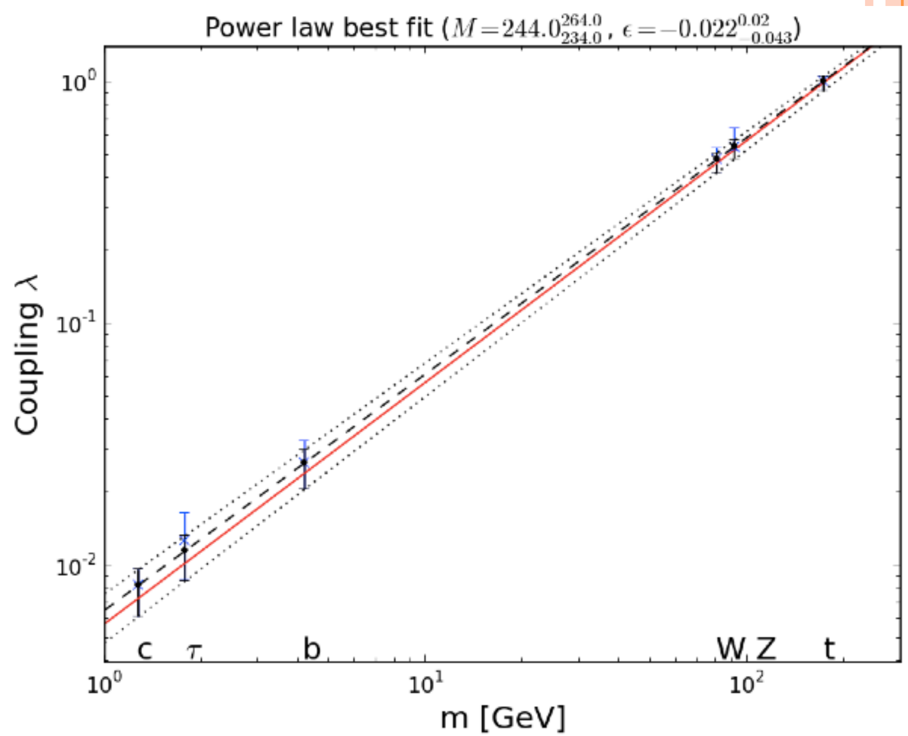
- Corresponds to rescaling:

$$c_f = \frac{\lambda_f'}{\lambda_f} = v\left(\frac{m_f^{\epsilon}}{M^{1+\epsilon}}\right), \quad a_V = \frac{g_V'}{g_V} = v\left(\frac{M_V^{2\epsilon}}{M^{(1+2\epsilon)}}\right)$$

