Higgs production constraints on anomalous fermion couplings

Some anomalous fermion-gauge boson couplings (in this talk dipole operators) imply anomalous Higgs* couplings and can be constrained by Higgs production

- *based on work with
  - Alper Hayreter, Ozyegin University (Istanbul)
  - Phys.Rev. D88 (2013) 034033, Phys.Rev. D88 (2013) 1, 013015

cmdm and cedm couplings

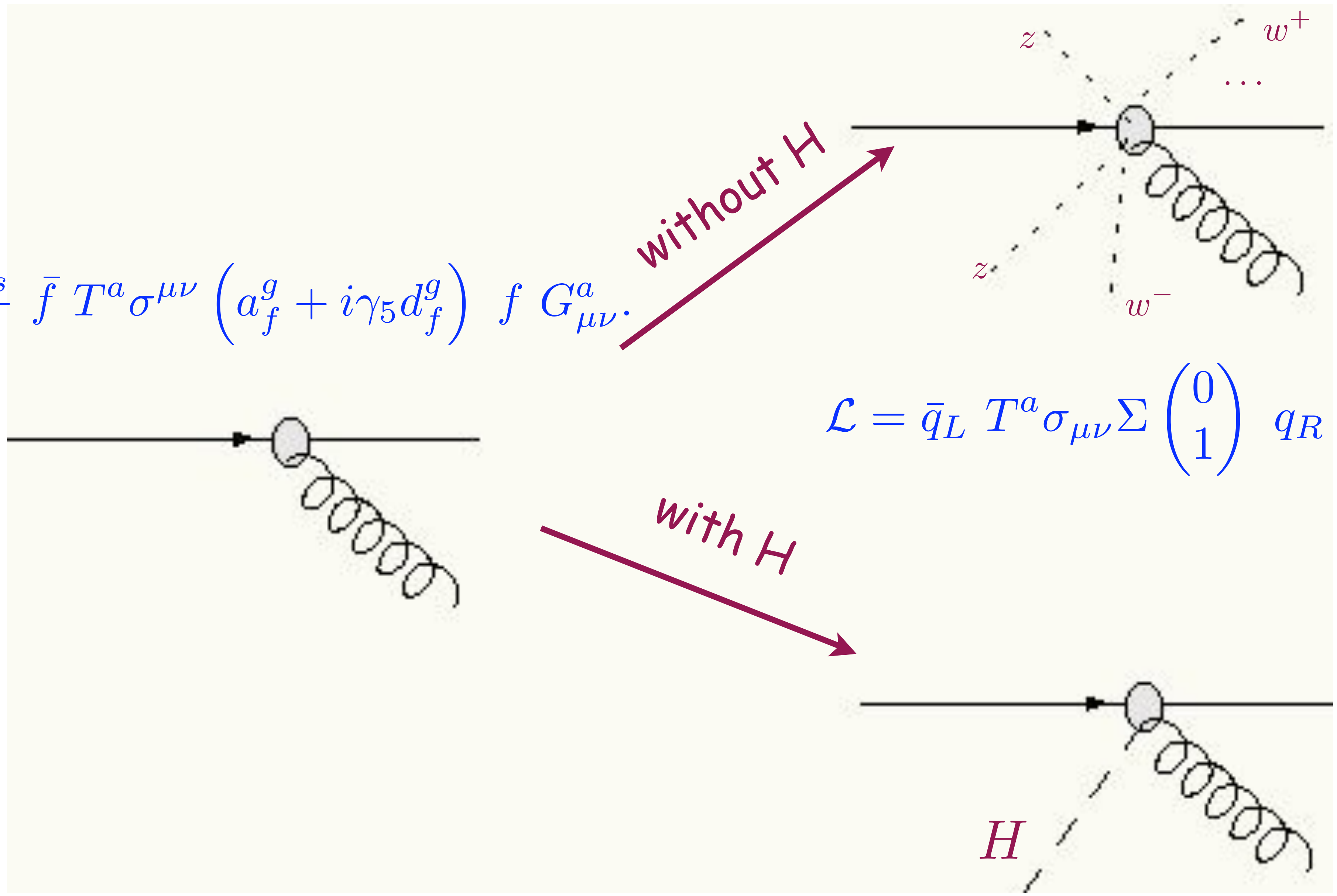
- consider new physics in the form of the usual anomalous color magnetic (CMDM) and electric (CEDM) dipole moments

