Theory overview of top-quark properties

Markus Schulze

- Many basic top quark properties have been explored at the Tevatron:

  - total cross section
  - mass
  - spin correlations, W-helicity fractions
  - FB asymmetry
  - electric charge
  - single top, $|V_{\mathrm{tb}}|$

- Quickly confirmed and superseded by ATLAS and CMS during run-I

  Two examples:

  - *spin correlations*
  - *electric charge*

- LHCb: First observation in the forward-region from run-I data

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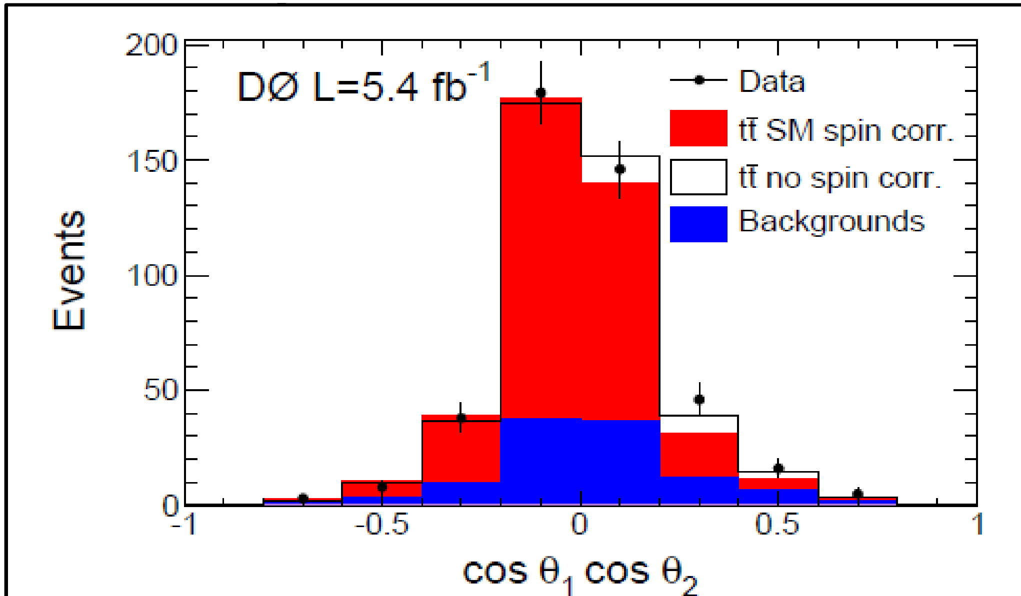
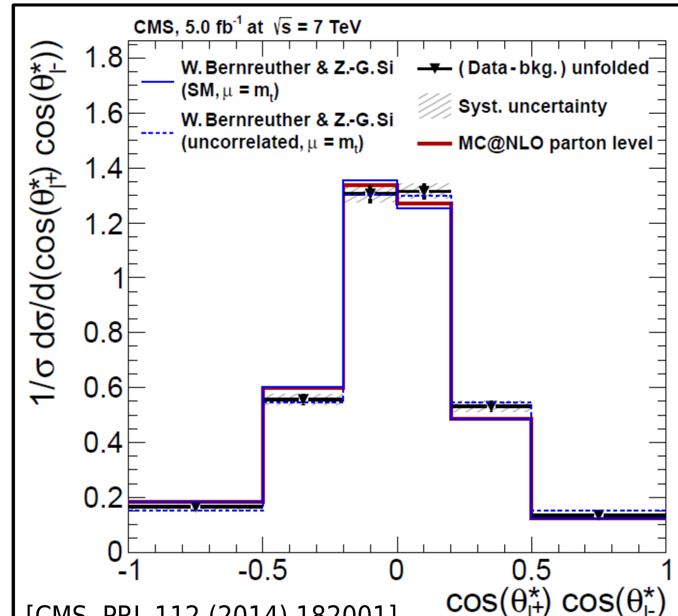


[DZero, PLB 702 , 16 (2011)]



[CMS, PRL 112 (2014) 182001]

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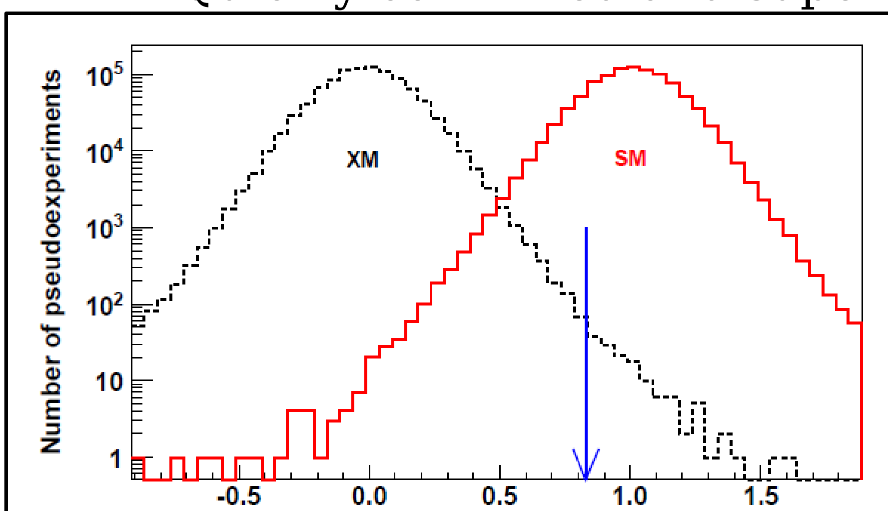
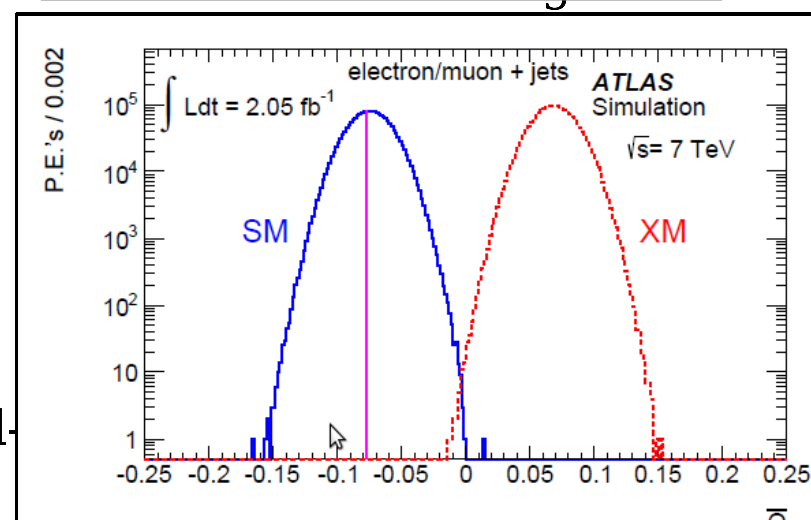


[CDF, PRD 88 032003]



[ATLAS, JHEP 1311 (2013) 031]

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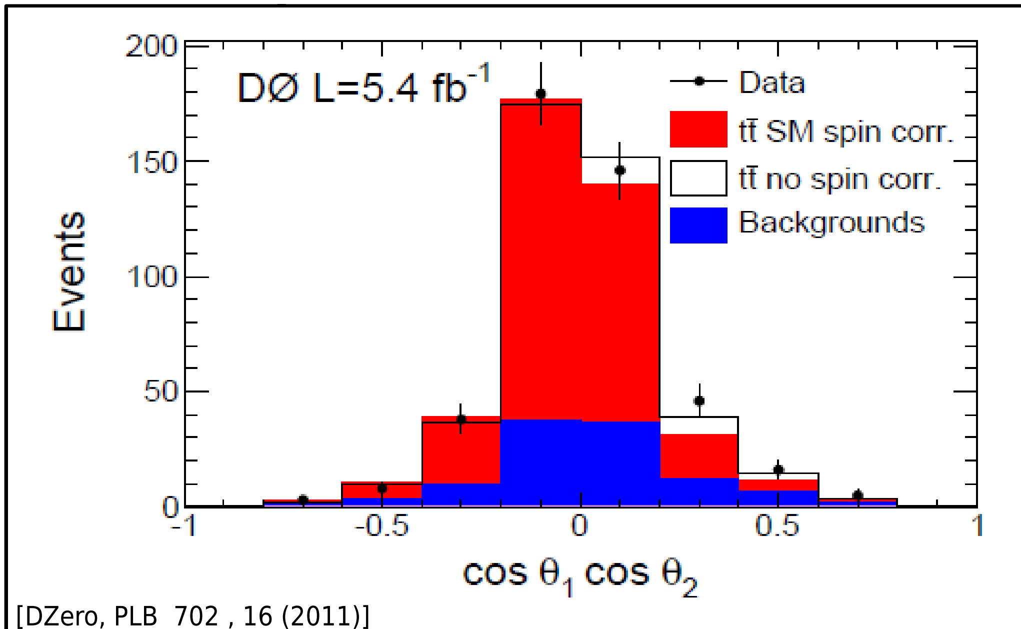

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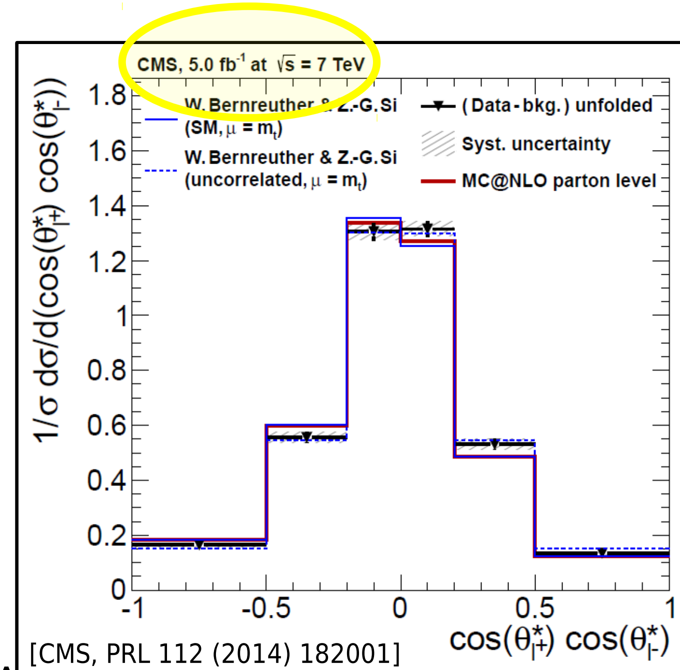

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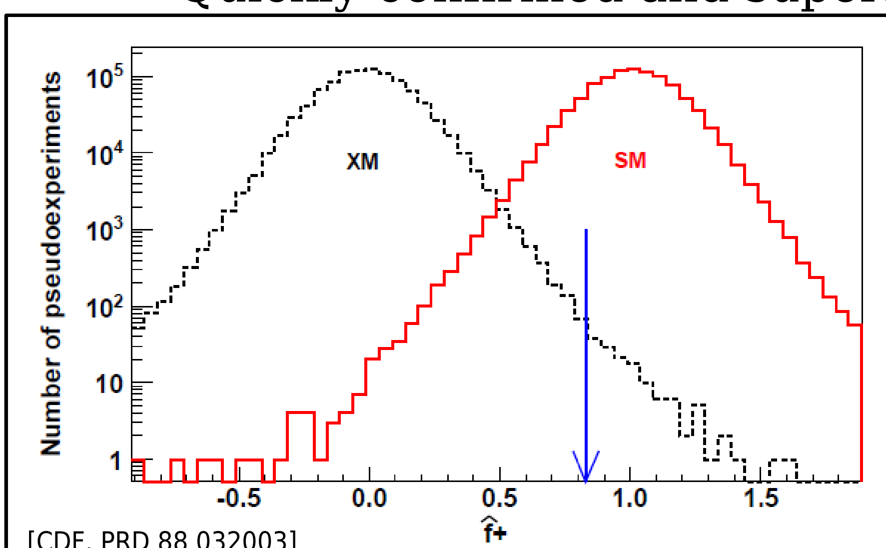

