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ETH Zürich, 16 July 2014

with Markus Schulze

arXiv:hep-ph/1404.1005
Motivation
  • Why top physics at the LHC is interesting
  • Why NLO calculation with spin-correlated decays

Top-Z Lagrangian in effective field theory

Details of calculation

Comparison with previous calculations

Constraints from current CMS data

Constraints from future LHC run

Conclusions and future work
- Discovered in 1995 by CDF and D0.
- **Largest mass** of known quarks – \( m_t = 173.34 \pm 0.76 \text{ GeV}. \)
  World Combination, hep-ph/1403.4427
- Decays before hadronization → insight into bare properties of quarks.
- Yukawa \( y_t = \sqrt{2}m_t/v \simeq 1. \)
- Special role in EWSB?
- Expect **top-EW couplings** to be highly sensitive to EWSB mechanism.

⇒ measurement of top-EW couplings is **part of the program of understanding EWSB**, as well as avenue for **finding/bounding New Physics effects**.
Top quark at the LHC

No direct constraint on top-EW couplings.

At LHC, energy and luminosity large enough to produce massive EW particles in association with $t\bar{t}$.
→ direct measurement of top-EW couplings

In $\sqrt{s} = 8$ TeV, $19.5 \text{ fb}^{-1}$ dataset:
- Evidence for $t\bar{t}W$ at 3.1-$\sigma$ in ATLAS (1.6-$\sigma$ at CMS).
- Evidence for $t\bar{t}Z$ at 3.2-$\sigma$ in ATLAS and CMS.
- Evidence for $t\bar{t}V$ at 4.9-$\sigma$ at ATLAS and 3.7-$\sigma$ at CMS.

hep-ex/1406.7830; ATLAS-COM-CONF-2014-051
Measurement of top-EW couplings is a long-term project requiring high luminosity at higher energy run.

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
Indirect constraints through LEP data:

- $Z_{bb}$ coupling and $\rho$ parameter closely constrained by fits to $\epsilon_1$ and $\epsilon_b$.
- $R_b$ and $A_{FB}^b$ also constrain $Zb_Lb_L$ couplings $\rightarrow$ constrain $Zt_Lt_L$ 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?

Cf. Baur, Juste, Orr, Rainwater:

hep-ph/0412021, hep-ph/0512262

1. Trileptonic channel $t\bar{t}Z \rightarrow (jjbbl\nu l^+ l^-)$ 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)!
Motivated by this, we perform a **partonic level** calculation to **NLO** in pQCD. 
→ decrease scale uncertainty

Work in **narrow width approximation** (≈ $O(1\%)$ error)

**Decays** of top quarks and Z-boson include **spin correlations** to NLO. 
→ realistic experimental cuts; use spin correlations as discriminating variable
Single top + Z \( (tZ + \bar{t}Z) \) similar rate to \( t\bar{t}Z \)

- Also sensitive to top-Z coupling.
- In \( tZ \to bl\nu l^+l^- \) decay, dominant background to trileptonic \( t\bar{t}Z \).
- Distinguished by number and behavior of jets.

\[ \Rightarrow \] defer study of top-Z couplings in single top+Z to later.
\[ \rightarrow \] negligible background to \( t\bar{t}Z \) signal.
In SM, top-Z coupling is

\[ \mathcal{L}^{SM}_{t\bar{t}Z} = ie\bar{u}(p_t) \left[ \gamma^\mu \left( C^{SM}_V + \gamma_5 C^{SM}_A \right) \right] \nu(p_{\bar{t}}) Z_\mu \]

Write New Physics in EFT

\[ \mathcal{L}^{NP}_{t\bar{t}Z} = \sum_i \frac{C_i}{\Lambda^2} O_i + \ldots \]

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

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

Aguilar-Saavedra, hep-ph/0811.3842
Top-Z Lagrangian

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

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

\[
\Delta C_{1,V} = \frac{C_{1,V}}{C_{1,V}^{SM}} - 1 ; \quad \Delta C_{1,A} = \frac{C_{1,A}}{C_{1,A}^{SM}} - 1.
\]
Details of calculation

Look at $pp \rightarrow t\bar{t} + Z \rightarrow t(\rightarrow \ell \nu b) \bar{t}(\rightarrow jj\bar{b}) Z(\rightarrow \ell\ell)$

- NLO in QCD
- Full NLO spin correlations for final state particles
- narrow-width approximation.

