Strong tW scattering at the LHC

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based on work with **Jeff Dror, Marco Farina and Javi Serra,**

1511.xxxxx

New Physics in the top sector

- Top quark has the largest coupling to the Higgs field, y_t

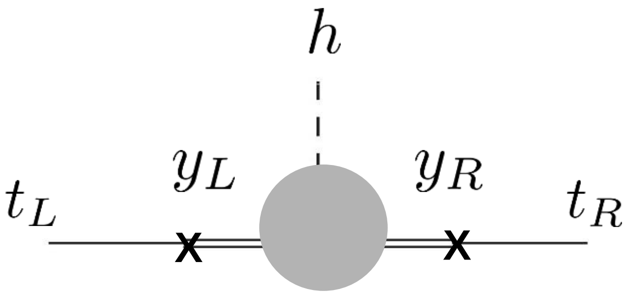
  Its role is prominent in models addressing the naturalness problem.

  Must have partners not too far above the weak scale.

- It is typically important in EWSB: large radiative contributions to Higgs potential

Minimal SUSY $\delta\lambda \sim \frac{3y_t^4}{16\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$

Partial compositeness $\delta\lambda \sim \frac{3y_{L,R}^2}{4\pi^2} \frac{m_T^2}{f^2}$



- Similar to the Higgs, in a natural theory expect top properties to deviate from the SM.

Top electroweak couplings

$$\begin{aligned}\mathcal{L}_t \;=\;& Z_\mu \,\bar{t}\gamma^\mu \left[c_L\, g_L^{\rm SM} P_L + c_R\, g_R^{\rm SM} P_R\right] t \\ &+ Z_\mu \,\bar{b}\gamma^\mu \left[c_L^b\, g_{L,b}^{\rm SM} P_L + c_R^b\, g_{R,b}^{\rm SM} P_R\right] b \\ &+ g_{W t_L b_L} W_\mu^+ \bar{t}\gamma^\mu \left[c_{LL} P_L + c_{RR} P_R\right] b + {\rm h.c.} \\ &- c_t \frac{m_t}{v} h\,\bar{t}t\end{aligned}$$

Current **direct** bounds:

For indirect bounds: Brod, Greljo, Stamou and Uttayarat, 2014; De Blas, Chala and Santiago, 2015

Top electroweak couplings

$$\begin{aligned}\mathcal{L}_t &= Z_\mu\,\bar{t}\gamma^\mu\left[c_L\,g_L^{\rm SM}P_L + c_R\,g_R^{\rm SM}P_R\right]t\\ &\quad + Z_\mu\,\bar{b}\gamma^\mu\left[c_L^b\,g_{L,b}^{\rm SM}P_L + c_R^b\,g_{R,b}^{\rm SM}P_R\right]b\\ &\quad + g_{W t_L b_L}W_\mu^+\bar{t}\gamma^\mu\left[c_{LL}P_L + c_{RR}P_R\right]b + \text{h.c.}\\ &\quad - c_t\frac{m_t}{v}h\,\bar{t}t\end{aligned}$$

Baur, Juste, Orr and Rainwater, 2004;
Berger, Cao and Low, 2009;
Roentsch and Schulze, 2014

Bernardo et al. 2014
Buckley et al. 2015

Current **direct** bounds:

- **LEP, 0.1% and 1%**
- **Single top + *W* helicity fractions, ~ 10%**
- ***ttZ* and *tth* production, worse than 100%**

Precision in *ttZ* limited to ~ 50/100% even at LHC 13 with 300 fb^{-1}

EFT for top couplings

$$Z_\mu \, \bar{t}\gamma^\mu \left[c_L \, g_L^{\rm SM} P_L + c_R \, g_R^{\rm SM} P_R \right] t$$

- If new physics is heavy, leading BSM effects parameterized by dim-6 operators. Those modifying *ttZ* couplings are

$$\bar{c} \lesssim \frac{g_*^2 v^2}{\Lambda^2} = \frac{v^2}{f^2}$$

$$\frac{i\bar{c}_L^{(1)}}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L + \frac{i\bar{c}_L^{(3)}}{v^2} H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu \sigma^a q_L + \frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

- They lead to

$$\delta c_L = \frac{\bar{c}_L^{(3)} - \bar{c}_L^{(1)}}{\left(1 - \frac{4}{3} s_w^2\right)}, \qquad \delta c_R = \frac{\bar{c}_R}{\frac{4}{3} s_w^2}, \qquad \boxed{\delta c_L^b = \frac{\bar{c}_L^{(1)} + \bar{c}_L^{(3)}}{\left(1 - \frac{2}{3} s_w^2\right)},} \qquad \delta c_{LL} = \bar{c}_L^{(3)}$$

LEP

$$\bar{c}_L^{(1)} + \bar{c}_L^{(3)} \simeq 0$$

Giudice, Grojean, Pomarol and Rattazzi, 2007
Pomarol and Serra, 2008

EFT for top couplings

$$Z_\mu \, \bar{t}\gamma^\mu \left[c_L \, g_L^{\rm SM} P_L + c_R \, g_R^{\rm SM} P_R\right] t$$

- If new physics is heavy, leading BSM effects parameterized by dim-6 operators. Those modifying *ttZ* couplings are

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$$\frac{i\bar{c}_L^{(1)}}{v^2} H^\dagger \overleftrightarrow{D_\mu} H \bar{q}_L \gamma^\mu q_L + \frac{i(-\bar{c}_L^{(1)})}{v^2} H^\dagger \sigma^a \overleftrightarrow{D_\mu} H \bar{q}_L \gamma^\mu \sigma^a q_L + \frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D_\mu} H \bar{t}_R \gamma^\mu t_R$$

- They lead to

$$\delta c_L = \frac{-2\,\bar{c}_L^{(1)}}{\left(1 - \frac{4}{3} s_w^2\right)}\,, \qquad \delta c_R = \frac{\bar{c}_R}{\frac{4}{3} s_w^2}\,, \qquad \delta c_L^b = 0\,, \qquad \delta c_{LL} = -\bar{c}_L^{(1)}$$

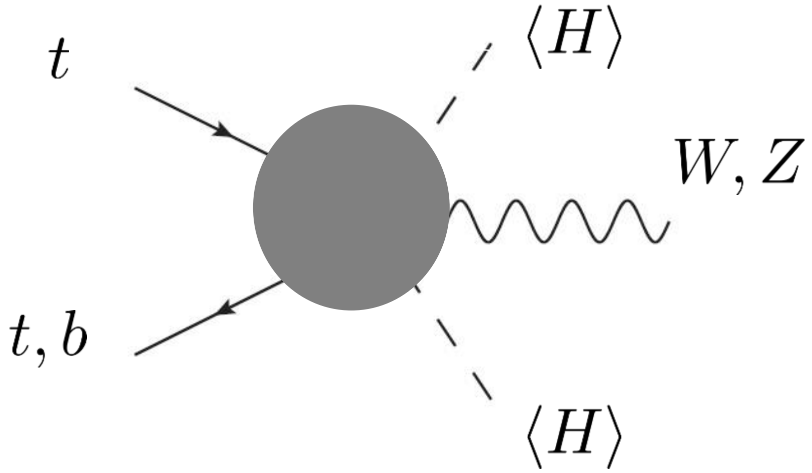
- Can be enforced by custodial parity.

