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

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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 ttH → tt$\gamma\gamma$, ttbb

- Outlook

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

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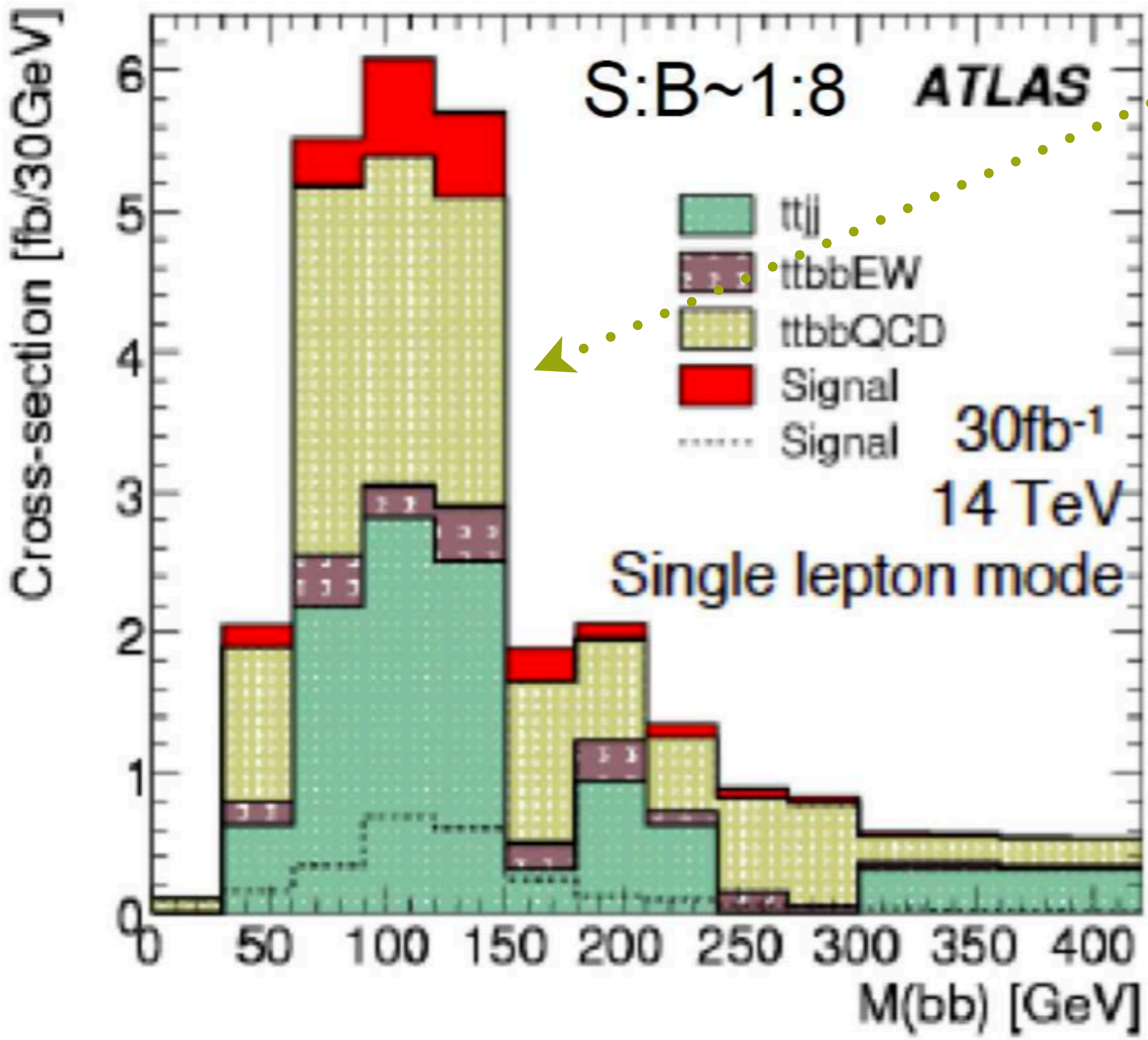
arXiv:1403.1790v1 [hep-ph] 7 Mar 2014

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



ttbb

⇒ background: normalization & shape uncertainties?

Top quark spin and spin correlations

- top lifetime shorter than hadronization time

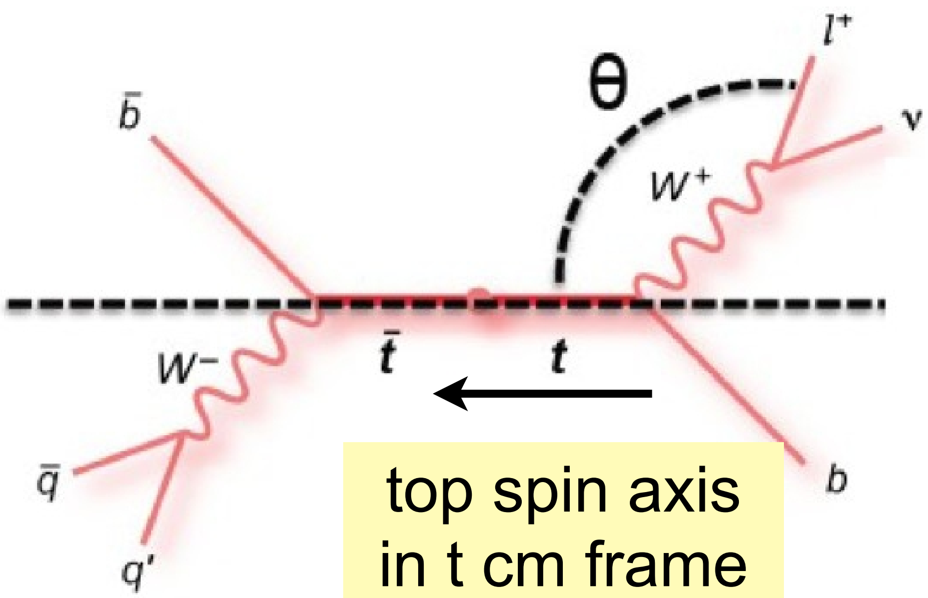
$$\tau_{top} = \frac{1}{\Gamma_{top}} \approx 5 \cdot 10^{-25}\ \mathrm{s} < \tau_{had} \approx \frac{1}{\Lambda_{QCD}} \approx 3 \cdot 10^{-24}\ \mathrm{s}$$

- top spin info fully transferred to decay products; their angular distributons are correlated with top spin axis

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

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

degree of top polarization



top spin axis in t cm frame

(at LHC one takes top helicity axis)

ω_f = 1.0 for charged lepton and down-type q

= -0.4 for the bottom q

= -0.3 for the neutrino and the up-type q

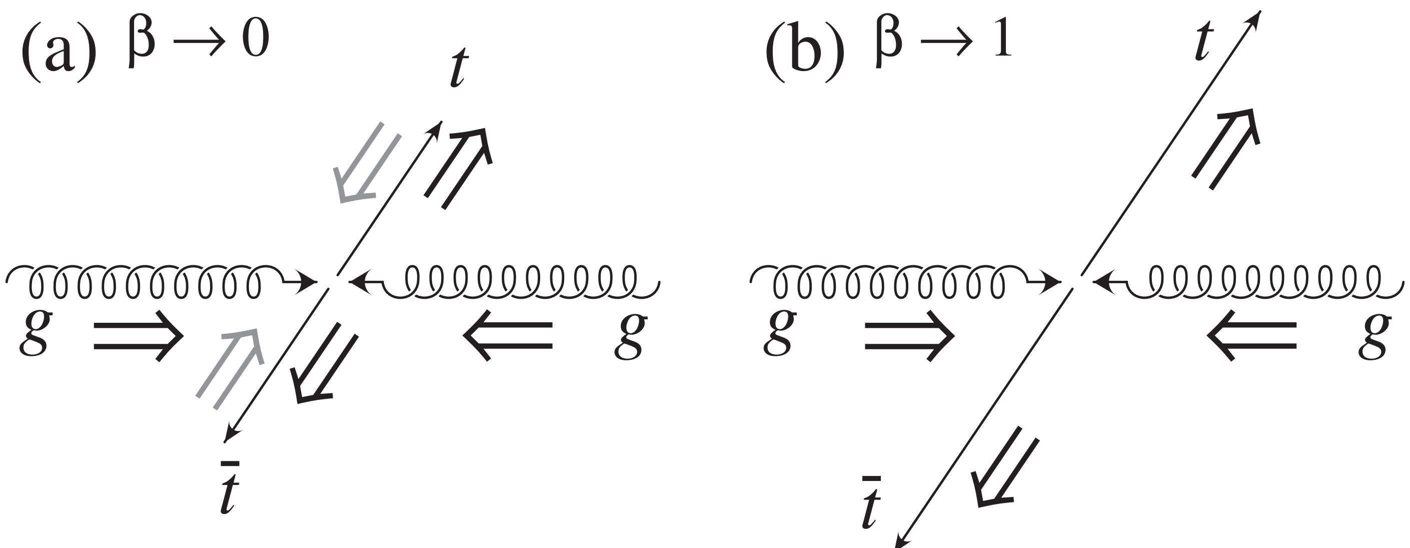
spin analysing power: maximum for charged leptons !

in SM ttbar : $P \approx 0.003$

driven by EW corr.s arXiv:1305.2066

spin configurations in ttbar at LHC

$g_R g_R \longrightarrow t\bar{t}$ $\quad$ $g_L g_L \longrightarrow t\bar{t}$



like-helicity gluons

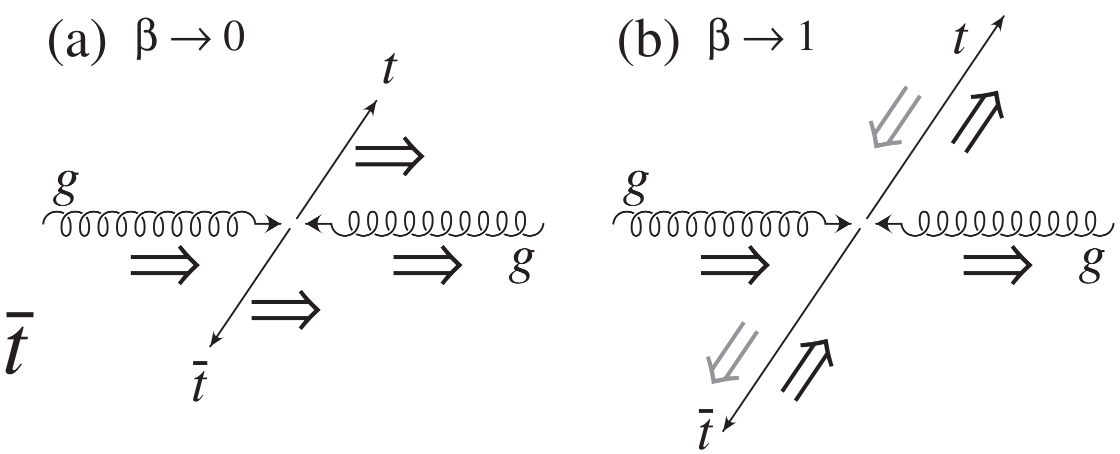
dominant at m(tt) < 400 GeV
(→ $t_L t_L$ + $t_R t_R$)

Mahlon Parke

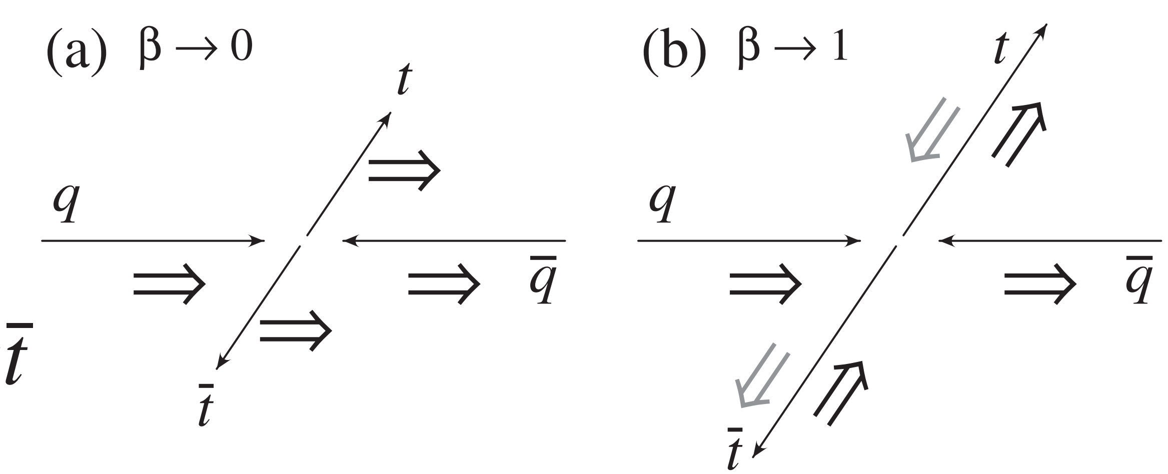
unlike-helicity gluons

dominant at large m(tt)
(→ $t_L t_R$ + $t_R t_L$)

