

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

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based on

S.Biswas, R. Frederix, EG, B.Mele
arXiv: 1403.1790 (to appear in JHEP)

special thanks to B. Mele for discussions

Outline

- A few experimental facts on $t\bar{t}H$
- top polarization effects in $pp \rightarrow t\bar{t}$
- spin-correlations in $t\bar{t}$ and $t\bar{t}H$ production
- spin-correlations in signal and irreducible bckgs:
 - $t\bar{t}(H \rightarrow \gamma\gamma)$
 - $t\bar{t}(H \rightarrow b\bar{b})$
- outlook

$t\bar{t}H$ production

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

$t\bar{t}(H \rightarrow b\bar{b})$

@ (7 + 8 TeV data)

ATLAS: observed (expected) 95% CL limit : **4.1 x SM** (**2.6 x SM**)

ATLAS-CONF-2014-011

CMS-PAS-HIG-13-019

CMS: observed (expected) 95% CL limit (including $H \rightarrow \tau\tau$) : **5.2 x SM** (**4.1 x SM**)

$t\bar{t}(H \rightarrow \gamma\gamma)$

@ (7 + 8 TeV data)

ATLAS: observed (expected) 95% CL limit: **5.3 x SM** (**6.4 x SM**)

ATLAS-CONF-2014-080

CMS: observed (expected) 95% CL limit: **5.4 x SM** (**5.3 x SM**)

CMS-PAS-HIG-13-015

$t\bar{t}$ Spin Correlations $\rightarrow$ useful tool
for enhancing sensitivity of S/B on $t\bar{t}H$!

Top quark spin

- top life time shorter than hadronization time

$$\tau_{top} = \frac{1}{\Gamma_{top}} \approx 5 \cdot 10^{-25} \text{ s} < \tau_{had} \approx \frac{1}{\Lambda_{QCD}} \approx 3 \cdot 10^{-24} \text{ s}$$

- top spin info fully transferred to decay products:
→ their angular distributions correlated

$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} (1 + \alpha_f P_t \cos\theta_f)$$

θ_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 $t\bar{t}$ production

$$\longrightarrow P_t \approx 0.003$$

$$\begin{aligned} \alpha_f &= 1.0 && \text{charged leptons} \\ &= -0.4 && \text{b-quark type} \\ &= -0.3 && \text{v and up-quark} \end{aligned}$$

Spin analyzing power

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

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

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

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

↗ angle between decay products and top spin axis

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

$$C_{t\bar{t}} \equiv \frac{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} - \sigma_{\uparrow\downarrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} + \sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow}} \rightarrow \text{correlation parameter: choice of spin axis and frame crucial to enhance it}$$

$\sigma_{\uparrow\downarrow}$ ➡ Polarized cross sections for top pairs , with up/down spin with respect to top/antitop spin axis respectively

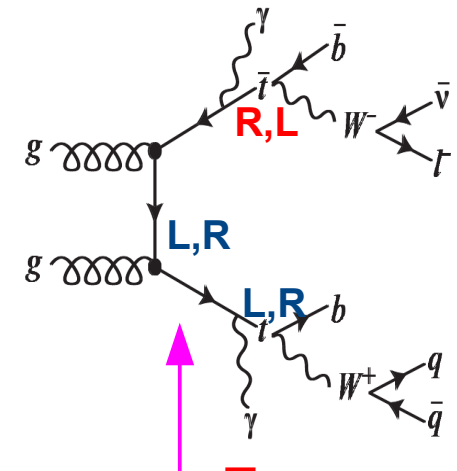
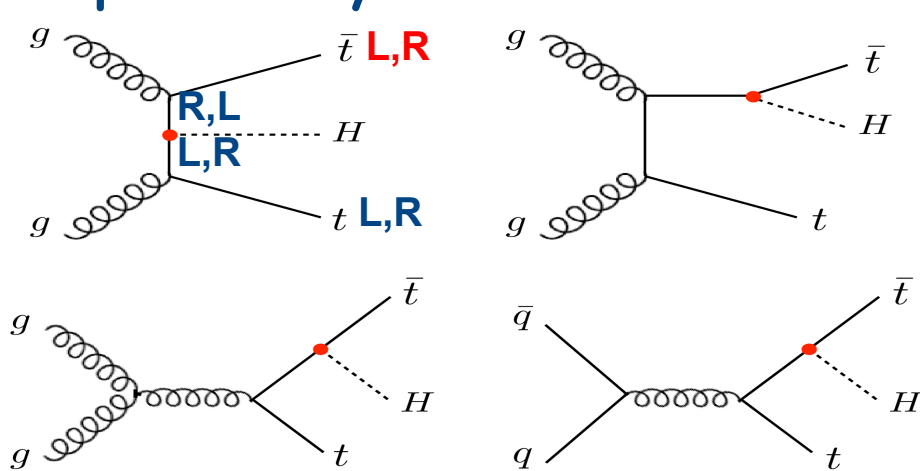
- many possible basis: commonly adopted at LHC is helicity basis (frame dependent)

