Higgs production and dipole-type anomalous couplings

- Many studies looking for new CP violation in top physics
- CEDM is a `benchmark' scenario for these searches
- gauge invariance implies anomalous Higgs couplings which can be constrained by Higgs production

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- based on work with
  - Alper Hayreter, Ozyegin University (Istanbul)
  - Phys.Rev. D88 (2013) 034033, Phys.Rev. D88 (2013) 1, 013015,
  - JHEP 1507 (2015) 174

effective Lagrangians

- BSM with a SM Higgs: since 1986- Buchmuller-Wyler, Grzadkowski- Iskrzynski -Misiak-Rosiek …

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- each operator completely gauge invariant under the SM gauge group
- with recent Higgs discovery at 126 GeV, Λ could be almost any scale up to M_P
- large number of operators at $1/\Lambda^2$.
- LHC14 sensitive to Λ a few TeV

cmdm and cedm couplings

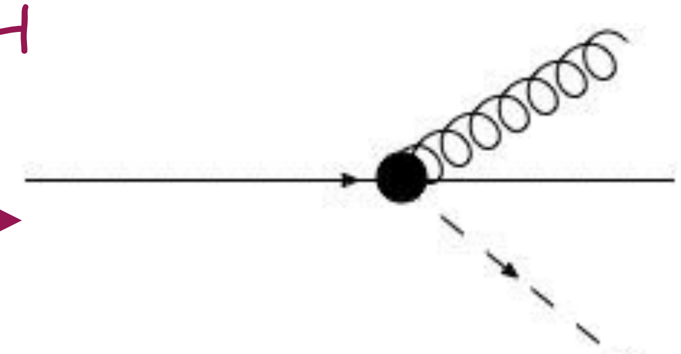
- consider new physics in the form of the usual anomalous color magnetic (CMDM) and electric (CEDM) dipole moments

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

- not fully gauge invariant under the SM with fundamental 126 GeV Higgs we fix

cmdm: anomalous (color) magnetic moment

with H



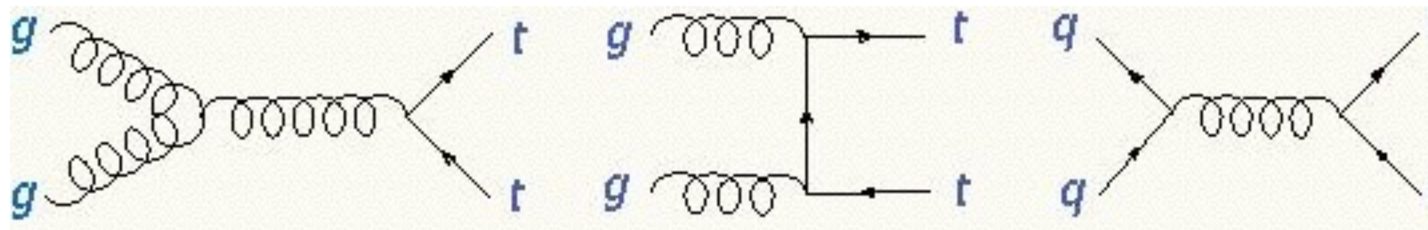
$$\mathcal{L} = \frac{g_s}{2}\ \bar{f}\ T^a \sigma^{\mu\nu} \left(a^g_f + i\gamma_5 d^g_f \right)\ f\ G^a_{\mu\nu}.$$

cedm: (color) electric moment

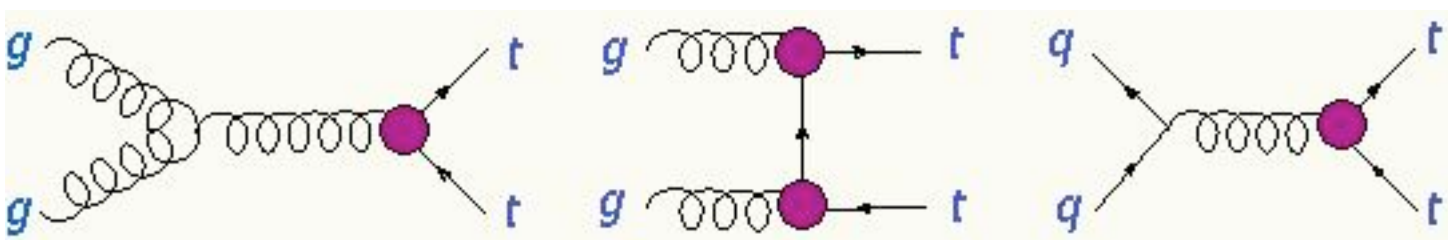
$$\mathcal{L} = g_s \frac{d_{uG}}{\Lambda^2}\ \bar{q}\sigma^{\mu\nu} T^a u\ \tilde{\phi} G^a_{\mu\nu} + g_s \frac{d_{dG}}{\Lambda^2}\ \bar{q}\sigma^{\mu\nu} T^a d\ \phi G^a_{\mu\nu}$$

top quark pair production

- SM at LO for LHC



- receives new contributions from modified couplings



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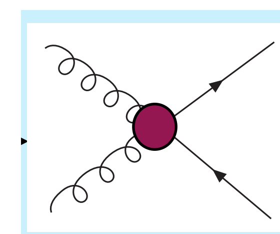
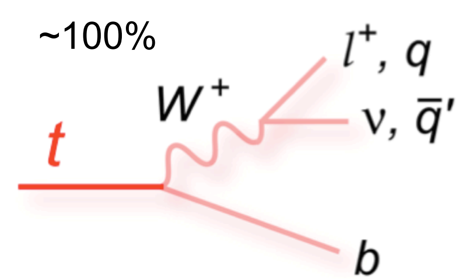


- and is followed by decay



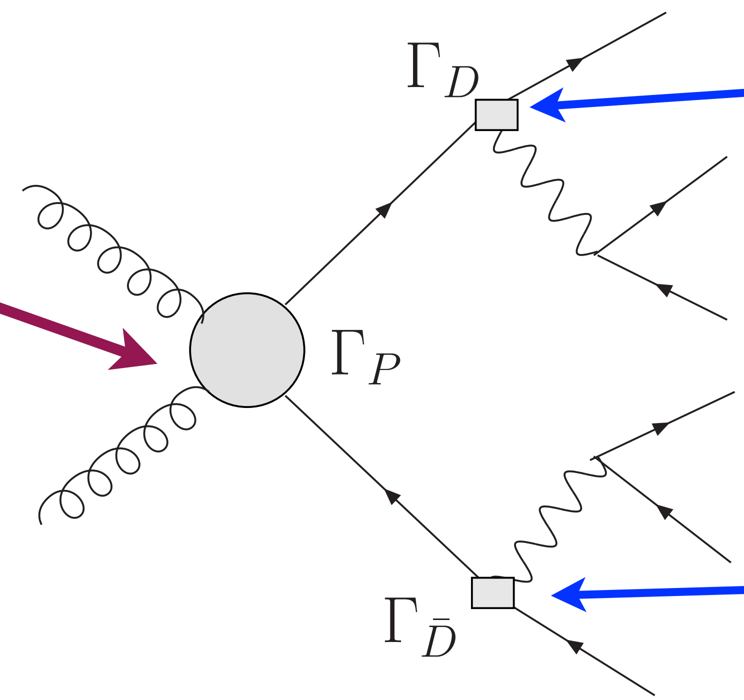
- the resulting cross-section is a quartic polynomial in the new couplings with only even powers of the CP-odd coupling