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

- 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
  - or we need to fix gauge invariance using a scalar doublet with a vev as in the SM - fundamental 126 GeV Higgs
- each has different consequences for phenomenology

gauge invariance - relates couplings

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



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

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

top-quark couplings at LHC

$$\mathcal{L} = \frac{g_s}{2}\,\bar{t}\,T^a\sigma^{\mu\nu}\left(a_t^g + i\gamma_5 d_t^g\right)\,t\,G^a_{\mu\nu} \quad \longrightarrow \quad \mathcal{L} = g_s\frac{d_{tG}}{\Lambda^2}\,\bar{q}_{3L}\sigma^{\mu\nu}T^a t_R\,\tilde{\phi}G^a_{\mu\nu} + \text{ h.c.}$$

$$a_t^g = \frac{\sqrt{2}\,v}{\Lambda^2}\,\text{Re}(d_{tG})$$

cmdm: anomalous (color) magnetic moment

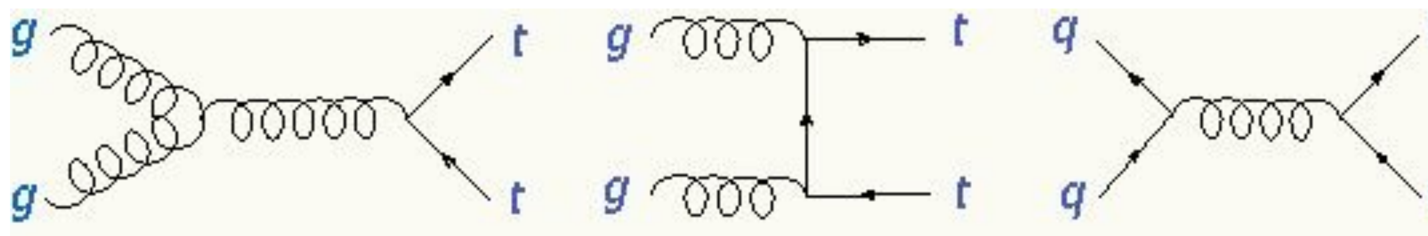
$$d_t^g = \frac{\sqrt{2}\,v}{\Lambda^2}\,\text{Im}(d_{tG})$$

cedm: CP-odd, (color) electric dipole moment

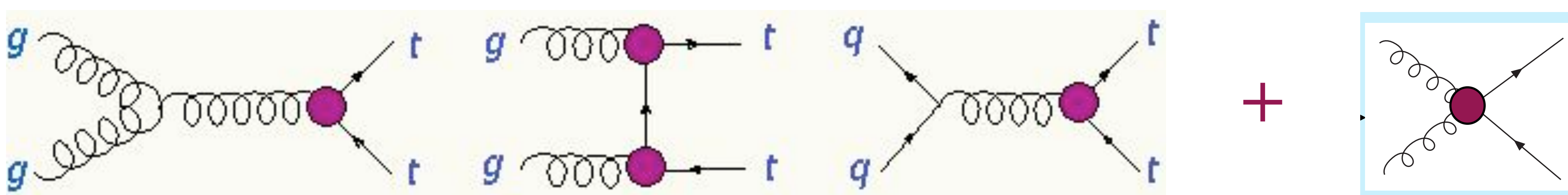
- usual constraints from top-quark pair production
- but they also affect and can be constrained by Higgs production associated with a top-quark pair
- here we compare the two

top quark pair production

- SM at LO for LHC



- receives new contributions from modified couplings



- the resulting cross-section is a quartic polynomial in the new couplings with only even powers of the CP-odd coupling
- simulate enough points with Madgraph (+ FeynRules) to fit the polynomial for NP and SM-NP interference, for SM add best known terms
- T-odd correlations can be linear in CP-odd couplings

bounds from the cross-section $\sigma(t\bar{t})$

- 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)

