Top quark effective couplings from associate tW photoproduction at the LHC

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[1] M. Aldana Franco, "Associate tW photoproduction at the LHC," Masters Thesis, Depto. de Física Aplicada, Cinvestav Mérida, Nov. (2018).

[2] A. B., F. Larios, "Top quark effective couplings from top-pair tagged photoproduction in pe^- collisions," Phys. Rev. D **105** (2022) 115002 [arXiv:2111.04723 [hep-ph]].

Proton form factors & Rosenbluth cross section

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We use FeynRules [1] to add p_{ntct} to the SM in MG5:

$$L_{\mathrm{free}} = \overline{\Psi}_{\mathrm{ntct}} i \not\partial \Psi_{\mathrm{ntct}} - M \overline{\Psi}_{\mathrm{ntct}} \Psi_{\mathrm{ntct}}$$

$$L_{\mathrm{int}} = e F_1(0) \overline{\Psi}_{\mathrm{ntct}} \gamma^{\mu} \Psi_{\mathrm{ntct}} A_{\mu} + \frac{e}{4M} F_2(0) \overline{\Psi}_{\mathrm{ntct}} \sigma^{\mu\nu} \Psi_{\mathrm{ntct}} F_{\mu\nu}$$

[1] A. Alloul et al., "FeynRules2.0—A complete toolbox for tree-level phenomenology," Comput. Phys. Commun. **185** (2014) 2250

Proton form factors & Rosenbluth cross section

We use FeynRules [1] to add $p_{\rm ntct}$ to the SM in MG5:

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This leads to the elastic $pe^- \to pe^-$ cross section [2]:

$$\frac{d\sigma}{dQ^2} = \pi\alpha^2\frac{M^2}{E^2Q^4}\left[F_1^2(Q^2)\left(4\frac{E^2}{M^2} - 2\frac{E}{M}\frac{Q^2}{M^2} + \left(\frac{1}{2}\frac{Q^2}{M^2} - 1\right)\frac{Q^2}{M^2}\right) + F_2^2(Q^2)\frac{Q^2}{M^2}\left(\frac{E^2}{M^2} + \frac{1}{4}\frac{Q^2}{M^2} - \frac{1}{2}\frac{E}{M}\frac{Q^2}{M^2}\right) + F_1(Q^2)F_2(Q^2)\frac{Q^4}{M^2}\right]$$

[1] A. Alloul et al., "FeynRules2.0—A complete toolbox for tree-level phenomenology," Comput. Phys. Commun. **185** (2014) 2250
[2] M. N. Rosenbluth, "High Energy Elastic Scattering of Electrons on Protons," Phys. Rev. **79** (1950) 615

Proton form factors & Rosenbluth cross section

Sachs form factors:

$$F_1(Q^2) = \frac{1}{1+\frac{Q^2}{4M^2}}\left(G_E(Q^2) + \frac{Q^2}{4M^2}G_M(Q^2)\right),$$
$$F_2(Q^2) = \frac{1}{1+\frac{Q^2}{4M^2}}\left(G_M(Q^2) - G_E(Q^2)\right)$$

[3] C. F. Perdrisat, V. Punjabi, M. Vanderhaeghen, "Nucleon Electromagnetic Form Factors," Prog. Part. Nucl. Phys. **59** (2007) 694.
[4] S. Pacetti, R. Baldini Ferroli, E. Tomasi-Gustafsson, "Proton electromagnetic form factors: Basic notions, present achievements and future perspectives," Phys. Rept. **550-551** (2015) 1.

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Dipolar form factors ($Q^2 \lesssim 3$ GeV^2):