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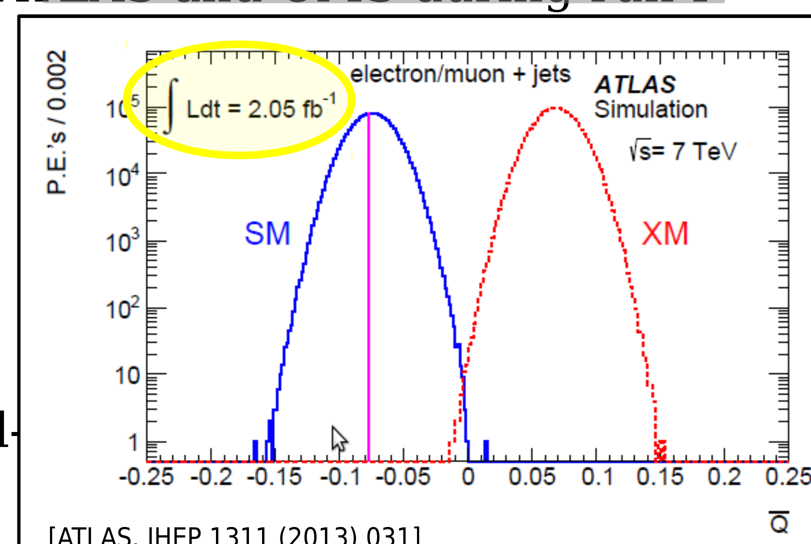

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Top quark properties

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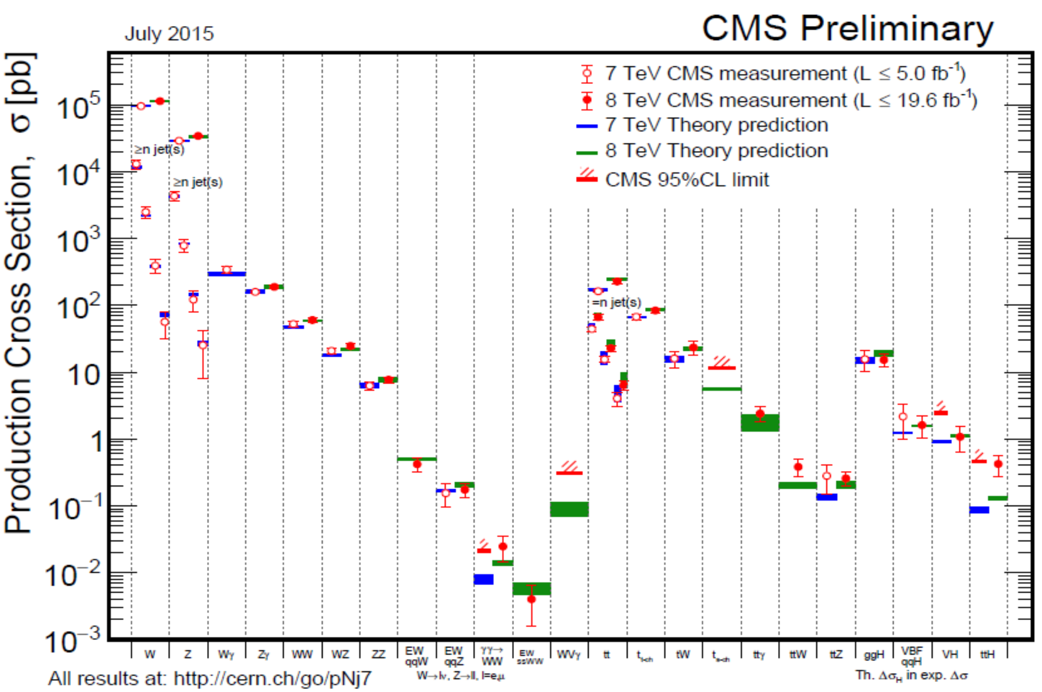
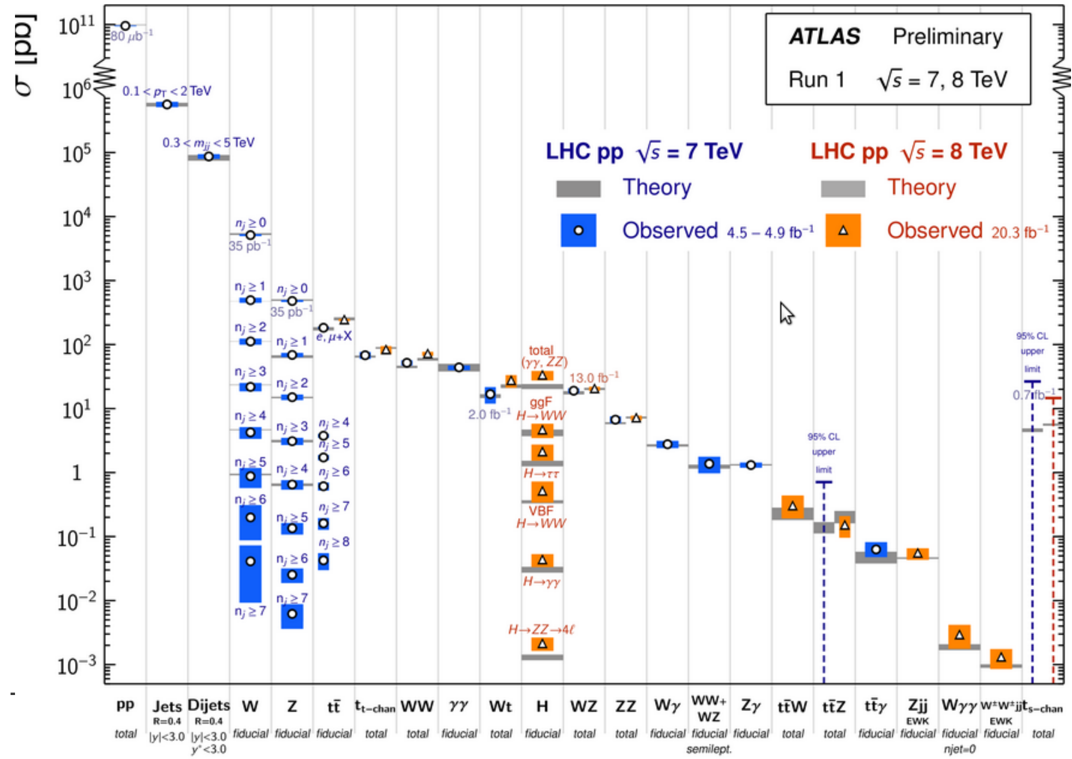
"Stairway to heaven?"



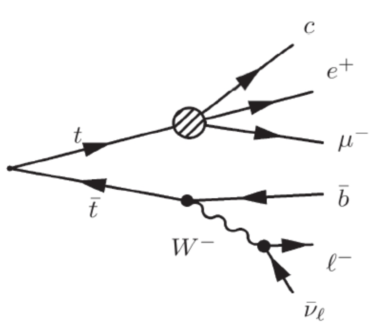


- In this talk, I want to focus on what can be achieved during run-II and beyond
- Most prominent property measurements (m_{top}, asymmetry, spin correlations,...) are topics of dedicated talks. I will discuss the rest.

- Exploit huge *ttbar* cross section to search for *rare* or *flavor-violating* top decays

[Snowmass Top Quark Working group] (2013)

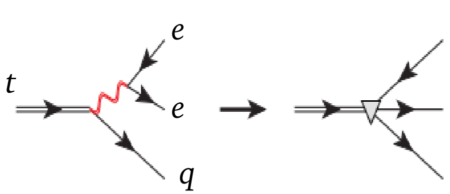
Process	Br Limit	Search	Dataset
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV



[Davidson,Mangano,Perries,Sordini] (2015)

	8 TeV (20 fb^{-1})	13 TeV (20 fb^{-1})	13 TeV (100 fb^{-1})	14 TeV (3000 fb^{-1})
$BR(t \to q\mu^{\pm}e^{\mp})$	$< 6.3 \cdot 10^{-5}$	$< 2.9 \cdot 10^{-5}$	$< 1.2 \cdot 10^{-5}$	$\lesssim 2 \cdot 10^{-6}$

Table 5: Expected upper limits on $BR(t \to q\mu^{\pm}e^{\mp})$, in the hypothesis of the absence of signal, for 8 TeV, 13 TeV (in two scenarios: the case of 20 fb^{-1} and 100 fb^{-1} collected luminosity) and 14 TeV for 3000 fb^{-1} collected luminosity.



[Durieux,Maltoni,Zhang] (2015)

$$\Gamma^{\text{on-peak}}_{t\to u\, e^+e^-} \;/10^{-5}\ \text{GeV} \ \times (\Lambda/1\ \text{TeV})^4$$
$$= 1.7\,|C^{-(1+3)}_{\varphi q}|^2 + 6.6\,|C^{(13)}_{uW}|^2 + 0.81\,|C^{3(13)}_{lequ}|^2$$

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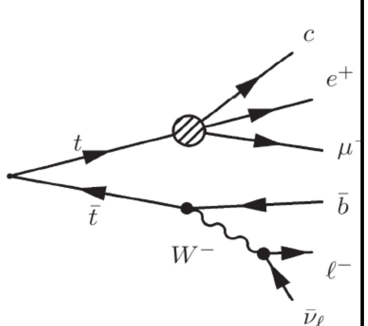
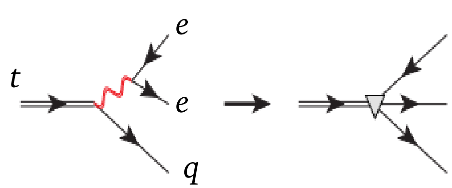
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$



3 TeV (in
uminosity.



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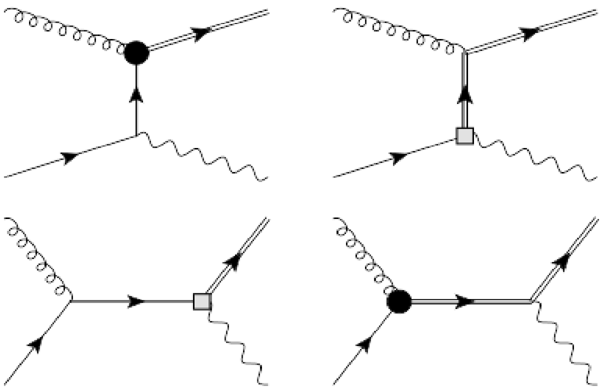
- *Flavor-violating* top couplings also induce new *single*-top processes



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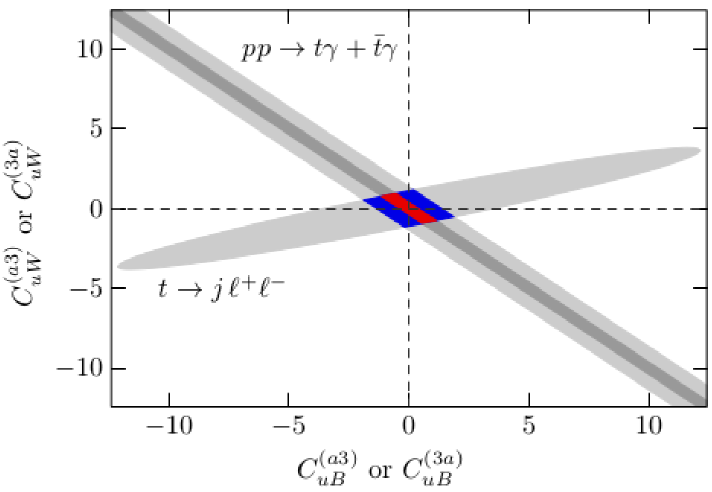