- T-odd correlations can be linear in CP-odd couplings

spin correlations

- underlying T-odd correlations are spin correlations
- different observables correspond to different spin analysers

$\epsilon(p_t, p_{\bar{t}}, s_t, s_{\bar{t}})$



$\epsilon(p_t, p_b, p_{\ell^+}, s_t)$

CP violation in the decay vertex

CP violation in the production vertex

$\epsilon(p_{\bar{t}}, p_{\bar{b}}, p_{\ell^-}, s_{\bar{t}})$

- covariant form of triple products

$$\epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-}) \equiv \epsilon_{\mu\nu\alpha\beta} p_t^\mu p_{\bar{t}}^\nu p_{\ell^+}^\alpha p_{\ell^-}^\beta$$

$$\vec{p}_b \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^+})$$

Decay distributions

$$gg \text{ or } q\bar{q} \to t\bar{t} \to (b\mu^+\nu_\mu)(\bar{b}\mu^-\bar{\nu}_\mu)$$

- dσ/dΩ contains the CP-odd correlations:

$$\begin{aligned}
\mathcal{O}_1 &= \epsilon(p_t, p_{\bar{t}}, p_{\mu^+}, p_{\mu^-}) \\
\mathcal{O}_2 &= q \cdot (p_{\bar{t}} - p_t)\, \epsilon(p_{\mu^+}, p_{\mu^-}, P, q) \\
\mathcal{O}_3 &= q \cdot (p_{\bar{t}} - p_t)\, \left(P \cdot p_{\mu^+}\, \epsilon(p_{\mu^-}, p_t, p_{\bar{t}}, q) + P \cdot p_{\mu^-}\, \epsilon(p_{\mu^+}, p_t, p_{\bar{t}}, q)\right)
\end{aligned}$$

- where the sum and difference of beam momenta are denoted by P and q.
  - for lepton plus jets: lepton $\longleftrightarrow$ d-jet momenta
- Notice that the T-odd observables are quadratic in q (beam direction)
- only the first one is CP odd at LHC

dilepton vs lepton plus jets

	$pp \to t\bar{t} \to b\bar{b}\ell^+\ell^- \not{E}_T$	$pp \to t\bar{t} \to b\bar{b}\ell^\pm jj \not{E}_T$
$\mathcal{O}_1$ A_1	$\epsilon(t, \bar{t}, \ell^+, \ell^-)$ -0.1540	$q_\ell\ \epsilon(t, \bar{t}, \ell, d)$ $-0.1535 \xrightarrow{p_t \to p_{t-vis}} -0.1114$
$\mathcal{O}_2$ A_2	$\epsilon(t, \bar{t}, b, \bar{b})$ -0.0358	$\epsilon(t, \bar{t}, b, \bar{b})$ $-0.0311 \xrightarrow{p_t \to p_{t-vis}} -0.0527$
$\mathcal{O}_3$ A_3	$\epsilon(b, \bar{b}, \ell^+, \ell^-)$ -0.0902	$q_\ell\ \epsilon(b, \bar{b}, \ell, d)$ -0.0838
$\mathcal{O}_4$ A_4	$\epsilon(b^+, b^-, \ell^+, \ell^-)$ -0.0340	$\epsilon(b^\ell, b^d, \ell, d)$ -0.0319
$\mathcal{O}_5$ A_5	$q \cdot (\ell^+ - \ell^-)\epsilon(b, \bar{b}, \ell^+ + \ell^-, q)$ -0.0309	$q_\ell q \cdot \ell\epsilon(b, \bar{b}, \ell, q)$ -0.0115
$\mathcal{O}_6$ A_6	$\epsilon(P, b - \bar{b}, \ell^+, \ell^-)$ 0.0763	$q_\ell\ \epsilon(P, b - \bar{b}, \ell, d)$ 0.0742
$\mathcal{O}_7$ A_7	$q \cdot (t - \bar{t})\epsilon(P, q, \ell^+, \ell^-)$ -0.0373	$q_\ell\ q \cdot (t - \bar{t})\epsilon(P, q, \ell, d)$ $-0.0325 \xrightarrow{p_t \to p_{t-vis}} -0.0257$
$\mathcal{O}_8$ A_8	$q \cdot (t - \bar{t})(P \cdot \ell^+ \epsilon(q, b, \bar{b}, \ell^-) + P \cdot \ell^- \epsilon(q, b, \bar{b}, \ell^+))$ 0.0074	$q \cdot (t - \bar{t})(P \cdot \ell\epsilon(q, b, \bar{b}, d) + P \cdot d\epsilon(q, b, \bar{b}, \ell))$ $0.0113 \xrightarrow{p_t \to p_{t-vis}} 0.0094$
$\mathcal{O}_9$ A_9	$q \cdot (\ell^+ - \ell^-)\epsilon(b + \bar{b}, q, \ell^+, \ell^-)$ 0.0089	$q \cdot \ell\epsilon(b + \bar{b}, q, \ell, d)$ 0.0051
$\mathcal{O}_{13}$ A_{13}	$\epsilon(P, b + \bar{b}, \ell^+, \ell^-)$ 0.0032	$q_\ell\epsilon(P, b + \bar{b}, \ell, d)$ 0.0025

Table 1: Comparison of asymmetries in the dilepton and semileptonic channels for $d_{tG} = 3$, $\Lambda = 1$ TeV. The latter do not yet correspond to observable asymmetries and serve only for this comparison.

need jet momenta

	$\mathcal{O}_i$	j	c_i
1	$q_\ell \;\; \epsilon(t, \bar{t}, \ell, j)$	1	-0.0094
		2	-0.0159
		3	-0.0163
		4	-0.0160
2	$\epsilon(t, \bar{t}, b, \bar{b})$	-	-0.0160
3	$q_\ell \;\; \epsilon(b, \bar{b}, \ell, j)$	1	-0.0148
		2	-0.0157
		3	-0.0198
		4	-0.0160
4	$\epsilon(b^\ell, b^j, \ell, j)$	1	-0.0041
		2	-0.0055
		3	-0.0057
		4	-0.0048

$$A_i = c_i \; d_{tG} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2$$

- j_1 hardest non-b jet
- j_2 second hardest non-b jet
- j_3 closest to the b (ΔR)
- j_4 W jet

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

- For LHC at 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)

