Tevong You

# Why is it a Higgs?

And what can we learn from it?

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# Introduction

CERN July 4th 2012

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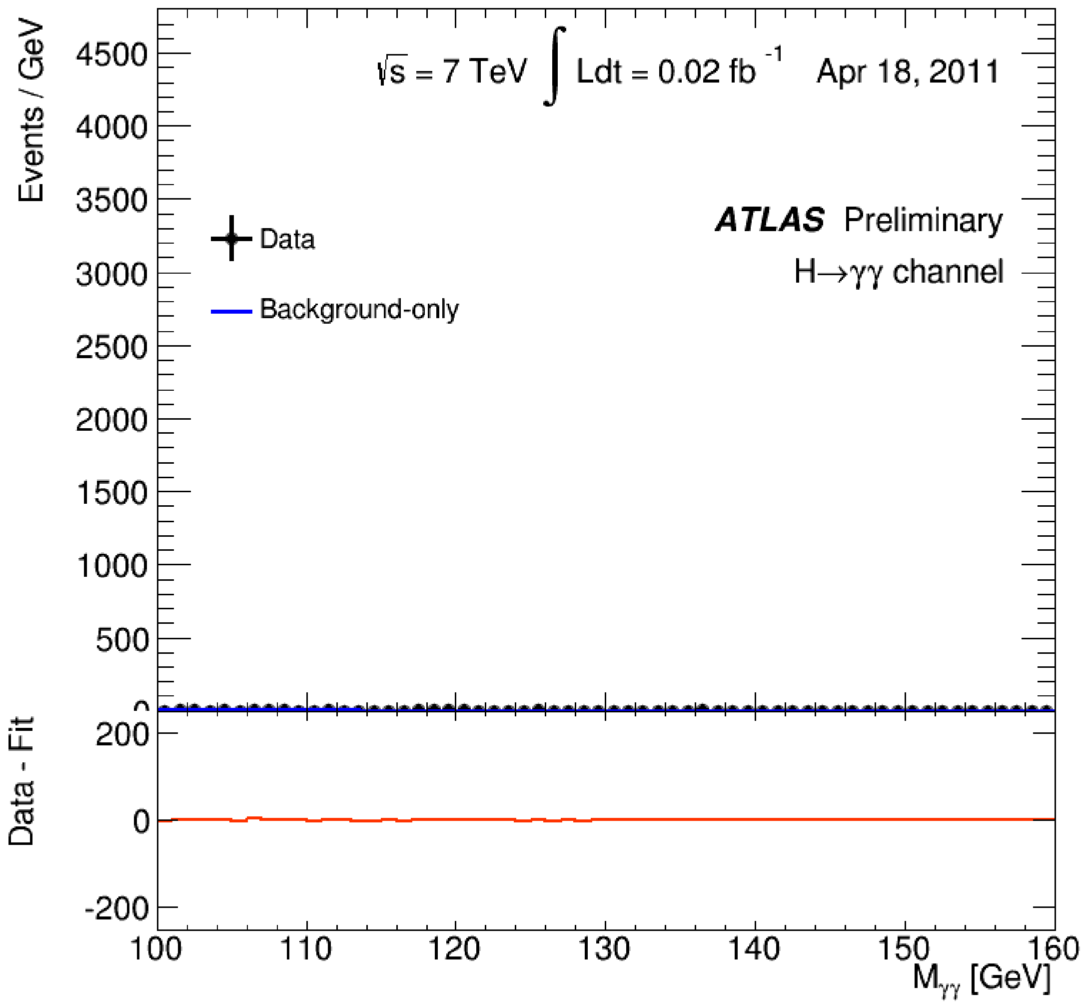
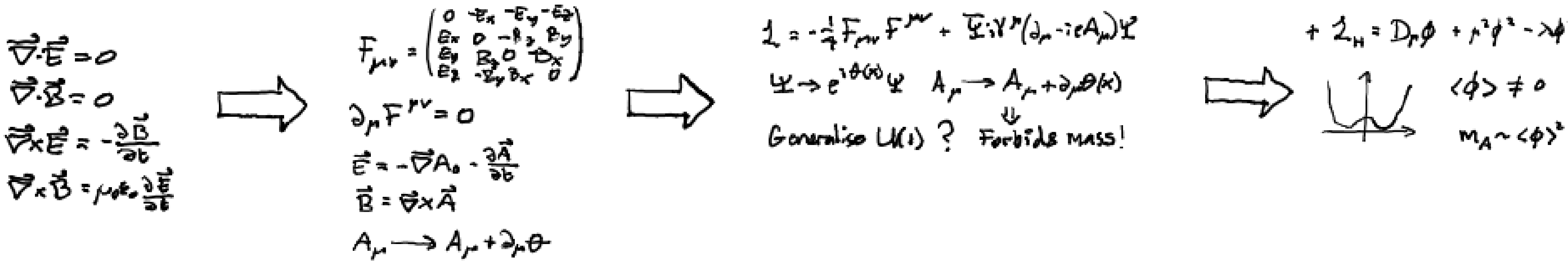


# Introduction

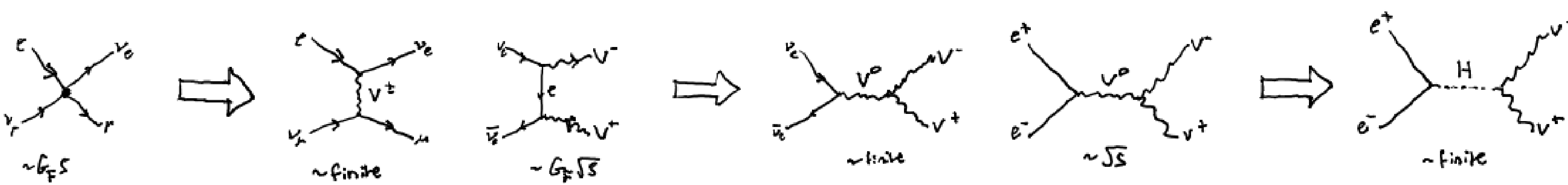
- From Maxwell to Higgs
- Non-Linear EFT parametrisation
- Global fit
- Spin Zero Scalar?
- Couplings proportional to mass?
- Higgs portal to new physics
- Beyond the Higgs

# From Maxwell to Higgs

- Historically




- Inevitably



# The Standard Model

- Most general renormalizable Lagrangian consistent with given field content and symmetries

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}$$

$$\mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^{L\mu} \phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

$$D^L_\mu = \partial_\mu - igW^a_\mu T^a - iYg' B_\mu \quad , \quad D^R_\mu = \partial_\mu - iYg' B_\mu$$

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4 \quad .$$

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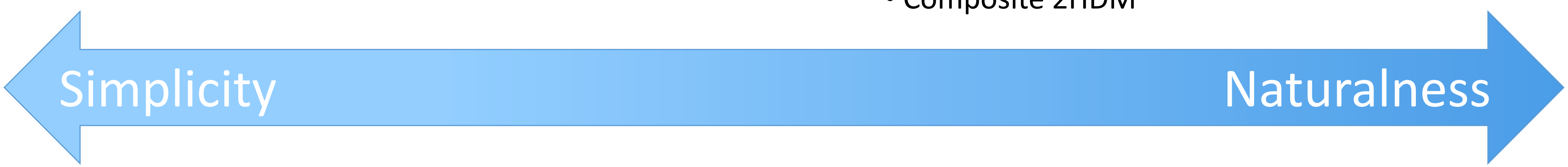
# The Standard Model?

- Many ways to break electroweak symmetry

- 2HDM
- Higgs + SUSY
- NMSSM
- Technicolor
- Composite 2HDM




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

(Pseudo-Dilaton)

# Non-Linear Effective Field Theory

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

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

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

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

# Non-Linear Effective Field Theory

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

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

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

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

# Non-Linear Effective Field Theory

- Standard model: a=c=1
- Composite Higgs:

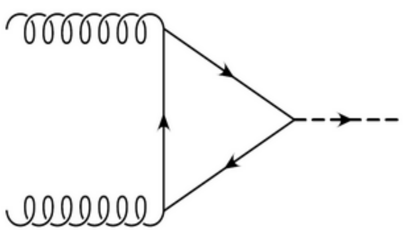
$$a = c = \sqrt{1-\xi} \qquad \xi \equiv (v/f)^2$$

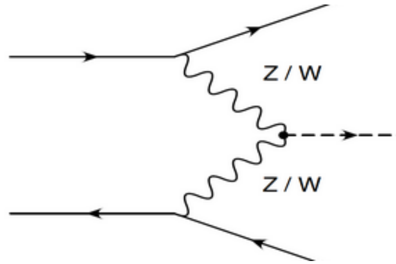
$$a = \sqrt{1-\xi}, \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

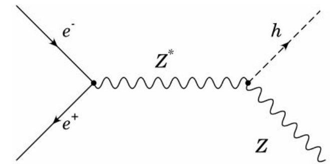
- Pseudo-dilaton:

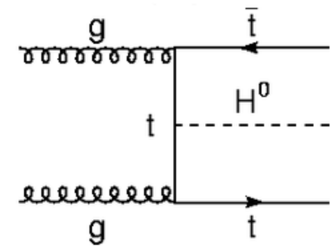
$$a = c = \frac{v}{V}$$

# Global Fit

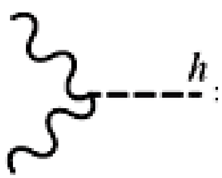


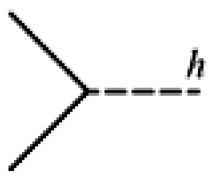


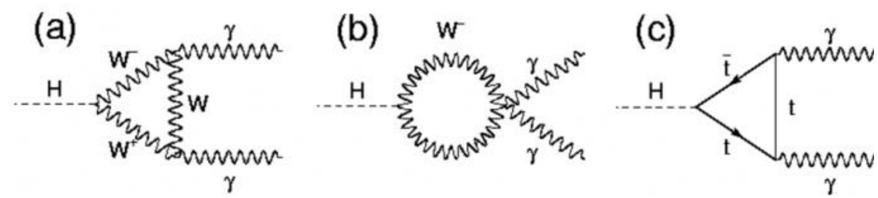




$$R_{gg} = \frac{(-\frac{v}{V}b_s + cF_t)^2}{F_t^2} \quad , \quad R_{\rm VBF} = a^2 \quad , \quad R_{\rm ap} = a^2 \quad , \quad R_{\rm hs} = c^2$$




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

# Global Fit

- Reinterpret likelihood $\mathcal{L}(\mu)$

$$\mu \equiv \frac{\sigma_{\text{prod}} \times \text{BR}_{\text{decay}}}{\sigma_{\text{prod}}^{\text{SM}} \times \text{BR}_{\text{decay}}^{\text{SM}}}$$

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

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

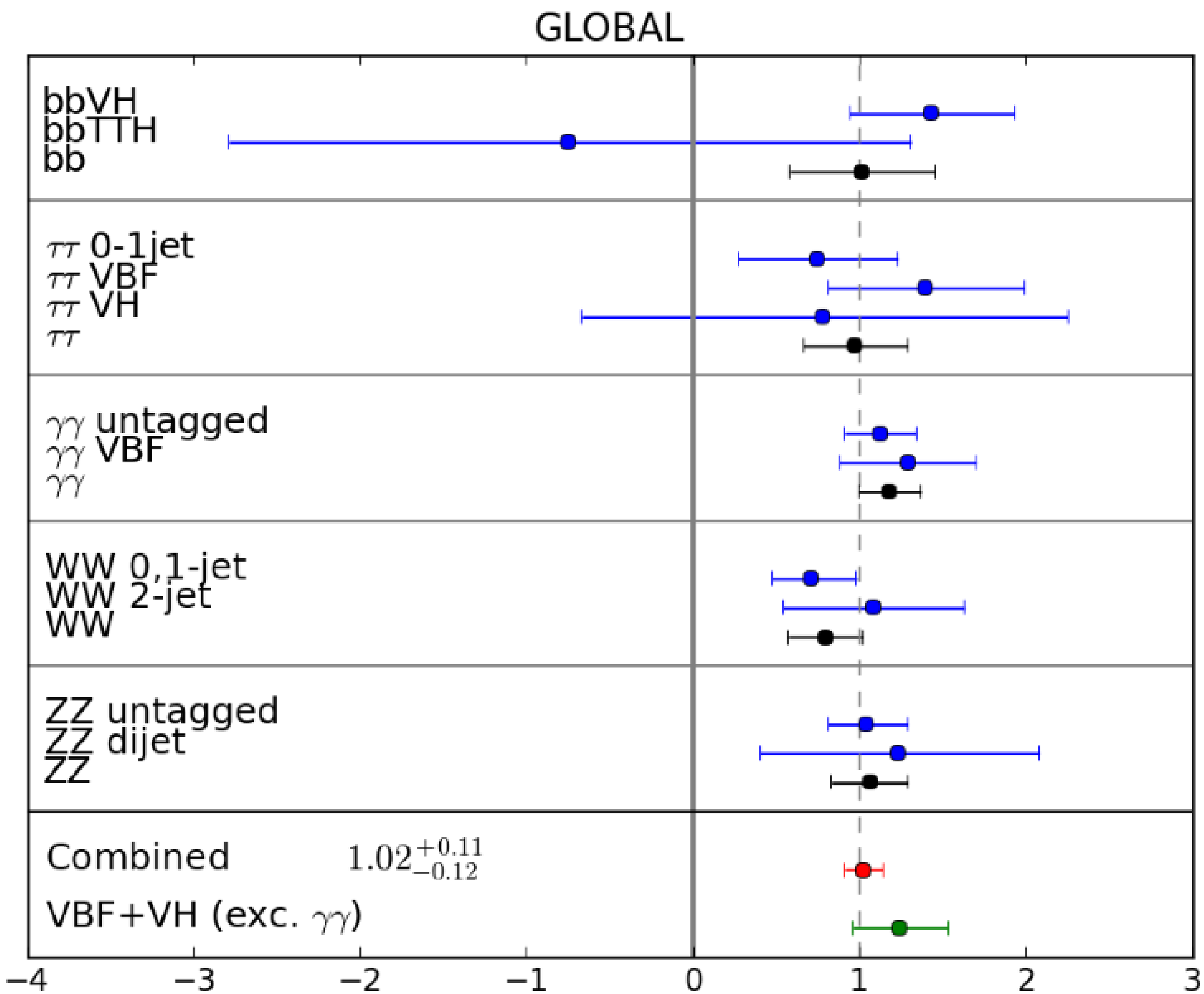
$$R_{\text{prod}}(a,c) = \frac{\sum_i \epsilon_i F_i R_i(a,c)}{\sum_i \epsilon_i F_i} \quad \text{where } F_i \equiv \frac{\sigma_i^{\text{SM}}}{\sigma_{\text{tot.}}^{\text{SM}}} \quad , \quad \epsilon_i = \text{eff}(i) \quad , \quad i = \text{ggF,VBF,VH,ttH}$$

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

See e.g. arXiv:1307.5865 “On the presentation of LHC Higgs Results”