- spin-correlation for $t\bar{t}$ and $t\bar{t}H$ easy to understand in the chiral limit

Spin configurations in $t\bar{t}$ and $t\bar{t}H$ at LHC

Naïve chiral limit

- vector-like interactions (gluons and photons) conserve chirality
- LR+RL $t\bar{t}$ helicity** configurations dominant at large $t\bar{t}$ invariant masses
- Higgs emission flips top_chirality** $\rightarrow$ **$t\bar{t}$ spin-correlation** expected to be complementary to the $t\bar{t}$ one in the chiral limit $\rightarrow$ **LL+RR**

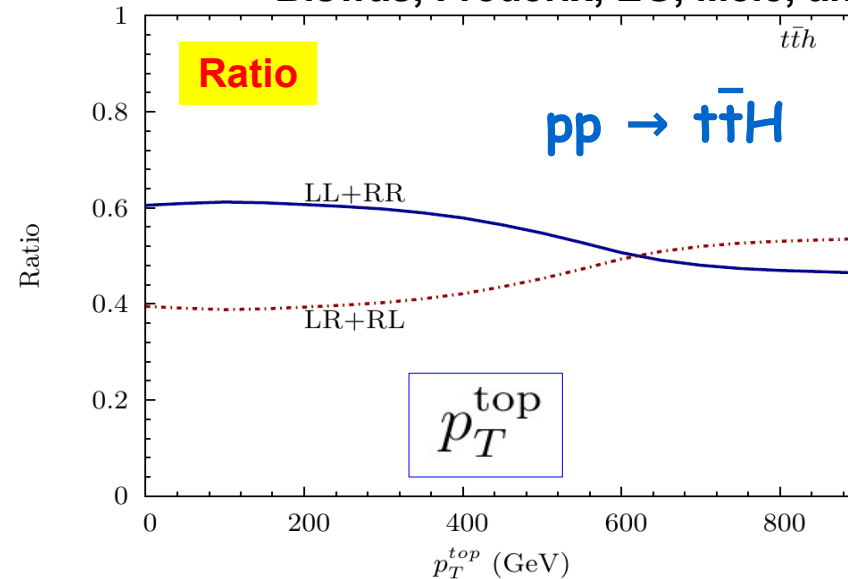
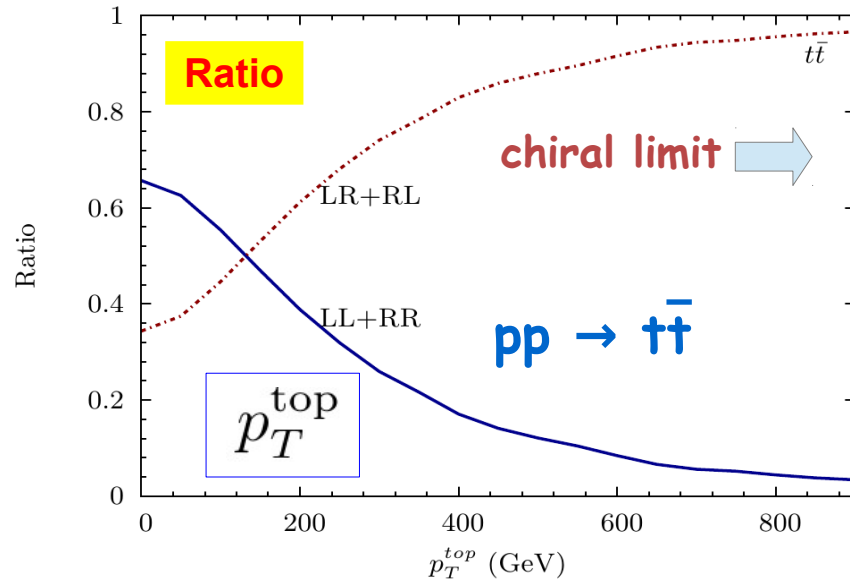


- in contrast**, in the chiral limit, (large $m(t\bar{t})$) irreducible **$t\bar{t}+\gamma\gamma$** and **$t\bar{t}+b\bar{b}$** bckgs behaves like **$t\bar{t} \rightarrow LR+RL$!**

- naïve expectations spoiled by top-quark mass effects at $t\bar{t}$ threshold**

$t\bar{t}$ versus $t\bar{t}H$ at LHC 14 TeV

Biswas, Frederix, EG, Mele, arXiv: 1403.1790



Ratio = $\frac{\sigma(\text{LL}) + \sigma(\text{RR}) \text{ or } \sigma(\text{LR}) + \sigma(\text{RL})}{\sigma(\text{unpolarized})}$

$\sigma(p_T > p_T^{\text{top}})$

p_T^{top} of hardest top

● trend of chiral-limit expectations seems to be quite recovered in total cross sections (except for $t\bar{t}b\bar{b}$ background)

