# From Tevatron's top and lepton-based asymmetries to the LHC

Adrián Carmona[1], Mikael Chala[2], Adam Falkowski[3], Sara Khatibi[4], Mojtaba Mohammadi Najafabadi[4], Gilad Perez[5], José Santiago[2]

[1] *Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*
[2] *CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*
[3] *Laboratoire de Physique Théorique, CNRS – UMR 8627, Université de Paris-Sud 11, F-91405 Orsay Cedex, France*
[4] *School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[5] *PH-TH Department, CERN, CH-1211 Geneva 23, Switzerland*

### Abstract

We define a lepton-based asymmetry in semi-leptonic $t\bar{t}$ production at the LHC. We show that the ratio of this lepton-based asymmetry and the $t\bar{t}$ charge asymmetry, measured as a function of the lepton transverse momentum or the $t\bar{t}$ invariant mass is a robust observable in the Standard Model. It is stable against higher order corrections and mis-modeling effects. We show that this ratio can also be a powerful discriminant among different new physics models and between them and the Standard Model.

## 1 Charge and lepton-based asymmetries in the SM

The top is unique among the known elementary fermions, it has several properties making it an object worth studying. Studying top physics is expected to shed light about the mechanism of electroweak scale stabilization. It transforms top physics into a window for new physics searches with a rough scale associated to them that is expected to be within the LHC reach. Not all precision top observables provide a direct link with the physics of naturalness. An example for such an observable is the top pair forward-backward asymmetry. In this paper we consider a set of $t\bar{t}$ asymmetries, where our starting point is related to the Tevatron anomalous forward–backward asymmetry. Within the SM, the $t\bar{t}$ forward–backward asymmetry, $A_{t\bar{t}}$, is an interesting variable because it tells us about QCD interactions beyond leading order but in a region that should be well described by perturbation theory. Furthermore, as the SM contributions are expected to be, the measurement of $A_{t\bar{t}}$ is sensitive to beyond-the-SM (BSM) contributions. As mentioned, the asymmetry is quite of a special observable since shifting it requires new physics with non-standard couplings both to the $t\bar{t}$ quark current as well as to the current of $u\bar{u}$ (or possibly $d\bar{d}$) initial-state quarks. Both Tevatron experiments, CDF and DØ, have observed an anomalously large forward-backward asymmetry in $t\bar{t}$ production, defined by

$$A_{t\bar{t}} = \frac{N(\Delta y^{t\bar{t}} > 0) - N(\Delta y^{t\bar{t}} < 0)}{N(\Delta y^{t\bar{t}} > 0) + N(\Delta y^{t\bar{t}} < 0)}, \tag{1}$$

where $\Delta y^{t\bar{t}} \equiv y_t - y_{\bar{t}}$ and $N$ is the total number of events satisfying the corresponding constraint. This asymmetry has been measured in semi-leptonic decays with the following result[2]: $A_{t\bar{t}}(\mathrm{CDF}) = 0.164 \pm 0.047$, $A_{t\bar{t}}(\mathrm{DØ}) = 0.196 \pm 0.065$, to be compared with the SM NLO prediction with electroweak corrections included [3], $0.088 \pm 0.006$. A puzzling aspect of the observed excess is that the large value of the measured asymmetries are not accompanied by any sizable deviation in other top observables, such as the total or differential $t\bar{t}$ production cross sections. This strongly constrains possible explanations of the anomalous forward-backward asymmetry. In [4] it was shown that the study of the correlation of $A_{t\bar{t}}$ with a lepton-based asymmetry $A_\ell$, measured as a function of some kinematical variable, such as the lepton $p_T$ can be a powerful discriminating observable from the following three reasons: The *first* is that the lepton-based asymmetry is simpler to measure just because of the fact that the lepton momenta are measured directly and the relevant corrections due to detector effects are rather small. The *second* is that within the SM the correlation between the $t\bar{t}$ forward–backward asymmetry $A_{t\bar{t}}$ and the corresponding lepton-based asymmetry $A_\ell$ – at the differential level – is strong and rather clean theoretically. In [4] the robustness of this correlation was successfully tested given various deformation of the SM distributions, namely scale dependence, the transverse momentum of the $t\bar{t}$ system and higher order effects in the decay and showering. The *third* is that beyond the SM this correlation is generically lost. The lepton asymmetry is sensitive to different aspects of the interaction depending on the kinematical regime.

