

May 2015

Top LHC WG meeting

Theoretical overview on $t\bar{t} + V$

Markus Schulze



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

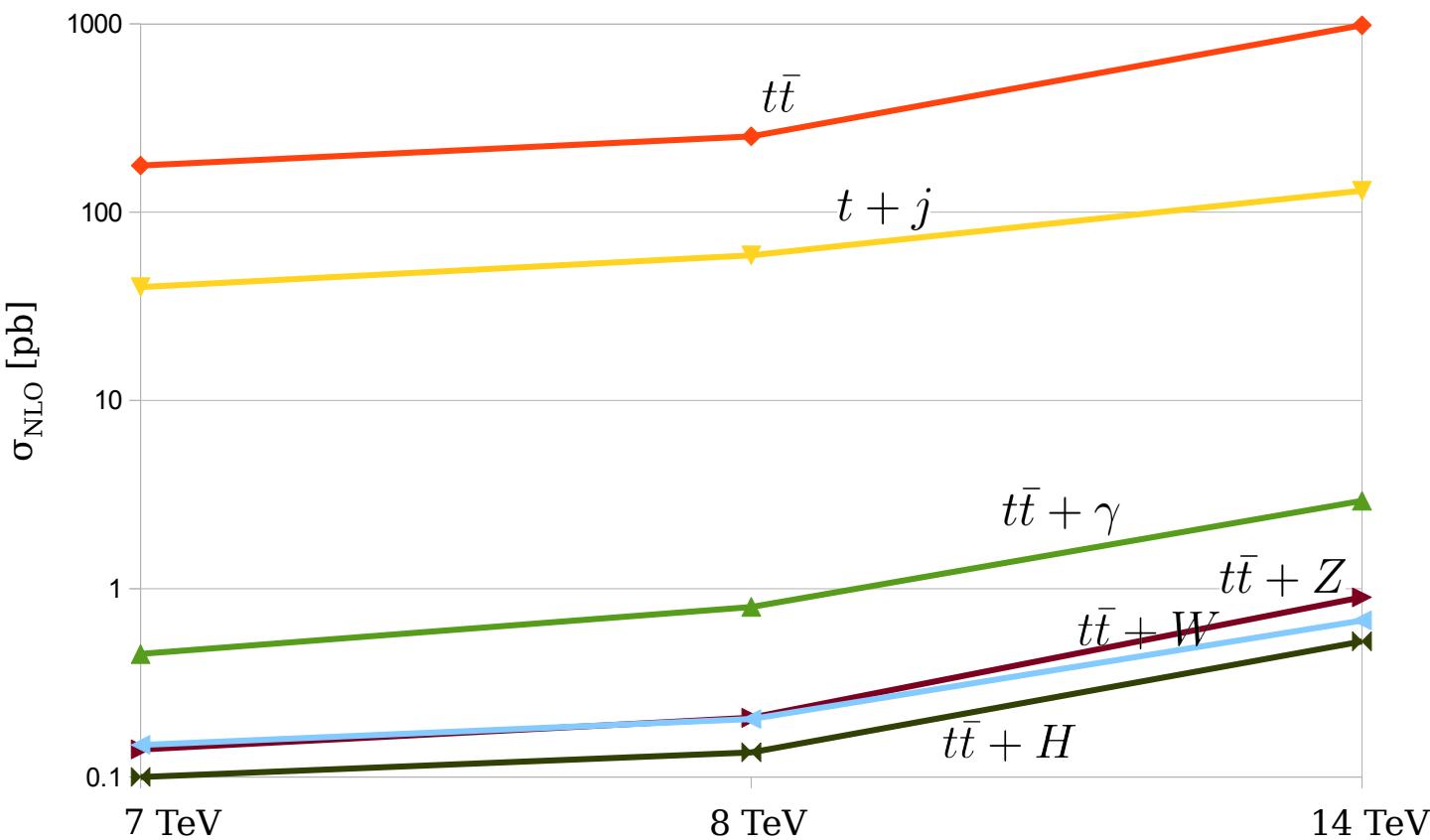
→ **What do we know about top quark interactions with γ , Z , W or H ?**

- This question immediately motivates the study of the processes

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

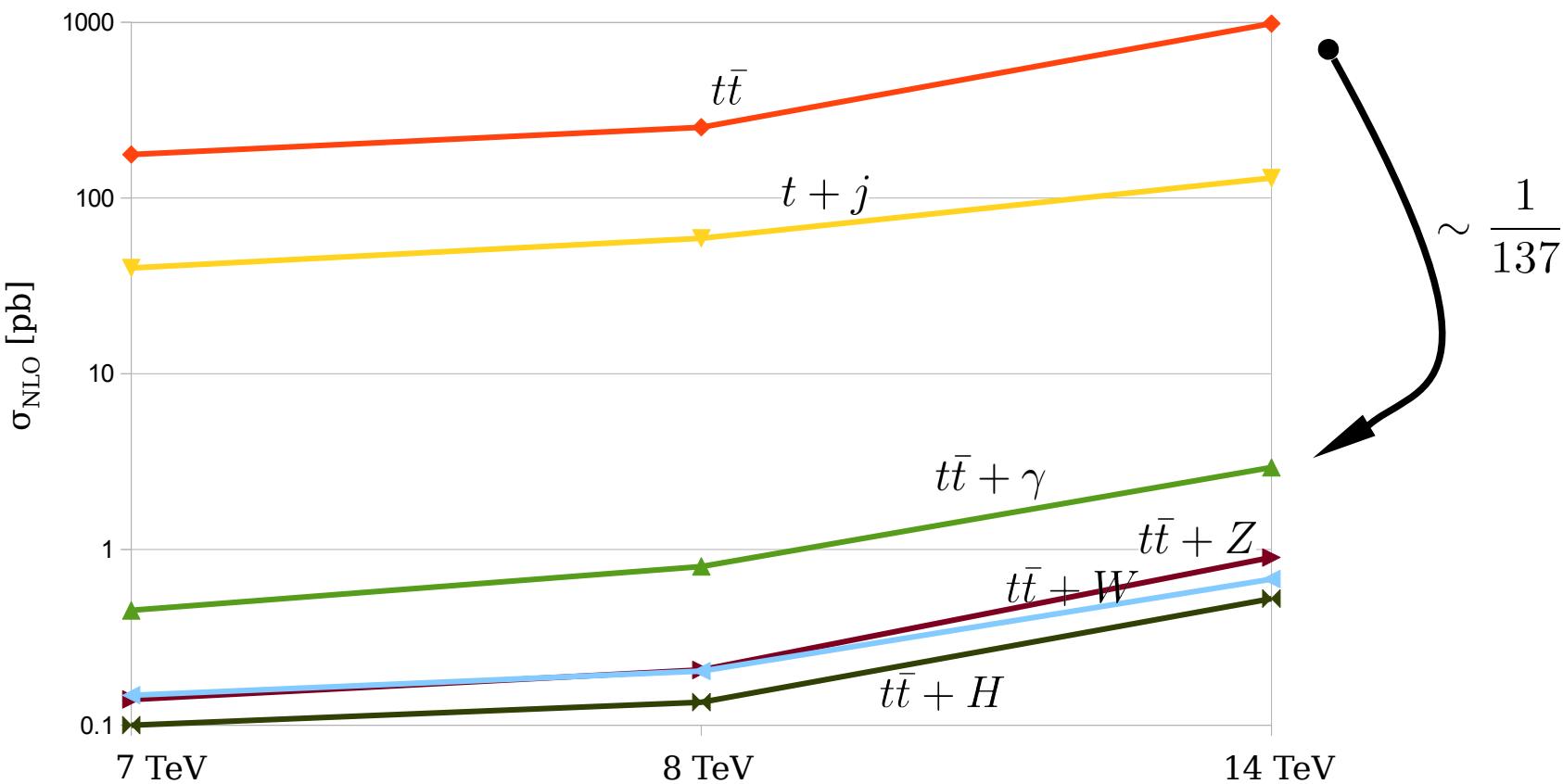
- CDF finds 30 $t\bar{t}b+\gamma$ events. All other processes have never been observed at the Tevatron (high threshold + penalties from branching fractions).
- Study of these processes at the LHC will open a new era in top quark physics
- What precision can be reached?