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

how much NP "fits" here

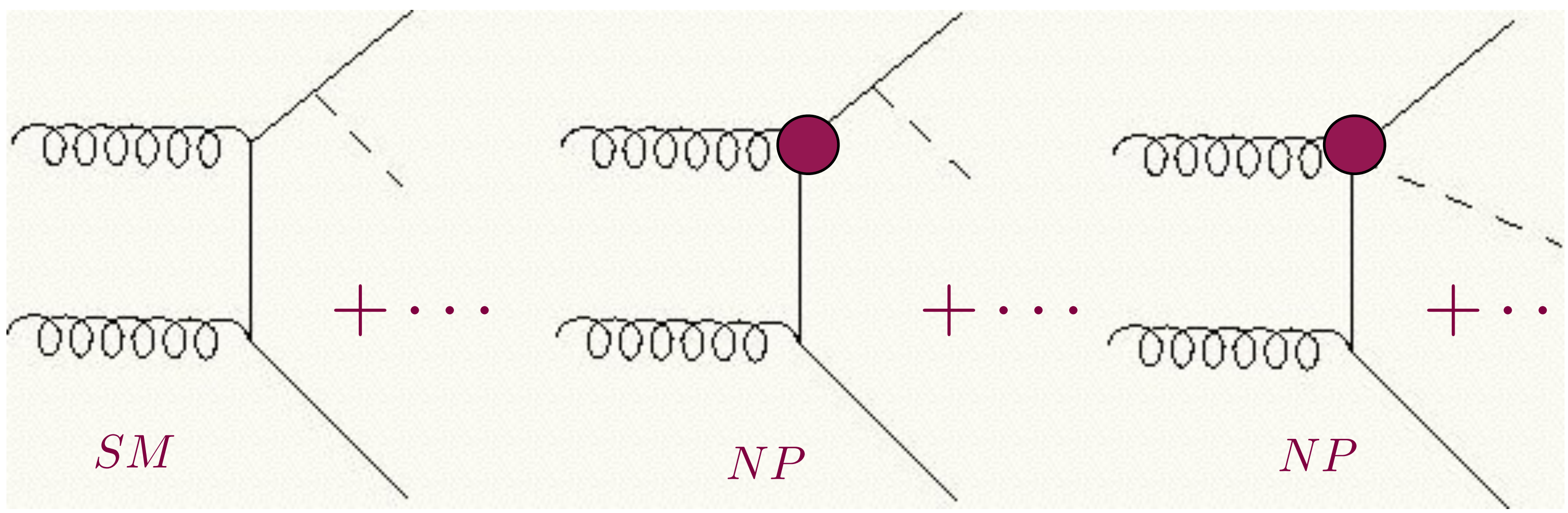
- For 14 TeV we use the NLO theoretical cross-section (M. Beneke, P. Falgari, S. Klein, C. Schwinn arXiv:1112.4606)

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

  - 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

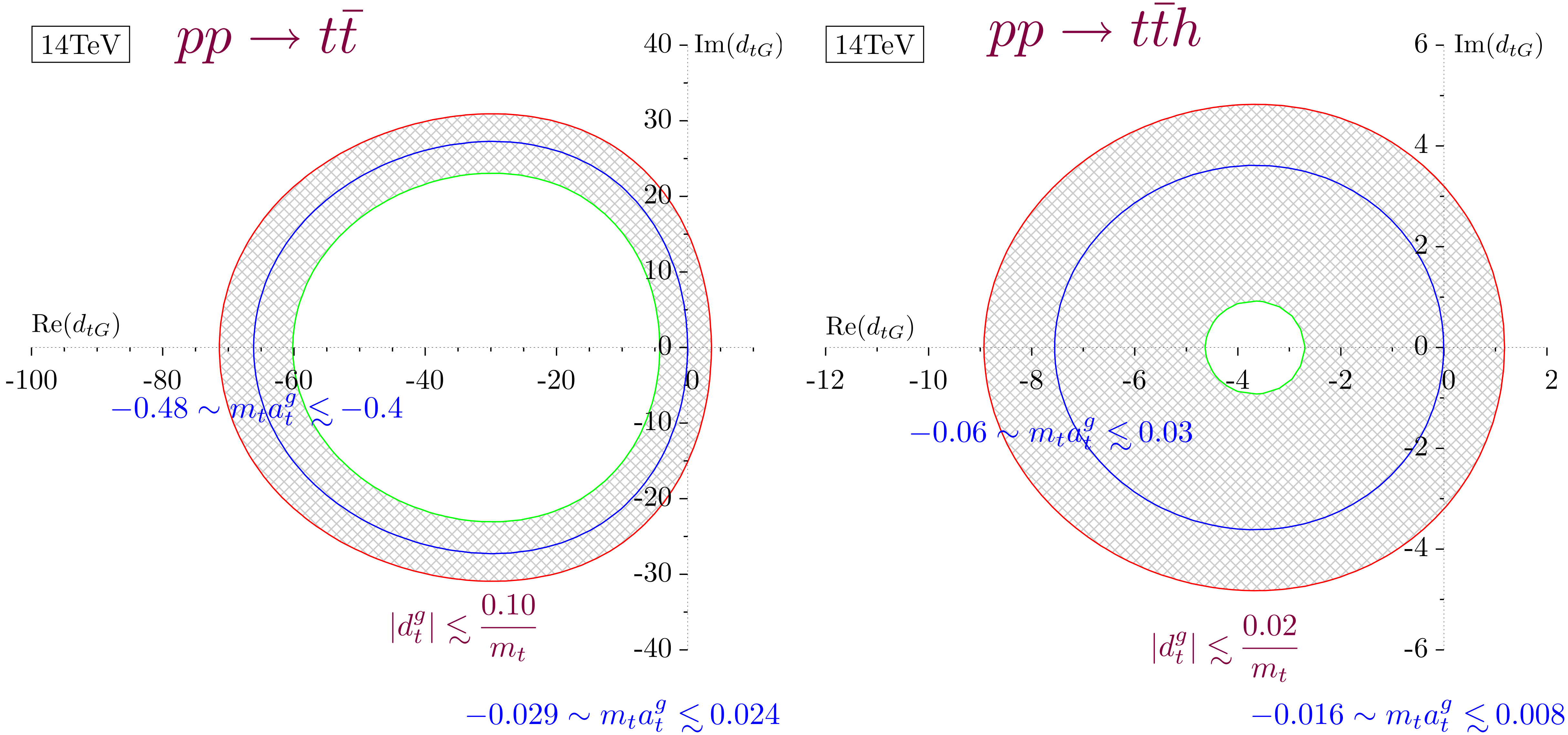


- cross-section is again a quartic polynomial in NP with only even powers of the CEDM
- constrain by comparing to SM at NLO (for 14 TEV), (15%-18%)

