Is it a (Beyond the) Standard Model Higgs?

Tevong You

Based on:
"Global Analysis of the Higgs Candidate with Mass ~125 GeV",
John Ellis and T. Y.,
arXiv:1207.1693 [hep-ph].

See also our previous paper: John Ellis and T. Y., JHEP **1206** (2012) 140, [arXiv:1204.0464 [hep-ph]].

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- Naturalness
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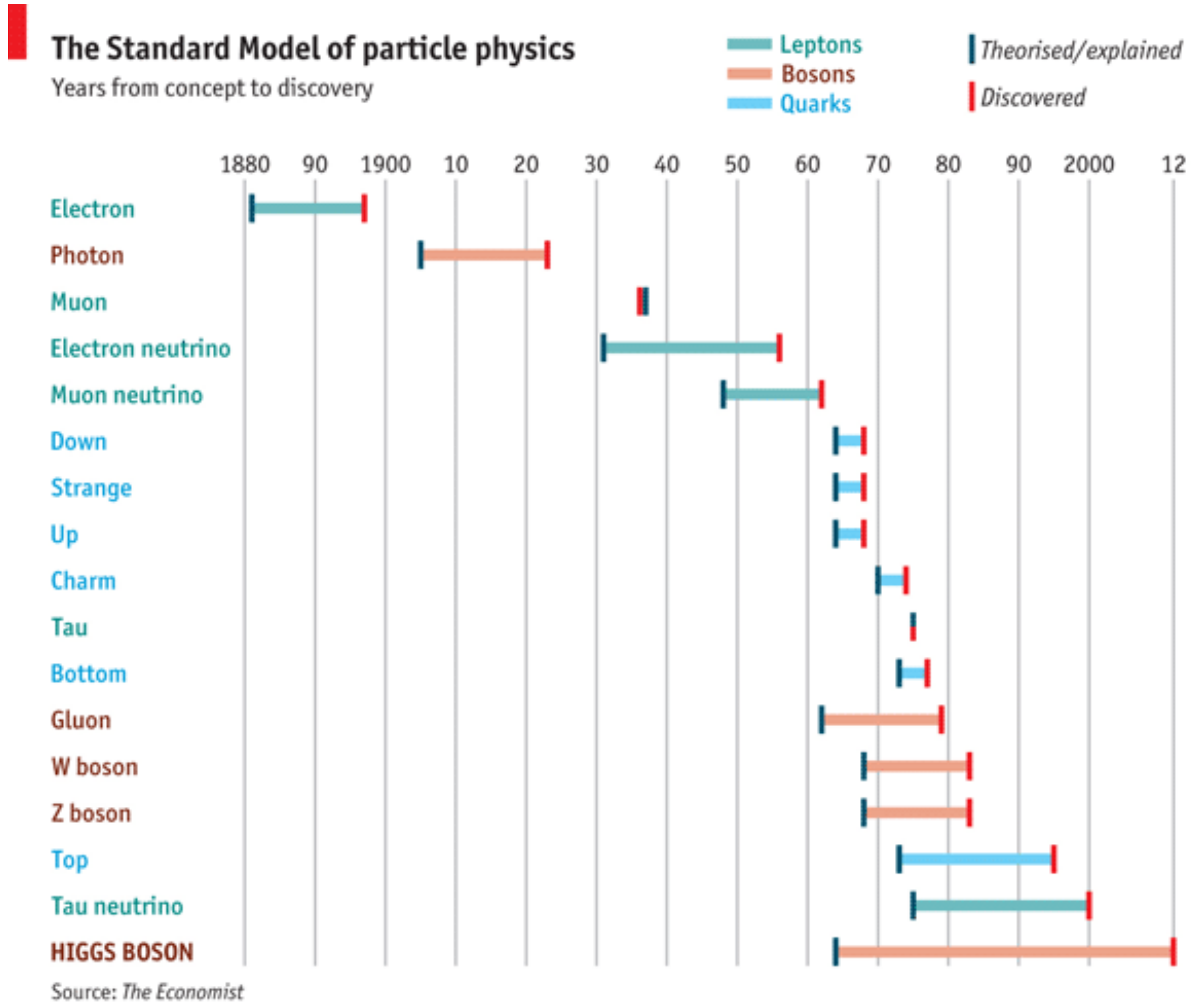
Introduction

Introduction

CERN July 4th 2012

Image Credit: J. Olsson, STFC, NY Times, AP

Introduction



Introduction

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

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

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

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

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

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

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

Introduction

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

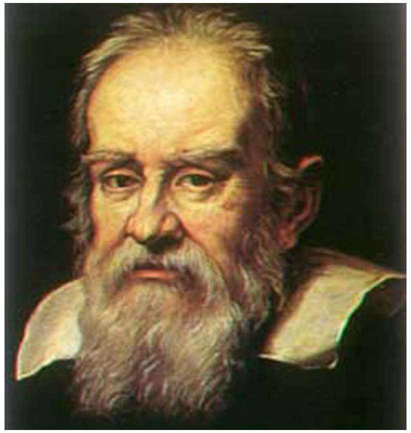
?

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

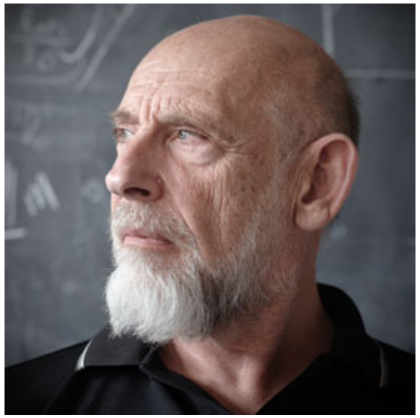
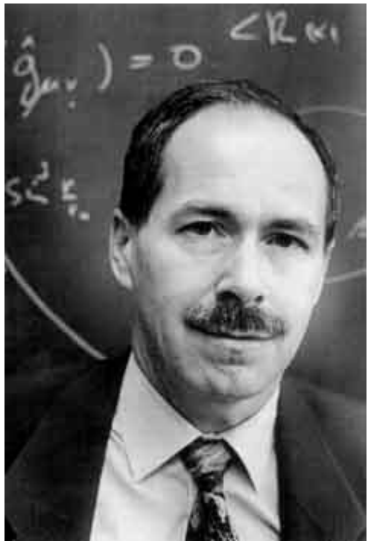
- Fundamental Scalar (SM Higgs)
- Composite Higgs
- Extra Dimensions
- Walking Technicolor
- Little Higgs

Naturalness

Naturalness




- Galileo (1589), Newton (1687):
- $m_{inertial} = m_{gravity}$
- Equivalence principle → General Relativity

- Susskind (1979), ‘t Hooft (1980):
- $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$
- Hierarchy problem → ?

Naturalness

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

- Not regularization-dependent:

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

- *A fundamental scalar is quadratically sensitive to high energies*
- EM analogy, electron rest energy contribution from Coulomb field:

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

- Avoid fine-tuning: Predicts new physics at ~10^-15m!
- Parametrize possible new physics at TeV scale? Start with what we know below TeV scale…

Phenomenological Framework

Phenomenological Framework

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

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

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

Phenomenological Framework

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

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

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

$$\mathcal{L}_\Delta \;=\; -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu}+\frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

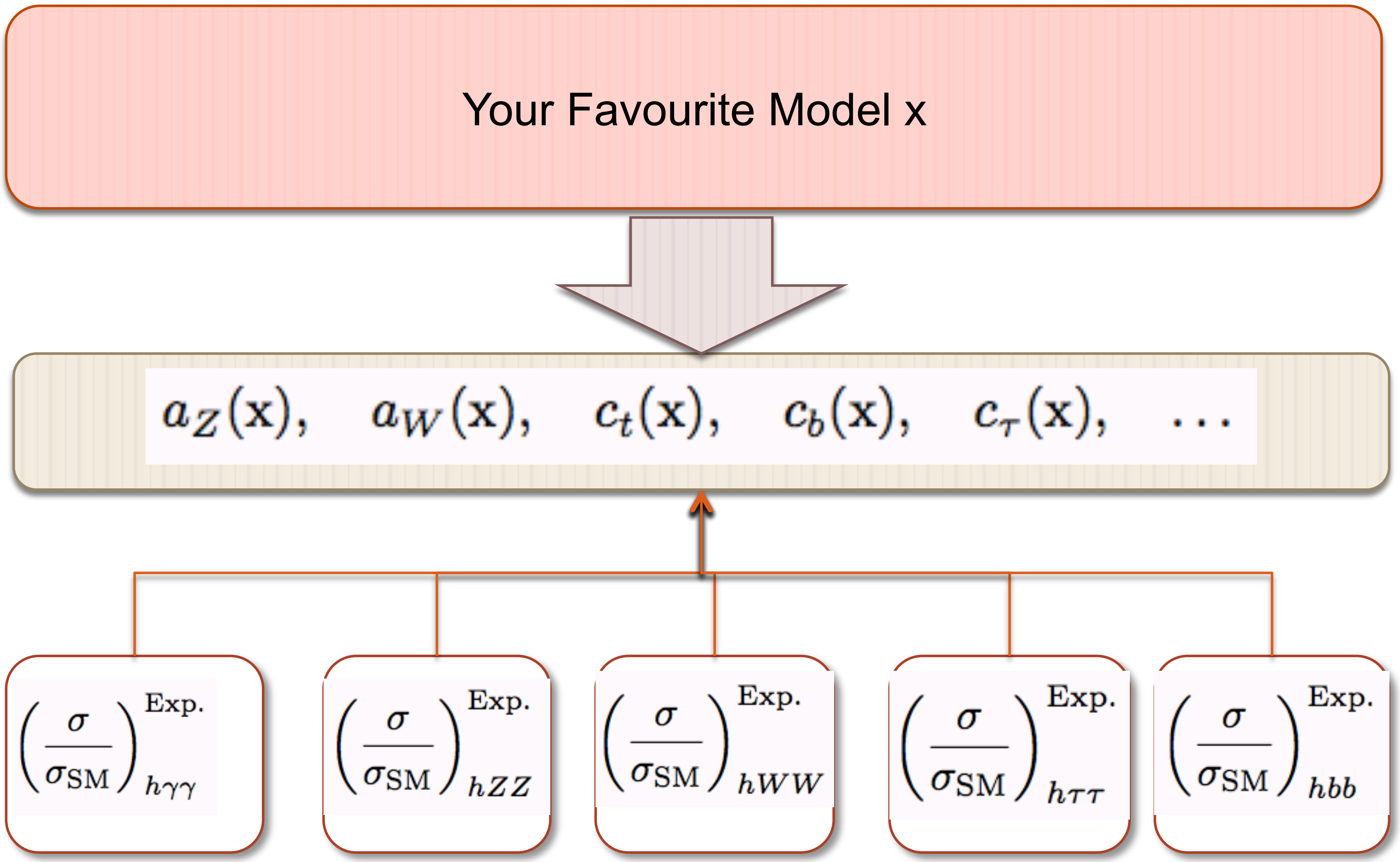
See previous paper: John Ellis and T. Y., JHEP **1206** (2012) 140, [arXiv:1204.0464 [hep-ph]].