$g_R g_L \longrightarrow t\bar{t}$



$q_R \bar{q}_L \longrightarrow t\bar{t}$



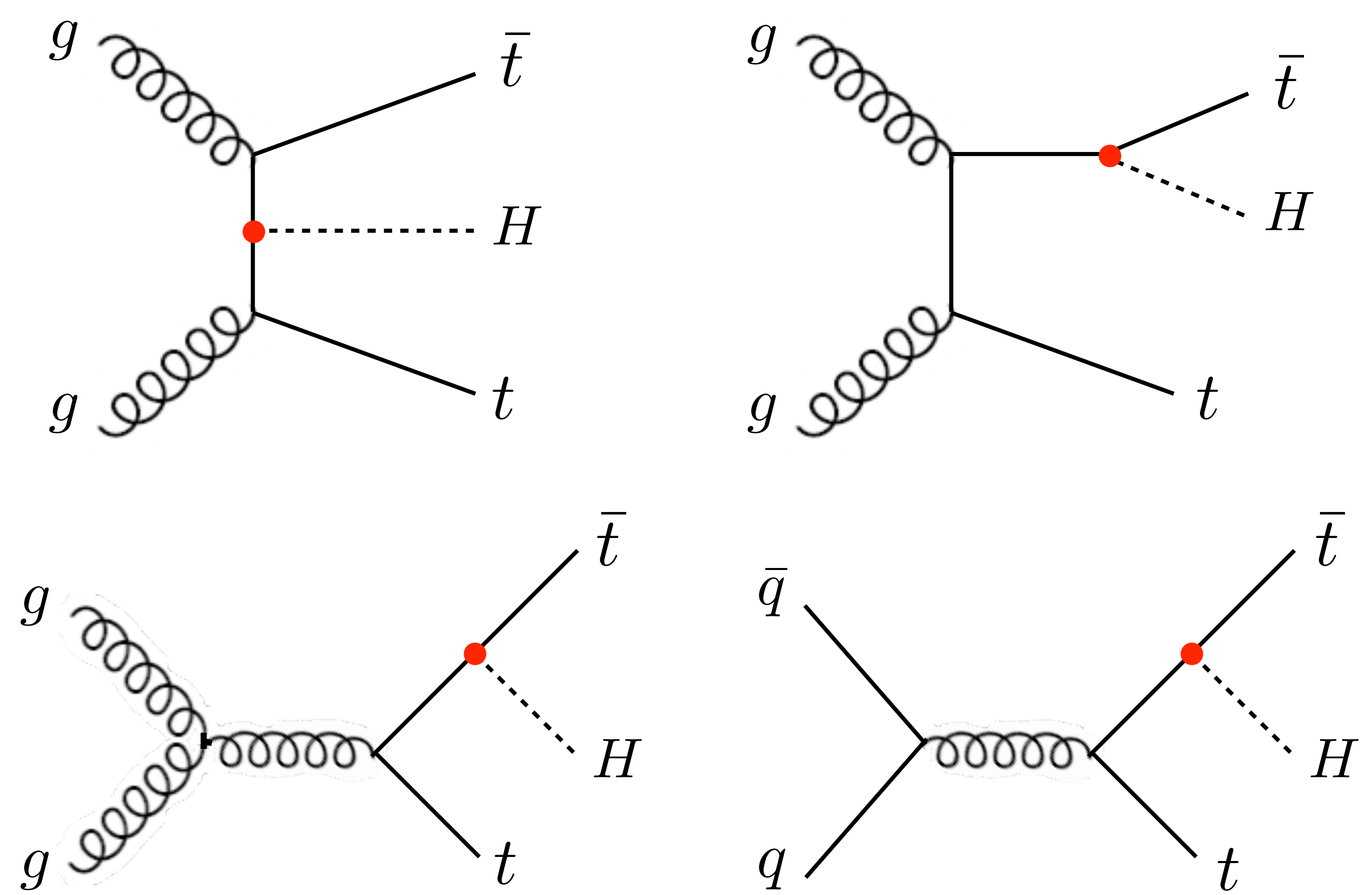
(same for qqbar)

spin configurations in ttH at LHC

- Higgs emission changes top chirality
- in the chiral limit ($m_{top} \to 0$) :

  $t_L t_L + t_R t_R \to t_L t_R + t_R t_L$

  $t_L t_R + t_R t_L \to t_L t_L + t_R t_R$

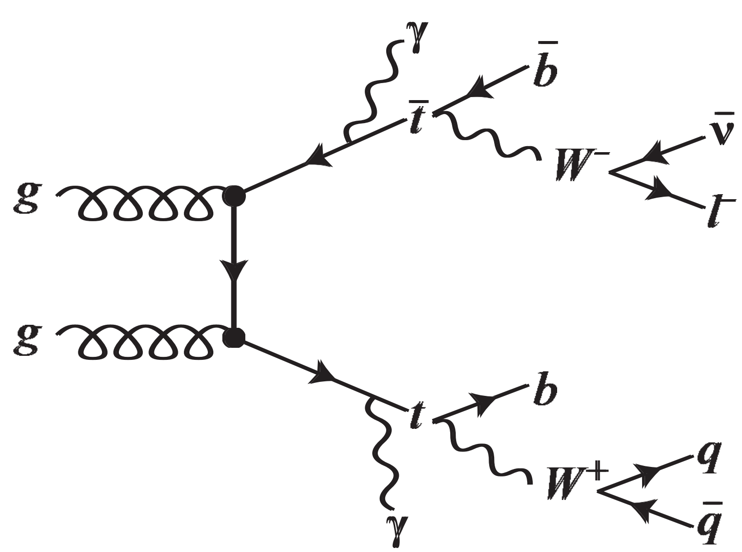


- in contrast,

  in the chiral limit,

  irreducible $tt\gamma\gamma$, ttbb

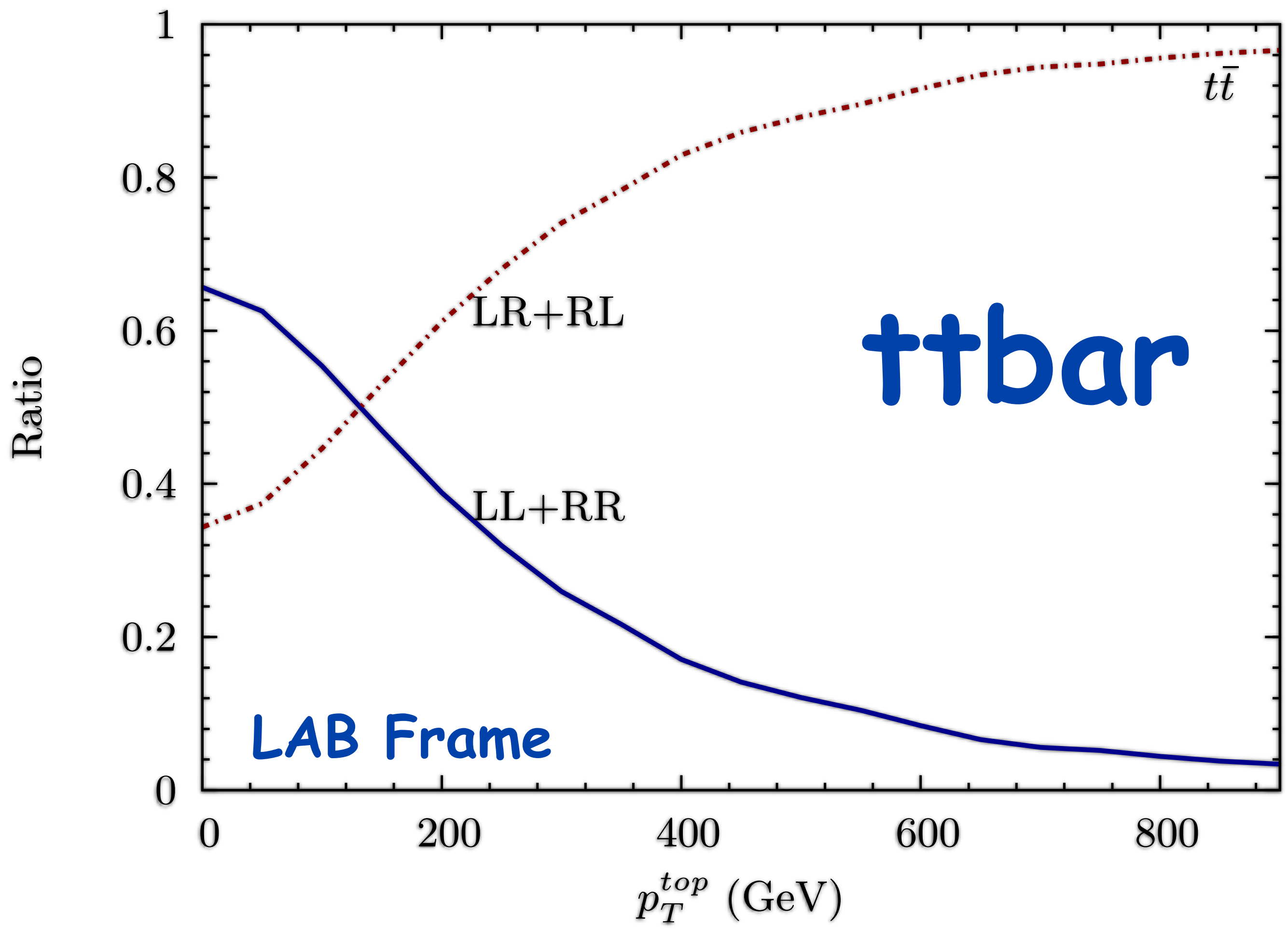
  bckgrs behave like ttbar !

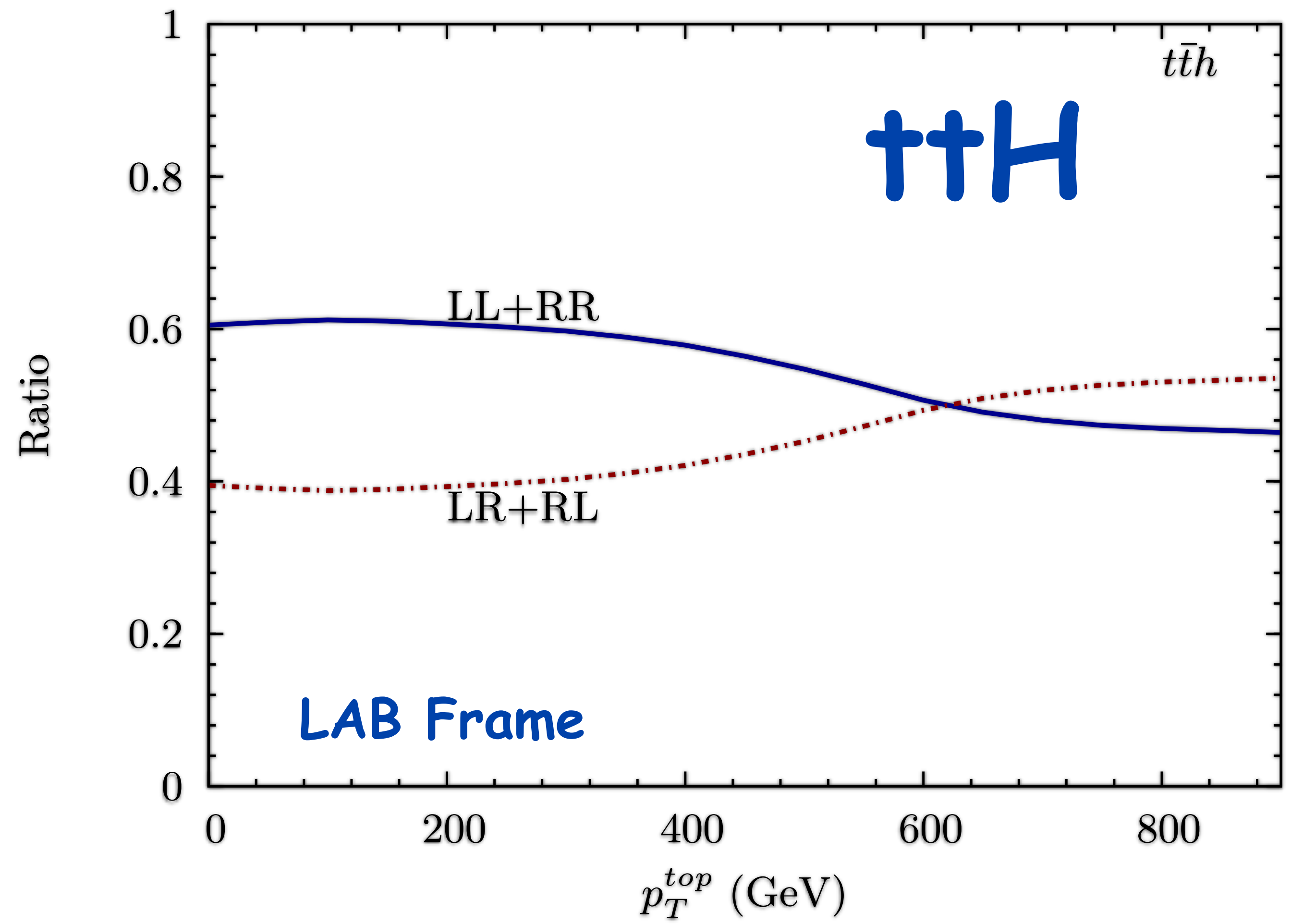


- these naive predictions are spoilt by m_{top} effects !

ttbar versus ttH at LHC (14 TeV)

- integrated p_T top distribution for like-helicity (LL+RR) versus unlike-helicity (LR+RL) top pairs





- chiral limit hard to reach in tth :
  needs 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 :

	LL+RR	LR+RL
ttH	61%	39%
$tt\gamma\gamma$	28%	72%
ttbb	50%	50%

populations more than reversed in $tt\gamma\gamma$ bckgd

spin correlations

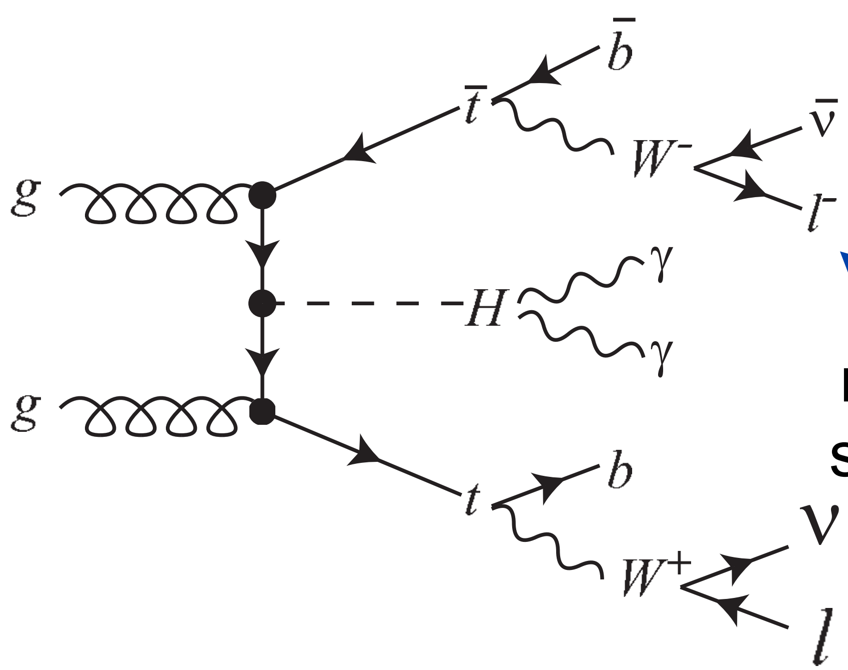
top pair spins correlated in tt, ttH production + **decay products correlated with top spin**

