Exploring the top quark electroweak interactions

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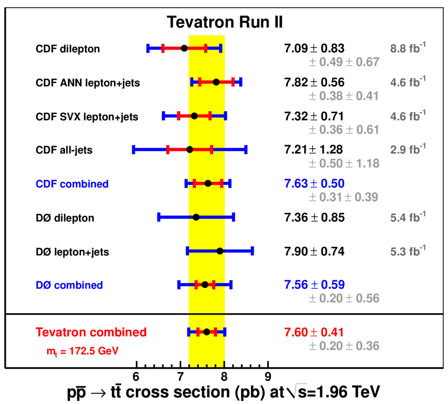
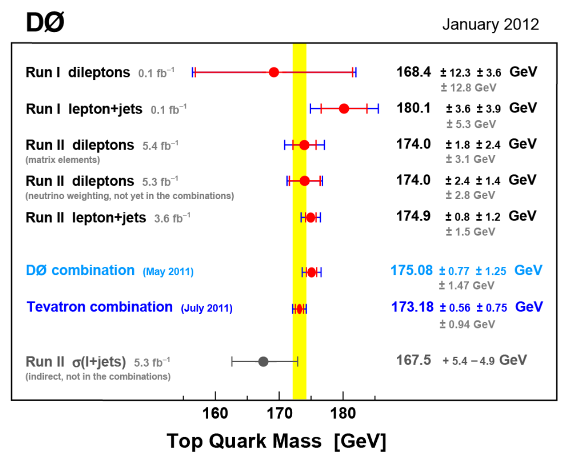
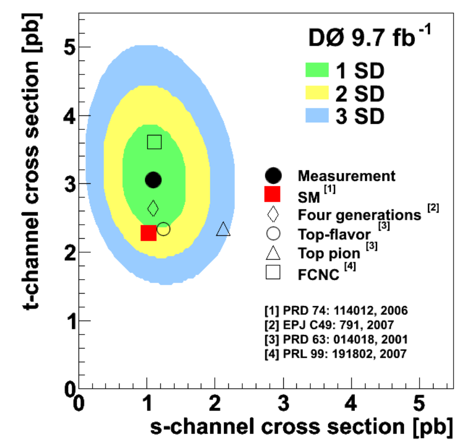
A.Gritsan, M.Xiao (CMS)

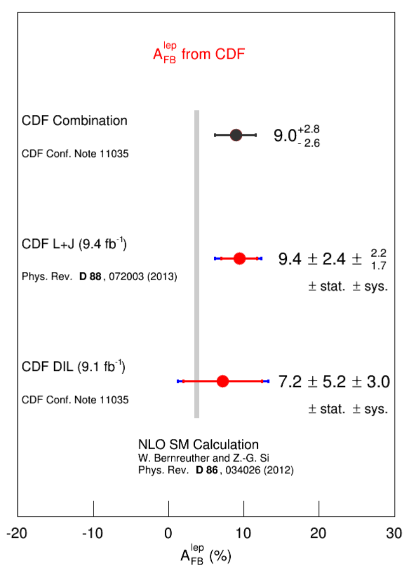
The Tevatron Legacy

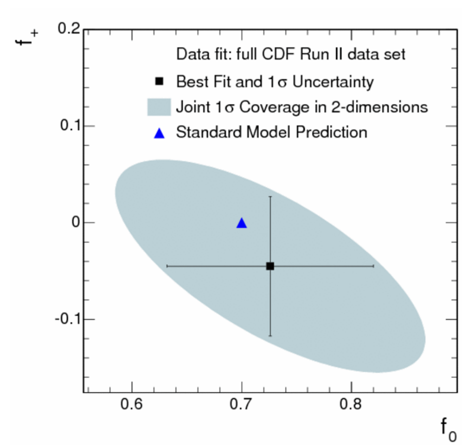
- Our understanding of the top quark as an elementary particle and its dynamics in QCD is very solid.
- Many of its properties were established at the Tevatron.

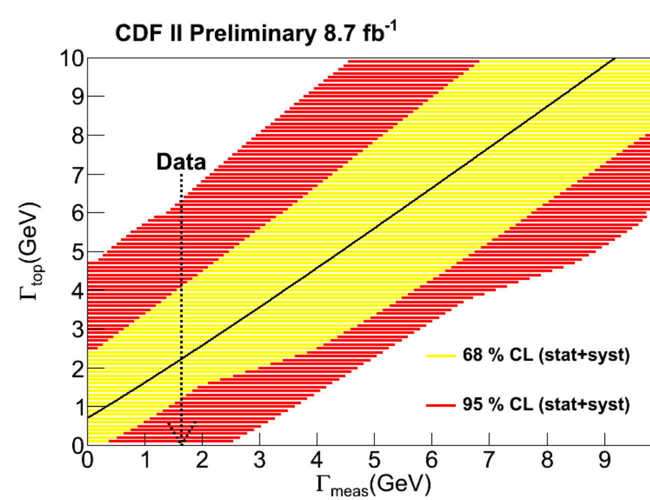








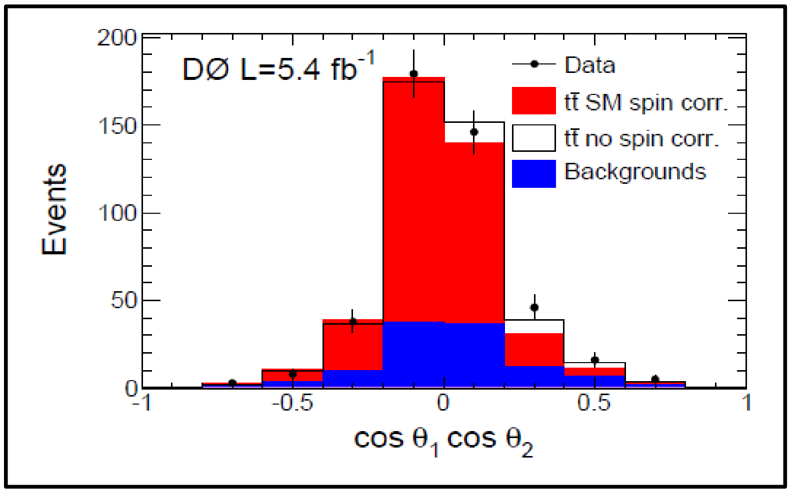


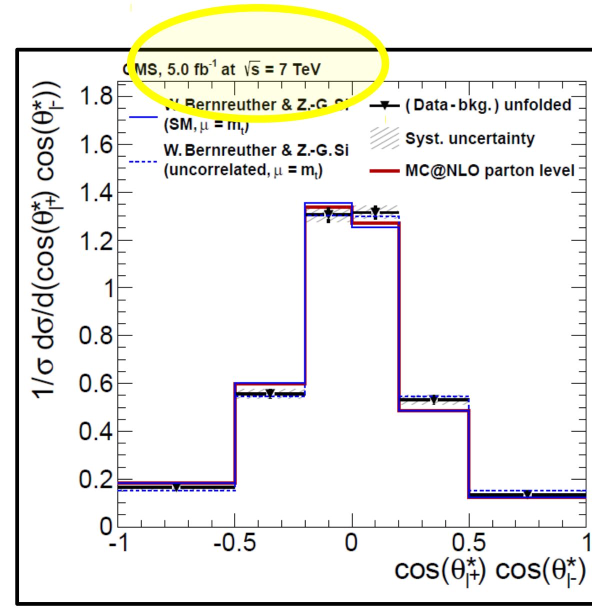


Early days of LHC experiments

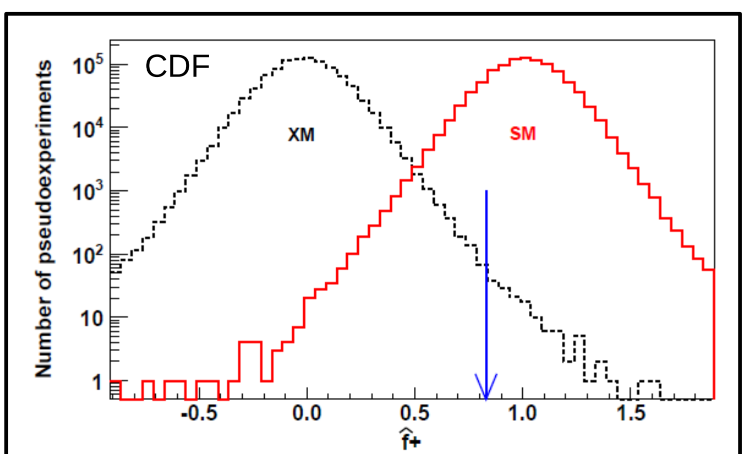
- Results were confirmed and superseded by LHC experiments at impressive pace

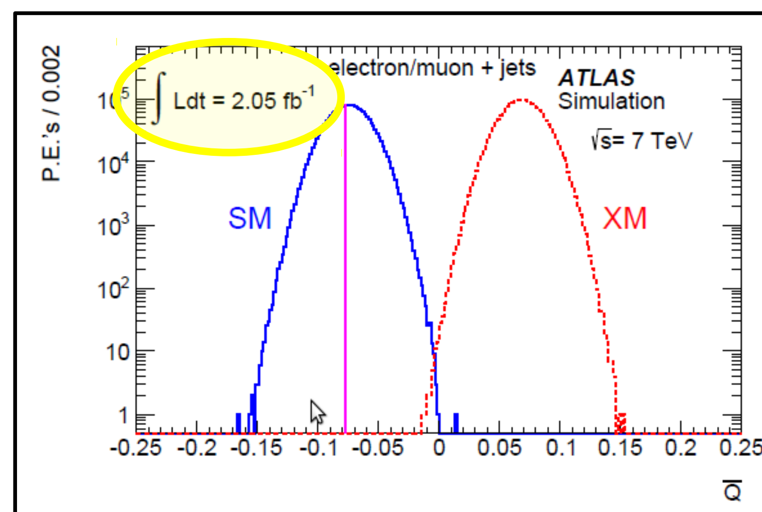
top spin-correlations





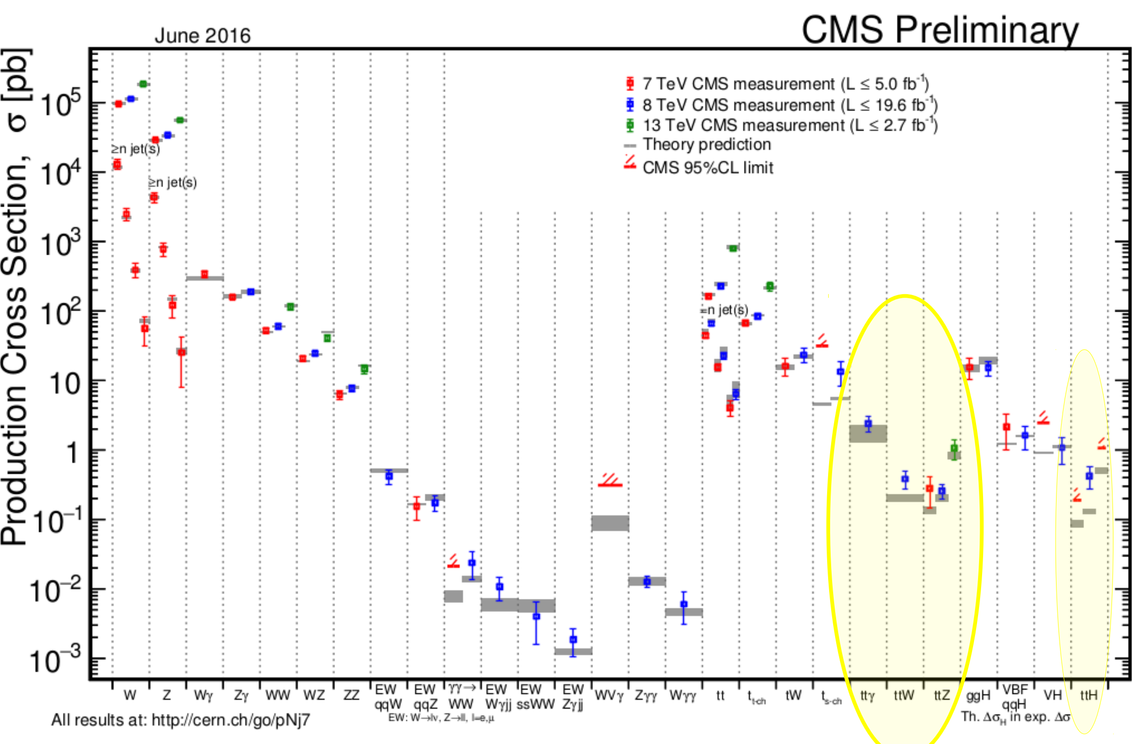
top electric charge

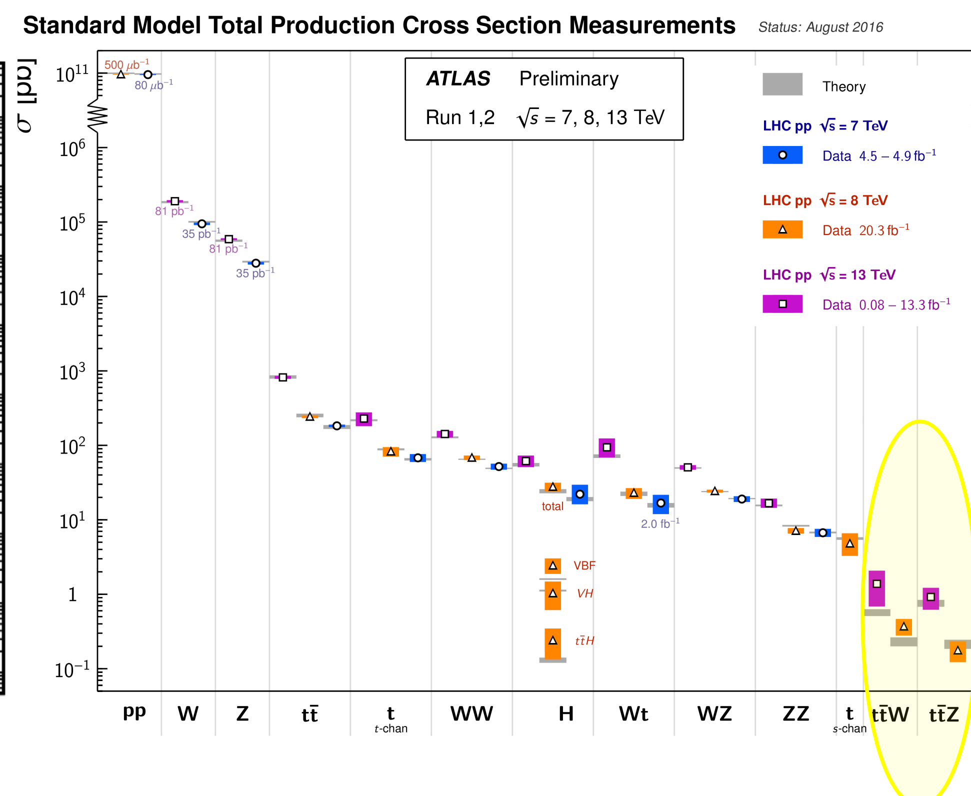




Beginning of a new era in top quark physics

- The LHC is not only a *top quark factory,* but it is opening the door to a whole new process class: $t\bar{t}+\gamma,\ t\bar{t}+Z,\ t\bar{t}+W^{\pm},\ t\bar{t}+H$ which was *never* observed at the Tevatron.