Agashe, Contino, Da Rold and Pomarol, 2006

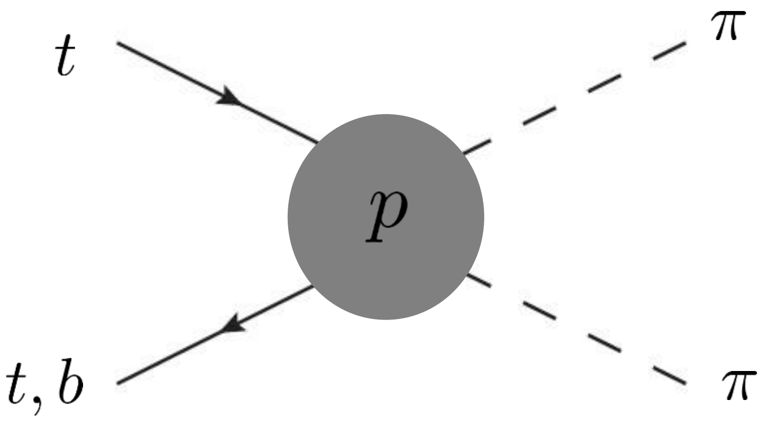
Probing top interactions

$$\frac{i\bar{c}_L^{(1)}}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L + \frac{i(-\bar{c}_L^{(1)})}{v^2} H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu \sigma^a q_L + \frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

- At low energies, they give rise to coupling modifications



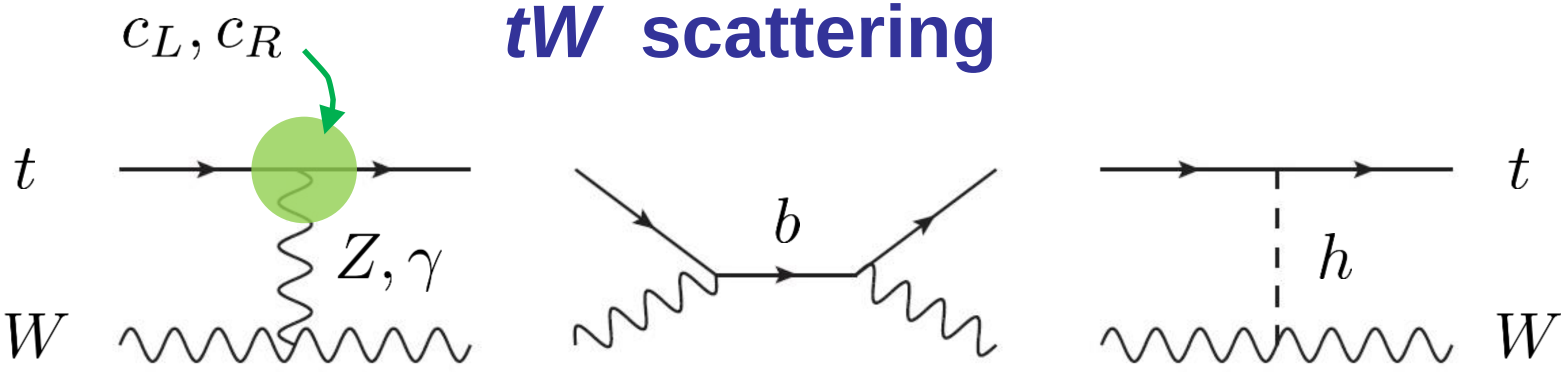
- **At high energies, 2 → 2 amplitudes that grow like energy (squared)**



- Analogy with *WW* scattering

Chanowitz and Gaillard, 1985
Contino, Grojean, Moretti, Piccinini and Rattazzi, 2010

tW scattering



$$\begin{pmatrix}\mathcal{M}_{LL} & \mathcal{M}_{RL}\\ \mathcal{M}_{LR} & \mathcal{M}_{RR}\end{pmatrix} = \frac{2}{v^2}\begin{pmatrix} e^{i\varphi}\sqrt{\hat{s}(\hat{s}+\hat{t})}\,\underline{A_{LL}} & m_t\sqrt{-\hat{t}}\,A_{RL}\\ -e^{i\varphi}m_t\sqrt{-\hat{t}}\,A_{LR} & \sqrt{\hat{s}(\hat{s}+\hat{t})}\,\underline{A_{RR}}\end{pmatrix} + \dots$$

- Coefficients of amplitudes that grow with energy:

***Ztt* couplings,**

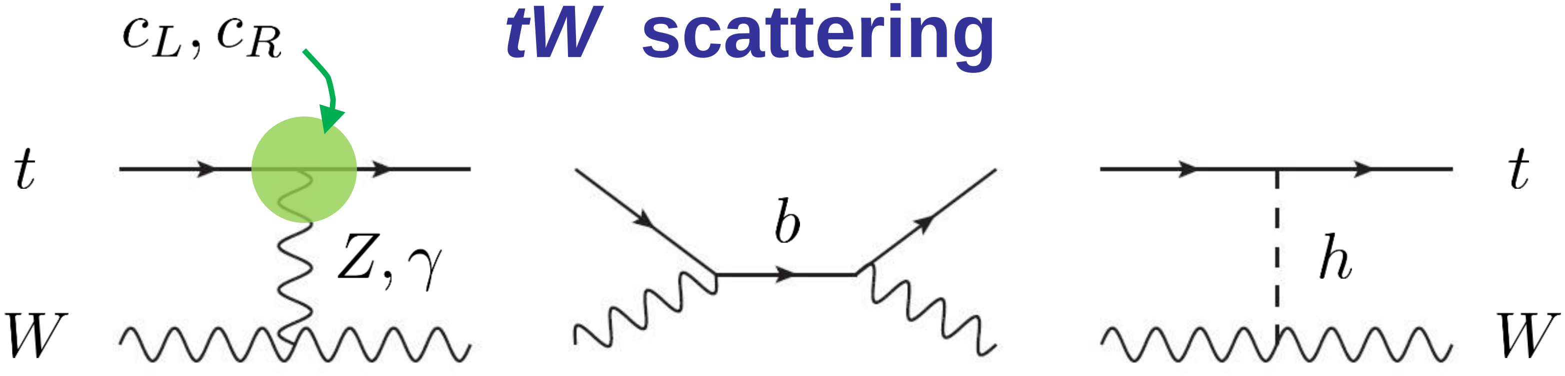
grow like

$\hat{\mathbf{s}}/\mathbf{v^2}$

$$\left\{\begin{aligned} A_{LL} &= -c_{LL}^2 + c_L - \tfrac{4}{3}s_w^2(c_L-1)\,,\\ A_{RR} &= -c_{RR}^2 - \tfrac{4}{3}s_w^2(c_R-1)\,,\end{aligned}\right.$$

$$A_{LR} = A_{RL} = \frac{1}{2}\left[(c_L - c_t c_V) - \frac{4}{3}s_w^2(c_L+c_R-2)\right]$$

tW scattering



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- Coefficients of amplitudes that grow with energy:

Ztt **couplings,**

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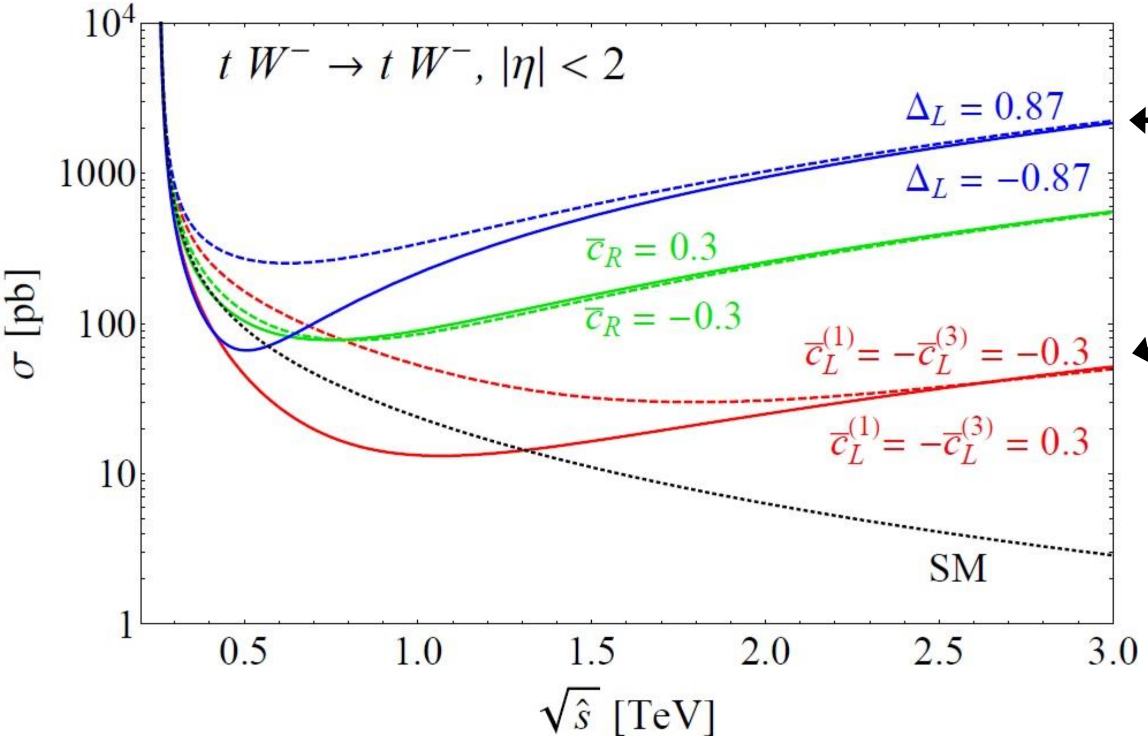
$$\left.\begin{aligned} A_{LL} &= -c_{LL}^2 + c_L - \tfrac{4}{3}s_w^2(c_L - 1)\,, \\ A_{RR} &= -c_{RR}^2 - \tfrac{4}{3}s_w^2(c_R - 1)\,, \end{aligned}\right.$$

$$A_{LR} = A_{RL} = \frac{1}{2}\left[(c_L - c_t c_V) - \frac{4}{3}s_w^2(c_L + c_R - 2)\right]$$

Higgs couplings, grow like $m_t\sqrt{\hat{s}}/v^2$

Appelquist and Chanowitz, 1987

Partonic cross section



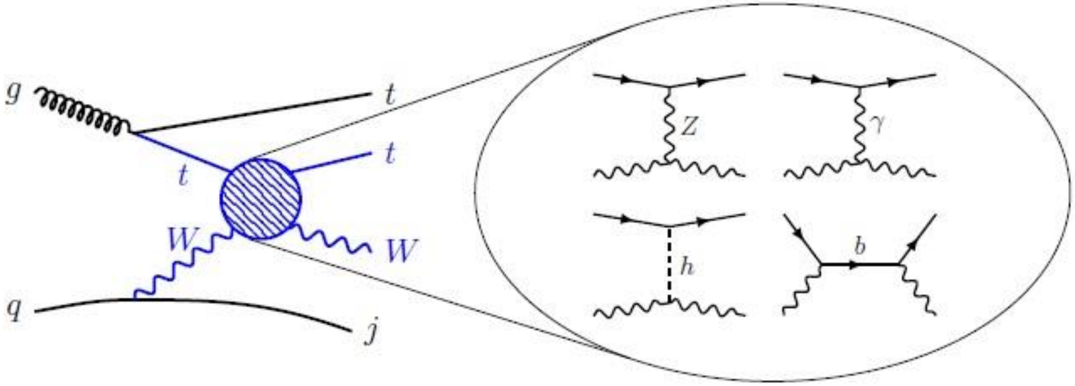
difference
due to *Wtb*
correction

$$Z_\mu \bar t\gamma^\mu\left[(1+\Delta_L)\,g_L^{\rm SM}P_L+(1+\Delta_R)\,g_R^{\rm SM}P_R\right]t$$

equivalent

$$\frac{i\bar c_L^{(1)}}{v^2}H^\dagger \overleftrightarrow{D}_\mu H\bar q_L\gamma^\mu q_L+\frac{i\bar c_L^{(3)}}{v^2}H^\dagger\sigma^a\overleftrightarrow{D}_\mu H\bar q_L\gamma^\mu\sigma^a q_L+\frac{i\bar c_R}{v^2}H^\dagger\overleftrightarrow{D}_\mu H\bar t_R\gamma^\mu t_R$$

tW scattering at the LHC



- Hadronic process is $pp \to t\bar{t}W + j$

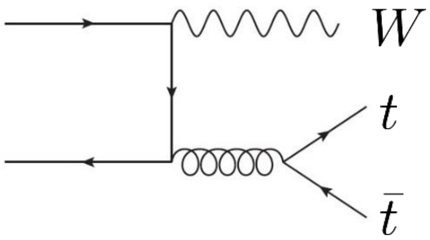
➡ picked up by $t\bar{t}W$ searches in same-sign leptons

- CMS cut-and-count search easy to recast.