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

→ **decay products of t and tbar are correlated**

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

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+\, d\cos\theta_-} = \frac{1}{4}(1 + A\,\alpha_+\alpha_- \cos\theta_+ \cos\theta_-)$$



maximal s.a.power

$$A = \frac{N_{\rm like} - N_{\rm unlike}}{N_{\rm like} + N_{\rm unlike}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

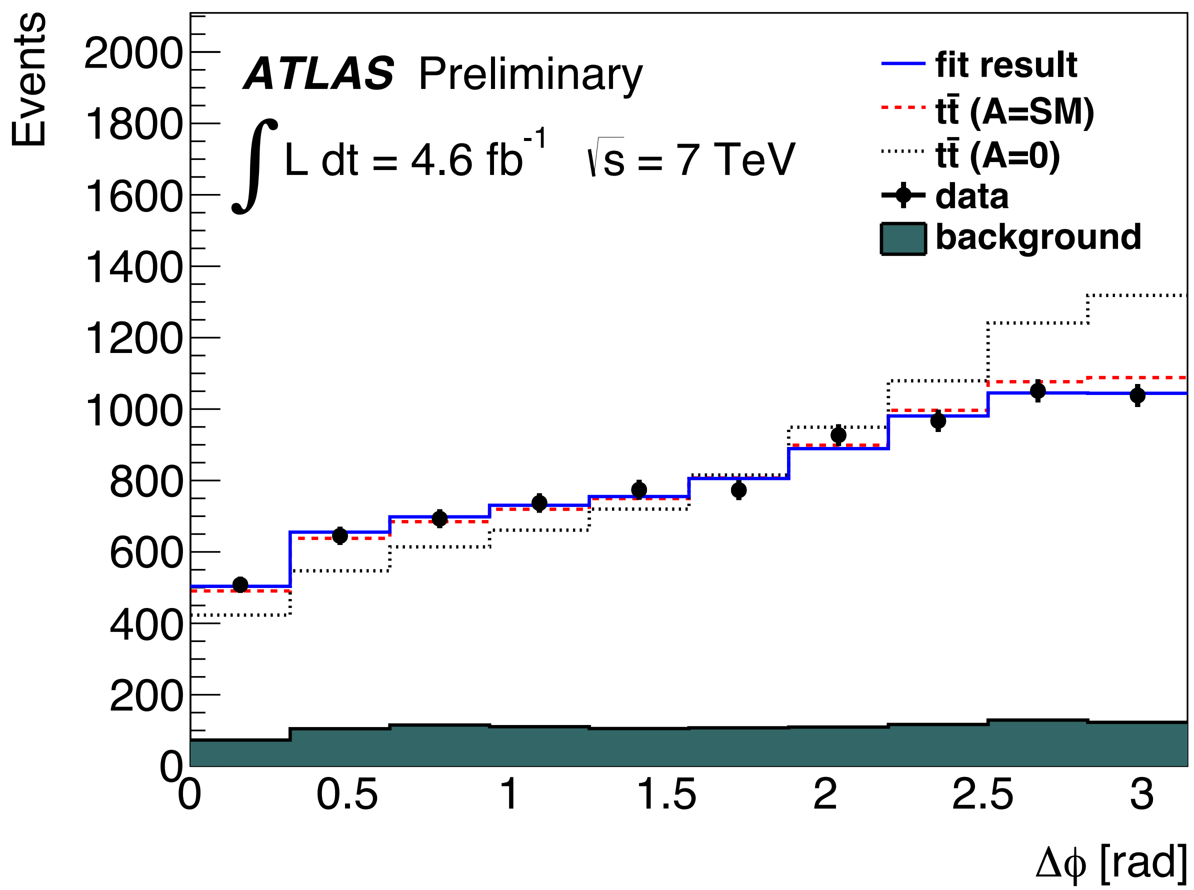
[ttbar spins (anti)parallel]

strength of spin correl. : $C = -A\,\alpha_+\alpha_-$

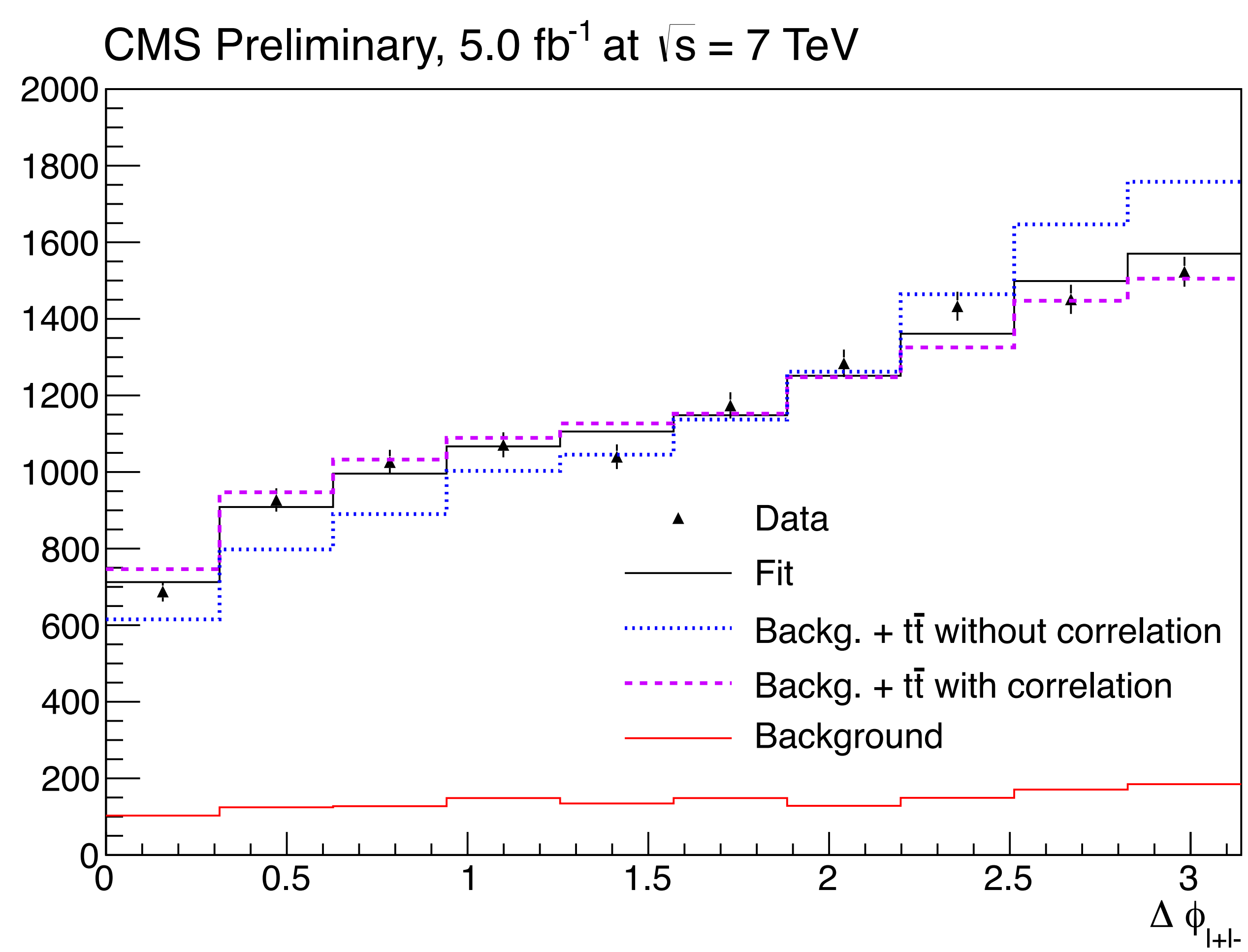
$C \sim A$ *for dileptons*

spin correlations in ttbar measured at LHC

(and at Tevatron !)



ATLAS-CONF-2013-101



CMS PAS TOP-12-004

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^- (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 :

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

Biswas et al. arXiv:1403.1790

correlated

for both signal and ttbb, ttγγ bckgd,

top decays are performed in MadGraph5 by retaining full spin information

uncorrelated

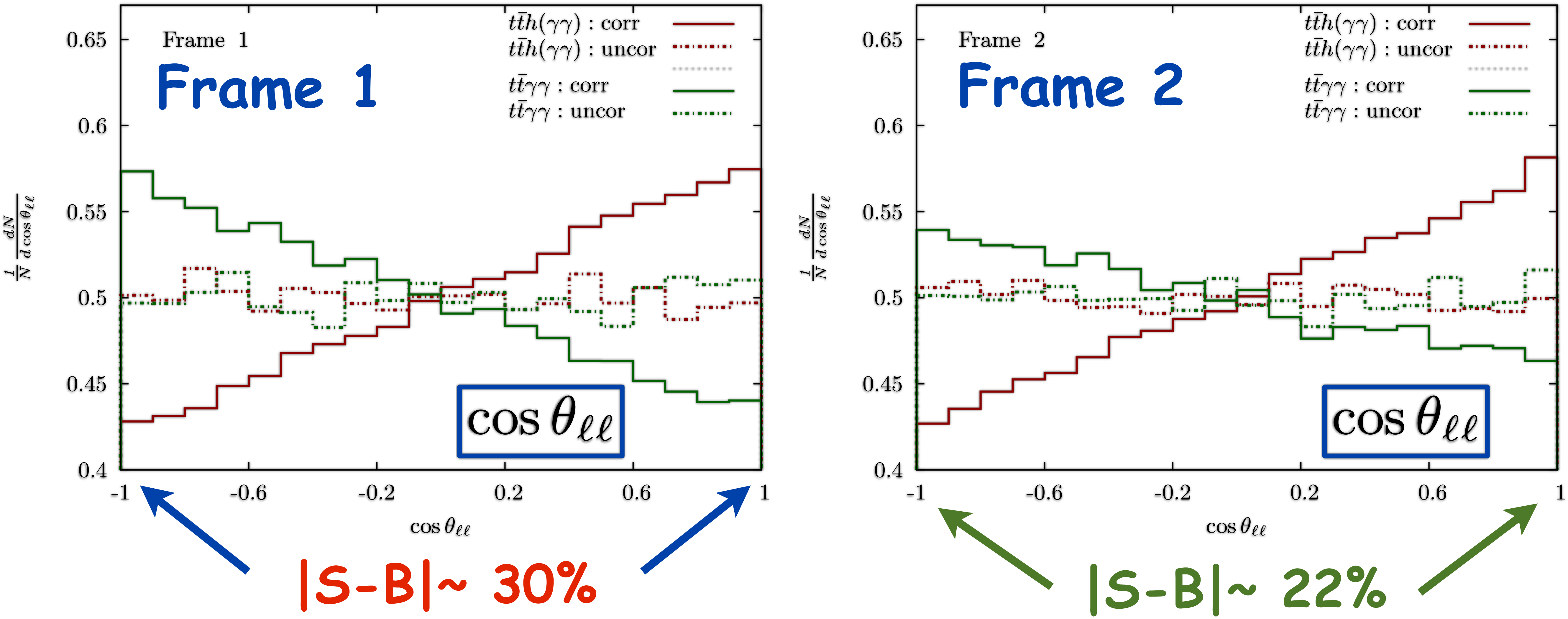
top decays are implemented by interfacing MadGraph5 (production) with PYTHIA (no spin info)

γγ,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

$t\bar{t}\gamma\gamma$: S vs B (Frame 1 and 2)

- solid (dashed) lines (do not) include spin correlations
- red → signal , green → bckgr

Biswas et al. arXiv:1403.1790



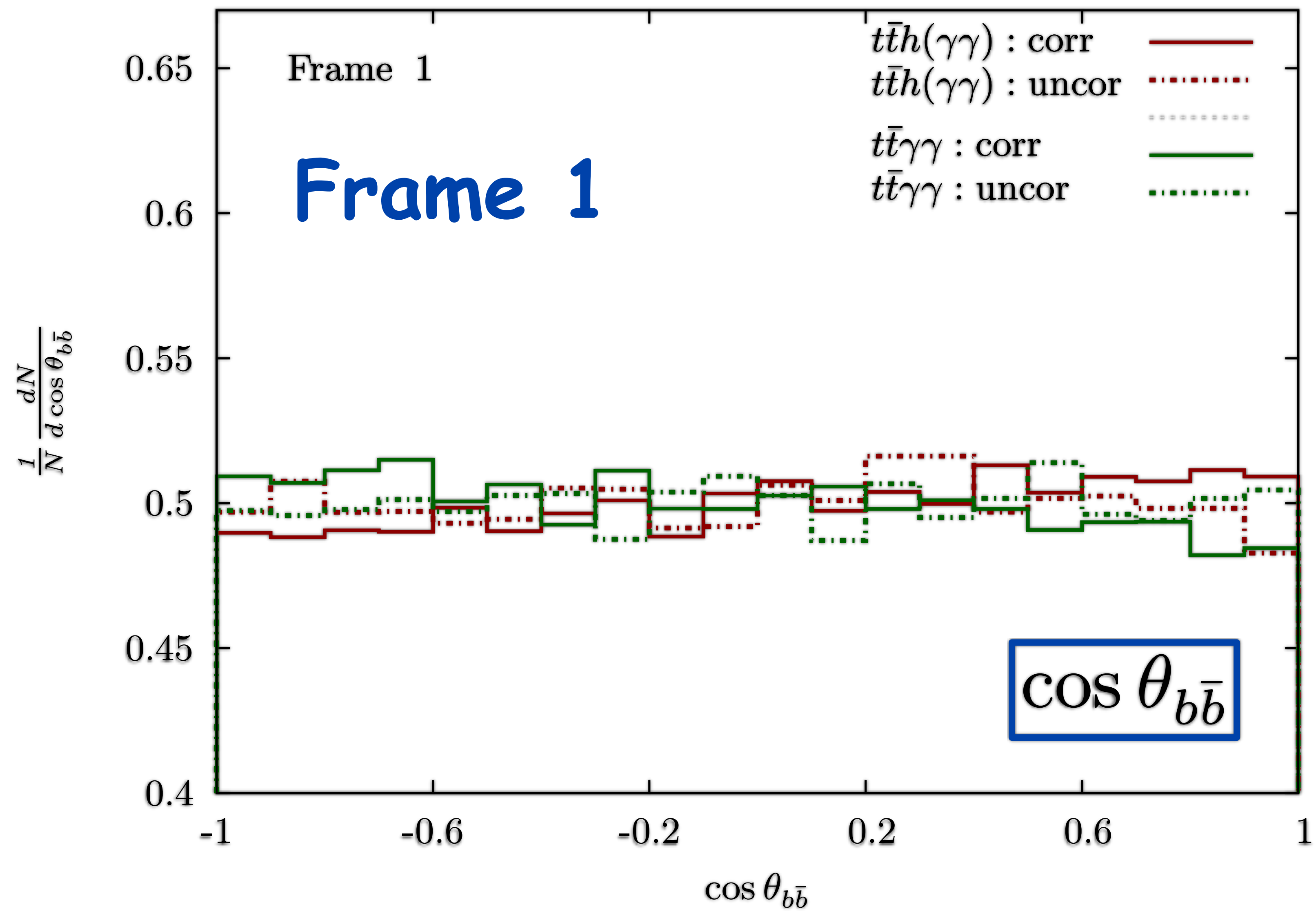
$\Delta(S/B)[\cos\vartheta_{\ell\ell}>0]$ ~ + 17%