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

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

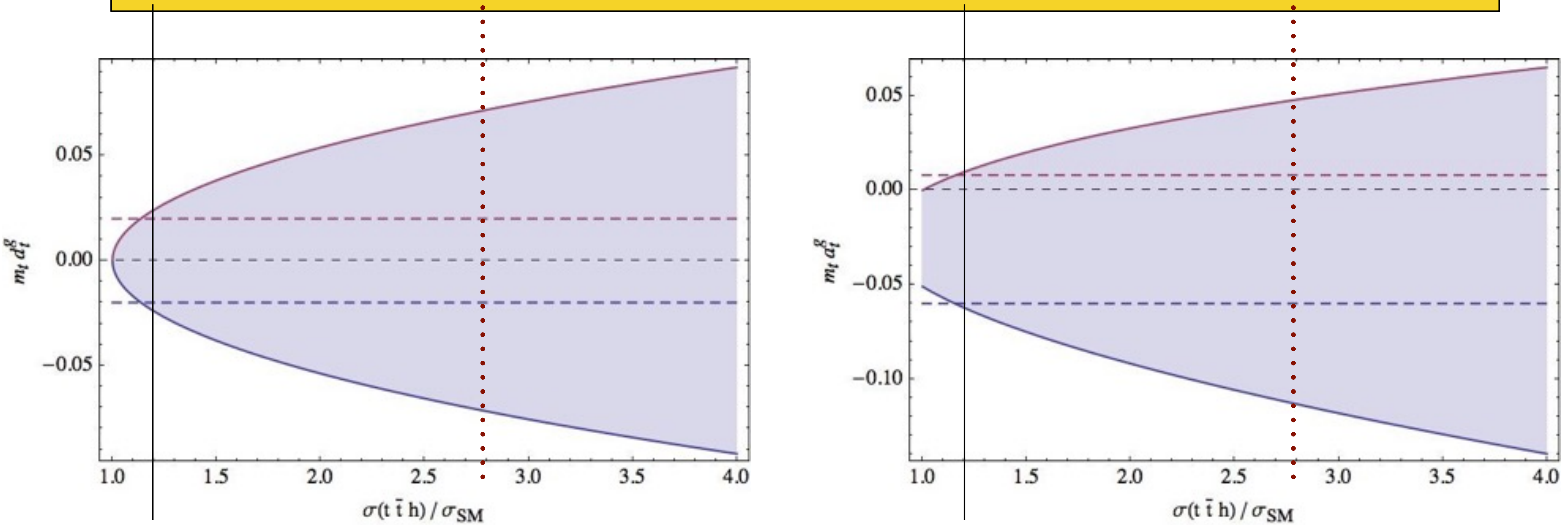
top pairs at LHC: σ($t\bar{t}$) vs σ($t\bar{t}h$)



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

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

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



- constraints based only on a limit on the cross-section
- vertical lines are CMS 2015 from 8 TeV data [Eur. Phys. J. C 75 (2015) 251]
  - $(1.2^{+1.6}_{-1.5})$
- horizontal dashed lines are the +15% contours of previous slide (no lower bound here)

comparison

- 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 possible possible to improve the bounds by measuring T-odd 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}

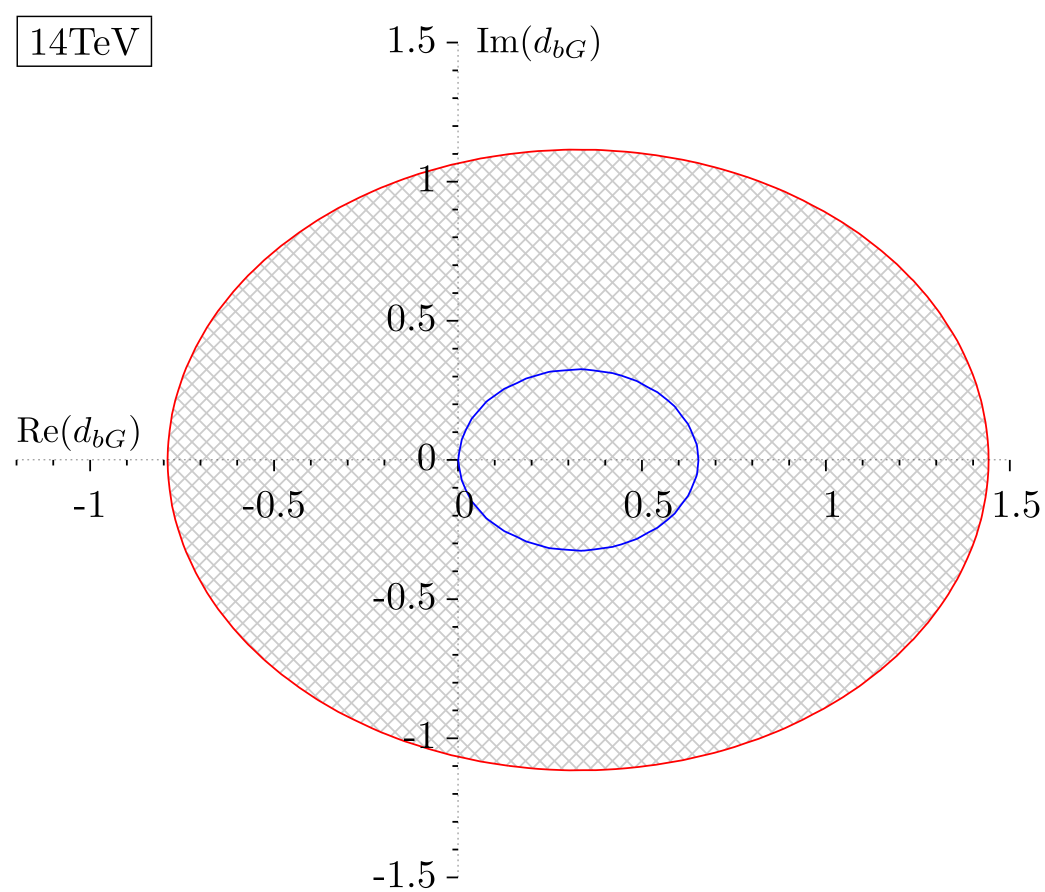
J Sjolin J.Phys. G29 (2003) 543-560 ,**Gupta, Mete, G.V. Phys.Rev. D80 (2009) 034013,** and many others *
Baumgart and Tweedie, JHEP 1303 (2013) **

b-quark couplings

- NP effects in $b\bar{b}$ pair production are overwhelmed by QCD
- not so much in 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%)