Factorization of production and decay:

$$\sigma_{pp \rightarrow \ell\ell\nu b\bar{b}jj} = \sigma_{pp \rightarrow t\bar{t}+Z}B_{t \rightarrow b\ell\nu}B_{\bar{t} \rightarrow \bar{b}jj}B_{Z \rightarrow \ell\ell} + \mathcal{O}(\Gamma_t/m_t, \Gamma_Z/M_Z)$$

- Neglects contributions suppressed by $\Gamma_t/m_t \lesssim 1\%$.
- Violated by using severe selection cuts or particular distributions (e.g. $p_T, W_b$).
- Valid approximation for our calculation.
- Off-shell $Z$ effects $\sim \mathcal{O}(\Gamma_Z/m_Z) \simeq 2\%$, but usually window cut on leptons, e.g. $|m_{ll} - m_Z| < 10$ GeV.
Details of calculation

- **LO production** through $gg \rightarrow t\bar{t}Z$ and $q\bar{q} \rightarrow t\bar{t}Z$.
- **Real corrections** open $qg$ and $\bar{q}g$ channels.
- **Soft and collinear singularities** regularized using Catani-Seymour dipoles.
- **Virtual corrections** to $gg$ and $q\bar{q}$ channels calculated using $D$-dimensional realization of Ossola-Papadopoulos-Pittau procedure.

Ossola, Papadopoulos, Pittau, hep-ph/0609007; Ellis, Giele, Kunszt, hep-ph/0708.2398;
Giele, Kunszt, Melnikov, hep-ph/0801.2237; Ellis, Giele, Kunszt, Melnikov, hep-ph/0806.3467
Review: Ellis, Kunszt, Melnikov, Zanderighi, hep-ph/1105.4319

- **Real and virtual corrections** to $t \rightarrow Wb$ and $W \rightarrow q\bar{q}$ decays calculated analytically.
- **CS dipoles** used to regularize soft/collinear singularities.

Note: $\mathcal{B}_{t \rightarrow WbZ} \sim 10^{-6}$ due to limited phase space $\rightarrow$ neglected entirely.
Details of calculation

Checks performed at **parton level:**
- LO and real emission matrix elements checked against MadGraph.
- Virtual matrix elements checked against GoSam.
- Singularities from integrated dipoles and virtual corrections cancel.

Checks performed at **cross-section level:**
- Cross-section and distributions independent of cut-off in finite dipole phase space.
- Factorization of decayed cross-section into undecayed cross-section $\times$ BR checked.
Comparisons with previous results

Two previous calculations:

Lazopoulos, McElmurry, Melnikov, Petriello

- No decays
- \( \sigma_{LO} = 0.808 \text{ pb}, \sigma_{NLO} = 1.09 \text{ pb} \)
  at \( \sqrt{s} = 14 \text{ TeV} \)

Garzelli, Kardos, Papadopoulos, Trocsanyi

- Decays through parton showering, hadronization effects
- \( \sigma_{LO} = 0.808 \text{ pb}, \sigma_{NLO} = 1.12 \text{ pb} \)
  at \( \sqrt{s} = 14 \text{ TeV} \) (same parameters)
- \( \sigma_{LO} = 103.5 \text{ fb}, \sigma_{NLO} = 136.9 \text{ fb} \)
  at \( \sqrt{s} = 7 \text{ TeV} \)

\( \sim 3\% \) tension between results
Results at LO and NLO

- Inclusive cross-section at $\sqrt{s} = 7$ TeV LHC:
  \[ \sigma_{t\bar{t}Z}^{\text{LO}} = 103.5 \text{ fb}; \]
  \[ \sigma_{t\bar{t}Z}^{\text{NLO}} = 137.0 \text{ fb} \]
  (perfect agreement with results of Garzelli, Kardos, Papadopoulos, Trocsanyi)

- In trileptonic decay $t\bar{t}Z \rightarrow (jjbbl\nu l^+ l^-)$ at $\sqrt{s} = 13$ LHC TeV:
  \[ \sigma_{t\bar{t}Z}^{\text{LO}} = 3.80^{+34\%}_{-25\%} \text{ fb}; \]
  \[ \sigma_{t\bar{t}Z}^{\text{NLO}} = 5.32^{+15\%}_{-14\%} \text{ fb} \]
  (using $\mu_0 = mt + m_z/2$)

- Scale uncertainty $\pm 28\%$ at LO and $\pm 14\%$ at NLO.
  
  \[ k = \sigma_{t\bar{t}Z}^{\text{NLO}} / \sigma_{t\bar{t}Z}^{\text{LO}} \simeq 1.4. \]
Results at LO and NLO

- Reduction in scale uncertainty at NLO visible
- $p_T,Z$ typically hard
- Shape changes $\sim 10\%$ from NLO effects in $\Delta \phi_{ll}$. 