all distributions normalized to 1

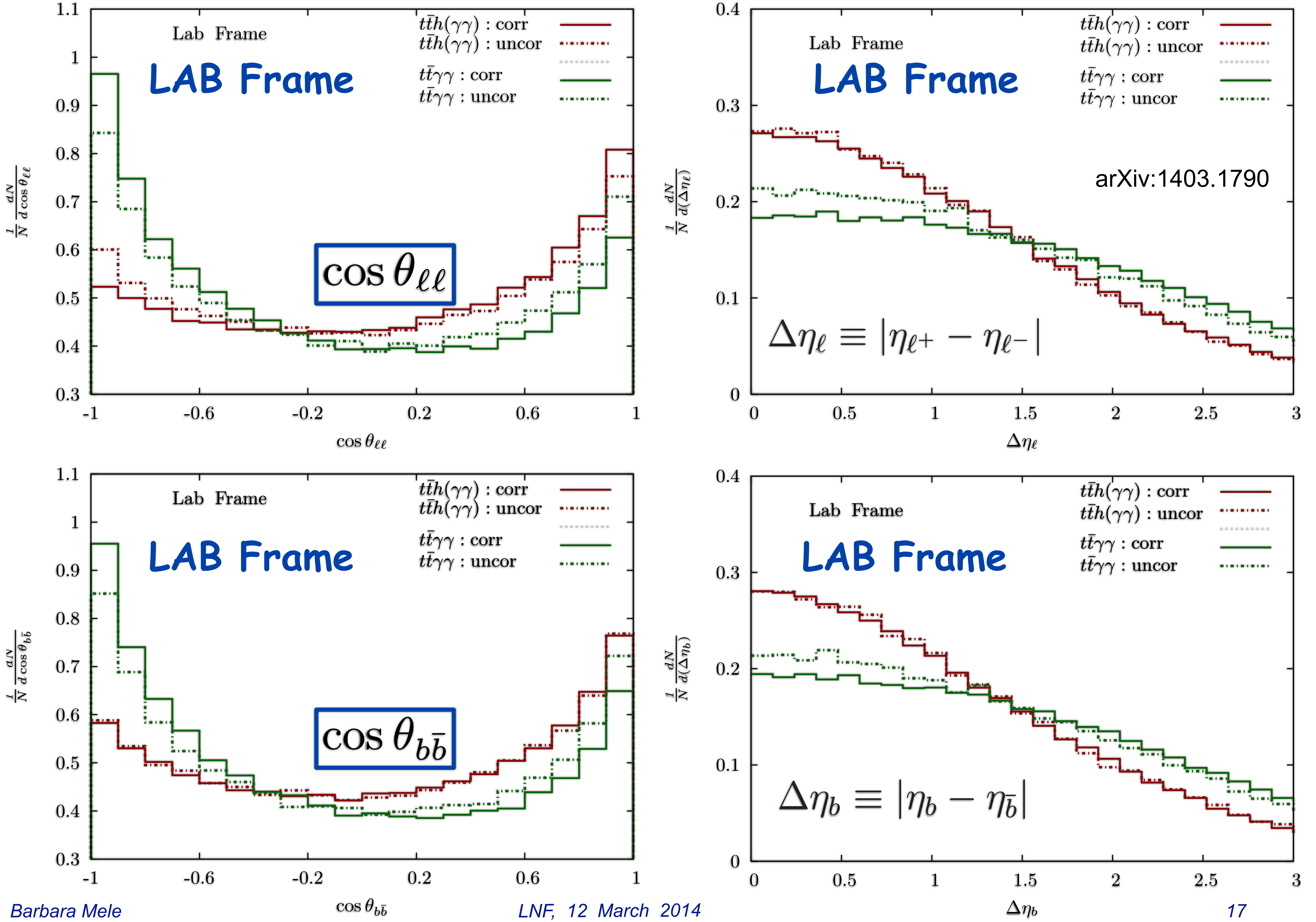
$\cos\vartheta_{bb}$ in $tt\gamma\gamma$ (Frame 1 [~2])

- not much gain (almost flat distributions !)

arXiv:1403.1790



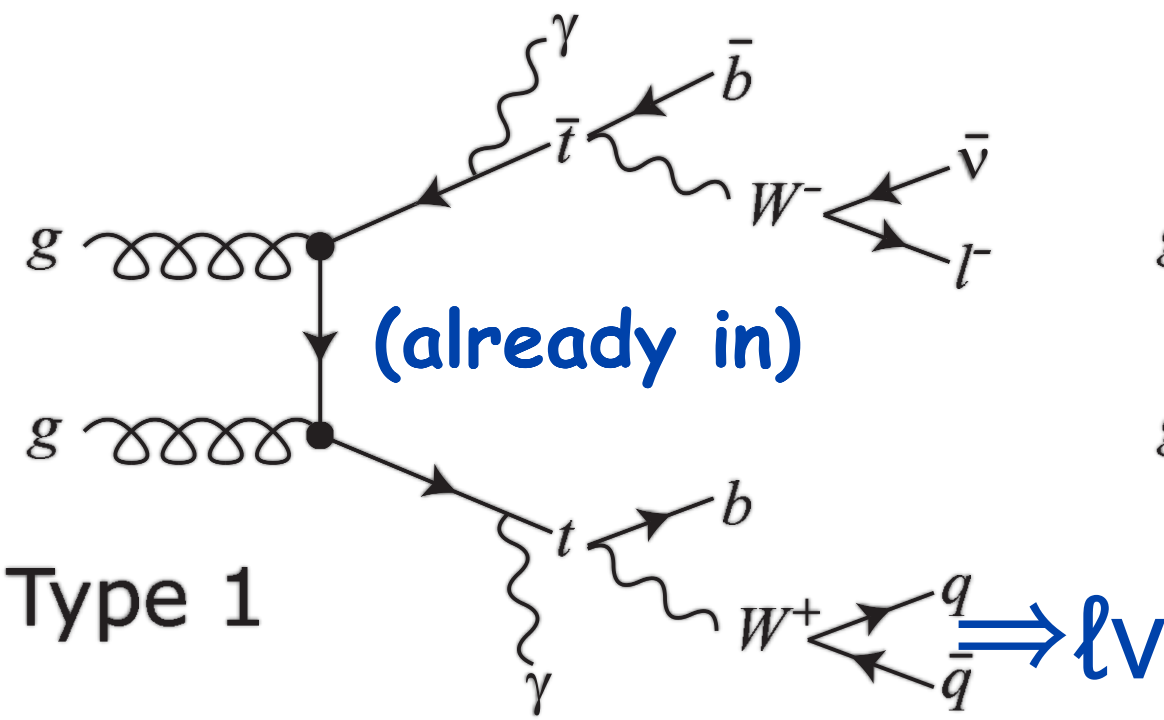
Lab frame (does not need top reconstruction !)



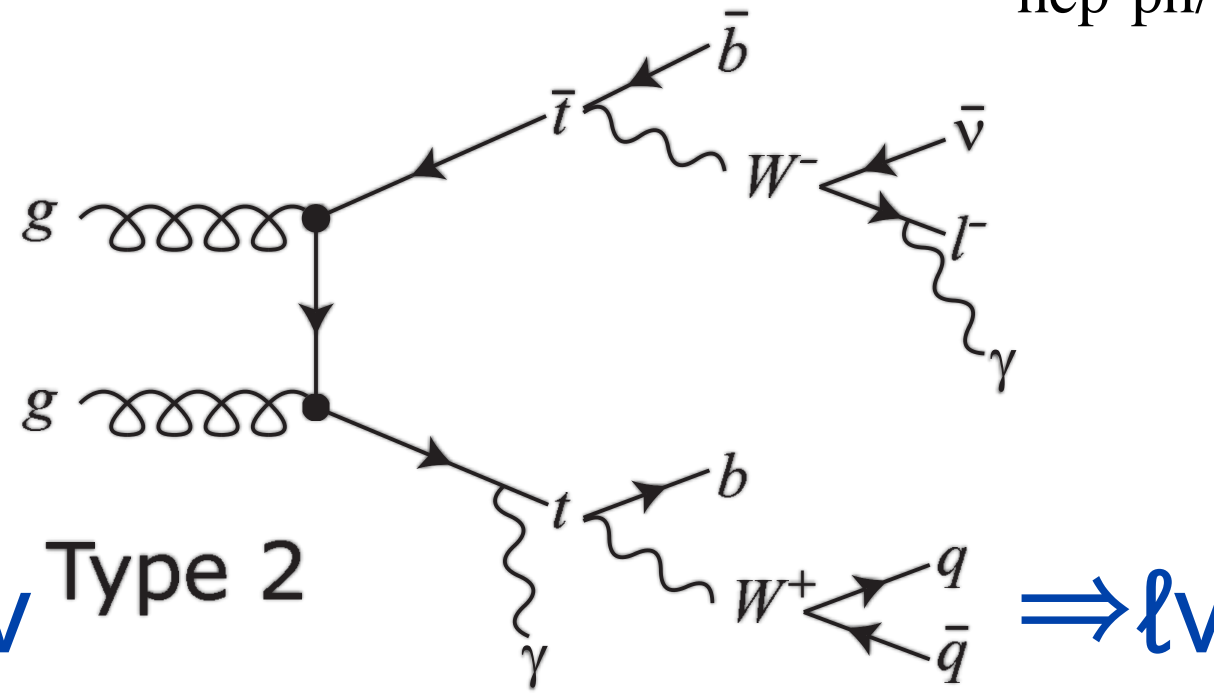
including γγ emission from tt decay products

- extra emission from charged $t\bar{t} \to l^+ \nu l^- \bar{\nu} b \bar{b}$ decay products

