GGI – Florence 2015

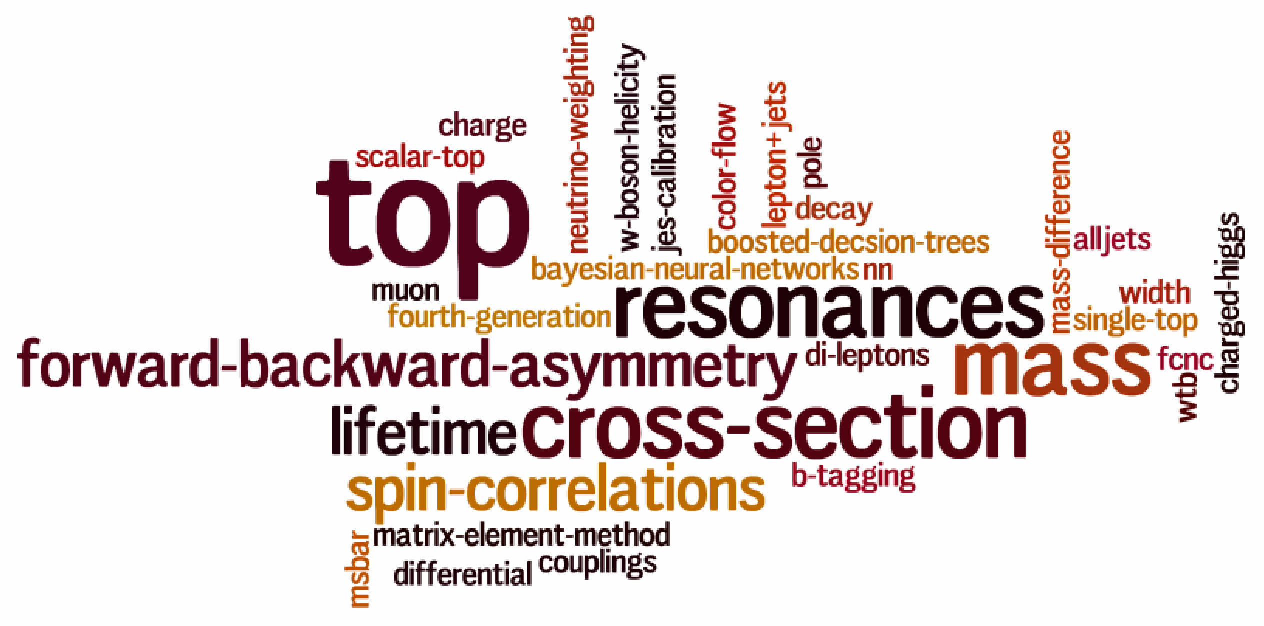
Standard Model at LHC

Electroweak top quark couplings at the LHC

Markus Schulze

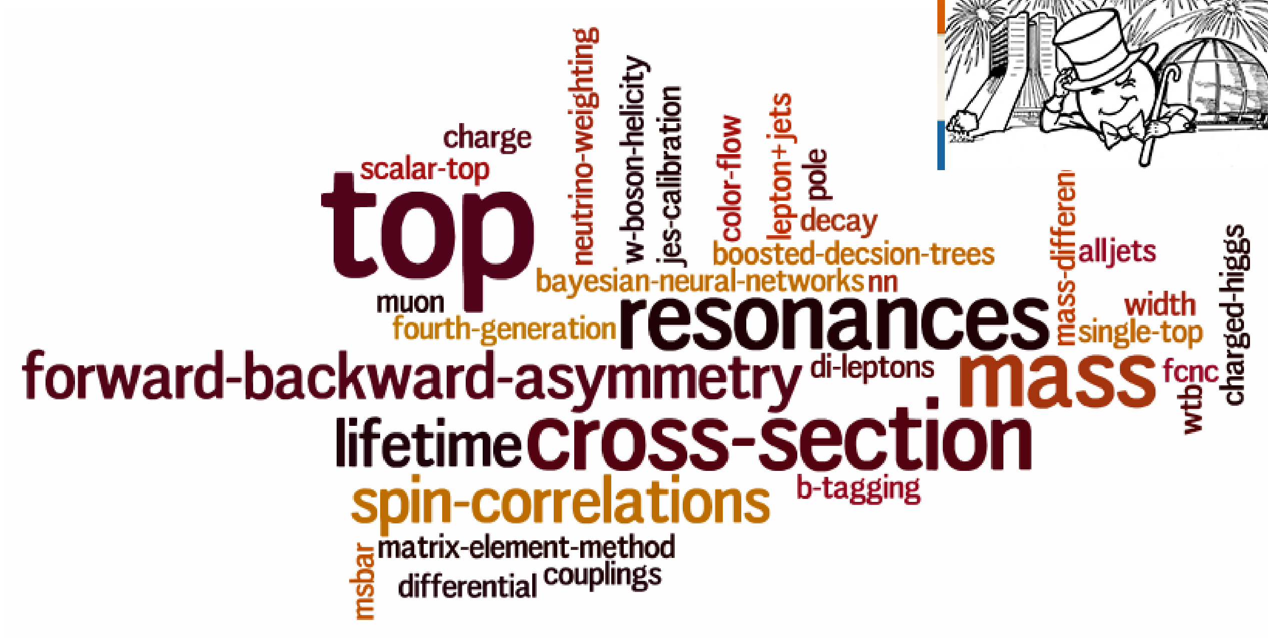
CERN

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?

Twenty years after the top quark discovery



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- 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?

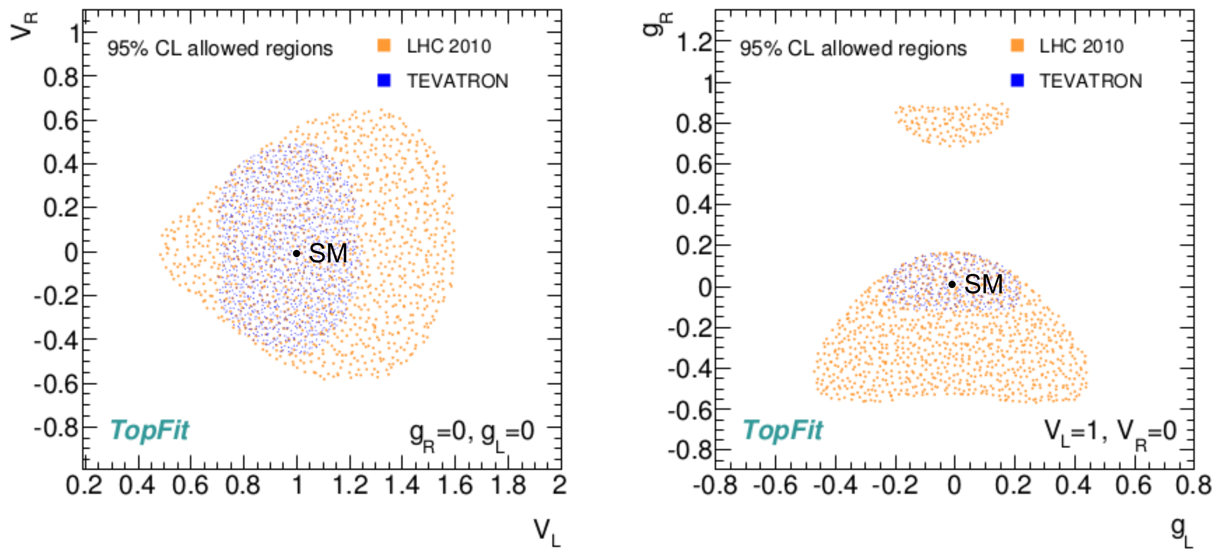
t-b-W Interactions

- $t\bar{t} + W^{\pm}$ 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

- t-b-W can also be probed in single top production and top decay dynamics [Aguilar-Saavedra,Castro,Onofre]

