Top! Hammertime

CMS Workshop @ CERN

TTγ TTZ QT EFT

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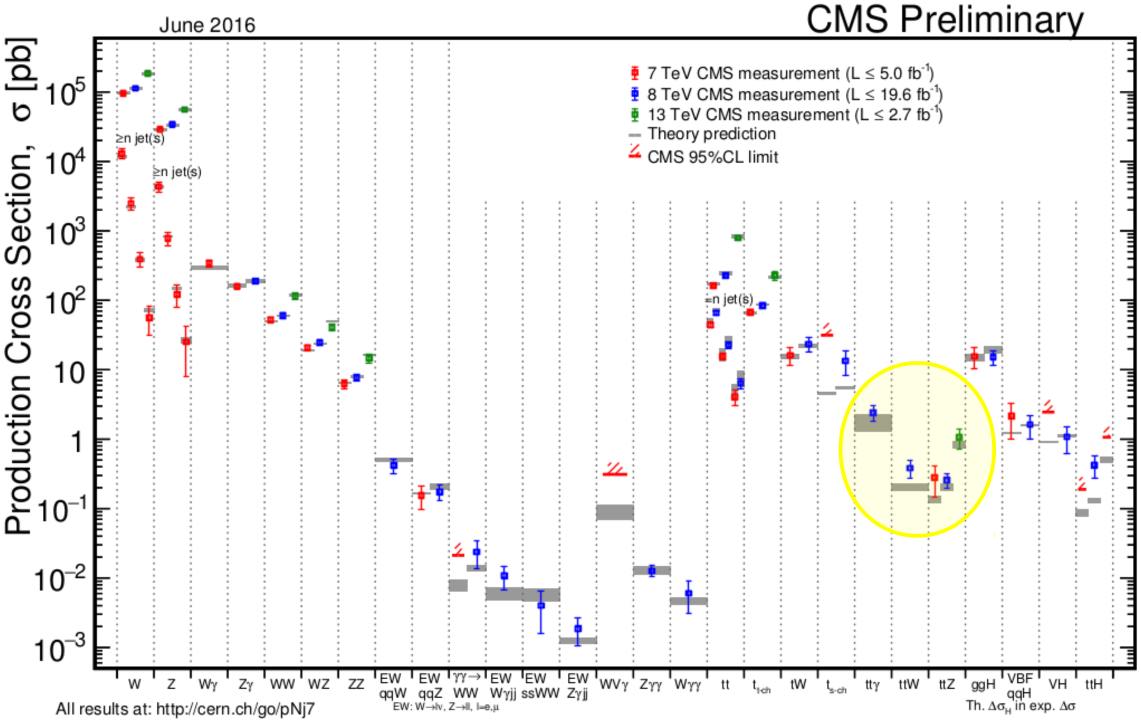
Introduction

- The LHC is opening the door to a whole new process class

$$t\bar{t}+\gamma,\ \ t\bar{t}+Z,\ \ t\bar{t}+W^{\pm},\ t\bar{t}+H$$

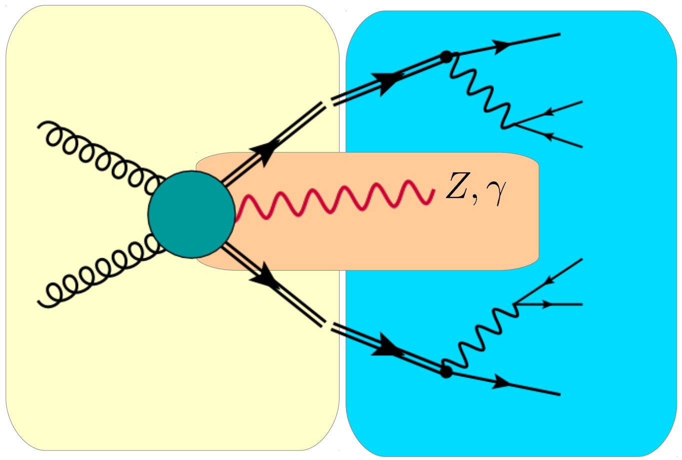
that was *never* observed at the Tevatron.

13 TeV	now	300 fb^{-1}
$t\bar{t}$	33 Mio.	250 Mio.
$t\bar{t}+\gamma$	100.000	900.000
$t\bar{t}+Z$	40.000	300.000
$t\bar{t}+H$	20.000	180.000



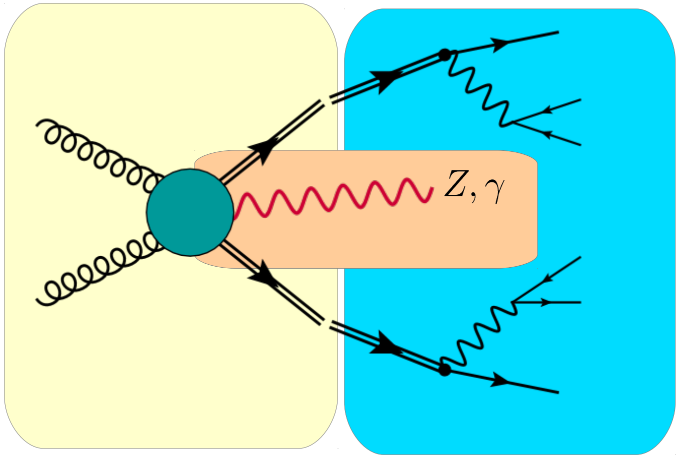
- *ttbar+X* is largely unexplored in the context of anomalous coupling studies. With ~100 fb^{-1} it gets really exciting!

Top quark anatomy



- NWA: Precise and systematic separation into production and decay dynamics.
- There are (at least) 28 anomalous operators affecting production & decay dynamics (*often affecting production and decay simultaneously*!)

