Anomalous Top Couplings at a Linear Collider with WHIZARD

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DESY Hamburg
LC top workshop, LPNHE Paris, 2014/03/06

Outline

1. Effective Field Theory & Anomalous Couplings
2. WHIZARD Implementation
3. Anomalous Couplings in ttbar LC Observables
4. Conclusions & Outlook

Effective Operator Approach

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

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

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> no dim5 top operator without new fields

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

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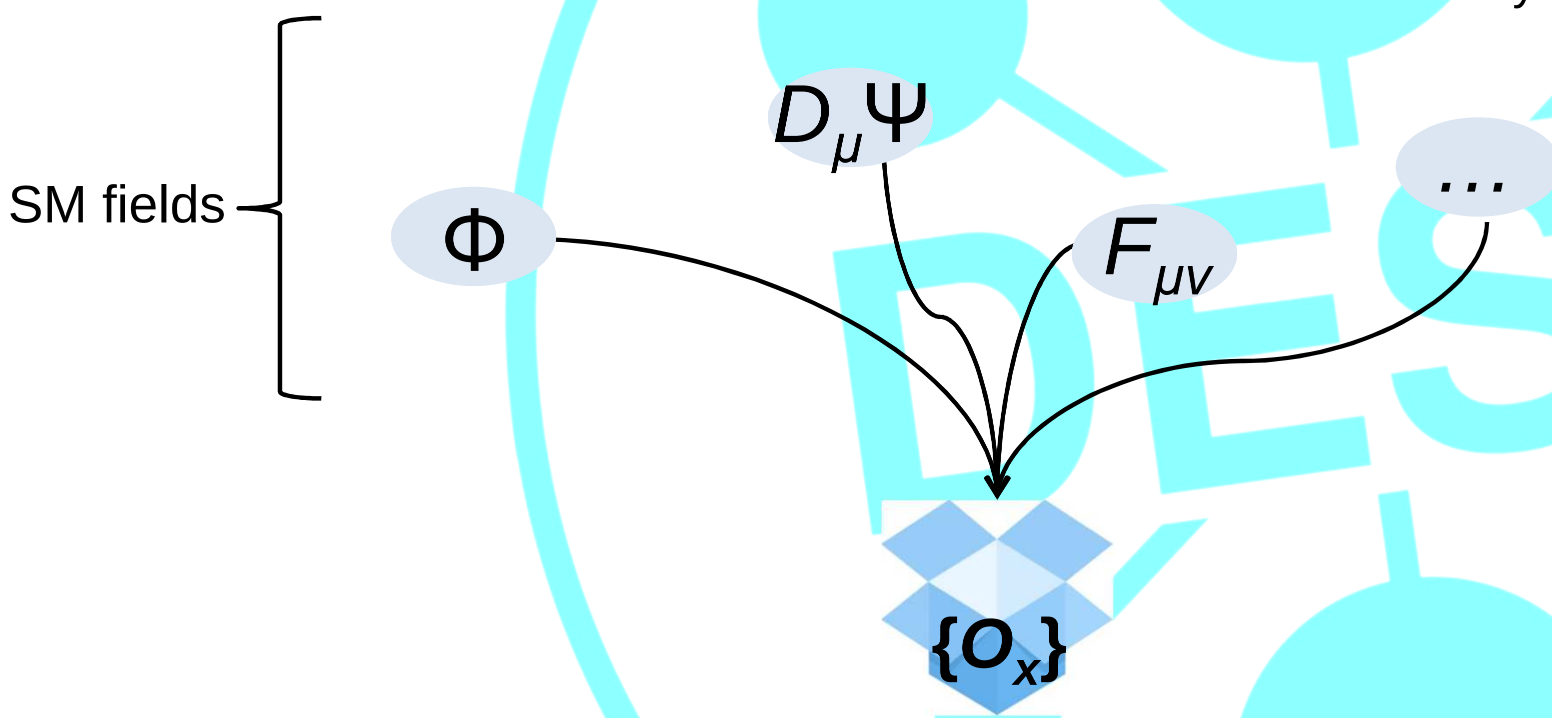
$$\rightarrow \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{C_x}{\Lambda^2} O_x$$

anom. top couplings: **all operators** with ≥ 1 heavy fermion fields



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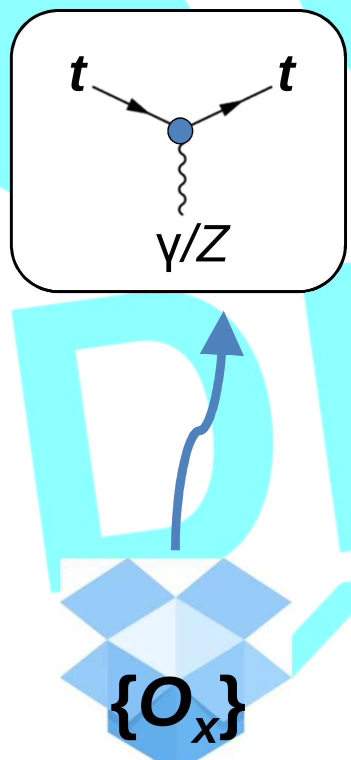

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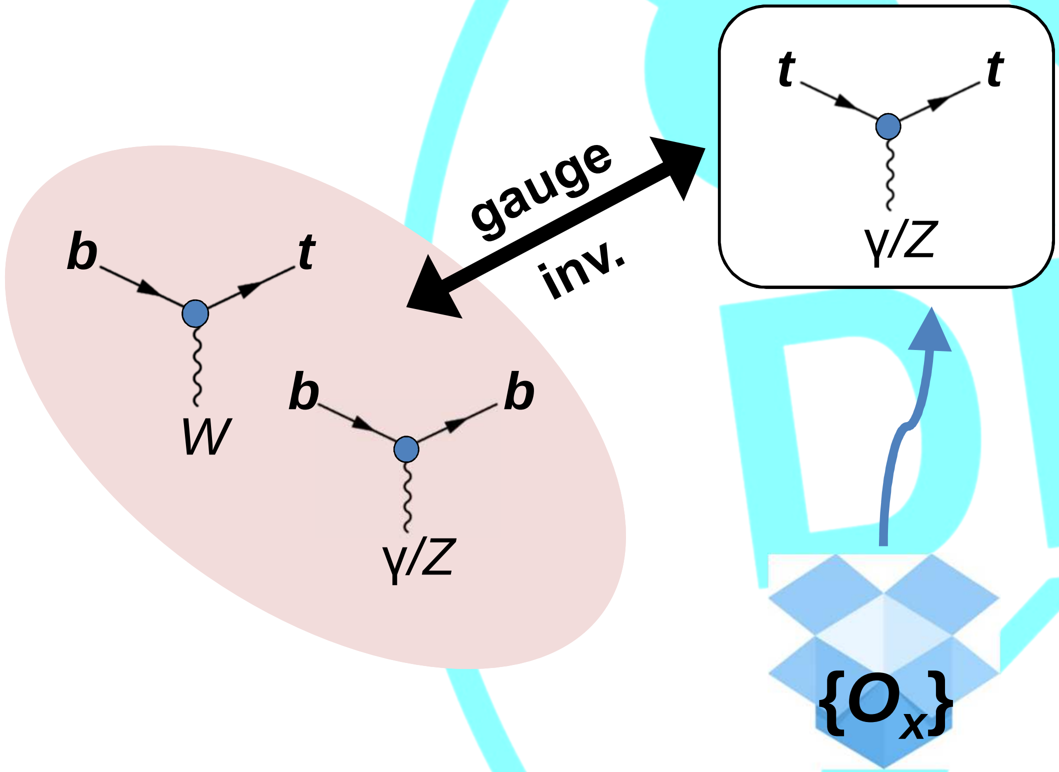