GLOBAL CONSTRAINTS – COUPLINGS

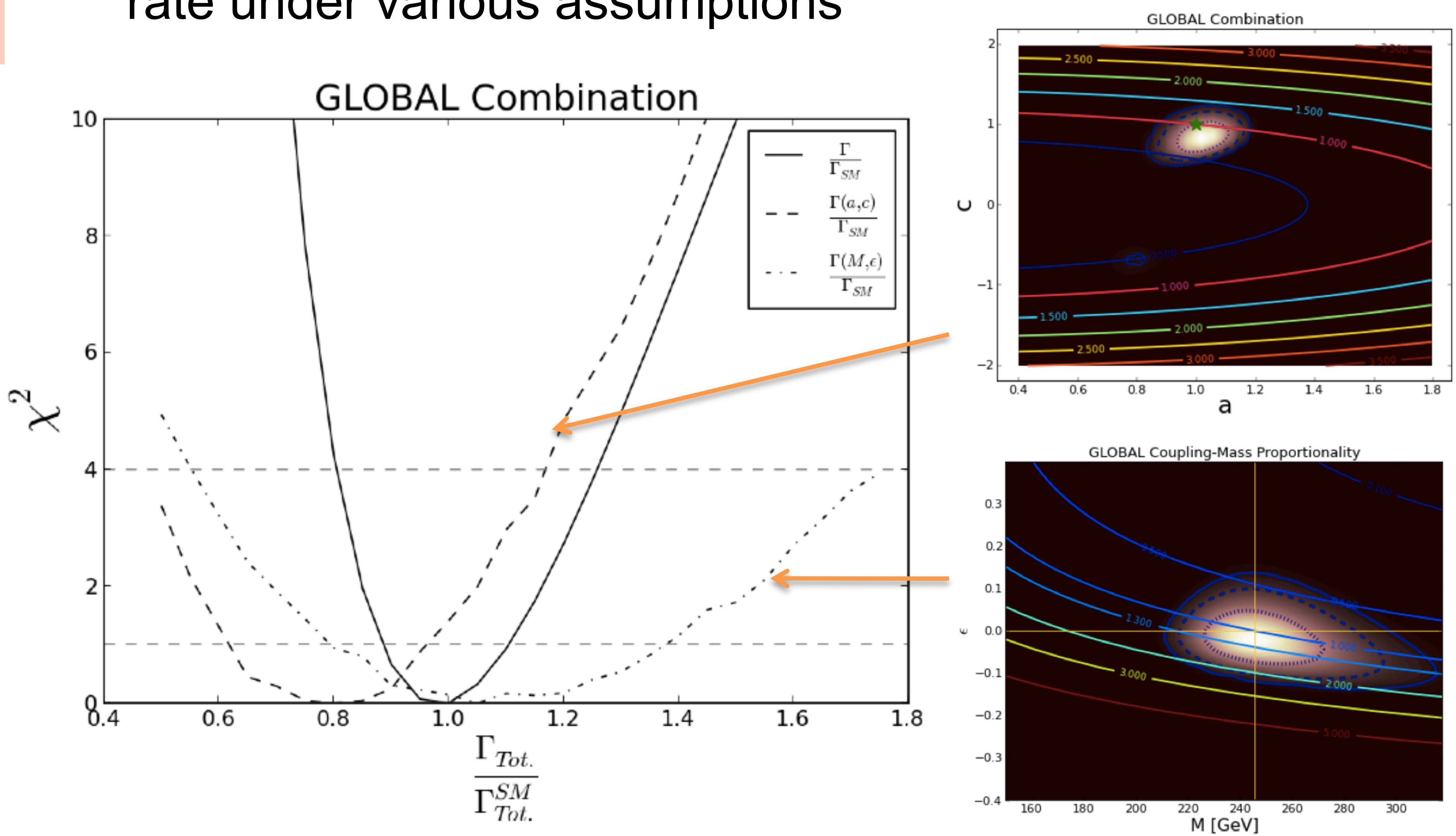
- Couplings proportional to mass?





GLOBAL CONSTRAINTS – DECAY

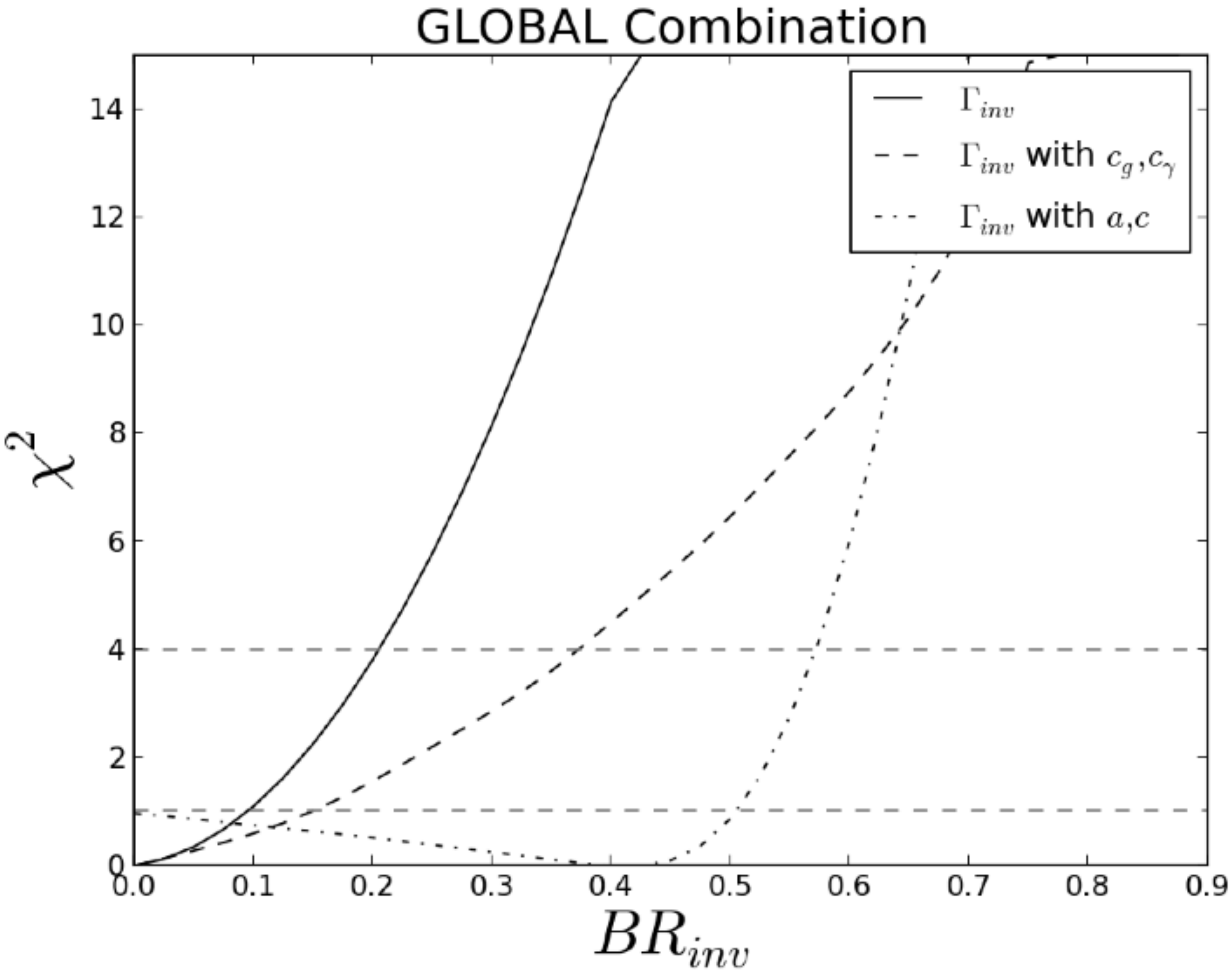
- No direct measurement.. fit the total Higgs decay rate under various assumptions



