TOP2017

10th International Workshop on Top Quark Physics

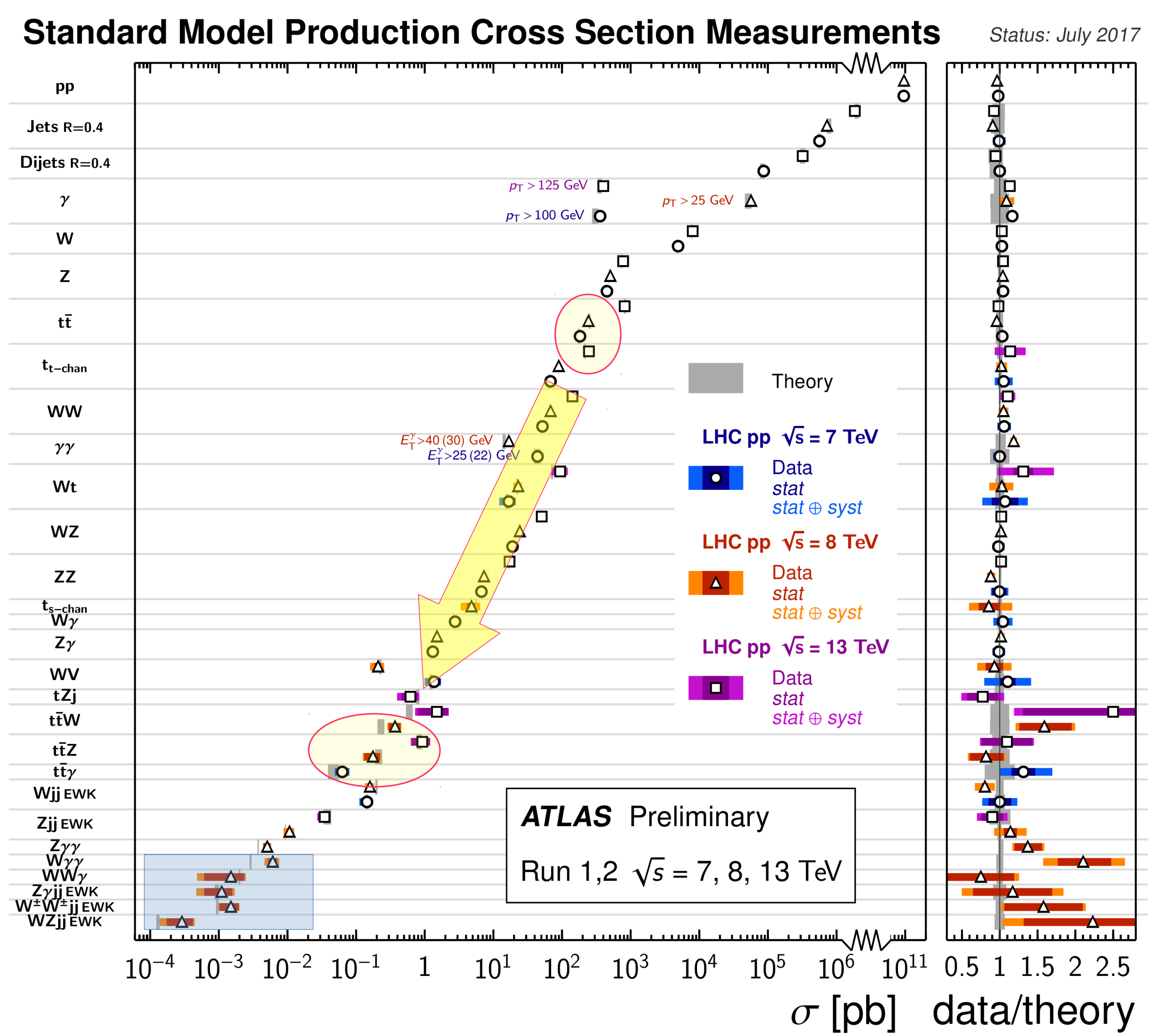
Overview:

Top Quarks and Gauge Bosons

Markus Schulze

Beginning of a new era in top quark physics

- The LHC is not only a top quark factory, it 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.



Beginning of a new era in top quark physics

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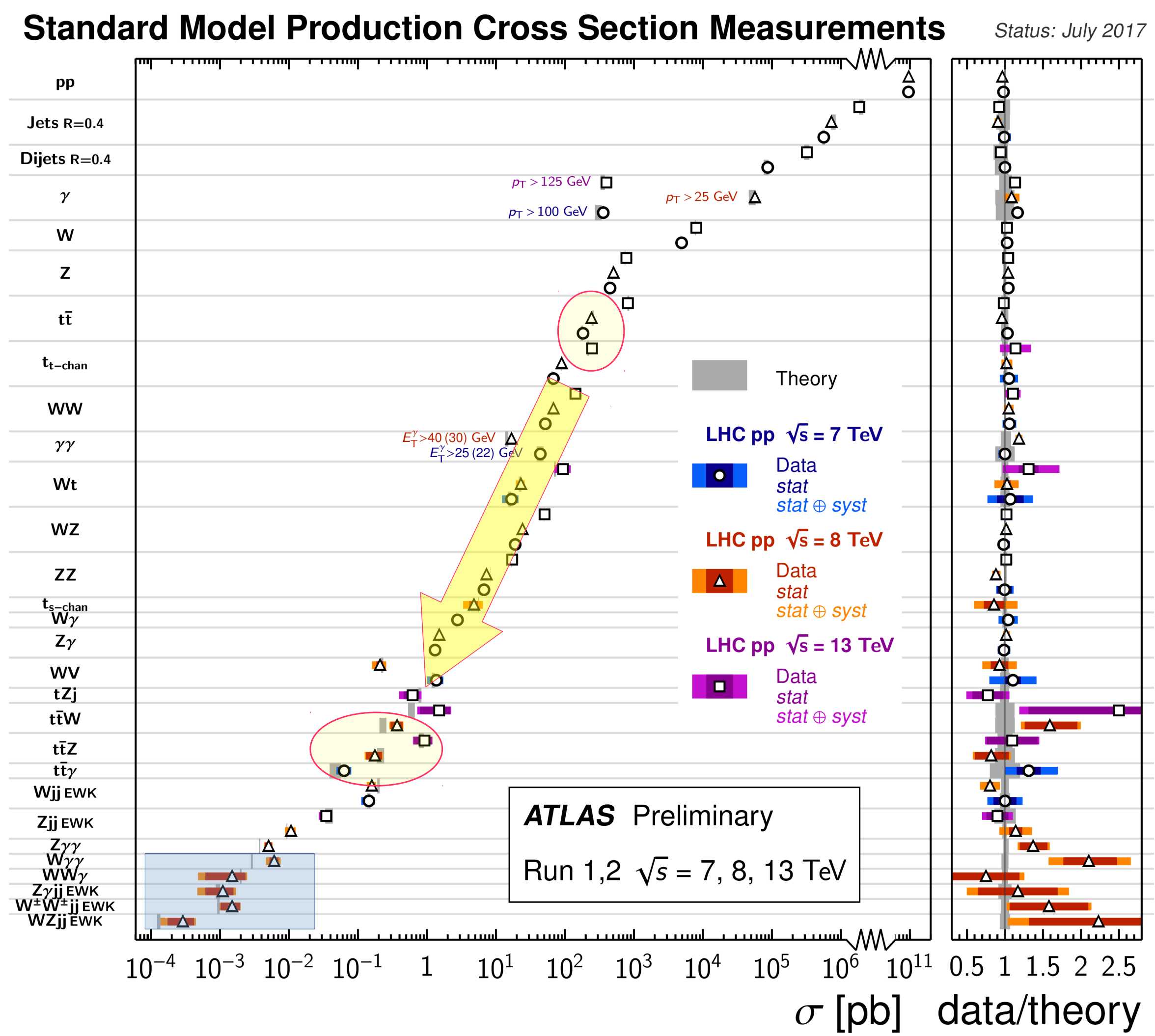
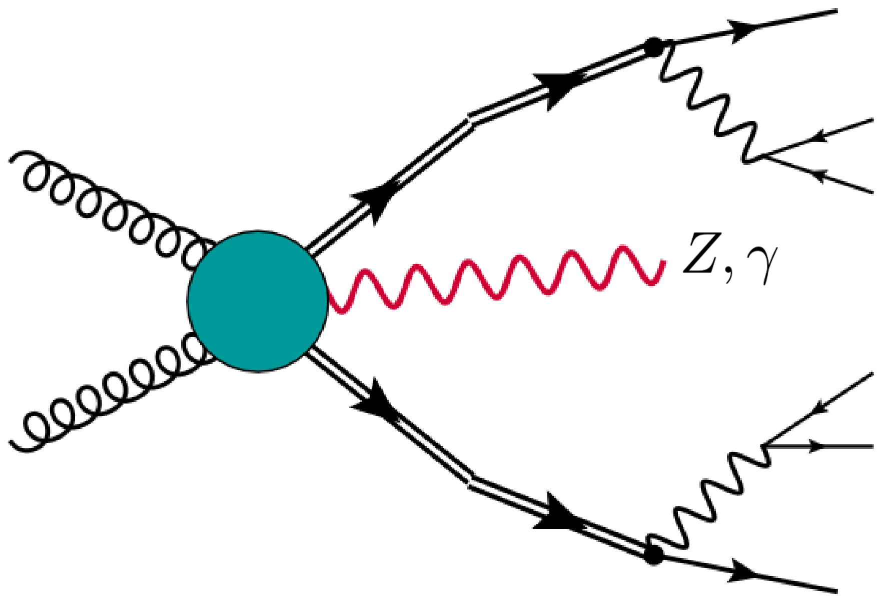
13 TeV	now	300 fb^{-1}
$t\bar{t}$	33 Mio.	250 Mio.
$t\bar{t}+\gamma$	100.000	900.000
$t\bar{t}+Z$	40.000	300.000

- *For comparison:* Tevatron produced 84.000 $t\bar{t}$ and 400 $t\bar{t}+\gamma$

- Already now we have as many $t\bar{t}+\gamma$ (LHC) as $t\bar{t}$ (Tevatron)



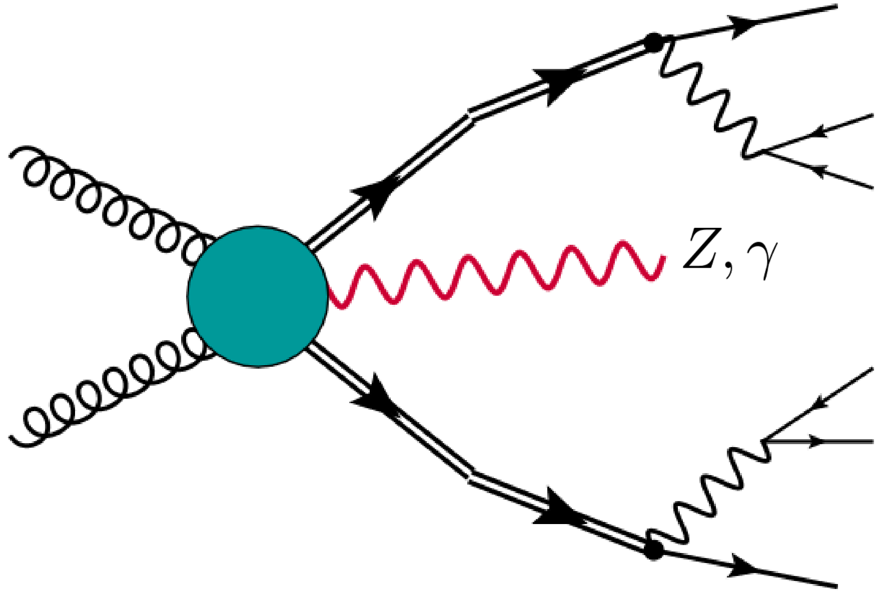
Top quark anatomy



Features:

- Very complex final state (up to 8 particles, reconstr. ambiguities)
- Clean signature & small backgrounds
- Direct sensitivity to weak top quark interactions
- Delicate ISR/FSR features in $t\bar{t} + \gamma$
- Asymmetries (forward-backward/charge)
- Interplay with B-physics

Top quark anatomy



+ single top + V

Features:

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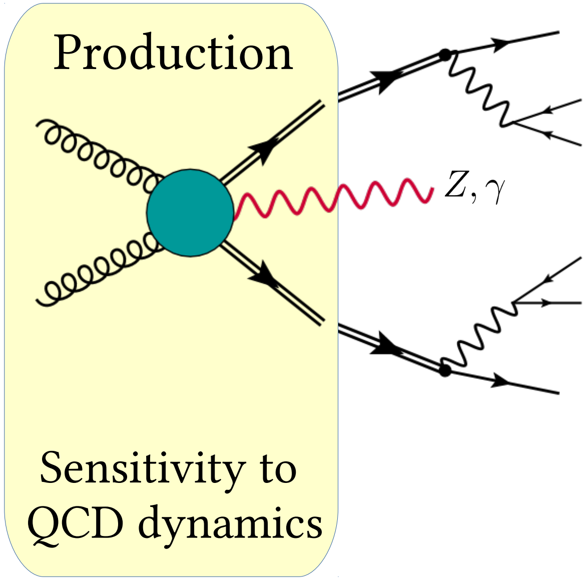
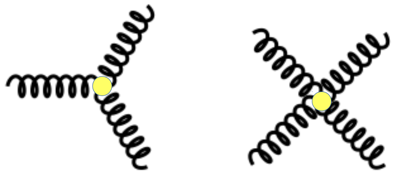
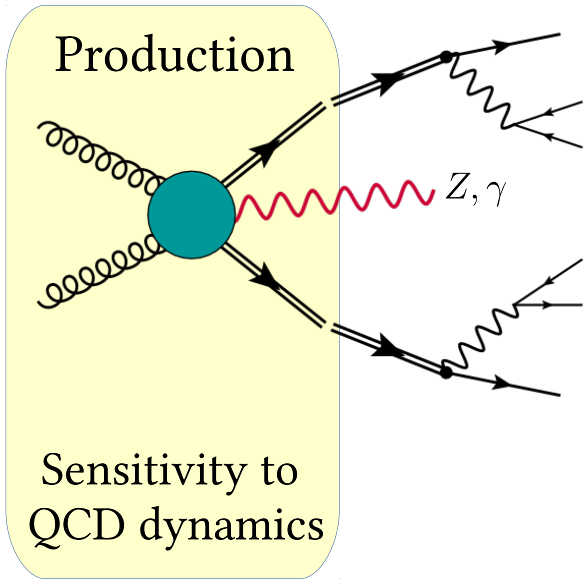
Top quark anatomy



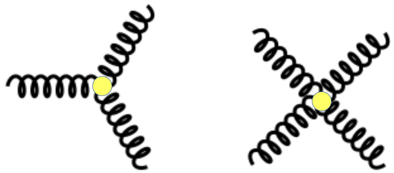
Top quark anatomy



$$c_G \mathcal{O}_G = \frac{g_s\, c_G}{\Lambda^2}\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$



Top quark anatomy



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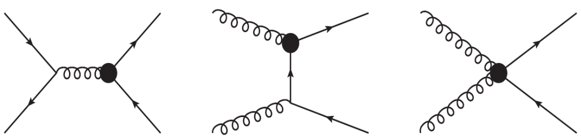
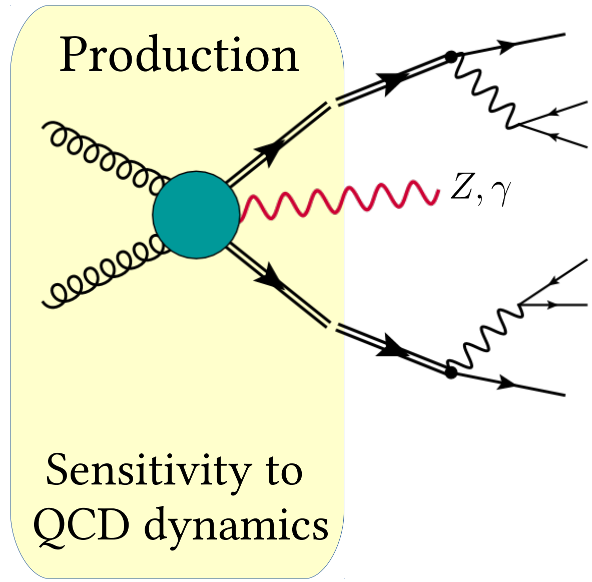
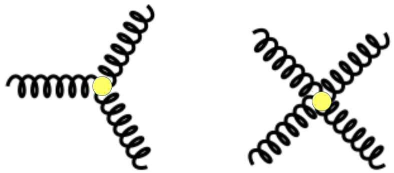


$$O_{tG} = y_t g_s \left(\bar{Q}\sigma^{\mu\nu} T^A t\right) \tilde{\phi} G^A_{\mu\nu}$$



Top quark anatomy



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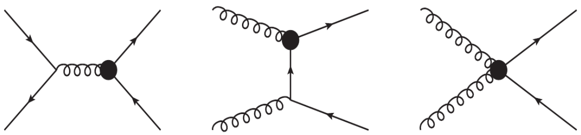

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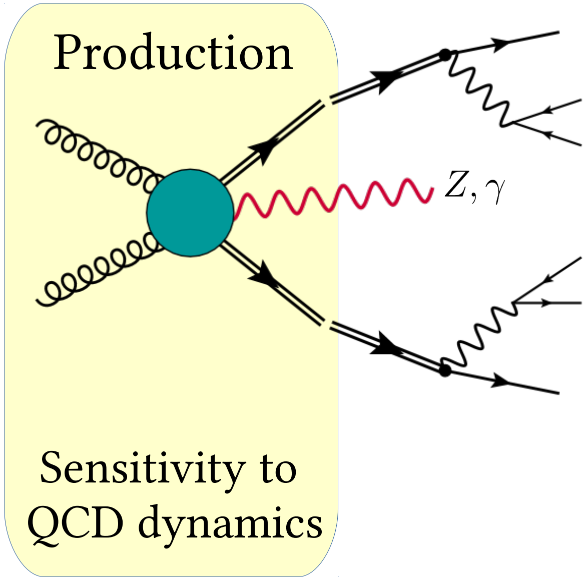

$$
\begin{aligned}
\mathcal{O}^{(8,3)}_{Qq} &= \left(\bar{Q}_L\gamma_\mu T^a \tau^i Q_L\right)\left(\bar{q}_L\gamma^\mu T^a \tau^i q_L\right)\\
\mathcal{O}^{(8,1)}_{Qq} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{q}_L\gamma^\mu T^a q_L\right)\\
\mathcal{O}^{(8)}_{td} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{d}_R\gamma^\mu T^a d_R\right)\\
\mathcal{O}^{(8)}_{tu} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{u}_R\gamma^\mu T^a u_R\right)\\
\mathcal{O}^{(8)}_{tq} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{q}_L\gamma^\mu T^a q_L\right)\\
\mathcal{O}^{(8)}_{Qd} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{d}_R\gamma^\mu T^a d_R\right)\\
\mathcal{O}^{(8)}_{Qu} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{u}_R\gamma^\mu T^a u_R\right)\\
\mathcal{O}^{(1,3)}_{Qq} &= \left(\bar{Q}_L\gamma_\mu \tau^i Q_L\right)\left(\bar{q}_L\gamma^\mu \tau^i q_L\right)\\
\mathcal{O}^{(1,1)}_{Qq} &= \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{q}_L\gamma^\mu q_L\right)\\
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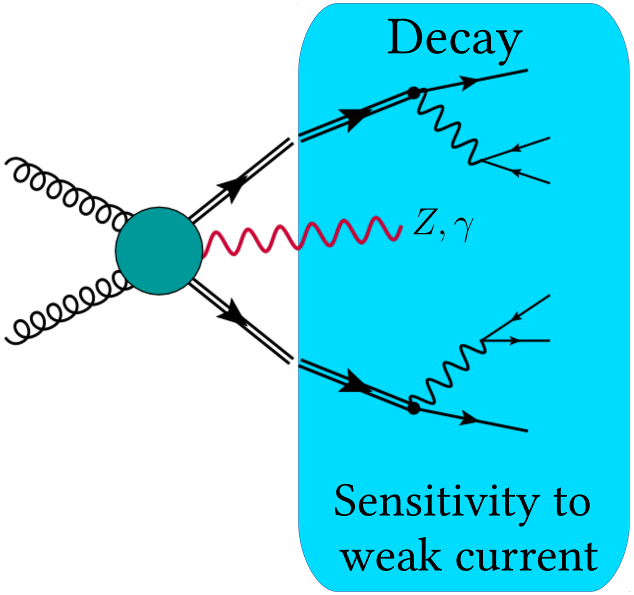
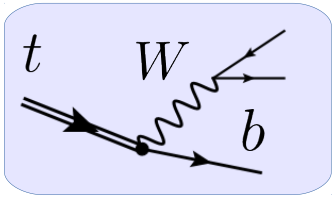
\mathcal{O}^{(1)}_{Qu} &= \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{u}_R\gamma^\mu u_R\right)
\end{aligned}
$$

Top quark anatomy





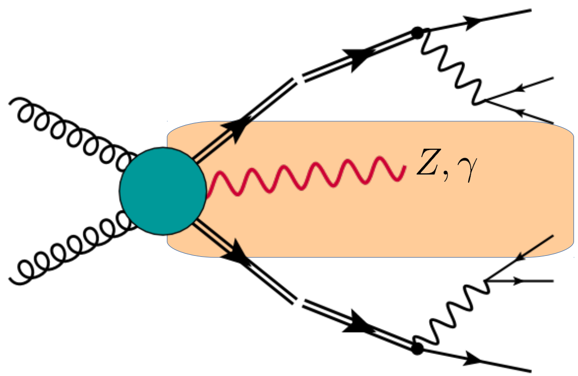
$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger \tau^a D_\mu \phi)\,(\bar{t}_\mathrm{L} \gamma^\mu \tau_a t_\mathrm{L}),$$

$$\mathcal{O}_{\phi\phi}^{33} = \mathrm{i}(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_R \gamma^\mu d_R)$$

$$\mathcal{O}_{uW}^{33} = \left(\bar{q}_\mathrm{L} \sigma^{\mu\nu} \tau^I t_\mathrm{R}\right) \tilde{H} W_{\mu\nu}^I,$$

$$\mathcal{O}_{dW}^{33} = \left(\bar{q}_\mathrm{L} \sigma^{\mu\nu} \tau^I b_\mathrm{R}\right) H W_{\mu\nu}^I,$$

Top quark anatomy



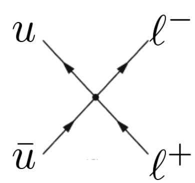
Associated production:

Sensitivity to neutral couplings

$$C_{u\phi}^{33} = (\tilde{\phi}^\dagger \phi)(\bar{q}_L u_R)$$
$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger \tau^a D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu \tau_a t_\mathrm{L}),$$
$$C_{\phi q}^{(1,33)} = \mathrm{i}\,(\phi^\dagger D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu t_\mathrm{L}),$$
$$C_{\phi u}^{33} = \mathrm{i}\,(\phi^\dagger D_\mu \phi)\,(\bar{t}_\mathrm{R}\gamma^\mu t_\mathrm{R}).$$

$$\mathcal{O}_{uW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I t_\mathrm{R})\,\tilde{H}W_{\mu\nu}^I,$$
$$\mathcal{O}_{dW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I b_\mathrm{R})\,HW_{\mu\nu}^I,$$
$$\mathcal{O}_{uB\phi}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu} t_\mathrm{R})\,\tilde{H}B_{\mu\nu},$$

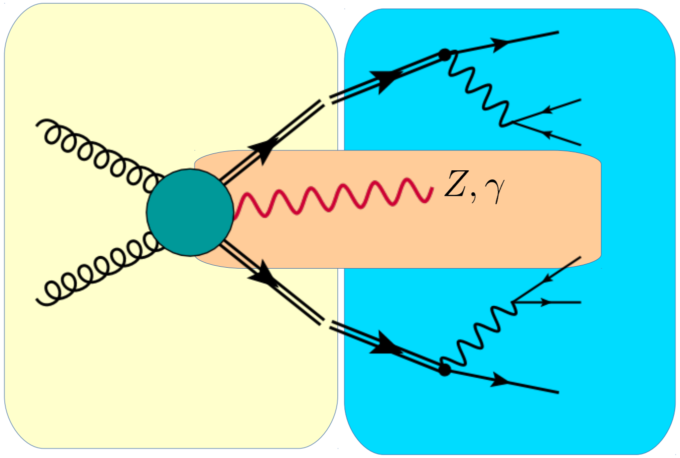
+



$$O_{lq}^1 \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q,$$
$$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u,$$
$$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q,$$
$$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u,$$

$$O_{lequ}^1 \equiv \bar{l}e \;\; \varepsilon \;\; \bar{q}u,$$
$$O_{lequ}^3 \equiv \bar{l}\sigma_{\mu\nu}e \quad \varepsilon \quad \bar{q}\sigma^{\mu\nu}u$$
$$O_{lq}^3 \equiv \bar{l}\gamma_\mu\tau^I l \quad \bar{q}\gamma^\mu\tau^I q,$$

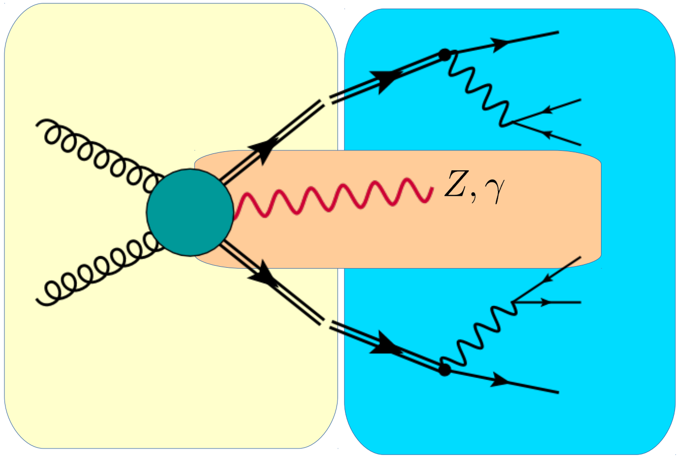
Top quark anatomy



- There are (at least) 28 anomalous operators affecting production & decay dynamics
- A global (28-dimensional) approach is impossible
- This completely obscures access to $t\bar{t}V$ interactions

$\longrightarrow$ Is there a way to simplify the analysis without diminishing the physics modeling?

