Constraining the top-Z coupling through $t\bar{t}Z$ production at the LHC

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RR and Markus Schulze
arXiv:hep-ph/1404.1005

Top quark

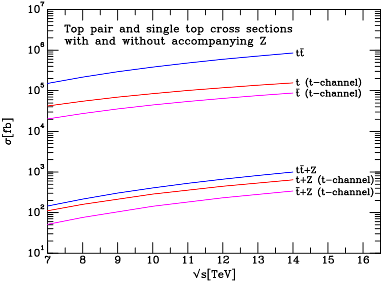
- Top quark has **largest mass** of known quarks.
- Decays before hadronization.
- "Natural" Yukawa $y_t \sim 1$.
- Special role in EWSB?
- Expect **top-EW couplings** to be **highly sensitive** to EWSB mechanism.

$\Rightarrow$ measurement of top-EW couplings is **part of the program of understanding EWSB**, as well as avenue for **finding/bounding New Physics effects**.

Top quarks at the LHC

LHC a **top factory**: $\sigma_{t\bar{t}} \sim nb$ at $\sqrt{s} = 14$ TeV

$\Rightarrow \quad \sim 10^9$ top pairs over lifetime of LHC.



Campbell, Ellis, RR, hep-ph/1302.3856

Energy and luminosity large enough to produce **massive EW particles** in association with $t\bar{t}$.

$\rightarrow$ **direct measurement of top-EW couplings**

- $t\bar{t} + \gamma$, $t\bar{t}Z$ and $t\bar{t}W$ observed in run I.

hep-ex/1307.4568, ATLAS-CONF-2012-126, hep-ex/1303.3239

- Low statistics in $t\bar{t}Z$ channel: CMS 9 events, ATLAS 1 event.

Long-term project requiring high luminosity at higher energy run.

Indirect constraints

No **direct constraints** placed on top-Z couplings to date.

Indirect constraints through LEP data:

- Zbb coupling and ρ parameter closely constrained by fits to ϵ_1 and ϵ_b.
- R_b and A^b_{FB} also constrain $Zb_L b_L$ couplings $\rightarrow$ constrain $Zt_L t_L$ coupling (under assumption of $SU(2)$ symmetry).
- Translate into $\sim 1\%$ **constraints** on top-Z coupling.

Unlikely that LHC will be able to improve on this.

COMPLEMENT, not COMPETE.

Top-Z Coupling

How well can the top-Z coupling be constrained at the $\sqrt{s} = 13$ TeV LHC?

- Luminosity – e.g. 30, 300, 3000 fb^{-1}
- Experimental accuracy
- Theoretical accuracy

Cf. Baur, Juste, Orr, Rainwater: hep-ph/0412021, hep-ph/0512262

1. Trileptonic channel $t\bar{t}Z \to (jjbbl\nu l^+l^-)$ best compromise between clean signal and overall rate.
2. Shape of opening angle between leptons from Z decay $\Delta\phi_{ll}$ sensitive to top-Z couplings.
3. Scale uncertainty is biggest obstacle (on theoretical side)!

ttb+Z calculation

Motivated by this, we perform a **partonic level** calculation to NLO in pQCD.
$\rightarrow$ decrease scale uncertainty

Work in **narrow width approximation** ($\sim \mathcal{O}(1\%)$ error)

Decays of top quarks and Z-boson include spin correlations to NLO.
$\rightarrow$ realistic experimental cuts; use spin correlations as discriminating variable

Top-Z Lagrangian

In SM, top-Z coupling is

$$\mathcal{L}_{t\bar{t}Z}^{\mathrm{SM}} = ie\bar{u}(p_t)\left[\gamma^\mu\left(C_V^{\mathrm{SM}}+\gamma_5 C_A^{\mathrm{SM}}\right)\right]v(p_{\bar{t}})Z_\mu$$

$$C_V^{\mathrm{SM}} = \frac{T^3 - 2Q_t \sin^2\theta_W}{2\sin\theta_W\cos\theta_W}$$

$$C_A^{\mathrm{SM}} = \frac{-T^3}{2\sin\theta_W\cos\theta_W}$$

Write New Physics in EFT

$$\mathcal{L}_{t\bar{t}Z}^{\mathrm{NP}} = \sum_i \frac{\mathcal{C}_i}{\Lambda^2} O_i + \ldots$$

Assuming dimension-six, **gauge invariant** operators, Lagrangian is

$$\boxed{\mathcal{L}_{t\bar{t}Z} = ie\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V}+\gamma_5 C_{1,A}\right) + \frac{i\sigma_{\mu\nu}q_\nu}{M}\left(C_{2,V}+i\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu}$$

