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

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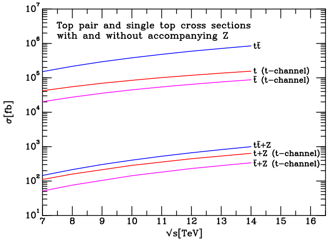
RR and Markus Schulze
arXiv:hep-ph/1404.1005

Top 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**

(Mass of top suggests connection to EWSB mechanism.)

- $t\bar{t} + \gamma$, $t\bar{t}Z$ 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_{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?

- 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

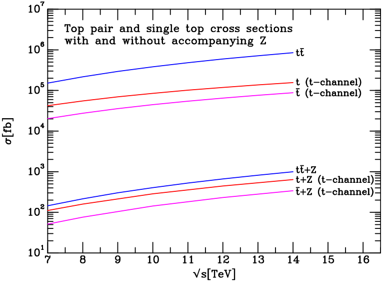
Motivated by this, we perform a **partonic level** calculation to NLO in pQCD.
→ decrease scale uncertainty

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 $tZ \to bl\nu l^+ l^-$ 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
$\to$ negligible background to $t\bar{t}Z$ signal.

Top-Z Lagrangian

In SM, top-Z coupling is

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

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

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

Write New Physics in EFT

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

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

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

Aguilar-Saavedra, hep-ph/0811.3842

Top-Z Lagrangian

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

- Electric and magnetic top dipole moment
- Zero at tree-level in SM
- Small loop-induced corrections in SM
- Non-renormalizable amplitudes - non-trivial implementation in OPP method for virtual corrections

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

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

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

Results at LO and NLO

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

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

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

  (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:

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

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

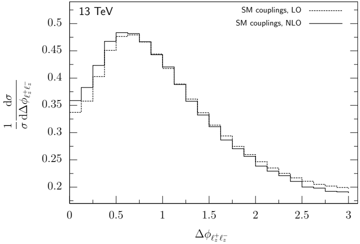
  (using $\mu_0 = mt + m_z/2$)

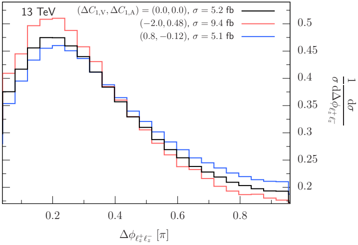
  Inclusive cuts:
  $p_{T,j} > 20 \text{ GeV}$
  $p_{T,l} > 15 \text{ GeV}$
  $p_{T,\mathrm{miss}} > 20 \text{ GeV}$
  $|y_l| < 2.5$, $|y_j| < 2.5$
  $R_{lj} > 0.4$

- 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

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.

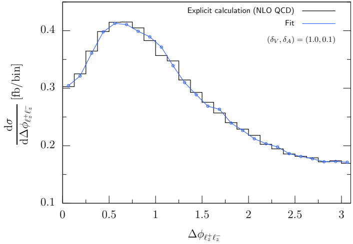
Fitting method

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

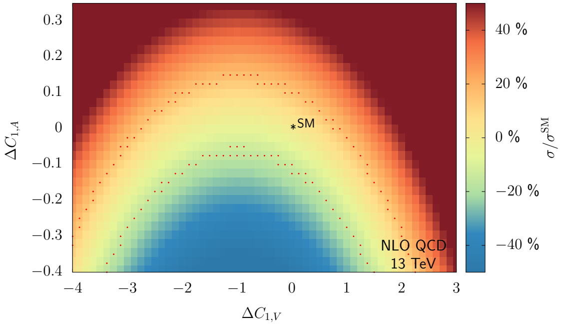
Notice that (at LO or NLO), $\mathcal{A}_{t\bar{t}Z} = A_0 + A_V C_{1,V} + A_A C_{1,A}$.
Then cross-section

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

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

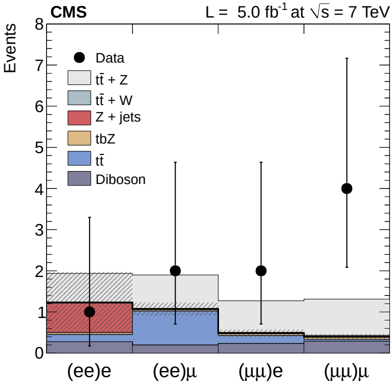
  e.g. $(\Delta C_{1,V}, \Delta C_{1,A}) = (1.7, -0.3)$

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. $\sigma_{\mathrm{NLO}} = 0.137\ \mathrm{pb.}$)



hep-ex/1303.3239

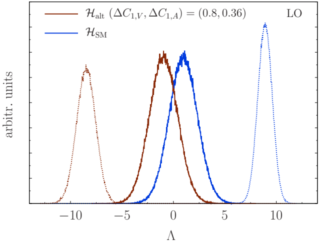
Use overall cross-section to put first direct constaints on top-Z coupling.