Spectrum of cross sections



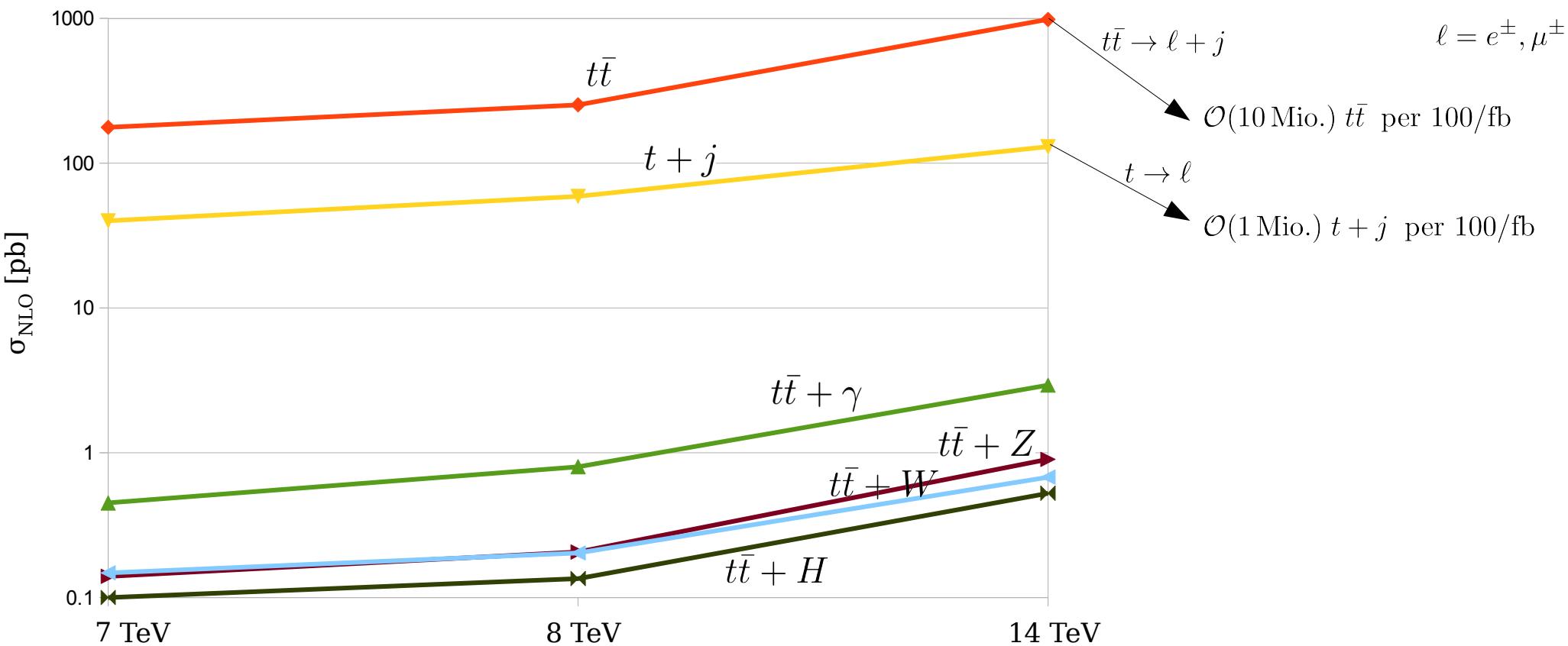
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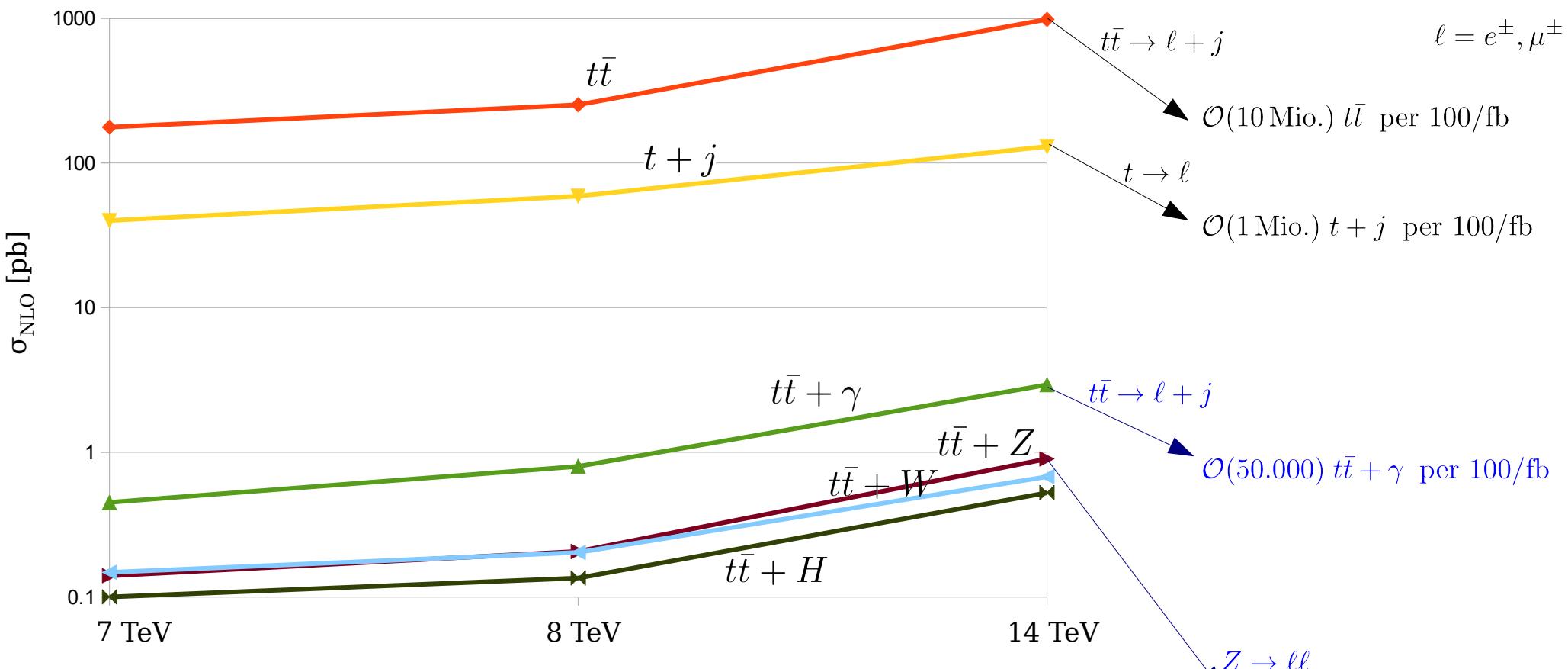
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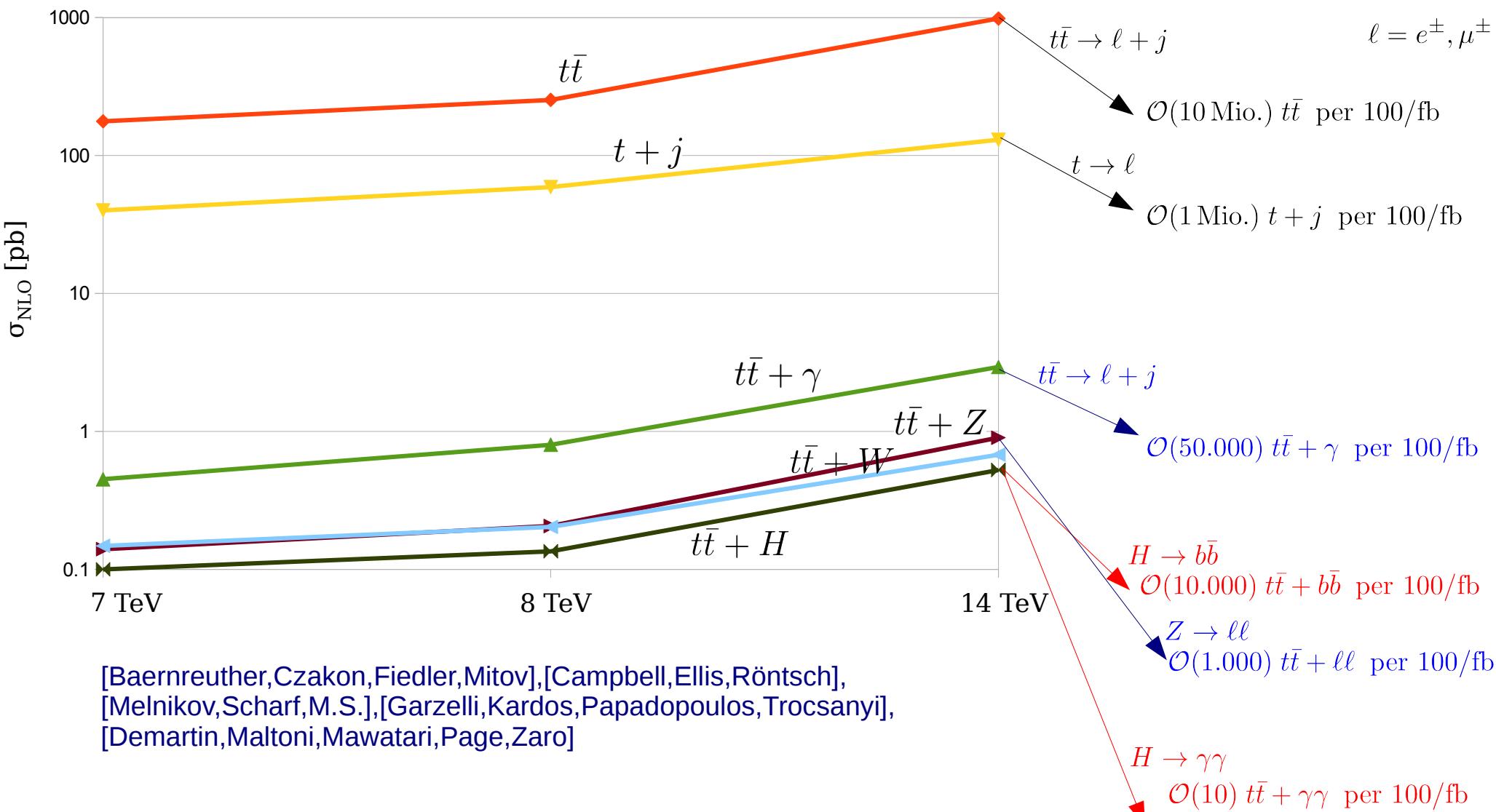
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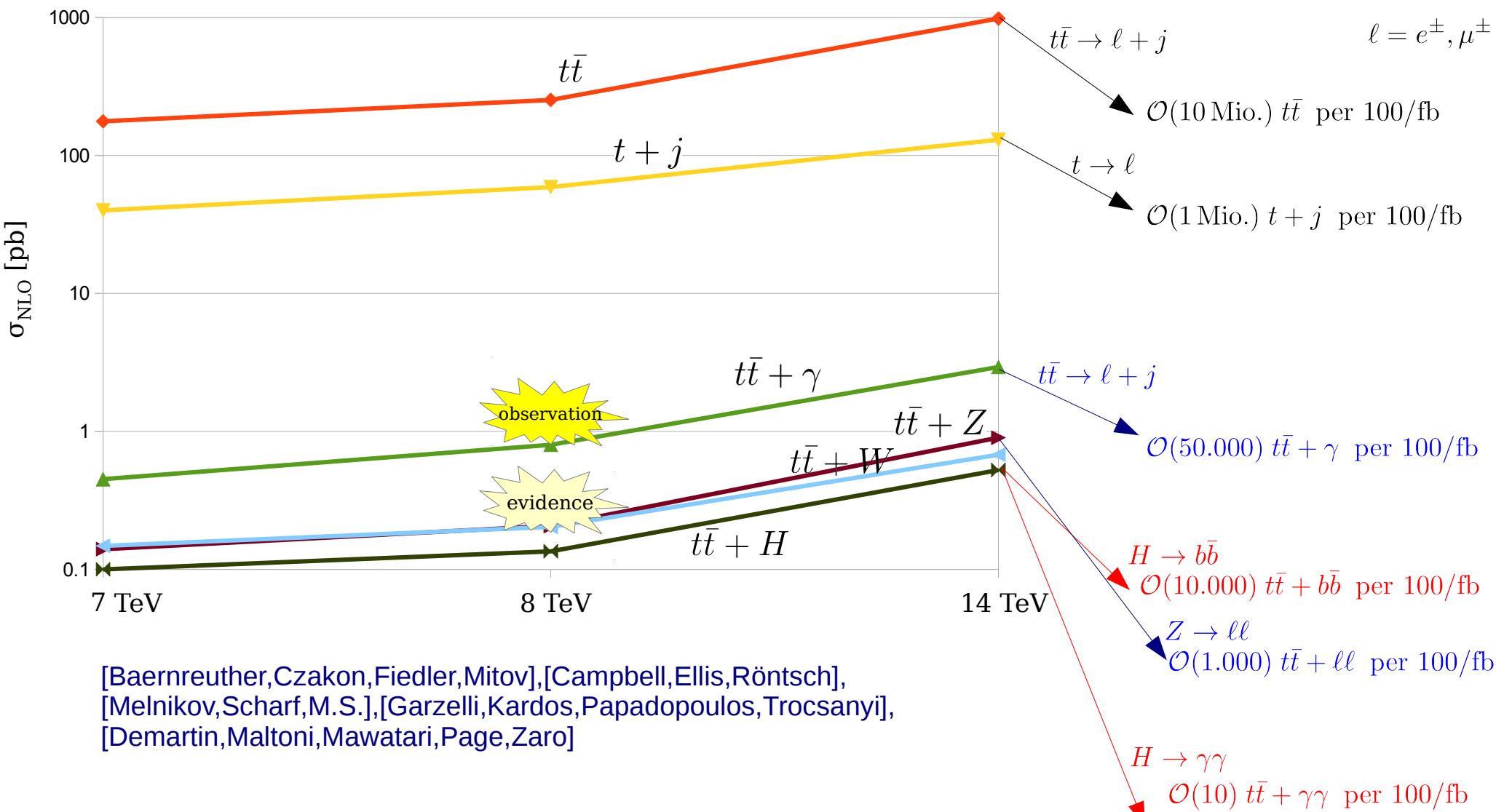


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Spectrum of cross sections



Spectrum of cross sections



Anomalous couplings

Minimal set of top quark anomalous couplings:

[Aguilar-Saavedra]

$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{H.c.}. \\ \mathcal{L}_{Ztt} &= -\frac{g}{2c_W} \bar{t} \gamma^\mu (X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t) t Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + i d_A^Z \gamma_5) t Z_\mu, \\ \mathcal{L}_{\gamma tt} &= -e Q_t \bar{t} \gamma^\mu t A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + i d_A^\gamma \gamma_5) t A_\mu.\end{aligned}$$

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

$$\begin{aligned}\delta g_L &= \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2} , & \delta V_L &= C_{\phi q}^{(3,33)*} \frac{v^2}{\Lambda^2} , & \delta d_V^\gamma &= \frac{\sqrt{2}}{e} \operatorname{Re} [c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}] \frac{vm_t}{\Lambda^2} , \\ \delta g_R &= \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2} , & \delta V_R &= \frac{1}{2} C_{\phi\phi}^{33} \frac{v^2}{\Lambda^2} , & \delta d_A^\gamma &= \frac{\sqrt{2}}{e} \operatorname{Im} [c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}] \frac{vm_t}{\Lambda^2} . \\ \delta X_{tt}^L &= \operatorname{Re} [C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)}] \frac{v^2}{\Lambda^2} , & \delta d_V^Z &= \sqrt{2} \operatorname{Re} [c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}] \frac{v^2}{\Lambda^2} , \\ \delta X_{tt}^R &= -\operatorname{Re} C_{\phi u}^{33} \frac{v^2}{\Lambda^2} , & \delta d_A^Z &= \sqrt{2} \operatorname{Im} [c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}] \frac{v^2}{\Lambda^2} . \\ \delta Y_t^V &= -\frac{3}{2} \operatorname{Re} C_{u\phi}^{33} \frac{v^2}{\Lambda^2} , \\ \delta Y_t^A &= -\frac{3}{2} \operatorname{Im} C_{u\phi}^{33} \frac{v^2}{\Lambda^2} .\end{aligned}$$

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

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[Aguilar-Saavedra]

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

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modifies strength
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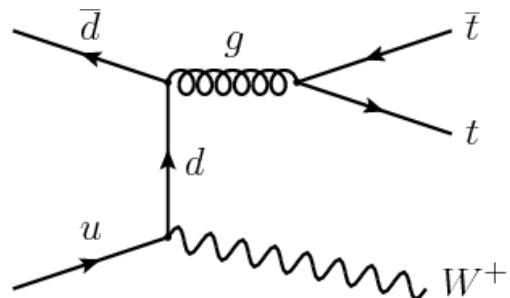
$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}} \bar{t} (Y_t^V + i Y_t^A \gamma_5) t H$$

SM-like
Higgs

CP-violating Higgs

t-*b*-*W* Interactions

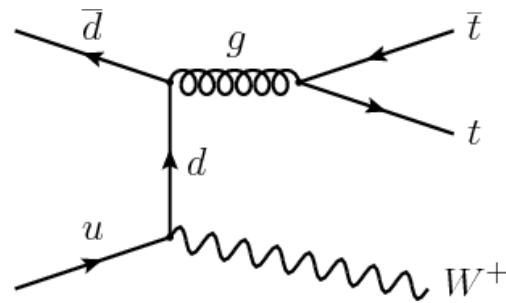
- $t\bar{t} + W^\pm$ at the 14TeV LHC has a total NLO cross section of 0.7 pb [Campbell,Ellis] [Garzelli,Kardos,Papadopoulos,Trocsanyi]



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

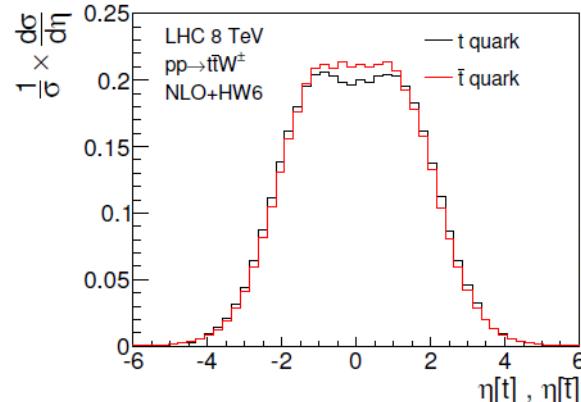
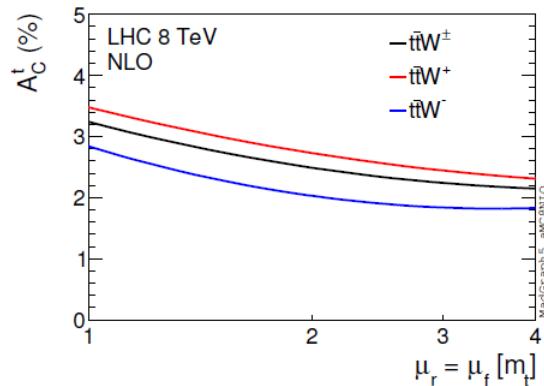
t - b - W Interactions