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

how much NP "fits" here

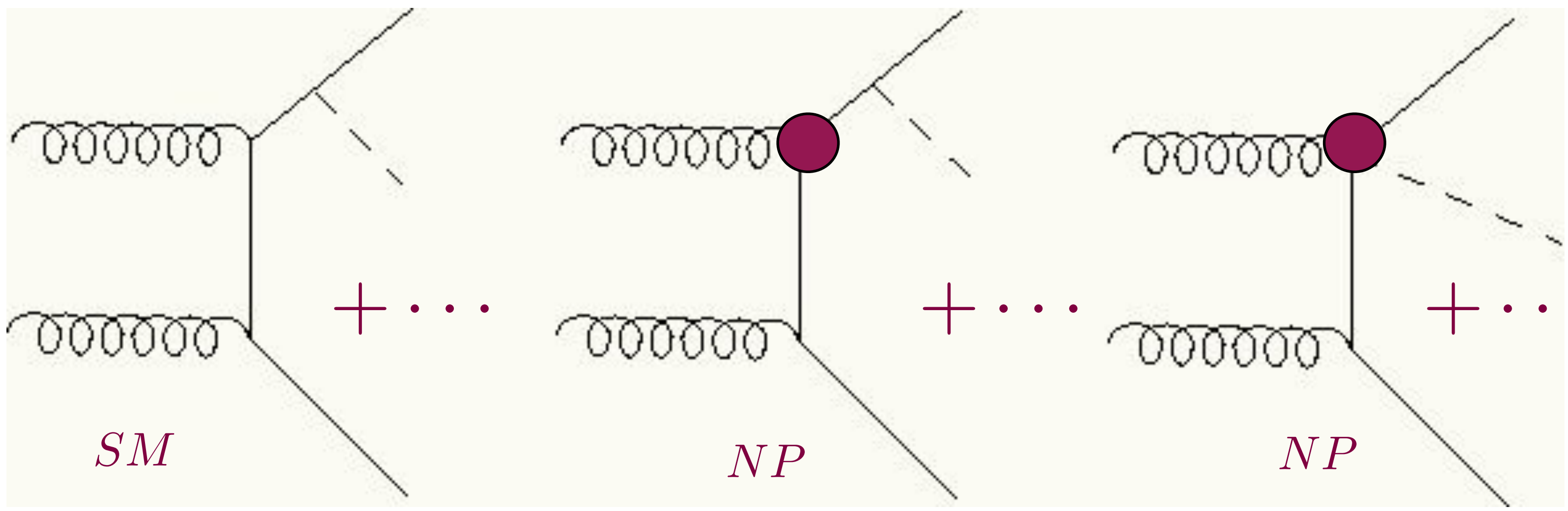
- For 14 TeV we use the NLO theoretical cross-section
  (M. Beneke, P. Falgari, S. Klein, C. Schwinn arXiv:1112.4606)

$$\sigma_{(NLO)} = (884^{+125}_{-121})\mathrm{pb}$$

  - and we assume experiment will eventually agree with SM and theory error will dominate
  - really comparing a 17% error at 8 TeV with a 14% error at 14 TeV