GLOBAL CONSTRAINTS – DECAY

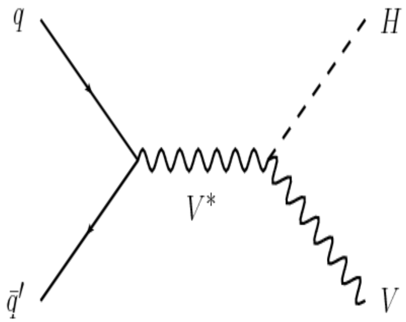
- Invisible branching ratio

$$\Gamma_{\rm Tot} = \Gamma_{\rm Vis} + \Gamma_{\rm Inv} = \left(\frac{R_{\rm Vis}}{1 - BR_{\rm Inv}}\right)\Gamma^{\rm SM}_{\rm Tot}$$



Global Constraints - Spin

- Use energy dependence in V+H associated production



Note: M_{VH} distribution can also be used as a powerful spin discriminant [arXiv:1208.6002]

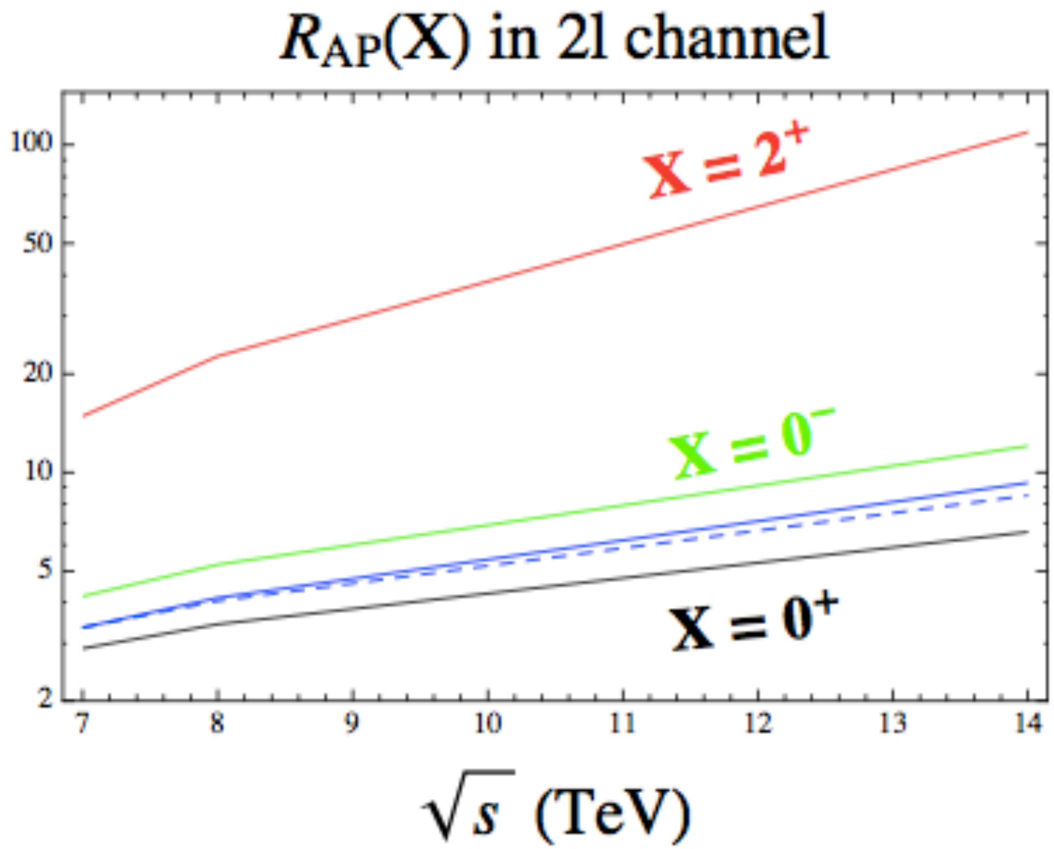
- Non-SM scalar couplings to massive gauge bosons have energy dependence through derivative couplings