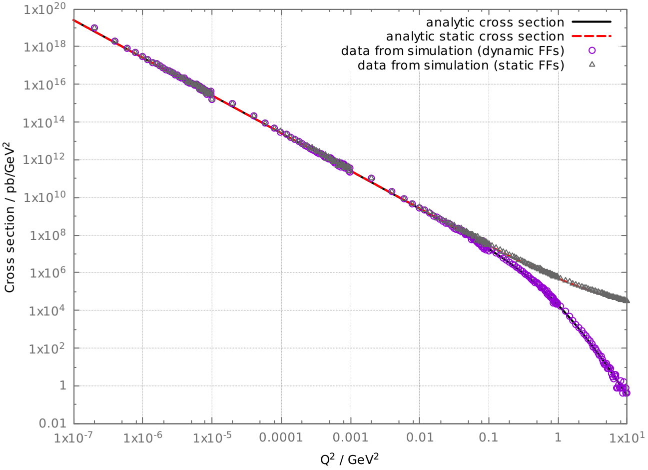
$$G_D(Q^2) = \frac{1}{(1+\frac{Q^2}{0.71\,\mathrm{GeV}^2})^2},$$

$$G_E(Q^2) = G_D(Q^2), \quad G_M(Q^2) = \mu_p G_D(Q^2),$$

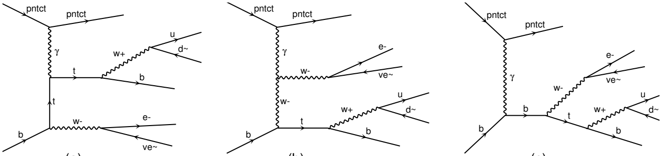
[3] C. F. Perdrisat, V. Punjabi, M. Vanderhaeghen, "Nucleon Electromagnetic Form Factors," Prog. Part. Nucl. Phys. **59** (2007) 694.
[4] S. Pacetti, R. Baldini Ferroli, E. Tomasi-Gustafsson, "Proton electromagnetic form factors: Basic notions, present achievements and future perspectives," Phys. Rept. **550-551** (2015) 1.

Proton form factors & Rosenbluth cross section

$p_{\rm ntct}\, e^- \to p_{\rm ntct}\, e^-$, $E_e = 7$ TeV, $E_p = m_p$:

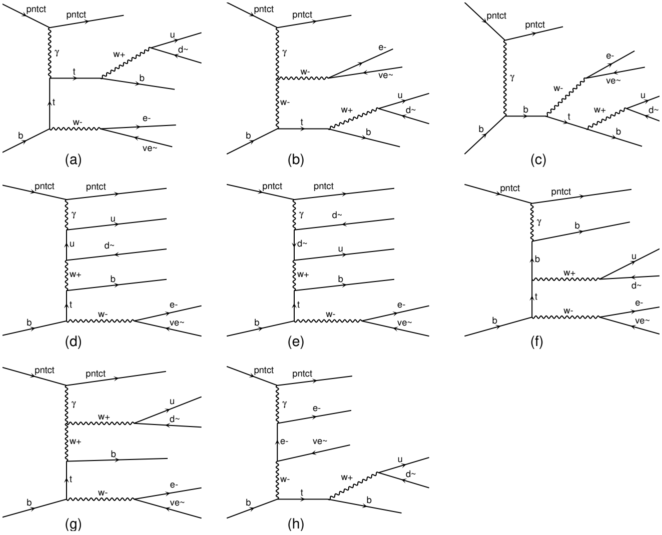


Associate tW photoproduction in semileptonic mode in SM



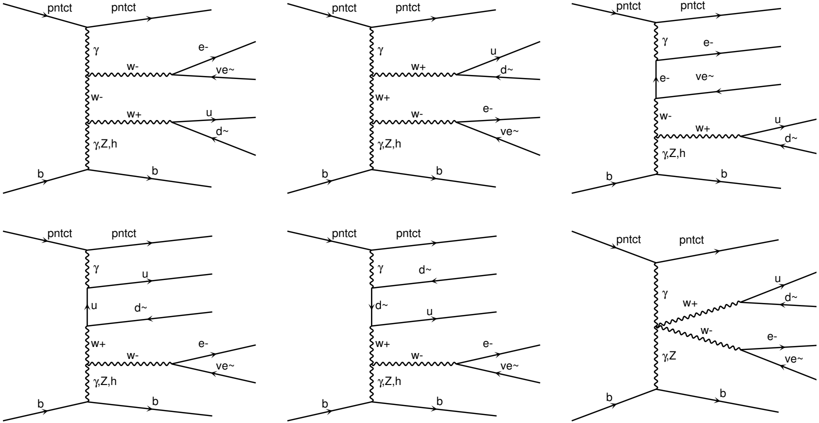
(a) (b) (c)