Top quark anatomy



- NWA: Precise and systematic separation into production and decay dynamics.
- There are (at least) 28 anomalous operators affecting production & decay dynamics

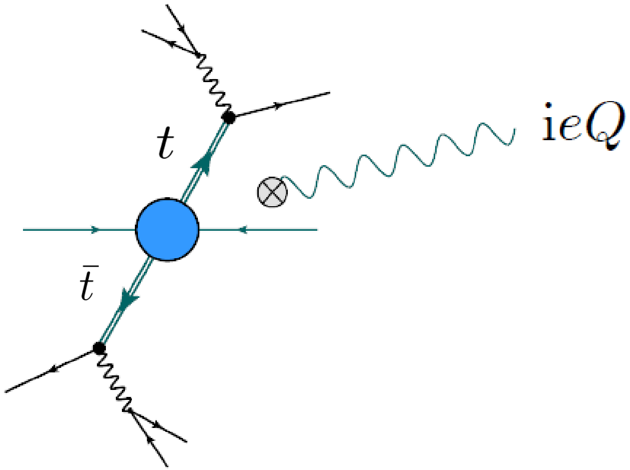
  (*often affecting production and decay simultaneously*!)
- A global 28-dimensional approach is impossible

$\longrightarrow$ There are ways to simplify the analysis (see TOP2017)

In short: First, study *ttbar* to constrain QCD production and weak decay,

then study additional pieces in *ttbar+V.*

$t\bar{t}$ + photon

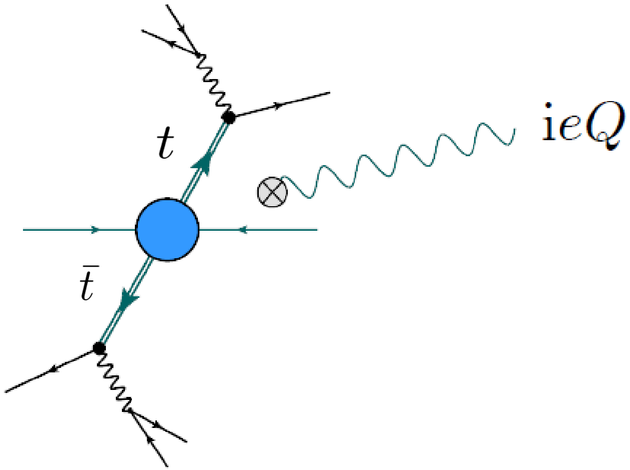


- Directly sensitive to top quark electric charge Q_t
- gg dominated (LHC: 80%), small ISR contamination ~Q_u, Q_d
- Feature: radiative top quark decay

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{t\bar{t}\gamma}\,\mathrm{d}\mathcal{B}_t\,\mathrm{d}\mathcal{B}_{\bar{t}} \;+\; \mathrm{d}\sigma_{t\bar{t}}\left(\mathrm{d}\mathcal{B}_{t\gamma}\,\mathrm{d}\mathcal{B}_{\bar{t}} + \mathrm{d}\mathcal{B}_t\,\mathrm{d}\mathcal{B}_{\bar{t}\gamma}\right)$$

- Has a charge asymmetry already at LO

$t\bar{t}$ + photon



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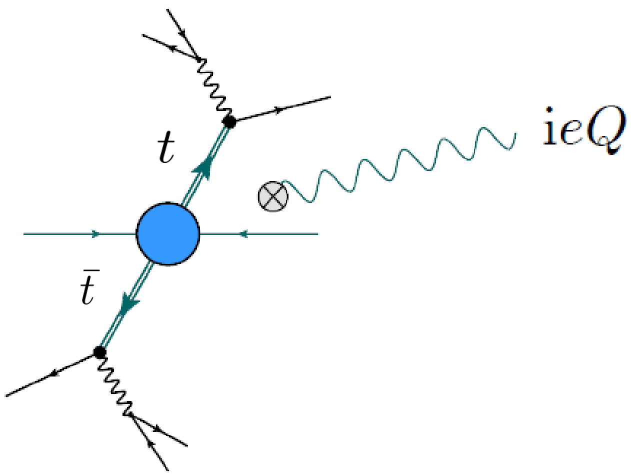
Interaction $$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\;A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + id_A^\gamma\gamma_5)\,t\;A_\mu\,.$$

$t\bar{t}$ + photon



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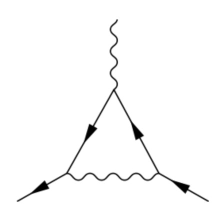
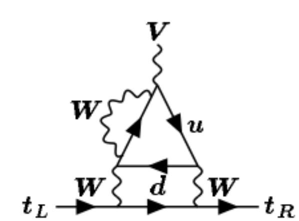
Magnetic dipole mom.

Electric dipole mom. (CP-violating)

[Martinez,Perez,Poveda]
[Hollik,Jose,Rigolin,Schappacher,Stöckinger]
[Shabalin,Khriplovich,Czarnecki,Krause]



