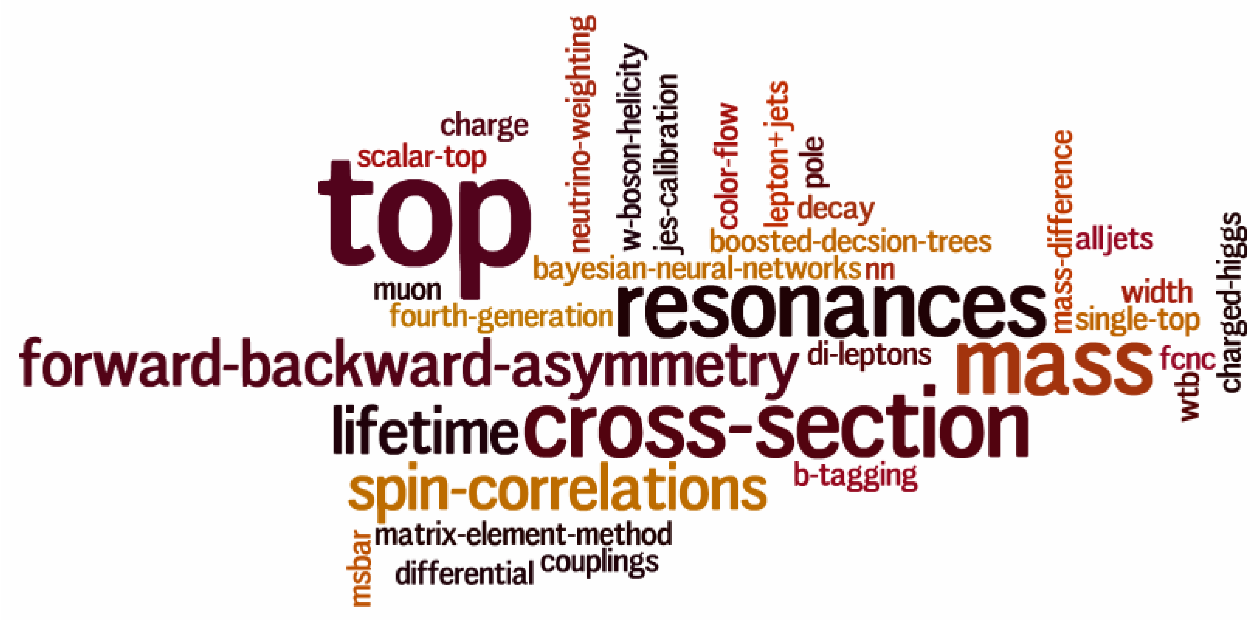
Constraining top quark Z-boson couplings at the LHC

Markus Schulze

in collaboration with R. Röntsch

based on
JHEP 1407 (2014) 091; arXiv:1501.05939

Twenty years after the top quark discovery



- Our understanding of the top quark as an elementary particle and its dynamics in QCD is very solid.

- Many of its properties were explored at the Tevatron.

- What about interactions with the electroweak sector of the SM?

The Top Quark and Electroweak Theory

→ **What do we know about top quark interactions with γ, Z, W or H** ?

- This question immediately motivates the study of the processes

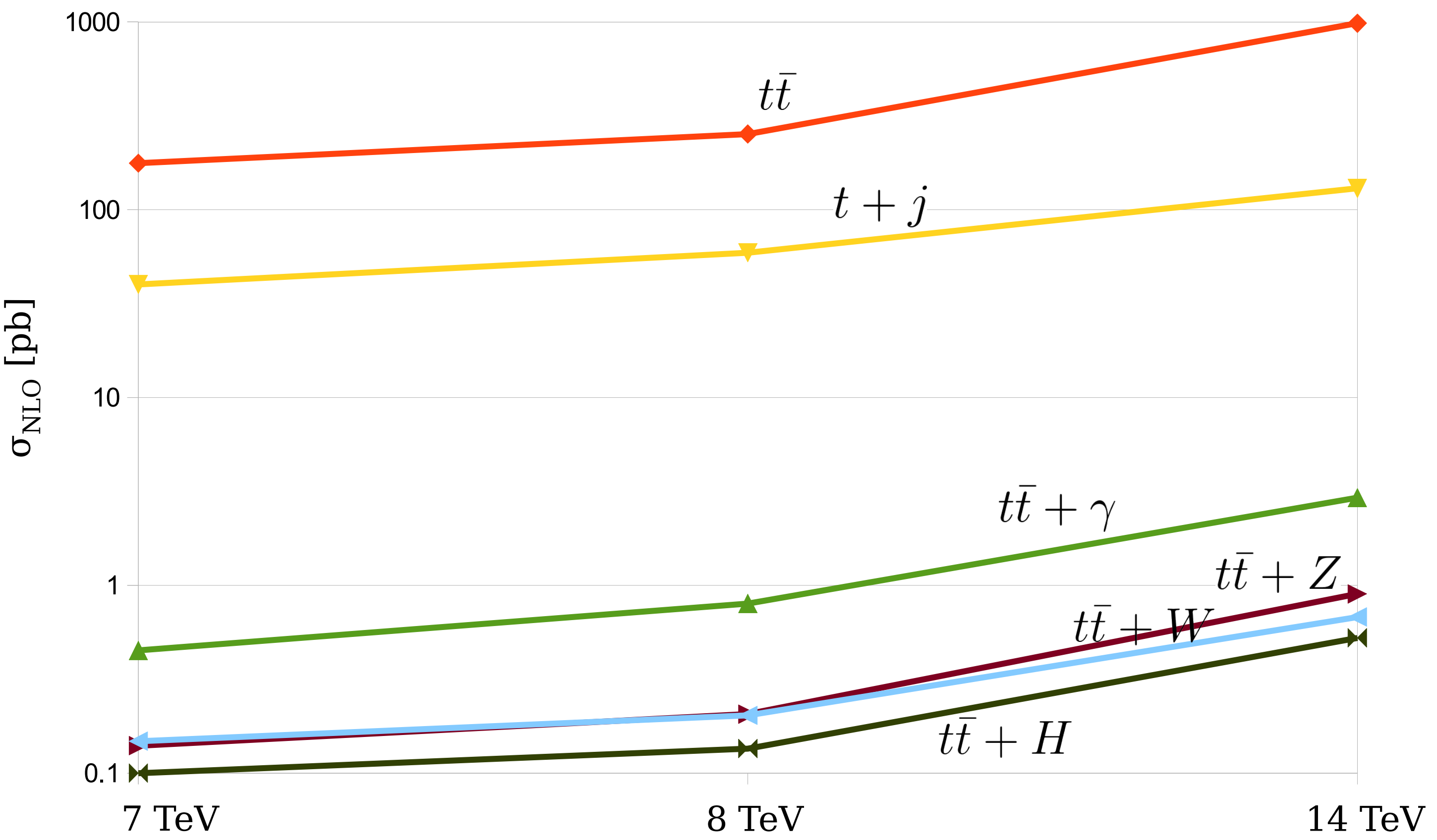
$$t\bar{t} + V \qquad t\bar{t} + H$$

- CDF finds 30 ttb+γ events. All other processes have never been observed at the Tevatron (high threshold + penalties from branching fractions).

→ Study of these processes at the LHC will open a new era in top quark physics

→ What precision can be reached?

Spectrum of cross sections



[Baernreuther,Czakon,Fiedler,Mitov],[Campbell,Ellis,Röntsch],
[Melnikov,Scharf,M.S.],[Garzelli,Kardos,Papadopoulos,Trocsanyi],
[Demartin,Maltoni,Mawatari,Page,Zaro]

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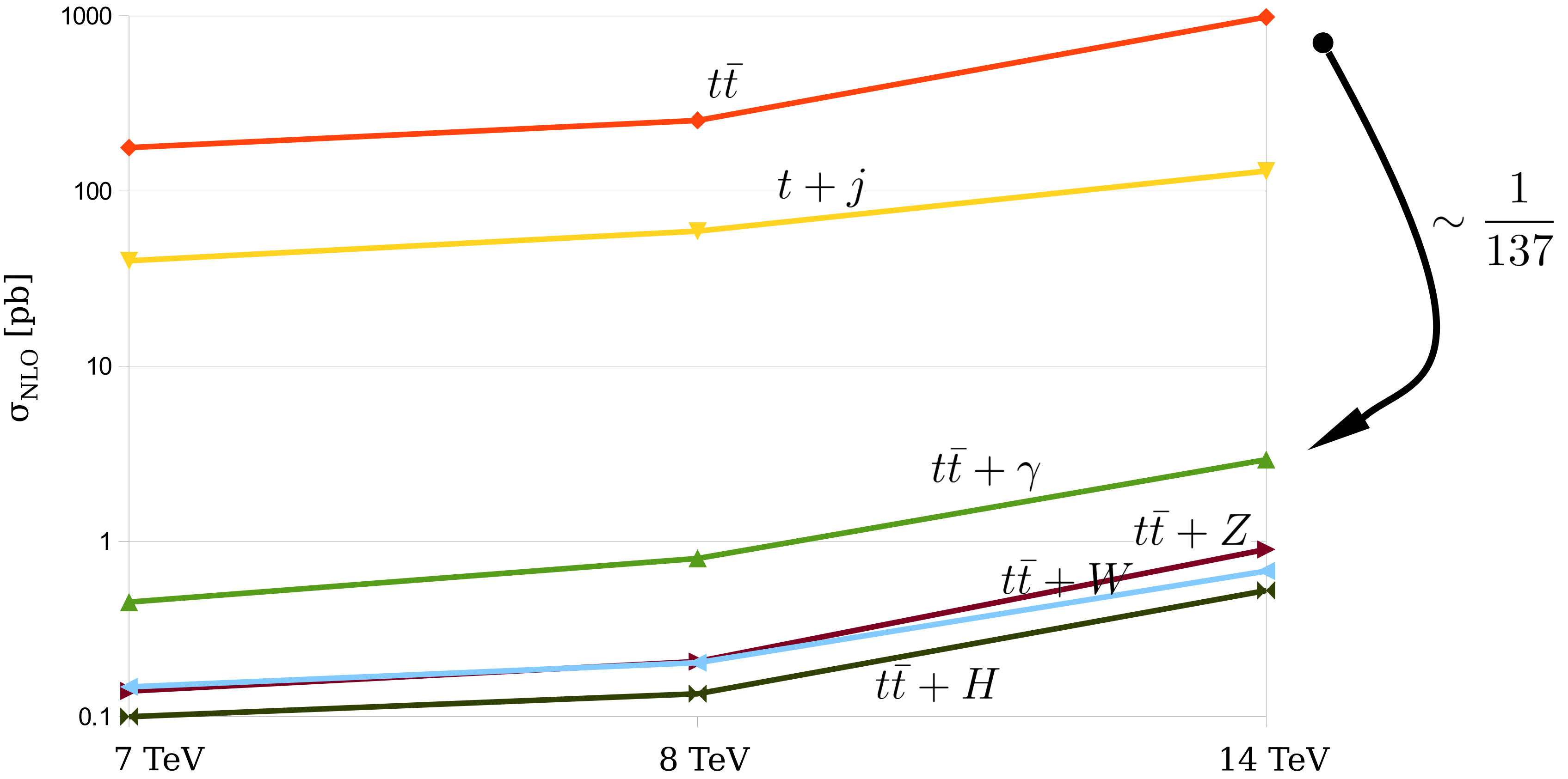

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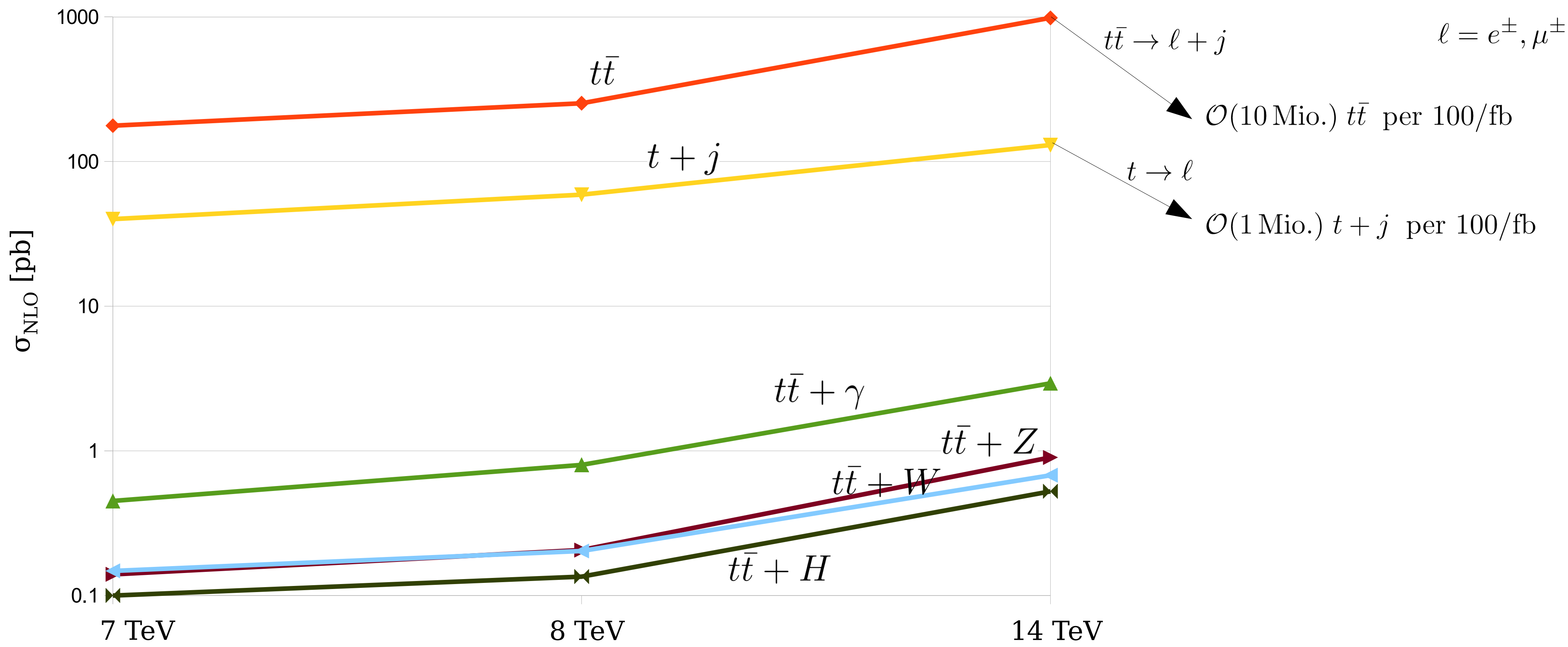

