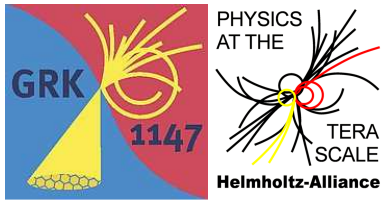
Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

Anomalous Top Couplings in WHIZARD

Fabian Bach
in collaboration with Thorsten Ohl

Institut für Theoretische Physik und Astrophysik, Uni Würzburg
WHIZARD Workshop, DESY Hamburg, 22.11.2011

funded by:

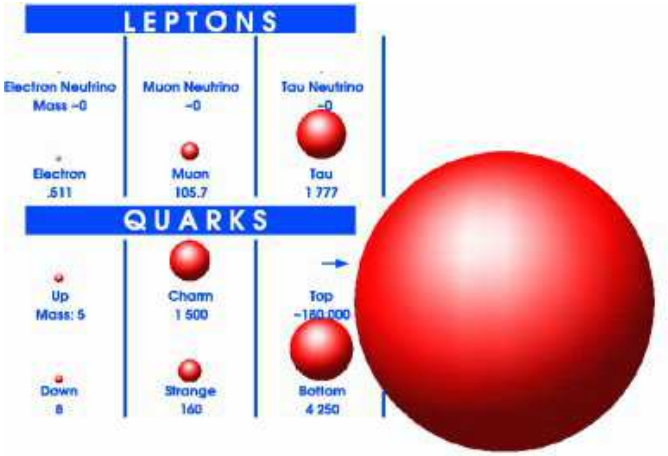


Outline

1. Motivation
2. Effective Lagrangian Approach
3. Gauge Invariance & Redundancies
4. Single Top Cross Section
5. Conclusions

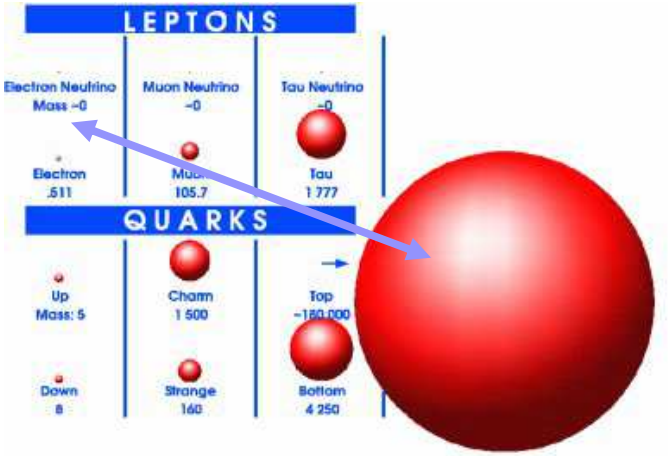
Motivation: the Standard Model and the top quark

- SM describes high energy physics up to *o*(100 GeV) very well, but…
  - ➔ **19 free parameters** (couplings, **masses** etc.)
- theoretical clue of gauge boson masses (EWSB…)
- fermion masses seem **arbitrary**



Motivation: the Standard Model and the top quark

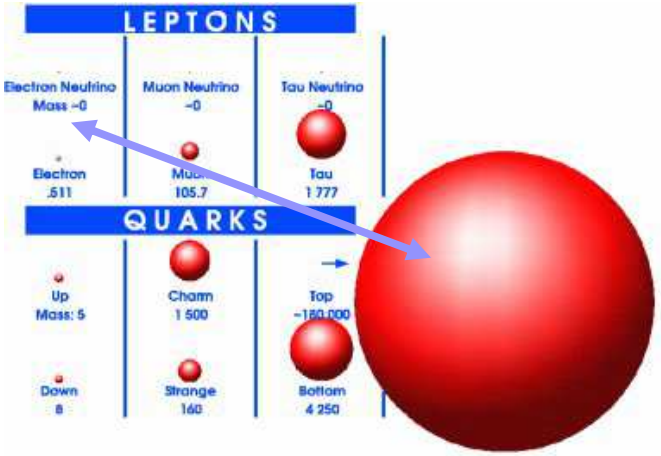
- SM describes high energy physics up to *o*(100 GeV) very well, but…
  - ➔ **19 free parameters** (couplings, **masses** etc.)
- theoretical clue of gauge boson masses (EWSB…)
- fermion masses seem **arbitrary**
  - ➔ no understanding of large mass hierarchy, i.e. $m_{e,\nu} \ll m_t \sim v / \sqrt{2}$ (top Yukawa coupl. ~ 1)



- exp. knowledge of top couplings from **indirect measurements** (e.g. *b* → *sγ* loop)

Motivation: the Standard Model and the top quark

- SM describes high energy physics up to *o*(100 GeV) very well, but…
  - ➔ **19 free parameters** (couplings, **masses** etc.)
- theoretical clue of gauge boson masses (EWSB…)
- fermion masses seem **arbitrary**
  - ➔ no understanding of large mass hierarchy, i.e. $m_{e,\nu} \ll m_t \sim v / \sqrt{2}$ (top Yukawa coupl. ~ 1)

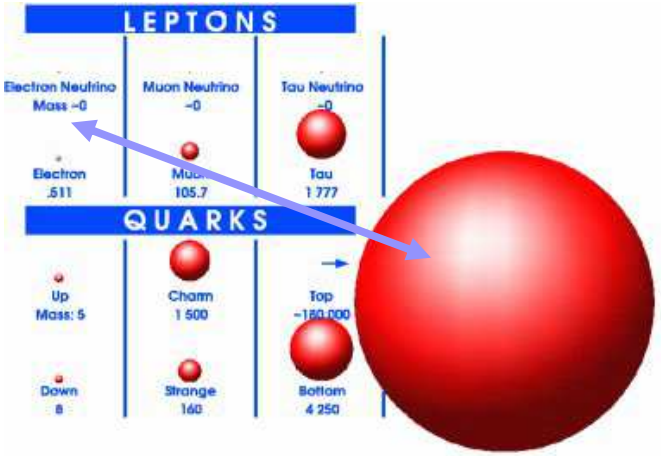


- exp. knowledge of top couplings from **indirect measurements** (e.g. *b* → *sγ* loop)

• **numbers on direct measurements:**	***Tevatron*** (1.96 TeV)	***LHC*** (14 TeV)
➔ ttbar production cross section:	7.5 *pb*	~ 900 *pb* (QCD prediction)
➔ number of top pairs:	50,000 tot. (Run II)	10^7 per year ($L = 10^{33}$ cm^{-2}s^{-1})

Motivation: the Standard Model and the top quark

- SM describes high energy physics up to *o*(100 GeV) very well, but…
  - ➔ **19 free parameters** (couplings, **masses** etc.)
- theoretical clue of gauge boson masses (EWSB…)
- fermion masses seem **arbitrary**
  - ➔ no understanding of large mass hierarchy, i.e. $m_{e,\nu} \ll m_t \sim v / \sqrt{2}$ (top Yukawa coupl. ~ 1)



- exp. knowledge of top couplings from **indirect measurements** (e.g. *b* → *sγ* loop)

• **numbers on direct measurements:**	***Tevatron*** (1.96 TeV)	***LHC*** (14 TeV)
➔ ttbar production cross section:	7.5 *pb*	~ 900 *pb* (QCD prediction)
➔ number of top pairs:	50,000 tot. (Run II) ⟷	10^7 per year ($L = 10^{33}$ cm^{-2}s^{-1})

large statistics at *LHC* makes **direct** precision top **measurements** possible

Phenomenological studies on anomalous top couplings

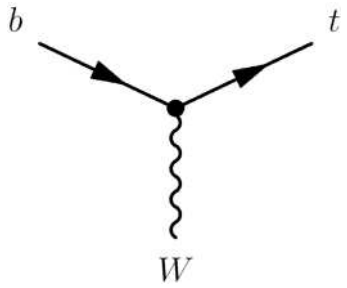
- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** anomalous trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics

Phenomenological studies on anomalous top couplings

- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** anomalous trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics

example: *tbW* coupling

SM



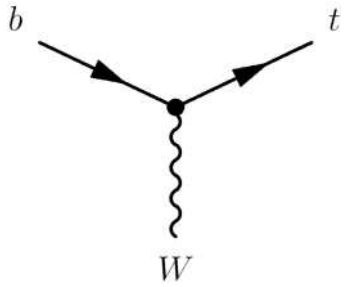
~ $\gamma^{\mu}(1-\gamma_5)$

Phenomenological studies on anomalous top couplings

- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** anomalous trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics

example: *tbW* coupling

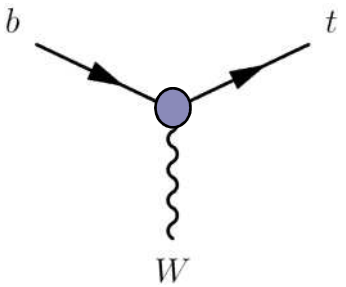
SM



~ $\gamma^{\mu}(1-\gamma_5)$

+

off-resonant
new physics



e.g. ~ $\sigma^{\mu\nu}q_{\nu}(1+\gamma_5)$

Phenomenological studies on anomalous top couplings

- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** anomalous trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics
- **what has been done:**
  - ➔ theoretical understanding of the relations and **redundancies** among different operators in a full gauge invariant operator set generating the various anomalous trilinear top couplings
  - ➔ first **phenomenological studies** on anomalous QCD and *tbW* couplings

Phenomenological studies on anomalous top couplings

- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** anomalous trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics
- **what has been done:**
  - ➔ theoretical understanding of the relations and **redundancies** among different operators in a full gauge invariant operator set generating the various anomalous trilinear top couplings
  - ➔ first **phenomenological studies** on anomalous QCD and *tbW* couplings
- **what we want to contribute:**
  - ➔ provide **all** possible anomalous top couplings in **one exhaustive MC tool**, i. e. WHIZARD 2 with anomalous tops
  - ➔ **automatically ensure gauge invariance** for all hard amplitudes relevant for detector level, including off-shell top production and subsequent decays
  - ➔ link to hadron shower/fragmentation to produce detector-relevant final states
  - ➔ do some phenomenological studies at *LHC*

Effective Lagrangian method

- integrate out model-dependent heavy excitations of new physics contributions
  ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

Effective Lagrangian method

- integrate out model-dependent heavy excitations of new physics contributions
  ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