Top quark anatomy



- There are (at least) 28 anomalous operators affecting production & decay dynamics
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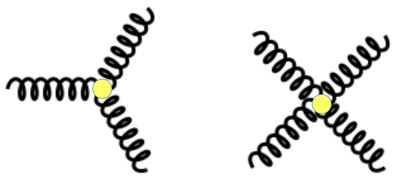
$\longrightarrow$ Is there a way to simplify the analysis without diminishing the physics modeling?

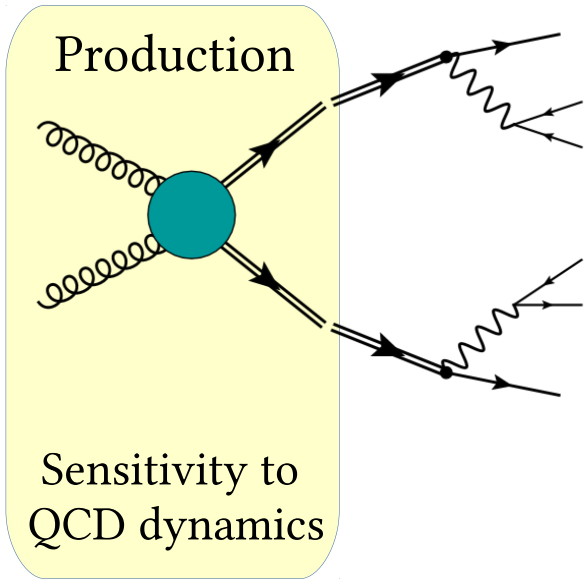
- One attempt: *Sequential approach*

1) Expose common features of $t\bar{t} + V$ and *ttbar, single-top and di-jets.*
2) If standard candles anomaly-free then tackle $t\bar{t} + V$ under this assumption.

Top quark anatomy



$$c_G \mathcal{O}_G = \frac{g_s\, c_G}{\Lambda^2}\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$



LHC multijet events as a probe for anomalous dimension-six gluon interactions

Frank Krauss
Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom

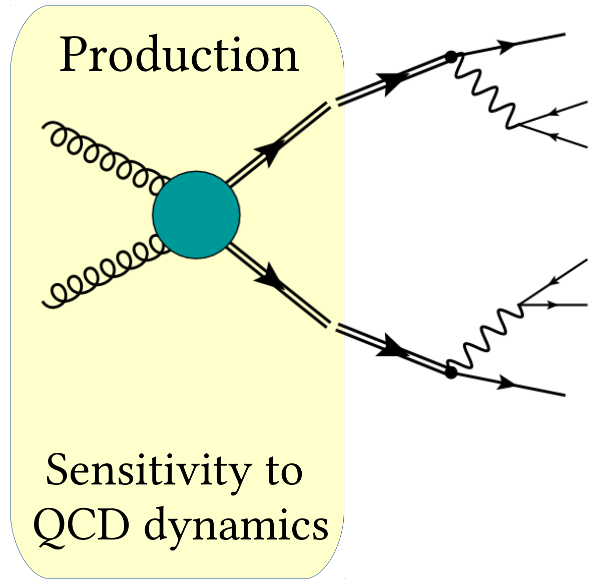
Silvan Kuttimalai
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA and Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom

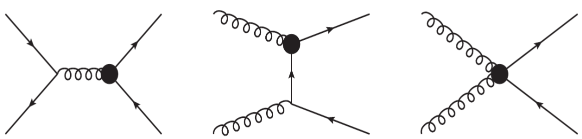
Tilman Plehn
Institut für Theoretische Physik, Universität Heidelberg, 69120 Heidelberg, Germany

[2016]

→ Anomalous QCD better tested in multi-jet production than in top quark physics.

Top quark anatomy





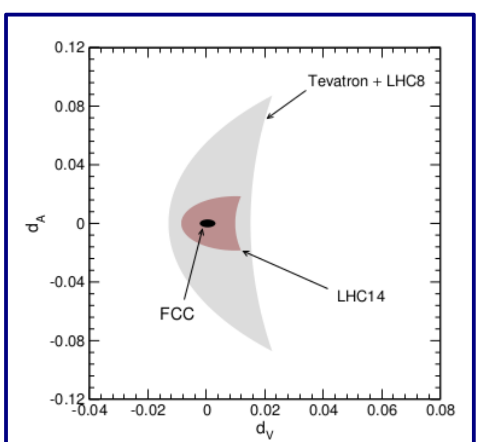
$$O_{tG} = y_t g_s \left(\bar{Q}\sigma^{\mu\nu}T^A t\right)\tilde{\phi}G^A_{\mu\nu}$$

[2015]

Pinning down top dipole moments with ultra-boosted tops

Juan A. Aguilar–Saavedra[(a)], Benjamin Fuks[(b,c)] and Michelangelo L. Mangano[(c)]

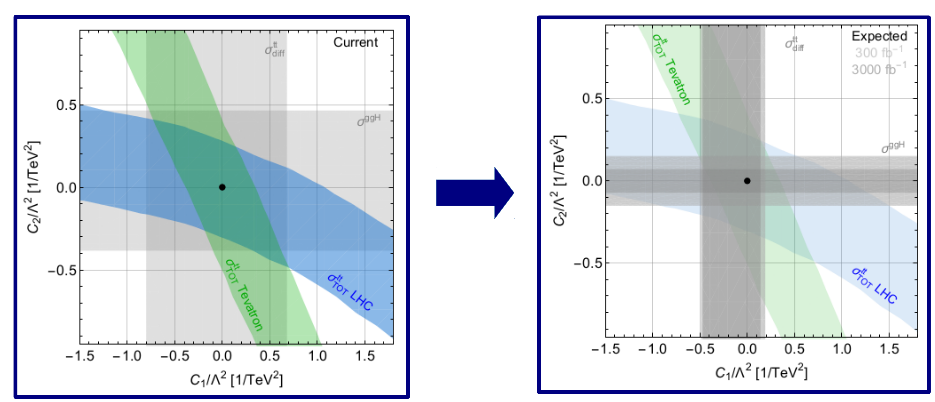
[(a)] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*
[(b)] *Institut Pluridisciplinaire Hubert Curien/Département Recherches Subatomiques, Université de Strasbourg/CNRS-IN2P3, 23 Rue du Loess, F-67037 Strasbourg, France*
[(c)] *CERN, PH-TH, CH-1211 Geneva 23, Switzerland*



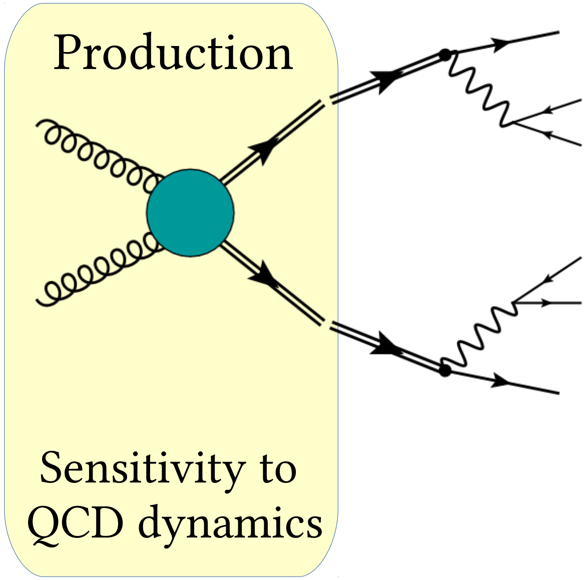
[2017]

Constraints on top quark non-standard interactions from Higgs and $t\bar{t}$ production cross sections

D. Barducci[†], M. Fabbrichesi[‡], and A. Tonero[°]
[†]*SISSA and INFN, Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy*
[‡]*INFN, Sezione di Trieste and*
[°] *UNIFAL-MG, Rodovia José Aurélio Vilela 11999, 37715-400 Poços de Caldas, MG, Brazil*
(Dated: April 20, 2017)



Top quark anatomy



$$
\begin{aligned}
\mathcal{O}_{Qq}^{(8,3)} &= (\bar{Q}_L\gamma_\mu T^a\tau^i Q_L)\,(\bar{q}_L\gamma^\mu T^a\tau^i q_L)\\
\mathcal{O}_{Qq}^{(8,1)} &= (\bar{Q}_L\gamma_\mu T^a Q_L)\,(\bar{q}_L\gamma^\mu T^a q_L)\\
\mathcal{O}_{td}^{(8)} &= (\bar{t}_R\gamma_\mu T^a t_R)\,(\bar{d}_R\gamma^\mu T^a d_R)\\
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\mathcal{O}_{Qq}^{(1,3)} &= (\bar{Q}_L\gamma_\mu \tau^i Q_L)\,(\bar{q}_L\gamma^\mu \tau^i q_L)\\
\mathcal{O}_{Qq}^{(1,1)} &= (\bar{Q}_L\gamma_\mu Q_L)\,(\bar{q}_L\gamma^\mu q_L)\\
\mathcal{O}_{td}^{(1)} &= (\bar{t}_R\gamma_\mu t_R)\,(\bar{d}_R\gamma^\mu d_R)\\
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\mathcal{O}_{Qu}^{(1)} &= (\bar{Q}_L\gamma_\mu Q_L)\,(\bar{u}_R\gamma^\mu u_R)
\end{aligned}
$$

[2016]

Eur. Phys. J. C (2016) 76:200
DOI 10.1140/epjc/s10052-016-4040-x

THE EUROPEAN PHYSICAL JOURNAL C

Letter

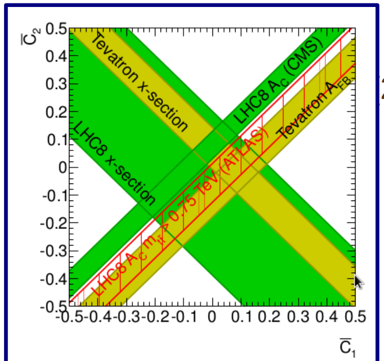
Constraints on four-fermion interactions from the $t\bar{t}$ charge asymmetry at hadron colliders

M. Perelló Roselló[a], M. Vos[b]
IFIC (UVEG/CSIC), Apartado de Correos 22085, 46071 Valencia, Spain

$$\frac{(\sigma - \sigma^{SM})}{\sigma^{SM}} = [\alpha_u(C_u^1 + C_u^2) + \alpha_d(C_d^1 + C_d^2)](\frac{1\ \mathrm{TeV}}{\Lambda})^2,$$

and [4]

$$(A_C - A_C^{SM}) = [\beta_u(C_u^1 - C_u^2) + \beta_d(C_d^1 - C_d^2)](\frac{1\ \mathrm{TeV}}{\Lambda})^2$$



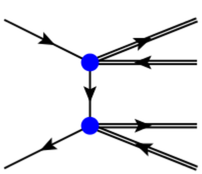
2016]

[2017]

Constraining $qqtt$ operators from four-top production: a case for enhanced EFT sensitivity*

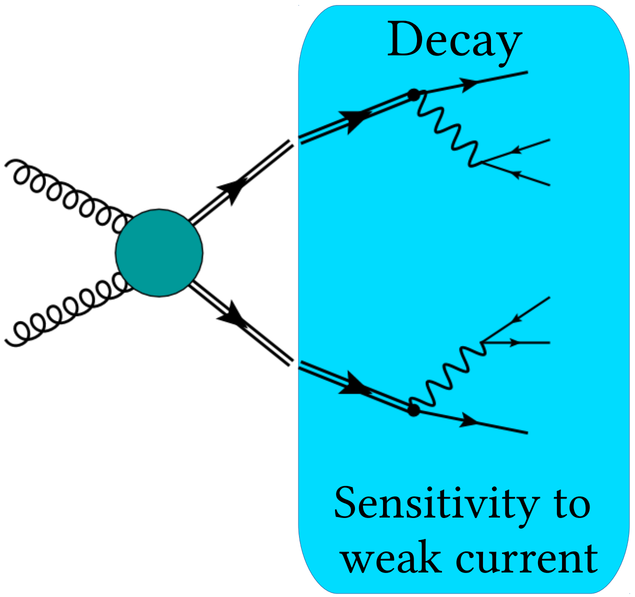
Cen Zhang[1]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China



"[…] the four-top process, with only a O(10) upper bound, is as powerful as tt measurements with a percentage error."