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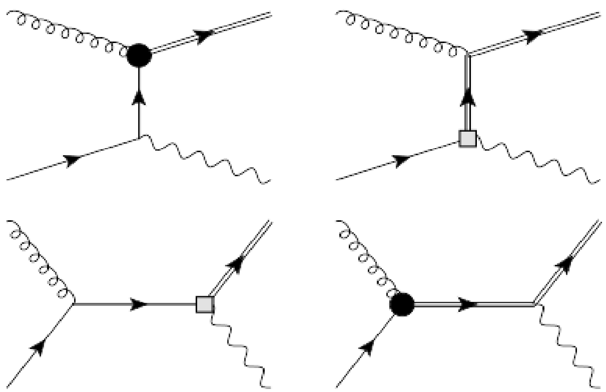

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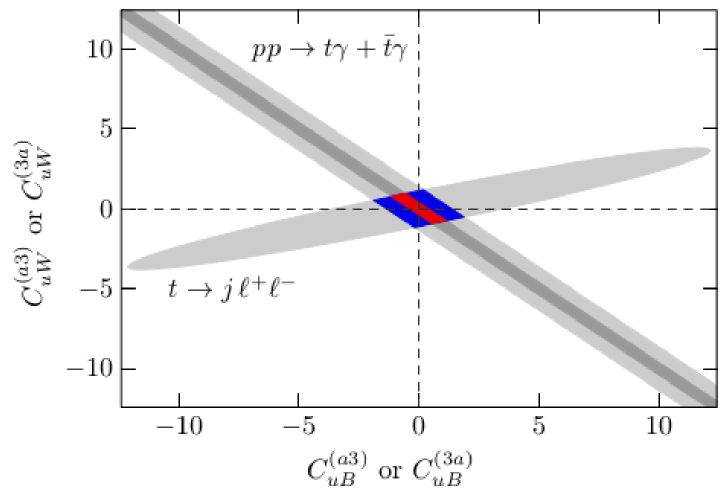


Global analysis at NLO QCD:

$$\begin{aligned} &\text{pp} \to t\gamma \\ &t \to j\ell\ell \\ &t \to j\gamma \\ &t \to \gamma\gamma \\ &ee \to tj \end{aligned}$$

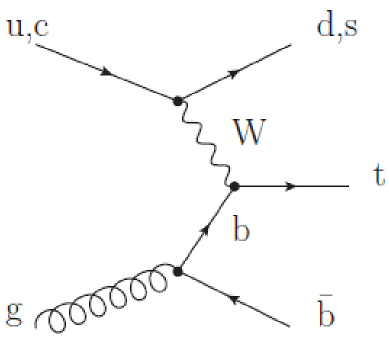
$$\sigma_{e^+e^-\to tj}^{\sqrt{s}=207\,\text{GeV}}\,[\text{fb}]\ \times (\Lambda/1\ \text{TeV})^4 =$$

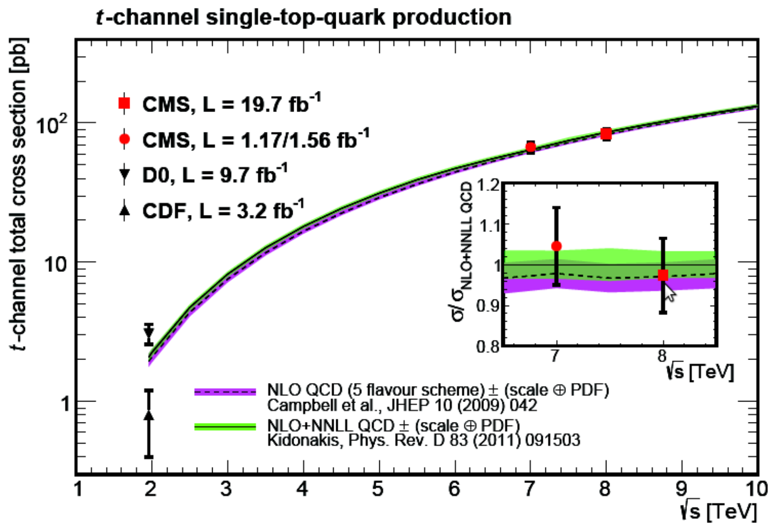
$$\text{Re}\begin{pmatrix} C_{lq}^{-(a+3)*} \\ C_{eq}^{(a+3)*} \\ C_{\varphi q}^{-(1+3)*} \\ C_{uB}^{(a3)*} \\ C_{uW}^{(a3)*} \\ C_{uG}^{(a3)*} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{+24\%}{+52} & 0 & \underset{+25\%}{+6.5} - 0.035\,i & \underset{+24\%}{-9} - 0.036\,i & \underset{+24\%}{-38} + 0.12\,i & \underset{-}{+1} \\ & \underset{+24\%}{+52} & \underset{+25\%}{-5.8} + 0.03\,i & \underset{+24\%}{-22} + 0.032\,i & \underset{+25\%}{+3.8} - 0.1\,i & \underset{-}{+0.04} \\ & & \underset{+25\%}{+0.37} & \underset{+24\%}{+0.63} - 0.00064\,i & \underset{+25\%}{-2.6} - 0.00064\,i & \underset{-}{+0.061} \\ & & & \underset{+25\%}{+2.7} & \underset{+23\%}{+2.5} - 0.003\,i & \underset{-}{-0.1} \\ & & & & \underset{+25\%}{+7.3} & \underset{-}{-0.37} \\ & & & & & \underset{-}{+1.6\times 10^{-5}} \end{pmatrix} \begin{pmatrix} C_{lq}^{-(a+3)*} \\ C_{eq}^{(a+3)*} \\ C_{\varphi q}^{-(a+3)*} \\ C_{uB}^{(a3)*} \\ C_{uW}^{(a3)*} \\ C_{uG}^{(a3)*} \end{pmatrix}$$

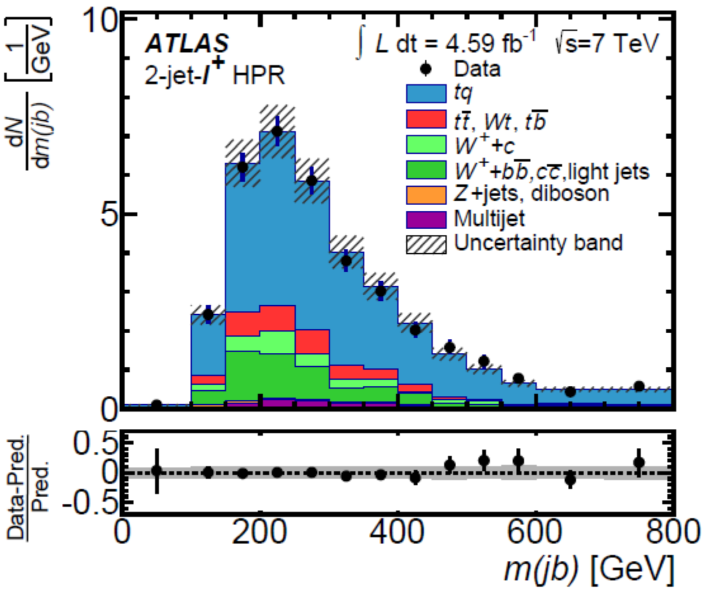
$$+\,\text{Re}\begin{pmatrix} C_{lu}^{(a+3)*} \\ C_{eu}^{(a+3)*} \\ C_{\varphi u}^{(a+3)*} \\ C_{uB}^{(3a)} \\ C_{uW}^{(3a)} \\ C_{uG}^{(3a)} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{+24\%}{+52} & 0 & \underset{+25\%}{+6.5} - 0.035\,i & \underset{+24\%}{-9} - 0.036\,i & \underset{+24\%}{-38} + 0.12\,i & \underset{-}{+1} \\ & \underset{+24\%}{+52} & \underset{+24\%}{-5.7} + 0.03\,i & \underset{+24\%}{-22} + 0.032\,i & \underset{+25\%}{+3.8} - 0.1\,i & \underset{-}{+0.71} \\ & & \underset{+25\%}{+0.37} & \underset{+24\%}{+0.63} - 0.00064\,i & \underset{+25\%}{-2.6} - 0.00064\,i & \underset{-}{+0.024} \\ & & & \underset{+24\%}{+2.7} & \underset{+23\%}{+2.5} - 0.003\,i & \underset{-}{-0.24} \\ & & & & \underset{+25\%}{+7.3} & \underset{-}{-0.35} \\ & & & & & \underset{-}{+1.6\times 10^{-5}} \end{pmatrix} \begin{pmatrix} C_{lu}^{(a+3)*} \\ C_{eu}^{(a+3)*} \\ C_{\varphi u}^{(1+3)*} \\ C_{uB}^{(3a)} \\ C_{uW}^{(3a)} \\ C_{uG}^{(3a)} \end{pmatrix}$$

$$+\,\underset{+42\%}{33}\left(|C_{lequ}^{1(a3)}|^2 + |C_{lequ}^{1(3a)}|^2\right) + \underset{+26\%}{370}\left(|C_{lequ}^{3(a3)}|^2 + |C_{lequ}^{3(3a)}|^2\right)$$

- *Single* top quark production in the SM yields sensitivity to $|V_{tb}|^2$







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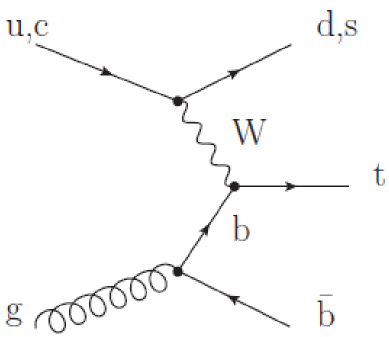

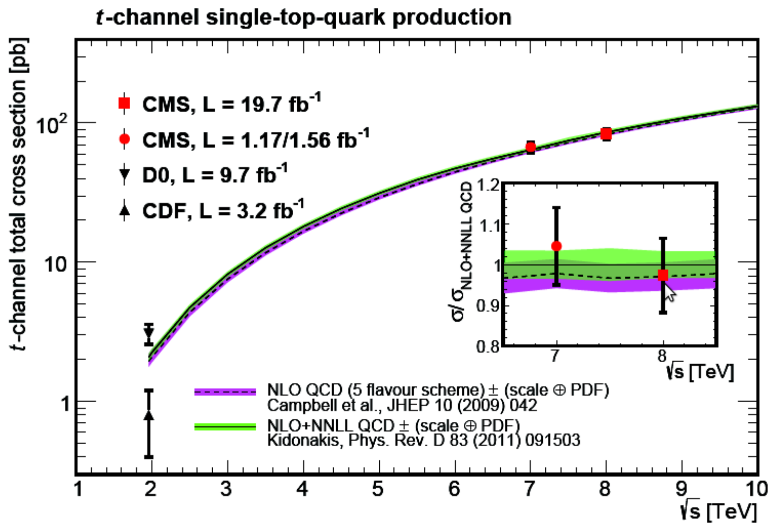

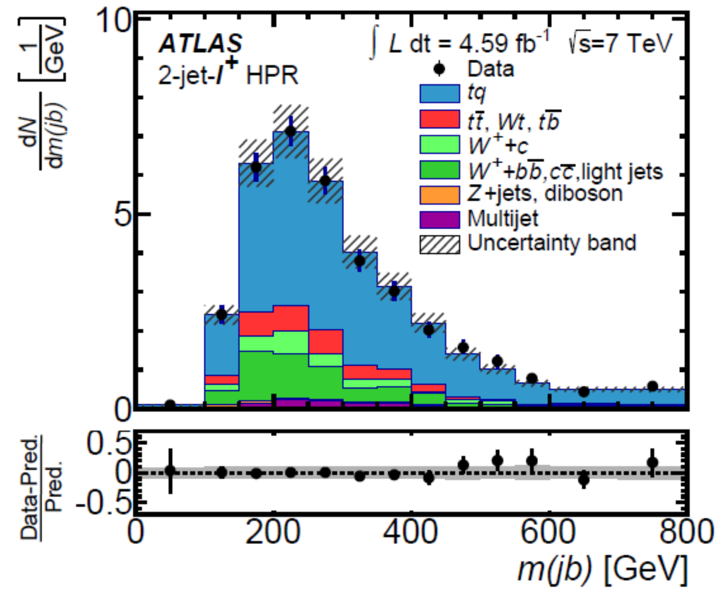

$$|f_{\rm Lv} V_{\rm tb}| = 0.979 \pm 0.045\,(\text{exp.}) \pm 0.016\,(\text{theo.}),$$ [CMS,JHEP06(2014)090]

$$|V_{tb}| = 1.02 \pm 0.01\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.02\,(\text{theo.})$$ [ATLAS,PRD90,112006 (2014)]