- dim5 greatly restricted by gauge invariance without new fields ($\Lambda \sim 10^{13}$ GeV)

  ➔ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{C_x}{\Lambda^2} O_x$

Effective Lagrangian method

- integrate out model-dependent heavy excitations of new physics contributions
  ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

- dim5 greatly restricted by gauge invariance without new fields ($\Lambda \sim 10^{13}$ GeV)

  ➔ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{C_x}{\Lambda^2} O_x$

- write down all gauge invariant dim6 O_x which contribute to **anomalous top couplings** of the form $f_i f_j V$ with fermions $f_{i,j} = t,b$ and vector bosons $V = A,Z,W,g$

Effective Lagrangian method

- integrate out model-dependent heavy excitations of new physics contributions
  - ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

- dim5 greatly restricted by gauge invariance without new fields (Λ ~ 10^{13} GeV)
  - ➔ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{C_x}{\Lambda^2} O_x$

- write down all gauge invariant dim6 O_x which contribute to **anomalous top couplings** of the form $f_i f_j V$ with fermions $f_{i,j} = t,b$ and vector bosons $V = A,Z,W,g$

- use **eqns of motion** to **rewrite redundant operators** (Aguilar-Saavedra 08)
  - ➔ simplify Lorentz structure of $f_i f_j V$: only **~ γ^μ** and **~ $\sigma^{\mu\nu} q_\nu$** with $q_\nu = (p_i - p_j)_\nu$
  - ➔ **remove off-shell contributions** (e.g. ~ q^μ) and some **quartic interactions** (e.g. *ttgA*) at the price of **introducing** additional **4-fermion contact terms**

Effective Lagrangian method

- integrate out model-dependent heavy excitations of new physics contributions
  - ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

- dim5 greatly restricted by gauge invariance without new fields (Λ ~ 10^{13} GeV)
  - ➔ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{C_x}{\Lambda^2} O_x$

- write down all gauge invariant dim6 O_x which contribute to **anomalous top couplings** of the form $f_i f_j V$ with fermions $f_{i,j} = t,b$ and vector bosons $V = A,Z,W,g$

- use **eqns of motion** to **rewrite redundant operators** (Aguilar-Saavedra 08)
  - ➔ simplify Lorentz structure of $f_i f_j V$: only **~ γ^μ** and **~ $\sigma^{\mu\nu} q_\nu$** with $q_\nu = (p_i - p_j)_\nu$
  - ➔ **remove off-shell contributions** (e.g. ~ q^μ) and some **quartic interactions** (e.g. *ttgA*) at the price of **introducing** additional **4-fermion contact terms**
  - ➔ parameterize $f_i f_j V$ in full generality:

$$\mathcal{L}^{\text{OS}}_{V f_i f_j} = \bar{f}_j \gamma^\mu \left(\mathcal{A}_L P_L + \mathcal{A}_R P_R\right) f_i \, V_\mu + \bar{f}_j \, i\sigma^{\mu\nu} q_\nu \left(\mathcal{B}_L P_L + \mathcal{B}_R P_R\right) f_i \, V_\mu + \text{H.c.}$$

➔ contains SM vertices!

+ quartic terms

Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)

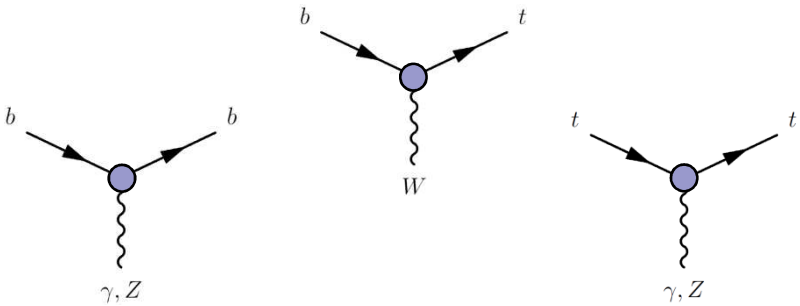
modular conception:
- take **SM** Lagrangian **objects** (fields, (covariant) derivative, etc...)
- combine group representations to build **singlets**

$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^{\mu}\tau^I D^{\nu} q_{Lj} W_{\mu\nu}^I$$

with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)

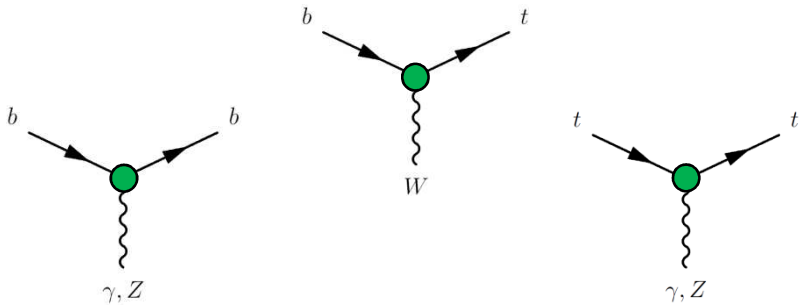


$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^{\mu}\tau^I D^{\nu} q_{Lj} W_{\mu\nu}^I$$

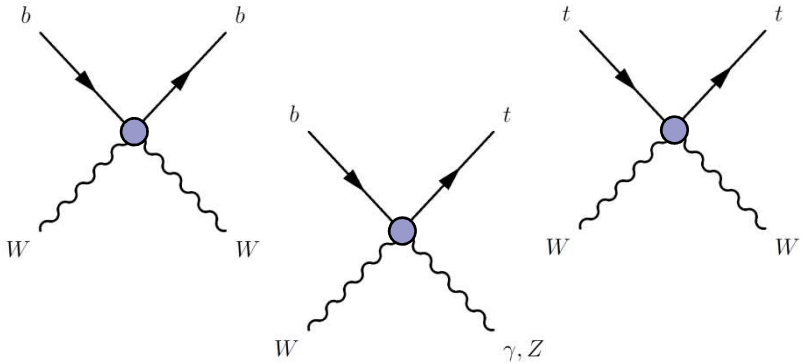
with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



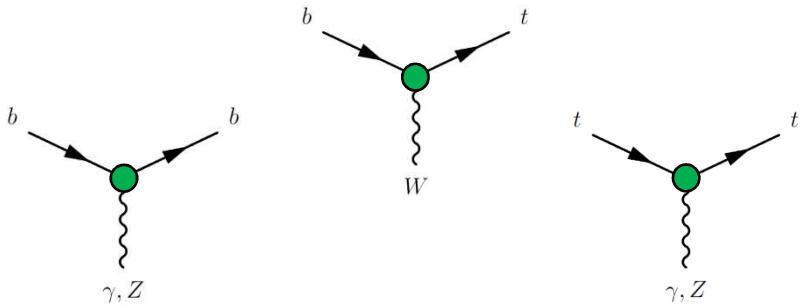
$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^{\mu}\tau^I D^{\nu} q_{Lj} W_{\mu\nu}^I$$



with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

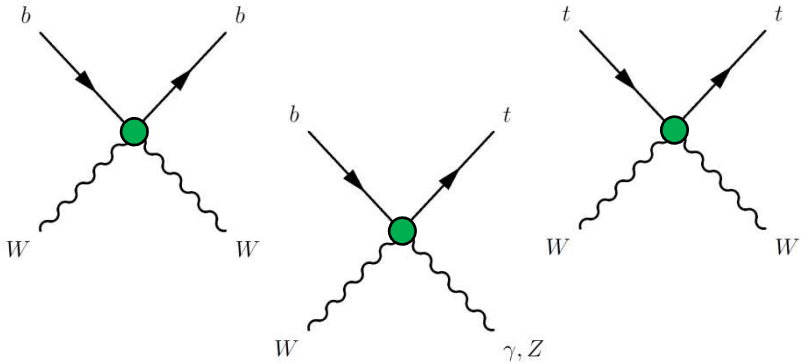
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

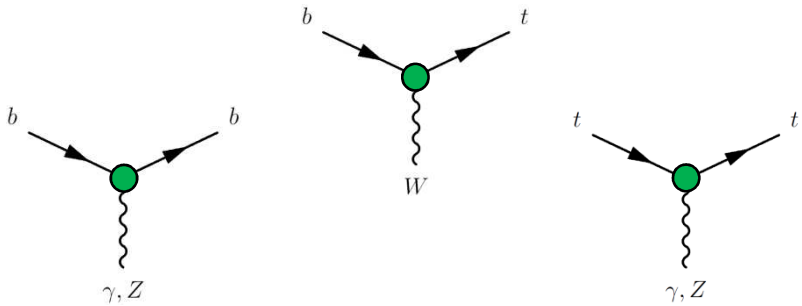
$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^\mu\tau^I D^\nu q_{Lj} W_{\mu\nu}^I$$

Use **eqn's of motion** to replace derivative

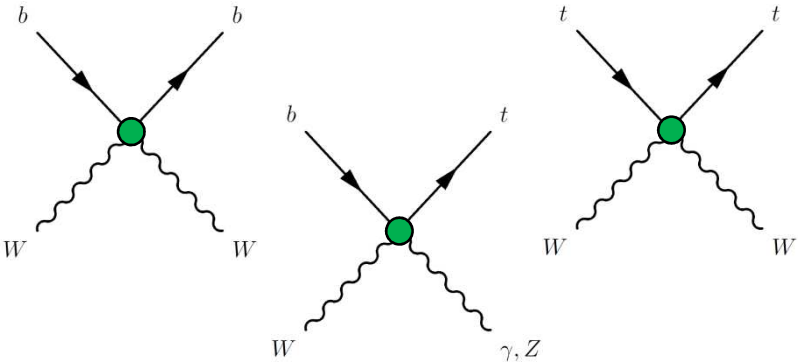


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

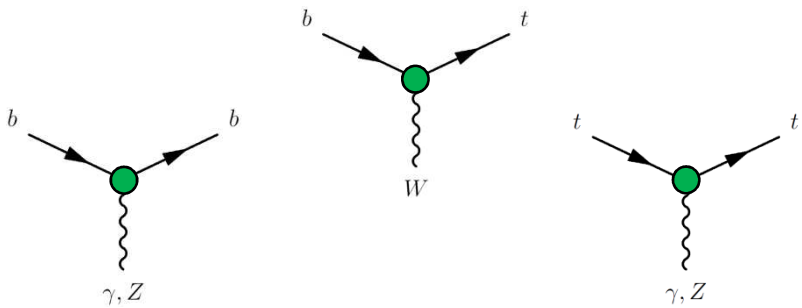


$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^\mu\tau^I D^\nu q_{Lj} W_{\mu\nu}^I$$