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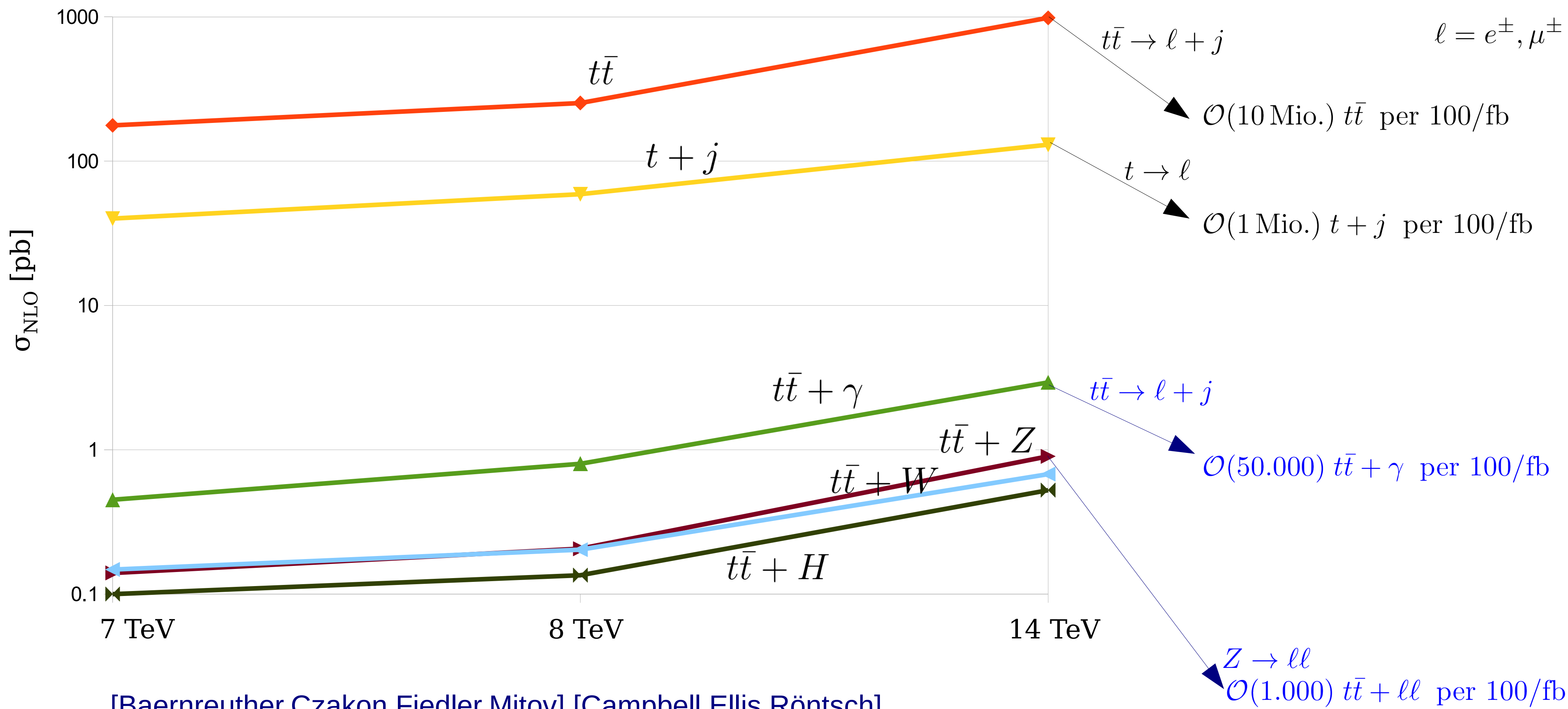

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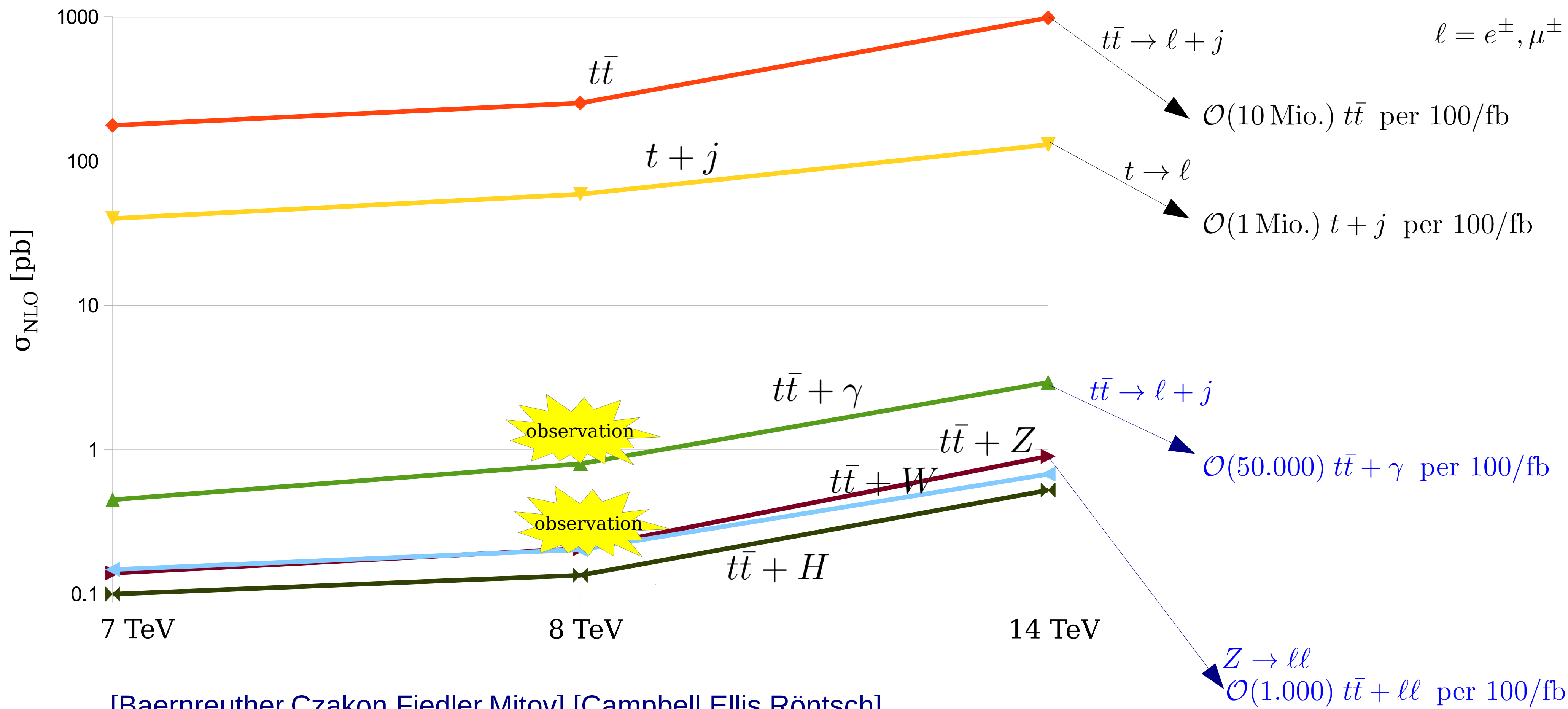

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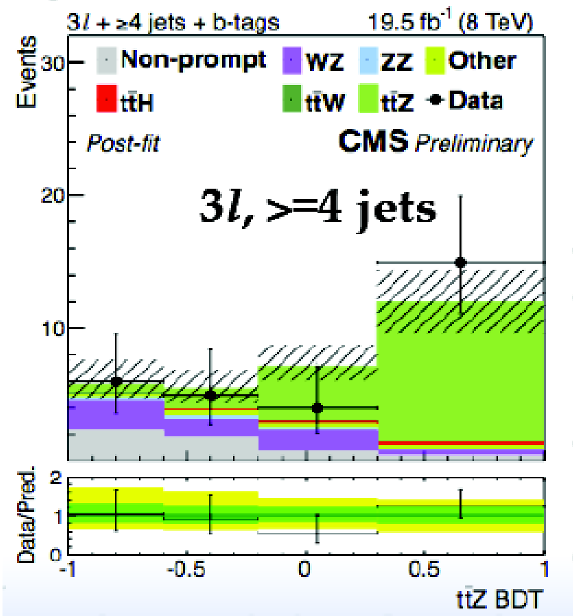
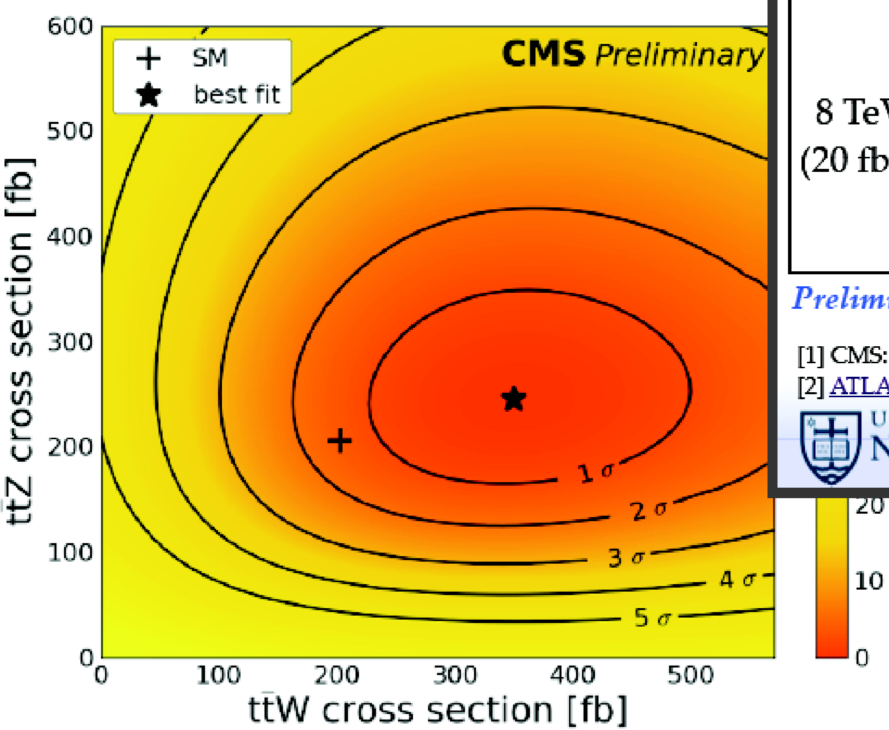
Experimental results from Run-1





Summary

ttW and ttZ measurements		ttW				ttZ			
		Cross section		Significance		Cross section		Significance	
Data	Analysis	Theory*	Obs.	Exp.	Obs.	Theory*	Obs.	Exp.	Obs.
7 TeV (5 fb^{-1})	CMS[1]	147^{+14}_{-16}	-	-	-	137^{+12}_{-16}	280^{+150}_{-110}	?	3.3
	ATLAS[2]		-	-	-		< 710	-	-
8 TeV (20 fb^{-1})	CMS[3]	203^{+20}_{-22}	170^{+110}_{-100}	2.0	1.6	206^{+19}_{-24}	200^{+90}_{-80}	3.1	3.1
	ATLAS[4]		300^{+140}_{-110}	2.3	3.1		150^{+58}_{-54}	3.4	3.1
	CMS *Preliminary*		**382^{+117}_{-102}**	**3.5**	**4.8**		**242^{+65}_{-55}**	**5.7**	**6.4**

Preliminary documentation: twiki.cern.ch/twiki/bin/view/CMSPublic/**PhysicsResultsTOP14021**

[1] CMS: *Phys. Rev. Lett.* 110 (2013) 172002
[2] ATLAS-CONF-12-126
[3] CMS: EPJ C74 (2014) 3060
[4] ATLAS-CONF-2014-038

* NLO cross sections with scale uncertainties from Garzelli et. al., JHEP 11 (2012) 056

UNIVERSITY OF NOTRE DAME 23 **Andrew Brinkerhoff**

Anomalous couplings

Minimal set of top quark anomalous couplings: [Aguilar-Saavedra]