The LHC cannot generate a forward-backward asymmetry in $t\bar{t}$ production because the $pp$ initial state is symmetric. However, the different parton distribution functions of quarks and anti-quarks inside the proton make it possible for he top and anti-top rapidity distributions to be different. Therefore one can define a non-vanishing charge asymmetry,

$$A_C^{t\bar{t}} = \frac{N(\Delta|y|^{t\bar{t}} > 0) - N(\Delta|y|^{t\bar{t}} < 0)}{N(\Delta|y|^{t\bar{t}} > 0) + N(\Delta|y|^{t\bar{t}} < 0)}, \tag{2}$$

where $\Delta|y|^{t\bar{t}} \equiv |y_t| - |y_{\bar{t}}|$. Due to the dominant symmetric contribution from initial state gluons the SM predicts a small charge asymmetry, $A_C^{t\bar{t}}(\mathrm{SM}) = 0.0123 \pm 0.0005$ for $\sqrt{s} = 7$ TeV LHC and $A_C^{t\bar{t}}(\mathrm{SM}) = 0.0111 \pm 0.0004$ for $\sqrt{s} = 8$ TeV LHC [3]. In the semi-leptonic channel ATLAS and CMS find the following (unfolded) values [5]: $A_C^{t\bar{t}}(\mathrm{CMS}, 7) = 0.004 \pm 0.010 \pm 0.011$, $A_C^{t\bar{t}}(\mathrm{CMS}, 8) = 0.005 \pm 0.007 \pm 0.006$.

Our goal is to define a new lepton-based asymmetry in semi-leptonic $t\bar{t}$ events that maintains the interesting properties of the lepton-based asymmetries at the Tevatron, namely a unique and robust discriminating power when correlated with the charge asymmetry as a function of $p_{T,\ell}$ or $m_{t\bar{t}}$. The following lepton-based asymmetry fulfills the requirements:

$$A_C^{t\ell} = \frac{N(\Delta|y|^{tl} > 0) - N(\Delta|y|^{tl} < 0)}{N(\Delta|y|^{tl} > 0) + N(\Delta|y|^{tl} < 0)}, \tag{3}$$

where we define

$$\Delta|y|^{tl} \equiv \begin{cases} |y_{l^+}| - |y_{\bar{t}}|, & \text{for leptonic top decays} \\ |y_t| - |y_{l^-}|, & \text{for leptonic anti-top decays.} \end{cases} \tag{4}$$

It is clear that at large $p_{T,\ell}$ or $m_{t\bar{t}}$ the lepton will inherit the top properties it decayed from and this asymmetry will approach $A_C^{t\bar{t}}$. At smaller values, however, it will become sensitive to other features like the polarization of the initial quarks and can therefore show deviations between the SM and new physics models. We are going to describe the behavior of the asymmetries defined above, $A_C^{t\bar{t}}$ and $A_C^{t\ell}$, as a function of $p_{T,\ell}$ and $m_{t\bar{t}}$ in the SM. We will focus on the $\sqrt{s} = 8$ TeV LHC run. We have generated our SM $t\bar{t}$ events using the next-to-leading order (NLO) event generator POWHEG [6], with the CT10 [7] parton distribution functions and with the renormalization and factorization scales set to $\mu_R = \mu_F = Q = \sqrt{m_t^2 + (p_{T,t})^2}$. We show in Fig. 1 the corresponding distributions for $A_C^{t\bar{t}}$ (red solid) and $A_C^{t\ell}$ (blue dashed) as a function of $p_{T,\ell}$ and $m_{t\bar{t}}$ in the left and right panels, respectively, in the SM with no cuts applied. We now proceed to investigate the robustness of the ratio of these asymmetries. As a first check we will test the dependence of the ratio on the renormalization and factorization scales. We show in Fig. 2, the $p_{T,\ell}$ and $m_{t\bar{t}}$ distributions of the $A_C^{t\ell}/A_C^{t\bar{t}}$ ratio for the three different choices of the renormalization and factorization scales $Q^2 = Q_0^2$, $Q^2 = 4 \times Q_0^2$ and $Q^2 = 0.25 \times Q_0^2$ where $Q_0^2 = m_t^2 + (p_{T,t})^2$. $A_C^{t\bar{t}}$ depends on the transverse momentum of the $t\bar{t}$ system, $p_{T,t\bar{t}}$, so as second check we show the $A_C^{t\ell}/A_C^{t\bar{t}}$ ratio as a function of $p_{T,\ell}$ and $m_{t\bar{t}}$ in two different $p_{T,t\bar{t}}$ regimes: $p_{T,t\bar{t}} < 20$ GeV and $p_{T,t\bar{t}} > 20$ GeV, together with the inclusive result. We see that the ratio is robust against the value of the $p_T$ of the $t\bar{t}$ system (Fig. 2).

