Constraining New Physics with the Higgs

Will discuss two cases:

I. Anomalous fermion-gauge boson couplings (dipole operators) in processes with a Higgs*

II. New physics in one-loop Higgs couplings hgg and $h\gamma\gamma$: color octet scalars and the top-quark Yukawa coupling**

- *based on work with
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- **based on work with
  - Han Phoon, ISU student
  - Xiao-Gang He, NTU Taipei
  - Yong Tang, NTHU Taiwan

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cmdm and cedm couplings

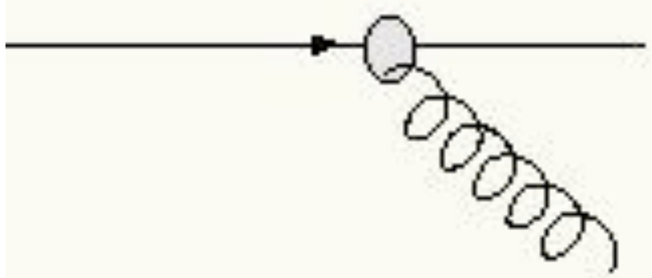
- consider new physics in the form of anomalous color magnetic (CMDM) and electric (CEDM) dipole moments

$$\mathcal{L} = \frac{g_s}{2}\, d_{qG}\; \bar{f}_L\; T^a \sigma^{\mu\nu}\; f_R\; G^a_{\mu\nu} + \;\mathrm{h.c.}$$

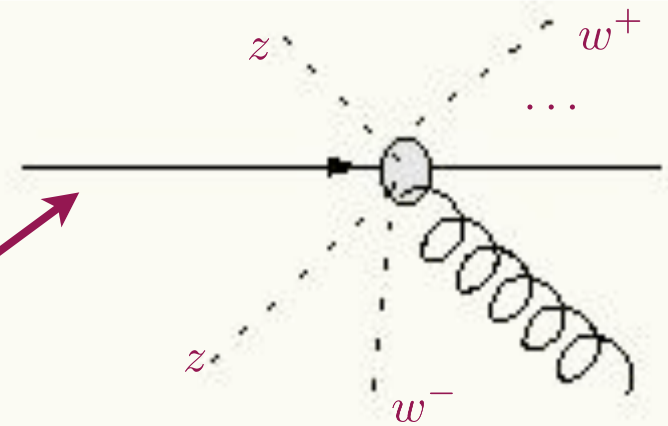
- as it stands, this is not fully gauge invariant under the SM
- there are a few ways to think about this:
  - this is just the unitary gauge version of a Lagrangian in which the spontaneously broken gauge symmetry is nonlinearly realized
  - we need to fix gauge invariance using a scalar doublet with a vev as in the SM

gauge invariance - related couplings

$$\mathcal{L} = \frac{g_s}{2}\ \bar{f}\ T^a \sigma^{\mu\nu} \left(a_f^g + i\gamma_5 d_f^g\right)\ f\ G^a_{\mu\nu}.$$

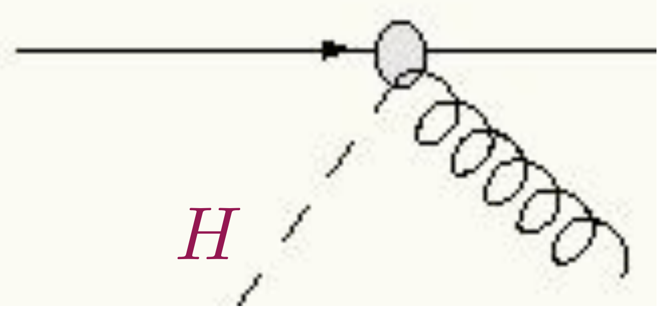


without H



$$\mathcal{L} = \bar{q}_L\ T^a \sigma_{\mu\nu} \Sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix}\ q_R\ G^{a\mu\nu}$$

with H



$$\mathcal{L} = g_s \frac{d_{uG}}{\Lambda^2}\ \bar{q}\sigma^{\mu\nu} T^a u\ \tilde{\phi} G^a_{\mu\nu} + g_s \frac{d_{dG}}{\Lambda^2}\ \bar{q}\sigma^{\mu\nu} T^a d\ \phi G^a_{\mu\nu}\ +\ \text{h.c.}$$

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top-quark couplings at LHC

- start from $\mathcal{L} = g_s \frac{d_{tG}}{\Lambda^2}\, \bar{q}_{3L}\sigma^{\mu\nu}T^a t_R\, \tilde{\phi} G^a_{\mu\nu} + \text{ h.c.}$
- usual constraints from processes without Higgs

$$\mathcal{L} = \frac{g_s}{2}\, \bar{t}\, T^a \sigma^{\mu\nu} \left(a_t^g + i\gamma_5 d_t^g\right)\, t\, G^a_{\mu\nu}$$

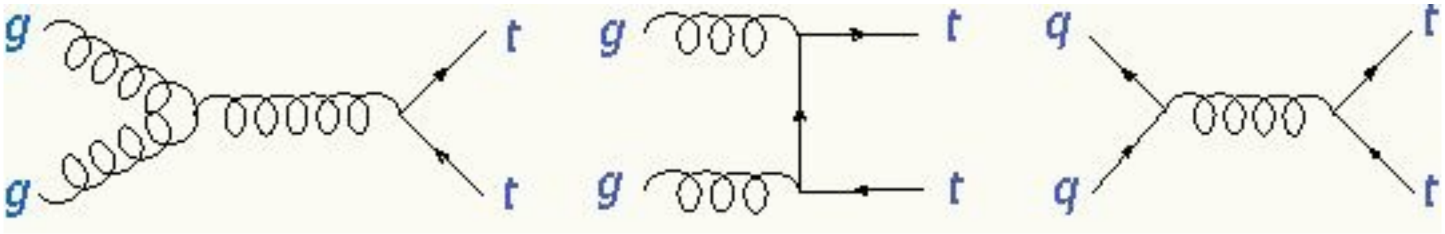
$$a_t^g = \frac{\sqrt{2}\, v}{\Lambda^2} \mathrm{Re}(d_{tG})$$ cmdm: CP conserving

$$d_t^g = \frac{\sqrt{2}\, v}{\Lambda^2} \mathrm{Im}(d_{tG})$$ cedm: CP violating

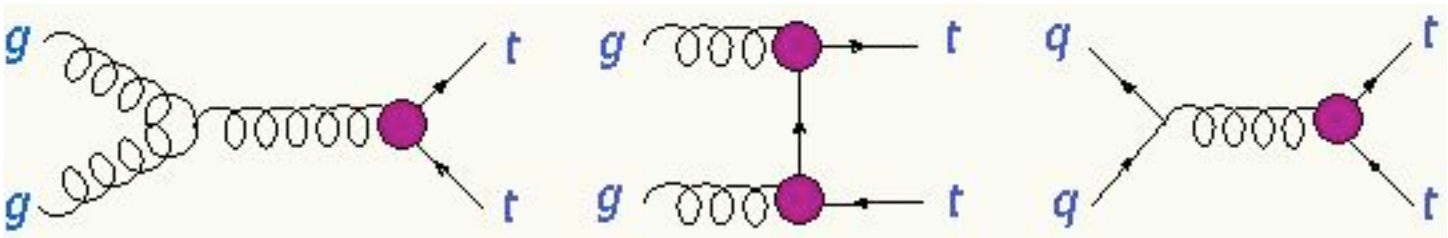
- but they also appear and can be constrained in Higgs production associated with a top-quark pair
- here we compare the two

top quark pair production

- SM at LO for LHC



- receives new contributions from modified couplings



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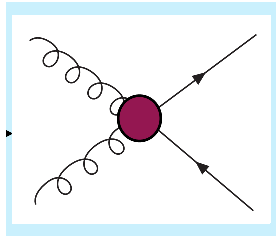

- the resulting cross-section is a quartic polynomial in the new couplings with only even powers of the CP-odd coupling

bounds from the cross-section

- Use SM NLO calculation from the literature but treat the NP as well as its interference with SM at LO (FeynRules + Madgraph)
- For 8TeV we extract constraints from comparing the ATLAS lepton plus jets cross-section to the theoretical expectation
  ATLAS-CONF-2012-149 + Aliev et. al Comput. Phys. Commun. 182, 1034 (2011) (HATHOR)

$$\frac{\sigma(t\bar{t})_{Exp}}{\sigma(t\bar{t})_{TH}} = \frac{(241 \pm 32)\ \text{pb}}{(238^{+22}_{-24})\ \text{pb}} = 1.01 \pm 0.17$$

- For 14 TeV we use the NLO theoretical cross-section
  (M. Beneke, P. Falgari, S. Klein, C. Schwinn arXiv:1112.4606) $\sigma_{(NLO)} = (884^{+125}_{-121})\text{pb}$
  - and we assume experiment will agree with SM and theory error will dominate
  - really comparing a 17% error at 8 TeV with a 14% error at 14 TeV