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

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

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

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$$\mathcal{L}^{\text{eff}} = \sum \frac{C_x}{\Lambda^2}O_x + \dots\,,$$

$$\delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}\,, \quad \delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2}\,, \quad \delta d_V^{\gamma} = \frac{\sqrt{2}}{e}\,\text{Re}\,\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,,$$

$$\delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}\,. \quad \delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2}\,, \quad \delta d_A^{\gamma} = \frac{\sqrt{2}}{e}\,\text{Im}\,\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,.$$

$$\delta X_{tt}^{L} = \text{Re}\,\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)}\right]\frac{v^2}{\Lambda^2}\,, \quad \delta d_V^Z = \sqrt{2}\,\text{Re}\,\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta X_{tt}^{R} = -\text{Re}\,C_{\phi u}^{33}\frac{v^2}{\Lambda^2}\,, \quad \delta d_A^Z = \sqrt{2}\,\text{Im}\,\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}\right]\frac{v^2}{\Lambda^2}\,.$$

$$\delta Y_t^V = -\frac{3}{2}\,\text{Re}\,C_{u\phi}^{33}\frac{v^2}{\Lambda^2}\,,$$

$$\delta Y_t^A = -\frac{3}{2}\,\text{Im}\,C_{u\phi}^{33}\frac{v^2}{\Lambda^2}\,.$$

$$O_{\phi q}^{(3,ij)} = i(\phi^{\dagger}\tau^I D_{\mu}\phi)(\bar{q}_{Li}\gamma^{\mu}\tau^I q_{Lj})\,,$$
$$O_{\phi q}^{(1,ij)} = i(\phi^{\dagger} D_{\mu}\phi)(\bar{q}_{Li}\gamma^{\mu} q_{Lj})\,,$$
$$O_{\phi\phi}^{ij} = i(\tilde{\phi}^{\dagger} D_{\mu}\phi)(\bar{u}_{Ri}\gamma^{\mu} d_{Rj})\,,$$
$$O_{\phi u}^{ij} = i(\phi^{\dagger} D_{\mu}\phi)(\bar{u}_{Ri}\gamma^{\mu} u_{Rj})\,,$$
$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\,W_{\mu\nu}^I\,,$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\,W_{\mu\nu}^I\,,$$
$$O_{uB\phi}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\,B_{\mu\nu}\,,$$

$$O_{Du}^{ij} = (\bar{q}_{Li}\,D_{\mu}u_{Rj})\,D^{\mu}\,\tilde{\phi}\,,$$
$$O_{\bar{D}u}^{ij} = (D_{\mu}\bar{q}_{Li}\,u_{Rj})\,D^{\mu}\,\tilde{\phi}\,,$$
$$O_{Dd}^{ij} = (\bar{q}_{Li}\,D_{\mu}d_{Rj})\,D^{\mu}\,\phi\,,$$
$$O_{\bar{D}d}^{ij} = (D_{\mu}\bar{q}_{Li}\,d_{Rj})\,D^{\mu}\,\phi\,,$$
$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^{\mu}\tau^I D^{\nu}q_{Lj}W_{\mu\nu}^I\,,$$
$$O_{qB}^{ij} = \bar{q}_{Li}\gamma^{\mu} D^{\nu}q_{Lj}B_{\mu\nu}\,,$$
$$O_{uB}^{ij} = \bar{u}_{Ri}\gamma^{\mu} D^{\nu}u_{Rj}B_{\mu\nu}\,,$$

Anomalous couplings

Minimal set of top quark anomalous couplings: [Aguilar-Saavedra]

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

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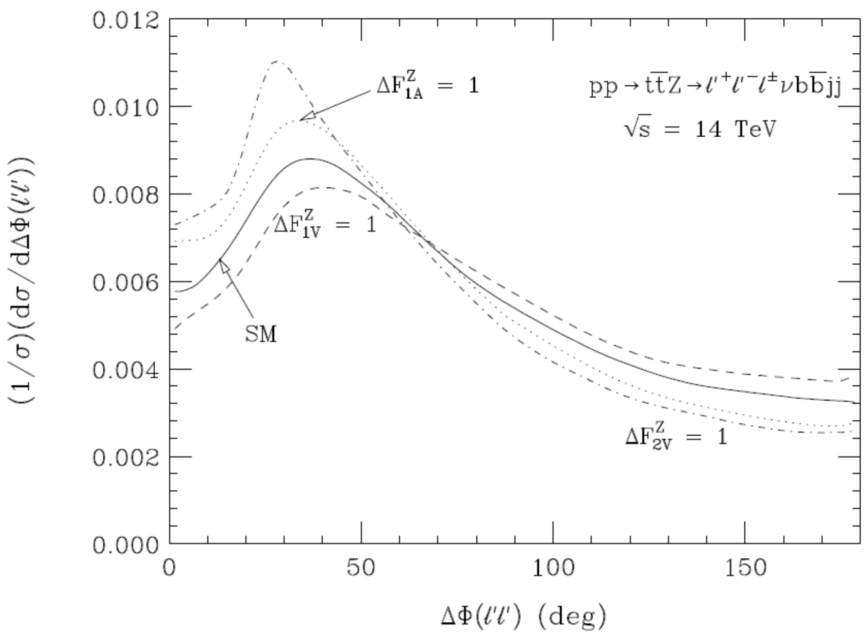
modifies strength of SM couplings

introduces anomalous weak *magnetic* and *electric dipole moments*

$t\bar{t} + Z$

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

[Baur,Juste,Orr,Rainwater] (2004)



LO coupling constraints

$$\Gamma_{\mu}^{ttV}(k^2,\, q,\, \bar{q}) = -ie \left\{ \gamma_\mu \, \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t} \, (q+\bar{q})^\nu \, \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right) \right\}$$

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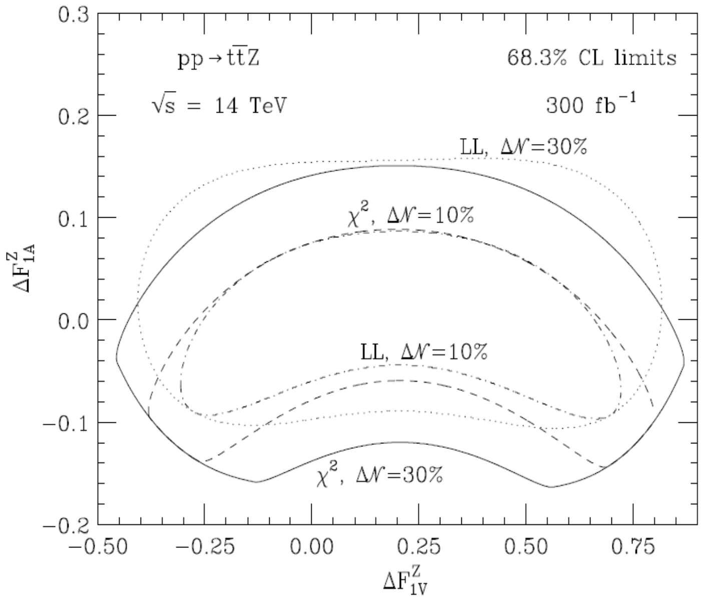
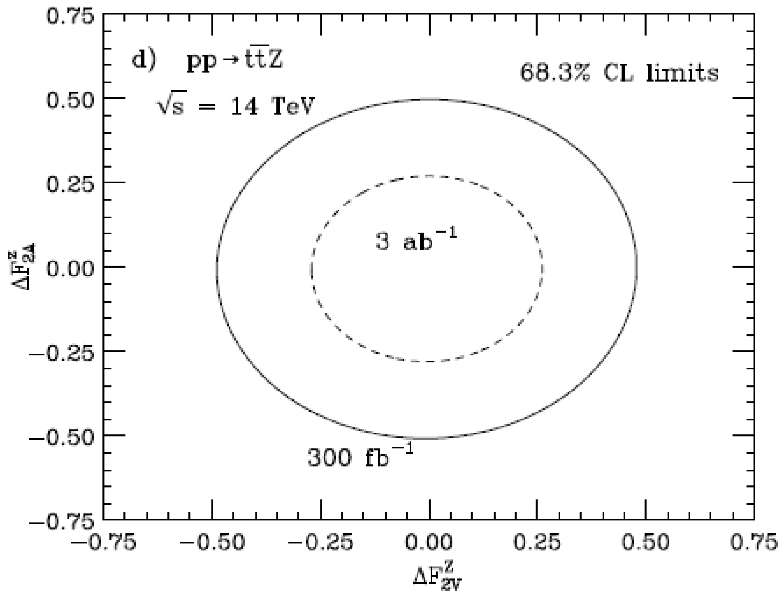


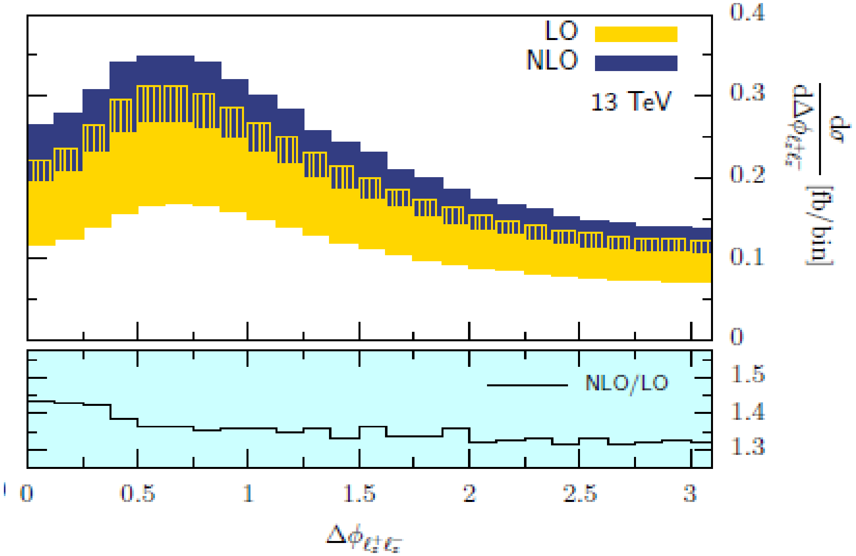


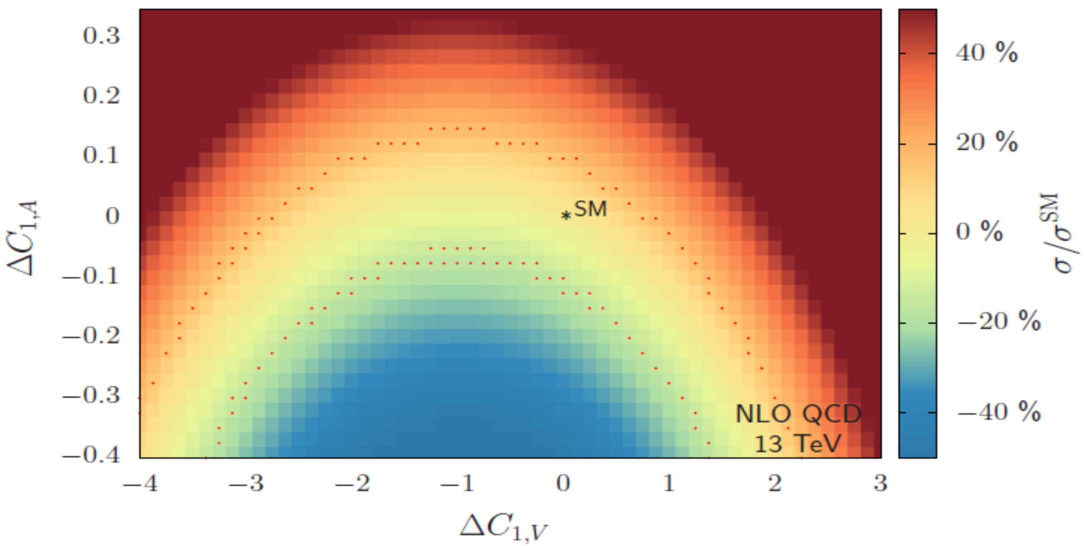
→ "Residual scale uncertainty is biggest limiting factor in these studies."

NLO coupling constraints

- Realistic final state with top and Z decays (here: 3 leptons + 4 jets)
- NLO QCD corrections in top quark production and decay with anomalous couplings
- Fully differential predictions with CMS and ATLAS acceptance cuts

[R. Röntsch, M.S.]