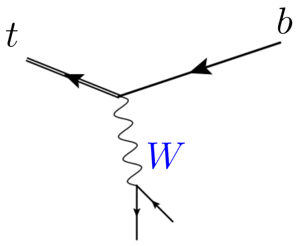


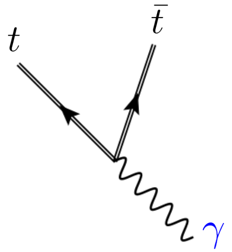


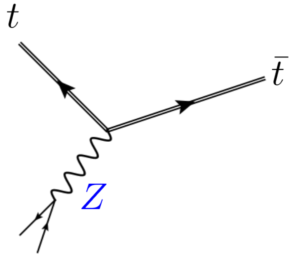
Stairway to heaven?

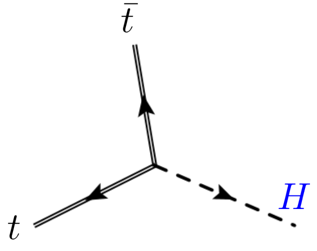
Top quark electroweak couplings

- $t\bar{t} + \gamma/Z/H$ yield *direct* sensitivity to anomalous couplings + dipole moments
- Largely unconstrained from hadron experiments. Indirect: LEP, *B*-factories









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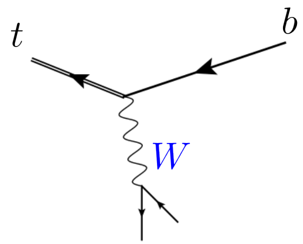
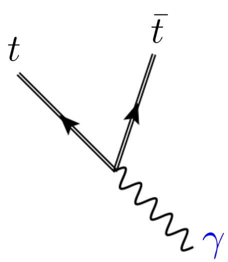
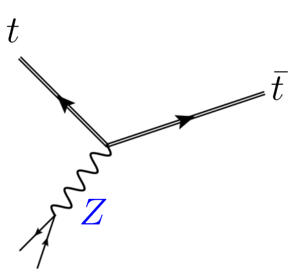


$$\mathcal{L}_{Wtb} \;=\; -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right)t\;W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right)t\;W^{-}_{\mu} + \text{H.c.}\,.$$



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



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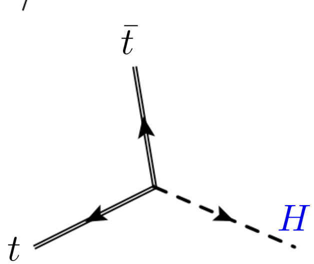

$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}}\,\bar{t}\left(Y_t^V + iY_t^A\gamma_5\right)t\;H$$

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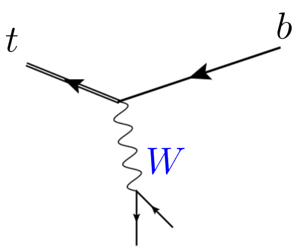

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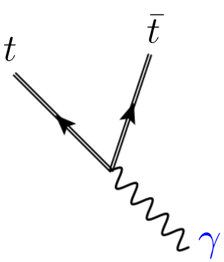

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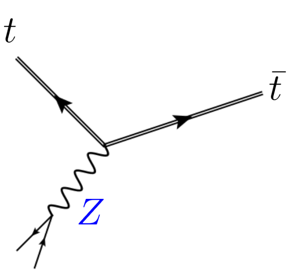

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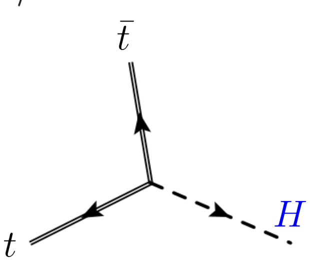

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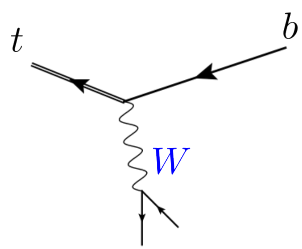

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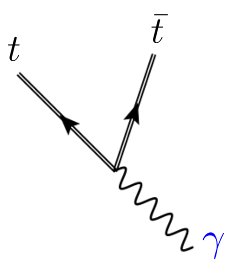

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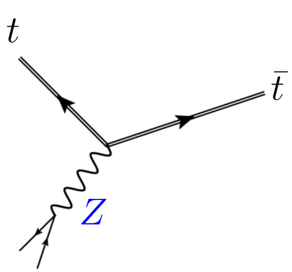

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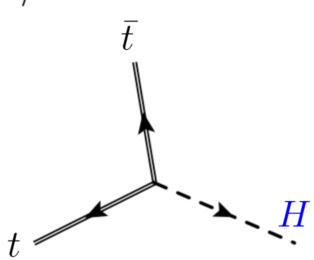

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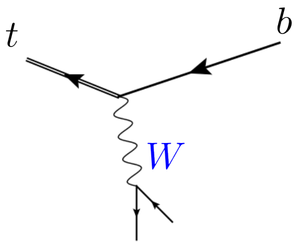

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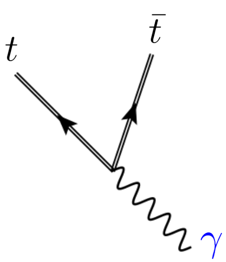

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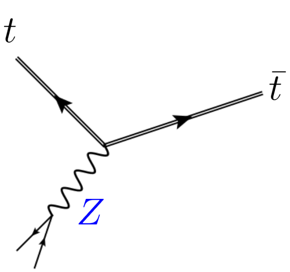

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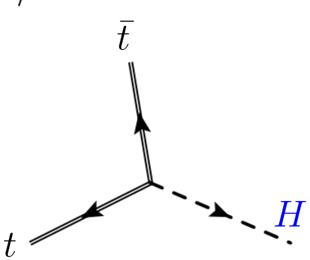

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Top dipole moments

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"Pinning down electroweak dipole operators of the top quark" *[Y. Soreq, M.S.]*

Eur.Phys.J. C76 (2016), 466; arXiv: 1603.08911

Study of dipole moments combining $t\bar{t}$, $t\bar{t}+\gamma$ and $t\bar{t}+Z$

in the final state $b\,\ell\,\nu\;\bar{b}\,j\,j\;(+\,\ell^+\ell^-/\gamma)$ at the 13 TeV LHC.

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	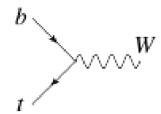	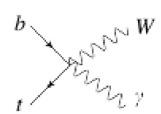	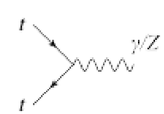
C^{33}_{uW}	$\otimes$	$\otimes$	$\otimes$
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$C^{33}_{uB\phi}$			$\otimes$

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	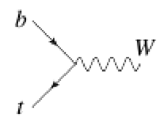	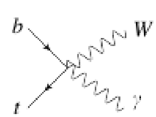	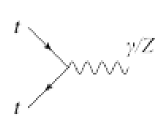
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→ Construct **ratios of cross sections** to cancel uncertainties and enhance sensitivity:

$$\mathcal{R}_\gamma = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}, \quad \mathcal{R}_Z = \frac{\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}}}$$

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	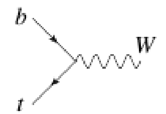	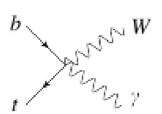	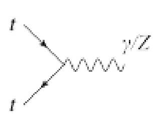
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$$g_{\mathrm{R}}^{W^-} = g_{\mathrm{L}}^{W^+*} = -\frac{e\,m_t}{s_{\mathrm{W}}M_W}\frac{v^2}{\Lambda^2}C_{uW}^{33},$$
$$g_{\mathrm{L}}^{\gamma} = g_{\mathrm{R}}^{\gamma*} = -\frac{\sqrt{2}\,m_t\,v}{\Lambda^2}\left(c_{\mathrm{W}}C_{uB\phi}^{33*} + s_{\mathrm{W}}C_{uW}^{33*}\right),$$
$$g_{\mathrm{L}}^{Z} = g_{\mathrm{R}}^{Z*} = -\frac{e\,m_t\,v^2}{\sqrt{2}s_{\mathrm{W}}c_{\mathrm{W}}M_Z\Lambda^2}\left(c_{\mathrm{W}}C_{uW}^{33*} - s_{\mathrm{W}}C_{uB\phi}^{33*}\right),$$

→ Construct **ratios of cross sections** to cancel uncertainties and enhance sensitivity:

$$\mathcal{R}_\gamma = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}},\quad \mathcal{R}_Z = \frac{\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}}}$$

$\langle E_{\mathrm{CMS}}\rangle \approx 525\,\mathrm{GeV}$

$\langle E_{\mathrm{CMS}}\rangle \approx 630\,\mathrm{GeV}$

$\langle E_{\mathrm{CMS}}\rangle \approx 860\,\mathrm{GeV}$

Top dipole moments

$$\mathcal{R}_\gamma = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}, \quad \mathcal{R}_Z = \frac{\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}}}$$

Properly cancel q^2-dependent uncertainties (pdfs, alpha_s):

enhance $\sigma_{t\bar{t}}$ threshold: $m_{t\bar{t}} \geq 470\,\text{GeV}$ in $\mathcal{R}_\gamma$, $m_{t\bar{t}} \geq 700\,\text{GeV}$ in $\mathcal{R}_Z$.

Top dipole moments

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$$\mathcal{R}_\gamma^{\mathrm{LO}} \times 10^{-3} = \begin{cases} 11.5 & \text{with NNPDF3.0,} \\ 11.4 & \text{with CTEQ6L1,} \\ 11.5 & \text{with MSTW08,} \end{cases}$$

$$\mathcal{R}_Z^{\mathrm{LO}} \times 10^{-4} = \begin{cases} 2.29 & \text{with NNPDF3.0,} \\ 2.27 & \text{with CTEQ6L1,} \\ 2.27 & \text{with MSTW08.} \end{cases}$$

→ *pdf variation*:

ratio: **±1%**

cross sections: **±10%**

$$\mathcal{R}_\gamma^{\mathrm{SM}} \times 10^{-3} = \begin{cases} 11.4^{-0.7\%}_{+0.7\%} & \text{at LO,} \\ 12.6^{+3.1\%}_{-1.8\%} & \text{at NLO QCD,} \end{cases}$$

$$\mathcal{R}_Z^{\mathrm{SM}} \times 10^{-4} = \begin{cases} 2.27^{-1.7\%}_{+2.0\%} & \text{at LO,} \\ 1.99^{-1.9\%}_{+2.8\%} & \text{at NLO QCD,} \end{cases}$$

→ *scale variation* (NLO):

ratio: **±2-3%**

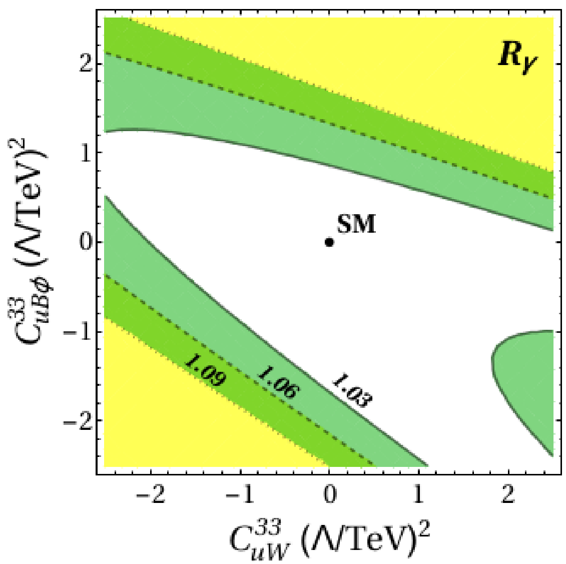
cross sections: **±20%**

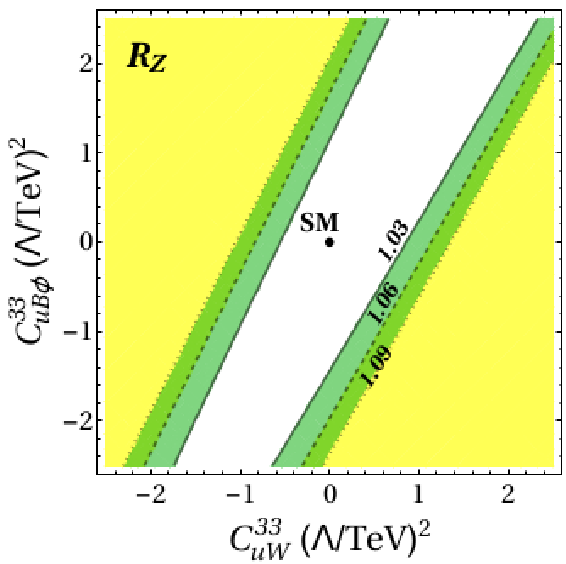
In the following we assume a theoretical uncertainty of **±3%.**