$\sigma(p_T > 0)$	LL+RR	LR+RL
$t\bar{t}H$	61%	39%
$t\bar{t}\gamma\gamma$	28%	72%
$t\bar{t}b\bar{b}$	50%	50%

Populations more than reversed in $t\bar{t}\gamma\gamma$ bckg

● 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^- ($\bar{b}$) 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 $\bar{t}$ 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:

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

Biswas et al, arXiv: 1403.1790

correlated

top decays performed in **Madgraph5** by retaining full spin information in both signal and $t\bar{t}b\bar{b}$, $t\bar{t}\gamma\gamma$ bckgs

uncorrelated (as done today by experiments)

top decays implemented by interfacing, in both signal and bckgs, **Madgraph5** (production) with **PYTHIA** (unpolarized decays)

$\gamma\gamma, bb$ selection : $p_T > 20$ GeV, $|\eta| < 2.5$ and $\Delta R > 0.4$

$123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}$, and $m_{b\bar{b}} > 100 \text{ GeV}$

$t\bar{t} \gamma\gamma$: S vs B for Frame1 and 2

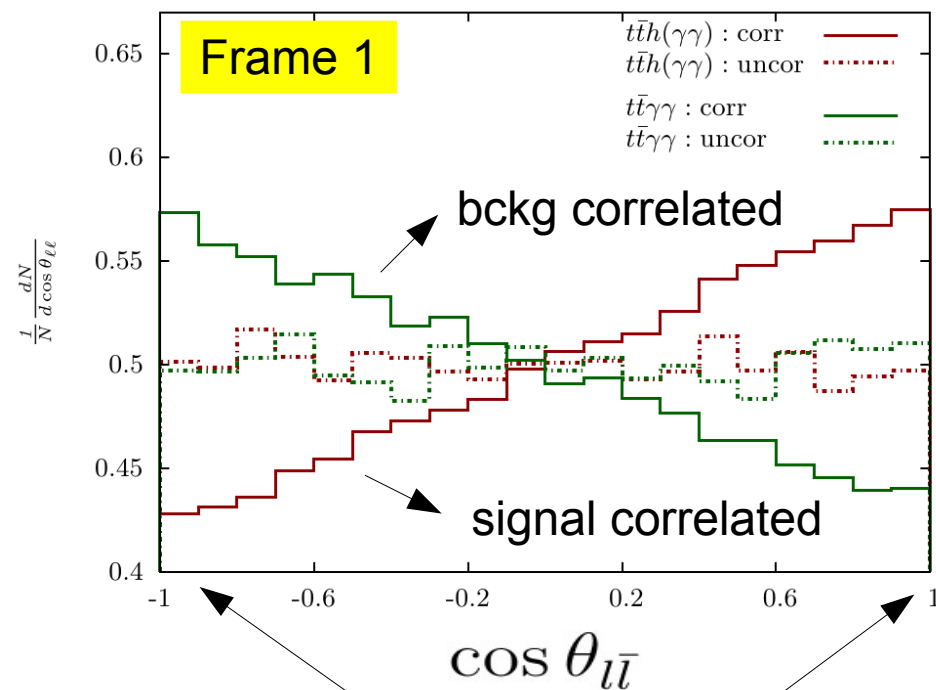
➤ solid → spin correlations included

➤ dashed → spin correlations NOT included

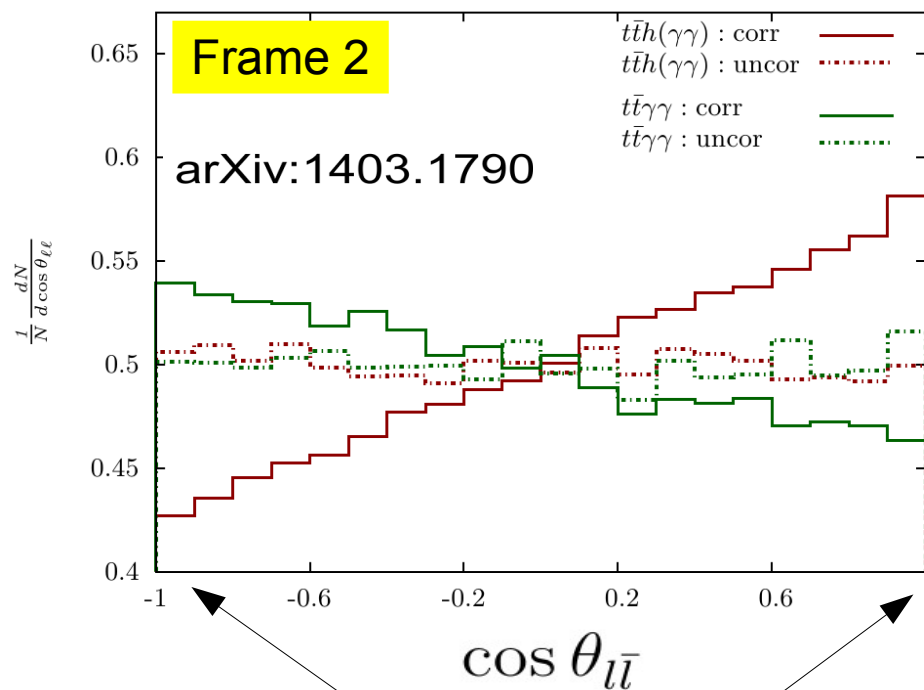
➤ signal → red bckg → green

all distributions
normalized to 1

($\gamma\gamma$ NOT emitted from top decays)



