# TOP QUARK COUPLINGS - THEORY

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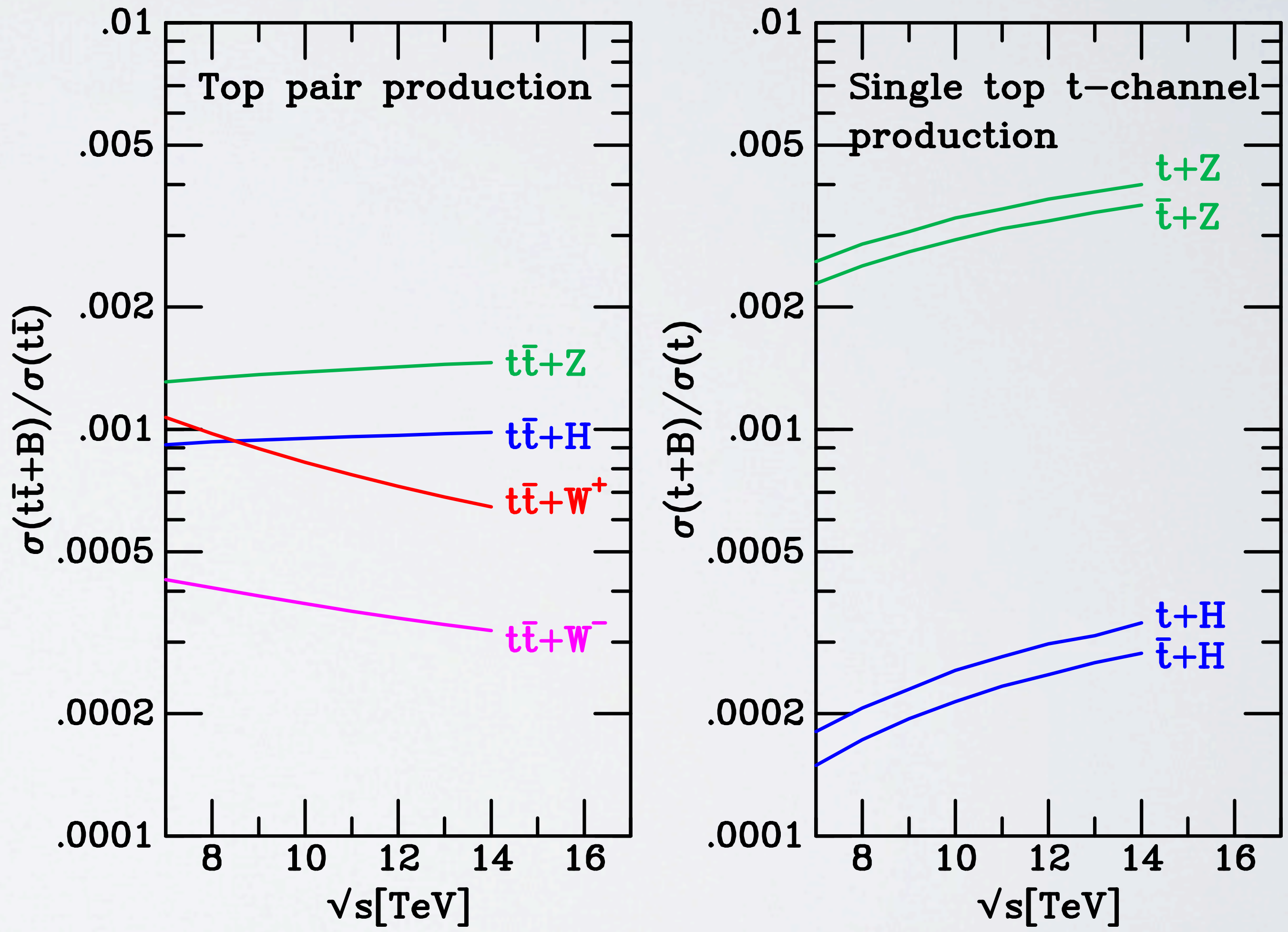
# STANDARD MODEL TOP COUPLINGS