First measurement by CMS: $\mathcal{R}_\gamma(8\,\mathrm{TeV}) = 10.7 \times 10^{-3} \pm 6.5\%(\mathrm{stat.}) \pm 25\%(\mathrm{syst.})$

stat.: sub-dominant after 250 fb^{-1}, syst.: ±23% from backgr. modeling

Top dipole moments

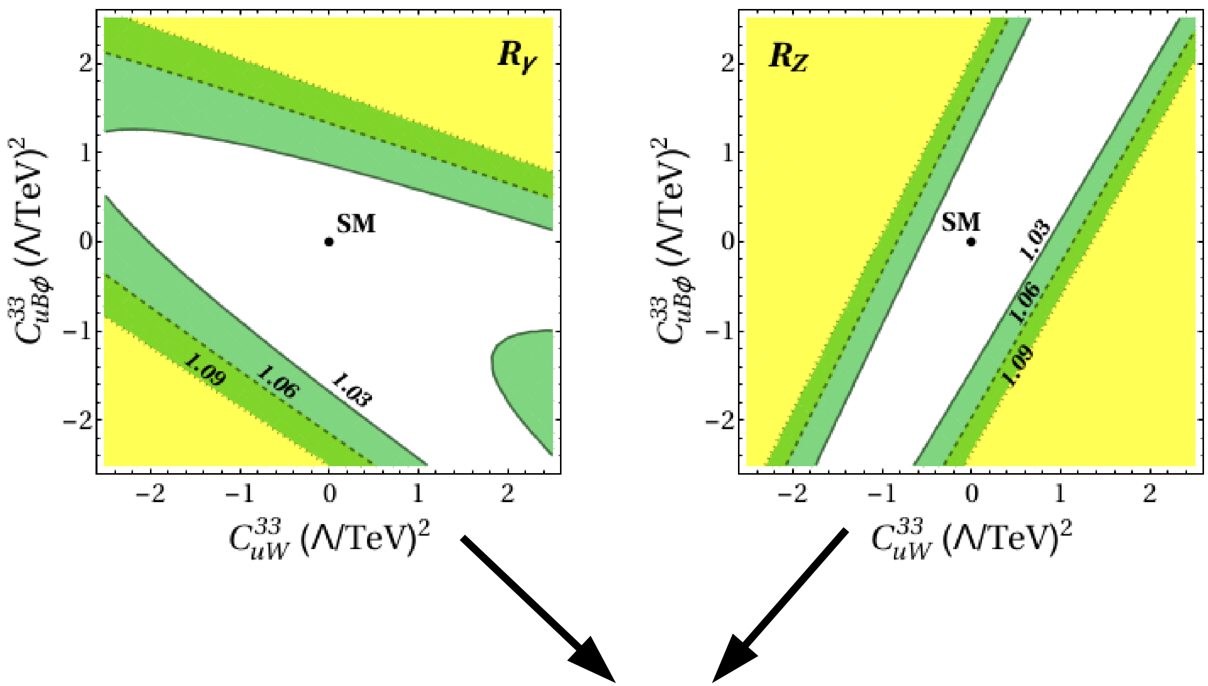




$$g_{\rm L}^{\gamma} = g_{\rm R}^{\gamma *} = -\frac{\sqrt{2}\, m_t\, v}{\Lambda^2} \left(c_{\rm W} C_{uB\phi}^{33*} + s_{\rm W} C_{uW}^{33*} \right),$$

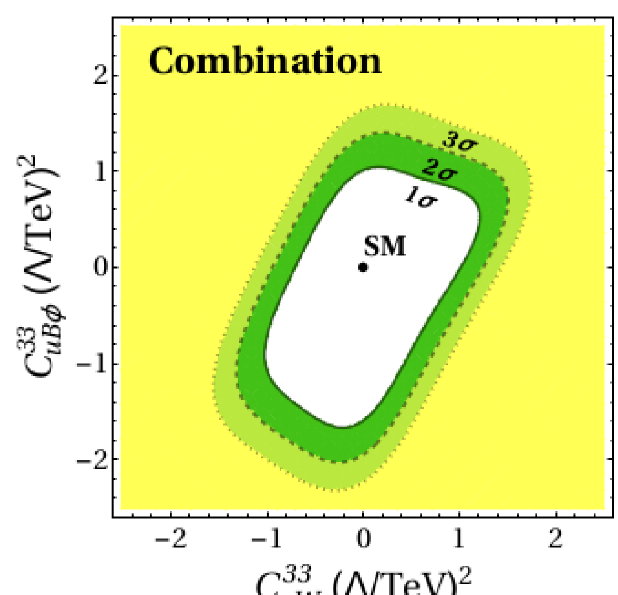
$$g_{\rm L}^{Z} = g_{\rm R}^{Z *} = -\frac{e\, m_t\, v^2}{\sqrt{2} s_{\rm W} c_{\rm W} M_Z \Lambda^2} \left(c_{\rm W} C_{uW}^{33*} - s_{\rm W} C_{uB\phi}^{33*} \right),$$

Top dipole moments



$$g_L^\gamma = g_R^{\gamma *} = -\frac{\sqrt{2}\, m_t\, v}{\Lambda^2} \left(c_W C_{uB\phi}^{33*} + s_W C_{uW}^{33*} \right),$$

$$g_L^Z = g_R^{Z*} = -\frac{e\, m_t\, v^2}{\sqrt{2} s_W c_W M_Z \Lambda^2} \left(c_W C_{uW}^{33*} - s_W C_{uB\phi}^{33*} \right),$$



$$C_{uW}^{33} = [-1.2, +1.4]\, (\Lambda/\text{TeV})^2$$

$$C_{uB\phi}^{33} = [-1.9, +1.2]\, (\Lambda/\text{TeV})^2$$

→ additional analysis of decay angles in *ttbar* to constrain remaining operator

Top-Z vector/axial couplings

Top-Z vector/axial couplings

"Constraining couplings of the top quark to the Z boson in $ttb+Z$ production at the LHC" *[R.Röntsch, M.S.]*

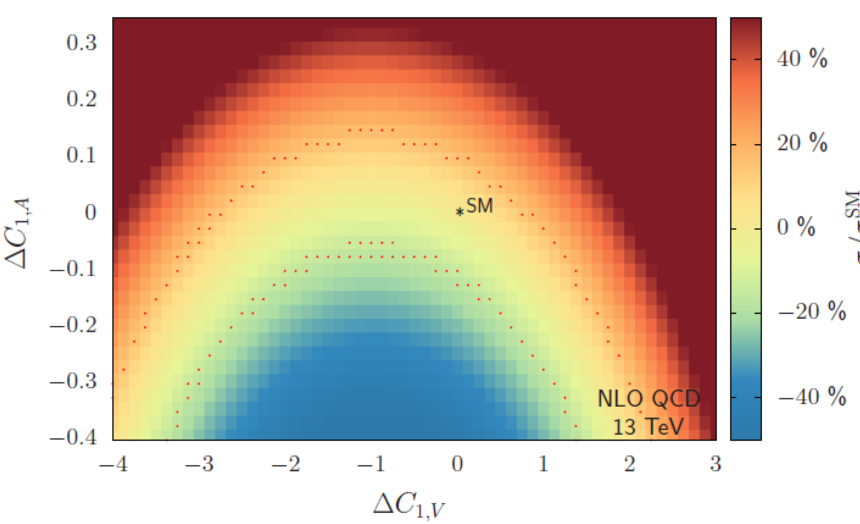
JHEP 1508(2015) 044; arXiv: 1501.05939

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

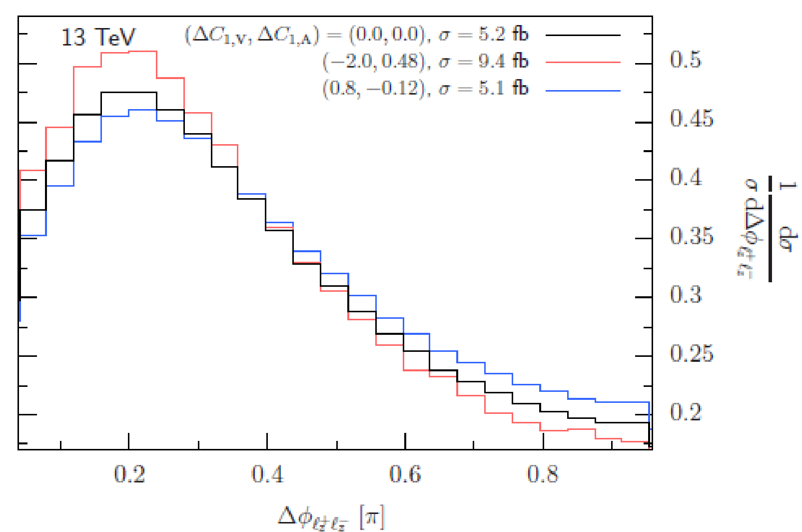
$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right],$$

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

Degeneracy: cross section dominantly ~ $C_{1,V}^2 + C_{1,A}^2$

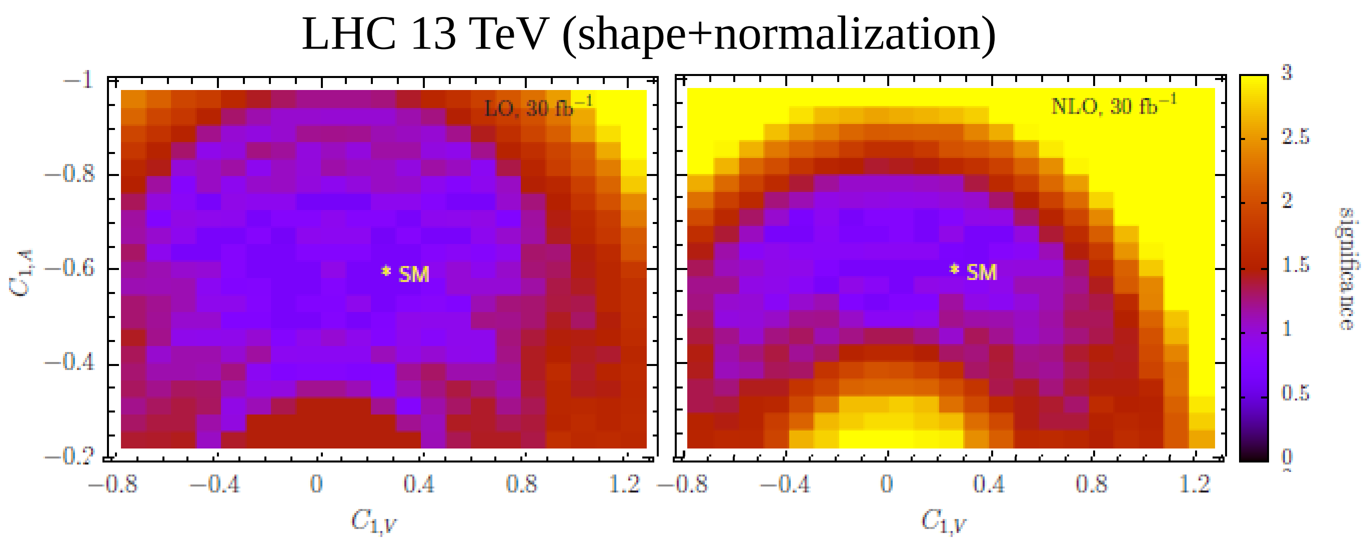


Differential observables resolve degeneracies



Top-Z vector/axial couplings

LO 30 fb^{-1}



NLO 30 fb^{-1}

Top-Z vector/axial couplings

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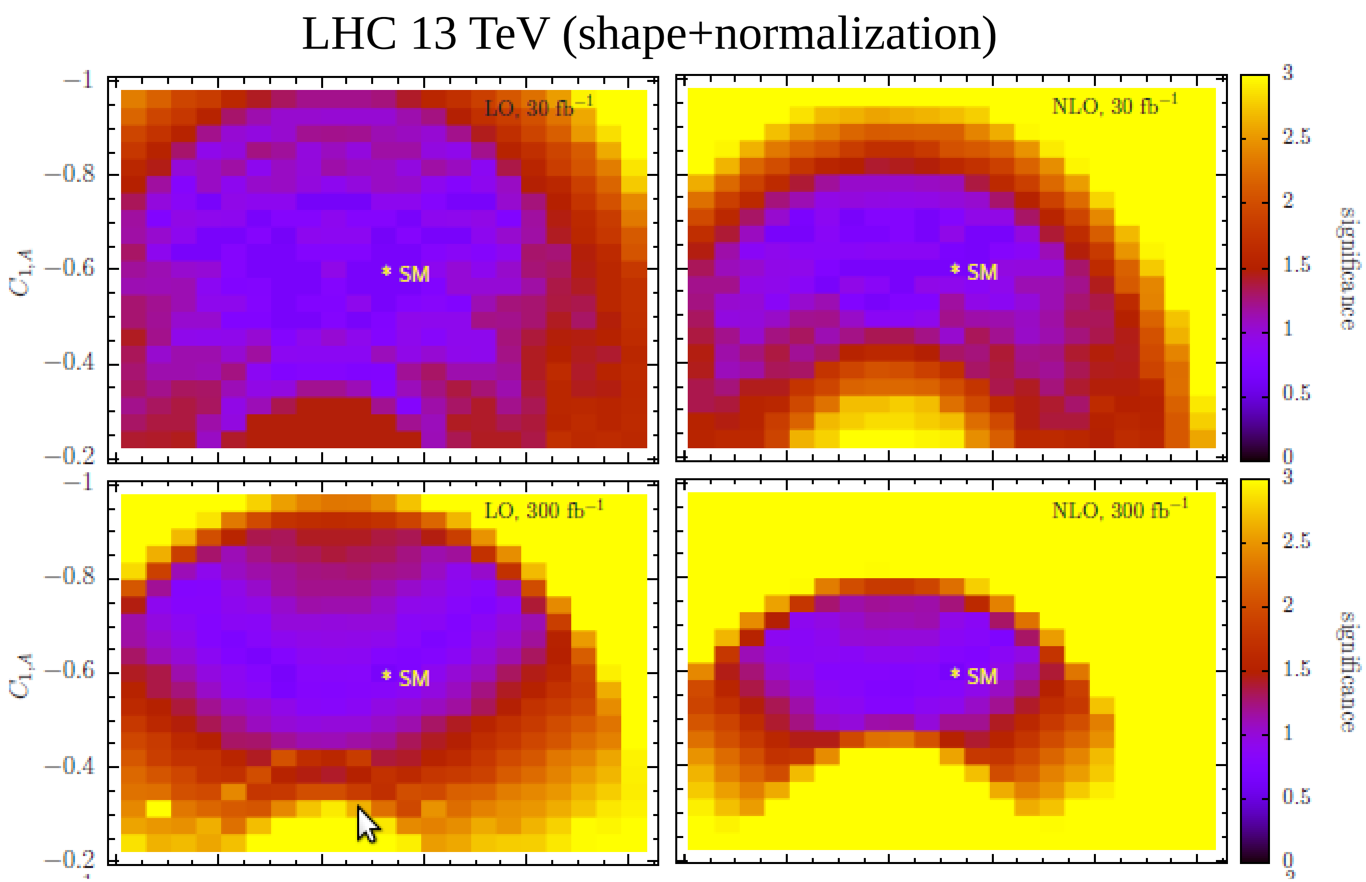