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

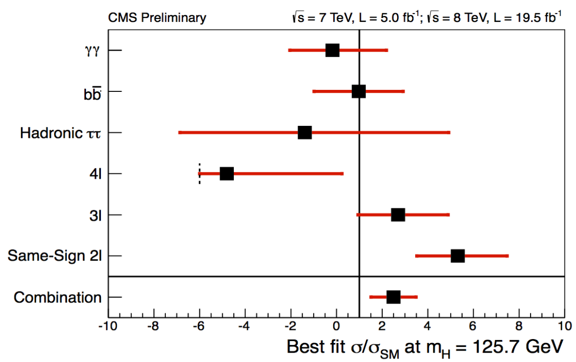


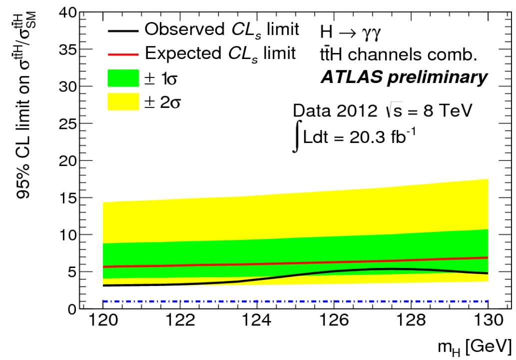
t-t-H Interactions

- $t\bar{t} + H$ at the 14TeV LHC has a total NLO cross section of 0.7 pb

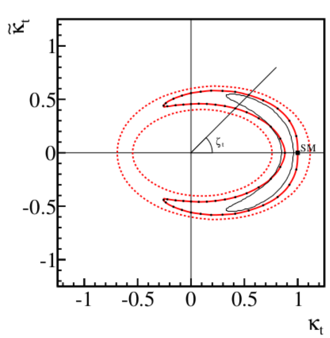
[Beenakker,Dittmaier,Kramer,Plumper,Spira,Zerwas], [Dawson,Jackson,Orr,Reina,Wackeroth]
[Frederix,Frixione,Hirschi,Maltoni,Pittau,Torielli]], [Garzelli,Kardos,Papadopoulos,Trocsanyi]

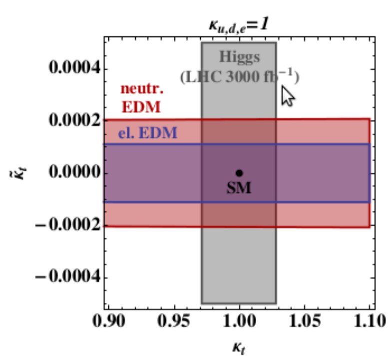
→ No observation yet (7+8 TeV)

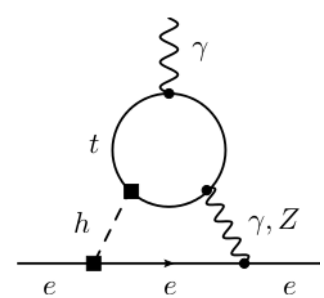




- Large backgrounds. Lots of work on improving S/B.
- Coupling sensitivity studied and summarized in [Ellis,Hwang,Sakurai,Takeuchi]

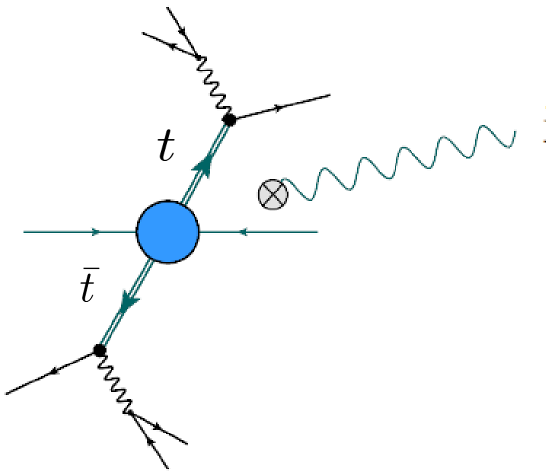






[Brod,Haisch,Zupan]

$t\bar{t}$ + photon



- Directly sensitive to top quark electric charge Q_t
- At LHC, gg dominated (small ISR contamination ~ $Q_{u,}\, Q_d$)
- Has an asymmetry already at LO
- Control sample for *ttb+H,*
  Background to composite/exited top quark models

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

$\bar{t}$

$$\delta d_V^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Re}\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,, \qquad \sim \text{Magn. dipole mom.}$$

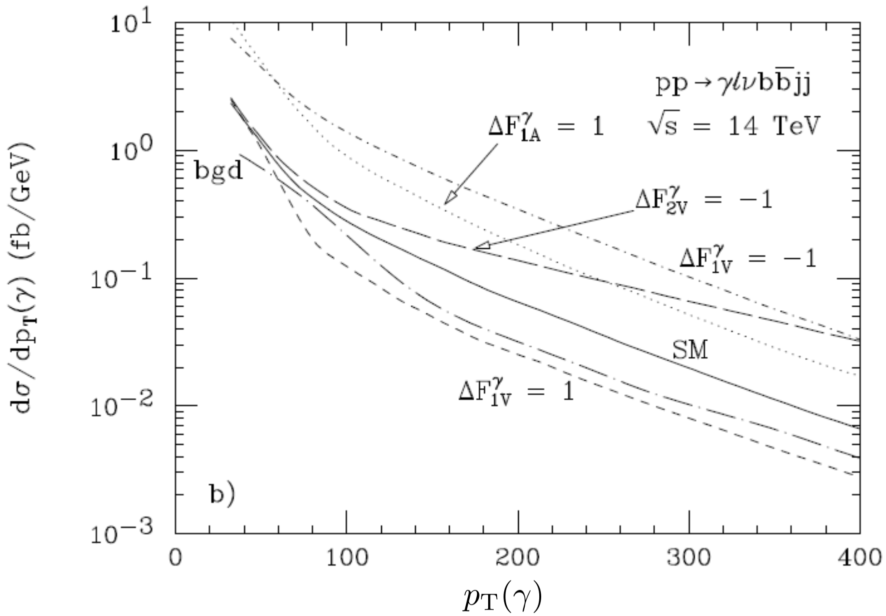
$$\delta d_A^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Im}\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,. \qquad \sim \text{Electr. dipole mom.}$$

- In the SM: $\delta d_V = \mathcal{O}(10^{-3} - 10^{-2}),\quad \delta d_A = \mathcal{O}(10^{-4}),$ [Hollik]

$t\bar{t} + \gamma$: Anomalous couplings

- LO studies in form factor approach [Baur,Juste,Orr,Rainwater] (2004)

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



- Photon transverse momentum is a good analyzer

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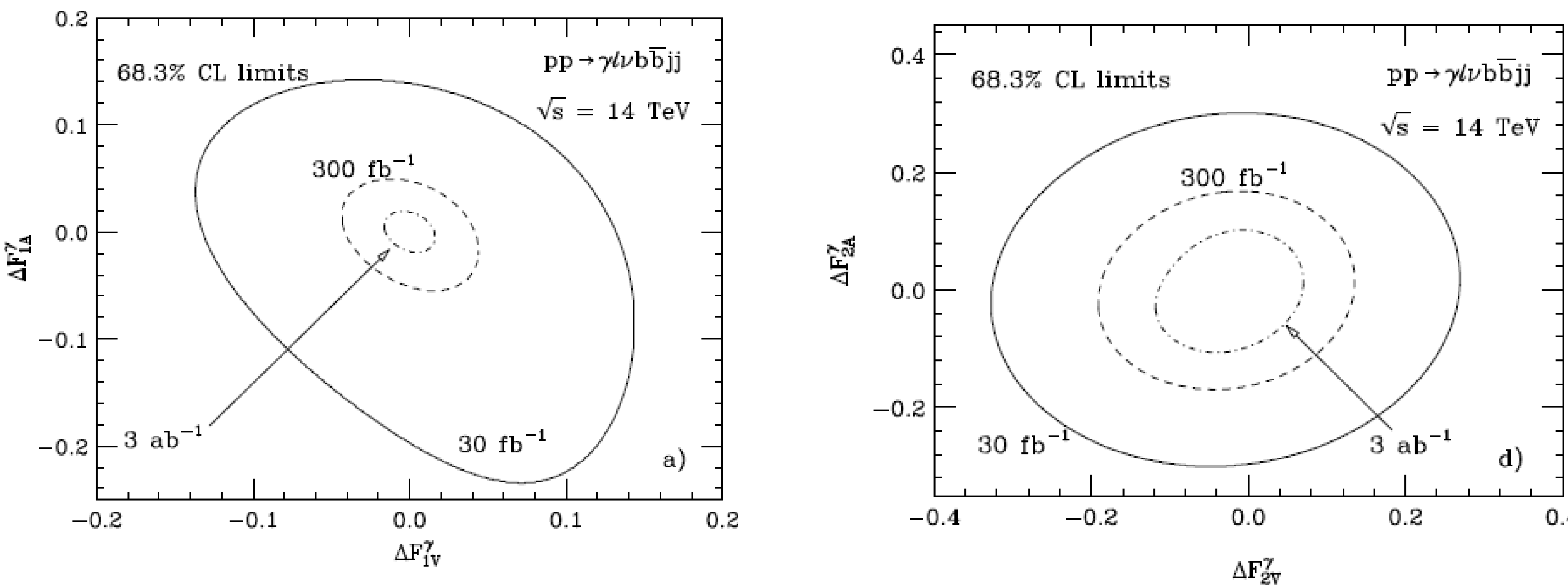