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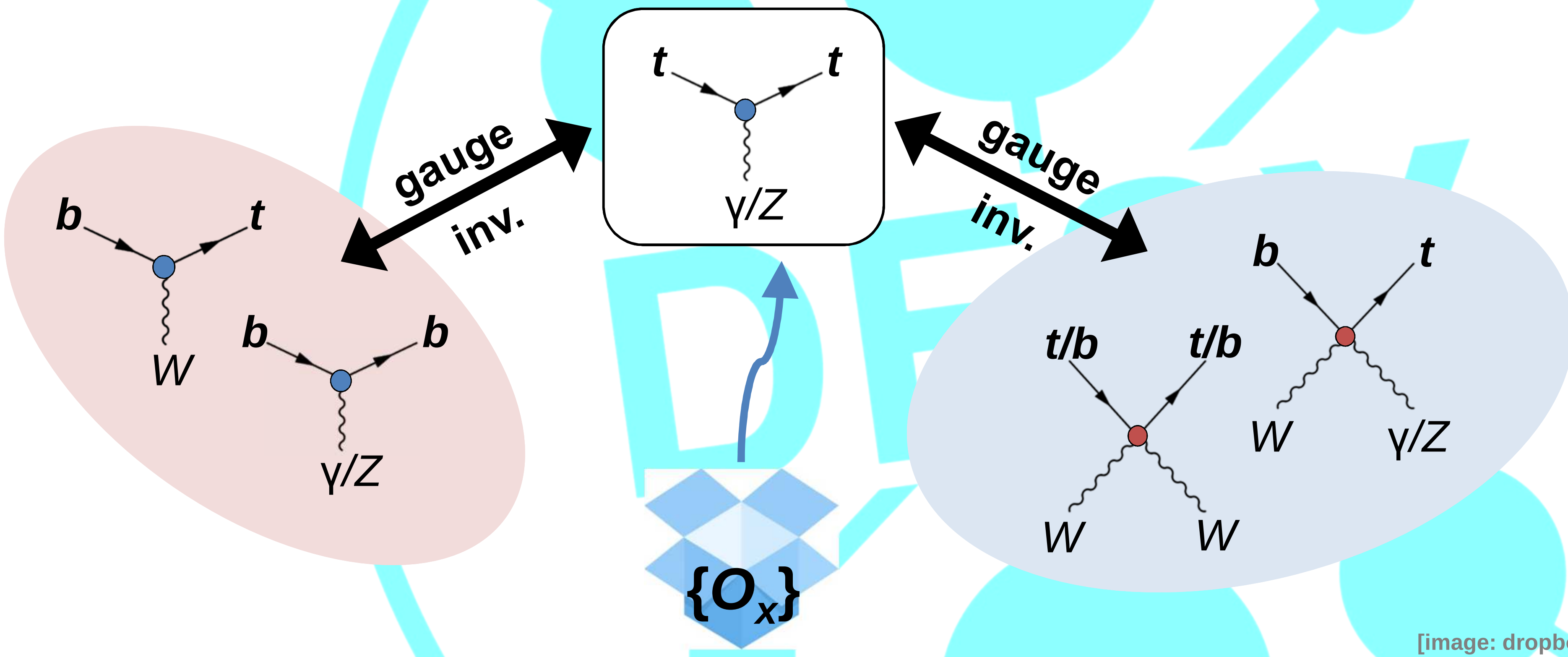

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Anomalous top–gauge couplings from effective dim6 operators

> effective operator approach:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4,i} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} + \text{h.c.}$$

new physics scale **Λ**
top couplings @ ***d*=6**

e.g.:

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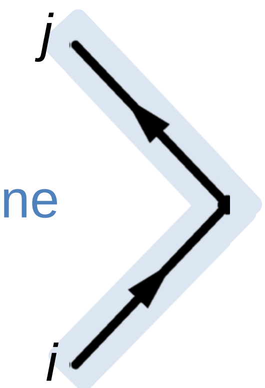
(heavy) fermion line



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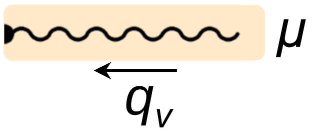
Electroweak gauge boson *γ/Z/W*



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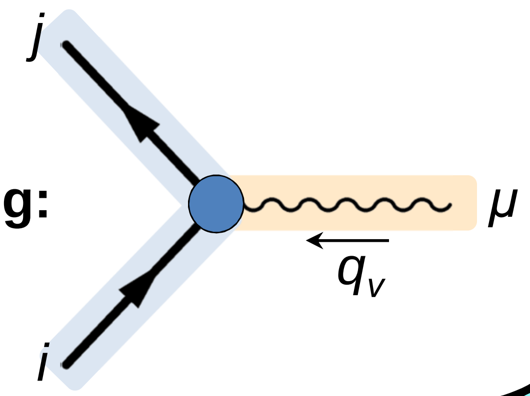
➔ **eff. coupling:**



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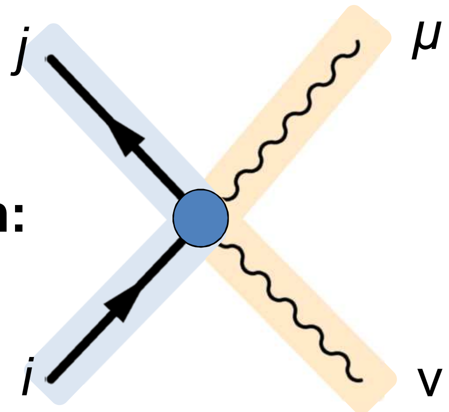
➔ non-Abelian:



Anomalous top–gauge couplings from effective dim6 operators

> parameterization of *ttZ/ttγ* couplings [e.g. Aguilar-Saavedra '08]:

$$\mathcal{L}_{ttZ} = -\frac{g}{2c_w}\bar{t}\gamma^\mu\left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_w^2 Q_t\right)t\, Z_\mu - \frac{g}{2c_w}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(d_V^Z + i d_A^Z\gamma_5\right)t\, Z_\mu$$

$$\mathcal{L}_{tt\gamma} = -\,\mathrm{e}Q_t\bar{t}\gamma^\mu t\, A_\mu - \mathrm{e}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + i d_A^\gamma\gamma_5\right)t\, A_\mu$$

$$\boxed{\text{SM:}\quad X_{tt}^L = 1,\ X_{tt}^R = 0,\quad d_V^{Z/\gamma} = d_A^{Z/\gamma} = 0}$$

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➔ **6 couplings**

Compare to e.g. [Amjad et al. '13]:

> $F_{1V}^{Z/\gamma},\, F_{1V}^{Z/\gamma},\, F_{2V}^{Z/\gamma},\, F_{2V}^{Z/\gamma}$?