$$\mathcal{L}_{0-} = \frac{c_V^A}{\Lambda} A F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$\mathcal{L}_{2+} = \frac{c_i^G}{\Lambda} G^{\mu\nu} T_{\mu\nu} \; .$$

$$\mathcal{L}_{d=6} = \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

GLOBAL CONSTRAINTS – SPIN

- Energy dependence of conservative 2-lepton channel, including experimental cuts



$$R_{AP}(X) = \frac{\sigma(pp \to V^* \to V + X, \sqrt{s})}{\sigma(p\bar{p} \to V^* \to V + X, \sqrt{s} = 1.96\text{TeV})}$$

- Stronger energy dependence for 0,1-lepton

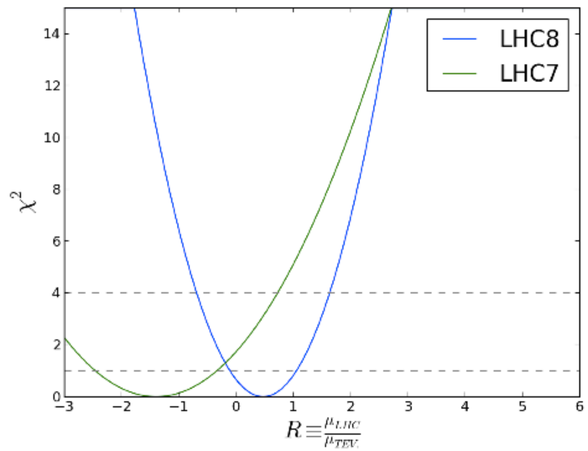
Global Constraints – Spin

- Spin 2 expectation for energy dependence double-ratio (LHC/Tevatron ratio for spin 2 to that of spin 0^+):

$$\mathcal{R}_{\text{Spin 2}} \equiv \left(\frac{\sigma^{\text{Spin 2}}_{\text{LHC 8}}}{\sigma^{\text{Spin 2}}_{\text{TeVatron}}}\right) \Big/ \left(\frac{\sigma^{0+}_{\text{LHC 8}}}{\sigma^{0+}_{\text{TeVatron}}}\right) \simeq 7.4$$

- What does the data tell us?

$$\mathcal{R}_{\text{data}} \equiv \left(\frac{\sigma^{\text{data}}_{\text{CMS LHC 8}}}{\sigma^{\text{data}}_{\text{TeVatron}}}\right) \Big/ \left(\frac{\sigma^{0+}_{\text{LHC 8}}}{\sigma^{0+}_{\text{TeVatron}}}\right) = \frac{\sigma^{0+}_{\text{TeVatron}}}{\sigma^{\text{data}}_{\text{TeVatron}}} \frac{\sigma^{\text{data}}_{\text{CMS LHC 8}}}{\sigma^{0+}_{\text{LHC 8}}} = \frac{\mu_{\text{LHC 8}}}{\mu_{\text{TeVatron}}} = 0.47 \pm 0.58$$