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

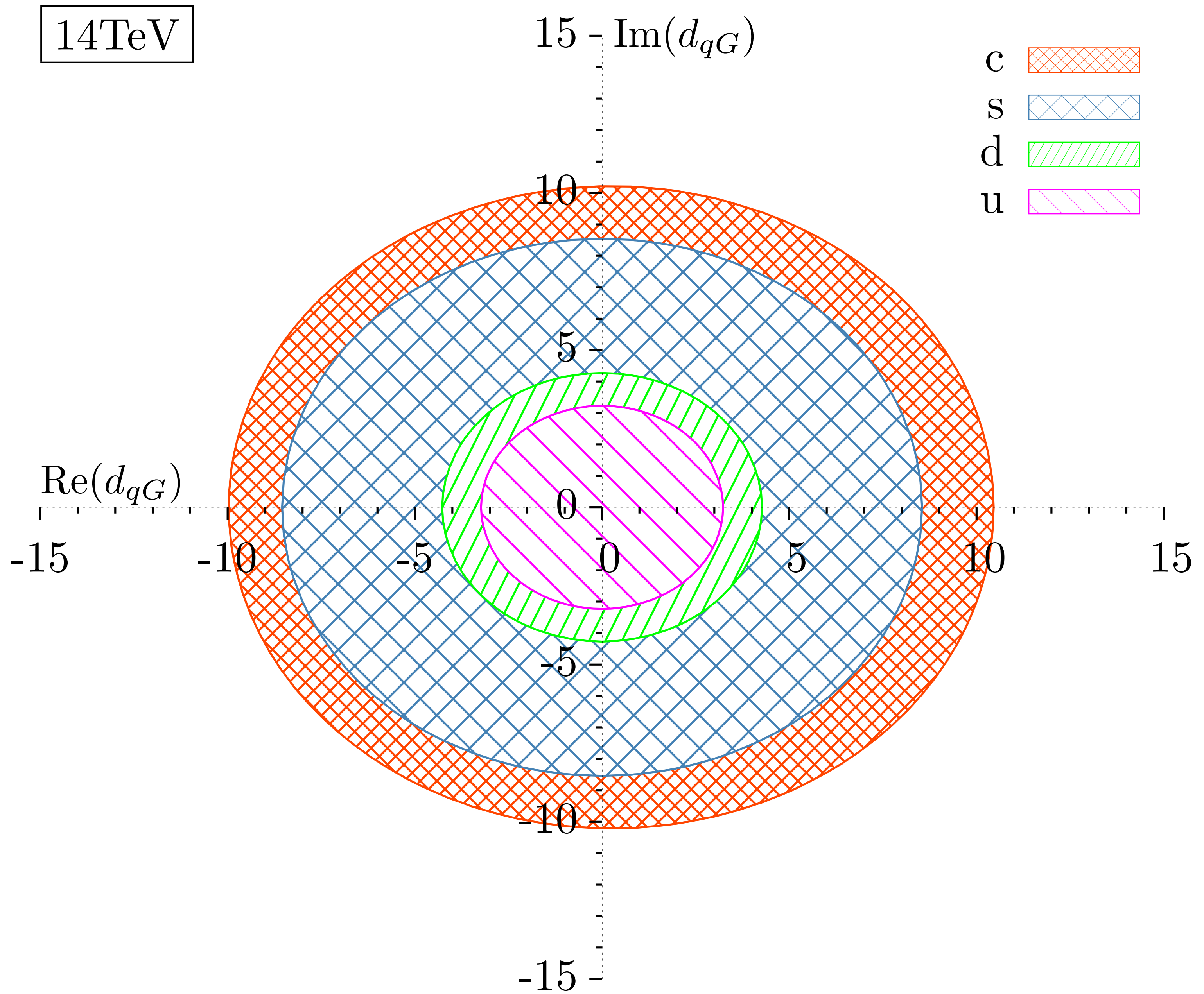
$$|d_b^g| \lesssim \frac{1.7 \times 10^{-4}}{m_b}$$

light quarks including charm

- NP is again buried in QCD background, only hope is in processes with a Higgs
- look for NP in pp $\to$ 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
  - 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 $q\bar{q} \to hg$



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.

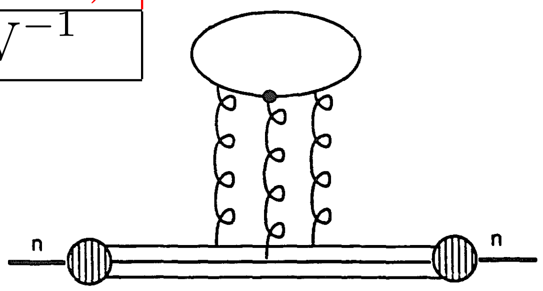
Process	CMDM	CEDM	Λ (TeV)
$\sigma(pp \to t\bar{t})$ 8 TeV	$-0.034 \lesssim m_t a_t^g \lesssim 0.031$	$\lvert m_t d_t^g \rvert \lesssim 0.12$	(1.5, .7)
$\sigma(pp \to t\bar{t})$ 14 TeV	$-0.029 \lesssim m_t a_t^g \lesssim 0.024$	$\lvert m_t d_t^g \rvert \lesssim 0.1$	(1.5, .7)
$A_1(pp \to t\bar{t})$ 14 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} (Λ − 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}

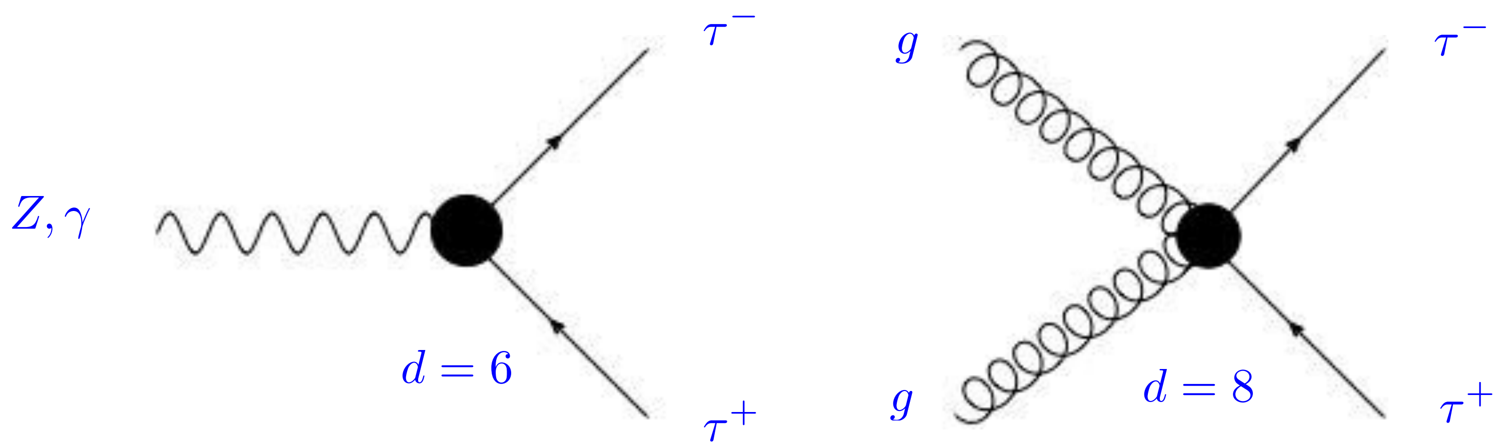


- for u,d (s) using neutron (Λ) edm and quark model
- for c,b,t using Weinberg three gluon operator