➔ **8 couplings?**

Anomalous top–gauge couplings from effective dim6 operators

> parameterization of *tbW* couplings [e.g. Aguilar-Saavedra '08]:

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> what about ***tbW* charged currents**?

> what about ***bbZ* neutral currents**?

Anomalous top–gauge couplings from effective dim6 operators

- gauge-invariant dictionary:

vertex		gauge boson		
		Z	γ	$W^{\pm}$
	$\sim \gamma^{\mu}$	$F^{Z}_{1V,1A}$	$F^{\gamma}_{1V,1A}$	
	$\sim i\sigma^{\mu\nu} q_{\nu}$	$F^{Z}_{2V,2A}$	$F^{\gamma}_{2V,2A}$	

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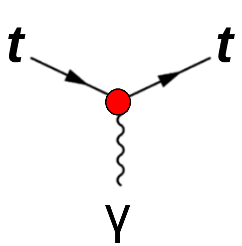

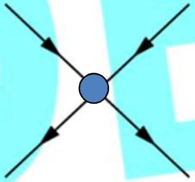

~ *exact* QED: **form factors ~ q^2** related to *ffff* couplings + higher dim. effects

Anomalous top–gauge couplings from effective dim6 operators

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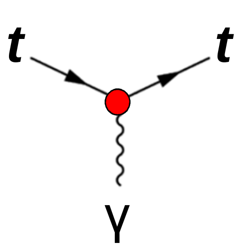
vertex		gauge boson		
		Z	γ	$W^\pm$
	$\sim \gamma^\mu$	$X_{tt}^{L,R}$		$\delta V_L \overset{!}{=} \frac{1}{2} X_{tt}^L$
	$\sim i\sigma^{\mu\nu} q_\nu$	$F^Z_{2V,2A}$	$F^\gamma_{2V,2A}$	



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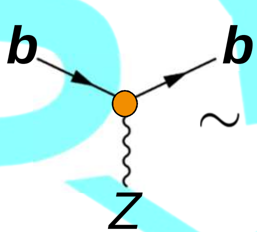

$\sim X^L_{bb} \overset{!}{=} 0$

~ heavily constrained
by LEP data!

Anomalous top–gauge couplings from effective dim6 operators

> gauge-invariant dictionary:

vertex		gauge boson		
		Z	γ	$W^\pm$
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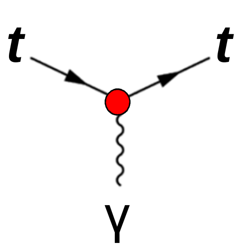
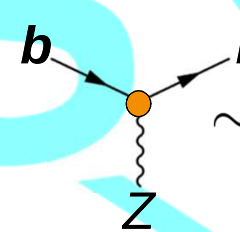
vertex	$\sim i\sigma^{\mu\nu} q_\nu$	$d_{V,A}^{Z}$	$d_{V,A}^{\gamma}$	$g_R \overset{!}{=} f\left(d_{V,A}^{Z/\gamma}\right)$



~ *exact* QED!

6 real numbers from **2 complex** operator coefficients!



$\sim X_{bb}^{L} \overset{!}{=} 0$

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Anomalous top–gauge couplings from effective dim6 operators

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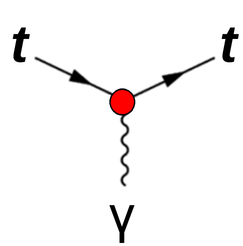

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6 real numbers for
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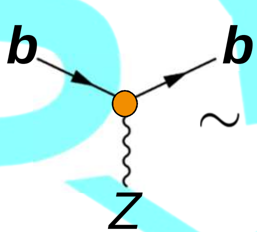

$\sim X_{bb}^L \stackrel{!}{=} 0$

~ *heavily constrained*
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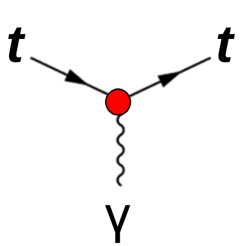
Anomalous top–gauge couplings from effective dim6 operators

> gauge invariance + **CP conservation**:

		gauge boson		
		Z	γ	$W^{\pm}$
vertex	$\sim \gamma^{\mu}$	$X_{tt}^{L,R}$		$\delta V_L \overset{!}{=} \frac{1}{2} X_{tt}^{L}$
	$\sim i\sigma^{\mu\nu} q_{\nu}$	$d^{Z}_{V,\cancel{A}}$	$d^{\gamma}_{V,\cancel{A}}$	$g_R \overset{!}{=} f\left(d^{Z/\gamma}_{V,A}\right)$



~ *exact* QED!

6 real numbers from
2 complex operator
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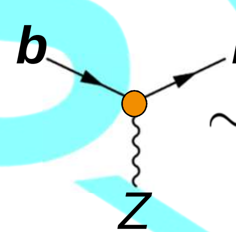
4 real numbers for
$e^+e^- \to tt \to bbW^+W^-$



$\sim X_{bb}^{L} \overset{!}{=} 0$

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Anomalous dim6 top couplings in WHIZARD

> **WHIZARD** implementation:

		gauge boson			
		Z	γ	$W^{\pm}$	g
vertex	$\sim \gamma^{\mu}$	$X_{tt}^{L,R}$	**QED**	$V_{L,R}$	**QCD**
	$\sim i\sigma^{\mu\nu}q_{\nu}$	$d_{V,A}^{Z}$	$d_{V,A}^{\gamma}$	$g_{L,R}$	$d_{V,A}^{g}$

Full package available in

WHIZARD

model including **all** *tbW*, *ttZ*, *ttA*, *ttg* and *ttH* couplings:

`SM_top_anom`

Anomalous dim6 top couplings in WHIZARD

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`SM_top_anom` **normalization**

`norm_conv`

- **> 0:** $g_x \propto \frac{v^2}{\Lambda^2} C_x \sim \frac{1}{(4\pi)^2}$
- **< 0:** $g_x \propto C_x \sim 1$

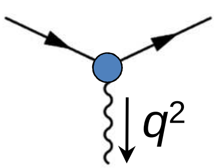
with fundamental operator coefficients C_x

Anomalous dim6 top couplings in WHIZARD

- WHIZARD implementation:

		gauge boson			
		Z	γ	$W^\pm$	g
vertex	$\sim \gamma^\mu$	$X_{tt}^{L,R}$	QED	$V_{L,R}$	QCD
	$\sim i\sigma^{\mu\nu}q_\nu$	$d_{V,A}^{Z}$	$d_{V,A}^{\gamma}$	$g_{L,R}$	$d_{V,A}^{g}$