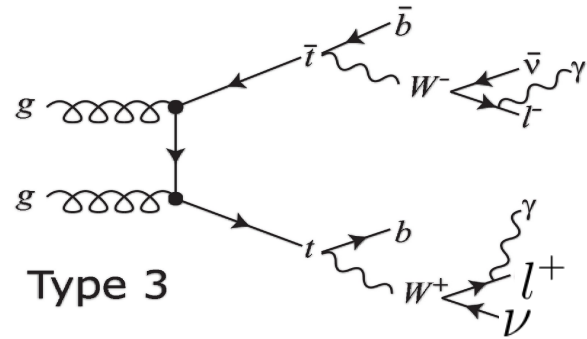
|S-B| ~ 30 %



|S-B| ~ 22 %

S/B can be improved up to **30%** in particular phase space regions

Including $\gamma\gamma$ emission from top decays



Kin cuts required for γ and b
isolation applied to both
signal and bckg



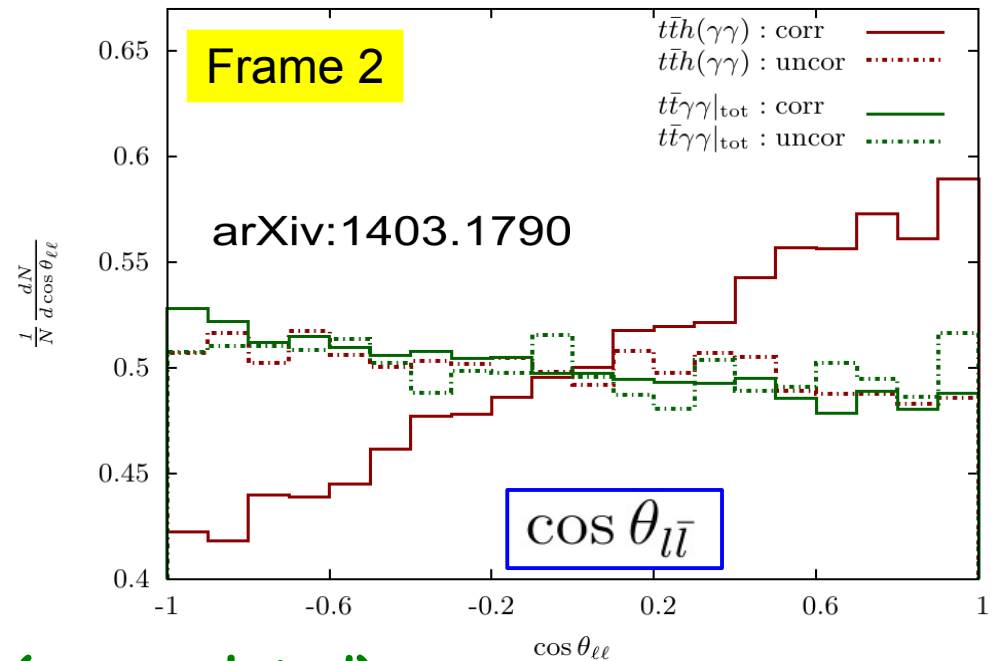
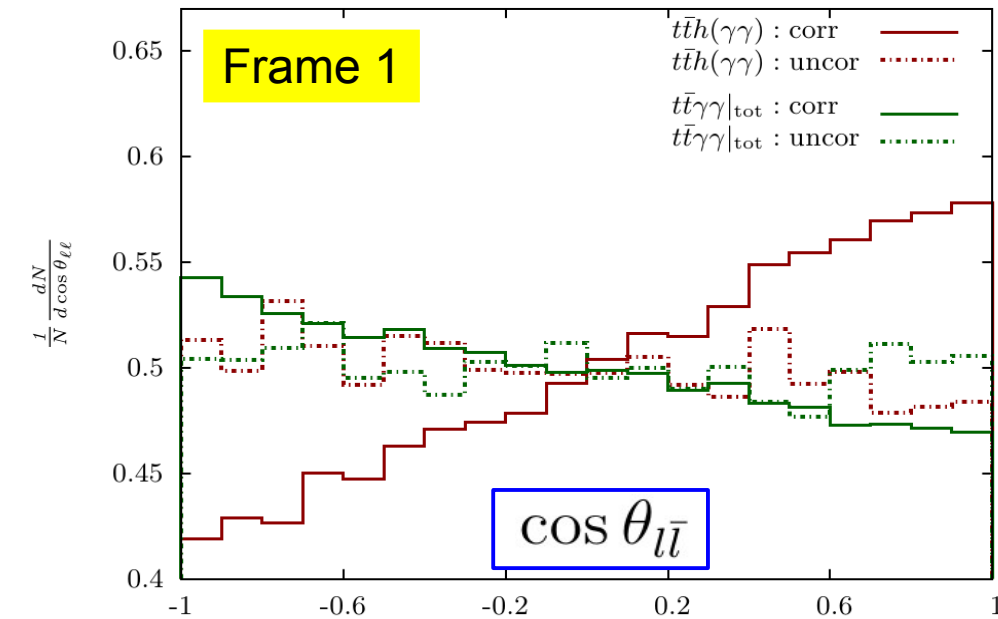
$$p_T^{b,\gamma_{1,2}} > 20 \text{ GeV and } p_T^\ell > 10 \text{ GeV}$$