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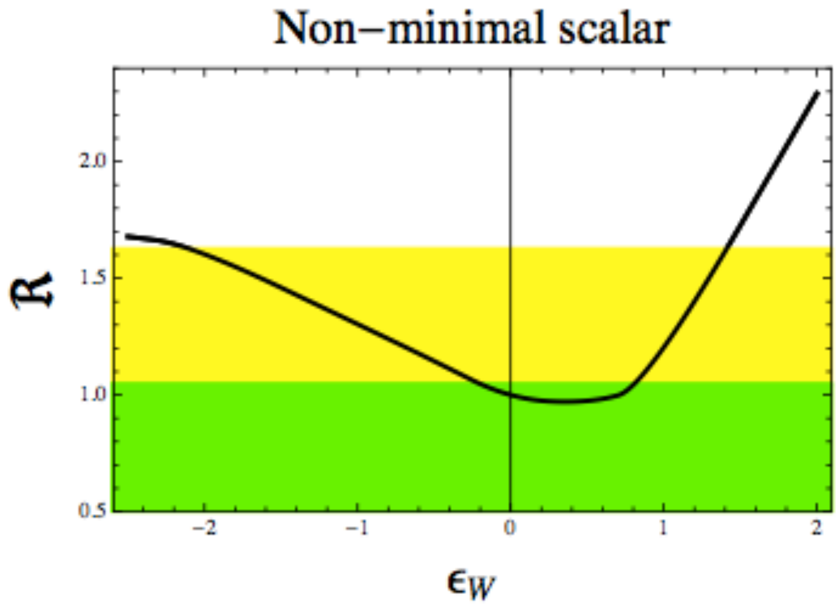
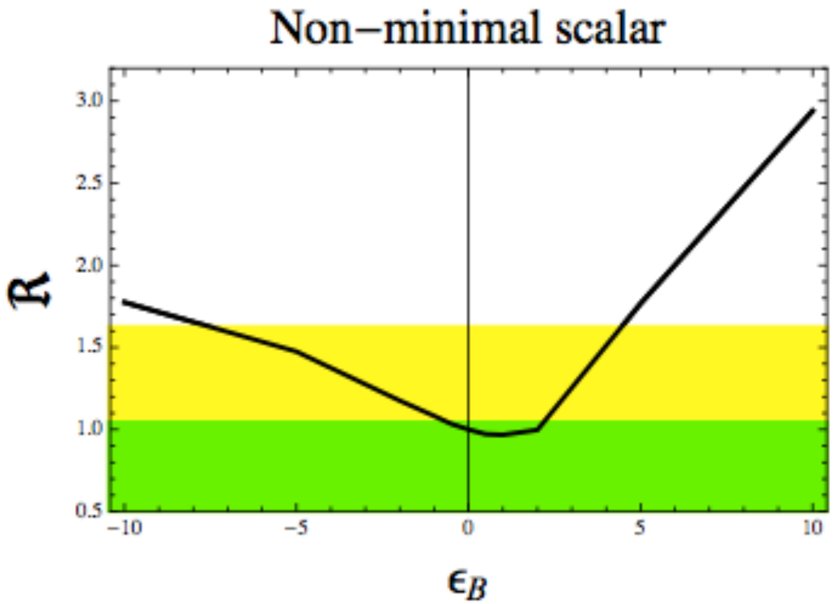
Global Constraints – Dim-6

- Can also use energy dependence to place limits on dim-6 operators

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_B = (D_\mu \Phi)^\dagger (D_\nu \Phi) \, \widehat{B}^{\mu\nu}$$

$$\epsilon_i = f_i \frac{v^2}{\Lambda^2} \qquad i = W, B$$





- Competitive bounds to direct LHC fits,

  c.f. $\epsilon_W \in [-1.3, 18.5]$ and $\epsilon_B > -9.7$ at 95 % CL.