  (Nucl.Phys. B357 (1991) 311-356, De Rujula et al)
- more recent estimate for $\lvert m_t d_t^g \rvert \sim 2 \times 10^{-3}$ — Phys.Rev. D85 (2012) 071501, Kamenik, Papucci, Weiler
- more recent estimate for $\lvert m_c d_c^g \rvert \sim 6.7 \times 10^{-9}$ — JHEP 1403 (2014) 061, F. Sala

Case of the τ-lepton

- why the τ-lepton?
  - decays analyse the spin so spin correlations are observable as they are for top (almost)
  - existing constraints for electron and muon are very strong so start with possible new physics for τ-lepton only



CP violation at dimension 6

- 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 with a light Higgs turns into

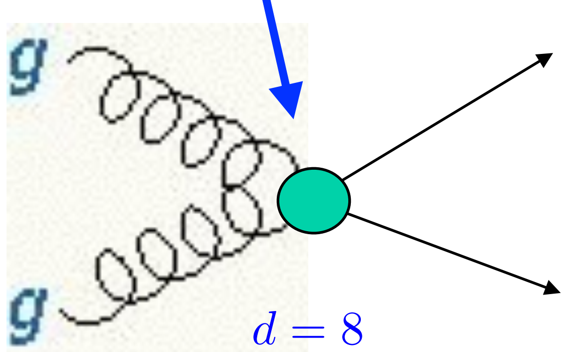
$$\mathcal{L} = g\frac{d_{\ell W}}{\Lambda^2}\,\bar{\ell}\sigma^{\mu\nu}\tau^i e\,\phi W^i_{\mu\nu} + g'\frac{d_{\ell B}}{\Lambda^2}\,\bar{\ell}\sigma^{\mu\nu}e\,\phi B_{\mu\nu} \;+\; \mathrm{h.c.}$$

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

power counting and L_{eff}

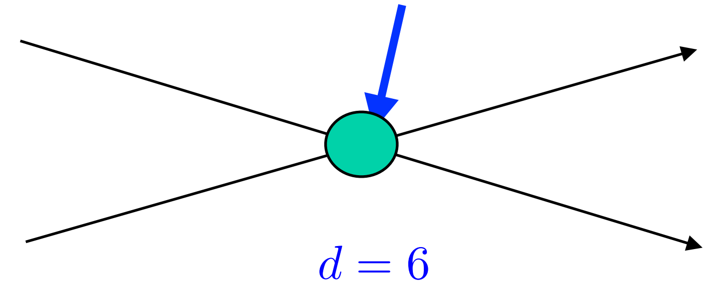
- LHC is a gluon factory, power counting of L_{eff} may be misleading if Λ_{NP} is sufficiently low (few TeV)
- operators of dimension 8 are suppressed by an additional Λ^2 with respect to those of dimension 6, so we usually ignore them
- but look at this dimension 8 term for example:

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



compare to

$$\mathcal{L}_6 = a\,\frac{g^2}{\Lambda^2}\;\bar{u}u\;\bar{\ell}\ell$$



parton luminosity for gluon gluon

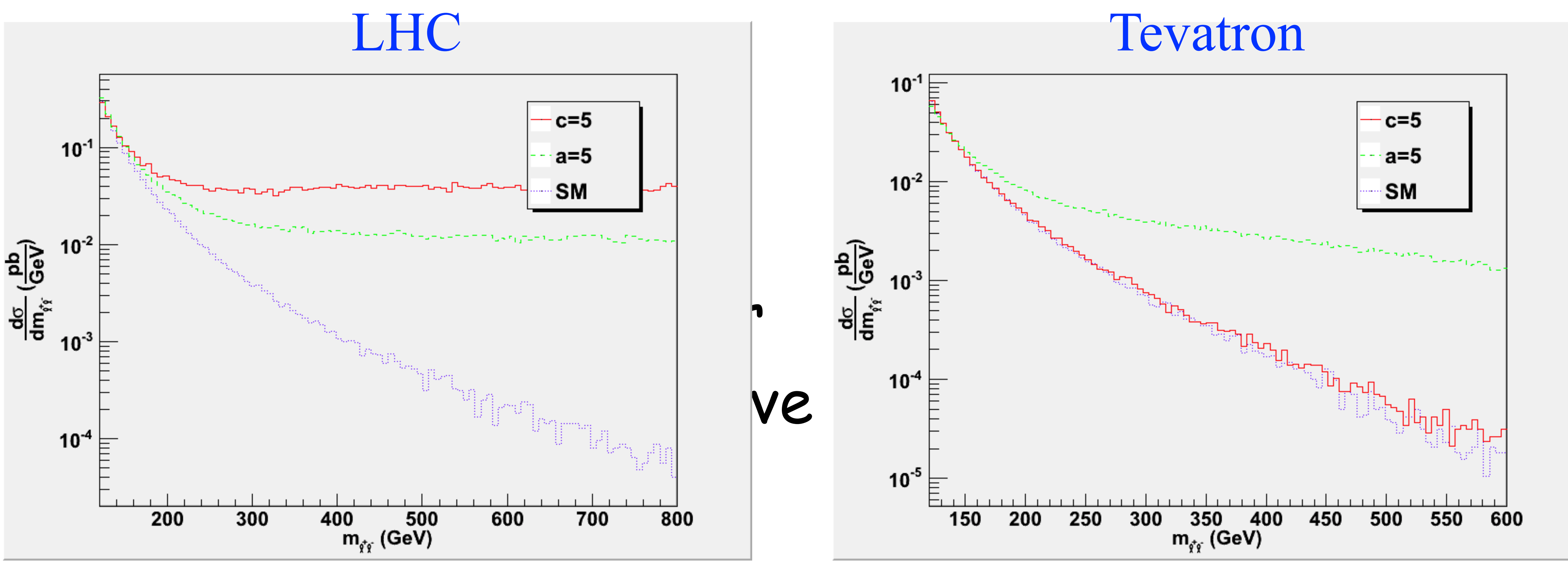
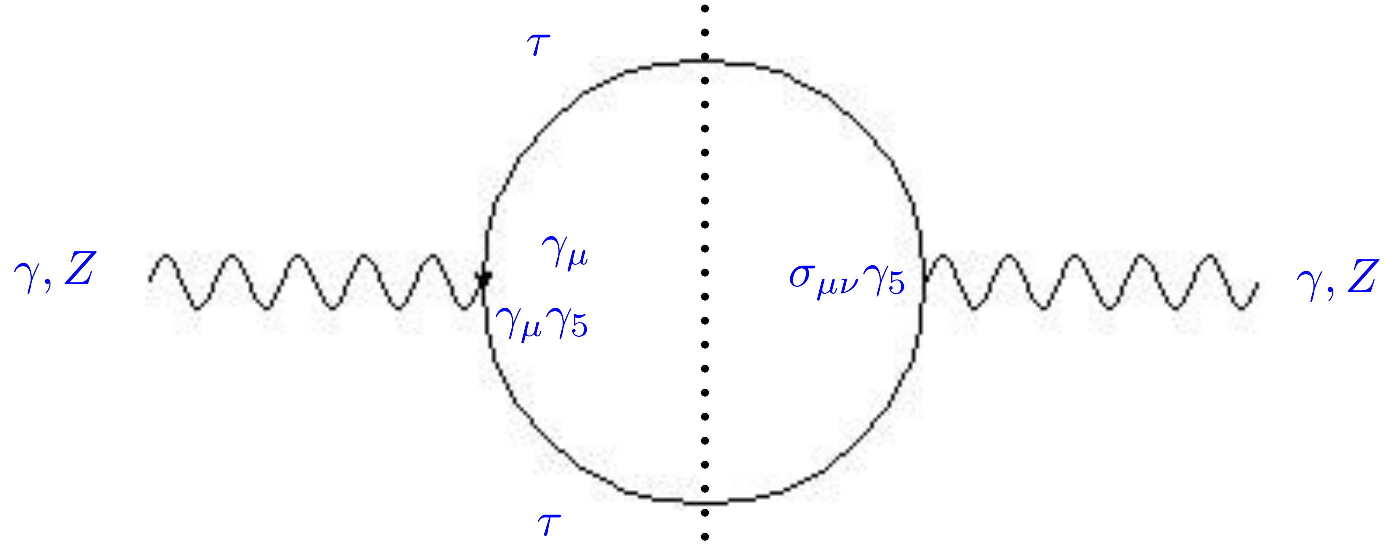