$$|\eta^b| < 4.7, |\eta^\ell| < 2.7 \text{ and } |\eta^\gamma| < 2.5$$

$$\Delta R(bb, \ell\ell, \gamma\gamma, b\ell, b\gamma, \ell\gamma) > 0.4$$

$$123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}.$$

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



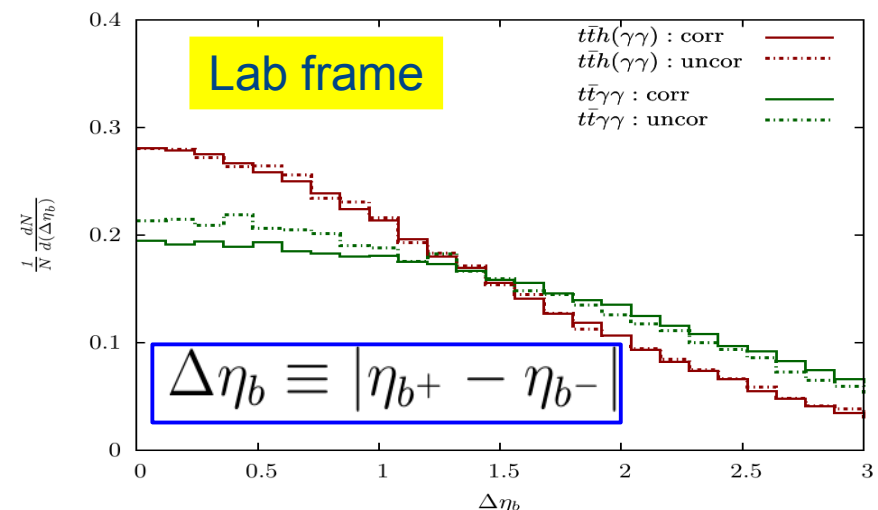
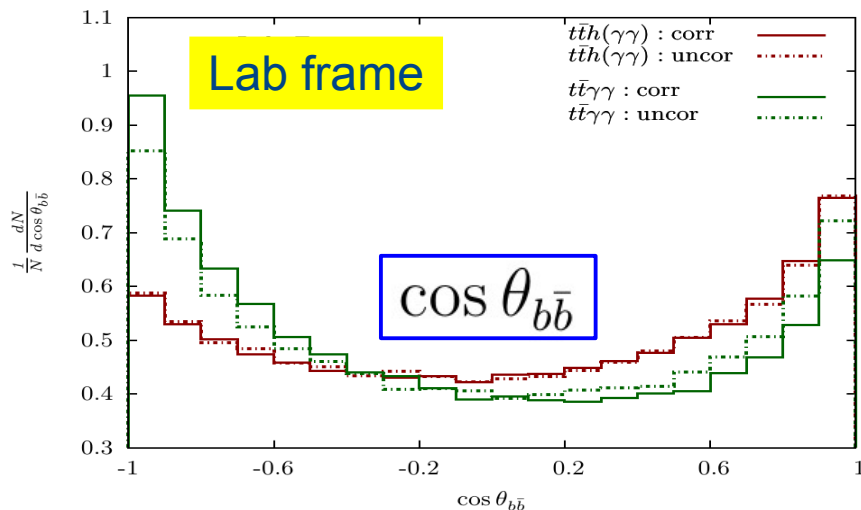
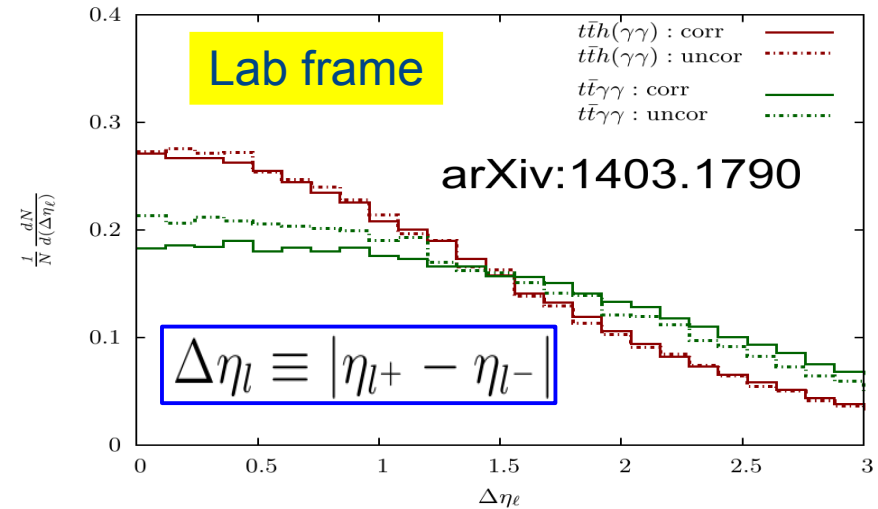
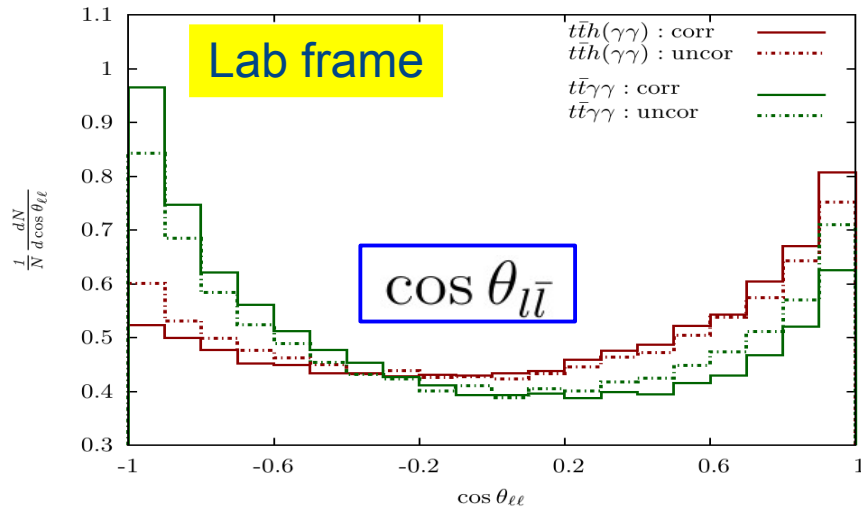
bckg(correlated) gets closer to bckg(uncorrelated)

