*Spring Institute 2014: High-energy physics after LHC Run I LNF, 12-14 March 2014*

# *Improving the ttH signal at the LHC through spin-polarization effects*

*LNF, 12 March 2014*



*Barbara Mele*

 *Sezione di Roma*

## **Outline**

 **pp** ➜ **ttH role at the LHC : see Laura's talk**

- ➜ **need to model irreducible bckgrs as accurately as possible !**
- **◎ top polarization effects in** pp → tt
- **spin-correlations in tt and ttH**
- **spin correlations in irreducible bckgrs for**   $\uparrow$ **tt** $\uparrow$ γ*γ*, **ttbb**



## Enhancing the  $t\bar{t}H$  signal through top-quark spin polarization effects at the LHC

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#### **ttbb, ttγγ are bound to become the hardest bckgrs to separate from ttH (H**➜**bb,γγ)**



 $\Rightarrow$  background: normalization & shape uncertainties?

#### **Top quark spin and spin correlations**  $T$ op2013, Durbach,September 14-19 2013 Measurements of top-quark spin correlation, polarization, polarization,  $\alpha$ **Physics** K Shin ang shin carrelations is to Top-quark spin and correlation  $\mathcal{L}_\mathcal{S}$  and correlation  $\mathcal{L}_\mathcal{S}$  and correlation  $\mathcal{L}_\mathcal{S}$ **Observables** Figure 9: *Left panel: The distributions in the semileptonic decay angle* ✓` *for the tHj final* Figure 9: *Left panel: The distributions in the semileptonic decay angle* ✓` *for the tHj final state for the indicated values of* ⇣*t. In the right panel we display the variation of the forward-*Figure 9: *Left panel: The distributions in the semileptonic decay angle* ✓` *for the tHj final* <u>I op quark spin and spin correlation</u> orrelations

#### <sup>●</sup> top lifetime shorter than hadronization time me shorter than hadronization time **Q** ton lifetime shorter than hadronization time *backward asymmetry in* ✓`*, Al, with* ⇣*<sup>t</sup> for tHj (tHj* ¯ *) production in red (blue): the shading* **Prop litetime shorter than naaronization time** *backward asymmetry in* ✓`*, Al, with* ⇣*<sup>t</sup> for tHj (tHj* ¯ *) production in red (blue): the shading* **Prop litetime shorter than naaronization time Q** ton lifetime shorter than hadronization time **& top lifetime shorter than hadronization time** dronization time **@top lifetime shorter than hadronization time**

Kevin Kröninger – University of Göttingen

For example, the following problem:

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$$
\frac{\tau_{top} = \frac{1}{\Gamma_{top}} \approx 5 \cdot 10^{-25} \text{ s} < \tau_{net} \approx 3 \cdot 10^{-24} \text{ s}}{\sigma \text{ deos}(\theta_0) \text{ deos}(\theta_1) + \text{Beos}(\theta_1) + \text{Beos}(\theta_1) + \text{Beos}(\theta_1) + \text{Ceos}(\theta_1) \cos(\theta_1)}
$$
\n9 top spin info fully transferred to decay products:

\ntheir angular distributions are **corrected** to **decay** products:

\n
$$
\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} \left( 1 + \frac{\sigma \text{ degos}(\theta_1)}{\omega_f \text{ Feos}(\theta_1)} \right)
$$
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$$
\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} \left( 1 + \frac{\sigma \text{ degos}(\theta_1)}{\omega_f \text{ Feos}(\theta_1)} \right)
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\omega_f = 1.0 \text{ for charged lepton and down-type q}
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\omega_f = -0.4 \text{ for the bottom q}
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= -0.3 \text{ for the neutrino and the up-type q}
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$$

### spin configurations in ttbar at LHC best described by the helicity basis for all ! [see Eq. (40)].

⇒



## **spin configurations in ttH at LHC**

*W W*

- **Higgs emission changes top chirality**
- $\Theta$  in the chiral limit  $(m_{top} \rightarrow 0)$ :
	- $t_Lt_L$  +  $t_Rt_R$   $\rightarrow$   $t_Lt_R$  +  $t_Rt_L$  $t_Lt_R$  +  $t_Rt_L$   $\rightarrow$   $t_Lt_L$  +  $t_Rt_R$
- **in contrast, in the chiral limit, irreducible ttγγ, ttbb bckgrs behave like ttbar !**





## **ttbar versus ttH at LHC (14 TeV)**

 $\Theta$  integrated p<sub>T</sub> top distribution for like-helicity (LL+RR) **versus unlike-helicity (LR+RL) top pairs**