Top quark anatomy



[2015]

A set of top quark spin correlation and polarization observables for the LHC: Standard Model predictions and new physics contributions

Werner Bernreuther,[a,1] Dennis Heisler[a] and Zong-Guo Si[b]

[a] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, 52056 Aachen, Germany*

[b] *School of Physics, Shandong University, Jinan, Shandong 250100, China*

[2015]

PHYSICAL REVIEW D **92,** 094013 (2015)

Looking for BSM physics using top-quark polarization and decay-lepton kinematic asymmetries

Rohini M. Godbole,[1] Gaurav Mendiratta,[1] and Saurabh D. Rindani[2]

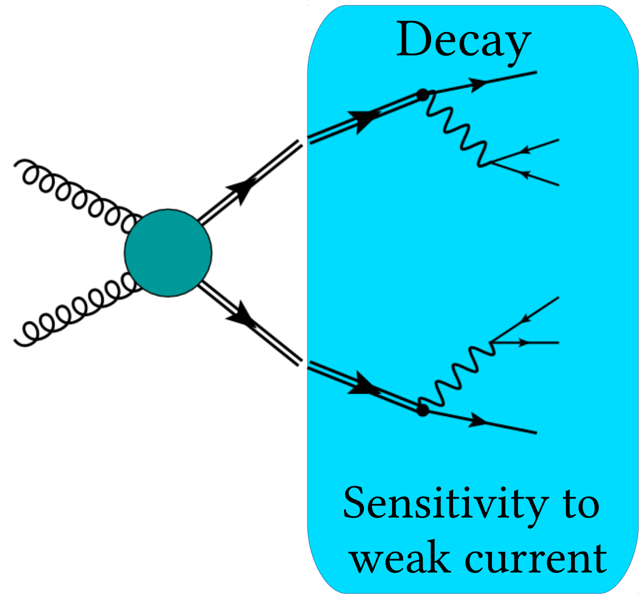
[1] *Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India*

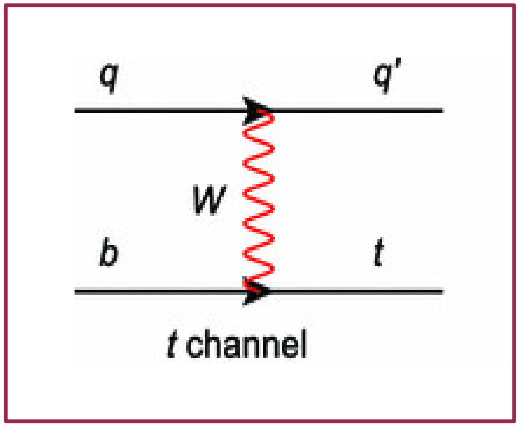
[2] *Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India*

(Received 13 July 2015; published 9 November 2015)

- Often reduction of sensitivity in: $\dfrac{|\mathcal{M}_{t\to bW}|^2}{\Gamma_t}$ because $\Gamma_t \sim |\mathcal{M}_{t\to bW}|^2$

Top quark anatomy





→ Study *single-top* where cancellation doesn't happen

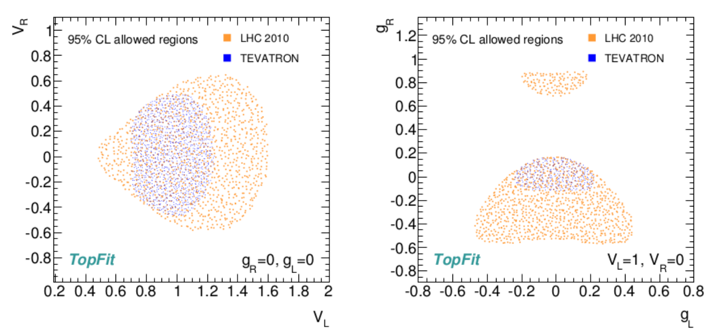
[2011]

PHYSICAL REVIEW D **84,** 019901(E) (2011)

Publisher's Note: Constraints on the *Wtb* vertex from early LHC data [Phys. Rev. D 83, 117301 (2011)]

J. A. Aguilar-Saavedra, N. F. Castro, and A. Onofre

(Received 23 June 2011; published 14 July 2011)

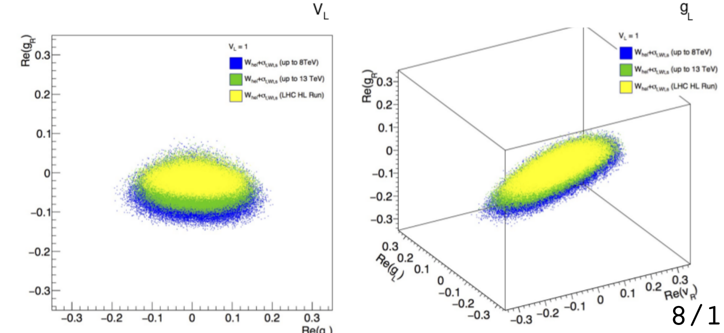


[2016]

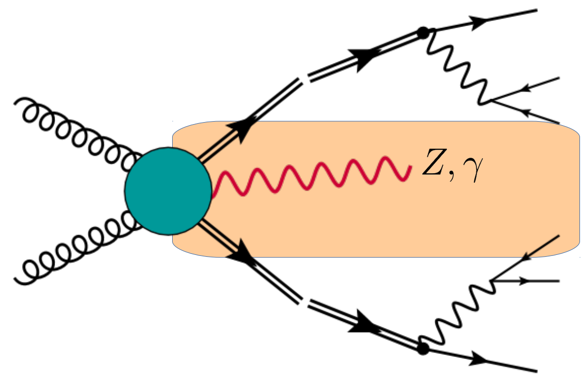
New limits on anomalous contributions to the *Wtb* vertex

J. L. Birman[1], F. Déliot[2], M. C. N. Fiolhais[1,3,4], A. Onofre[5], C. M. Pease[1]

[1] *Department of Physics, City College of the City University of New York, 160 Convent Avenue, New York 10031, NY, USA*
[2] *Institute of Research into the Fundamental Laws of the Universe, CEA, Saclay, France*
[3] *Department of Physics, New York City College of Technology, 300 Jay Street, Brooklyn, NY 11201, USA*
[4] *LIP, Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal*
[5] *LIP, Departamento de Física, Universidade do Minho, Campus de Gualtar, 4710-057 Braga, Portugal*



Top quark anatomy



Associated production

- Careful investigation of *standard candles*: *di-jet*, *ttbar*, *single-top*, (*4 tops*), allows to restrict the number of anomalous terms and opens the case for coupling studies in $t\bar{t} + V$ processes.

  Essentially 4 operators left:

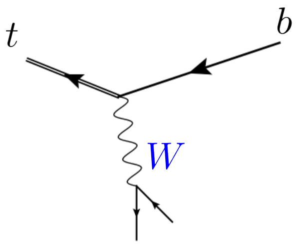
$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger \tau^a D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu \tau_a t_\mathrm{L}), \qquad \mathcal{O}_{uW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I t_\mathrm{R})\,\tilde{H} W_{\mu\nu}^I,$$

$$C_{\phi u}^{33} = \mathrm{i}\,(\phi^\dagger D_\mu \phi)\,(\bar{t}_\mathrm{R}\gamma^\mu t_\mathrm{R}). \qquad \mathcal{O}_{uB\phi}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu} t_\mathrm{R})\,\tilde{H} B_{\mu\nu},$$

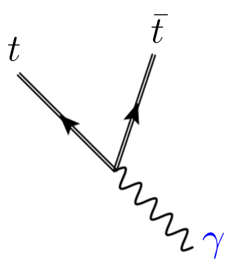
- Remaining $q\bar{q}\ell\ell$ contact terms can be neglected (in a first step) because they drop out when integrating over Z-peak (effectively dimension-8).

Top quark electroweak couplings

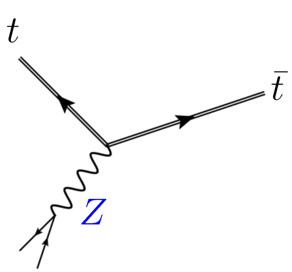
- Anomalous couplings can enter in various production and decay stages
- SU(2)xU(1) symmetry relates the left-handed couplings



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



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



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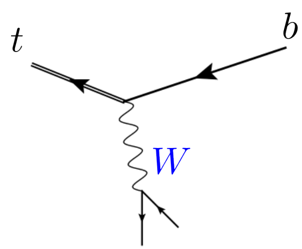

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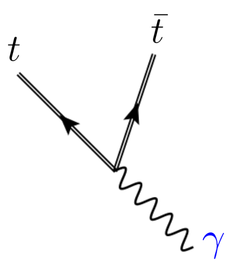

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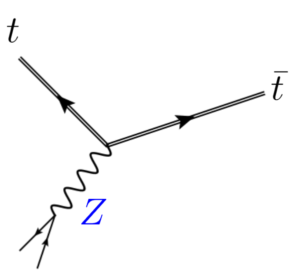

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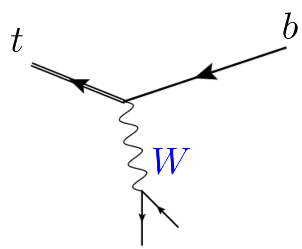

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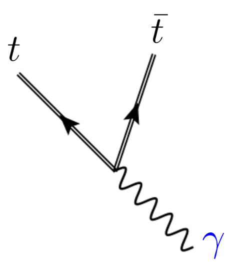

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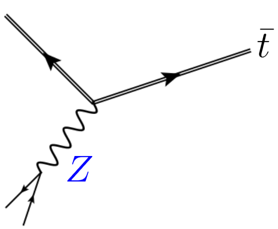

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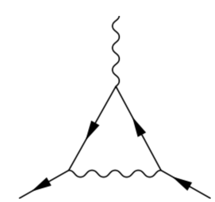
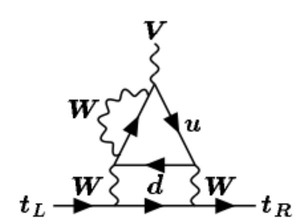
- Weak dipole couplings arise radiatively in the SM and they are small.

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



$d_V \approx -0.007$



$d_A \leq 10^{-5}$

Top quark electroweak couplings

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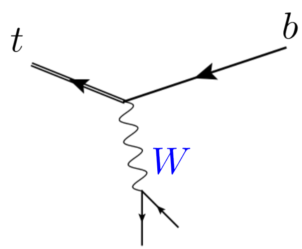

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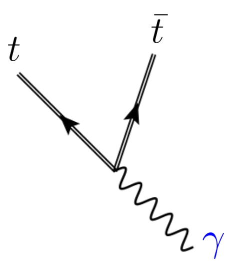

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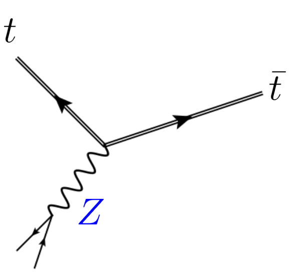

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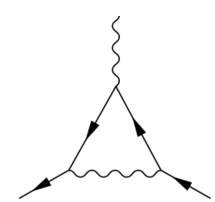

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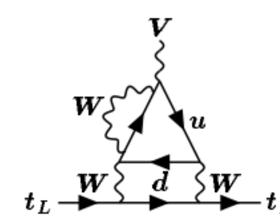
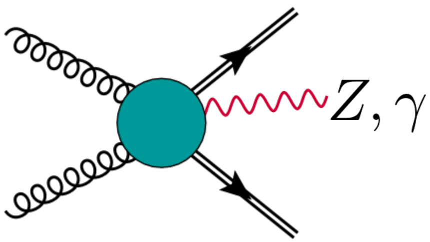


$d_A \leq 10^{-5}$

Associated production: *ttbar+Z/γ*

First pioneering studies:



PHYSICAL REVIEW D **71,** 054013 (2005)

Probing electroweak top quark couplings at hadron colliders

U. Baur*
Department of Physics, State University of New York, Buffalo, New York 14260, USA

A. Juste†
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

L. H. Orr‡ and D. Rainwater§
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 1 December 2004; published 11 March 2005)

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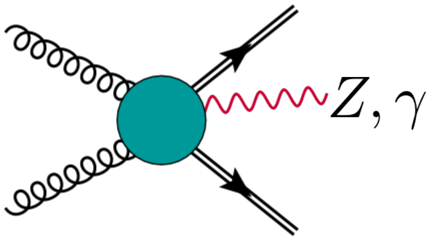

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[2016]

Probing top quark neutral couplings in the Standard Model Effective Field Theory at NLO QCD

Olga Bessidskaia Bylund,[a] **Fabio Maltoni,**[b] **Ioannis Tsinikos,**[b] **Eleni Vryonidou**[b] **and Cen Zhang**[c]

[a] *Oskar Klein Centre and Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden*

[b] *Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

[c] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

[2016]

Constraining top quark effective theory in the LHC Run II era

The TopFitter Collaboration

Andy Buckley, Christoph Englert, James Ferrando, David J. Miller, Liam Moore, Michael Russell, and Chris D. White

SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom

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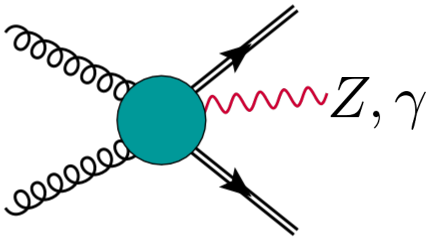

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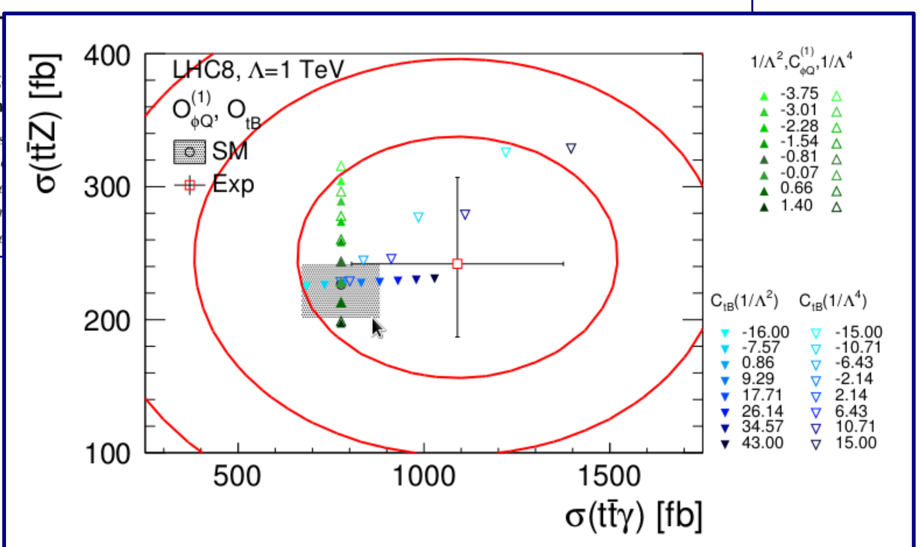

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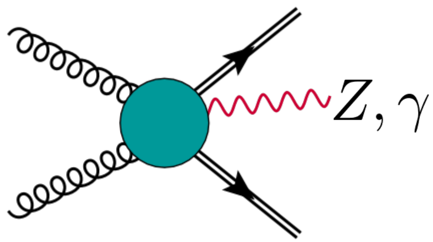

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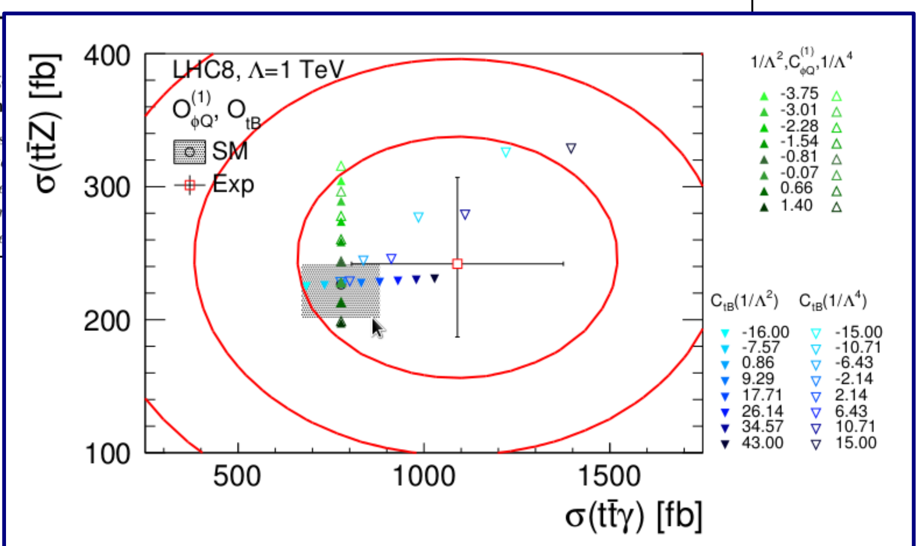
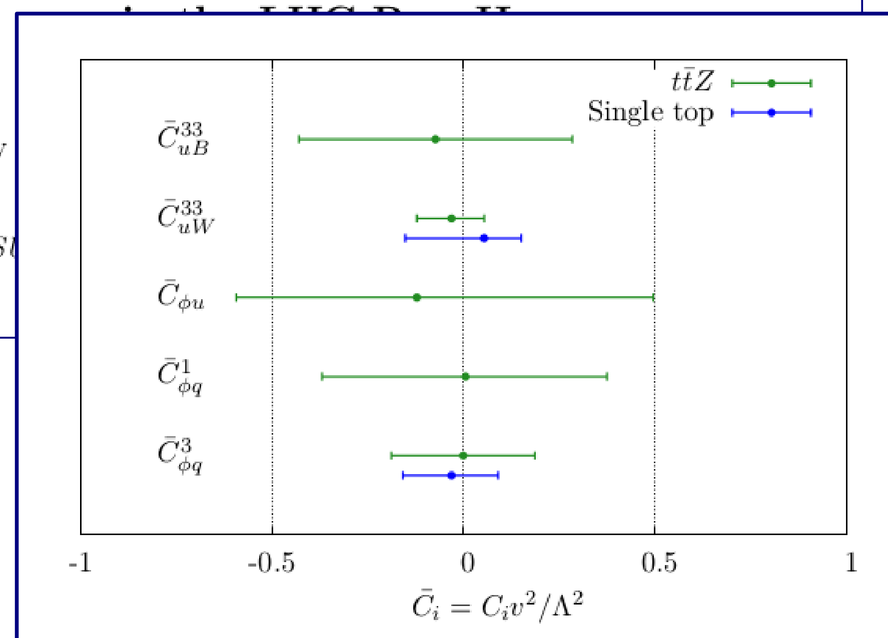


[2016]

Constraining top quark effective theory

Andy



Associated production: *ttbar+Z/γ*

NLO differential distributions to constrain couplings:

Probing top-Z dipole moments at the LHC and ILC

Raoul Röntsch

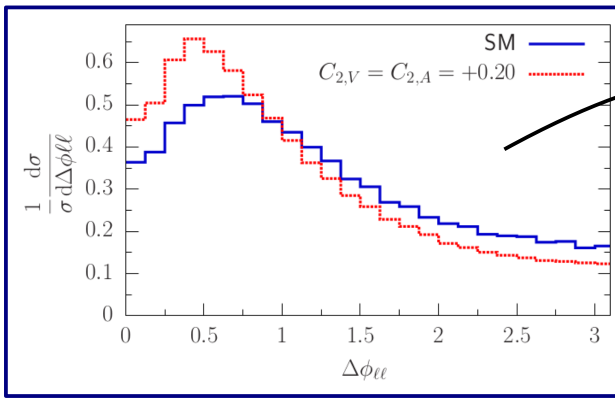
Fermilab, Batavia, IL 60510, USA

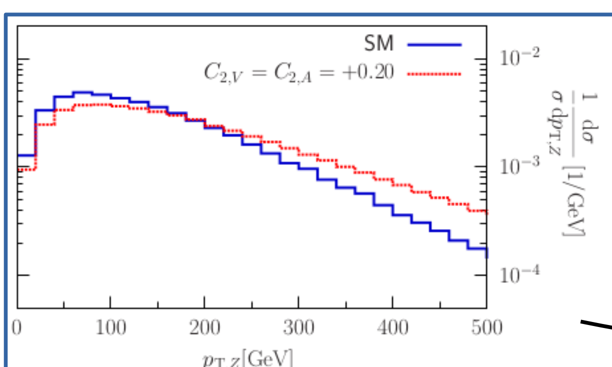
Email: rontsch@fnal.gov

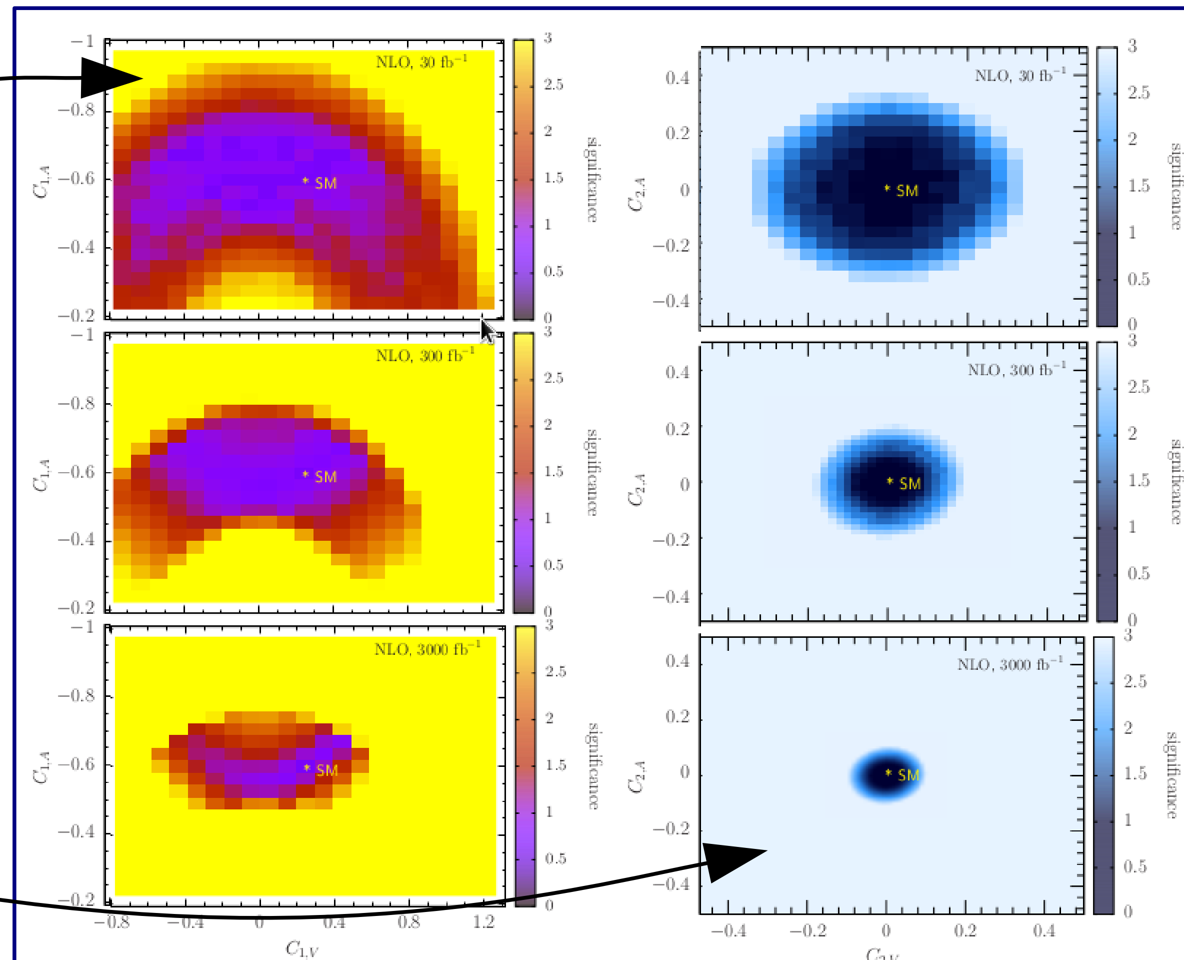
Markus Schulze

PH Department, TH Unit, CERN, 1211 Geneva 23, Switzerland

[2015]







Associated production: *ttbar+Z/γ*

[2016]

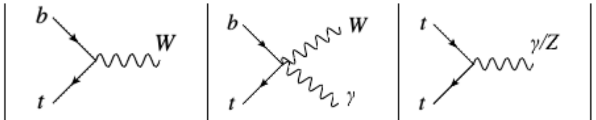
Pinning down electroweak dipole operators of the top quark

Markus Schulze[1,*] and Yotam Soreq[2,†]

[1] *CERN Theory Division, 1211 Geneva 23, Switzerland.*

[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*

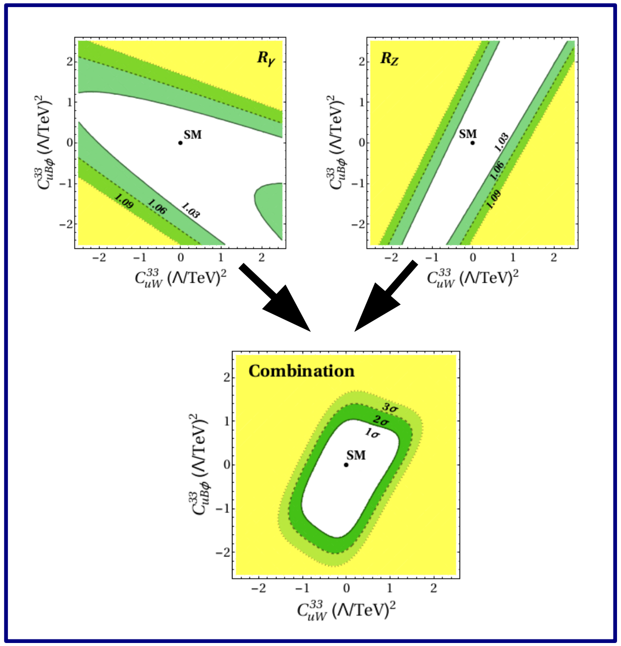
Include all correlations:
(at LO)



