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

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Fermilab

ETH Zürich, 16 July 2014

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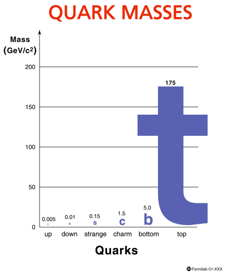
arXiv:hep-ph/1404.1005

Outline

- 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

Top Quark

- Discovered in 1995 by CDF and D0.
- **Largest mass** of known quarks –
  $m_t = 173.34 \pm 0.76$ GeV.
  World Combination, hep-ph/1403.4427
- Decays before hadronization
  $\rightarrow$ 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.



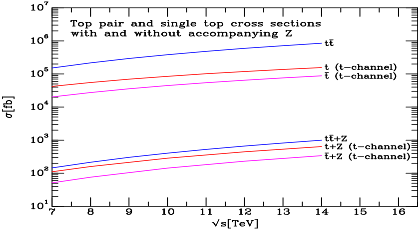
$\Rightarrow$ measurement of top-EW couplings is **part of the program of understanding EWSB**, as well as avenue for **finding/bounding New Physics effects**.

Top 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 $t\bar{t}$.

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



Campbell, Ellis, RR, hep-ph/1302.3856

In $\sqrt{s} = 8\ \mathrm{TeV},\ 19.5\ \mathrm{fb}^{-1}$ dataset:

- Evidence for $t\bar{t}W$ at 3.1-σ in ATLAS (1.6-σ at CMS).
- Evidence for $t\bar{t}Z$ at 3.2-σ in ATLAS and CMS.
- Evidence for $t\bar{t}V$ at 4.9-σ at ATLAS and 3.7-σ at CMS.

hep-ex/1406.7830; ATLAS-COM-CONF-2014-051

Top-EW couplings at LHC

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

Caveat: Indirect Measurements

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_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.

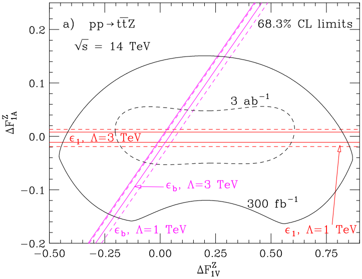
COMPLEMENT, not COMPETE.

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)!



ttb+Z calculation

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

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

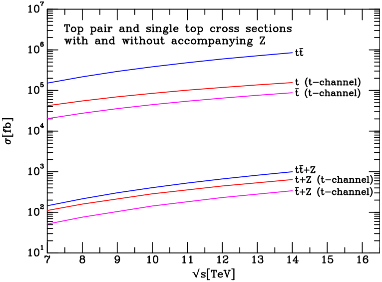
Decays of top quarks and Z-boson include spin correlations to NLO.
→ realistic experimental cuts; use spin correlations as discriminating variable

Single top + Z

Single top + Z ($tZ + \bar{t}Z$) similar rate to $t\bar{t}Z$

Campbell, Ellis, RR, hep-ph/1302.3856

- Also sensitive to top-Z coupling.
- In $tZ \to b l \nu l^+ l^-$ 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.
$\to$ **negligible background** to $t\bar{t}Z$ signal.

Top-Z Lagrangian

In SM, top-Z coupling is

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

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

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

Write New Physics in EFT

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

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

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

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

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

Details of calculation

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

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

Factorization of production and decay :

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

- Neglects contributions suppressed by $\Gamma_t/m_t \lesssim 1\%$.
- Violated by using **severe selection cuts** or **particular distributions** (e.g. $p_{T,Wb}$).
- 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 $gg \to t\bar{t}Z$ and $q\bar{q} \to t\bar{t}Z$.
- 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 $t \to Wb$ and $W \to q\bar{q}$ decays calculated analytically.
- CS dipoles used to regularize soft/collinear singularities.

