# TOP QUARK COUPLINGS - EFFECTIVE OPERATOR ANALYSIS

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# EFFECTIVE OPERATORS FOR HEAVY, NEW PHYSICS

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

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

- Systematic approach to finding new physics is to bound the $C_i$ coefficients.

# 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 $O(1/\Lambda^2)$]

# TOP COUPLINGS

- Effective operators give us a theoretically consistent description of modified couplings to SM bosons, e.g.

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

- Rewrite these vertex functions in terms of operator contributions, which take advantage of gauge invariance, can be used at NLO, etc.

$$\delta c_L^W = C_{\phi q}^{(3)*}\,\frac{v^2}{\Lambda^2}\ ,\ \delta d_L^W = \sqrt{2}\,C_{dW}\,\frac{v^2}{\Lambda^2}\,,$$

$$\delta c_R^W = \frac{1}{2}\,C_{\phi\phi}^{(3)*}\,\frac{v^2}{\Lambda^2}\ ,\ \delta d_R^W = \sqrt{2}\,C_{uW}\,\frac{v^2}{\Lambda^2}\,.$$

# THE CAUTIONARY TALE OF GLUONS

- How might we modify the top's coupling to the gluon?

$$\mathcal{L} \supset \bar{f}\,\gamma^{\mu}\left(\mathcal{C}_V + \gamma^5 \mathcal{C}_A\right) f\, A_{\mu}$$
$$+\,\mathcal{C}_{\text{dip.}}\,\bar{f}\,i\,\sigma^{\mu\nu} q_{\nu}\, f\, A_{\mu}$$

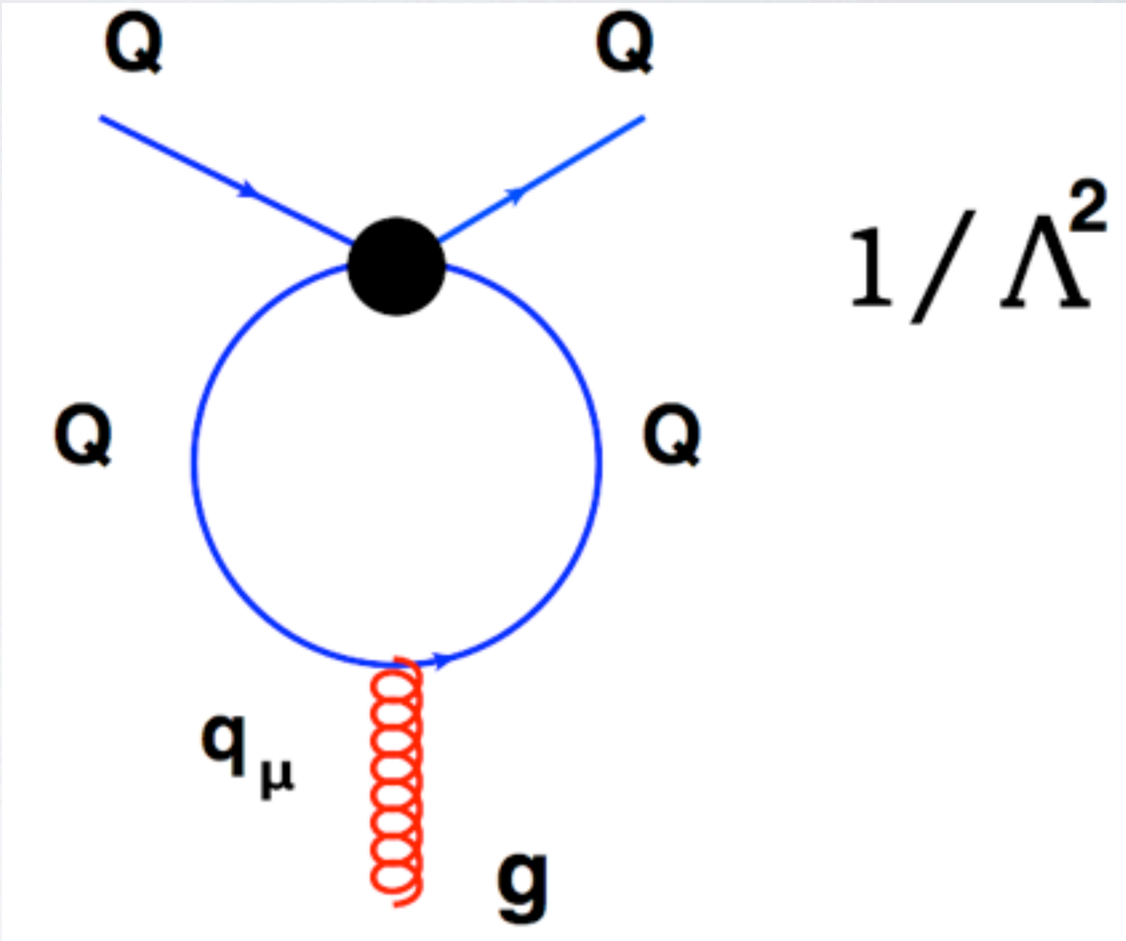
- Could axial form factor for gluon resolve $A_{FB}$?*
- Gauge invariance dictates that $C_A$=0.
- Can't just add this form factor.