→ Residual scale uncertainty is biggest limiting factor in these studies

NLO QCD $t\bar{t}+\gamma$ at the 14 TeV LHC

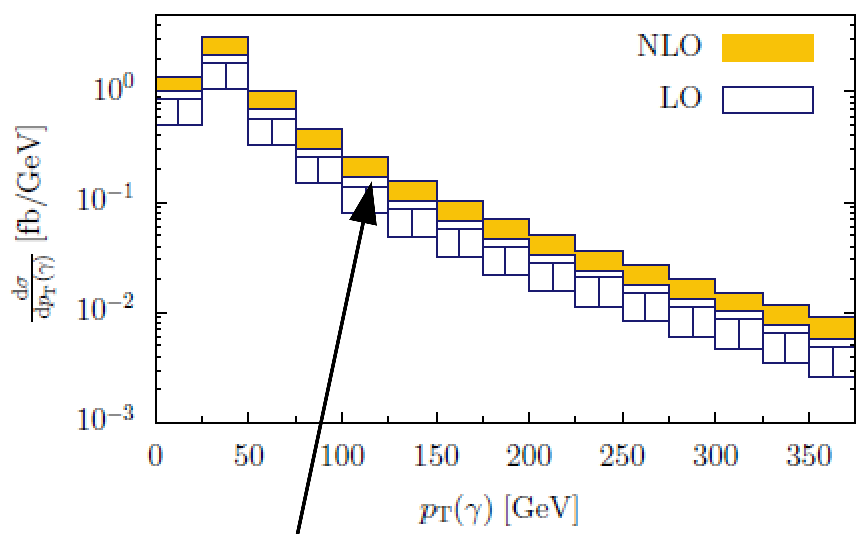
$$p_{\perp,\gamma} > 20 \text{ GeV}, \quad |y_\gamma| < 2.5, \quad R_{\gamma,b} > 0.4, \quad R_{\gamma,j} > 0.4, \quad R_{\gamma,\ell} > 0.4,$$

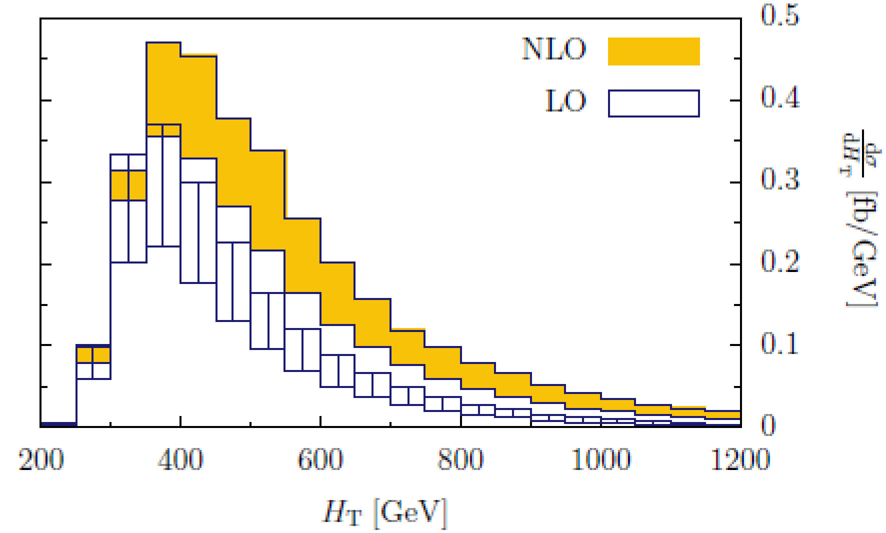
$$p_{\perp,b} > 20 \text{ GeV}, \quad p_{\perp,j} > 20 \text{ GeV}, \quad p_{\perp,\ell} > 20 \text{ GeV}, \quad E_{\perp,\text{miss}} > 20 \text{ GeV},$$

$$|y_b| < 2.0, \quad |y_j| < 2.5, \quad |y_\ell| < 2.5.$$ Smooth-cone photon isolation [Frixione]

$$\sigma_{\text{LO}} = 74.50^{+23.98}_{-16.89} \text{ fb}, \quad \sigma_{\text{NLO}} = 138^{+30}_{-23} \text{ fb}.$$

[Melnikov, Scharf, MS]
Phys.Rev. D83 (2011) 074013





More than 500 events with $p_{T\gamma}$>100 GeV from 100 fb^{-1}

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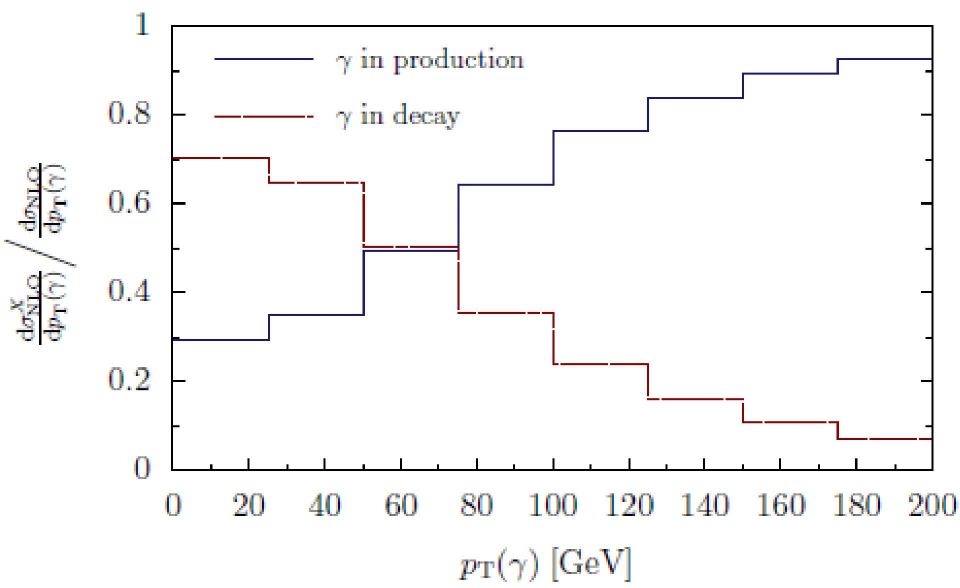