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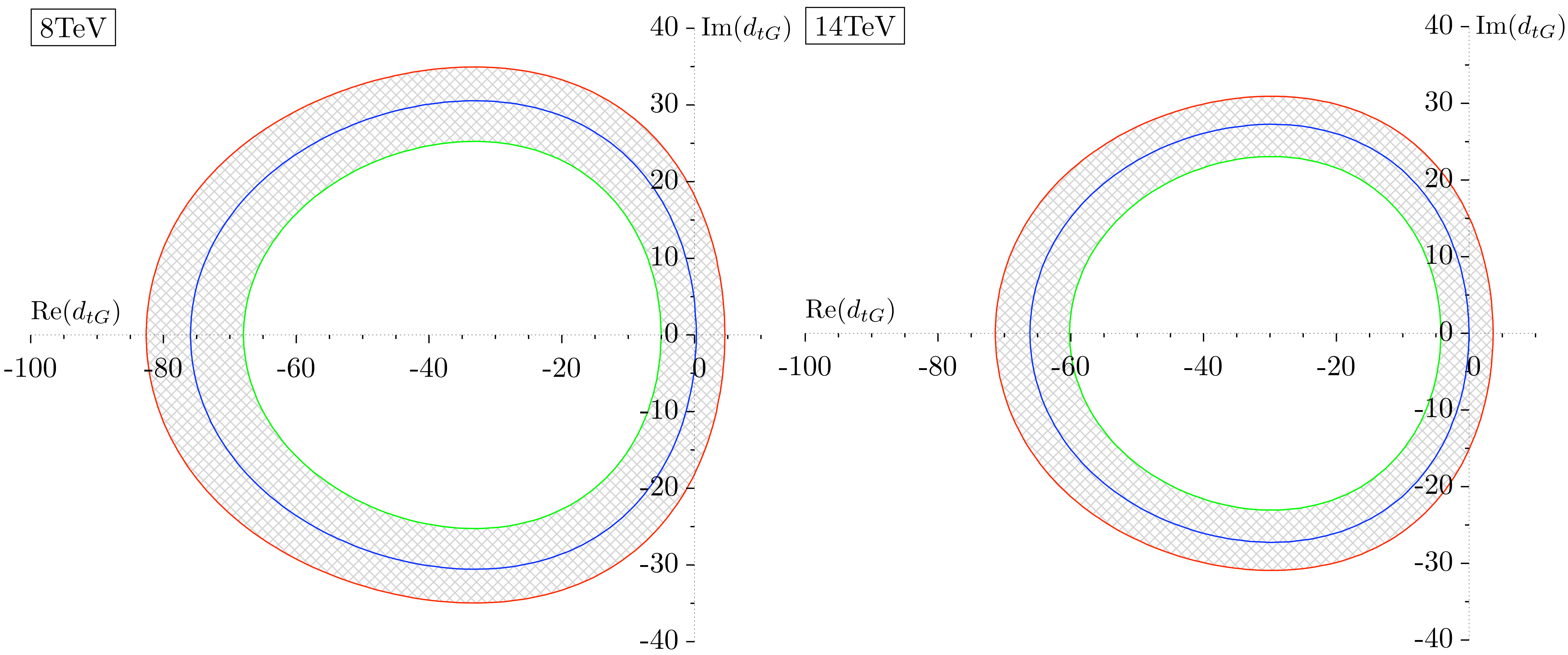
top quark pair production



$$-0.034 < m_t a_t^g < 0.031 \quad \text{or} \quad -0.55 < m_t a_t^g < -0.46, \quad \text{and} \quad |d_t^g| < 0.12/m_t$$

$$-0.029 < m_t a_t^g < 0.024 \quad \text{or} \quad -0.478 < m_t a_t^g < -0.402, \quad \text{and} \quad |d_t^g| < 0.10/m_t.$$

see also Hioki, and Ohkuma [Phys. Rev. D 83, 114045 (2011)

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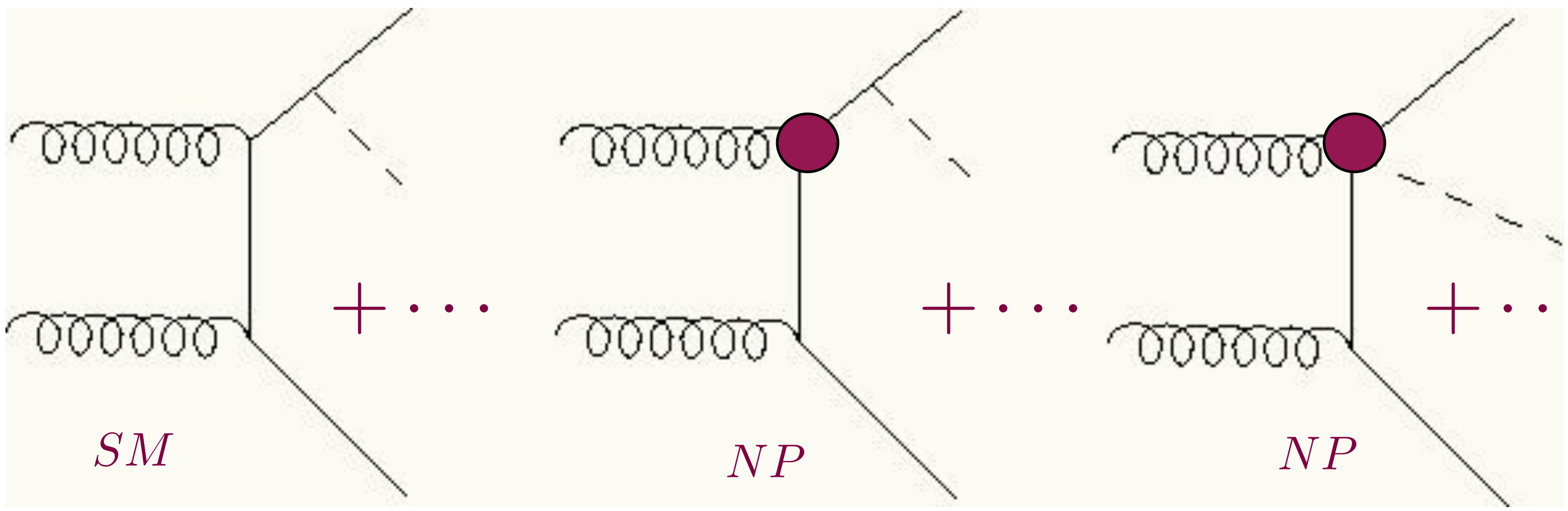
Higgs production associated with top-quark pair

- affected by the same NP couplings

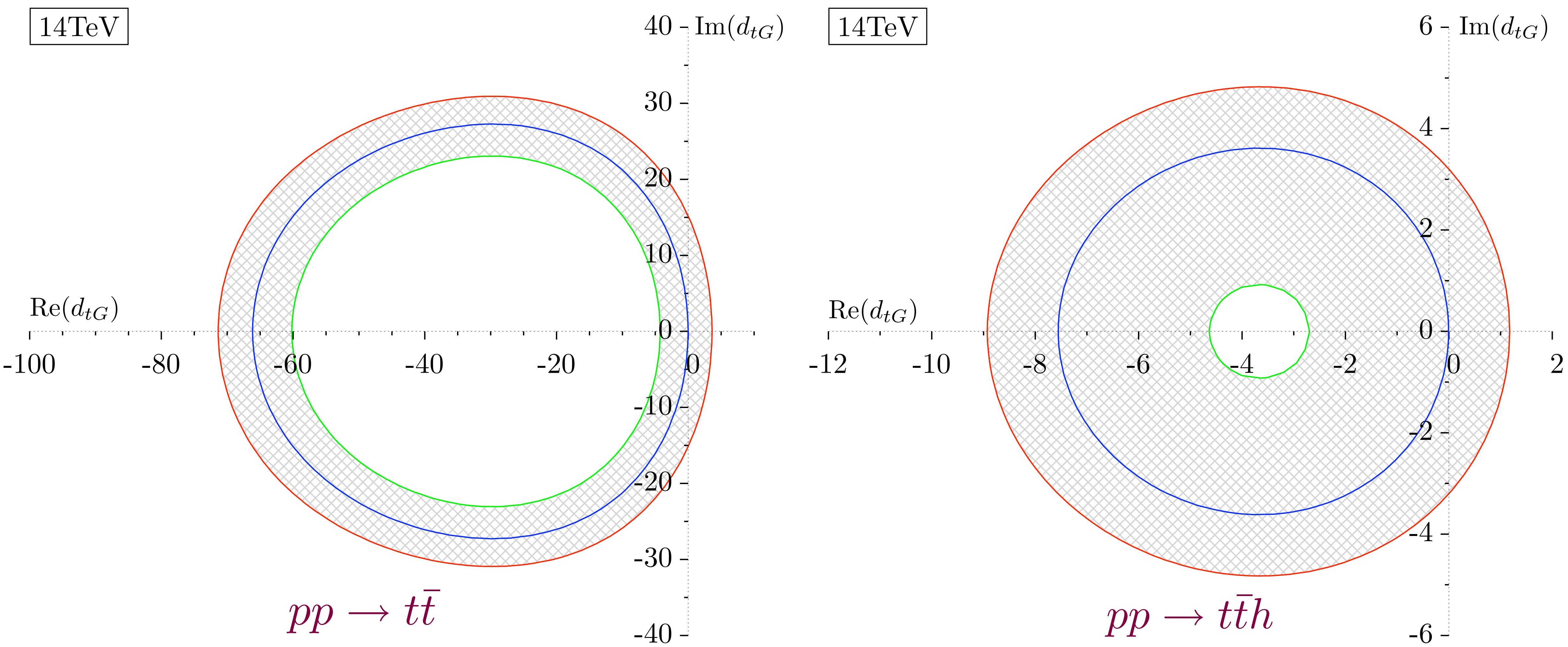


- cross-section is again a quartic polynomial in NP with only even powers of the CEDM
- constrain by comparing to SM at NLO (15%-18%)

$$\sigma(pp \to t\bar{t}h)_{NLO} = (611^{+92}_{-110})\text{fb}$$

S. Dittmaier et al. (LHC Higgs Cross Section Working Group Collaboration), arXiv:1101.0593.

$pp \to t\bar{t}$ vs $pp \to t\bar{t}h$



- better for "natural" CMDM (values near 0)
- much better overall (allowing cancellation with SM)
- much better for CEDM (imaginary part)

$-0.06 < m_t a_t^g < 0.03$ or $-0.016 < m_t a_t^g < 0.008$,
and $|d_t^g| < 0.02/m_t$.