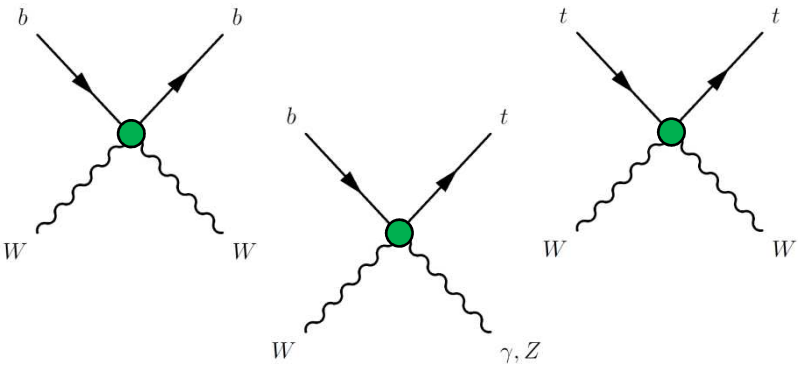
Use **eqn's of motion** to replace derivative and identify $O_{uW/dW}$

with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

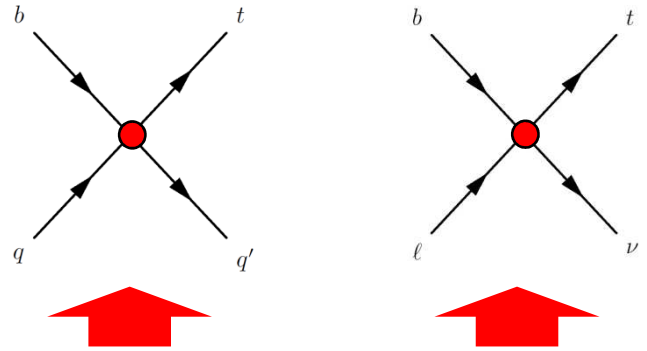
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

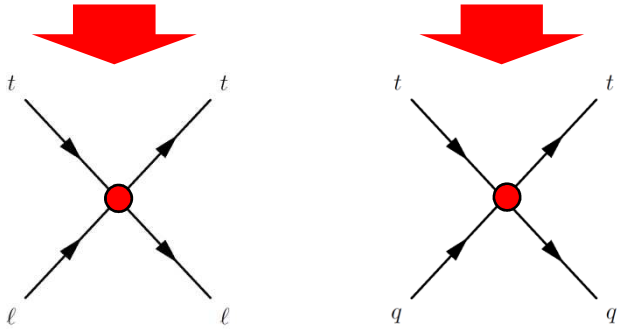


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

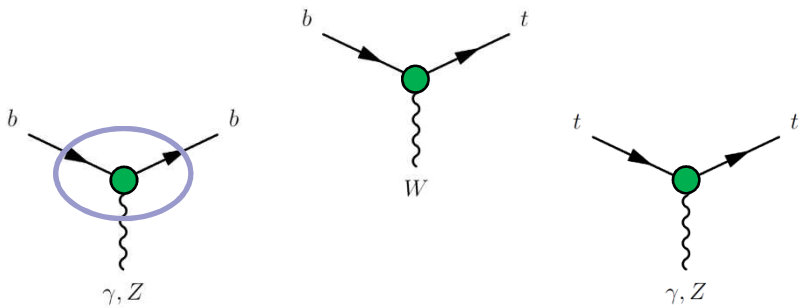


$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^\mu\tau^I D^\nu q_{Lj} W_{\mu\nu}^I$$

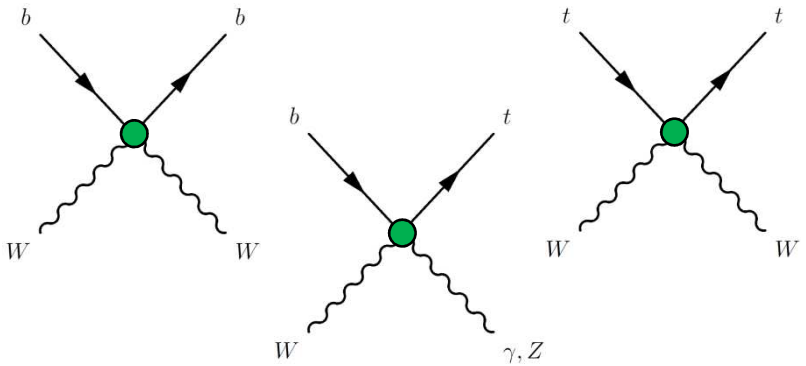
Use **eqn's of motion** to replace derivative and identify $O_{uW/dW}$ + **contact terms**



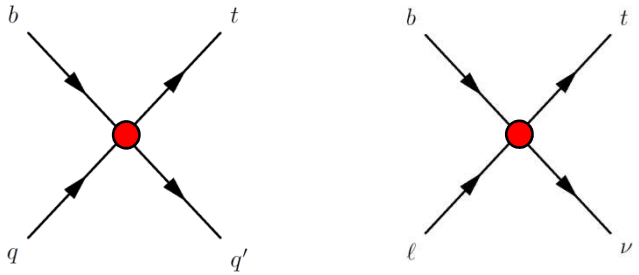
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

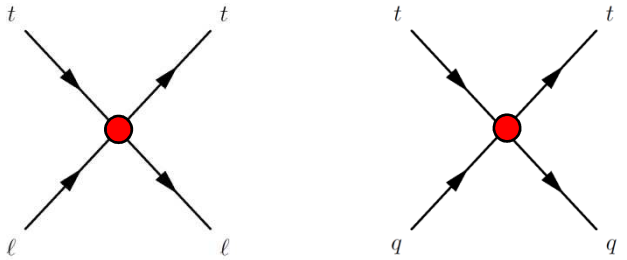


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

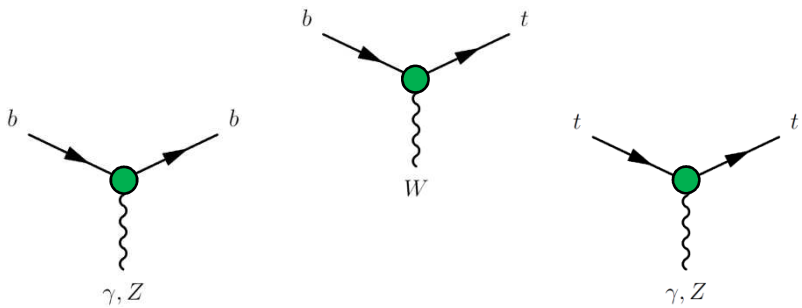


Some remarks:

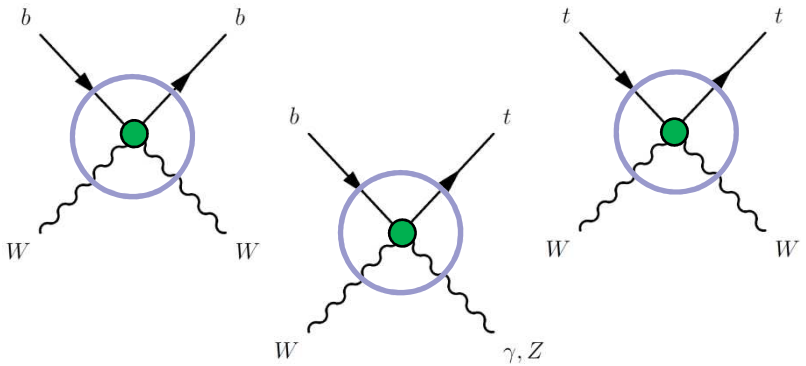
- anomalous top couplings imply anomalous ***b* couplings**



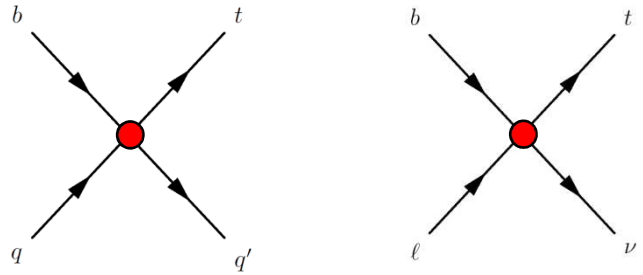
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

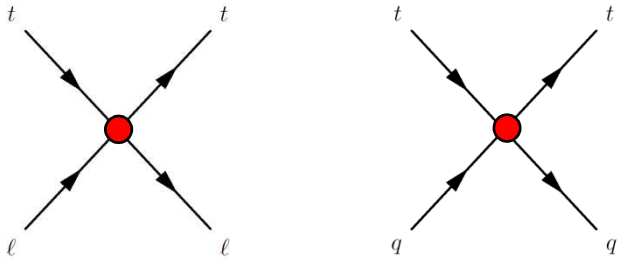


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

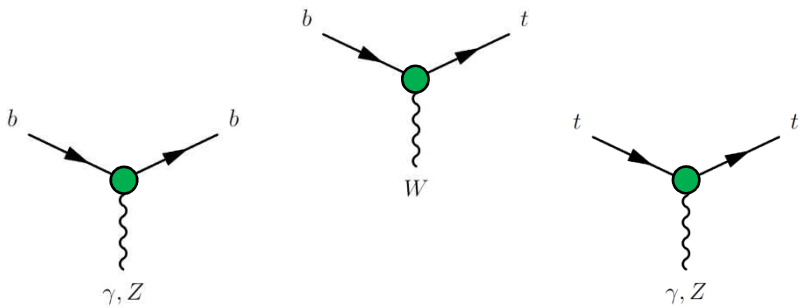


Some remarks:

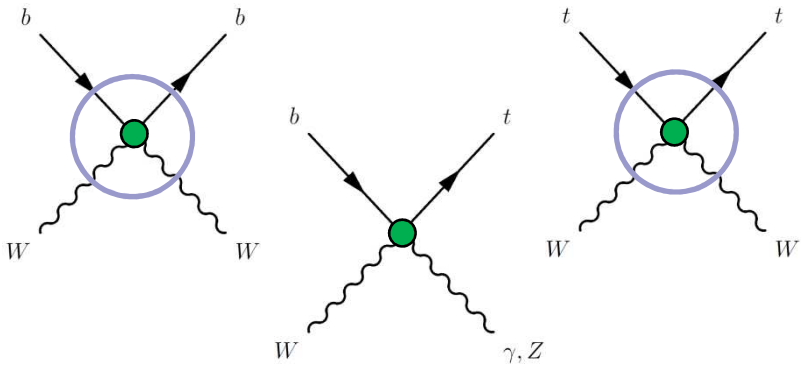
- anomalous top couplings imply anomalous ***b* couplings**
- *ffVV* contact terms required by **gauge invariance**



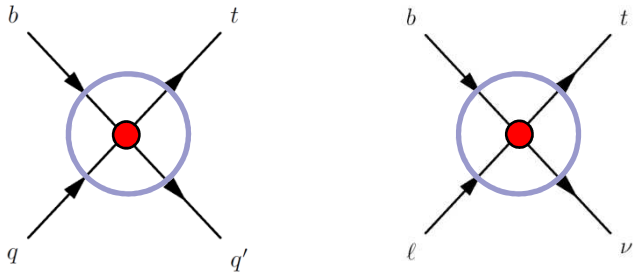
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

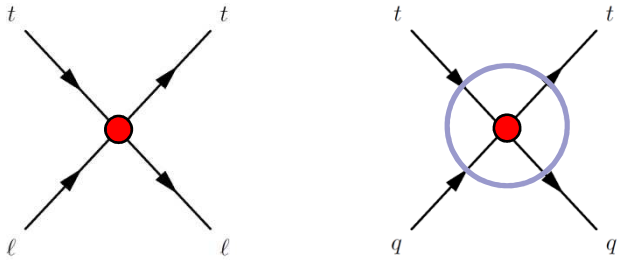


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

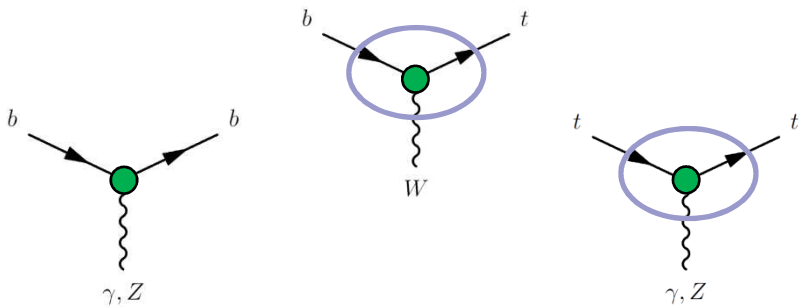


Some remarks:

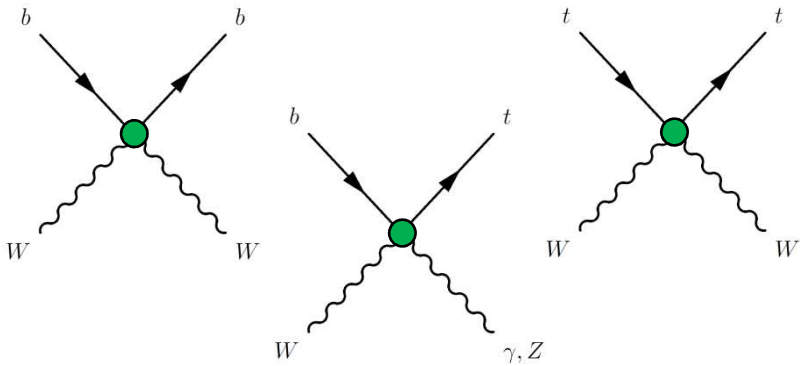
- anomalous top couplings imply anomalous ***b* couplings**
- *ffVV* contact terms required by **gauge invariance**
- some *ffVV* and *ffff* contact terms may contribute to single top and top pair **production** as well as top **decays**



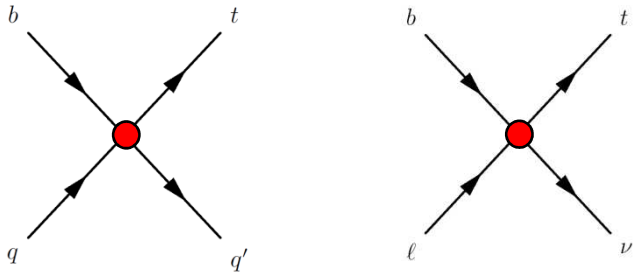
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

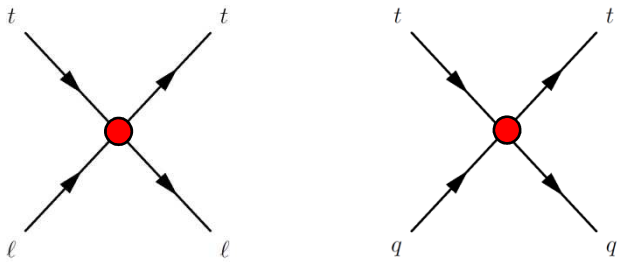


with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

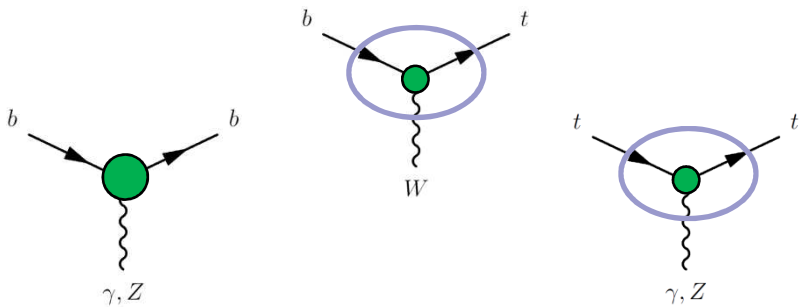


Conclusion:

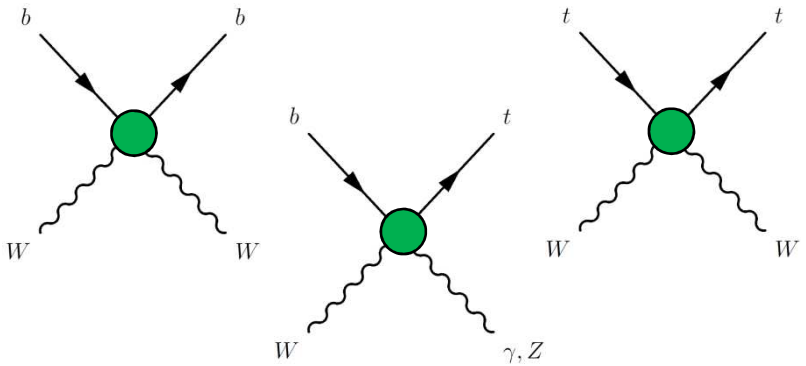
If you try to bound **trilinear couplings**…



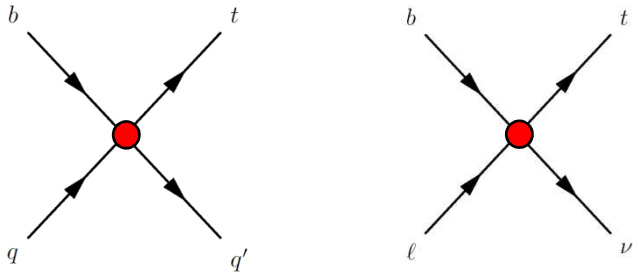
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$



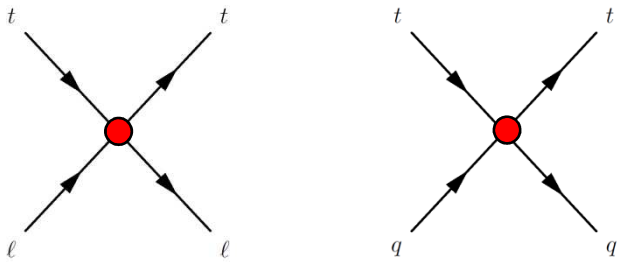
with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$



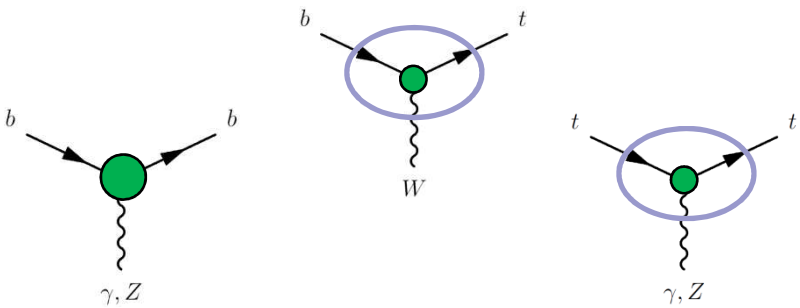
Conclusion:

If you try to bound **trilinear couplings**…

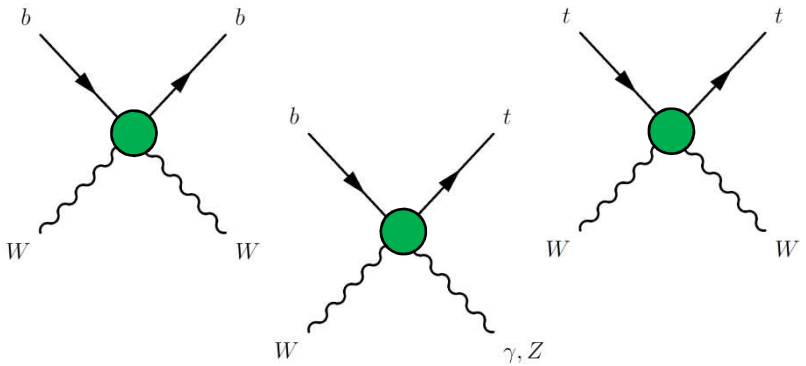
… respect the **ward identities**



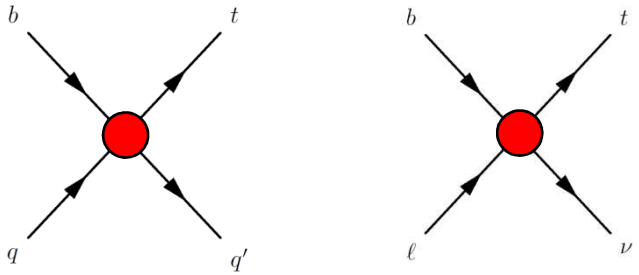
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$



with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

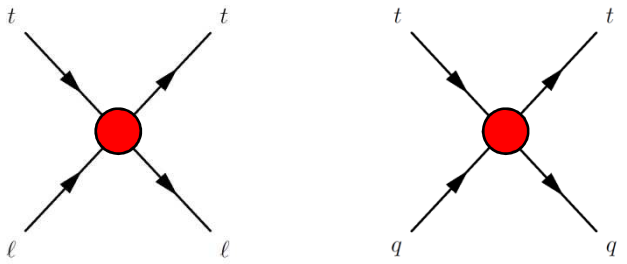


Conclusion:

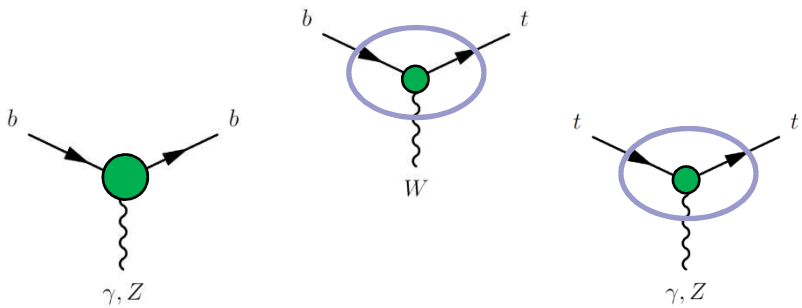
If you try to bound **trilinear couplings**…

… respect the **ward identities**

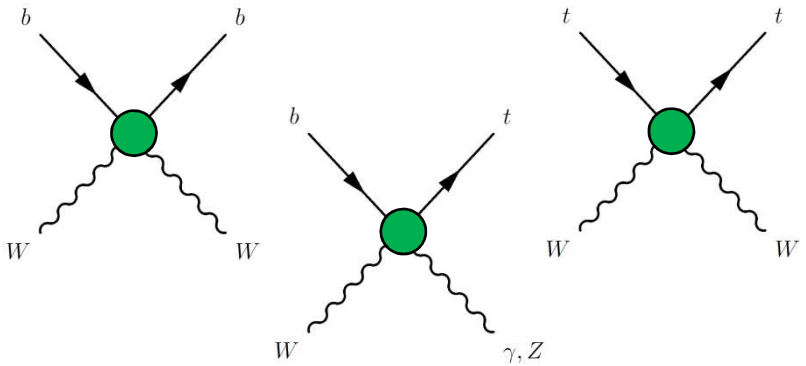
… stay **fully general**



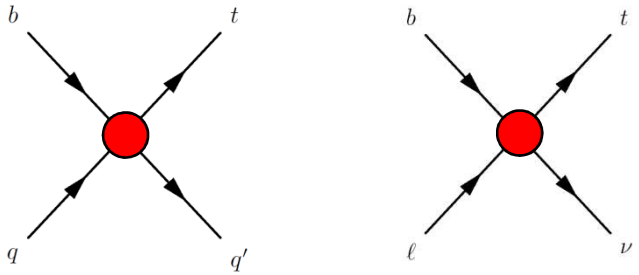
Example: Electroweak SU(2)$_L$ operators O_{uW}, O_{dW} and O_{qW} ($i = j = 3$)



$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$



with $W_{\mu\nu}^I = \partial_\mu W_\nu^I - \partial_\nu W_\mu^I - g\epsilon_{IJK} W_\mu^J W_\nu^K$

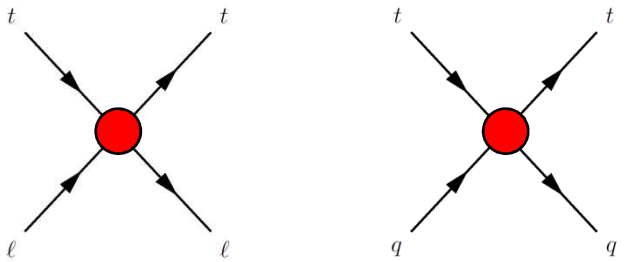


Luckily

WHIZARD 2

has the **full package**!

Including *tbW*, *ttZ*, *ttA* and *ttg* couplings



Studies on anomalous *tbW* couplings (Aguilar-Saavedra et al. 07-09)

• parameterization of the vertex (Aguilar-Saavedra et al.):

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

SM: $V_L = V_{tb} \approx 1$,
$V_R = g_L = g_R = 0$

➔ *remember*: **not fully general**

Studies on anomalous *tbW* couplings (Aguilar-Saavedra et al. 07-09)

• parameterization of the vertex (Aguilar-Saavedra et al.):

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

SM: $V_L = V_{tb} \approx 1$,
$V_R = g_L = g_R = 0$

➔ *remember*: **not fully general**

• *general remarks:*

1) **top pair production** largely QCD
   ➔ cross sections **not sensitive** on anomalous *tbW* couplings
2) **singe top production** closely dependent on the *tbW* couplings
   ➔ cross sections **sensitive** on anomalous *tbW* couplings
   ➔ potentially sensitive on charged-current ***ffff*** **term ~** $C_{qW}\,O_{qW}$
3) **top decay products sensitive** on ratios of anomalous *tbW* couplings

Studies on anomalous *tbW* couplings (Aguilar-Saavedra et al. 07-09)

• parameterization of the vertex (Aguilar-Saavedra et al.):

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

SM: $V_L = V_{tb} \approx 1$,
$V_R = g_L = g_R = 0$

➔ *remember*: **not fully general**

• *general remarks:*

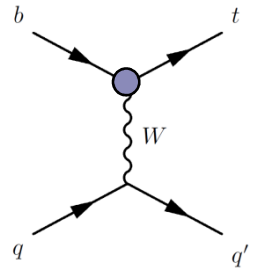
1) **top pair production** largely QCD
   ➔ cross sections **not sensitive** on anomalous *tbW* couplings
2) **singe top production** closely dependent on the *tbW* couplings
   ➔ cross sections **sensitive** on anomalous *tbW* couplings
   ➔ potentially sensitive on charged-current ***ffff*** **term ~** $C_{qW}\,O_{qW}$
3) **top decay products sensitive** on ratios of anomalous *tbW* couplings

➔ **combine measurements** of single top coss sections and distributions of top decay products to get a hold of the **abolute size** and **relative contributions** of the various effective operators

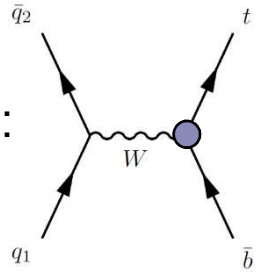
Single top cross sections (Aguilar-Saavedra 2008)

• different types of single top production considered

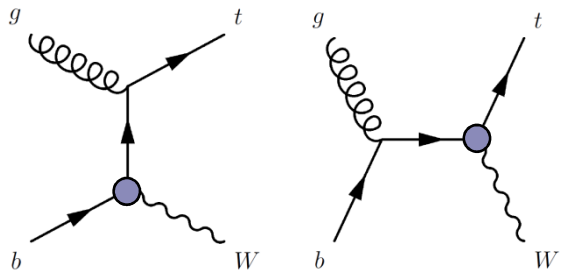
1) t-channel *tj* production:



2) s-channel *tb* production:



3) *tW* production:

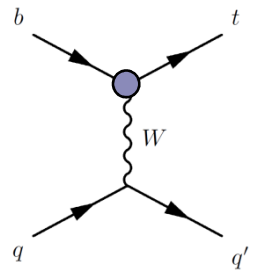


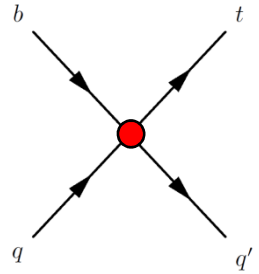
Single top cross sections (Aguilar-Saavedra 2008)

• different types of single top production considered

contact terms

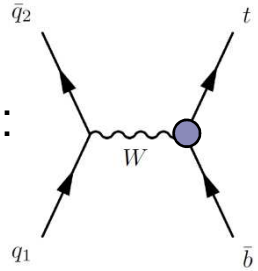
1) t-channel *tj* production:

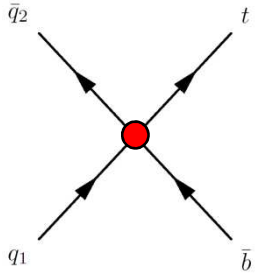




not included

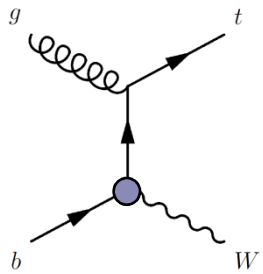
2) s-channel *tb* production:

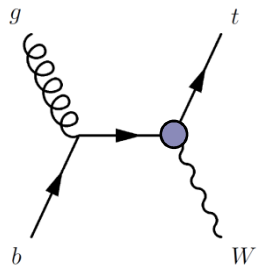


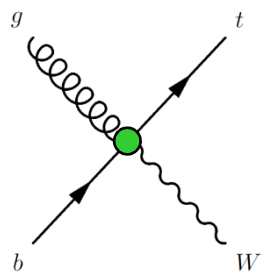


not included

3) *tW* production:



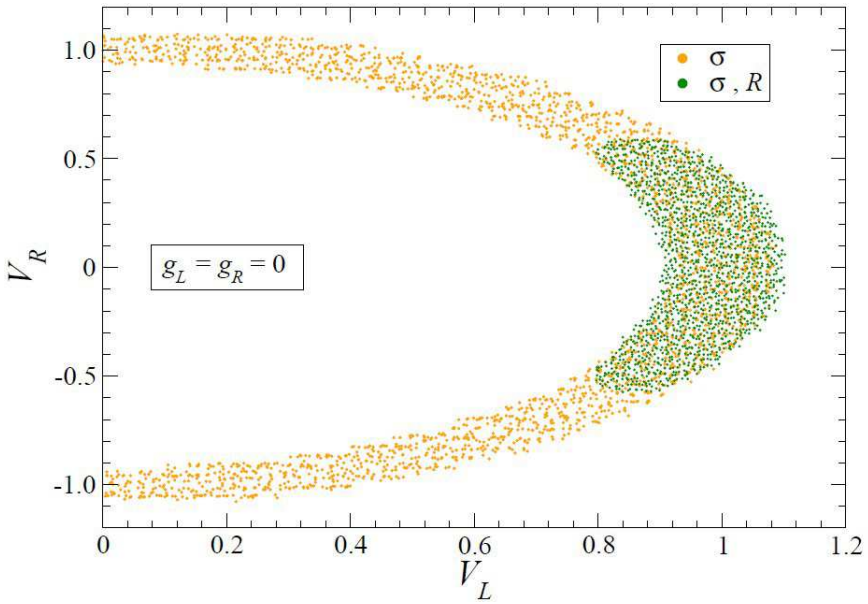


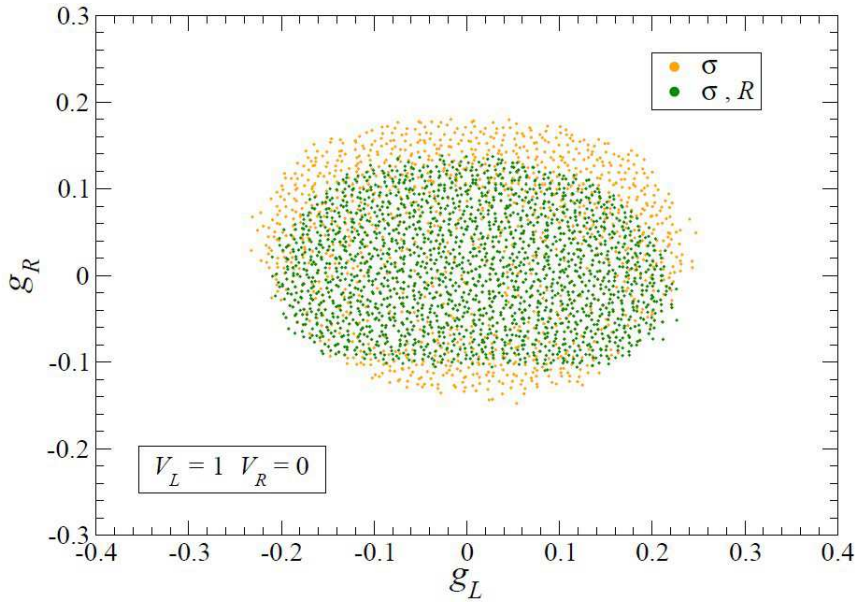


shown to be redundant

Single top cross sections (Aguilar-Saavedra 2008)

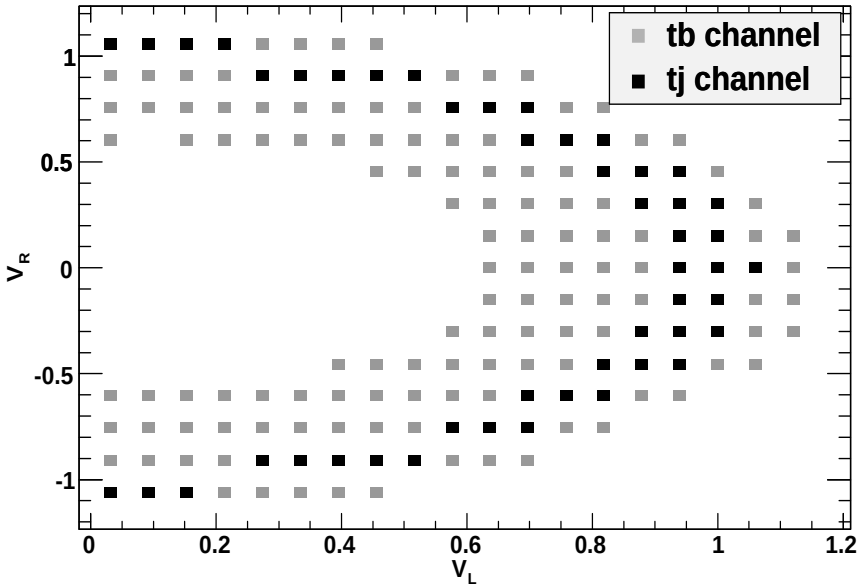
- estimated **absolute bounds** on V_L, V_R, g_L, g_R from a fast ATLAS detector simulation (corresponds to exp. 1σ deviations from SM x-sec's, 10 fb^{-1} @ 14 TeV)
  ➔ **separate bounds** on V_L, V_R (g_L, g_R = 0) and vice versa:

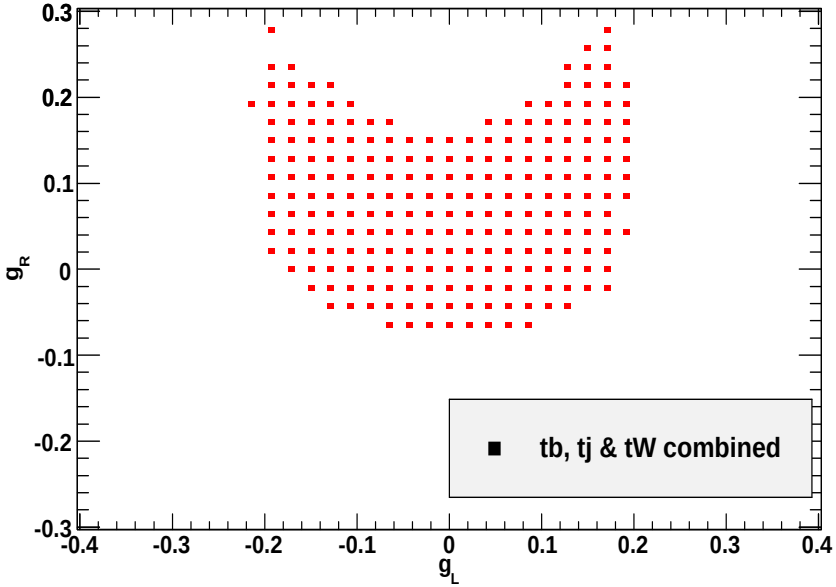




Single top cross sections (WHIZARD 2 implementation)

- same parameter scan in the V_L/V_R and g_L/g_R planes carried out in **WHIZARD**
  - ➔ ***tb* and *tj* channel** with potential *ffff* contributions
  - ➔ **parton level** with b-tagging efficiency/impurity taken into account





- **good agreement** in the vector couplings
- **good agreement** in the tensor couplings as soon as the ***tW* channel** is included
- now look at potential contributions to *tb*/*tj* channels from the **contact terms**…

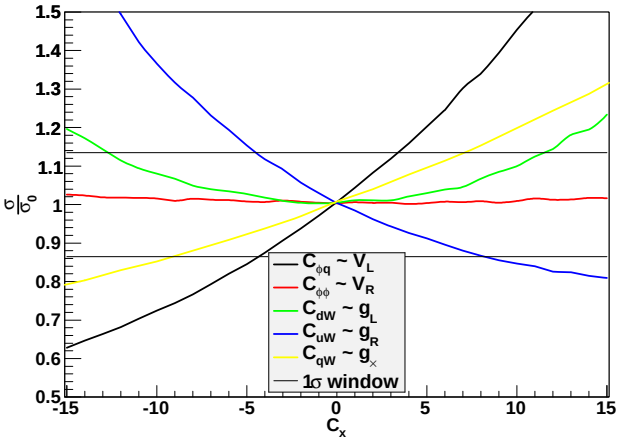
Single top cross sections (WHIZARD 2 implementation)

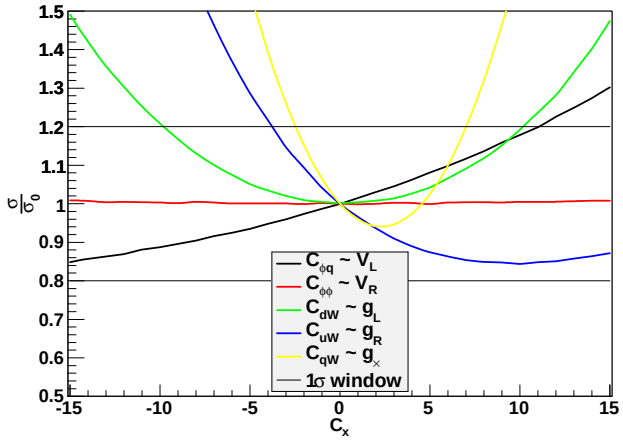
- compare separate sensitivities to the **operators coefficients** generating the trilinear couplings with the one of the 4-fermion contact coupling C_{qW}