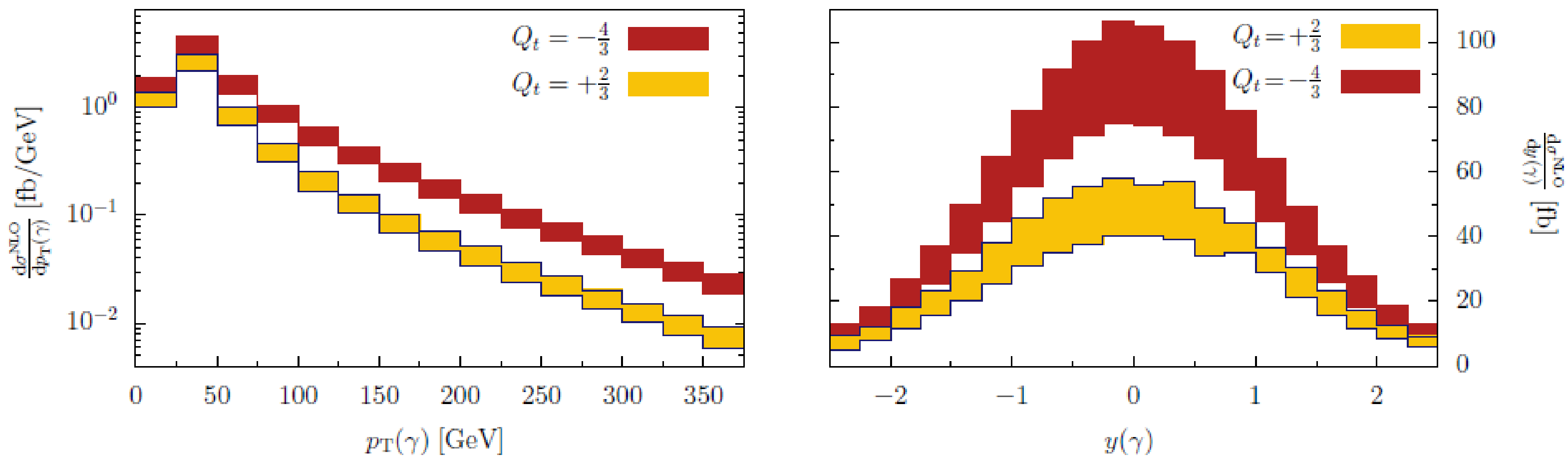
$$\sigma^{\text{NLO}}_{\text{prod}} = 61\,\text{fb}$$

$$\sigma^{\text{NLO}}_{\text{decay}} = 77\,\text{fb}$$

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

Sensitivity to Q_t at the LHC

→ Compare SM vs. Exotic (Q_t=-4/3) hypotheses

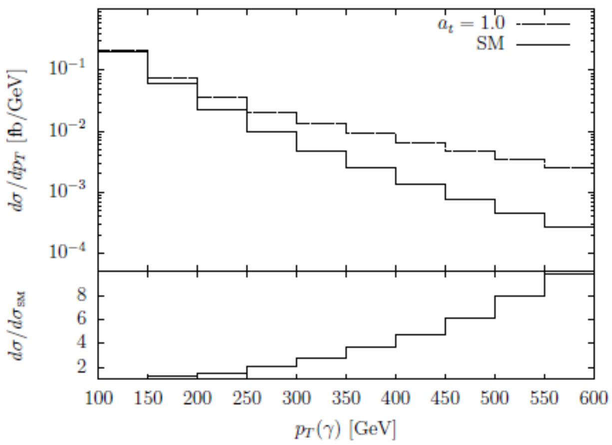


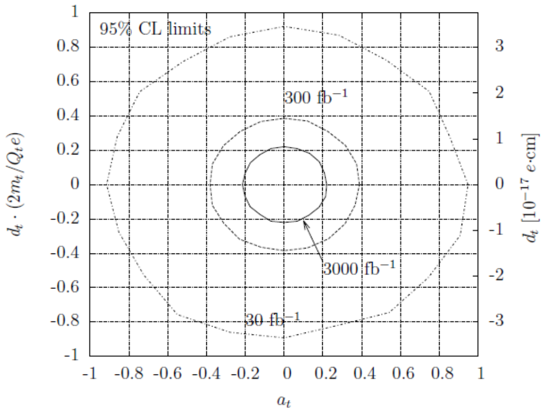
$$\sigma^{\rm NLO}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{\rm NLO}_{t\bar{t}\gamma} = 243 \text{ fb}$$

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

Other anomalous couplings limits

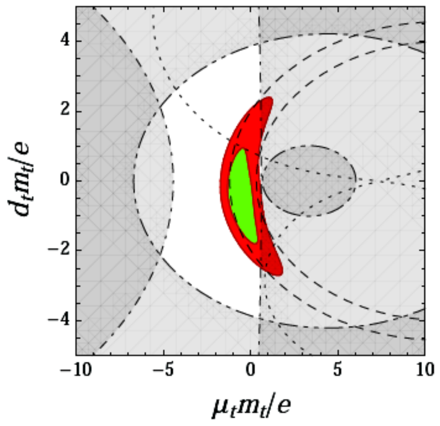
- LO study of dipole moments in single $t\,j+\gamma$ [Fael,Gehrmann]





coupling	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
a_t	$+0.94$ -0.92	$+0.39$ -0.38	$+0.22$ -0.21
d_t [$10^{-17} e\cdot$cm]	$+3.5$ -3.4	$+1.5$ -1.5	$+0.83$ -0.82

- Constraint on dipole moments from $B_s \to X_s + \gamma$



$$-1.5 < \mu_t m_t/e < 1.0 \ (95\%\,\text{C.L.}),$$
$$-2.3 < d_t m_t/e < 1.7 \ (95\%\,\text{C.L.})\,.$$

[Kamenik,Papucci,Weiler]

$t\bar{t} + Z$

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

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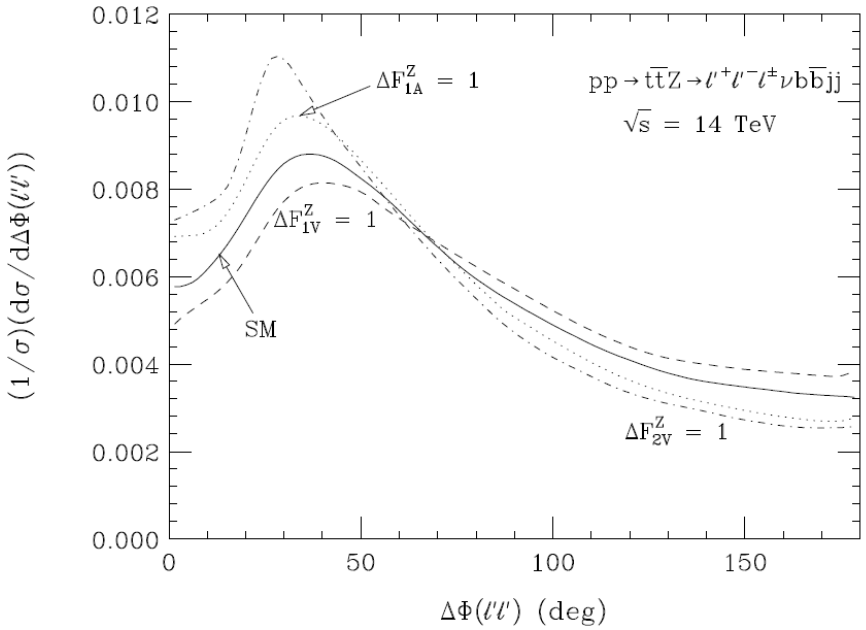

LO coupling constraints

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

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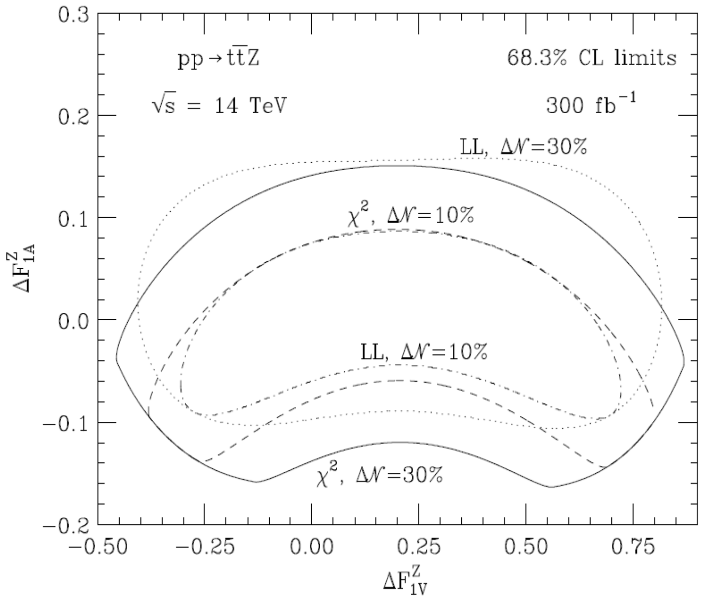