Phenomenological Framework

- *a* parametrizes couplings of *h* to massive gauge bosons
- *c* parametrizes couplings of *h* to fermions

- Standard Model: $a = c = 1$
- Composite Higgs MCHM4: $a = c = \sqrt{1-\xi}$ $\quad \xi \equiv (v/f)^2$
- Composite Higgs MCHM5: $a = \sqrt{1-\xi}, \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$
- Pseudo-Dilaton: $a = c = \frac{v}{V}$

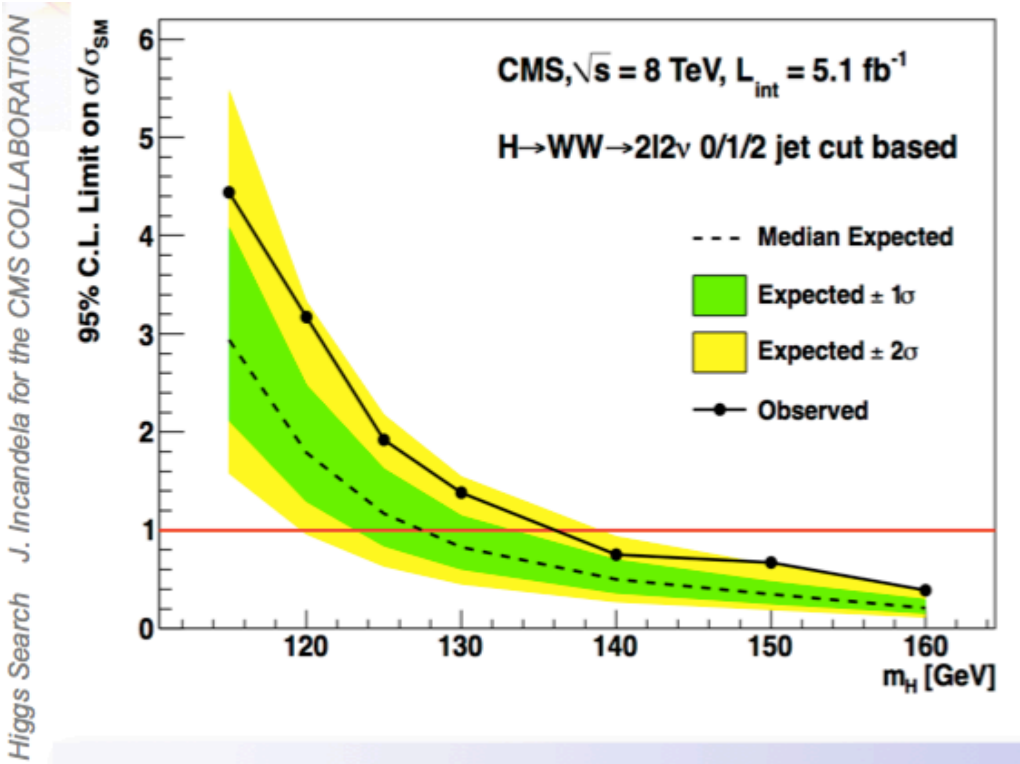
Phenomenological Framework

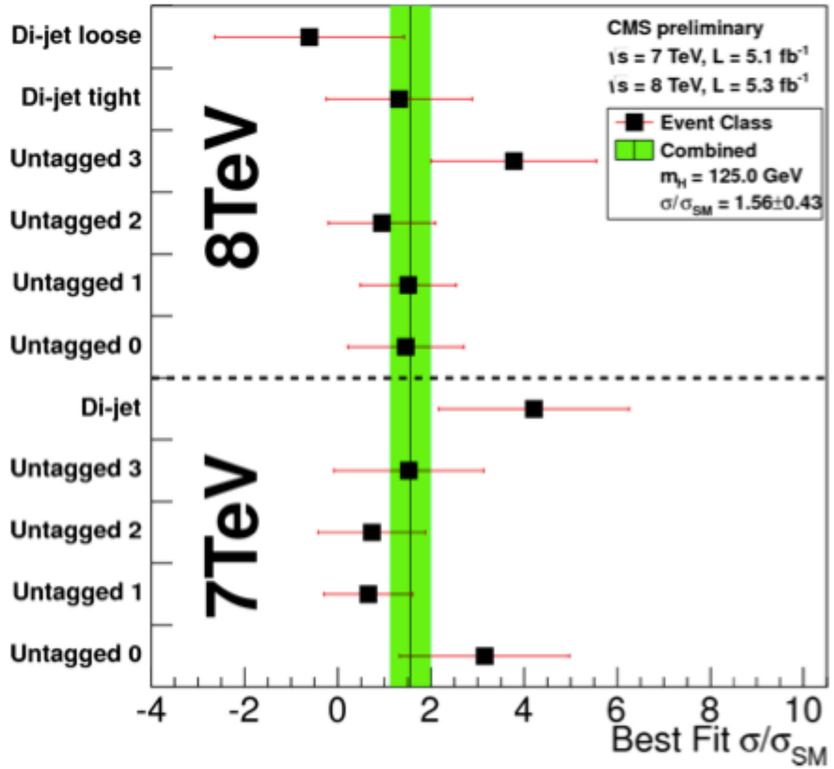


Re-interpreting SM Higgs Searches

Re-interpreting SM Higgs Searches

- Example





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Re-interpreting SM Higgs Searches

- Extract Likelihood $\mathcal{L}(\mu)$ using expected and observed 95% CL limit on mu
- Assume Gaussian limit of Poisson-distributed Likelihood*:

$$\sigma_{\rm obs} \simeq \sigma_{\rm exp} = \mu^{95\%}_{\rm exp}/1.96 \qquad \frac{\int_0^{\mu^{95\%}{}_{\rm obs}} e^{-\frac{(\mu-\hat{\mu})^2}{2\sigma^2_{\rm obs}}}\, d\mu}{\int_0^{\infty} e^{-\frac{(\mu-\hat{\mu})^2}{2\sigma^2_{\rm obs}}}\, d\mu} = 0.95$$

$$p(\mu|n_{\rm obs}) = p(n_{\rm obs}|\mu n_s^{\rm SM} + n_b)\cdot \pi(\mu) \approx \frac{1}{\sqrt{2\pi\sigma^2_{\rm obs}}} e^{-\frac{(\mu-\hat{\mu})^2}{2\sigma^2_{\rm obs}}}$$

- If best fit mu provided, use that instead assuming Gaussian error bars

*See A. Azatov, R. Contino and J. Galloway, arXiv:1202.3415.

Re-interpreting SM Higgs Searches

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

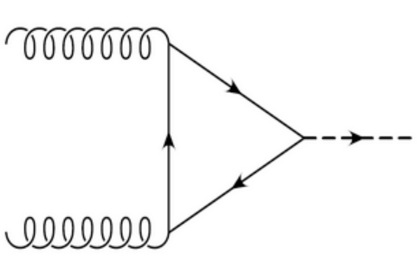
$$\sigma_{\text{prod}} = R_{\text{prod}}(a,c) \cdot \sigma_{\text{prod}}^{\text{SM}} \quad , \quad BR_{\text{decay}} = R_{\text{decay}}(a,c) \cdot \text{BR}_{\text{decay}}^{\text{SM}}$$

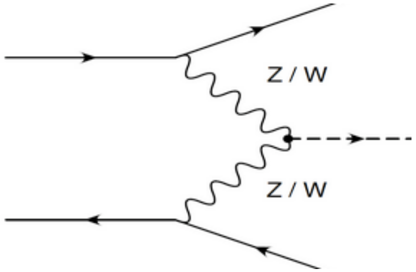
$$\Longrightarrow \mu = R_{\text{prod}}(a,c) \cdot R_{\text{decay}}(a,c)$$

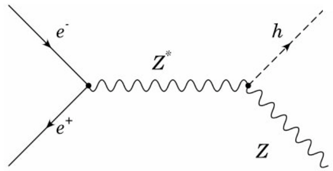
$$R_{\text{prod}}(a,c) = \frac{\sum_i \epsilon_i F_i R_i(a,c)}{\sum_i \epsilon_i F_i} \quad \text{where } F_i \equiv \frac{\sigma_i^{\text{SM}}}{\sigma_{\text{tot.}}^{\text{SM}}} \quad , \quad \epsilon_i = \text{eff}(i) \quad , \quad i = \text{ggF,VBF,VH,ttH}$$

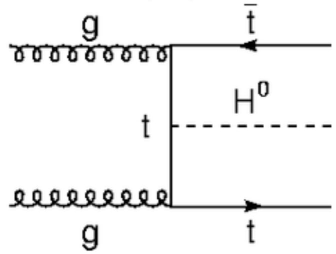
$$R_{\text{decay}}(a,c) = \frac{R_j(a,c)}{R_{\text{tot.}}(a,c)} \quad , \quad j = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\tau$$

Re-interpreting SM Higgs Searches

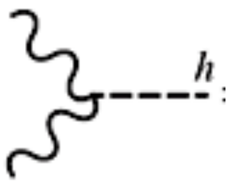


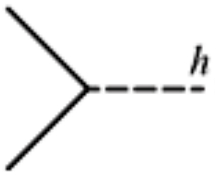


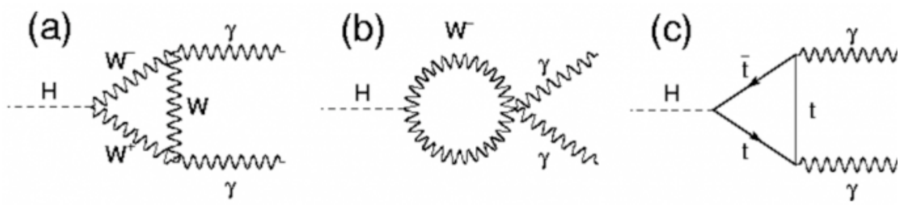




$$R_{gg} = \frac{(-\frac{v}{V}b_s + cF_t)^2}{F_t^2} \quad , \quad R_{\rm VBF} = a^2 \quad , \quad R_{\rm ap} = a^2 \quad , \quad R_{\rm hs} = c^2$$