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→ 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

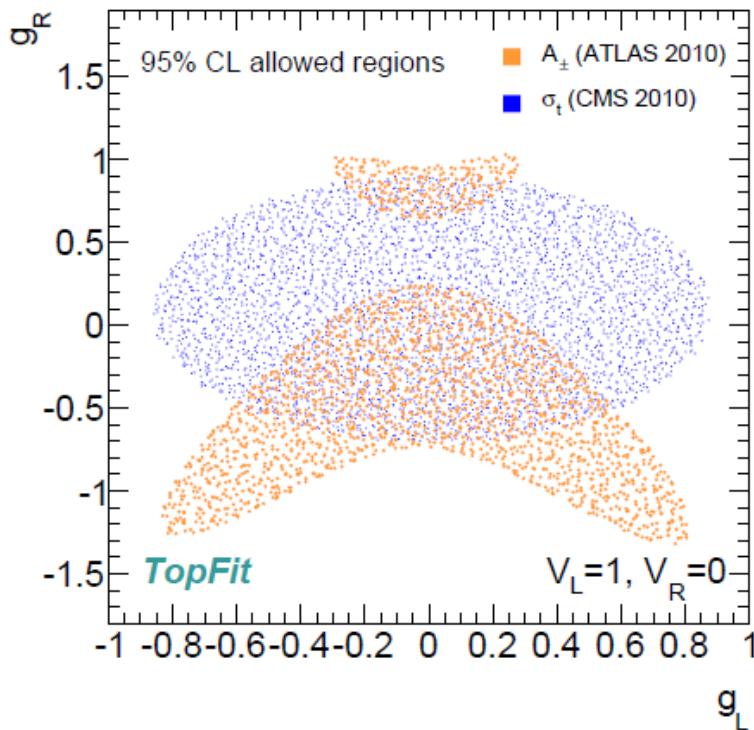
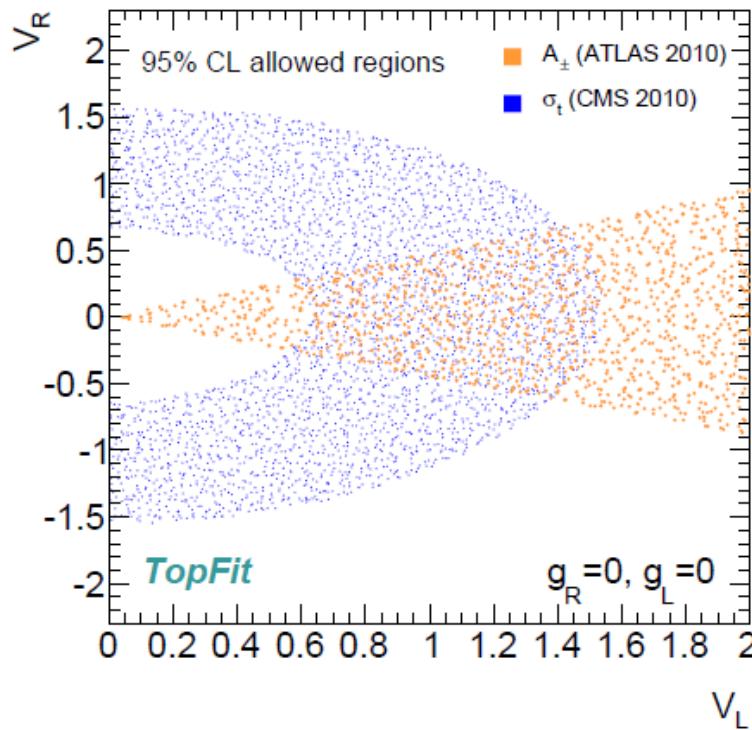


relative precision:

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

t - b - W Interactions

- t - b - W can also be probed in *single-top production* and *top decay in $t\bar{t}$ bar* [> 30 papers]
- one example: Recent combination of both [Aguilar-Saavedra,Castro,Onofre]



- $t\bar{t}$ bar process is also ideal for studying chromo-dipole moments

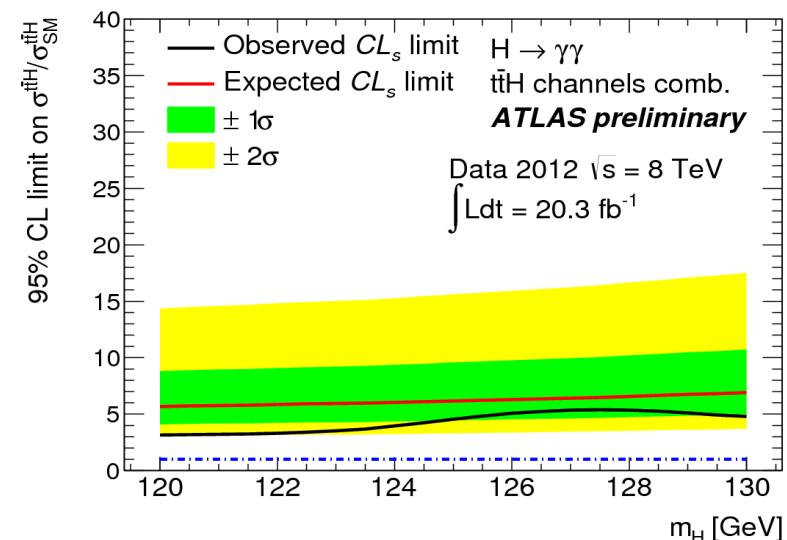
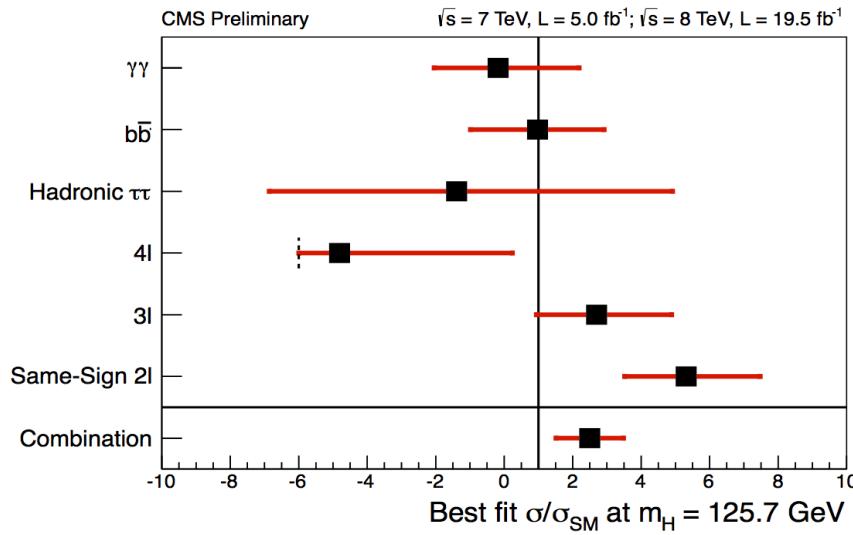
$t\bar{t}$ - H Interactions

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

$t\bar{t}+H$ Interactions

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→ No observation yet (7+8 TeV). Upper limit $\sim 3 \times$ SM cross section.



t - t - H Interactions

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

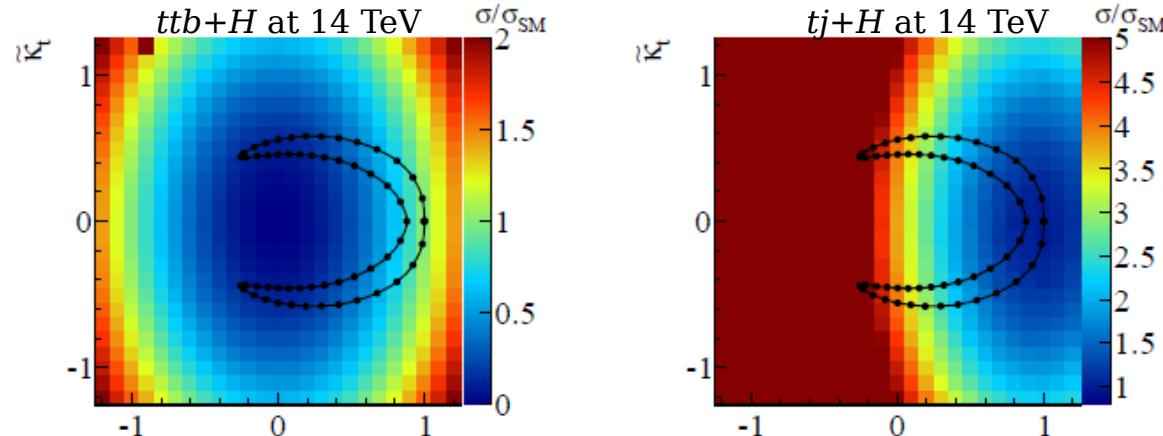


Figure 3: The ratios of $\sigma(\bar{t}tH)$ to the Standard Model value (left panel) and of $\sigma(tH)$ to the Standard Model value (right panel) are shown using the indicated colour codes. Also shown is the crescent-shaped region in Fig. 1 that is allowed by present data at the 68% CL.

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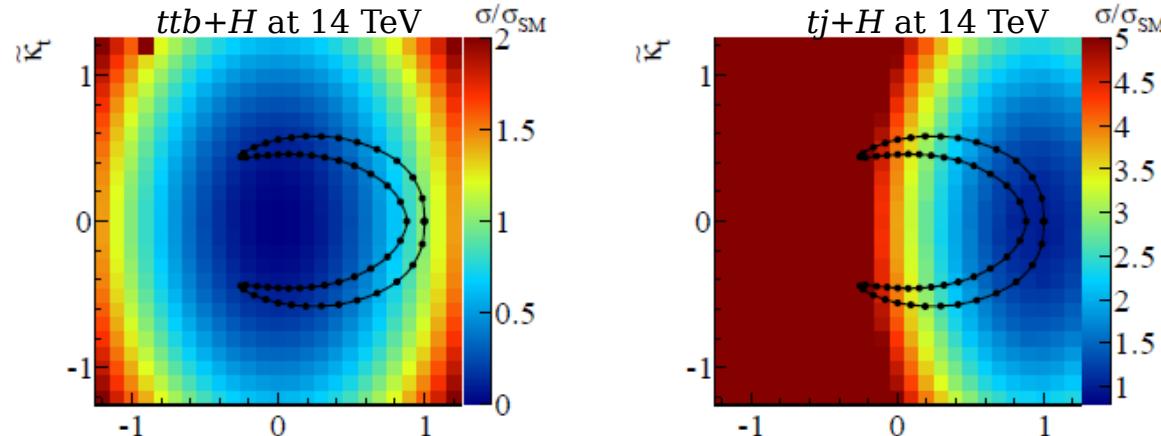
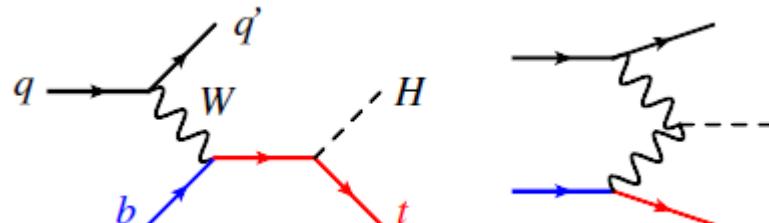
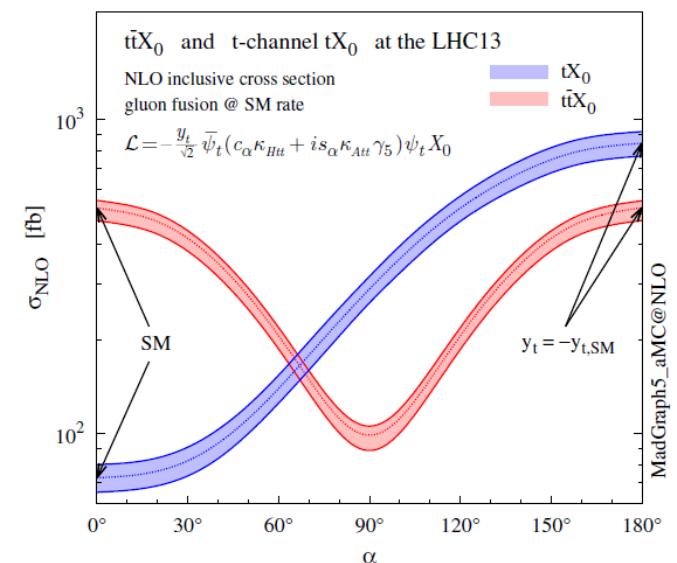


Figure 3: The ratios of $\sigma(t\bar{t}H)$ to the Standard Model value (left panel) and of $\sigma(tH)$ to the Standard Model value (right panel) are shown using the indicated colour codes. Also shown is the crescent-shaped region in Fig. 1 that is allowed by present data at the 68% CL.