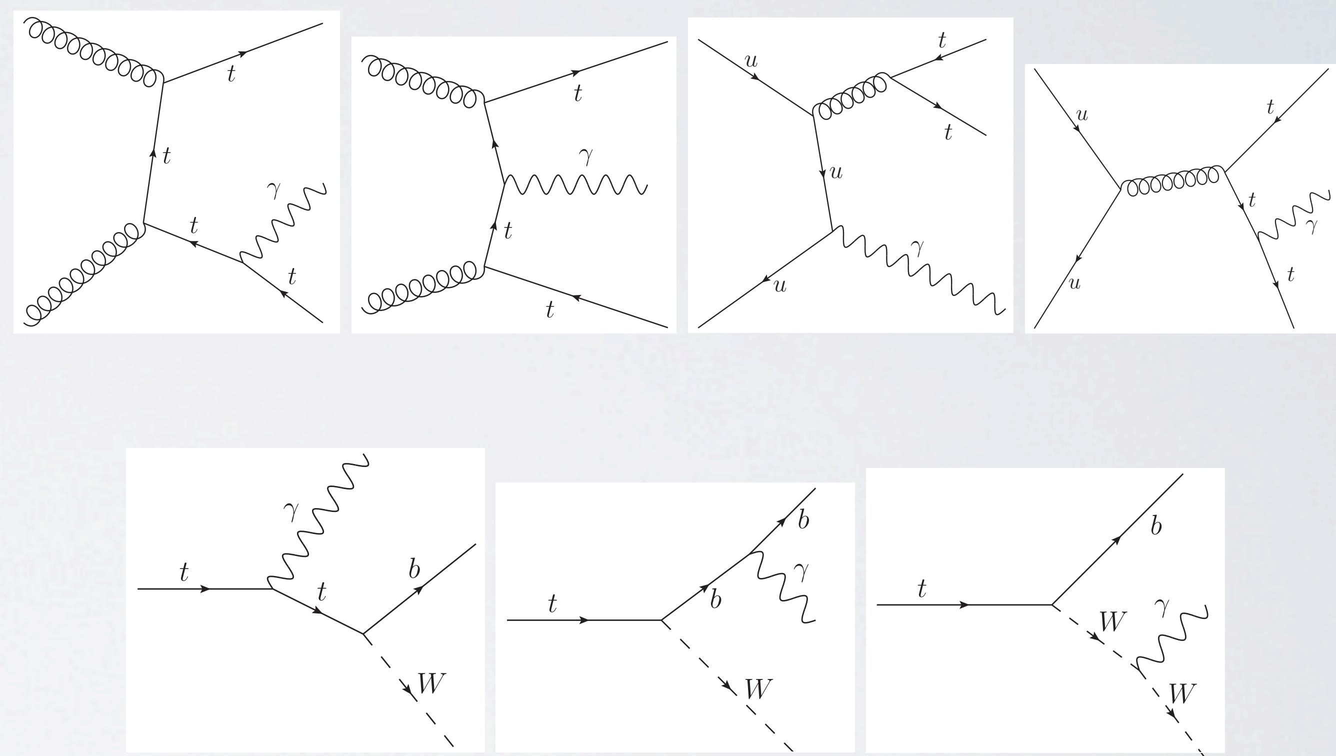
- Electroweak-scale mass makes top a prime candidate to manifest BSM physics.
- Measure the gauge and Yukawa couplings predicted by SM to look for deviations.




Associated production rates for single and double top with SM bosons

# TOP COUPLINGS TO γ & Z

- What is the top's electric charge?
- What are its vector and axial couplings to γs and Zs?
- Measure the overall cross section of ttbar+V events



Top production and decay diagrams with γ in the final state

# TOP COUPLING TO W

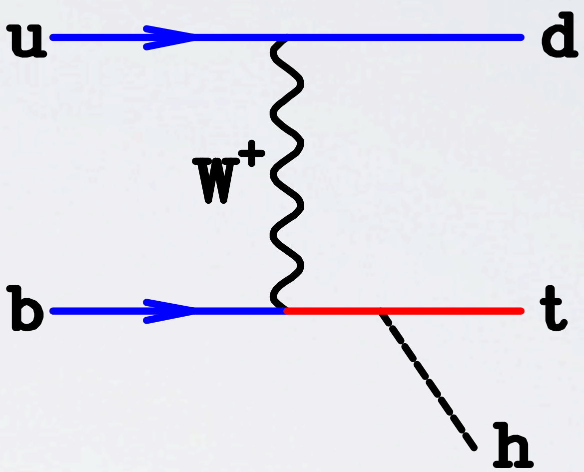
- Top decays help determine structure of coupling to Ws.
- Different W polarizations give different lepton angular distributions:

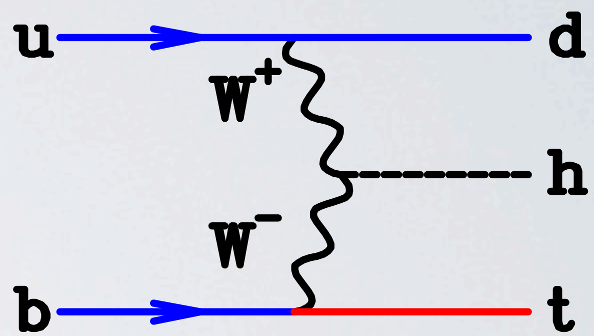
$$\frac{1}{N}\frac{dN(W\to e\nu)}{d\cos\theta_e^*} = \left[\frac{3}{4}\sin^2\theta_e^* F_0 + \frac{3}{8}(1-\cos\theta_e^*)^2 F_L + \frac{3}{8}(1+\cos\theta_e^*)^2 F_R\right]$$

- Fractions determined in SM, e.g. $F_0 = \frac{m_t^2}{m_t^2 + 2M_w^2}$ , $F_R = 0$
- Single top production in association with W constrains $V_{tb}$.

# TOP COUPLING TO HIGGS

- Indirect evidence of coupling from gluon fusion production and $H \rightarrow \gamma\gamma$
- More information will come from ttbar+H final states
- Single top + Higgs is challenging for LHC. Observation could be new physics sign.




Large cancellation in SM between these diagrams

# NEW PHYSICS IN THE TOP SECTOR

- Effects on tops from very massive states, O(1 TeV), can be parametrized by higher-dimension operators:

$$\mathcal{L}^{\rm eff} = \mathcal{L}^{\rm SM} + \sum \frac{C_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

- Companion note* to this talk provides a table of 26 dimension-6 operators affected by new physics in top sector.

- Alternate approach works in terms of vertex functions/form factors, about which more...

* http://www.snowmass2013.org/tiki-download_file.php?fileId=40

# VERTEX FUNCTIONS

- If New Physics affects the ttbar-V vertex, we can write it as the following interaction where $c_{L,R}$, $d_{L,R}$ coefficients are functions of gauge boson momentum (e.g. for W):

$$\mathcal{L}_{int} \supset -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(c_L^W P_L + c_R^W P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\,\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(d_L^W P_L + d_R^W P_R\right) t\, W_{\mu}^{-} + h.c.$$

- Similar terms for other gauge bosons

- If NP were at low mass scales, we may be forced into such a description.

- Taking Precision Electroweak seriously, this approach has drawbacks...

# THE TROUBLE WITH VERTEX FUNCTIONS

$$\mathcal{L}_{int} \supset -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(c_L^W P_L + c_R^W P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(d_L^W P_L + d_R^W P_R\right) t W_{\mu}^{-} + h.c.$$

- One issue with vertex functions is they obscure parametric hierarchy.

- Naively, $c_L^W$, $c_R^W$, $d_L^W$, and $d_R^W$ appear on equal footing with arbitrary W-momentum ($Q^2$) dependence.

- From effective operator approach, we see that $d_L^W$ and $c_R^W$ only contribute at $O(m_b)$ and $O(1/\Lambda^4)$.

- Operators also tell us $O(v^2/\Lambda^2)$ corrections to $c_L^W$ and $d_R^W$ are $Q^2$-independent.

# MORE TROUBLE WITH VERTEX FUNCTIONS*

- There are further theoretical advantages to higher-dimension operators:
  - Gauge symmetries of the SM are manifest.
  - Contact interactions (e.g. four-quark) and vertex corrections treated consistently.
  - Works equally well for on- or off-shell quarks. Minimal vertex-functions assume the former.
  - EFTs are renormalizable in the modern sense (hep-th/9510087). Consistent to use operators in loops. NP might be virtual.