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Decay distributions

- The cross-sections would allow at 1σ (LHC14)
  - $0.1/m_t$ CEDM and $0.03/m_t$ CMDM (top pairs)
  - $0.02/m_t$ CEDM and $0.01/m_t$ CMDM (top pairs + h)
- It may be possible to improve the bounds by measuring asymmetries
  - CEDM of top from literature: 5σ statistical sensitivity with 10 fb^{-1} to d^g_t of order $0.1/m_t$ possible **Gupta, Mete, G.V. Phys.Rev. D80 (2009) 034013, J Sjolin** J.Phys. G29 (2003) 543-560, Hioki, and Ohkuma, ...
  - CEDM and CMDM at the $0.05/m_t$, $0.03/m_t$ possible with 20 fb^{-1} of LHC8 data at 2σ using spin correlations **Baumgart and Tweedie, JHEP 1303 (2013) 117**

T-odd asymmetries

- Compare $pp \to t\bar{t},\ pp \to t\bar{t}h$
  - take muonic decay for all top quarks
  - construct T-odd asymmetries with momenta of muon, beam and top (b-jet)
  - impose basic acceptance and separation cuts for muons and b, as well as require missing E_T but do nothing about Higgs
- 1σ statistical sensitivity to CEDM

$$\begin{array}{rcl} \vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) & \to & 0.009/m_t \text{ with } 10\text{fb}^{-1} \text{ in } t\bar{t} \\ \vec{p}_{beam} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})\ \vec{p}_{beam} \cdot (\vec{p}_{\mu^+} - \vec{p}_{\mu^-}) & \to & 0.007/m_t \text{ with } 1000\text{fb}^{-1} \text{ in } t\bar{t}h \end{array}$$

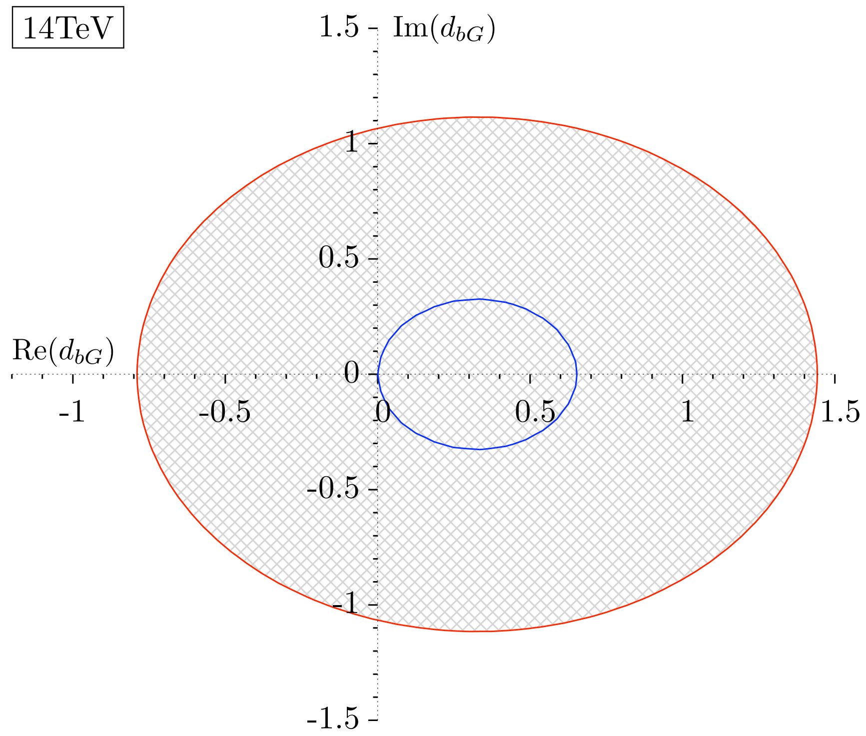
- a bit better than cross-sections but very hard in the second case (with h) as at least 10^4 events to measure an asymmetry at the % level and the cross section is tiny.

b-quark couplings

- NP effects in pair production are overwhelmed by QCD
- need b-pair production in association with Higgs
- compare to SM NLO prediction (Phys.Rev. D70 (2004) 074010: Dittmaier, Kramer, Spira)

$$\sigma(pp \to b\bar{b}hX)_{SM} \quad = \quad (5.8 \pm 1.0) \times 10^2 \text{ fb}$$

- require NP corrections to remain below 1 σ (17%)



$$-1.3 \times 10^{-4} < m_b a_b^g < 2.4 \times 10^{-4}$$
$$|d_b^g| < (1.7 \times 10^{-4})/m_b$$

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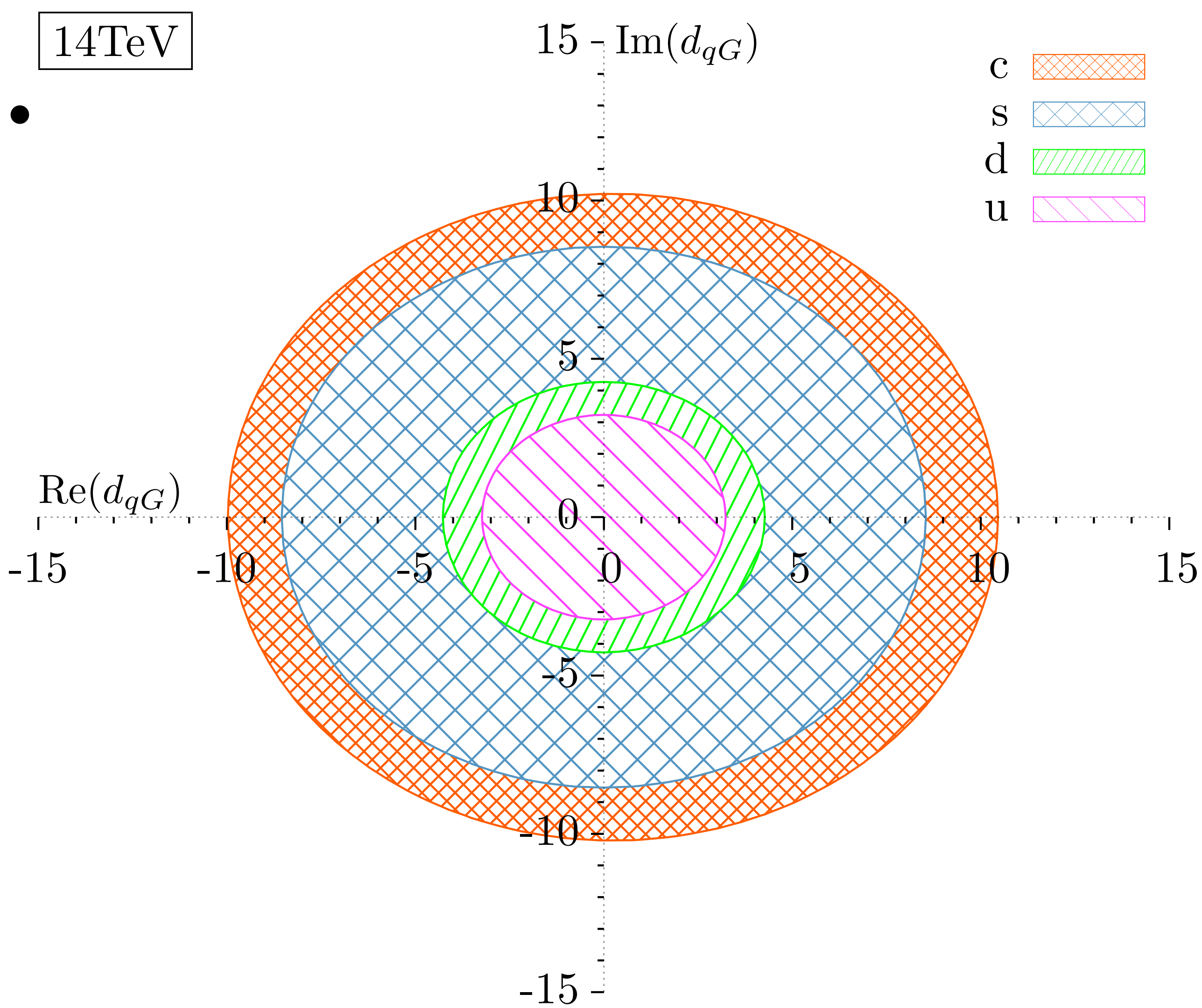
light quarks including charm

- NP is again buried in QCD background, only hope in processes with a higgs
- look for NP in pp $\to$ hX ($qg \to qh$ and $q\bar{q} \to hg$)
- in SM these subprocesses are dominated by charm
  - interference between NP and SM is negligible
- could look in higgs plus one jet mode ... not now
- require NP to fall below theoretical uncertainty of dominant gluon fusion SM process

Results for LHC 14 TeV

- From $qg \to qh$ and $q\bar{q} \to hg$

$$\begin{aligned}\sigma(pp \to hX)_{NP} &\approx 0.7\left[\mathrm{Re}(d_{uG})^2+\mathrm{Im}(d_{uG})^2\right] \\ &+ 0.4\left[\mathrm{Re}(d_{dG})^2+\mathrm{Im}(d_{dG})^2\right]+0.1\left[\mathrm{Re}(d_{sG})^2+\mathrm{Im}(d_{sG})^2\right] \\ &- 0.034\,\mathrm{Re}(d_{cG})+0.07\left[\mathrm{Re}(d_{cG})^2+\mathrm{Im}(d_{cG})^2\right]\ \mathrm{pb.}\end{aligned}$$



- whereas SM at NLO for m_h=125 (Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables , Dittmaier et. al.)

$$\sigma(pp \to hX) = (49.97^{+7.3}_{-7.0})\ \mathrm{pb}$$

- require NP < 1 σ theory error

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Summary

TABLE I. Summary of results for 1σ bounds that can be placed on the CEDM and CMDM couplings of quarks at the LHC. The last column shows the effective new physics scale than can be probed by the LHC with the given process, the two numbers corresponding to the CMDM and the CEDM respectively.

