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

Emidio Gabrielli
University and INFN, Trieste, Italy
NICPB, Tallinn, Estonia

based on
S.Biswas, R. Frederix, EG, B.Mele

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Outline

- A few experimental facts on $t\bar{t}H$
- Top polarization effects in $pp \to t\bar{t}$
- Spin-correlations in $t\bar{t}$ and $t\bar{t}H$ production
- Spin-correlations in signal and irreducible bckgs:
  - $t\bar{t}(H \to \gamma\gamma)$
  - $t\bar{t}(H \to b\bar{b})$
- Outlook
**ttH production**

- Large QCD bckg for $\bar{t}t(H \rightarrow b\bar{b}) \rightarrow$ mainly from $\bar{t}tbb\bar{b}$, $\bar{t}tjj$
- $H \rightarrow b\bar{b}$ resonance also plagued by combinatorial bckg
- Rarest channels $\bar{t}t(H \rightarrow \gamma\gamma)$ and multileptons $\rightarrow$ more favorable $S/B$ compensate for the lack of statistics...

$\bar{t}t(H \rightarrow b\bar{b})$ @ (7 + 8 TeV data)

**ATLAS:** observed (expected) 95% CL limit: $4.1 \times$ SM ($2.6 \times$ SM)  
**CMS:** observed (expected) 95% CL limit (including $H \rightarrow$ taus): $5.2 \times$ SM ($4.1 \times$ SM)

$\bar{t}t(H \rightarrow \gamma\gamma)$ @ (7 + 8 TeV data)

**ATLAS:** observed (expected) 95% CL limit: $5.3 \times$ SM ($6.4 \times$ SM)  
**CMS:** observed (expected) 95% CL limit: $5.4 \times$ SM ($5.3 \times$ SM)

**ttbar Spin Correlations → useful tool for enhancing sensitivity of S/B on ttH !**
Top quark spin

- Top life time shorter than hadronization time
  \[ \tau_{\text{top}} = \frac{1}{\Gamma_{\text{top}}} \approx 5 \cdot 10^{-25} \text{ s} < \tau_{\text{had}} \approx \frac{1}{\Lambda_{\text{QCD}}} \approx 3 \cdot 10^{-24} \text{ s} \]

- Top spin info fully transferred to decay products:
  - Their angular distributions correlated
  \[ \frac{1}{\Gamma_f} \frac{\mathrm{d}\Gamma_f}{\mathrm{d}\cos\theta_f} = \frac{1}{2} \left( 1 + \alpha_f P_t \cos \theta_f \right) \]

  \( \theta_f \) Angle between momenta of decay products with top-spin axis (top at rest)

  \( P_t = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \)

  Degree of top polarization

- Spin analyzing power is maximum for charged leptons

- Top-quarks mainly unpolarized in SM \( \bar{t}t \) production
  \[ P_t \approx 0.003 \]

- \( \alpha_f = 1.0 \) charged leptons
- \( \alpha_f = -0.4 \) b-quark type
- \( \alpha_f = -0.3 \) \( \nu \) and up-quark

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Spin correlations in $\bar{t}t$ production

- Top pair spin correlated in $\bar{t}t$ production (as predicted by QCD) +
- Decay products correlated with top/antitop spin

Decay products of $\bar{t}t$ are correlated!

$$\frac{1}{\sigma_T} \frac{d^2\sigma}{d\cos\chi_i d\cos\chi_{\bar{i}}} = \frac{1}{4} \left( 1 + C_{t\bar{t}} \alpha_i \bar{\alpha}_{\bar{i}} \cos\chi_i \cos\chi_{\bar{i}} \right)$$

$$C_{t\bar{t}} \equiv \frac{\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow} - \sigma_{\downarrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} + \sigma_{\downarrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

\(\sigma_{\uparrow\downarrow}\) correlation parameter: choice of spin axis and frame crucial to enhance it

- Many possible basis: commonly adopted at LHC is helicity basis (frame dependent)
- Spin-correlation for $\bar{t}t$ and $\bar{t}tH$ easy to understand in the chiral limit

Bemreuther, Brandenburg, Si and Uwer, Mahlon and Parke, Baumgart and Tweedie, ...
Spin configurations in $\bar{t}t$ and $\bar{t}tH$ at LHC

**Naïve chiral limit**

- Vector-like interactions (gluons and photons) conserve chirality

- $LR + RL \bar{t}t$ helicity configurations dominant at large $\bar{t}t$ invariant masses

- Higgs emission flips top chirality $\rightarrow \bar{t}t$ spin-correlation expected to be complementary to the $\bar{t}t$ one in the chiral limit $\rightarrow LL + RR$

- In contrast, in the chiral limit, (large $m(\bar{t}t)$) irreducible $\bar{t}t + \gamma\gamma$ and $\bar{t}t + b\bar{b}$ backgrounds behaves like $\bar{t}t \rightarrow LR + RL$!

- Naïve expectations spoilt by top-quark mass effects at $\bar{t}t$ threshold
The trend of chiral-limit expectations seems to be quite recovered in total cross sections (except for $t\bar{t}b\bar{b}$ background) of hardest top.

<table>
<thead>
<tr>
<th>$\sigma(p_T&gt;0)$</th>
<th>LL+RR</th>
<th>LR+RL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$</td>
<td>61%</td>
<td>39%</td>
</tr>
<tr>
<td>$t\bar{t}\gamma\gamma$</td>
<td>28%</td>
<td>72%</td>
</tr>
<tr>
<td>$t\bar{t}bb$</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Choice of frame and spin-correlation observables are crucial to enhance spin-correlations strength.