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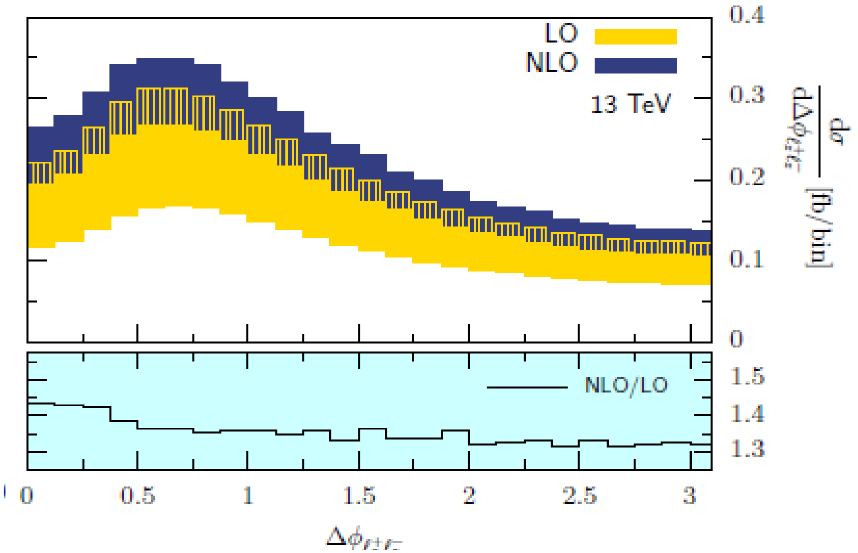
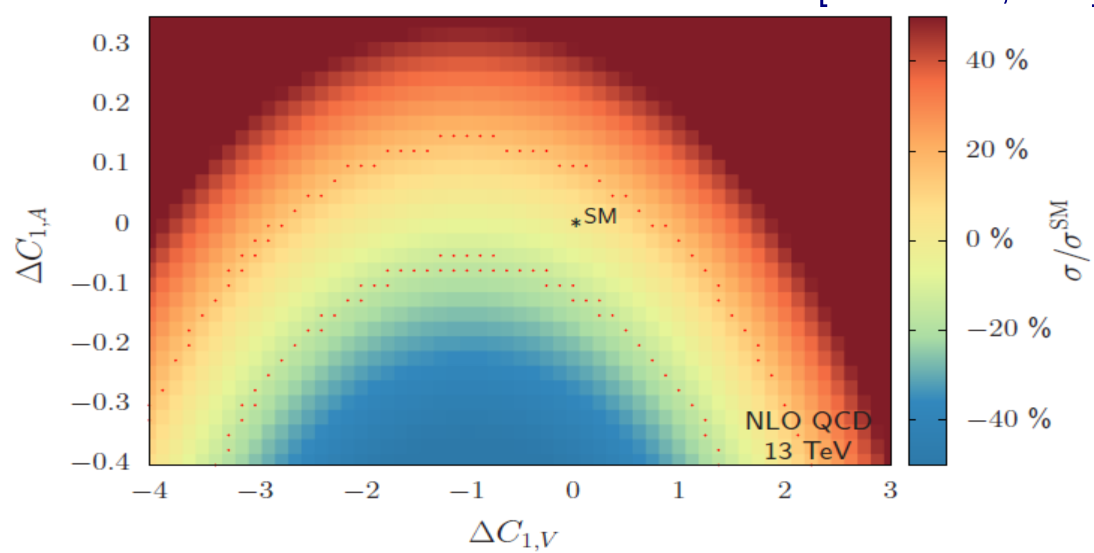
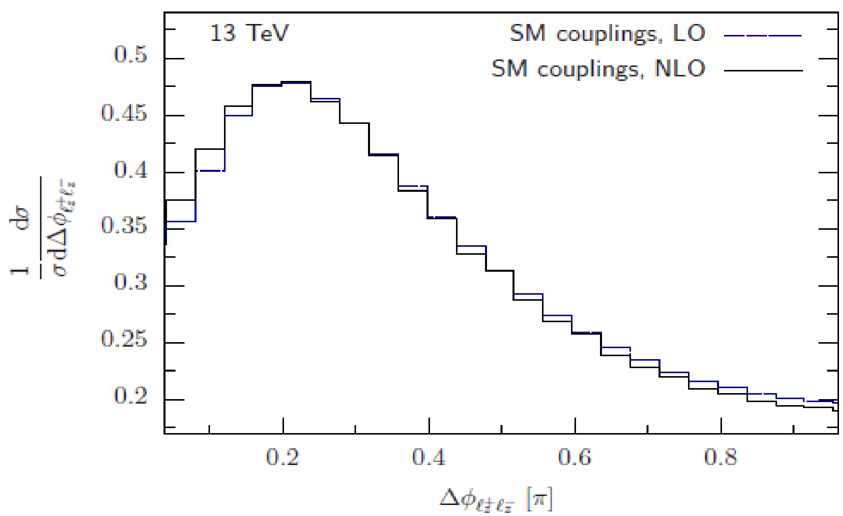
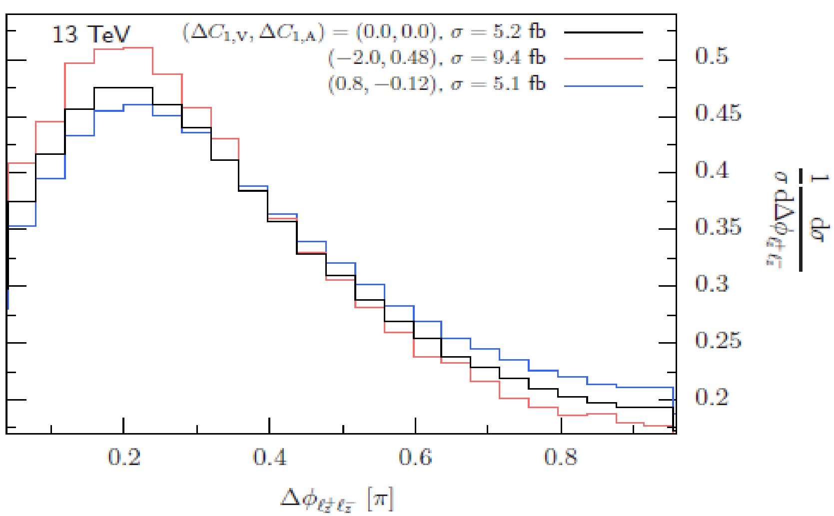




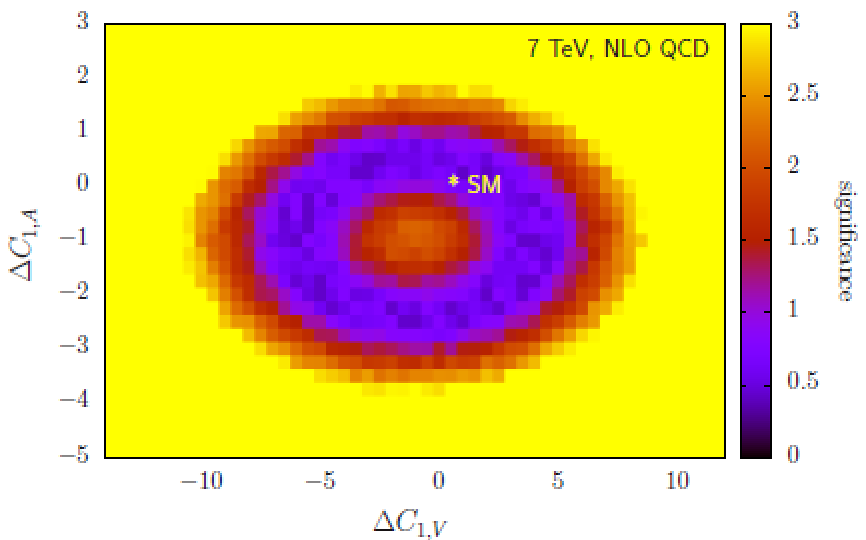




NLO coupling constraints

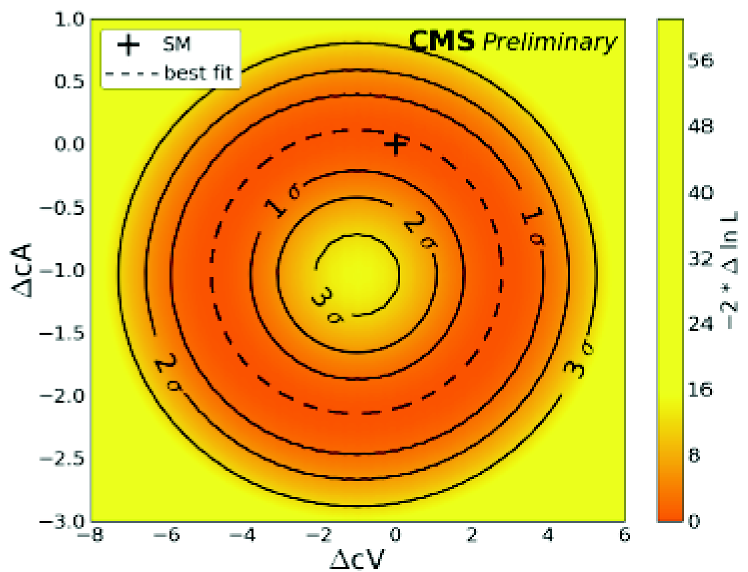
- Realistic final state with top and Z decays (here: 3 leptons + 4 jets)
- NLO QCD corrections in top quark production and decay with anomalous couplings
- Fully differential predictions with CMS and ATLAS acceptance cuts
- log-Likelihood ratio test to calculate exclusion of non-SM hypotheses (incl. uncertainties)

Our estimates for 7 TeV



[R. Röntsch, M.S.]

Application in CMS at 8 TeV



Difference between SM C_V and $C_{1,V}$

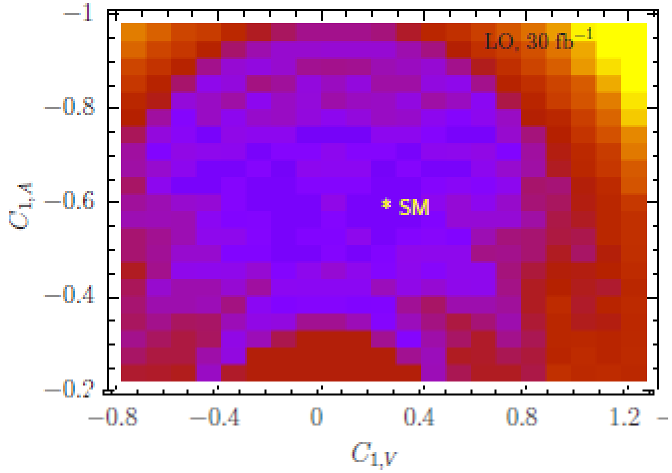
- Our estimates are compatible with experimental findings in [CMS (no PAS) TOP-14-021]

(no shape information used)

Constraints for LHC run-2

LHC 13 TeV (shape+normalization)

LO 30 fb^{-1}



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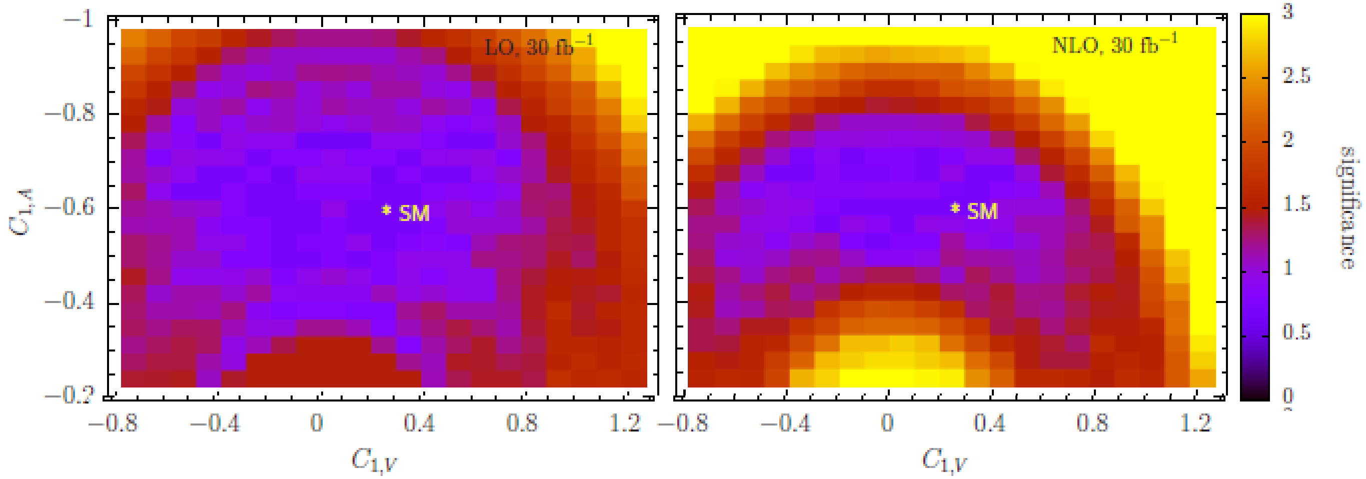