Process	CMDM	CEDM	Λ (TeV)
$\sigma(pp \to t\bar{t})$ 8 TeV	$-0.034 \lesssim m_t a_t^g \lesssim 0.031$	$\lvert m_t d_t^g \rvert \lesssim 0.12$	(1.5, 0.7)
$\sigma(pp \to t\bar{t})$ 14 TeV	$-0.029 \lesssim m_t a_t^g \lesssim 0.024$	$\lvert m_t d_t^g \rvert \lesssim 0.1$	(1.5, 0.7)
$A_1(pp \to t\bar{t})$ 14 TeV	$\cdots$	$\lvert m_t d_t^g \rvert \lesssim 0.009$	(-, 2.5)
$\sigma(pp \to t\bar{t}h)$ 14 TeV	$-0.016 \lesssim m_t a_t^g \lesssim 0.008$	$\lvert m_t d_t^g \rvert \lesssim 0.02$	(2, 1.7)
$A_{1,2}(pp \to t\bar{t}h)$ 14 TeV	$\cdots$	$\lvert m_t d_t^g \rvert \lesssim 0.007$	(-, 3)
$\sigma(pp \to b\bar{b}h)$ 14 TeV	$-1.3 \times 10^{-4} \lesssim m_b a_b^g \lesssim 2.4 \times 10^{-4}$	$\lvert m_b d_b^g \rvert \lesssim 1.7 \times 10^{-4}$	2.7
$\sigma(pp \to hX)$ 8 TeV	$\lvert a_u^g \rvert \lesssim 3.5 \times 10^{-4}$ GeV^{-1}	$\lvert d_u^g \rvert \lesssim 3.5 \times 10^{-4}$ GeV^{-1}	1
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_u^g \rvert \lesssim 1.2 \times 10^{-4}$ GeV^{-1}	$\lvert d_u^g \rvert \lesssim 1.2 \times 10^{-4}$ GeV^{-1}	1.7
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_d^g \rvert \lesssim 1.6 \times 10^{-4}$ GeV^{-1}	$\lvert d_d^g \rvert \lesssim 1.6 \times 10^{-4}$ GeV^{-1}	1.5
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_s^g \rvert \lesssim 3.3 \times 10^{-4}$ GeV^{-1}	$\lvert d_s^g \rvert \lesssim 3.3 \times 10^{-4}$ GeV^{-1}	1
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_c^g \rvert \lesssim 3.9 \times 10^{-4}$ GeV^{-1}	$\lvert d_c^g \rvert \lesssim 3.9 \times 10^{-4}$ GeV^{-1}	1

constraints can be translated into saying that the LHC can reach 1σ sensitivity to a new physics scale between 1 and 3 TeV

compared to neutron edm

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Process	CMDM	CEDM	neutron edm
$\sigma(pp \to t\bar{t})$ 8 TeV	$-0.034 \lesssim m_t a_t^g \lesssim 0.031$	$\lvert m_t d_t^g \rvert \lesssim 0.12$	
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$A_1(pp \to t\bar{t})$ 14 TeV	$\cdots$	$\lvert m_t d_t^g \rvert \lesssim 0.009$	
$\sigma(pp \to t\bar{t}h)$ 14 TeV	$-0.016 \lesssim m_t a_t^g \lesssim 0.008$	$\lvert m_t d_t^g \rvert \lesssim 0.02$	
$A_{1,2}(pp \to t\bar{t}h)$ 14 TeV	$\cdots$	$\lvert m_t d_t^g \rvert \lesssim 0.007$	2×10^{-4}
$\sigma(pp \to b\bar{b}h)$ 14 TeV	$-1.3 \times 10^{-4} \lesssim m_b a_b^g \lesssim 2.4 \times 10^{-4}$	$\lvert m_b d_b^g \rvert \lesssim 1.7 \times 10^{-4}$	2×10^{-8}
$\sigma(pp \to hX)$ 8 TeV	$\lvert a_u^g \rvert \lesssim 3.5 \times 10^{-4}$ GeV^{-1}	$\lvert d_u^g \rvert \lesssim 3.5 \times 10^{-4}$ GeV^{-1}	
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_u^g \rvert \lesssim 1.2 \times 10^{-4}$ GeV^{-1}	$\lvert d_u^g \rvert \lesssim 1.2 \times 10^{-4}$ GeV^{-1}	1.8×10^{-11} GeV^{-1}
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_d^g \rvert \lesssim 1.6 \times 10^{-4}$ GeV^{-1}	$\lvert d_d^g \rvert \lesssim 1.6 \times 10^{-4}$ GeV^{-1}	1.8×10^{-11} GeV^{-1}
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_s^g \rvert \lesssim 3.3 \times 10^{-4}$ GeV^{-1}	$\lvert d_s^g \rvert \lesssim 3.3 \times 10^{-4}$ GeV^{-1}	0.1 GeV^{-1}
$\sigma(pp \to hX)$ 14 TeV	$\lvert a_c^g \rvert \lesssim 3.9 \times 10^{-4}$ GeV^{-1}	$\lvert d_c^g \rvert \lesssim 3.9 \times 10^{-4}$ GeV^{-1}	4.6×10^{-10} GeV^{-1}

- using neutron edm for u,d, Λ edm for s and quark model
- using Weinberg three gluon operator for c,b,t (Nucl.Phys. B357 (1991) 311-356, De Rujula et al)
- existing estimates for top-quark case vary by an order of magnitude

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Same thing may be possible for leptons

- consider again the dipole-type couplings

$$\mathcal{L} = \frac{e}{2}\,\bar\ell\,\sigma^{\mu\nu}\left(a_\ell^\gamma + i\gamma_5 d_\ell^\gamma\right)\,\ell\,F_{\mu\nu} + \frac{g}{2\cos\theta_W}\,\bar\ell\,\sigma^{\mu\nu}\left(a_\ell^Z + i\gamma_5 d_\ell^Z\right)\,\ell\,Z_{\mu\nu}$$

- which gauge invariance turns into

$$\mathcal{L} = g\frac{d_{\ell W}}{\Lambda^2}\,\bar\ell\sigma^{\mu\nu}\tau^i e\,\phi W^i_{\mu\nu} + g'\frac{d_{\ell B}}{\Lambda^2}\,\bar\ell\sigma^{\mu\nu}e\,\phi B_{\mu\nu} + \text{h.c.}$$

- and a dimension 8 coupling that is enhanced

$$\mathcal{L} = \frac{g_s^2}{\Lambda^4}\left(d_{\tau G}\,G^{A\mu\nu}G^A_{\mu\nu}\bar\ell_L\ell_R\phi + d_{\tau\tilde G}\,G^{A\mu\nu}\tilde G^A_{\mu\nu}\bar\ell_L\ell_R\phi\right) + \text{h. c.}$$

Possible observables (for tau-lepton)

- deviation from Drell-Yan cross section in the high invariant mass region $m_{\ell\ell} > 120\ \mathrm{GeV}$
- Assume a comparison at the 14% level will be possible (current main systematic uncertainty in high invariant mass di-tau pairs at CMS, > 300 GeV, is from estimation of background and in the range 6-14% **Phys.Lett. B716 (2012) 82-102, CMS Collaboration**)
- Limit on the $pp \to \tau^+\tau^- h$ cross section. Perhaps this can be set from the searches for $pp \to Zh$ with a di-tau reconstruction of Z?

constraints from Drell-Yan

- Typical NP scale probed is ~ TeV, with Λ = 1 TeV we find a 1 σ sensitivity $|d_{\tau W}| < 6, \; |d_{\tau B}| < 10, \; |d_{\tau G}| < 0.96$
- slightly better for the dimension 8 coupling!
- In the γ ,Z basis requiring deviations in high invariant mass Drell-Yan pairs to be at most 14%

$$\begin{array}{ccc} -0.0064 & (m_\tau d_\tau^\gamma, \; m_\tau d_\tau^Z) & 0.0064 \\ -0.0061 & m_\tau a_\tau^\gamma & 0.0068 \\ -0.0063 & m_\tau a_\tau^Z & 0.0066 \end{array}$$

- Whereas existing bounds are

$$\begin{array}{rcl} -0.002 < & m_\tau d_\tau^\gamma & < 0.0041 \text{ Belle} \\ -0.026 < & m_\tau a_\tau^\gamma & < 0.007 \text{ Delphi} \\ -0.00067 < & m_\tau d_\tau^Z & < 0.00067 \text{ Aleph} \\ -0.0016 < & m_\tau a_\tau^Z & < 0.0016 \text{ Aleph} \end{array}$$

Does h help?