$d_V^{SM} \approx -0.007$



$d_A^{SM} \leq 10^{-5}$

$pp \to t\bar{t}+\gamma$ at NLO QCD

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

$t\bar{t}$ + photon

Full NLO QCD: NLO prod.+ NLO decay with all spin correlations

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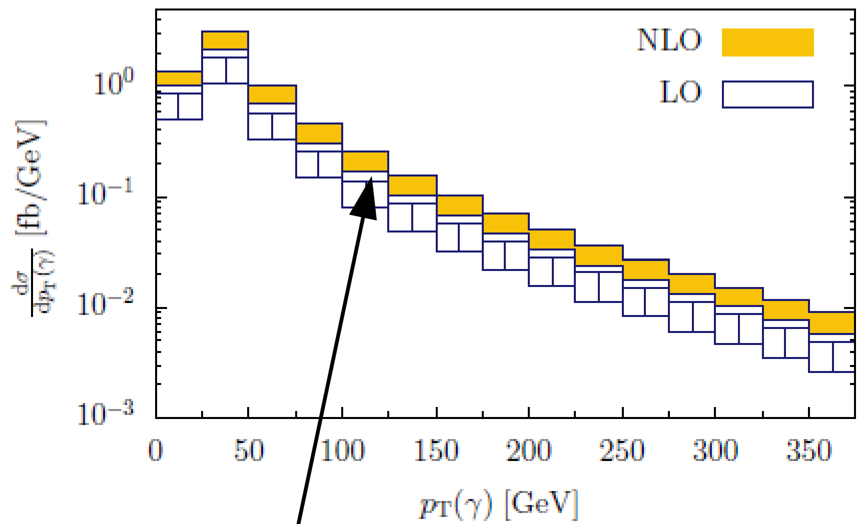
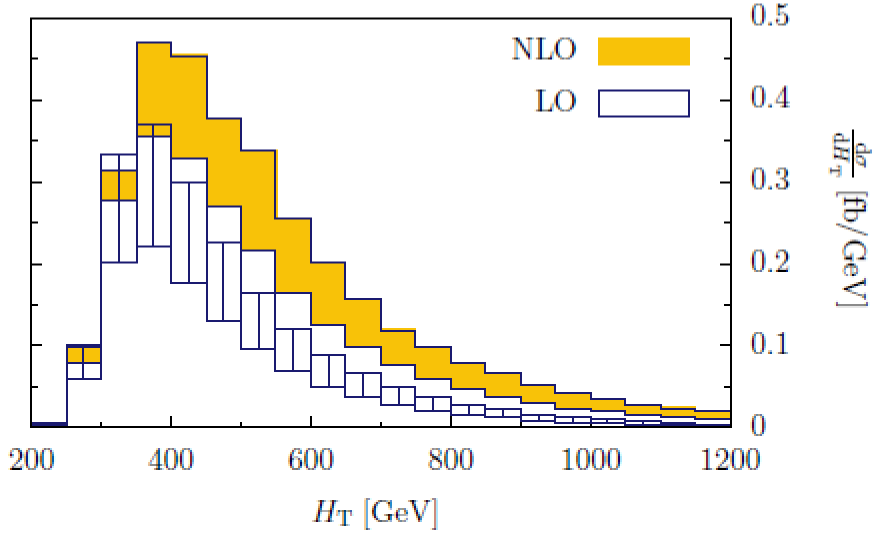
$$p_{\perp,\gamma} > 20 \text{ GeV}, \quad |y_\gamma| < 2.5, \quad R_{\gamma,b} > 0.4, \quad R_{\gamma,j} > 0.4, \quad R_{\gamma,\ell} > 0.4,$$

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

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

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





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

$t\bar{t}$ + photon

Full NLO QCD: NLO prod.+ NLO decay with all spin correlations

[Melnikov, Scharf, MS]
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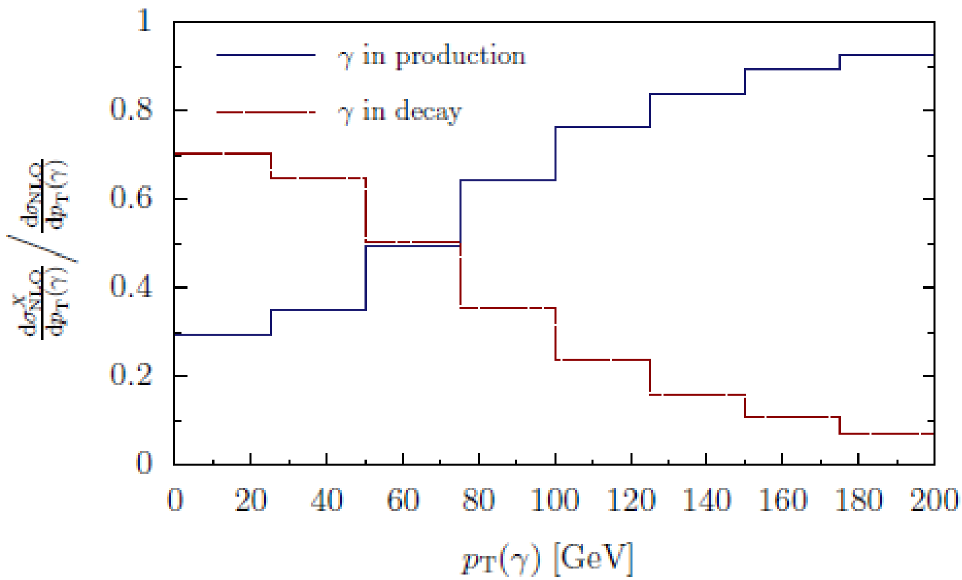