NLO 30 fb^{-1}

Constraints for LHC run-2

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LO 300 fb^{-1}

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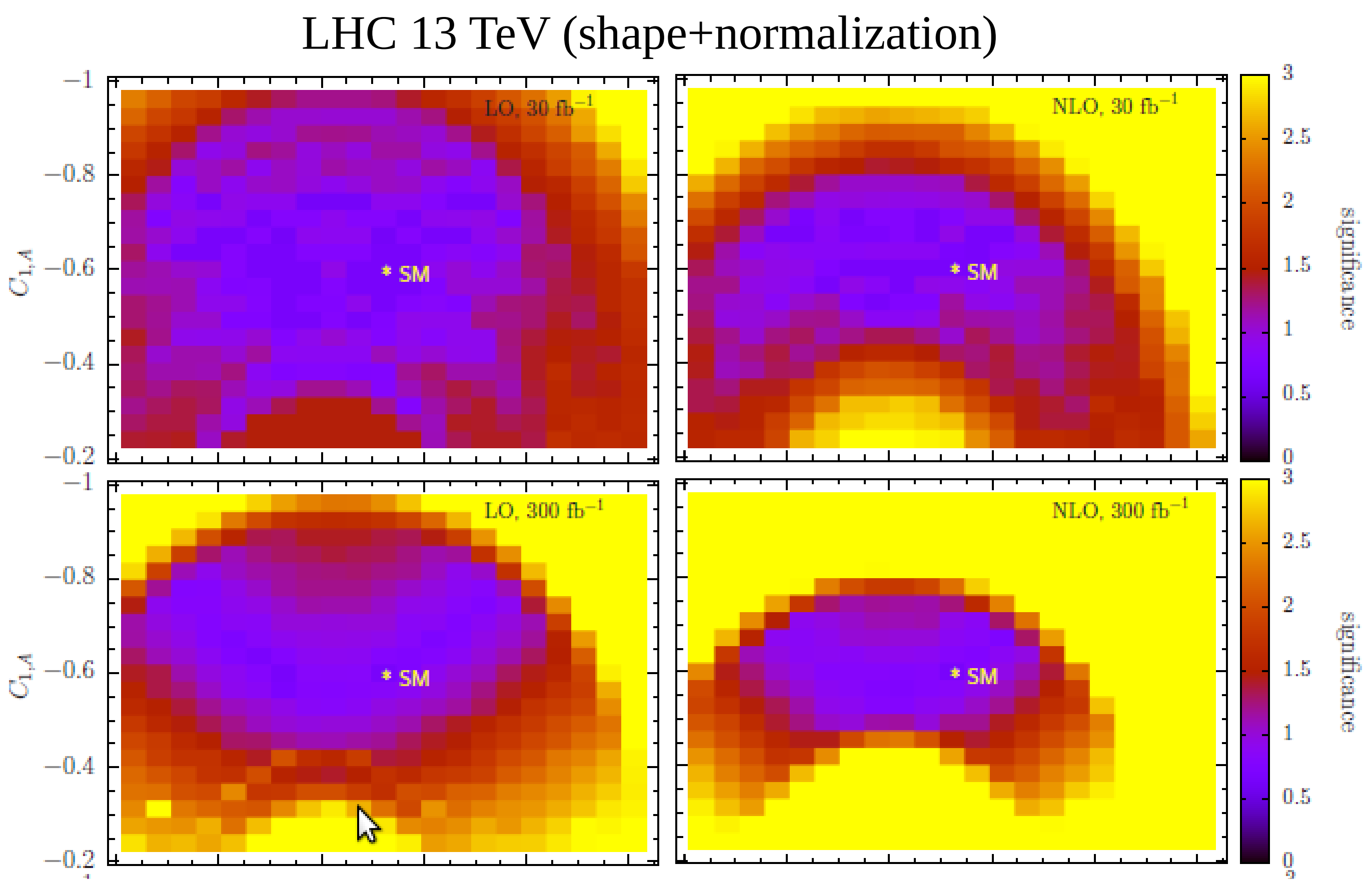
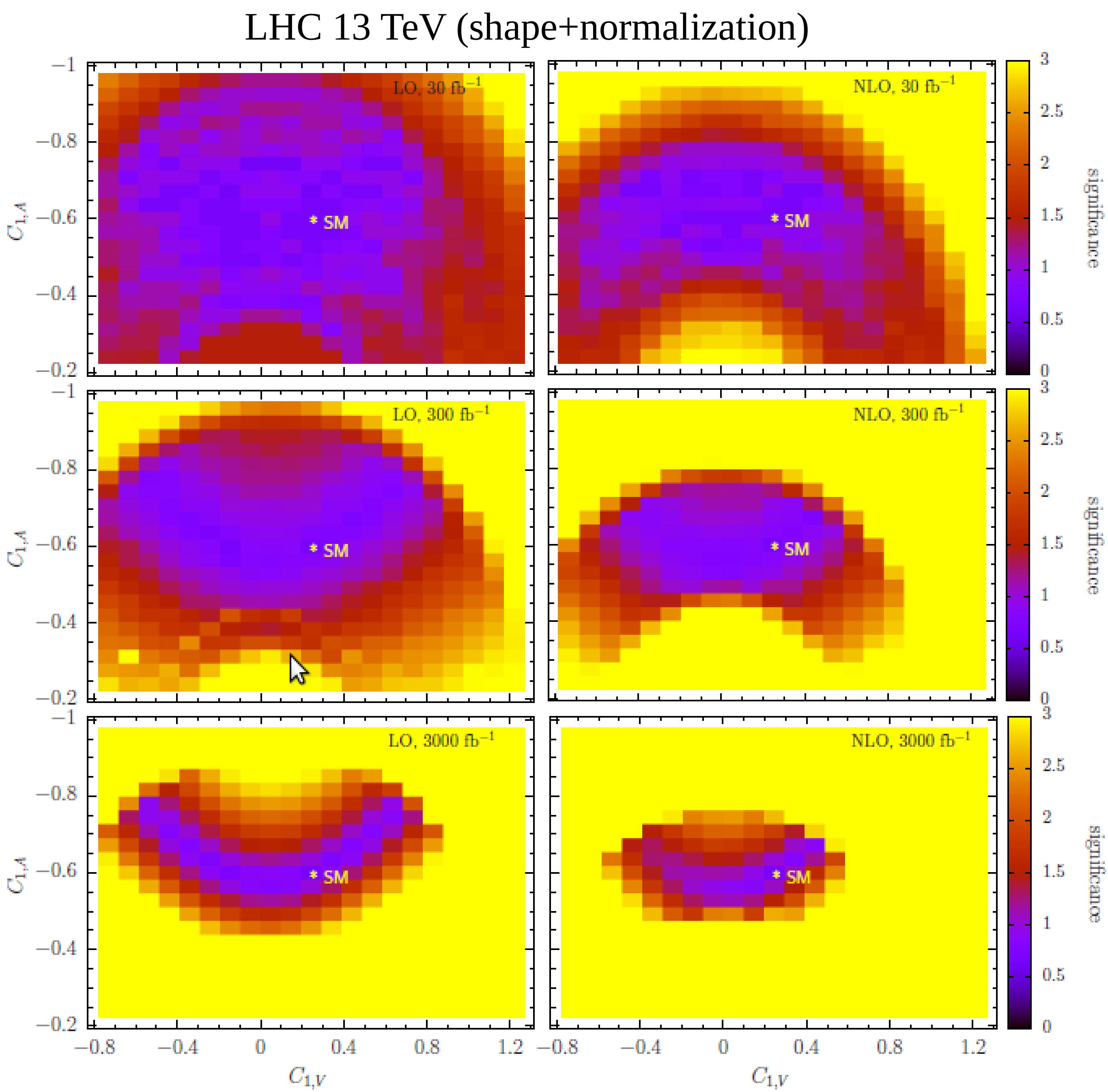


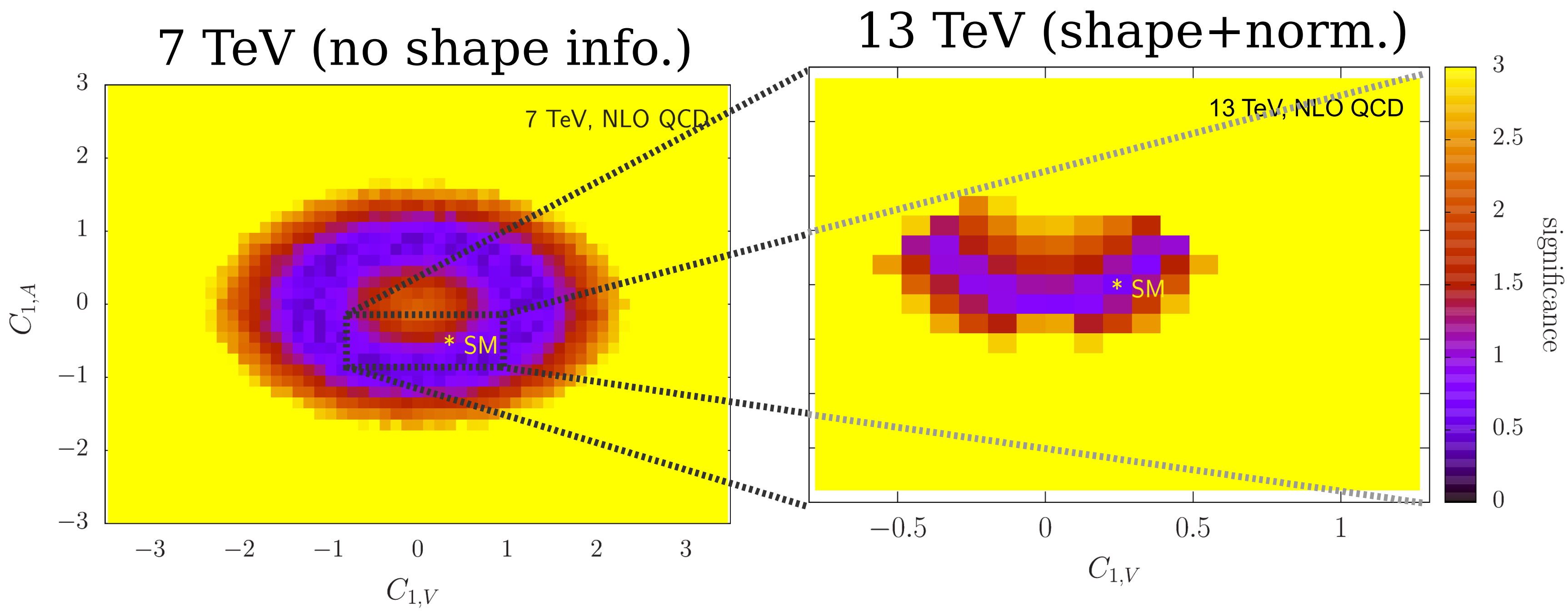
Constraints for LHC run-2

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

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

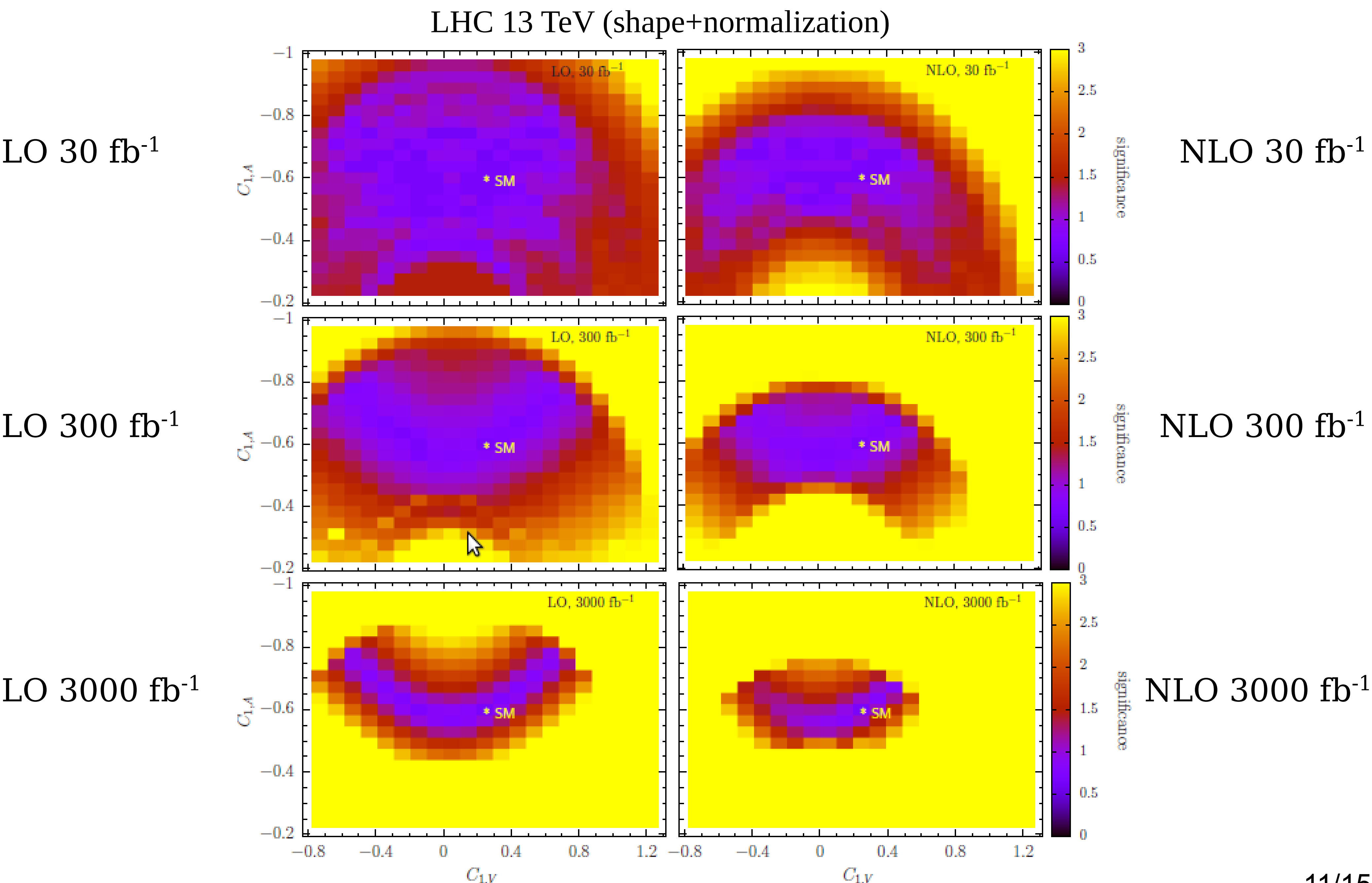
LO 3000 fb^{-1} / NLO 3000 fb^{-1}





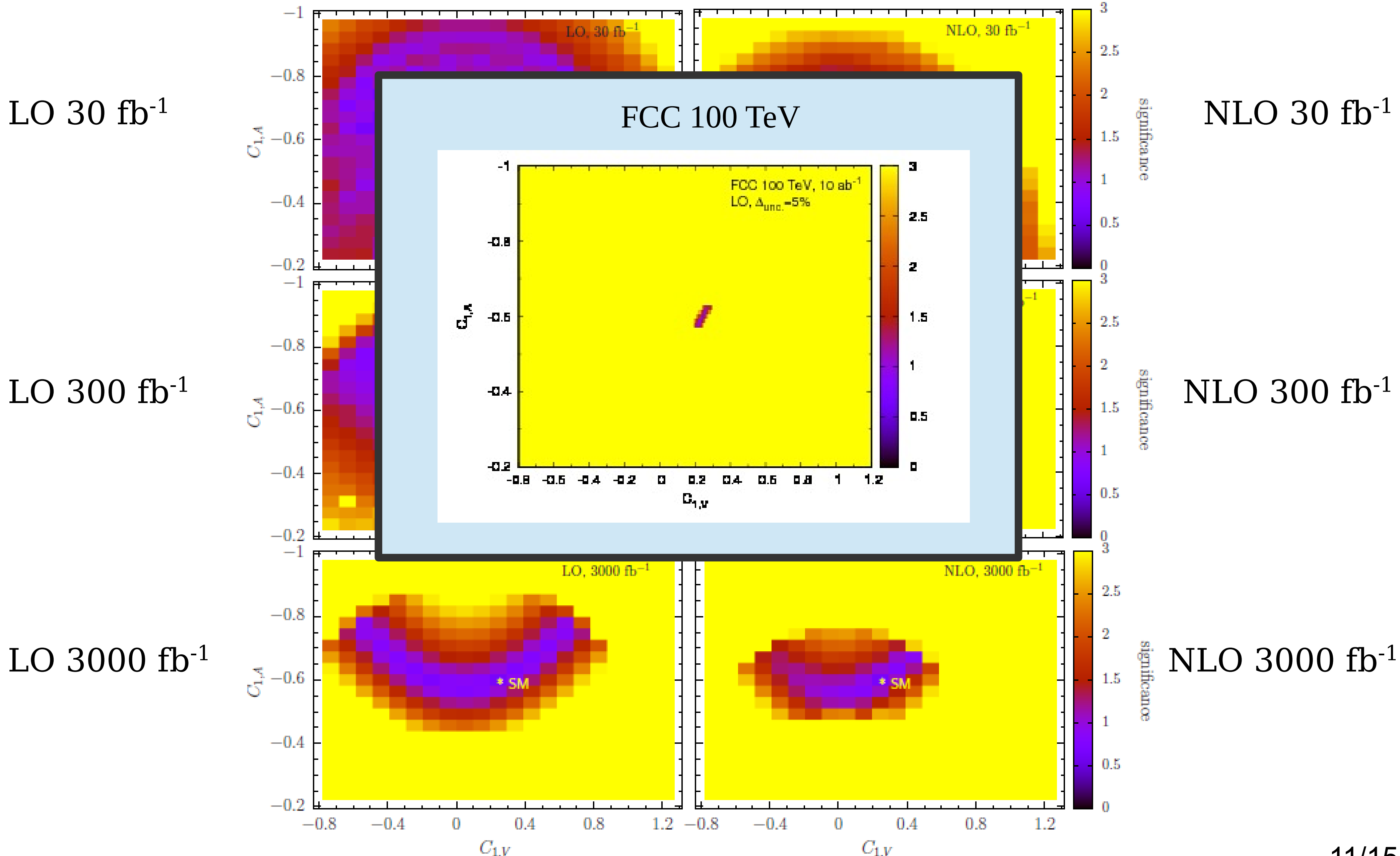
7 TeV (no shape info.)
13 TeV (shape+norm.)
7 TeV, NLO QCD
13 TeV, NLO QCD
* SM
* SM
$C_{1,A}$
$C_{1,V}$
$C_{1,V}$
significance