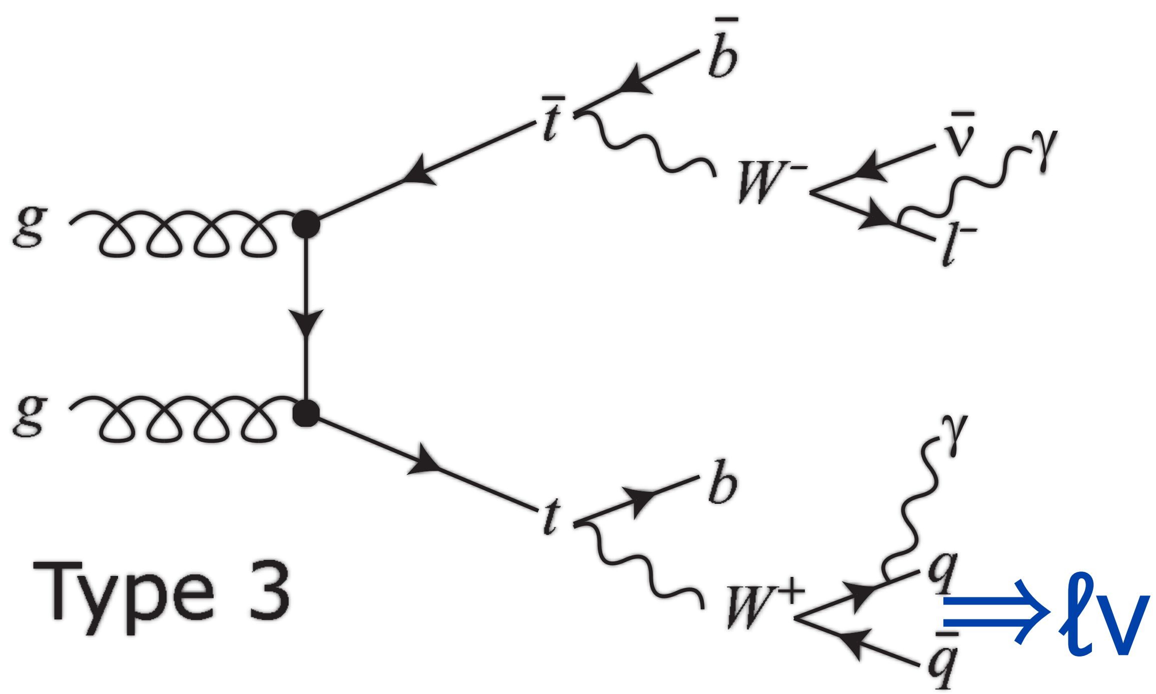
hep-ph/0604120



Type 1



Type 2



Type 3

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

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

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

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

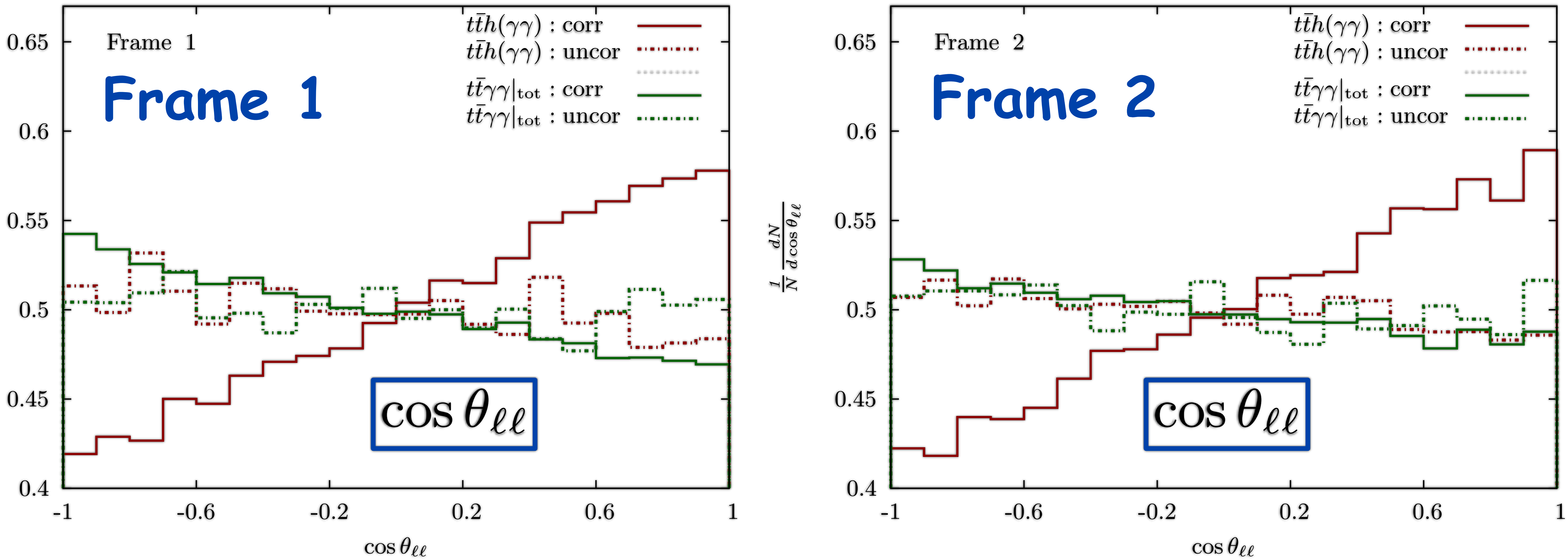
Warning

- extra photon emission from ttbar decay products could eventually be suppressed by requiring (m_{top}) invariant mass reconstruction of the top system

including γγ emission from tt decay products

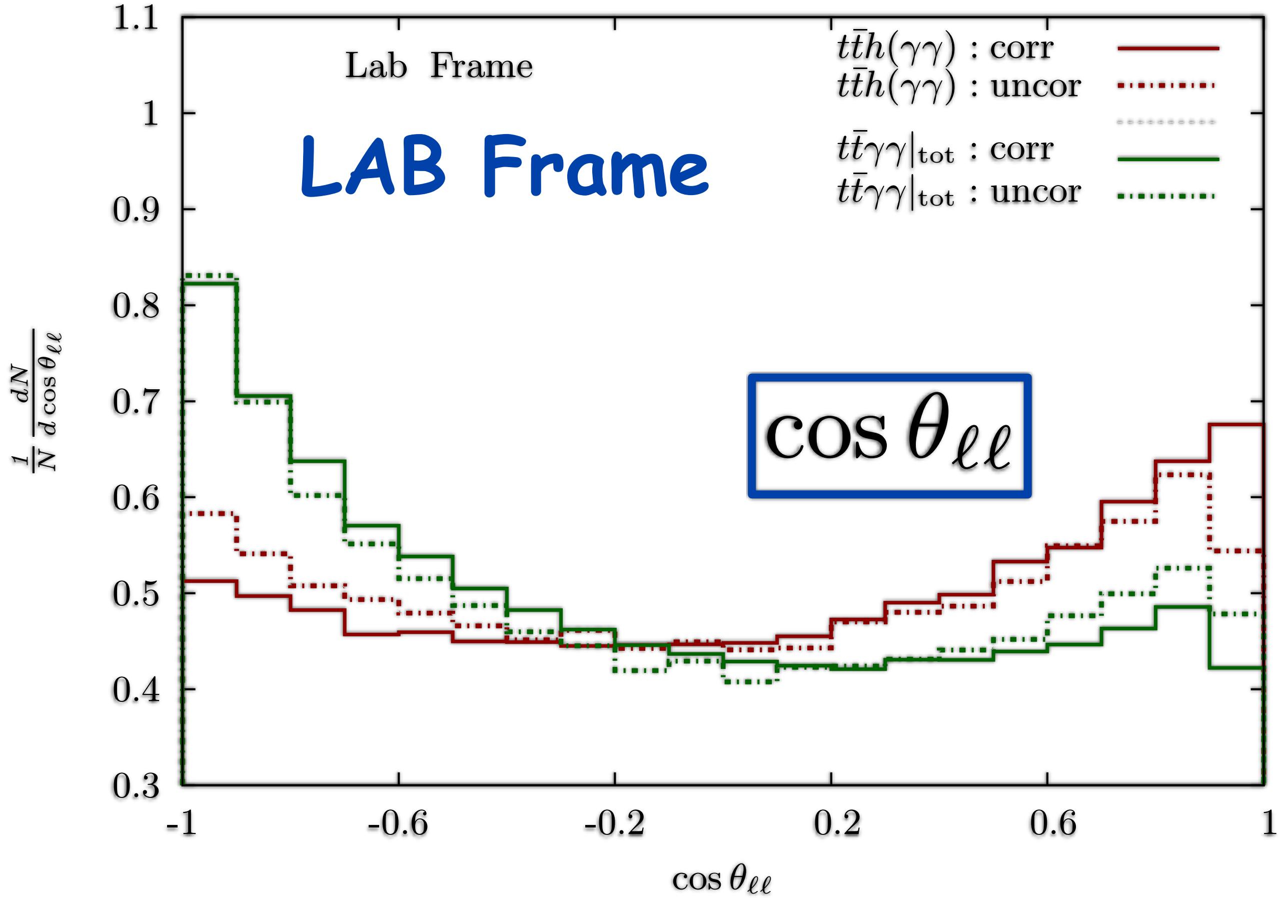
- cos $\vartheta_{\ell\ell}$ in tt γγ (Frame 1 and 2)