	$b\,t \to W$	$b\,t \to W\gamma$	$t\,t \to \gamma/Z$
C^{33}_{uW}	$\otimes$	$\otimes$	$\otimes$
C^{33}_{dW}	$\otimes$	$\otimes$	
$C^{33}_{uB\phi}$			$\otimes$

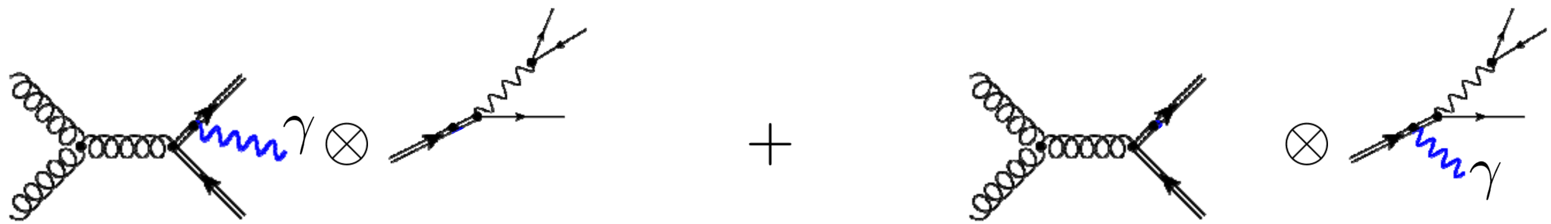
Cross section ratios to boost sensitivity:

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



Associated production: *ttbar+γ*

- Feature: $t\bar{t}+\gamma$ introduces additional *radiative decays*



A) γ emission *before* top goes on-shell

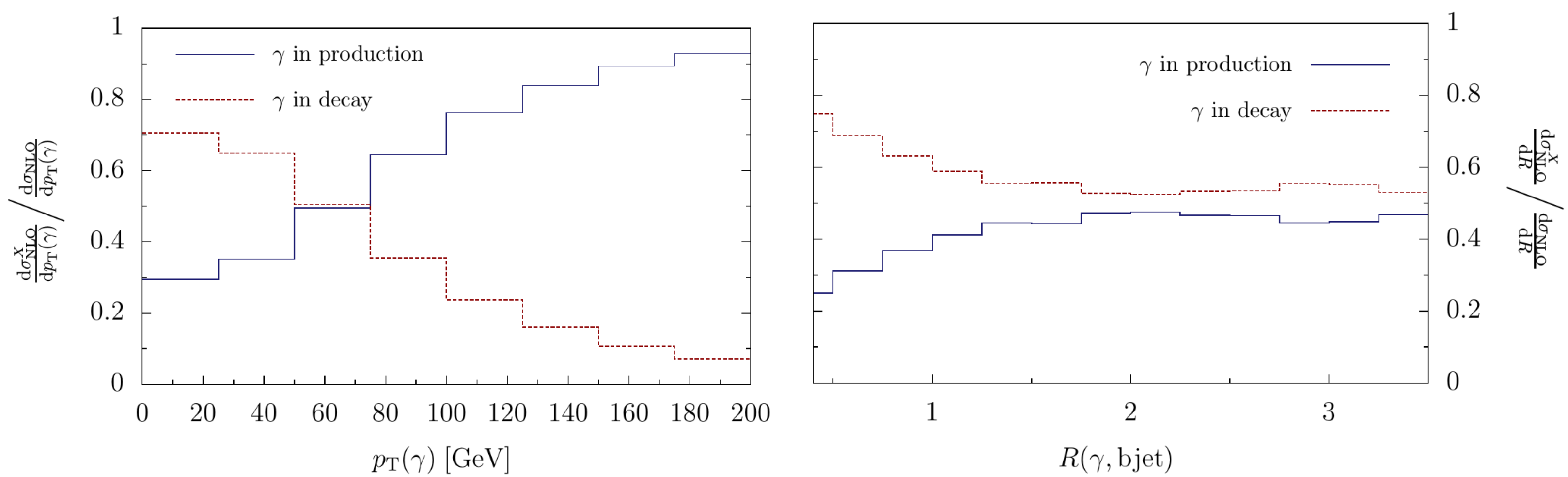
B) γ emission *after* top goes on-shell

- More than half of the total cross section from contribution *B)*

$p_T^\gamma \geq 30\,\mathrm{GeV}$

$$\sigma^{\mathrm{NLO}}_{\mathrm{prod}} = 61\,\mathrm{fb}$$
$$\sigma^{\mathrm{NLO}}_{\mathrm{decay}} = 77\,\mathrm{fb}$$

$$\sigma^{\mathrm{NLO}}_{\mathrm{total}} = 138\,\mathrm{fb}$$

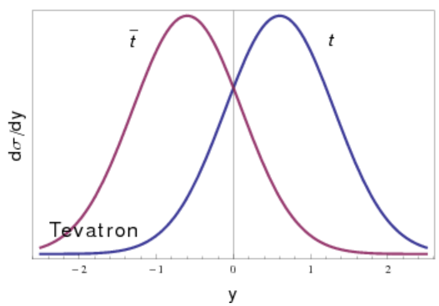


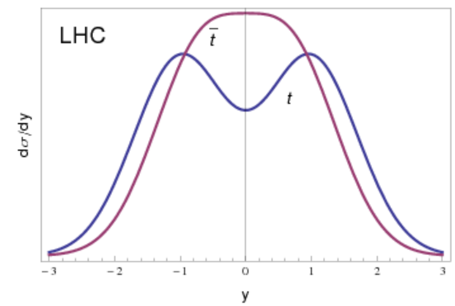
- Dominant decay contribution does not arise from collinearly enhanced photons!

Associated production: *ttbar+γ*

- Feature: $t\bar{t}+\gamma$ has a large *asymmetry*

$$A^{\rm FB}_{t\bar{t}} = \begin{cases} 0\% & \text{LO}, \\ +6\% & \text{NLO}, \\ +7\% & \text{NNLO}, \end{cases}$$





$$A^{\rm C}_{t\bar{t}} = \begin{cases} 0\% & \text{LO}, \\ +0.7\% & \text{NLO}, \\ +0.8\% & \text{NNLO}, \end{cases}$$

In contrast $t\bar{t}+\gamma$ has a non-zero asymmetry *already one order lower*

$$A^{\rm FB}_{t\bar{t}\gamma} = \begin{cases} -17\% & \text{LO}, \\ -11\% & \text{NLO} \end{cases} \qquad A^{\rm C}_{t\bar{t}\gamma} = \begin{cases} -4\% & \text{LO}, \\ ??\% & \text{NLO} \end{cases}$$

(+6% shift from LO $\longrightarrow$ NLO can be understood and is generic) [Melnikov,Schulze, 2010]

- Asymmetry in $t\bar{t}+\gamma$ is strongly dependent on various dynamics:
  - *gg* vs. *qqbar* production
  - photon emission in *production* vs. *decay*
  - anomalous couplings

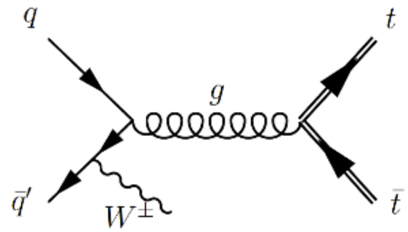
[2014]

Shedding ***light*** on the $t\bar{t}$ asymmetry: the photon handle

J. A. Aguilar–Saavedra[a], E. Álvarez[b], A. Juste[c,d], F. Rubbo[d]
[a] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*
[b] *CONICET, IFIBA Universidad de Buenos Aires, 1428 Buenos Aires, Argentina*
[c] *Institució Catalana de Recerca i Estudis Avançats (ICREA), E-08010 Barcelona, Spain*
[d] *Institut de Física d'Altes Energies (IFAE), E-08193 Bellaterra, Barcelona, Spain*

Associated production: *ttbar+W*

Note: *ttb+W* no gluon-induced channel. *W* does not couple to top quark line



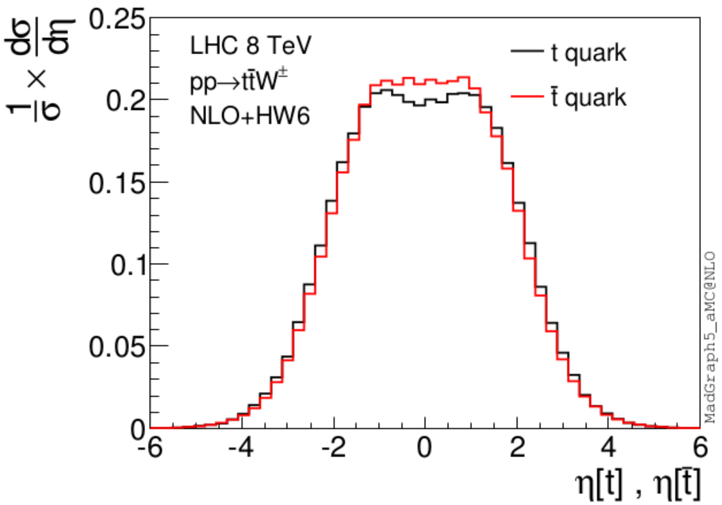
Top-quark charge asymmetry and polarization in $t\bar{t}W^{\pm}$ production at the LHC

F. Maltoni[a], M. L. Mangano[b], I. Tsinikos[a], M. Zaro[c,d]

[a] *Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain*
[b] *CERN, PH-TH, Geneva, Switzerland*
[c] *Sorbonne Universités, UPMC Univ. Paris 06, UMR 7589, LPTHE, F-75005, Paris, France*
[d] *CNRS, UMR 7589, LPTHE, F-75005, Paris, France*

[2014]

	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	$2.37^{+0.56}_{-0.38}$	$2.51^{+0.62}_{-0.42}$	$1.90^{+0.51}_{-0.35}$



Cross talk with Flavor-physics

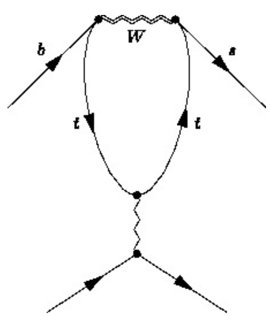
- Constraint on $t\bar{t}Z$ vec./axial couplings from $B_s \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$

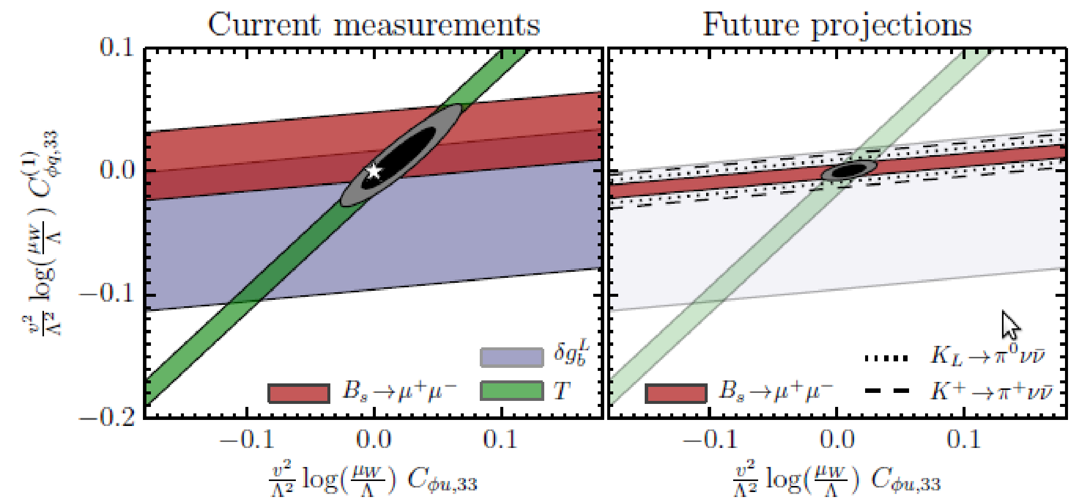
Journal of High Energy Physics
February 2015, 2015:141

Probing anomalous $t\bar{t}Z$ interactions with rare meson decays

Authors | Authors and affiliations

Joachim Brod, Admir Greljo, Emmanuel Stamou, Patipan Uttayarat

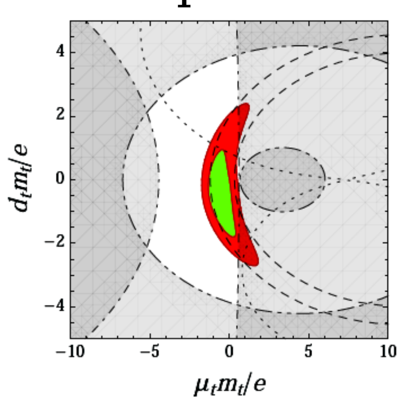




Order of magnitute stronger bounds than direct reach with 3000/fb!