*For more on the advantages of Effective Field Theory for tops, see Zhang and Willenbrock 1008.3155

# WHAT ARE THESE OPERATORS OF WHICH YOU SPEAK?

$$
\begin{aligned}
O_{\phi q}^{(3,ij)} &= i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}_{Li}\gamma^\mu \tau^I q_{Lj})\,,\\
O_{\phi q}^{(1,ij)} &= i(\phi^\dagger D_\mu \phi)(\bar{q}_{Li}\gamma^\mu q_{Lj})\,,\\
O_{\phi\phi}^{ij} &= i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu d_{Rj})\,,\\
O_{\phi u}^{ij} &= i(\phi^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu u_{Rj})\,,\\
O_{uW}^{ij} &= (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I\,,\\
O_{dW}^{ij} &= (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I\,,\\
O_{uB\phi}^{ij} &= (\bar{q}_{Li}\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, B_{\mu\nu}\,,
\end{aligned}
$$

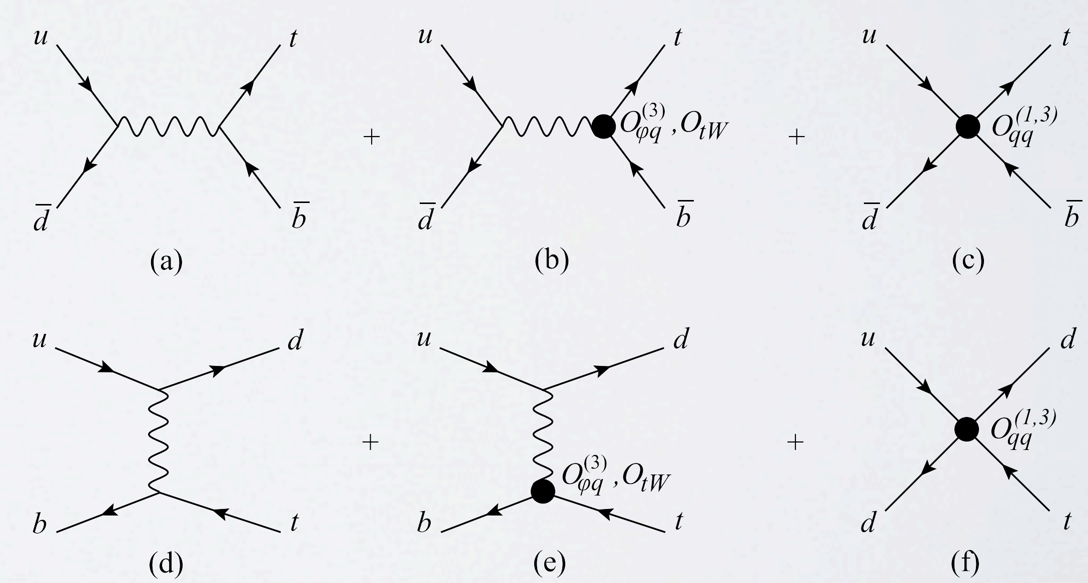
| operator | process |
|---|---|
| $O_{\phi q}^{(3)} = i(\phi^+\tau^I D_\mu\phi)(\bar{q}\gamma^\mu\tau^I q)$ | top decay, single top |
| $O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I$ (with real coefficient) | top decay, single top |
| $O_{qq}^{(1,3)} = (\bar{q}^i\gamma_\mu\tau^I q^j)(\bar{q}\gamma^\mu\tau^I q)$ | single top |
| $O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G_{\mu\nu}^A$ (with real coefficient) | single top, $q\bar{q}, gg \to t\bar{t}$ |
| $O_G = f_{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $gg \to t\bar{t}$ |
| $O_{\phi G} = \frac{1}{2}(\phi^+\phi)G_{\mu\nu}^A G^{A\mu\nu}$ | $gg \to t\bar{t}$ |
| 7 four-quark operators | $q\bar{q} \to t\bar{t}$ |

- Many parametrizations of dimension-6 operators for tops in the literature (e.g.):
    - Aguilar-Saavedra 0811.3842 [operators equivalent to vertex functions]
    - Zhang & Willenbrock 1008.3869 [affect observables at O(1/$\Lambda^2$)]

# MODIFICATIONS TO KNOWN PROCESSES

- We can first consider those operators with tops that modify:
  - Charged current single-top production
  - top decay
  - ttbar production
- Look for modifications to: overall rate, differential rate in decay product energy, angle.