Constraints for LHC run-2



Constraints for LHC run-2

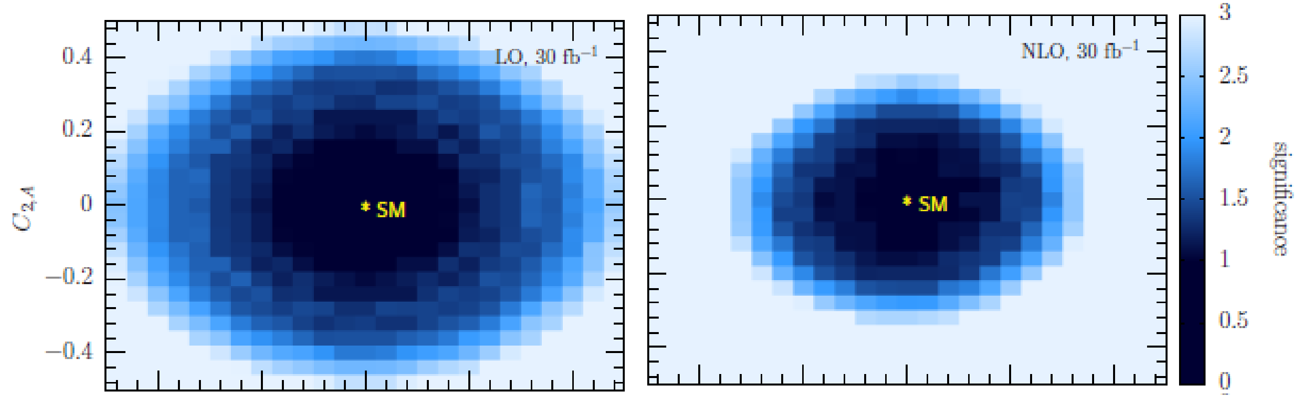
LHC 13 TeV (shape+normalization)



Constraints for LHC run-2

Weak dipole moments (~zero in the SM)

LO 30 fb^{-1}



NLO 30 fb^{-1}

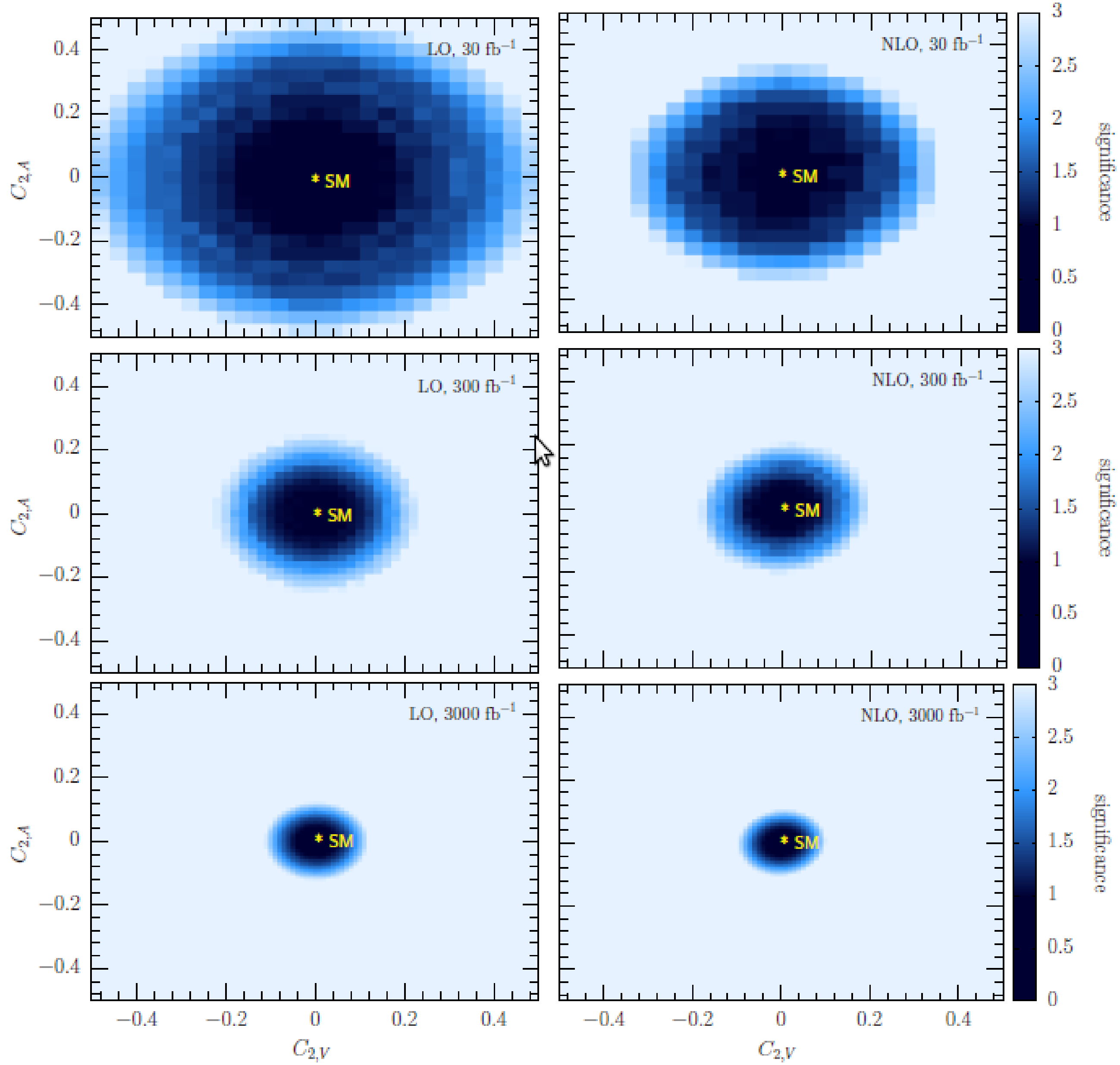
Constraints for LHC run-2

Weak dipole moments (~zero in the SM)

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

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

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



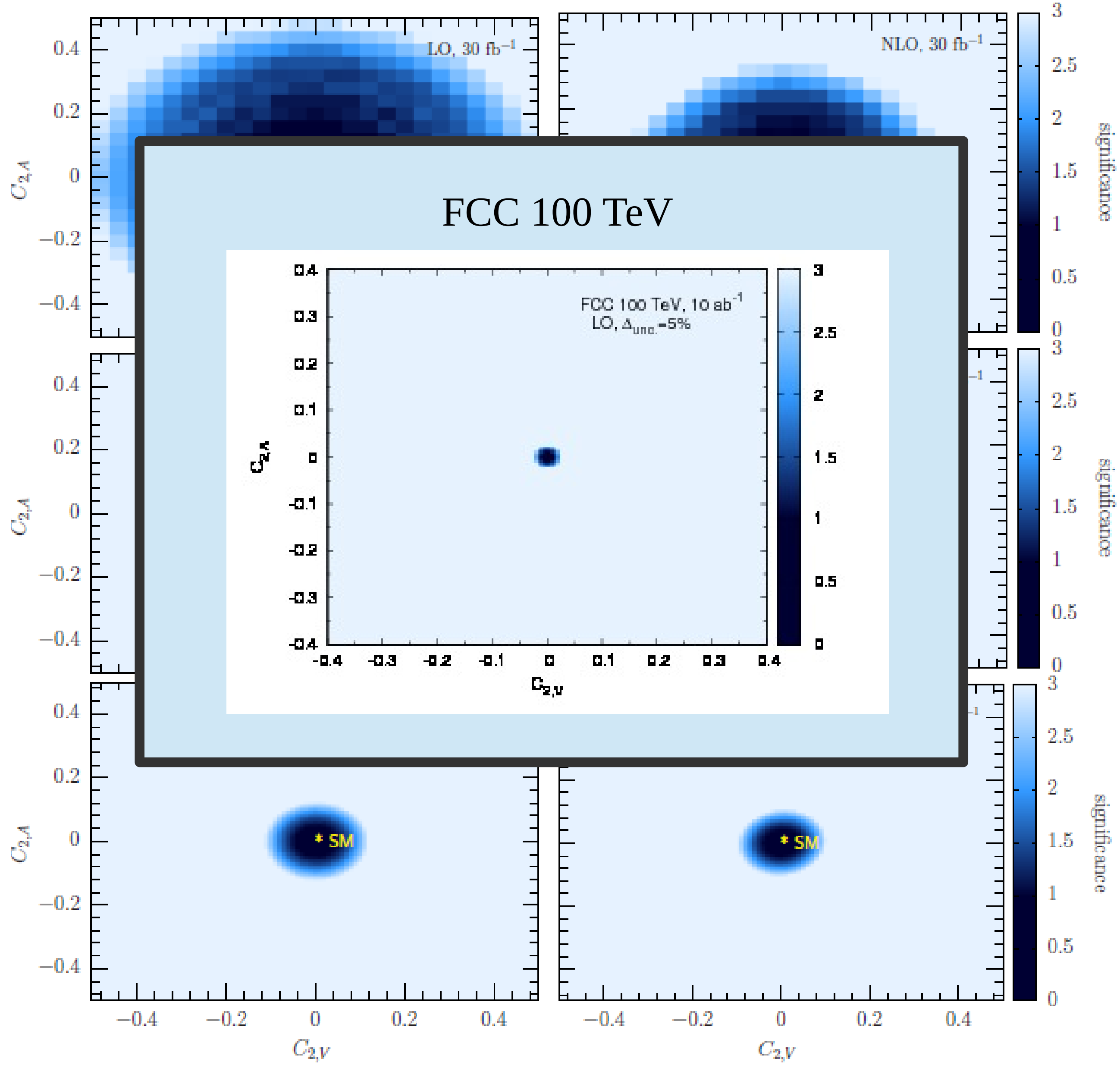
Constraints for LHC run-2

Weak dipole moments (~zero in the SM)

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

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

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



Correlations with other processes

- Constraints can be further strengthened by combining results from *ttbar, ttbar+Z, ttbar+γ*, single-top.

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

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

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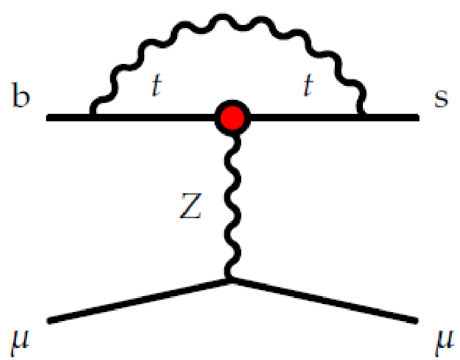
$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t}\,\gamma^{\mu} t\,A_{\mu} - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}(d_V^{\gamma} + i d_A^{\gamma}\gamma_5)\,t\,A_{\mu}\,.$$

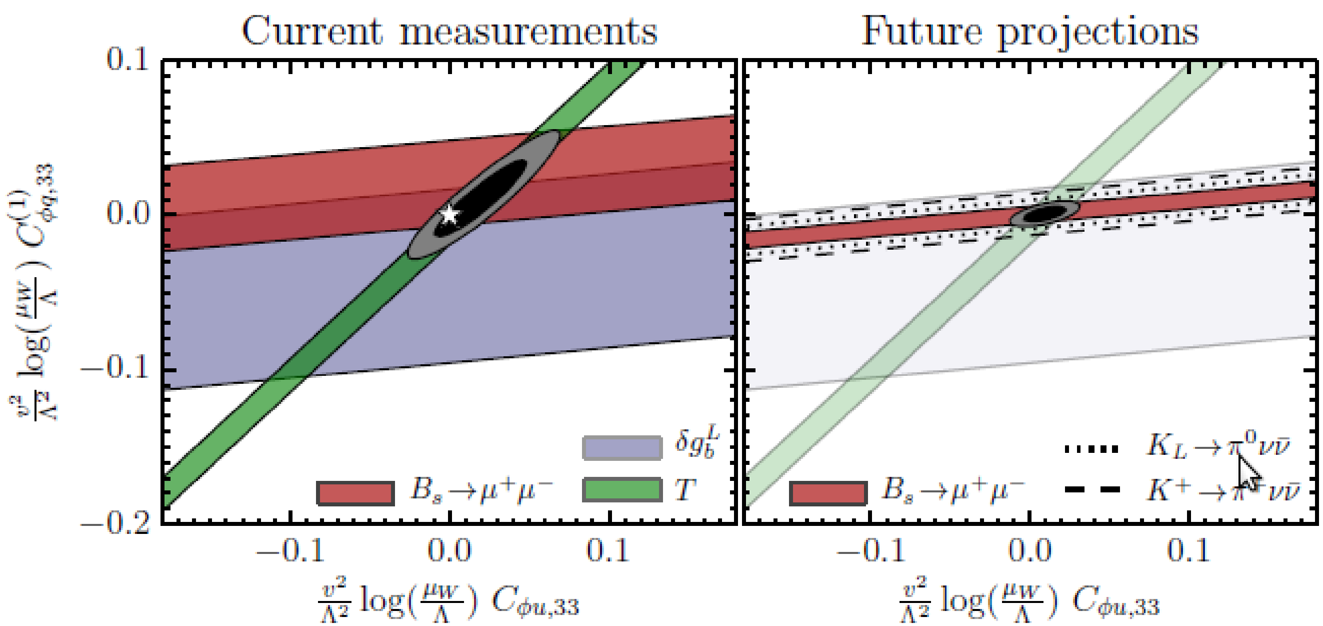
"A minimal set of top anomalous couplings" [J.A. Aguilar-Saavedra]