- single top + Higgs: [Campbell,Ellis,Röntsch]
[Demartin,Maltoni,Mawatari,Page,Zaro]



destructive interference leads to
very small SM cross section

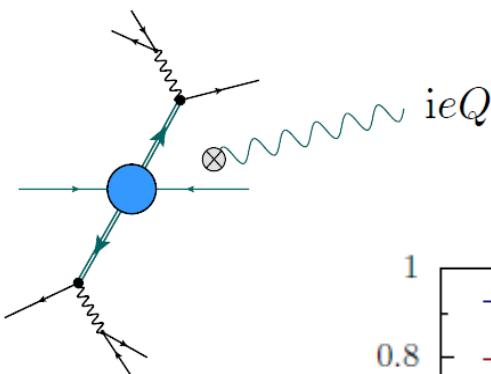


$t\bar{t} + \text{photon}$

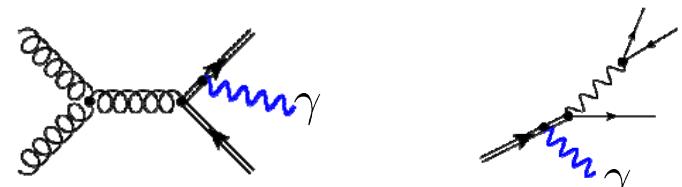
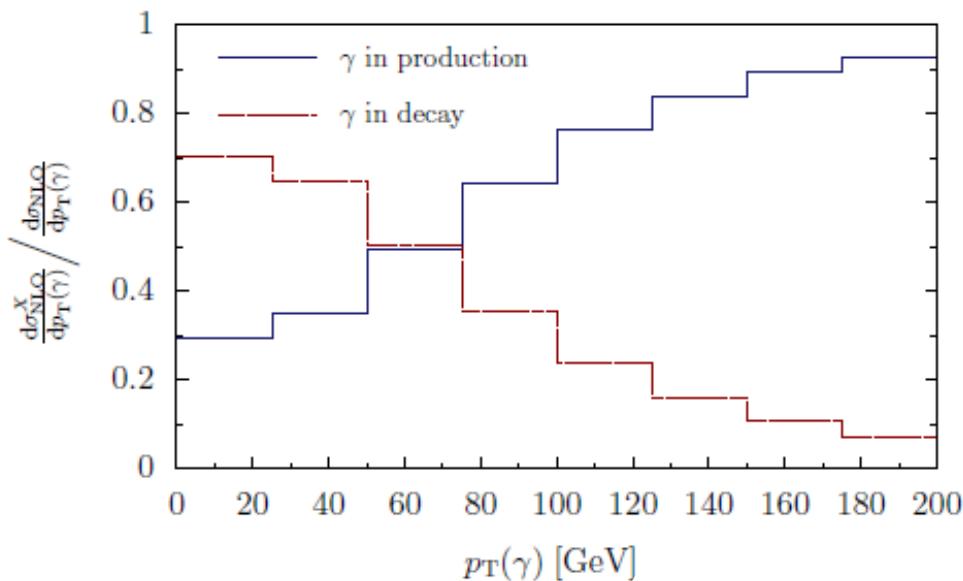
- $t\bar{t} + \gamma$ at the 14 TeV LHC has a total NLO cross section of 2.9 pb
[Duan,Ma,Zhang,Han,Guo,Wang], [Melnikov,Scharf,M.S.], [Kardos,Trocsanyi]
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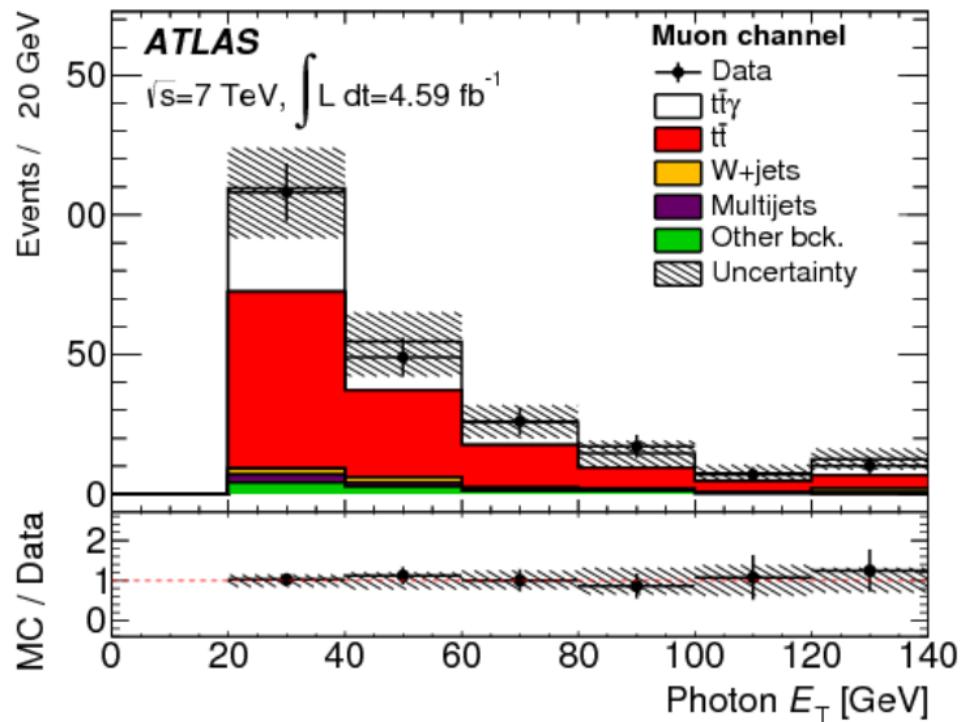


Lepton+Jets Channel + acceptance cuts: $p_T^\gamma > 20 \text{ GeV}$
 $\sigma_{\ell+j}^{\text{NLO}} = 138 \text{ fb} = 61(\text{production}) + 77(\text{decay}) \text{ fb}$

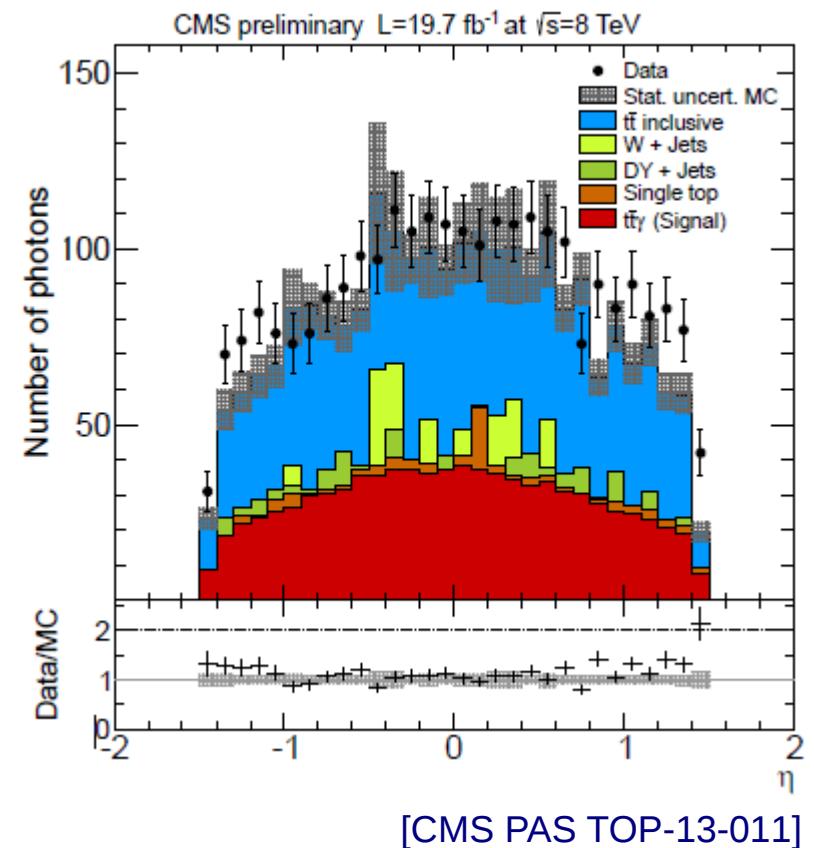


→ Photons with $p_{T\gamma} < 50 \text{ GeV}$ are dominantly emitted in the decay
[[Melnikov, Scharf, M.S.](#)]

$t\bar{t} + \text{photon}$



[Phys. Rev. D 91, 072007]

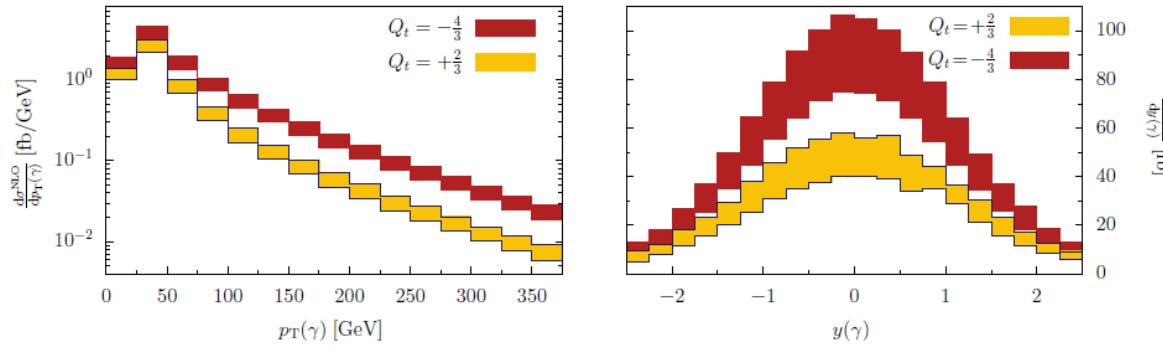


[CMS PAS TOP-13-011]

$t\bar{t} + \text{photon}$

Effects of radiative top decays:

- Simple BSM study: top quark charge measurement in $t\bar{t}\text{bar}+\text{photon}$



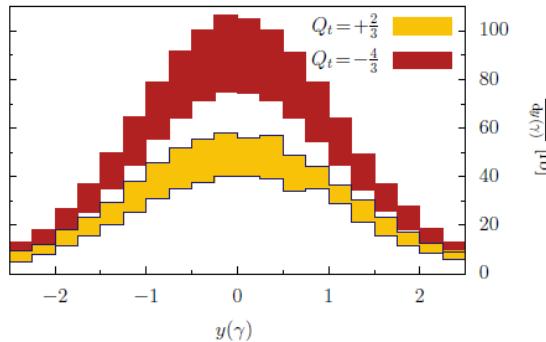
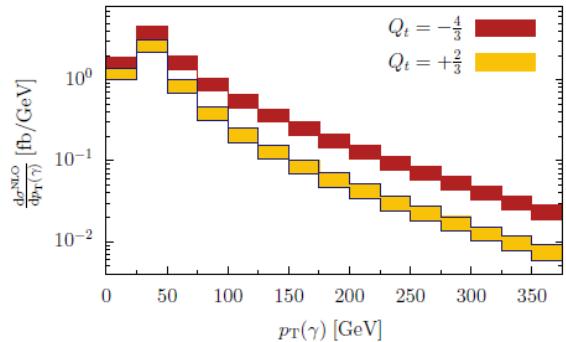
$$\sigma_{t\bar{t}\gamma}^{\text{NLO}} = 138 \text{ fb} \quad \xrightarrow{Q_t = \frac{2}{3} \rightarrow -\frac{4}{3}} \quad \sigma_{t\bar{t}\gamma}^{\text{NLO}} = 243 \text{ fb}$$

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

$t\bar{t} + \text{photon}$

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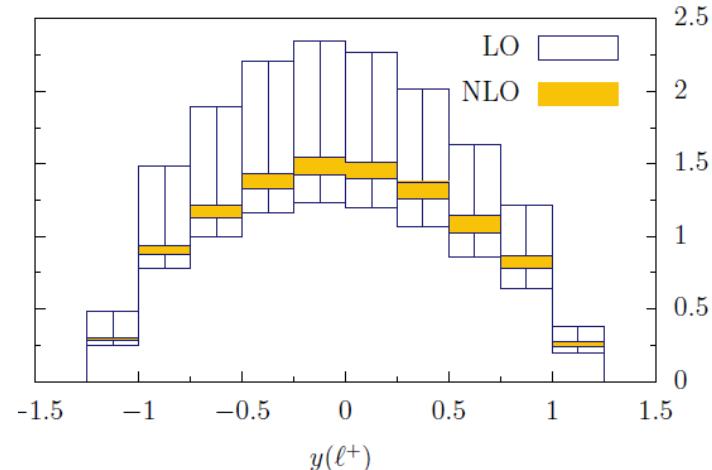
$$\rightarrow \text{Naive expectation of } Q_t^2 \text{ scaling fails: } \mathcal{R}^{\text{NLO}} = \frac{\sigma_{t\bar{t}\gamma}^{Q_t=-4/3}}{\sigma_{t\bar{t}\gamma}^{Q_t=2/3}} = 1.76^{+0.01}_{-0.02}.$$

- Implications for FB asymmetry:

$$A_{t,\text{FB}}^{\text{LO}} = -17\%$$

$$A_{t,\text{FB}}^{\text{NLO}} = -12\%$$

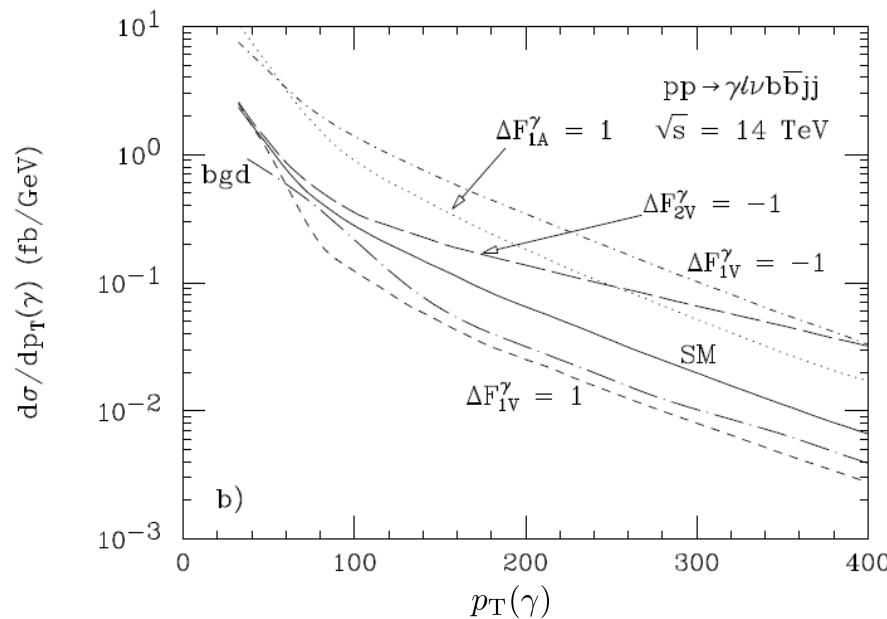
$$\underbrace{A_{t,\text{FB}}^{\text{NLO}} = -12\%}_{\text{stable tops}} \longrightarrow \underbrace{A_{\ell,\text{FB}}^{\text{NLO}} \approx \text{few}\%}_{\text{decayed tops} + \text{radiative decays}}$$