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

Re-interpreting SM Higgs Searches

- Experimental search (sub)channels:

channel	Production sensitive to a	Production sensitive to c	Decay sensitive to a	Decay sensitive to c
$\gamma\gamma$	✓	✓	✓	✓
$\gamma\gamma$ VBF	✓	×	✓	✓
WW	✓	✓	✓	×
WW 2-jet	✓	×	✓	×
WW 0,1-jet	×	✓	✓	×
$b\bar{b}$ (VH)	✓	×	×	✓
$b\bar{b}$ ($\bar{t}tH$)	×	✓	×	✓
ZZ	✓	✓	✓	×
$\tau\tau$	✓	✓	×	✓
$\tau\tau$ (VBF, VH)	✓	×	×	✓

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Global Experimental Constraints

Global Experimental Constraints

- Couplings proportional to masses?
- Assumed SM couplings:

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

- Generalize scale and power couplings:

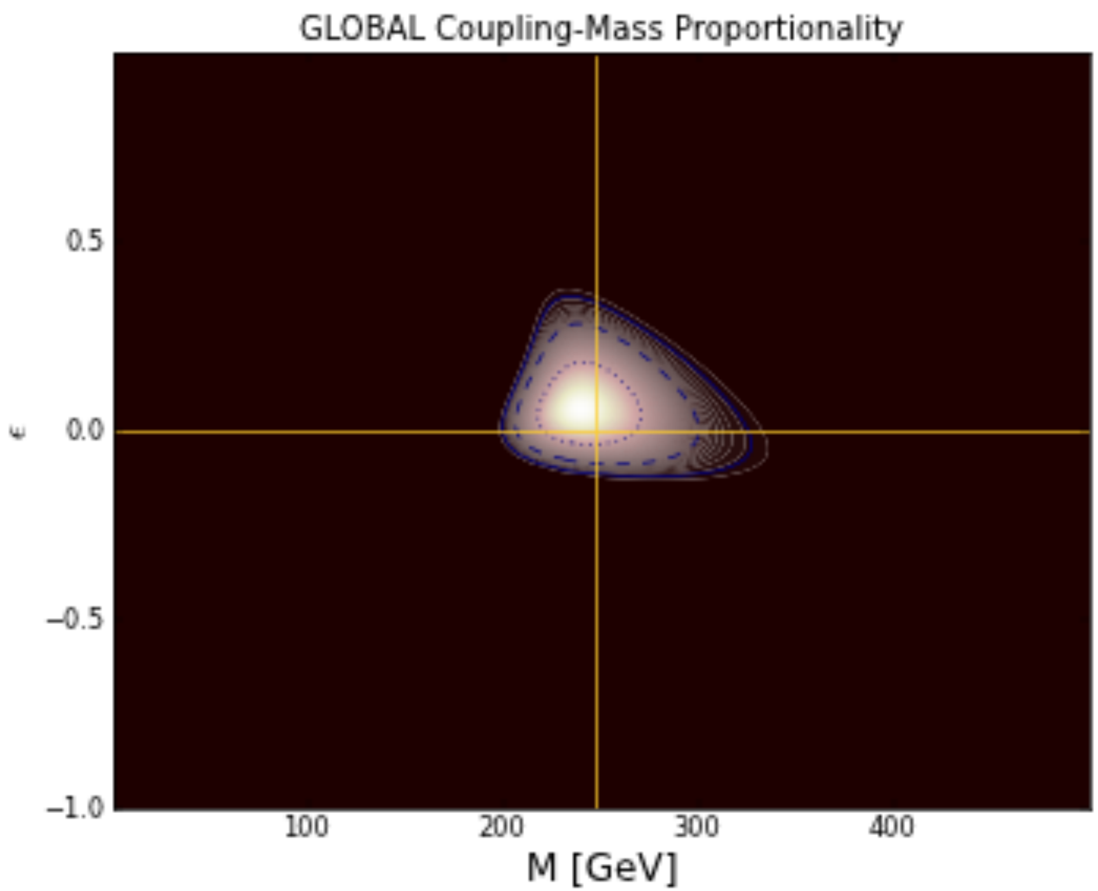
$$\lambda'_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g'_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

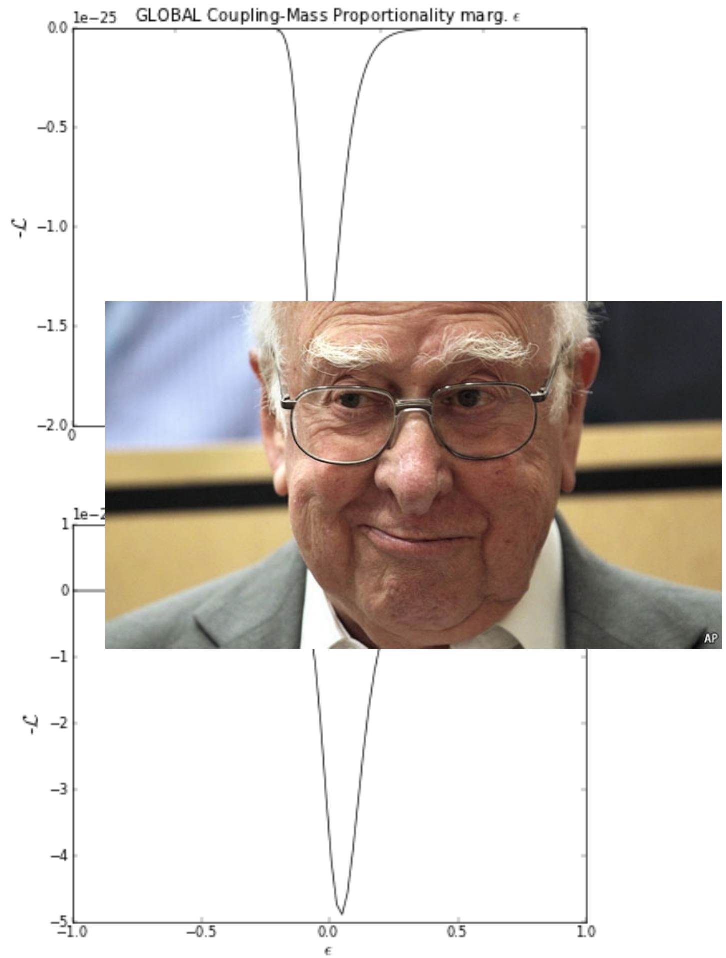
- Corresponding to rescaling factors

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

Global Experimental Constraints

- Fit for our anomalous scaling model:





Global Experimental Constraints

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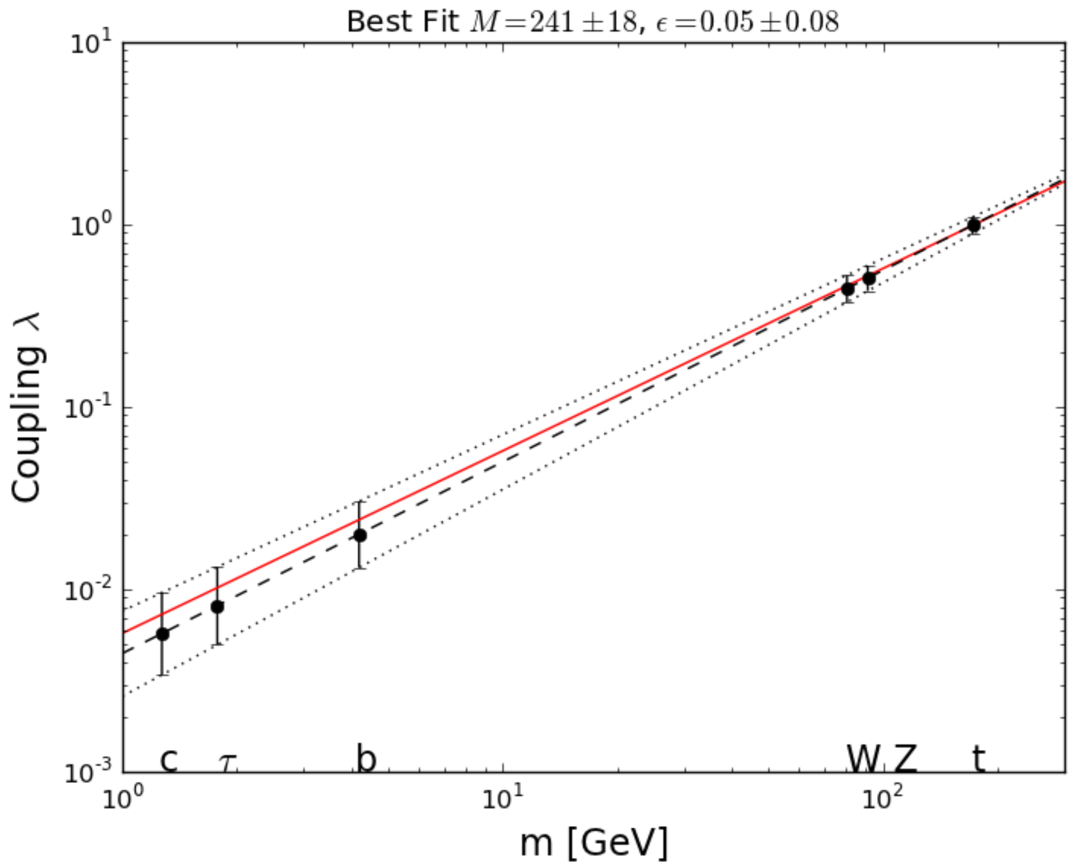