Higgs production associated with top-quark pair: $\sigma(t\bar{t}h)$

- affected by the same NP couplings

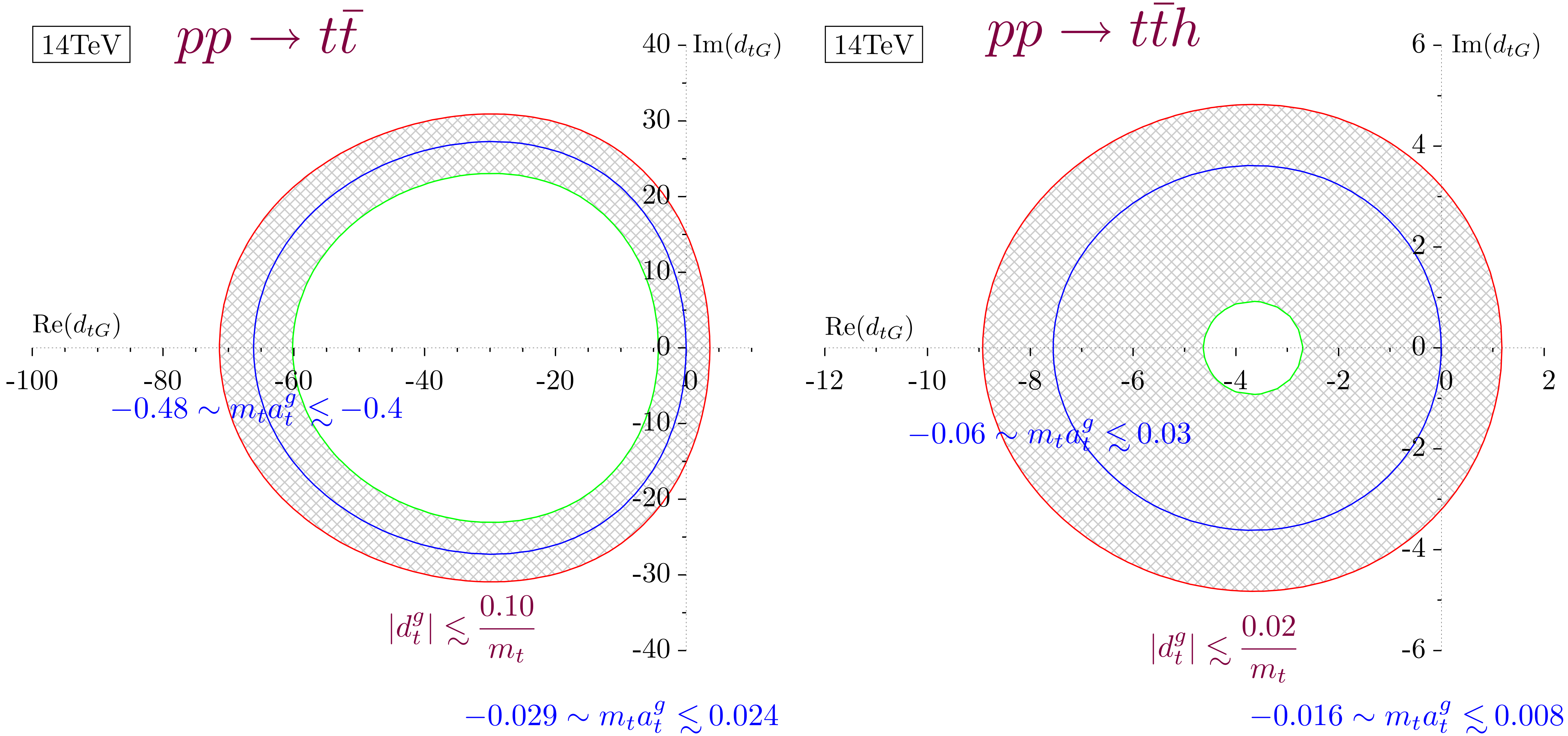


- cross-section is again a quartic polynomial in NP with only even powers of the CEDM
- constrain by comparing to SM at NLO (for 14 TEV), (15%-18%)

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

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

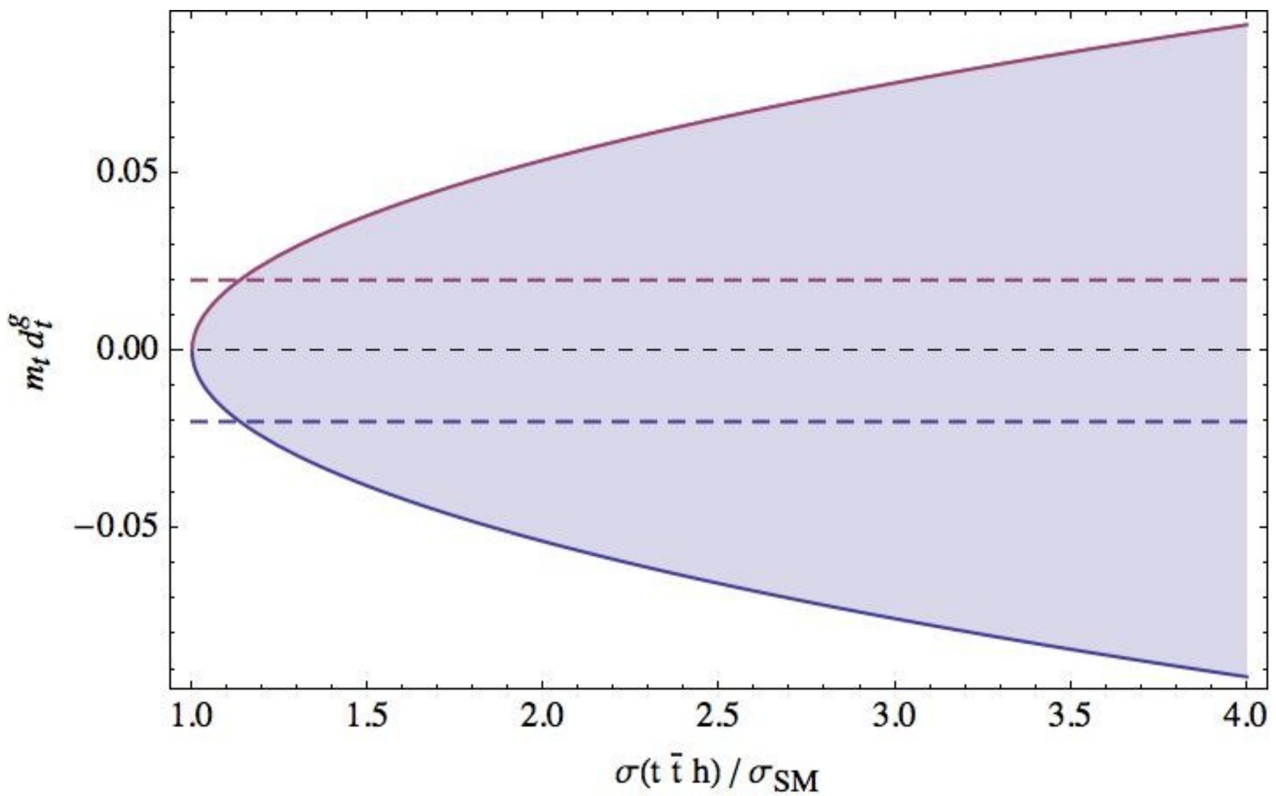
top pairs at LHC: σ($t\bar{t}$) vs σ($t\bar{t}h$)