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Constraining the top-Z coupling through $t\bar{t}Z$ product

ETH Zürich, 16 July 2014
Shape changes can be important:

- NLO corrections shift $\Delta \phi_{ll}$ to lower values
- Couplings may shift $\Delta \phi_{ll}$ to lower values.

Don’t confuse deviations from SM and NLO QCD effects.
Fitting method

Compute $d\sigma_{LO}(\Delta C_{1,\nu}, \Delta C_{1,A})$ and $d\sigma_{NLO}(\Delta C_{1,\nu}, \Delta C_{1,A})$ at $\mu = \mu_0$.

$\Rightarrow$ large number of computations!

Notice that (at LO or NLO), $A_{t\bar{t}Z} = A_0 + A_{\nu} C_{1,\nu} + A_{A} C_{1,A}$.

Then cross-section

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

1. Compute for six values of $C_{1,\nu}$ 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

\[ (\Delta C_{1,V}, \Delta C_{1,A}) = (1.7, -0.3) \]

[Recall:
\[ \Delta C_{1,V} = \frac{C_{1,V}}{C_{SM}^V} - 1 \]
\[ \Delta C_{1,A} = \frac{C_{1,A}}{C_{SM}^A} - 1. \]]
Detour – Binned Log Likelihoods

Binned likelihood function with Poisson distribution $P_i$,

$$\mathcal{L}(\mathcal{H}|\vec{n}) = \prod_{i=1}^{N_{\text{bins}}} P_i(n_i|\nu_i^{\mathcal{H}}),$$

with $n_i$ events observed and $\nu_i$ predicted under hypothesis $\mathcal{H}$.

Log-likelihood is then

$$\log \mathcal{L}(\mathcal{H}|\vec{n}_{\text{obs}}) = \sum_{i=1}^{N_{\text{bins}}} \left[ n_{i,\text{obs}} \log(\nu_i^{\mathcal{H}}) - \log(n_{i,\text{obs}}!) - \nu_i^{\mathcal{H}} \right],$$

and log-likelihood ratio is test statistic

$$\Lambda(\vec{n}_{\text{obs}}) = \log \left( \frac{\mathcal{L}(\mathcal{H}_0|\vec{n}_{\text{obs}})}{\mathcal{L}(\mathcal{H}_1|\vec{n}_{\text{obs}})} \right) = \sum_{i=1}^{N_{\text{bins}}} \left[ n_{i,\text{obs}} \log\left( \frac{\nu_i^{\mathcal{H}_0}}{\nu_i^{\mathcal{H}_1}} \right) - \nu_i^{\mathcal{H}_0} + \nu_i^{\mathcal{H}_1} \right].$$
Binned Log Likelihoods

- LL ratio derived from Poisson distribution:

\[ \Lambda(\vec{n}_{\text{obs}}) = \sum_{i=1}^{N_{\text{bins}}} n_{i,\text{obs}} \log \left( \frac{\nu_i^{{\mathcal{H}_0}}}{\nu_i^{{\mathcal{H}_1}}} \right) - \nu_i^{{\mathcal{H}_0}} + \nu_i^{{\mathcal{H}_1}} \].

- \( \nu_i^{{\mathcal{H}_0}} \) and \( \nu_i^{{\mathcal{H}_1}} \) are calculated/measured binned data according to two hypotheses.
- \( n_{i,\text{obs}} \) are pseudoexperimental data, generated around one of the hypotheses \( \mathcal{H}_0 \) or \( \mathcal{H}_1 \).
- Generates two distributions for \( P(\Lambda|\mathcal{H}_0) \) and \( P(\Lambda|\mathcal{H}_1) \).
- Overlap is a measure of statistical separation of hypotheses.
Type-I error (falsely reject \( \mathcal{H}_0 \)):

\[
\alpha = \int_{\hat{\Lambda}}^{\infty} d\Lambda \ P(\Lambda | \mathcal{H}_0)
\]

Type-II error (falsely reject \( \mathcal{H}_1 \)):

\[
\beta = \int_{-\infty}^{\hat{\Lambda}} d\Lambda \ P(\Lambda | \mathcal{H}_1).
\]

We choose \( \alpha = \beta \) – equal chance of incorrectly rejecting each hypothesis in favor of the other.