- $V_{\rm tb}$ extraction relies on *normalization* measurement (currently NLO)

[Brucherseifer,Caola,Melnikov] (2014)

- *Fully-differential* NNLO QCD predictions are available

→ Lessons: - small NNLO correction for incl. cross section is accidental
- large cancellations among different partonic channels
- N^xLL dressing of LO contributions is dangerous

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

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

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

chromo-EDM *violate* CP:

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

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complex coupling

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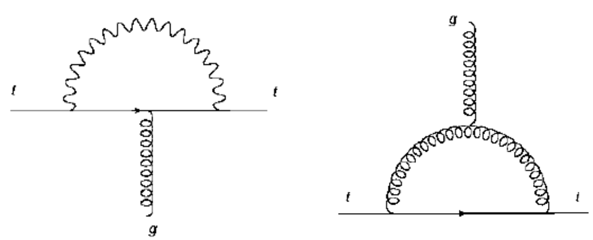
complex coupling

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

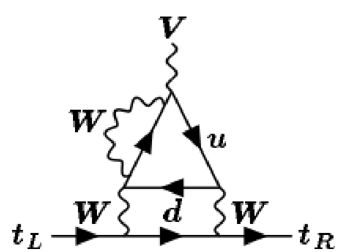
chromo-MDM:



$\sim d_V \approx -0.007$

[Martinez,Perez,Poveda] (2007)

chromo-EDM:



$\sim d_A \approx$ tiny

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

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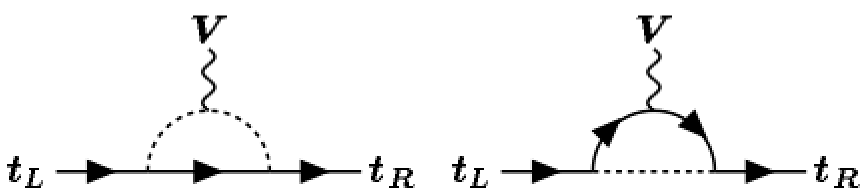
- Beyond the SM, dipole moment couplings can arise already at tree level



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

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

Top quark properties

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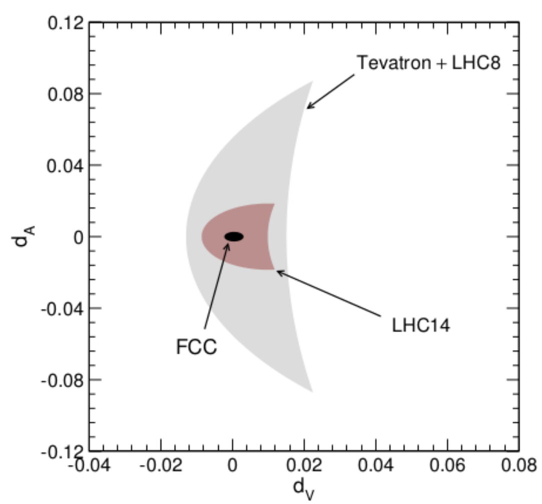
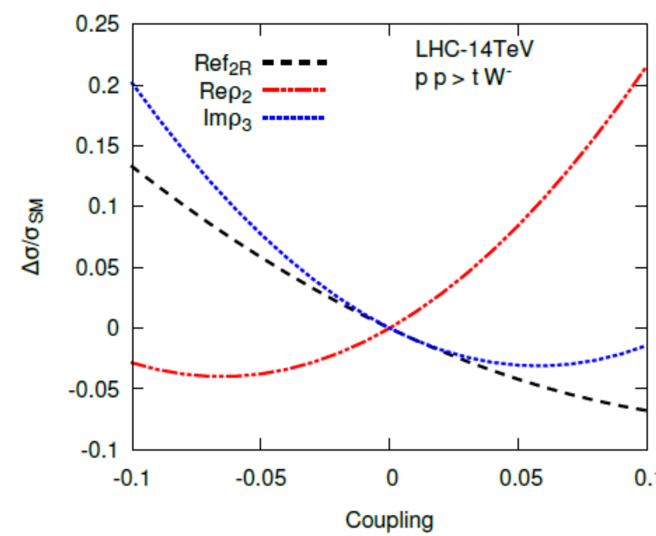


[Aguilar-Saavedra,Fuks,Mangano] 2014

$$\begin{aligned} A_{FB} &= \frac{N_{\rm EW} + \alpha_s^3 N_3 + \alpha_s^4 N_4 + \alpha_s^3 \frac{C_{tG}}{\Lambda^2} N_{tG} + \mathcal{O}(\alpha_s^5, \alpha_s^4\Lambda^{-2})}{\alpha_s^2 D_2 + \alpha_s^3 D_3 + \alpha_s^4 D_4 + \alpha_s^3 \frac{C_{tG}}{\Lambda^2} D_{tG} + \mathcal{O}(\alpha_s^5, \alpha_s^4\Lambda^{-2})} \\ &= A_{FB}(SM) + \frac{C_{tG}}{\Lambda^2}\frac{\alpha_s N_{tG}}{D_2} + \mathcal{O}(\alpha_s^3, \alpha_s^2\Lambda^{-2}) \\ &= 0.095 \pm 0.007 + C_{tG}\, 0.021^{+0.003}_{-0.002}\left(\frac{\rm TeV}{\Lambda}\right)^2 \end{aligned}$$

[Franzosi,Zhang] 2015



[Rindani,Sharma,Thoma] 2015

+many others

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

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

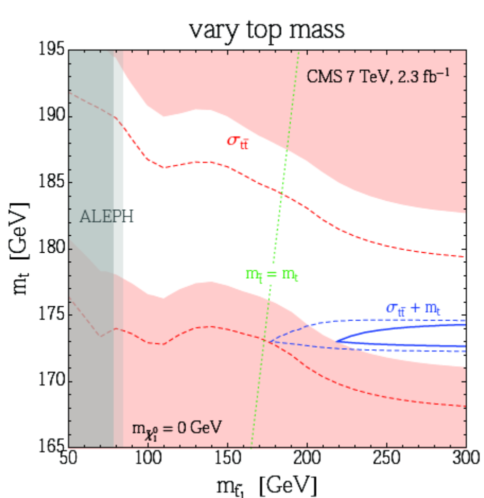
chromo-EDM *violate* CP:

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

complex coupling

- All these measurements *significantly* benefit from high precision theory predictions, in particular the NNLO QCD

[Bärnreuther,Czakon,Fiedler,Heymes,Mitov] 2013



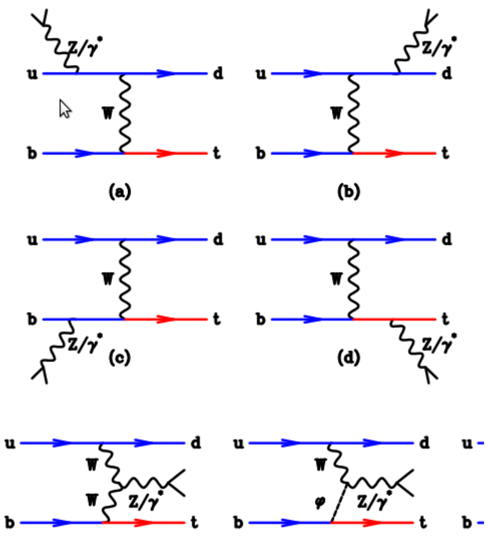
[Czakon,Mitov,Papucci,Ruderman,Weiler] 2014

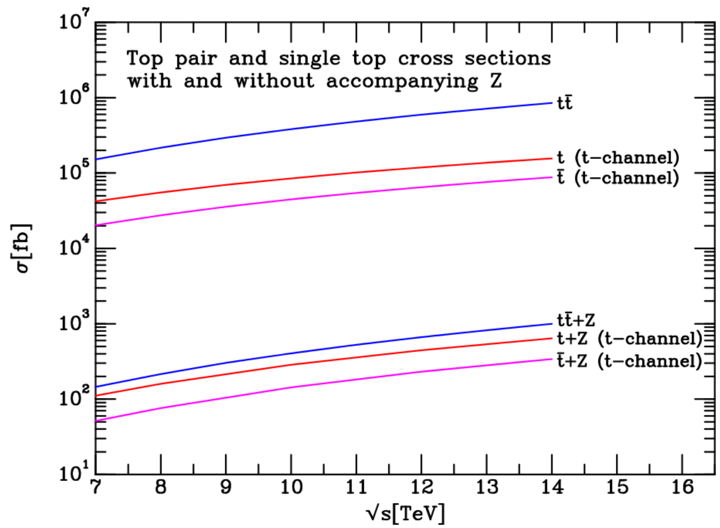
- Top quarks in association with *electroweak gauge bosons* or the *Higgs*

  → *direct* sensitivity top quark electroweak interactions
  (almost unconstrained from Tevatron experiments)

single top + Z: NLO QCD

[Campbell,Ellis,Rontsch] (2014)

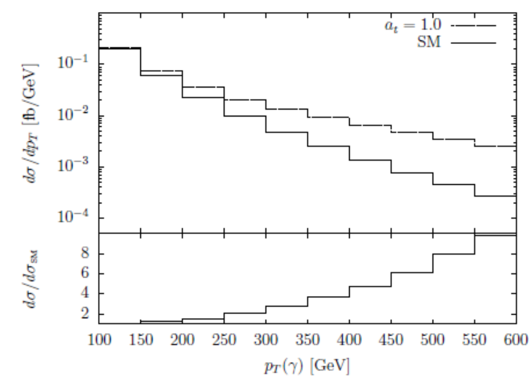


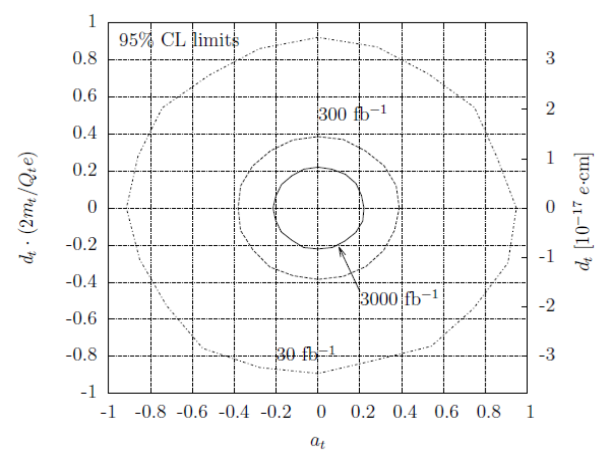


→ possibility to study top-Z interactions
and interplay with WWZ

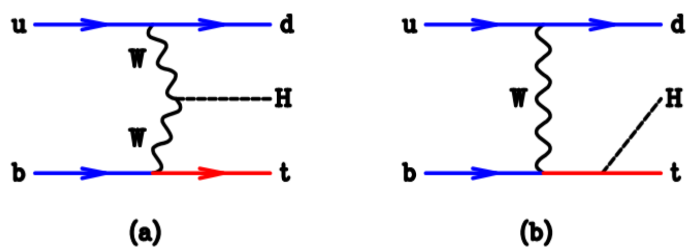
single top + γ: LO QCD

[Fael,Gehrmann] (2013)