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

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



Constraining the dipole moments of the top quark

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[2] Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia
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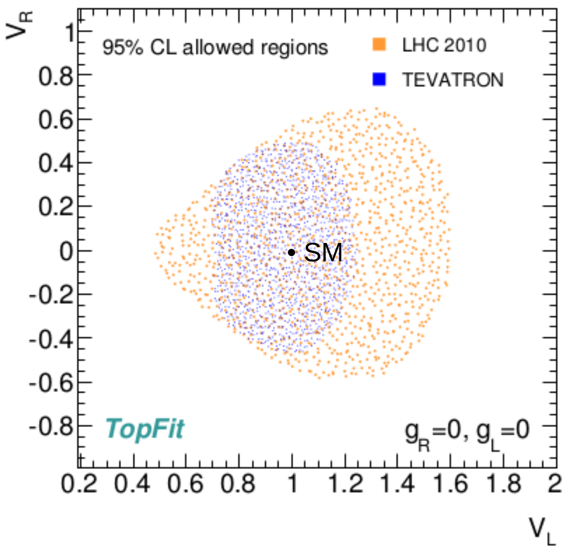
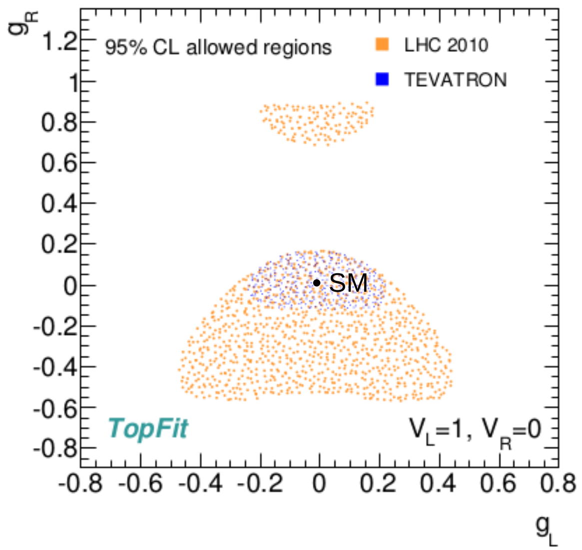
[5] DESY, Notkestrasse 85, D-22607 Hamburg, Germany

Thank you for your attention!

[Aguilar-Saavedra,Castro,Onofre]

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





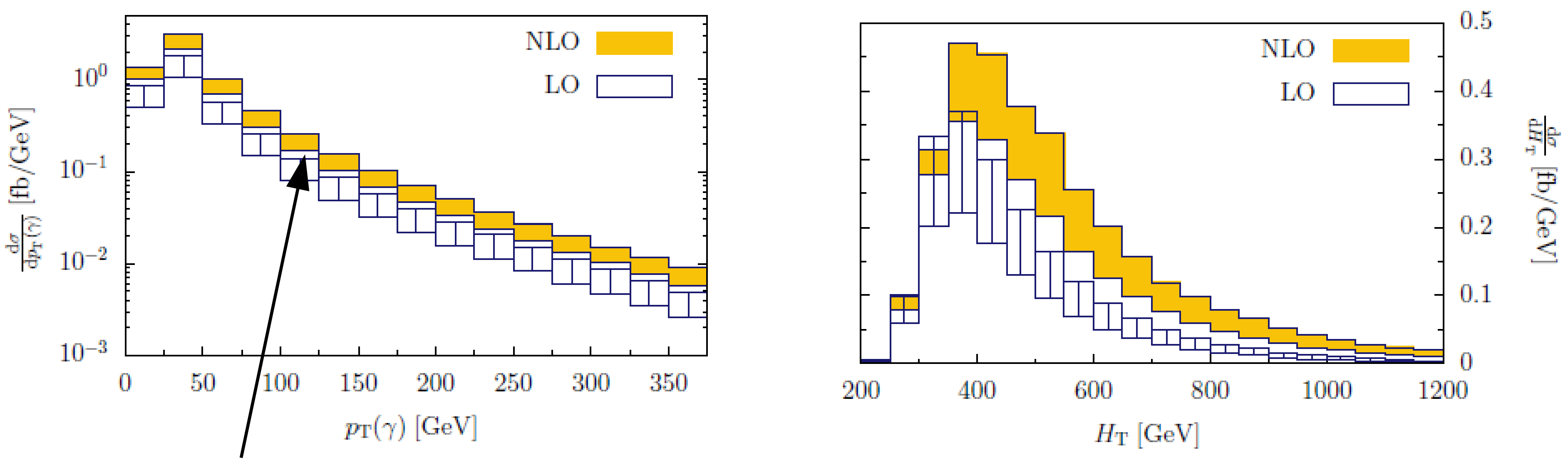
NLO QCD $t\bar{t}+\gamma$ at the 14 TeV LHC

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

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

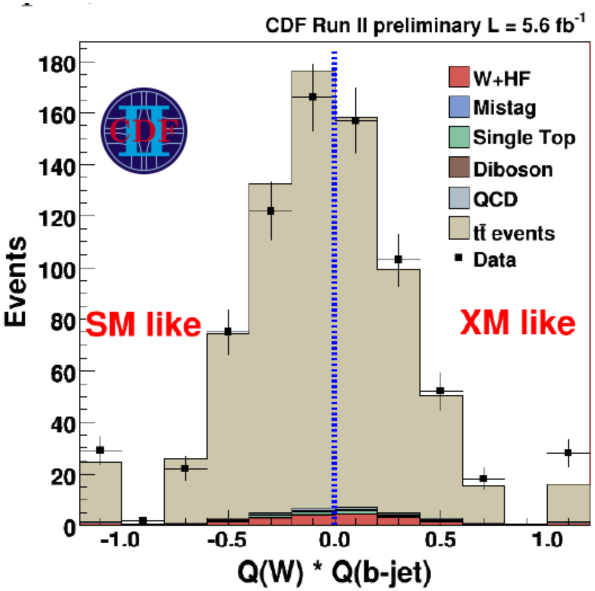
$$|y_b| < 2.0,\quad |y_j| < 2.5,\quad |y_\ell| < 2.5.$$ Smooth-cone photon isolation [Frixione]

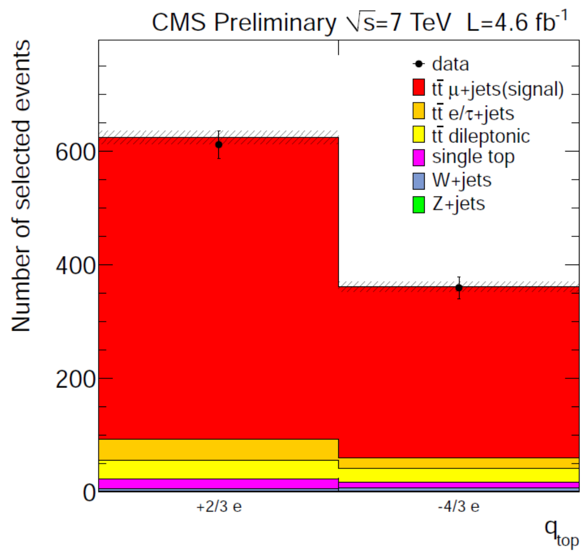
$$\sigma_{\text{LO}} = 74.50^{+23.98}_{-16.89}\ \text{fb},\quad \sigma_{\text{NLO}} = 138^{+30}_{-23}\ \text{fb}.$$

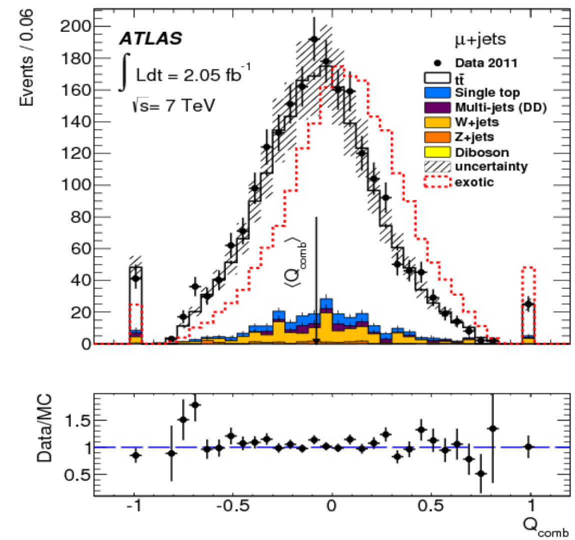


More than 500 events with $p_{T\gamma}$>100 GeV from 100 fb^{-1}

Current Q_t determination







1) Identify W-boson charge through lepton charge

2) Pair W-boson with correct b-jet

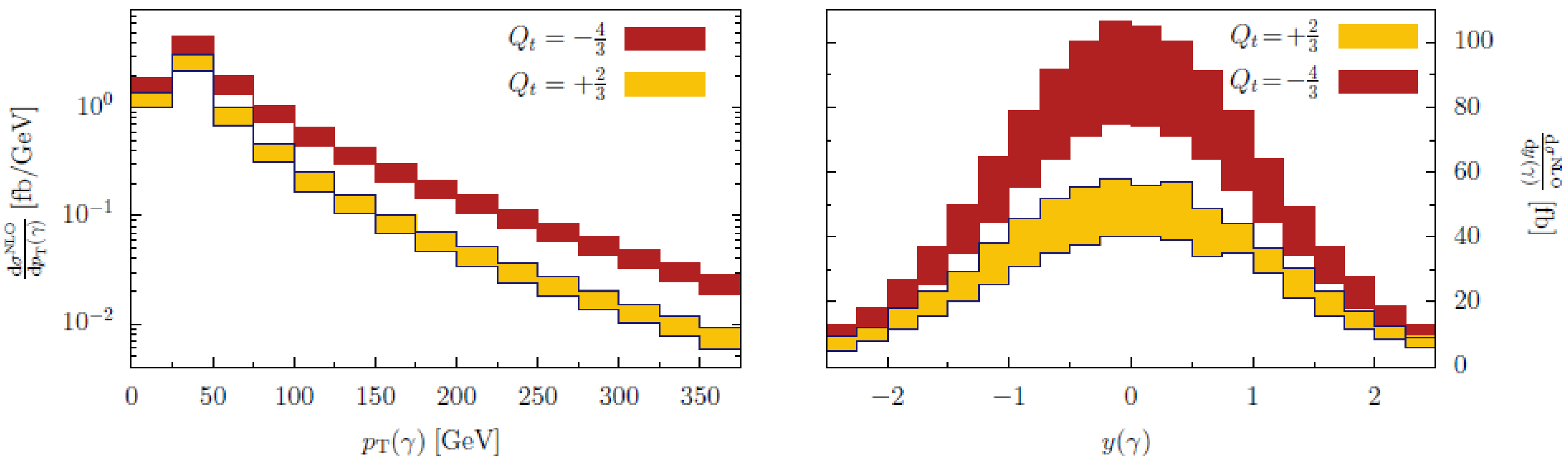
3) Measure b-jet charge

→ Exotic top quark charge is excluded at 8+ sigma

→ No sensitivity to EDM and MDM from these experiments

Sensitivity to Q_t at the LHC

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



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

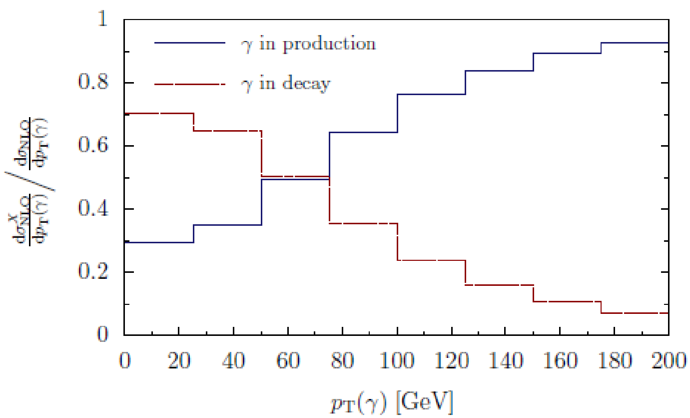
- Naive expectation of Q_t^2 scaling fails:

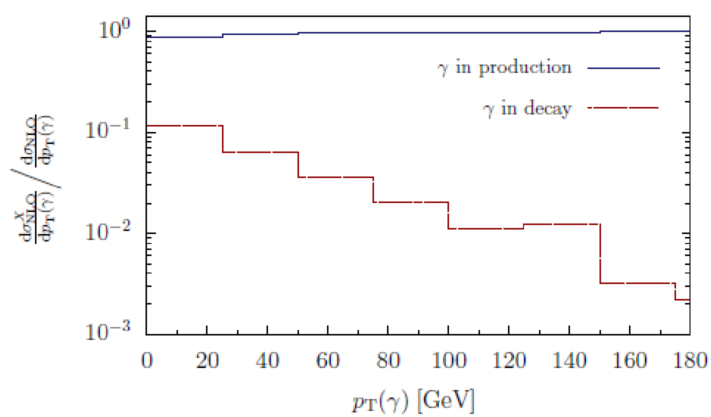
$$\mathcal{R}^{NLO} = \frac{\sigma^{Q_t=-4/3}_{NLO}}{\sigma^{Q_t=2/3}_{NLO}} = 1.76^{+0.01}_{-0.02}.$$