Anomalous couplings beyond Q_t

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

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

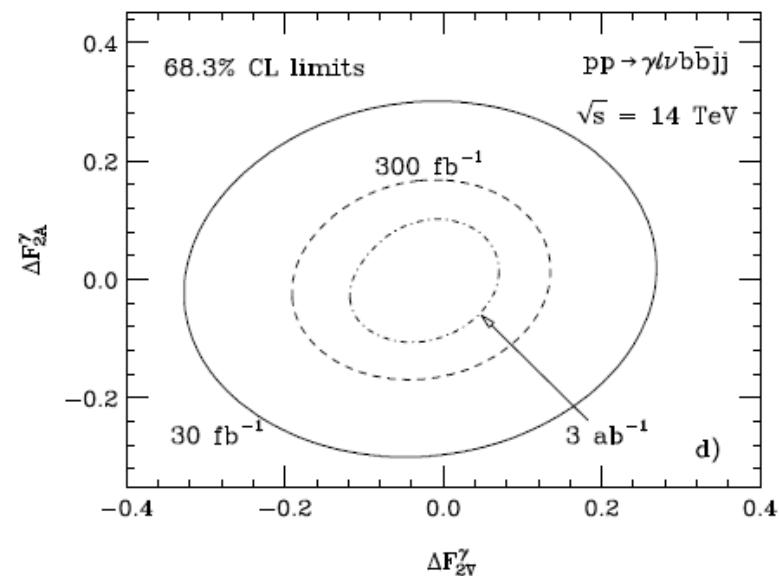
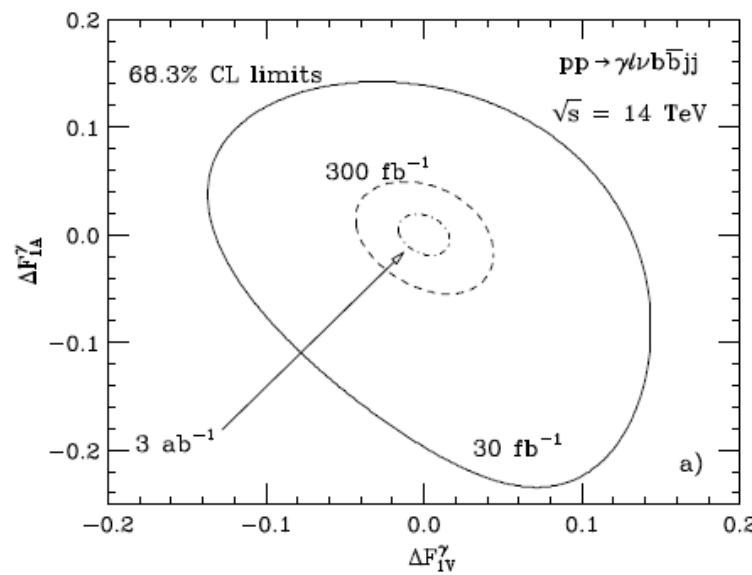


- Photon transverse momentum is a good analyzer

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

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

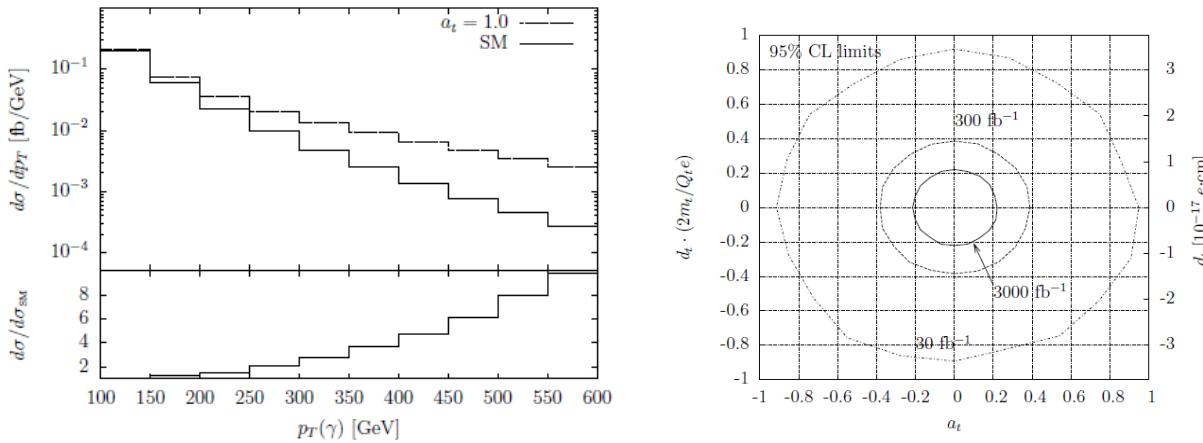


→ “Residual scale uncertainty is biggest limiting factor in these studies”

Other anomalous couplings limits

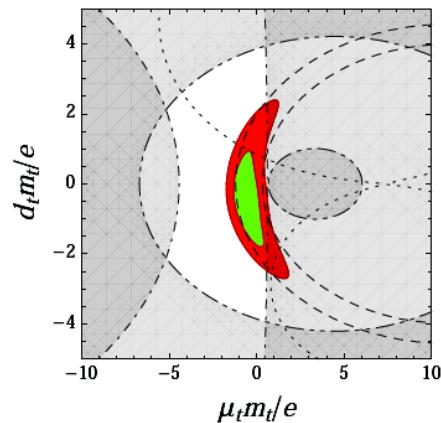
- LO study of dipole moments in single $t j + \gamma$

[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 |
| $d_t [10^{-17} e \cdot \text{cm}]$ | +3.5 -3.4 | +1.5 -1.5 | +0.83 -0.82 |

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



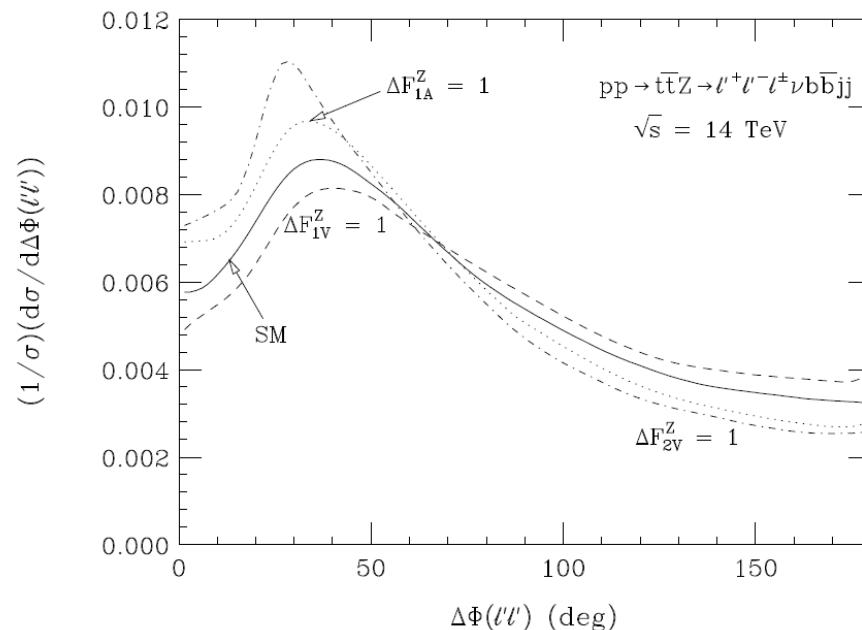
$$\begin{aligned} -1.5 < \mu_t m_t/e &< 1.0 \text{ (95\% C.L.)}, \\ -2.3 < d_t m_t/e &< 1.7 \text{ (95\% C.L.)}. \end{aligned}$$

[Kamenik,Papucci,Weiler]

$t\bar{t} + Z$

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

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

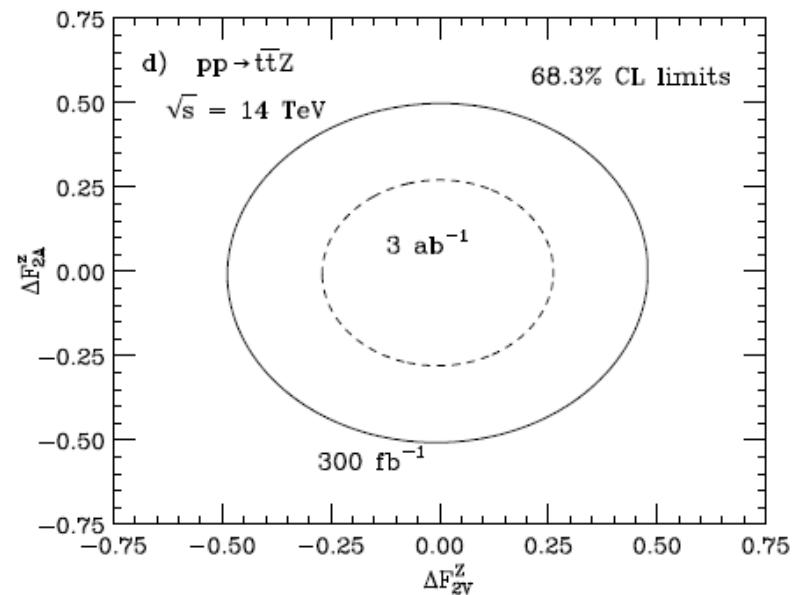
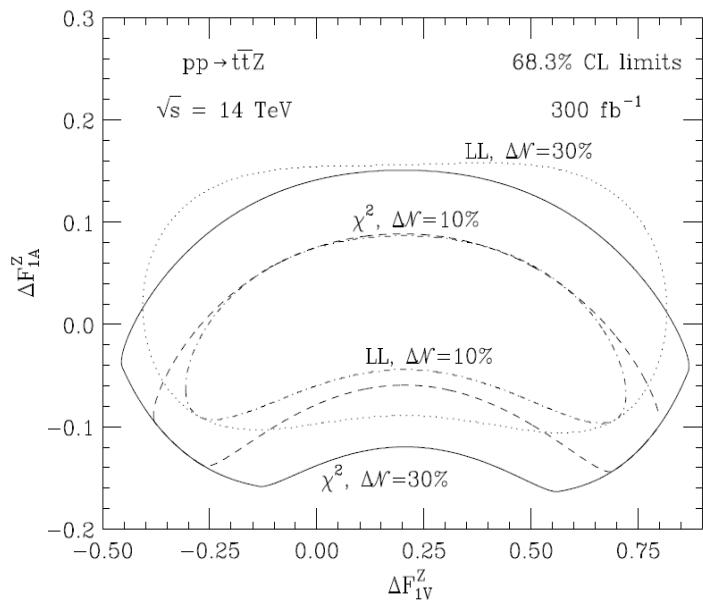