CMS, 1406.7830

Our signal is at $O(g_s g_w^3)$, instead CMS only considered

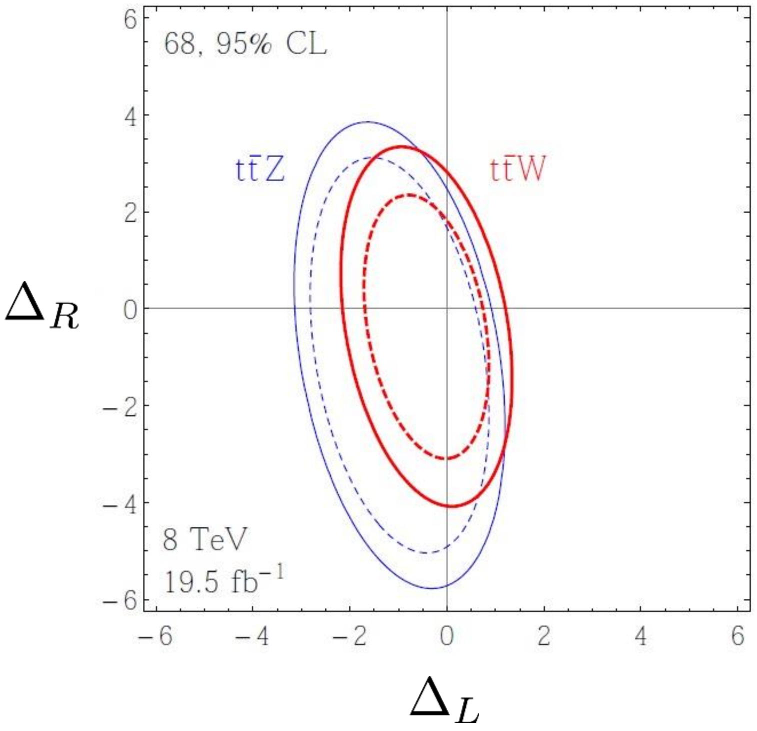
$O(g_s^2 g_w)$

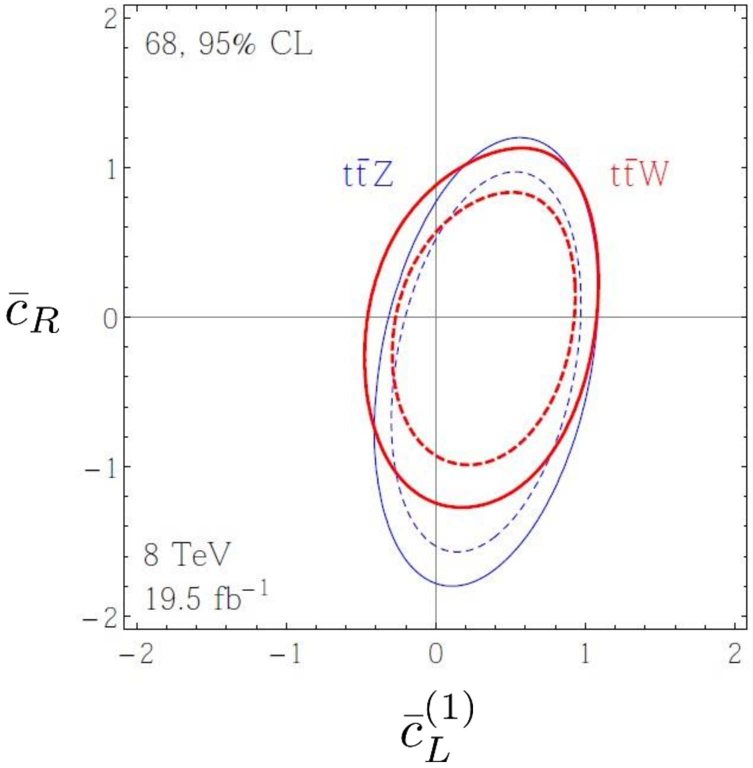


+ jets

this is our main background

8 TeV bounds



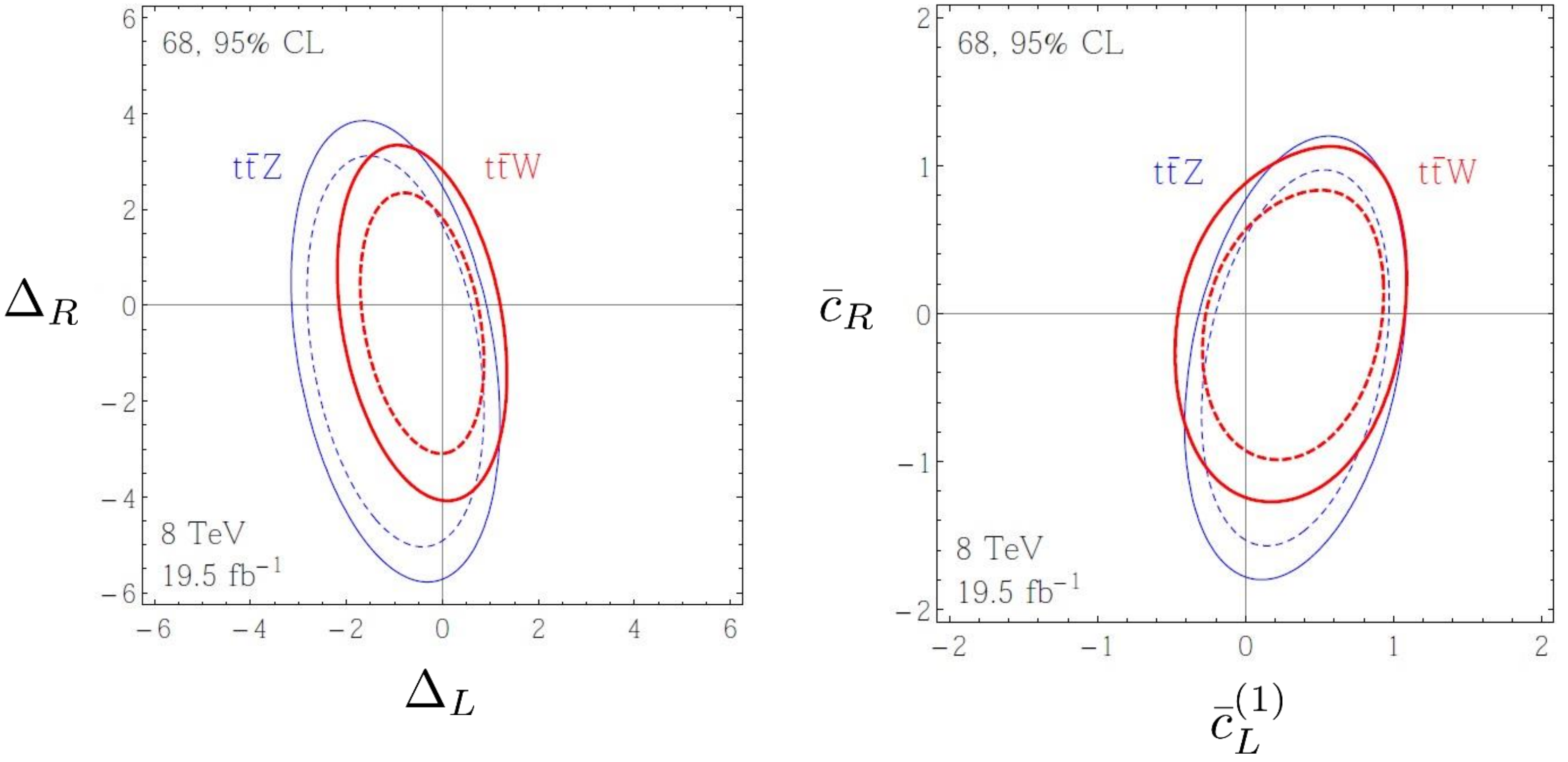


- Simulate $t\bar{t}Wj$ signal in same-sign leptons → **red**

- Compare to $t\bar{t}Z$ in trileptons → **blue**

Better than the conventional strategy, without any optimization!

8 TeV bounds

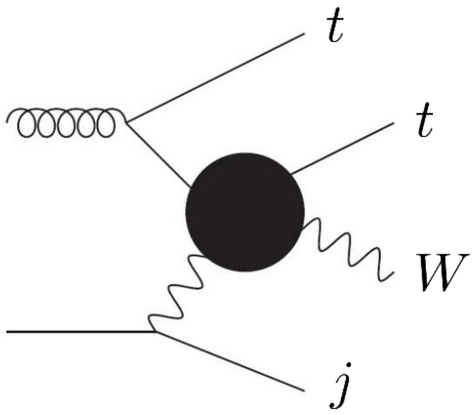


- Simulate $t\bar{t}Wj$ signal in same-sign leptons → **red**

$$-3.6 < \Delta_R < 2.4 \qquad (95\%\ \mathrm{CL})$$

Better than the conventional strategy, without any optimization!