Note: $\mathcal{B}_{t\to WbZ} \sim 10^{-6}$ due to limited phase space $\to$ 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 hep-ph/0804.0610

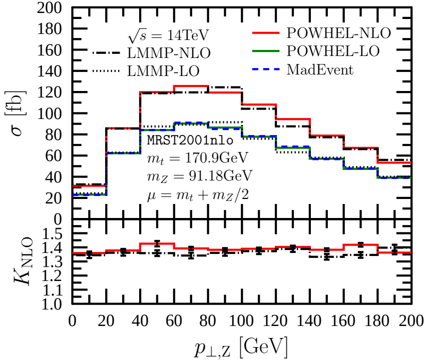
- No decays
- $\sigma_{\mathrm{LO}} = 0.808$ pb, $\sigma_{\mathrm{NLO}} = 1.09$ pb, at $\sqrt{s} = 14$ TeV

Garzelli, Kardos, Papadopoulos, Trocsanyi

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

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

$\sim$ 3% tension between results

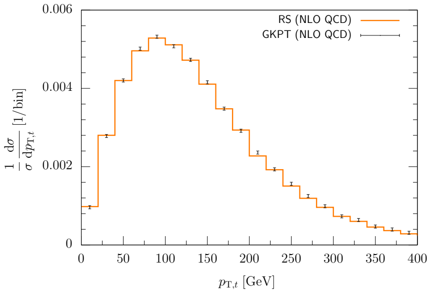


- Inclusive cross-section at $\sqrt{s} = 7$ TeV LHC:

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

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

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



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

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

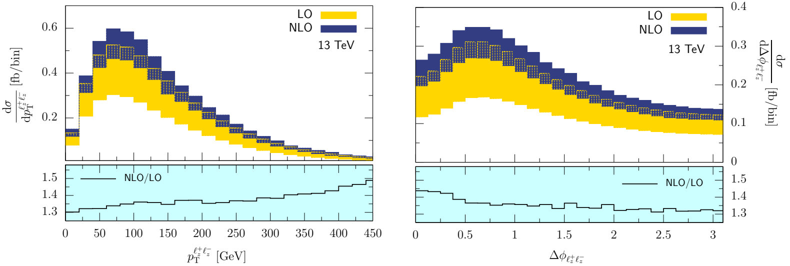
  $\sigma^{\mathrm{NLO}}_{t\bar{t}Z} = 5.32^{+15\%}_{-14\%}$ fb

  (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
$|y_l| < 2.5$, $|y_j| < 2.5$
$R_{lj} > 0.4$

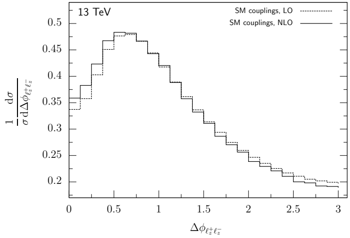
- Scale uncertainty $\pm 28\%$ at LO and $\pm 14\%$ at NLO.
- $k = \sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \simeq 1.4$.

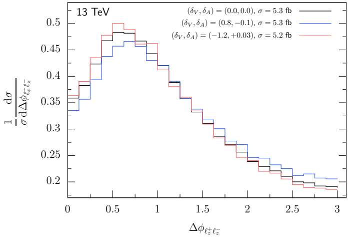
Results at LO and NLO



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

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.

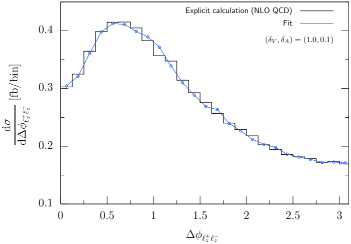
Fitting method

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

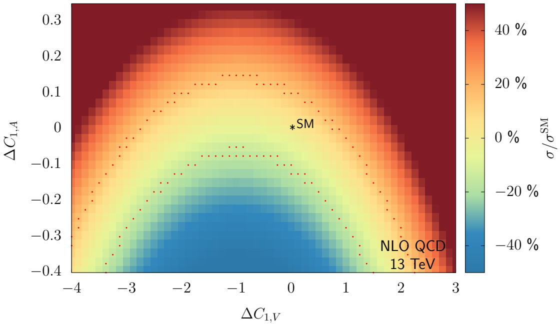
Notice that (at LO or NLO), $\mathcal{A}_{t\bar{t}Z} = A_0 + A_V C_{1,V} + A_A C_{1,A}$.
Then cross-section