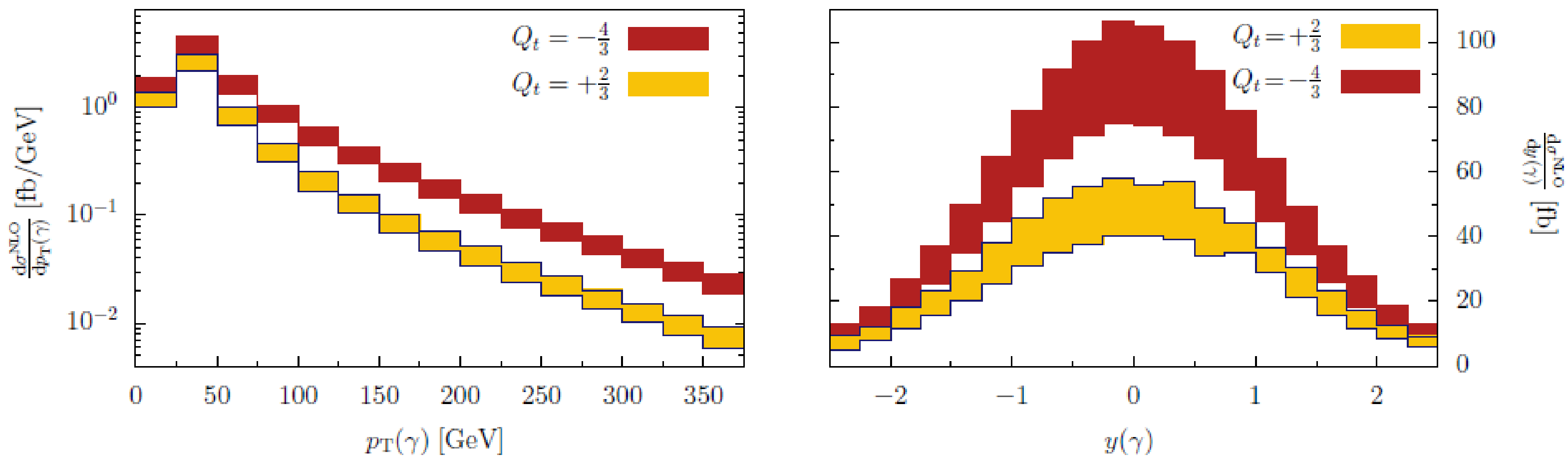
$$\sigma^{\text{NLO}}_{\text{prod}} = 61 \text{ fb}$$

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

→ 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) hypothesis



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

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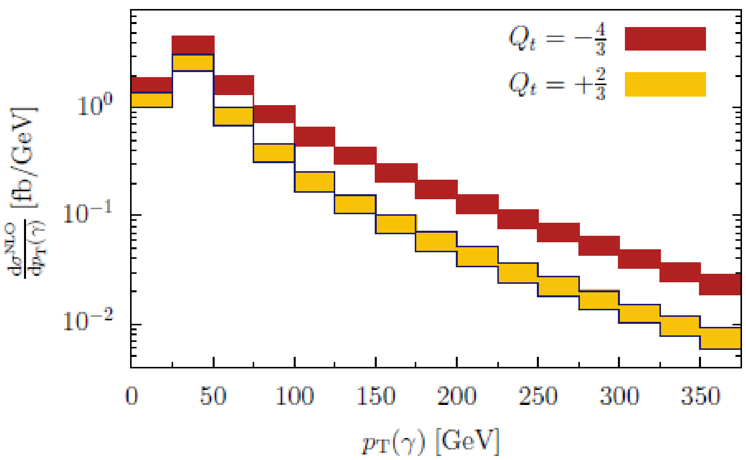

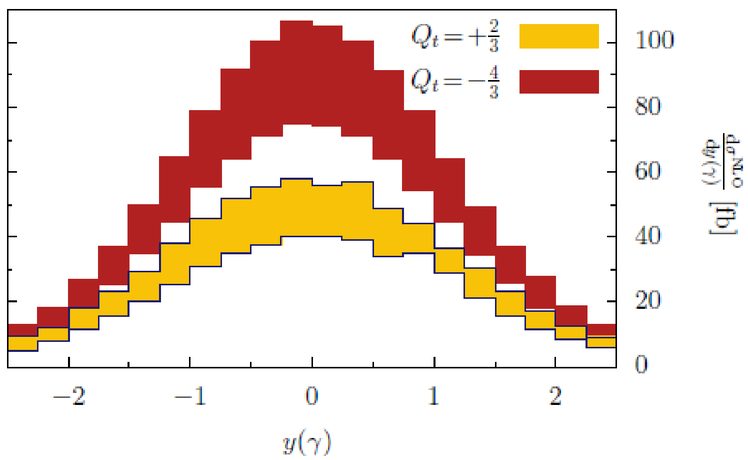

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- Naive expectation of Q_t^2 scaling (i.e. factor 4) fails:

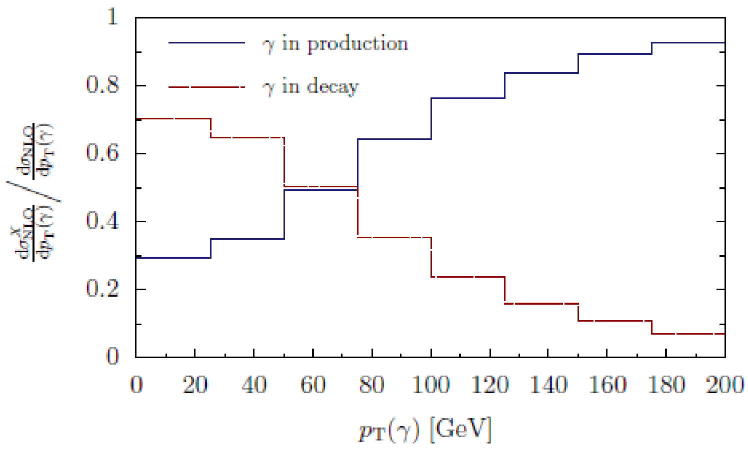
$$\mathcal{R}^{NLO} = \frac{\sigma_{NLO}^{Q_t=-4/3}}{\sigma_{NLO}^{Q_t=2/3}} = 1.76^{+0.01}_{-0.02}.$$