| | |
|---|---|
| Charged current single top production and top decay | |
| $\mathcal{O}^{(3)}_{\phi q} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$ | $\mathcal{O}_{\phi\phi} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}\gamma^\mu d)$ |
| $\mathcal{O}_{uW} = (\bar{q}\tau^I \sigma^{\mu\nu} u)\tilde{\phi} W^I_{\mu\nu}$ | $\mathcal{O}_{dW} = (\bar{q}\tau^I \sigma^{\mu\nu} d)\phi W^I_{\mu\nu}$ |
| Single top and $t\bar{t}$ production | |
| $\mathcal{O}_{uG} = (\bar{q}\lambda^a \sigma^{\mu\nu} u)\tilde{\phi} G^a_{\mu\nu}$ | $\mathcal{O}^{(1,3)}_{qq} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$ |
| $t\bar{t}$ production | |
| $\mathcal{O}^{(8,1)}_{qq} = (\bar{q}^i \gamma_\mu \lambda^a q^j)(\bar{q}\gamma^\mu \lambda^a q)$ | $\mathcal{O}^{(8,3)}_{qq} = (\bar{q}^i \gamma_\mu \lambda^a \tau^I q^j)(\bar{q}\gamma^\mu \lambda^a \tau^I q)$ |
| $\mathcal{O}^{(8)}_{ut} = (\bar{u}^i \gamma_\mu \lambda^a u^j)(\bar{u}\gamma^\mu \lambda^a u)$ | $\mathcal{O}^{(8)}_{dt} = (\bar{d}^i \gamma_\mu \lambda^a d^j)(\bar{u}\gamma^\mu \lambda^a u)$ |
| $\mathcal{O}^{(1)}_{quS} = (\bar{q}u^i)(\bar{u}^j q)$ | $\mathcal{O}^{(1)}_{qdS} = (\bar{q}d^i)(\bar{d}^j q)$ |
| $\mathcal{O}^{(1)}_{qtS} = (\bar{q}u)(\bar{u}q)$ | |



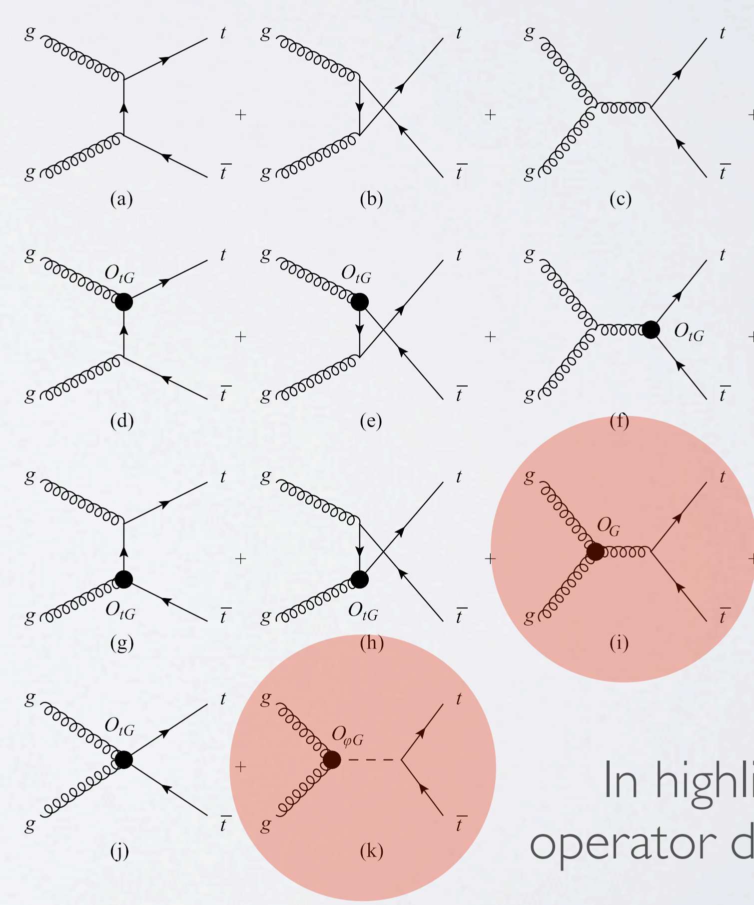

Modifications to s- and t-channel single top production.
Right diagrams can't be written as vertex function.

# HIGHER DIMENSION OPERATORS WITHOUT TOPS

- ttbar production is sensitive to New Physics that doesn't directly involve tops.

- We can probe corrections to gluon self-coupling, gluon-Higgs, and gluon-γ/Z.

| Gluon operators that affect $t\bar{t}$ production | |
|---|---|
| $\mathcal{O}_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $\mathcal{O}_{\tilde{G}} = f_{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ |
| $\mathcal{O}_{\phi G} = \phi^\dagger \phi \, G_{\mu\nu}^A G^{A\mu\nu}$ | $\mathcal{O}_{\phi\tilde{G}} = \phi^\dagger \phi \, \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$ |
| $\mathcal{O}_{GB} = G_\mu^{A\nu} \tilde{G}_\nu^{A\rho} B_\rho^{C\mu}$ | |




In highlighted diagrams, operator doesn't involve tops.