By contrast, we can sensibly talk about adding a chromoelectromagnetic dipole operator, and can bound it, cf. Kamenik et al. 1107.3143, Baumgart & Tweedie 1212.4888

Proposed in Gabrielli, Raidal et al., 1106.4553, 1112.5885, 1212.3272

# HOW TO GET AN AXIAL FORM FACTOR

- Can't write a standalone axial interaction
- Can generate form factor from four-fermion operators for off-shell gluon
- Operators involved have parity-odd structures




Four-fermi operator generating axial coupling

# NON-INTERFERING OPERATORS

- Rather than bound loop suppressed process, look at four-fermion interaction directly
- Analysis simplified by non-interference with QCD
- Most attention in literature to date has ignored this set (cf. Willenbrock et al. 1008.3869)

$$\mathcal{O}^{1,8}_{AV} = [\bar{q}\, T_{1,8}\gamma^\mu\gamma_5 q]\ [\bar{t}\, T_{1,8}\gamma^\mu t]\,,$$
$$\mathcal{O}^{1,8}_{VA} = [\bar{q}\, T_{1,8}\gamma^\mu q]\ [\bar{t}\, T_{1,8}\gamma^\mu\gamma_5 t]\,,$$
$$\mathcal{O}^{1,8}_{PS} = [\bar{q}\, T_{1,8}\gamma_5 q]\ [\bar{t}\, T_{1,8} t]\,,$$
$$\mathcal{O}^{1,8}_{SP} = [\bar{q}\, T_{1,8} q]\ [\bar{t}\, T_{1,8}\gamma_5 t]$$

# SELECTING A TARGET

- We start with one pair of up-top operators.

$$\mathcal{O}_{AV}^{1,8} = [\bar{u}\, T_{1,8}\gamma^\mu \gamma_5 u]\ [\bar{t}\, T_{1,8}\gamma^\mu t]$$

- We perform a simple cut and count analysis with a two-bin ("hi" vs. "lo") ratio

- Knowing that ratio for the SM and at two different parameter points lets us scale our sensitivity