Statistical Approach

- Use log-likelihood ratio test, with LL ratio derived from Poisson distribution

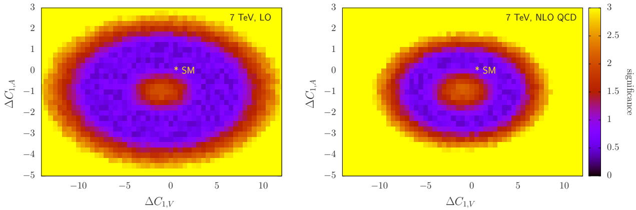
$$\Lambda(\vec{n}_{\rm obs}) = \sum_{i=1}^{N_{\rm bins}} \left[n_{i,\rm obs} \log\left(\frac{\nu_i^{\rm SM}}{\nu_i^{\rm alt}}\right) - \nu_i^{\rm SM} + \nu_i^{\rm alt} \right],$$

- $\nu_i^{\rm SM}$ and $\nu_i^{\rm alt}$ are *calculated* binned data according to two hypotheses
- $n_{i,\rm obs}$ are pseudoexperimental data, generated around one of the hypotheses
- Generates two distributions for Λ – overlap is a measure of statistical separation of hypotheses
- Include theoretical uncertainty by uniformly rescaling all bins.



Current LHC constraints

- Use Gaussian multiplicative factor for experimental uncertainty (20%)



- SM at $(\Delta C_{1,V}, \Delta C_{1,A}) = (0,0)$ consistent with measurement $[C_V^{\mathrm{SM}} \simeq 0.24$ and $C_A^{\mathrm{SM}} \simeq -0.60]$
- Rough guide: red excluded at 1-σ, orange at 2-σ, yellow at 3-σ.
- $-11 \lesssim \Delta C_{1,V} \lesssim 10$ and $-4 \lesssim \Delta C_{1,A} \lesssim 2$ at LO (95% C.L.)
- $-8 \lesssim \Delta C_{1,V} \lesssim 7$ and $-3 \lesssim \Delta C_{1,A} \lesssim 1$ at NLO (95% C.L.)
- Much tighter constraints at NLO (reduced scale uncertainty; k-factor)
- But constraints are very loose

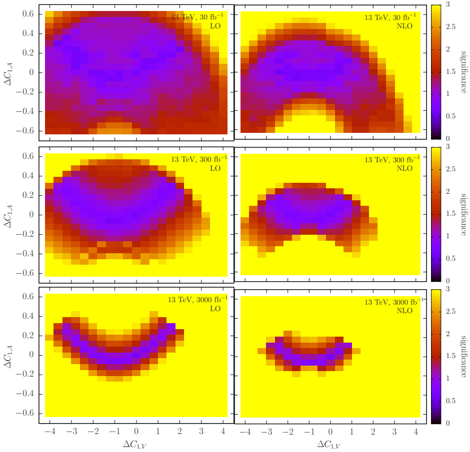
Future LHC Constraints

Good start – how can it be improved?

- Better statistics: larger luminosity, higher energy
- Use **shape information**

$\Rightarrow$ use $\Delta\phi_{ll}$ distribution at $\sqrt{s} = 13$ TeV for 30, 300, 3000 fb^{-1}.

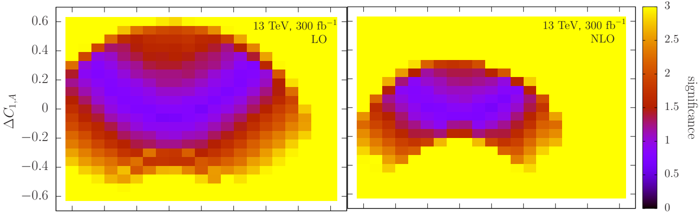
Future LHC constraints



- Use 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

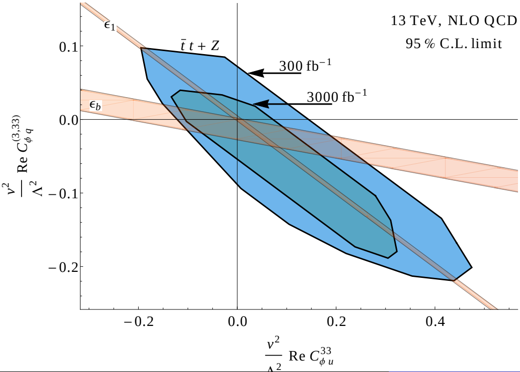
Higher dimensional operators in EFT $\leftrightarrow$ deviations from SM couplings:

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

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

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 $\sigma \simeq \sigma_{\rm SM}$ 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 $t\bar{t} + \gamma$.
- Relation to ILC constraints?