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

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



[Recall:

$$\Delta C_{1,V} = \frac{C_{1,V}}{C_V^{\mathrm{SM}}} - 1$$

$$\Delta C_{1,A} = \frac{C_{1,A}}{C_A^{\mathrm{SM}}} - 1.]$$

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

Detour – Binned Log Likelihoods

Binned likelihood function with Poisson distribution P_i,

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

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

Log-likelihood is then

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

and **log-likelihood ratio** is test statistic

$$\begin{aligned} \Lambda(\vec{n}_{\rm obs}) &= \log\Big(\mathcal{L}(\mathcal{H}_0|\vec{n}_{\rm obs}) / \mathcal{L}(\mathcal{H}_1|\vec{n}_{\rm obs}) \Big) \\ &= \sum_{i=1}^{N_{\rm bins}} \left[n_{i,{\rm obs}} \log\left(\frac{\nu_i^{\mathcal{H}_0}}{\nu_i^{\mathcal{H}_1}} \right) - \nu_i^{\mathcal{H}_0} + \nu_i^{\mathcal{H}_1} \right], \end{aligned}$$

Binned Log Likelihoods

- LL ratio derived from Poisson distribution:

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

- $\nu_i^{\mathcal{H}_0}$ and $\nu_i^{\mathcal{H}_1}$ are calculated/measured binned data according to two hypotheses.
- $n_{i,{\rm obs}}$ 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.

Binned Log Likelihoods

- Type-I error (falsely reject $\mathcal{H}_0$):

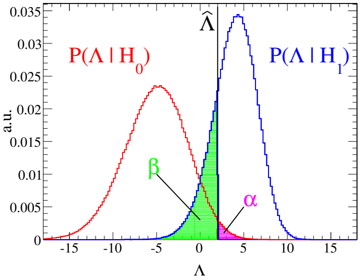
$$\alpha = \int_{\hat{\Lambda}}^{\infty} \mathrm{d}\Lambda \, P(\Lambda|\mathcal{H}_0)$$

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

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

- We choose $\alpha = \beta$
  – equal chance of incorrectly rejecting each hypothesis in favor of the other.
- Can convert to sigma-level through

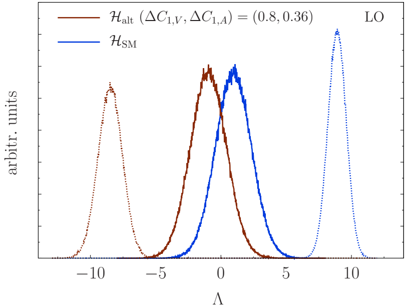
$$\sigma = \sqrt{2}\,\mathrm{erf}^{-1}(1-\alpha),$$



De Rújula *et. al*,, hep-ph/1001.5300

Inclusion of Theoretical Uncertainties

- Need to include theoretical (scale + pdf) uncertainties.
- For $\mathcal{H}_0$ and $\mathcal{H}_1$, 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 – Λ distributions are closer.



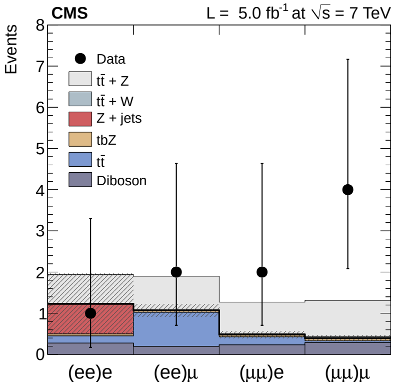
First observation of $t\bar{t}Z$ at the LHC:

ATLAS sees 1 event with 4.7fb^{-1}, CMS sees 9 events with 4.9 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. $\sigma_{\text{NLO}} = 0.137$ pb.)