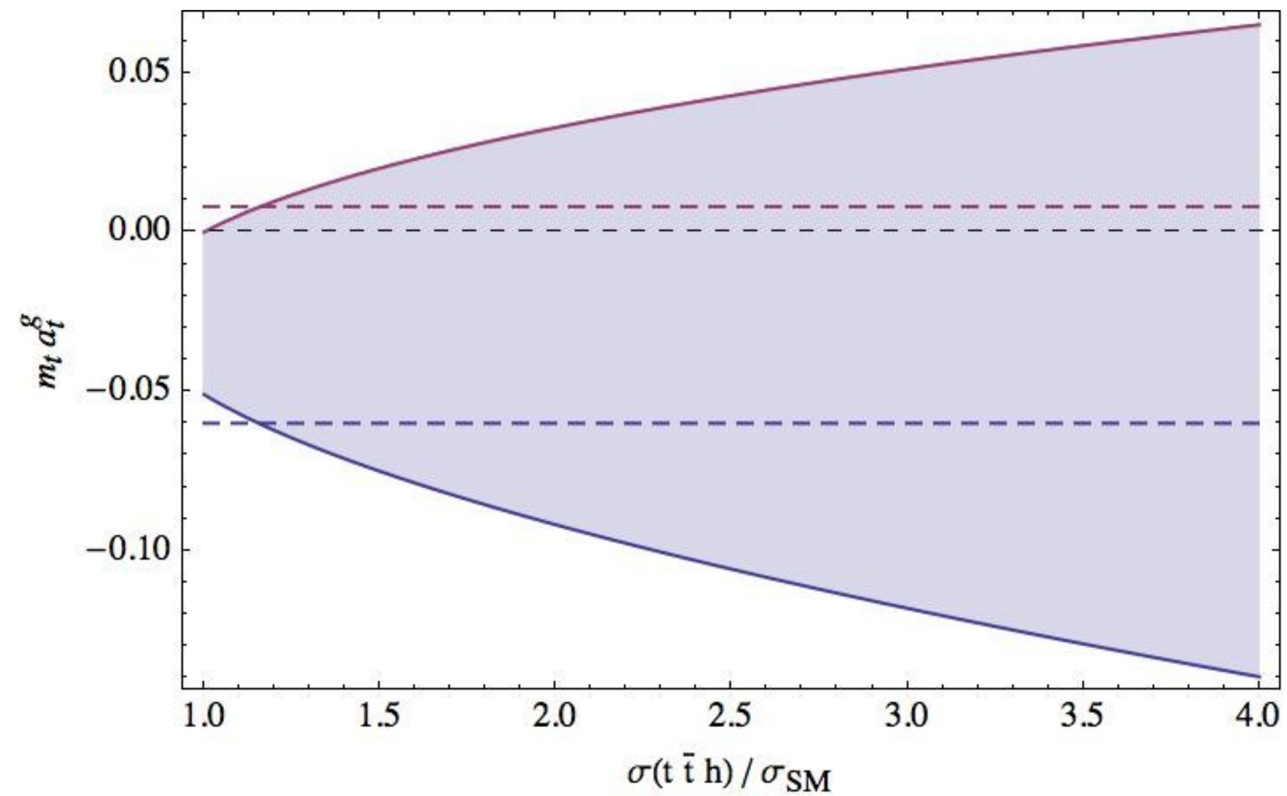


$pp \longrightarrow t\bar{t}h$

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

constraints from limits on $\sigma(t\bar{t}h)$





- we heard yesterday that this is a very difficult measurement so here I illustrate the constraints based only on a limit on the cross-section
- dashed lines are the +15% contours of previous slide (no lower bound here)

Decay distributions

- So far at 1σ and at 14 TeV we found
  - $0.1/m_t$ CEDM and $0.03/m_t$ CMDM from $\sigma(t\bar{t})$
  - $0.02/m_t$ CEDM and $0.01/m_t$ CMDM from $\sigma(t\bar{t}h)$
- For top-pairs it is known that it may be possible to improve the bounds by measuring asymmetries:
  - CEDM at 5σ with 10 fb^{-1} $0.1/m_t$ with T-odd asymmetry at 14 TeV *
  - CEDM and CMDM at the $0.05/m_t$, $0.03/m_t$ possible with 20 fb^{-1} of LHC8 at 2σ using spin correlations **
- asymmetries in $t\bar{t}h$ are also somewhat better than cross-sections but very hard to get: more than 10^4 events needed to measure an asymmetry at the % level, ~ 1000 fb^{-1}