Backup Slides – Comparisons with previous results

Two previous calculations:

Lazopoulos, McElmurry, Melnikov, Petriello hep-ph/0804.0610

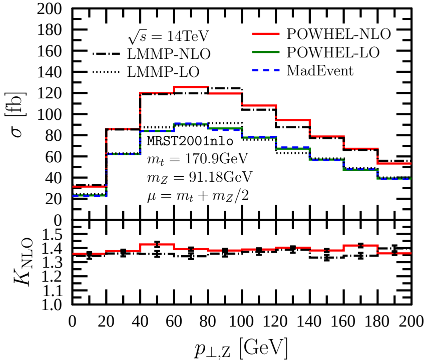
- No decays
- $\sigma_{\mathrm{LO}} = 0.808$ pb, $\sigma_{\mathrm{NLO}} = 1.09$ pb, at $\sqrt{s} = 14$ TeV

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

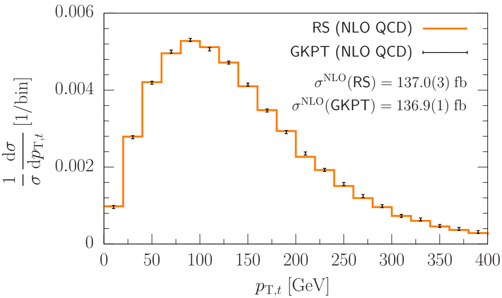
$\sim 3\%$ tension between results



Same setup as GKPT:

$$\sigma^{\mathrm{RS}}_{\mathrm{LO}} = 103.5\mathrm{fb}; \qquad \sigma^{\mathrm{RS}}_{\mathrm{NLO}} = 137.0\mathrm{fb}$$

- **excellent agreement** at LO and NLO for both cross-sections and distributions.



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-likelihoods for predictions under $\mathcal{H}_{\rm SM}$ and $\mathcal{H}_{\rm alt}$ are

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

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

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

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

Use **pseudoexperimental data** for $\vec{n}_{\rm obs}$.

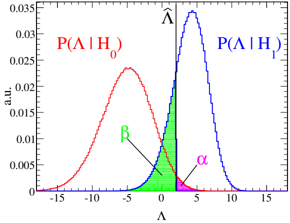
- Generated using bin-by-bin Poisson distribution around $\vec{\nu}^{\rm SM}$
- Repeat many times $\to$ **distribution** $P(\Lambda|\mathcal{H}_{\rm SM})$.
- Now generate $P(\Lambda|\mathcal{H}_{\rm alt})$ by using $\vec{\nu}^{\rm alt}$ to generate $\vec{n}_{\rm obs}$.
- Overlap of $P(\Lambda|\mathcal{H}_{\rm SM})$ and $P(\Lambda|\mathcal{H}_{\rm alt})$ gives statistical separation of hypotheses

Backup Slides – LHC Constraints – Statistical Overview

Type-I error (falsely reject $\mathcal{H}_{\rm alt}$) and type-II error (falsely reject $\mathcal{H}_{\rm SM}$) given by

$$\alpha = \int_{\hat{\Lambda}}^{\infty} \mathrm{d}\Lambda \; P(\Lambda|\mathcal{H}_{\rm SM})$$

$$\beta = \int_{-\infty}^{\hat{\Lambda}} \mathrm{d}\Lambda \; P(\Lambda|\mathcal{H}_{\rm alt}).$$



De Rújula *et. al*,, hep-ph/1001.5300

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

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

Backup Slides – Operators in EFT

Three operators involved in top-Z coupling:

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

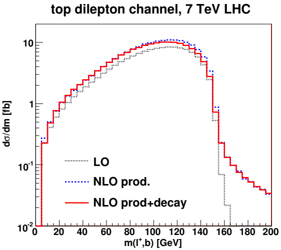
and

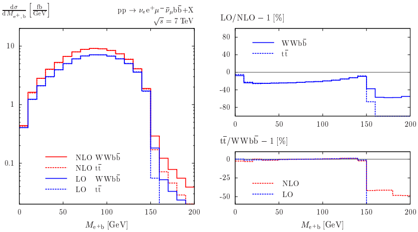
$$\begin{aligned}\delta C_L =& \mathrm{Re}\left(C_{\phi q}^{(3)} - C_{\phi q}^{(1)}\right)\frac{v^2}{\Lambda^2}\\ \delta C_R =& -\mathrm{Re}\, C_{\phi t}\frac{v^2}{\Lambda^2}\end{aligned}$$

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 $t\bar{t}Z$ → get $|V_{tb}|$

Backup slides – Effect of NWA

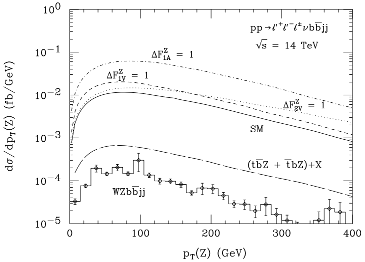




Study by Denner, Dittmaier, Kallweit, Pozzorini, Schulze, for SM NLOWG, hep-ph/1203.6803

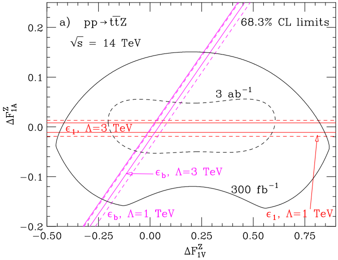
- Shape changes when including decay
- No difference using NWA vs. full calculation for $m_{lb} \lesssim 2m_t$.
- Shape changes $m_{lb} \simeq 2m_t$.

Backup slides – Background estimates



Baur, Juste, Orr, Rainwater: hep-ph/0412021

Backup slides – Constraints from Baur et. al.



Baur, Juste, Orr,

Rainwater;

hep-ph/0412021