Associate *tW* photoproduction in semileptonic mode in SM



Irreducible background: *bWW* production

$$b p_{\mathrm{ntct}} \to b q_u \overline{q}_d \ell^- \overline{\nu}_\ell p_{\mathrm{ntct}} + b \ell^+ \nu_\ell \overline{q}_u q_d p_{\mathrm{ntct}}, \quad \ell = e,\ \mu$$



Phase-space cuts. SM cross sections

$$b p_{\rm ntct} \to t W^- p_{\rm ntct} \to b q_u \overline{q}_d \ell^- \overline{\nu}_\ell p_{\rm ntct} + b \overline{q}_u q_d \ell^+ \nu_\ell p_{\rm ntct}, \qquad \ell = e^-, \mu^-$$

Phase-space cuts. SM cross sections

$$bp_{\text{ntct}} \to tW^- p_{\text{ntct}} \to bq_u\overline{q}_d\ell^-\overline{\nu}_\ell p_{\text{ntct}} + b\overline{q}_u q_d\ell^+\nu_\ell p_{\text{ntct}}, \qquad \ell = e^-,\, \mu^-$$

$$4 \times \sigma(bp_{\text{ntct}}) = \sigma(bp_{\text{ntct}}) + \sigma(p_{\text{ntct}}b) + \sigma(\overline{b}p_{\text{ntct}}) + \sigma(p_{\text{ntct}}\overline{b})$$

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cut	σ [pb] sgnl	σ [pb] bckg
$0.003 < \xi < 0.15$	34.87	2.955
$p_T(b) > 30$, $p_T(j) > 20$ GeV	24.50	1.757
$\lvert y(b)\rvert$, $\lvert y(j)\rvert$, $\lvert y(\ell)\rvert < 2.5$	16.50	1.389
$\lvert m_{bjj} - m_t\rvert < 30$ GeV	9.86	0.067

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{\substack{\mathcal{O} \\ \mathrm{Herm}}} \frac{C_{\mathcal{O}}}{\Lambda^2}\mathcal{O} + \sum_{\substack{\mathcal{O} \\ \not{Herm}}} \left(\frac{C_{\mathcal{O}}}{\Lambda^2}\mathcal{O} + \frac{C^*_{\mathcal{O}}}{\Lambda^2}\mathcal{O}^\dagger \right) + \cdots$$

$$= \mathcal{L}_{\mathrm{SM}} + \sum_{\substack{\mathcal{O} \\ \mathrm{Herm}}} \frac{\overline{C}_{\mathcal{O}}}{v^2}\mathcal{O} + \sum_{\substack{\mathcal{O} \\ \not{Herm}}} \left(\frac{\overline{C}_{\mathcal{O}}}{v^2}\mathcal{O} + \frac{\overline{C}^*_{\mathcal{O}}}{v^2}\mathcal{O}^\dagger \right) + \cdots$$

$$\overline{C}_{\mathcal{O}} = \frac{v^2}{\Lambda^2} C_{\mathcal{O}}, \quad \Lambda = 1\ \mathrm{TeV}, \quad v = 246\ \mathrm{GeV}$$

Effective d6 operators: ttA and tbW, unitary gauge

$$O_{uB}^{33} = \sqrt{2} y_t g' (v+h)(\cos\theta_W \partial_\mu A_\nu - \sin\theta_W \partial_\mu Z_\nu)\, \bar{t}_L \sigma^{\mu\nu} t_R \ ,$$

$$O_{\varphi q}^{(-)33} = -y_t^2 \frac{g}{\sqrt{2}} (v+h)^2 \left(W_\mu^+ \, \bar{t}_L \gamma^\mu b_L + W_\mu^- \, \bar{b}_L \gamma^\mu t_L \right) - y_t^2 \frac{g}{c_W} (v+h)^2 Z_\mu \, \bar{t}_L \gamma^\mu t_L \ , \leftarrow \not{bbZ}$$

[5] B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek, "Dimension-six terms in the Standard Model Lagrangian," JHEP **10** (2010) 085.
[6] C. Zhang, "Effective field theory approach to top-quark decay at next-to-leading order in QCD," Phys. Rev. D **90** (2014) 014008.