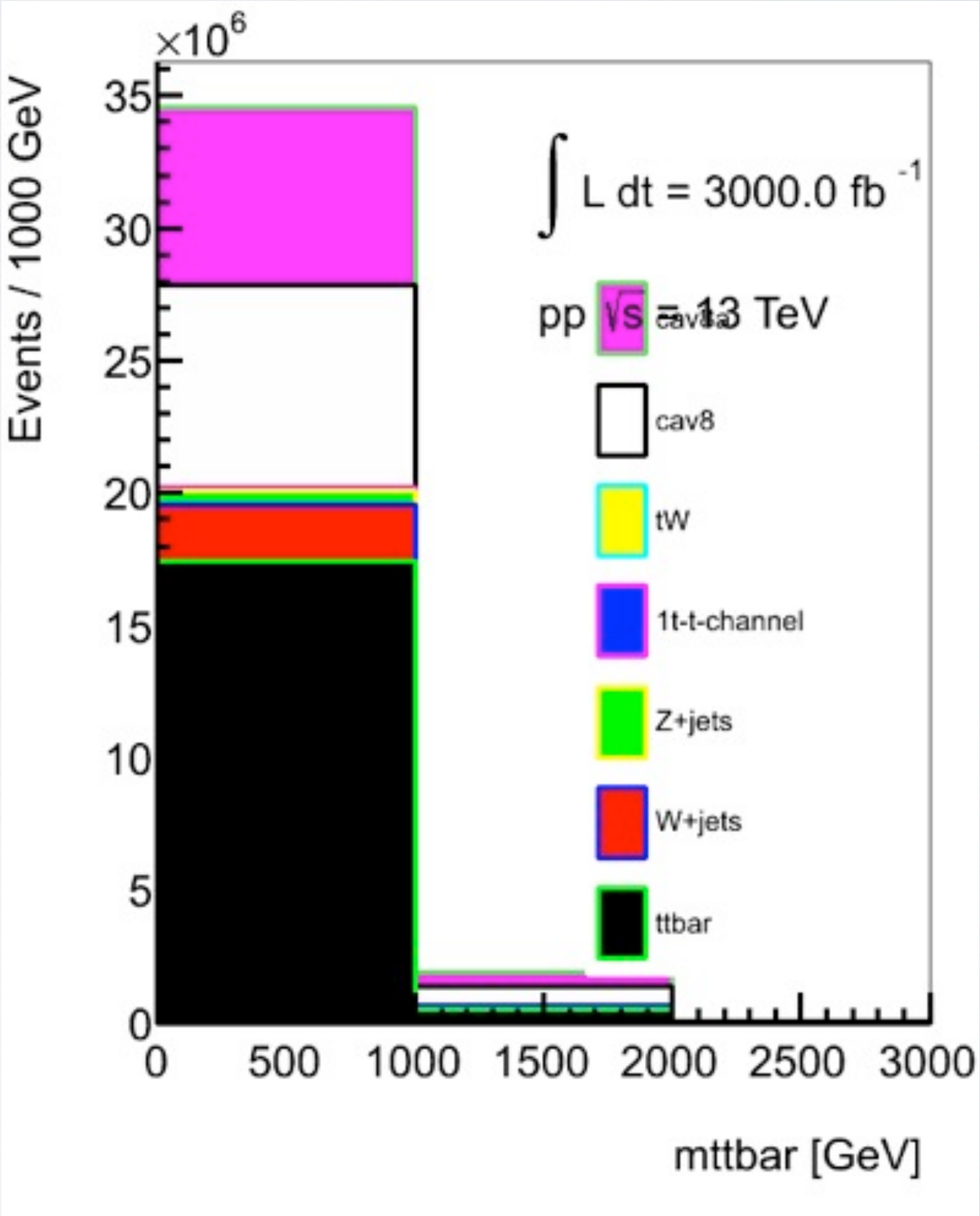
$$r = \frac{r_{SM} + C_{AV}^2\, H_{NP}}{1 + C_{AV}^2\, L_{NP}}$$

# EVENT SELECTION AND RECONSTRUCTION

- We take events with
  - Single charged lepton
  - MET
  - >4 jets
  - >0 btags
- Can make a “topological top pair” by taking scalar $p_T$ sum of above and bin hi vs. lo.

# RECONSTRUCTION AND BACKGROUNDS

- We can also group our jets into hadronic top and W by taking chi2 with the heavy particle masses.
- This also gives us ability to cut on invariant mass and binning by invariant mass
- Backgrounds considered include: W+jets, Z+jets, single-top (t-channel and tW)




"Two" bin mttbar (white and pink are different NP points)

# LIMITS

| cuts, bin | 300 fb$^{-1}$ (TeV) | 3 ab$^{-1}$ (TeV) |
|---|---|---|
| none, $h_T$ | 1.4 | 1.8 |
| $m_t$, $h_T$ | 2.1 | 2.8 |
| $m_t$, $m_W$, $h_T$ | 1.8 | 2.4 |
| $m_t$, $m_{t\bar{t}}$ | 2.2 | 3.0 |
| $m_t$, $m_{t\bar{t}}$, $C_{AV}^{(8)}$ | 1.5 | 2.0 |

95% CL limits on effective coupling scale for cuts ($m_t$ and $m_W$ windows), binning ($h_T$ and $m_{ttbar}$), bounding $C^{(1)}_{AV}$ except where indicated

# CONCLUSIONS

- This is work in progress and there remains much to do
    - Account for NLO
    - Charge asymmetry as complementary observable
    - Fits besides two-bin?
    - Other operators
- Despite the lack of interference, we can bound these four-quark operators at the partonic interaction scale. Worthy of further study beyond Snowmass.