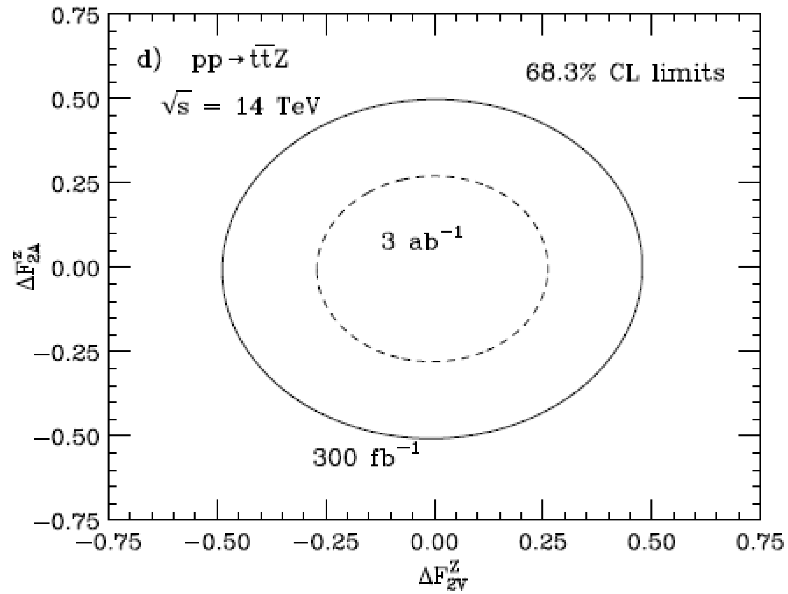

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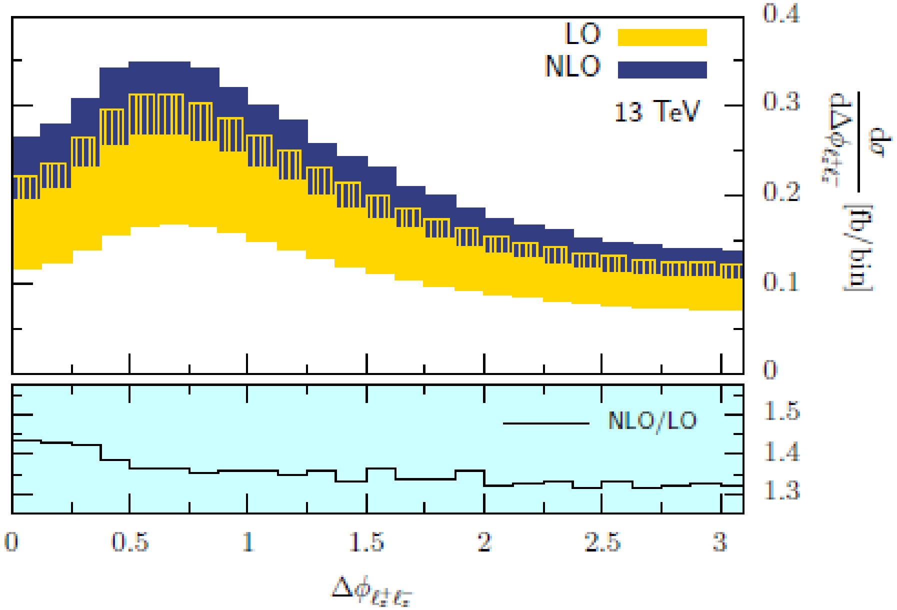
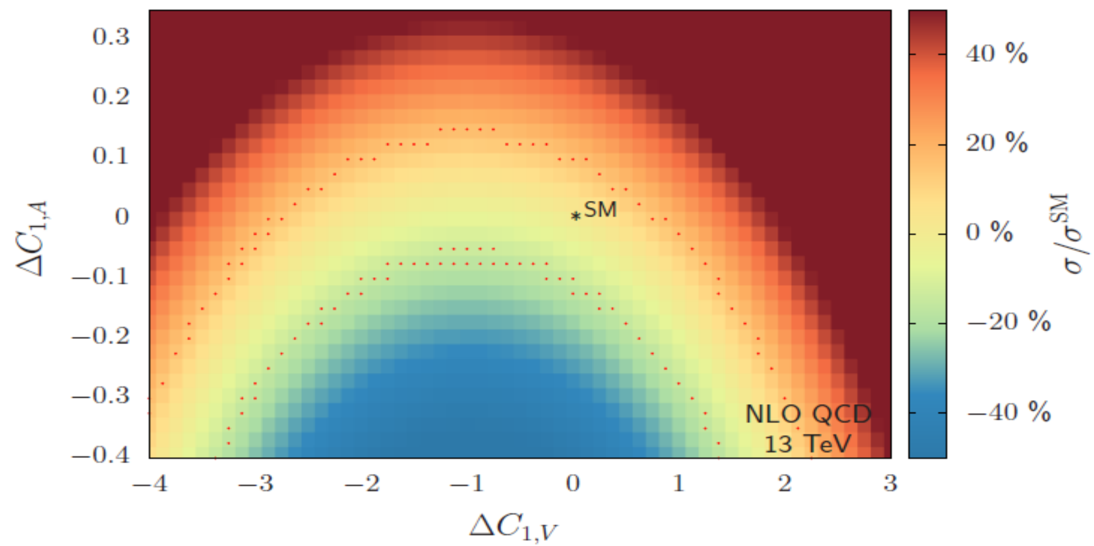
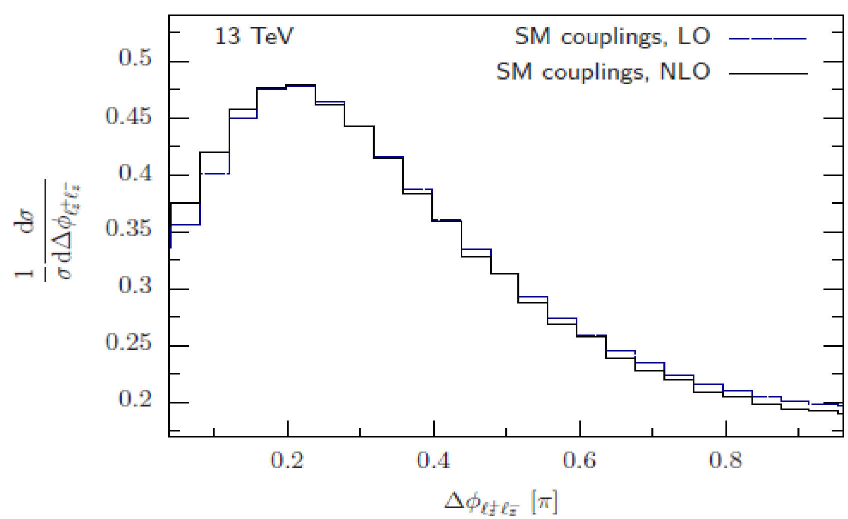
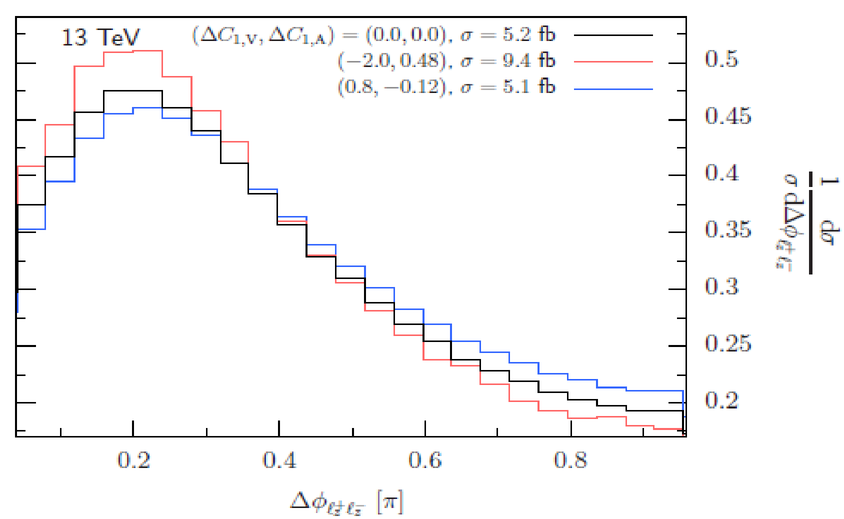
NLO coupling constraints