signal ~ unaffected

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

(photons NOT emitted from top decays)

does not need top reconstruction

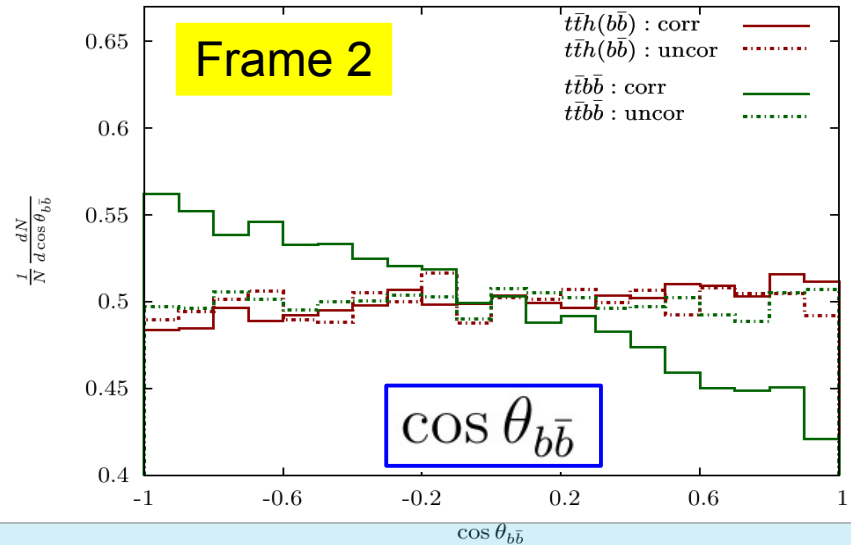
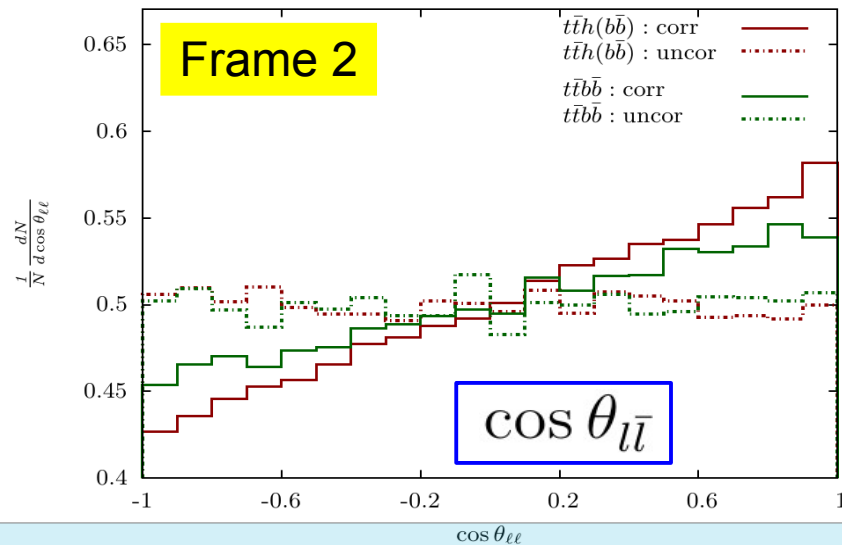
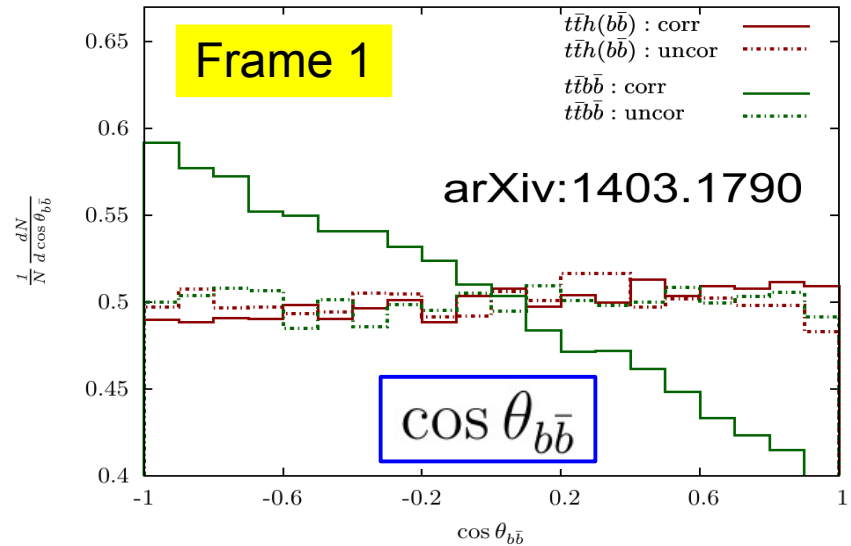
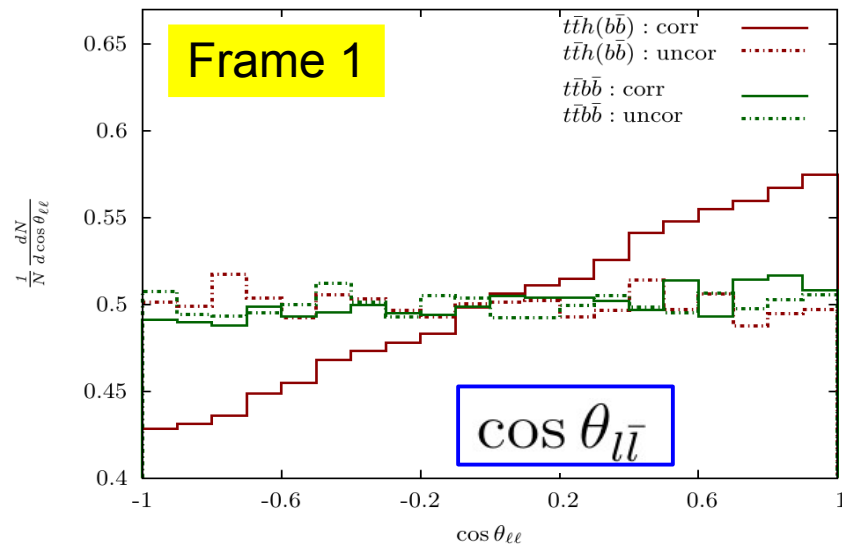


■ deviations from correlated vs uncorrelated less pronounced than in Frame1 and 2

$t\bar{t} \ b\bar{b}$ channel

- We consider only **irreducible bckg**
(bound to become dominant for larger data set at 14 TeV)
- **irreducible bckg** 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**