`SM_top_anom` **form factors**



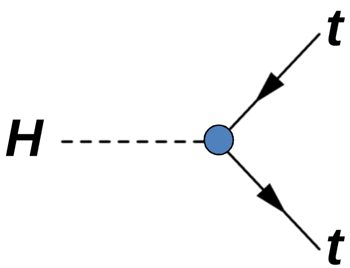
$$\texttt{fun} \begin{cases} \textbf{= 0:} \quad g_x = \text{const}\,(q^2) \\ \textbf{> 0:} \quad g_x\,(q^2) \quad \textbf{e.g.} \quad g_x \propto \dfrac{1}{(1+q^2/\Lambda^2)^2} \end{cases}$$

Anomalous dim6 top couplings in WHIZARD

> WHIZARD implementation:

		gauge boson			
		Z	γ	$W^{\pm}$	g
vertex	$\sim \gamma^{\mu}$	$X_{tt}^{L,R}$	**QED**	$V_{L,R}$	**QCD**
	$\sim i\sigma^{\mu\nu}q_{\nu}$	$d_{V,A}^{Z}$	$d_{V,A}^{\gamma}$	$g_{L,R}$	$d_{V,A}^{g}$

`SM_top_anom` ***ttH* couplings**



$$\mathcal{L}_{ttH} = -\frac{1}{\sqrt{2}}\bar{t}\left(Y_t^V + iY_t^A\gamma_5\right) t\, H$$

Anomalous dim6 top couplings in WHIZARD

> **WHIZARD** implementation:

vertex	gauge boson Z	gauge boson γ	gauge boson $W^{\pm}$
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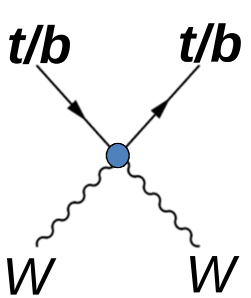
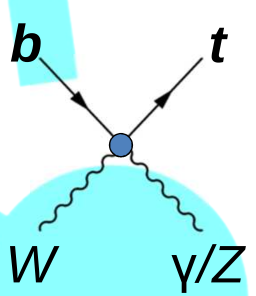


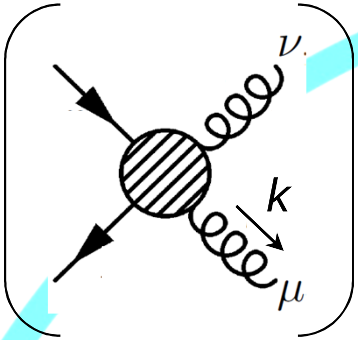
`SM_top_anom` **gauge invariance**

`gauge_inv`
- **> 0:** automatically enforce these relations in a consistent manner (cf. manual/me)
- **< 0:** relations switched off



WHIZARD Validation

- **Ward identities**:

k_μ 

$\stackrel{!}{=}$ **0**

for *ttgg*, *ttWW*, *tbWA*, *tbWZ* amplitudes

WHIZARD Validation

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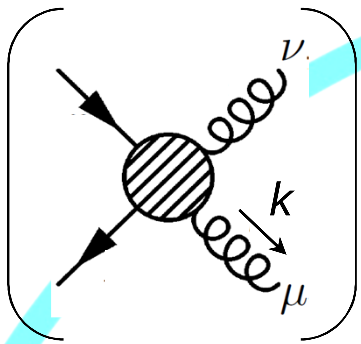
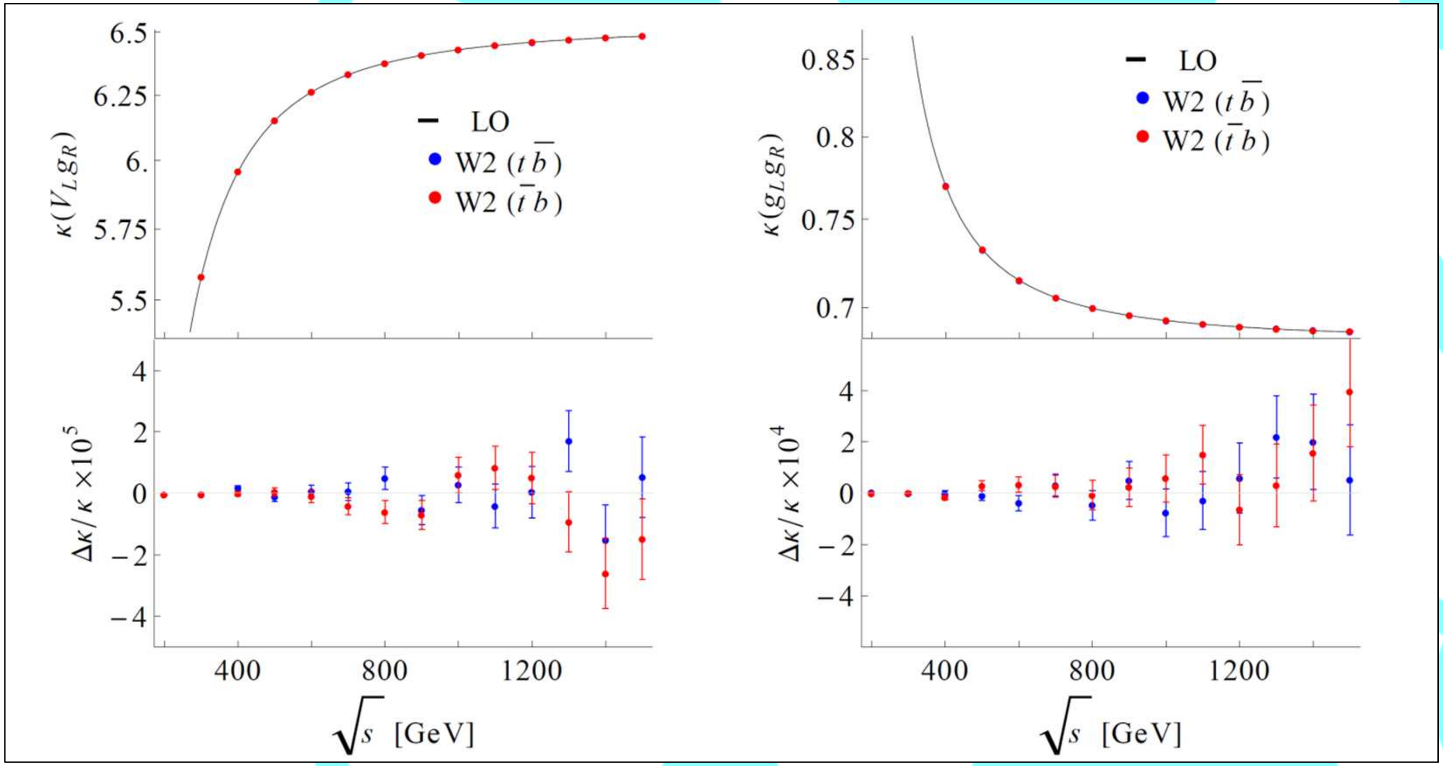
k_μ  $\stackrel{!}{=} 0$ for *ttgg*, *ttWW*, *tbWA*, *tbWZ* amplitudes