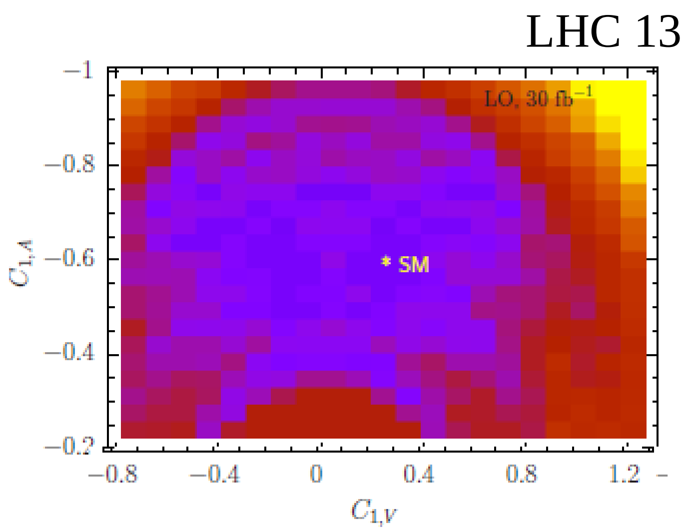
[R. Röntsch, MS]





Constraints from LHC run-2

LO 30 fb^{-1}



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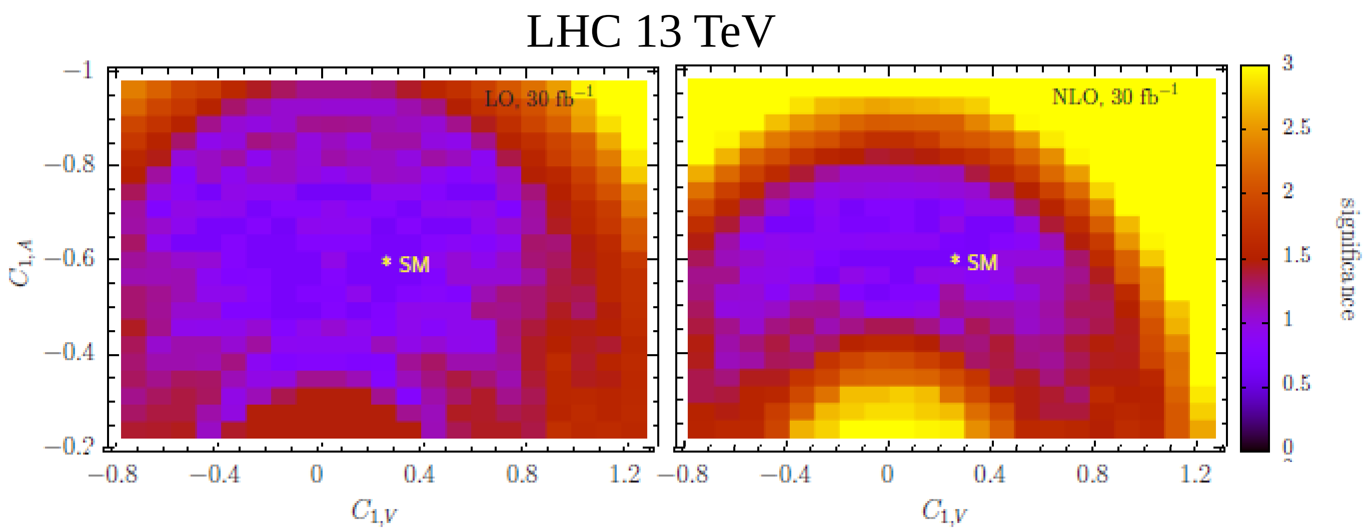