- Lepton azimuthal opening angle is optimal observable

LO coupling constraints

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

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



→ Residual scale uncertainty is biggest limiting factor in these studies

NLO coupling constraints

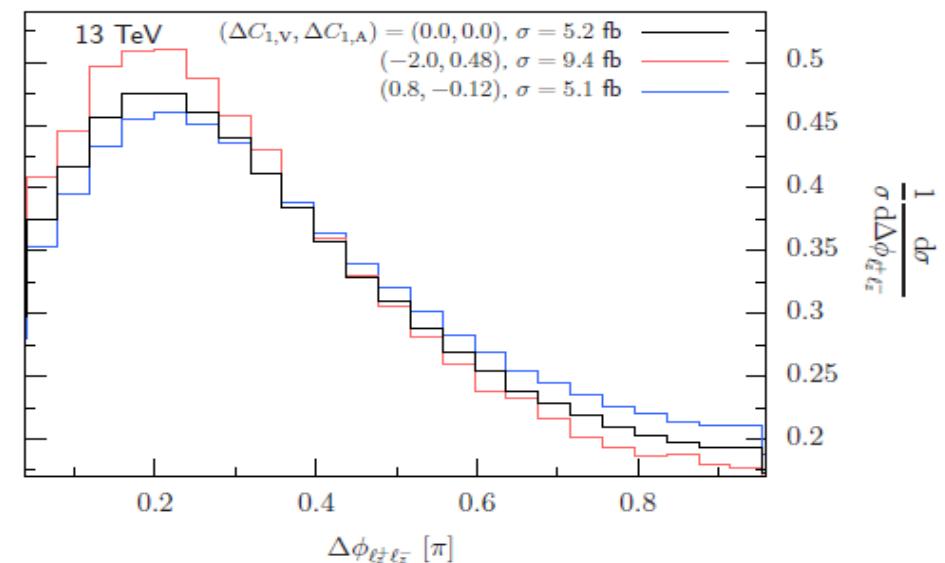
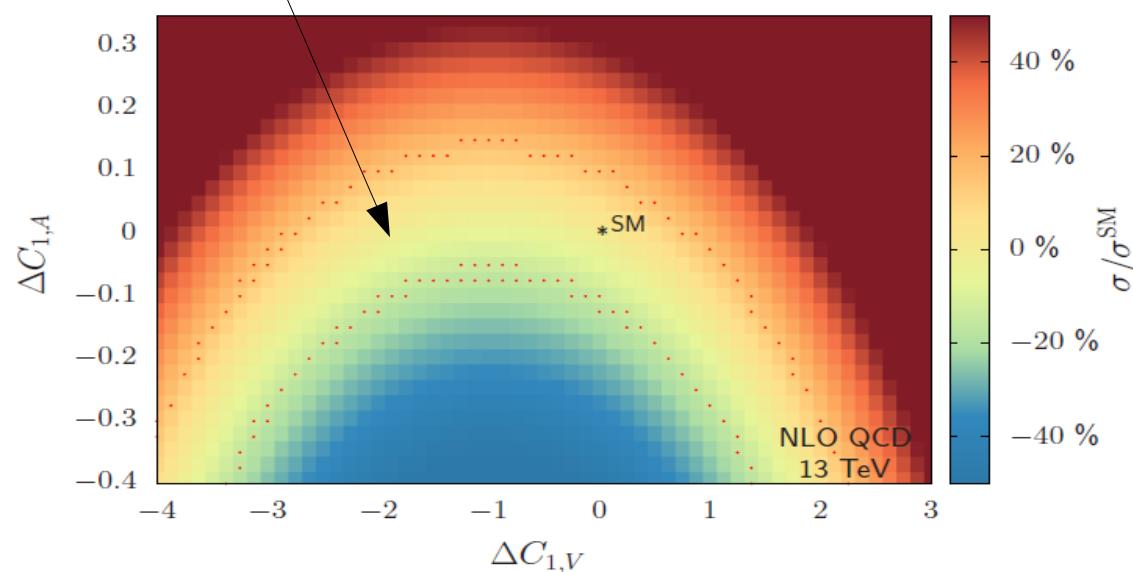
- $t\bar{t} + Z$ at the 14 TeV LHC has a total NLO cross section of 1.1 pb
[[Lazopoulos,McElmurry,Melnikov,Petriello](#)], [[Garzelli,Kardos,Papadopoulos,Trocsanyi](#)]
[R.Röntsch, M.S.]

- Parametrize, fit and extrapolate NLO cross section/histogr. bins:

$$\mathcal{M} = \mathcal{M}_0 + C_{1,V}\mathcal{M}_V + C_{1,A}\mathcal{M}_A,$$

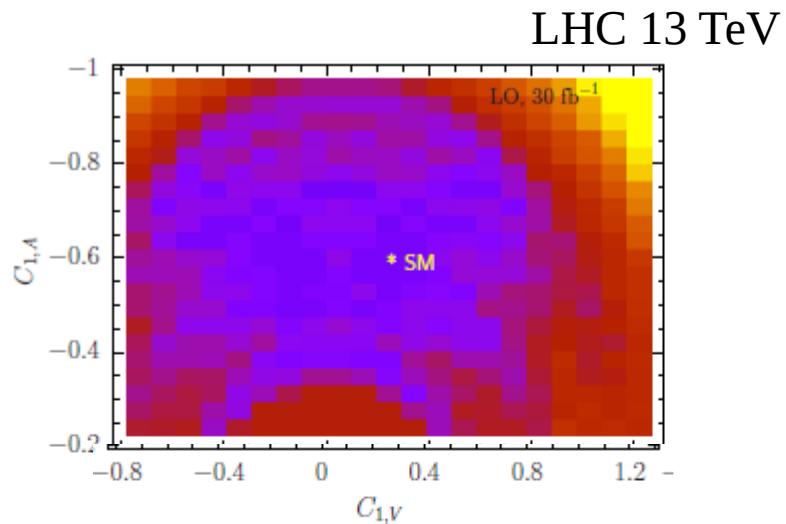
$$d\sigma = s_0 + s_1 C_{1,V} + s_2 C_{1,V}^2 + s_3 C_{1,A} + s_4 C_{1,A}^2 + s_5 C_{1,V} C_{1,A}.$$