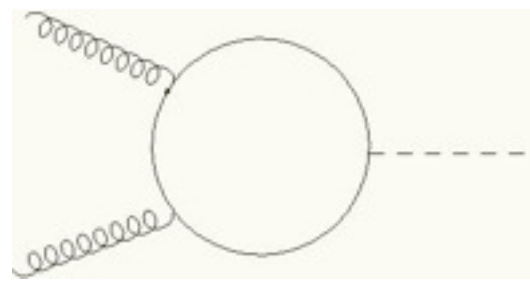
- a constraint $\sigma(pp \to \tau^+\tau^- h) < 5 \text{ fb}$ with $m_{\tau\tau} > 120 \text{ GeV}$ (50 times larger than SM) would result in comparable constraints to a 14% measurement of Drell-Yan for $d_\tau^{\gamma,Z}$
- For the gluonic couplings $d_{\tau G,\tilde{G}}$ one gets similar sensitivity to a 14% measurement of Drell-Yan with a bound $\sigma(pp \to \tau^+\tau^- h) < 50 \text{ fb}$ (500 times larger than SM)

II. Higgs couplings hgg and $h\gamma\gamma$

- constraints on new scalars (color octet electroweak doublet) from partial wave unitarity
- constraints from effective one-loop higgs couplings
  - constraints on parameters of scalar color octet
  - constraints on top-quark Yukawa coupling
  - interplay between the two

New color octet scalars

- One of first examples of NP ruled out by the Higgs observation was the fourth generation



- gluon fusion production of h would be ~ 10 times bigger with extra, heavy, t' and b' in the loop
- Can `fix' this by changing the scalar sector, one way is to add new, colored, scalars that might reduce Higgs production

color octet scalars

- Scalar sector of SM extended with a color-octet electroweak-doublet (motivated by MFV) **Phys.Rev. D74 (2006) 035009, Manohar and Wise**
- Yukawa sector

$$\mathcal{L} = -\frac{\sqrt{2}}{v}\eta_U \; e^{i\alpha_U} \; \bar{U}_R T^A \hat{M}^u U_L \; S^{A0} + \; \text{h.c.} + \cdots$$

- Scalar potential

$$\begin{aligned} V &= \lambda\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_s^2 \text{Tr}\; S^{\dagger i}S_i + \lambda_1 H^{\dagger i}H_i \text{Tr}\; S^{\dagger j}S_j + \lambda_2 H^{\dagger i}H_j \text{Tr}\; S^{\dagger j}S_i \\ &+ \left[\lambda_3 e^{i\alpha_3} H^{\dagger i}H^{\dagger j}\text{Tr}\; S_i S_j + \lambda_4 e^{i\alpha_4} H^{\dagger i}\text{Tr}\; S^{\dagger j}S_j S_i + \lambda_5 e^{i\alpha_5} H^{\dagger i}\text{Tr}\; S^{\dagger j}S_i S_j + h.c\right] + \lambda_6 \text{Tr}\; S^{\dagger i}S_i S^{\dagger j}S_j \\ &+ \lambda_7 \; \text{Tr}S^{\dagger i}S_j S^{\dagger j}S_i + \; \lambda_8 \; \text{Tr}S^{\dagger i}S_i \; \text{Tr}S^{\dagger j}S_j \\ &+ \lambda_9 \; \text{Tr}S^{\dagger i}S_j \; \text{Tr}S^{\dagger j}S_i + \; \lambda_{10} \; \text{Tr}S_i S_j \; \text{Tr}S^{\dagger i}S^{\dagger j} + \; \lambda_{11} \; \text{Tr}S_i S_j S^{\dagger j}S^{\dagger i}. \end{aligned}$$

  - 14 new parameters...
  - custodial symmetry relates some of the parameters

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A few features

- custodial SU(2) $2\lambda_3 = \lambda_2,\ 2\lambda_6 = 2\lambda_7 = \lambda_{11},\ \lambda_9 = \lambda_{10},\ \lambda_4 = \lambda_5^\star.$

- scalar masses constrained by non-observation of these states

$$\begin{aligned} m^2_{S^\pm} &= m^2_S + \lambda_1 \frac{v^2}{4}, \\ m^2_{S^0_R} &= m^2_S + (\lambda_1 + \lambda_2 + 2\lambda_3)\,\frac{v^2}{4}, \\ m^2_{S^0_I} &= m^2_S + (\lambda_1 + \lambda_2 - 2\lambda_3)\,\frac{v^2}{4}, \end{aligned}$$

$S = -0.07 \pm 0.09$

- S parameter $S = \frac{\lambda_2}{6\pi}\frac{v^2}{m_S^2}$

- gluon fusion production of Higgs

-0.49 ± 0.64

$$\mathcal{L} = (\sqrt{2}G_F)^{1/2}\frac{\alpha_s}{12\pi}\ G^A_{\mu\nu}G^{A\mu\nu}h\left(n_{hf} + \frac{v^2}{m_S^2}\frac{3}{8}(\lambda_2 + 2\lambda_1)\right)$$

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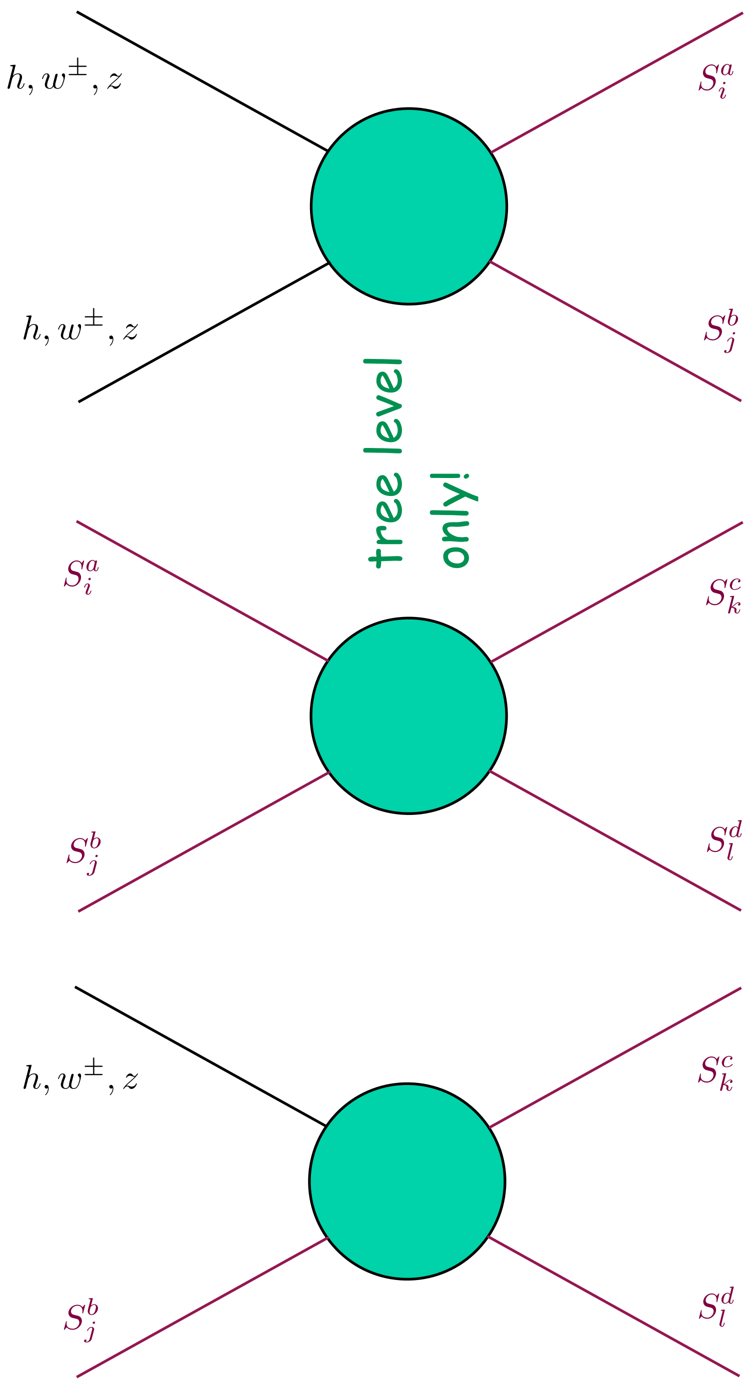
partial wave unitarity at high energy

Lee Quigg and Thacker: J=0, I =0 ww scattering in SM Higgs mass bound



$$\frac{5\lambda}{16\pi} < \frac{1}{2}, \qquad \lambda = \frac{G_F m_h^2}{\sqrt{2}}$$

color singlet, zeroth partial wave with I =0

$$s >> m_s^2 \rightarrow |2\lambda_1 + \lambda_2| < 18$$

color singlet, zeroth partial wave with I =0

$$s >> m_s^2 \rightarrow \left| \frac{1}{32\pi} \left(17\lambda_8 + 13\lambda_9 + 13\lambda_{11}\right) \right| < \frac{1}{2}$$

symmetric color octet, J=0, I =0

$$s >> m_s^2 \rightarrow |\lambda_4 \cos\phi_4 + \lambda_5 \cos\phi_5| < 26$$

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running couplings

- compute beta functions and consider partial sets of RGE
- for example: scalar couplings that appear at one-loop in h g g and h γ γ in with custodial symmetry

$$\frac{d\lambda_1}{d\ln\mu} = \frac{1}{8\pi^2}\left(\lambda_1^2+\lambda_2^2+2\lambda(3\lambda_1+\lambda_2)\right)$$
$$\frac{d\lambda_2}{d\ln\mu} = \frac{1}{8\pi^2}\lambda_2\left(2\lambda+2\lambda_1+3\lambda_2\right)$$
$$\frac{d\lambda}{d\ln\mu} = \frac{1}{8\pi^2}\left(12\lambda^2+2\lambda_1^2+2\lambda_1\lambda_2+2\lambda_2^2\right)$$