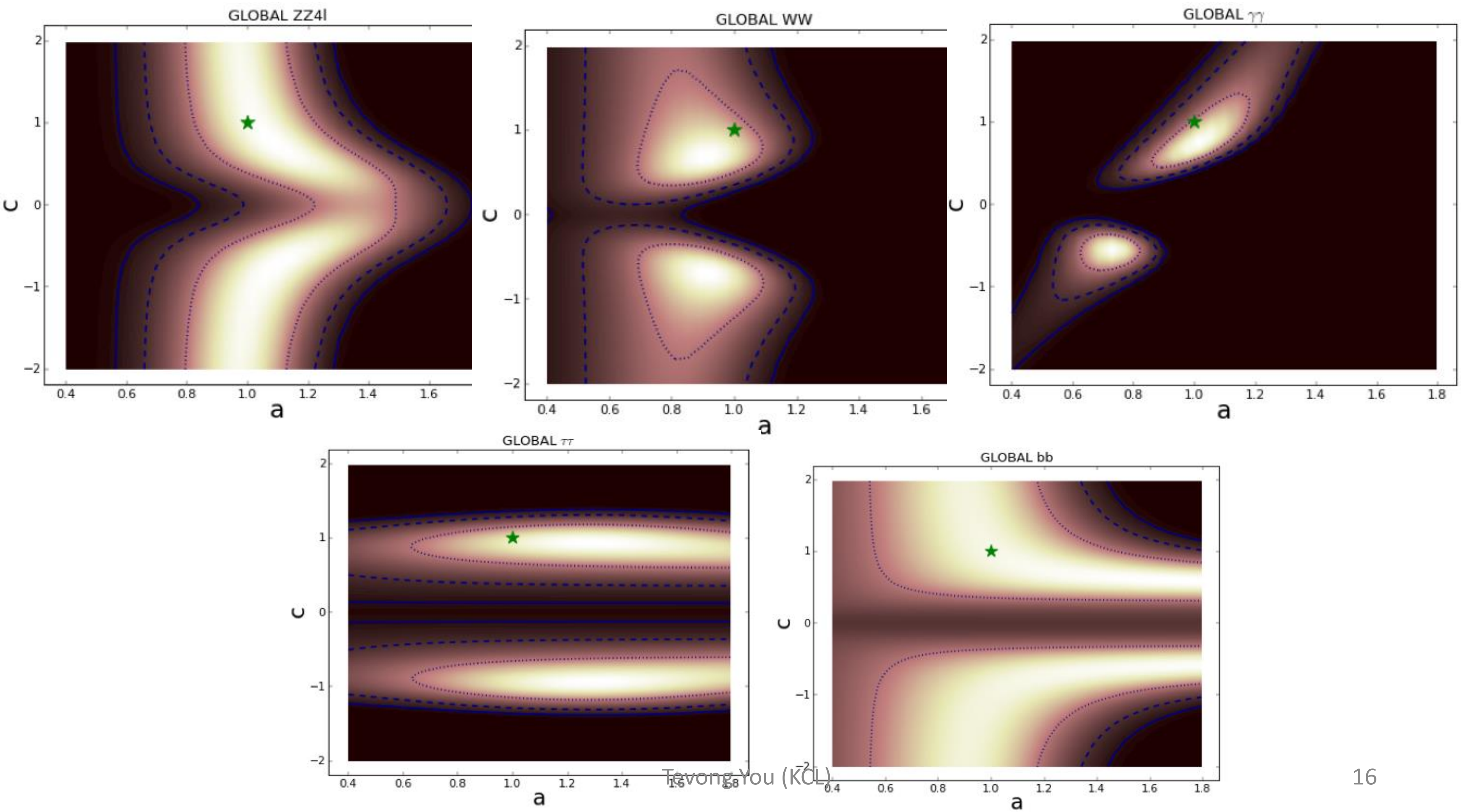
# Global Fit

- ATLAS+CMS+Tevatron signal strengths



# Global Fit

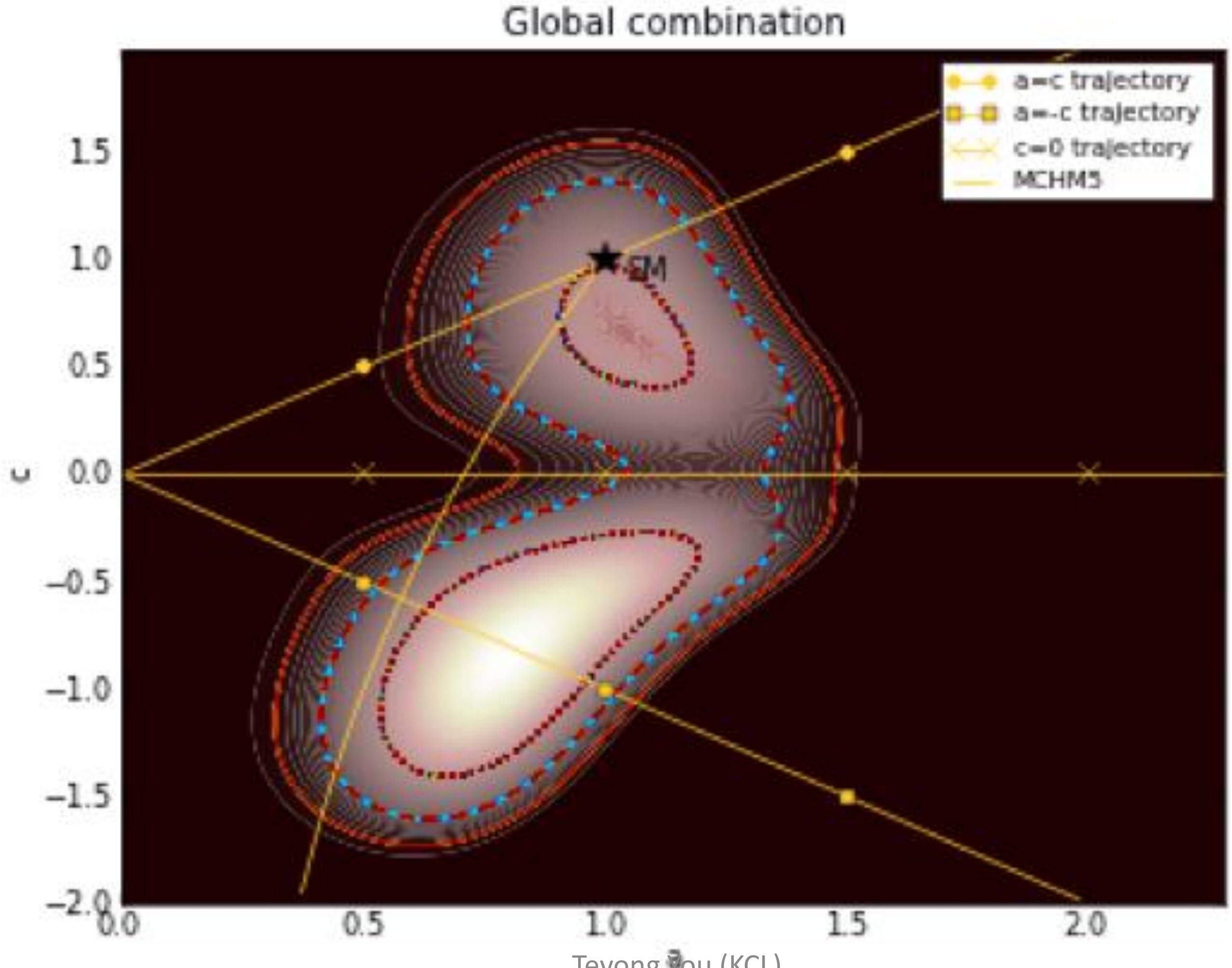
- Maximise information from combination of channels



# Global Fit

- March 2012 – pre-discovery

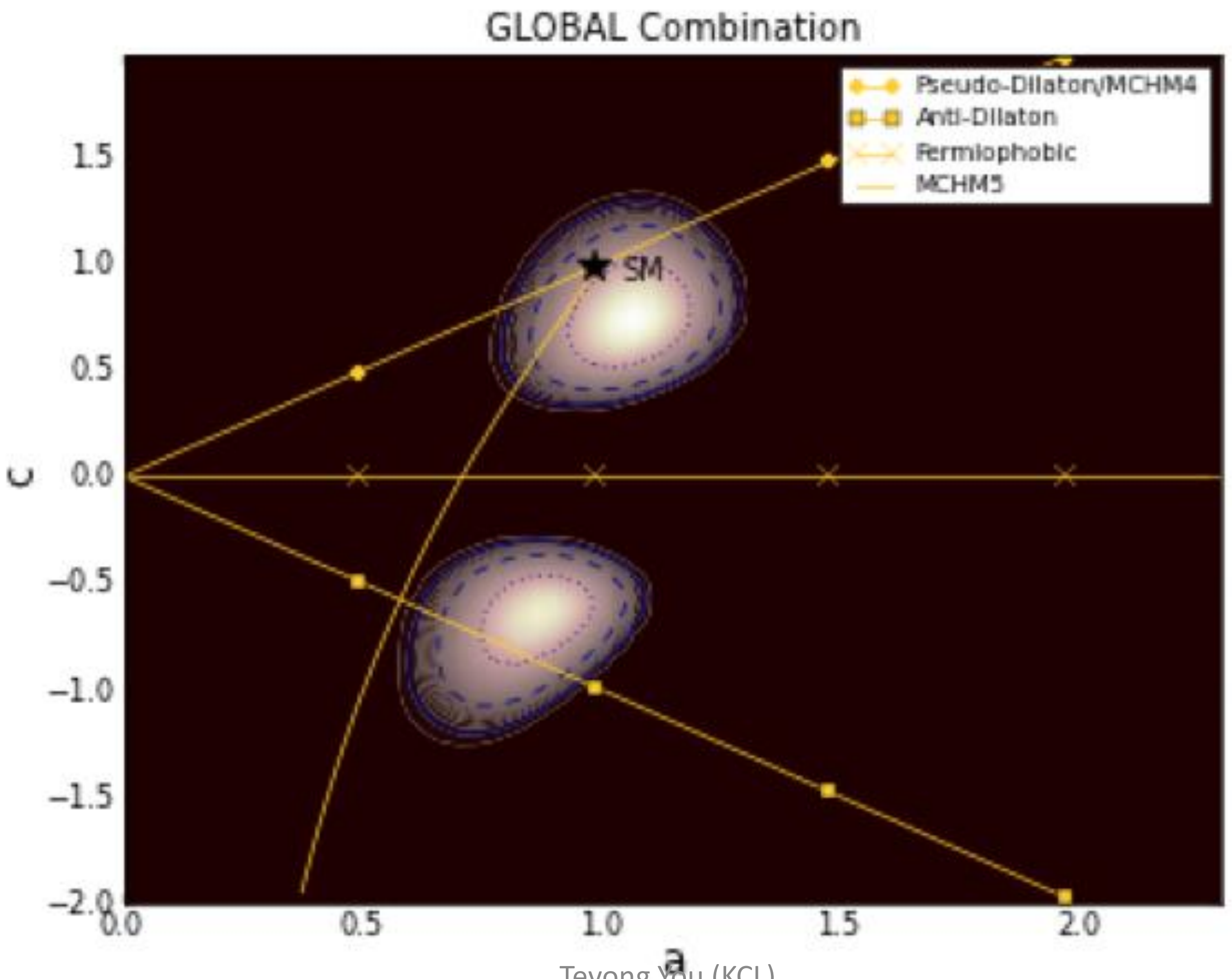
J. Ellis and T.Y. [arXiv:1204.0464]