# NEUTRAL CURRENTS

- Neutral current decays of the top are very suppressed in the SM.
- E.g. BR(t→Zc)~$10^{-13}$ by loop and GIM suppression.
- Can thus look for rare decays and rare single-top production.

| Neutral current top production and top decay | |
|---|---|
| $\mathcal{O}^{(1)}_{\phi q} = i(\phi^\dagger D_\mu \phi)(\bar{q}^i \gamma^\mu q^j)$ | $\mathcal{O}_{\phi u} = i(\phi^\dagger D_\mu \phi)(\bar{u}^i \gamma^\mu u^j)$ |
| $\mathcal{O}_{uB} = (\bar{q}^i \sigma^{\mu\nu} u^j)\tilde{\phi} B_{\mu\nu}$ | |

# tt AND ttbar + HIGGS

- Another process heavily suppressed in the SM is tt production (distinct from ttbar).
- tt operators can also give ttbar correction, but this is color singlet, $O(1/\Lambda^4)$.
- ttbar-Higgs coupling modified at dimension-6.

| $tt$ production and color singlet $t\bar{t}$ production | |
|---|---|
| $\mathcal{O}_{qqV}^{(1)} = (\bar{q}^i \gamma_\mu q^j)(\bar{q}^k \gamma^\mu q^l)$ | $\mathcal{O}_{qq}^{(3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}^k \gamma^\mu \tau^I q^l)$ |
| $\mathcal{O}_{quV}^{(1)} = (\bar{q}^i \gamma_\mu q^j)(\bar{u}^k \gamma^\mu u^l)$ | $\mathcal{O}_{uuV}^{(1)} = (\bar{u}^i \gamma_\mu u^j)(\bar{u}^k \gamma^\mu u^l)$ |
| $t\bar{t}h$ coupling | |
| $\mathcal{O}_{3\phi} = \phi^\dagger \phi \, \tilde{\phi} \, \bar{q} \, u$ | |

# ~~CP~~ IN TOPS FROM NEW PHYSICS

- CP-violation in SM top sector small because large $m_t$ means large GIM-suppression.
- Would be clear signal of New Physics.
- Operators at right only interfere with SM when top spin taken into account ($T_N$-Theorem*).

| operator | process |
|---|---|
| $O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$ (with imaginary coefficient) | top decay, single top |
| $O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$ (with imaginary coefficient) | single top, $q\bar{q}, gg \to t\bar{t}$ |
| $O_{\tilde{G}} = f_{ABC}\tilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$ | $gg \to t\bar{t}$ |
| $O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$ | $gg \to t\bar{t}$ |