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$$O_{\varphi ud}^{33} = \frac{y_t^2}{2\sqrt{2}} g (v+h)^2 W_\mu^+ \bar{t}_R \gamma^\mu b_R \ ,$$

$$O_{uW}^{33} = 2 y_t g (v+h) \left(\partial_\mu W_\nu^- + i g W_\mu^3 W_\nu^- \right) \bar{b}_L \sigma^{\mu\nu} t_R$$

$$+ \sqrt{2} y_t g (v+h) \left(c_W \partial_\mu Z_\nu + s_W \partial_\mu A_\nu + i g W_\mu^- W_\nu^+ \right) \bar{t}_L \sigma^{\mu\nu} t_R \ ,$$

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Physical interpretation

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$$\mathcal{L}_{\text{SM+anom,CC}} = \frac{g}{\sqrt{2}} f_V^L \left(W_\mu^+(\bar{t}_L\gamma^\mu b_L) + W_\mu^-(\bar{b}_L\gamma^\mu t_L)\right)$$

$$f_V^L = V_{tb} + \delta f_V^L$$

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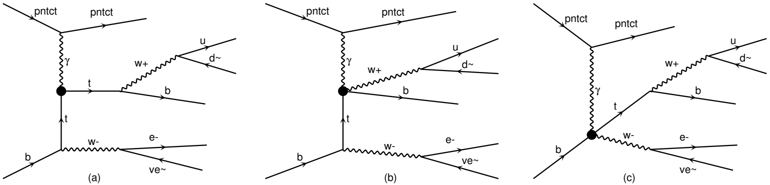
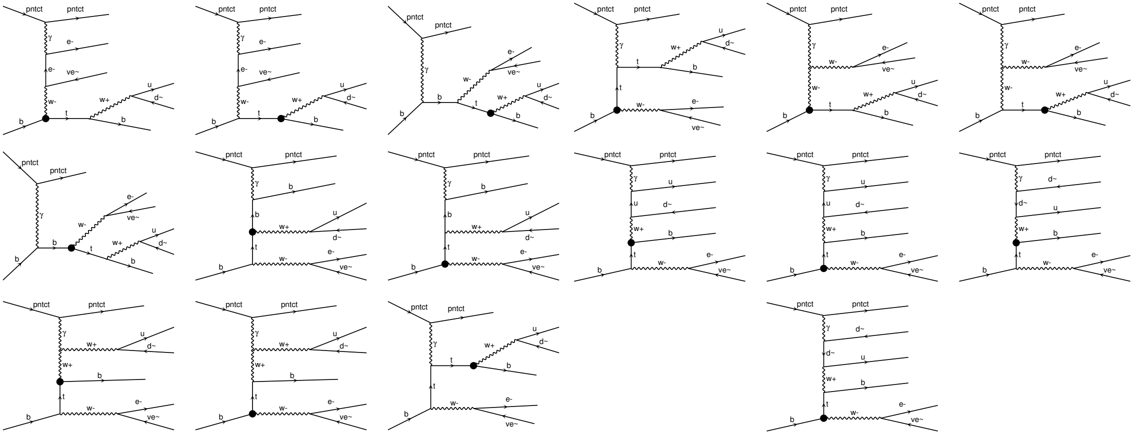
$$\delta f_V^L = -y_t^2\overline{C}_{\varphi q}^{(-)33}$$

Anomalous tW production



$\overline{C}_{uB}, \overline{C}_{uW}$ $\overline{C}_{uW}, \overline{C}_{dW}$ $\overline{C}_{uW}, \overline{C}_{dW}$

Anomalous tW production



$$\overline{C}_{\varphi q}^{(-)},\ \overline{C}_{\varphi ud},\ \overline{C}_{uW},\ \overline{C}_{dW}$$

Limits on effective couplings (68% CL)