# Global Fit

- July 2012 – post-discovery

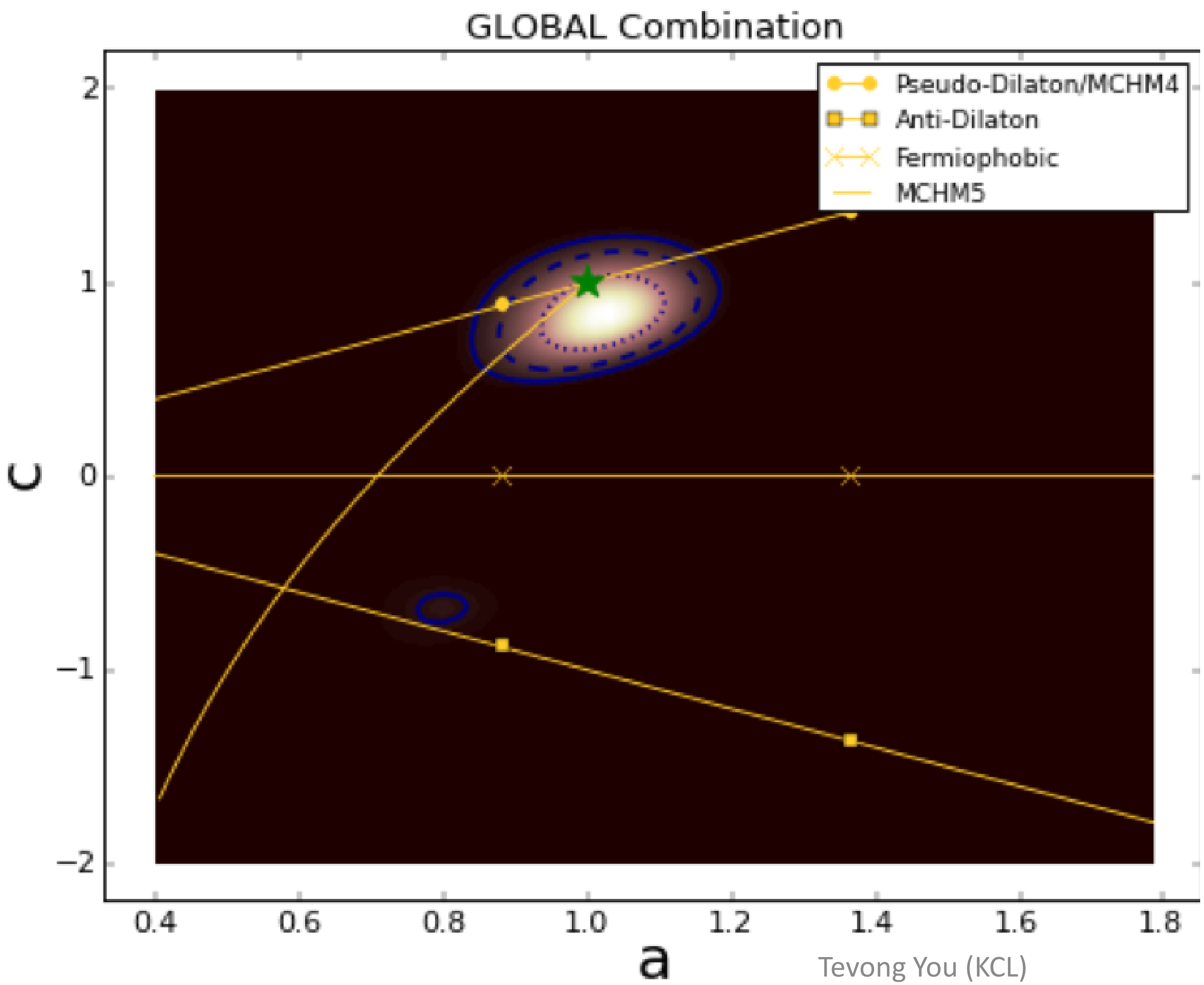
J. Ellis and T.Y. [arXiv:1207.1693]

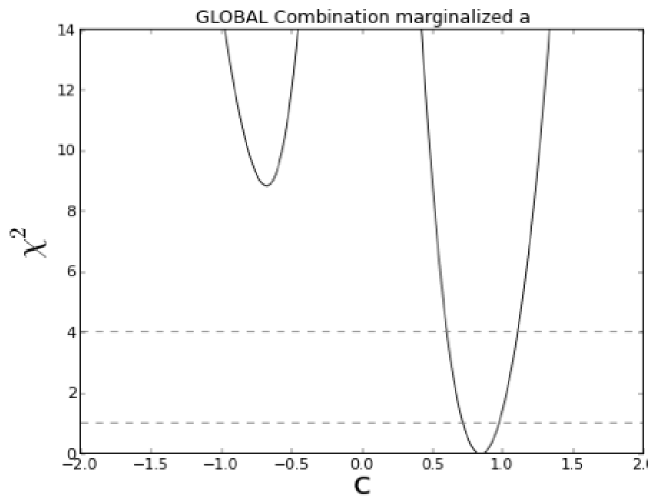


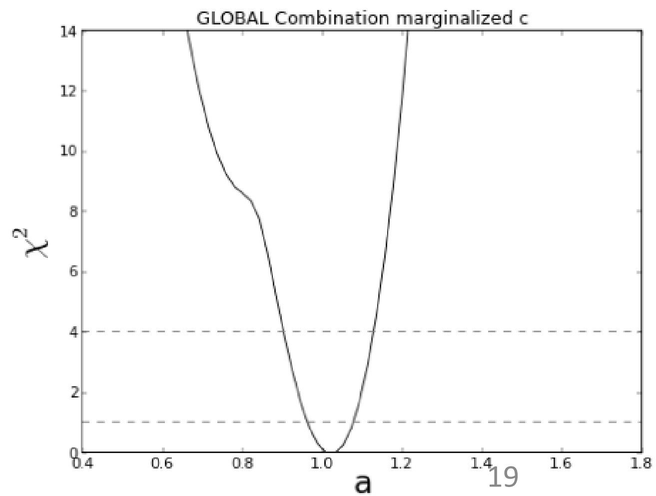
# Global Fit

- 2013 post-Moriond

J. Ellis and T.Y. [arXiv:1303.1879]



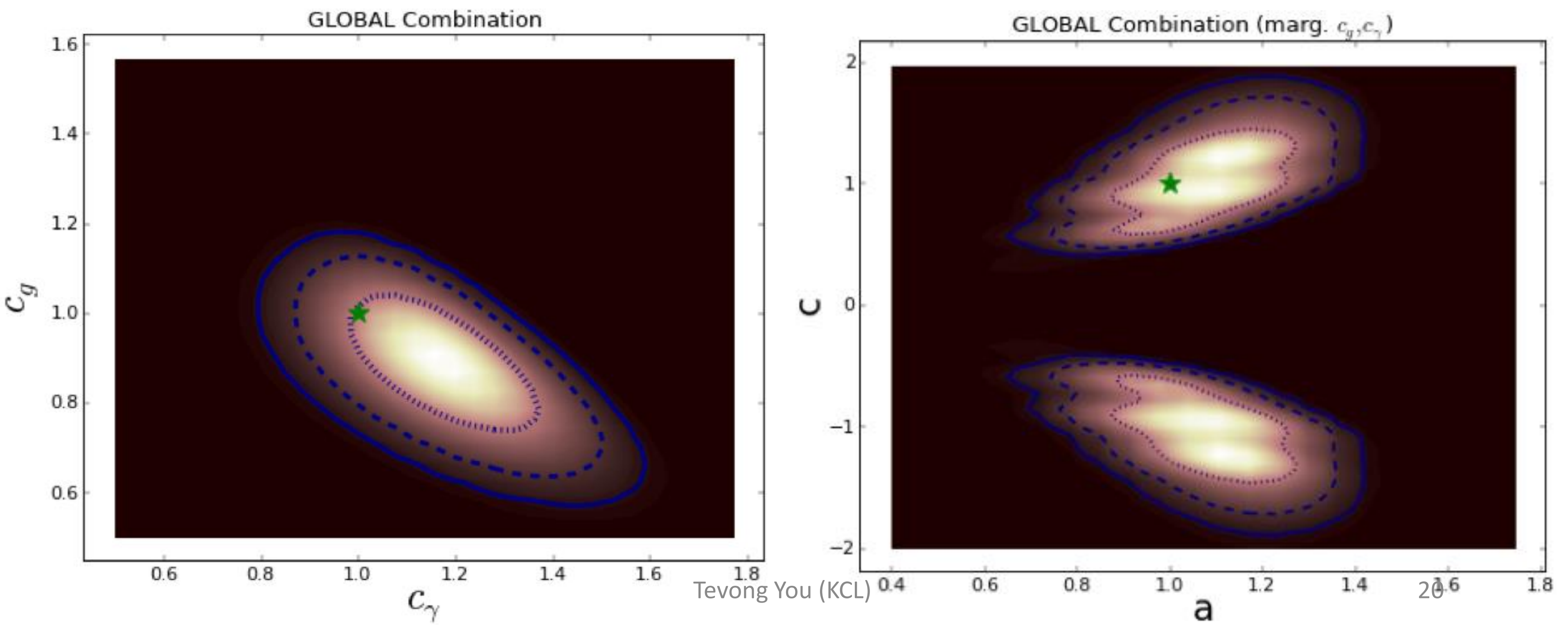



# Global Fit

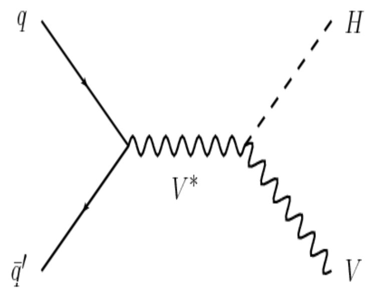
- More freedom by allowing loop-induced couplings to float independently