NLO 30 fb^{-1}

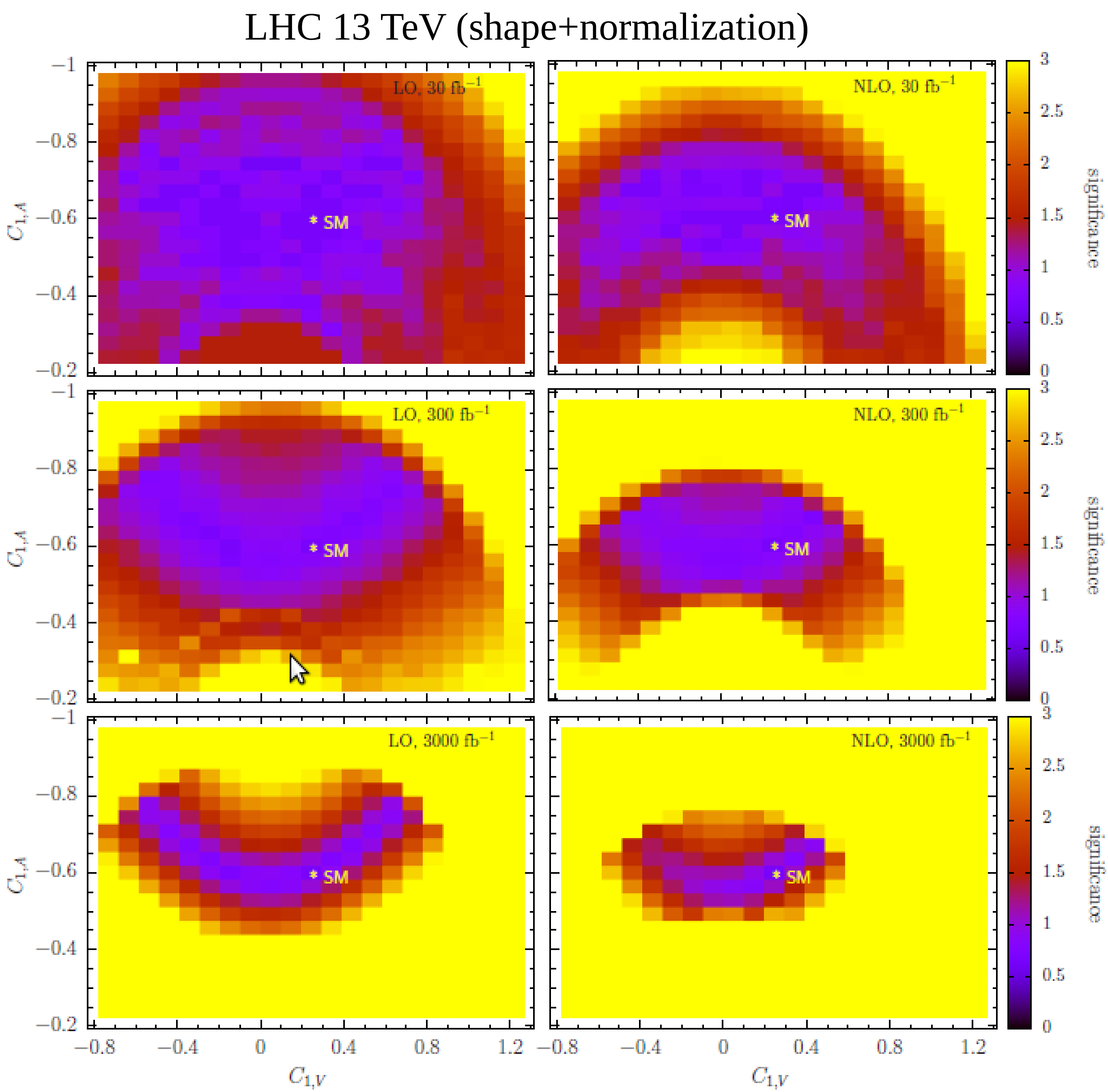
NLO 300 fb^{-1}

Top-Z vector/axial couplings

LO 30 fb^{-1} — NLO 30 fb^{-1}

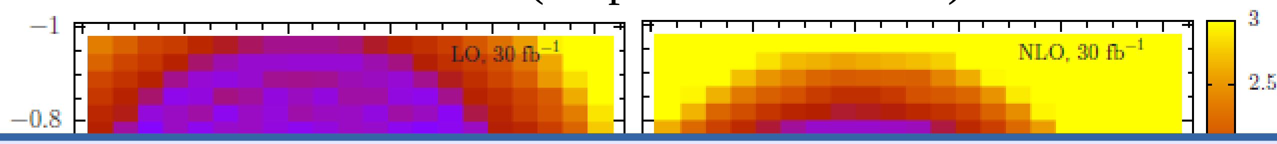
LO 300 fb^{-1} — NLO 300 fb^{-1}

LO 3000 fb^{-1} — NLO 3000 fb^{-1}



Top-Z vector/axial couplings

LHC 13 TeV (shape+normalization)



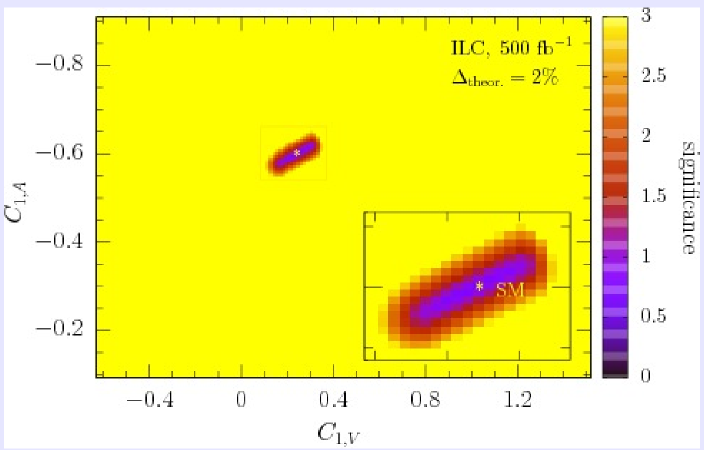
LO 30 fb^{-1} | LO 30 fb^{-1}

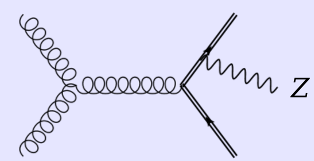
LO 300 fb^{-1} | O 300 fb^{-1}

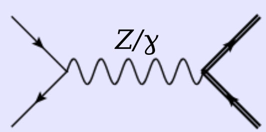
LO 3000 fb | O 3000 fb^{-1}

Future collider bounds

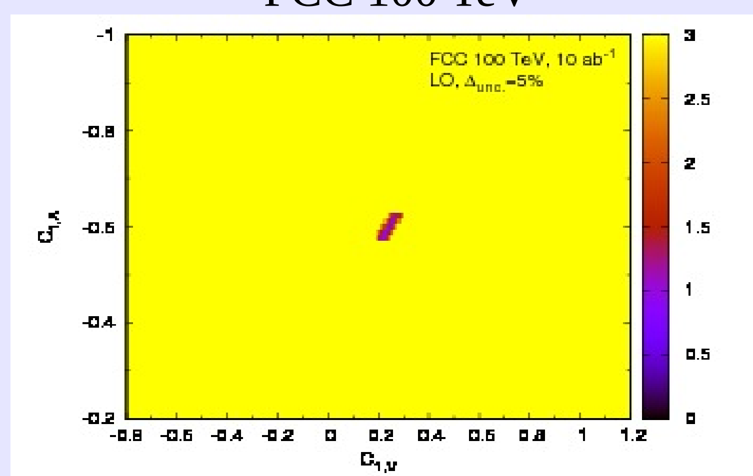
ILC 500 GeV

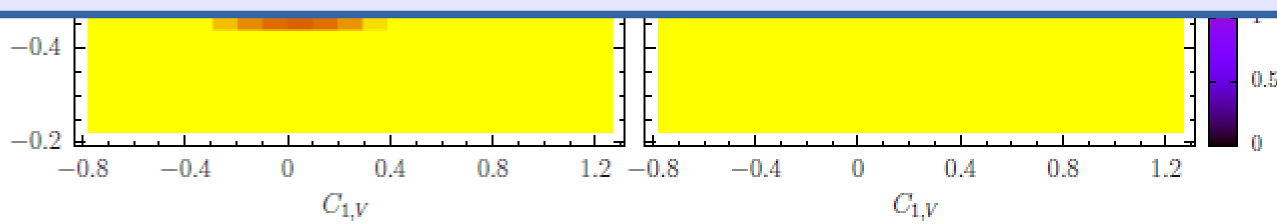






FCC 100 TeV





Top-Z vector/axial couplings

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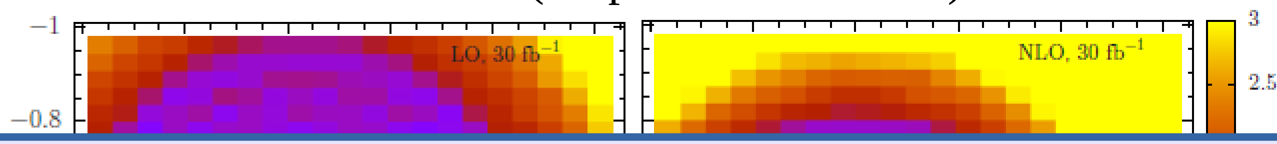
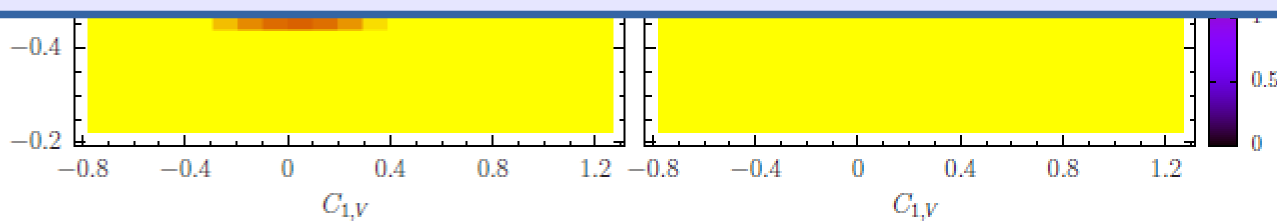


LO 30 fb^{-1}

LO 300 fb^{-1}

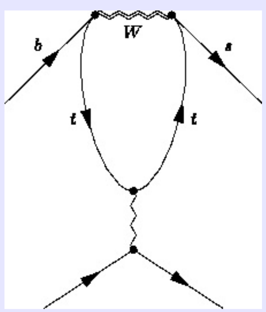
LO 3000 fb

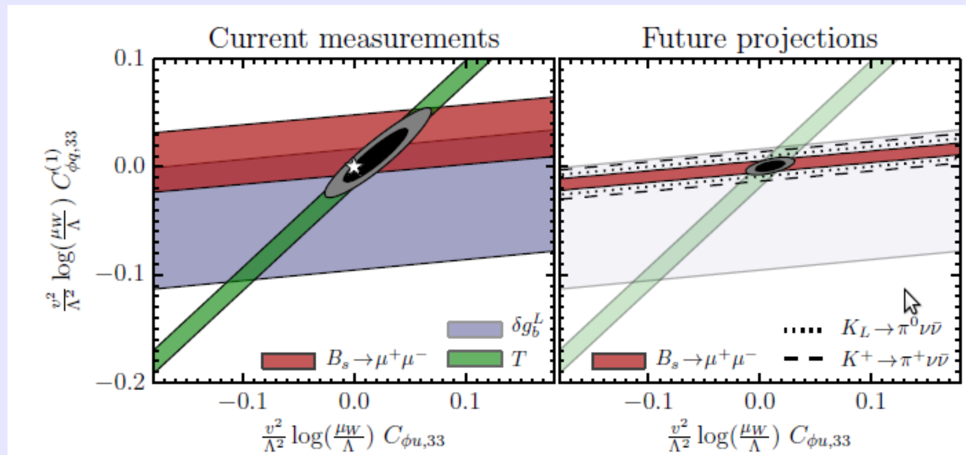


LO 30 fb^{-1}

Future collider bounds

[Brod,Greljo,Stamou,Uttayarat]





Order of magnitute stronger bounds than direct reach with 3000/fb!

T	0.08 ± 0.07	[Ciuchini et al., arxiv:1306.4644]
δg_L^b	0.0016 ± 0.0015	[Ciuchini et al., arxiv:1306.4644]
Br($B_s \to \mu^+\mu^-$) [CMS]	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	[CMS, arxiv:1307.5025]
Br($B_s \to \mu^+\mu^-$) [LHCb]	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$	[LHCb, arxiv:1307.5024]
Br($K^+ \to \pi^+\nu\bar{\nu}$)	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	[E949, arxiv:0808.2459]

Top-Higgs interactions

Top-Higgs interactions

"Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques" [Gritsan,Röntsch,Xiao,M.S.]