RG improved unitarity

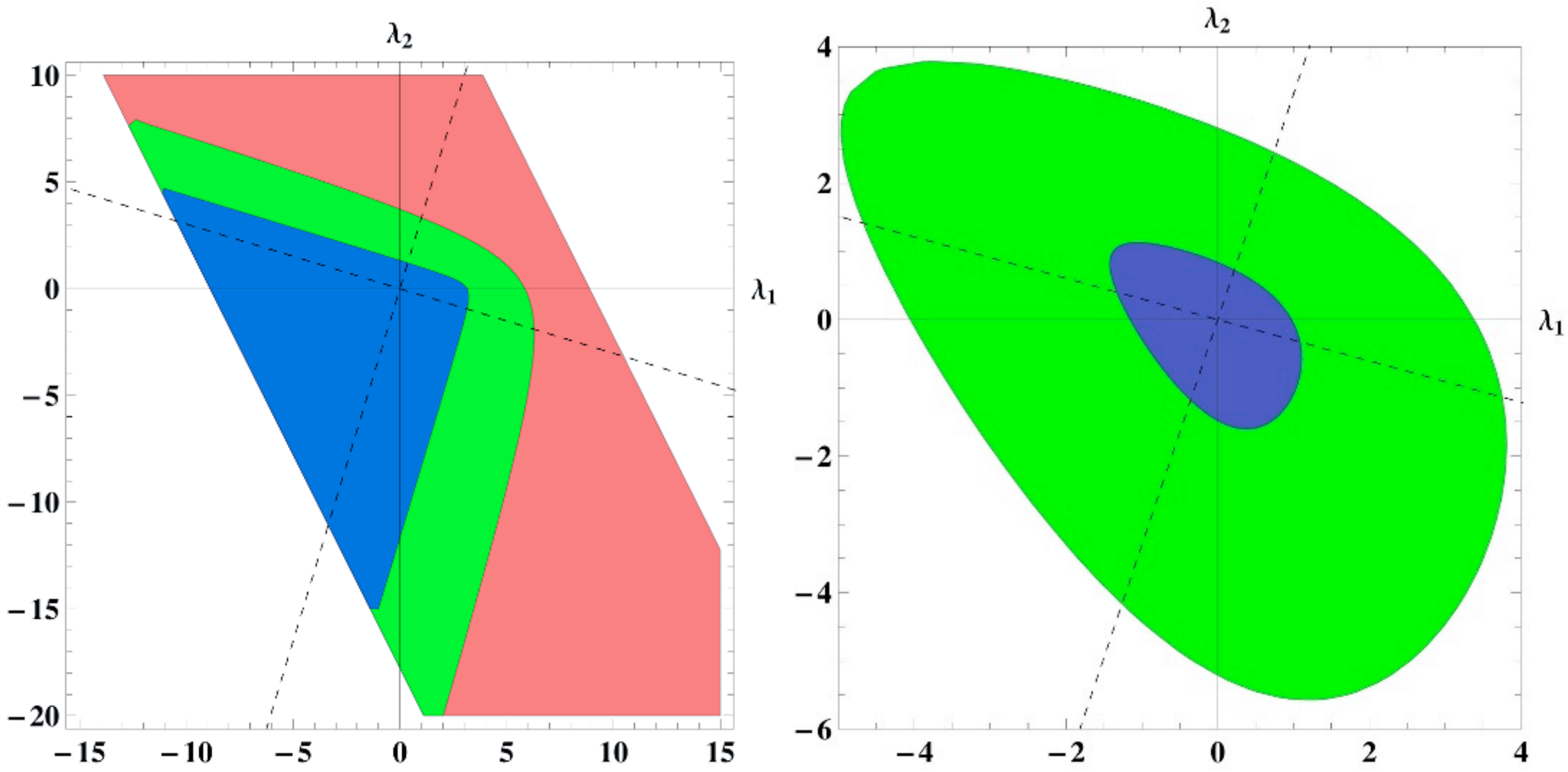

Figure 3. The left plot shows the region in the $\lambda_1 - \lambda_2$ (at 1 TeV) plane that satisfies the unitarity constraint, eq. (3.4) at 1 TeV in red, up to 100 TeV in green and up to 10^{10} GeV in blue. The dashed lines show the conditions $a_\pm = 0$. In the right plot, this region is further reduced by requiring unitarity up to 100 TeV in green and up to 10^{10} GeV in blue for the $\lambda - \lambda_{1,2}$ coupled system.

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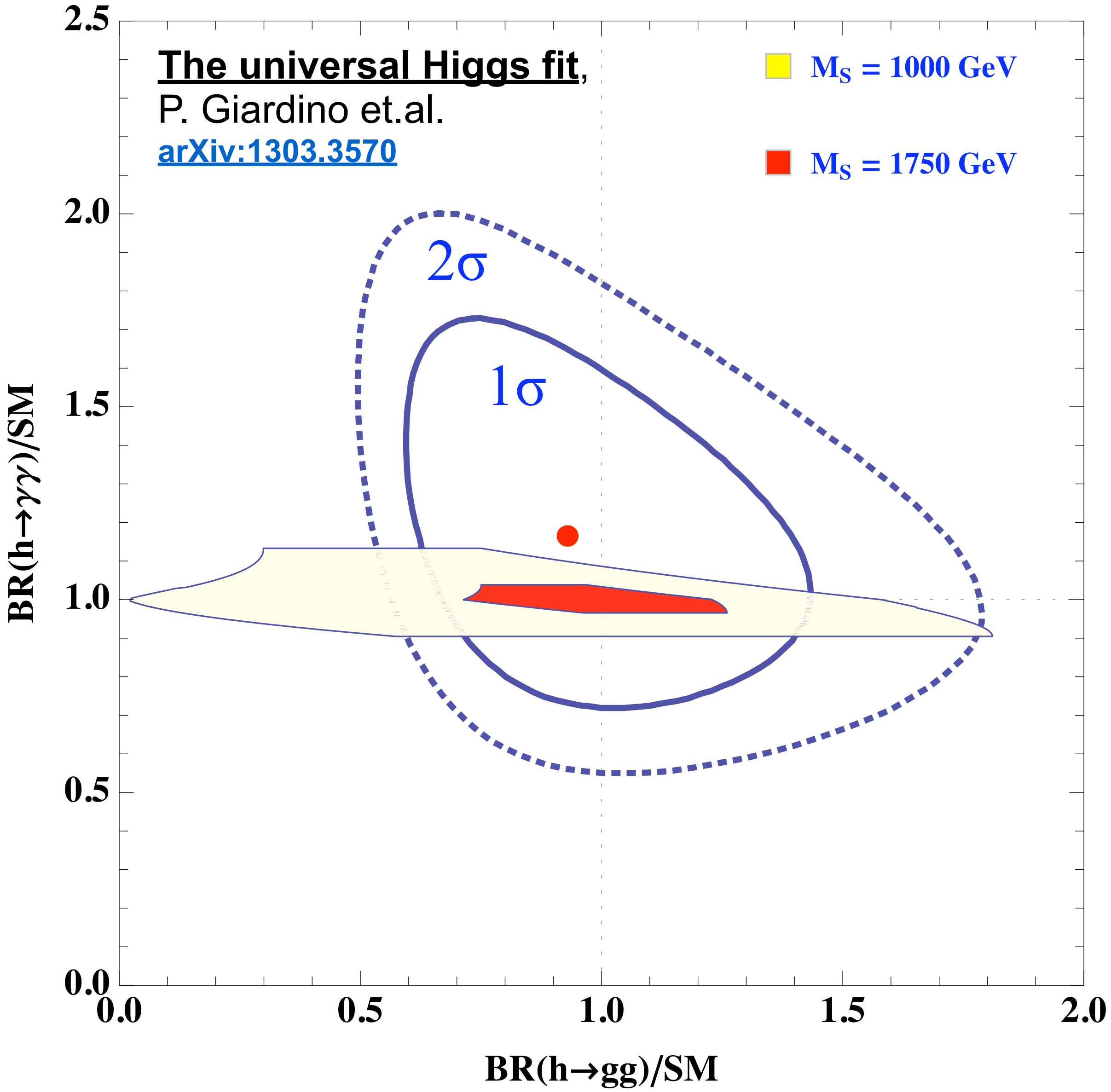
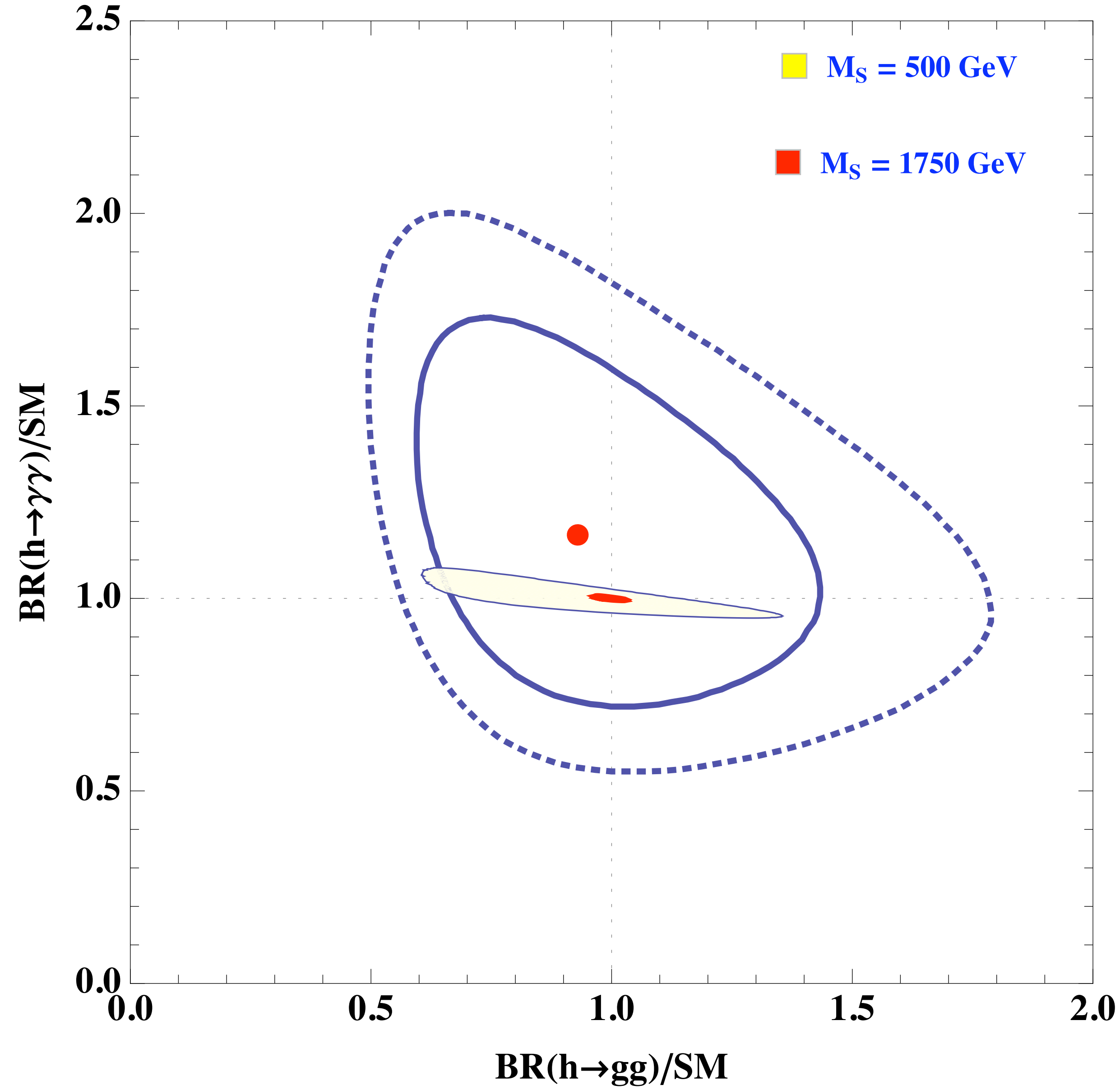
best fit to $h \to \gamma\gamma$ and $h \to gg$