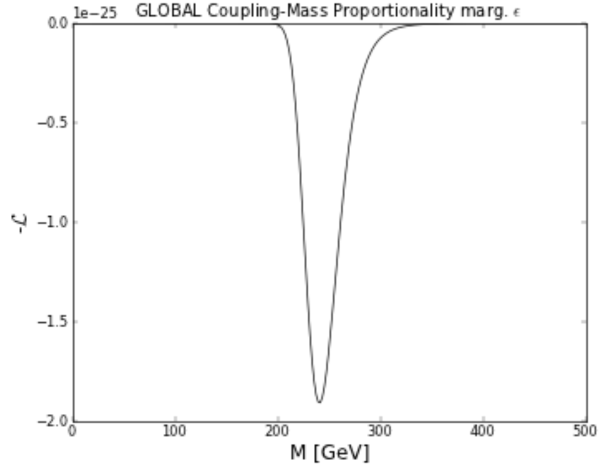

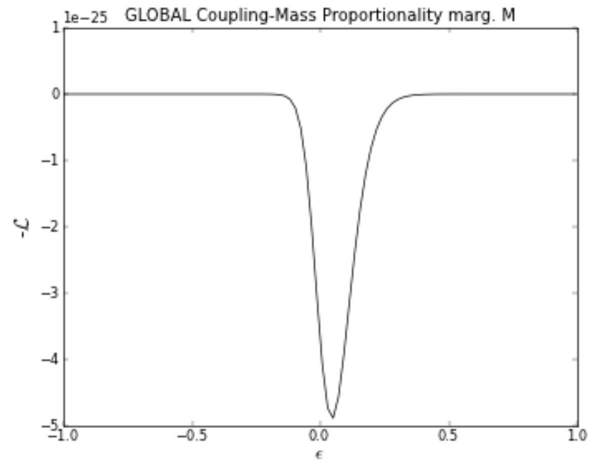

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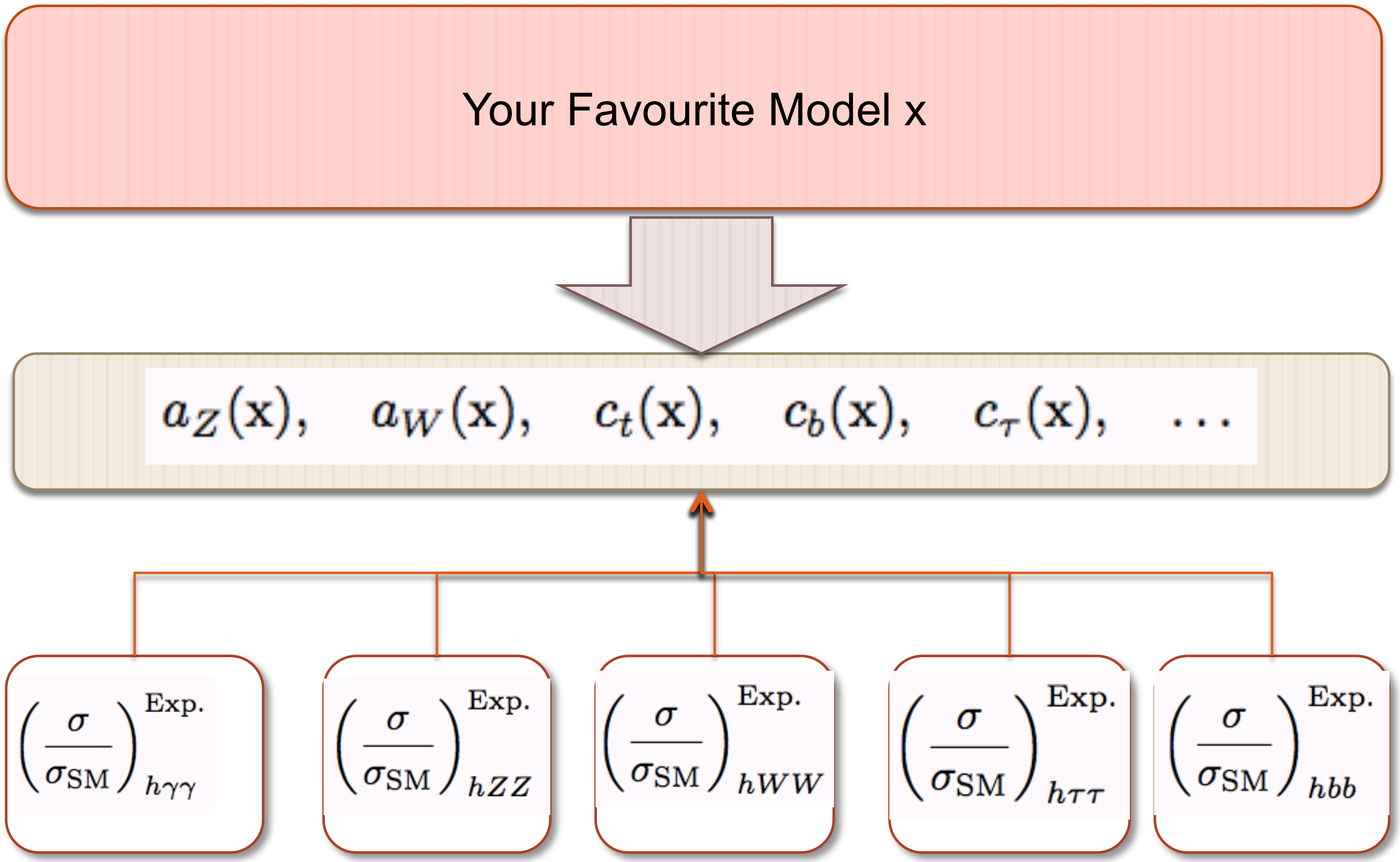

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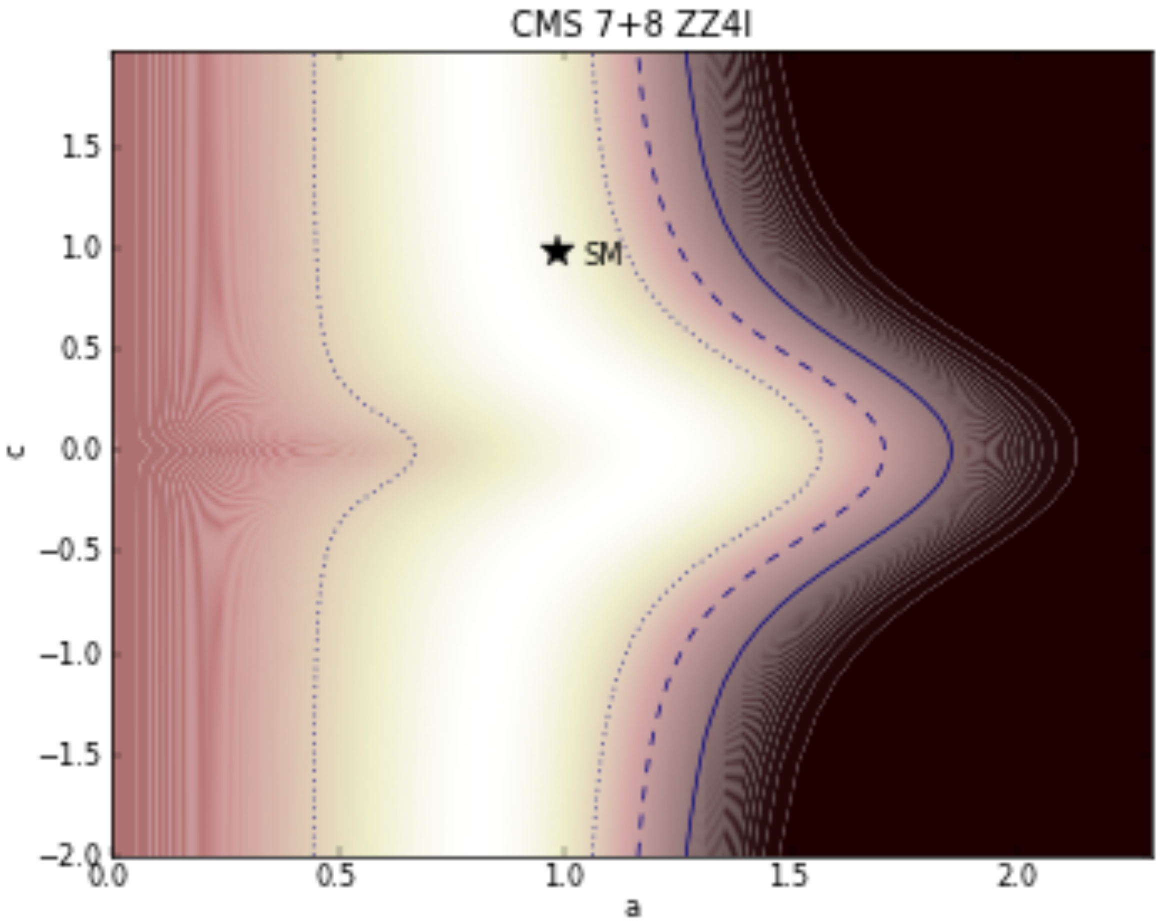
Global Experimental Constraints

- CMS



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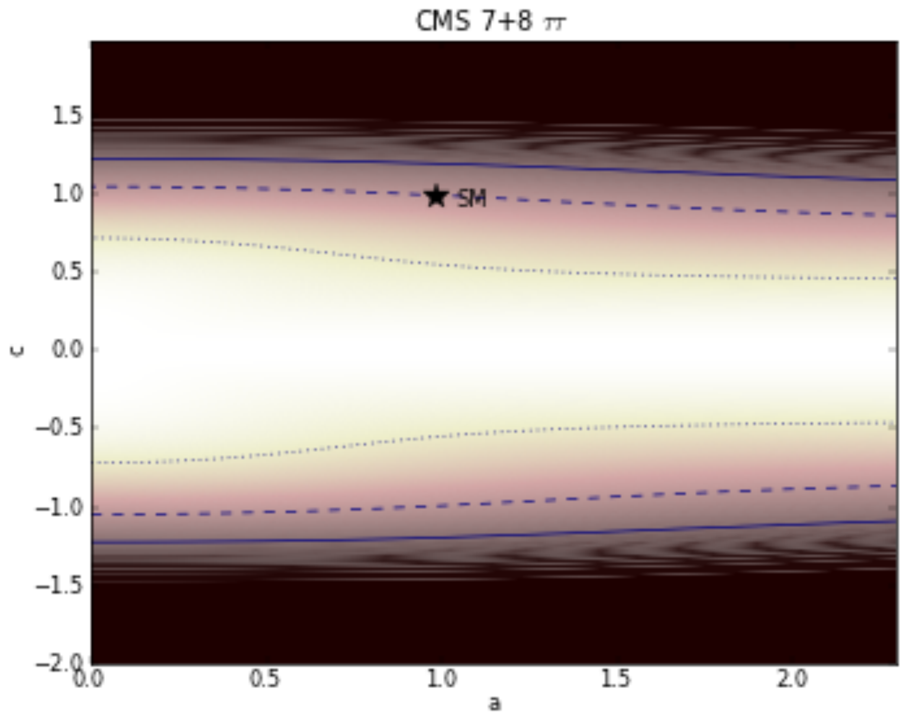