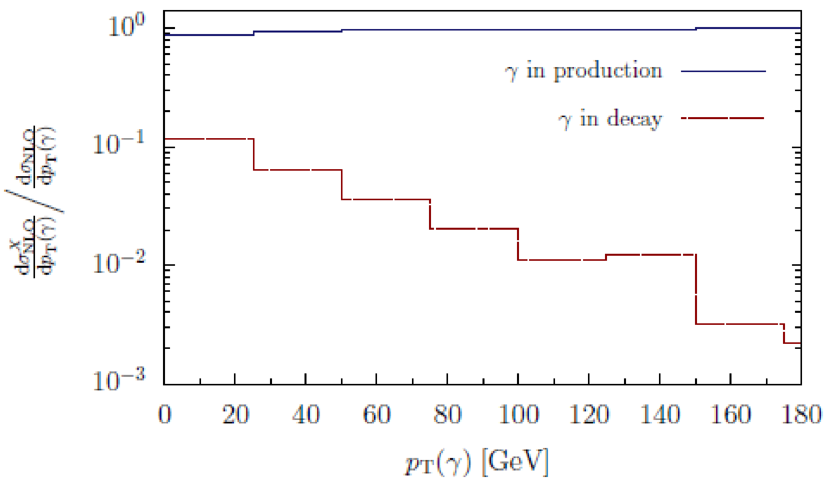
Why? Radiative decay and interference effects!

Sensitivity to Q_t at the LHC

- Apply additional cuts to suppress radiative decays

$$m_{\mathrm{T}}(b\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 180\ \mathrm{GeV}, \qquad m_{\mathrm{T}}(\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 90\ \mathrm{GeV},$$
$$160\,\mathrm{GeV} < m(bjj) < 180\ \mathrm{GeV},\ 70\,\mathrm{GeV} < m(j,j) < 90\ \mathrm{GeV}$$





BEFORE:

Radiative decay dominates

AFTER:

Radiative decay strongly suppressed, but still relevant

Sensitivity to Q_t at the LHC

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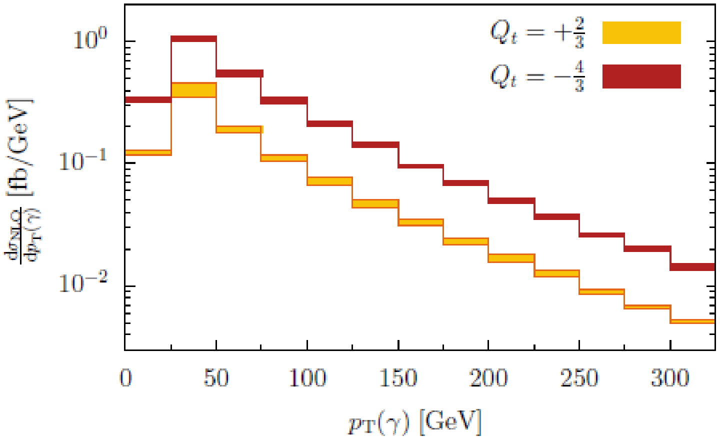
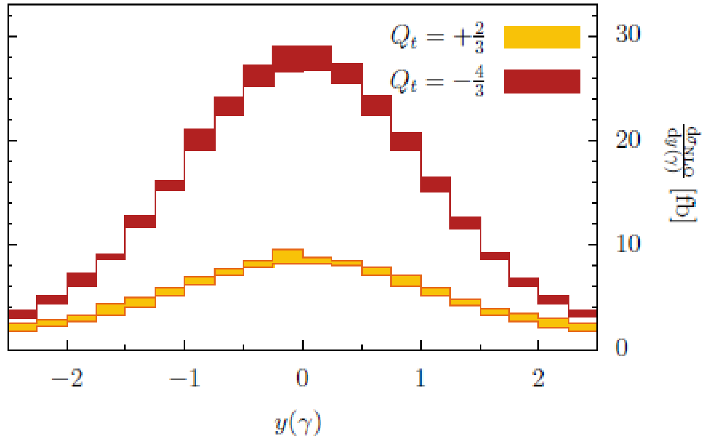




→ Significantly stronger separation power:

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

But total cross section is reduced by x5.

Sensitivity to Q_t at the LHC

- Compare two approaches:

  1) No cuts: Large cross section, less separation power

  2) Cuts: Small cross section, strong separation power

  → What is the luminosity required for 3-sigma separation between the two hypotheses?

$$\frac{\mathcal{L}}{\mathcal{L}_{\mathrm{RDS}}} = \frac{\sigma_{\mathrm{RDS}}^{Q_t=2/3}}{\sigma^{Q_t=2/3}} \frac{(\mathcal{R}_{\mathrm{RDS}}-1)^2}{(\mathcal{R}-1)^2} \qquad \frac{\mathcal{L}}{\mathcal{L}_{\mathrm{RDS}}} = \begin{cases} 1.98 \pm 0.02, & \mathrm{LO;} \\ 1.12 \pm 0.08, & \mathrm{NLO.} \end{cases}$$

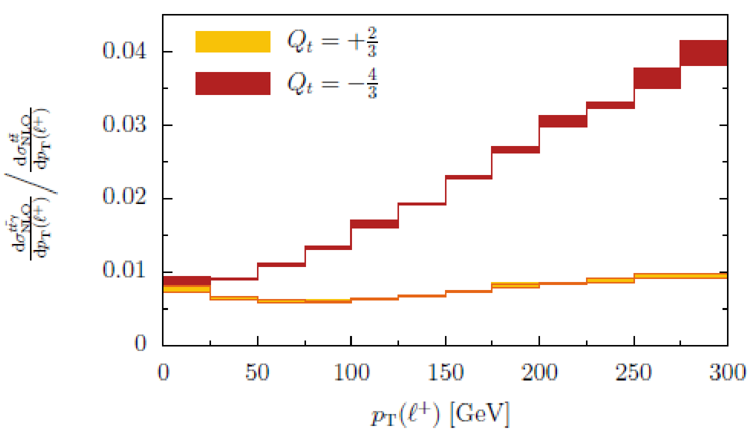
- While it seems beneficial to apply the cuts at LO. The gain is much smaller at NLO QCD.