Sensitivity to Q_t at the LHC

- Apply cuts to suppress radiative top quark decays

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





Sensitivity to Q_t at the LHC

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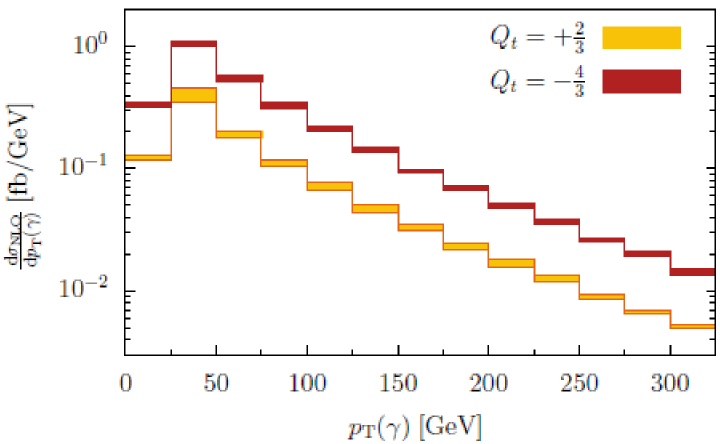
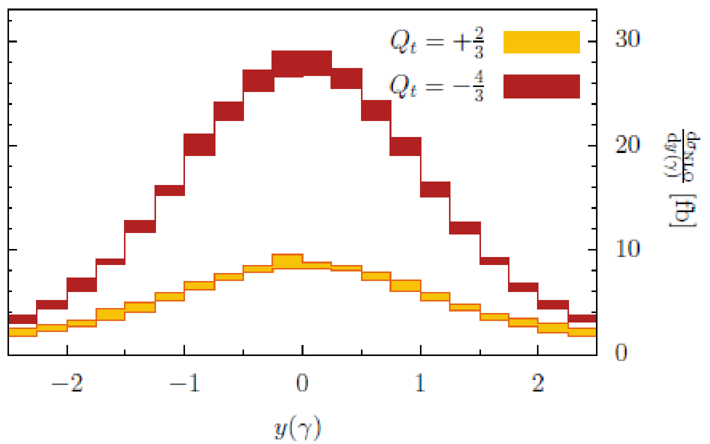




→ Significantly stronger separation power:

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

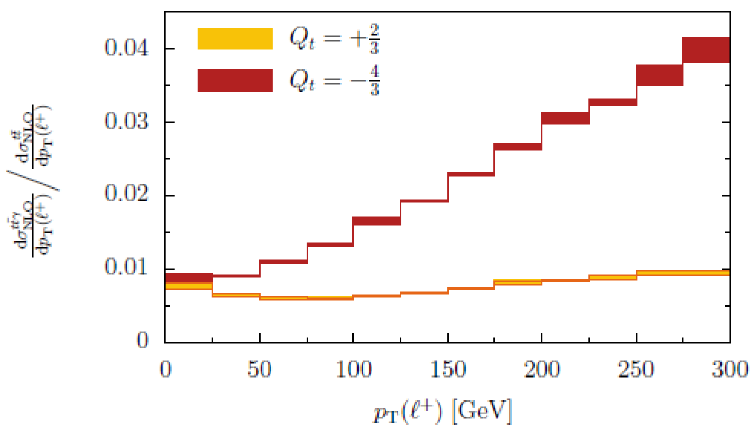
But total cross section is reduced by x5.

Sensitivity to Q_t from cross section ratios

- Normalizing to ttbar cross section cancels many 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 kinematic distributions show good shape sensitivity

Forward-Backward Asymmetry

(Tevatron)

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$A^{t\bar{t}}_{\rm LO} = 0\%$ $\xrightarrow{+5\%}$ $A^{t\bar{t}}_{\rm NLO} = +5\%$ [Kühn,Rodrigo]

$A^{t\bar{t}+{\rm jet}}_{\rm LO} = -8\%$ $\xrightarrow{+6\%}$ $A^{t\bar{t}+{\rm jet}}_{\rm NLO} = -2\%$ [Dittmaier,Weinzierl,Uwer] [Melnikov,Schulze]

$A^{t\bar{t}+\gamma}_{\rm LO} = -17\%$ $\xrightarrow{+6\%}$ $A^{t\bar{t}+\gamma}_{\rm NLO} = -11\%$ [Duan,Ma,Zhang,Han,Guo,Wang] [Melnikov,Scharf,Schulze]

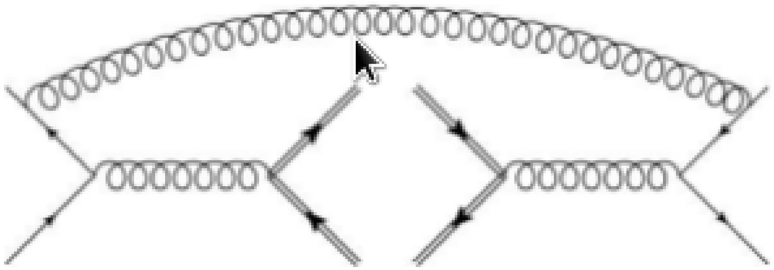
$A^{t\bar{t}+2{\rm jet}}_{\rm LO} = -10\%$ $\xrightarrow{+5\%}$ $A^{t\bar{t}+2{\rm jet}}_{\rm NLO} = -5\%$ [Bevilacqua,Czakon,Papadopoulos,Worek]

Forward-Backward Asymmetry
(Tevatron)

Is it possible to understand this seemingly universal shift of +5% ?

[Melnikov,M.S.]

LO QCD:



$$\sigma_+ - \sigma_- \sim \log(m_t/p_T^{\rm jet})\,\sigma_A$$ soft singularity

$$\sigma_+ + \sigma_- \sim 2C_F\frac{\alpha_s}{\pi}\,\log^2(m_t/p_T^{\rm jet})\,\sigma_{t\bar{t}}$$ soft-coll. double log

$$\Rightarrow \quad A_{\rm LO}^{t\bar{t}+{\rm jet}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \sim \log^{-1}(m_t/p_T^{\rm jet})$$

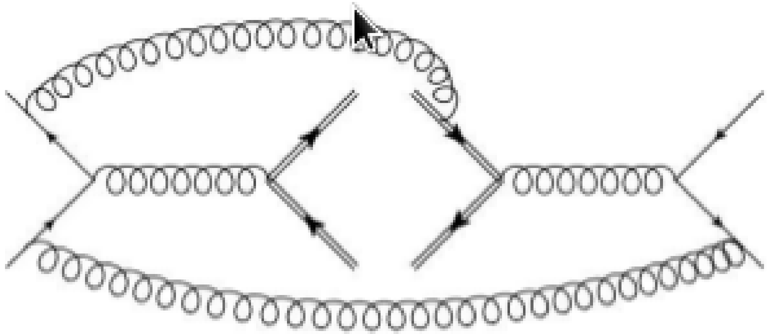
Forward-Backward Asymmetry

(Tevatron)

Is it possible to understand this seemingly universal shift of +5% ?

[Melnikov,M.S.]

NLO QCD:



$$\sigma_+ - \sigma_- \sim 2C_{\rm F}\,\frac{\alpha_s}{\pi}\,\log^2(m_t/p_{\rm T}^{\rm jet})\,A_{\rm NLO}^{t\bar t}\,\sigma_{t\bar t}$$

double log enhanced

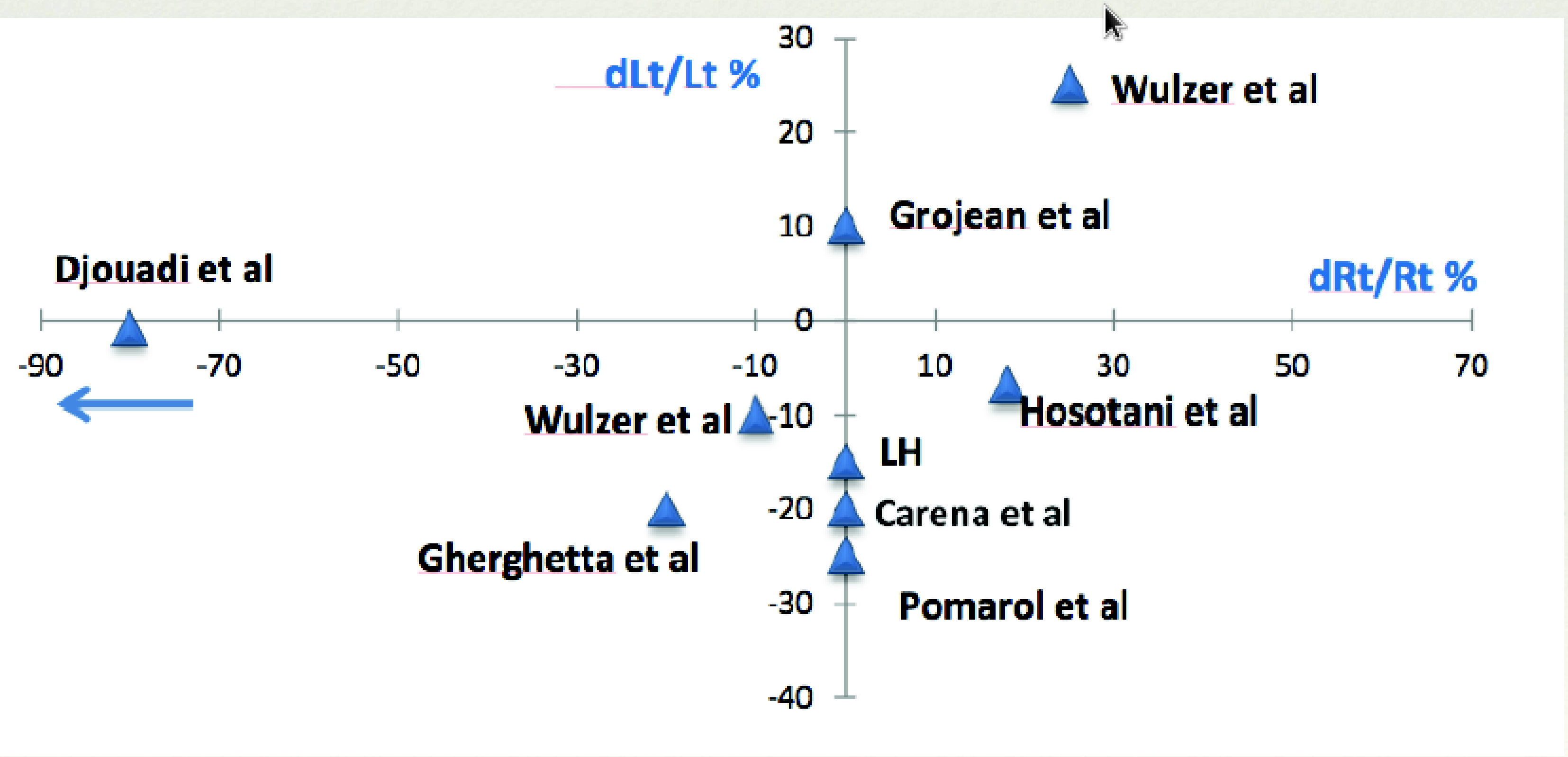
$$A_{\rm NLO}^{t\bar t+{\rm jet}} = A_{\rm LO}^{t\bar t+{\rm jet}} + A_{\rm NLO}^{t\bar t}$$

with $A_{\rm NLO}^{t\bar t} = +5\%$

and $\lim_{p_{\rm T}^{\rm jet}\to 0} A_{\rm NLO}^{t\bar t+{\rm jet}} = A_{\rm NLO}^{t\bar t}$

...e Higgs models, ...

[Richard, 2014]



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

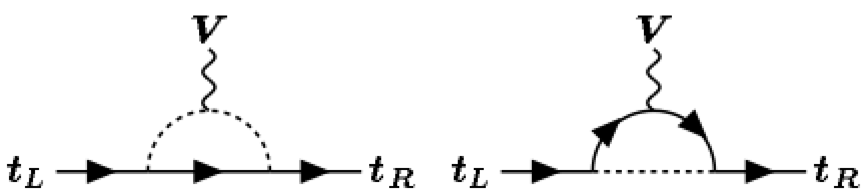
$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S} \qquad \mathcal{L}_{\rm tg} = -g_s\bar{t}\gamma^\mu\frac{\lambda_a}{2}t\,G^a_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + id_A\gamma_5)\frac{\lambda_a}{2}t\,G^a_{\mu\nu}\,,$$

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

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



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

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