Phys.Rev. D94 (2016) 055023
arXiv:1606.03107

$$\mathcal{L}(Hf\bar{f}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\tilde{\kappa}_f\gamma_5\right)\psi_f\, H,$$

$$f_{\mathrm{CP}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2},\ \phi_{\mathrm{CP}} = \arg(\tilde{\kappa}_f/\kappa_f)$$

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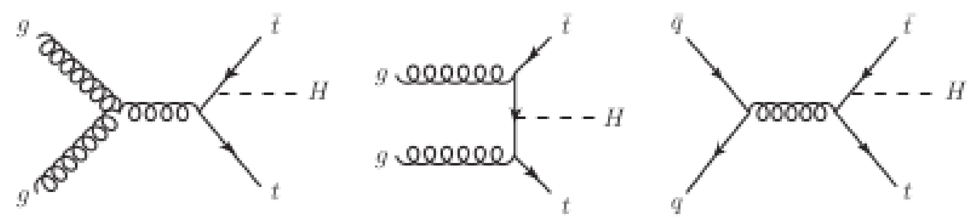
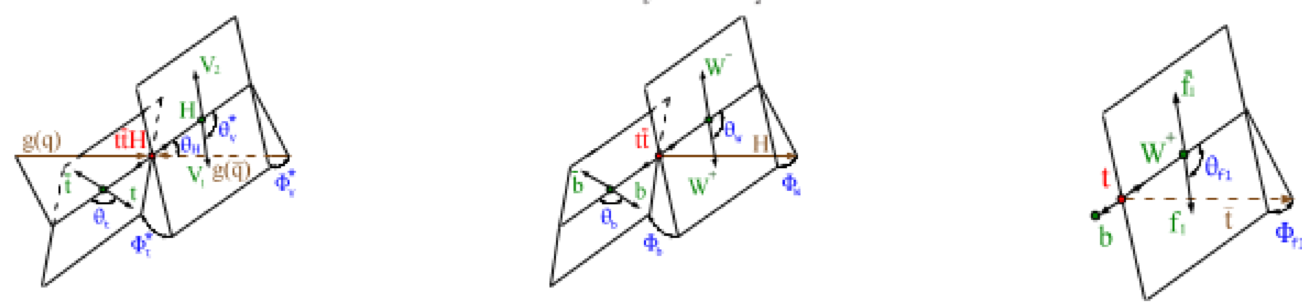
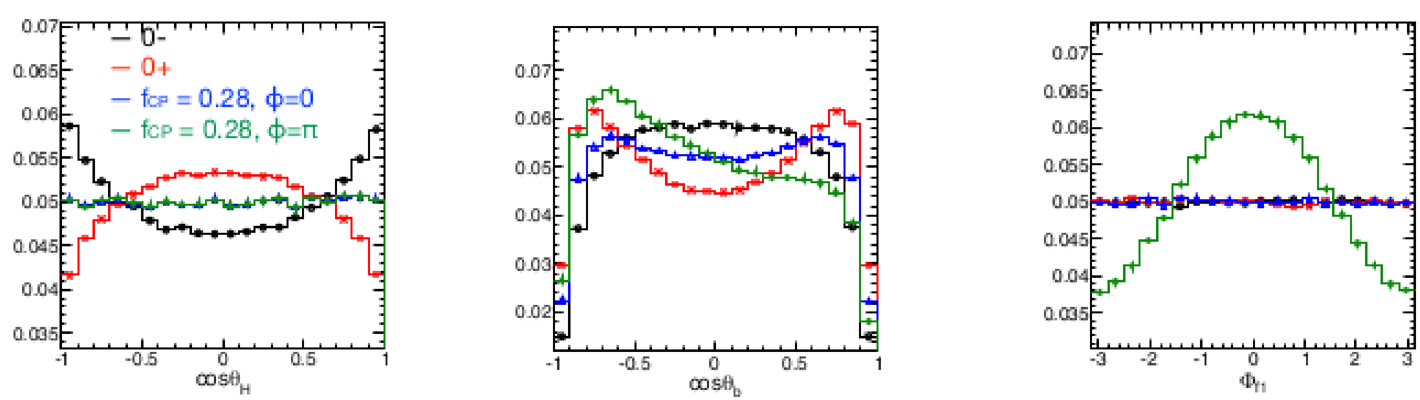
$pp \to t\bar{t} + H$:



Fully describe the system through angles, decay planes, inv. masses:





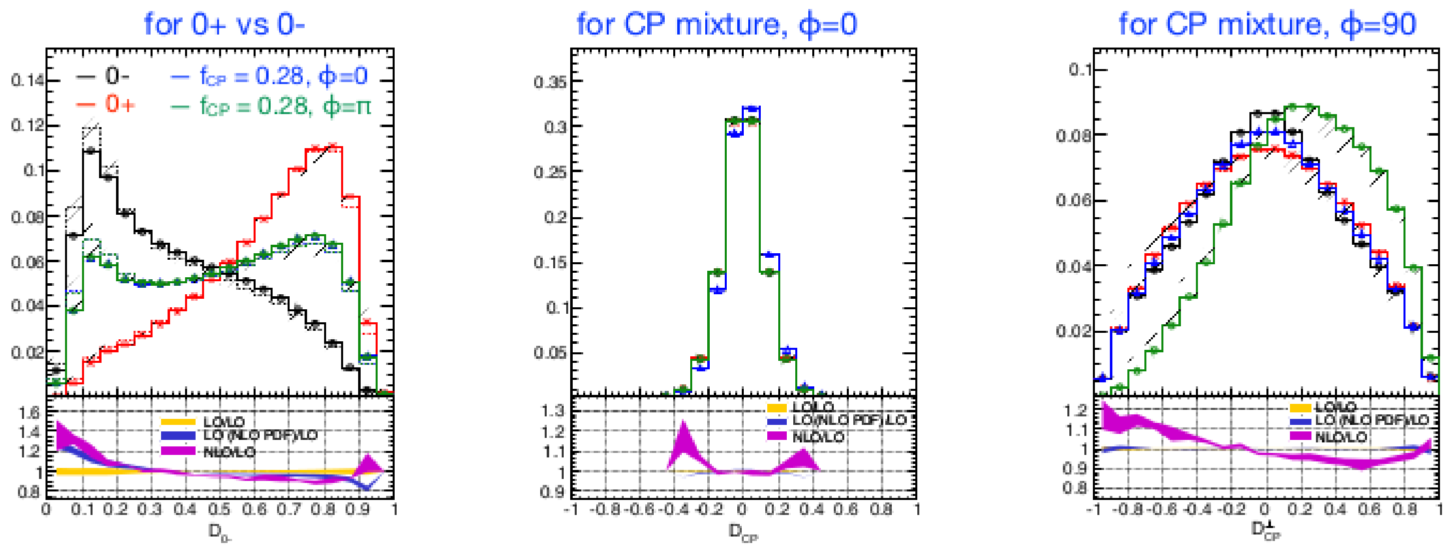
Top-Higgs interactions

MELA: Use matrix element likelihood analysis to gain optimal sensitivity.

Input: 4-momenta of ttH system in its rest frame.

$$\mathcal{P}(\{p\}_{t\bar{t}H}) = \frac{1}{2\hat{s}} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1)\, f_2(x_2)\, |\mathcal{M}_{t\bar{t}H}|^2$$

$$\mathcal{D}_{0-} = \frac{\mathcal{P}_{0+}}{\mathcal{P}_{0+} + \mathcal{P}_{0-}}, \qquad \mathcal{D}_{0-} = \frac{\mathcal{P}_{\mathrm{int}}}{\mathcal{P}_{0+} + \mathcal{P}_{0-}}, \qquad \mathcal{D}_{0-} = \frac{\mathcal{P}_{\mathrm{int}}^{\perp}}{\mathcal{P}_{0+} + \mathcal{P}_{0-}}$$

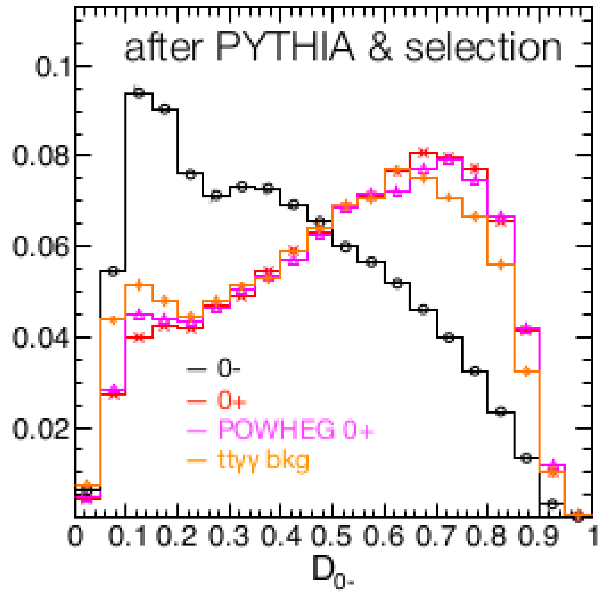


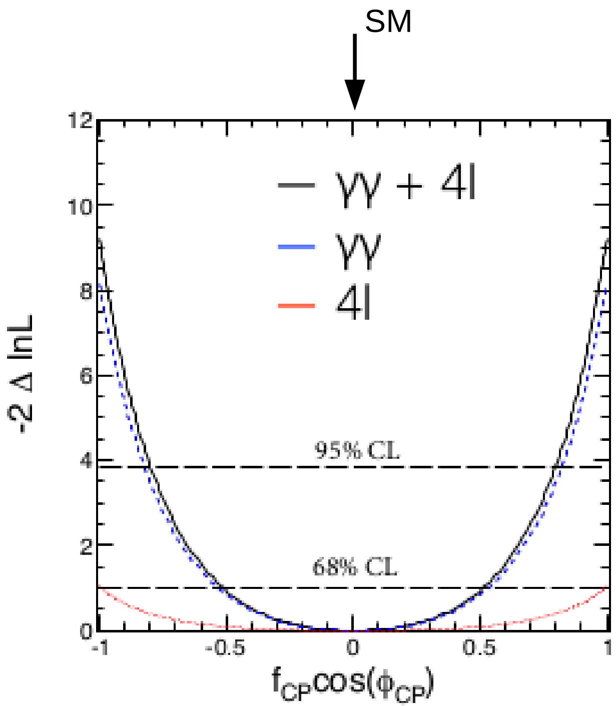
Study robustness of MELA (LO ME) with events at NLO QCD.

→ Discrimination power almost unaltered by virtual corrections and additional jet emissions.

Top-Higgs interactions

Realistic simulation of *H→4l* and *H→γγ,* including backgrounds for 300 fb^{-1}:



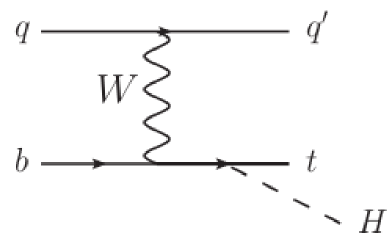


→ pure CP-odd Higgs can be excluded at 99.5% C.L.

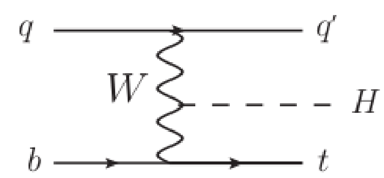
50% CP-odd admixture can be excluded at the 68% C.L.

Top-Higgs interactions

$pp \to t\, j + H$:



+



(+ *s*-channel)

→ Strong destr. interference between *t*-*H* and *W*-*H* diagrams

→ Sensitive to the sign of the *t*-*H* coupling

→ Simultaneous measurement of *t*-*H* and *W*-*H* possible

Top-Higgs interactions

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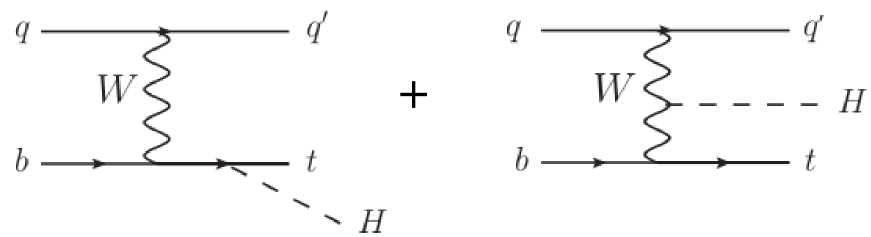


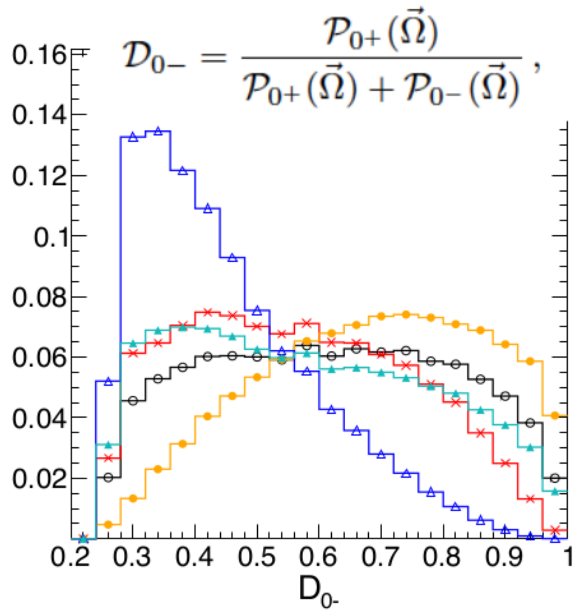
(+ s-channel)

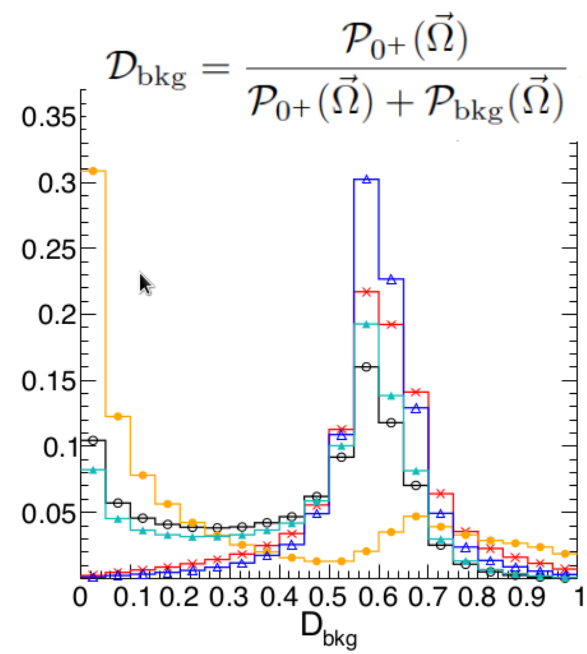
→ Strong destr. interference between t-H and W-H diagrams

→ Sensitive to the sign of the t-H coupling

→ Simultaneous measurement of t-H and W-H possible

MELA discriminants:





Top-Higgs interactions

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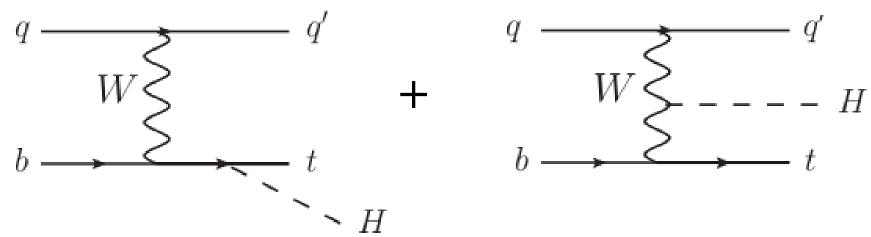