Sensitivity to Q_t from cross section ratios

- Instead of applying additional cuts: Normalize to *ttbar* cross section

  Cancels systematics (e.g. α_s , pdfs, luminosity..)

$$\frac{\sigma_{t\bar{t}\gamma}^{Q_t=2/3}}{\sigma_{t\bar{t}}} = \begin{cases} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{cases} \qquad \frac{\sigma_{t\bar{t}\gamma}^{Q_t=-4/3}}{\sigma_{t\bar{t}}} = \begin{cases} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{cases}$$



- Some differential ratio distributions show good shape sensitivity

$pp \to t\bar{t}+Z$ at NLO QCD

[R. Röntsch, MS]

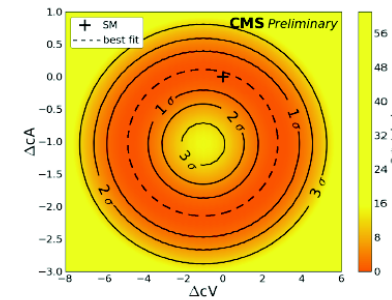
JHEP 1407 (2014) 091;

$t\bar{t} + Z$

Full NLO QCD: NLO prod.+ NLO decay with all spin correlations

Feature: No radiative decays.

[CMS PAS TOP-14-021]

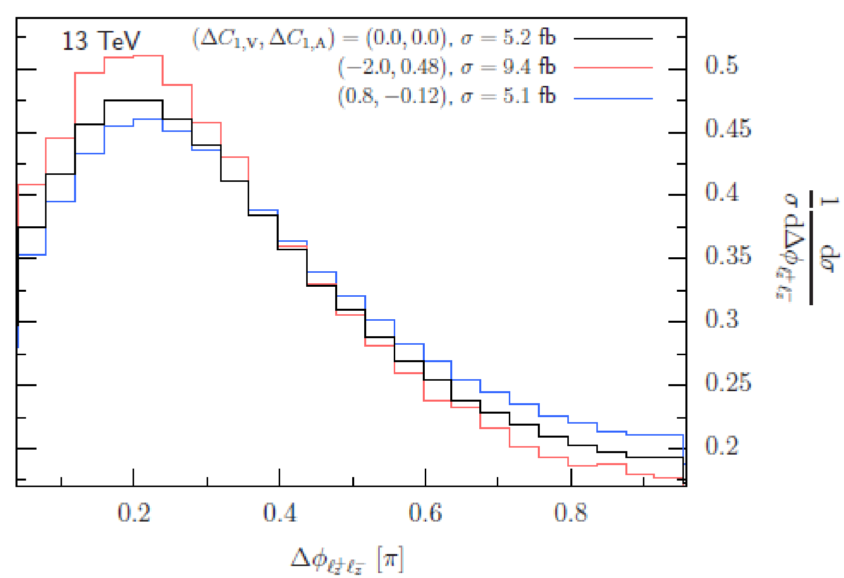


Difference between SM C_V and $C_{1,V}$

SM couplings C_1 are not protected by gauge symmetries

Weak magn./electr. dipole moments C_2

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



Constraints from LHC run-II

LO 30 fb^{-1}

NLO 30 fb^{-1}

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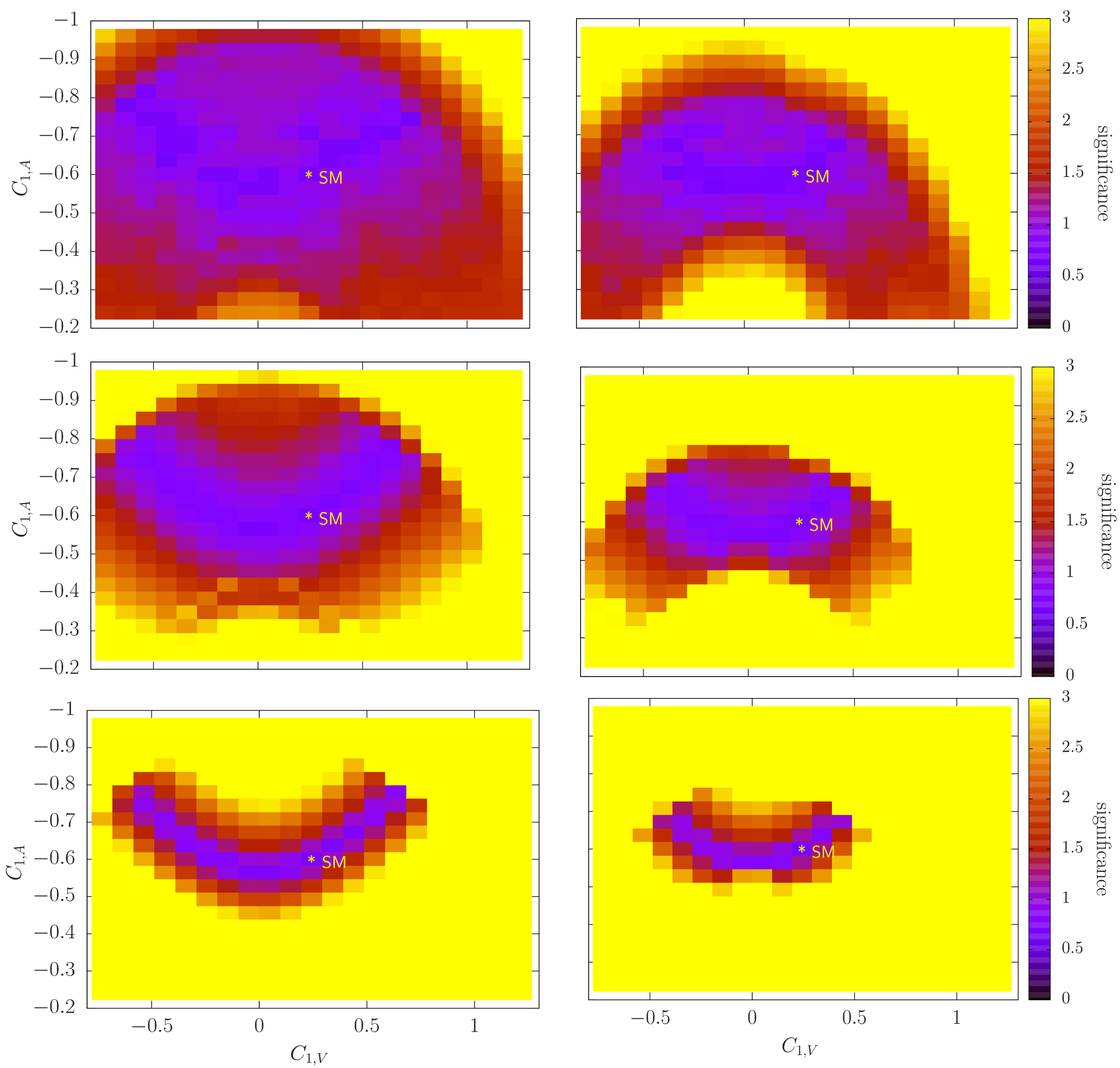