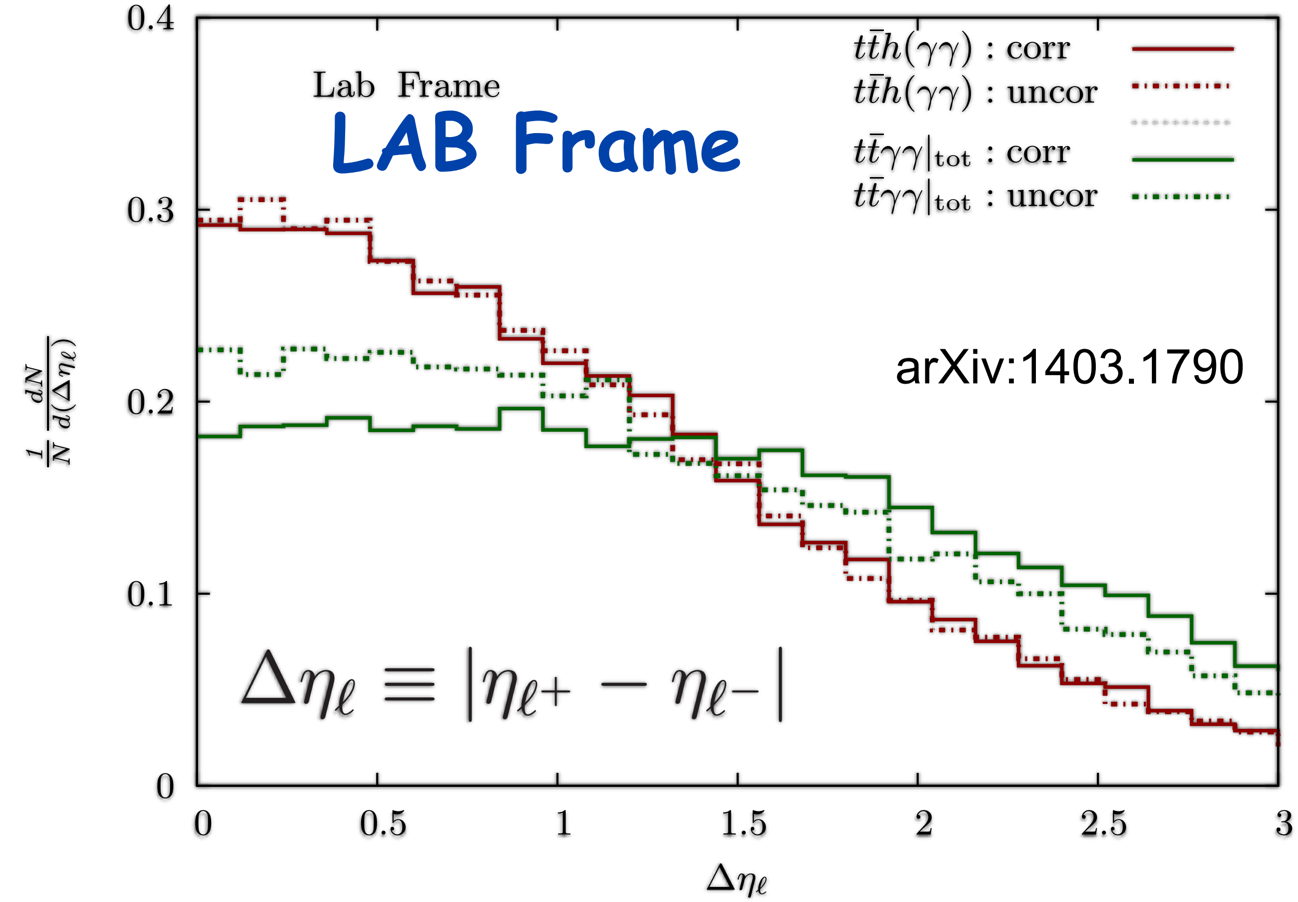
arXiv:1403.1790

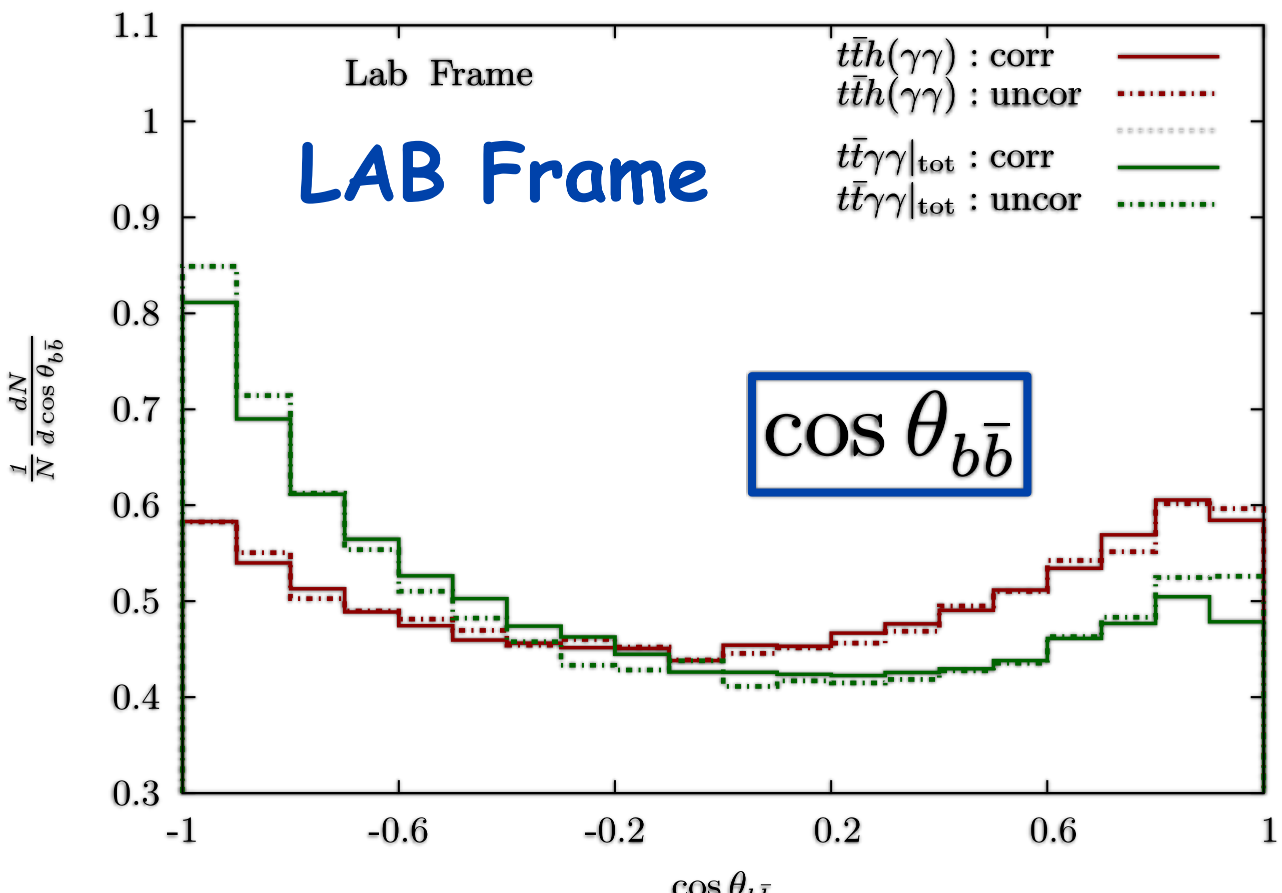


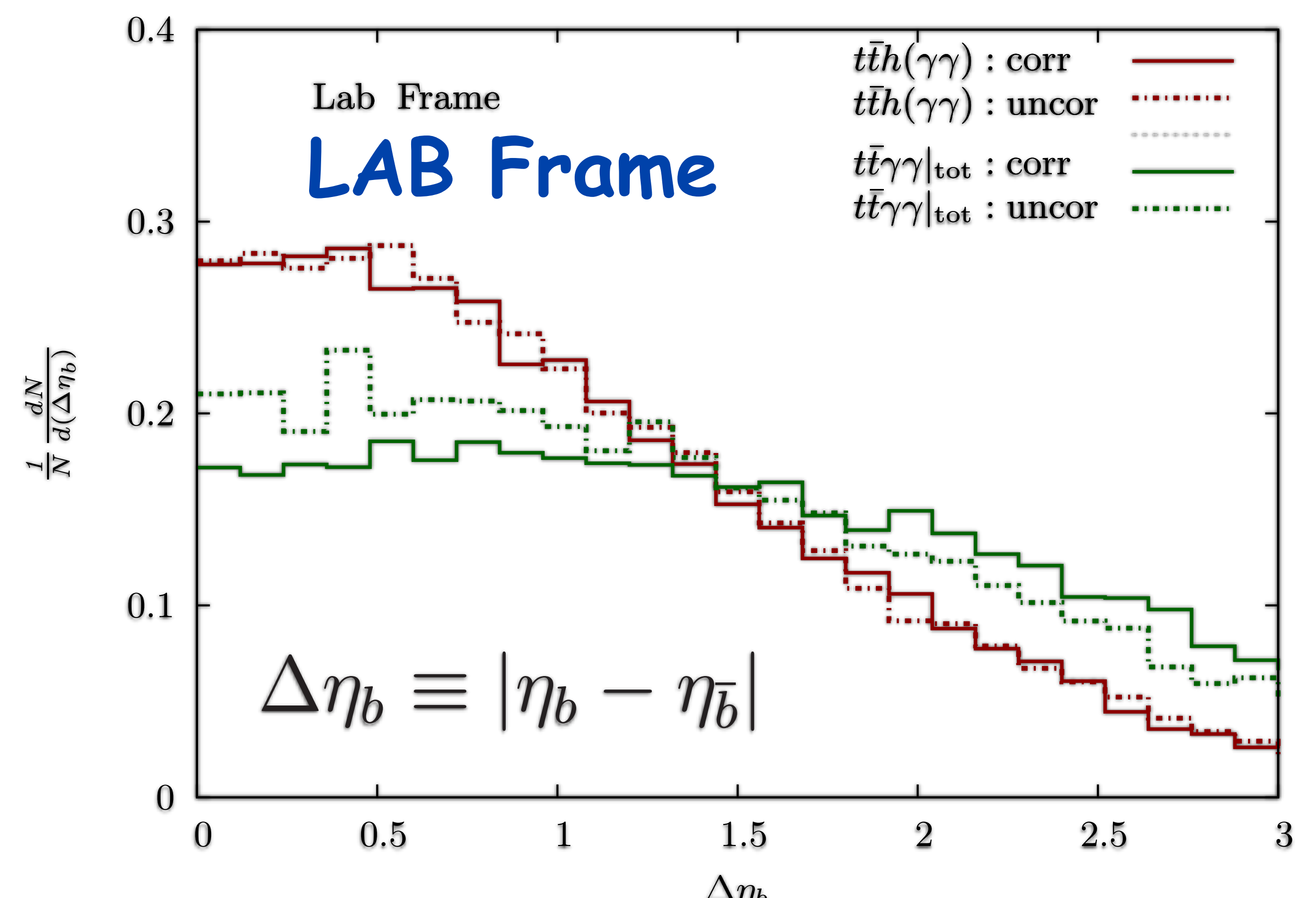
- tt γγ signal ~ unaffected
- Bckgd_{corr} gets closer to Bckgd_{uncor}

differences from extra emission at $\cos\theta_{\ell\ell}, \cos\theta_{b\bar{b}}$ ~±1 $\Delta\eta_\ell, \Delta\eta_b < 1$