13 TeV dedicated analysis

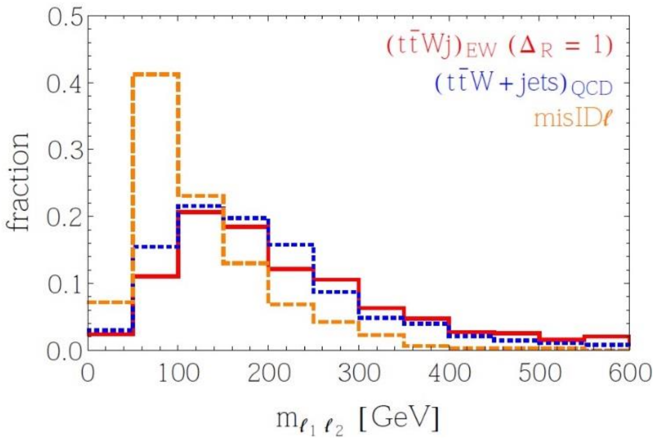


Main backgrounds (validated at 8 TeV):

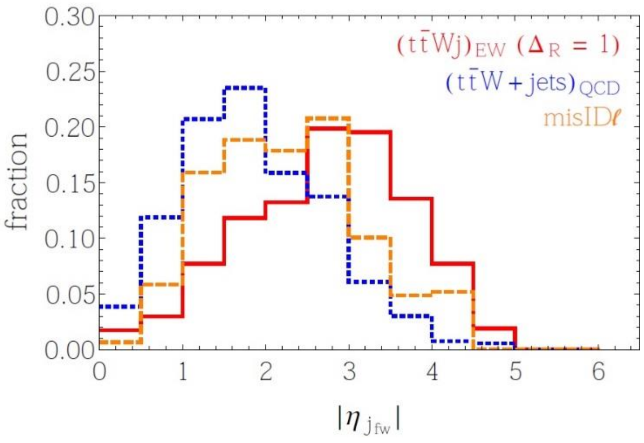
- $(t\bar{t}W+\text{jets})_{\text{QCD}}$
- ‘Mis-identified’ leptons from $t\bar{t}+\text{jets}$

Exploit signal features:

tW system with large invariant mass



forward jet



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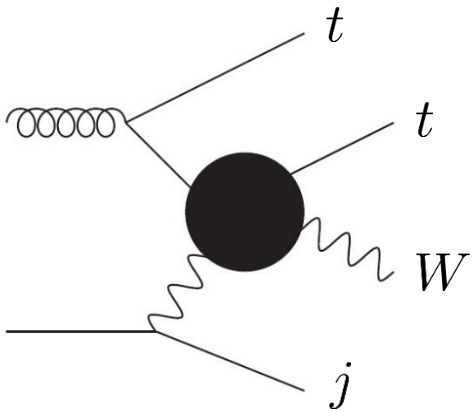
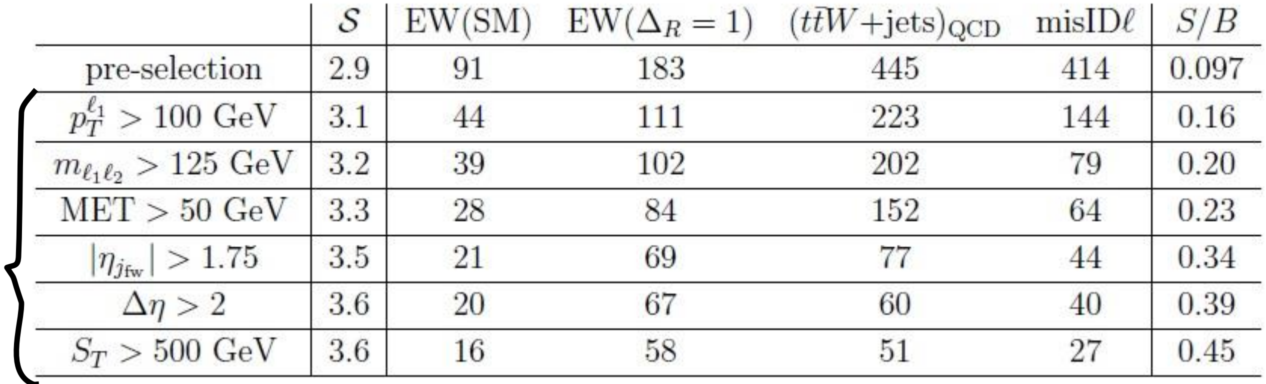


Exploit signal features:

tW system with large invariant mass

forward jet

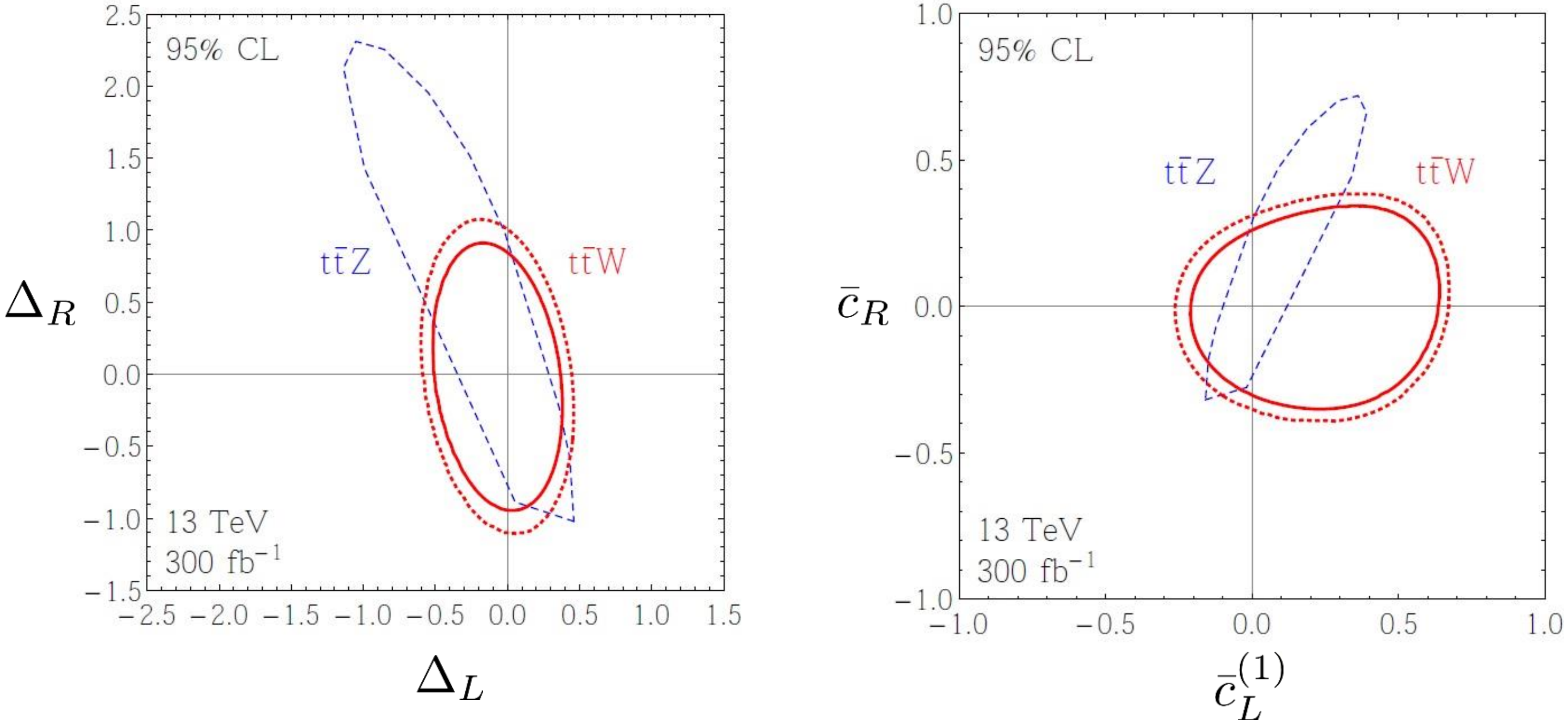
optimized cuts



	$\mathcal{S}$	EW(SM)	EW($\Delta_R = 1$)	$(t\bar{t}W+\text{jets})_{\text{QCD}}$	misIDℓ	S/B
pre-selection	2.9	91	183	445	414	0.097
$p_T^{\ell_1} > 100$ GeV	3.1	44	111	223	144	0.16
$m_{\ell_1\ell_2} > 125$ GeV	3.2	39	102	202	79	0.20
MET > 50 GeV	3.3	28	84	152	64	0.23
$\lvert\eta_{j_{\text{fw}}}\rvert > 1.75$	3.5	21	69	77	44	0.34
$\Delta\eta > 2$	3.6	20	67	60	40	0.39
$S_T > 500$ GeV	3.6	16	58	51	27	0.45

Table 5: Cut-flow for the $4j$ optimization at 13 TeV. EW stands for $(t\bar{t}Wj)_{\text{EW}}$.