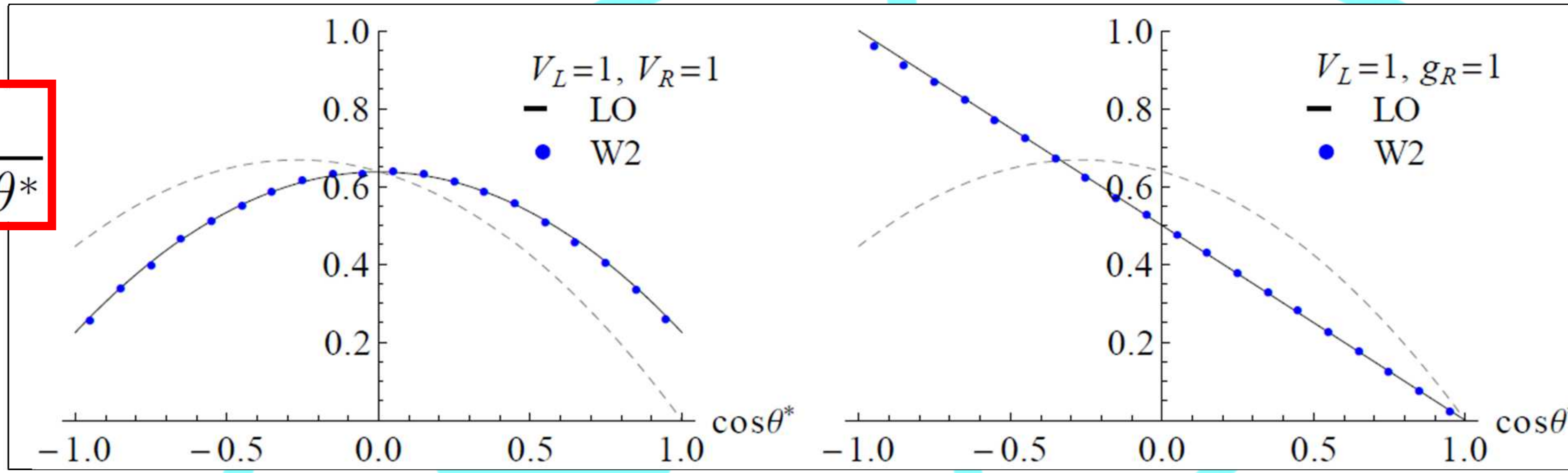
> single top **cross sections** (*s* channel, no pdfs vs. LO analytical):



WHIZARD Validation

> top decay ***W* helicities** vs. LO analytical:

$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*}}$$



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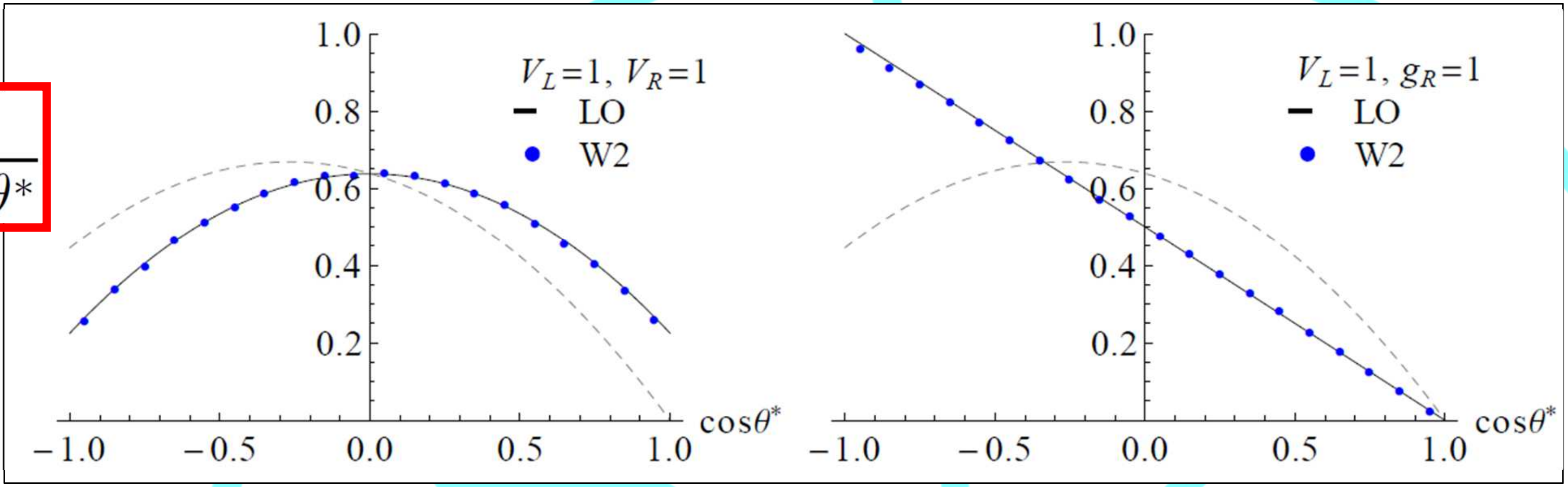


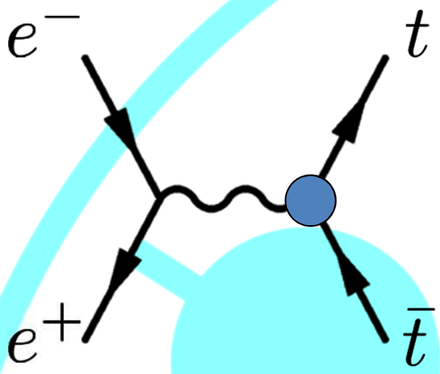
- top **spin analyzers**[Aguilar-Saavedra et al. '06] (vs. LO analytical):

$$\boxed{A_X = \frac{1}{2}\rho_z \alpha_X(\vec{g})}$$

sample				A_ℓ		A_b		A_ν	
V_L	V_R	g_L	g_R	LO	W2	LO	W2	LO	W2
1	0	0	0	0.500	0.500	-0.198	-0.199	-0.167	-0.164
1	1	0	0	0.329	0.326	0.000	0.000	-0.329	-0.327
1	0	1	0	0.502	0.500	-0.324	-0.322	-0.195	-0.194
1	0	0	1	-0.242	-0.232	0.166	0.161	0.055	0.056
0	1	1	0	-0.055	-0.057	-0.166	-0.159	0.242	0.230
0	1	0	1	0.195	0.195	0.324	0.322	-0.502	-0.501
0	0	1	1	0.353	0.355	0.000	0.000	-0.353	-0.354