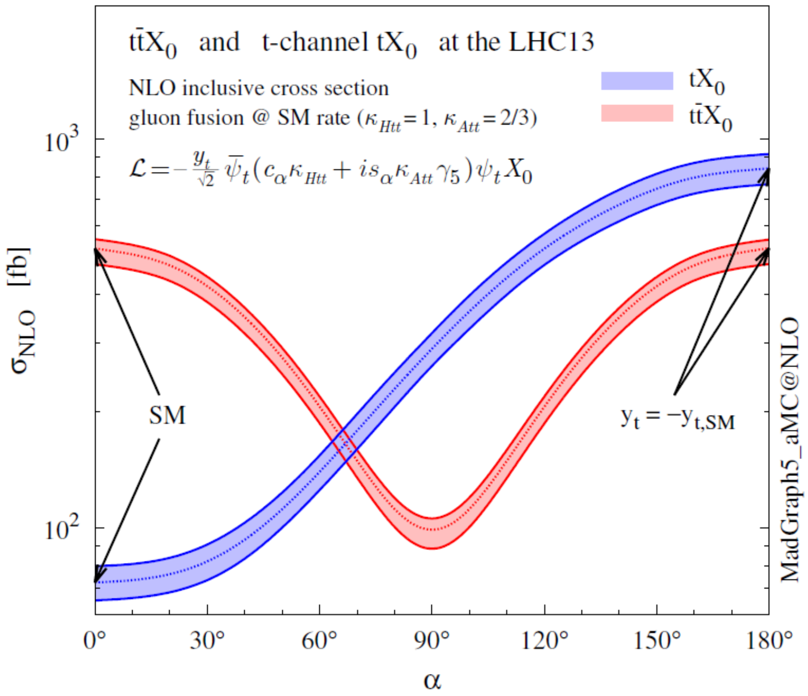




single top + H:
NLO QCD



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



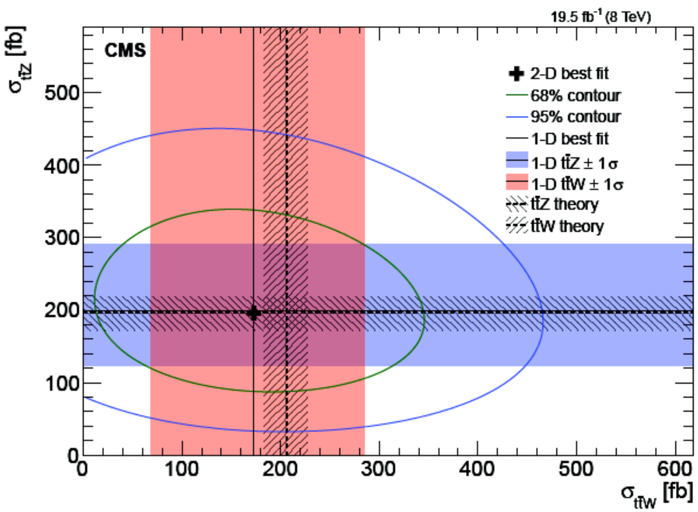
[Biswas,Gabrielli,Mele] (2012),
[Farina,Grojean,Maltoni,Salvioni,Thamm] (2012),
[Campbell,Ellis,Rontsch] (2014),
[Demartin,Maltoni,Mawatari,Zaro] (2015)

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

Top quark properties

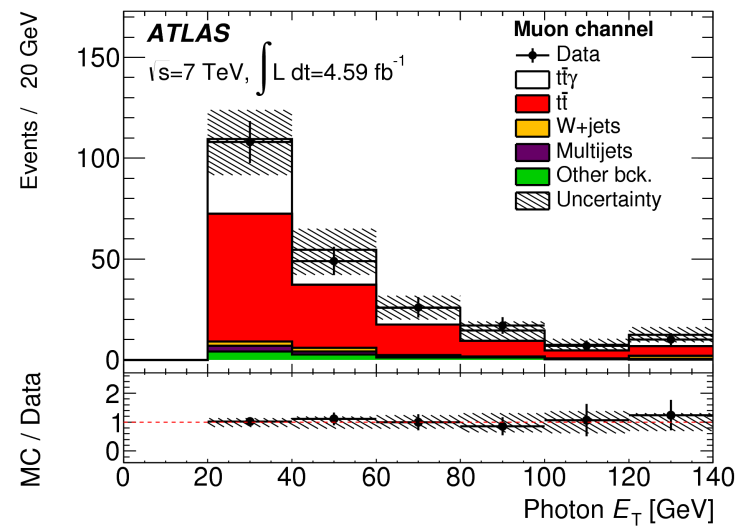
ttbar + Z / photon:

- relatively large cross sections
- *direct* sensitivity to electroweak couplings + weak dipole moments



	Yield
$t\bar{t}Z$ (expected)	7.8 ± 0.9
Irreducible	0.8 ± 0.4
$t\bar{t}W$	0.2 ± 0.1
Non-top-quark	2.3 ± 1.2
Misidentified lepton	1.1 ± 0.8
Total background	4.4 ± 1.6
Total expected	12.2 ± 1.8
Observed	12

[CMS, EPJ C74 (2014) 3060]



Contribution	Electron chan.	Muon chan.	Total
Signal	52 ± 14	100 ± 28	152 ± 31
Hadrons	38 ± 26	55 ± 38	93 ± 46
Prompt photons	41 ± 5	65 ± 9	106 ± 10
Total background	79 ± 26	120 ± 39	199 ± 47
Total	131 ± 30	220 ± 48	351 ± 59
Data candidates	140	222	362

[ATLAS, Phys. Rev. D 91, 072007 (2015)]

- cross sections increase by ~ factor 10 for 7 → 13 TeV *ttbar* + *Z* → *3-lepton* + $b\bar{b}$ *jj* + $E_{\mathrm{T,miss}}$ at NLO QCD: [Röntsch, M.S.] (2014,2015)

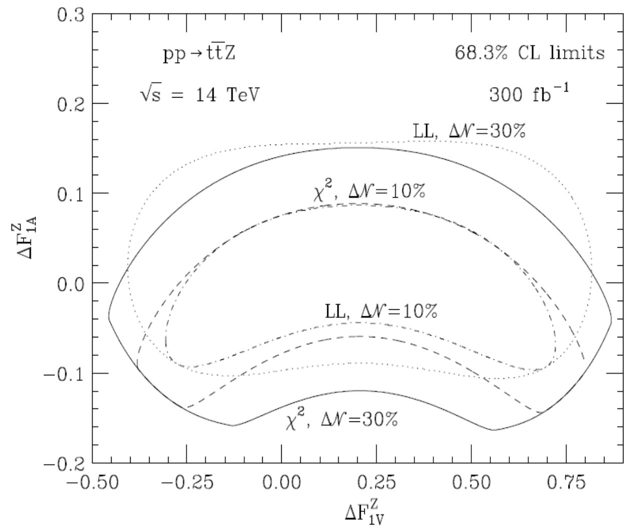
$$\mathcal{L}^{\mathrm{OS}}_{Vf_if_j} = \bar{f}_j\,\gamma^\mu\,(\mathcal{A}_L P_L + \mathcal{A}_R P_R)\,f_i\,V_\mu + \bar{f}_j\,i\sigma^{\mu\nu}q_\nu\,(\mathcal{B}_L P_L + \mathcal{B}_R P_R)\,f_i\,V_\mu + \mathrm{H.c.}\,,$$

modifies strength of SM couplings

introduces anomalous weak *magn*. and *electric dipole moments*

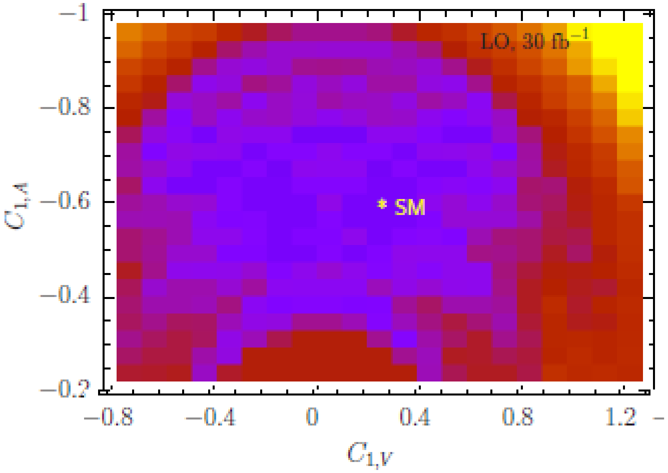
- Early studies show that *"...residual scale uncertainty is biggest limiting factor in these studies"*

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

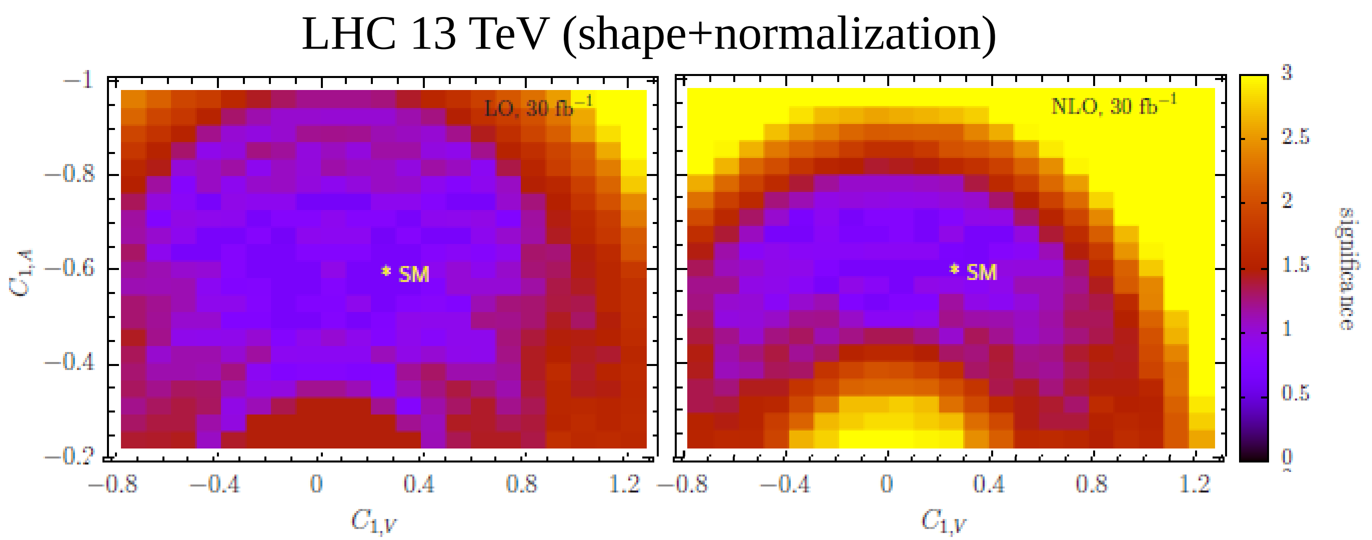


LHC 13 TeV (shape+normalization)