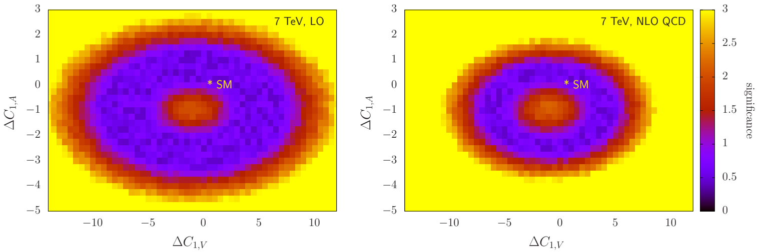


hep-ex/1303.3239

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

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-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**.

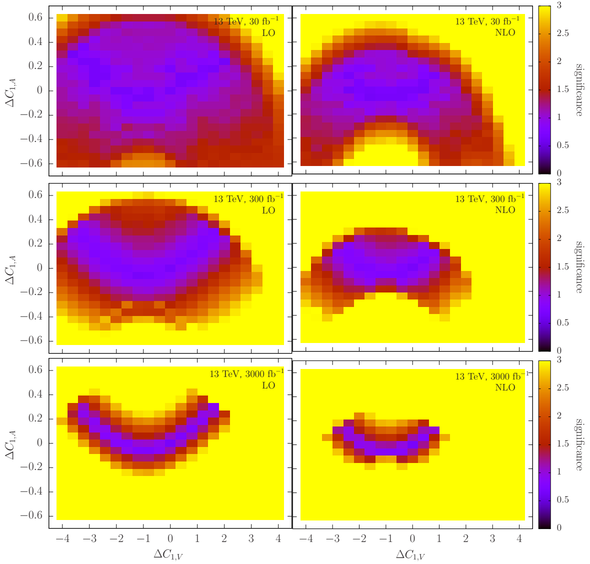
Future LHC Constraints

Look ahead to $\sqrt{s} = 13$ TeV run, with $30,\ 300,\ 3000\ \mathrm{fb}^{-1}$ 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**.

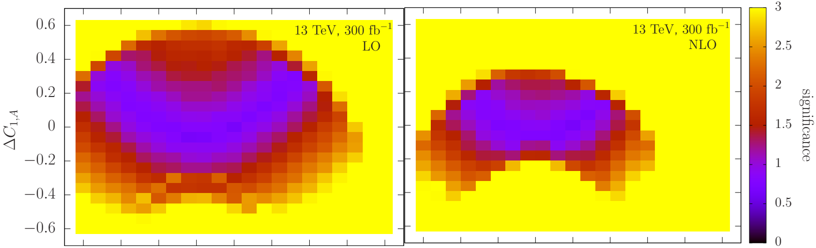
Future LHC constraints



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

Future LHC constraints

Focus on 300 fb^{-1}:



- 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 $-0.24 \lesssim \Delta C_{1,A} \lesssim 0.30$.
- $\Rightarrow C_{\mathrm{V}} = 0.24^{+0.39}_{-0.85}$ and $C_{\mathrm{A}} = -0.60^{+0.14}_{-0.18}$ at NLO QCD.

Higher dimensional operators

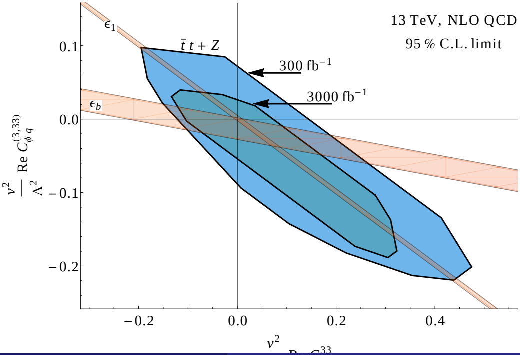
Higher dimensional operators in EFT $\leftrightarrow$ deviations from SM couplings:

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

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

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

Backup Slides – Operators in EFT

Three operators involved in top-Z coupling:

$$\begin{aligned}
\mathcal{O}_{\phi q}^{(1)} &= i\left(\phi^{+} D_{\mu}\phi\right)\left(\bar{q}\gamma^{\mu} q\right)\\
\mathcal{O}_{\phi q}^{(3)} &= i\left(\phi^{+}\tau^{I} D_{\mu}\phi\right)\left(\bar{q}\gamma^{\mu} q\right)\\
\mathcal{O}_{\phi t} &= i\left(\phi^{+} D_{\mu}\phi\right)\left(\bar{t}_R\gamma^{\mu} t_R\right)
\end{aligned}$$

and

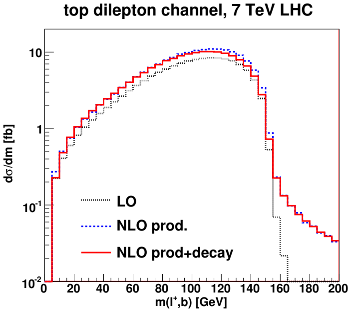
$$\begin{aligned}
\delta C_L &= \mathrm{Re}\left(C_{\phi q}^{(3)} - C_{\phi q}^{(1)}\right)\frac{v^2}{\Lambda^2}\\
\delta C_R &= -\mathrm{Re}\, C_{\phi t}\frac{v^2}{\Lambda^2}
\end{aligned}$$

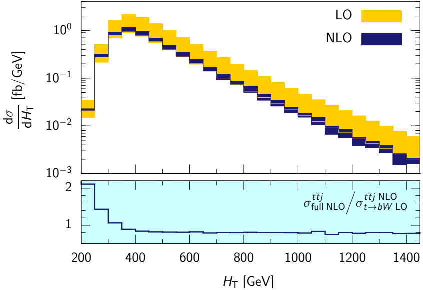
Aguilar-Saavedra, hep-ph/0811.3842; Berger, Cao, Low, hep-ph/0907.2191

- $C_{\phi q}^{(3)} + C_{\phi q}^{(1)}$ 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 $t\bar{t}Z \to$ get $|V_{tb}|$

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

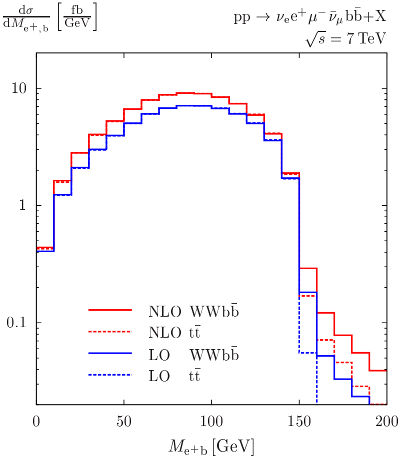
Study by Denner, Dittmaier, Kallweit, Pozzorini, Schulze, for SM NLOWG, hep-ph/1203.6803

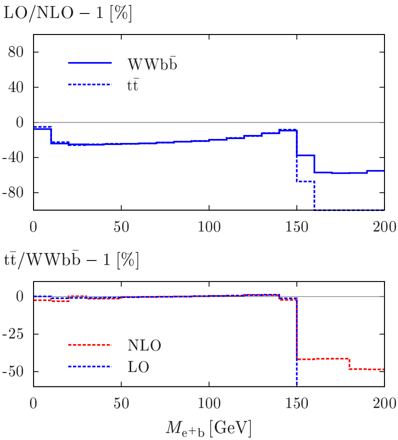




Backup slides – Effect of NWA

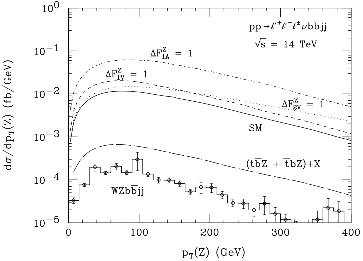
NWA misses threshold effects due to top mass.





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

Backup slides – Background estimates



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