Indirect constraints

Probing anomalous top-Z interactions with rare meson decays

[Brod,Greljo,Stamou,Uttayarat]





Order of magnitude 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]

Conclusions

- LHC run-2 allows detailed studies of *ttb+Z* final states for the 1st time

- Subsequent coupling constraints yield *direct* sensitivity to physics beyond the SM and complement indirect determinations from low energy experiments

- State-of-the-art NLO QCD predictions for anomalous electroweak top couplings are available and significantly improve coupling constraints

- Combination with other processes (*ttbar, ttbar+γ, single-top Z*) will further strengthen the limits

Extras

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

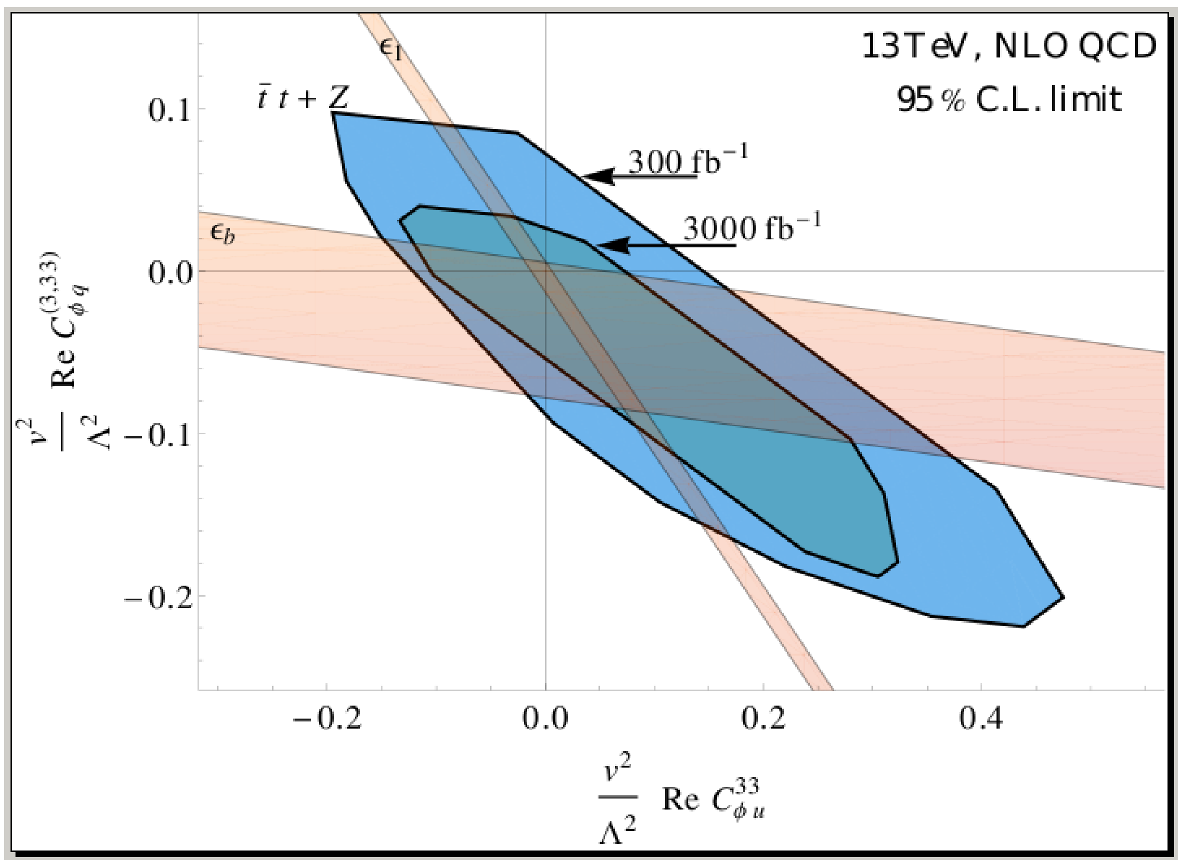
$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right],$$

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

$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger\tau^a D_\mu\phi)\,(\bar{t}_\mathrm{L}\gamma^\mu\tau_a t_\mathrm{L}),$$

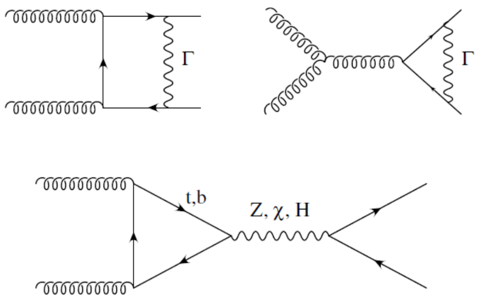
$$C_{\phi q}^{(1,33)} = \mathrm{i}\,(\phi^\dagger D_\mu\phi)\,(\bar{t}_\mathrm{L}\gamma^\mu t_\mathrm{L}),$$

$$C_{\phi u}^{33} = \mathrm{i}\,(\phi^\dagger D_\mu\phi)\,(\bar{t}_\mathrm{R}\gamma^\mu t_\mathrm{R}).$$

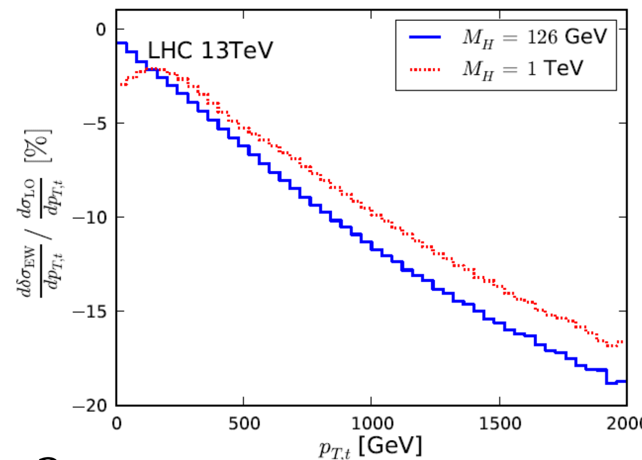


Electroweak corrections

- El.weak corrections to *ttbar* [Kühn,Scharf,Uwer], [Bernreuther,Fücker,Si]



inclusive (13 TeV): ~ -3+0.2(real) % = -2.5 % [Baur]



$$\frac{\delta\sigma_{EW}^{13TeV}}{\sigma_{LO}} = (-2.63 + 0.0029 g_Y + 0.63 g_Y^2)\%,$$

Sensitivity to anomalous *top-Z/W* couplings?

- El.weak corrections to *ttbar+Z,W,H* [Frixione,Hirschi,Pagani,Shao,Zaro]

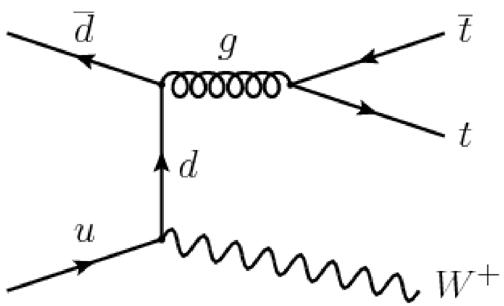
inclusive *ttbar+Z* (13 TeV): ~ -3.8+0.9(real) % = -2.9 %

inclusive *ttbar+W* (13 TeV): ~ -7.7+3.9(real) % = -3.8%

inclusive *ttbar+H* (13 TeV): ~ 0.0+0.9(real) % = +0.9 %

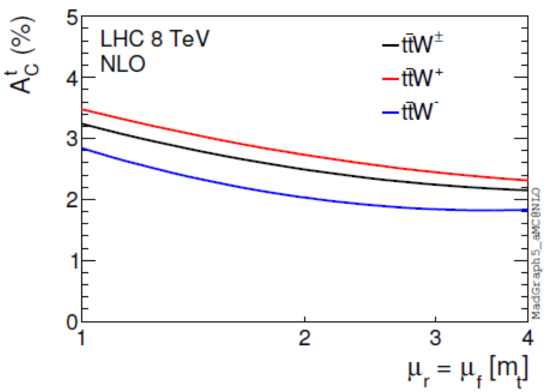
t-b-W Interactions

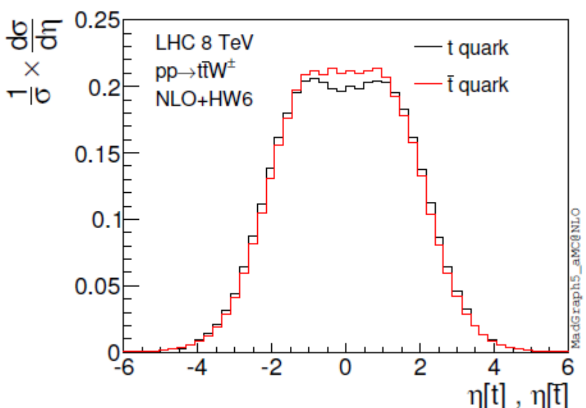
- $t\bar{t} + W^{\pm}$ at the 14TeV LHC has a total NLO cross section of 0.7 pb [Campbell,Ellis] [Garzelli,Kardos,Papadopoulos,Trocsanyi]



→ No sensitivity to t-b-W couplings at the LHC

- The absence of a gluon-gluon channels enhances sensitivity to (radiatively generated) asymmetry. [Maltoni,Mangano,Tsinikos, Zaro]
- Moreover, the W-boson polarizes the IS and enhances sensitivity





relative precision:

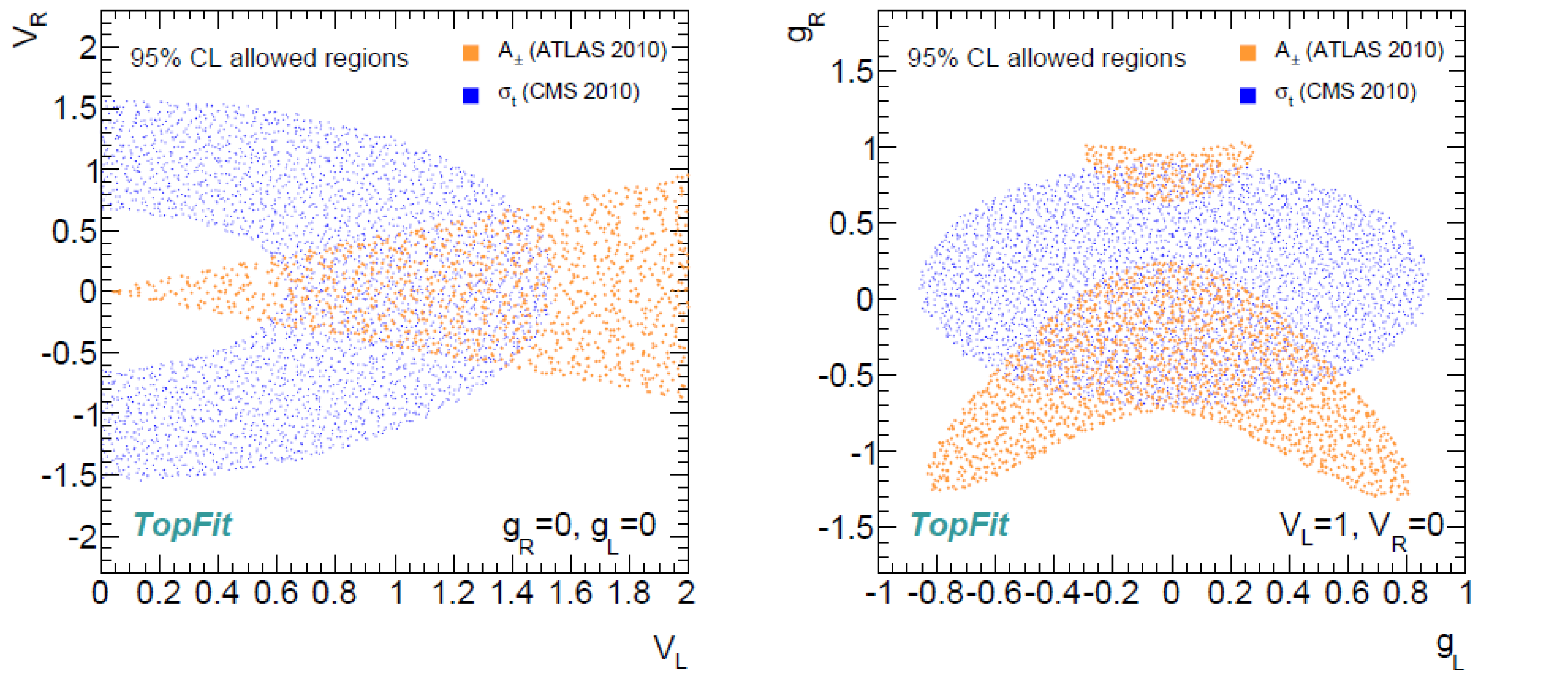
$$\begin{cases} 45\% \text{ with } 14\,\text{TeV} + 300\,\text{fb}^{-1} \\ 14\% \text{ with } 14\,\text{TeV} + 3000\,\text{fb}^{-1} \\ 3\% \text{ with } 100\,\text{TeV} + 3000\,\text{fb}^{-1} \end{cases}$$

t-b-W Interactions

- *t-b-W* can also be probed in *single-top production* and *top decay in ttbar*

[> 30 papers]