LO 30 fb^{-1}



LO 30 fb^{-1}



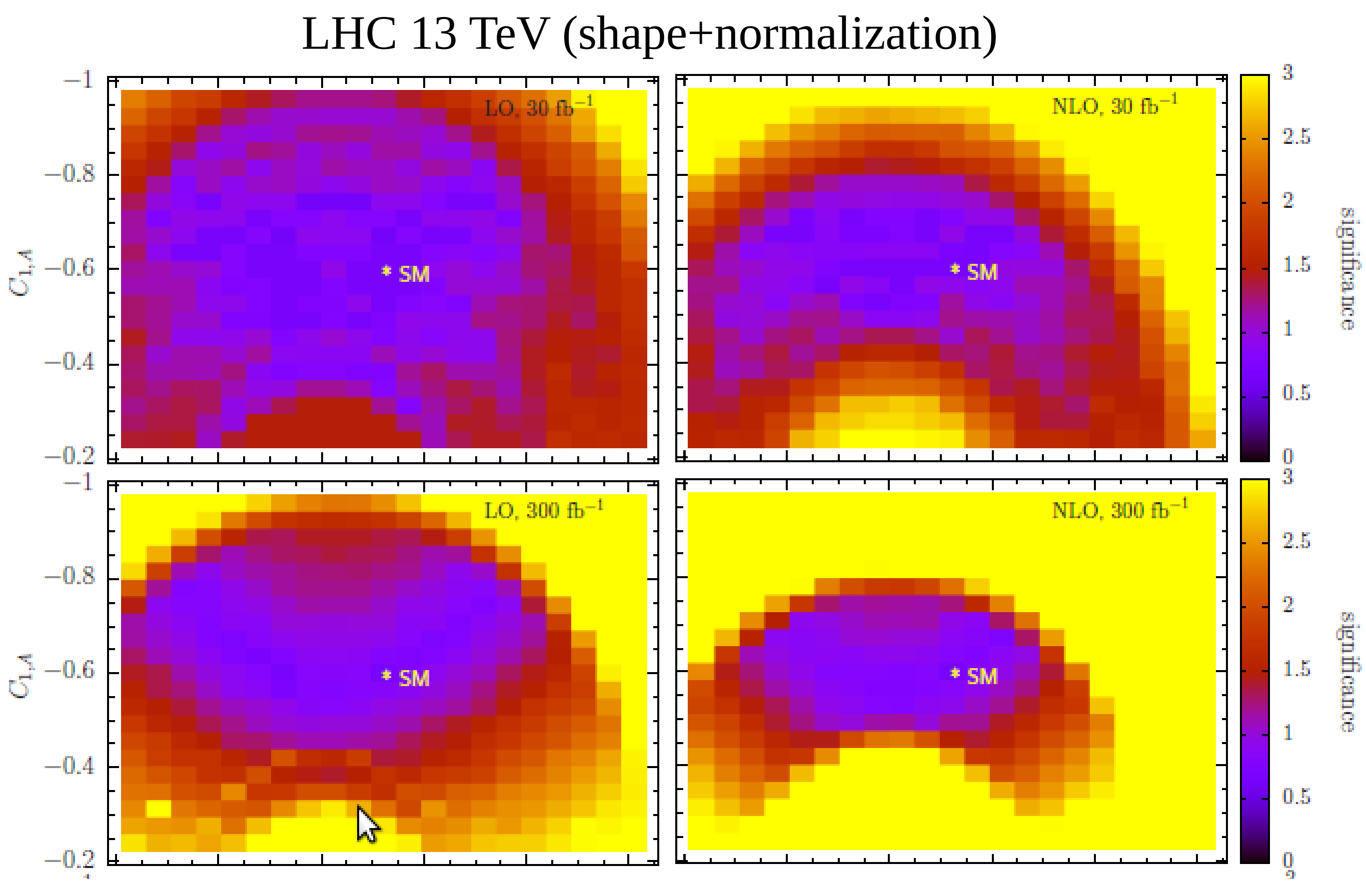
NLO 30 fb^{-1}

LO 30 fb^{-1}

NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}



LO 30 fb^{-1}

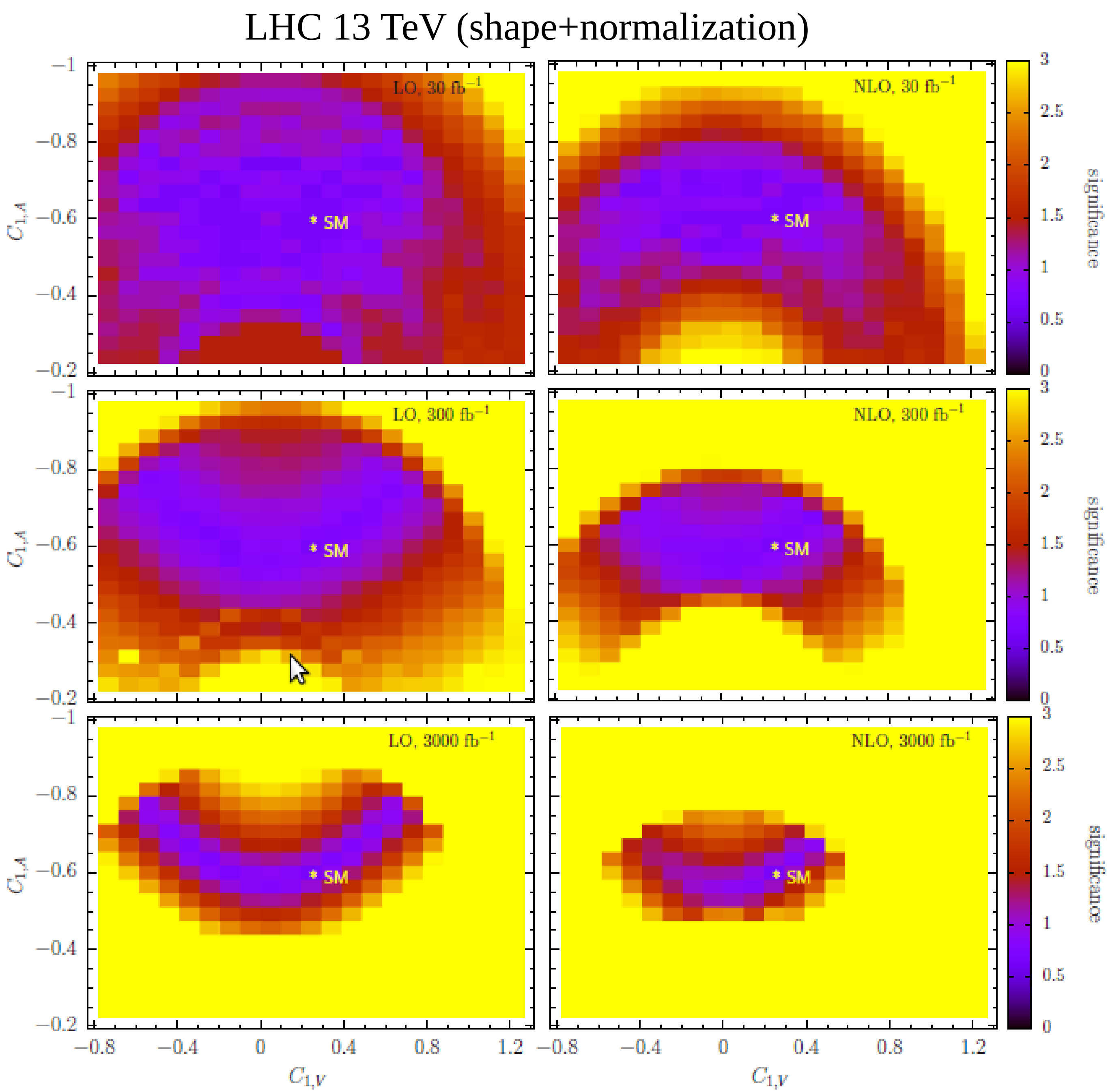
NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}

LO 3000 fb^{-1}

NLO 3000 fb^{-1}



LHC 13 TeV (shape+normalization)

LO 30 fb^{-1}

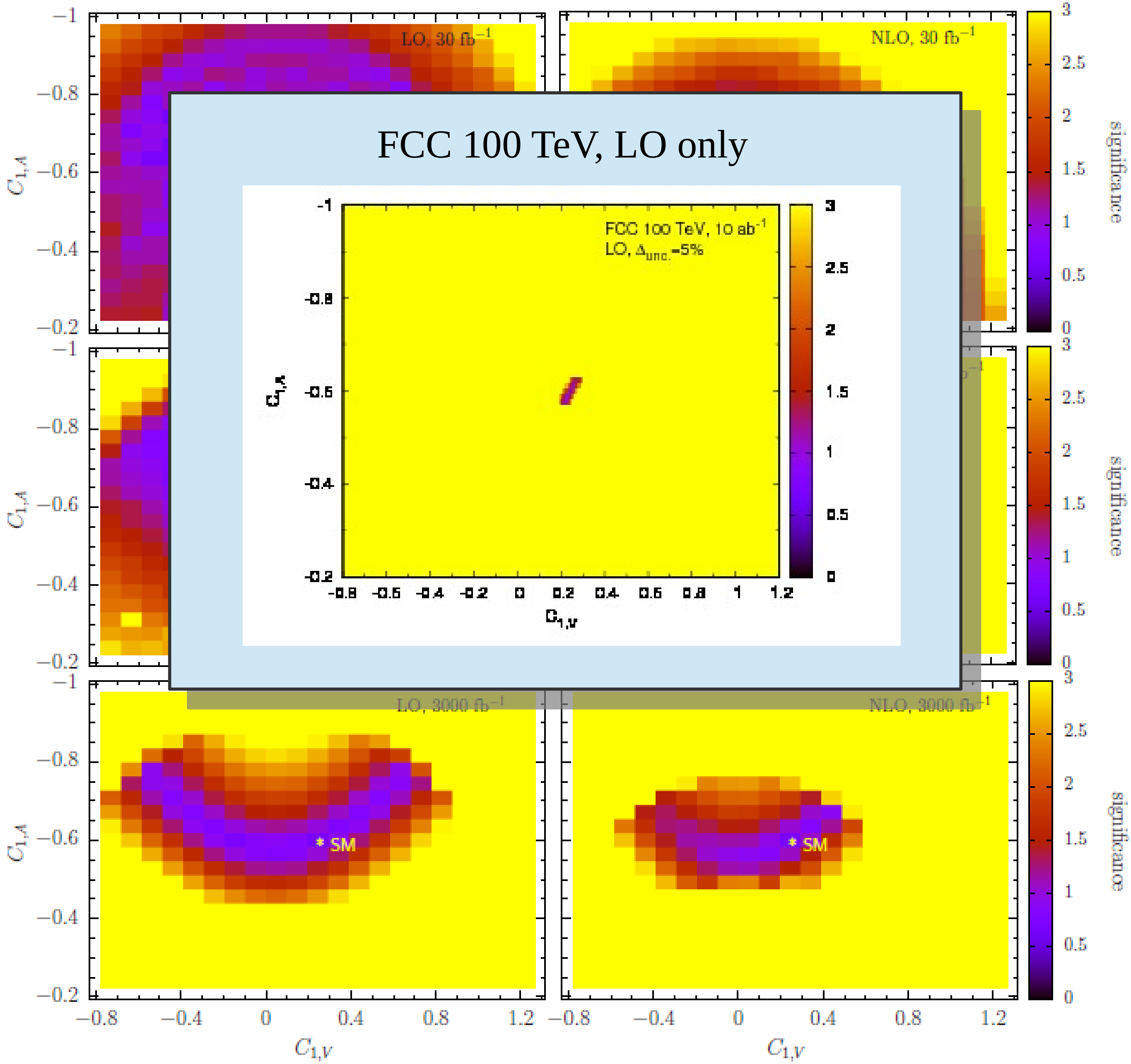
NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}