Constraints from LHC run-II

Weak dipole moments

LO 30 fb^{-1}

NLO 30 fb^{-1}

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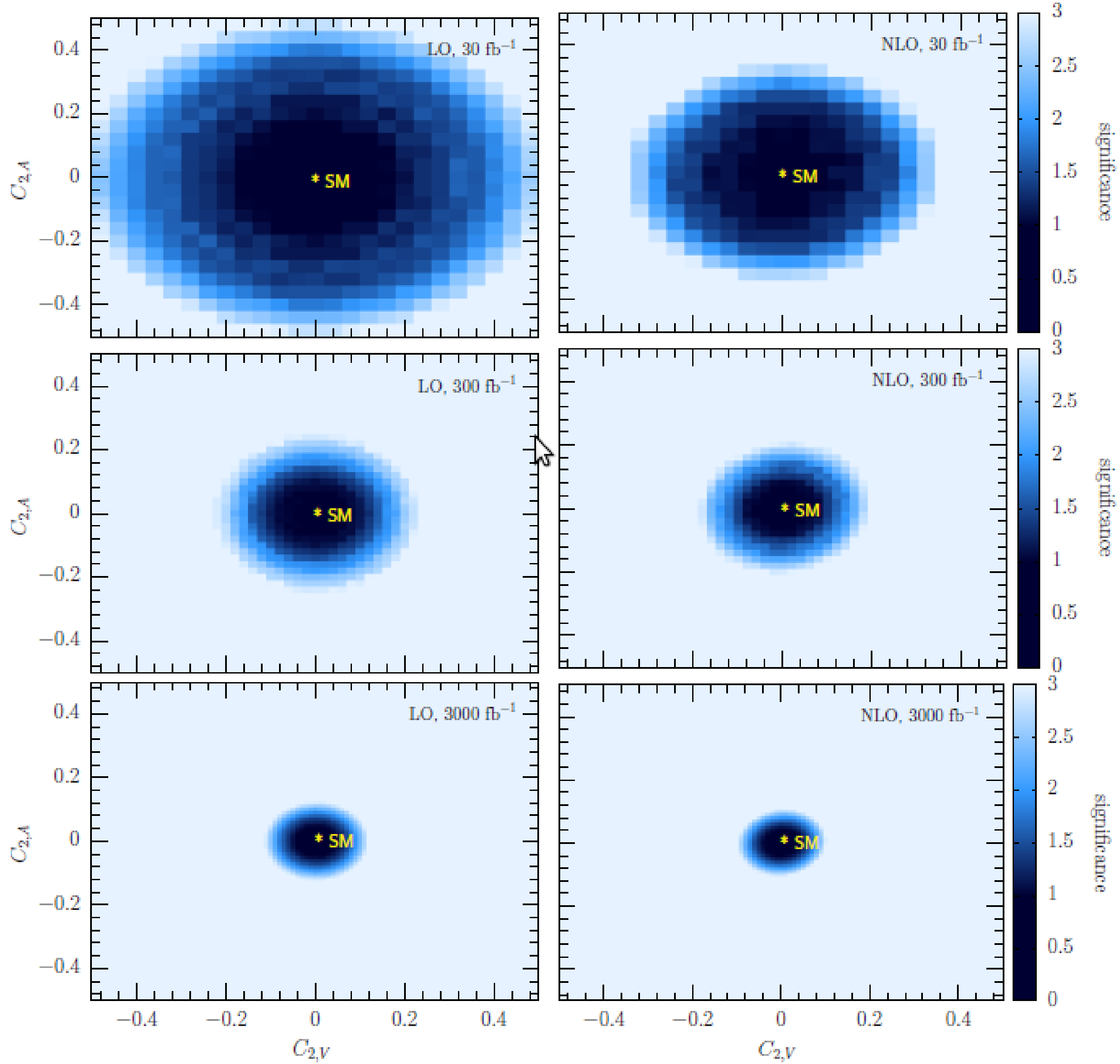

EFT in action

- Demanding SU(2)xU(1) symmetry of BSM physics leads to relations amongst EFT coeffs.

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

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

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

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- As a result, *top decay, ttbar+Z, ttbar+γ, single-top* are related
- A consistent EFT treatment of –for example– the left-handed *ttZ* coupling requires modification of top decay and top quark width.

Top dipole moments

Simultaneous study of $t\bar{t}$, $t\bar{t}+\gamma$ and $t\bar{t}+Z$ including *all* EFT relations in the $b\,\ell\,\nu\;\bar{b}\,j\,j\;(+\ell^+\ell^-/\gamma)$ final state.