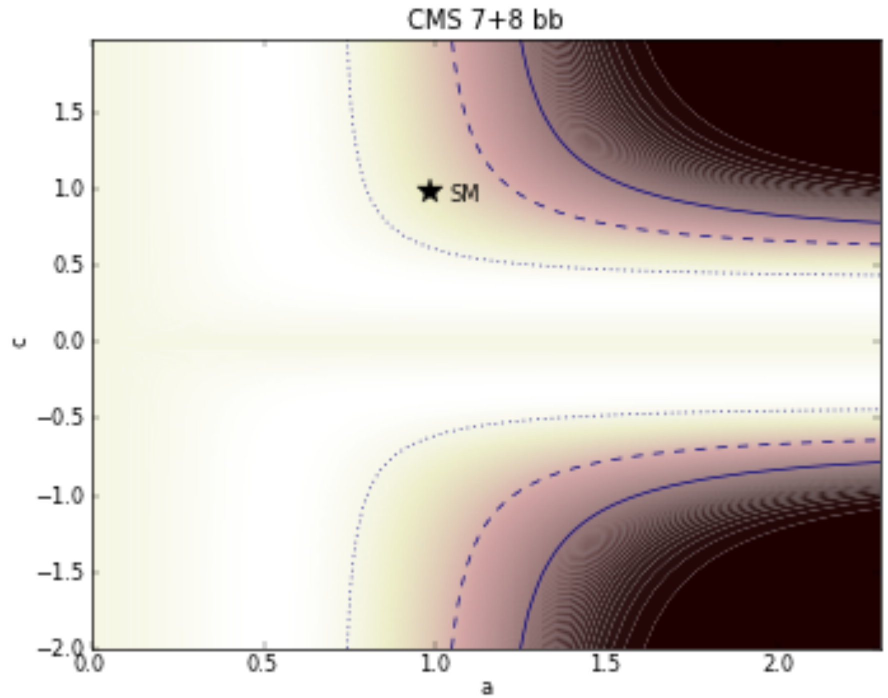

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Global Experimental Constraints

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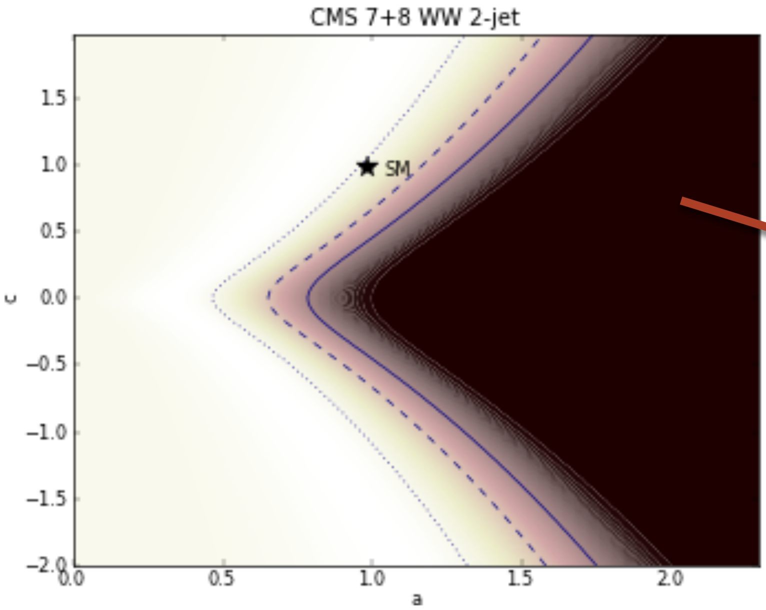

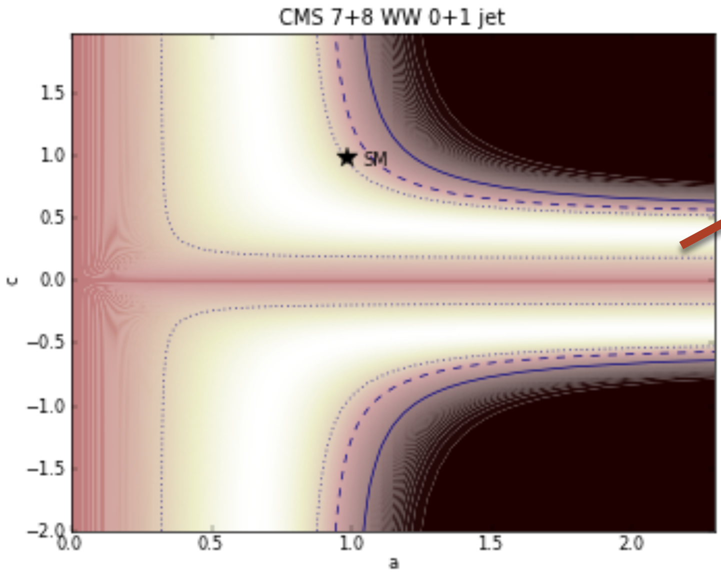

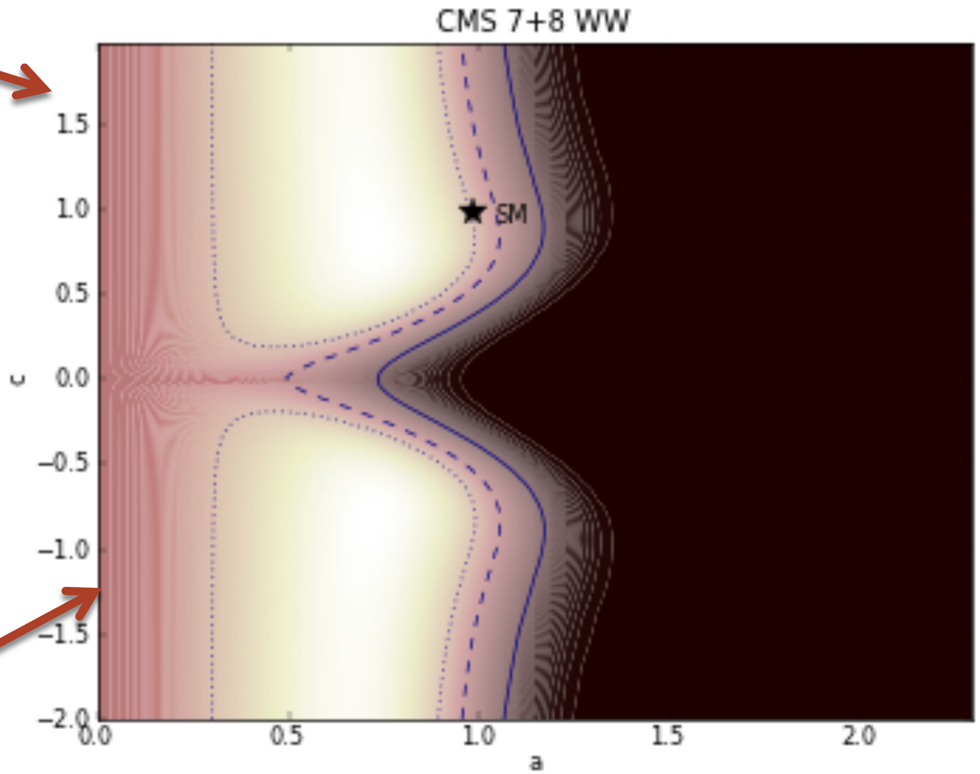

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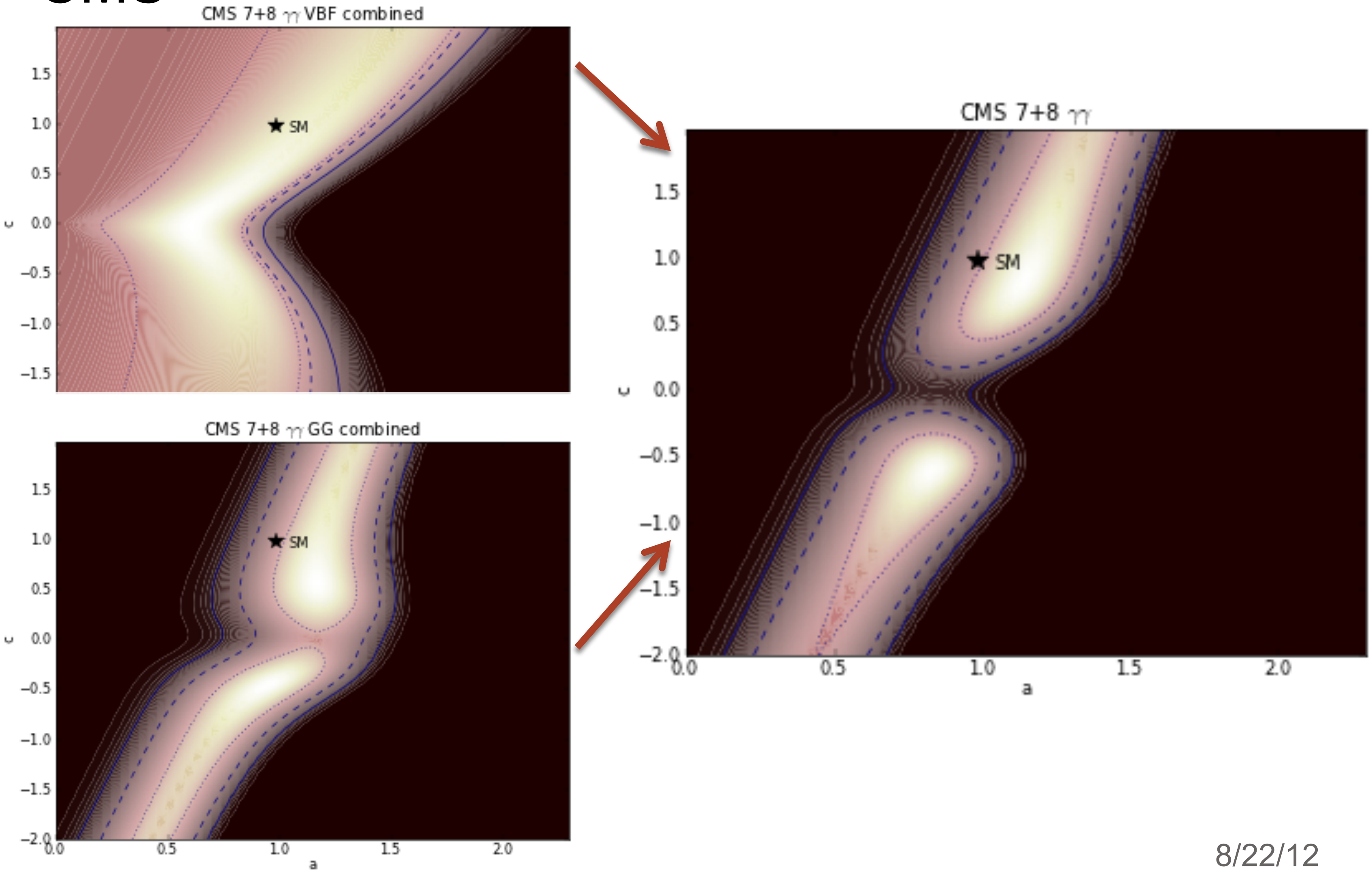