LO 3000 fb^{-1}

NLO 3000 fb^{-1}

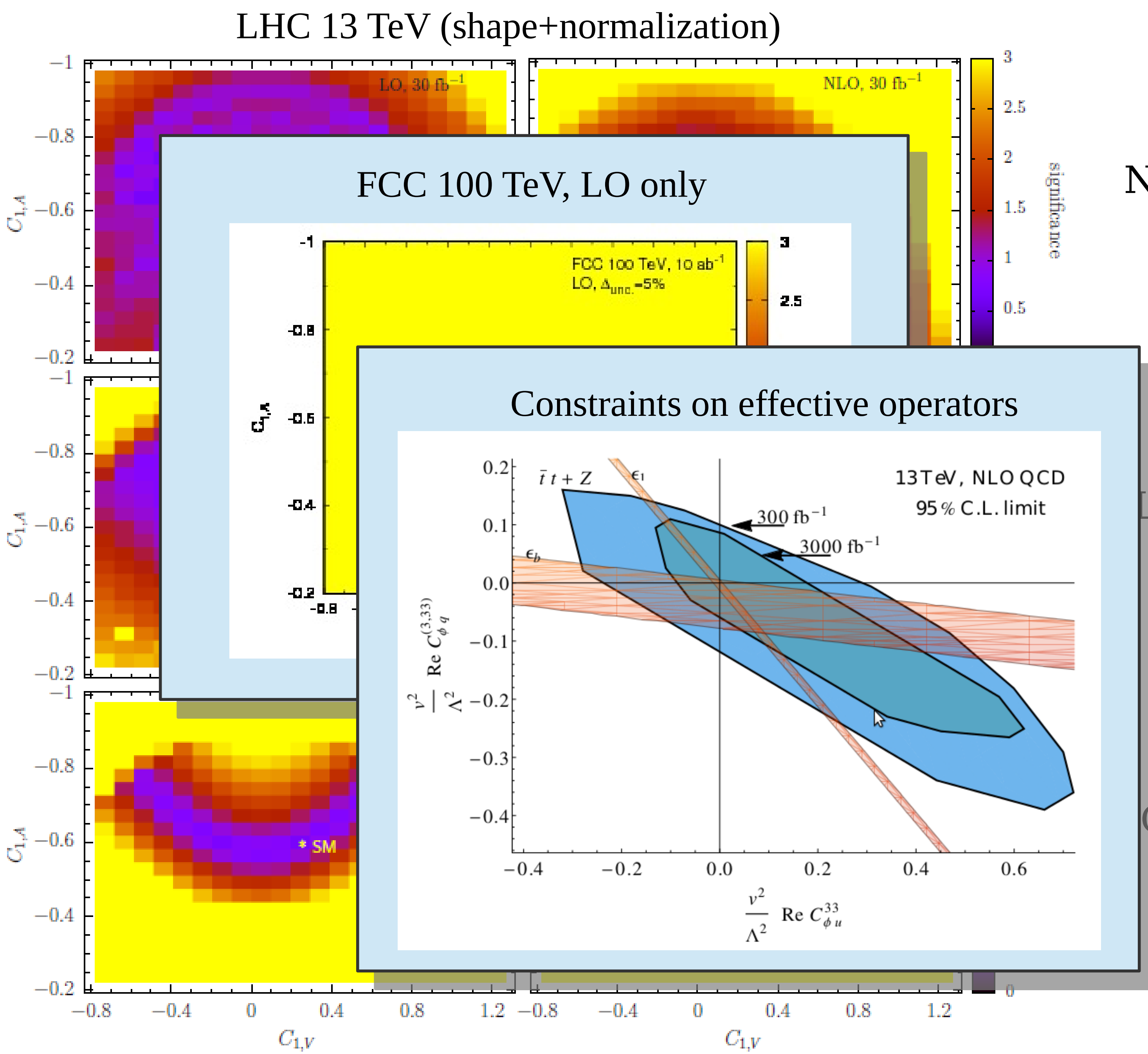


FCC 100 TeV, LO only

LO 30 fb^{-1}

LO 300 fb^{-1}

LO 3000 fb^{-1}



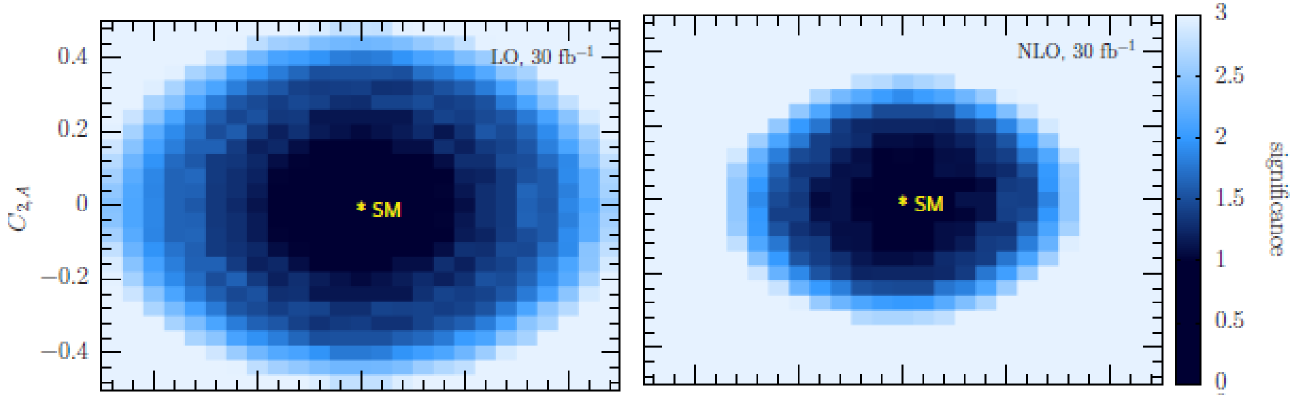
NLO 30 fb^{-1}

LO 300 fb^{-1}

O 3000 fb^{-1}

Weak dipole moments (~zero in the SM)

LO 30 fb^{-1}



NLO 30 fb^{-1}

Weak dipole moments (~zero in the SM)

LO 30 fb^{-1}

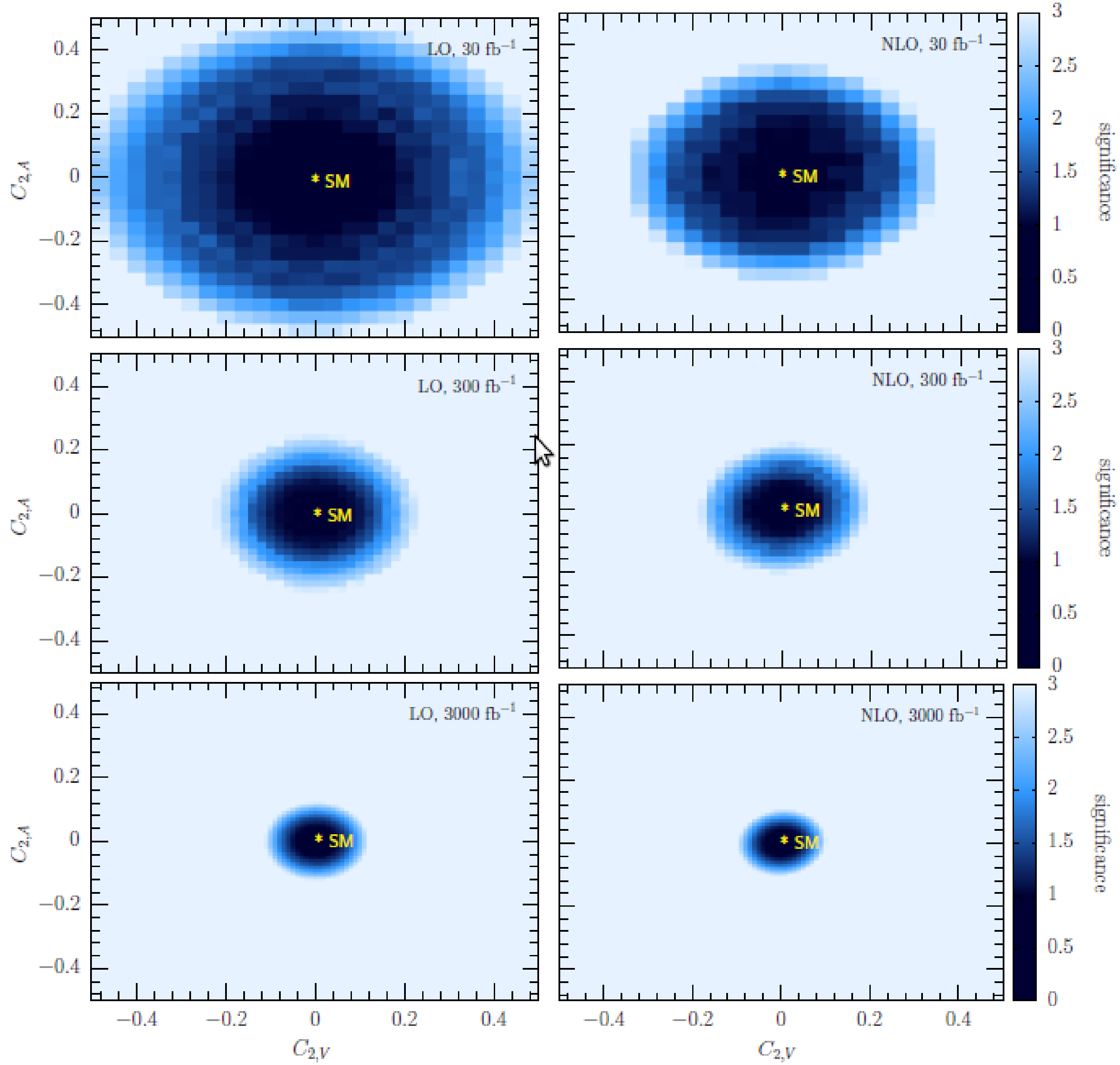
NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}