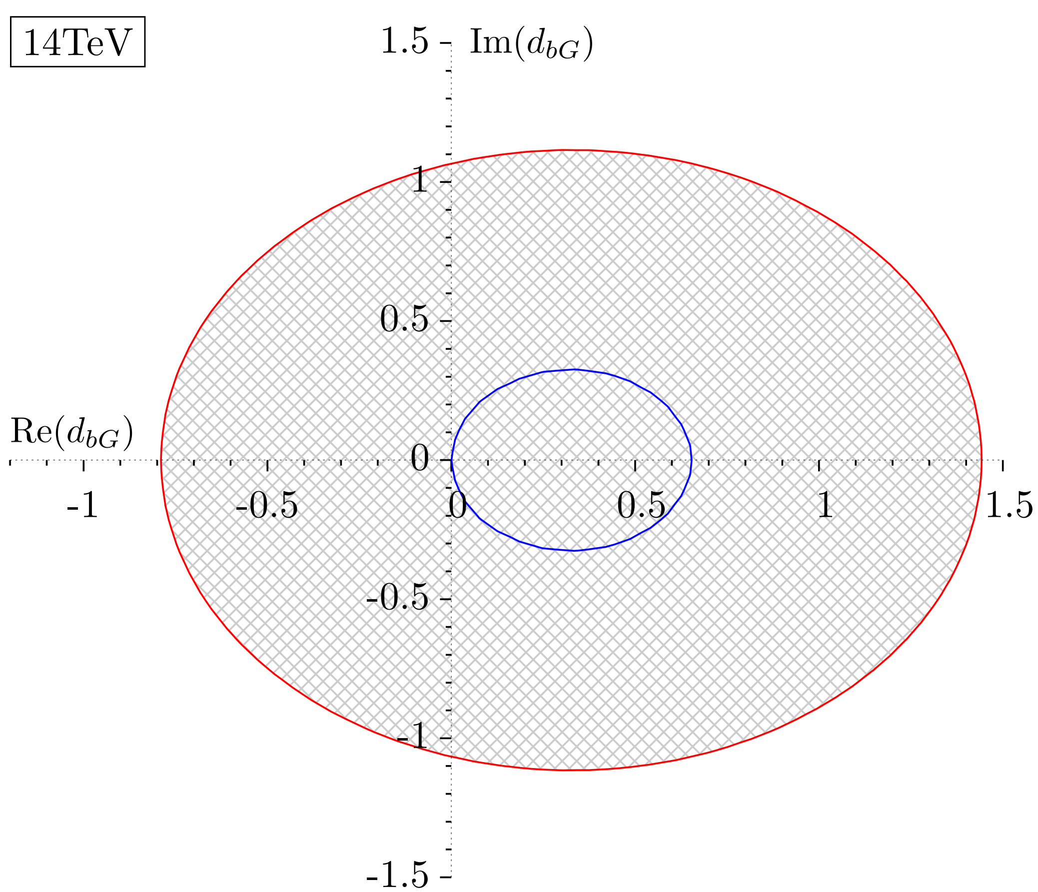
J Sjolin J.Phys. G29 (2003) 543-560 ,**Gupta, Mete, G.V. Phys.Rev. D80 (2009) 034013,** and many others *
Baumgart and Tweedie, JHEP 1303 (2013) **

b-quark couplings

- NP effects in $b\bar{b}$ pair production are overwhelmed by QCD
- need b-pair production in association with Higgs: $b\bar{b}h$
- should get bounds from non-SM Higgs searches (large tanβ)
- compare to SM NLO prediction (Phys.Rev. D70 (2004) 074010: Dittmaier, Kramer, Spira)