degeneracy of total cross section

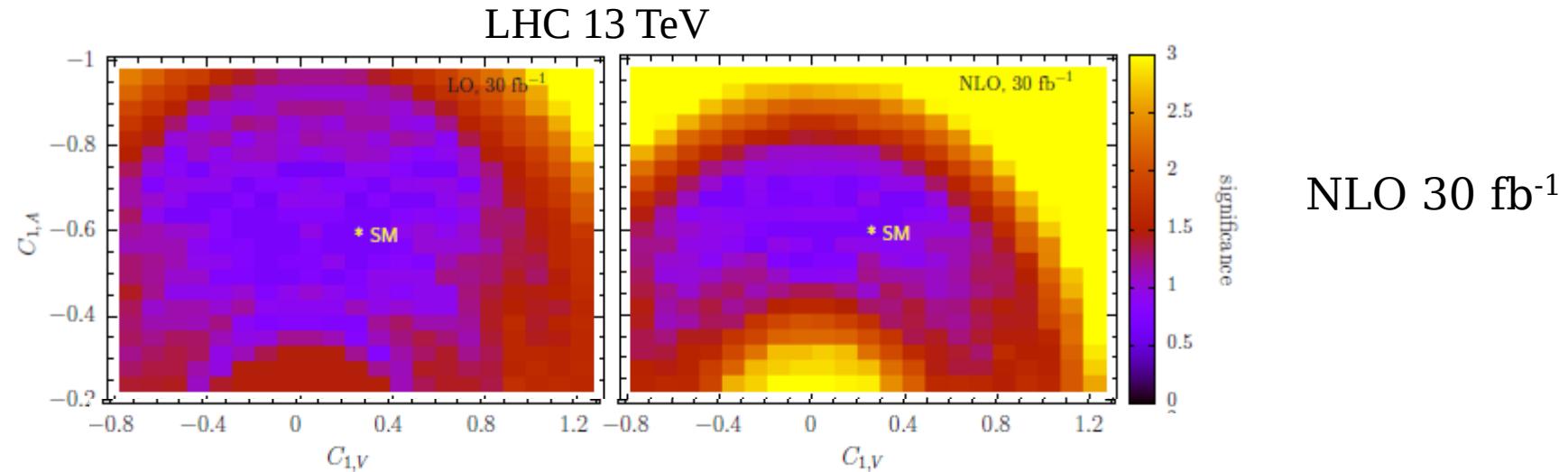


Constraints for LHC run-2

LO 30 fb^{-1}

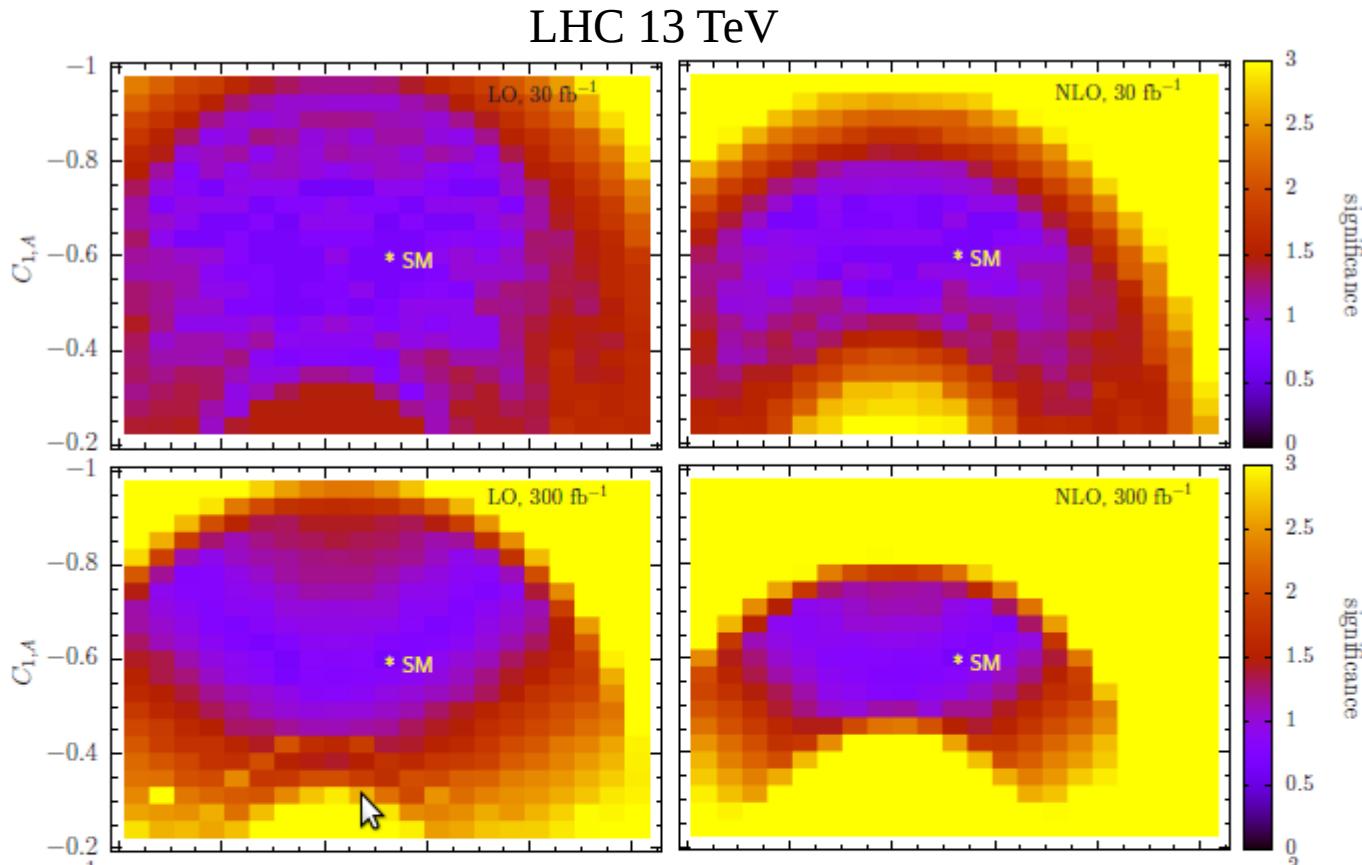


Constraints for LHC run-2



Constraints for LHC run-2

LO 30 fb^{-1}



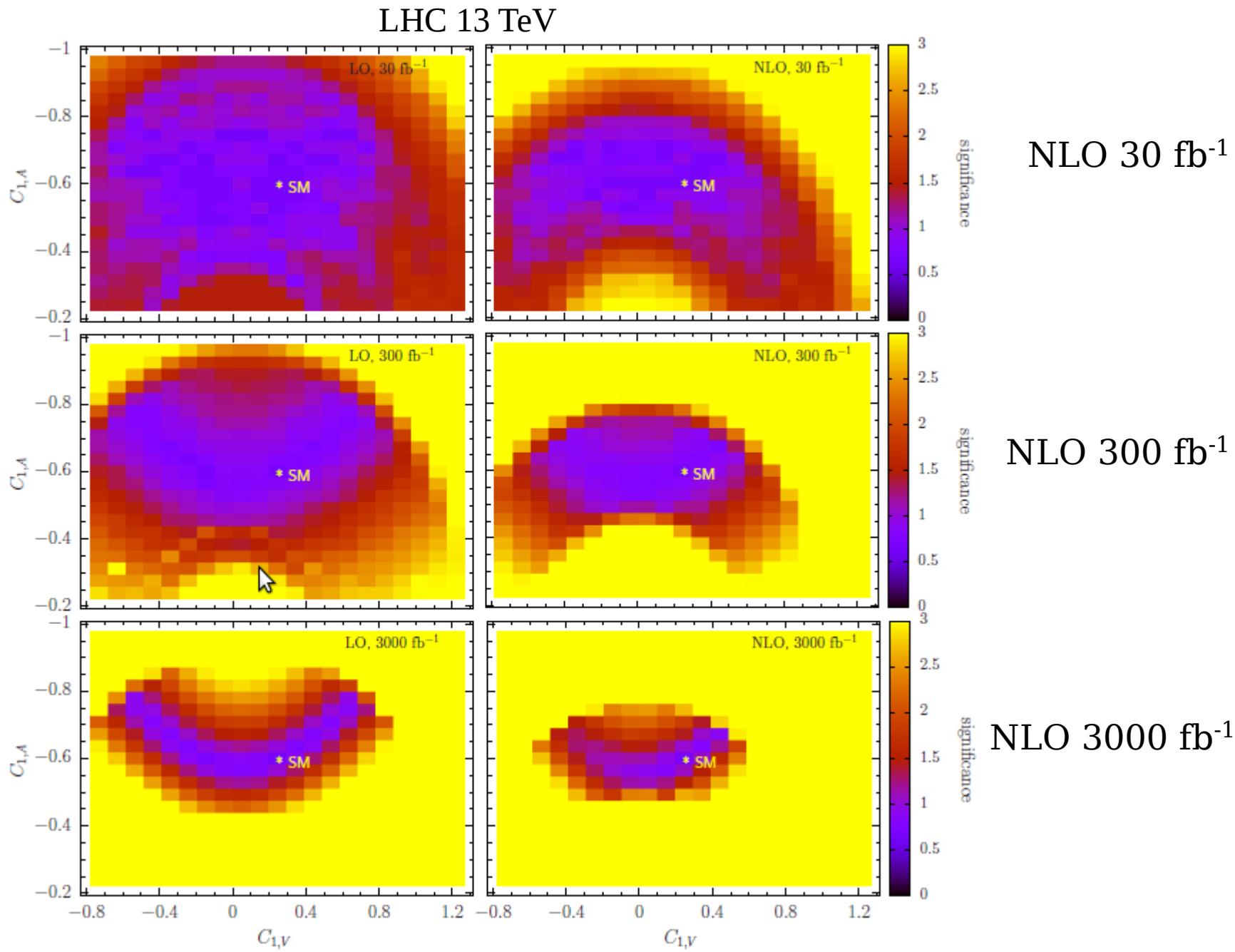
NLO 30 fb^{-1}

LO 300 fb^{-1}

NLO 300 fb^{-1}

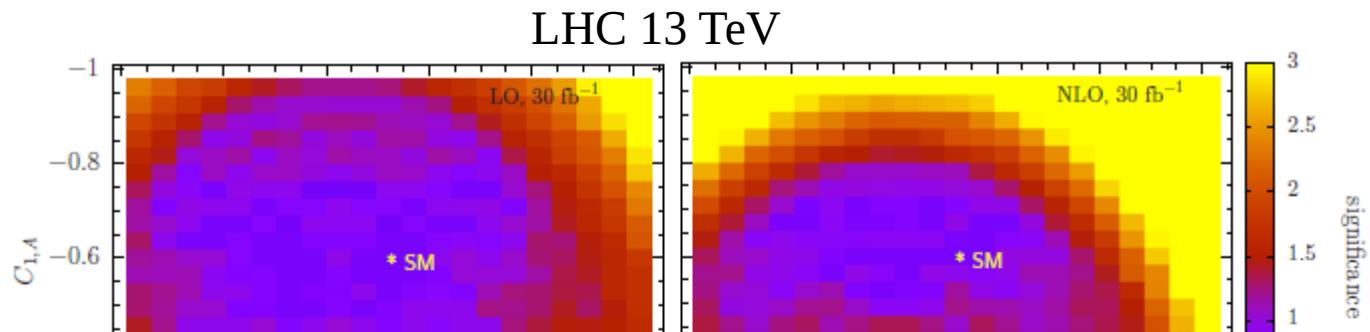
Constraints for LHC run-2

LO 30 fb^{-1}

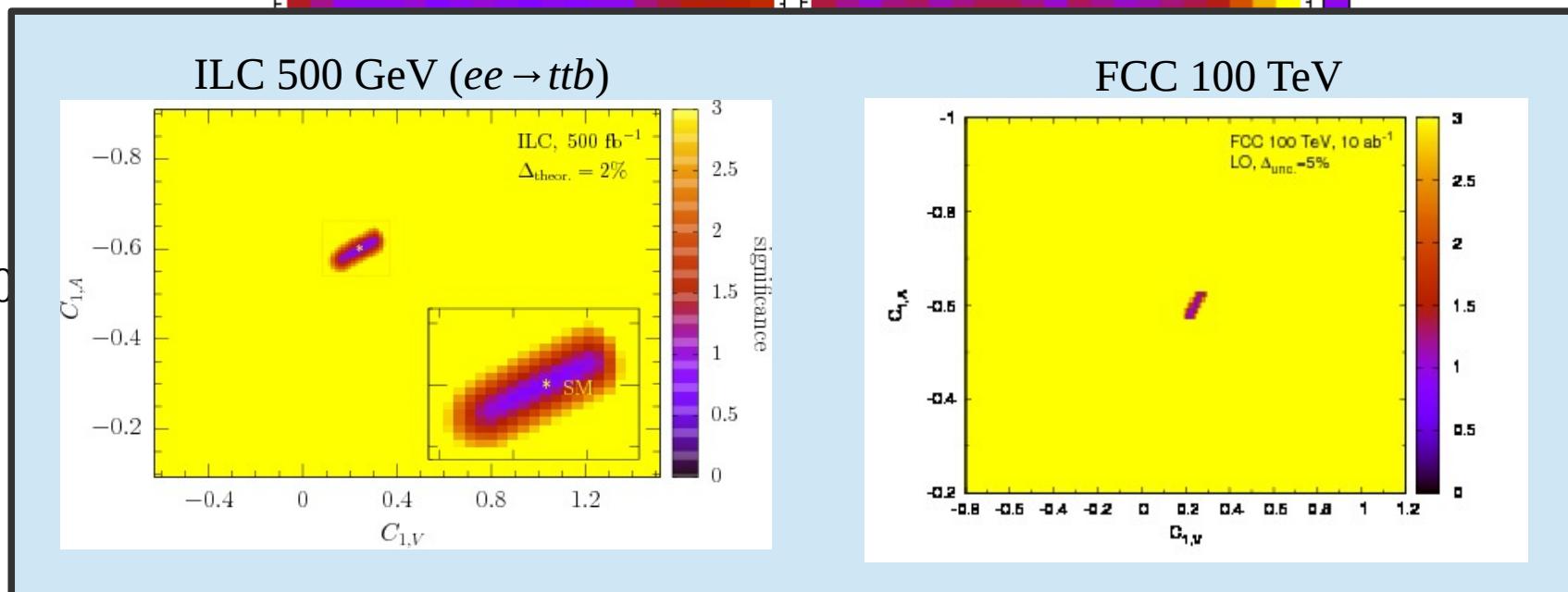


Constraints for LHC run-2

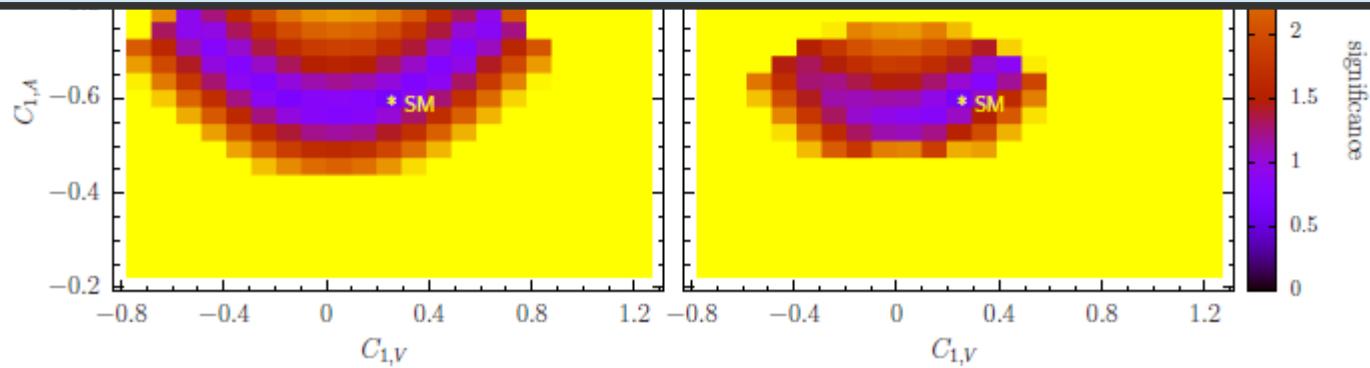
LO 30 fb^{-1}



LO 300 fb^{-1}



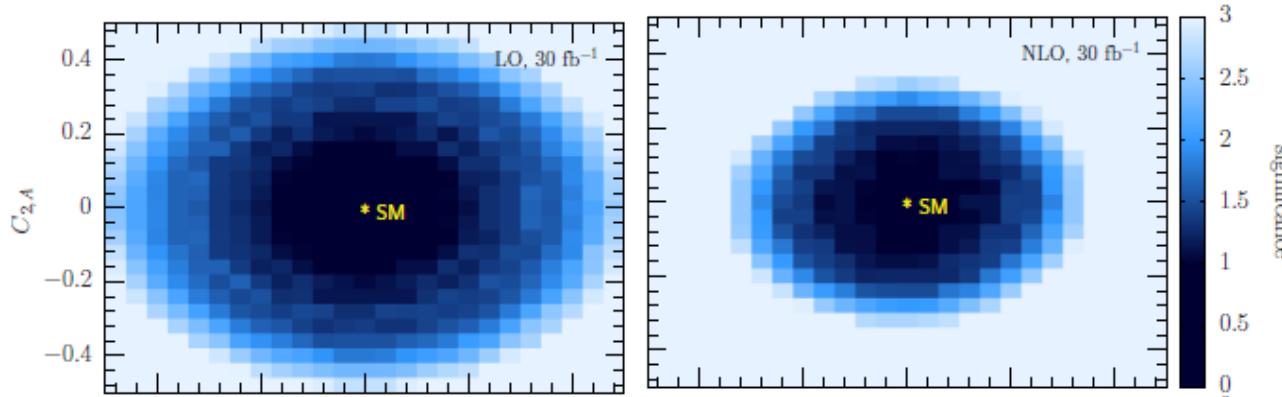
LO 3000 fb^{-1}



Constraints for LHC run-2

Weak dipole moments (\sim zero in the SM)

LO 30 fb^{-1}

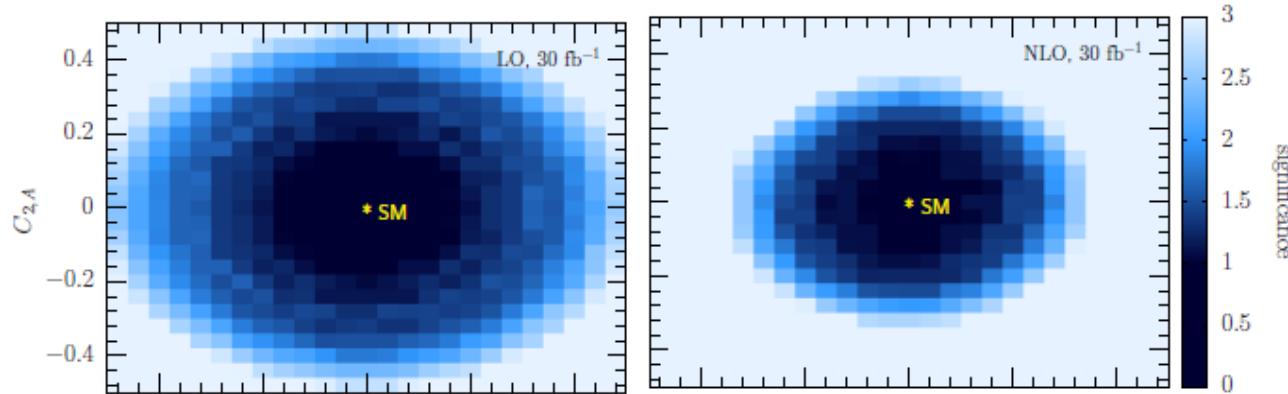


NLO 30 fb^{-1}

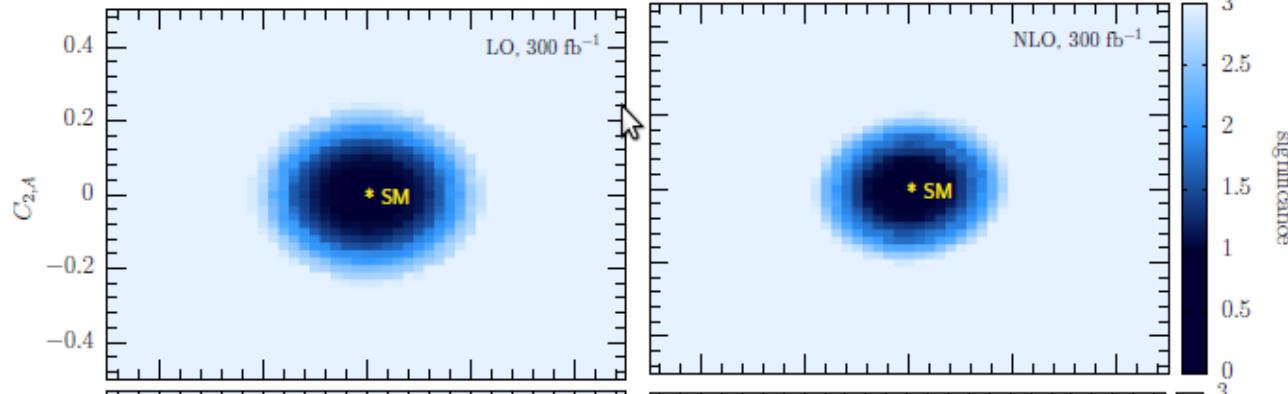
Constraints for LHC run-2

Weak dipole moments (\sim zero in the SM)