FIG. 2: $d\sigma/dm_{\ell\ell}$ for the SM; the SM plus new physics in the gluon fusion process ($c = 5$); and the SM plus new physics in the $u\bar{u}$ annihilation process ($a = 5$). The scale of new physics is taken to be $\Lambda = 1$ TeV. The figure on the left corresponds to $pp \to \ell^+\ell^-$ at the LHC and the figure at the right to $p\bar{p} \to \ell^+\ell^-$ at the Tevatron.

single spin asymmetry

- interference with SM proportional to m_τ
- double spin correlation proportional to m_τ, or quadratic in NP



- single spin correlation not zero as $m_\tau \to 0$

$$\mathcal{O}_{2s} \sim m_\tau d_\tau^{Z,\gamma} \epsilon_{\mu,\nu,\alpha,\beta}\ p^\mu_{\tau^+} p^\nu_{\tau^-} s^\alpha_{\tau^+} s^\beta_{\tau^-} \qquad \mathcal{O}_{2s} \sim d_\tau^{Z,\gamma}\ a_\tau^{Z,\gamma}\ \epsilon_{\mu,\nu,\alpha,\beta}\ p^\mu_{\tau^+} p^\nu_{\tau^-} s^\alpha_{\tau^+} s^\beta_{\tau^-}$$

$$\mathcal{O}_{1s} \sim d_\tau^Z g_A (\hat{t} - \hat{u})\ \epsilon_{\mu,\nu,\alpha,\beta}(p_1 - p_2)^\mu p^\nu_{\tau^+} p^\alpha_{\tau^-}\ (s_{\tau^-} - s_{\tau^+})^\beta$$

$$\mathcal{O}_1 \ = \ \left[\vec{q}_{beam} \cdot (\vec{p}_{\mu^+} - \vec{p}_{\mu^-})\ \vec{q}_{beam} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})\right]_{lab}$$

From cross-sections

- 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

- For the Z region assume a 7% comparison which is the current systematic error

cross-sections

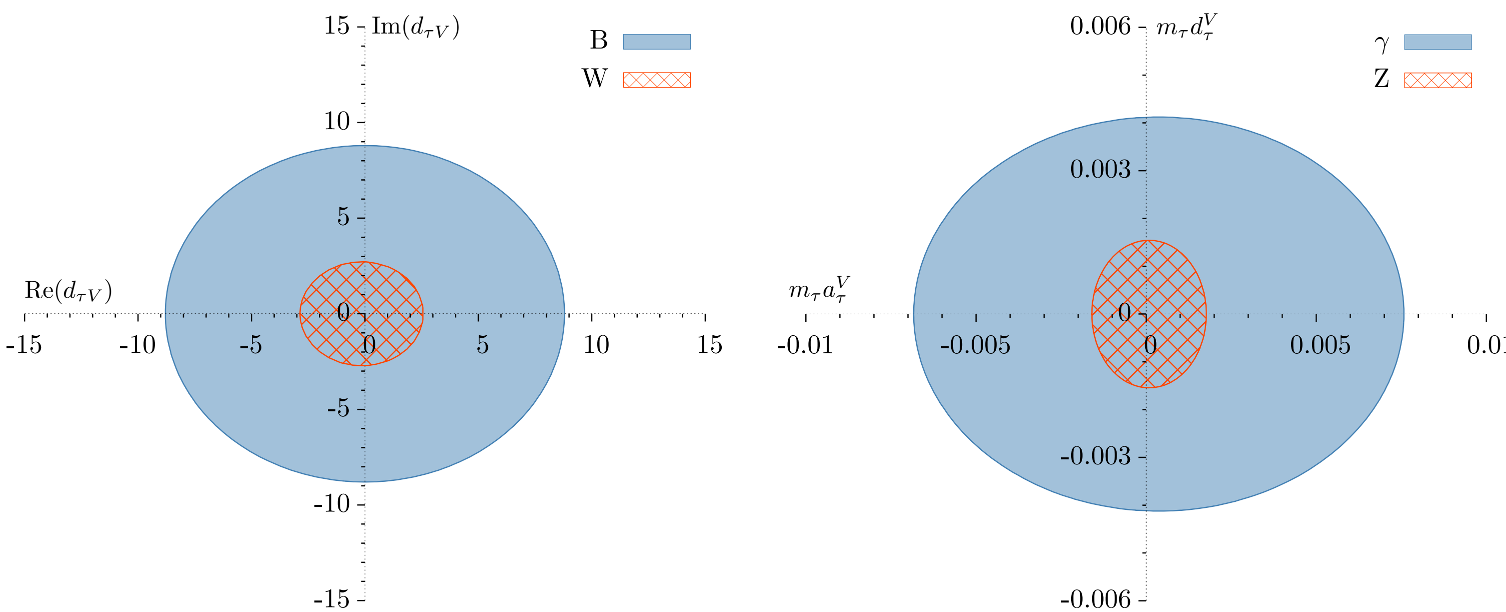


FIG. 1: Regions of $d_{\tau V}$ (left) and the corresponding $d_\tau^{\gamma,Z}$, $a_\tau^{\gamma,Z}$ (right) allowed by a maximum 14% deviation from the SM cross-section with the cuts described in the text.