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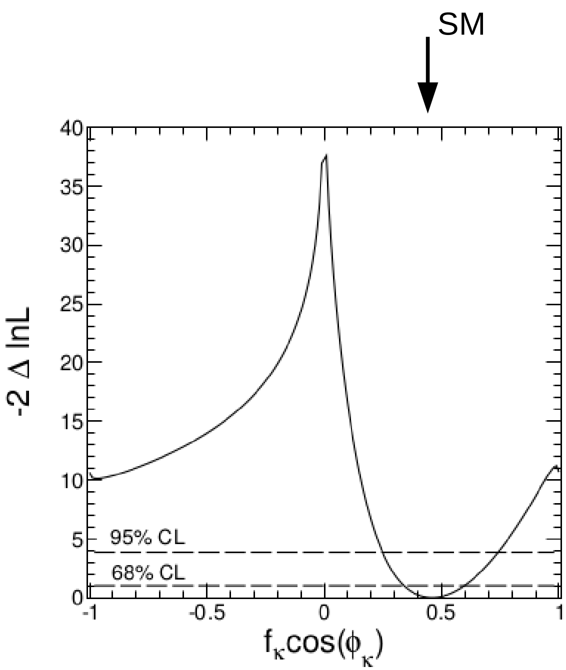
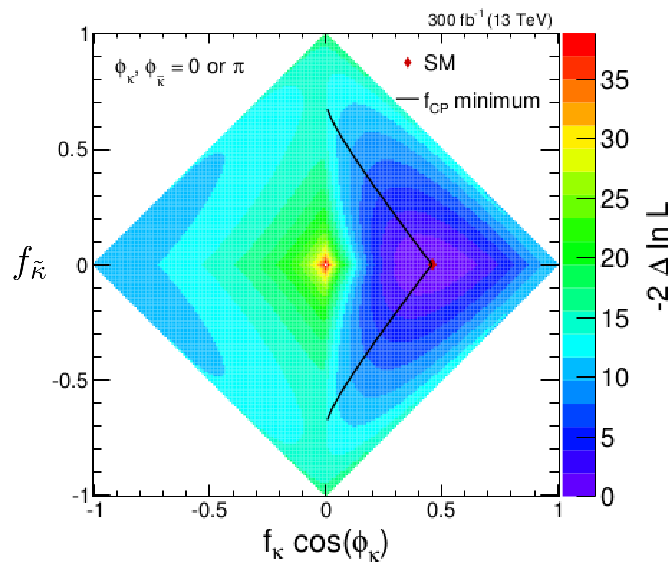
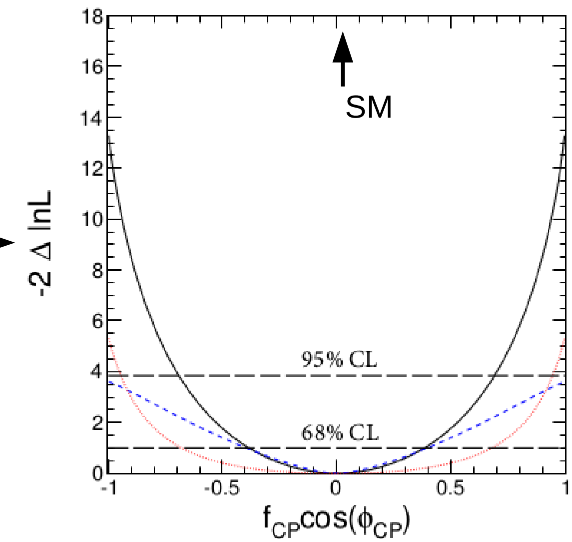




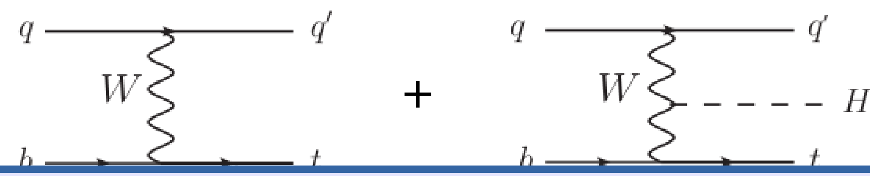


ttH is "background", precision is driven by both *tt*+*H* and *tj*+*H*.

99.5% C.L. exclusion of pure CP-odd and negative *t*-*H* coupling possible.

Top-Higgs interactions

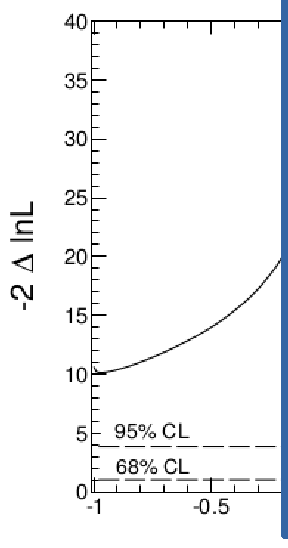
$pp \to t\,j + H$:



(+ s-channel)

diagrams

ible



First 13 TeV constraints

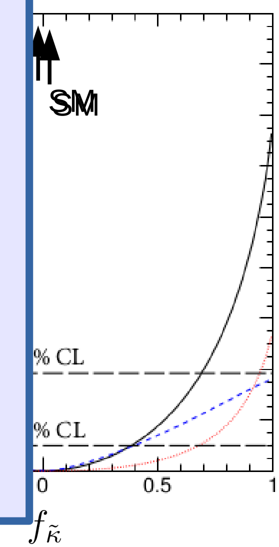
[CMS PAS HIG-16-019]

upper limit on $y_t = +y_{SM}$

upper limit on $y_t = -y_{SM}$

	Region	Observed Limit	Expected Limit		
			Median	$\pm 1\sigma$	$\pm 2\sigma$
SM scenario	3 tag	124.0	114.3	[73.6, 184.4]	[52.0 , 295.2]
	4 tag	195.8	174.6	[112.9, 287.4]	[78.8 , 464.4]
	Combination	**113.7**	**98.6**	**[64.0 , 159.2]**	**[45.3 , 254.8]**
ITC scenario	3 tag	7.4	7.4	[4.9 , 11.6]	[3.5 , 17.8]
	4 tag	9.2	10.0	[6.5 , 16.3]	[4.5 , 26.3]
	Combination	**6.0**	**6.4**	**[4.2 , 10.1]**	**[3.0 ,15.7]**

f_κ



ttH is "background", precision is driven by both tt+H and tj+H.

99.5% C.L. exclusion of pure CP-odd and negative t-H coupling possible.

Summary

- For the first time, the LHC allows the study of $t\bar{t} + \gamma/Z/H$ final states which are *direct* probes of the top quark electroweak interactions.

- There is a rich interplay of anomalous terms between the associated top pair production processes and the top decay dynamics. + B-physics.

- NLO precision significantly improves the sensitivity to anomalous interactions. NLO QCD for production+decay dynamics is available for almost all processes.

- We studied a variety of approaches to boost sensitivity:

  - Cross section ratios
  - Differential analysis
  - Matrix element methods
  - ttbar vs. single top

- Towards the end of the 13 TeV run, these studies will fill empty gaps in our understanding of the top quark electroweak couplings and dipole moments, and provide a clear picture of the role tops in the electroweak model.

Extras

$$f_{\kappa} = \frac{\kappa^2 \sigma_{0+}^{tqH}}{(a_1^2 \sigma_{\rm bkg}^{tqH} + \kappa^2 \sigma_{0+}^{tqH} + \tilde{\kappa}^2 \sigma_{0-}^{tqH})}\,, \qquad \phi_{\kappa} = \arg(\kappa/a_1) = 0 \text{ or } \pi\,,$$

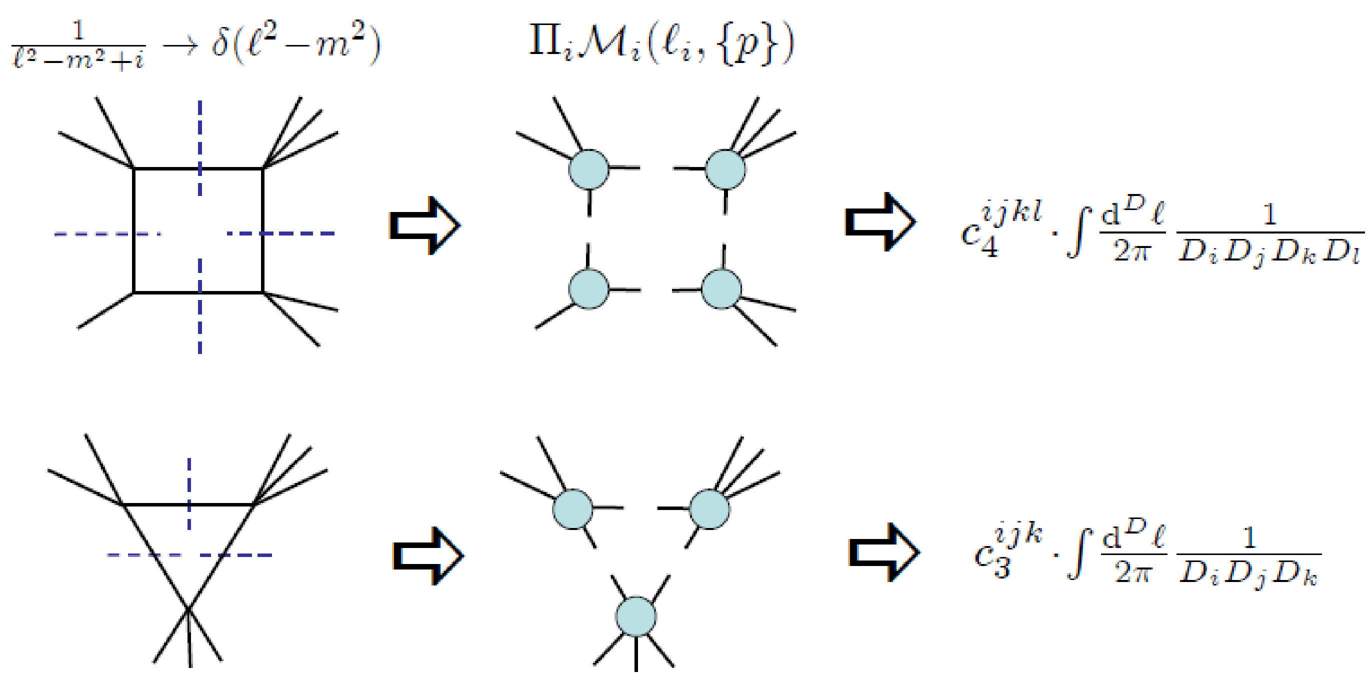
$$f_{\tilde{\kappa}} = \frac{\tilde{\kappa}^2 \sigma_{0-}^{tqH}}{(a_1^2 \sigma_{\rm bkg}^{tqH} + \kappa^2 \sigma_{0+}^{tqH} + \tilde{\kappa}^2 \sigma_{0-}^{tqH})}\,, \qquad \phi_{\tilde{\kappa}} = \arg(\tilde{\kappa}/a_1) = 0 \text{ or } \pi\,.$$

Technology

- Numerical OPP integrand reduction
- Generalized D-dimensional unitarity

→ Basic ingredients are tree level amplitudes

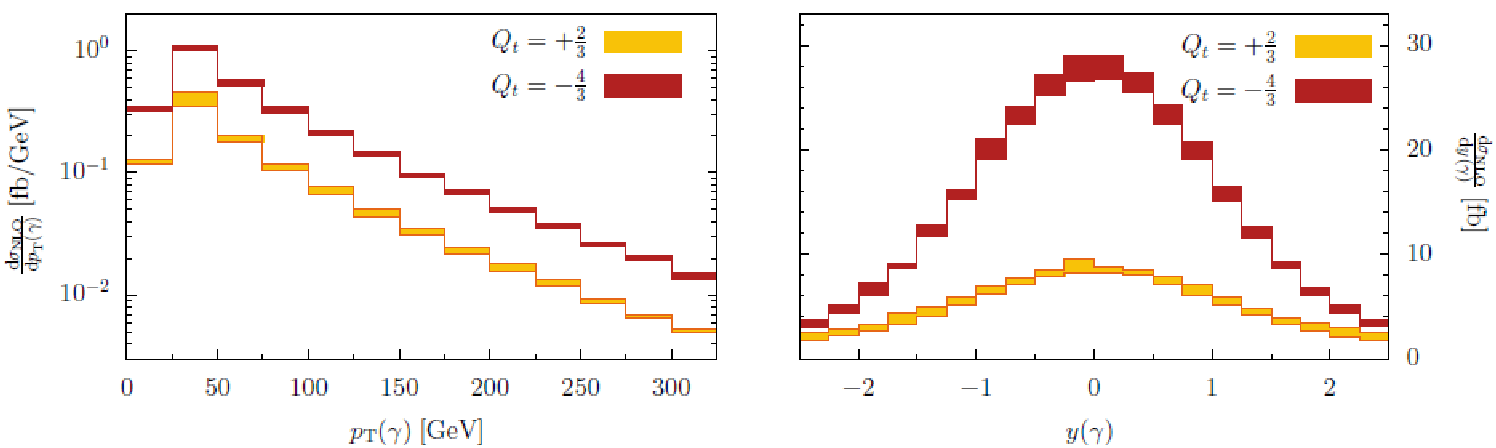
→ Rational part obtained from calculation in D=6, D=8 → D=4-2eps



Sensitivity to Q_t at the LHC

- Apply cuts to suppress radiative top quark decays

$$m_T(b\ell\gamma; E_T^{\text{miss}}) > 180\ \text{GeV}, \qquad m_T(\ell\gamma; E_T^{\text{miss}}) > 90\ \text{GeV},$$
$$160\ \text{GeV} < m(bjj) < 180\ \text{GeV},\ 70\ \text{GeV} < m(j,j) < 90\ \text{GeV}$$



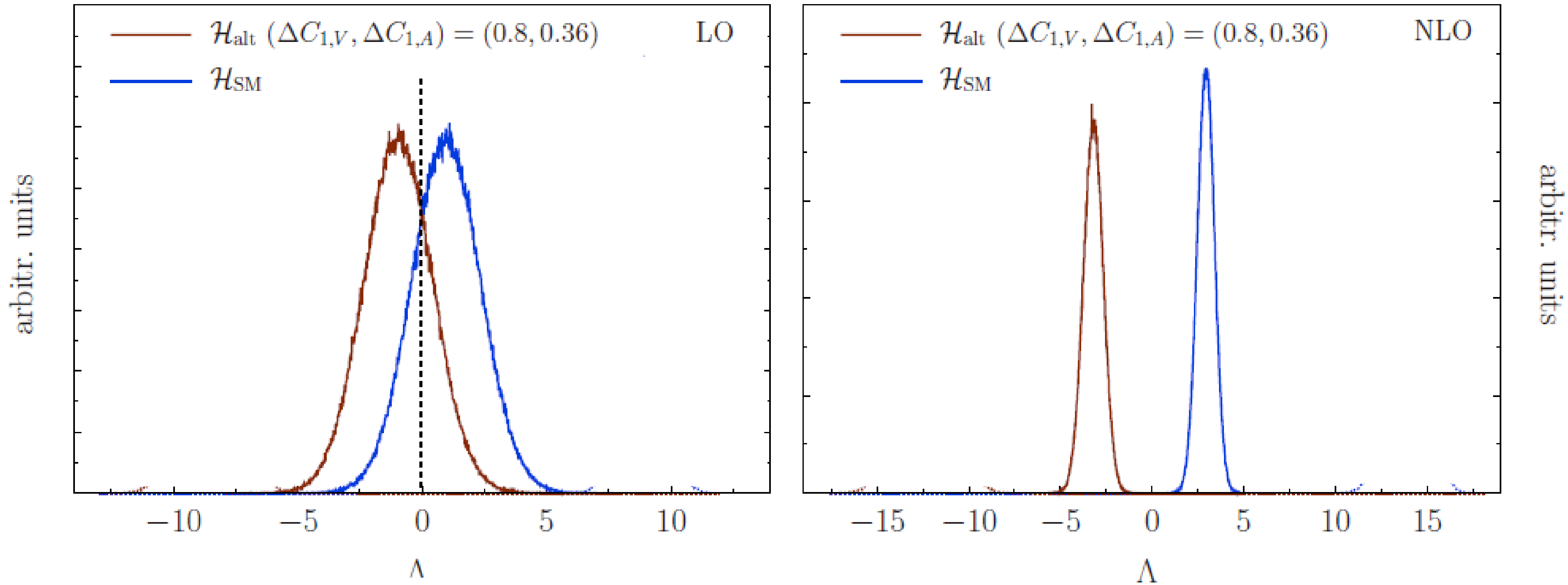
→ Significantly stronger separation power:

$$\mathcal{R}^{\text{NLO}}_{\text{RDS}} = \frac{\sigma^{Q_t=-4/3}_{\text{NLO}}}{\sigma^{Q_t=2/3}_{\text{NLO}}} = 2.88^{+0.05}_{-0.12}$$

But total cross section is reduced by x5.