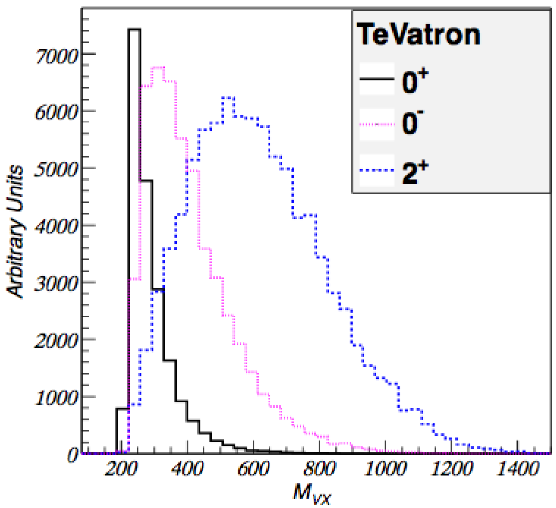
$$\mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi} c_g b_g G_{a\mu\nu} G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \left(\frac{H}{V}\right)$$



# Spin Zero?

- $M_{VH}$ distribution can also be used as a powerful spin discriminant
- excludes spin 2 at 99.9% CL for D0 alone [Conf. Note 6387]




J.Ellis, D.S.Hwang, V.Sanz and T.Y. [arXiv:1208.6002]

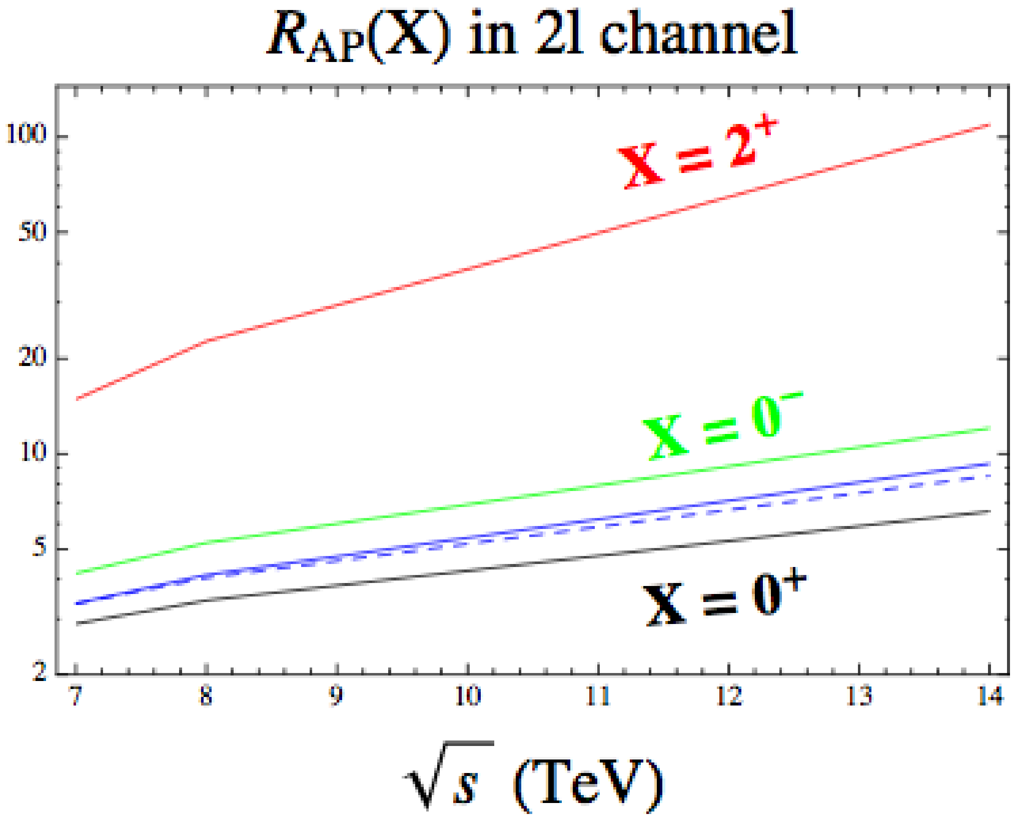
- Also: Non-SM scalar couplings to massive gauge bosons have energy dependence through derivative couplings

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

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

# Spin Zero?

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




J.Ellis, V.Sanz and T.Y. [arXiv:1303.0208]

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

- Stronger energy dependence for 0,1-lepton!

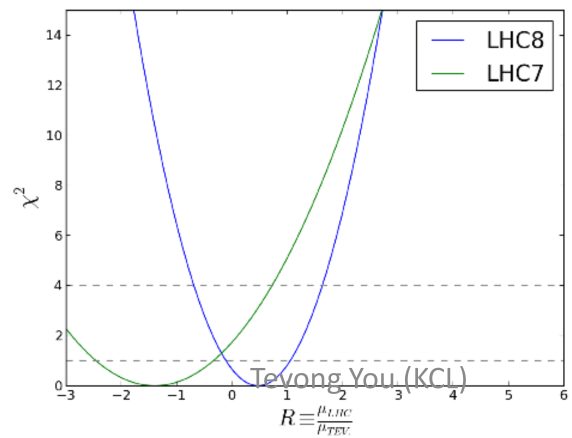
# Spin Zero?

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

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

- What does that data tell us?

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



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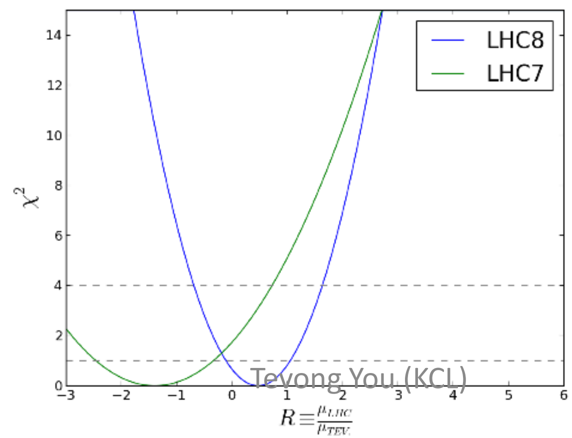


# Mass-coupling proportionality

- 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

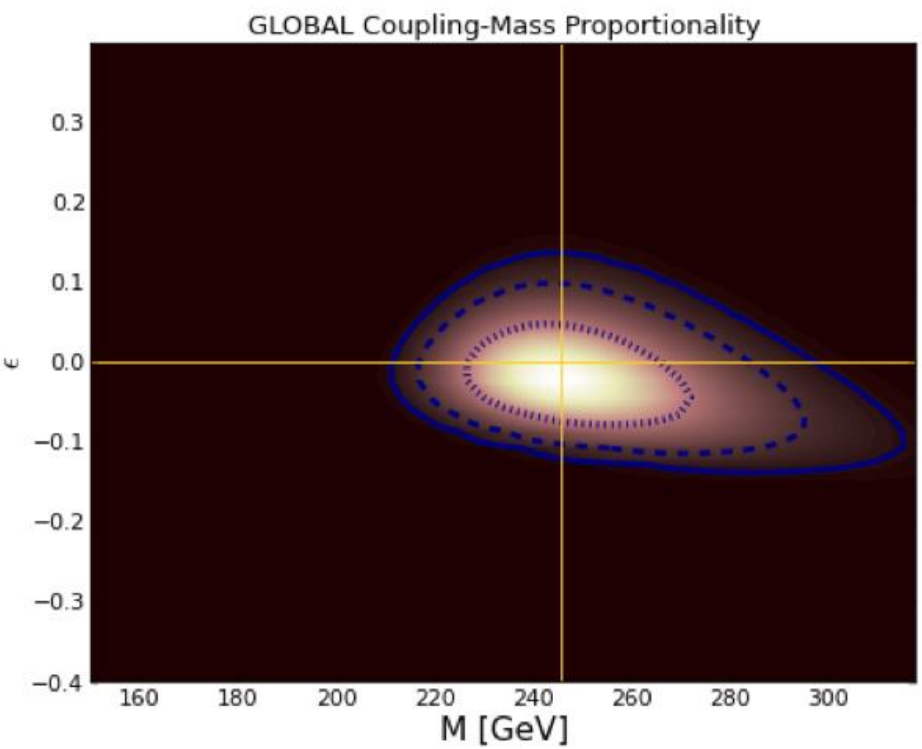
$$\lambda_f' = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V' = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