tj channel

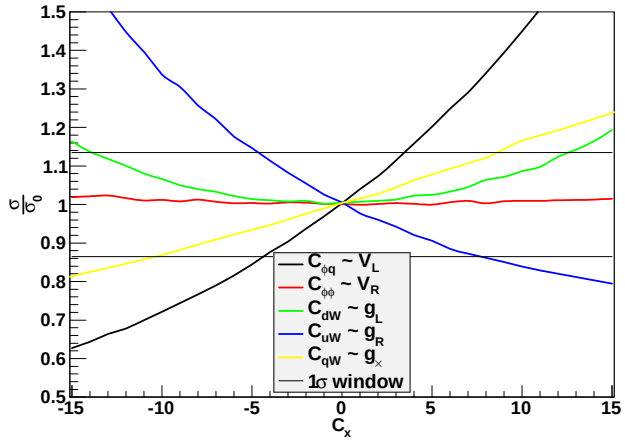
tb channel

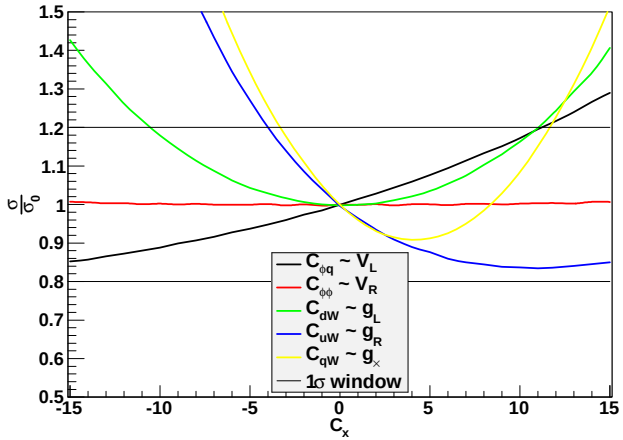
14 TeV





7 TeV





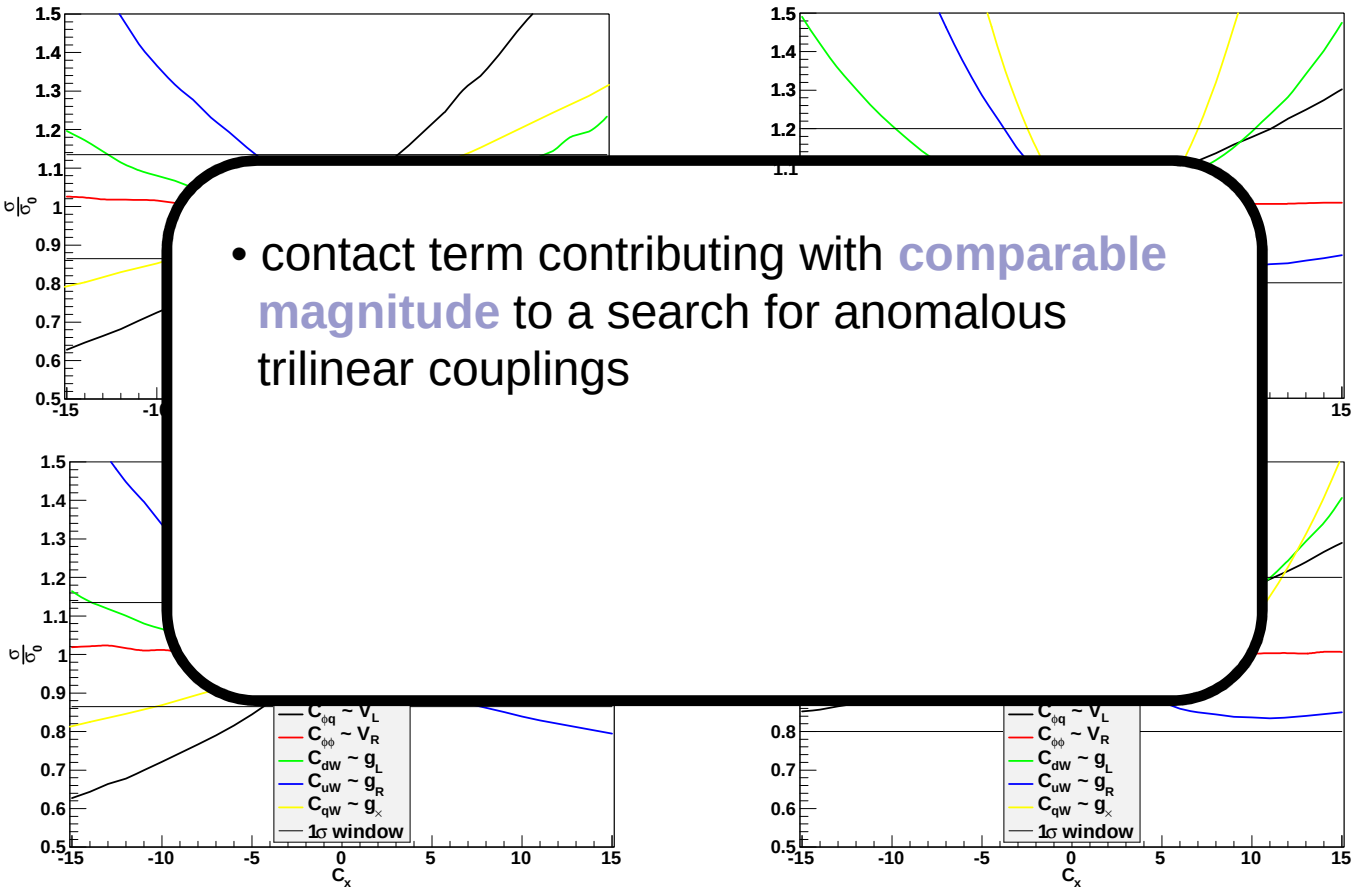
Single top cross sections (WHIZARD 2 implementation)

- compare separate sensitivities to the **operators coefficients** generating the trilinear couplings with the one of the 4-fermion contact coupling C_{qW}

tj channel | *tb* channel

14 TeV

7 TeV



- contact term contributing with **comparable magnitude** to a search for anomalous trilinear couplings

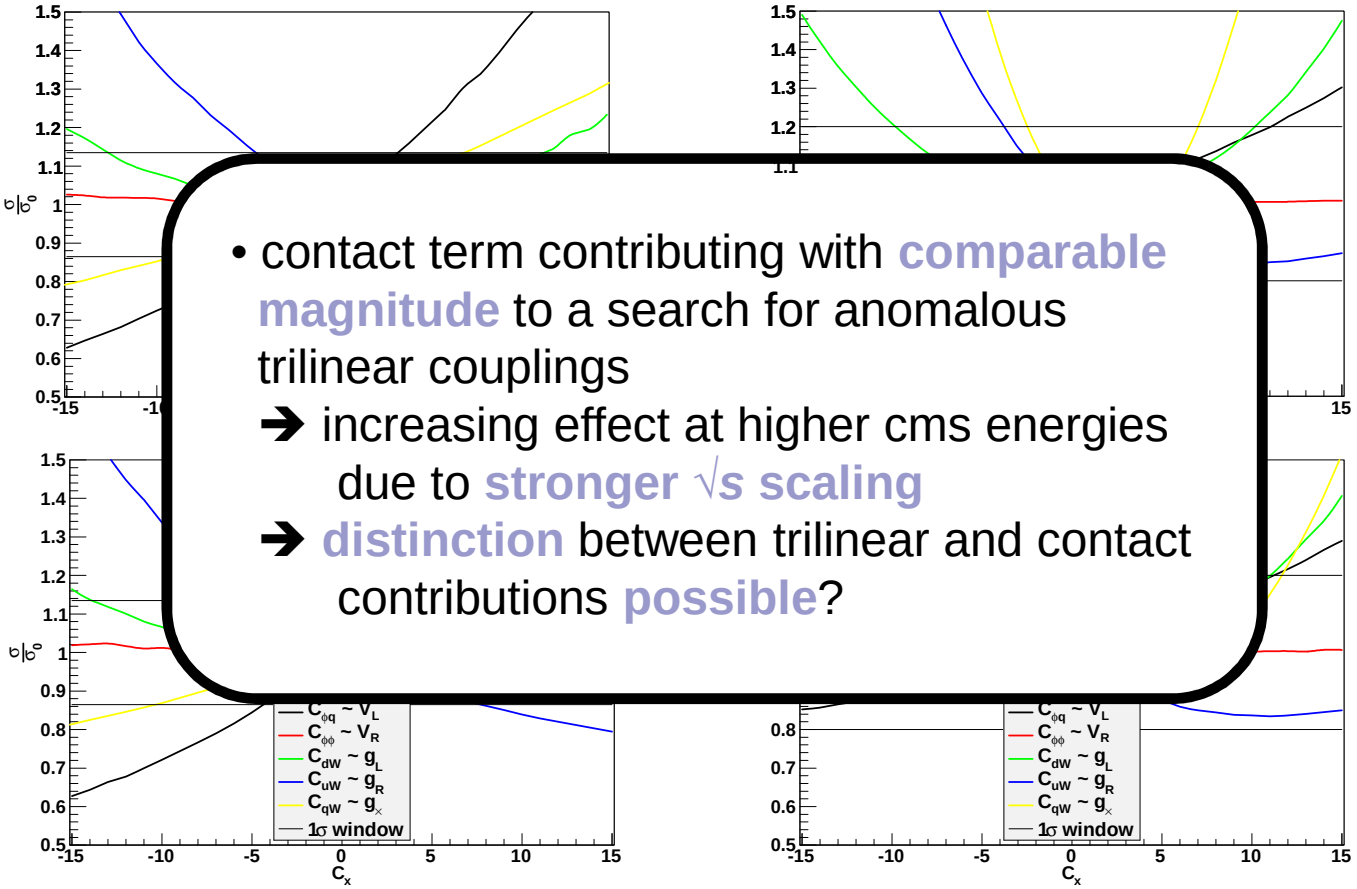
Single top cross sections (WHIZARD 2 implementation)

- compare separate sensitivities to the **operators coefficients** generating the trilinear couplings with the one of the 4-fermion contact coupling C_{qW}

tj channel | *tb* channel

14 TeV

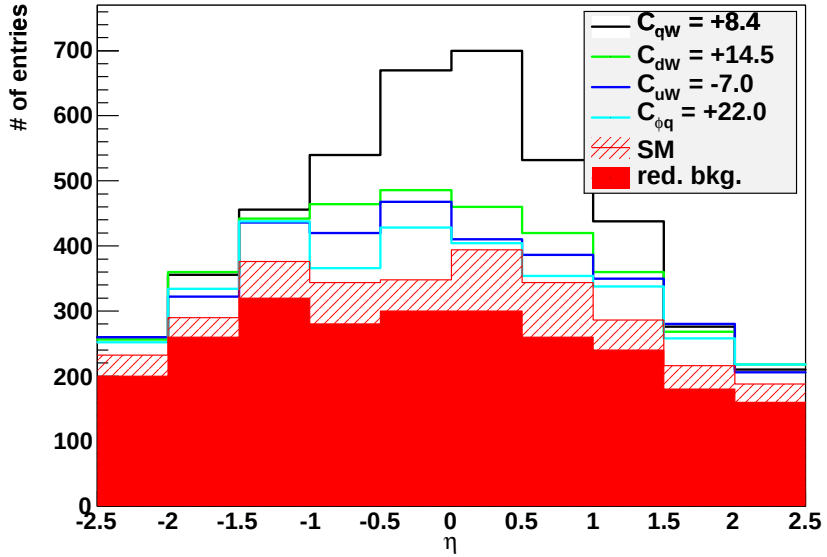
7 TeV



- contact term contributing with **comparable magnitude** to a search for anomalous trilinear couplings
  - ➔ increasing effect at higher cms energies due to **stronger √s scaling**
  - ➔ **distinction** between trilinear and contact contributions **possible**?