ε_{exp}	$10\,\%$	$15\,\%$	$20\,\%$
$\overline{C}_{uB\,r}$	$-6.16, 6.10$	$-7.54, 7.47$	$-8.70, 8.64$
$\overline{C}_{\varphi q}^{(-)}$	$-3.90 \times 10^{-2}, 3.58 \times 10^{-2}$	$-5.99 \times 10^{-2}, 5.28 \times 10^{-2}$	$-8.18 \times 10^{-2}, 6.91 \times 10^{-2}$
$\overline{C}_{\varphi ud\,r}$	$-0.65, 0.79$	$-0.81, 0.95$	$-0.95, 1.08$
$\overline{C}_{uW\,r}$	$-0.49, 0.47$	$-0.74, 0.70$	$-1.0, 0.96$
$\overline{C}_{dW\,r}$	$-0.38, 0.41$	$-0.47, 0.50$	$-0.54, 0.58$

Limits on effective couplings: $\overline{C}_{\varphi q}^{(-)} = \delta f_V^L$

$\varepsilon_{\mathrm{exp}}$:	10%	15%	20%
		68% C.L.	
δf_V^L	−0.039, 0.036	−0.060, 0.053	−0.082, 0.069
		95% C.L.	
δf_V^L	−0.082, 0.069	−0.13, 0.10	−0.19, 0.13

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δf_V^L	0.075 $-0.039,\ 0.036$	0.11 $-0.060,\ 0.053$	0.15 $-0.082,\ 0.069$
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	68%	95%
[7] : δf_V^L	0.12 $-0.024,\ 0.094$	0.19 $-0.062,\ 0.13$

[7] CMS Coll., JHEP **02** (2017) 028 [arXiv:1610.03545 [hep-ex]] (fig. 6).

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[8] : $\overline{C}^{(3)}_{\varphi q}$	$\overset{0.18}{-0.16,\ 0.020}$	$\overset{0.27}{-0.23,\ 0.04}$

[7] CMS Coll., JHEP **02** (2017) 028 [arXiv:1610.03545 [hep-ex]] (fig. 6).
[8] CMS Coll., Eur. Phys. J. C **79** (2019) 886 [arXiv:1903.11144 [hep-ex]].

Limits on effective couplings: $\overline{C}_{uB}$

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$$[9]\, B \to X_s\gamma: \qquad -1.0 < \overline{C}_{uBr} < 0.15 \qquad (68\%\ \mathrm{C.L.})$$

[9] A.B., F. Larios, "Electromagnetic dipole moments of the top quark," Phys. Rev. D **87** (2013) 074015

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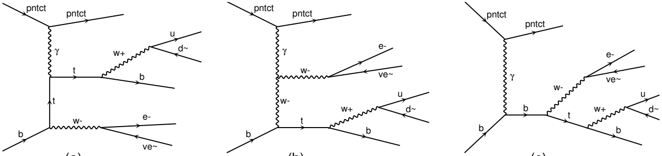
$$[10] \ell\ell : \quad -0.065 < \overline{C}_{uBr} < 0.045 \quad (95\% \text{ C.L.})$$

[9] A.B., F. Larios, "Electromagnetic dipole moments of the top quark," Phys. Rev. D **87** (2013) 074015
[10] CMS Coll., "Measurement of the inclusive and differential $t\bar{t}\gamma$ cross section . . . at $\sqrt{s} = 13$ TeV," JHEP **05** (2022) 091.

Associate *tW* photoproduction in semileptonic mode in SM



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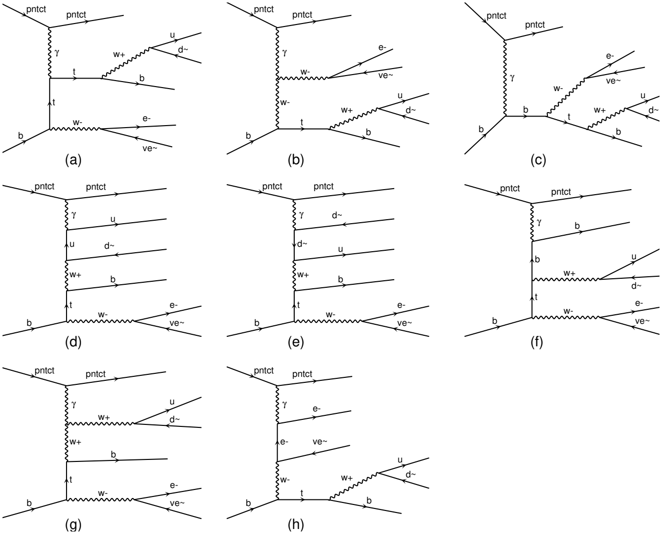