13 TeV bounds



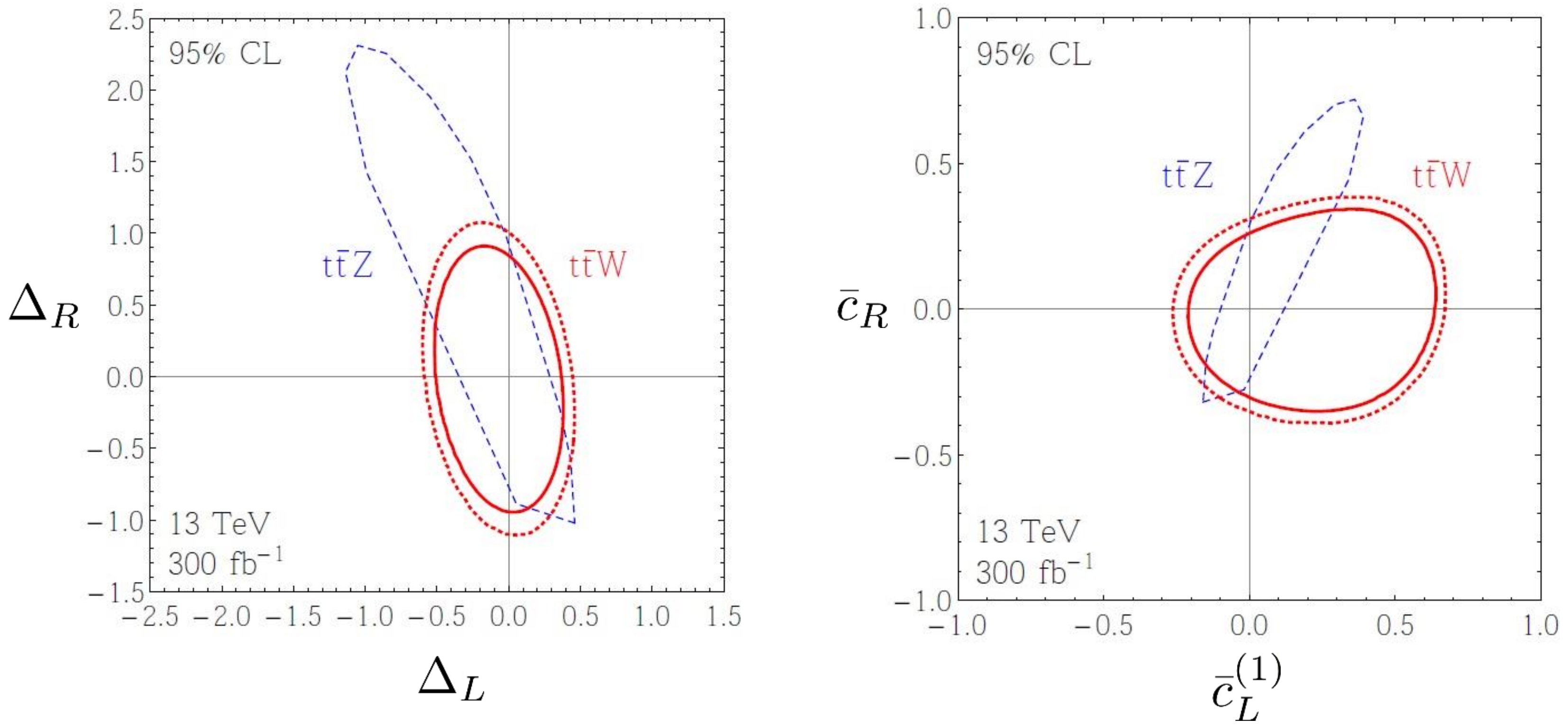
$$-0.98 < \Delta_R < 0.88$$

$$-0.30 < \bar{c}_R < 0.28$$

50% syst. unc. on misID-lepton bkg.

- $t\bar{t}Z$ projection taken from **Roentsch and Schulze, 1404.1005** (NLO, signal only)

13 TeV bounds



$$-0.98 < \Delta_R < 0.88$$

$$-0.30 < \bar{c}_R < 0.28$$

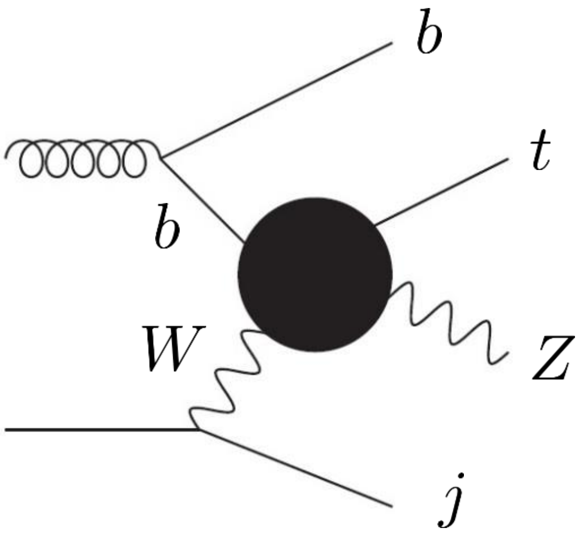
50% syst. unc. on misID-lepton bkg.

$t\bar{t}W$ production as sensitive as $t\bar{t}Z$ (or more!) to top-Z couplings

Other applications/1

- $bW \rightarrow tZ$?

probed in tZj , large cross section



Campbell, Ellis and Roentsch, 2013
Roentsch and Schulze, 2014

Other applications/1

- $bW \to tZ$?