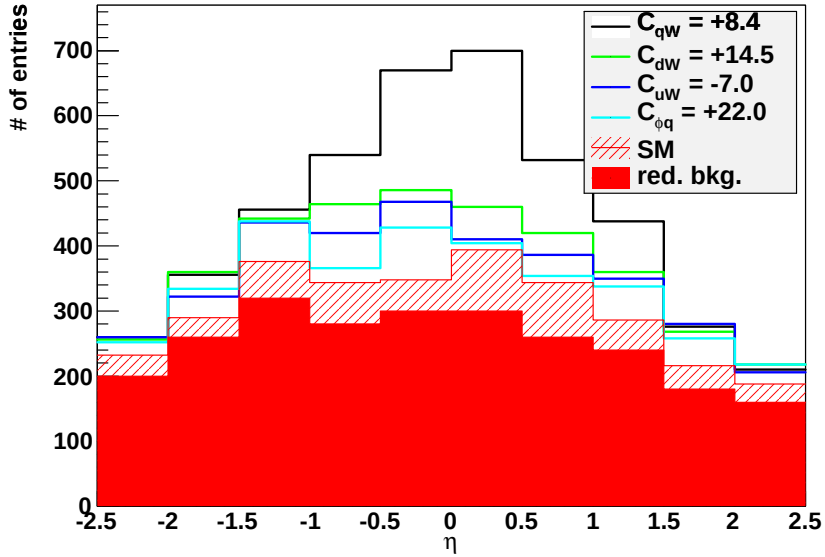
Single top cross sections (WHIZARD 2 implementation)

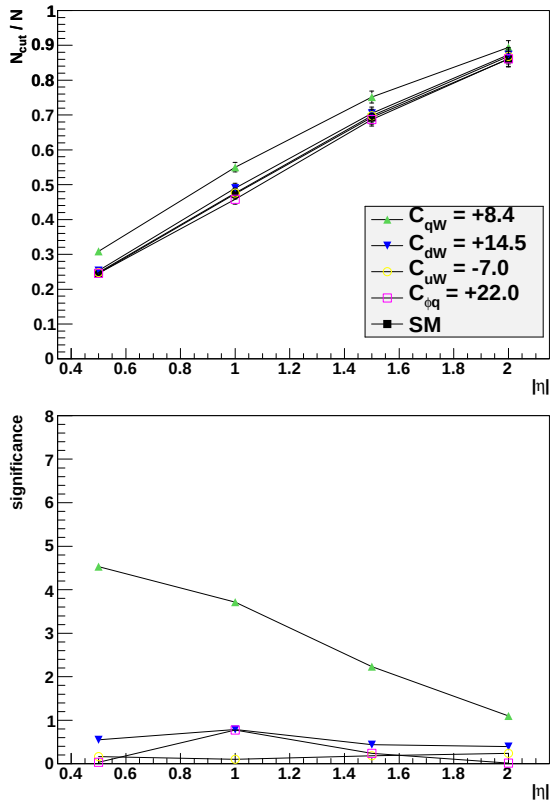
- take samples with **x-section** deviations **significant at 3*σ*** compared to the SM expectation and look at distributions (normalized to 10 fb^{-1} @ 14 TeV)
  - ➔ make use of the fact that the intermediate ***W* boson** in diagrams with trilinear couplings is **strongly boosted** in *s*-channel ***tb* production**
  - ➔ look at the ***η*** distribution of the ***b*-jet** **not** reconstructing the top mass in the ***tb* channel** (DELPHES detector level)



Single top cross sections (WHIZARD 2 implementation)

- take samples with **x-section** deviations **significant at 3σ** compared to the SM expectation and look at distributions (normalized to 10 fb^{-1} @ 14 TeV)
  - ➔ make use of the fact that the intermediate ***W* boson** in diagrams with trilinear couplings is **strongly boosted** in *s*-channel ***tb* production**
  - ➔ look at the ***η*** distribution of the ***b*-jet** **not** reconstructing the top mass in the ***tb* channel** (DELPHES detector level)





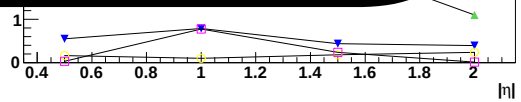
➔ **extraction** of contact term seems **possible**

Single top cross sections (WHIZARD 2 implementation)

- take samples with **x-section** deviations **significant at 3σ** compared to the SM expectation
  - ➔ m
  - ➔
  - ➔ e

Outlook: decay products in top pair production

- relevant **scale** changes: $\sqrt{s}_{parton} \rightarrow m_t \ll \Lambda$
  - ➔ off-resonant *ffff* contact interactions "switched off" kinematically
  - ➔ sensitive only to trilinear *tbW* couplings

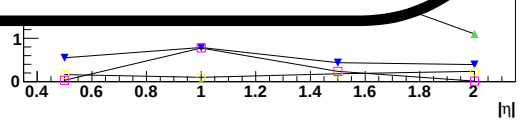


Single top cross sections (WHIZARD 2 implementation)

- take samples with **x-section** deviations **significant at 3σ** compared to the SM expectation
  - ➔ m
  - ➔ ne
  - ➔ e

Outlook: decay products in top pair production

- relevant **scale** changes: $\sqrt{s}_{parton} \rightarrow m_t \ll \Lambda$
  - ➔ off-resonant *ffff* contact interactions "switched off" kinematically
  - ➔ sensitive only to trilinear *tbW* couplings
- probes non-standard **helicity** structures
  - ➔ sensitive to anomalous V_R and $g_{L/R}$ but **not** V_L



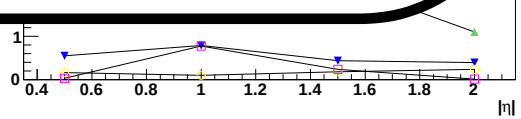
Single top cross sections (WHIZARD 2 implementation)

- take samples with **x-section** deviations **significant at 3σ** compared to the SM expectation
  - ➔ m
  - ➔ ne
  - ➔ e

Outlook: decay products in top pair production

- relevant **scale** changes: $\sqrt{s}_{parton} \rightarrow m_t \ll \Lambda$
  - ➔ off-resonant *ffff* contact interactions "switched off" kinematically
  - ➔ sensitive only to trilinear *tbW* couplings
- probes non-standard **helicity** structures
  - ➔ sensitive to anomalous V_R and $g_{L/R}$ but **not V_L**

➔ non-SM single top x-sections in **combination** with SM-like top decays might hint at new physics parameterized by effective 4-fermion **contact interactions** (or V_L)



Conclusions

- abundant **top production** at the ***LHC***
  - ➔ high statistics allows for precise measurements of top couplings etc.
  - ➔ look for deviations from the SM in the trilinear top couplings $f_i f_j V$, *ttH*

Conclusions

- abundant **top production** at the ***LHC***
  - ➔ high statistics allows for precise measurements of top couplings etc.
  - ➔ look for deviations from the SM in the trilinear top couplings $f_i f_j V$, *ttH*
- write down all effective **dim6 operators** contributing to trilinear top couplings
  - ➔ use equations of motion to **remove redundancies**
- most general parameterization of all anomalous trilinear top couplings:
  - ➔ just two different Lorentz structures: ~ γ^μ and ~ $\sigma^{\mu\nu} q_\nu$
  - ➔ gauge invariance requires inclusion of quartic terms (e.g. *ttgg,* 4-fermion)

Conclusions

- abundant **top production** at the ***LHC***
  - ➔ high statistics allows for precise measurements of top couplings etc.
  - ➔ look for deviations from the SM in the trilinear top couplings $f_i f_j V$, *ttH*
- write down all effective **dim6 operators** contributing to trilinear top couplings
  - ➔ use equations of motion to **remove redundancies**
- most general parameterization of all anomalous trilinear top couplings:
  - ➔ just two different Lorentz structures: ~ γ^μ and ~ $\sigma^{\mu\nu} q_\nu$
  - ➔ gauge invariance requires inclusion of quartic terms (e.g. *ttgg,* 4-fermion)
- the **WHIZARD 2** front: provide an **exhaustive, integrated and consistent MC tool** for phenomenological studies of **all possible anomalous top couplings**, up to detector-level final states (collaboration with I. Fleck, ATLAS, Uni Siegen)

Conclusions

- abundant **top production** at the ***LHC***
  - ➔ high statistics allows for precise measurements of top couplings etc.
  - ➔ look for deviations from the SM in the trilinear top couplings $f_i f_j V$, *ttH*
- write down all effective **dim6 operators** contributing to trilinear top couplings
  - ➔ use equations of motion to **remove redundancies**
- most general parameterization of all anomalous trilinear top couplings:
  - ➔ just two different Lorentz structures: ~ γ^μ and ~ $\sigma^{\mu\nu} q_\nu$
  - ➔ gauge invariance requires inclusion of quartic terms (e.g. *ttgg,* 4-fermion)
- the **WHIZARD 2** front: provide an **exhaustive, integrated and consistent MC tool** for phenomenological studies of **all possible anomalous top couplings**, up to detector-level final states (collaboration with I. Fleck, ATLAS, Uni Siegen)
  - ➔ additional **vertex structure** ~ $\sigma^{\mu\nu} q_\nu$ implemented
  - ➔ full set of **anomalous** trilinear top **couplings** (including *ttH*) provided
  - ➔ optional $\boldsymbol{q^2}$ dependence of the coupling parameters provided
  - ➔ all relevant **quartic** interactions included
  - ➔ significant contribution of **4-fermion** terms illustrated

References

- W. Buchmüller, D. Wyler: *Nucl. Phys. B* **268**, 621 (1986).
- G. L. Kane, G. A. Ladinsky, C. P. Yuan: *Phys. Rev. D* **45**, 124 (1992).
- P. Haberl, O. Nachtmann, A. Wilch: *Phys. Rev. D* **53**, 4875 (1997).
- B. Grzadkowski et al.: *arXiv:*0310.0159 [hep-ph] (2004).
- J. A. Aguilar-Saavedra et al.: *arXiv:*0605190v2 [hep-ph] (2007);
  *arXiv:*0705.3041v2 [hep-ph] (2007).
- J. A. Aguilar-Saavedra: *arXiv:*0803.3810 [hep-ph] (2008);
  *arXiv:*0811.3842v2 [hep-ph] (2008).
- CDF Collaboration: *Public CDF note* 9448 (2008).
- D0 Collaboration: *arXiv:*0903.5525 [hep-ex] (2009).
- ATLAS Collaboration: *arXiv:*0901.0512v2 [hep-ex] (2009).
- Z. Hioki, K. Ohkuma: *arXiv:*0910.3049v2 [hep-ph] (2009).
- D. Choudhury, P. Saha: *arXiv:*0911.5016v2 [hep-ph] (2009).