Optimization can require "cumbersome" procedures.

Bernreuther, Brandenburg, Si and Uwer, Mahlon and Parke, Baumgart and Tweedie, ...
Reference-frames (other than Lab) definitions

(assume $t\bar{t}$ system can be fully reconstructed)

- consider the angle between directions of flight of:
  - $l^+$ (b) in top rest system
  - $l^-$ (bbar) in antitop rest system

- two different systems are involved!

- to avoid ambiguities: the common initial frame, where Lorentz boosts are applied to separately bring $t$ and $t\bar{t}$ at rest, needs to be specified

FRAME 1: start from $t\bar{t}$ c.m. frame

FRAME 2: start from Lab frame

Bernereuther et al.
NPB 690 (2004) 81
(LO) Correlated vs Uncorrelated predictions:

$$t\bar{t}H \rightarrow l^+ \nu b \ l^- \bar{\nu} \bar{b} \ H$$

Biswa et al, arXiv: 1403.1790

**correlated**

Top decays performed in Madgraph5 by retaining full spin information in both signal and $t\bar{t}b\bar{b}$, $t\bar{t}\gamma\gamma$ backgrounds.

**uncorrelated** (as done today by experiments)

Top decays implemented by interfacing, in both signal and backgrounds, Madgraph5 (production) with PYTHIA (unpolarized decays).

**$\gamma\gamma, bb$ selection:**

- $p_T > 20$ GeV, $|\eta| < 2.5$ and $\Delta R > 0.4$
- $123$ GeV $< m_{\gamma\gamma} < 129$ GeV, and $m_{b\bar{b}} > 100$ GeV
**$tt \gamma\gamma$: S vs B for Frame 1 and 2**

- solid → spin correlations included
- dashed → spin correlations NOT included
- signal → red  bckg → green

(\gamma\gamma NOT emitted from top decays)

- all distributions normalized to 1

Frame 1

Frame 2

$|S-B| \sim 30\%$

$|S-B| \sim 22\%$

*S/B can be improved up to 30% in particular phase space regions*
Including $\gamma\gamma$ emission from top decays

- $p_{T}^{b,\gamma 1,2} > 20$ GeV and $p_{T}^{\ell} > 10$ GeV
- $|\eta^{b}| < 4.7$, $|\eta^{\ell}| < 2.7$ and $|\eta^{\gamma}| < 2.5$
- $\Delta R(bb, \ell \ell, \gamma\gamma, b \ell, b\gamma, \ell\gamma) > 0.4$
- $123$ GeV $< m_{\gamma\gamma} < 129$ GeV

$\gamma\gamma$ emission from top-decay products can also be suppressed by requiring top invariant mass reconstruction

- Kin cuts required for $\gamma$ and $b$
- Isolation applied to both signal and bckg

- bckg(correlated) gets closer to bckg(uncorrelated)
- Signal $\sim$ unaffected

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\( t\bar{t} \gamma\gamma : S \text{ vs } B \text{ for Lab frame} \)

(photons NOT emitted from top decays)

does not need top reconstruction

\[
\Delta \eta_l \equiv |\eta_l^+ - \eta_l^-| 
\]

\[
\Delta \eta_b \equiv |\eta_b^+ - \eta_b^-| 
\]

deviations from correlated vs uncorrelated less pronounced than in Frame1 and 2
We consider only irreducible background (bound to become dominant for larger data set at 14 TeV).

Irreducible background receives contributions from many amplitudes components that have different top spin correlations.

Our analysis is an idealized one: we assume to be able to distinguish the b-quarks coming from top (antitop) decays.

NLO QCD and parton shower effects NOT included.
**tt \(\bar{b}b\) : S vs B for Frame1 and 2**

**Frame 1**
- Spin effects quite relevant: uncorrelated distributions are quite flat
- (Frame 1) S/B improvement up to \(~15\%) using \(\cos \theta_{l\bar{l}}\) and \(~20\%) using \(\cos \theta_{b\bar{b}}\)

**Frame 2**

*Images showing distributions of\(\cos \theta_{l\bar{l}}\) and \(\cos \theta_{b\bar{b}}\) for Frame 1 and 2,*

*arXiv:1403.1790*
requiring boosted tops increases lepton angular separation

no gain in $\bar{t}t\gamma\gamma$ !

$S$ vs $B$ separation improves for correlated $\bar{t}t\bar{b}b$
Outlook

\( \bar{t}t \) Spin-Correlation useful tool for studying interplay between EW and QCD physics in top-quark physics

Cleanest probe → dileptons final states

(robust under higher orders QCD and parton showers)

we investigated the advantages of including spin-correlation effects in the \( \bar{t}tH \) analysis for the channels \( \bar{t}t(H\to\gamma\gamma) \) and \( \bar{t}t(H\to b\bar{b}) \) vs irreducible bckgs

(\( b\bar{b} \) bound to become dominant for larger data set at LHC 14 TeV)

We found angular variables in specific frames that can enhance \( S/B \) by 15% up to 30%

NLO QCD and parton shower not included in the analysis

Spin-correlations features should definitively be included in future high luminosity studies of \( \bar{t}tH \)!