Can convert to sigma-level through

\[
\sigma = \sqrt{2} \text{erf}^{-1}(1 - \alpha),
\]

De Rújula et. al., hep-ph/1001.5300
Need to include theoretical (scale + pdf) uncertainties.

For $H_0$ and $H_1$, minimize the difference between the total cross-sections within uncertainty.

If cross-sections lie within each other's uncertainty bands, set them both equal to their average.

Rescale all bins by uniformly.

Has effect of minimizing the differences – $\Lambda$ distributions are closer.
Constraints from CMS data

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

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

$\Rightarrow$ CMS finds

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

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

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

hep-ex/1303.3239
Log-likelihood analysis
- using theoretical uncertainty of 40% at LO and 15% at NLO and
- Gaussian multiplicative factor for experimental systematic uncertainty (20%).

- Rough guide: red excluded at 1-\(\sigma\), orange at 2-\(\sigma\), yellow at 3-\(\sigma\).
- 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.
Look ahead to $\sqrt{s} = 13$ TeV run, with 30, 300, 3000 fb$^{-1}$ data:

- 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).

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Constraining the top-Z coupling through $\bar{t}tZ$ product

ETH Z"urich, 16 July 2014
Find $-4.0 \lesssim \Delta C_{1,V} \lesssim 2.8$ and $-0.36 \lesssim \Delta C_{1,A} \lesssim 0.54$ at LO.

At NLO $-3.6 \lesssim \Delta C_{1,V} \lesssim 1.6$ and $-0.24 \lesssim \Delta C_{1,A} \lesssim 0.30$.

$\Rightarrow C_V = 0.24^{+0.39}_{-0.85}$ and $C_A = -0.60^{+0.14}_{-0.18}$ at NLO QCD.
Higher dimensional operators

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

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

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

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 → **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 $\sigma \sim \sigma_{SM}$ 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 $K \approx 1.5$ boost constraining capability.**
- Can be related to operators, constrain scale $\Lambda$.

**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 $t\bar{t} + \gamma$.  

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Three operators involved in top-Z coupling:

\[ O_{\phi q}^{(1)} = i \left( \phi^+ D_\mu \phi \right) \left( \bar{q} \gamma^\mu q \right) \]

\[ O_{\phi q}^{(3)} = i \left( \phi^+ \tau^I D_\mu \phi \right) \left( \bar{q} \gamma^\mu q \right) \]

\[ O_{\phi t} = i \left( \phi^+ D_\mu \phi \right) \left( \bar{t}_R \gamma^\mu t_R \right) \]

and

\[ \delta C_L = \text{Re} \left( C_{\phi q}^{(3)} - C_{\phi q}^{(1)} \right) \frac{v^2}{\Lambda^2} \]

\[ \delta C_R = - \text{Re} C_{\phi t} \frac{v^2}{\Lambda^2} \]

Aguilar-Saavedra, hep-ph/0811.3842; Berger, Cao, Low, hep-ph/0907.2191

- \( C_{\phi q}^{(3)} + C_{\phi q}^{(1)} \) tightly constrained by \( Z \to bb \) (assuming \( SU(2)_L \times U(1)_Y \) symmetry).
- \( t \to Wb \) depends on \( C_{\phi q}^{(3)} - C_{\phi q}^{(1)} \) and \( |V_{tb}| \)
- Accurate measurement of top-Z coupling in \( t\bar{t}Z \to \text{get} |V_{tb}| \)
Backup slides – Effect of NWA

- LO Production only **misses threshold effects**.
- Included by NLO production.
- Further corrections to decay may be important.

Study by Denner, Dittmaier, Kallweit, Pozzorini, Schulze, for SM NLOWG, hep-ph/1203.6803

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top dilepton channel, 7 TeV LHC

![Graph showing the impact of LO, NLO production, and NLO production+decay on the top dilepton channel at 7 TeV LHC.](image)

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NWA misses threshold effects due to top mass.

\[ \frac{d\sigma}{dM_{e^+b}} \left[ \text{fb} \right] \left[ \text{GeV} \right] \]

\[ pp \rightarrow \nu_e e^+ \mu^- \bar{\nu}_\mu b \bar{b} + X \]

\[ \sqrt{s} = 7 \text{ TeV} \]

Study by Denner, Dittmaier, Kallweit, Pozzorini, Schulze, for SM NLOWG, hep-ph/1203.6803
Constraining the top-Z coupling through $\bar{t}tZ$ product