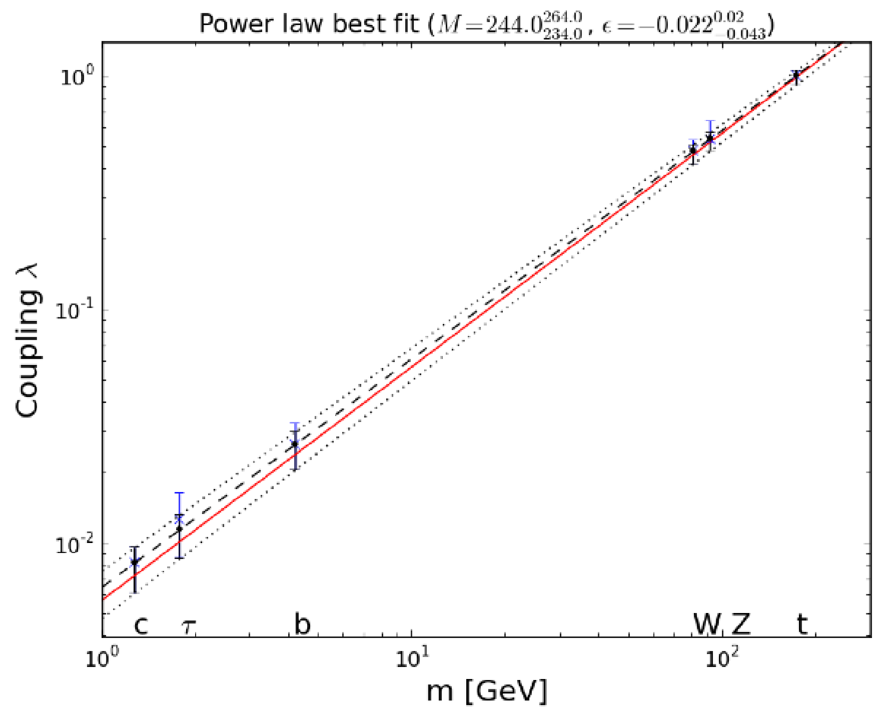
- Corresponds to rescaling

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

# Mass-coupling proportionality

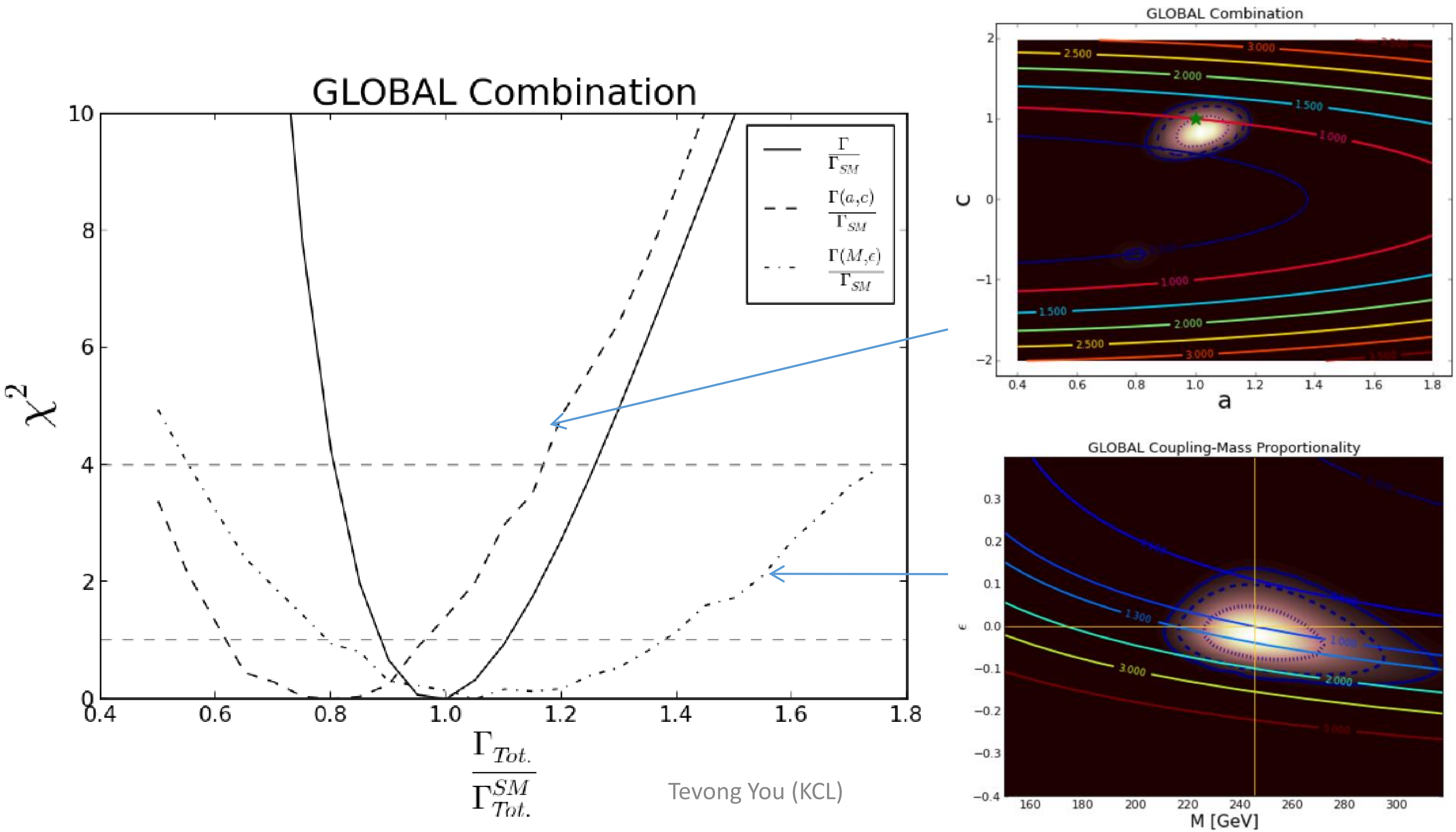
- Couplings proportional to mass?



# Higgs Portal

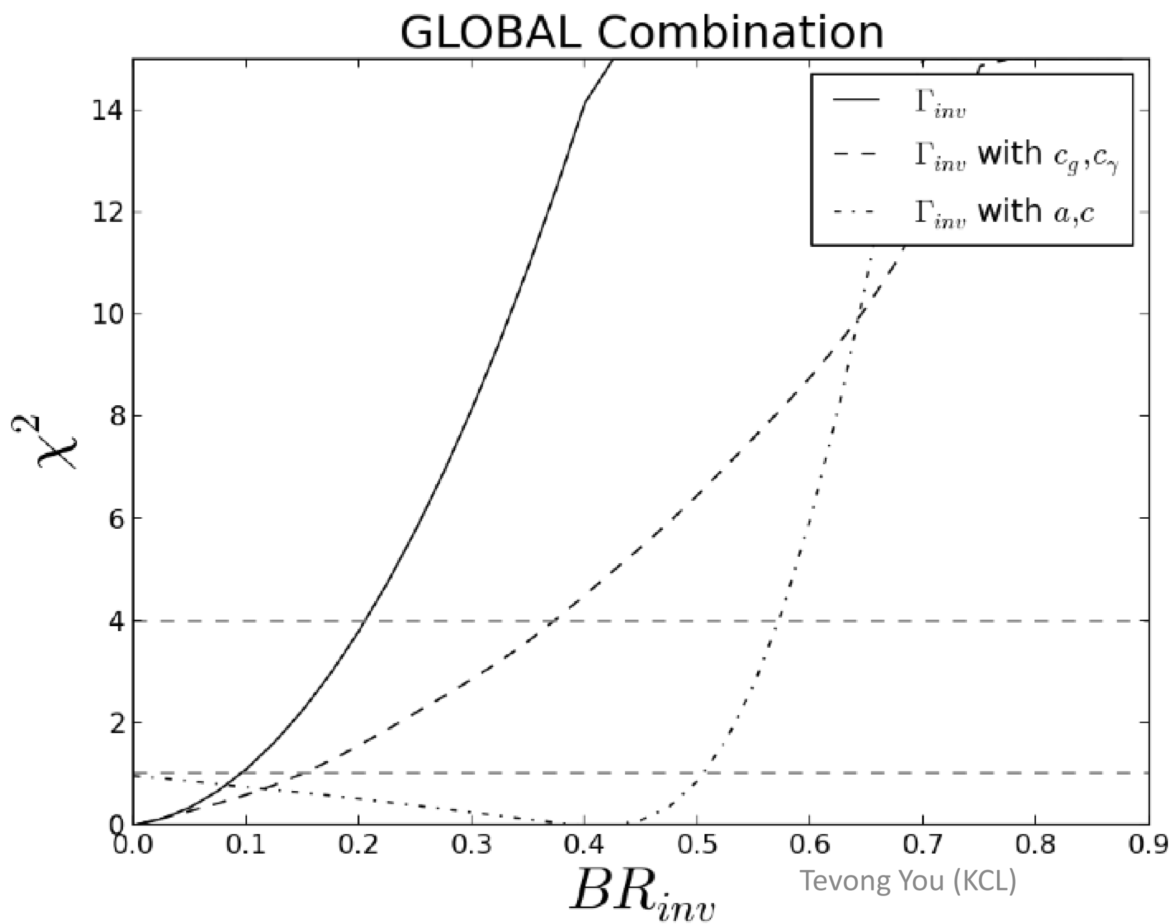
- No direct measurement of total Higgs decay rate, fit under various assumptions