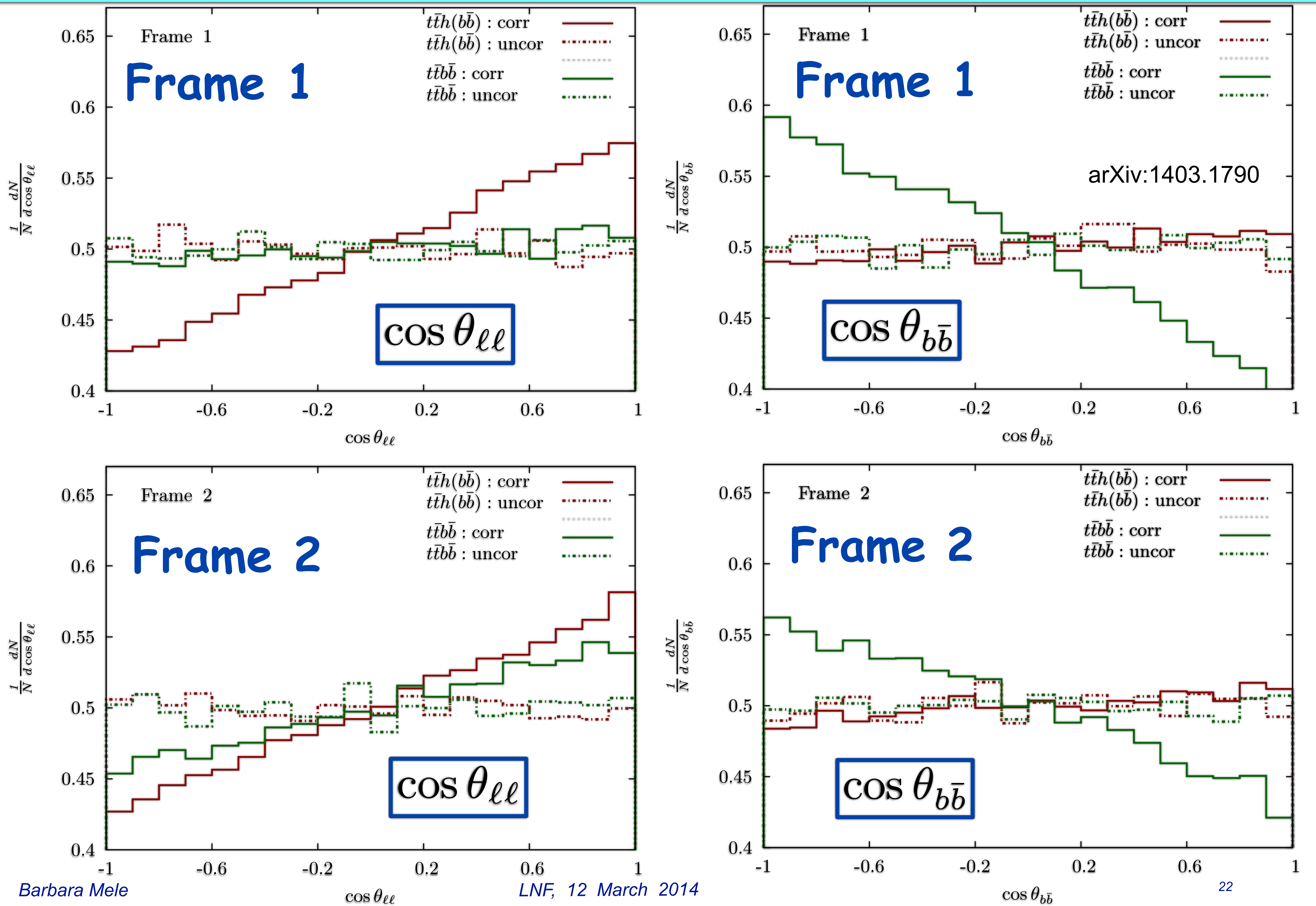




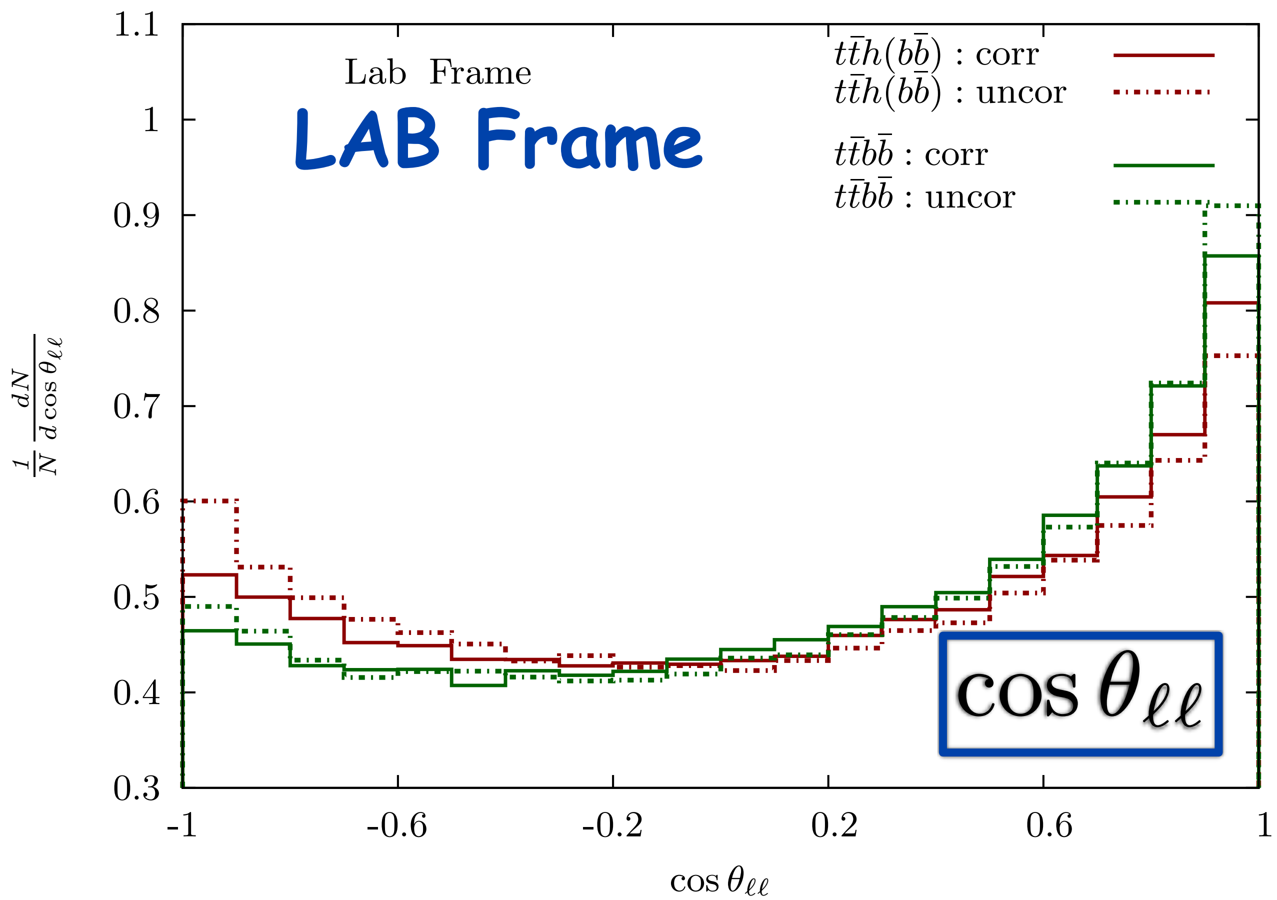


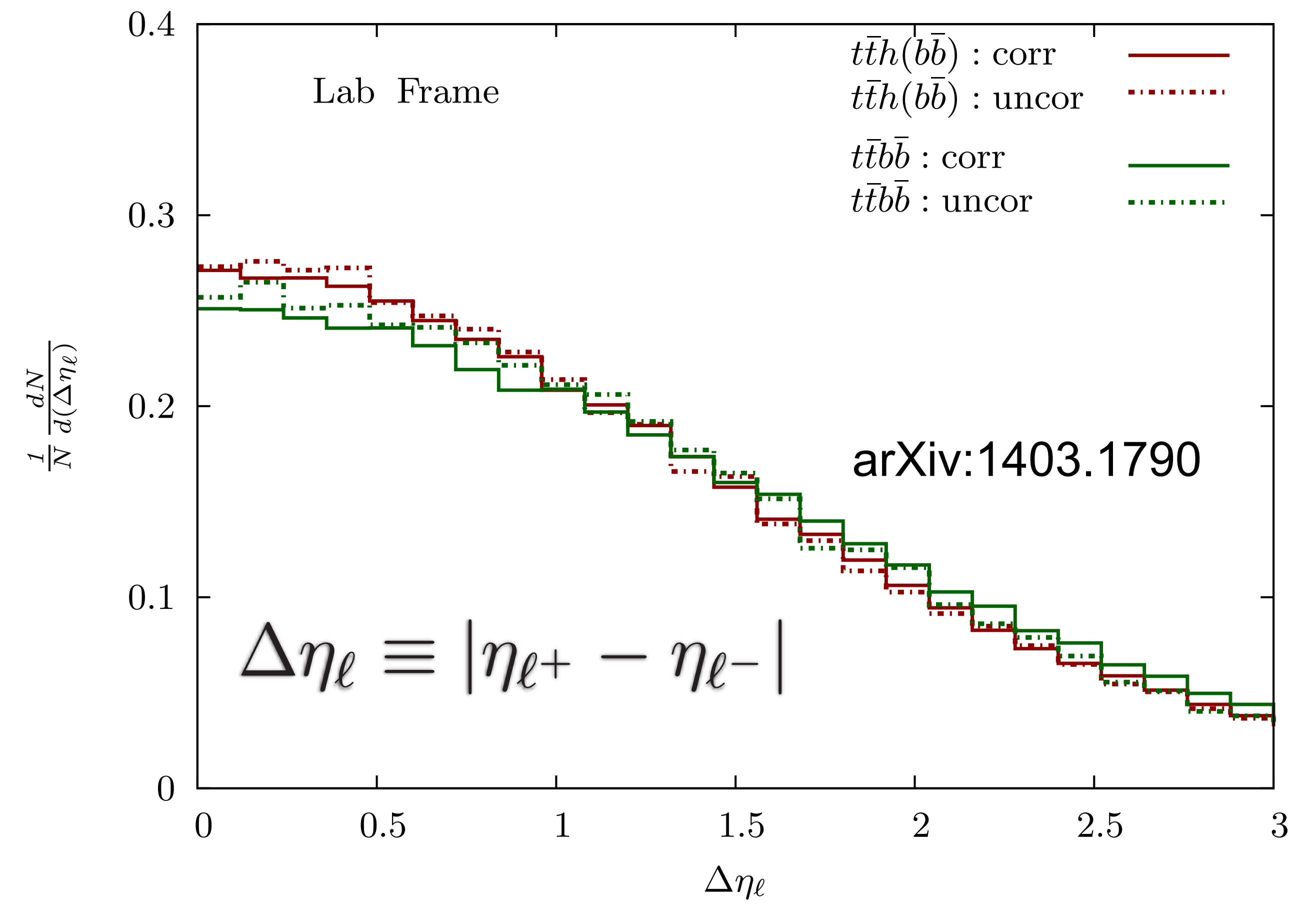


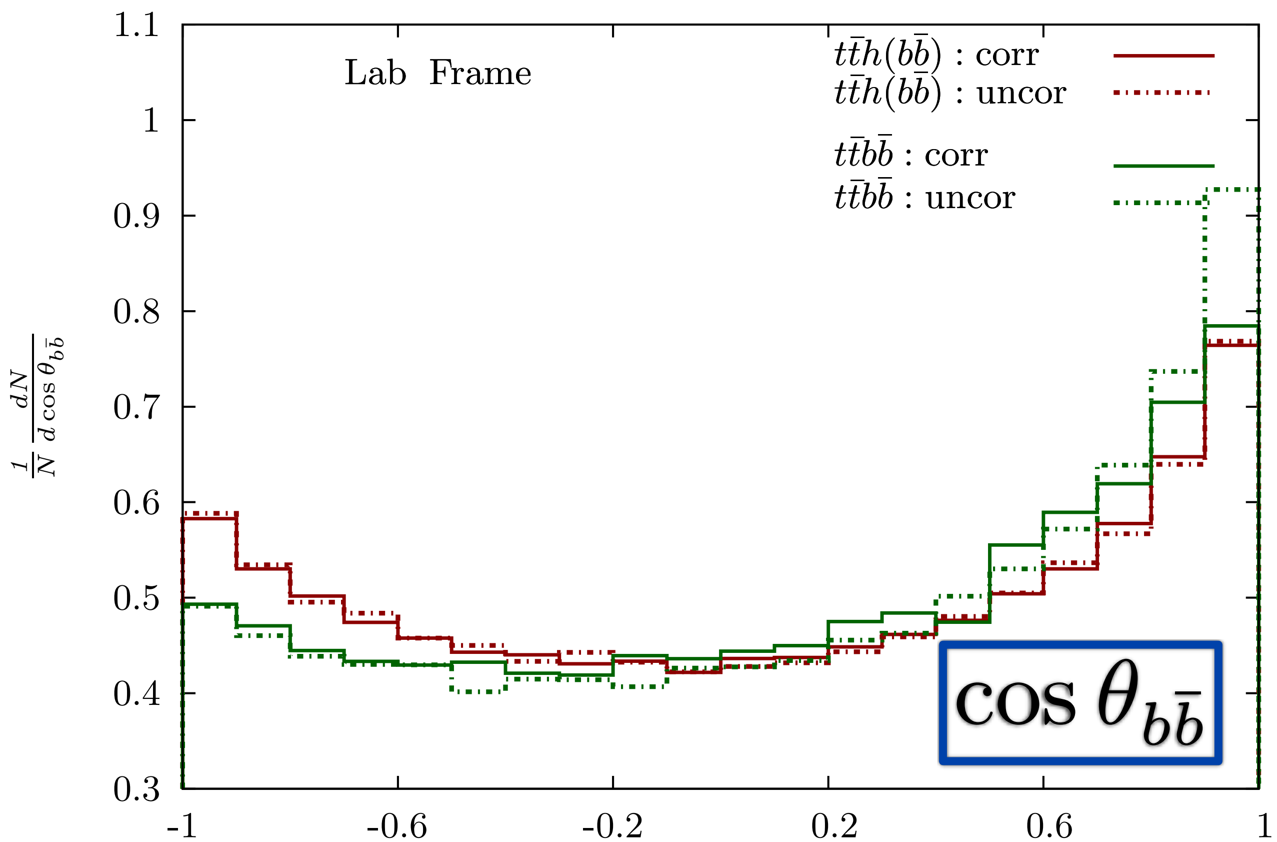
tt bb : cos ϑ ℓℓ and cos ϑ bb in Frame 1 and 2

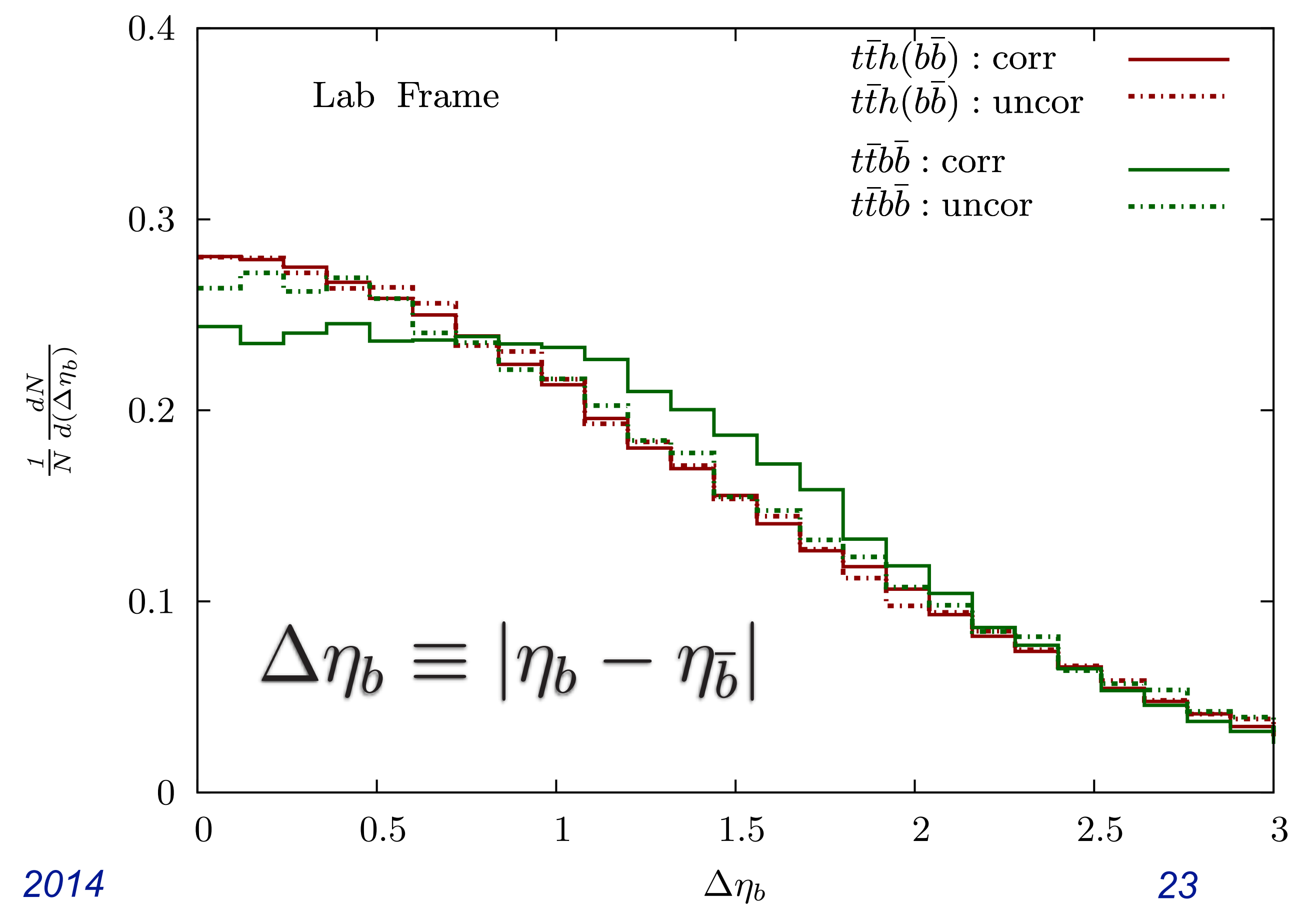


$t\bar{t}\,b\bar{b}$: $\cos\vartheta_{\ell\ell}$ and $\cos\vartheta_{bb}$ in Lab (S_{corr} and B_{corr} get closer !)