Observables in top pair production at a Linear Collider

> ttbar **production** neutral-current:



$\sim X_{tt}^{L,R},\ d_V^{Z/\gamma}$

Observables in top pair production at a Linear Collider

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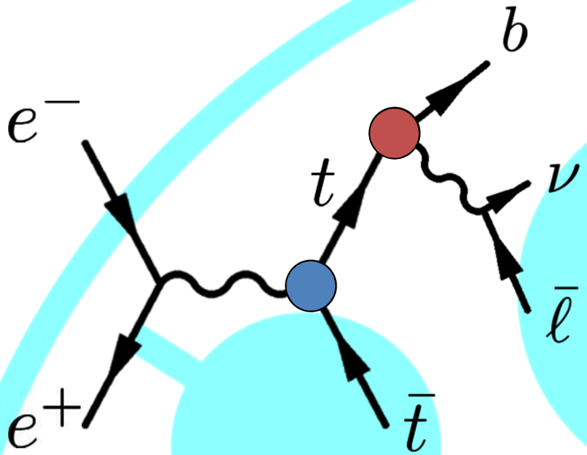

$\sim V_{L,R},\ g_{L,R}$

$\sim X_{tt}^{L,R},\ d_V^{Z/\gamma}$

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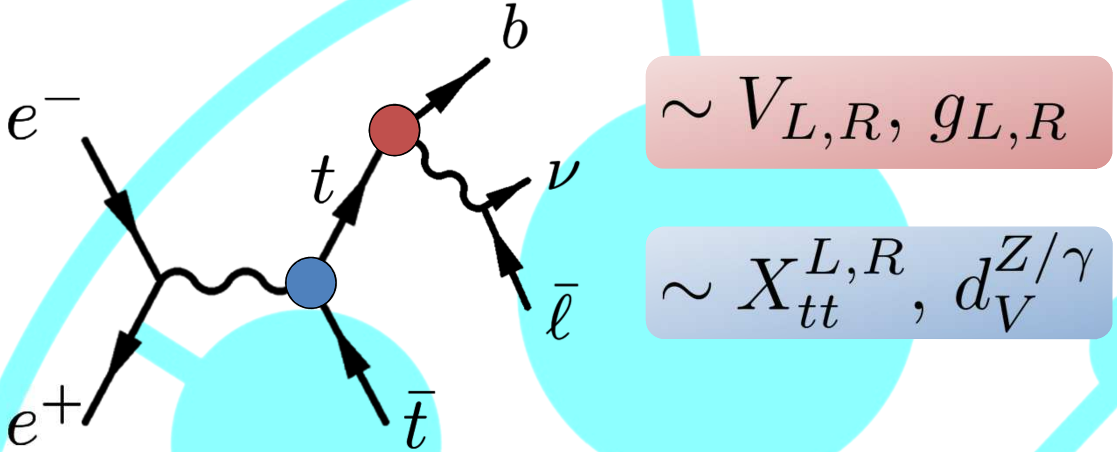

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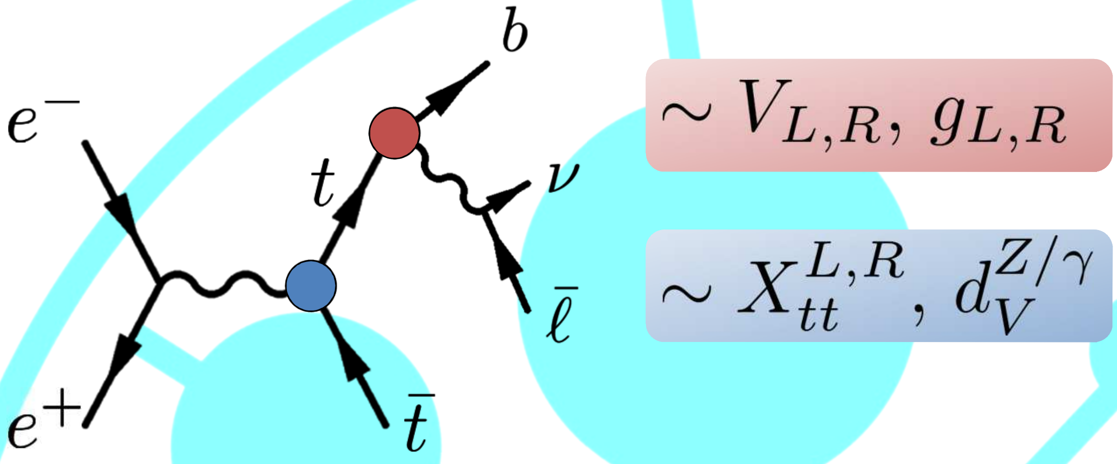

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> **6 observables** considered in [Amjad et al. '13]:

➔ cross section

➔ ttbar asymmetry $A_{t\bar{t}} = \dfrac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$

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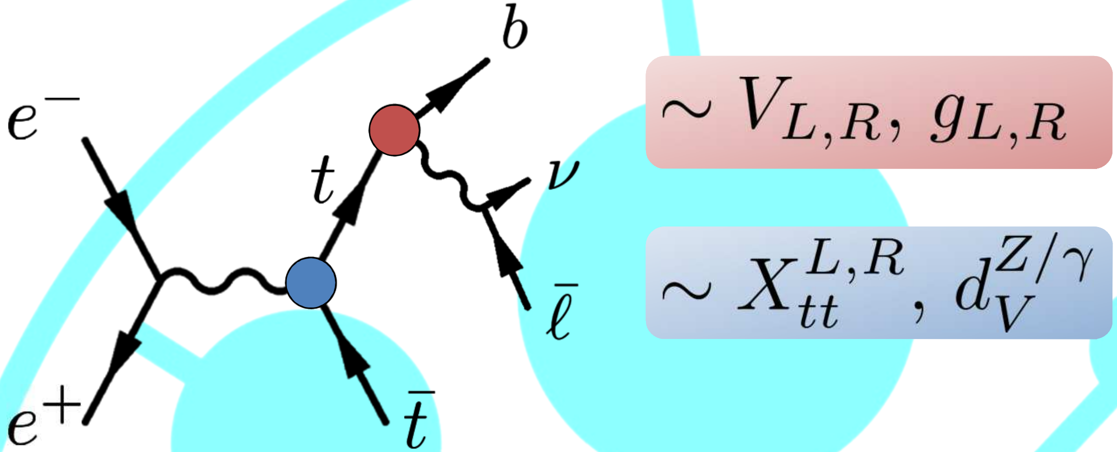

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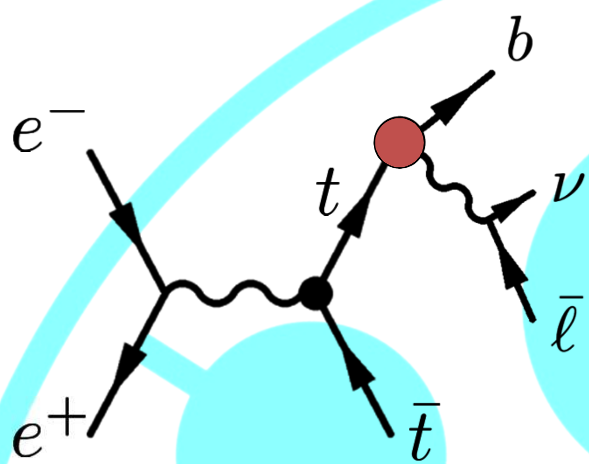
influence of **charged current in decay**?