Statistical Analysis

- LL ratio distributions evaluated with SM and alternative hypothesis



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

Type-I error: prob. accepting $H_{\rm alt}$ even though $H_{\rm SM}$ is correct

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

Type-II error: prob. accepting $H_{\rm SM}$ even though $H_{\rm alt}$ is correct

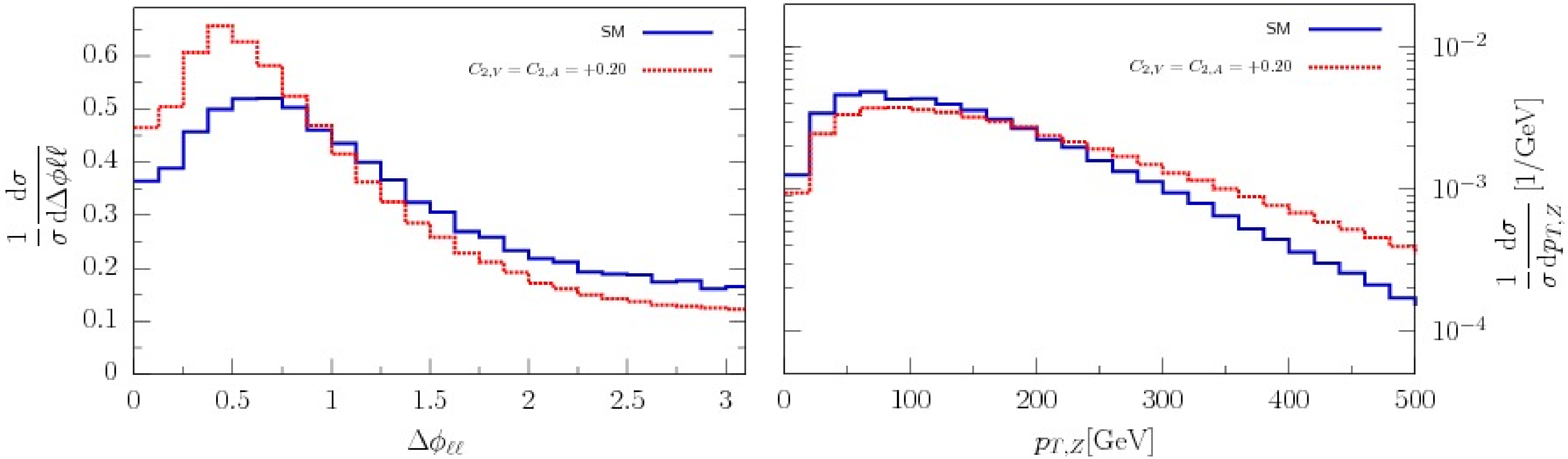
- Study projected limits from future LHC run
- Consider E_{cm}=13 TeV and luminosities L=30, 300, 3000 fb^{-1}
- Null Hypothesis = SM couplings

  Alternative Hyp. = non-SM couplings
- Flat uncertainties, **±30%** at LO and **±15%** at NLO

Constraints from LHC run-II

Weak dipole moments

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



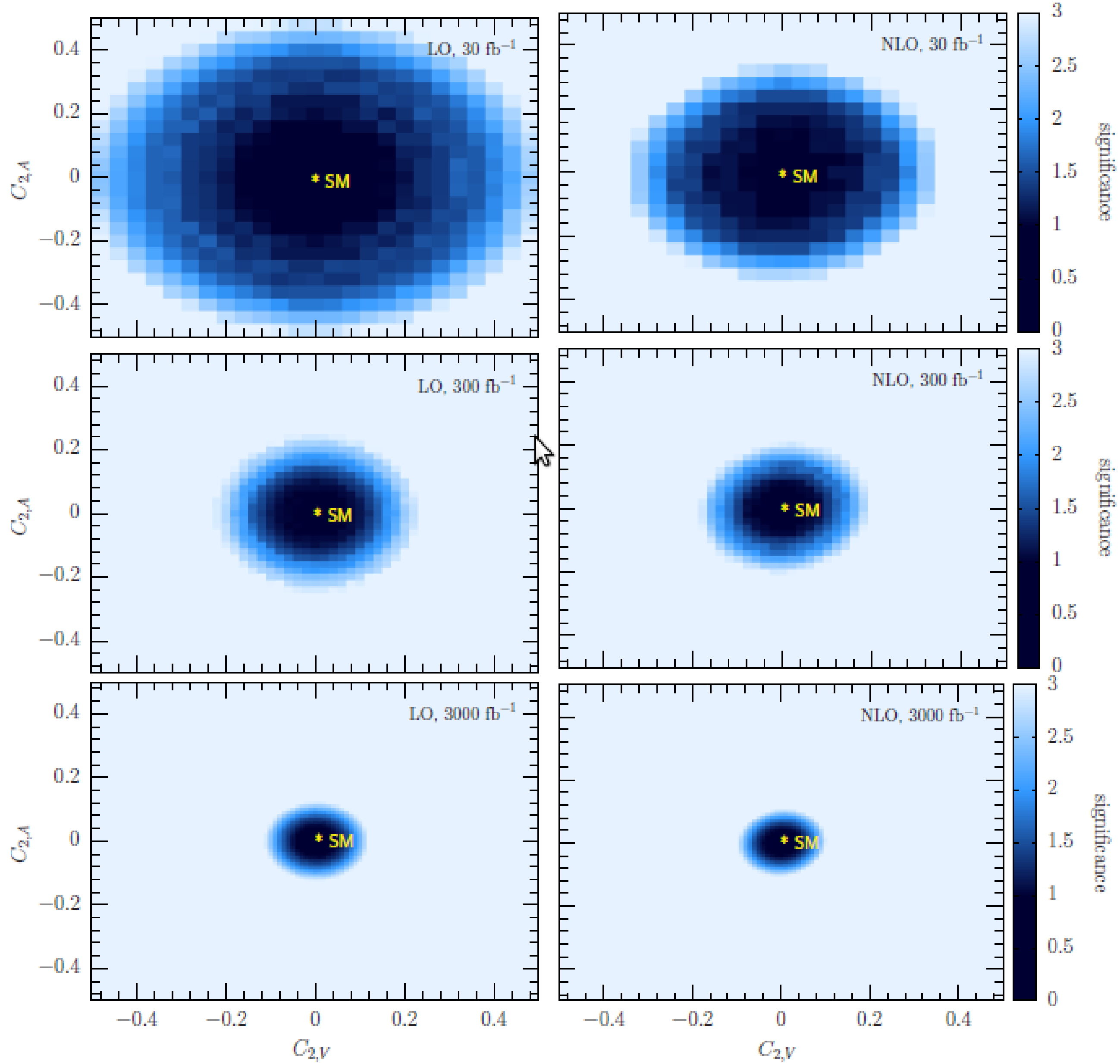
Constraints from LHC run-II

Weak dipole moments

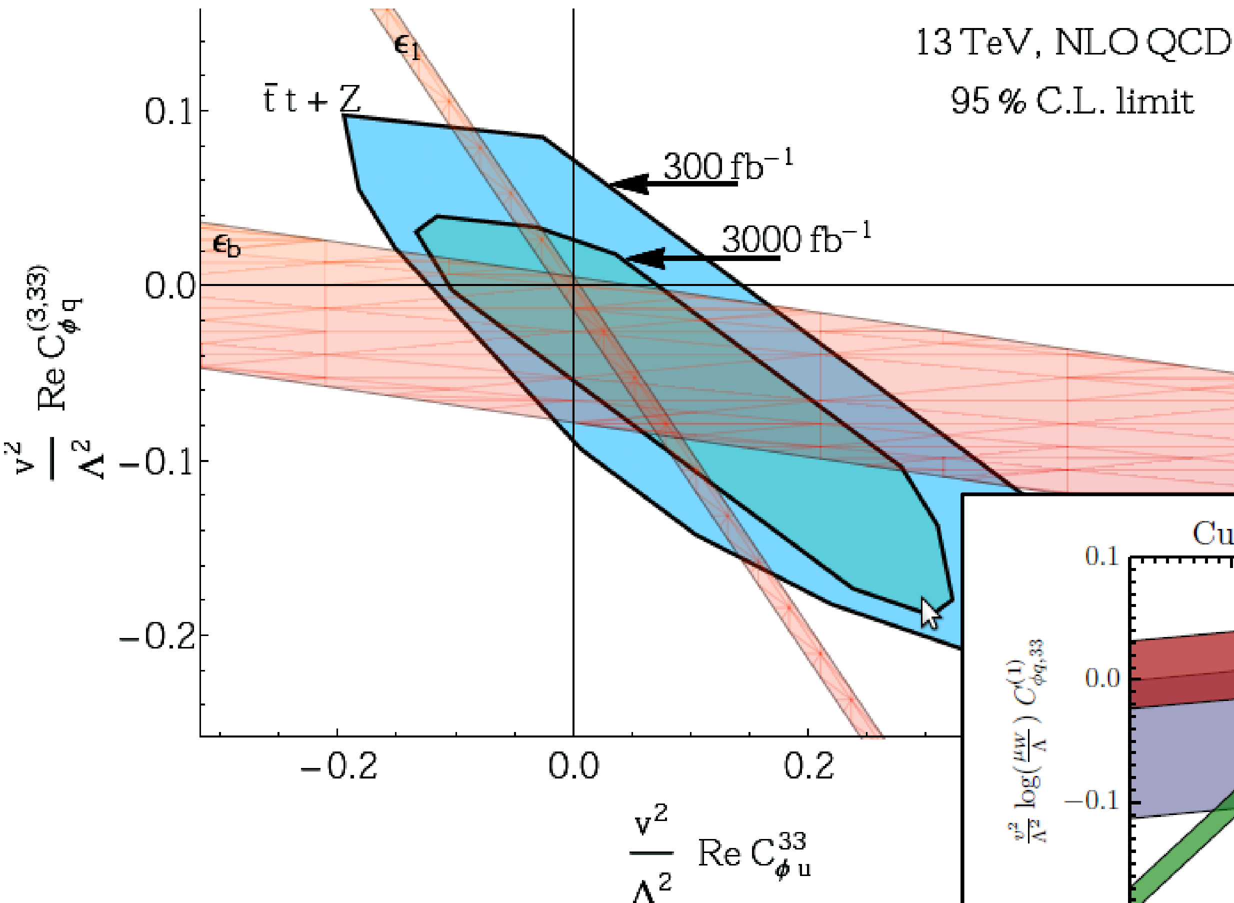
LO 30 fb^{-1} NLO 30 fb^{-1}

LO 300 fb^{-1} NLO 300 fb^{-1}

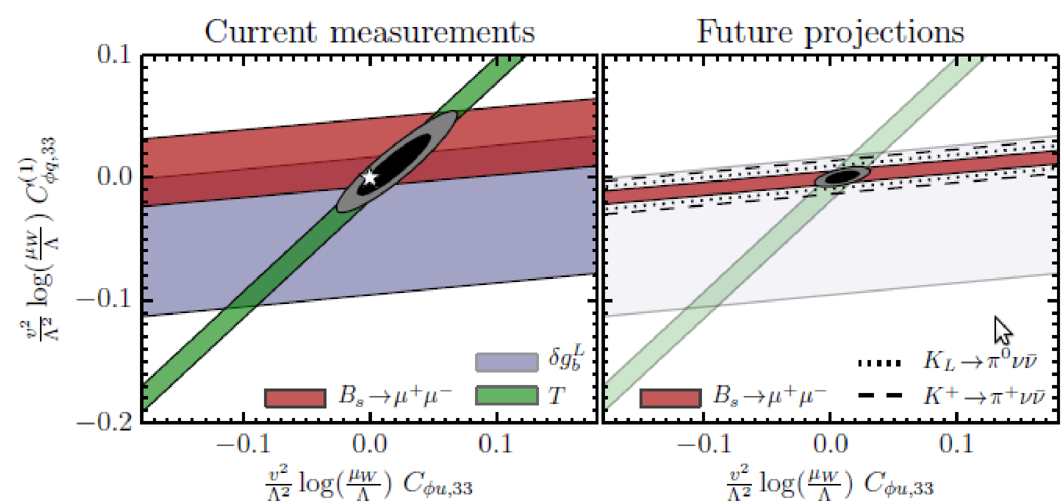
LO 3000 fb^{-1} NLO 3000 fb^{-1}



Constraints on dim-six operators



[Brod,Greljo,Stamou,Uttayarat]