# Higgs Portal

- Dark matter lighter than Higgs constrained by invisible branching ratio

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

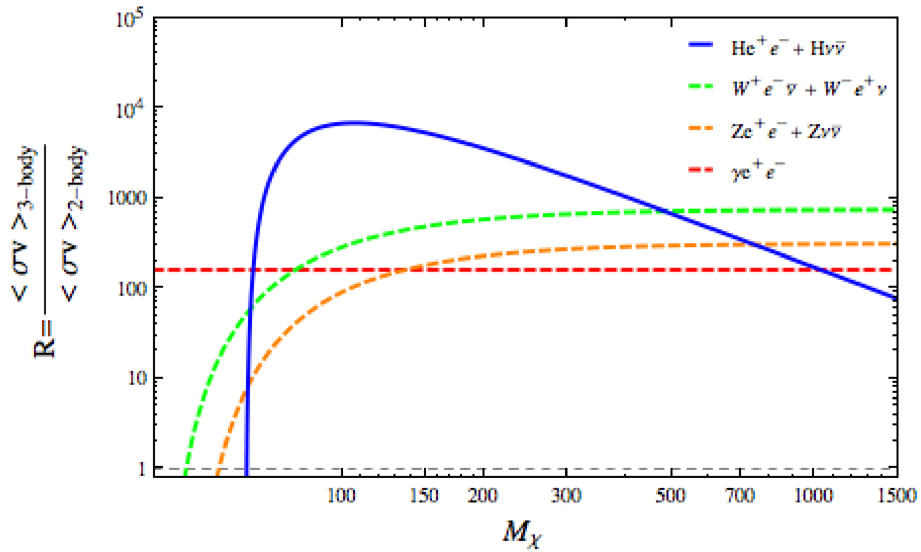


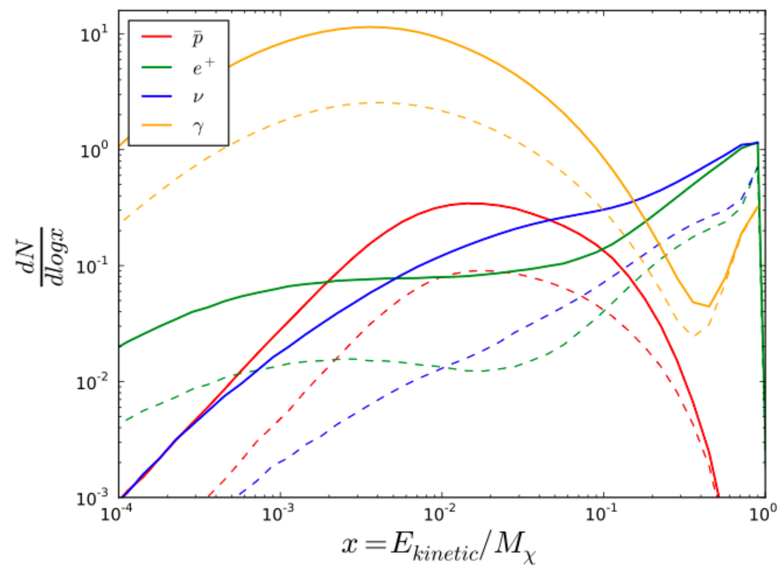

See e.g. Curtin et al. [arXiv:1312.4992] for exotic Higgs decays potential

# Higgs Portal

- Heavy dark matter can decay into Higgs
- e.g. Majorana or real scalar DM, annihilation to two fermions is helicity-suppressed
- Suppression removed by three-body decays
- Higgs bremsstrahlung can be the dominant contribution

Feng Luo and T.Y. [arXiv:1320.5129]



# Beyond the Higgs

- Why do we expect something more?

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

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

- $(m_h)^2_{\rm tree} + (m_h)^2_{\rm radiative} = (m_h)^2_{\rm v}$

- Earliest example of naturalness problem: $m_{\rm inertial} = m_{\rm gravity}$

- Classical EM:

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

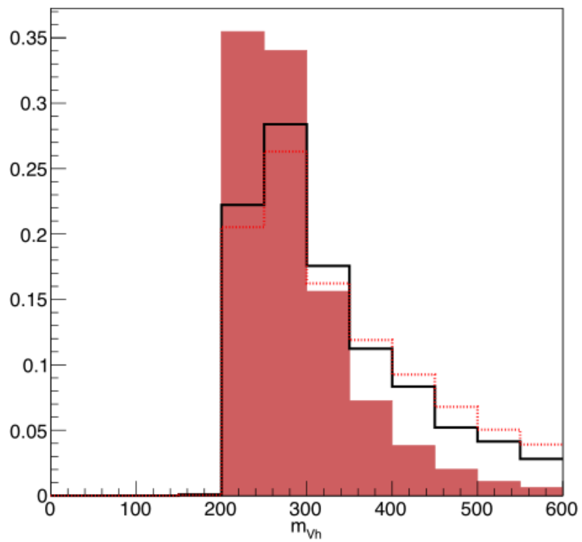
# Beyond the Higgs

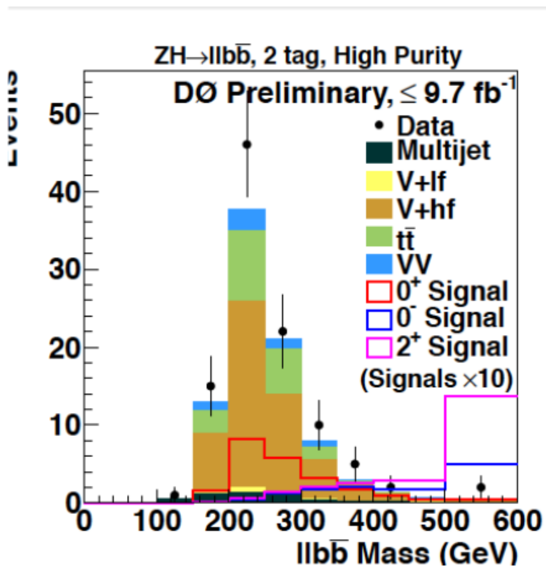
- Fermi theory of weak interactions was a successful phenomenological EFT
- Treat SM the same way, linearly realized EFT:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