NLO 30 fb^{-1}

Constraints from LHC run-2

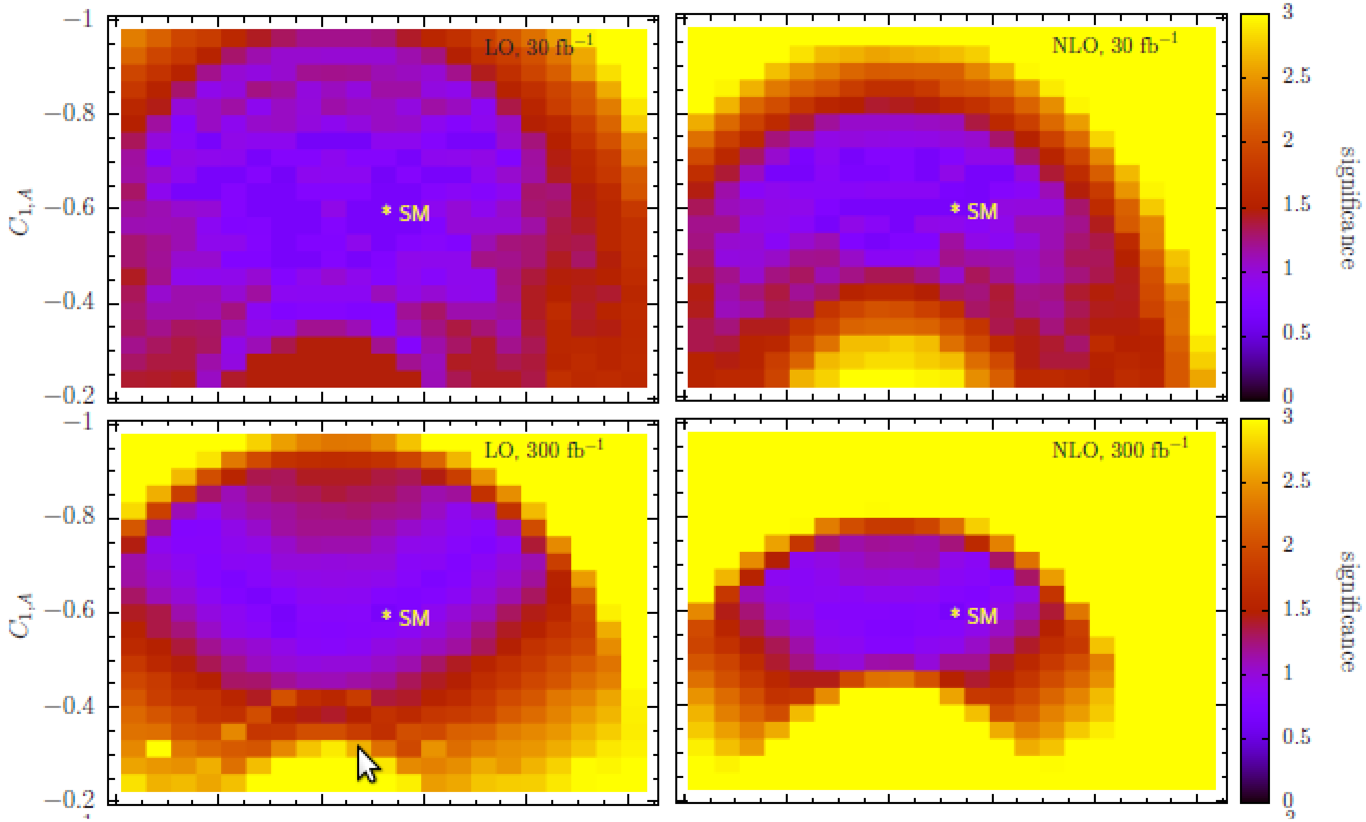
LHC 13 TeV

LO 30 fb^{-1}

NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}



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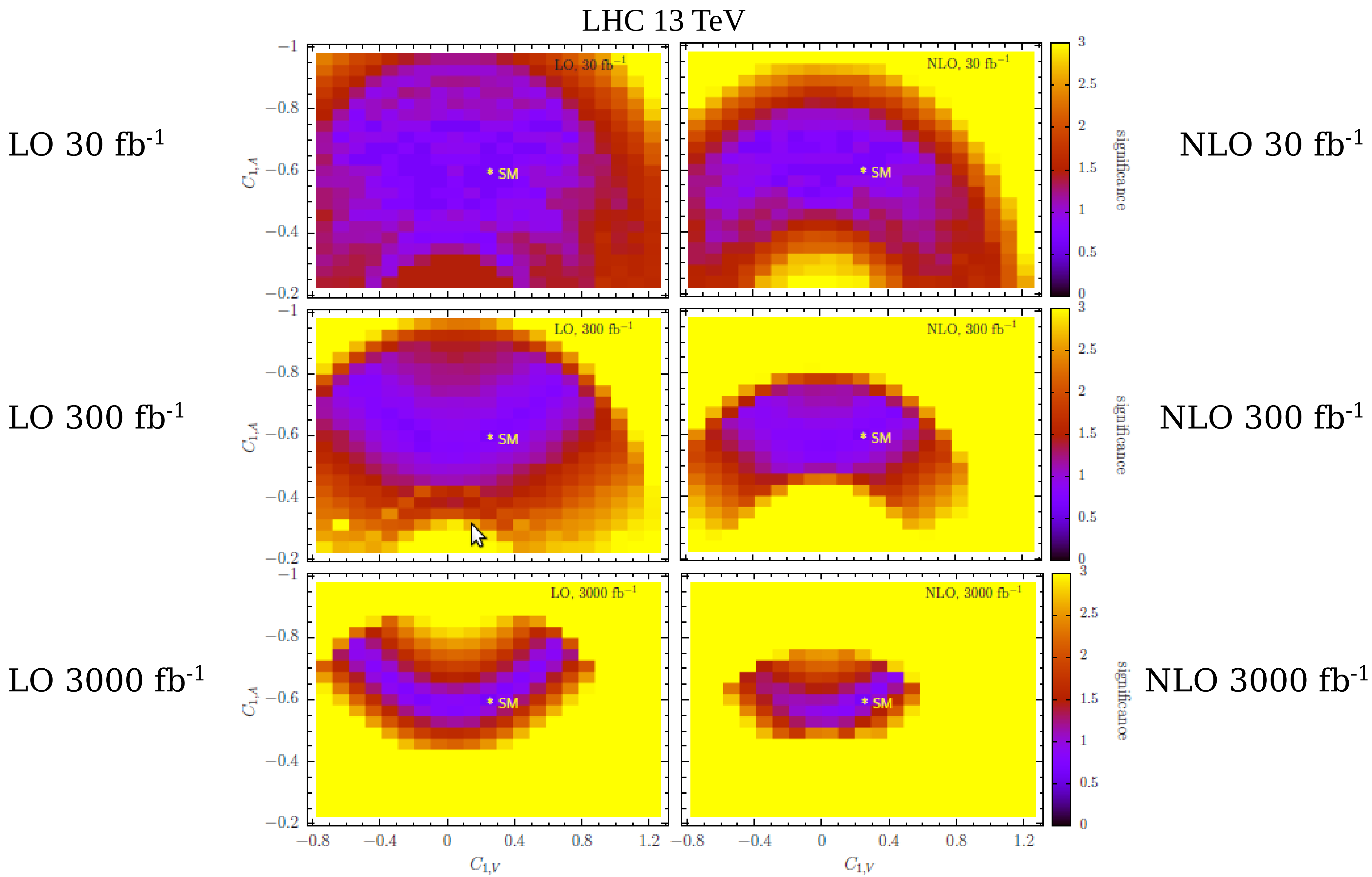