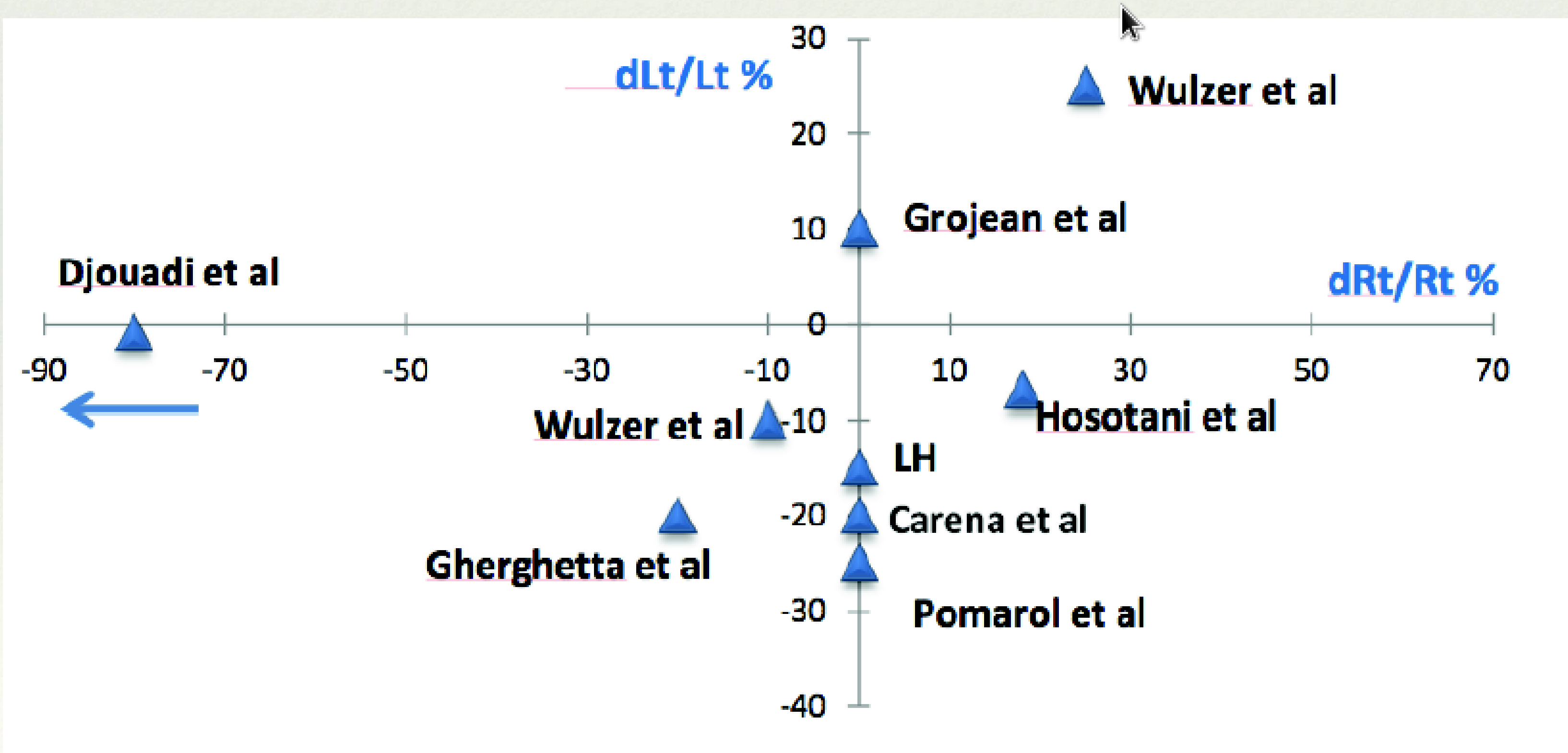


Order of magnitute stronger bounds than direct reach with 3000/fb!

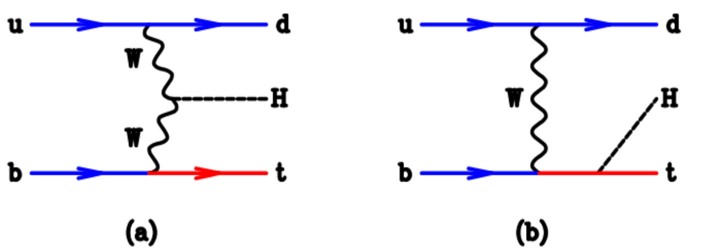
T	0.08 ± 0.07	[Ciuchini et al., arxiv:1306.4644]
δg_L^b	0.0016 ± 0.0015	[Ciuchini et al., arxiv:1306.4644]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [CMS]	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	[CMS, arxiv:1307.5025]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [LHCb]	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$	[LHCb, arxiv:1307.5024]
$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	[E949, arxiv:0808.2459]

le Higgs models, …

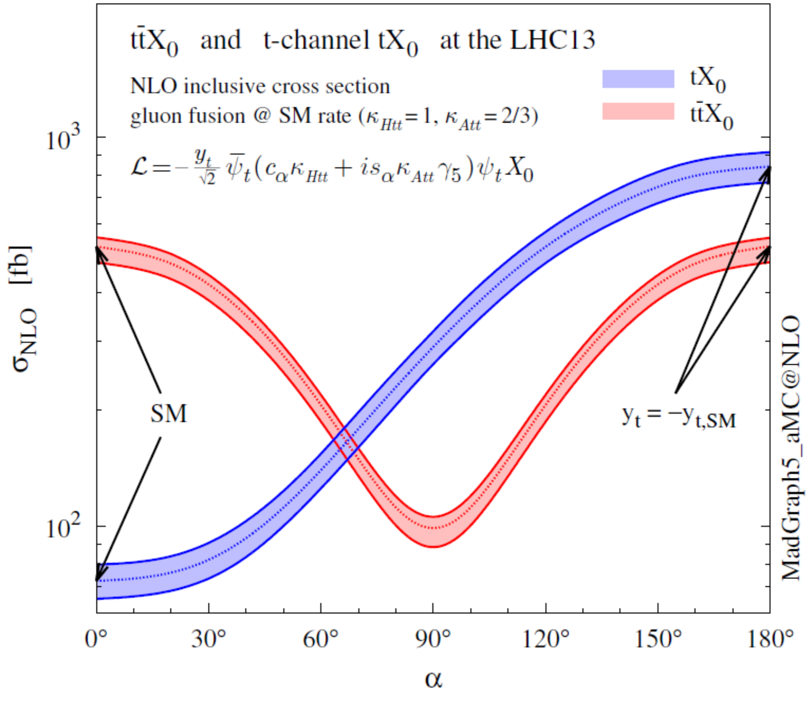
[Richard, 2014]



single top + H:
NLO QCD



$$\mathcal{L}_0^t = -\bar{\psi}_t \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5\big) \psi_t \, X_0 \,,$$



- ttb+H cannot resolve the sign of y_t
- t+qH anomalous cross section grows large

Top quark properties

- Top quark pair production yields sensitivity to *chromo-magnetic/electric dipole moments*

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$

$$\mathcal{L}_{\rm tg} = -g_s \bar{t}\gamma^{\mu}\frac{\lambda_a}{2} t\, G^a_{\mu} + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}\,,$$

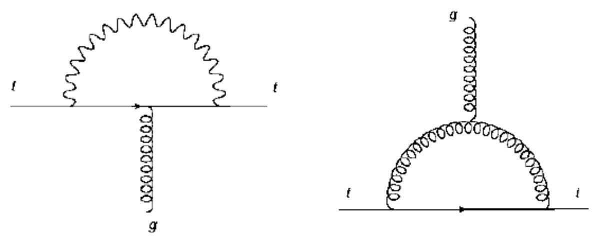
EDM *violate* CP:

$$P(\vec{E}\cdot\vec{S}) = -\vec{E}\cdot\vec{S}$$
$$T(\vec{E}\cdot\vec{S}) = -\vec{E}\cdot\vec{S}$$

complex coupling

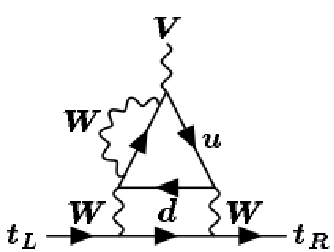
- In the SM, dipole moments are generated *radiatively*

MDM:



$\sim d_V \approx -0.007$

EDM:



$\sim d_A \approx$ tiny

[Shabalin,Khriplovich,Czarnecki,Krause] (1980-90)

- Top quark pair production yields sensitivity to *chromo-magnetic/electric dipole moments*

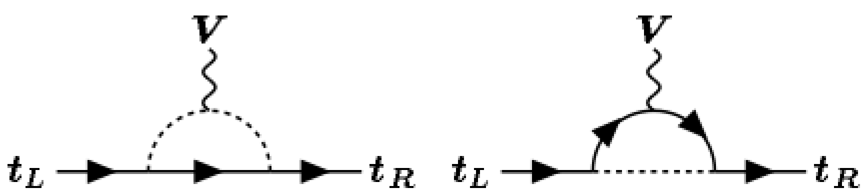
$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S} \qquad \mathcal{L}_{\rm tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}\,,$$

EDM *violate* CP:

$$P(\vec{E}\cdot\vec{S}) = -\vec{E}\cdot\vec{S}$$
$$T(\vec{E}\cdot\vec{S}) = -\vec{E}\cdot\vec{S}$$

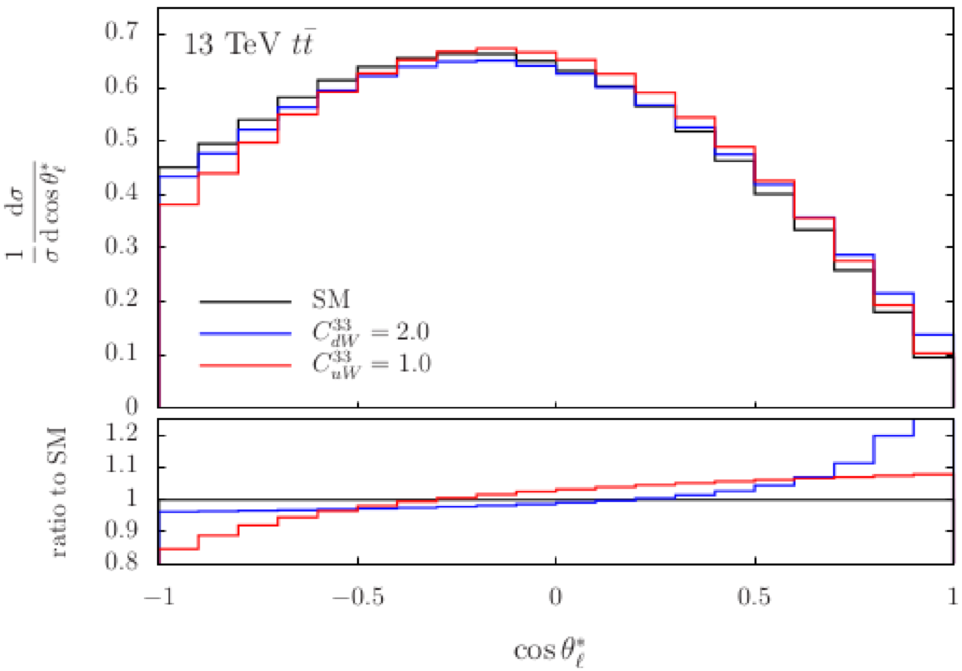
complex coupling

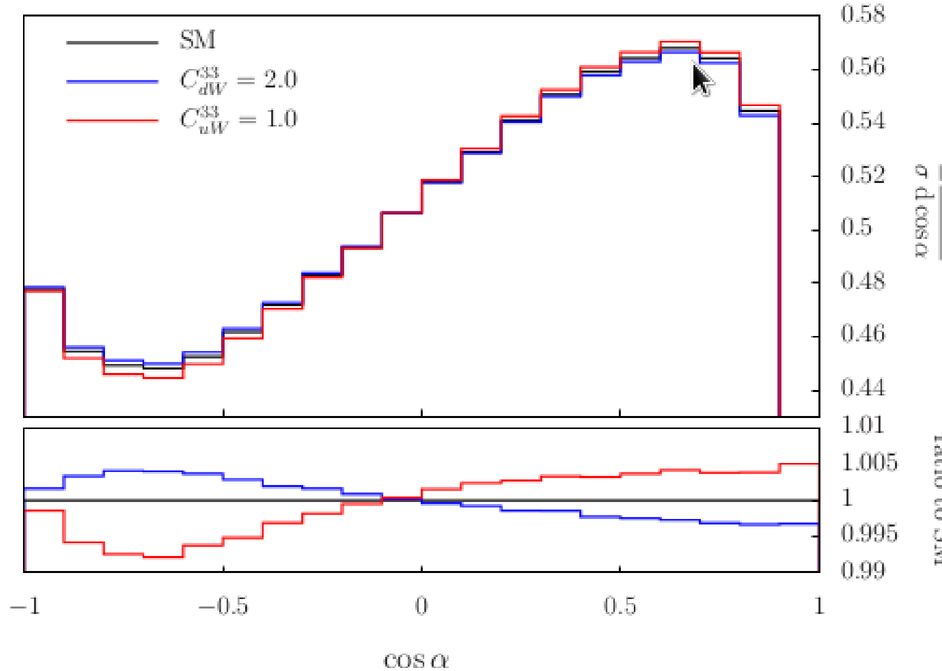
- Beyond the SM, dipole moment couplings can arise already at tree level



$$O^{33}_{uG\phi} = (\bar{q}_{L3}\lambda_a \sigma^{\mu\nu} t_R)\tilde{\phi}\, G^a_{\mu\nu}\;, \quad d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} {\rm Re}\, C^{33}_{uG\phi}\,, \quad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} {\rm Im}\, C^{33}_{uG\phi}$$

$$\text{For } \Lambda \approx 1\,\text{TeV}:\; d_{V,A} \approx 0.05 = \text{big!}$$





$$\cos\theta_\ell^* = \frac{\vec{\hat{p}}_\ell \cdot \vec{\tilde{p}}_W}{|\vec{\hat{p}}_\ell|\,|\vec{\tilde{p}}_W|}, \qquad \cos\alpha = \frac{\vec{p}_t \cdot \vec{\tilde{p}}_W}{|\vec{p}_t|\,|\vec{\tilde{p}}_W|}, \qquad A_\phi(c_0) = \frac{\sigma(\cos\phi < c_0) - \sigma(\cos\phi > c_0)}{\sigma(\cos\phi < c_0) + \sigma(\cos\phi > c_0)},$$