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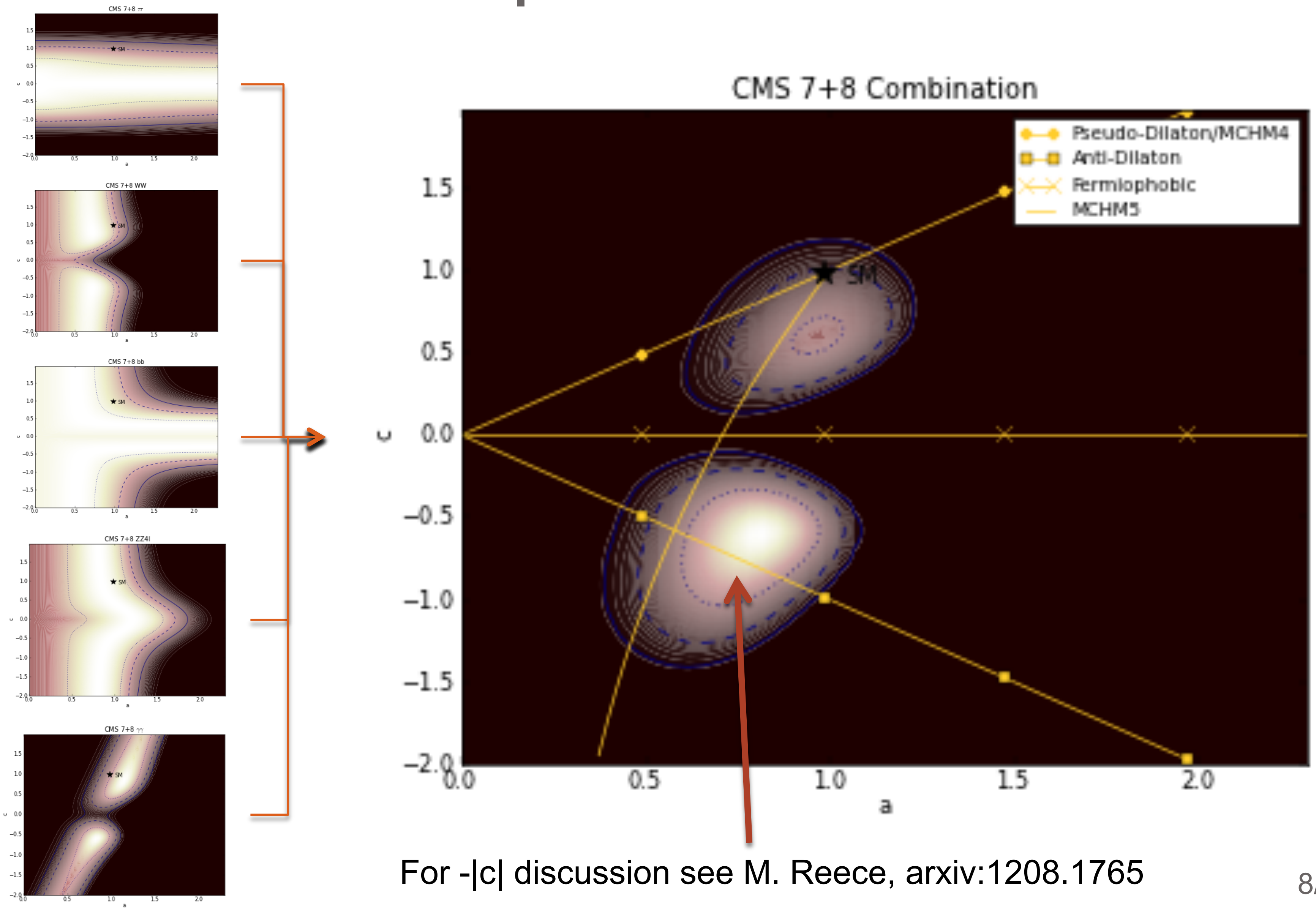

For -|c| discussion see M. Reece, arxiv:1208.1765

Global Experimental Constraints

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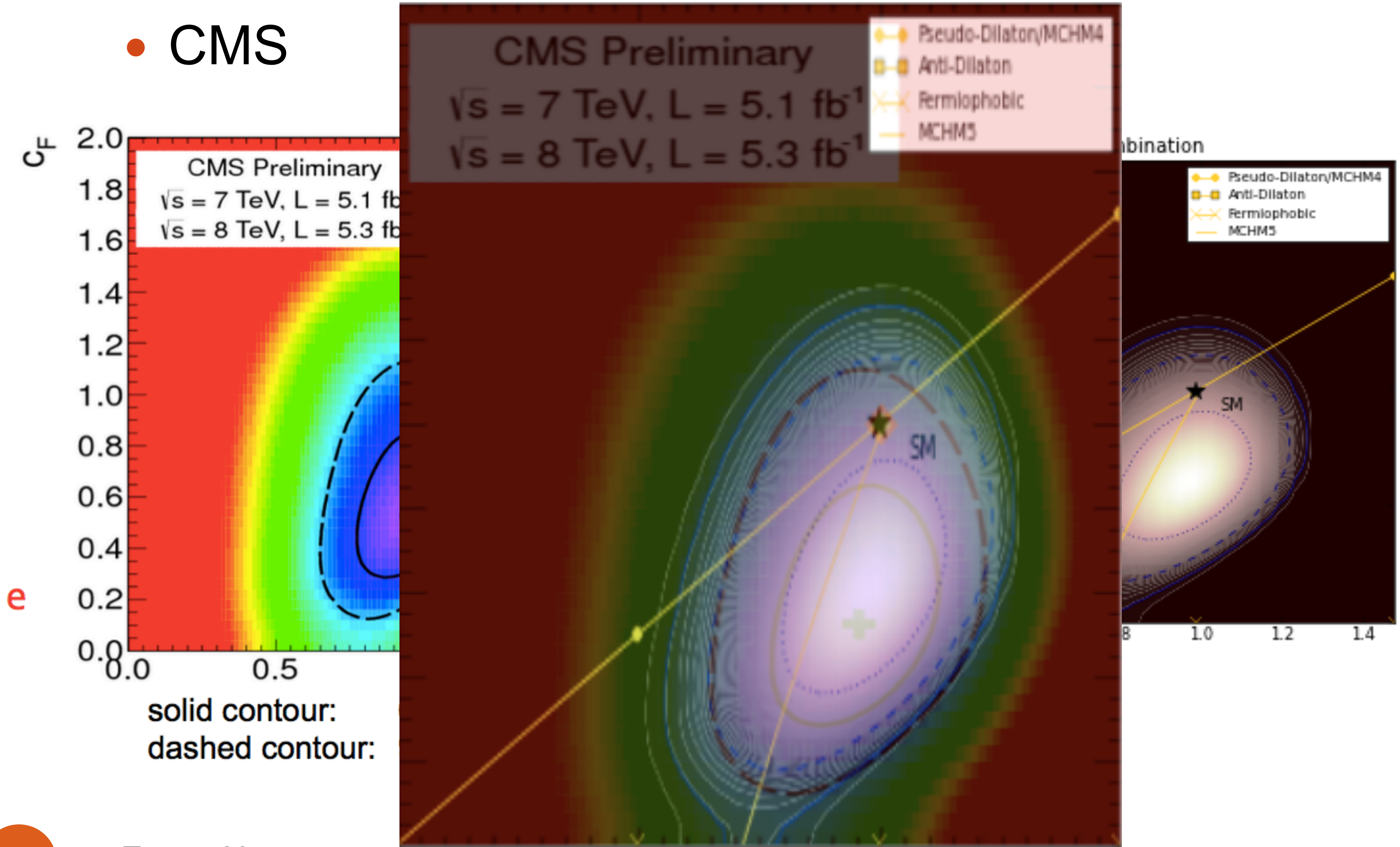
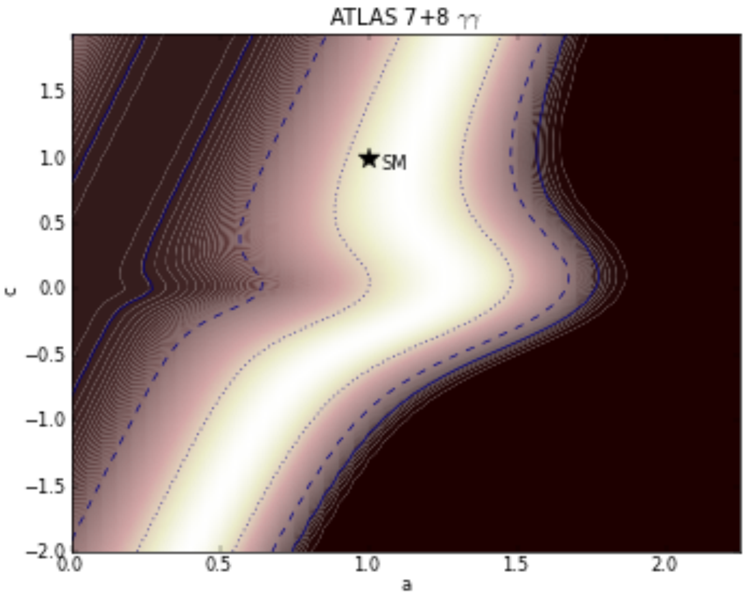
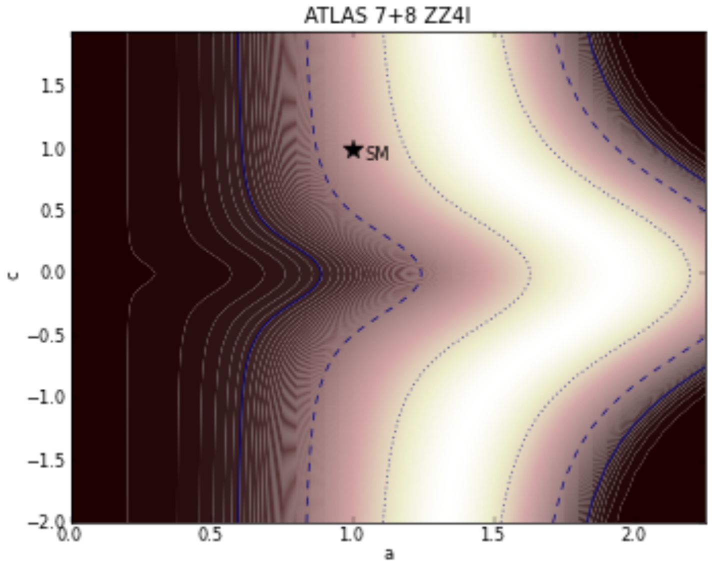
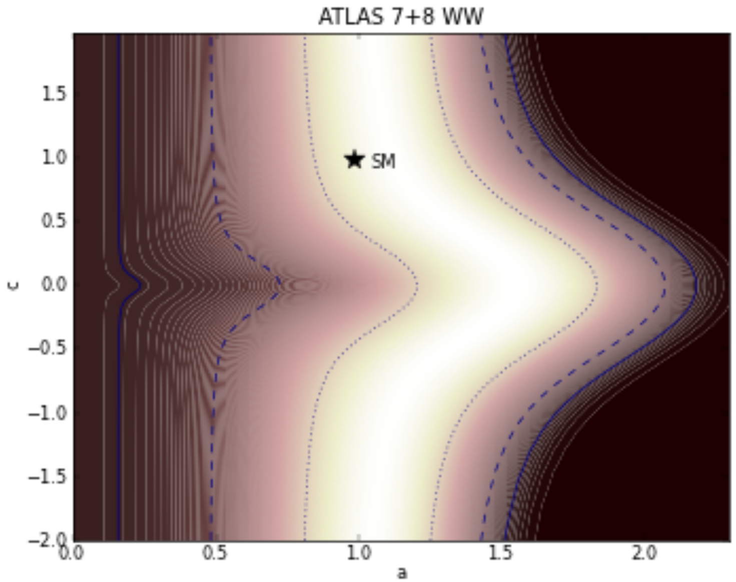