$t\bar{t} \ b\bar{b}$: S vs B for Frame1 and 2

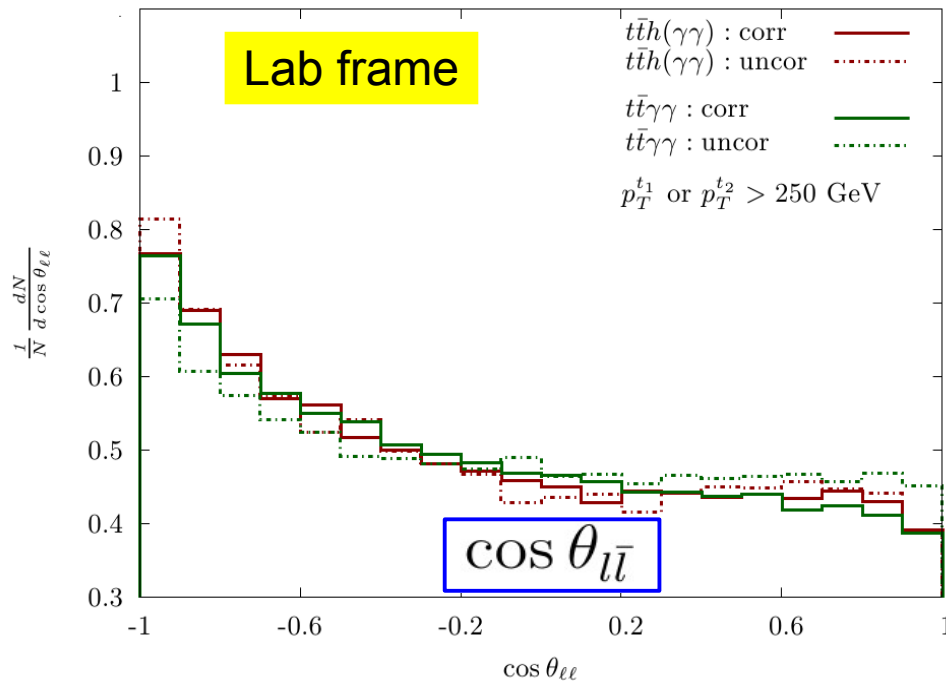


■ **spin effects quite relevant:** uncorrelated distributions are quite flat

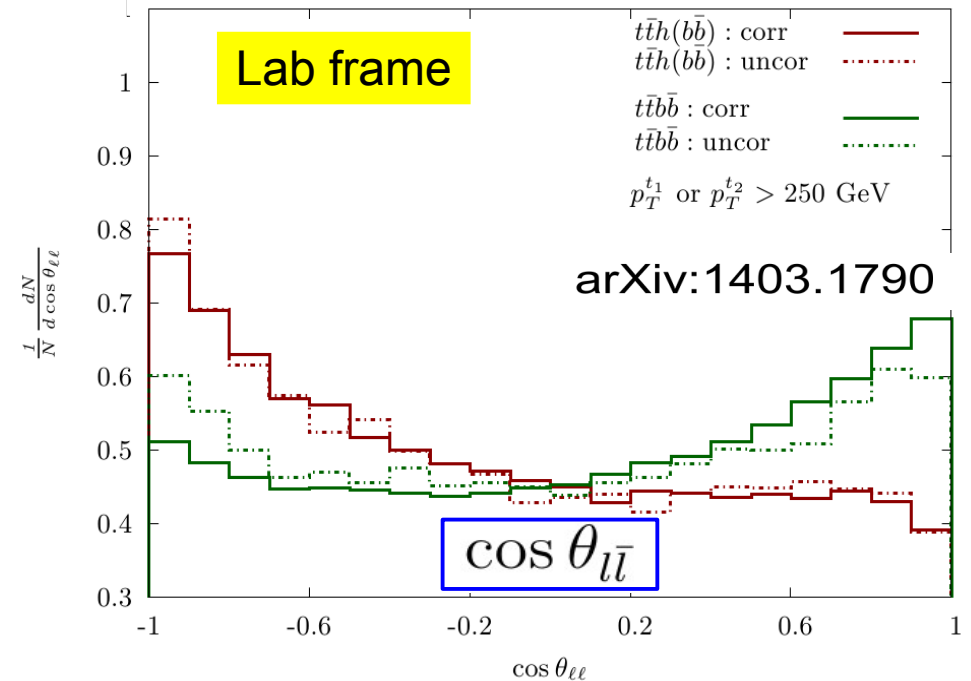
■ **(Frame 1) S/B improvement** up to $\sim 15\%$ using $\cos \theta_{\ell\bar{\ell}}$ and $\sim 20\%$ using $\cos \theta_{b\bar{b}}$

bootstped tops in Lab frame ($p_T > 250$ GeV)

$t\bar{t} \gamma\gamma$



$t\bar{t} b\bar{b}$



■ requiring boosted tops increases lepton angular separation

■ no gain in $t\bar{t} \gamma\gamma$!

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

Outlook

- $t\bar{t}$ Spin-Correlation useful tool for studying interplay between EW and QCD physics in top-quark physics
- Cleanest probe $\rightarrow$ dileptons final states
(robust under higher orders QCD and parton showers)
- we investigated the advantages of including spin-correlation effects in the $t\bar{t}H$ analysis for the channels $t\bar{t}(H \rightarrow \gamma\gamma)$ and $t\bar{t}(H \rightarrow b\bar{b})$ 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 $t\bar{t}H$!