  (E. Masso´ and V. Sanz, arXiv:1211.1320 [hep-ph])

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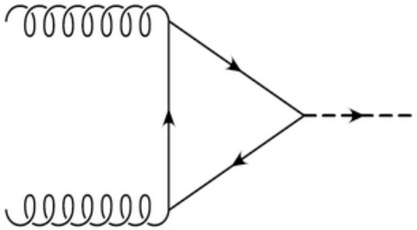
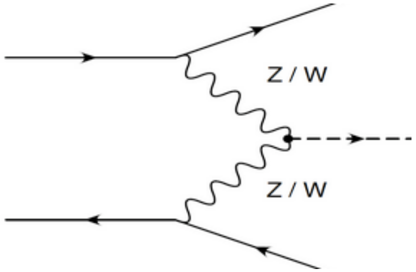
Conclusion

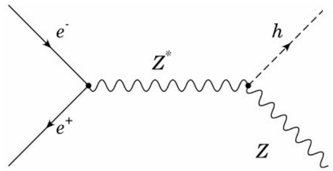
- Very exciting to directly probe a new fundamental mechanism
- Whether naturalness problem is resolved or not at the LHC, still an important question mark on SM
- Couplings constrained at ~few 10% level in simple 2D fits
- Approximately proportional to mass with expected electroweak scale
- Complementarity between Tevatron and LHC provides another way of strongly excluding spin-2
- Energy dependence also places competitive limits on some dim-6 operators
- Sharpening this picture will require better experiment-theory interface to confront models with likelihoods

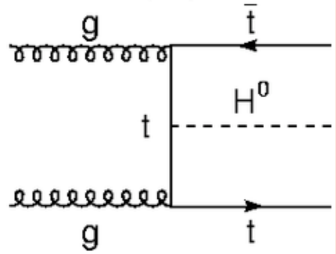
BACKUP SLIDES

PHENOMENOLOGICAL FRAMEWORK

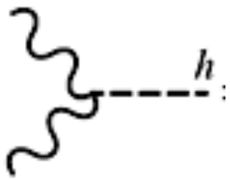


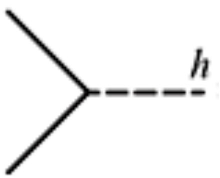


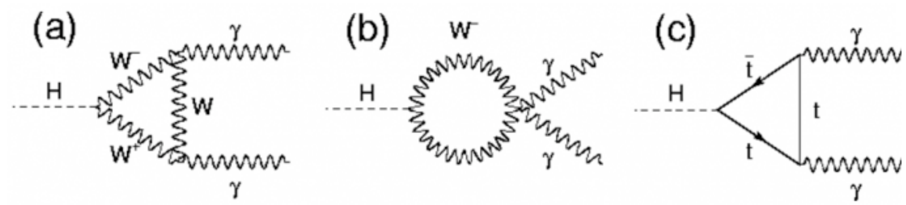




$$R_{gg} = \frac{(-\frac{v}{V} b_s + cF_t)^2}{F_t^2} \quad , \quad R_{\mathrm{VBF}} = a^2 \quad , \quad R_{\mathrm{ap}} = a^2 \quad , \quad R_{\mathrm{hs}} = c^2$$







$$R_{VV} = a^2 \quad , \quad R_{\bar{f}f} = c^2 \quad , \quad R_{\gamma\gamma} = \frac{(-\frac{v}{V} b_{em} - \frac{8}{3} cF_t + aF_w)^2}{(-\frac{8}{3} F_t + F_w)^2}$$

Phenomenological Framework

- Likelihood $\mathcal{L}(\mu)$ where $\mu \equiv \frac{\sigma_{\text{prod}} \times \text{BR}_{\text{decay}}}{\sigma_{\text{prod}}^{\text{SM}} \times \text{BR}_{\text{decay}}^{\text{SM}}}$

$$\sigma_{\text{prod}} = R_{\text{prod}}(a,c) \cdot \sigma_{\text{prod}}^{\text{SM}} \quad , \quad BR_{\text{decay}} = R_{\text{decay}}(a,c) \cdot \text{BR}_{\text{decay}}^{\text{SM}}$$

$$\Longrightarrow \mu = R_{\text{prod}}(a,c) \cdot R_{\text{decay}}(a,c)$$

$$R_{\text{prod}}(a,c) = \frac{\sum_i \epsilon_i F_i R_i(a,c)}{\sum_i \epsilon_i F_i} \quad \text{where } F_i \equiv \frac{\sigma_i^{\text{SM}}}{\sigma_{\text{tot.}}^{\text{SM}}} \quad , \quad \epsilon_i = \text{eff}(i) \quad , \quad i = \text{ggF,VBF,VH,ttH}$$

$$R_{\text{decay}}(a,c) = \frac{R_j(a,c)}{R_{\text{tot.}}(a,c)} \quad , \quad j = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\tau$$