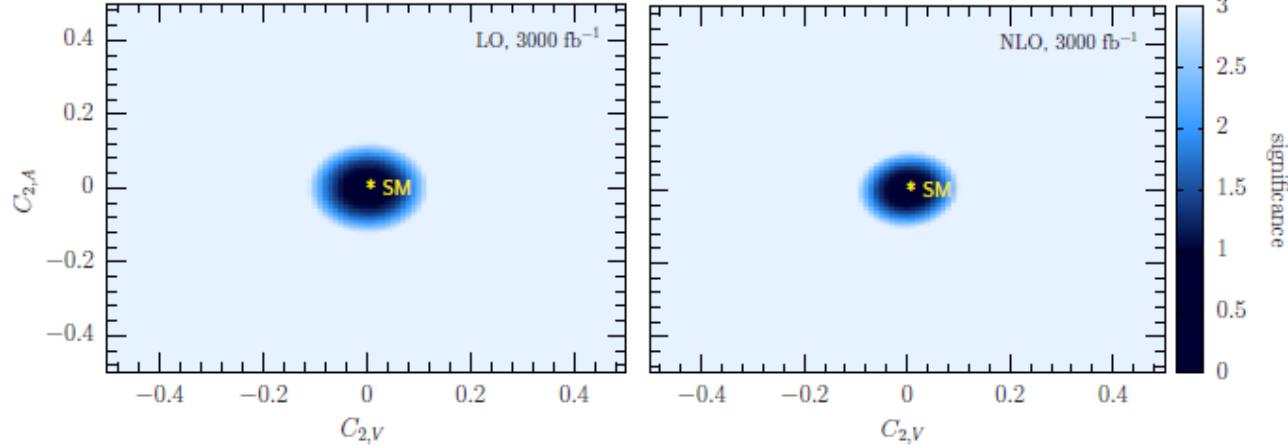
LO 30 fb^{-1}



LO 300 fb^{-1}



LO 3000 fb^{-1}

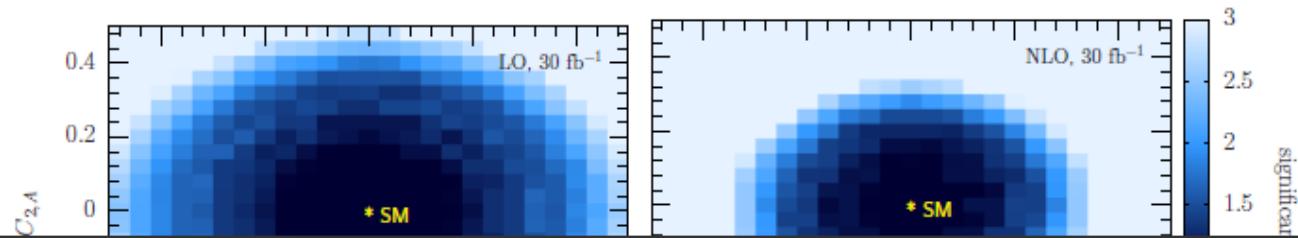


$C_{2,V}$

Constraints for LHC run-2

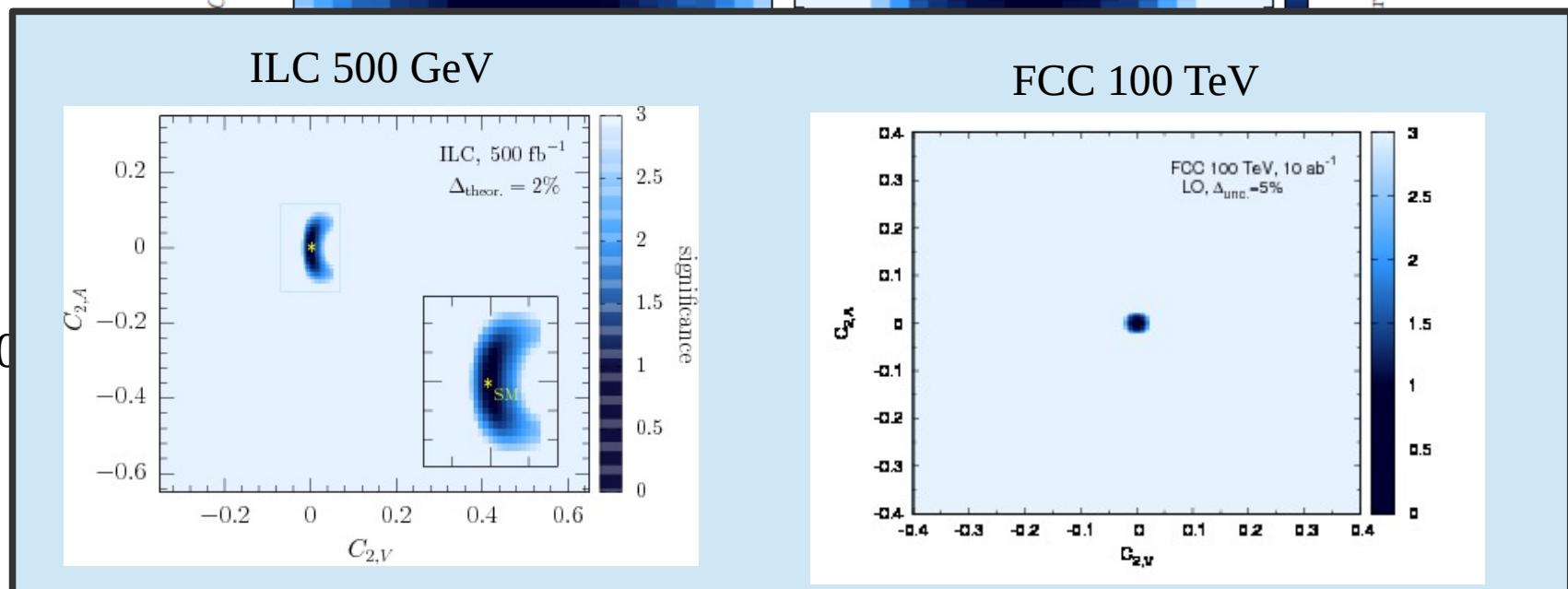
Weak dipole moments (\sim zero in the SM)

LO 30 fb^{-1}

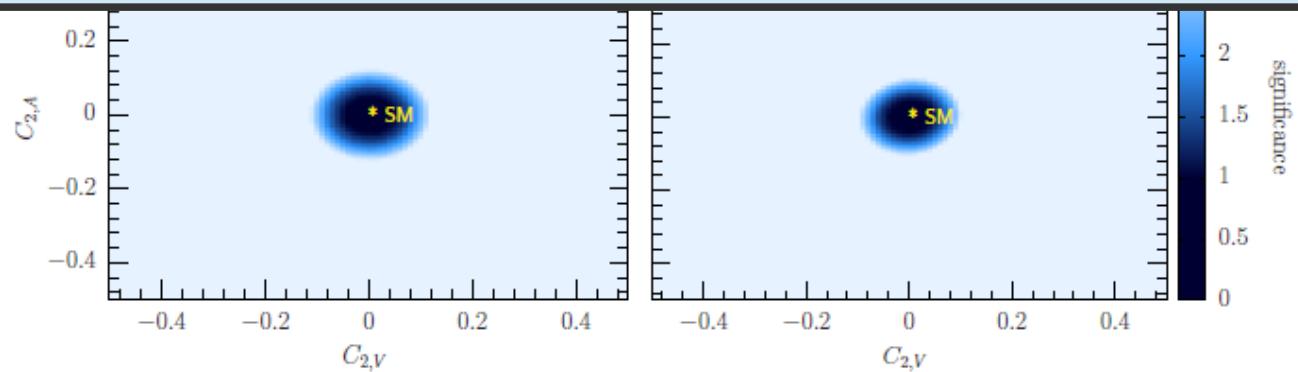


NLO 30 fb^{-1}

LO 300 fb^{-1}



LO 3000 fb^{-1}



Constraints for LHC run-2

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

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L - V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{H.c.} .$$
$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W} \bar{t} \gamma^\mu (X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t) t Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + i d_A^Z \gamma_5) t Z_\mu ,$$
$$\mathcal{L}_{\gamma tt} = -e Q_t \bar{t} \gamma^\mu t A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + i d_A^\gamma \gamma_5) t A_\mu .$$

Constraints for LHC run-2

- Constraints can be further strengthened by combining results from $t\bar{t}bar$, $t\bar{t}bar+Z$, $t\bar{t}bar+\gamma$, single-top.

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

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

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

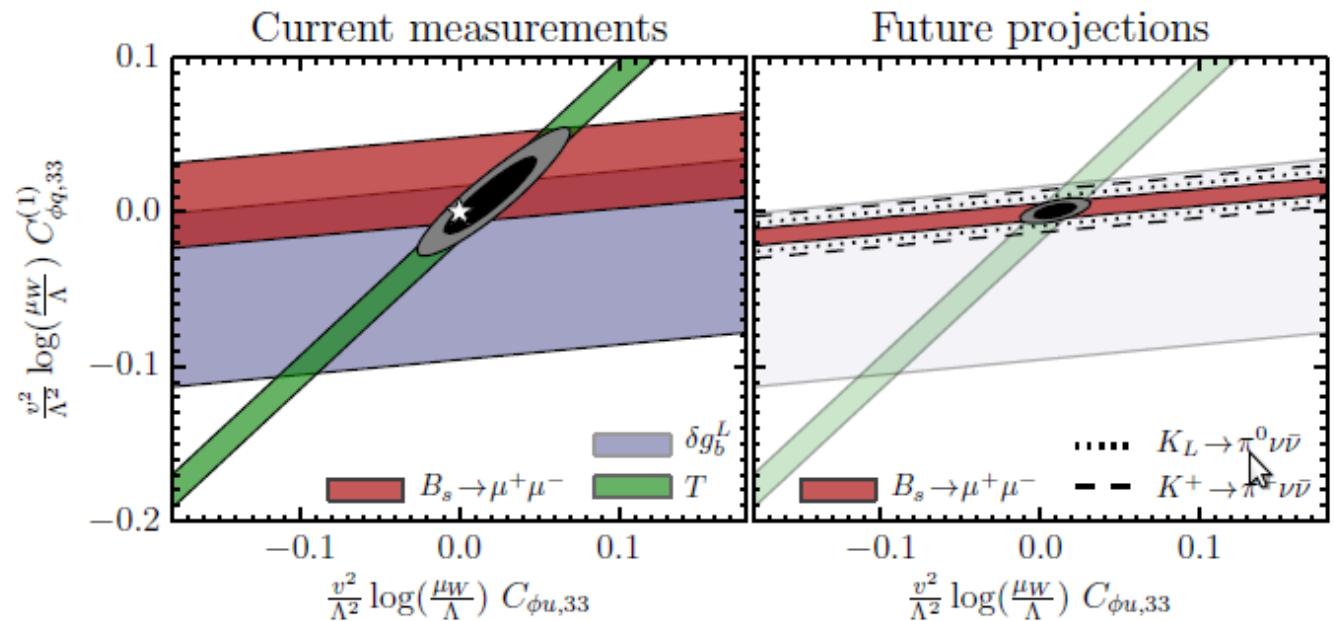
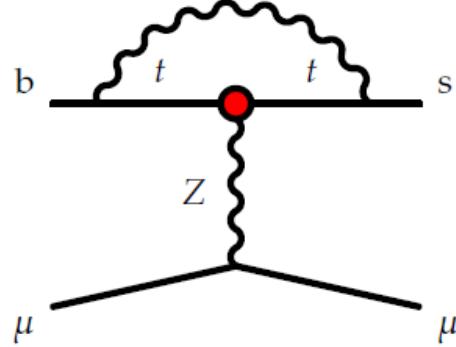
- Cross section ratios enhance sensitivity and reduce uncertainties
e.g. $\sigma(t\bar{t} + \gamma)/\sigma(t\bar{t})$, $\sigma(t\bar{t} + Z)/\sigma(t\bar{t} + H)$

[Melnikov,Scharf,Schulze], [Mangano,Shao]

Indirect constraints

Probing anomalous top-Z interactions with rare meson decays

[Brod,Greljo,Stamou,Uttayarat]

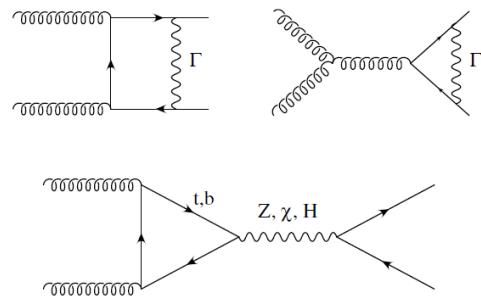


Order of magnitude stronger bounds than direct reach with 3000/fb!

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

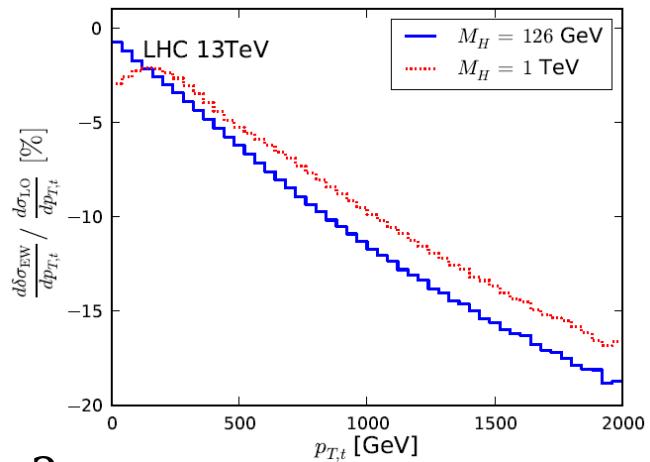
Electroweak corrections

- El.weak corrections to $t\bar{t}bar$ [Kühn,Scharf,Uwer], [Bernreuther,Fücker,Si]



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

inclusive (13 TeV): $\sim -3+0.2(\text{real})\% = -2.5\%$ [Baur]



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

- El.weak corrections to $t\bar{t}bar+Z,W,H$ [Frixione,Hirschi,Pagani,Shao,Zaro]

inclusive $t\bar{t}bar+Z$ (13 TeV): $\sim -3.8+0.9(\text{real})\% = -2.9\%$

inclusive $t\bar{t}bar+W$ (13 TeV): $\sim -7.7+3.9(\text{real})\% = -3.8\%$

inclusive $t\bar{t}bar+H$ (13 TeV): $\sim 0.0+0.9(\text{real})\% = +0.9\%$

Conclusions

- LHC run-2 will allow detailed studies of $t\bar{t}b+V, H$ final states.
First measurements have already been done in run-1.
Theory predictions are in good shape. SM QCD+EW is known at NLO.
- Subsequent coupling measurements yield *direct* sensitivity
and complement indirect determinations, allowing to probe the role
of top quarks in electroweak symmetry breaking.
- NLO QCD predictions for anomalous weak top couplings are available.
Higher orders generally improve the separation power and enhance
the exclusion reach.