- one example: Recent combination of both [Aguilar-Saavedra,Castro,Onofre]



- *ttbar* process is also ideal for studying chromo-dipole moments

t-t-H Interactions

- $t\bar{t} + H$ at the 14TeV LHC has a total NLO cross section of 0.7 pb
  [Beenakker,Dittmaier,Kramer,Plumper,Spira,Zerwas], [Dawson,Jackson,Orr,Reina,Wackeroth]
  [Frederix,Frixione,Hirschi,Maltoni,Pittau,Torielli]], [Garzelli,Kardos,Papadopoulos,Trocsanyi]

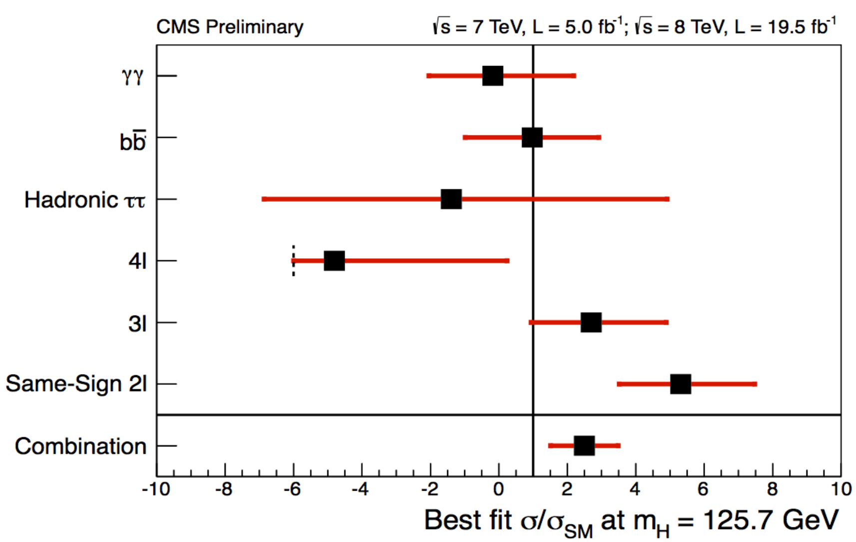
- Large QCD backgrounds in *H→bbar*. Lots of work on improving S/B.

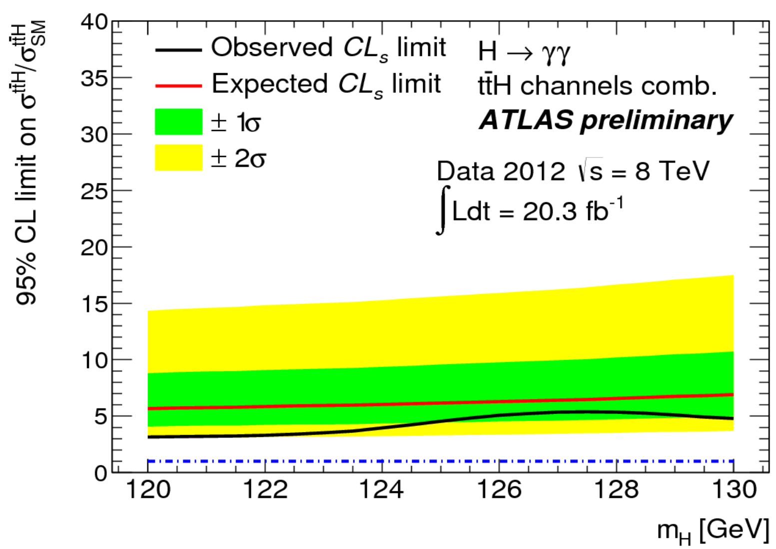
  E.g. *boosted jets*: [Seymour] [Butterworth et.al], [Plehn,Salam,Spannowsky]

  matrix element method: [Artoisenet,Aquino,Maltoni,Mattelaer]

  top spin correlations: [Biswas,Frederix,Gabrielli,Mele]

→ No observation yet (7+8 TeV). Upper limit ~ 3x SM cross section.





t-t-H Interactions

- Studies of coupling sensitivity: [Ellis,Hwang,Sakurai,Takeuchi]

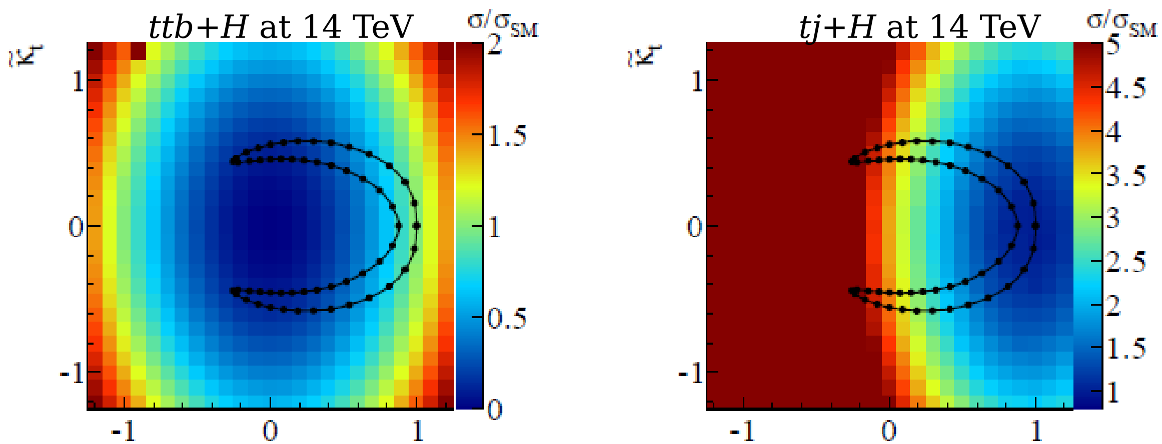
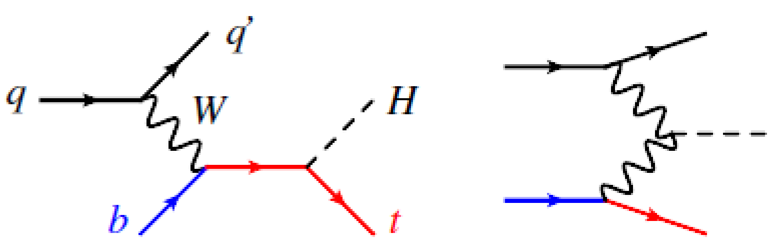


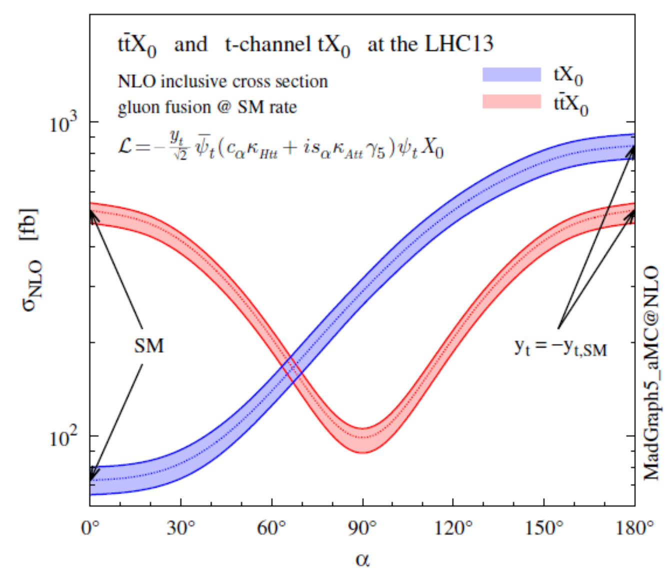
Figure 3: *The ratios of $\sigma(\bar{t}tH)$ to the Standard Model value (left panel) and of $\sigma(tH)$ to the Standard Model value (right panel) are shown using the indicated colour codes. Also shown is the crescent-shaped region in Fig. 1 that is allowed by present data at the 68% CL.*

- single top + Higgs: [Campbell,Ellis,Röntsch]

  [Demartin,Maltoni,Mawatari,Page,Zaro]



destructive interference leads to very small SM cross section

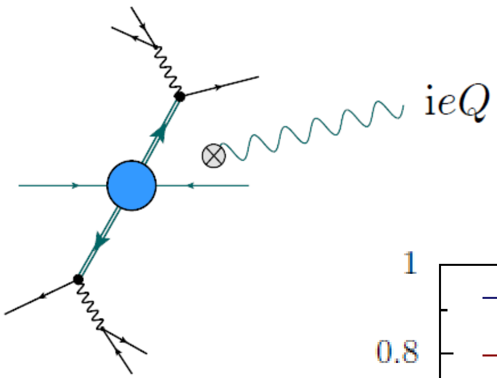


$t\bar{t}$ + photon

- $t\bar{t}+\gamma$ at the 14 TeV LHC has a total NLO cross section of 2.9 pb

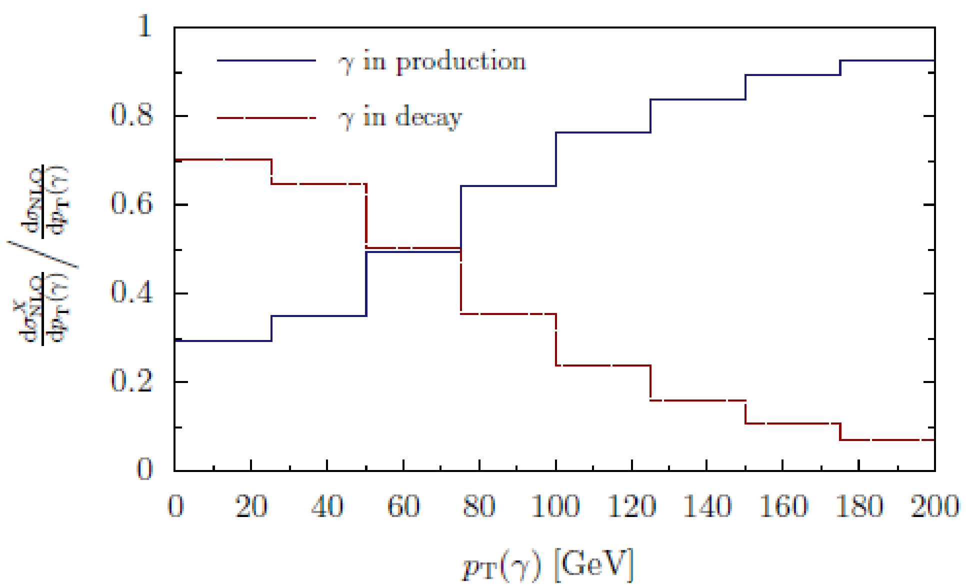
[Duan,Ma,Zhang,Han,Guo,Wang], [Melnikov,Scharf,M.S.], [Kardos,Trocsanyi]

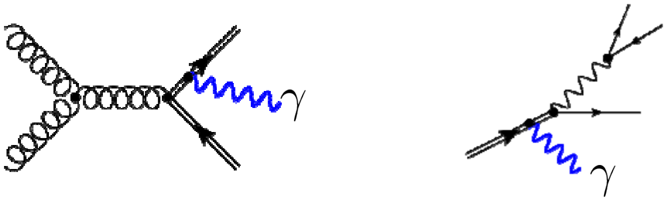
- In contrast to *ttbar+H,Z,W,* photon can be radiated off top decay products



Lepton+Jets Channel + acceptance cuts: $p_T^\gamma > 20\,\text{GeV}$

$$\sigma^{\text{NLO}}_{\ell+\text{j}} = 138\,\text{fb} = 61(\text{production}) + 77(\text{decay})\,\text{fb}$$





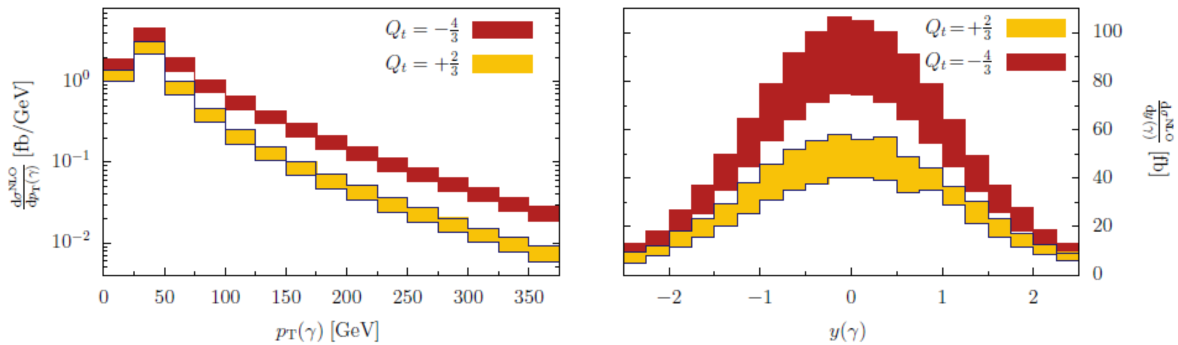
→ Photons with $p_{T\gamma}$<50 GeV are dominantly emitted in the decay

[Melnikov,Scharf,M.S.]

$t\bar{t}$ + photon

Effects of radiative top decays:

- Simple BSM study: top quark charge measurement in *ttbar+photon*



$$\sigma^{NLO}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{NLO}_{t\bar{t}\gamma} = 243 \text{ fb}$$

→ Naive expectation of Q_t^2 scaling fails: $\mathcal{R}^{NLO} = \frac{\sigma_{NLO}^{Q_t=-4/3}}{\sigma_{NLO}^{Q_t=2/3}} = 1.76^{+0.01}_{-0.02}$.

- Implications for FB asymmetry:

$$A^{LO}_{t,FB} = -17\%$$
$$A^{NLO}_{t,FB} = -12\% \longrightarrow A^{NLO}_{\ell,FB} \approx \text{few}\%$$

stable tops

decayed tops +radiative decays