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

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



$$-1.3 \times 10^{-4} \lesssim m_b \; a_b^g \lesssim 2.4 \times 10^{-4}$$

$$|d_b^g| \lesssim \frac{1.7 \times 10^{-4}}{m_b}$$

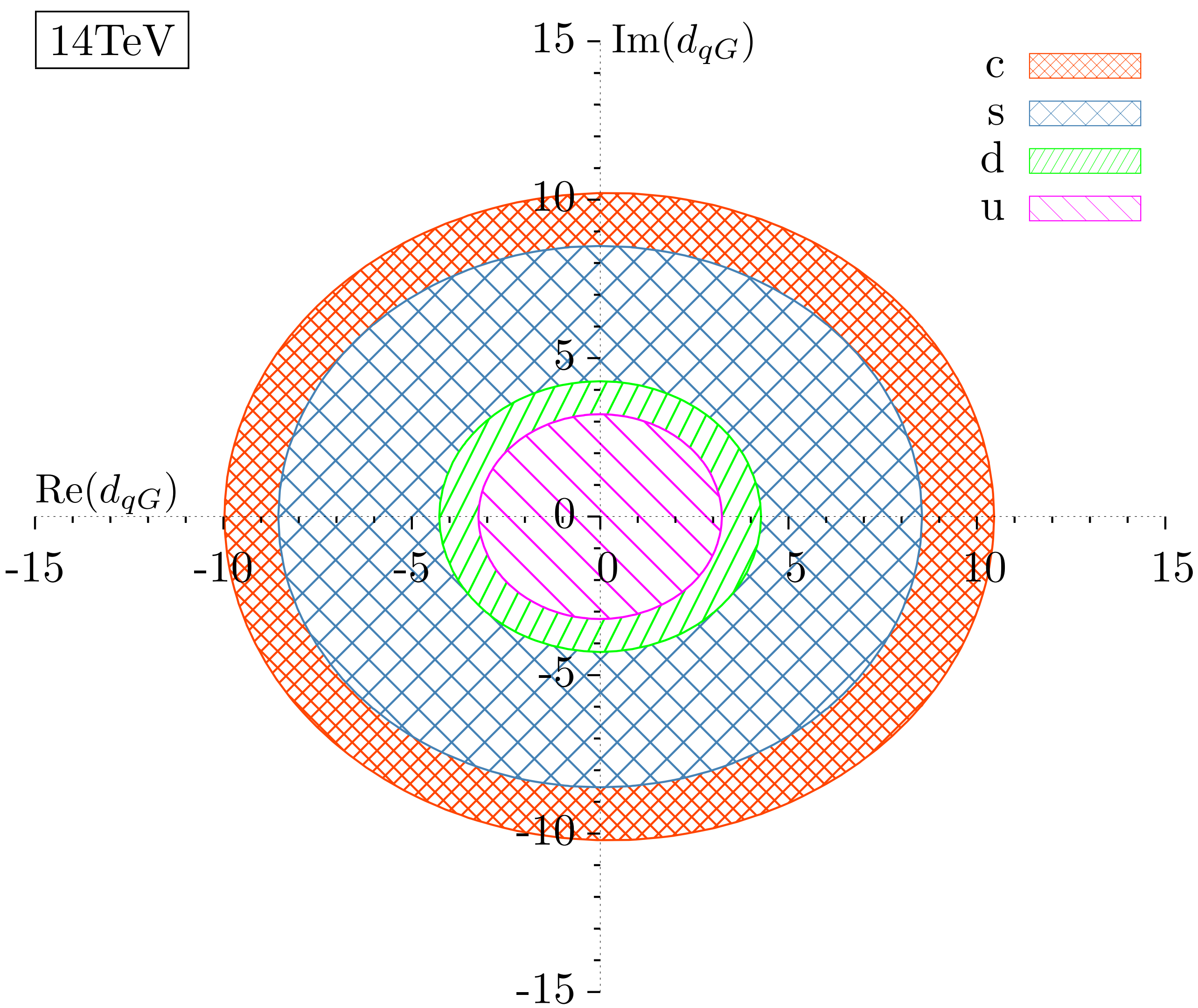
light quarks including charm

- NP is again buried in QCD background, only hope is in processes with a Higgs
- look for NP in pp $\rightarrow$ hX ($qg \rightarrow qh$ and $q\bar{q} \rightarrow hg$)
- in SM these subprocesses are dominated by charm
  - interference between NP and SM is negligible
  - cross section is only quadratic in NP
- require NP to fall below theoretical uncertainty of dominant gluon fusion SM process
- This picture fails beyond LO where heavy quark loops give larger SM contributions
  - could try higgs plus one jet mode
  - better as NP/SM increases at high p_T
  - too hard for now

Results for light quarks

- 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 14 TeV and m_h=125 predicts *

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

- require NP < 1σ theory error

(Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables , Dittmaier et. al.) *

summary of constraints for quarks

Table 1: Summary of results for 1σ bounds that can be placed on the CEDM and CMDM couplings of quarks at the LHC.

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, .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, .7)
$A_1(pp \to t\bar{t})$ 14 TeV	-	$\lvert m_t d_t^g \rvert \lesssim 0.009$	(-, 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	-	$\lvert m_t d_t^g \rvert \lesssim 0.007$	(-, 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

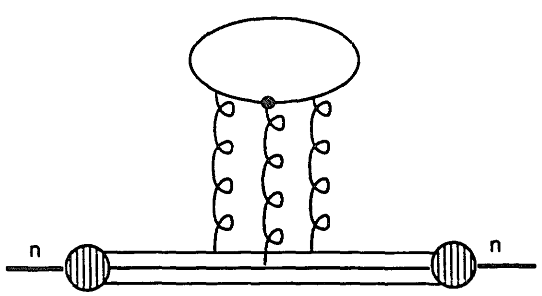
constraints can be translated into an effective new physics scale that the LHC can reach at 1σ sensitivity: between 1 and 3 TeV

compared to neutron edm

Table 1: Summary of results for 1σ bounds that can be placed on the CEDM at LHC and indirect constraints from neutron edm.