Observables in top pair production at a Linear Collider

- isolate effect of g_R:



$\sim g_R = \pm 0.5,\ \pm 0.05$

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Influence of the charged current at decay

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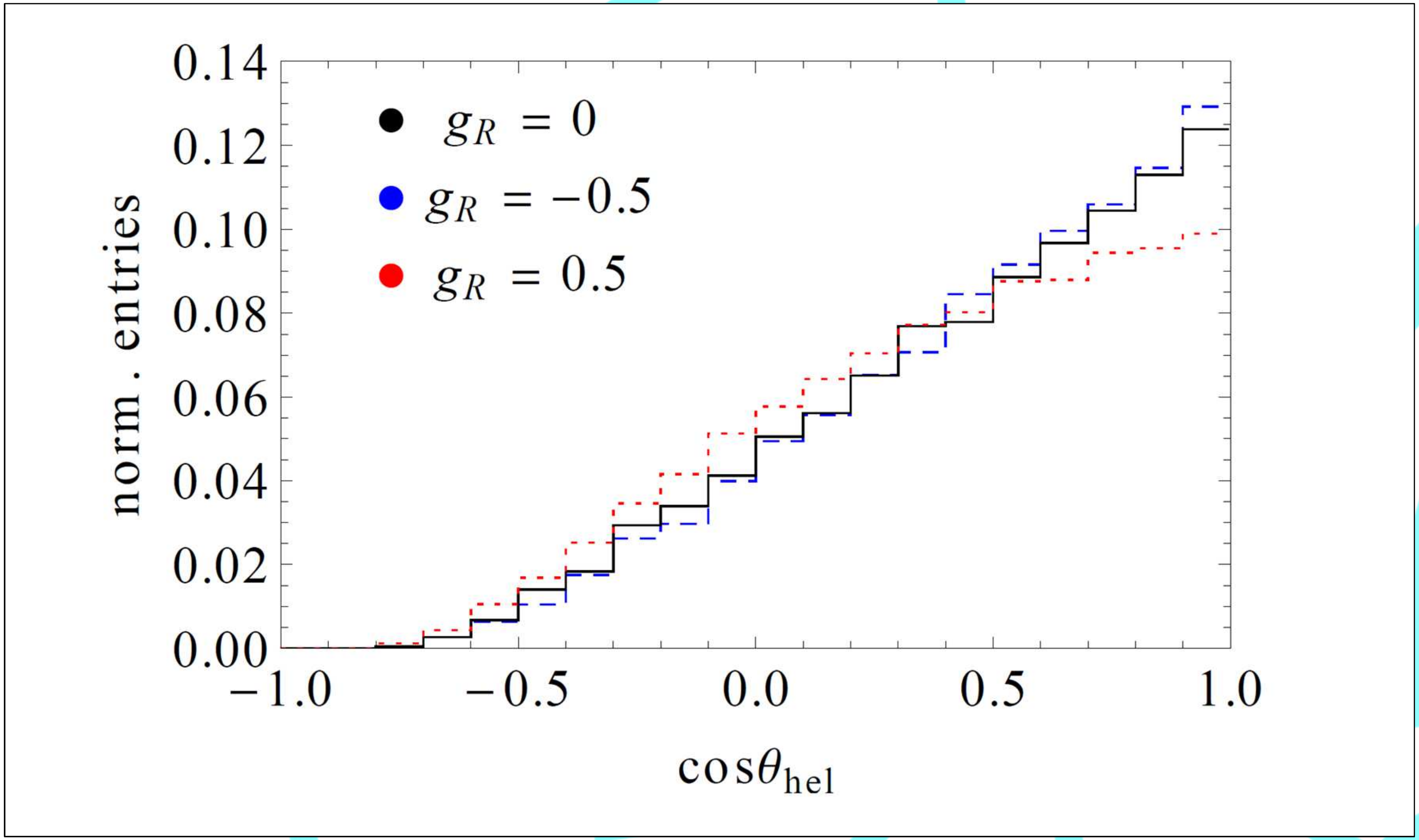

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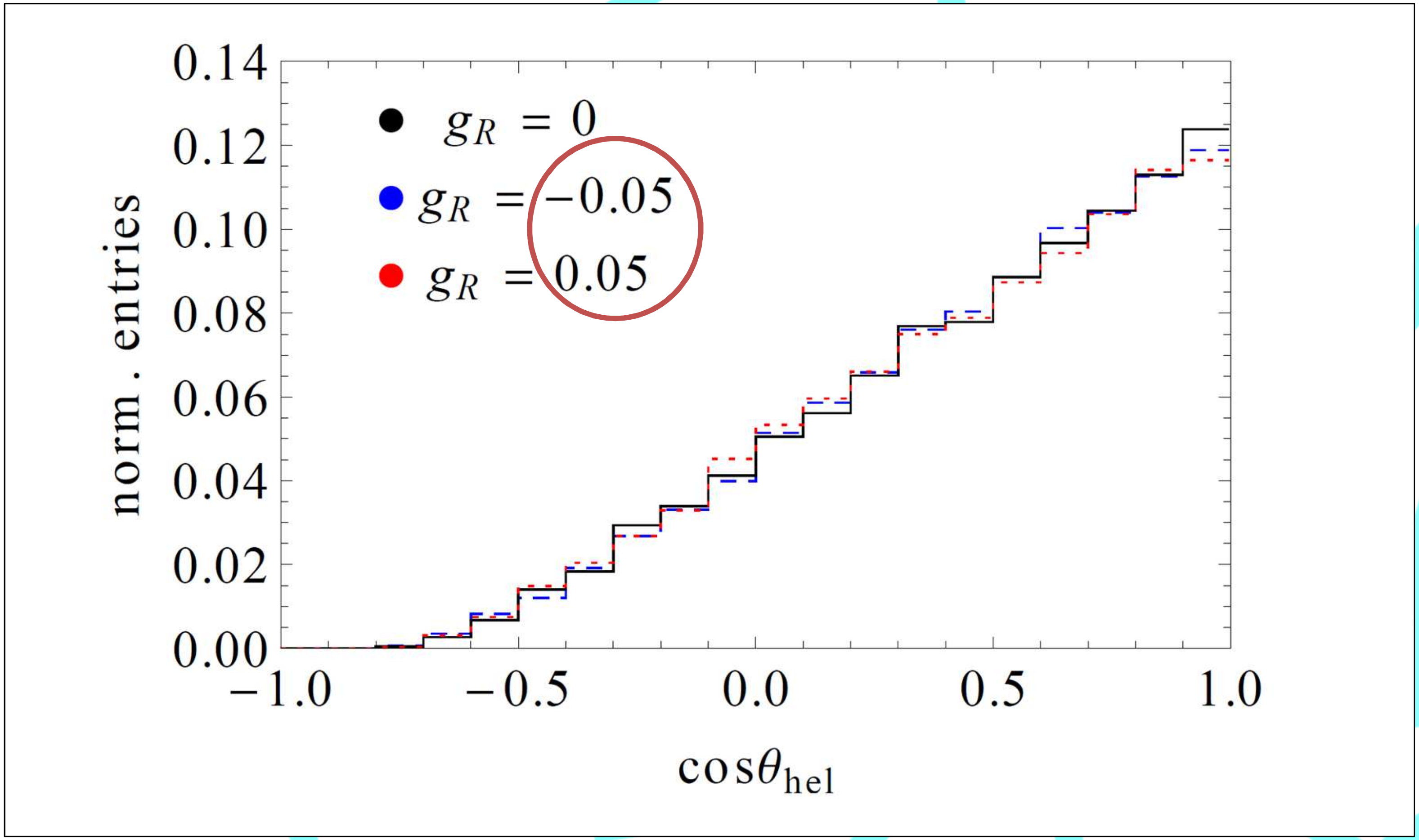