LO 3000 fb^{-1}

NLO 3000 fb^{-1}



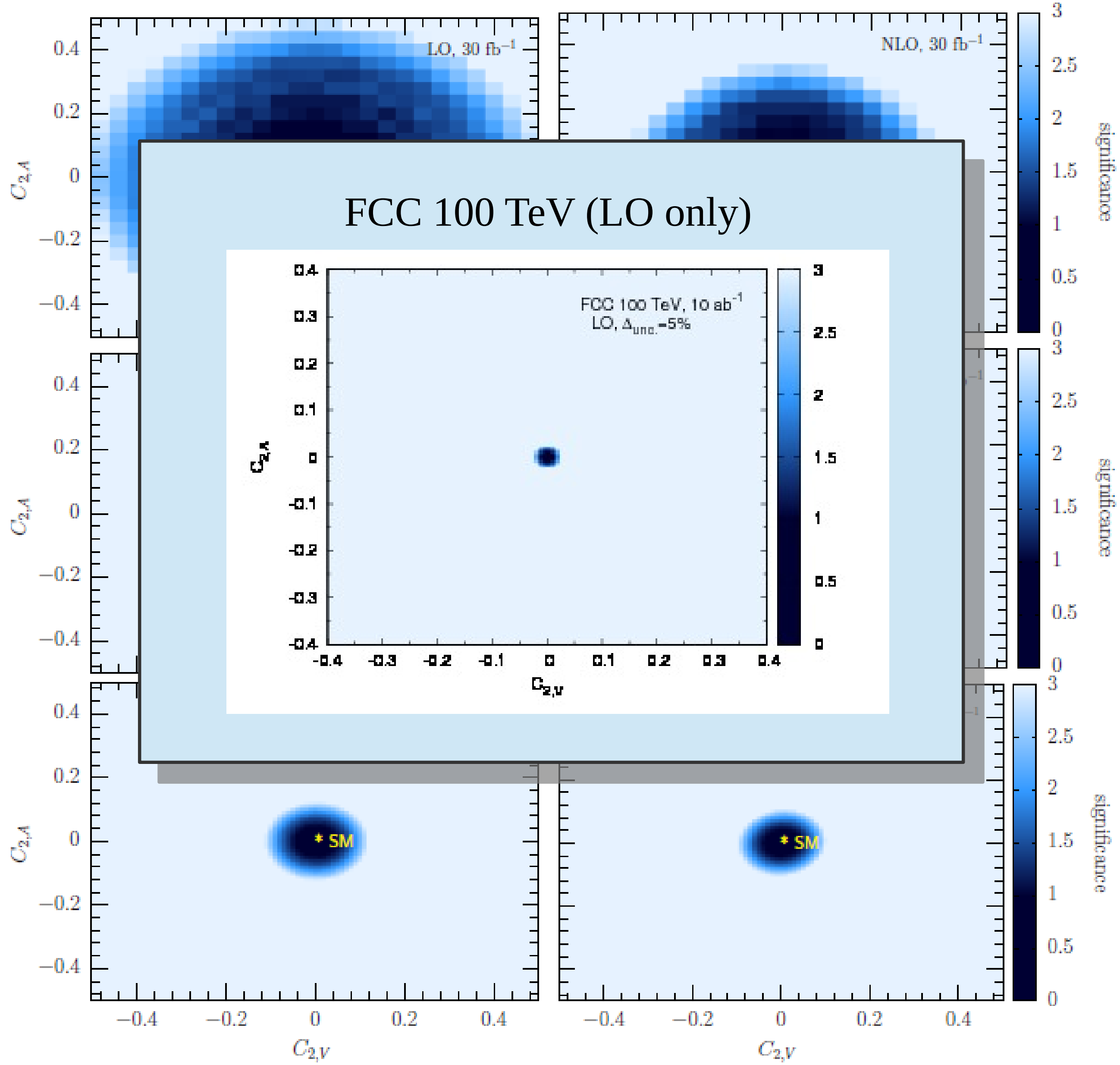
Top quark properties

Weak dipole moments (~zero in the SM)

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

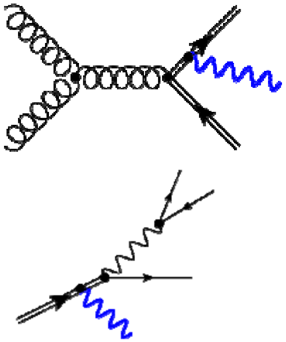
LO 300 fb^{-1} | NLO 300 fb^{-1}

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



ttbar + $\gamma \to$ *lepton* + $b\bar{b}\,jj$ + $E_{\mathrm{T,miss}}$ at NLO QCD: [Röntsch, M.S.] (to appear)

NEW: *electric* and *magnetic* top dipole moments

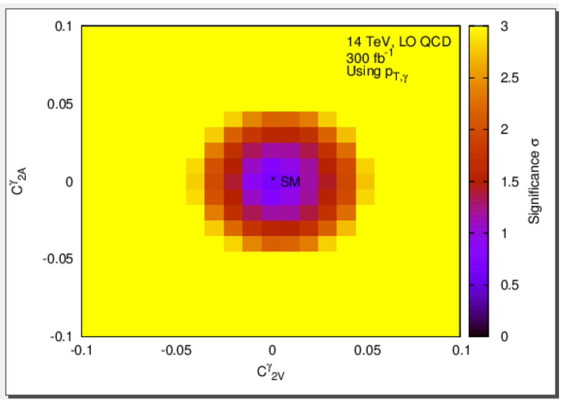


- Interesting aspect:

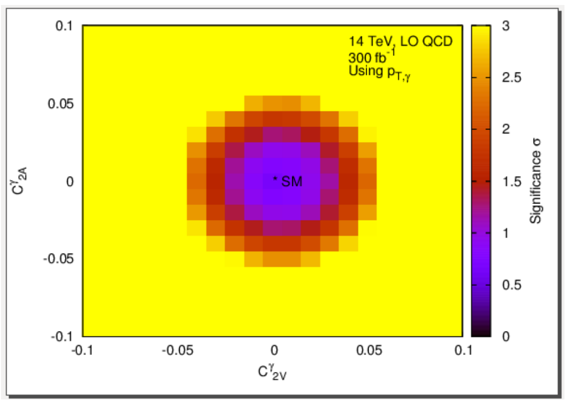
  Photon can also be radiated in top decay stage

  → interplay between *t-tb-γ and W-t-b* interactions

- Radiative (anomalous) top decays have non-negligible impact on limits:

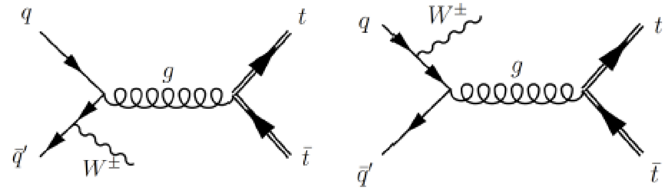


anomalous prod. + SM top decay



anomalous prod. + anomalous decay

ttbar + W:



- No sensitivity to top couplings, but charge asymmetry:

	Order	$t\bar{t}W^{\pm}$	$t\bar{t}W^{+}$	$t\bar{t}W^{-}$
σ(fb)	LO	$140.5^{+27\%}_{-20\%}$	$98.3^{+27\%}_{-20\%}$	$42.2^{+27\%}_{-20\%}$
	NLO	$210^{+11\%}_{-11\%}$	$146^{+11\%}_{-11\%}$	$63.6^{+11\%}_{-11\%}$
A_c^t (%)	NLO	$2.49^{+0.75}_{-0.34}$	$2.73^{+0.74}_{-0.42}$	$2.03^{+0.81}_{-0.19}$
	NLO+PS	$2.37^{+0.56}_{-0.38}$	$2.51^{+0.62}_{-0.42}$	$1.90^{+0.51}_{-0.35}$

[Maltoni,Mangano,Tsinikos,Zaro] (2014)

cross section ratios:

- Many uncertainties cancel in the ratio

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

[Mangano,Plehn,Reimitz,Schell,Shao] (2015)

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

[Melnikov,Scharf,M.S.] (2010)

- Combination of several processes allows for a global analysis

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	$O_{4\mathrm{f}}$	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\tilde{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H,\ H \to \gamma\gamma$	N						N			L

[Durieux,Maltoni,Zhang]

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

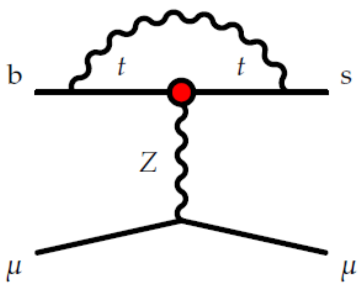
$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\,\gamma^\mu\left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t\right)t\,Z_\mu - \frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d_V^Z + i d_A^Z\gamma_5\right)t\,Z_\mu\,,$$

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

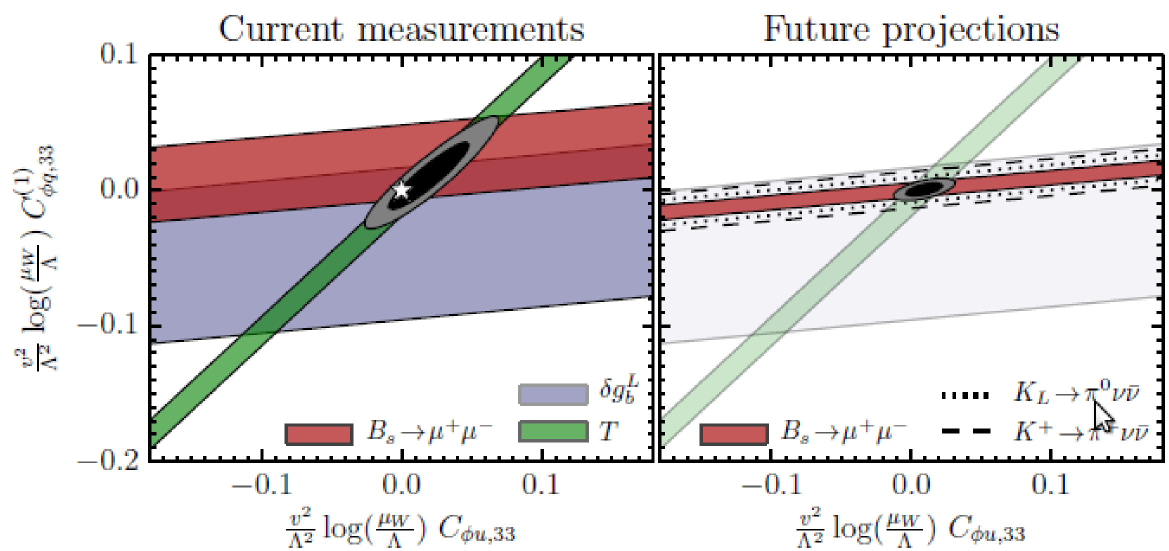
$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}}\bar{t}\left(Y_t^V + iY_t^A\gamma_5\right)t\,H$$

[Aguilar-Saavedra]

- *Beyond the LHC*: Probing anomalous top interactions with rare meson decays



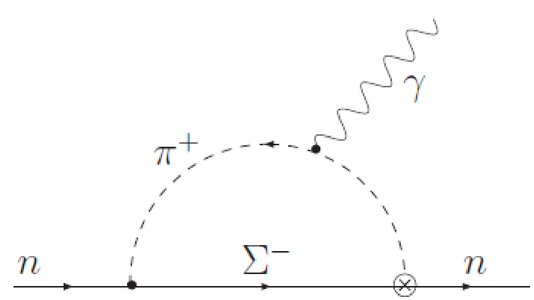
[Brod,Greljo,Stamou,Uttayarat]



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

Neutron EDM:

[Martinez, Rodriguez] (2001)
[Prospelov,Ritz] (2005)
[Kamenik,Papucci,Weiler] (2011)



$$d_{Hg} = -1.8\cdot 10^{-4}\,\mathrm{GeV}^{-1}\, e\,\bar g^{(1)}_{\pi NN}\,,$$
$$d_n = (1\pm 0.5)\,[1.1\, e\,(\tilde d_d + 0.5\,\tilde d_u) + 1.4\,(d_d - 0.25\, d_u)] + (22\pm 10)\cdot 10^{-3}\,\mathrm{GeV}\, e\, w\,,$$

$$|\tilde d_t| < 2.1\cdot 10^{-19}\,\mathrm{cm} \quad (90\%\ \mathrm{C.L.})$$

Top quark properties: SUMMARY

- Run-II will allow us fully exploit SM *ttbar* production
  → rare top quark decays
  → anomalous QCD interactions (chromo magn./electr. dipole moments)

- Single top quark production will become a standard-candle process
  → $|V_{tb}|$, *W-t-b*, flavor-violating interaction

- Associated production will allow us to directly probe top electroweak interactions and explore the top quark's role in the mechanism of electroweak symmetry breaking

- Theory is in good shape. We have robust and precise frameworks

- Technological development for high precision phenomenology will continue and make significant differences in the interpretation of data