high energy

$m_{\ell\ell \not{E}_T} > 120\ GeV$

$p_{T\ell} > 15\ GeV$

$|\eta_\ell| < 2.4$

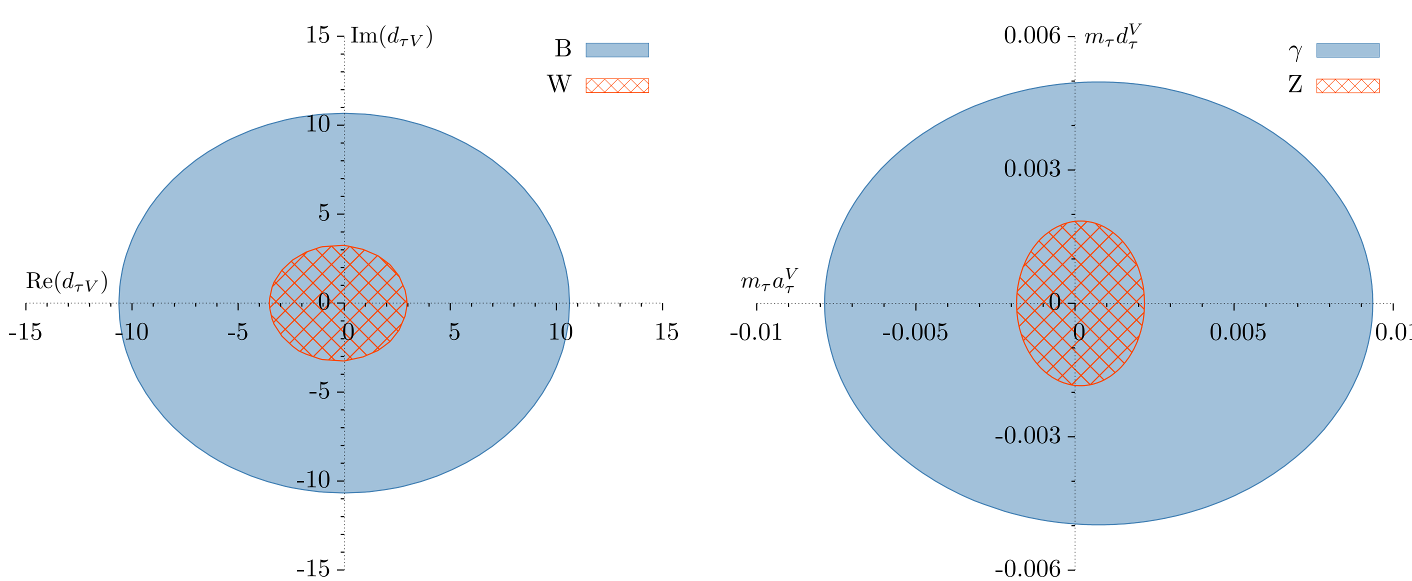


FIG. 2: Regions of $d_{\tau V}$ (left) and the corresponding $d_\tau^{\gamma,Z}$, $a_\tau^{\gamma,Z}$ (right) allowed by a maximum 7% deviation from the SM cross-section with the cuts described in the text.

Z region

$60 < m_{\ell\ell \not{E}_T} < 120\ GeV$

constraints

	$m_\tau a_\tau^\gamma$	$m_\tau a_\tau^Z$
pre-LHC	(-0.026,0.007) Delphi	(-0.0016,0.0016) Aleph
$\sigma(m_{\tau\tau} > 120)$ to 14%	(-0.0068,0.0076)	(-0.0016,0.0018)
A_C 100 fb^{-1}	(-0.019,0.019)	(-0.0043,0.0043)
$\sigma(60 < m_{\tau\tau} < 120)$ to 7%	(-0.0078,0.0093)	(-0.0018,0.0021)
A_C 100 fb^{-1}	(-0.0045,0.0045)	(-0.001,0.001)

	$m_\tau d_\tau^\gamma$	$m_\tau d_\tau^Z$
pre-LHC	(-0.002,0.0041) Belle	(-0.00067,0.00067) Aleph
$\sigma(m_{\tau\tau} > 120)$ to 14%	(-0.004,0.004)	(-0.0015,0.0015)
A_1 100 fb^{-1}	(-0.001,0.001)	(-0.0002,0.0002)
$\sigma(60 < m_{\tau\tau} < 120)$ to 7%	(-0.005,0.005)	(-0.0018,0.0018)
A_1 100 fb^{-1}	(-0.0002,0.0002)	(-0.00004,0.00004)

$\sigma(m_{\tau\tau} > 120)$ to 14%	$\left(\|d_{\tau G}\|^2 + \|d_{\tau\tilde{G}}\|^2\right) < 0.9$
A_{ss} 100 fb^{-1}	$\left\|\mathrm{Re}(d_{\tau G,\tilde{G}})\mathrm{Im}(d_{\tau G,\tilde{G}})\right\| < 0.16$

- These numbers correspond to a NP scale $\Lambda \sim$ 0.5 TeV
- For comparison, for the dimension 8 gluonic couplings the reach is $\Lambda \sim$ 1 TeV

Does h help?

- measuring $\tau^+ \tau^-$ h will be very hard
- 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

$$\frac{\sigma}{\sigma_{SM}} < 50$$

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

or

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

$$\frac{\sigma}{\sigma_{SM}} < 500$$

CP properties

- the single spin asymmetry does not have definite CP for LHC, although it does for the parton level process

$$\mathcal{O}_1 = [\vec{q}_{beam} \cdot (\vec{p}_{\mu^+} - \vec{p}_{\mu^-})\ \vec{q}_{beam} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})]_{lab} \qquad A_1(pp) \xrightarrow{CP} -A_1(\bar{p}\bar{p})$$

$$\mathcal{O}_2 = [\vec{q}_{beam} \cdot (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})\ \vec{q}_{beam} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})]_{lab} \qquad A_2(pp) \xrightarrow{CP} A_2(\bar{p}\bar{p})$$

$$\mathcal{O}_{test} = [\vec{q}_{beam} \cdot (p_{\mu^+} \times p_{\mu^-})]_{lab}$$

Collider	σ(fb)	A_1	A_2	A_{test}
pp	276.0	-0.15	0.10	0.00
$\bar{p}\bar{p}$	275.8	-0.14	-0.10	0.00
$p\bar{p}$	313.6	-0.15	0.00	0.17

Table 1: Comparison of T-odd and T-even asymmetries with Re$(d_{\tau W})$=0, Im$(d_{\tau W})$=10 for different colliders to exhibit their transformation properties under CP.

Summary

- We propose the use of processes with a Higgs to constrain anomalous couplings between SM fermions and gauge bosons
- we discussed the quark cedm and tau-lepton edm as well as a dimension 8 lepton gluonic coupling
- With a fundamental, 126 GeV Higgs, gauge invariance relates these anomalous couplings to others between the same SM fermions and gauge bosons + h
- we presented simple estimates for the constraints that can be expected at 14 TeV.
  - T-odd correlations are useful for top and tau
  - for quarks other than top, associated production with Higgs yields constraints that would be very hard to obtain otherwise at LHC.