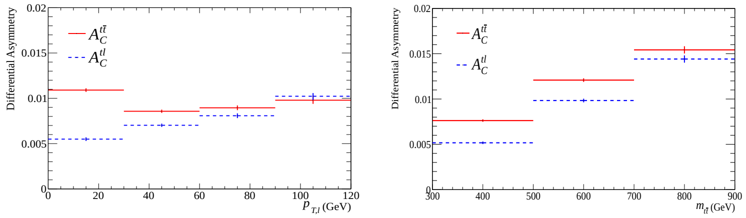

Figure 1: Charge and lepton-based asymmetry dependence on $p_{T,\ell}$ (left panel) and $m_{t\bar{t}}$ (right panel) in the SM with no cuts applied.

## 2 Top versus Lepton Asymmetry beyond the SM

The ratio of differential asymmetries is also a powerful discriminant between the SM and new physics models explaining the Tevatron anomaly. The reason is that, in the SM, the lepton-based asymmetry is inherited from the top asymmetry: the direction of the lepton in semi-leptonic top decays is correlated with the direction of the decaying top. Beyond the SM, however, $A_C^{t\ell}$ becomes independent of $A_C^{t\bar{t}}$ because polarization effects in the $t\bar{t}$ production may affect these two in a completely different way. This suggests we can use the *shape* of $A_C^{t\ell}/A_C^{t\bar{t}}$ as function of $m_{t\bar{t}}$ or $p_{T,\ell}$ to differentiate between the SM and BSM interpretations of the measured asymmetries. To design our benchmarks we have taken into account the following constraints:

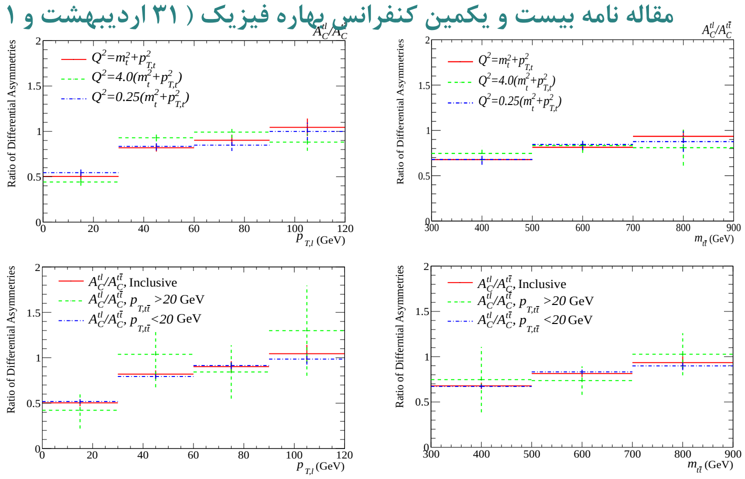

Figure 2: Distribution of the $A_C^{t\ell}/A_C^{t\bar t}$ ratio as a function of $p_{T,\ell}$ (left) and $m_{t\bar t}$ (right) for three different choices of the renormalization and factorization scale (top) and for two different values of the $t\bar t$ system transverse momentum (bottom) in the SM with no cuts applied.