Global Experimental Constraints

- ATLAS







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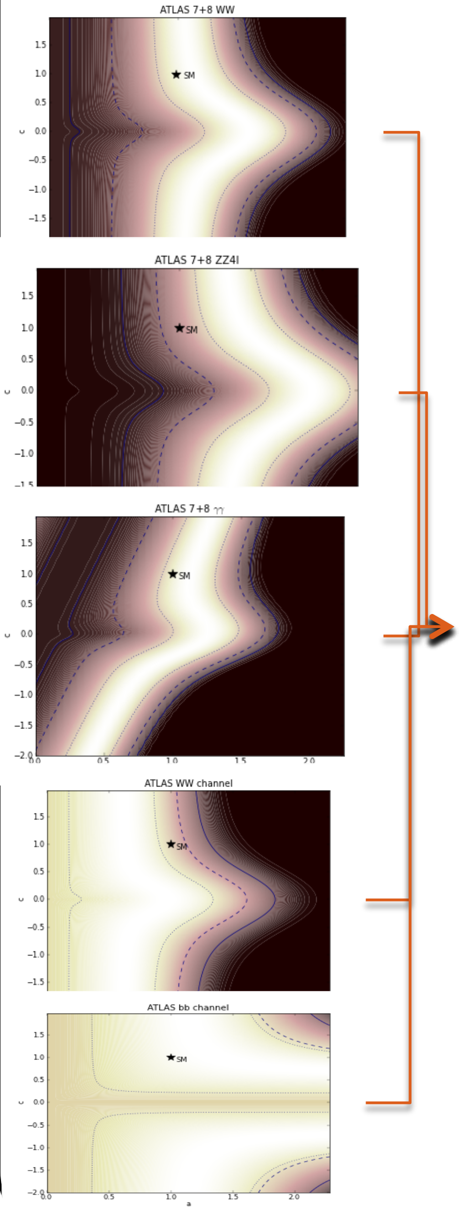

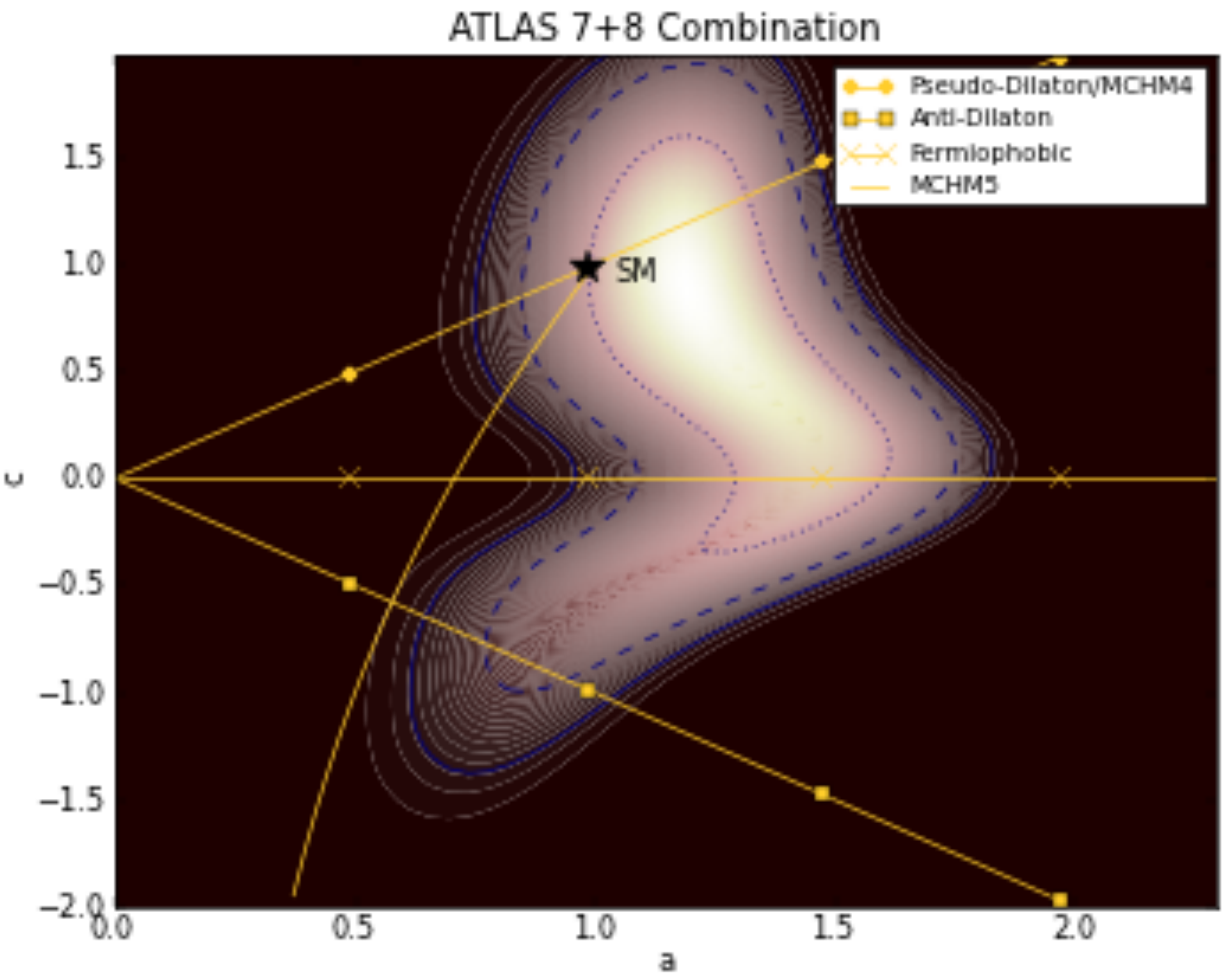

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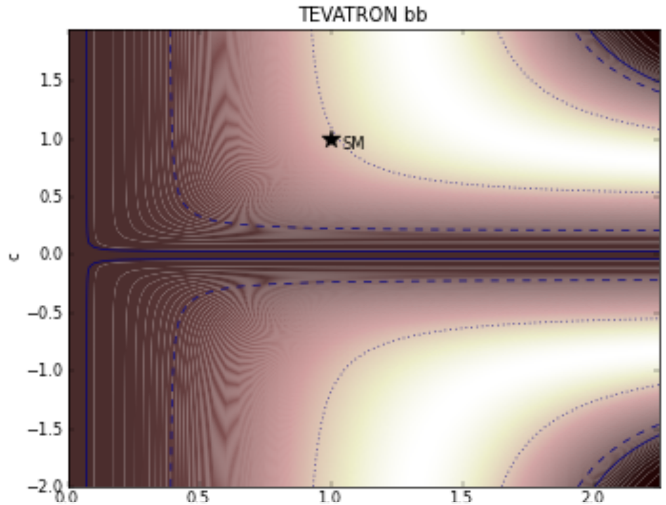