**chiral limit hard to reach in tth :**   $n$ eeds extreme (unpopulated)  $p_T^{top}$  values!

### **ttH (LL+RR,LR+RL) : signal vs bckgrs**

**nevertheless one finds a trend towards chiral-limit expectations in integrated cross sections :**





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### **spin correlations in ttbar measured at LHC**



## **Warning on spin-correlation observables**

- **many possible basis (helicity, maximal, off-diagonal,...) as top quantization axis : spin correlation strength depends on basis choice !**
- **many different angular observables can be constructed (involving also different decay products)**
- **try to look at the most sensitive ones**
- **structure of spin correlations varies significantly over top production phase space**
- **optimization can require "cumbersome" procedures (ex. additional cuts can increase correlation strength...)**

Bernreuther, Brandenburg, Si and Uwer, Mahlon and Parke, Baumgart and Tweedie , ...

#### **Reference-frame (other than LAB) definitions : (assume ttbar can be fully reconstructed,cf."**ν **weighting technique")**

➜ **angle between directions of flight of** ℓ**+ (b) in top rest system and** ℓ**<sup>−</sup> (bbar) in antitop rest system.** ➜ **two different rest systems are involved**  ➜ **to avoid ambiguities one has to specify the common initial frame where Lorentz boosts are applied to separately bring the t and tbar at rest : FRAME 1** ➜ **start from ttbar cm frame FRAME 2** ➜ **start from Lab frame**

**(LO) Correlated vs Uncorrelated predictions :** 0.4 0.4

$$
t\bar t H \to \ell^+ \nu\ b\ \ell^- \bar \nu\ \bar b\ H
$$

#### $F(X|X|Y|Y) = F(X|X|Y)$  (top left), and  $F(X|X) = F(X|X)$ , and  $F(X|X) = F(X|X)$ , and  $F(X|X) = F(X|X)$ , and  $F(X|X) = F(X|X)$  $\frac{1}{2}$  (top left),  $\frac{1}{2}$  (top left), and  $\frac{1}{2}$  (bottom right), and  $\frac{1}{2}$  (bottom right **correlated**

Biswas et al. arXiv:1403.1790

for both signal and ttbb, ttγγ bckgd, **top decays are performed in MadGraph5** by retaining full spin information white and popularmed in Had cuts be  $\frac{1}{\sqrt{2}}$  (top left), and  $\frac{1}{\sqrt{2}}$  (top right), and  $\frac{1}{\sqrt{2}}$ for both signal and ttbb, ttyy bckgd, top decays are performed in MadGraph5 correlation and uncorrelated cases. The advantage of employees of employees and the advantage of employees and th signal and ttbb, ttyy bckgd, white and penformad in the Lab frame. Same cuts as in Fig. 7 have been in Fig. 7 have been in Fig. 7 have been imposed.  $\frac{1}{\sqrt{2}}$ for both signal and ttbb, ttyy bckgd, top decays are performed in MadGraph5 correlation and uncorrelated cases. The advantage of employees of employees and the advantage of employees and

in the Lab frame is quite modest. | uncorre in the Lab frame is quite modest. | uncorrelated

top decays are implemented by interfacing Fig. 9 we easy are implemented by importancing  $\sqrt{s}$  are implemented by interfacing Finally, in the explorer top regime, by the strategy of the boosted top property that the highest top property

**MadGraph5 (production) with PYTHIA (no spin info)**  $s = 250$  in the cut pT  $\sim$  250 GeV in the laboratory frame. In particular, we plot the cos  $\sim$  0.1 MadGraph5 (production) with PYTHIA (no spin info)  $s = 250$  in the cut pT  $\frac{1}{250}$  distribution frame. In particular, we plot the cos  $\frac{1}{250}$  distribution frame. In particular, we plot the cos  $\frac{1}{250}$  distribution frame. In particular, we plot the cos  $\frac{1}{250$ MadGraph5 (production) with PYTHIA (no spin info)