1. The Tevatron combination of the $t\bar t$ inclusive cross section [8]: $\sigma_{t\bar t}^{\text{TeV}} = (7.62 \pm 0.42)$ pb, where the SM next-to-next-to-leading order (NNLO) prediction is $\sigma_{t\bar t,\,\text{SM}}^{\text{TeV}} = 7.16^{+0.20}_{-0.23}$ pb [9].
2. The last bin of the CDF and DØ differential $t\bar t$ cross section measurement as a function of $m_{t\bar t}$ [10]:
$$\textbf{CDF}: \quad \int_{0.8\text{TeV}}^{1.4\text{TeV}} \frac{d\sigma_{t\bar t}^{\text{TeV}}}{dm_{t\bar t}} = (0.041 \pm 0.21)\ \text{pb}, \textbf{DØ}: \quad \int_{0.75\text{TeV}}^{1.2\text{TeV}} \frac{d\sigma_{t\bar t}^{\text{TeV}}}{dm_{t\bar t}} = 0.067^{+0.052}_{-0.050}\ \text{pb}, \tag{5}$$
where the SM prediction is quoted as $\int_{0.8\text{TeV}}^{1.4\text{TeV}} \frac{d\sigma_{t\bar t,\text{SM}}^{\text{TeV}}}{dm_{t\bar t}} \approx 0.03$ pb, and $\int_{0.75\text{TeV}}^{1.2\text{TeV}} \frac{d\sigma_{t\bar t,\text{SM}}^{\text{TeV}}}{dm_{t\bar t}} \approx 0.06$ pb.
3. The 95% CL limit on the $t\bar t$ cross section at the high $m_{t\bar t}$ tail at CMS [11]:
$$\frac{\int_{1\text{TeV}}^{8\text{TeV}} \Delta \frac{d\sigma_{t\bar t}^{\text{TeV}}}{dm_{t\bar t}}}{\int_{1\text{TeV}}^{8\text{TeV}} \Delta \frac{d\sigma_{t\bar t,\text{SM}}^{\text{TeV}}}{dm_{t\bar t}}} < 1.2\ . \tag{6}$$

One class of BSM models generating the top forward–backward asymmetry at tree-level contains a color-octet vector boson $G_\mu^a$ (the so-called *axigluon*) with non-zero mass $m_G$ and chiral couplings. The axigluon couplings to the SM quarks are assumed to be flavor diagonal but otherwise arbitrary:

$$\mathcal{L} \supset g_{L,i}\, \bar q_i\, \gamma^\mu\, G_\mu^a\, T^a P_L\, q_i \;+\; g_{R,i}\, \bar q_i\, \gamma^\mu\, G_\mu^a\, T^a\, P_R\, q_i\,, \tag{7}$$

where $q_i$ are the SM quarks fields, and $P_{L,R}$ are the projection operators into left- and right-handed spinors. In this model the top pair production amplitude $q\bar q \to t\bar t$ receives a contribution from the axigluon in the s-channel which interferes with the SM gluon exchange. First, we choose three benchmarks with a light axigluon:

$$\begin{aligned} &\textbf{Axi200R}: && m_G = 200\ \text{GeV}, && \Gamma_G = 50\ \text{GeV}, && g_{R,i} = 0.5 g_s, && g_{L,i} = 0; \\ &\textbf{Axi200L}: && m_G = 200\ \text{GeV}, && \Gamma_G = 50\ \text{GeV}, && g_{R,i} = 0, && g_{L,i} = 0.5 g_s; \\ &\textbf{Axi200A}: && m_G = 200\ \text{GeV}, && \Gamma_G = 50\ \text{GeV}, && g_{R,i} = 0.4 g_s, && g_{L,i} = -0.4 g_s, \end{aligned} \tag{8}$$

where $g_s$ is the strong coupling.

We also choose 2 benchmarks with a heavy axigluon:

$$\begin{aligned} &\textbf{Axi2000A}: && m_G = 2\ \text{TeV}, && \Gamma_G = 0.96\ \text{TeV}, && g_{R,u} = -g_{L,q_1} = -0.6 g_s, && g_{R,t} = -g_{L,t} = 4 g_s; \\ &\textbf{Axi2000R}: && m_G = 2\ \text{TeV}, && \Gamma_G = 1.0\ \text{TeV}, && g_{R,u} = -0.8 g_s, \quad g_{R,t} = 6 g_s, && g_{L,i} = 0. \end{aligned} \tag{9}$$

Finally, we consider a different model with a complex gauge boson $Z'_\mu$ coupled to right-handed up-type quarks in a flavor-violating way,

$$\mathcal{L} \supset g_{Z'} Z'_\mu \bar t_R \gamma^\mu u_R + \text{h.c.}. \tag{10}$$