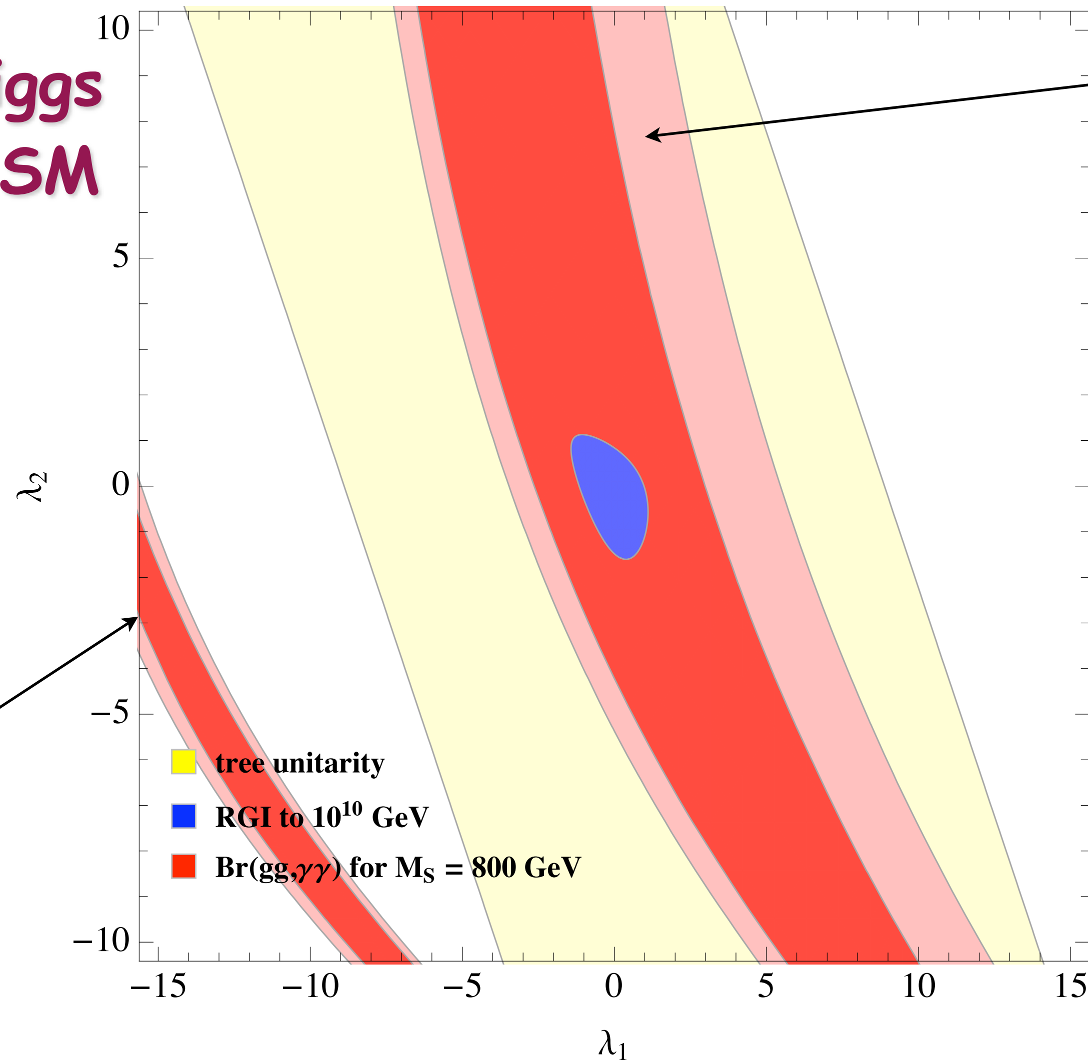
$\lambda_{1,2}$ satisfying tree unitarity



$\lambda_{1,2}$ satisfying RGI unitarity

as constraints on λ_1, λ_2

assume top-Higgs coupling as in SM



constructive interference between SM and octet scalars

destructive interference

- effective one-loop couplings are more restrictive than tree unitarity but less restrictive than RGI unitarity for $\lambda_{1,2}$

FIG. 2: Allowed $\lambda_1 - \lambda_2$ parameter space from Ref. [9] (yellow and blue regions as discussed in the text), superimposed with the regions allowed by the $BR(h \to \gamma\gamma)$ and $BR(h \to gg)$ at 1σ (dark red) and 2σ (light red).

for scalars only:

$h\gamma\gamma \sim \lambda_1$

$hgg \sim (2\lambda_1 + \lambda_2)$

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the top-quark Yukawa

- In general the mechanisms of EW symmetry breaking and fermion mass generation need not be the same
- Even with a SM-like Higgs, new physics can spoil the relation between the top-quark mass and its Yukawa

$$
\begin{aligned}
\mathcal{L}_{htt} &= y_t \bar{q}\, t\, \tilde{\phi} + \frac{g_{u\phi}}{\Lambda^2}(\phi^\dagger \phi)\bar{q}\, t\, \tilde{\phi} + \text{ h.c.} \\
g_{ht\bar{t}} &= \frac{y_t}{\sqrt{2}} + 3 g_{u\phi}\frac{v^2}{2\sqrt{2}\Lambda^2} \\
m_t &= y_t \frac{v}{\sqrt{2}} + g_{u\phi} v \frac{v^2}{2\sqrt{2}\Lambda^2}
\end{aligned}
$$

$$g_{ht\bar{t}} \rightarrow (g_{ht\bar{t}})_{SM}\; r_t$$

- what values of r_t are still allowed by h g g and h γ γ ?
  - direct measurement not yet very restrictive:

$\sigma(pp \rightarrow t\bar{t}h) < 5.8\sigma_{SM}$ CMS, JHEP 05 (2013) 145

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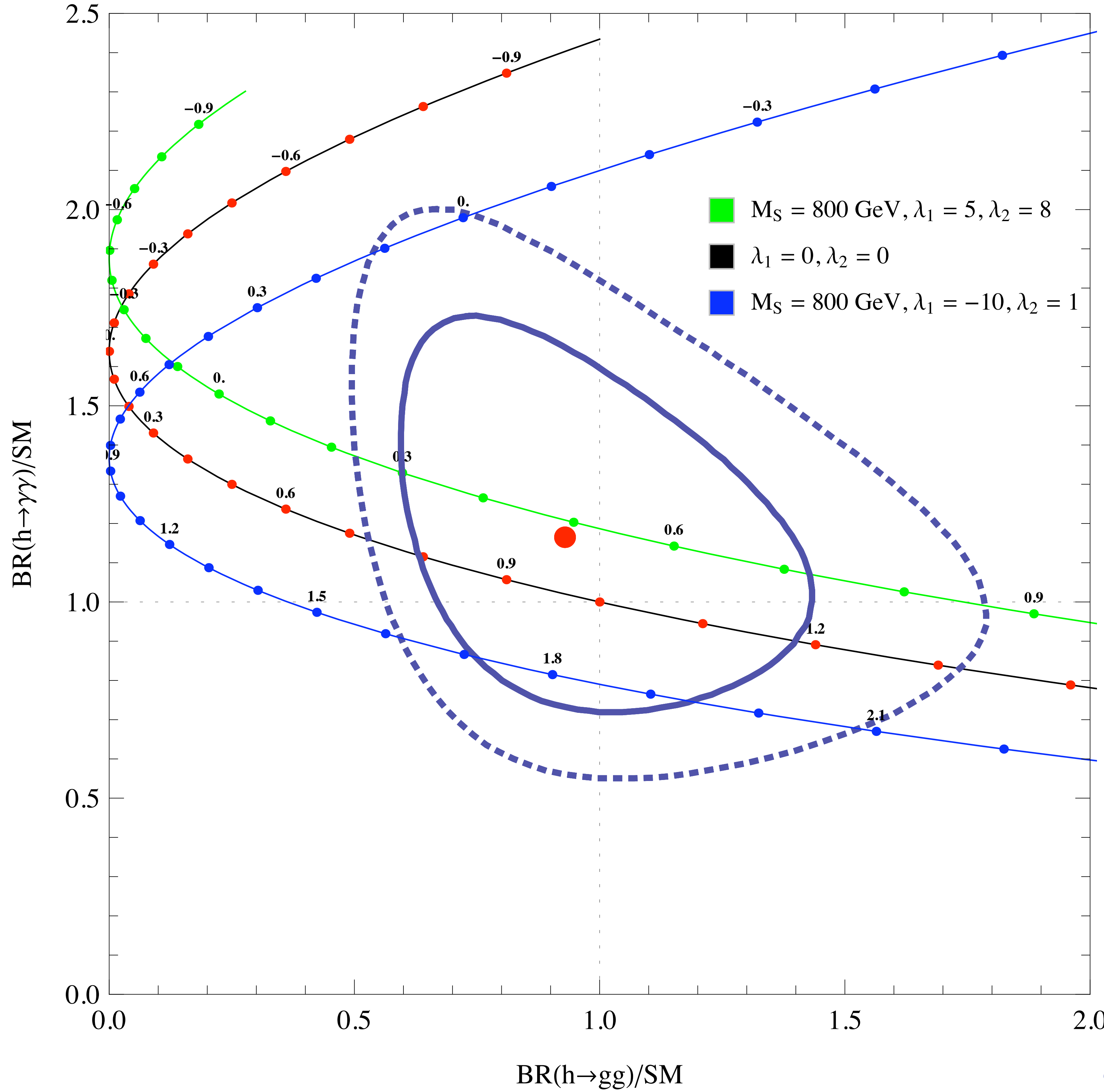
arbitrary $ht\bar{t}$ coupling



with color octets

with only SM particles in loop: at 1 σ

r_t ~ (0.8-1.2)