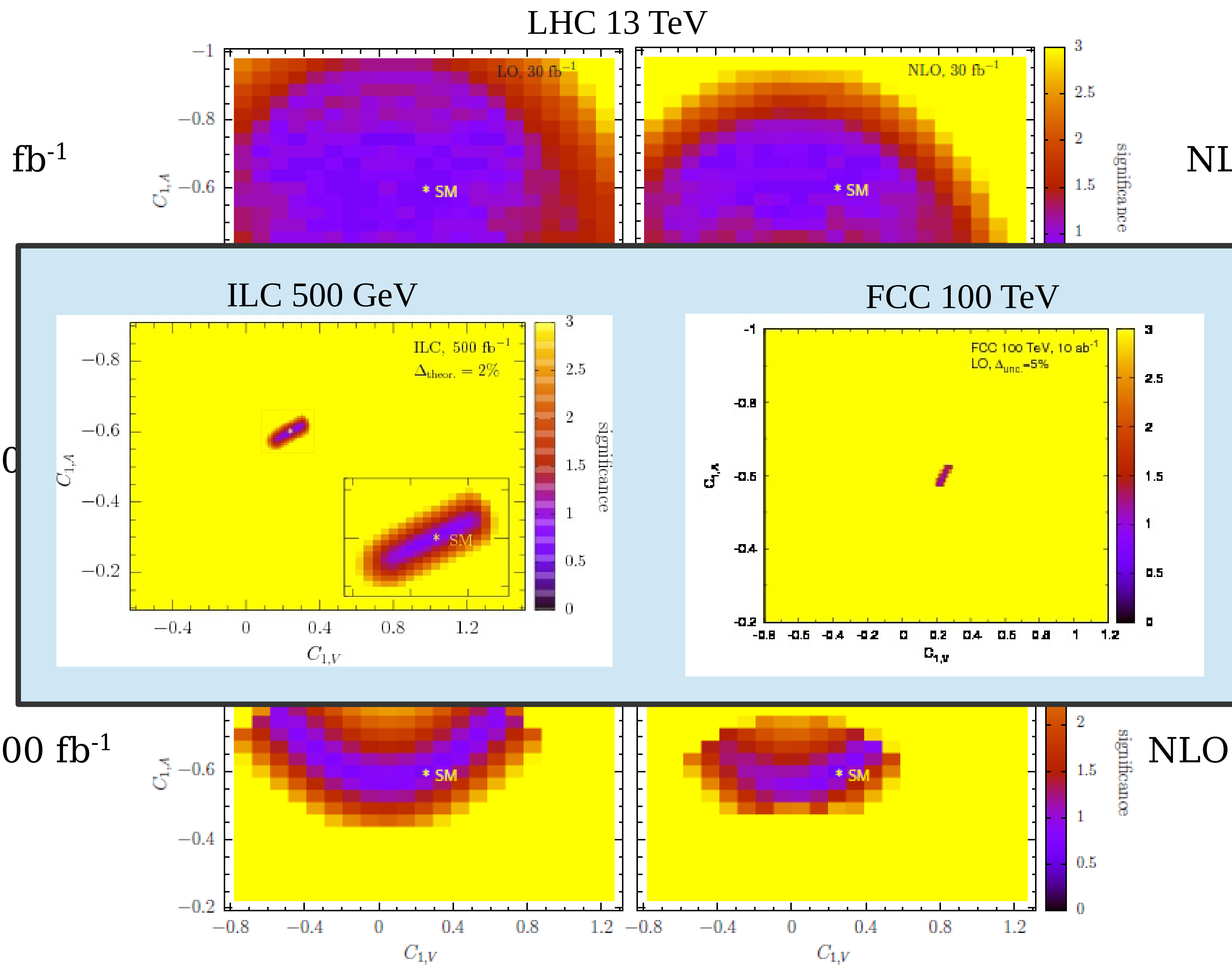
Constraints from LHC run-2

LO 30 fb^{-1}

NLO 30 fb^{-1}

LO 300

300 fb^{-1}



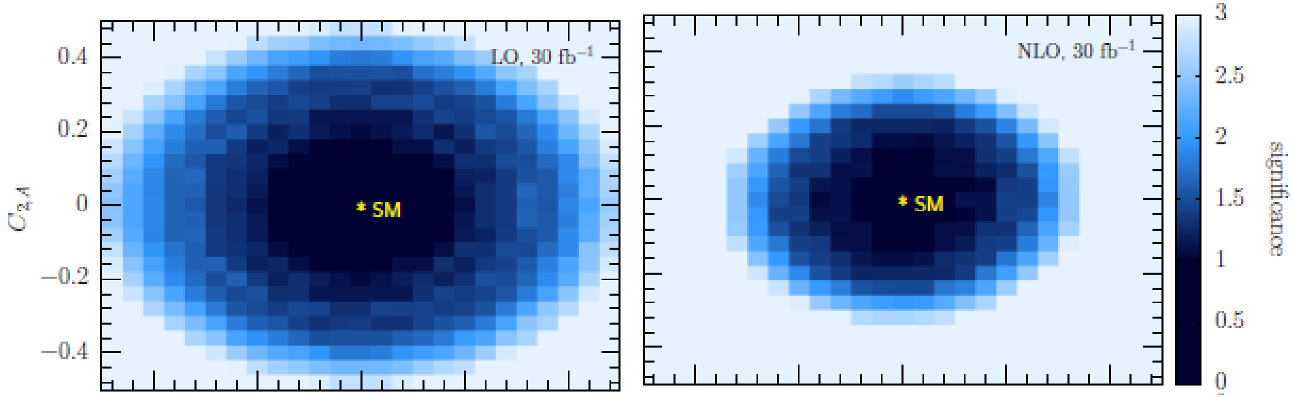
LO 3000 fb^{-1}

NLO 3000 fb^{-1}

Constraints from LHC run-2

Weak dipole moments, zero in the SM

LO 30 fb^{-1}



NLO 30 fb^{-1}

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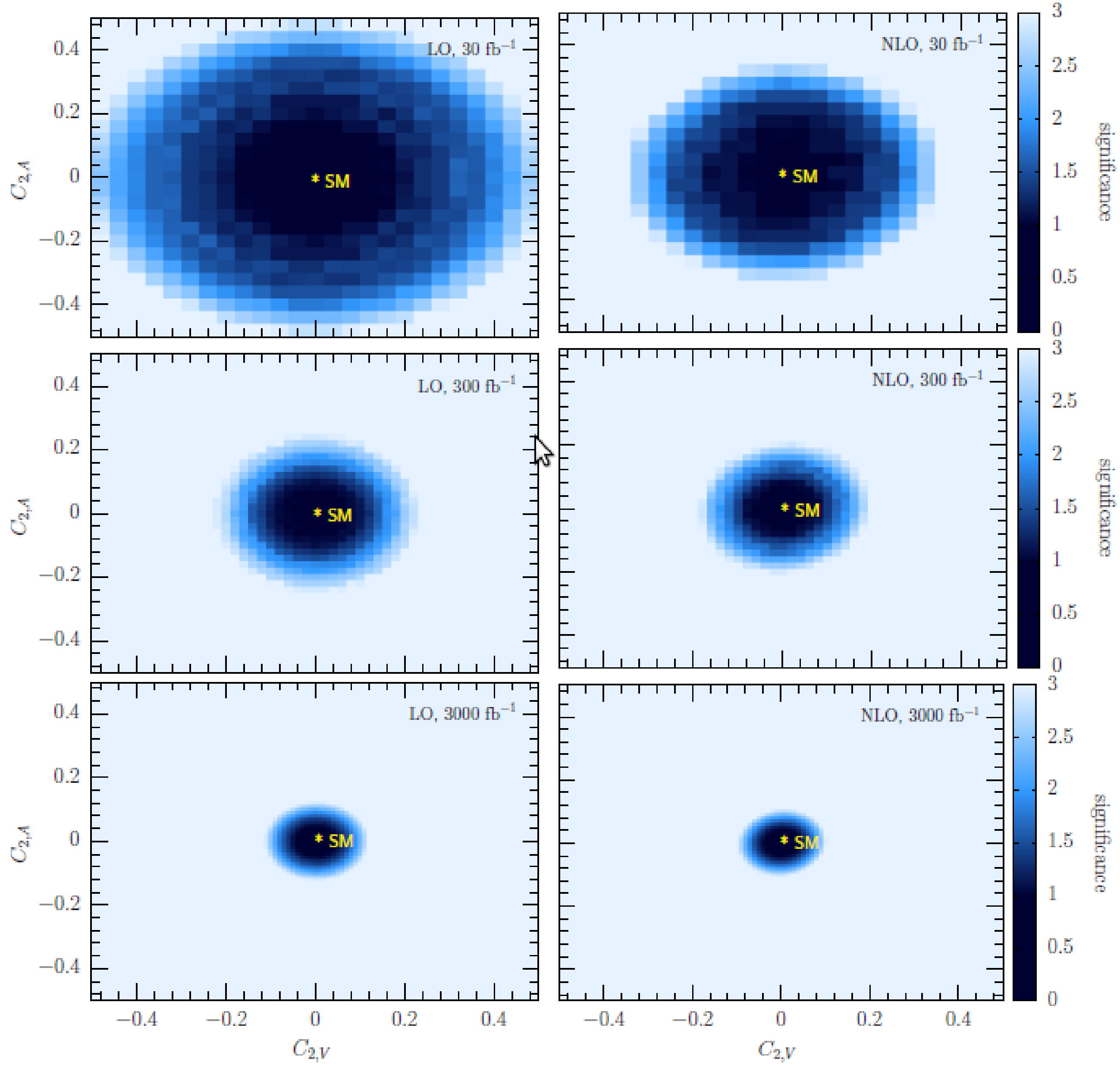
Weak dipole moments, zero in the SM

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 from LHC run-2

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

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

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

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

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

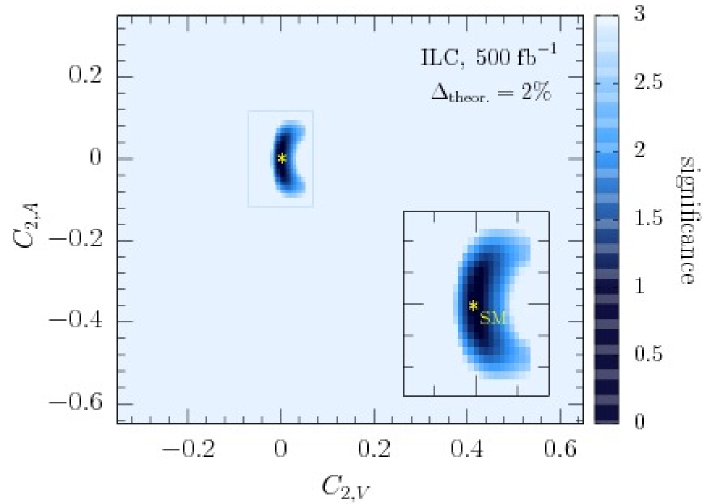
"A minimal set of top anomalous couplings" [J.A. Aguilar-Saavedra]

Conclusions

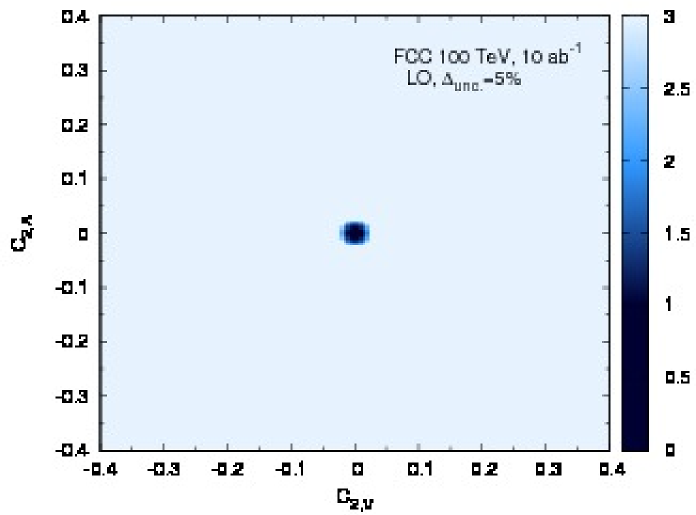
- The LHC will allow detailed studies of *ttb+V,H* final states
- Subsequent coupling constraints yield *direct* sensitivity to physics beyond the SM and complement indirect determinations from low energy experiments
- NLO QCD predictions for anomalous weak top couplings are available. Higher orders generally improve constraints. More work on weak dipole moments and global operator analysis needs to be done.

Extras

ILC 500 GeV



FCC 100 TeV



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

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

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

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

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

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