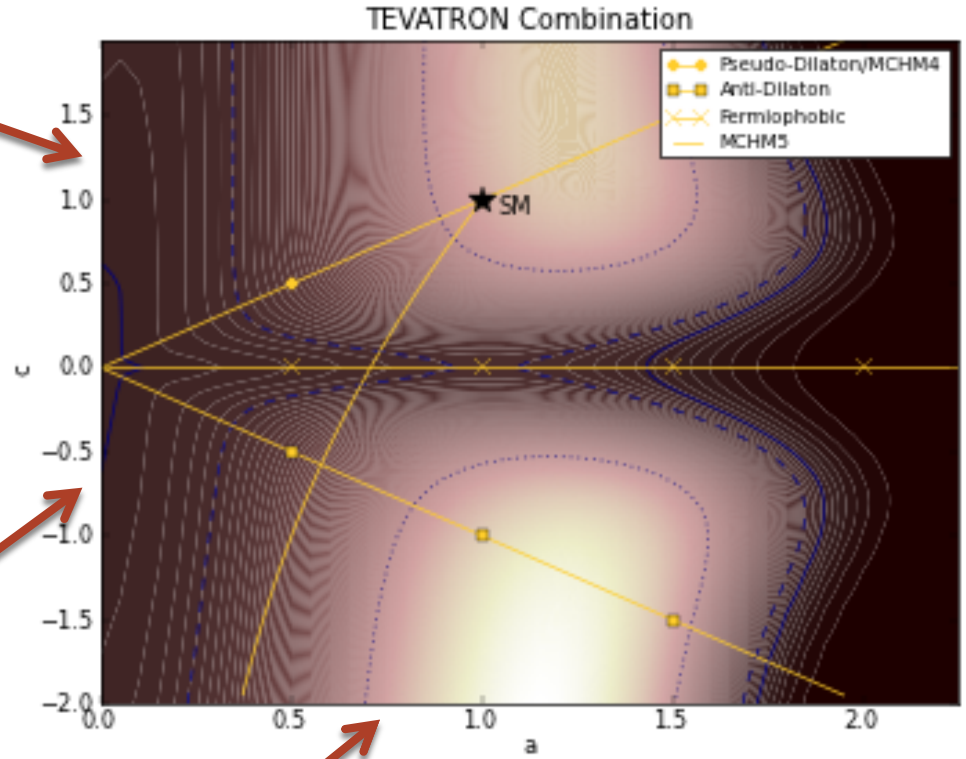

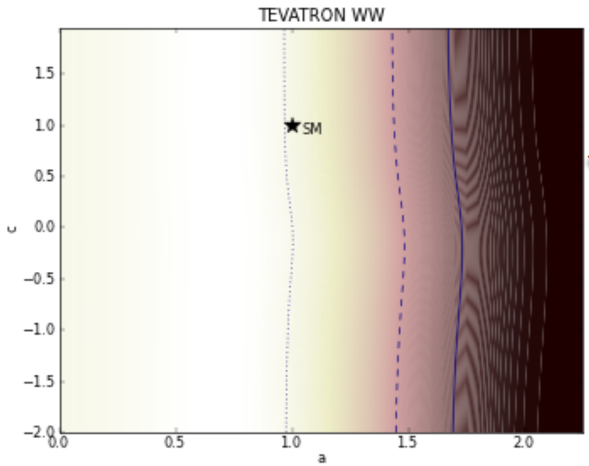

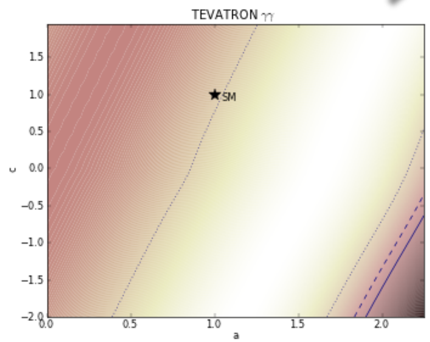

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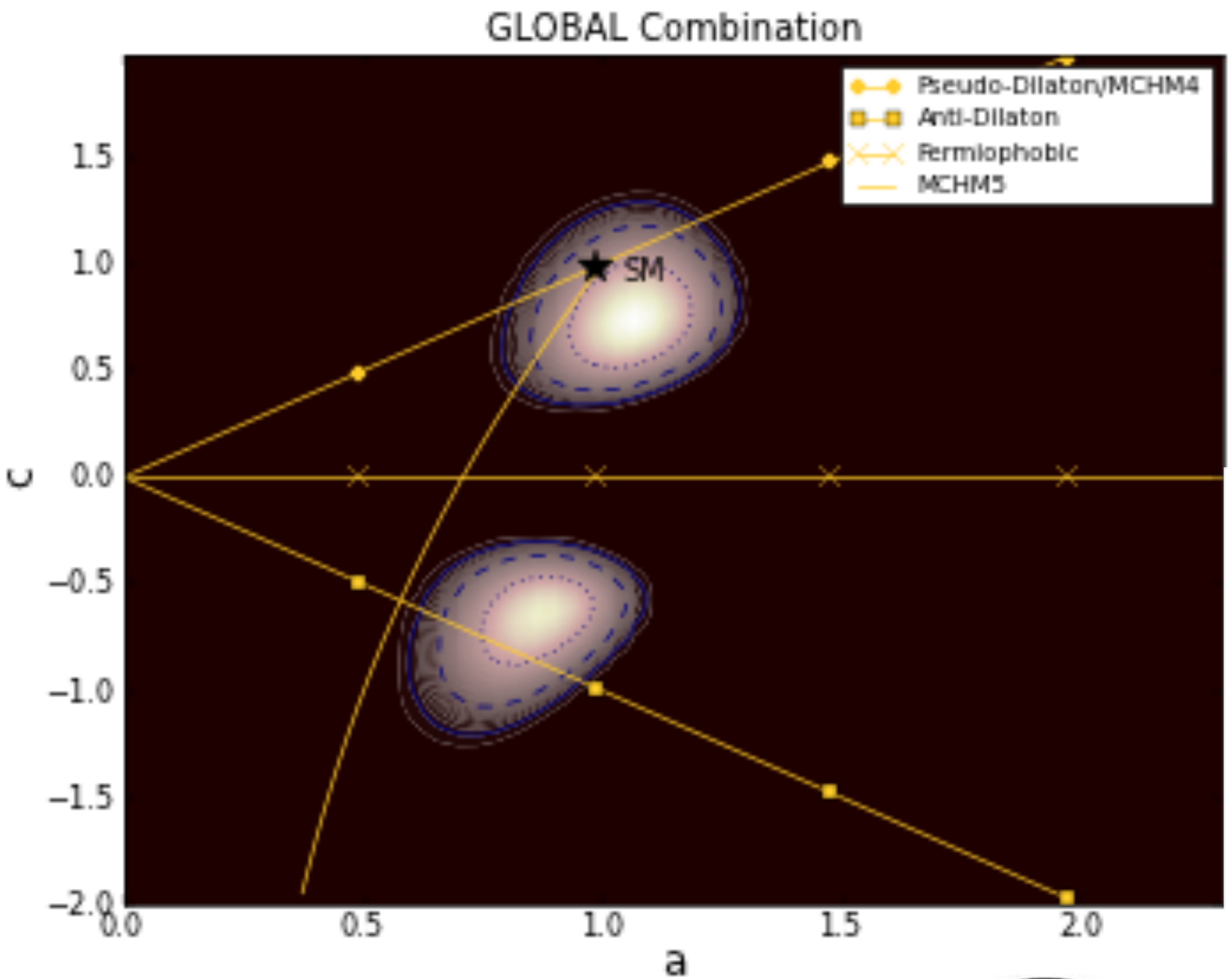
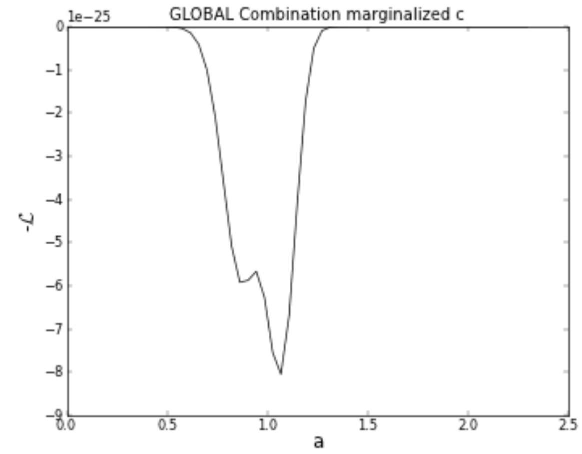
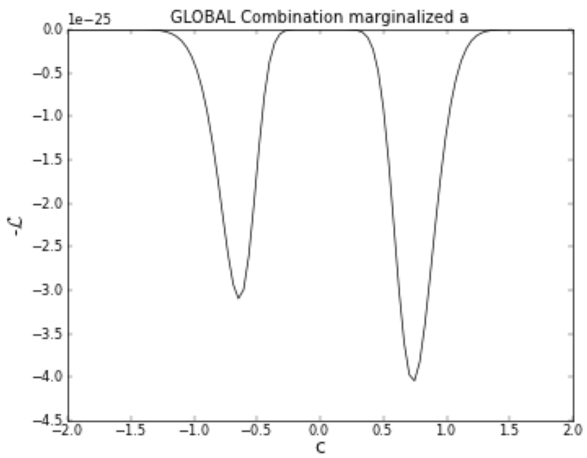
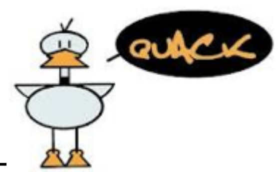








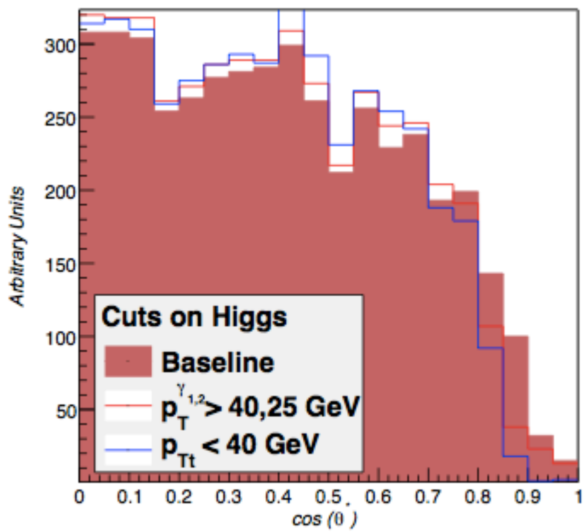
Other Higgs Properties

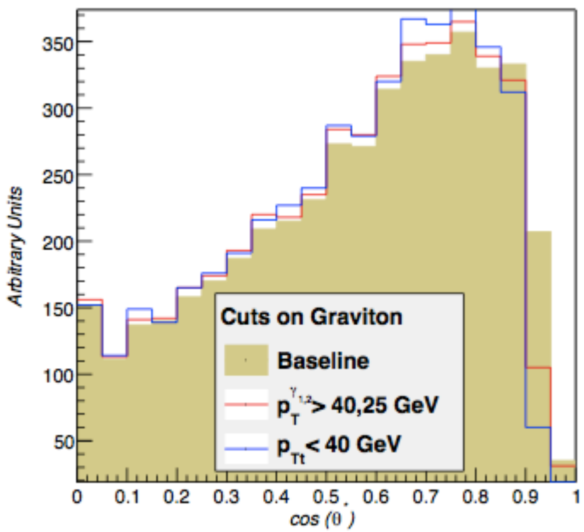
Other Higgs Properties

- Spin determination, 0 or 2?
- Many studies on 'golden' ZZ channel
- WW and diphoton channel also worth considering

See e.g. S.Y. Choi et al (0210077), E. De Sanctis et al (1103.1973), Y. Gao et al (1001.3396), J.S. Gainer et al (1108.2274)

J. Ellis and D.S. Hwang (1202.6660)





J. Ellis, R. Fok, D.S. Hwang, V. Sanz and T.Y (in progress)

- Best discrimination may come from combination!

Just appeared: S. Bolognesi et al (1208.4018)

Conclusion

Conclusion

- Discovery of a new boson of fundamental significance (it's real!)
- Consistent with SM Higgs couplings to fermions/ gauge bosons with expected power law and scale
- Spin yet to be determined
- Picture is still blurry, BSM physics could lie beneath statistical fluctuations
- Hopeful that closing the door on SM chapter will open up a new one… Wait and see!

Thank You

"Theorists used to have difficulty believing anything that wasn't experimentally proven. Now they believe anything that isn't experimentally disproven."

-Unknown