[Y. Soreq, M.S.] Eur.Phys.J. C76 (2016),466

$$\mathcal{O}^{33}_{uW} = \left(\bar{q}_{\rm L}\sigma^{\mu\nu}\tau^I t_{\rm R}\right)\tilde{H}W^I_{\mu\nu},$$
$$\mathcal{O}^{33}_{dW} = \left(\bar{q}_{\rm L}\sigma^{\mu\nu}\tau^I b_{\rm R}\right)HW^I_{\mu\nu},$$
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	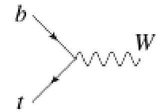	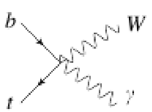	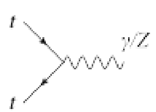
C^{33}_{uW}	$\otimes$	$\otimes$	$\otimes$
C^{33}_{dW}	$\otimes$	$\otimes$	
$C^{33}_{uB\phi}$			$\otimes$

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

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	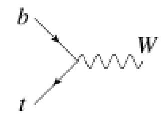	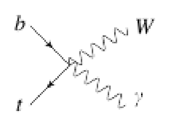	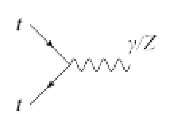
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C_{dW}^{33}	$\otimes$	$\otimes$	
$C_{uB\phi}^{33}$			$\otimes$

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

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

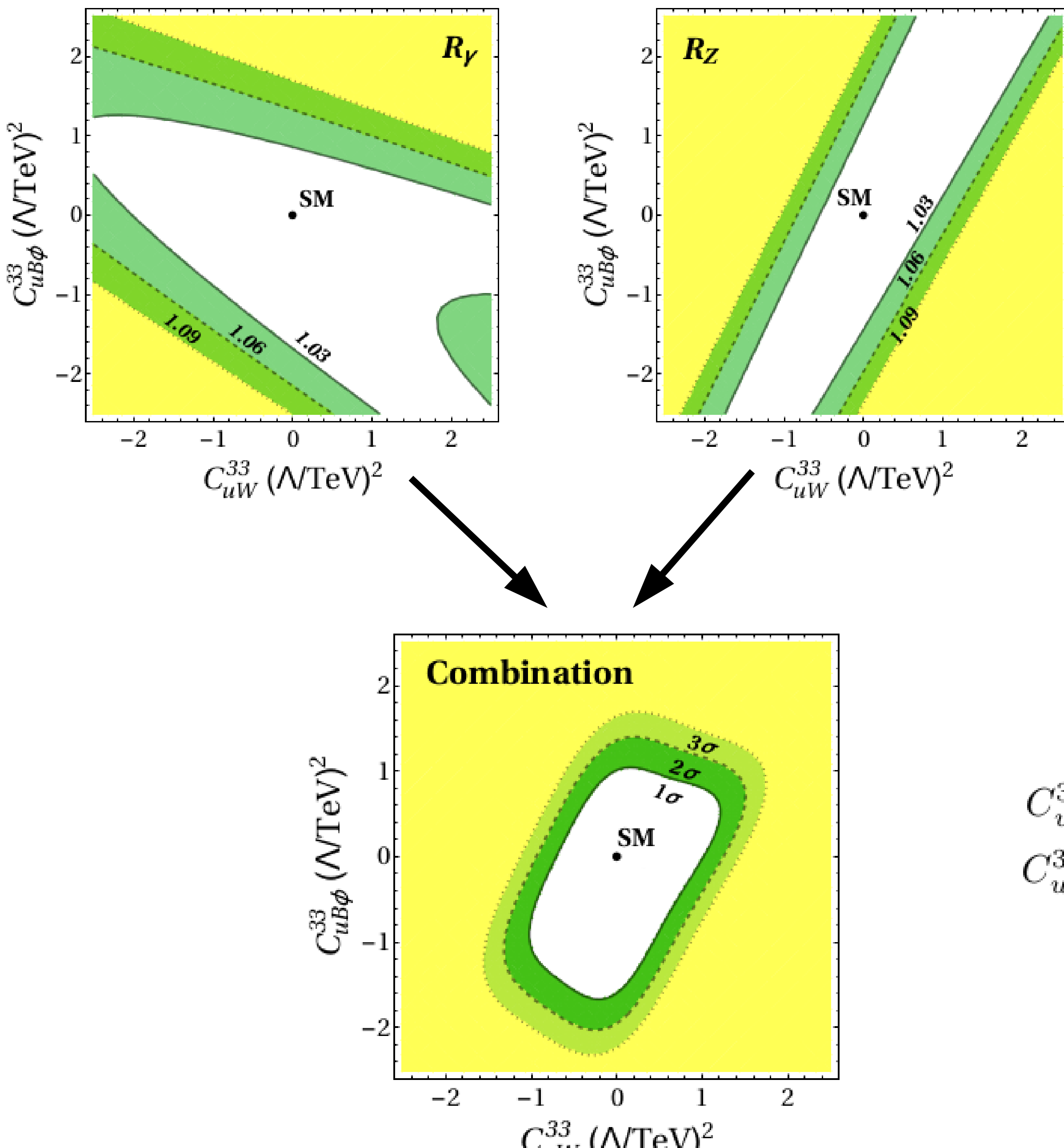
$$\mathcal{R}_\gamma = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}},\quad \mathcal{R}_Z = \frac{\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}}}$$

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

First measurement by CMS:

$$\mathcal{R}_\gamma(8\,\text{TeV}) = 10.7\times 10^{-3} \pm 6.5\%(\text{stat.}) \pm 25\%(\text{syst.})$$

Top dipole moments



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

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

$$C_{uW}^{33} = [-1.2, +1.4]\, (\Lambda/\mathrm{TeV})^2$$
$$C_{uB\phi}^{33} = [-1.9, +1.2]\, (\Lambda/\mathrm{TeV})^2$$

Thank you for your attention!