Aguilar-Saavedra, hep-ph/0811.3842

Top-Z Lagrangian

$$\mathcal{L} = ie\bar{u}(p_t)\Big[\gamma^\mu\big(C_{1,V}+\gamma_5 C_{1,A}\big) + \underbrace{\frac{i\sigma_{\mu\nu}q_\nu}{M}\big(C_{2,V}+i\gamma_5 C_{2,A}\big)}\Big]v(p_{\bar{t}})Z_\mu$$

Treat $C_{1,V}$, $C_{1,A}$, $C_{2,V}$, $C_{2,A}$ as **anomalous couplings** - independent of kinematics

- Electric and magnetic top dipole moment.
- Zero at tree-level in SM.
- Small loop-induced corrections in SM.
- Non-renormalizable amplitudes.

- Dipole coefficients $C_{2,V}$ and $C_{2,A}$ set to zero.
- Focus on $C_{1,V}$ and $C_{1,A}$.
- Define

$$\boxed{\Delta C_{1,V} = \frac{C_{1,V}}{C_V^{\mathrm{SM}}} - 1 \;; \qquad \Delta C_{1,A} = \frac{C_{1,A}}{C_A^{\mathrm{SM}}} - 1.}$$

- Inclusive cross-section at $\sqrt{s} = 7$ TeV LHC:

  $\sigma_{t\bar{t}Z}^{\mathrm{LO}} = 103.5\ \mathrm{fb};$

  $\sigma_{t\bar{t}Z}^{\mathrm{NLO}} = 137.0\ \mathrm{fb}$

  (perfect agreement with results of Garzelli, Kardos, Papadopoulos, Trocsanyi)

  hep-ph/1111.0610, hep-ph/1111.1444, hep-ph/1208.2665

- In trileptonic decay $t\bar{t}Z \to (jjbbl\nu l^+ l^-)$ at $\sqrt{s} = 13$ LHC TeV:

  $\sigma_{t\bar{t}Z}^{\mathrm{LO}} = 3.80^{+34\%}_{-25\%}\ \mathrm{fb};$

  $\sigma_{t\bar{t}Z}^{\mathrm{NLO}} = 5.32^{+15\%}_{-14\%}\ \mathrm{fb}$

  (using $\mu_0 = mt + m_z/2$)

  Inclusive cuts:
  $p_{T,j} > 20$ GeV
  $p_{T,l} > 15$ GeV
  $p_{T,\mathrm{miss}} > 20$ GeV
  $|y_l| < 2.5$, $|y_j| < 2.5$
  $R_{lj} > 0.4$

- Scale uncertainty $\pm 28\%$ at LO and $\pm 14\%$ at NLO.
- $k = \sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \simeq 1.4$.

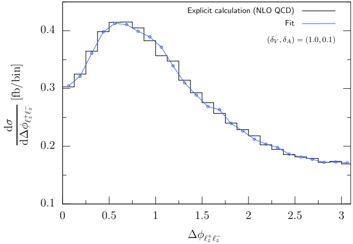
Fitting method

Compute $d\sigma_{\mathrm{LO}}\left(\Delta C_{1,V}, \Delta C_{1,A}\right)$ and $d\sigma_{\mathrm{NLO}}\left(\Delta C_{1,V}, \Delta C_{1,A}\right)$ at $\mu = \mu_0$.
$\Rightarrow$ large number of computations!

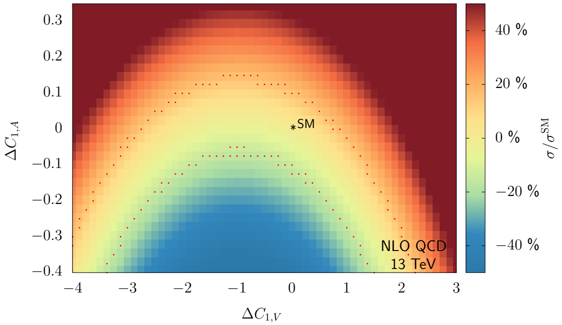
Notice that (at LO or NLO), $\mathcal{A}_{t\bar{t}Z} = A_0 + A_V C_{1,V} + A_A C_{1,A}$.
Then cross-section

$$d\sigma = s_0 + s_1 C_{1,V} + s_2 C_{1,V}^2 + s_3 C_{1,A} + s_4 C_{1,A}^2 + s_5 C_{1,V} C_{1,A}$$

1. Compute for **six** values of $C_{1,V}$ and $C_{1,A}$.
2. Solve for s_i.
3. Generate all other values of $d\sigma$.
4. Works on **overall cross-sections** and **distributions**.