We choose the benchmark point as **Zp220** : $m_{Z'} = 220$ GeV, $g_{Z'} = 0.7$, $\Gamma_G = 2.9$ GeV. The mass and the coupling are chosen such that a sizable Tevatron top asymmetry is generated. However at the LHC the asymmetry approximately cancels between $u\bar{u} \to t\bar{t}$ (contributing with a positive sign) and $gu \to tZ' \to t\bar{t}u$ (contributing with a negative sign). As we have stressed previously, the most interesting observable is the $A_C^{t\ell}/A_C^{t\bar{t}}$ ratio, that we show in Fig 3 as a function of $p_{T,\ell}$ (left) and $m_{t\bar{t}}$ (right). We can see that the discriminating power of this observable, previously pointed out in the context of the Tevatron asymmetry [4], survives at the LHC.

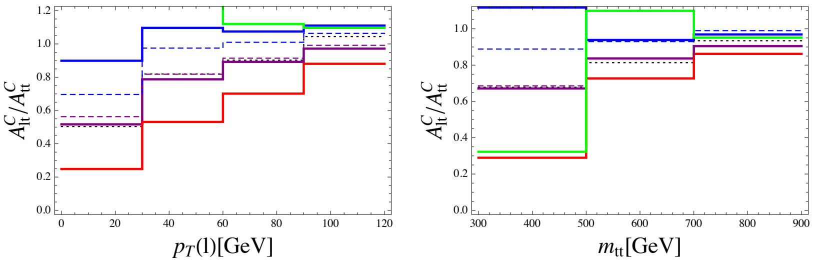

Figure 3: Distribution of the ratio $A_C^{t\ell}/A_C^{t\bar{t}}$ at the LHC as a function of $p_{T,\ell}$ (left) and $m_{t\bar{t}}$ (right) for the SM (dotted black) and for the BSM benchmarks studied in this paper: Axi200R (solid blue), Axi200L (solid red), Axi200A (solid purple), Axi2000R (dashed blue), Axi2000A (dashed purple), and Zp220 (solid green).

## 3 Conclusions

In this article we defined a new lepton-based asymmetry at the LHC and showed that the ratio of this asymmetry and the $t\bar{t}$ charge asymmetry, measured as a function of the $p_T$ of the lepton in semi-leptonic channel or the $t\bar{t}$ pair invariant mass, fulfills all the requirements of a robust observable. Furthermore, the ratio of lepton-based and $t\bar{t}$ charge asymmetries can be a powerful probe of new physics. We have considered a number of benchmark models beyond the SM that improve the agreement with current experimental data. More details of this work can be found in [1].

## References

[1] A. Carmona, M. Chala, A. Falkowski, S. Khatibi, M. M. Najafabadi, G. Perez and J. Santiago, arXiv:1401.2443 [hep-ph].

[2] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87**, 092002 (2013) [arXiv:1211.1003 [hep-ex]]; V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84**, 112005 (2011) [arXiv:1107.4995 [hep-ex]].

[3] W. Bernreuther and Z. -G. Si, Phys. Rev. D **86**, 034026 (2012) [arXiv:1205.6580 [hep-ph]].

[4] A. Falkowski, M. L. Mangano, A. Martin, G. Perez and J. Winter, Phys. Rev. D **87** (2013) 034039 [arXiv:1212.4003 [hep-ph]].

[5] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **717** (2012) 129 [arXiv:1207.0065 [hep-ex]]; CMS conference note CMS PAS TOP-12-033.

[6] S. Alioli, P. Nason, C. Oleari and E. Re, JHEP **1006**, 043 (2010) [arXiv:1002.2581 [hep-ph]].

[7] H. -L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin and C. -P. Yuan, Phys. Rev. D **82**, 074024 (2010) [arXiv:1007.2241 [hep-ph]].

[8] T. A. Aaltonen *et al.* [ CDF and D0 Collaborations], arXiv:1309.7570 [hep-ex].

[9] M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. **110** (2013) 252004 [arXiv:1303.6254 [hep-ph]].

[10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102** (2009) 222003 [arXiv:0903.2850 [hep-ex]]; DØ Conference note 6379.

[11] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1309.2030 [hep-ex].