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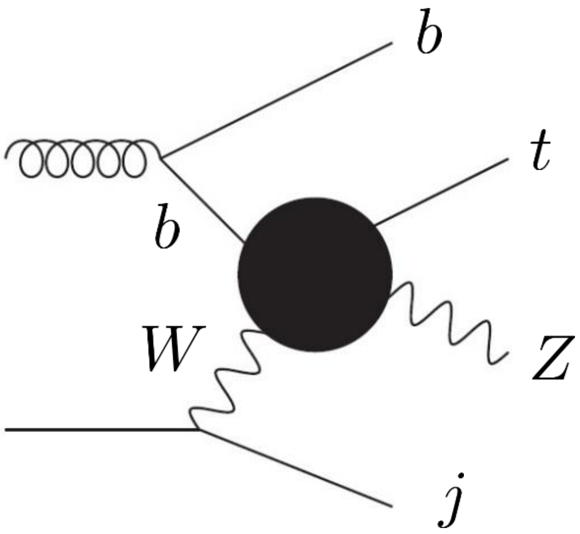
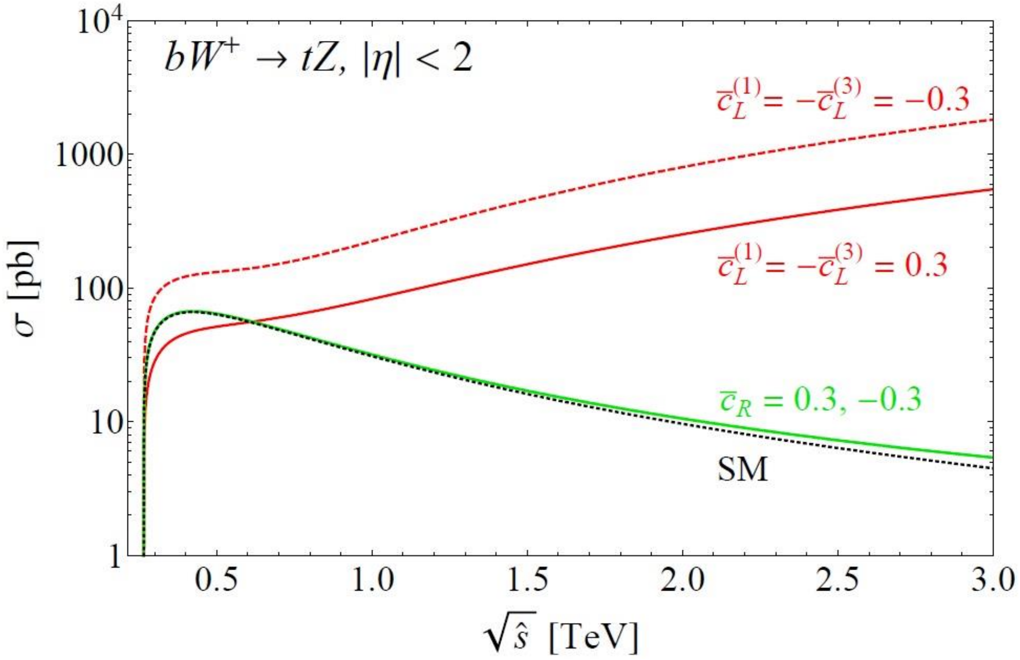


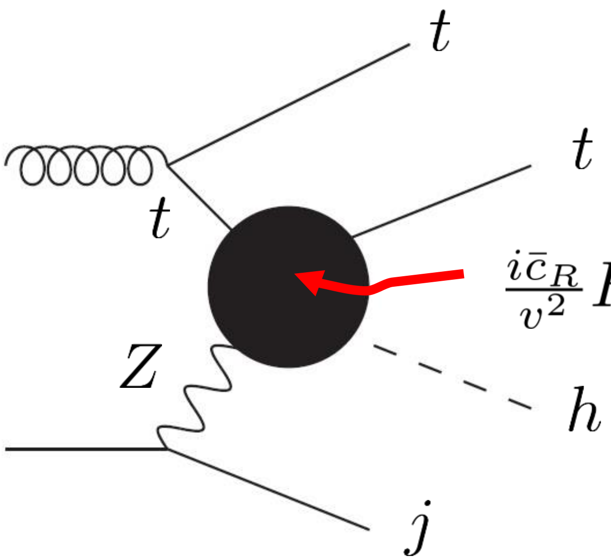


however, **no** sensitivity to Zt_Rt_R

Other applications/2

- $tZ \to th$?

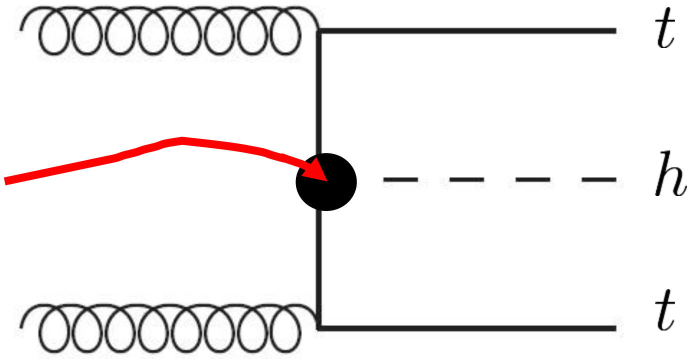
probed in $t\bar{t}hj$



$$\frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

Interplay with

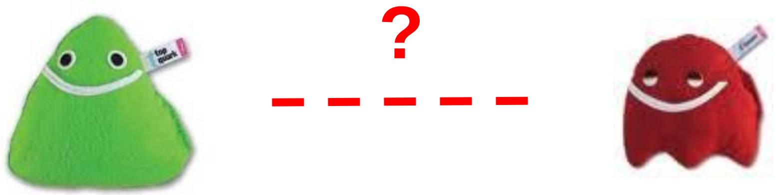
$$\frac{\bar{c}_u y_t}{v^2} H^\dagger H \bar{q}_L \tilde{H} t_R + \text{h.c.}$$

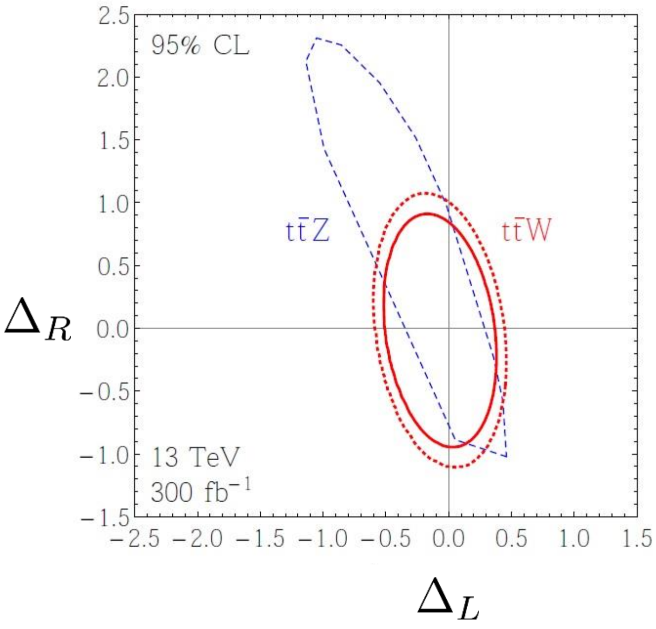


Summary

- High energy scattering of *t* and *W*, *Z*, *h* is a different approach to test top EW couplings.
  Analogy to *WW* scattering.