Dependence of Cross-sections on Top-Z Couplings



- Cross-section changes by approx. 50% in $(\Delta C_{1,V}, \Delta C_{1,A})$ plane.
- Symmetric about $\Delta C_{1,V} = -1$, expected around $\Delta C_{1,A} = -1$.
- Far greater sensitivity to $\Delta C_{1,A}$ than $\Delta C_{1,V}$.
- Cross-sections within scale uncertainty band $\sim 15\%$ **cannot be distinguished** from SM

  e.g. $(\Delta C_{1,V}, \Delta C_{1,A}) = (1.7, -0.3)$

Constraints from current CMS data

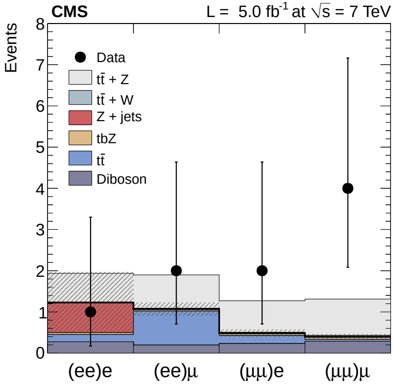
First observation of $t\bar{t}Z$ at the LHC:

- ATLAS sees 1 event with $4.7\mathrm{fb}^{-1}$.
- CMS sees 9 events with $4.9\ \mathrm{fb}^{-1}$ (bg. expectation 3.2 events).

$\Rightarrow$ CMS finds
$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\ (\mathrm{stat.})^{+0.06}_{-0.03}\ (\mathrm{syst.})$ pb

(Good agreement w. $\sigma_{\mathrm{NLO}} = 0.137\ \mathrm{pb.}$)

Use overall cross-section to put first direct constaints on top-Z coupling.

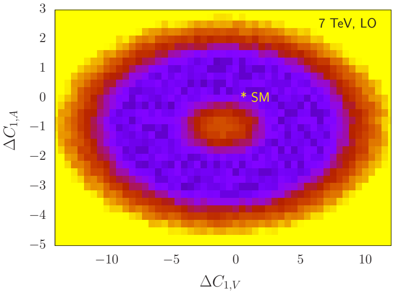


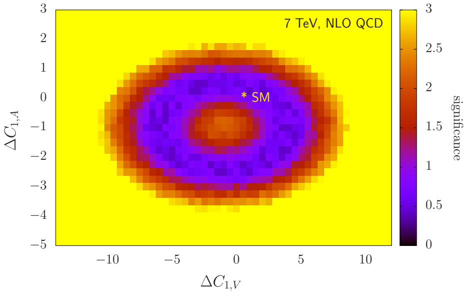
hep-ex/1303.3239

Current LHC constraints

Log-likelihood analysis

- using theoretical (scale+pdf) uncertainty of 40% at LO and 15% at NLO and
- Gaussian multiplicative factor for experimental systematic uncertainty (20%).





- Rough guide: red excluded at 1-σ, orange at 2-σ, yellow at 3-σ.
- SM at $(\Delta C_{1,V}, \Delta C_{1,A}) = (0, 0)$ consistent with measurement.
- Much tighter constraints at NLO (reduced scale uncertainty; k-factor).
- **But constraints are very loose**.

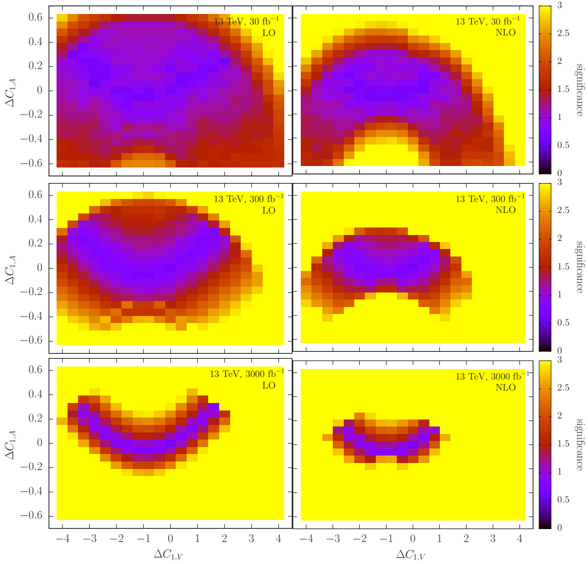
Future LHC Constraints

Look ahead to data from $\sqrt{s} = 13$ TeV run:

- Use shape information from $\Delta\phi_{ll}$ distributions.
- Compare **SM** calculation to **anomalous coupling** calculation

  – measure **statistical separation** between SM and anomalous top-Z couplings.
- Correspond (approximately) to constraints **if expt. reproduces SM**.