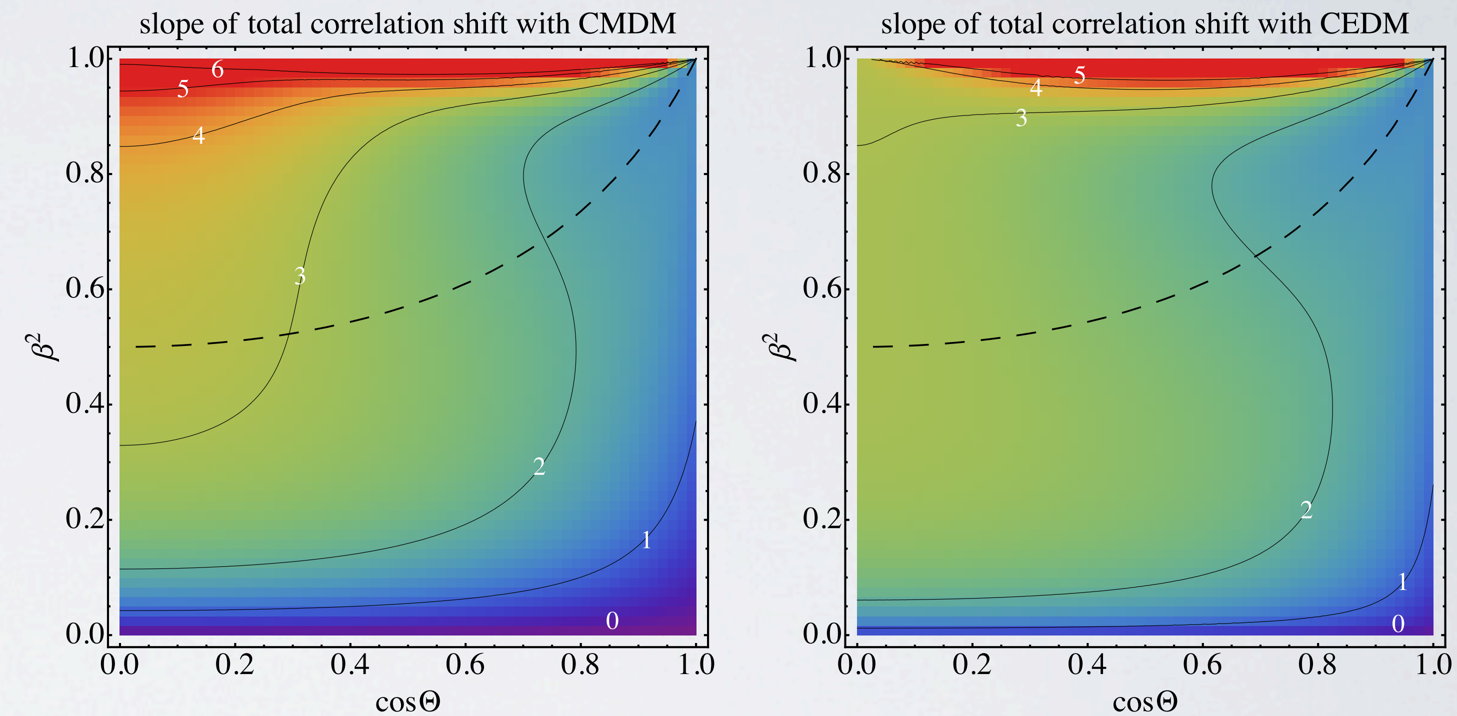
CP-odd operators that contribute at $O(1/\Lambda^2)$



*Atwood et al. hep-ph/0006032

# SPIN POLARIZATION & CORRELATION*

- Top spin can reveal more than CP-violating NP
- Single top polarization can reveal e.g. new chiral coupling in production.
- ttbar spin correlation matrix has particular form dictated by C, P, and CP symmetries




Phase space dependence of total ttbar spin correlation shift in the presence of chromomagnetic (L) and chromoelectric (R) dipole moments. Respectively the real and imaginary coefficients of $O_{uG}$

*Frederix & Maltoni 0712.2355, MB & Tweedie 1212.4888

# TESTS BEYOND THE LHC & TEVATRON

- Some dimension-6 operators affecting top physics have prefactors $O(v^2/\Lambda^2)$.

- Thus, we don't necessarily gain sensitivity by going to higher energies.

- Some constraints beyond high-$p_T$ hadron colliders:†

  - Gauge invariance lets us use constraints on b-quarks, precision electroweak, $B \to X_s \gamma$, and B-Bbar mixing

  - ZEUS searches for $tc\gamma$, $tu\gamma$, $tcZ$, $tuZ$ couplings

  - Best limit on top chromo-EDM ($10^{-4}/m_t$) from neutron and Hg EDMs.*

*Kamenik et al. 1107.3143

†See Zhang et al. 1201.6670

# CONCLUSIONS

- Couplings of top quarks give us a useful test of the SM and a probe for New Physics
- Parametrizing New Physics is best done with effective operators (manifest hierarchy, symmetry, consistency)
- In some cases tops will help us constrain non-top operators
- Can go beyond picture here with new fields (e.g. WIMP dark matter) or d>6-operators (e.g. 4-top final states)
- Observables that use tops' spin give us another (or the only) handle.

# BACKUP SLIDES

# $T_N$-THEOREM*

- $T_N$ refers to "naive" time reversal:
  - Reverse spins and momenta
  - Don't exchange initial and final states
- In the absence of final state rescattering, CPT = $CPT_N$. Wanting to observe interference of CP-odd NP with the CP-even SM requires a $T_N$-odd observable.
- $T_N$-odd → Levi-Civita $\varepsilon^{\mu\nu\rho\sigma}$, 2-to-2 process → only 3 independent momenta, → top spin needed in observable.

*Atwood et al. hep-ph/0006032