backgrounds to the control of the c<br>and the control of t  $\gamma$  and  $\gamma$  and the cuts produced the cuts position  $\gamma$  $\boxed{\gamma\gamma, \text{bb selection}: p_T > 20 \text{ GeV}, |\eta| < 2.5 \text{ and } \Delta R > 0.4}$  $123 \text{ GeV}$   $< m_{\gamma\gamma} < 129 \text{ GeV}, \text{ and } m_{b\bar{b}} > 100 \text{ GeV}$ butions for the signals ttH¯ (<sup>H</sup> <sup>→</sup> γγ) (left) and ttH¯ (<sup>H</sup> <sup>→</sup> <sup>b</sup>¯b) (right) with their corresponding final state photons or b  $123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}$ , and  $m_{h\bar{h}} > 100 \text{ GeV}$ mass cut 123  $G$ ev $\sim$  123  $G$ ev $\sim$  129  $G$ ev $\sim$  129  $G$ ev $\sim$  100  $G$ ev $\sim$  120  $G$ ev $\sim$  12 backgrounds to the control of the c<br>In the control of th  $p_0 \sim 20 \Omega \Omega \sqrt{N}$  and  $\Omega$   $\sim 25$  and  $\Delta D \sim 0.4$  $\boxed{\gamma \gamma, \text{bb selection}: p_T > 20 \text{ GeV}, |\eta| < 2.5 \text{ and } \Delta R > 0.4}$  $123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}, \text{ and } m_{b\bar{b}} > 100 \text{ GeV}$ butions for the signals ttH¯ (<sup>H</sup> <sup>→</sup> γγ) (left) and ttH¯ (<sup>H</sup> <sup>→</sup> <sup>b</sup>¯b) (right) with their corresponding final state photons or b  $123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}$ , and  $m_{\overline{\mu} \overline{\lambda}} > 100 \text{ GeV}$ mass cut 123  $\mu$  GeV, and mass cut 123  $\mu$  129  $\mu$  129  $\mu$  120  $\mu$  120  $\mu$  120  $\mu$  120  $\mu$ 

## **tt γγ : S vs B (Frame 1 and 2)**

## **solid (dashed) lines (do not) include spin correlations red** ➜ **signal , green** ➜ **bckgr**

Frame 1  $t\bar{t}h(\gamma\gamma)$ : corr Frame 2  $t\bar{t}h(\gamma\gamma):\text{corr}$ 0.65 0.65  $t\bar{t}h(\gamma\gamma)$  : uncor  $t\bar{t}h(\gamma\gamma)$ : uncor **Frame 1** *Form* **Frame 2 Frame** 2  $t\bar{t}\gamma\gamma: \text{corr}$  $t\bar{t} \gamma \gamma$  : corr  $t\bar{t}\gamma\gamma:$  uncor  $t\bar{t}\gamma\gamma:$  uncor 0.6 0.6  $d\cos\theta_{\ell\ell}$  $d\cos\theta_{\ell\ell}$ 0.55 0.55 dN  $\mathbb{R}$  $\mathbb{R}$ <del>....</del>....  $0.5$   $\leftarrow$ 0.5 0.45 0.45  $\cos \theta_{\ell\ell}$   $\Box$   $\Box$   $\cos \theta_{\ell\ell}$ 0.4 0.4  $-1$   $-0.6$   $-0.2$   $0.2$   $0.6$   $1$  $-1$   $-0.6$   $-0.2$   $0.2$   $0.6$   $1$  $\cos\theta_{\ell\ell}$  $\cos\theta_{\ell\ell}$ **|S-B|~ 30% |S-B|~ 22%**

**∆(S/B)[cos**ϑℓℓ**>0] ~ + 17%**

dN

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Biswas et al. arXiv:1403.1790

all distributions

normalized to 1

## **cos**ϑ**bb in tt γγ (Frame 1 [~2])**

#### **not much gain (almost flat distributions !)**

arXiv:1403.1790



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#### **Lab frame (does not need top reconstruction !)**



#### **including γγ emission from tt decay products**  $\sum_{n=1}^{n}$ including  $\gamma\gamma$  emission trom tt decay products  $|$  $\sum_{n=1}^{n}$ including  $\gamma\gamma$  emission trom tt decay products  $|$

extra emission from charged  $t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b \bar{b}$  decay products  $(1 + \frac{1}{2})$ , which give identical configurations that one produced by  $\frac{1}{2}$ **G** extra emission from charged  $t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b \bar{b}$  decay products  $(1 + \frac{1}{2})$ , which give identical configurations that one produced by  $\frac{1}{2}$ **G** extra emission from charged  $t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b \bar{b}$  decay products





**extra photon emission from ttbar decay products could eventually be suppressed by requiring (mtop) invariant mass reconstruction of the top system**

### **including γγ emission from tt decay products**

### **cos**ϑ**ℓℓ in ttγγ (Frame 1 and 2)**

 $t\bar{t}\gamma\gamma|_{\rm tot}$  : uncor  $t\bar{t}\gamma\gamma|_{\rm tot}:\rm corr$  $t\bar{t}h(\gamma\gamma)$ : uncor Frame 1  $t\bar{t}h(\gamma\gamma)$ : corr  $\cos\theta_{\ell\ell}$  $-1$   $-0.6$   $-0.2$   $0.2$   $0.6$   $1$ 0.65 0.6 0.55 0.5 0.45 0.4  $t\bar{t}\gamma\gamma|_{\rm tot}$  : uncor  $t\bar{t}\gamma\gamma|_{\rm tot}:\rm corr$  $t\bar{t}h(\gamma\gamma)$  : uncor Frame 2  $t\bar{t}h(\gamma\gamma)$ : corr  $\cos\theta_{\ell\ell}$  $\mathbb{R}$ dN d cos  $\theta$ el  $-1$   $-0.6$   $-0.2$   $0.2$   $0.6$   $1$ 0.65 0.6 0.55 0.5 0.45 0.4  $\cos \theta_{\ell\ell}$   $\left| \cos \theta_{\ell\ell} \right|$   $\cos \theta_{\ell\ell}$ Frame 1  $\frac{t\bar{t}\gamma\gamma_{\text{tot}}:\text{corr}}{t\bar{t}\gamma\gamma_{\text{tot}}:\text{uncor}}$  | Frame 2