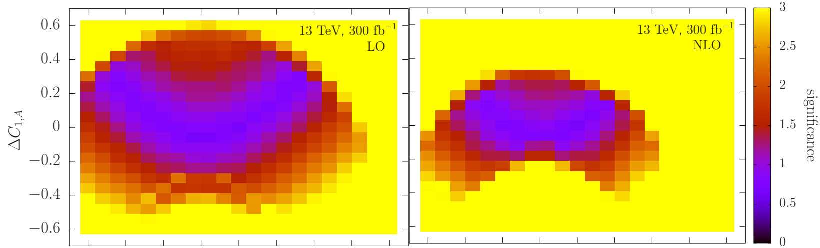
Future LHC constraints



- Scale uncertainty: 30% at LO and 15% at NLO.
- Obvious improvement with increased luminosity.
- Notable improvement using NLO corrections (reduced scale uncertainty + k-factor).

Future LHC constraints

Focus on 300 fb^{-1}:



- Find $-4.0 < \Delta C_{1,V} < 2.8$ and $-0.36 < \Delta C_{1,A} < 0.54$ at LO.
- At NLO $-3.6 < \Delta C_{1,V} < 1.6$ and $-0.24 < \Delta C_{1,A} < 0.30$.
- $\Rightarrow$ $C_\mathrm{V} = 0.24^{+0.39}_{-0.85}$ and $C_\mathrm{A} = -0.60^{+0.14}_{-0.18}$ at NLO QCD.

Higher dimensional operators

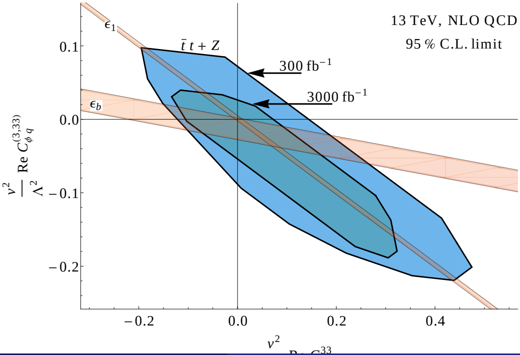
Higher dimensional operators in EFT $\leftrightarrow$ deviations from SM couplings:

$$C_{1,V} = C_{1,V}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right], \tag{1}$$

$$C_{1,A} = C_{1,A}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33}\right],$$

Assuming $SU(2)$ symmetry $\rightarrow C_{\phi q}^{(3,33)} \approx -C_{\phi q}^{(1,33)}$.

Translate constraints on $\Delta C_{1,V}, \Delta C_{1,A}$ into constraints on $C_{\phi q}^{(3,33)}$ and $C_{\phi u}^{33}$



Red: Indirect constraints from LEP

Blue: Projected direct constraints from LHC

Conclusions

- $t\bar{t}Z$ production at the LHC calculated to NLO in QCD, including all decays with spin correlation, and using NWA.
- Calculation performed with different values of vector and axial-vector top-Z coupling.
- **Cross-section** compared to that from CMS $\rightarrow$ first direct detection bounds on top-Z coupling (very loose).
- Log-likelihood analysis using $\Delta\phi_{ll}$ distribution reveals:
  - $\sim$ factor 2 increase in sensitivity due to decrease in scale uncertainty
  - Couplings giving $\sigma \simeq \sigma_{\mathrm{SM}}$ may be distinguished by $\Delta\phi_{ll}$ shape.
  - Constraints $-3.6 \lesssim \Delta C_{1,V} \lesssim 1.6$ and $-0.24 \lesssim \Delta C_{1,A} \lesssim 0.3$ at NLO.
- Reduced scale at NLO and $K \simeq 1.5$ boost constraining capability
- Can be related to operators, constrain scale Λ.

Future Work

- Look at constraining coefficients dipole terms $\sim \sigma_{\mu\nu} q^{\nu}/M$.
- Look at bounds from single top + Z results
- Extend analysis to $t\bar{t} + \gamma$.