See e.g. Willenbrock and Zhang [arXiv:1401.0470] for a review

- Go beyond signal strength: Differential distributions




J. Ellis, V. Sanz and T.Y. (in progress)

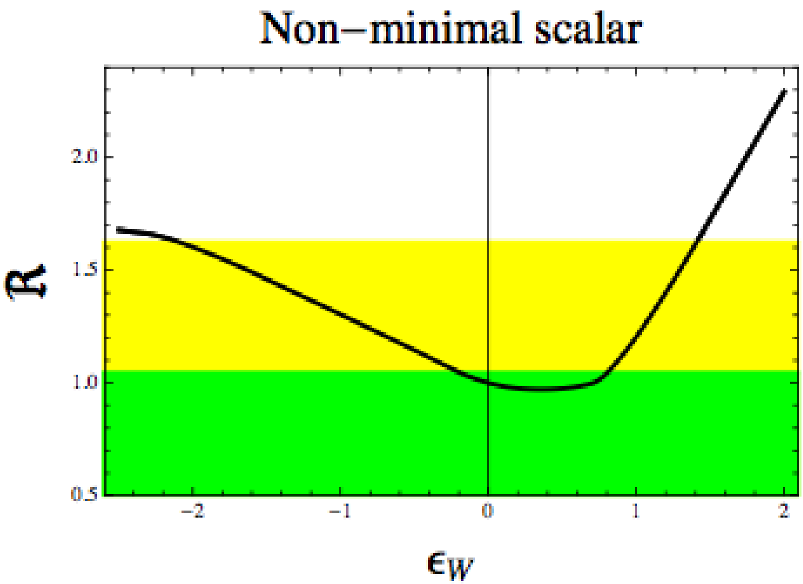
cHW (red), cW (black) = 0.1

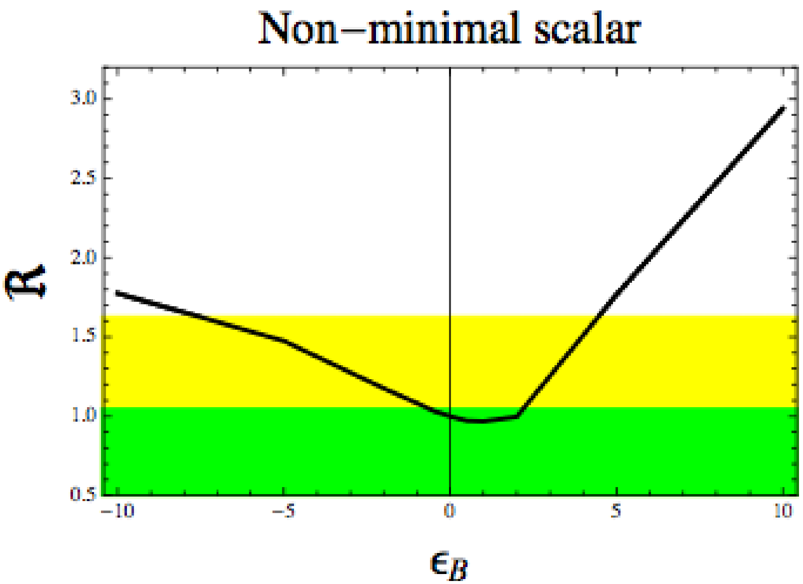
# Beyond the Higgs

- Energy dependence also constrains Dim-6 coefficients

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

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

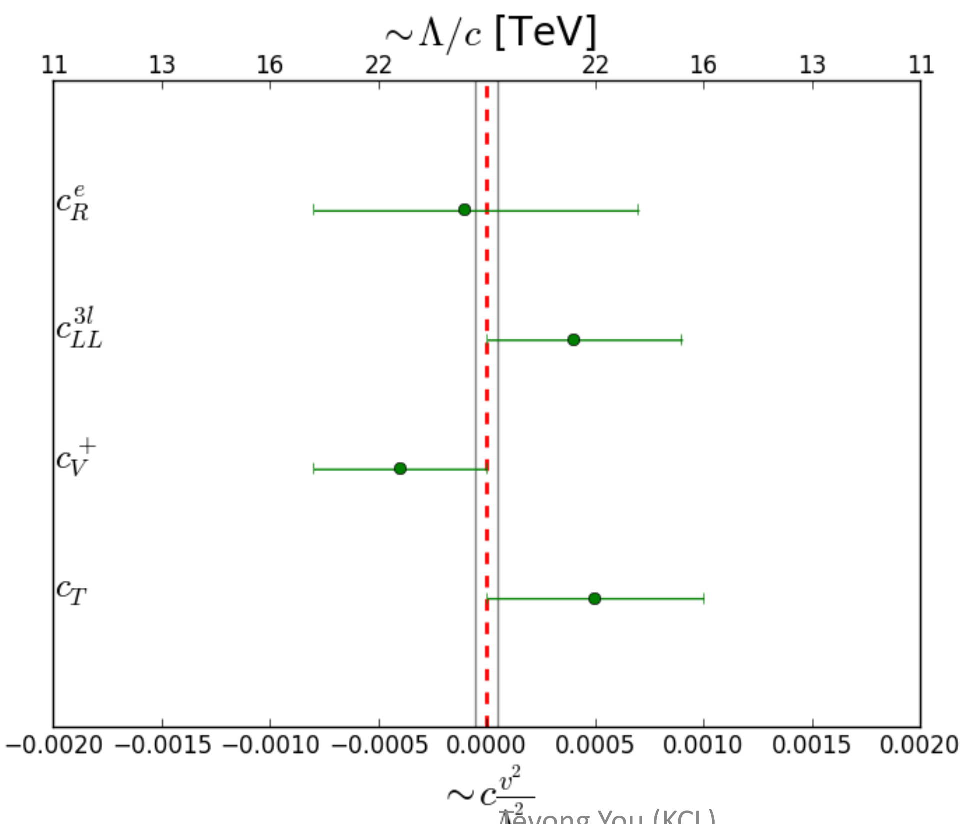



- Competitive bounds to direct LHC fits (c.f. E. Masso and V. Sanz [arXiv:1211.1320])

# Beyond the Higgs

- Constraining Dim-6 operators: Combination of electroweak precision tests, triple-gauge couplings, and Higgs data (see e.g. Pomarol and Riva [arXiv:1308.2803])
- EWPT at LEP: Constraints on Top and Higgs, sensitive to TeV scale

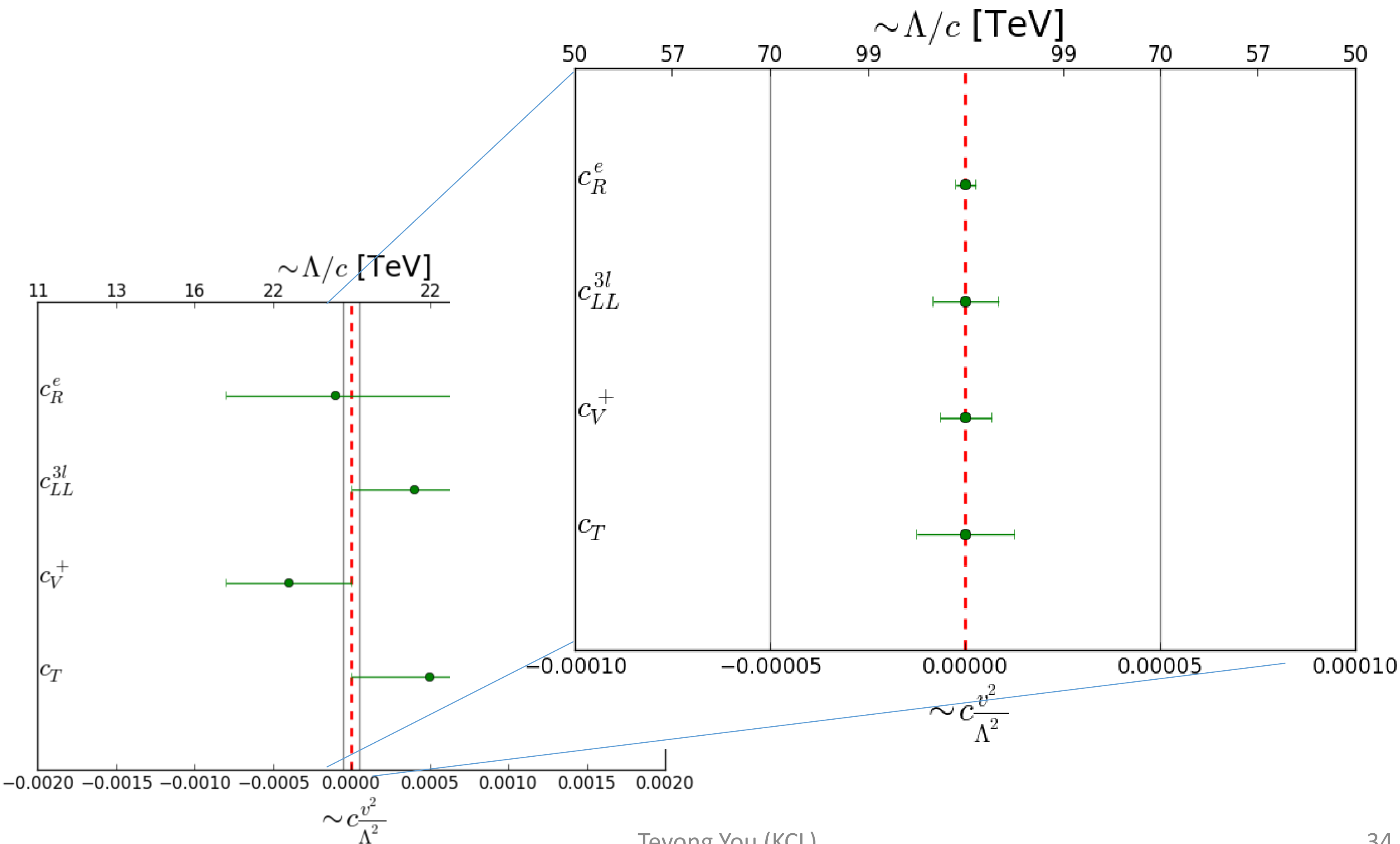



J. Ellis, T. You and V. Sanz (in progress)

# Beyond the Higgs

- EWPT at TLEP

J. Ellis, T. You and V. Sanz (in progress)



# Conclusion

- It's **a** Higgs!
- Parametrise in non-linear EFT
- Global fit to couplings
- Mass-proportional and spin zero
- Still room for exotic Higgs decays/dark matter
- Differential distributions and complementary between measurements at different energies/colliders useful
- SM as an EFT: Dim-6 operators