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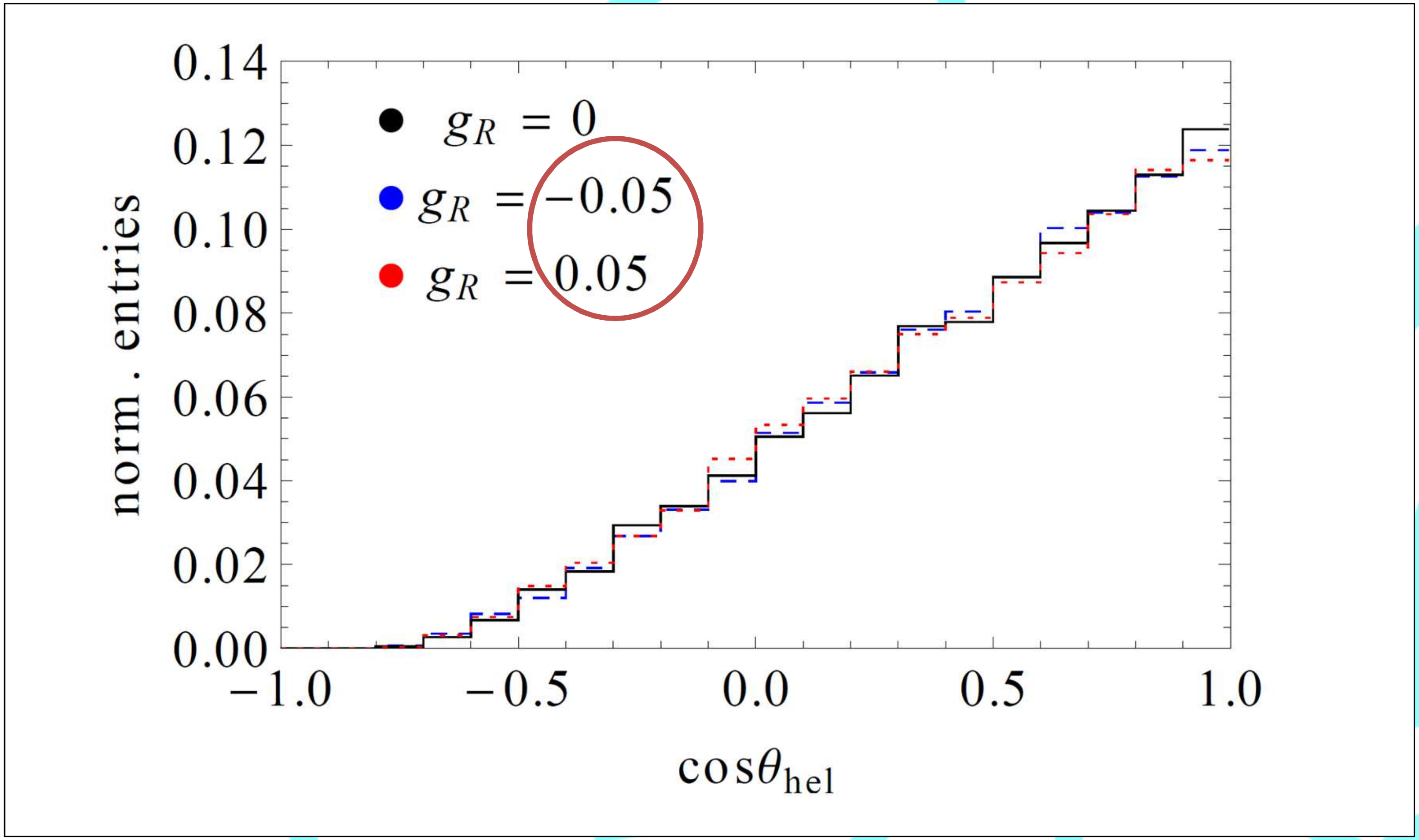

Remaining effect @ g_R = ± 0.05? → closer look…

Influence of the charged current at decay

> asymmetries and selection efficiencies:

g_R	A_{tt} (+-)	A_{tt} (-+)	A_{hel} (+-)	A_{hel} (-+)	eff. (+-)	eff. (-+)
-0.5	0.426(8)	0.183(7)	0.734(6)	0.545(6)	0.145(1)	0.176(1)
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basic p_T and |η| cuts on final state particles

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➔ Dedicated analysis with neutral vs. charged current relations?

Conclusions & outlook

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➔ validated in algebraic identities and various physics processes

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  - → reduced overall number of independent parameters
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- **WHIZARD front**
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  - → validated in algebraic identities and various physics processes
- **dedicated analysis** of neutral/charged current interplay in prod. and decay?

Backup

WHIZARD's anomalous couplings vs. form factors dictionary

$$F_{1V}^{\gamma} = 0 \text{ or } \sim q^2 \qquad F_{2V}^{\gamma} = -2d_V^{\gamma}$$

$$F_{1A}^{\gamma} = 0 \text{ or } \sim q^2 \qquad F_{2A}^{\gamma} = 2d_A^{\gamma}$$

$$F_{1V}^{Z} = -\frac{1}{4s_w c_w}\left(X_{tt}^L + X_{tt}^R - 4s_w^2 Q_t\right) \qquad F_{2V}^{Z} = -\frac{1}{s_w c_w}\frac{m_t}{m_Z}d_V^Z$$

$$F_{1A}^{Z} = \frac{1}{4s_w c_w}\left(X_{tt}^L - X_{tt}^R\right) \qquad F_{2A}^{Z} = \frac{1}{s_w c_w}\frac{m_t}{m_Z}d_A^Z$$