Photoproduction regions [2]

$$PhP_I : -4.74 < y(e^-) < -3.0, \quad \Big| \quad PhP_{II} : -5.44 < y(e^-) < -3.0, \quad \Big| \quad PhP_{III} : -6.22 < y(e^-) < -3.0$$

Photoproduction regions [2]

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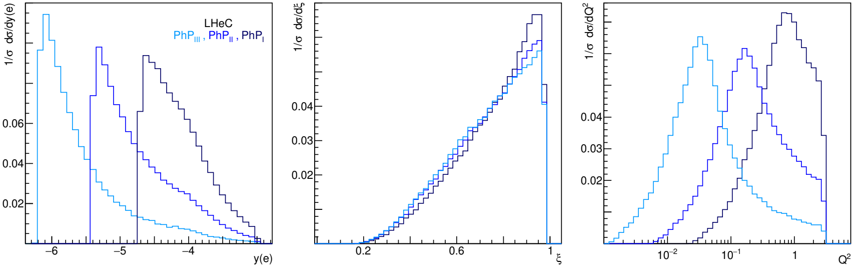
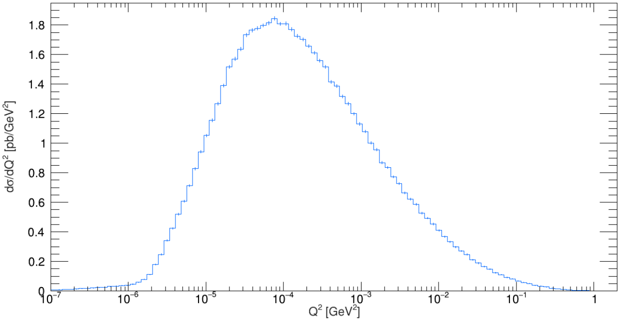


[2] A. B., F. Larios, "Top quark effective couplings from top-pair tagged photoproduction in pe^- collisions," Phys. Rev. D **105** (2022) 115002 [arXiv:2111.04723 [hep-ph]]

$d\sigma/dQ^2$: $-0.003 < \xi < 0.15$



Conclusions

- We obtained the cross section for tW associated photoproduction in semileptonic mode in full tree-level QED, without EPA [12]. With the cuts shown above we obtain $\sigma \simeq 40$ pb.

[12] V. M. Budnev, I. F. Ginzburg, G. V. Meledin, V. G. Serbo, "The Two-Photon Particle Production Mechanism. Physical Problems. Applications. Equivalent Photon Approx- imation," Phys. Rep. 15 (1975) 181.

Conclusions

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- In the photoproduction region considered here we find high sensitivity to the tbW anomalous coupling $\overline{C}_{\varphi q}^{(-)} = \delta f_V^L$. The limits obtained at the parton level are similar or better than the current ones, and the ones projected at the HL-LHC, if the measurement uncertainty is $\lesssim 20\%$.

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- Other photoproduction phase-space regions, with moderate Q^2_{min}, should yield good sensitivity to the top e.m. dipole moments. With cross sections of $\mathcal{O}(1 - 10)$ pb, statistics should be enough to measure differential cross sections.

[12] V. M. Budnev, I. F. Ginzburg, G. V. Meledin, V. G. Serbo, "The Two-Photon Particle Production Mechanism. Physical Problems. Applications. Equivalent Photon Approx- imation," Phys. Rep. 15 (1975) 181.

Thanks!

Parametrization of cross section

$$R = \frac{\sigma(\{\overline{C}_{\mathcal{O}}\})}{\sigma_{\mathrm{SM}}} = 1 + a\overline{C}_{\mathcal{O}} + b\overline{C}_{\mathcal{O}}^{2} + \cdots$$

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$$R \lessgtr 1 + \varepsilon_{\mathrm{exp}}$$