- $tW \to tW$ gives the **best bounds** on *Ztt* couplings

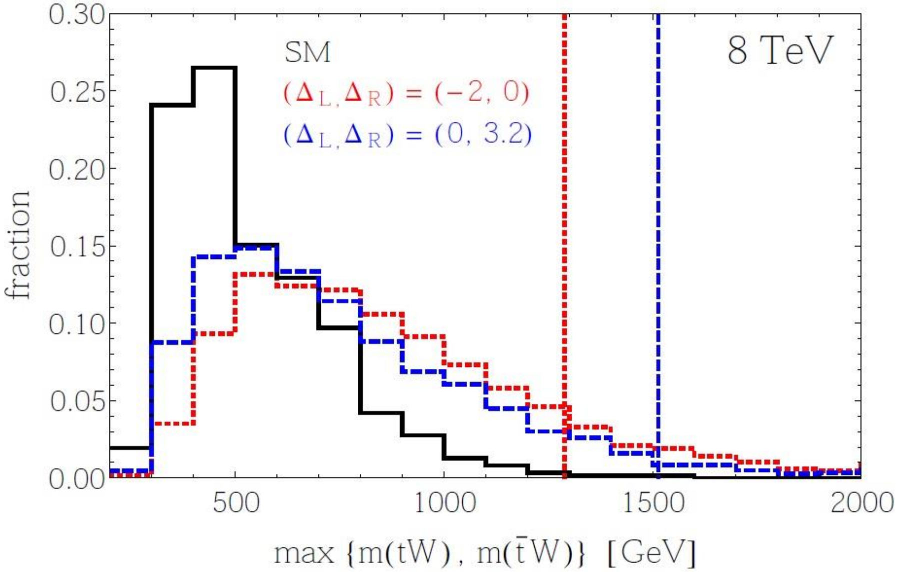


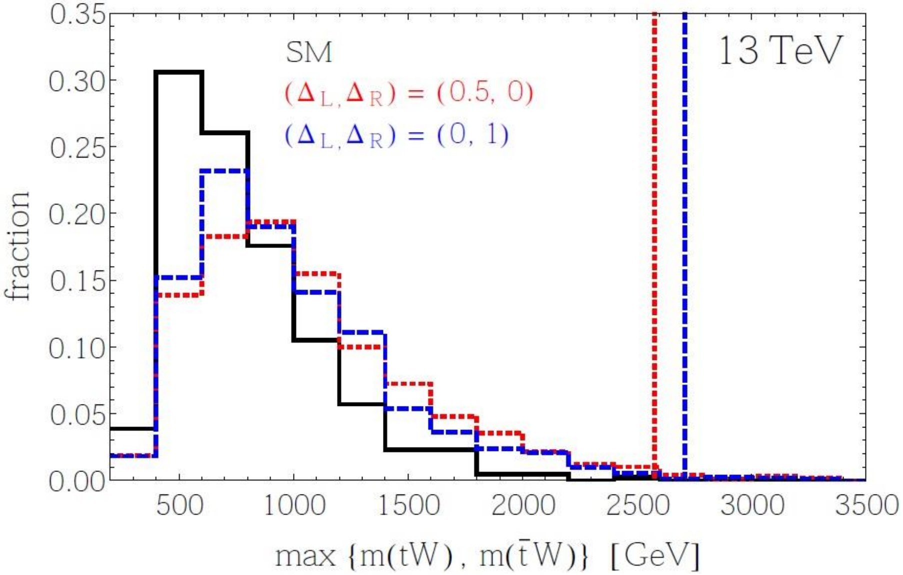


- Several other processes are worth exploring.
  Ex. $tZ \to th$: combined test of Zt_Rt_R and *htt*
  …

Backup

Perturbative unitarity

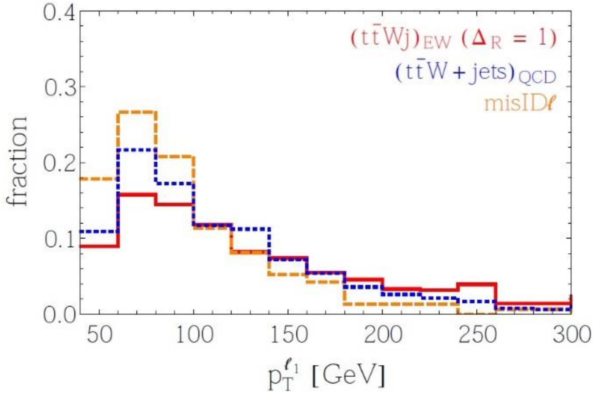


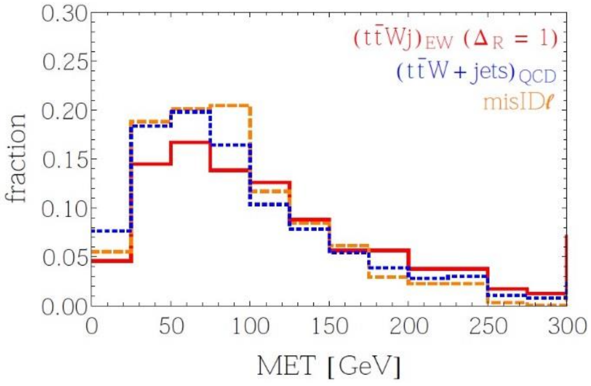


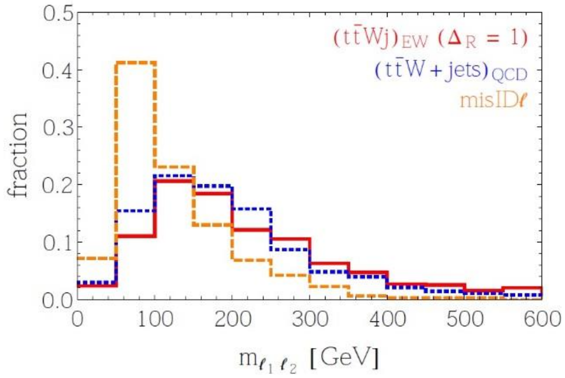
$$a_0 = \frac{1}{16\pi s} \int_{-s}^{0} dt \mathcal{M} \,, \qquad |a_0| < 1$$

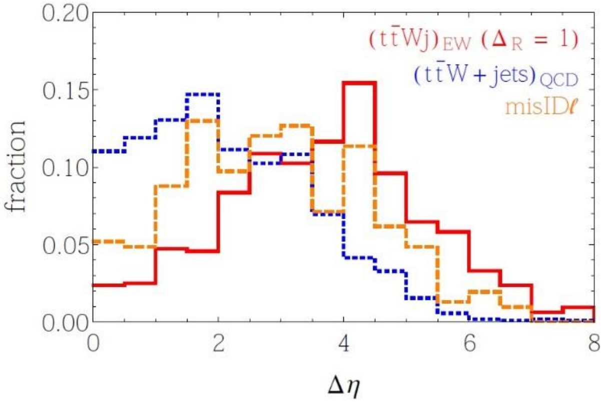
$$\Lambda = \frac{2\sqrt{3\pi}\, v}{\sqrt{1 - \frac{4}{3} s_w^2}\, \sqrt{|\Delta_L|}} \qquad\qquad \Lambda = \frac{3\sqrt{\pi}\, v}{s_w \sqrt{|\Delta_R|}}$$

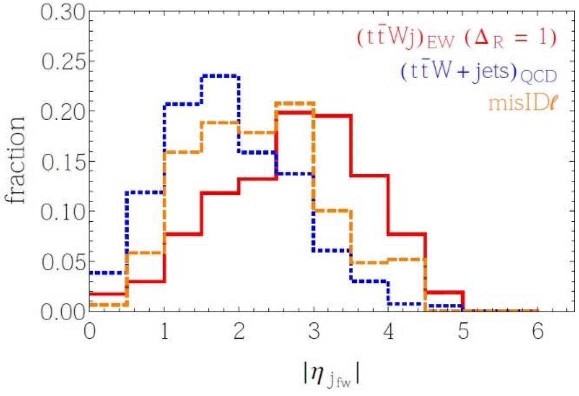
13 TeV analysis, 4*j*

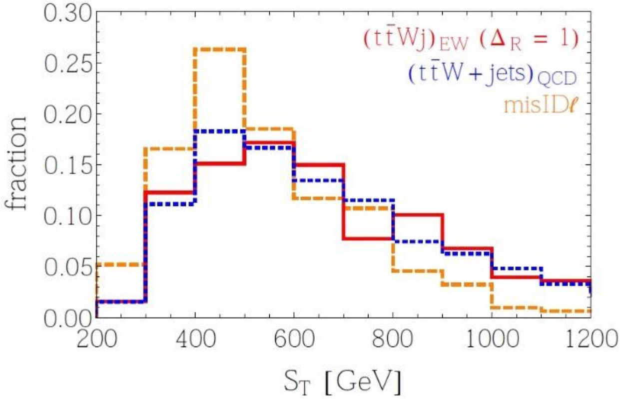












13 TeV analysis, 3*j*

- Forward jet tagging performance at high pileup is not trivial.

  Do also 'conservative' analysis with only central jets (same pre-selection as 8 TeV). **Very robust**