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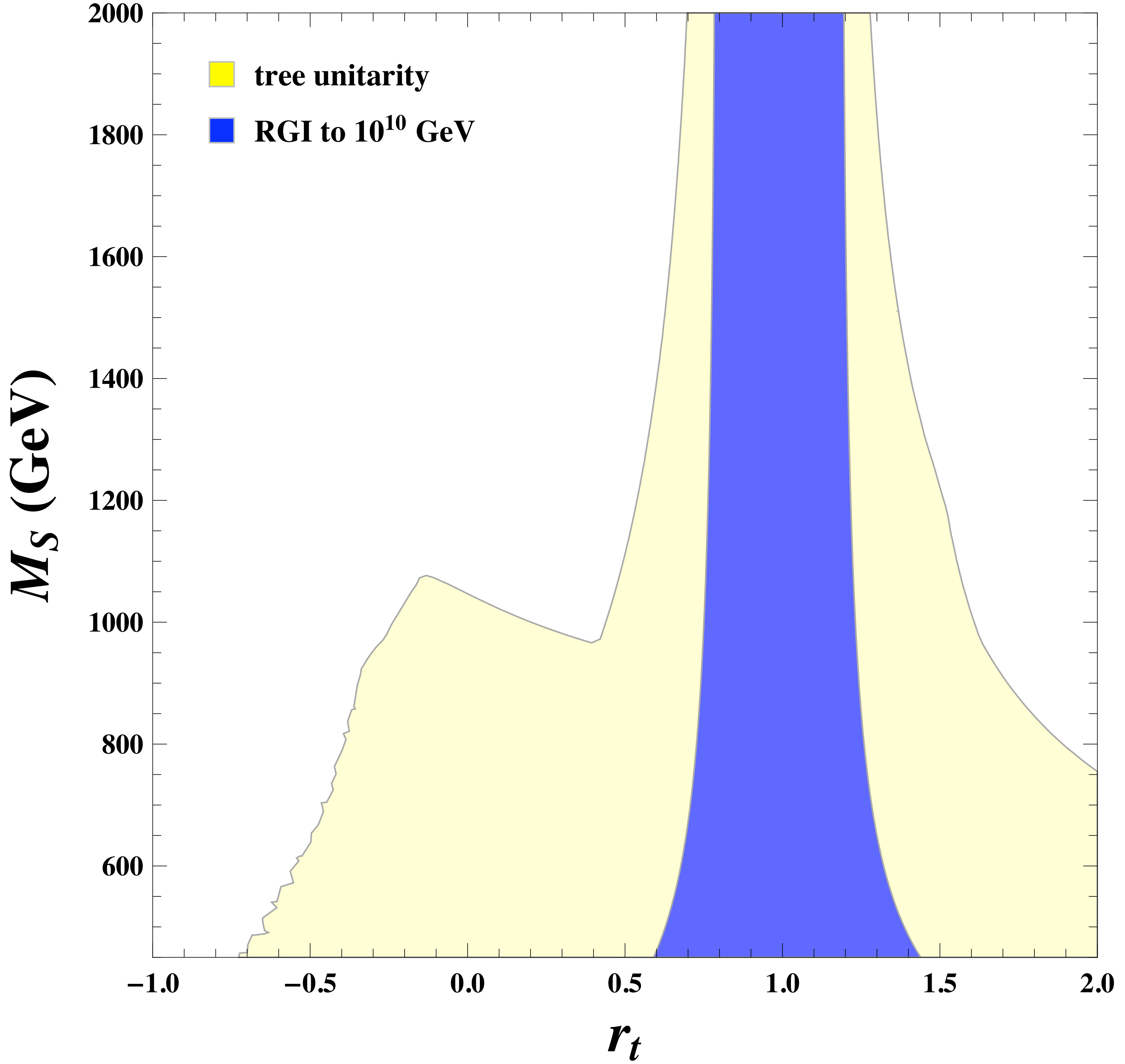
another view of parameter space



- without color octet scalars $0.8 < r_t < 1.2$ is allowed at 1 σ
- allowing $\lambda_{1,2}$ and M_s to vary while satisfying RGI unitarity up to 10^{10} GeV relaxes this to $0.6 < r_t < 1.4$

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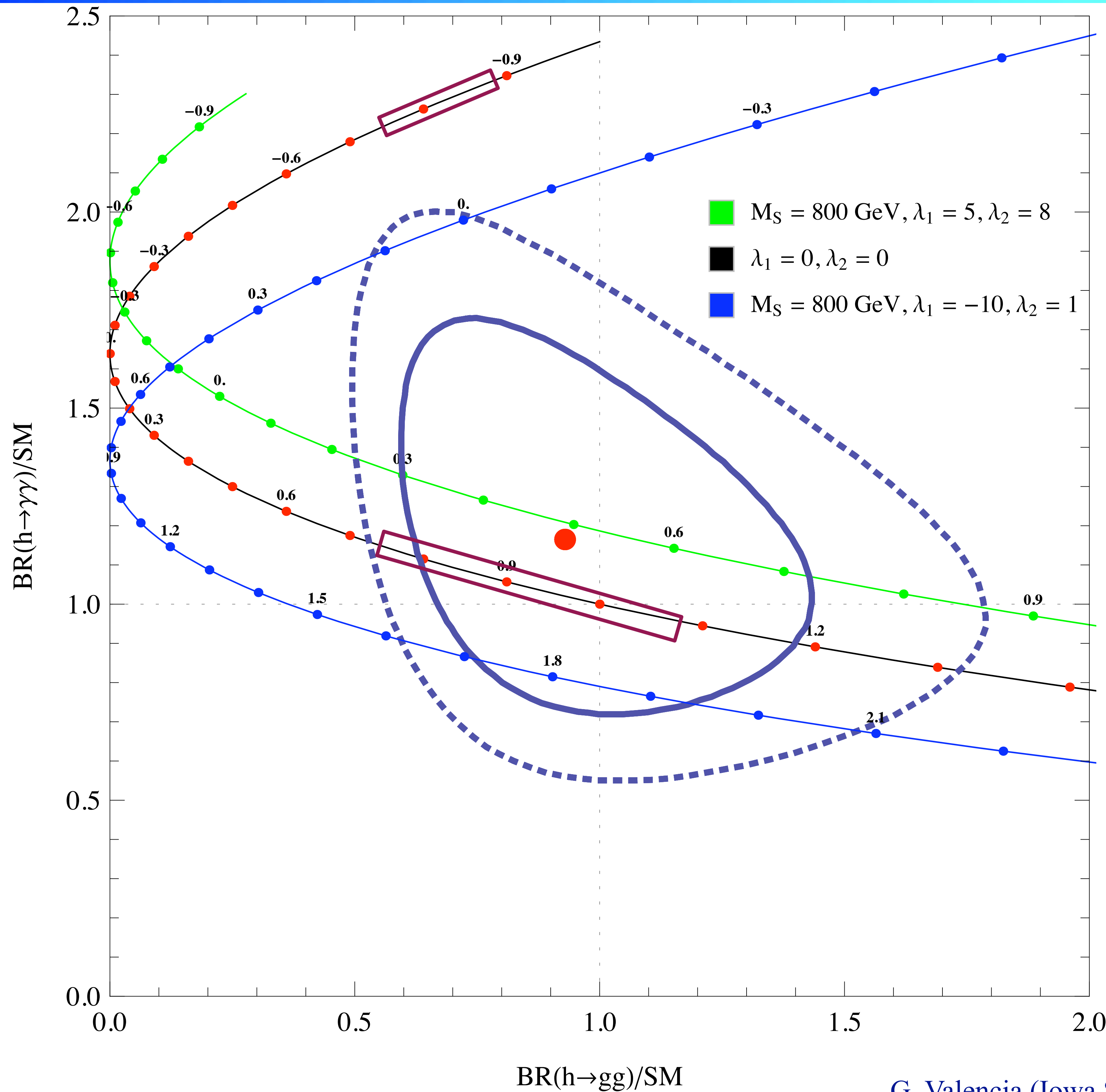
arbitrary $h t \bar{t}$ coupling



$(-0.88, -0.75)$

Atlas all channels
3/2013 68% c.l.
ATLAS-CONF-2013-034

$(0.73, 1.07)$

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Summary

- The effective $h\,g\,g$ and $h\,\gamma\,\gamma$ couplings are in agreement with the SM, but there is still room for new physics at the ~50% level.
- We considered the $h\,t\,\bar{t}$ coupling and see that 20% deviations from SM are allowed at $1\,\sigma$ if there is no other new physics
- We considered a new multiplet of color octet scalars and found that the Higgs one-loop effective couplings place constraints on the model that fall between those that follow from tree level unitarity and those from RGI unitarity.
- Finally we considered the interplay between these two cases finding that a color octet significantly relaxes the constraint on $h\,t\,\bar{t}$