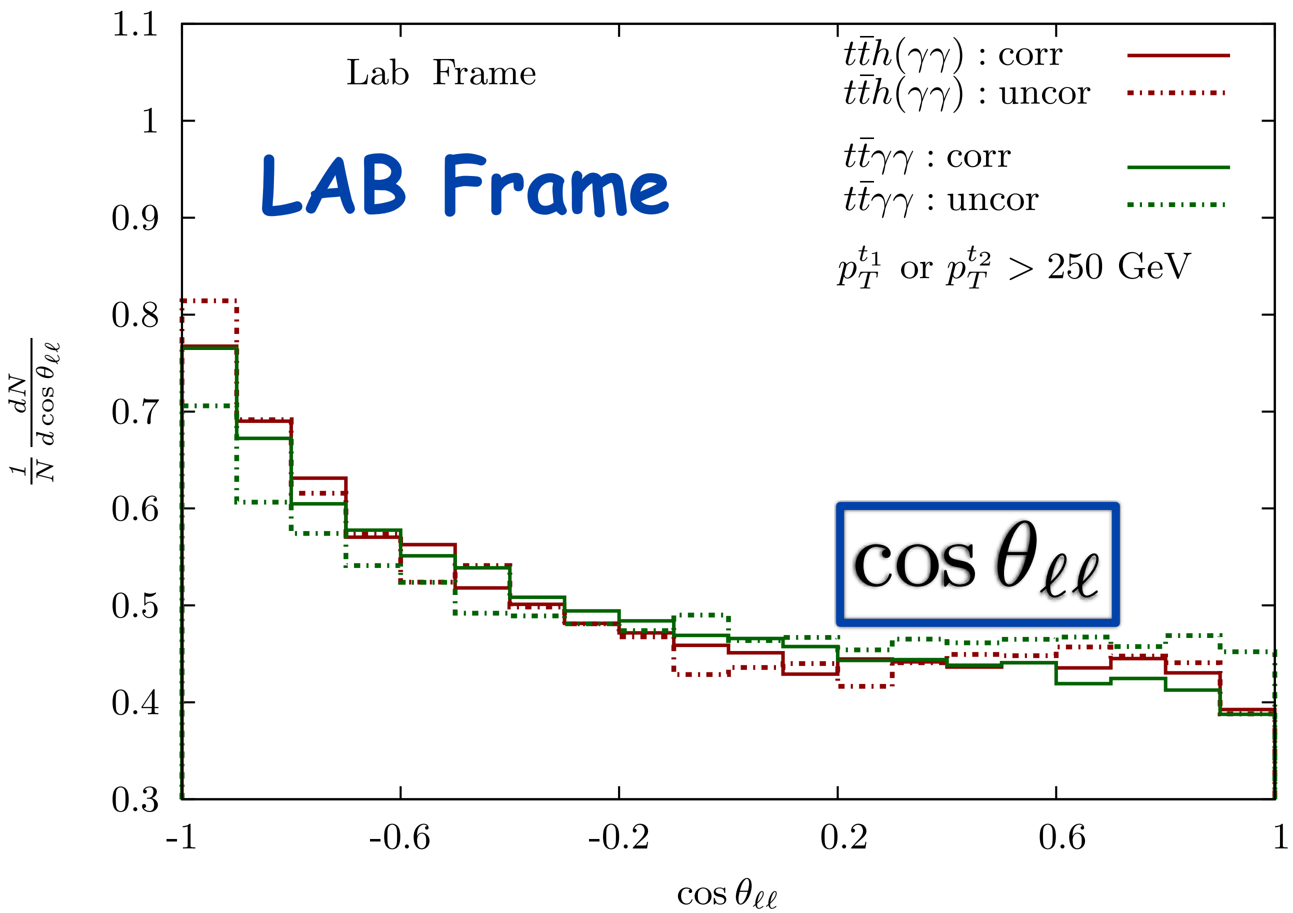


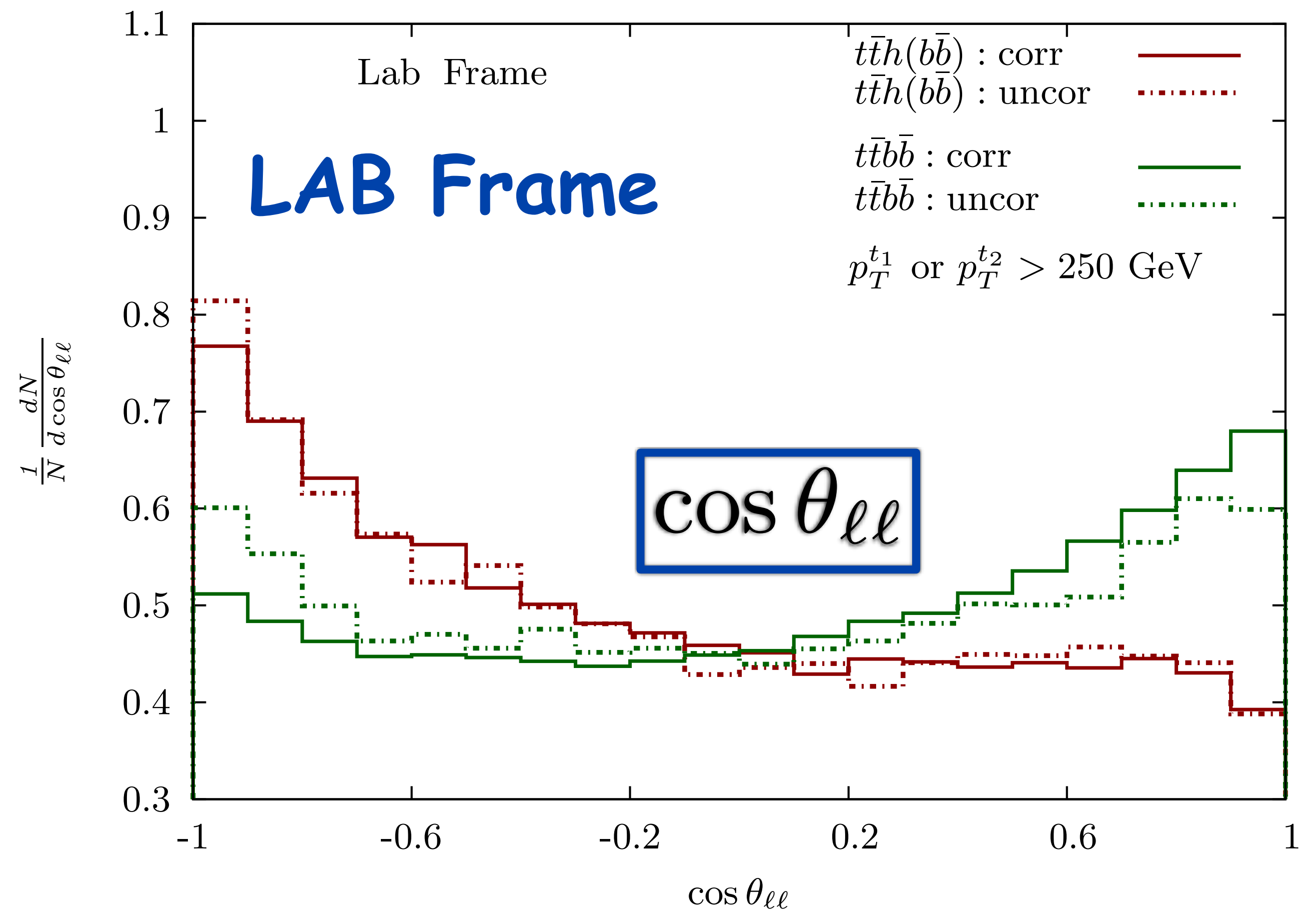


boosted tops (p_T>250 GeV)

tt $\gamma\gamma$ | tt bb

arXiv:1403.1790

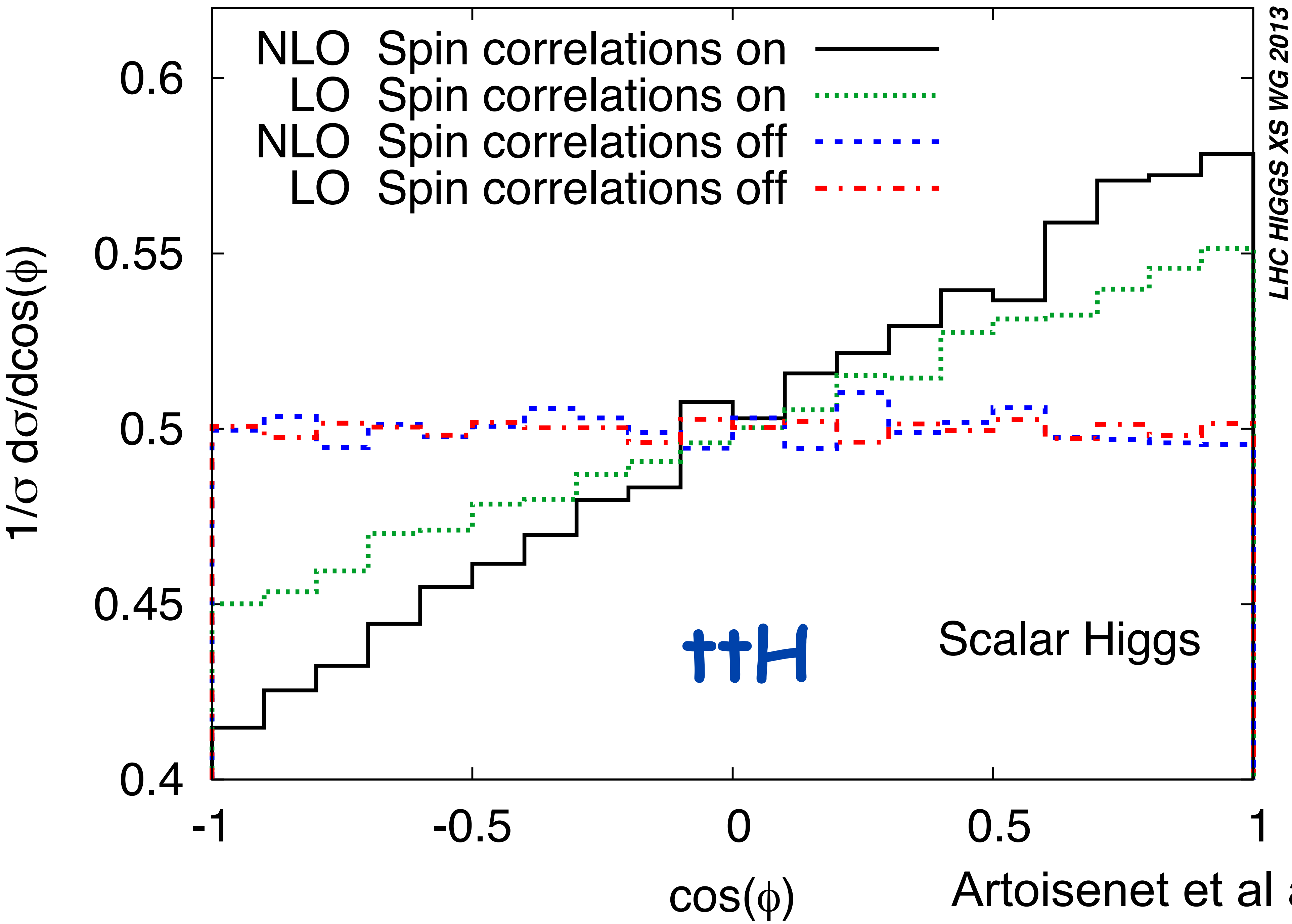




- requiring boosted tops increases lepton angular separation
- no gain in tt $\gamma\gamma$!
- S-vs-B separation improves for correlated tt bb !

NLO effects vs spin correlations in ttH

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



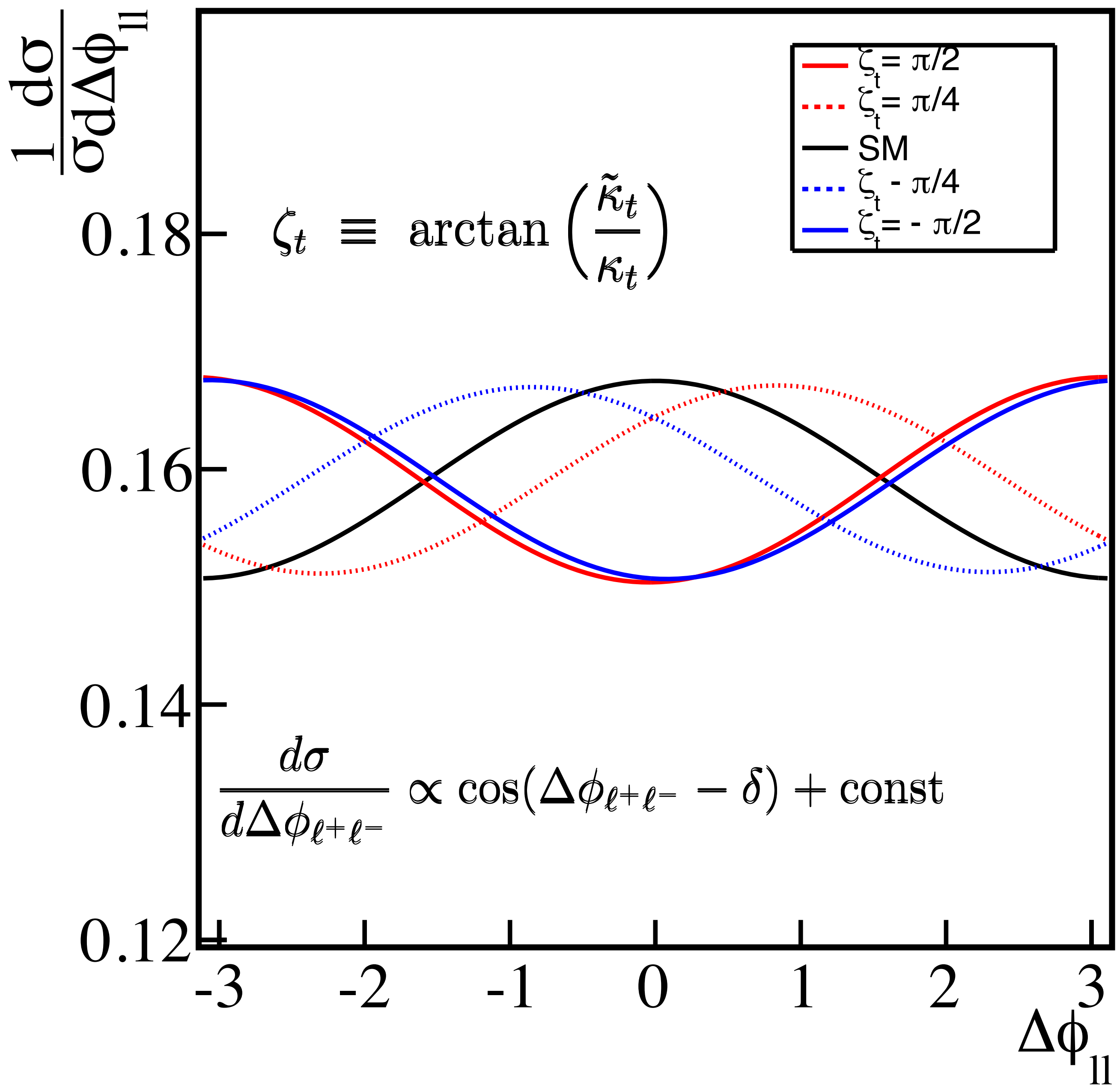
(Frame 2)

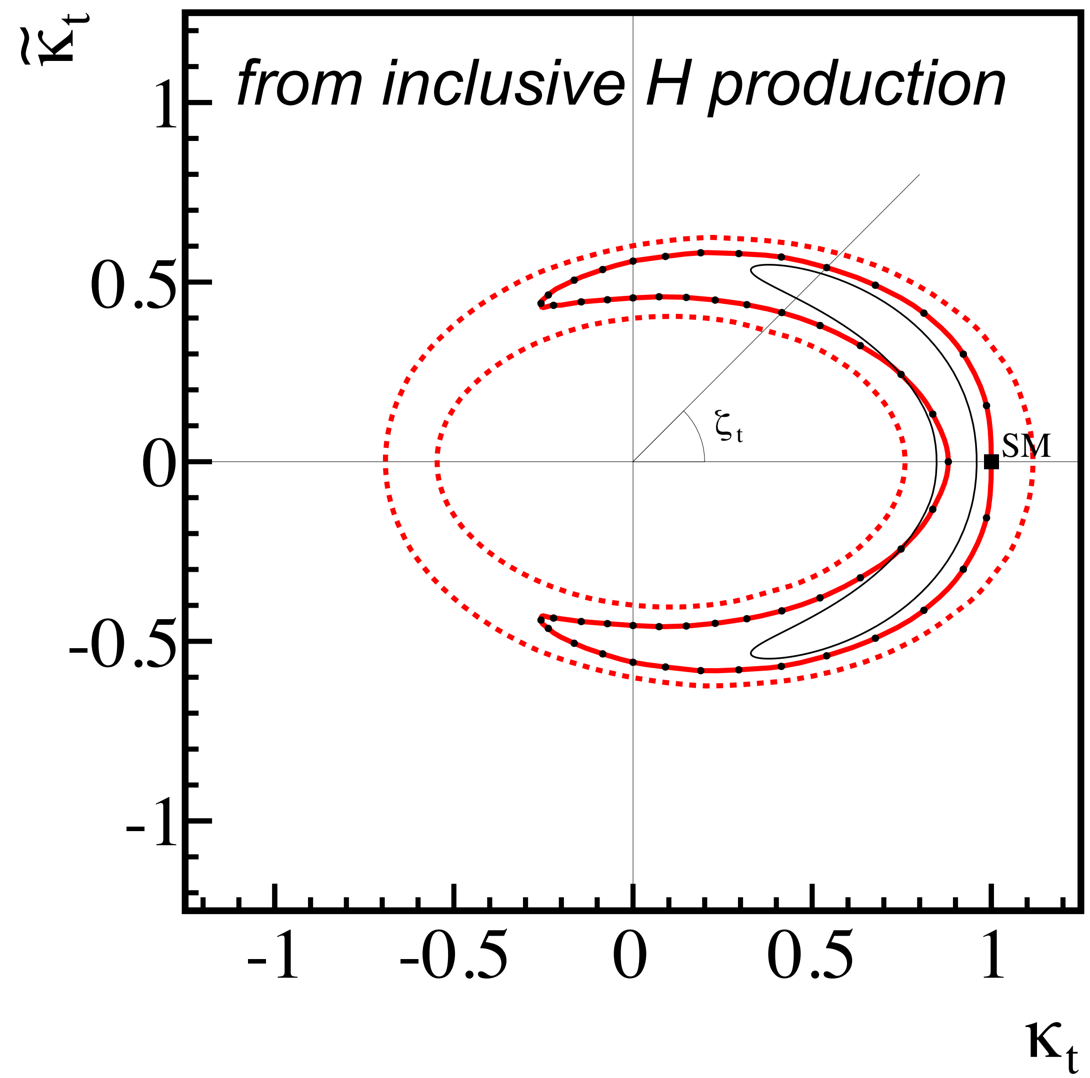
Artoisenet et al arXiv:1212.3460

CP violations vs spin correlations in ttH

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

Ellis et al. arXiv:1312.5736





- **gives information on both magnitude and sign of** $\frac{\tilde{\kappa}_t}{\kappa_t}$

Outlook

- 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 → tt$\gamma\gamma$, 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 !