 **ttγγ signal ~ unaffected Bckgdcorr** gets closer to Bckgduncor arXiv:1403.1790

#### differences from extra emission at  $\cos\theta_{\ell\ell}, \cos\theta_{b\bar b} \sim$ ± $1\;\, \Delta\eta_\ell, \Delta\eta_b < 1\;\,$ are found mainly for low separations of lepton and b pairs (that is for cos  $\mathbb{R}^n$ , cos

affect the previous results where the previous results where ignored (cf.  $\mathbb{F}_q$  and  $\mathbb{F}_q$  and  $\mathbb{F}_q$ 

affect the previous results where the previous results where ignored (cf.  $\mathbb{F}_q$  and  $\mathbb{F}_q$  and  $\mathbb{F}_q$ 



## **ttbb : cos**ϑ**ℓℓ and cos**ϑ**bb in Frame 1 and 2**



#### **ttbb : cos**ϑ**ℓℓ and cos**ϑ**bb in Lab (Scorr and Bcorr get closer !)** frame. Spin effects are quite milder in this case and in this case and in general do not improve much the signal- $\mathbf{f}$  this cose  $\mathfrak{g}_{ee}$  and cose  $\mathfrak{g}_{bb}$  in Lab (S<sub>cann</sub> and B<sub>cann</sub> get closer  $\mathfrak{g}_{ee}$





**@ requiring boosted tops increases lepton angular** and the position of the signal of  $\theta$ conomation with the corresponding backgrounds (green) to the corresponding backgrounds (green) to the corresponding of the corresponding o  $\mathbf{v}_i = \mathbf{v}_i + \mathbf{v}_i$  and the Lab frame, after  $\mathbf{v}_i$  and  $\mathbf{v}_i$ demanding one highly-boosted top by imposing that the highest top p<sup>T</sup> satisfies the cut p<sup>T</sup> > 250 **separation**

**8** no gain in ttγγ !

**@** S-vs-B separation improves for correlated ttbb! and background increases both increases both increases both in the correlated and uncorrelated and uncorrelated<br>The correlated case of the correlated and uncorrelated case. The correlated case of the correlated case of the

## **NLO effects vs spin correlations in ttH**

#### **in ttH, spin correlations have much more dramatic effects on shapes than NLO QCD corrections**



**CP violations vs spin correlations in ttH** WE WIOIC  $cos\theta_1$  $\zeta_{\rm t}$  $\zeta_{\rm t}$ *discussed in [29] (solid black contour). Black dots represent the simulated model points. discussed in [29] (solid black contour). Black dots represent the simulated model points.* WE WIOIC

 $\overline{2}$  1 0 1 2

 $\overline{2}$  1 0 1 2

$$
\mathcal{L}_t = -\frac{m_t}{v} \left( \kappa_t \bar{t} t + i \tilde{\kappa}_t \bar{t} \gamma_5 t \right) H
$$
Ellis et al. arXiv:1312.5736  
Ellis et al. arXiv:1312.5736

 $\cos \theta$ 

 $\cos \theta$ 

Ellis et al. arXiv:1312.5736



*t t*

 $\begin{array}{ccc} 0 & \cdots & 0 & 0 & 0 \\ \end{array}$ 

 $\begin{array}{ccc} 0 & \cdots & 0 & 0 & 0 \end{array}$ 

## **Outlook**

- **Q ttbar Spin Correlations unique tool for studying interplay between EW and QCD physics in top physics**
- **cleanest probe** ➜ **dilepton final states (robust under higher orders and parton shower)**
- **potential to probe New Physics effects in both tt and ttH**
- **we investigated the advantages of including spin correlations in the analysis of ttH in channels ttH** ➜ **ttγγ, ttbb versus irreducible bckgds (bound to become dominant for larger data sets at 14 TeV !)**
- **we found angular variables that increase S/B by ~ 15 % up to ~ 30 % in dedicated phase-space regions**

**NLO QCD and parton-shower effects to be included...**

**spin-correlation features should definitely be taken into account in high-luminosity studies of ttH !**