Process	CEDM	neutron (Λ) edm
$\sigma(pp \to t\bar{t})$ 8 TeV	$\lvert m_t d_t^g \rvert \lesssim 0.12$	$2.4\times10^{-4*}$
$\sigma(pp \to t\bar{t})$ 14 TeV	$\lvert m_t d_t^g \rvert \lesssim 0.1$	
$A_1(pp \to t\bar{t})$ 14 TeV	$\lvert m_t d_t^g \rvert \lesssim 0.009$	
$\sigma(pp \to t\bar{t}h)$ 14 TeV	$\lvert m_t d_t^g \rvert \lesssim 0.02$	
$A_{1,2}(pp \to t\bar{t}h)$ 14 TeV	$\lvert m_t d_t^g \rvert \lesssim 0.007$	
$\sigma(pp \to b\bar{b}h)$ 14 TeV	$\lvert m_b d_b^g \rvert \lesssim 1.7 \times 10^{-4}$	2×10^{-8}
$\sigma(pp \to hX)$ 8 TeV	$\lvert d_u^g \rvert \lesssim 3.5 \times 10^{-4}$ GeV^{-1}	$1.8\ \times10^{-11}$ GeV^{-1}
$\sigma(pp \to hX)$ 14 TeV	$\lvert d_u^g \rvert \lesssim 1.2 \times 10^{-4}$ GeV^{-1}	
$\sigma(pp \to hX)$ 14 TeV	$\lvert d_d^g \rvert \lesssim 1.6 \times 10^{-4}$ GeV^{-1}	$1.8\ \times10^{-11}$ GeV^{-1}
$\sigma(pp \to hX)$ 14 TeV	$\lvert d_s^g \rvert \lesssim 3.3 \times 10^{-4}$ GeV^{-1}	0.1 GeV^{-1} ($\Lambda -$ edm)
$\sigma(pp \to hX)$ 14 TeV	$\lvert d_c^g \rvert \lesssim 3.9 \times 10^{-4}$ GeV^{-1}	$4.7\ \times10^{-10}$ GeV^{-1}

- for u,d (s) using neutron (Λ) edm and quark model
- for c,b,t using Weinberg three gluon operator
  (Nucl.Phys. B357 (1991) 311-356, De Rujula et al)
- more recent estimate for top cedm ~ 2×10^{-3}



Phys.Rev. D85 (2012) 071501, Kamenik, Papucci, Weiler

Similarly 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

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

- bounds for electron and muon are very strong so look at tau only

Possible observables (for tau-lepton)

- deviation from Drell-Yan cross section in the high invariant mass region $m_{\ell\ell} > 120$ GeV at LHC14 (or in the Z region which gives very similar results)

- Assume a comparison at the 14% level will be possible

  Why 14%? the 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 from 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?

τ anomalous magnetic moment, electric dipole moment and weak dipole moments

	$m_\tau\ a_\tau^V$ LHC14	$m_\tau\ a_\tau^V$ Existing	$m_\tau\ d_\tau^V$ LHC14	$m_\tau\ d_\tau^V$ Existing
V = γ	$(-0.0061,\ 0.0068)$	$(-0.026,\ 0.007)$ Delphi	$(-0.0064,\ 0.0064)$	$(-0.002,\ 0.0041)$ Belle
V = Z	$(-0.0063,\ 0.0066)$	$(-0.0016,\ 0.0016)$ Aleph	$(-0.0064,\ 0.0064)$	$(-0.00067,\ 0.00067)$ Aleph

- These numbers correspond to a NP scale Λ ~ 0.5 TeV
- For comparison, for the dimension 8 gluonic couplings the reach is Λ ~ 1 TeV

Does h help?

- measuring $\tau^+ \tau^- h$ will be very hard so ask: what would be necessary to compete with a 14% measurement of Drell-Yan?
- For $d_\tau^{\gamma,Z}$ one would need

$$\sigma(pp \to \tau^+\tau^- h) < 5 \text{ fb} \qquad m_{\tau\tau} > 120 \text{ GeV}$$

or less than 50 times the SM value

- For the gluonic couplings $d_{\tau G,\tilde{G}}$ one needs

$$\sigma(pp \to \tau^+\tau^- h) < 50 \text{ fb}$$

or less than 500 times the SM value

Summary

- After the discovery of the Higgs boson there is a concerted effort to measure its couplings to other SM particles.
- We propose the use of processes with a Higgs to constrain anomalous couplings between SM fermions and gauge bosons.
- With a fundamental, 126 GeV Higgs, breaking EWS, gauge invariance relates these anomalous couplings to others between the same SM fermions and gauge bosons + h
- We have presented simple estimates for the constraints that can be expected at 14 TeV.
  - In some cases it would not be possible to constrain the couplings at the LHC in processes without a Higgs
  - In some cases the constraints are better from processes with a Higgs